Future of Heavy Flavour Physics
(on the occasion of 70th anniversary of Peter, Gentleman of Heavy Flavour !!!)

• Next 3-5 years: Prospects to discover New Physics (NP) in heavy flavours (Tevatron & LHCb)

• 2012-2020: If NP found at LHC what are the opportunities with heavy flavours?? Kaon experiments & SuperB & SuperLHCb Who is the best suited for what?

• If nothing but SM Higgs found at LHC ? νMSM could be an elegant solution to solve the problems of SM Prospects to search for O(1 GeV) neutrino in heavy flavor decays
Successes of the Standard Model

LEP, SLC, Tevatron and B-factories established that Standard Model really describes the physics at energies up to $\sqrt{s} \sim 200$ GeV.

State-of-art is given by UT:

- Accuracy of sides is limited by theory:

  Extraction of $|V_{ub}|$

  Calculation of $\xi^2 = \frac{\hat{B}_B f_{B_s}^2}{\hat{B}_B f_{B_d}^2}$

- Accuracy of angles is limited by experiment:

  $\sigma(\alpha) \sim 5^\circ$, $\sigma(\beta) \sim 1^\circ$, $\sigma(\gamma) \sim 20^\circ$

  $\phi_s (= 2\beta_s \text{ in SM})$ is not well measured!

  Hint for a large value (well beyond SM) from Tevatron

Standard Model is a precisely tested theory however does not provide the whole picture...

The quark sector is well described by the CKM mechanism.

- Neutrino mass & oscillations
- Dark matter
- Baryon asymmetry of the Universe
- Higgs mass divergence (Higgs is not found yet !!!)
LHC Physics Goals

Main Goals:
• Search for the SM Higgs boson in mass range \(115 < m_H < 1000\) GeV
• Search for New Physics beyond the SM

- Explore TeV-scale directly (ATLAS & CMS) and indirectly (LHCb)

<table>
<thead>
<tr>
<th></th>
<th>ATLAS CMS high (p_T) physics</th>
<th>BSM</th>
<th>Only SM</th>
<th>BSM</th>
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<tbody>
<tr>
<td>LHCb flavour physics</td>
<td>Only SM</td>
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<tr>
<td>Particle Physics</td>
<td>😊</td>
<td>😊</td>
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No space left for the 4\(^{th}\) possibility

Even if 4\(^{th}\) possibility → Measurements of virtual effects will set the scale of New Physics
The LHCb Experiment

- Advantages of beauty physics at hadron colliders:
  - High value of \( bb \) cross section at LHC:
    \[ \sigma_{bb} \sim 300 - 500 \, \mu b \text{ at } 10 - 14 \, \text{TeV} \]
    \((\text{e+e- cross section at } \Upsilon(4s) \text{ is } 1 \, \text{nb})\)
  - Access to all quasi-stable \( b \)-flavoured hadrons

- The challenge
  - Multiplicity of tracks (~30 tracks per rapidity unit)
  - Rate of background events: \( \sigma_{\text{inel}} \sim 100 \, \text{mb} \)

- LHCb running conditions:
  - Luminosity limited to \( \sim 2\times10^{32} \, \text{cm}^{-2} \, \text{s}^{-1} \) by not focusing the beam as much as ATLAS and CMS
    - Maximize the probability of single interaction per bunch crossing
      - At LHC design luminosity pile-up of >20 pp interactions/bunch crossing while at LHCb \( \sim 0.7 \, \text{pp interaction/bunch} \)
    - LHCb will reach nominal luminosity soon after start-up
  - 2fb\(^{-1}\) per nominal year (\(10^7\) s), \(\sim 10^{12} \, bb\) pairs produced per year
The LHCb Detector

Muon System

RICH Detectors
specific feature of LHCb

Vertex Locator
VELO

Movable device
35 mm from beam out of physics / 7 mm from beam in physics

pp collision Point

Calorimeters

Tracking System

~ 1 cm
**LHCb Trigger**

Trigger is crucial as $\sigma_{bb}$ is less than 1% of total inelastic cross section and B decays of interest typically have $BR < 10^{-5}$

- **Hardware level (L0)**
  - Search for high-$p_T$ $\mu$, $e$, $\gamma$ and hadron candidates

- **Software level (High Level Trigger, HLT)**
  - Farm with $O(2000)$ multi-core processors
  - **HLT1**: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts
  - **HLT2**: B reconstruction + selections

- **Storage**: Event size ~35kB

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon$(L0)</th>
<th>$\epsilon$(HLT1)</th>
<th>$\epsilon$(HLT2)</th>
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<tr>
<td>Electromagnetic</td>
<td>70 %</td>
<td>&gt; ~80 %</td>
<td>&gt; ~90 %</td>
</tr>
<tr>
<td>Hadronic</td>
<td>50 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>90 %</td>
<td></td>
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</table>
Ready for physics!
Main LHCb objective is to search for the effects induced by New Physics in CP violation and Rare decays using the FCNC processes mediated by loop (box and penguin) diagrams.

NP effects could be different in boxes and penguins → study different topologies separately!

\[ \Phi_s \neq \Phi_s^{SM} \]

Sensitivity to masses, couplings, spins and phases of New Particles
New Physics Search Strategy

- **Phases**
  CPV processes are the only measurements sensitive to the phases of New Physics e.g. measurements of $\beta$, $\beta_s$ & $\gamma$

- **Masses and magnitude of the couplings of new particles**
  Inclusive $BR(b \rightarrow s\gamma)$ indirectly constrains the scale of NP masses $\Lambda > 10^3$ TeV for generic coupling (flavour problem)

  Look at specific cases with enhanced sensitivity e.g. helicity suppression in $Bs \rightarrow \mu\mu$ decay gives increased sensitivity to SUSY with extended Higgs sector

- **Helicity structure of the couplings**
  Use the correlation between photon polarization and $b$ flavour in $b \rightarrow s\gamma$

  $b \rightarrow \gamma_L + (m_s/m_b) \times \gamma_R$

  $\phi\gamma$ produced in $B_s$ and $\bar{B}_s$ decays do not interfere

  $\Rightarrow$ corresponding CP asymmetry vanishes

  Significantly non-zero $A_{CP}$ indicates a presence of right-handed current in the penguin loop

  Similar study using $B \rightarrow K^*\mu^+\mu^- & K^*e^+e^-$
**CPV measurements: UT angles**

*Box diagrams (I)*

Note: UT geometry is such that the main constraint on NP comes from the comparison of the opposite elements i.e. angles vs sides

\[ \beta \quad \text{vs} \quad |V_{ub} / V_{cb}| \] is largely limited by theory (~10% precision in \(|V_{ub}|\))

Note a discrepancy in \(|V_{ub}|\) determined in inclusive and exclusive measurements: \(|V_{ub}|^{\text{incl}} \sim (4.0-4.9) \times 10^{-3} \) and \(|V_{ub}|^{\text{excl}} \sim (3.3-3.6) \times 10^{-3}\)

\[ \gamma \quad \text{vs} \quad \Delta m_d / \Delta m_s \] is limited by experiment: \( \gamma \) is poorly measured (± 20°)

**Indirectly, \( \gamma \) is determined to be \((68\pm5)°\)**

from processes involving boxes

LHCb will measure \( \gamma \) directly in tree decays using the global fit to the rates of \( B \to D^0K, \)
\( D^0K^* \) decays and time-dependent measurements with \( B_s \to D_s K \) and \( B^0 \to D \pi \) decays

**Expected \( \sigma(\gamma_{\text{trees}}) \approx 4° \) with 2 fb\(^{-1}\)**
CPV measurements: phase of $B_s$ mixing

- **Box diagrams (II)**

  $\phi_s^{J/\psi\phi} = -2\beta_s$ in SM is the $B_s$ meson counterpart of $2\beta$
  penguin contribution $\leq 10^{-3}$

  $\phi_s^{J/\psi\phi}$ is not presently well measured (indication of large value from CDF/D0)
  Theoretical uncertainty is very small

  $2\beta_s = -0.0368\pm0.0017$ (CKMfitter 2007)

- **LHCb prospects (2 fb$^{-1}$ sample)**
  Expected yield $117k B_s \rightarrow J/\psi\phi$ events
  $\sigma(\phi_s) \sim 0.03$

Other channels are under study e.g.
$B_s \rightarrow J/\psi f^0, f^0 \rightarrow \pi^+\pi^-$. Looks promising if this CP-eigenstate mode has BR indicated by CLEO
CPV measurements: phases in penguins

- Penguin diagrams:

\[
\phi_d(NP) = \phi_d^{Ks} - \phi_d^{J/\psi Ks} \\
\phi_s(NP) \approx \phi_s^{\phi} - \phi_s^{J/\psi \phi} = O(\text{a few degrees}) \text{ if NP !!!}
\]

Thanks to B-factories
\[
\phi_d(NP) \sim -0.23 \pm 0.18 \text{ rad}
\]

\[\phi_s(NP) \text{ not measured}\]

LHCb sensitivity with 2 fb\(^{-1}\) \(\sim 0.11\) rad
(stat. limited)
Rare Decays: couplings and their helicity structure

Current experiments are only now approaching an interesting level of sensitivity in exclusive decays:

- $BR (B_s \rightarrow \mu \mu)$ (CDF /D0)
- $BR (B_d \rightarrow \mu \mu)$
- Photon polarization in $B \rightarrow K^{*}\gamma$ (BELLE/BaBar)
- $A_{FB}$ in $B \rightarrow K^{*}\mu\mu$ (BELLE/BaBar)

LHCb will study rare decays in depth !!!
$B_s \rightarrow \mu\mu$

- Super rare decay in SM with well predicted $BR(B_s \rightarrow \mu\mu) = (3.55\pm0.33)\times10^{-9}$
- Sensitive to NP, in particular new scalars
  - In MSSM: $BR \propto \tan^6\beta / M_A^4$
- Present best limit is from Tevatron: $BR(B_s \rightarrow \mu\mu) < 4.3\times10^{-8}$ @ 90% CL
- For the SM prediction
  - LHCb expects 21 signal and 180 background events with 2 fb$^{-1}$. Background is dominated by muons from two different semileptonic $b$-decays
- LHCb sensitivity for the SM BR:
  - $3\sigma$ evidence with 3 fb$^{-1}$
  - $5\sigma$ observation with 10 fb$^{-1}$
Measurement of the photon polarization in $B_s \rightarrow \phi \gamma$ decay

- BaBar & BELLE used CPV analysis in $B \rightarrow K^*(K^0\pi^0)\gamma$ decay

\[ \sigma \left( \frac{A(B \rightarrow f_{CP} \gamma_R)}{A(B \rightarrow f_{CP} \gamma_L)} \right) \sim 0.16 \ (HFAG) \]

(~0.03 within SM due to $m_s/m_b$ and gluon effects)

- CPV analysis in the $B_s \rightarrow \phi \gamma$ decay can be performed without flavour tagging

\[
\Gamma(B_q(\bar{B}_q) \rightarrow f_{CP} \gamma) \propto e^{-\Gamma_q t} \left( \cosh \frac{\Delta \Gamma_q t}{2} - A^{\Delta} \sinh \frac{\Delta \Gamma_q t}{2} \pm \right.
\]

\[
\left. \pm C \cos \Delta m_q t \mp S \sin \Delta m_q t \right) .
\]

**SM:**

- $C = 0$ direct CP-violation
- $S = \sin 2\psi \ \sin \phi_s$
- $A^\Delta = \sin 2\psi \ \cos \phi_s$

\[
\tan \psi \equiv \left| \frac{A(\bar{B} \rightarrow f_{CP} \gamma_R)}{A(B \rightarrow f_{CP} \gamma_L)} \right|
\]

- Expected signal yield at LHCb is 11k for 2 fb$^{-1}$

**Sensitivity:** $\sigma \left( \frac{A(B \rightarrow f_{CP} \gamma_R)}{A(B \rightarrow f_{CP} \gamma_L)} \right) = 0.11$ for 2fb$^{-1}$
$B \rightarrow K^*\mu\mu$

In SM this $b \rightarrow s$ penguin decay contains well calculable right-handed contribution but corresponding angular distributions could be modified by NP

Forward-backward asymmetry $A_{FB}(q^2=m_{\mu\mu}^2)$ is of particular interest at zero-point, since dominant theor. uncert. from hadronic form-factors cancels at LO

Intriguing indications from B-factories:

Belle: 657 million BBbars analysed
~250 $K^{*+}\mu^+\mu^-$ events

BaBar: 384 million BBbars analysed
~100 $K^{*+}\mu^+\mu^-$ events

$A_{FB}$ at B-factories is defined with opposite sign to LHCb
**B → K*μμ**

LHCb expects ~7k events / 2fb\(^{-1}\) with B/S ~ 0.2. After 2 fb\(^{-1}\) zero of \(A_{FB}\) will be located to ±0.5 GeV\(^2\). Full angular analysis gives even better discrimination between NP models.

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More on photon polarization using \(B \rightarrow K^{*}\text{ee}\):

- Contribution not coming from virtual photons can be neglected at low \(q^2 < (1 \text{ GeV})^2\) → \(B_d \rightarrow K^{*0}e^+e^-\) with electrons in the final state can be used to measure photon polarization complementary to \(B_s \rightarrow \phi\gamma\)

- Expected LHCb yield with 2 fb\(^{-1}\): ~ 200 – 250 events with B/S ~ 1

**Expected sensitivity** \(\sigma(A(B \rightarrow f^{CP} \gamma_R)/A(B \rightarrow f^{CP} \gamma_L)) \approx 0.1\) limited by statistics and comparable to \(B_s \rightarrow \phi\gamma\) accuracy
LHCb key measurements  
(to search for NP in CP violation and Rare Decays)

Key Measurements

- In CP – violation
  - $\phi_s$
  - $\gamma$ in trees
  - $\gamma$ in loops

- In Rare Decays
  - $B_s \rightarrow \mu\mu$
  - $B \rightarrow K^*\mu\mu$
  - Polarization of photon

Accuracy in 1 nominal year  
(2 fb$^{-1}$)

- $\phi_s$  
  - 0.03

- $\gamma$ in trees  
  - 4°

- $\gamma$ in loops  
  - 7°

Measurements highlighted in red will become competitive first
**LHCb key measurements**  
(to search for NP in CP violation and Rare Decays)

### Key Measurements

- **In CP – violation**
  - $\phi_s$  
  - $\gamma$ in trees  
  - $\gamma$ in loops

- **In Rare Decays**
  - $B \to K^{*}\mu\mu$  
  - $B_s \to \mu\mu$  
  - Polarization of photon  

### Sensitivity with 10 fb$^{-1}$

(few years of data taking)

- $\phi_s$  
  - $0.01$  
- $\gamma$ in trees  
  - $\sim 2^\circ$  
- $\gamma$ in loops  
  - $\sim 3^\circ$  

- $B \to K^{*}\mu\mu$  
  - $\sigma(s0) = 0.28$ GeV$^2$

- $B_s \to \mu\mu$  
  - $5\sigma$ measurement down to SM prediction

- Polarization of photon  
  - $\sigma(H_R/H_L) = 0.03$ (in $B_s \to \phi\gamma$ & $B_d \to K^{*}\mu^\+\mu^-$)
If NP is discovered at LHC within a few years (LHCb will analyze a data sample of about 10 fb$^{-1}$) the NP models should be studied.

What will be the possibilities in heavy flavor physics: (to measure experimental observables not limited by theoretical uncertainties)

- SuperLHCb is being planned in order to collect a data sample of ~ 100 fb$^{-1}$ at LHC

- SuperB (and gradually SuperKEKB) factory is being planned to get 75 ab$^{-1}$

- Kaon experiments KOTO & NA62 to measure super rare $K \rightarrow \pi\nu\nu$ decays

Who is best suited for what?
Super LHCb
(\(\sim100 \text{ fb}^{-1}\))

*Unique for:*

- study of \(B_s\) sector
- gives access to all \(b\)-hadrons
CP Violation

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Improvement with 100 fb⁻¹?</th>
</tr>
</thead>
<tbody>
<tr>
<td>with 10 fb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

NP in boxes:

- $\phi_s$ is the most sensitive measurement
  - $\sigma(\phi_s) \sim 0.01$
  - Yes (theor. uncert. 0.002)

NP in penguins:

- Probably the best sensitivity:
  - $\phi_s$ in $B_s \rightarrow J/\psi\phi$
    - vs $B_s \rightarrow \phi\phi$
    - $\sigma(\phi_s(NP)) \sim 0.05$
  - or $\phi_d$ in $B \rightarrow J/\psi K_s$
    - vs $B \rightarrow \phi K_s$
    - $\sigma(\phi_d(NP)) \sim 0.1$

In addition, $\gamma$ will be measured to a precision of $\sim2^\circ$ with 10 fb⁻¹ data sample.
Rare Decays

NP in penguins

- Photon polarization in $B_s \to \phi \gamma$ decay:
  - Sensitivity with 10 fb$^{-1}$: $\sigma(H_R/H_L) = 0.03$
  - Improvement with 100 fb$^{-1}$?

NP in a mixture of loop diagrams:

- $B \to K^*\mu\mu$
- $B_s \to \phi\mu\mu$
  - $\sigma(s0) \sim 0.3$ GeV$^2$
  - Already very rich choice of observables, e.g. $A_T^3$, $A_T^4$ etc…

- $B_s \to \mu\mu$
  - $>5\sigma$ observation if SM

Charm Physics

- Measured CP asymmetries approach SM prediction

LVF in $\tau$ decays

- $BR(\tau \to 3\mu) < 10^{-8}$
- Using $\tau$ from $D_s \to \tau\nu$

There could be great possibilities to be explored!
Super B-factory
(I do not distinguish here between SuperB & SuperKEKB)

**Unique for:**

- $V_{ub}$ determination (one of the two observables, which can be measured in trees)

- Study of rare decays with neutrinos and neutrals in the final states
$B \rightarrow \tau \nu_\tau$ decay

- Within the SM, sensitive to $f_B$ and $|V_{ub}|$: $B_{SM} \sim 1.6 \times 10^{-4}$.
- $B$ affected by new physics.
  - MFV models like 2HDM / MSSM.
  - Unparticles.
- Fully reconstruct the event (modulo $\nu$).

$$B_{SM}(B^+ \rightarrow l^+ \nu_l) = \frac{G_F^2 m_B m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

![Graph showing the relationship between $B_{WA}$ and $E_{ECL}$](image_url)

![Diagram of 2HDM](image_url)
At Super B factory exclusive $b \rightarrow u$ transitions will be measured in the whole $q^2$ interval → $V_{ub}$ can be extracted with minimal theoretical uncertainty!
**SuperB physics**

**B_d physics @Y(4S)** in tables

<table>
<thead>
<tr>
<th>Observable</th>
<th>B factories (2 ab^{-1})</th>
<th>SuperB (75 ab^{-1})</th>
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<tbody>
<tr>
<td>sin(2β) / (J/ψ K^0)</td>
<td>0.018</td>
<td>0.005 (+)</td>
</tr>
<tr>
<td>cos(2β) / (J/ψ K^0)</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>sin(2β) / (DK^0)</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>cos(2β) / (DK^0)</td>
<td>0.20</td>
<td>0.04</td>
</tr>
<tr>
<td>S(J/ψ π^0)</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>S(D^+π^-)</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>S(ωK^0)</td>
<td>0.13</td>
<td>0.03 (+)</td>
</tr>
<tr>
<td>S(κ^0)</td>
<td>0.05</td>
<td>0.01 (+)</td>
</tr>
<tr>
<td>S(K_{2}^0K_{2}^0)</td>
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<td>0.02 (+)</td>
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<tr>
<td>S(K_{2}^0π^0)</td>
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<td>0.02 (+)</td>
</tr>
<tr>
<td>S(ωK^0)</td>
<td>0.17</td>
<td>0.03 (+)</td>
</tr>
<tr>
<td>S(K_{0}K_{0}^*)</td>
<td>0.12</td>
<td>0.02 (+)</td>
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<table>
<thead>
<tr>
<th>Channel</th>
<th>Sensitivity</th>
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</thead>
<tbody>
<tr>
<td>D^0 \to c^+c^-</td>
<td>1 \times 10^{-3}</td>
</tr>
<tr>
<td>D^0 \to \mu^+\mu^-</td>
<td>1 \times 10^{-2}</td>
</tr>
<tr>
<td>D^0 \to \nu \tau</td>
<td>1 \times 10^{-3}</td>
</tr>
<tr>
<td>D^0 \to \pi^+\pi^-</td>
<td>1 \times 10^{-3}</td>
</tr>
<tr>
<td>D^0 \to \pi^+\pi^-</td>
<td>1 \times 10^{-3}</td>
</tr>
<tr>
<td>D^0 \to K^+K^-</td>
<td>1 \times 10^{-3}</td>
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<tr>
<td>D^0 \to K^+K^-</td>
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<td>1 \times 10^{-3}</td>
</tr>
<tr>
<td>D^0 \to K^+K^-</td>
<td>1 \times 10^{-3}</td>
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</table>

**τ physics**

<table>
<thead>
<tr>
<th>Process</th>
<th>Sensitivity</th>
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<tbody>
<tr>
<td>B(τ → μγ)</td>
<td>2 \times 10^{-5}</td>
</tr>
<tr>
<td>B(τ → eγ)</td>
<td>2 \times 10^{-5}</td>
</tr>
<tr>
<td>B(τ → μμμ)</td>
<td>2 \times 10^{-10}</td>
</tr>
<tr>
<td>B(τ → eee)</td>
<td>2 \times 10^{-10}</td>
</tr>
<tr>
<td>B(τ → μγ)</td>
<td>4 \times 10^{-10}</td>
</tr>
<tr>
<td>B(τ → eγ)</td>
<td>6 \times 10^{-10}</td>
</tr>
</tbody>
</table>

**+ τ FC physics (CPV, ...)**

**+B_s physics @Y(5S)**

**SuperB**

a "treasure chest" of new physics-sensitive observables
Kaon experiments
(KOTO & NA62)

( Crucial element: super high intensity proton beams )

Unique for:

- Measurements of the super rare $K \rightarrow \pi \nu \nu$ decays mediated by loop diagrams (penguin & box)

- Improve predictive power of the Unitarity Triangle test (by releasing some QCD uncertainties)

- Rate is very sensitive to non-SM contributions
$K \rightarrow \pi \nu \nu$ decays

- Receive EW loop contribution from boxes and penguins

- Strongly suppressed ($BR \sim 10^{-11}$) and reliably calculated in SM

NLO Calculation:
Misiak, Urban: 1999

$\lambda = V_{cs}, \lambda_c = V_{cs}^*V_{cd}, \lambda_t = V_{ts}^*V_{td}$

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ \cdot \left[ \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda_t}{\lambda^5} X(x_t) + \frac{\text{Re} \lambda_c}{\lambda} P_c(X) \right)^2 \right]$  

$B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = \kappa_L \cdot \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2$

$\kappa_+ = r_{K^+} \cdot \frac{3\alpha^2 Br(K^+ \rightarrow \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \cdot \lambda^8$

charm contribution

NNLO
Buras, Gorbahn, Haisch, Nierste
hep-ph/0508165
PRL 95
E14: K0 at TOkai
for $K_L \rightarrow \pi^0 \nu \bar{\nu}$

- new beamline
- Move and modify E391a detector
  - CsI calorimeter (KTeV crystals)
  - readout: waveform digitization
- photon veto in the beam

(a long Japanese musical instrument (zither) with thirteen strings)
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ “3 $\sigma$” discovery

Branching Ratio

- KEK E391a
- New Physics
- SM
- Step 1
- Step 2

- Grossman-Nir limit
- Standard Model

KOTO goal
- 2E14 pps
- 3 Snowmass years

PoT

10% intensity one month
decay in flight to $\pi^+$ plus “nothing”

**Particle ID**

75 GeV/c
800 MHz beam
$\pi/K/p$ (unseparated)
$x50$ K+ flux of NA48/2
Background rejection

- timing
- tracking
- veto

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal: $K^* \rightarrow \pi^+ \nu \bar{\nu}$ [$\text{flux} = 4.8 \times 10^{12}$ decay/year]</td>
<td>55 events/year</td>
</tr>
<tr>
<td>$K^* \rightarrow \pi^+ \pi^0$ [$\eta_{ud} = 2 \times 10^{-8}$ (3.5$\times$10$^{-8}$)]</td>
<td>4.3% (7.5%)</td>
</tr>
<tr>
<td>$K^* \rightarrow \mu^+ \nu$</td>
<td>2.2%</td>
</tr>
<tr>
<td>$K^* \rightarrow e^+ \pi^+ \pi^0 \nu$</td>
<td>$\leq$3%</td>
</tr>
<tr>
<td>Other 3 – track decays</td>
<td>$\leq$1.5%</td>
</tr>
<tr>
<td>$K^* \rightarrow \pi^+ \pi^0 \gamma$</td>
<td>$\sim$2%</td>
</tr>
<tr>
<td>$K^* \rightarrow \mu^+ \nu \gamma$</td>
<td>$\sim$0.7%</td>
</tr>
<tr>
<td>$K^* \rightarrow \mu^+ (\mu^0) \pi^0 \nu$, others</td>
<td>negligible</td>
</tr>
<tr>
<td>Expected background</td>
<td>$\leq$13.5% ($\leq$17%)</td>
</tr>
</tbody>
</table>

- veto
- particle ID
What can be done in flavour physics
(with very modest investment)
If nothing but SM Higgs is found at LHC

We all know that SM has problems !!!
SM problems and possible solutions

Hierarchy problem: stability of the Higgs mass against radiative corrections

Possible solutions:

☑ Compensation of divergent diagrams by new particles at TeV scale (supersymmetry, composite Higgs boson). **Consequence: new physics at LHC !!!**

Alternative

☑ New symmetry – exact, but spontaneously broken scale invariance. Higgs mass is kept small as photon mass kept zero by gauge invariance. **Consequence: validity of SM all the way up to the Planck scale; nothing but the SM Higgs at LHC in the mass interval** \[ m_{\text{min}} < m < m_{\text{max}} \]

\[
m_{\text{min}} = \left[ 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5 \right] \text{GeV}
\]

\[
m_{\text{max}} = \left[ 173.5 + \frac{m_t - 171.2}{2.1} \times 1.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.3 \right] \text{GeV}
\]
SM problems and possible solutions

Neutrino masses and oscillations

Possible solutions:

- **See-saw mechanism:** Existence of several super heavy ($M \sim 10^{10} \text{ GeV}$) neutral leptons. Direct experimental consequences: none, as the mass is too large to be accessed

Alternative

- **Existence of new lepton flavours with masses similar to those of known quarks and leptons** → **possibility of direct experimental search !!!**
Dark matter

Possible solutions:

- WIMPs with masses of the order of 100 GeV and roughly electroweak cross-sections (e.g. SUSY neutralino).
  Consequences: new particles at LHC, success of WIMP searches

Alternative

- Super-WIMPs (non-stable, very long life-time) with masses in keV range
  Natural possibility: new lepton flavour with a mass of a few keV

  Consequences: no Dark Matter candidates at LHC, failure of WIMP searches. Possibility of search through radiative processes $N \rightarrow \nu \gamma$, which leads to existence of narrow X-ray line in direction of DM concentrations
SM problems and possible solutions

Baryon asymmetry of the Universe

Possible solution:

- Baryogenesis due to new physics above the electroweak scale

  **Potential consequences:** new particles at LHC (for electroweak baryogenesis)

Alternative

- Baryogenesis due to new neutral lepton flavours with masses in the range from $m_\pi$ to a few GeV  \(\rightarrow\) **possibility of direct experimental search in heavy flavours decays**
Search for neutral lepton flavours in heavy flavour decays

ν Minimal Standard Model:

- Takehiko Asaka, Steve Blanchet, Mikhail Shaposhnikov  March 2005
  Published in Phys.Lett.B631:151-156,2005
- Takehiko Asaka, Mikhail Shaposhnikov, May 2005
  Published in Phys.Lett.B620:17-26,2005

νMSM can simultaneously explain

- neutrino masses & oscillations,
- dark matter
- baryon asymmetry of the Universe
\[\nu\textbf{Minimal Standard Model realization:}\]

\[\checkmark \text{Role of } N_e, \text{ with mass in keV range } \rightarrow \text{dark matter}\]

\[\checkmark \text{Role of } N_\mu, N_\tau, \text{ with mass in } O(1\text{GeV}) \text{ range } \rightarrow \text{“give” masses to neutrinos and generate baryon asymmetry of our Universe}\]
Search for $N_e$

X-ray telescopes similar to Chandra or XMM-Newton but with better energy resolution to identify narrow X-ray line from the $N_e \rightarrow \nu \gamma$ decay

One needs:

- Improvement of the spectral resolution up to the natural line width ($\delta E/E \sim 10^{-3}$)

- FoV $\sim 1^\circ$ (size of a dwarf galaxies)

- Wide energy scan from $O(100 \text{ eV})$ to $O(50 \text{ keV})$
Search for $N_\mu$, $N_\tau$

Challenge (from baryon asymmetry): $\theta^2 \leq 5 \times 10^{-7} \ (\text{GeV} / M) \\
\quad (\theta = m_D / M)$

- Experimental signature:

  peak in 2-body decay and missing energy signal in 3-body decays
  of $K$, $D$ and $B$ mesons (sensitive to $\theta^2$)

  Example:
  $K^+ \rightarrow \mu^+ N, \ M^2 = (p_K - p_\mu) \neq 0$

- Similar for charm and beauty decays:

  - $M_N < M_K$ KLOE, NA62, E787, K0TO
  - $M_K < M_N < M_D$ charm- & $\tau$-factories, CLEO-II
  - $M_N < M_B$ (super) $B$-factories
Typical decay BR’s expected in νMSM range from $10^{-9}$ to few $\times 10^{-7}$ depending on $M_N$
Search for $N_\mu$, $N_\tau$

- Two charged tracks from a common vertex

Decay processes:
$$N \rightarrow \mu^+\mu^-\nu,$$
(etc. sensitive to $\theta^4$)

First step: $N$ is produced in the decays of $K$, $D$ or $B$ mesons ($\theta^2$)

Second step: search for decays of $N$ in a near detector ($\theta^2$)

- $M_N < M_K$ Any intense source of $K$-mesons
- $M_N < M_D$ CERN SPS beam + near detector
- $M_N > M_D$ Very difficult experimentally
Conclusion

- LHCb is ready for data taking

- First data will be used for calibration of the detector and trigger in particular. First exploration of low Pt physics at LHC energies. High class measurements in the charm sector may be possible

- With 150 – 200 \( \text{pb}^{-1} \) data sample LHCb will reach Tevatron sensitivity in a few golden channels in the beauty sector

- With 10 \( \text{fb}^{-1} \) LHCb has an excellent opportunity to both discover New Physics and to elucidate its nature. LHCb have an important role to complement physics programme of ATLAS and CMS
Dear Peter,

LHC experiments are opening a nice bottle of NP for your health.

Happy Birthday to You !!!

Next 5 years will be very exciting for physics, and for heavy flavour physics as well.

→ Good occasion to get together with Peter in 5 years to review progress and to agree on future strategy !!!
Spare Slides
Thanks to B-factories and CDF/D0 the CKM mechanism of CP violation is proven to be the leading one.

Still a lot of room left for New Physics in heavy flavor sector.

Extend the parameterization to include possible New Physics contributions to $B$-$\bar{B}$ oscillations.

$$\text{Re}(\Delta_q) + i\text{Im}(\Delta_q) = \frac{\langle B^0 | H^{\text{full}} | \bar{B}^0 \rangle}{\langle B^0 | H^{\text{SM}} | \bar{B}^0 \rangle}$$

Large range of NP allowed!
Phases of New Particles

\[ (\bar{\rho}, \bar{\eta}) = \left(1 - \frac{\lambda^2}{2}\right) (\rho, \eta) \]

\[ B_d \text{box} / B_s \text{box} \]

\[ \beta \text{ is very small in Standard Model} \]

\[ B_s \text{box} \]
Prospects for most competitive measurements in 2010

$B_s \rightarrow \mu\mu$

With data sample of $\sim 200 \text{ pb}^{-1}$, LHCb should be able to improve Tevatron sensitivity for $B_s \rightarrow \mu\mu$ and $\phi_s$ (present ‘central’ value from Tevatron would be confirmed at $5\sigma$ level)
### LHCb sensitivities for integrated lumi of 100 fb$^{-1}$

<table>
<thead>
<tr>
<th>Observable</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S(B_s \rightarrow \phi\phi)$</td>
<td>0.01 – 0.02</td>
</tr>
<tr>
<td>$S(B_d \rightarrow \phi K^0_S)$</td>
<td>0.025 – 0.035</td>
</tr>
<tr>
<td>$\phi_s (J/\psi\phi)$</td>
<td>0.003</td>
</tr>
<tr>
<td>$\sin(2\beta) (J/\psi K^0_S)$</td>
<td>0.003 – 0.010</td>
</tr>
<tr>
<td>$\gamma (B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>$&lt; 1^\circ$</td>
</tr>
<tr>
<td>$\gamma (B_s \rightarrow D_s K)$</td>
<td>1 – 2$^\circ$</td>
</tr>
<tr>
<td>$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$</td>
<td>5 – 10$%$</td>
</tr>
<tr>
<td>$\mathcal{B}(B_d \rightarrow \mu^+\mu^-)$</td>
<td>3$\sigma$</td>
</tr>
<tr>
<td>$A_T^{(2)}(B \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>0.05 – 0.06</td>
</tr>
<tr>
<td>$A_{FB}(B \rightarrow K^{*0}\mu^+\mu^-)$ $s_0$</td>
<td>0.07 GeV$^2$</td>
</tr>
<tr>
<td>$S(B_s \rightarrow \phi\gamma)$</td>
<td>0.016 – 0.025</td>
</tr>
<tr>
<td>$A^{\Delta\Gamma_s}(B_s \rightarrow \phi\gamma)$</td>
<td>0.030 – 0.050</td>
</tr>
<tr>
<td>charm $x^2$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>mixing $y'$</td>
<td>$2.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>CP $y_{CP}$</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Also studying Lepton Flavour Violation in $\tau\rightarrow\mu\mu\mu$
CPV measurements: $\gamma$ in penguins

- **Large penguin contribution in both $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ sensitive to NP**

- **Time-dependent CP asymmetries**
  \[ A_{CP}(t) = A_{dir} \cos(\Delta mt) + A_{mix} \sin(\Delta mt) \]
  depend on $\gamma$, mixing phases, and ratio of penguin to tree $= d e^{i\theta}$

  - Assume $d_{\pi\pi} \approx d_{KK}$ within ±20% and $\theta_{\pi\pi} \approx \theta_{KK}$ within ±20°
  - 4 measurements and 3 unknowns, if mixing phase $2\beta$ taken from $B^0 \rightarrow J/\psi K_S$

- **Expected sensitivity:**
  \[ \sigma(\gamma) \sim 7^\circ \text{ in 1 year/2fb}^{-1} \]
  assuming U-spin symmetry to be held within 20%
  \[ \sigma(\phi_{J/\psi\phi}) \sim 0.05 \text{ rad comparable to J/\psi\phi analysis} \]

- $59k B^0 \rightarrow \pi^+\pi^-$ with B/S~0.5
- $72k B_s \rightarrow K^+K^-$ with B/S~0.07