The physics prospects and status of the LHCb experiment

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Outline

- The Unitarity Triangle - where we are today
- The LHCb experiment and its current status
- Highlights of the physics programme of LHCb
 - Focus on LHCb uniqueness over and above the B-factories and the Tevatron
 - ◆ The B_s mixing phase ϕ_s : $B_s \rightarrow J/\psi \phi$ (tree) and $\phi \phi$ (penguin)
 - ◆ Measurement of unitarity angle γ via a number of methods
 - ◆ The rare decay $B_s \rightarrow \mu^+ \mu^-$
- Performance summary

The Unitarity Triangle: where we are today

The B-factories and the Tevatron have made huge inroads into extending our understanding

Where LHCb comes in: B production at the LHC

LHCb takes advantage of:

- Large $b\bar{b}$ cross-section (~ 230 mb)
- Forward Geometry =>
 - $b\bar{b}$ production sharply peaked forward-backward
 - Vertex detector can be placed close to interaction region.
- Low luminosity is sufficient ($2.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$) gives 10^{12} $b\bar{b}$ pairs produced per year !

$b\bar{b}$ angular
distribution

The long and winding road

The LHCb detector
and its status

The LHCb spectrometer

Forward spectrometer (running in pp collider mode). Inner acceptance 10 mrad from conical beryllium beam pipe. Outer Acceptance (250) 300 mrad (non) - bending plane

Vertex detector (VELO)

VELO module production

- VELO has silicon microstrips with $r\phi$ geometry
- Approaches 8 mm from beam (inside secondary vacuum)
- Gives an impact parameter resolution $\sim 30 \mu\text{m}$
- Proper time resolution for $(B_s \rightarrow D_s^- \pi^+) \sim 40 \text{ fs}$

Tracking system

- Tracking system and dipole magnet measure track angles and momenta (straw tubes and silicon)
- $\Delta p/p \sim 0.5\%$ gives mass resolution ~ 14 MeV (for $B_s \rightarrow D_s K$)

Particle ID: RICH system

- Two RICH detectors for charged hadron identification
- Provides π -K separation for $1 < p < 100 \text{ GeV}/c$

LHCb commissioning is well underway....

The B_s weak mixing phase ϕ_s

The phase ϕ_s in B_s mixing

- V_{ts} appears twice in the $B_s^0 - \bar{B}_s^0$ mixing process

CKM phases to order λ^4

$$\begin{matrix} & d & s & b \\ \begin{matrix} u \\ c \\ t \end{matrix} & \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & e^{-i\chi} & 1 \end{pmatrix} \end{matrix}$$

→ Mixing process in B_s^0 introduces a relative CP-violating weak phase of $\phi_s = -2\chi$ within SM (cf. B_d^0 mixing which introduces a phase 2β)

Angle ϕ_s from $B_s \rightarrow J/\psi \phi$

- B_s mixing phase is very small in SM: $\phi_s = -0.042 \pm 0.001$ rad *See Lenz and Nierste*
 - ◆ Not yet measured with any accuracy
 - ◆ ϕ_s could be much larger if New Physics contributes to $B_s^0 - \bar{B}_s^0$ transitions

- Method: measure time-dependent asymmetry in decay rates:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0(t) \rightarrow f) - \Gamma(B_s^0(t) \rightarrow f)}{\Gamma(\bar{B}_s^0(t) \rightarrow f) + \Gamma(B_s^0(t) \rightarrow f)}$$

- ◆ Flavour tagging $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} D^2 = 7.08 \pm 0.23 \%$
- ◆ Need very good proper time resolution to resolve $B_s^0 - \bar{B}_s^0$ oscillations $B_s \rightarrow J/\psi \phi$: $\sigma(t) = 36.0$ fs

ϕ_s : $B_s \rightarrow J/\Psi \phi$ angular analysis

- $B_s \rightarrow J/\Psi(l^+l^-)\phi(K^+K^-)$: theoretically clean
 - ◆ Also experimentally “easy”: $\mu\mu$ trigger and 4 charged tracks
 - ◆ LHCb: yield in 2 fb^{-1} : 131k, $B/S=0.12$
- Vector-vector final state: angular analysis
 - ◆ Define transversity angle θ_{tr} : disentangle mixture of **CP-even** and **CP odd** states
 - ◆ Get wrong-tag fraction: ω_{tag} from control sample $B_s \rightarrow D_s \pi$
 - Better accuracy with external Δm_s
 - gives: ϕ_s , $\Delta\Gamma_s$
- Sensitivity for 1 year, 2 fb^{-1} :
 $\sigma(\phi_s) = 0.021 \text{ rad}$ (cf. SM value 0.042)

Constraints on New Physics in B_s mixing from ϕ_s measurement

- New Physics in B_s mixing amplitude parametrized by A_s^{NP}/A_s^{SM} and phase ϕ_s^{NP}

$$\frac{\langle B_s^0 | H_{\text{eff}}^{\text{full}} | \overline{B_s^0} \rangle}{\langle B_s^0 | H_{\text{eff}}^{\text{SM}} | \overline{B_s^0} \rangle} = 1 + \frac{A_s^{NP}}{A_s^{SM}} e^{2i\phi_s^{NP}}$$

- Can already exclude significant region of allowed phase space with the very first data (2008?)

After LHCb measurement of ϕ_s with $\sigma(\phi_s) = \pm 0.1$ ($\sim 0.2 \text{ fb}^{-1}$)

Z.Ligeti: allowed regions $\text{CL} > 0.90, 0.32, 0.05$

New Physics through Tree-Penguin comparison

β : (tree) - (penguin)

Babar/Belle have shown comparative measurements are important. Prior to summer conferences, recall a 2.6σ effect $\delta\beta(\text{NP}) = 8^\circ$

ϕ_s : (tree) - (penguin)

Expect a similar difference in B_s mixing if new physics is realised.

LHCb very well positioned to study this in a single measurement in the B_s sector.

The decay $B_s \rightarrow \phi\phi$

- FCNC gluonic penguin.
=> Same technique, interference of direct decay and mixing

- V_{ts} appears in both decay and mixing.
=> cancellation of SM contribution of amplitudes
=> $(V_{tb} V_{ts}^* / V_{tb}^* V_{ts}) (V_{tb}^* V_{ts} / V_{tb} V_{ts}^*) \sim 1$

mixing
decay

=> But new physics wont cancel

- CP violation in SM $< 1\%$.
=> Observation of any CP violation is signature for NP.
- Again, decay to two vector particles requires an angular analysis to extract CP asymmetries.

Time-dependent analysis

Expect 4000 signal events in 1 year, 2fb^{-1} , $0.4 < B/S < 2.1$ at 90% CL.

• Sensitivity for LHCb in 2fb^{-1}

$$\sigma(\phi_s (\phi\phi)) \sim 0.10 \text{ rad} \quad (0.04 \text{ rad in } 10 \text{ fb}^{-1})$$

The angle γ

Angle γ : window on appearance of new physics

- Tree processes insensitive to New Physics
- But expect NP to appear in loop diagrams
- Missing so far in UT evaluation:
a precision measurement of γ

Unitarity triangle from tree-level processes only: $|V_{ub}/V_{cb}|$ and γ from $B \rightarrow D^{(*)}K$ decays.

Unitarity triangle from loop-level processes (contains SM physics and possible new physics)

Possible scenario after 5 years (10 fb^{-1}) of LHCb running. γ from tree processes compared to loops.

LHCb measurement of the angle γ

B mode	D mode	Method	$\sigma(\gamma)$ with 2 fb ⁻¹
$B^+ \rightarrow DK^+$	$K\pi + KK/\pi\pi + K3\pi$	ADS+GLW	5°–13°
$B^+ \rightarrow D^*K^+$	$K\pi$ ($D^* \rightarrow D+\pi, \gamma$)	ADS+GLW	Under study
$B^+ \rightarrow DK^+$	$K_S\pi\pi$	Dalitz	~8–12°
$B^+ \rightarrow DK^+$	$KK\pi\pi$	4-body “Dalitz”	18°
$B^+ \rightarrow DK^+$	$K\pi\pi\pi$	4-body “Dalitz”	Under study
$B^0 \rightarrow DK^{*0}$	$K\pi + KK + \pi\pi$	ADS+GLW	~6–12°
$B^0 \rightarrow DK^{*0}$	$K_S\pi\pi$	Dalitz	Under study
$B_s \rightarrow D_s K$	$KK(\phi)\pi$	tagged, $A(t)$	~10°
$B^0 \rightarrow \pi^+\pi^-, B_s \rightarrow K^+K^-$	N/A	U-spin symmetry	5° – 10°

- Importance of redundancy
- Importance of particle ID
- Importance of using methods with different systematics

Combined after 2 fb⁻¹:
 $\sigma(\gamma) \sim 4^\circ$ (From tree only)

γ from $\bar{B}_s^0 \rightarrow D_s^\pm K^\mp$

- $B_s^0 \rightarrow D_s^- K^+$ ($b \rightarrow c$ transition) and $\bar{B}_s^0 \rightarrow D_s^- K^+$ ($b \rightarrow u$ transition) both tree decays, interfere via B_s mixing, both of order λ^3

- Also charge conjugate states $\rightarrow$ 4 tree-level time-dependent decay rates are measured
- Final states are NOT CP-eigenstates

γ from $\bar{B}_s^0 \rightarrow D_s^\pm K^\mp$

S.Cohen et al. LHCb Note 2007-41

- Simultaneous fit to $B_s^0 \rightarrow D_s^\pm K^\mp$ and $B_s^0 \rightarrow D_s^- \pi^+$
- Get four decay rates for $\bar{B}_s^0, B_s^0 \rightarrow D_s^\pm K^\mp, B_s^0 \rightarrow D_s^\mp K^\pm$
- Extract $\gamma + \phi_s$, strong phase difference δ , amplitude ratio and Δm_s

- Spectacular asymmetries
- Expect 6200 events in 1 year of data taking (2 fb^{-1})
- In 1 year $\sigma(\gamma + \phi_s) \sim 10^\circ$ (statistics limited).
 $\sigma(\Delta m_s) \sim 0.007 \text{ ps}^{-1}$
- $\sigma(\gamma + \phi_s)$ depends quite weakly on $(\gamma + \phi_s)$, B/S , and strong phase diff.
- Use ϕ_s obtained from $B_s \rightarrow J/\psi \phi$ to extract γ

After 5 years, with $\Delta m_s = 17.5 \text{ ps}^{-1}$

γ from $B^\pm \rightarrow D^0 K^\pm$

- Here $b \rightarrow c$ transition interferes with $b \rightarrow u$

Colour **favoured** $b \rightarrow c$ amplitude

Colour **suppressed** $b \rightarrow u$ amplitude

- **Counting experiment: no flavour tagging, no proper time analysis**
 - ♦ charged B decays (time-independent, direct CP violation)
 - ♦ Select modes where $D^0/\bar{D}^0$ decay to SAME final state f
 - ♦ $b \rightarrow u \rightarrow f$ is doubly Cabibbo suppressed (and colour suppressed)
 - ♦ “Tree-level” dominates. No penguin pollution

$\gamma: B^\pm \rightarrow D^0 K^\pm$ ADS+GLW method

G. Wilkinson LHCb Note 2005-66

M. Patel LHCb Note 2007-43

Atwood, Dunietz and Soni, Phys. Rev. Lett. 78, 3257 (1997).

Gronau, London, Wyler, PLB. 253, 483 (1991), PLB 265, 172 (1991).

- The ADS analysis has 4 possible rates for each D decay mode.
 - ♦ $B^+ \rightarrow \tilde{D}(K^+\pi^-)K^+$ favoured, $B^+ \rightarrow \tilde{D}(K^-\pi^+)K^+$ suppressed
 - ♦ $B^- \rightarrow \tilde{D}(K^-\pi^+)K^-$ favoured, $B^- \rightarrow \tilde{D}(K^+\pi^-)K^-$ suppressed
- Where $\tilde{D}$ is either D or $\bar{D}$
- Fit 5 parameters:
 - amplitude ratios (r_B, r_D), strong phase differences (δ_B, δ_D) and γ
 - ♦ r_D well measured; δ_D with help from CLEO-c
 - ♦ Add D^0 decay modes to CP eigenstates: $D^0 \rightarrow KK/\pi\pi$ (GLW method)

Method	$D \rightarrow f$	LHCb yield / 2 fb^{-1}	$\sigma(\gamma) / 2 \text{ fb}^{-1}$
ADS, GLW	$K\pi$	~ 400 (56k [†])	5-13° (depends on strong phase δ_D)
	$KK, \pi\pi$	7.8k	

[†] favoured decay

- $K\pi\pi\pi$ modes will also be added
- A similar analyses is possible with $B^{*-} \rightarrow D^* K^{*-}$ decays - under study

The rare decay

$$B_s \rightarrow \mu^+ \mu^-$$

The decay: $B_s \rightarrow \mu^+ \mu^-$

- $B_s \rightarrow \mu^+ \mu^-$: very rare loop decay, sensitive to New Physics:
 - ◆ $BR \sim 3.5 \times 10^{-9}$ in SM, can be strongly enhanced in SUSY
 - ◆ Current 90% CL limit from CDF+D0 with 1 fb^{-1} is ~ 20 times SM
- Main issue is background rejection
 - ◆ With limited MC statistics, indication that main background is $b \rightarrow \mu$

LHCb sensitivity to $B_s \rightarrow \mu^+\mu^-$

0.05 $\text{fb}^{-1} \Rightarrow$ overtake CDF+D0
0.5 $\text{fb}^{-1} \Rightarrow$ exclude BR values down to SM
2 $\text{fb}^{-1} \Rightarrow$ 3 σ evidence of SM signal
10 $\text{fb}^{-1} \Rightarrow$ $>5\sigma$ observation of SM signal

Current limit from CDF
 $\text{BR}(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8}$
at 95% confidence level.

Summary of performance and the future

LHCb sensitivities with 2 fb⁻¹

	Channel	Yield	Precision
γ	From tree channels		$\sigma(\gamma) \sim 4^\circ$
α	$B_d \rightarrow \pi^+ \pi^- \pi^0$ $B \rightarrow \rho^+ \rho^0, \rho^+ \rho^-, \rho^0 \rho^0$	14k 9k, 2k, 1k	$\sigma(\alpha) \sim 10^\circ$
β	$B_d \rightarrow J/\psi(\mu\mu)K_S$ $B_d \rightarrow \phi K_S$	240k 0.8k	$\sigma(\sin 2\beta) \sim 0.02$ $\sigma(\sin 2\beta) \sim 0.32$
ϕ_s	$B_s \rightarrow J/\psi(\mu\mu)\phi$ $B_s \rightarrow \phi\phi$	131k 4k	$\sigma(\phi_s) \sim 0.021$ $\sigma(\phi_s) \sim 0.10$
Rare decays	$B_s \rightarrow \mu^+ \mu^-$ $B_d \rightarrow K^{*0} \mu^+ \mu^-$ $B_d \rightarrow K^{*0} \gamma$ $B_s \rightarrow \phi \gamma$	20 7.2 k 35k 11 k	$\sim 3\sigma$ SM value $\sigma(C_7^{\text{eff}}/C_9^{\text{eff}}) \sim 0.13$ $\sigma(A_{\text{CP}}) \sim 0.01$
charm	$D^{*+} \rightarrow D^0 (K^- \pi^+) \pi^+$	50 M	

Contribution of LHCb to UT

Summer 2007

LHCb at $L=10\text{fb}^{-1}$

Lattice QCD improvements assumed: $\sigma(\xi)/\xi=1.5\%$
 $\sigma(\sin(2\beta)) = 0.01$; $\sigma(\gamma) = 2.4^\circ$; $\sigma(\alpha) = 4.5^\circ$

Summary

- The LHCb experiment will take B physics a significant step further than the B factories and Tevatron:
 - ◆ Access to other b hadron species
 - ◆ Very high statistics
- LHCb combines excellent vertexing and particle ID with flexible trigger, dedicated to B physics.
- LHCb detector currently being commissioned. First physics data in 2008; Stable running in 2009 → 2fb^{-1} per year

LHCb will be ready to take physics data in 2008 with a fully commissioned and complete detector

- LHCb has a RICH physics programme. Plans already in place to upgrade LHCb to increase statistics by factor of 10-20 from ~2014!

Spare slides

LHCb trigger

HLT rate	Event type	Calibration	Physics
200 Hz	Exclusive B candidates	Tagging	B (core program)
600 Hz	High mass di-muons	Tracking	J/ψ , $b \rightarrow J/\psi X$ (unbiased)
300 Hz	D^* candidates	PID	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. $b \rightarrow \mu$)	Trigger	B (data mining)

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

■ Flavour Changing Neutral Current Decay

- ◆ BR $\sim 1.2 \times 10^{-6}$
- ◆ Forward-backward asymmetry $A_{FB}(s)$ in the $\mu\mu$ rest-frame is a sensitive NP probe
- ◆ Predicted zero of $A_{FB}(s)$ depends on Wilson coefficients $C_7^{\text{eff}}/C_9^{\text{eff}}$

■ Sensitivity

- ◆ 7.2k signal events/2fb⁻¹, $B_{bb}/S = 0.4 \pm 0.1$
- ◆ After 10 fb⁻¹: zero of $A_{FB}(s)$ located to ± 0.28 GeV²
- ◆ determine $C_7^{\text{eff}}/C_9^{\text{eff}}$ with 7% stat error

LHCb upgrade (10x design lumi)

■ LHCb Upgrade

- ◆ Upgrade LHCb experiment such that it can operate at $\mathcal{L} \sim 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$: 10 times design luminosity
- ◆ Collect $\sim 100 \text{ fb}^{-1}$ data sample in ~ 5 yrs
- ◆ Is compatible with LHC luminosity upgrade (Super-LHC)

■ LHCb Upgrade - Detectors, Trigger and DAQ

- ◆ Add Vertex Detector and Tracker to Level-0 Trigger, possible factor 3 improvement of hadron trigger
- ◆ Readout full detector at 40 MHz
- ◆ All Front-end electronics must be redesigned
- ◆ Need to replace all silicon sensors

■ Example: $\phi_s (B_s \rightarrow \phi\phi)$ Sensitivity

- ◆ Estimated precision in 10 fb^{-1}
 $\sigma(\phi_s (\phi\phi)) \sim 0.04$
- ◆ precision statistically limited
- ◆ With 100 fb^{-1} and
1st level detached vertex trigger
 $\sigma(\phi_s (B_s \rightarrow \phi\phi)) \sim 0.006$

Charm mixing with LHCb

Patrick Spradlin

Estimated reconstructible yields
in 2 fb^{-1} from $B \rightarrow D^{*+} X$

(Similar yields expected from prompt production)

$D^0 \rightarrow K^- \pi^+$	50×10^6
$D^0 \rightarrow K^- K^+$	5×10^6
$D^0 \rightarrow \pi^- \pi^+$	2×10^6
$D^0 \rightarrow \pi^- K^+$	0.2×10^6

	Data set	N_{WS}	$x'^2 (\times 10^{-3})$	$y' (\times 10^{-3})$
BaBar	384 fb^{-1}	4030	$-0.22 \pm 0.30 \pm 0.21$	$9.7 \pm 4.4 \pm 3.1$
Belle	400 fb^{-1}	4024	< 0.72	$-9.9 < y' < 6.8$
HFAG average			$-0.01^{+0.20}_{-0.20}$	$5.5^{+2.8}_{-3.7}$
<i>B</i> factories	2 ab^{-1}		$x'^2 \pm 0.15$	$y' \pm 3.0$
LHCb	10 fb^{-1}	232500	$x'^2 \pm 0.064$ (stat)	$y' \pm 0.87$ (stat)