Potential for precise Unitarity Triangle angles measurements in LHC

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$$\alpha = 94.6^\circ \pm 4.6^\circ$$

$$\beta = 23.9^\circ \pm 1.0^\circ$$

$$\gamma = 61.3^\circ \pm 4.5^\circ$$

$$\phi_s = 2.1^\circ \pm 0.2^\circ$$

But: New particles may show up in loop diagrams, overconstrain will allow to disentangle SM components from the New Physics ones → need very high precision!

LHC experiments with a B in the menu

B physics using high- p_T muon, mostly with modes involving dimuons.

B physics dedicated experiment:

Pythia production cross section

Trigger & Tagging

- **Atlas**: B trigger output rate: 10-15 Hz,
Tagging ε_{eff} : $\sim 4\%$

CMS: 5 Hz inclusive + ~ 1 Hz exclusive
will both run a few years at $L < 2 \times 10^{33} \text{ cm}^2/\text{s}$
with $n(\text{pileup}) < 5$, after that $n \sim 25$

LHCb: $L \sim 2 \times 10^{32} \text{ cm}^2/\text{s}$, $n(\text{pileup}) \sim 0.5$
Tagging ε_{eff} : $4\% - 5\% (B_d)$ $7\% - 9\% (B_s)$
Trigger output:

Rate	Event type	Use for physics	Use for calibration/systematics
200 Hz	Exclusive B	B (core program)	Control channels (tagging, ...)
600 Hz	High mass dimuon	130 Hz of $B \rightarrow J/\psi X$	Tracking
300 Hz	D^*	65 Hz D^* (mixing + CPV)	Hadron PID
900 Hz	Inclusive b (e.g. $b \rightarrow \mu$)	550 Hz of B (data mining)	Trigger

β

β from $B^0 \rightarrow J/\psi K_s$

- ❑ The 'gold plated' channel at B-factories already well measured by Babar/Belle
- ❑ Still an important measurement:

$$A_{CP}^{th}(t) = A_{CP}^{dir} \cdot \cos(\Delta m_d \cdot t) + A_{CP}^{mix} \cdot \sin(\Delta m_d \cdot t)$$

$= 0$ in SM

$= \sin 2\beta$

LHCb In one year, 2/fb, with 216k events, $\sigma(\sin 2\beta) \sim 0.02$, $\sigma(\beta) \sim 0.6^\circ$

Atlas will achieve similar sensitivity with 30/fb

Comparing with other channels may indicate NP in penguin diagrams

Scaling of 1 year sensitivity from $J/\psi K_s$ to ϕK_s :
 $\sigma(\sin 2\beta_{\text{eff}}) \sim 0.4$, Yield: 0.8k, B/S < 2.4 (preliminary).

Φ_s

ϕ_s from $B_s \rightarrow J/\psi \phi (\eta, \eta' \dots)$

$B_s \rightarrow J/\psi \phi$ is the B_s counterpart of $B^0 \rightarrow J/\psi K_S$

- ❑ In SM $\phi_s = -2\arg(V_{ts}) = -2\lambda^2\eta \sim -0.04$
- ❑ Sensitive to New Physics effects in the B_s - $\bar{B}_s$ system if NP in mixing $\rightarrow \phi_s = \phi_s(\text{SM}) + \phi_s(\text{NP})$
- ❑ 2 CP-even, 1 CP-odd amplitudes, angular analysis needed to separate, then fit to ϕ_s , $\Delta\Gamma_s$, CP-odd fraction

Channels used	Yield ($10^3/2 \text{ fb}^{-1}$)	B/S	$\langle \delta_\tau \rangle$ (fs)	σ_{mass} (MeV/c ²)
$B_s \rightarrow J/\psi (\mu^- \mu^+) \phi (K^+ K^-)$	131	0.12	36	14
$B_s \rightarrow \eta_c (h^- h^+ h^- h^+) \phi (K^+ K^-)$	3	0.6	30	12
$B_s \rightarrow J/\psi (\mu^- \mu^+) \eta (\gamma\gamma)$	8.5	2.0	37	34
$B_s \rightarrow J/\psi (\mu^- \mu^+) \eta (\pi^+ \pi^- \pi^0 (\gamma\gamma))$	3.0	3.0	34	20
$B_s \rightarrow J/\psi (\mu^- \mu^+) \eta' (\pi^+ \pi^- \eta (\gamma\gamma))$	2.2	2.0	32	19
$B_s \rightarrow D_s (K^+ K^- \pi^-) D_s (K^+ K^- \pi^+)$	4.0	0.3	56	6

With SM inputs: $\Delta m_s = 17.5/\text{ps}$, $\phi_s = -0.04$, $\Delta\Gamma_s/\Gamma_s = 0.15$
and 2/fb stat:

LHCb	Channels	$\sigma(\phi_s)$ [rad]	Weight $(\sigma/\sigma_i)^2$ [%]
	$B_s \rightarrow J/\psi \eta(\pi^+ \pi^- \pi^0)$	0.142	2.3
	$B_s \rightarrow D_s D_s$	0.133	2.6
	$B_s \rightarrow J/\psi \eta(\gamma \gamma)$	0.109	3.9
	$B_s \rightarrow \eta_c \phi$	0.108	3.9
	Combined (pure CP eigenstates)	0.060	12.7
	$B_s \rightarrow J/\psi \phi$	0.023	87.3
	Combined (all CP eigenstates)	0.022	100.0

Atlas will reach $\sigma(\phi_s) \sim 0.08$ (10/fb, $\Delta m_s = 20/\text{ps}$, 90k $J/\psi \phi$ evts)

CMS will reach $\sigma(\phi_s) \sim 0.07$ (10/fb, on $J/\psi \phi$ evts, no tagging)

γ

γ from $B_s \rightarrow D_s^\pm K^\mp$

□ 2 same order tree level amplitudes ($\propto \lambda^3$) : large asymmetries, *NP components unlikely!*

□ From the measurement 4 rates and 2 time-dependent asymmetries one gets $\gamma + \phi_s$ (with ϕ_s from $B_s \rightarrow J/\psi \phi$)

$D_s K$ asymmetries (5 years, $\Delta m_s = 20 \text{ ps}^{-1}$)

Yield: 5.4k signal events in 2/fb,
 residual contamination from
 $B_s \rightarrow D_s \pi \sim 10\%$
 $S/B > 1$ at 90% CL

Precision: $\sigma(\gamma) \sim 13^\circ$
 $(\Delta m_s = 17.3/\text{ps}, -20^\circ < \Delta_{\text{strong}} < 20^\circ)$
 Discrete ambiguities in γ can be
 resolved if $\Delta \Gamma_s$ large enough, or
 using $B^0 \rightarrow D \pi$ and U-spin symmetry

γ from $B^0 \rightarrow D^0 K^*$

[Phys. Lett. B270, 75 (1991)]

$A_1 = A(B^0 \rightarrow \bar{D}^0 K^{*0})$: $b \rightarrow c$ transition, phase 0

$A_2 = A(B^0 \rightarrow D^0 K^{*0})$: $b \rightarrow u$ transition, **phase $\Delta + \gamma$**

$A_3 = \sqrt{2} A(B^0 \rightarrow D_{CP}^0 K^{*0}) = A_1 + A_2$, because $D_{CP}^0 = (\bar{D}^0 + D^0)/\sqrt{2}$

- Measuring 6 decay rates (*self-tagged* and *time-integrated*) allows extraction of γ

LHCb

Modes (+CP conj.)	Yield (2/fb)	S/B _{bb} (90%CL)
$B^0 \rightarrow D^0 (K^+ \pi^-) K^{*0} (K^+ \pi^-)$	3.4 k	> 2.0
$B^0 \rightarrow D^0 (K^- \pi^+) K^{*0} (K^+ \pi^-)$	0.5 k	> 0.3
$B^0 \rightarrow D_{CP}^0 (K^+ K^-) K^{*0} (K^+ \pi^-)$	0.6 k	> 0.3

Precision: $\sigma(\gamma) \sim 8^\circ$ (in 1year, 2/fb, for $55^\circ < \gamma < 105^\circ$, $-20^\circ < \Delta < 20^\circ$)

γ from $B^\pm \rightarrow D K^\pm$

[Atwood, Dunietz, Soni method]

- Measure relative rates of $B^- \rightarrow D(K\pi) K^-$ and $B^+ \rightarrow D(K\pi) K^+$
 - Two interfering tree B-diagrams, one colour-suppressed ($r_B \sim 0.077$)
 - Two interfering tree D-diagrams, one Double Cabibbo-suppressed ($r_D^{K\pi} \sim 0.06$)
- large interference because of similar amplitudes!*

New value

Weak phase diff.: γ
 Magnitude ratio: r_B
 Strong phase diff.: δ_B

Magnitude ratio: $r_D^{K\pi}$
 Strong phase diff.: $\delta_D^{K\pi}$

measure:

$$\Gamma(B^- \rightarrow (K^- \pi^+)_D K^-) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B - \delta_D^{K\pi} - \gamma)$$

$$\Gamma(B^- \rightarrow (K^+ \pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} - \gamma)$$

$$\Gamma(B^+ \rightarrow (K^+ \pi^-)_D K^+) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B - \delta_D^{K\pi} + \gamma)$$

$$\Gamma(B^+ \rightarrow (K^- \pi^+)_D K^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} + \gamma)$$

favoured $\sim 60k$ evts

suppressed $\sim 0.5k$ evts

- 2 observables, 5 parameters ($\gamma, \delta_B, r_B, \delta_D^{K\pi}, r_D^{K\pi}$), $r_D^{K\pi} \sim 0.06$ known
add more D-decays to constrain further:

$D \rightarrow K\pi\pi\pi$ (Cabibbo favoured + DCS)

- ✓ 4 new rates with 2 new parameters, $\delta_D^{K3\pi}$; $r_D^{K3\pi} \sim 0.06$

$D \rightarrow KK$ (CP eigenstate)

- ✓ 2 new rates, no new unknown: $r_D^{KK} = 1$; $\delta_D^{KK} = 0$

➔ 7 relative rates and 5 unknowns: $\gamma, r_B, \delta_B, \delta_D^{K\pi}, \delta_D^{K3\pi}$ this may come from CLEO-C

Precision: $\sigma(\gamma) \sim 4 - 13$ in 1 year, 2/fb

depending on $\delta_D^{K\pi}$ ($-25 < \delta_D^{K\pi} < 25$)

and on $\delta_D^{K3\pi}$ ($-180 < \delta_D^{K3\pi} < 180$)

- Extraction of γ via Dalitz study ($D \rightarrow K_s \pi\pi$) is under investigation.

γ from $B \rightarrow \pi\pi$, $B_s \rightarrow KK$

❑ Large penguin contributions, sensitive to NP!

❑ Evaluation of A_{CP}^{dir} and A_{CP}^{mix} parameters from time-dependent measured asymmetry depend on γ , mixing phases, and ratio of penguin/tree = $d e^{i\theta}$

❑ Assume U-spin symmetry $d_{\pi\pi} = d_{KK}$ $\theta_{\pi\pi} = \theta_{KK}$
(and $\phi_{s,d}$ from $B_s \rightarrow J/\psi\phi$, $B \rightarrow J/\psi K_S$)
→ solve for γ

$$A_{CP}^{th}(\tau) = \frac{A_{CP}^{dir} \cdot \cos(x \cdot \tau) + A_{CP}^{mix} \cdot \sin(x \cdot \tau)}{\cosh\left(\frac{\Delta\Gamma}{2} \cdot \tau\right) - A_{\Delta\Gamma} \cdot \sinh\left(\frac{\Delta\Gamma}{2} \cdot \tau\right)}$$

LHCb

Precision: $\sigma(\gamma) \sim 5^\circ$
(but model dependent)

Expected Yield (1year, 2/fb)

- 26k $B^0 \rightarrow \pi^+\pi^-$,
- 37k $B_s \rightarrow K^+K^-$,
- 135k $B^0 \rightarrow K^+\pi^-$

$\gamma (^\circ)$

15

α

α from $B^0 \rightarrow \rho \pi$

[Snyder, Quinn, 1993]

Thanks to the interferences between the transitions $B \rightarrow \rho \pi \rightarrow \pi^- \pi^0 \pi^+$ we can simultaneously extract α with amplitudes and strong phases from the time dependence of the tagged Dalitz plot

- ❑ Simulate the experimental effects: resolution, acceptance, wrong tag, ... Assume B/S=1 (mix of flat and resonant ρ)
- ❑ Maximize the likelihood wrt α^{fit} and the background ratios r^{fit} (12D fit)

85% converge to the correct solution*

90% of experiments have $\sigma_\alpha < 10^\circ$

*prob. of mirror solutions decreases with stats, down to $\sim 0.2\%$ for 10/fb

α from $B^0 \rightarrow \rho \rho$

Measuring the time dependent asymmetry of $B \rightarrow \rho^+ \rho^-$ provide $\alpha_{\text{eff}} = \alpha + \Delta\alpha$

$$A_{\rho\rho}^{+-}(t) = S_{\rho\rho}^{+-} \sin(\Delta m_d t) - C_{\rho\rho}^{+-} \cos(\Delta m_d t)$$

$$\text{with } S_{\rho\rho}^{+-} = \sqrt{1 - C_{\rho\rho}^{+-2}} \sin(2\alpha_{\text{eff}})$$

LHCb is not competitive with current B-factory performance in $\rho^+ \rho^-$. The main contribution of LHCb to the $\rho\rho$ analysis could be the measurement of the $B \rightarrow \rho^0 \rho^0$ mode

Yields in 2/fb:

$B \rightarrow \rho^+ \rho^-$: 2k ($B/S < 5$, 90%CL)

$B^\pm \rightarrow \rho^\pm \rho^0$: 9k ($B/S \sim 1$)

$B \rightarrow \rho^0 \rho^0$: $\sim 0.5\text{k}$, assuming a $\text{BR} = 0.5 \cdot 10^{-6}$
 (Babar: $B^{00} = (0.54_{-0.32}^{+0.36} \pm 0.19) 10^{-6}$)

α from $B^0 \rightarrow \rho\pi, \rho\rho$ combined

LHCb

Summary table

Angle	Channel	Yield*	B_{bb}/S	LHC (2/fb)	Theoretical limit
β	$B_d \rightarrow J/\Psi K_S$ $B_d \rightarrow \phi K_S$	216k 0.8k	0.8 <2.4	$\sigma(\beta) \approx 0.6^\circ$ $\sigma(\beta) \approx 12^\circ$	$\sigma(\beta) \sim 0.2^\circ$ $\sigma(\beta) \sim 2^\circ$
ϕ_s	$B_s \rightarrow J/\Psi \Phi$ $B_s \rightarrow J/\Psi \eta$ $B_s \rightarrow \eta_c \Phi$	125k 12k 3k	0.3 2-3 0.7	$\sigma(\phi_s) \approx 1.2^\circ$	$\sigma(\phi_s) \sim 0.2^\circ$
γ	$B_s \rightarrow D_s K$ $B_d \rightarrow \pi\pi$ $B_s \rightarrow KK$ $B_d \rightarrow D^0(K^-\pi^+)K^{*0}$ $B_d \rightarrow D^0(K^+\pi^-)K^{*0}$ $B_d \rightarrow D_{CP}(K^+K^-)K^{*0}$ $B^- \rightarrow D^0(K^+\pi^-)K^-$ $B^- \rightarrow D^0(K^-\pi^+)K^-$	5.4k 26k 37k 0.5k 2.4k 0.6k 60k 2k	<1.0 <0.7 0.3 <0.3 <2.0 <0.3 0.5 0.5	$\sigma(\gamma) \approx 13^\circ$ $\sigma(\gamma) \approx 5^\circ$ $\sigma(\gamma) \approx 8^\circ$ $\sigma(\gamma) \approx 4^\circ-13^\circ$	$\sigma(\gamma) \ll 1^\circ$ if U-spin symmetry — $\sigma(\gamma) \ll 1^\circ$
α	$B_d \rightarrow \pi\rho, \rho\rho$	14k	0.8	$\sigma(\alpha) < 10^\circ$	$\sigma(\alpha) \sim 1^\circ$

* Untagged annual yield after trigger

Conclusion

- ◆ LHC experiments will allow to measure the Unitarity Triangle very precisely
- ◆ loop processes in the flavour sector will probe high energy scale!

..why penguins have short lives