The Abdus Salam International Centre for Theoretical Physics

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Workshop on the original of P, CP and T Violation

2 - 5 July 2008

Prospects for CP Violation Studies @ LHCb

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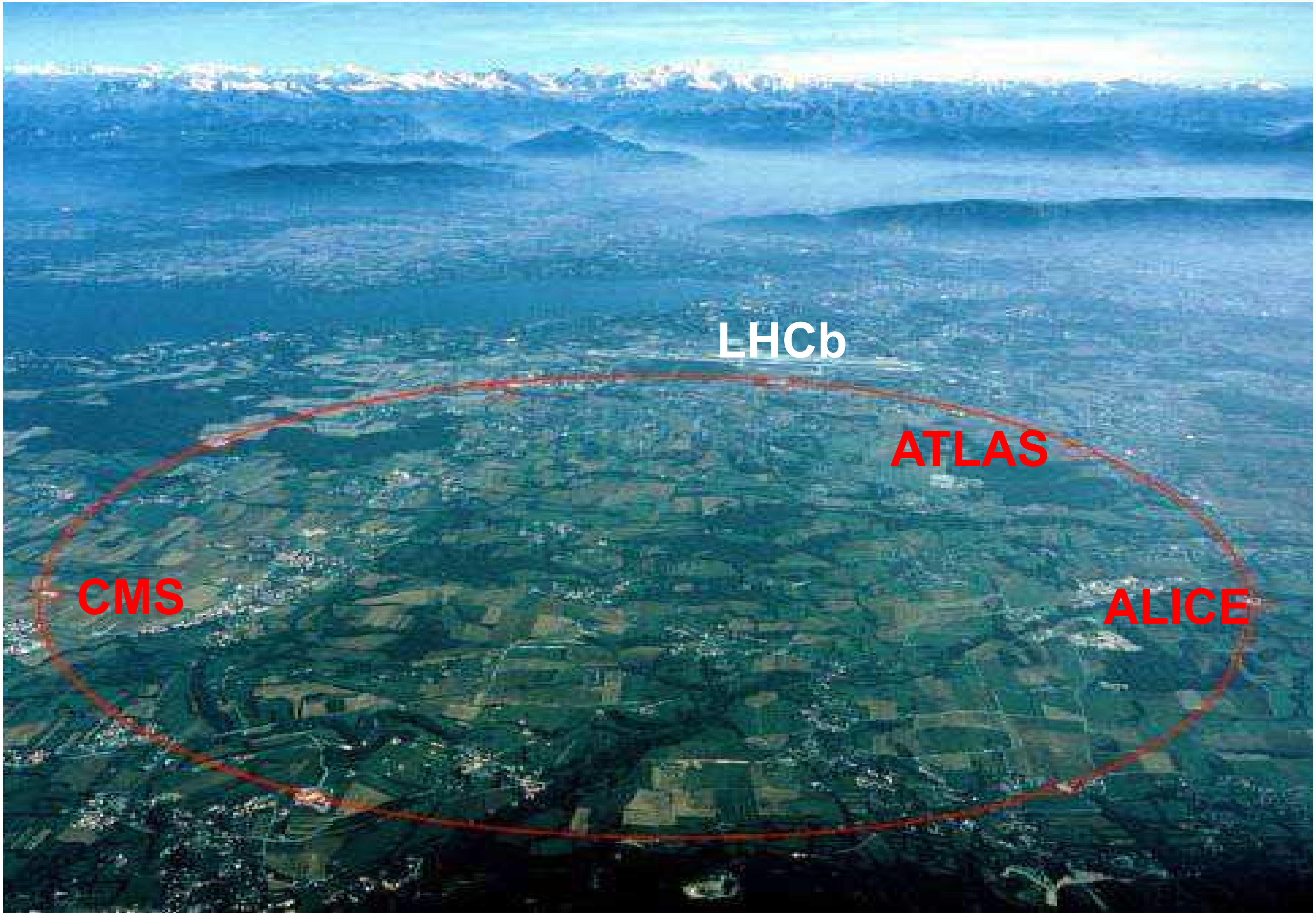
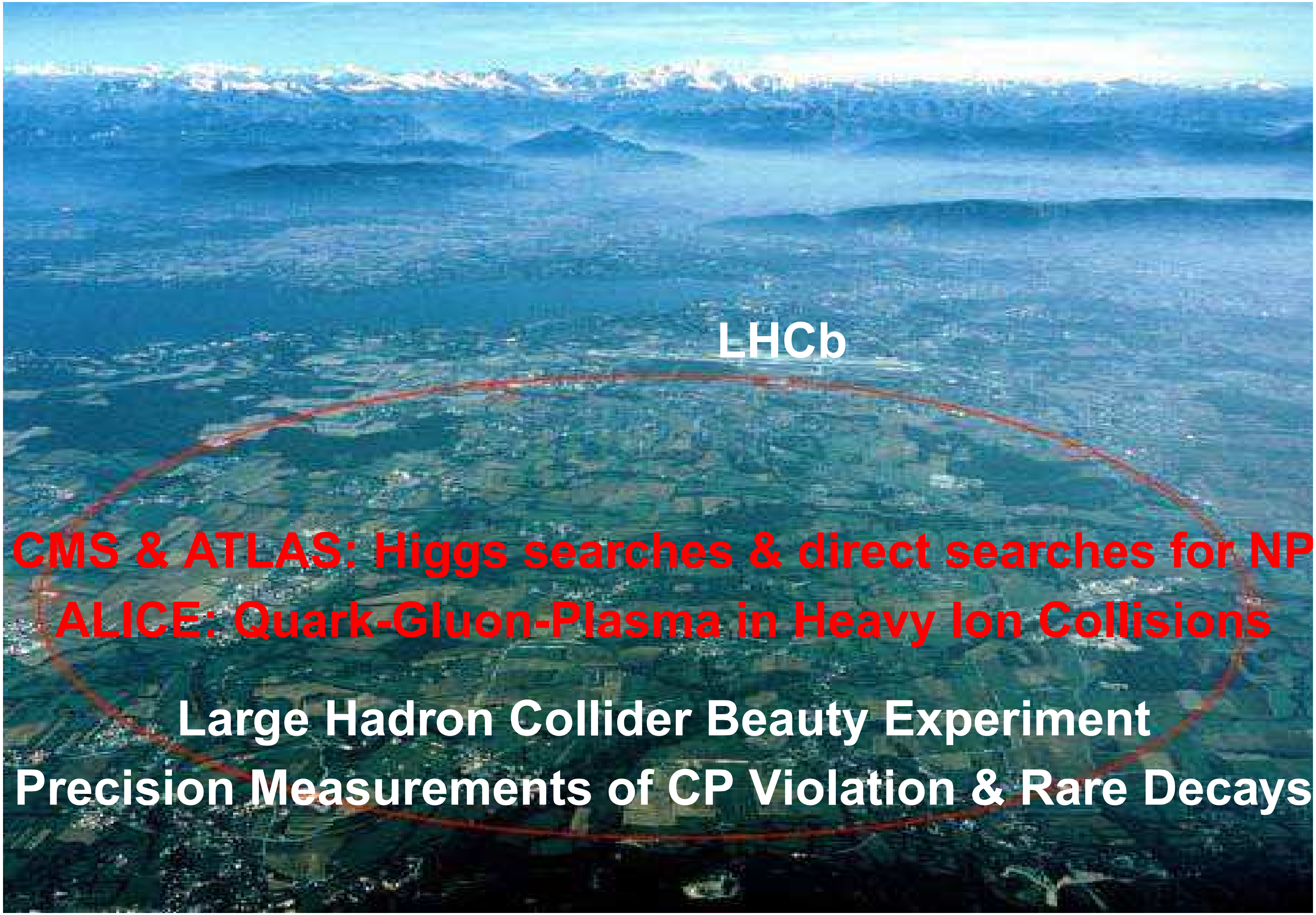
for the LHCb Collaboration

Workshop on the origins of P, CP & T violation, July 2008


LHCb
ATLAS
CMS
ALICE


LHCb
CMS & ATLAS: Higgs searches & direct searches for NP
ALICE: Quark-Gluon-Plasma in Heavy Ion Collisions
Large Hadron Collider Beauty Experiment
Precision Measurements of CP Violation & Rare Decays

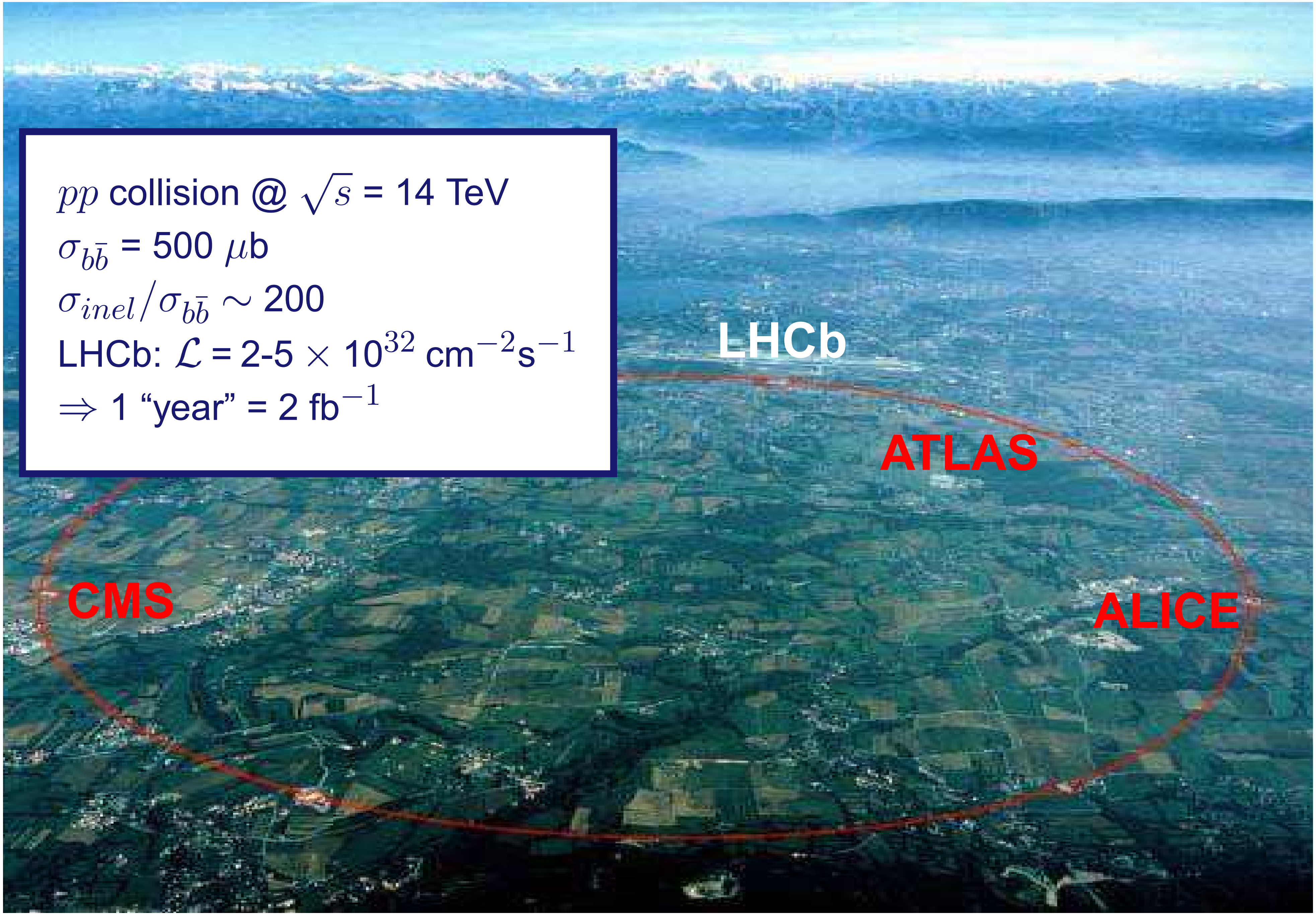
pp collision @ $\sqrt{s}$ = 14 TeV

$\sigma_{b\bar{b}}$ = 500 μb

$\sigma_{inel}/\sigma_{b\bar{b}} \sim$ 200

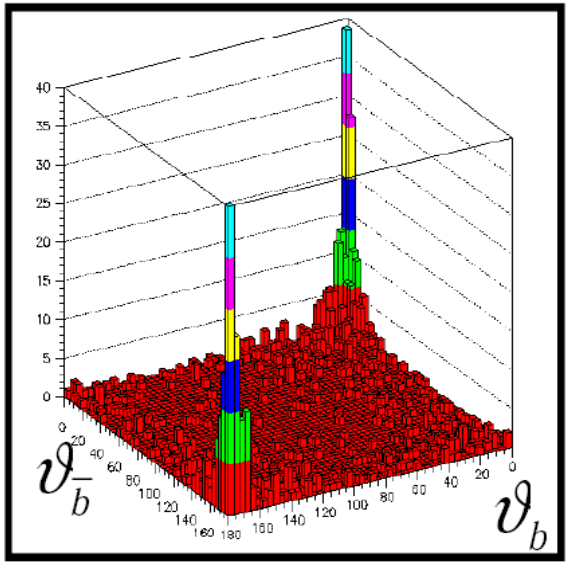
LHCb: $\mathcal{L}$ = 2-5 $\times$ 10^{32} cm^{-2}s^{-1}

$\Rightarrow$ 1 “year” = 2 fb^{-1}



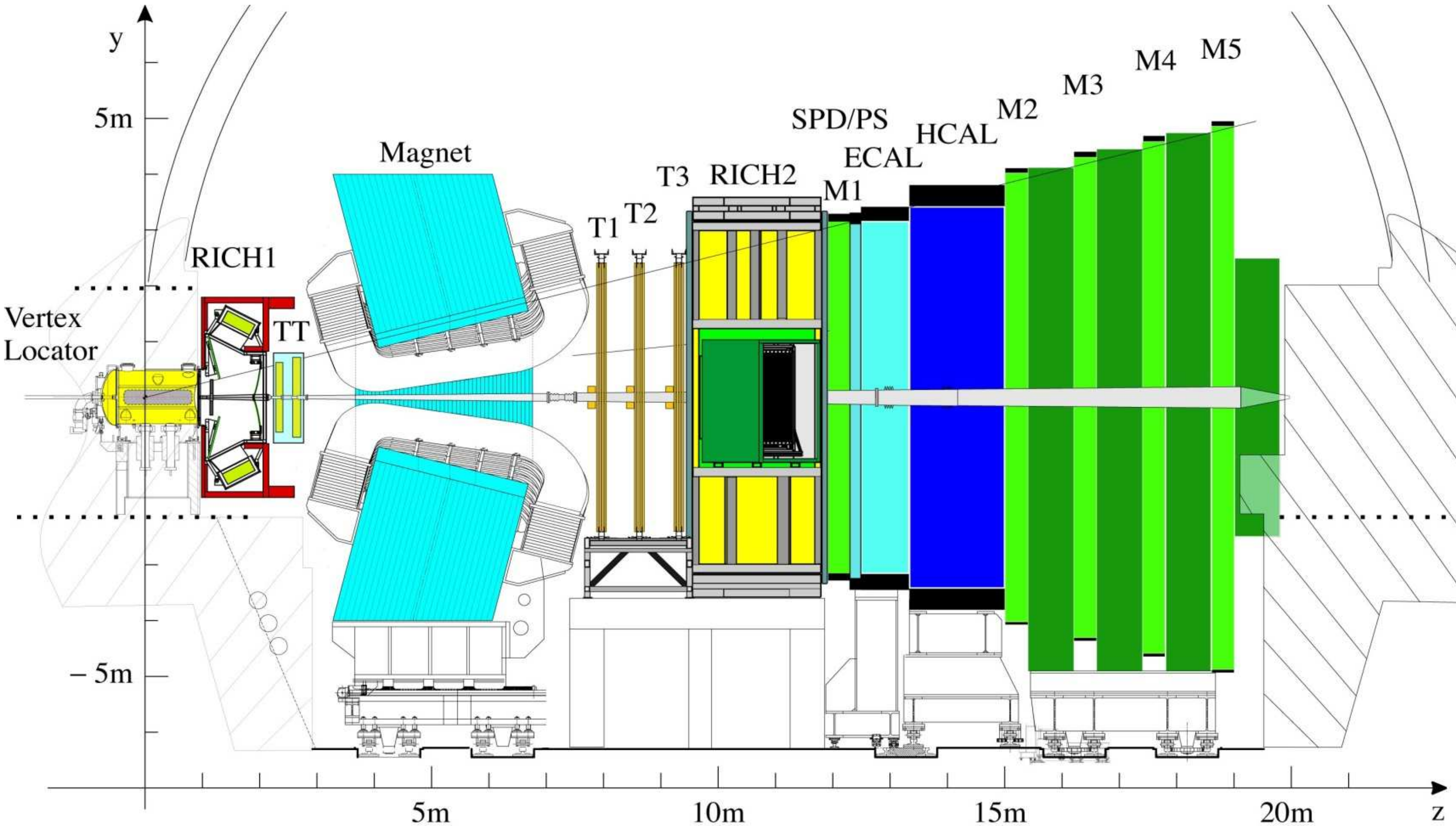
Some Facts about LHCb

- Single arm forward spectrometer
  $B\bar{B}$ production correlated,
  peaks in forward-backward direction
- B mesons in acceptance are highly boosted
  - average B momentum $\sim$ 80 GeV
  - typical lifetime resolution 40 fs ($\sim$ 3 % τ_B)
  - typical mass resolution 14-18 MeV
- Access to all flavours of B hadrons,
  B_s, B_c, Λ_b, ...
- in average 0.5 interactions per bunch crossing;
  $\sim$ 150 tracks per event

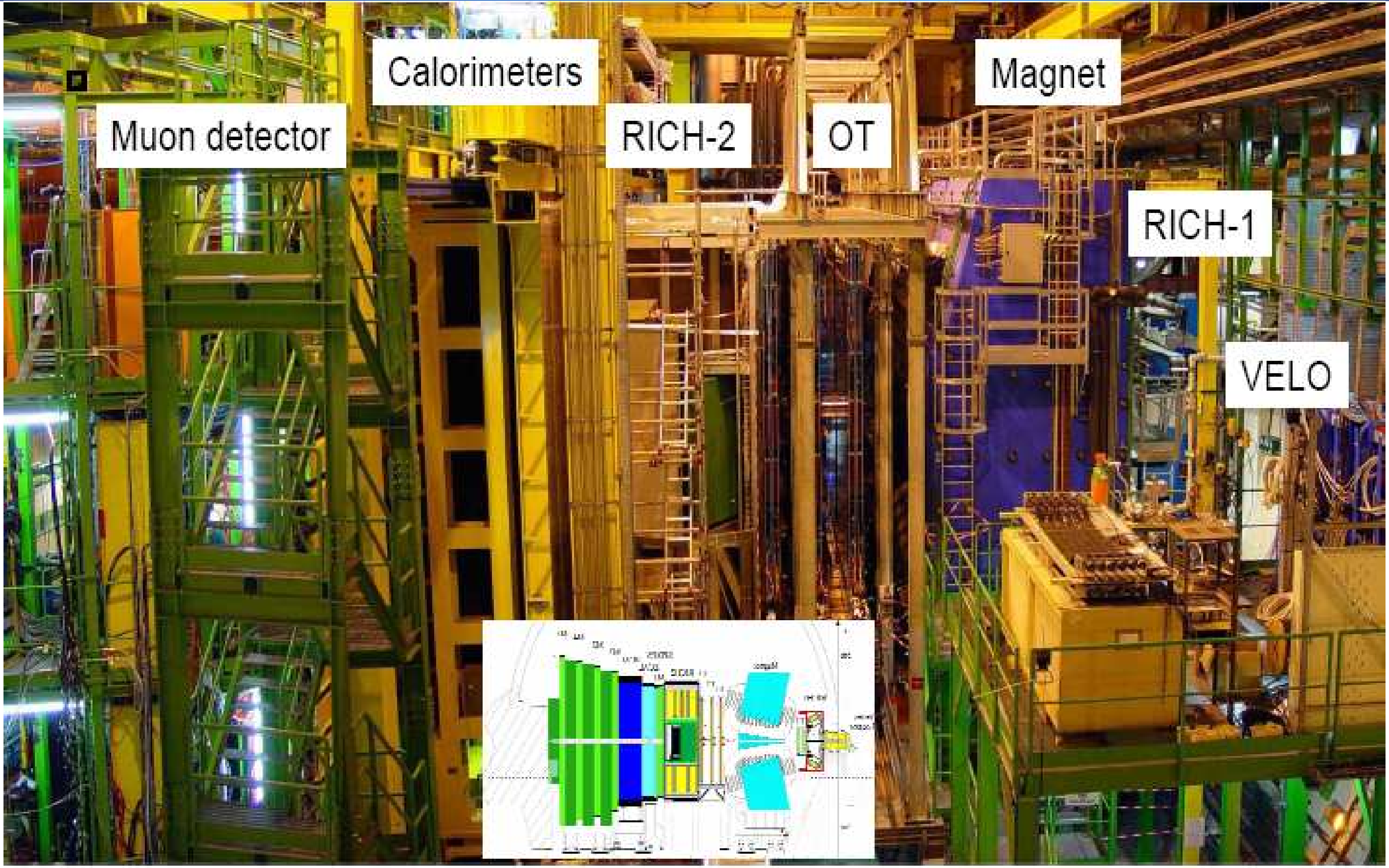


LHCb: Dedicated B physics experiment

The LHCb Experiment



The LHCb Experiment



Installation of major components completed!

Time Scale of LHCb

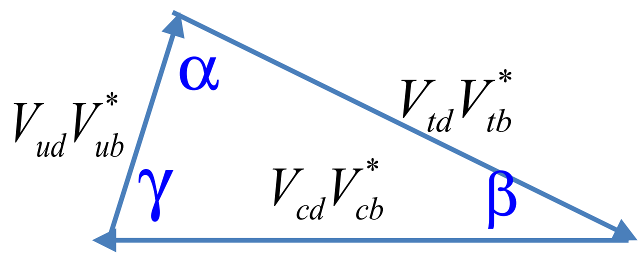
- Currently cooling down of magnets
  commissioning of the experiments with cosmics
- End of July, closure of the experiments
- First collisions autumn this year, only low level trigger
  $\sim$ 5 pb^{-1} $\longrightarrow$ detector alignment & calibration
- 2009: design lumi = 2$\times$10^{32} cm^{-2}s^{-1}; $\longrightarrow$ $\sim$ 0.5 fb^{-1},
  B physics data, high level triggers on
  calibration measurements: $\Delta m_{d/s}$, $\sin(2\beta)$, τ_B, ...
- from 2010 on: $\mathcal{L}$ = 2-5$\times$10^{32}cm^{-2}s^{-1}; $\sim$ 2 fb^{-1},
  full B physics programme
- by end of 2013 about 10 fb^{-1}
- .... then upgrade?

Definition of CKM Angles

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3 e^{-i\beta_d} & -A\lambda^2 e^{i\beta_s} & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

($\lambda \sim 0.22$)

B_d triangle:

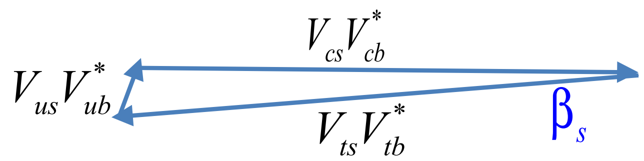


$$\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right);$$

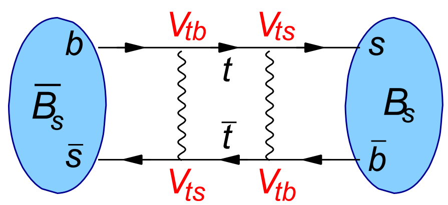
$$\beta = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right);$$

$$\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right);$$

B_s triangle:



$$\beta_s = arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right);$$



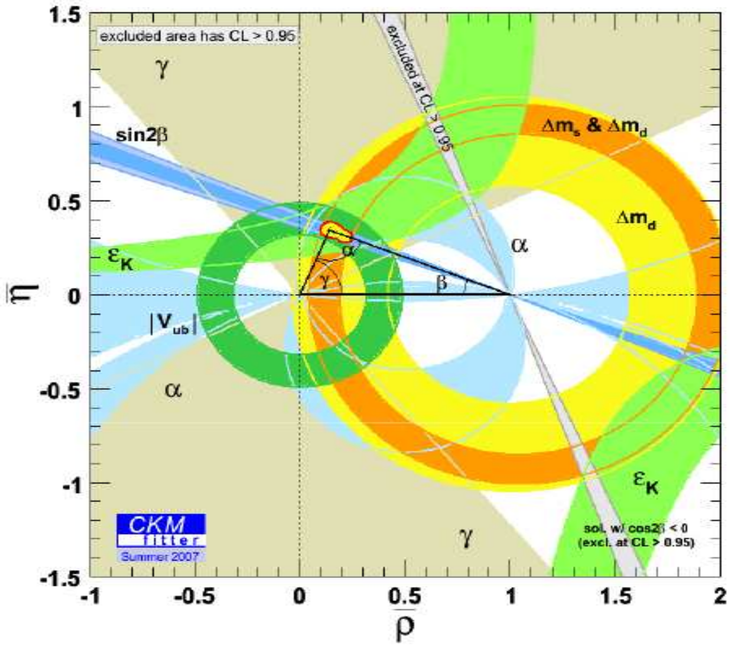
- $2\beta_s$ = ϕ_s (B_s mixing phase (SM))

2β = ϕ_d (B_d mixing phase (SM))

Status of Unitarity Triangle

Plot and precisions taken from CKM Fitter Summer 2007 update

parameter	value
α [°]	$87.5^{+6.2}_{-5.3}$
$\sin(2\beta)$	0.688 ± 0.025
γ [°]	$76.8^{+30.4}_{-31.5}$
ϕ_s	first results from Tevatron



Is CKM picture fully consistent for trees, boxes and penguins?

Do measurements of angles and sides give consistent results?

LHCb CP programme:

γ from trees & penguins; β_s from mixing box & penguins;

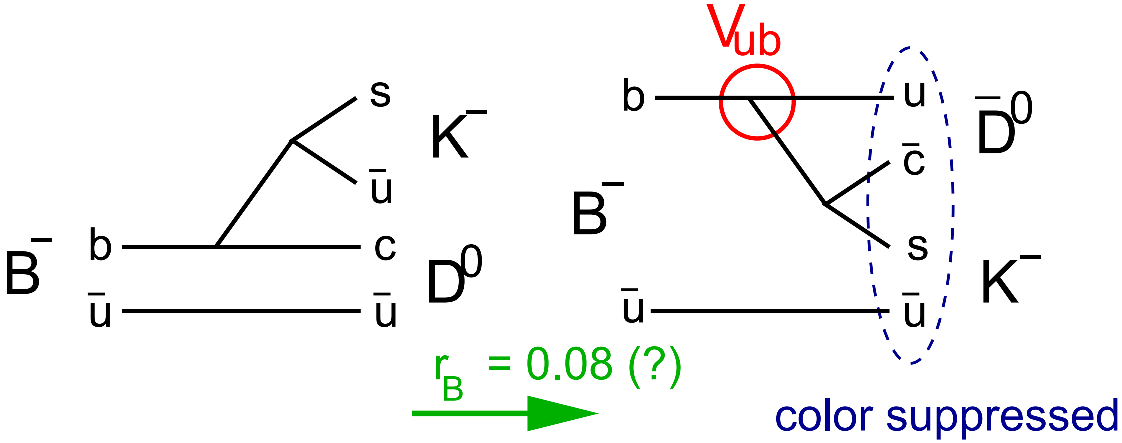
Measurements of the CKM angle γ:

- in tree diagrams - not sensitive to New Physics:
  - $B^{\pm} \longrightarrow D^0 K^{\pm}$
  - $B_s \longrightarrow D_s K^{\pm}$
- including loop diagrams - sensitive to New Physics:
  - $B_{(s)} \longrightarrow hh$

Different results in both approaches $\longrightarrow$ sign of New Physics

Current knowledge on CKM triangle mainly from loop diagrams,
γ from tree level is important cross check

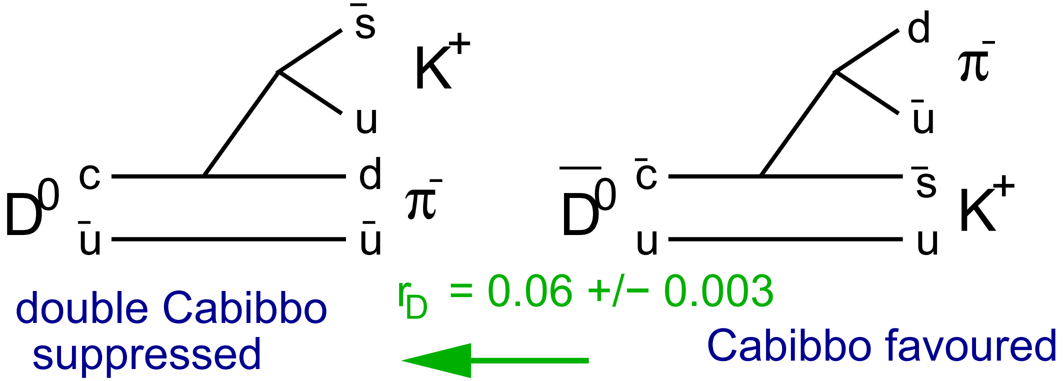
γ from Trees: $B \to DK$



▶ $D^0/\bar{D}^0$ decay in common flavour state ($K^+\pi^-$, $K^+3\pi$ ...)

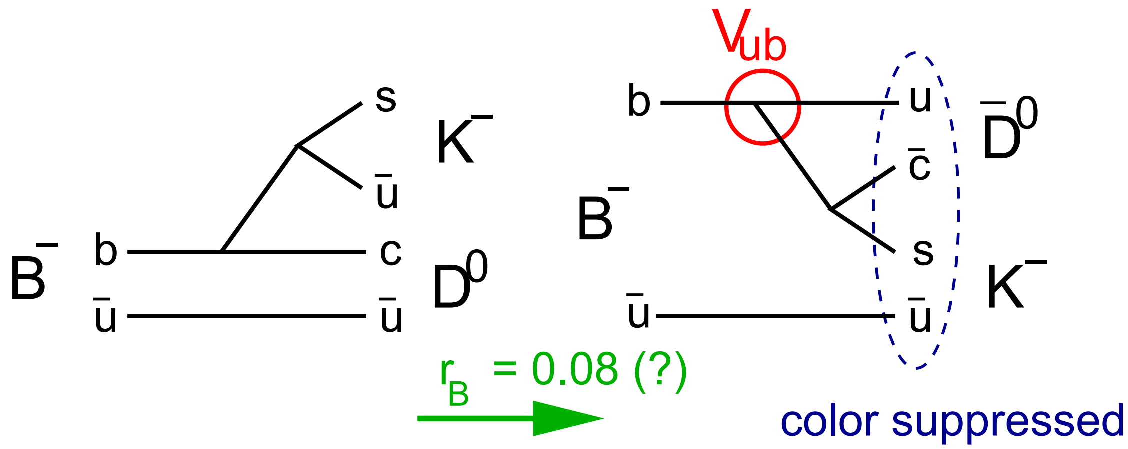
5 param.: $r_B = |\frac{A(B^- \to D^0 K^-)}{A(B^- \to \bar{D}^0 K^-)})|$, δ_B, γ, δ_D^{π}, $\delta_D^{3\pi}$ (r_D from CLEO-c)

Low event rate; large interference



Atwood-Dunietz-Soni Method

γ from Trees: $B \to DK$



- $D^0/\bar{D}^0$ decay in common CP eigenstate (K^+K^-, $\pi^+\pi^-$, ...)
  3 parameters: r_B, δ_B, γ
  Large event rate; small interference (r_B small)

Both analyses are decay time independent,
no flavour tagging needed!

Gronau-London-Wyler Method

γ from Trees: $B \to DK$

2fb^{-1}	Signal Yield	Background Yield
$B \to D(K\pi)K$, favoured	56k	35k
$B \to D(K\pi)K$, suppressed	0.7k	1.5k
$B \to D(K\pi\pi\pi)K$, favoured	62k	40k
$B \to D(K\pi\pi\pi)K$, suppressed	0.8k	2.4k
$B \to D(hh)K$	7.8k	14k

numbers depend on r_B

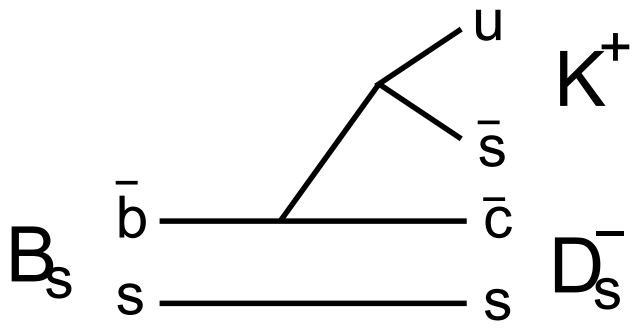
- $\sigma(\gamma) \sim$ 5-13° (2fb^{-1}), depend on strong phases in D decays
- Additional channels under study for global analysis

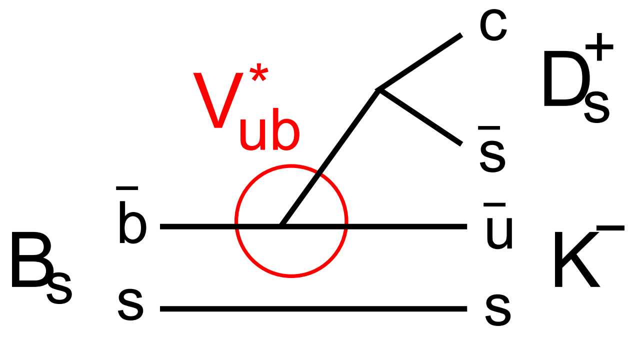
  complete list in the backup

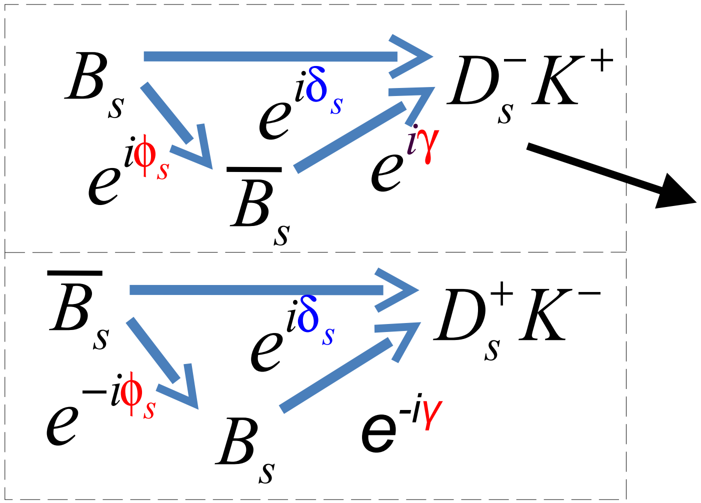
  Expect a combined precision of $\sim 5^\circ$ with 2 fb^{-1} of data

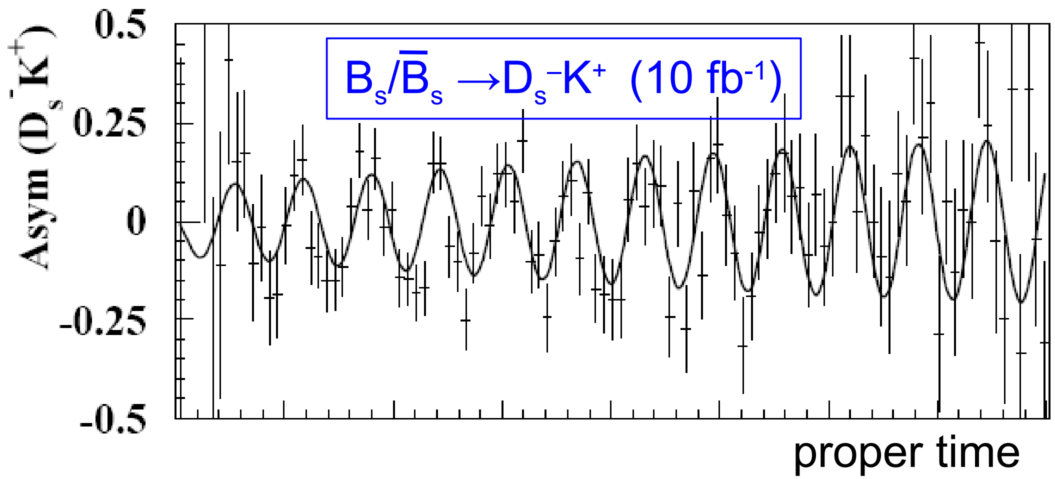
γ from Trees: $B_{(s)} \to D_{(s)}K$

- Time dependent CPV in interference of $b \to c$ and $b \to u$ decays:





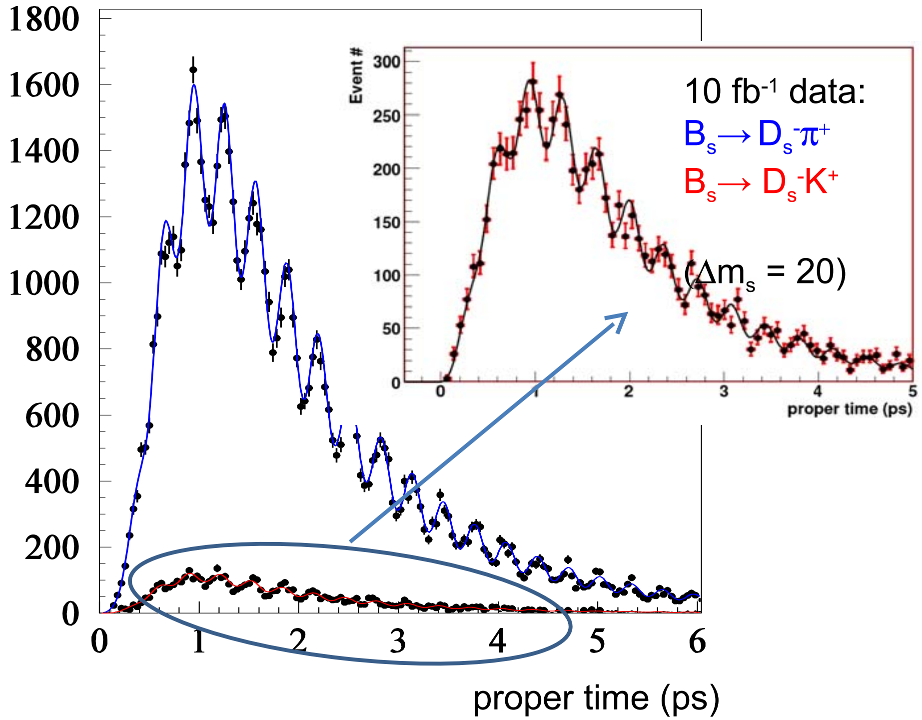




$$A^{B_s/\bar{B}_s}_{D_s^{\mp}K^{\pm}} = \frac{(1-|\lambda|^2)\cos(\Delta m_s t)-2|\lambda|\sin(\delta_s \mp(\gamma+\phi_s))\sin(\Delta m_s)}{(1+|\lambda|^2)\cosh\frac{\Delta\Gamma t}{2}-2|\lambda|\cos(\delta_s\mp(\gamma+\phi_s))\sinh\frac{\Delta\Gamma t}{2}}$$

γ from Trees: $B_{(s)} \to D_{(s)}K$

- Combine $B_s \to D_s K$, $B_s \to D_s \pi$ to fit for Δm_s, $\Delta\Gamma_s$, mis-tag rate & CP phase $\gamma + \phi_s$
- Use $\Delta\Gamma_s$ to resolve some ambiguities (2 remain)

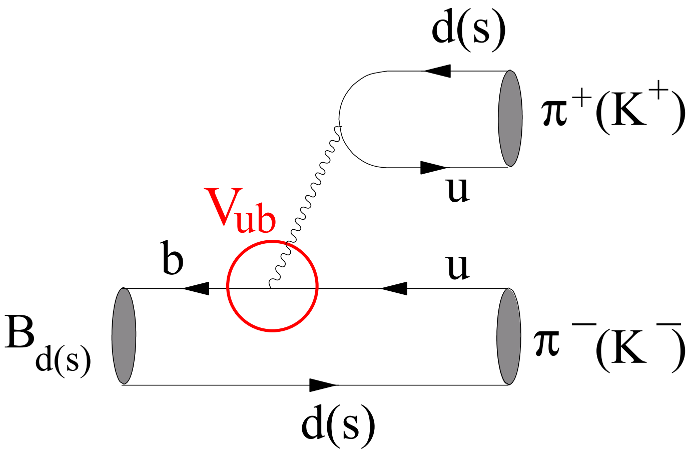


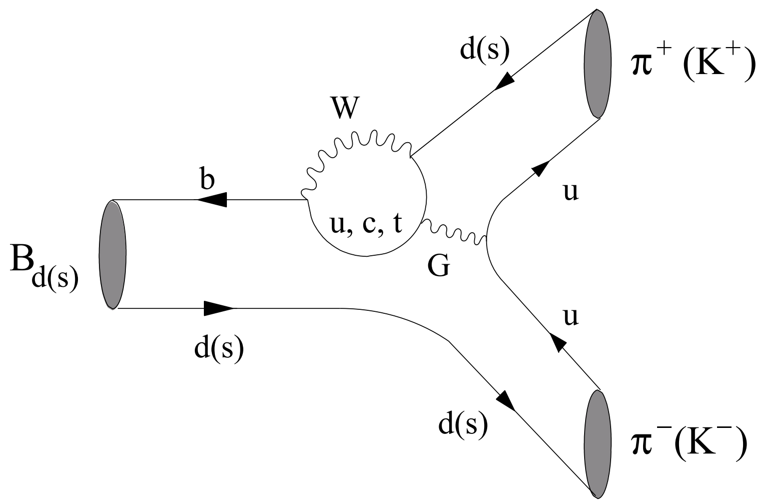
$\sigma(\gamma + \phi_s)$ = 9-12°

Channel	Yield (2 fb^{-1})	B/S (90% C.L.)
$B_s \to D_s K$	6.2 k	[0.08,0.4]
$B_s \to D_s \pi$	140 k	[0.08,0.4]

γ including Loops: $B_{(s)} \longrightarrow hh$

Sensitive to New Physics contribution in penguin diagram!





$$A_f^{CP}(t) = \frac{A_f^{dir}\cos(\Delta m t) + A_f^{mix}\sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_f^{\Delta}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

$$A_{dir}^{\pi\pi} = f_1(r_B, \delta_B, \sin(\gamma)); \qquad A_{mix}^{\pi\pi} = f_2(r_B, \delta_B, \sin(\phi_d));$$

$$A_{dir}^{KK} = f_3(r'_B, \delta'_B, \sin(\gamma)); \qquad A_{mix}^{KK} = f_4(r'_B, \delta'_B, \sin(\phi_s));$$

- $r_B(r'_B)$, $\delta_B(\delta'_B)$: strength & strong phase of penguins vs. tree diagram
- 5 parameters (ϕ_d & ϕ_s from external input), 4 measurements

Exploiting U-Spin Symmetry

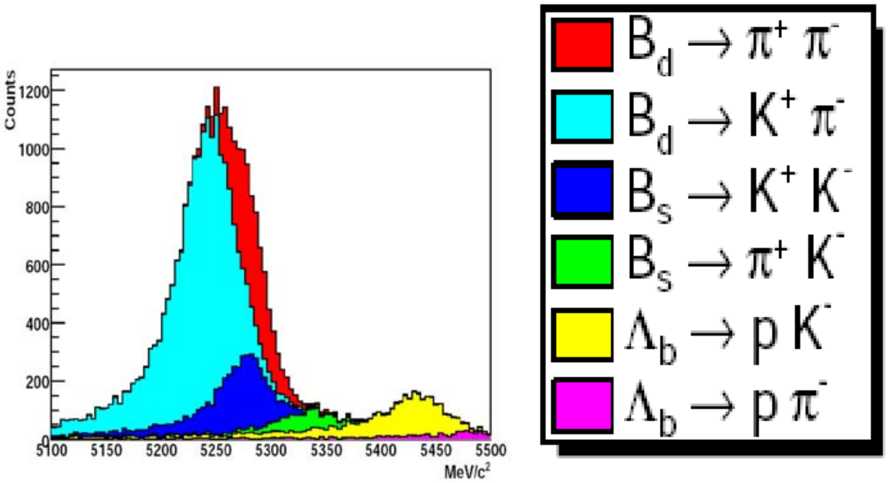
- U-spin symmetrie: no change in strong parameters by exchange of $d \leftrightarrow s$ (approximative symmetry) $\Rightarrow r_B \sim r'_B, \delta_B \sim \delta'_B$
- Only one of the assumptions needed, e.g. constraint $r_B = r'_B \pm 20\%$ fit for δ_B and δ'_B (check for U-spin sym.)
- Additional U-spin check: $A_{dir}^{KK} = A_{dir}^{\pi K}$; $A_{dir}^{\pi\pi} = A_{dir}^{K\pi}$

Fleischer Method

channel	Yield (2 fb^{-1})	B/S
$B \to \pi\pi$	36k	0.5
$B_s \to KK$	36k	0.15
$B \to K\pi$	138k	$<$0.06
$B_s \to \pi K$	10k	1.9

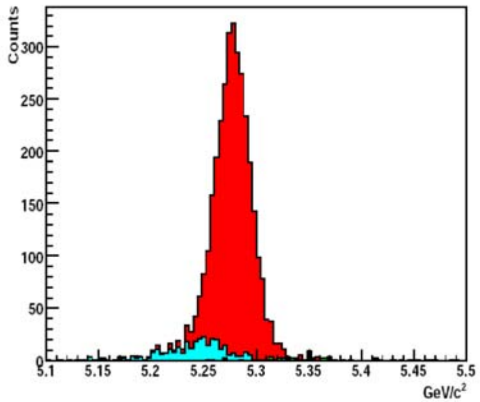
Particle Identification

Combined PID of RICH detectors & calorimeters allow clean separation of different $B \to hh$ mass peaks



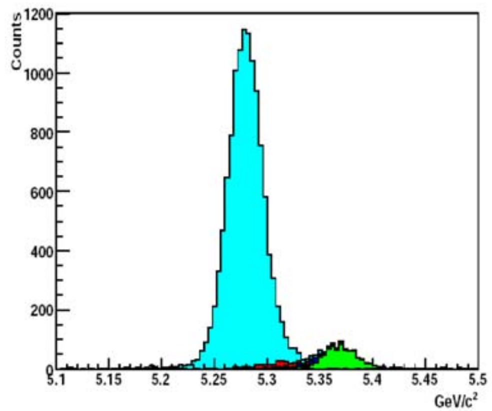
no PID, assuming pion hypothesis

(preselection cuts only)



$B_d \to \pi\pi$

(final selection cuts + PID)



$B_s \to \pi K, B_d \to K\pi$

$\sigma(m) \sim 16 MeV \to B_d/B_s$ separation

Sensitivity on γ

Sensitivity to CP violation parameters 2fb^{-1}

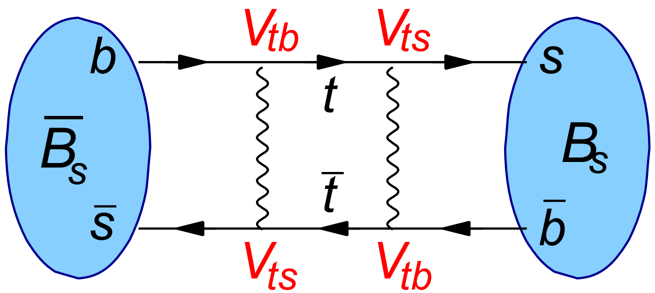
$\sigma(A^{\pi\pi}_{dir})$	$\sigma(A^{\pi\pi}_{mix})$	$\sigma(A^{KK}_{dir})$	$\sigma(A^{KK}_{mix})$
0.043	0.037	0.042	0.044

- $\sigma(\gamma)$ = 10° with 2 fb^{-1}
- $\sigma(\gamma)$ = 5° with 10 fb^{-1}

Including weak U-spin assumption r$^{'}_{B}$ = r$_{B}$ $\pm$ 20%

New Physics in B_s Mixing?

B_s system is uniquely accessible at hadron colliders!



B_s mixing described by three quantities: Δm_s, $\Delta\Gamma_s$, ϕ_s

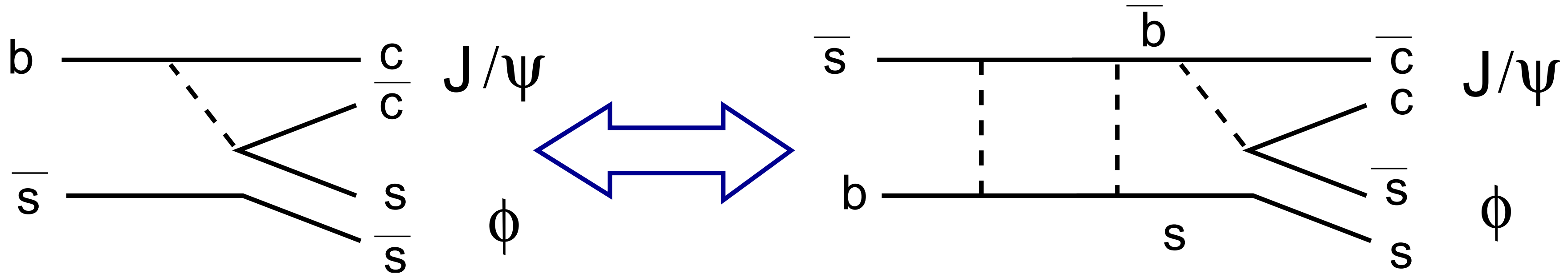
Δm_s precisely measured at the Tevatron, consistent with SM

$\Delta\Gamma_s$ not yet well measured, however no New Physics expected.

There can be potential NP involved in phase ϕ_s.
Extremely precise theoretical prediction ϕ_s = 0.04 $\pm$ 0.001 (SM)

Measurements from CDF & D0 from this winter indicate both a 2 σ deviation (see M. Rescigno's talk)!

$B_s \longrightarrow J/\psi\phi$



no CP violation in mixing, no CP violation in decay
$\longrightarrow$ plain CP violation in interference of mixing+decay & decay

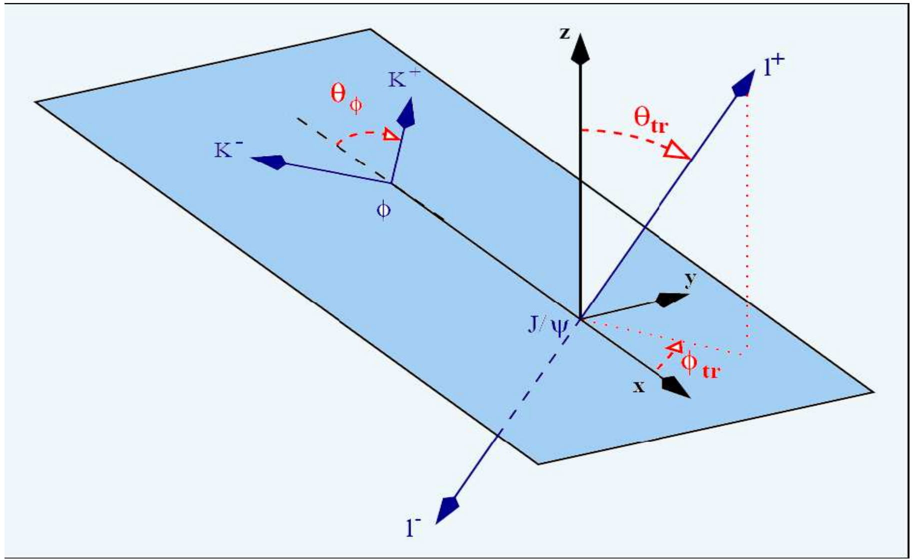
Final state $J/\psi\phi$ is linear combination of CP eigenstates.

relative angular momentum of J/ψ and ϕ: L=0,2 $\longrightarrow$ CP even
relative angular momentum of J/ψ and ϕ: L=1 $\longrightarrow$ CP odd

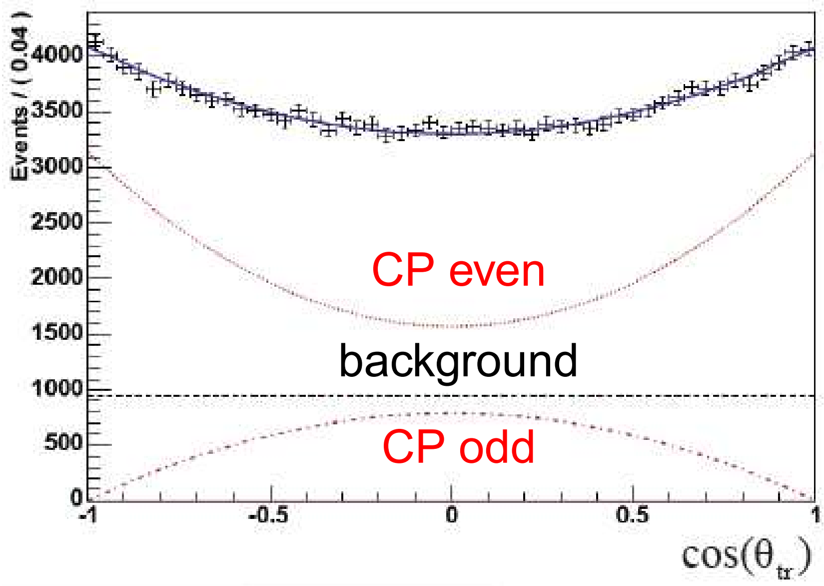
Use relative angular distribution of J/ψ and ϕ daughters to disentangle statistically CP even and CP odd contribution.

Angular Analysis

$\longrightarrow$ 3 angles define rel. angular distribution of 4 daughter tracks.

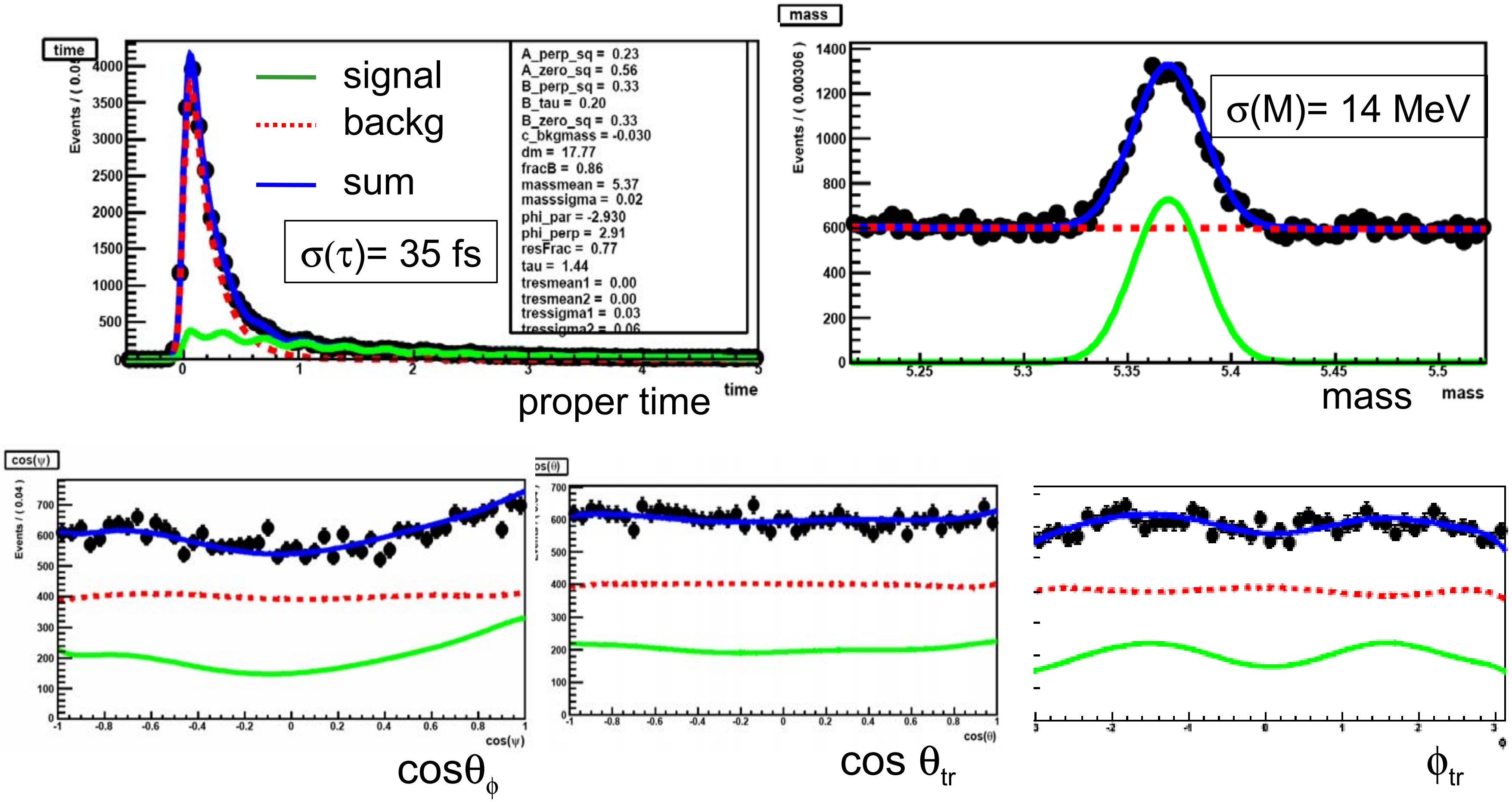


Transversity base



$B_s \rightarrow J/\psi\phi$ Analysis

Combined likelihood of mass, lifetime & angular distributions:



Results

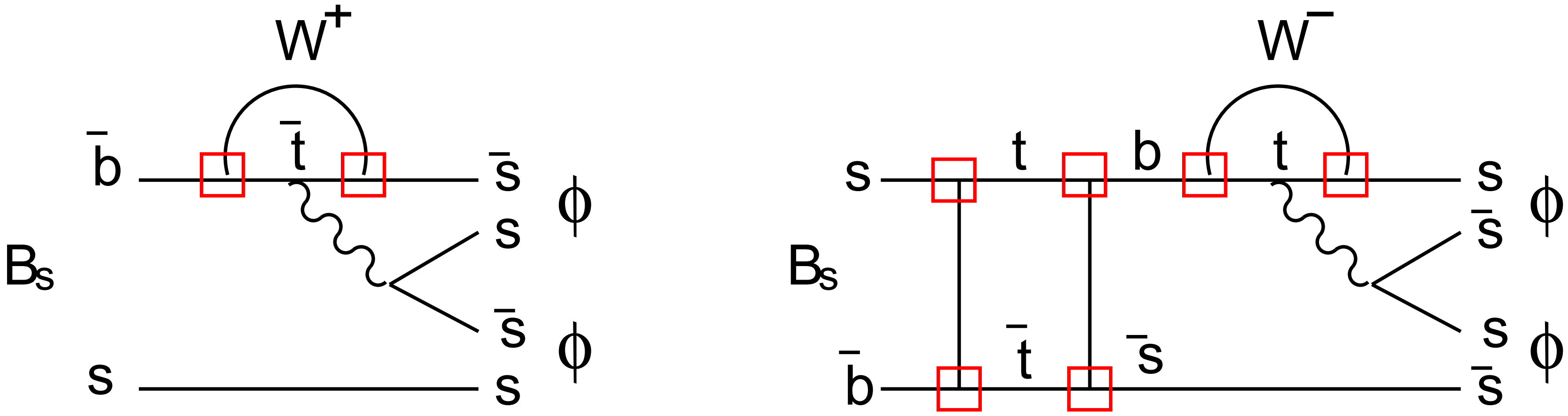
1. Admixture of CP eigenstates
"Golden mode": $B_s \to J/\psi\phi$
Large yield, nice signature
However requires angular analysis to disentangle CP-even and CP-odd

2. Pure CP eigenstates:
Low yield, high background

Decay	Yield (2fb^{-1})	$\sigma(\phi_s)$
$J/\psi\phi$	130k	0.023
$J/\psi\eta_{\gamma\gamma}$	8.5 k	0.109
$J/\psi\eta_{\pi\pi\pi}$	3k	0.142
$J/\psi\eta^{'}_{\pi\pi\eta}$	2.2k	0.154
$J/\psi\eta^{'}_{\rho\gamma}$	4.2k	0.008
$\eta_c\phi$	3k	0.108
$D_s^+D_s^-$	4k	0.133
All CP eig	-	0.046
All	-	0.021

Input: ϕ_s = 0.04, $\Delta\Gamma_s$=0.1 ps^{-1}; δ_1 = 0; δ_s = π; R_0=0.6; $R_\perp$=0.2;

Penguin Decay: $B_s \longrightarrow \phi\phi$



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 $B_s \longrightarrow J/\psi\phi$

20k expected candidates per year
Lower yield rel. to $B_s \longrightarrow J/\psi\phi$ due to penguin suppression.
$\sigma(\phi_s)$: 0.08

Summary

LHCb will see first collisions in autumn 2008

- Possible early significant measurement of ϕ_s if New Physics contributions are large!
- Will achieve a precision of few degrees on γ with first year of nominal running

Many more tests for New Physics will be performed at LHCb:

- Branching ratio of $B_s \to \mu^+\mu^-$
- Forward-backward asymmetrie in $B_d \to K^*\mu^+\mu^-$
- Asymmetry measurements in decays including $b \to s\gamma$ transitions
- ...

U-spin Symmetric Modes

$B_d \to \pi^+\pi^-$ $T+P+P^C_{EW}+PA+E$	$\Leftrightarrow$	$B_s \to K^+K^-$ $T+P+P^C_{EW}+PA+E$
$B_d \to \pi^+\pi^-$ $T+P+P^C_{EW}+PA+E$	$\Leftrightarrow$	$B_s \to \pi^+K^-$ $T+P+P^C_{EW}$
$B_s \to K^+K^-$ $T+P+P^C_{EW}+PA+E$	$\Leftrightarrow$	$B_d \to K^+\pi^-$ $T+P+P^C_{EW}$

- T: tree
- P: penguin
- P^C_{EW}: colour suppressed electroweak penguin
- PA: penguin annihilation
- E: exchange

- Not all exactly U-spin symmetric, E and PA contributions missing from flavour specific decays
- E and PA contributions expected to be relatively small, and can be experimentally probed by measuring the still unobserved $B_s \to \pi^+\pi^-$ and $B_d \to K^+K^-$ branching ratios (BR~10^{-8})

Other CPV Measurements

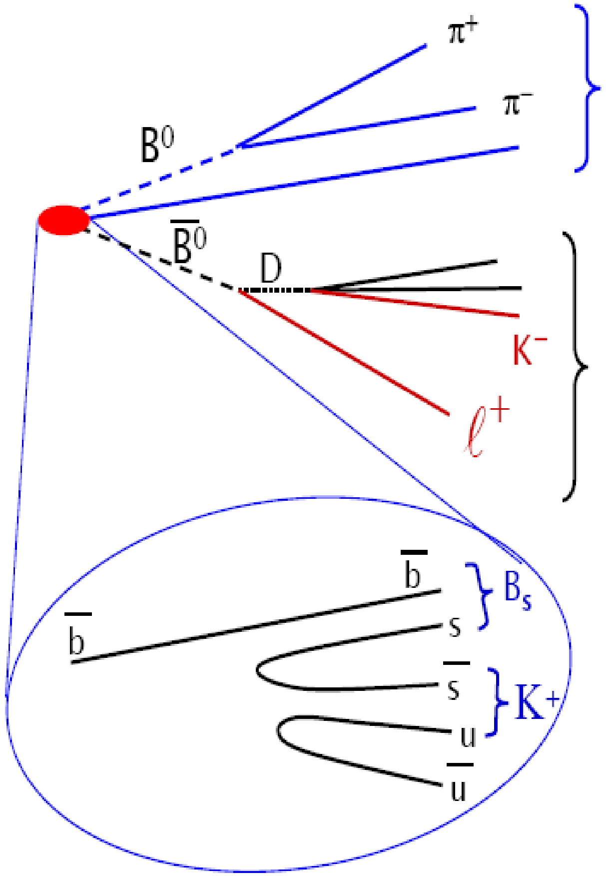
	Measurement Channel	Precision after 2fb^{-1}	Precision after 10fb^{-1}
α	$B^0 \longrightarrow \pi^+\pi^-\pi^0$	8.5°	$\sim 5^\circ$
$\sin(2\beta)$	$B^0 \longrightarrow J/\psi K_s$	0.020*	0.010

* Compare to 0.019 expected from B factories after 2 ab^{-1}

Additional $B \rightarrow DK$ Channels

- $B^{\pm} \rightarrow DK^{\pm}$, with $D \rightarrow K_s\pi\pi$ (Dalitz analysis) $\sigma(\gamma)$ = 8-12°
- $B^{\pm} \rightarrow DK^{\pm}$, with $D \rightarrow KK\pi\pi$ (Dalitz analysis) $\sigma(\gamma)$ = 18°
- $B^{\pm} \rightarrow D^{*}K^{\pm}$, with $D \rightarrow KK, K\pi, \pi\pi$ (high background)
- $B^{0} \rightarrow DK^{*0}$, with $D \rightarrow KK, K\pi, \pi\pi$ $\sigma(\gamma)$ = 6-12°

Necessary Tool: Flavour Tagging



Same Side Tagging

- fragmentation pion/kaon near B

Opposite Side Tagging

- lepton
- kaon
- vertex charge

tag	ϵ_{tag}[%]	ω[%]	ϵ_{eff}[%]
muon	11	35	1.0
electron	5	36	0.4
kaon	17	31	2.4
vertex charge	24	40	1.0
frag. kaon (B_s)	18	33	2.1
Σ			$\sim$ 6

wrong tag probability: ω

dilution: $\mathcal{D}$ = 1-2ω

effective tagging power:

$$\epsilon_{eff} = \epsilon_{tag}\,\mathcal{D}^2$$