LHCb experiment and its expected physics performance

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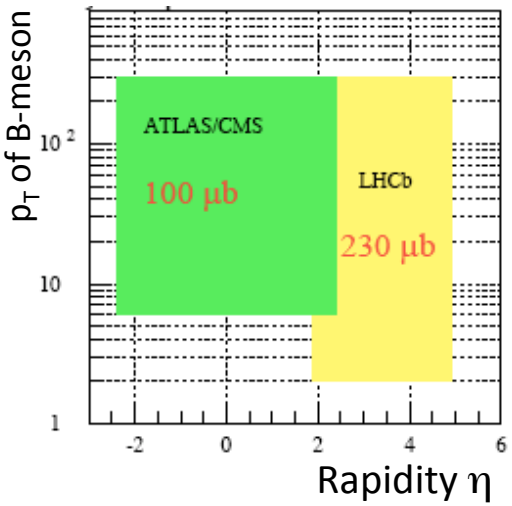
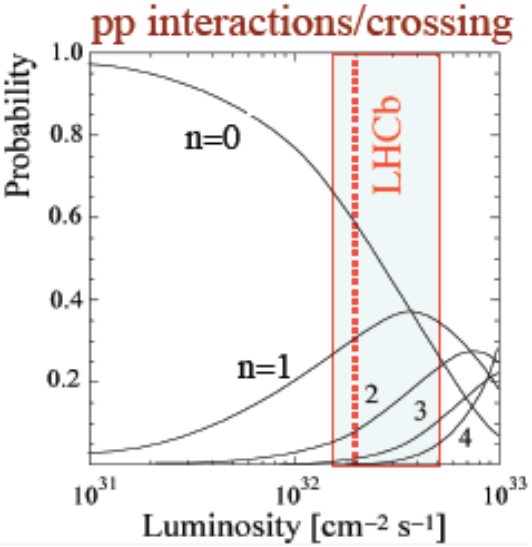
The LHCb experiment

- Dedicated B-physics experiment @LHC collider:
  - CP-violation
  - Rare decays
  - Standard Model / indirect evidence of New Physics

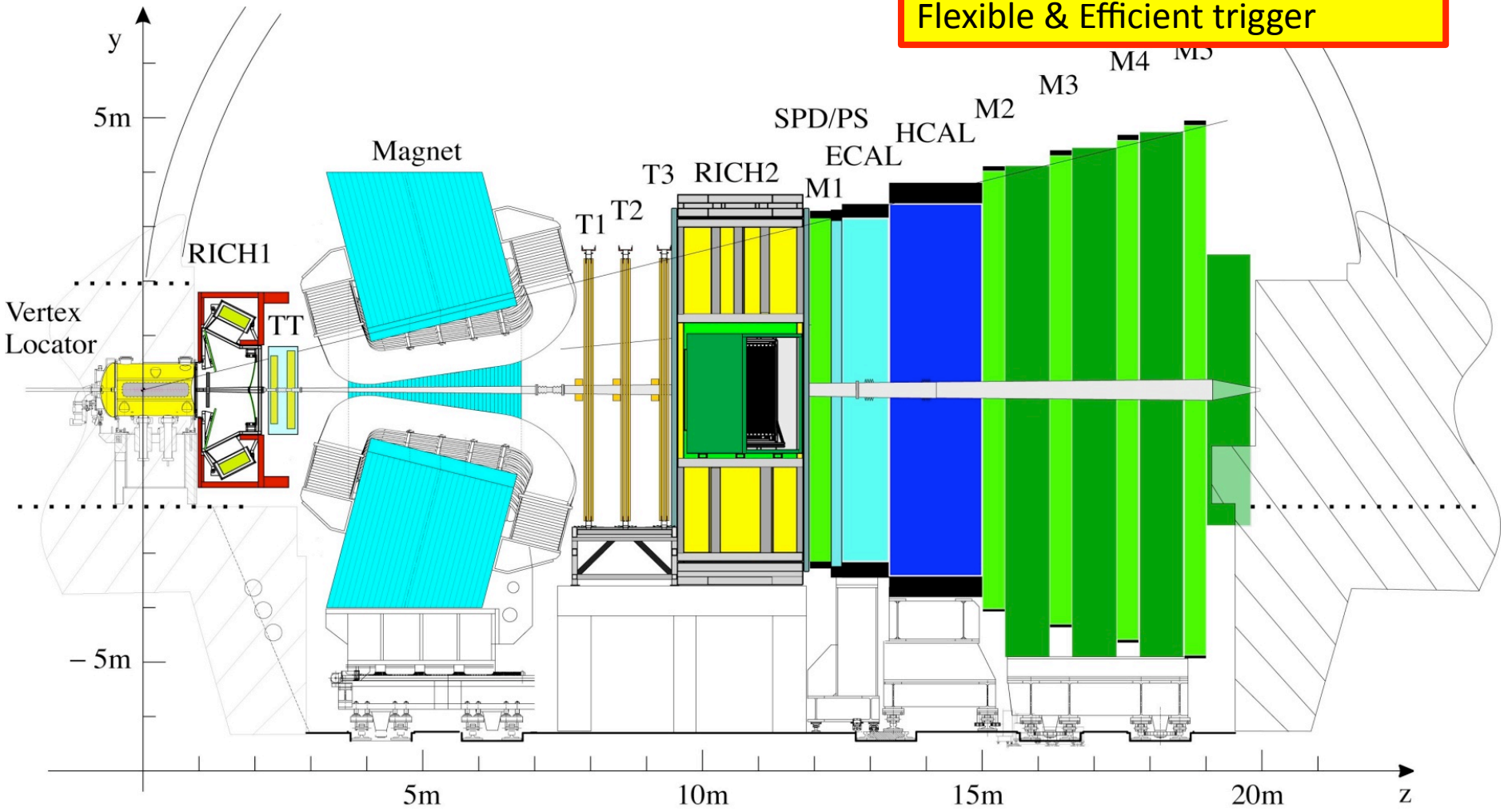
- LHCb@LHC
  - $\sqrt{s}$=14 TeV σ_{bb}~500μb σ_{vis}/σ_{bb} ~120
  - Forward spectrometer 1.9<|η|<4.9
  - Luminosity=2-5 x10^{32}cm^{-2}s^{-1}
    - Max probability of single interaction
    - Low radiation damage / available since the beginning
  - 1 "year" (10^7 s) = 2 fb^{-1} ~10^{12} bb pairs produced in acceptance
- Detector and Trigger are especially designed for B-physics studies





The LHCb spectrometer

Requirements:
Excellent tracking & vertexing
Excellent particle ID (e/μ/π/K/p)
Flexible & Efficient trigger



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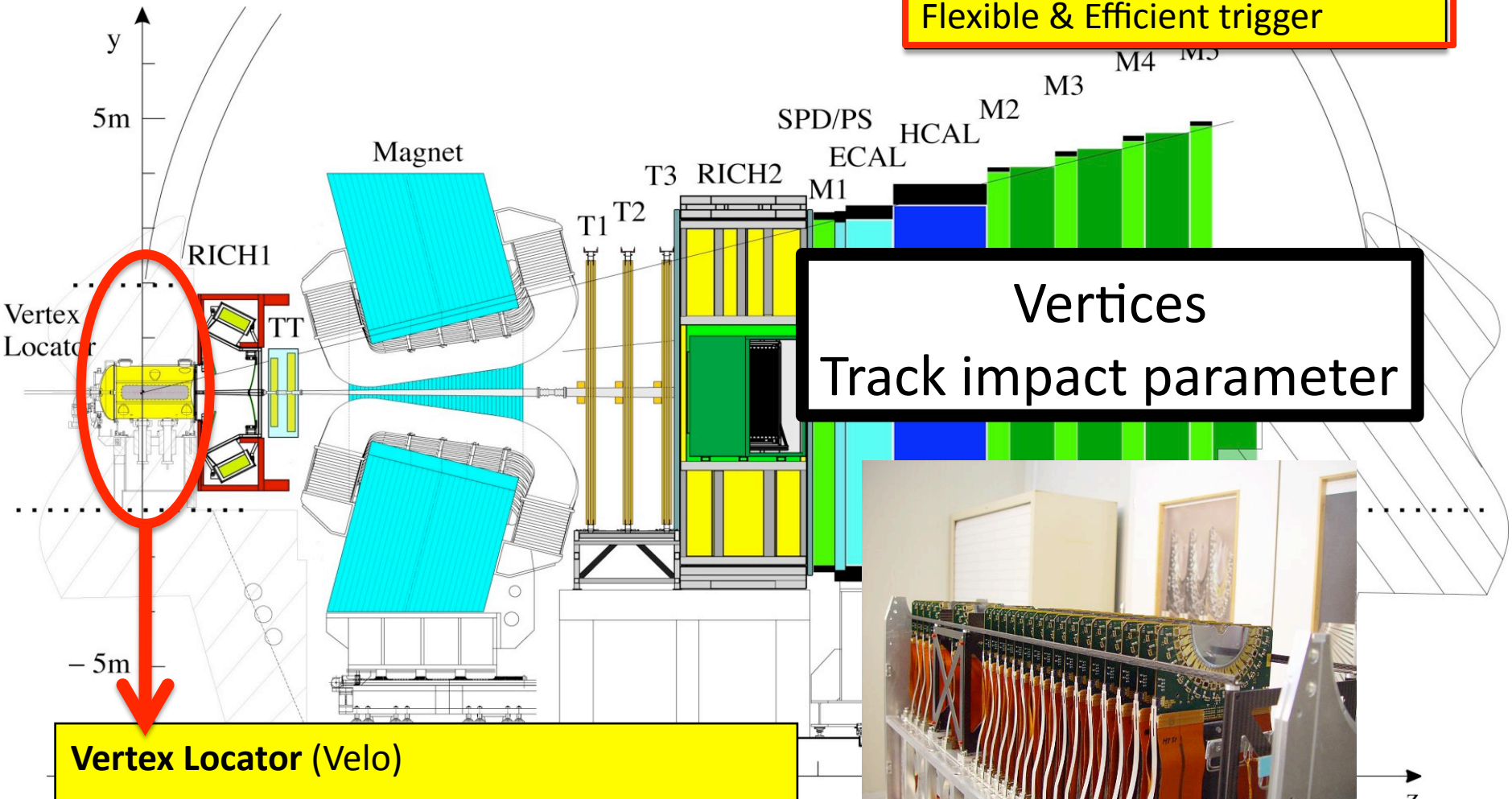

Vertices

Track impact parameter

Vertex Locator (Velo)

21 modules silicon strip ~ 5 μm hit resolution

Pileup veto Trigger L0 / HLT trigger

The LHCb spectrometer

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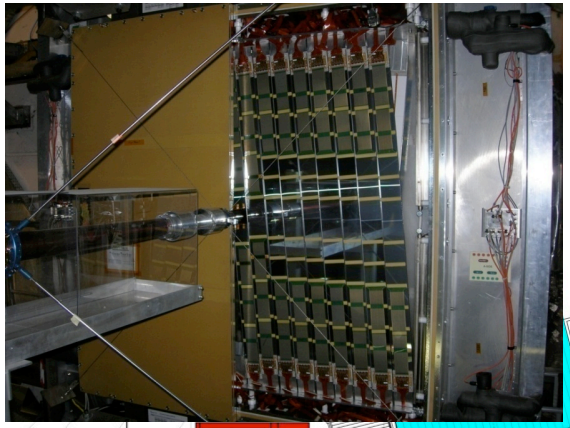

Tracking + B-field
Momentum & mass

2 Tracking systems: TT T1/T2/T3 & B-field 4Tm

silicon strips and straw tubes

Trigger HLT

The LHCb spectrometer

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Excellent particle ID (e/μ/π/K/p)
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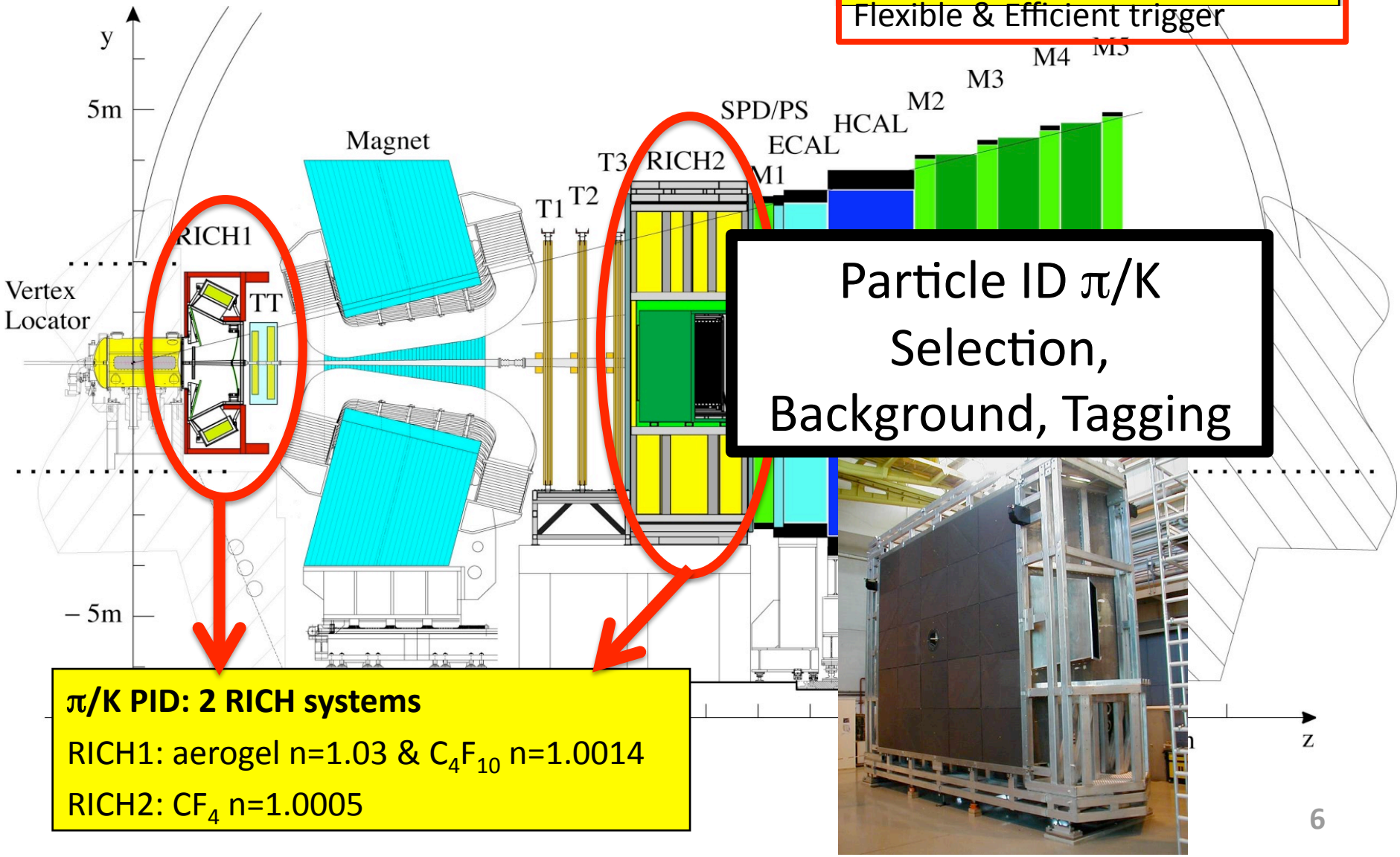

Particle ID π/K Selection, Background, Tagging

π/K PID: 2 RICH systems

RICH1: aerogel n=1.03 & C_4F_{10} n=1.0014

RICH2: CF_4 n=1.0005

The LHCb spectrometer

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Excellent tracking & vertexing
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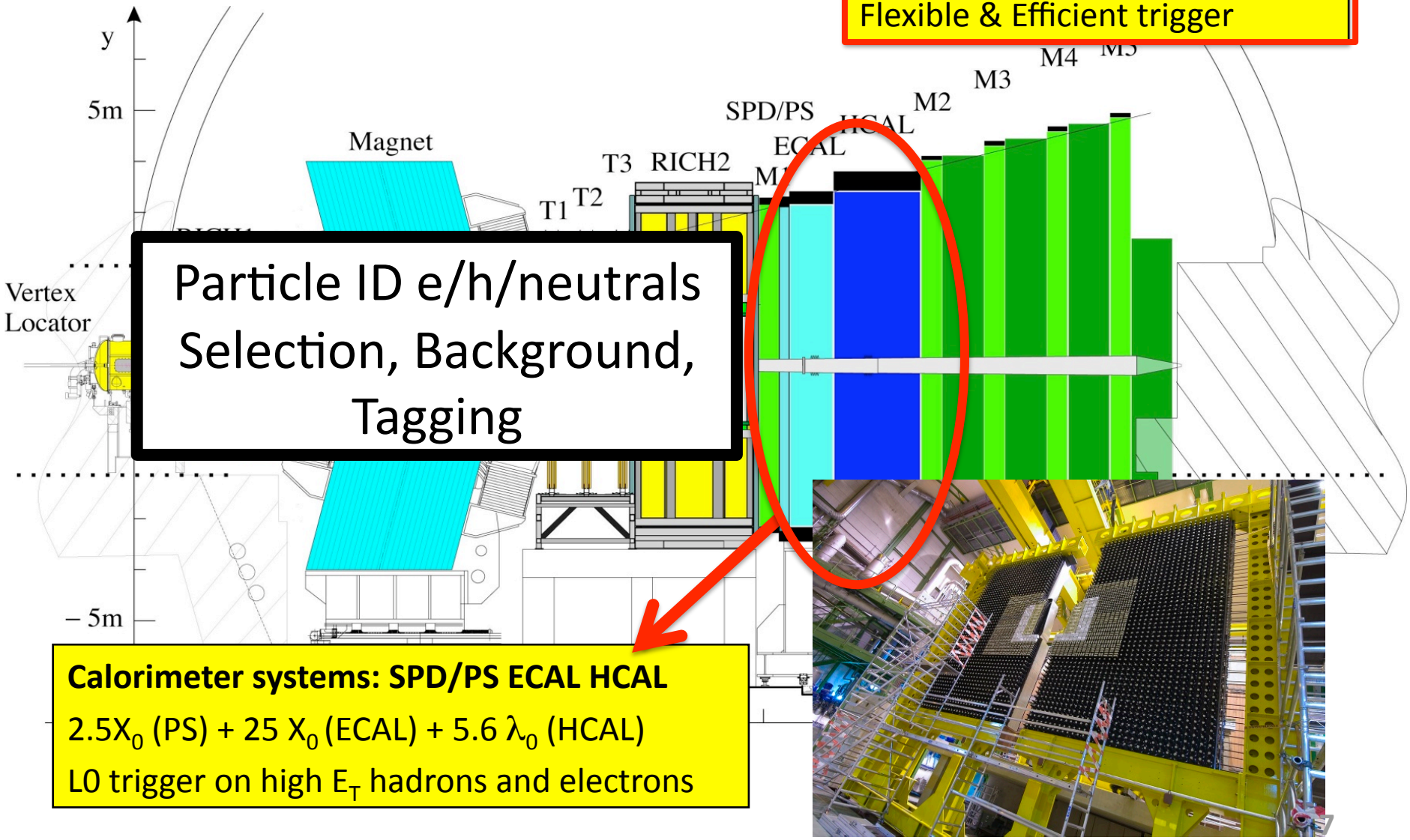


Particle ID e/h/neutrals
Selection, Background,
Tagging

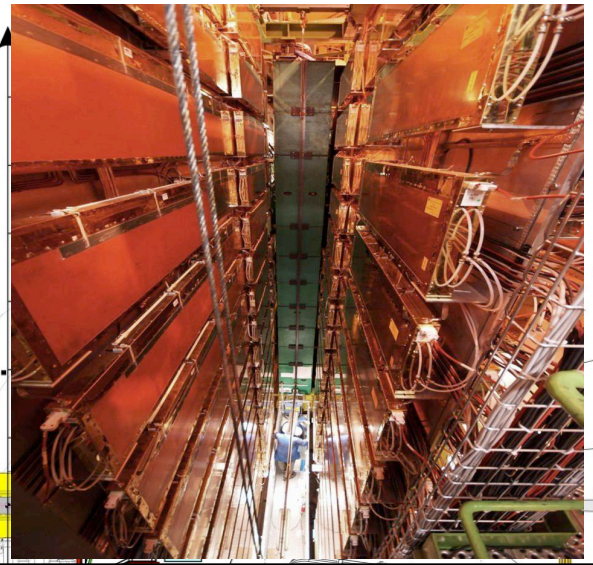
Calorimeter systems: SPD/PS ECAL HCAL

$2.5X_0$ (PS) + 25 X_0 (ECAL) + 5.6 λ_0 (HCAL)

L0 trigger on high E_T hadrons and electrons

The LHCb spectrometer

Requirements:
Excellent tracking & vertexing
Excellent particle ID (e/μ/π/K/p)
Flexible & Efficient trigger



μ Particle ID
Selection, Background, Tagging

Muon systems: 5 stations/ 4 Filters (E-HCAL+MF)
L0 trigger on high p_T muons

Event reconstruction performances

quantity	performance	
Track Impact Parameter	**$\langle\sigma(IP)\rangle$ ~ 30 μm**	Signal selection Background suppression Tagging
Track efficiency	ε>95% (tracks from B) ~4% ghost Ks→$\pi\pi$ ε~75% in VELO	
Track momentum	$\sigma(p)/p$ = [0.3,0.5]%	
PID π/K	Kaon ID $\langle\varepsilon\rangle$~97% Mis ID ($\pi$) ~ 5% range p=[2,100]GeV/c	
B decay time	**$\sigma(t)$ ~ 40 fs**	**Time dependent analyses Bs**
Invariant mass	**$\sigma(m_B)$=15-20 MeV/c^2**	**Signal selection** **Background suppression B_d/B_s**
Tagging B^0	**$\langle\varepsilon D^2\rangle$ = 4-5% B^0** **$\langle\varepsilon D^2\rangle$ = 7-9% B^0_S**	**CP asymmetry**

The LHCb trigger

Detector

40 MHz — Custom electronics

L0: "high" p_T (μ, e, γ, *h*) Pileup-VETO [hardware] 4 μs

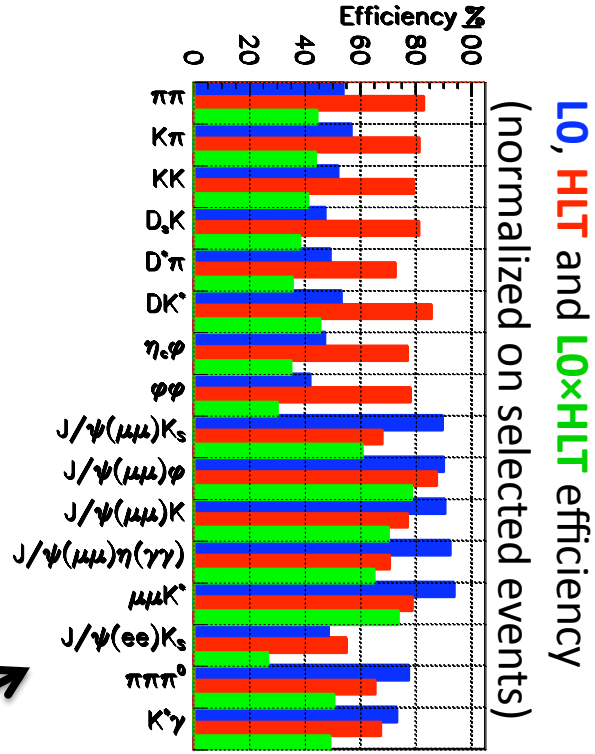
1 MHz — PC farm

HLT: high IP, "high" p_T tracks [software]
then full reconstruction of event

2 kHz

Storage (event size ~ 30 kB)

HLT rate	Event type	Physics
200 Hz	Exclusive B candidates	B (core program)
600 Hz	High mass di-muons	J/ψ, b→J/ψX (time unbiased)
300 Hz	D* candidates	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. b→μ)	B (data mining)



Inclusive streams for calibration to control systematics (trigger/ tracking/tagging/PID) but also for physics

Running scenario & physics program

2008: start up

Low luminosity ~10^{31} $cm^{-2}s^{-1}$ 50 days (pile-up)

Minimum trigger -->L0 Hope to get **~5 pb^{-1}**

Detector calibrations
Alignment
No CP physics run

2009

LHCb design Luminosity=$2x10^{32}$ $cm^{-2}s^{-1}$ 140 days

L0+HLT **~0.5 fb^{-1}**

B physics run:
"calibration" CP measurements (ΔMd, sin2β, ΔMs, τ)
CP & some Rare decays

>2010

Luminosity=2-5x10^{32} $cm^{-2}s^{-1}$ 140 days

~2 fb^{-1}

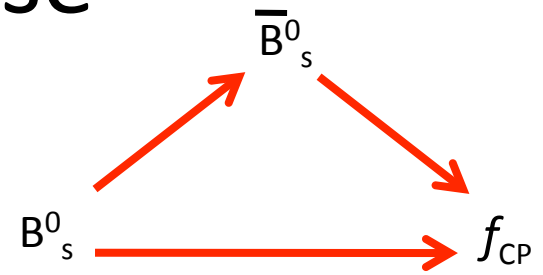
Full physics program

By the end 2013 **Σ~10 fb^{-1}**

LHCb upgrade?

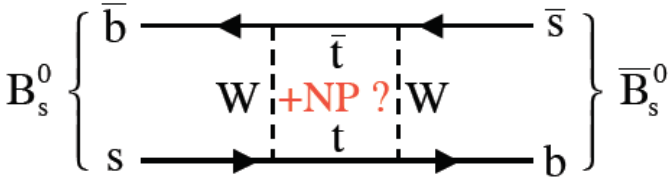
The B_s mixing phase

- Time dependent CP violation in the interplay between mixing and decay

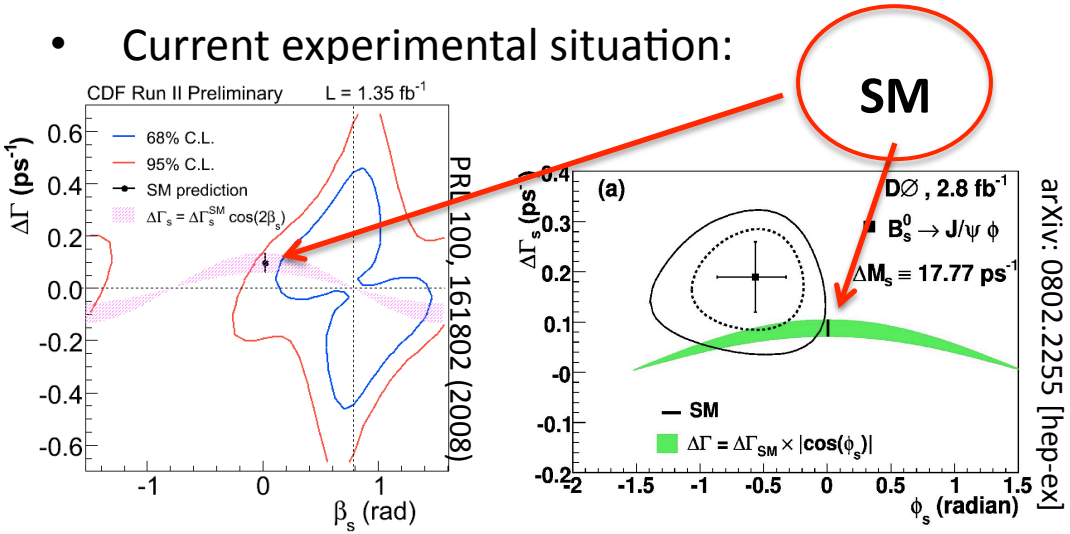


$$A_{CP}(t) = \frac{-\eta_f \sin\phi_s \sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s t/2)} \qquad \eta_f = \pm 1$$

- Can probe NP phases in the box:
  - $\phi_s = \phi_s^{NP} + \phi_s^{SM}$
  - $\phi_s^{SM} = -2\beta_s = -0.0368 \pm 0.0017$ UTfit



- Current experimental situation:



See L. Silvestrini and J. Charles talks

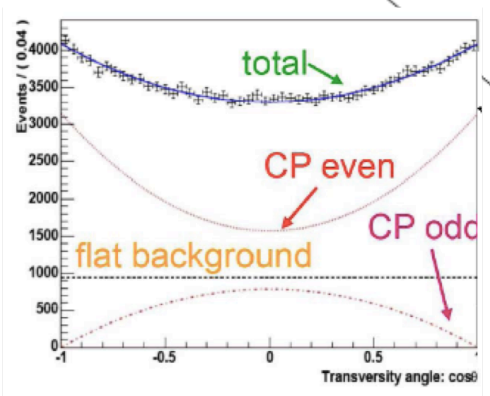
The B_s mixing phase

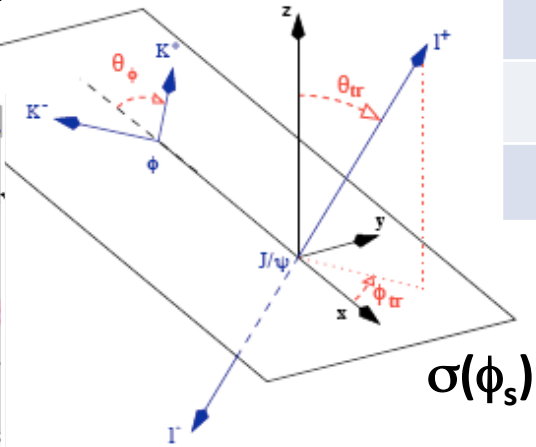
LHCb-2006-047
LHCb-2007-027
LHCb-2007-101

- Tree transition $b \to c\bar{c}s$ (single weak phase)
  - **Pure CP eigenstates:** many channels (low yield) time dependent analysis
  - **Admixtures of CP eigenstates:** $B_s \to J/\psi\phi$ (PS $\to$ VV; L=0,1,2)

    Large yield, low background

    BUT: disentangling CP admixture (η_f=-1,+1) need also angular analysis: **1 angle** (θ_{tr}) or **3 angles** (θ_{tr}, ϕ_{tr}, θ_ϕ)





decay	Yield ($2fb^{-1}$)	B/S	$\sigma(\phi_s)$ rad $2fb^{-1}$
$B_s \to J/\psi_{\mu\mu}\eta_{\gamma\gamma}$	8.5k	2	0.109
$B_s \to J/\psi_{\mu\mu}\eta_{\pi\pi\pi}$	3k	3	0.142
$B_s \to J/\psi_{\mu\mu}\eta'_{\pi\pi\eta}$	2.2k	<1.14	0.154
$B_s \to J/\psi_{\mu\mu}\eta'_{\rho\gamma}$	4.2k	<0.5	0.08
$B_s \to \eta_{c(4h)}\phi_{KK}$	3k	0.6	0.108
$B_s \to D_s^+{}_{KK\pi} D_s^-{}_{KK\pi}$	4k	0.3	0.133
all CP eig.			**0.046**
$B_s \to J/\psi_{\mu\mu}\phi_{KK}$	131k	0.12	**0.023**(*)
combined			**0.021**

(*) full angular analysis $\sigma(\Delta\Gamma_s)$=0.008ps^{-1}

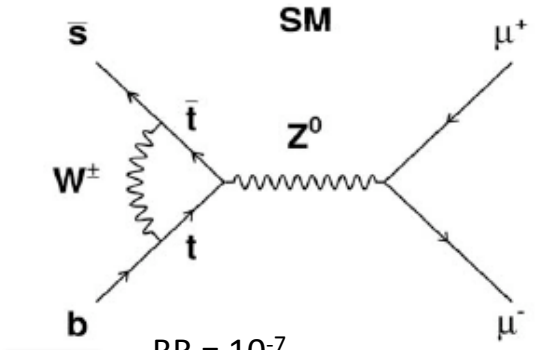
Control channels: $B_{u/d} \to J/\psi K^{+(*)}$, $B_s \to D_s\pi$

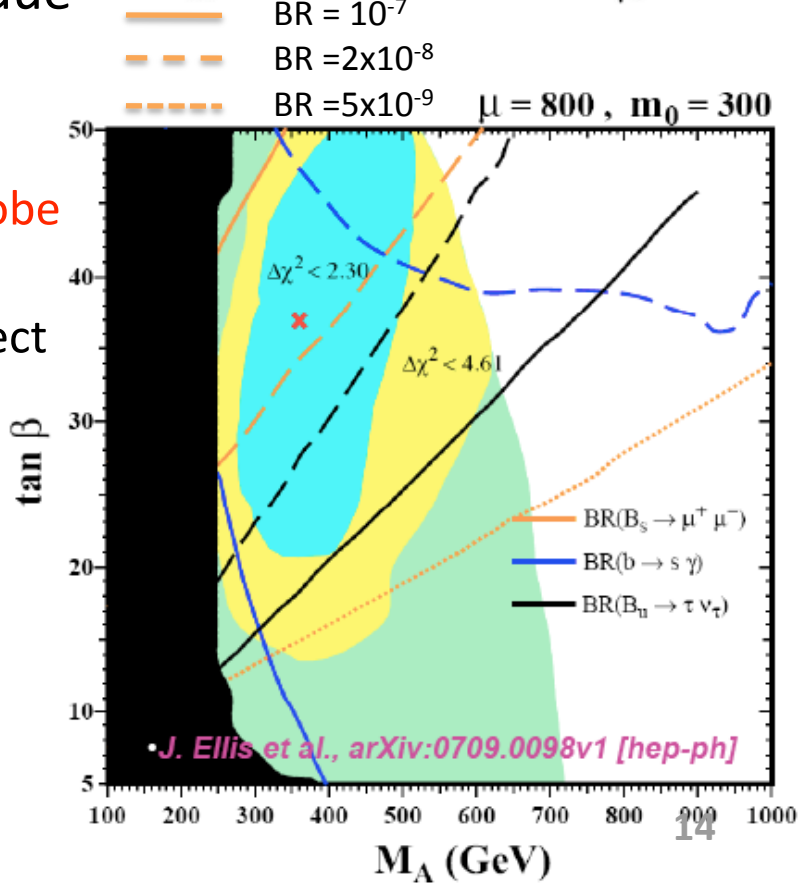
$\sigma(\phi_s)$~0.042 @0.5fb^{-1} (~1/2 CDF+D0 end 2009)

20% more statistics including $J/\psi \to e^+e^-$ decays

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

- $B_s \rightarrow \mu^+\mu^-$ is helicity suppressed in the SM
  - $BR^{SM}=(3.35\pm0.32)\times10^{-9}$ hep-ph/0604057v5
- Enhancement (suppression) possible due to SUSY contributions
  - $(\tan\beta)^6/M_A^4$ MSSM with large $\tan\beta$
  - one of the most sensitive channel to probe SUSY models and put constraints.
  - (Complementary information to the direct search of SUSY at LHC)
- Present experimental limits:
  - $BR^{exp}<47\times10^{-9}$ 90% CL (CDF $2fb^{-1}$)
  - $BR^{exp}<75\times10^{-9}$ 90% CL (D0 $1.3fb^{-1}$)



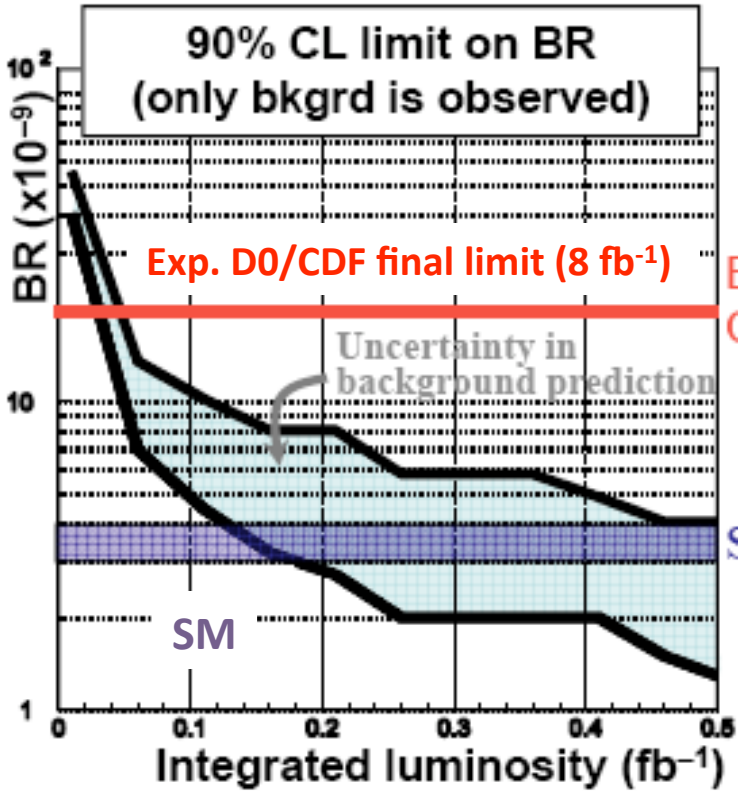


$B_s \rightarrow \mu^+\mu^-$ BR measurement

LHCb-2007-033
LHCb-2008-018

- **Trigger**: HTL single and di-muon (inclusive): high efficiency
- **Selection:** events are classified according to their distribution in a 3D space:
  - Geometrical Likelihood / Particle ID Likelihood / Invariant mass
- Main **background**:
  - $bb \rightarrow \mu\mu X$ suppressed by mass& Vertex resolution
  - ($B \rightarrow hh$ suppressed by PID)
- **Efficiencies** calibrated on control channels
  - $B \rightarrow hh$, $J/\Psi \rightarrow \mu\mu$, $B \rightarrow J/\Psi(\mu\mu)X$, $K_s \rightarrow \pi\pi$, $\Lambda \rightarrow \pi p$, $D^* \rightarrow D0(\pi K)\pi$ and side-bands
- Branching Ratio **normalized** to $B^+ \rightarrow J/\Psi K^+$
  - Huge Yied/ same trigger&similar selection/ well measured BR
  - main systematics: hadronization factor ratio $f(B_u)/f(B_s)$ (13%)

channel	Yield ($2fb^{-1}$)	B
$B_s \rightarrow \mu\mu$	~30	~83



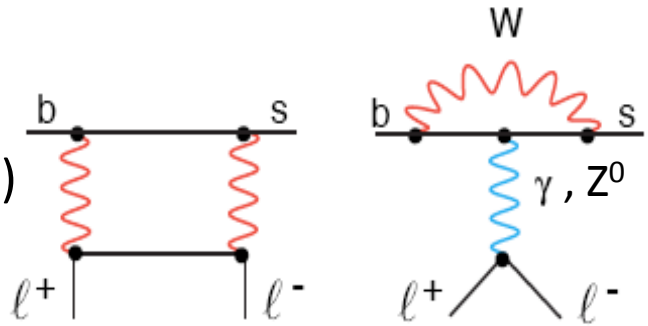
Limits (no signal observed):
$0.05fb^{-1}$ overtake CDF+D0
$0.5\ fb^{-1}$ BR limits down to the SM

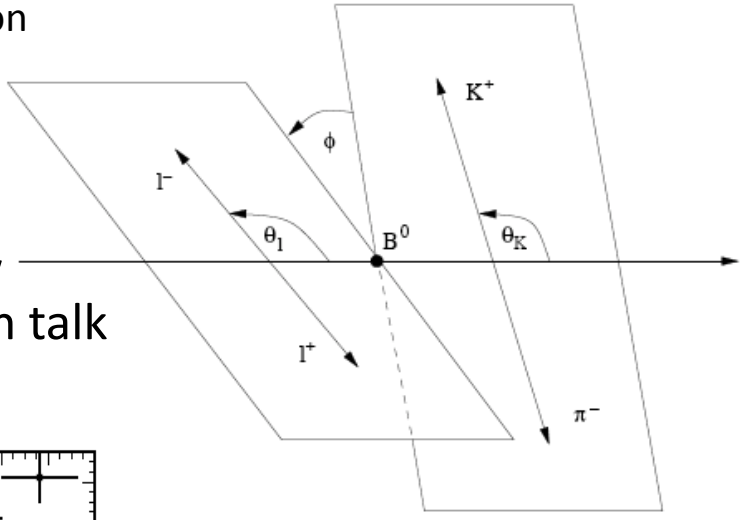
Signal observed:
$2fb^{-1}$ 3σ evidence of SM signal
$6fb^{-1}$ 5σ observation of SM signal

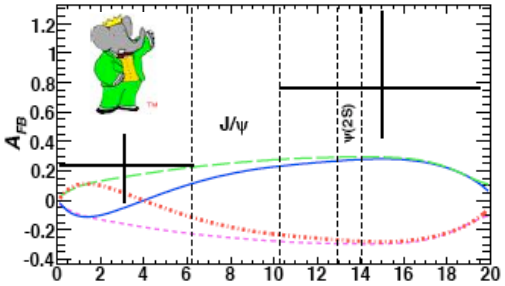
$B^0 \rightarrow K^{0*} \mu^+ \mu^-$

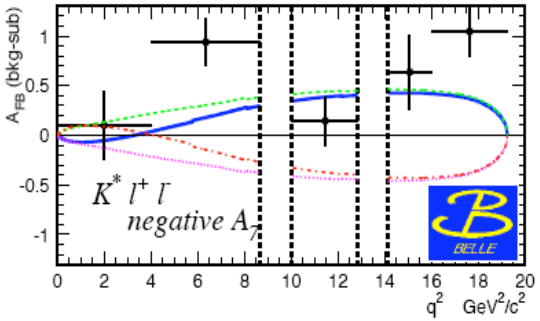
- Suppressed Loop FCNC process (EW penguins)
- Several observables to test the dynamics (NP ?)
  - Angular distributions: θ_l, ϕ, θ_{K^*}
  - Invariant mass $\mu^+\mu^-$ $s = (m_{\mu\mu})^2 = q^2$
- NP can affect:
  - Forward-backward asymmetry $A_{FB}(s)$ in θ_l distribution

    Dependence on s (predicted by several models)
    Zero of $A_{FB}(s)$
    SM $s_0 = 4.36^{+0.33}_{-0.31}$ GeV^2/c^4 hep-ph/0505155
- Present experimental situation limited by low statistics (O(100)@B-factories) → see J. Walsh talk









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

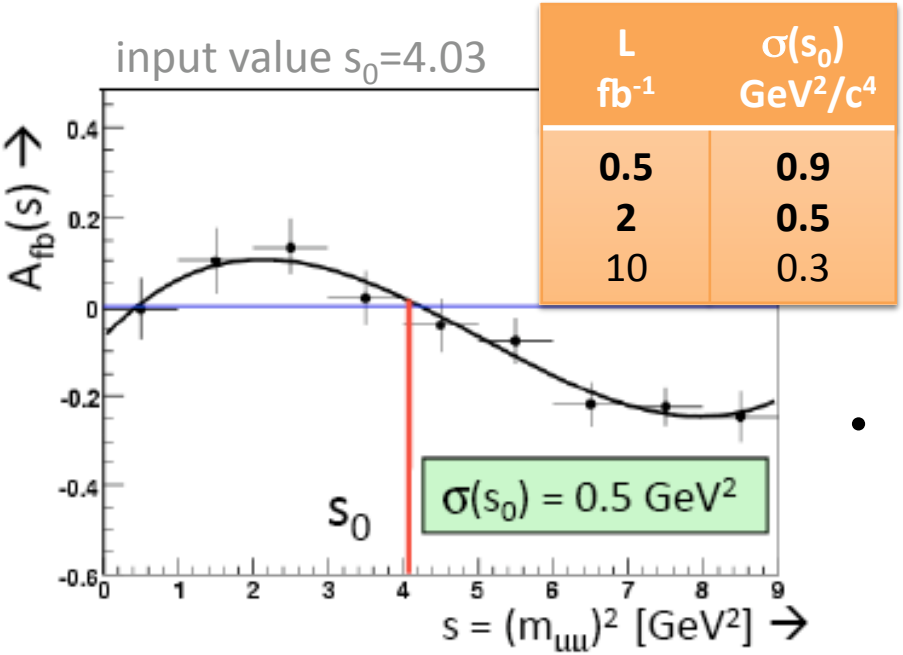
LHCb-2007-038
LHCb-2007-039

- **Trigger:** L0-muon, HLT inclusive (single and di-muon), HLT exclusive
- Main **background**:

  Non resonant $B \to K \pi \mu\mu$ (BR~signal) (50%)

  Inclusive $bb \to \mu\mu X$, $b \to \mu$ $b \to c \to \mu$

channel	Yield ($2fb^{-1}$)	B/S
$B \to K^* \mu\mu$	7200±180±2200 50% $s<m^2_{J/\psi}$	0.5



L fb^{-1}	$\sigma(s_0)$ GeV^2/c^4
0.5	**0.9**
2	**0.5**
10	0.3

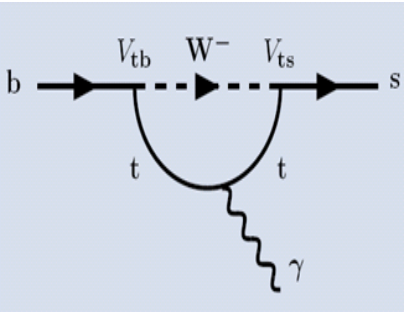
Opposite sign convention wtr BaBar&Belle

- **Systematics**:
  - distorsions in mass and θ_l to be known and corrected for == > A_{FB}
  - Background distribution (correlated -> asymmetry, uncorrelated->symmetry). Need to correctly subtract in shape and size

- Decays contain more information than A_{FB}, s_0
  - Fit projections on angles θ_l, θ_K, ϕ adds information on the tranversity amplitudes (A_{perp},$A_{//}$, A_0) F_L and $A_T^{(2)}$
  - → See T. Hurth & backup slides

LHCb-2007-030
LHCb-2007-147

Radiative decay $B_s \rightarrow \phi\gamma$



- $B_s \rightarrow \phi\gamma$ FCNC radiative penguin
- Time dependent CP asymmetry probe SM/NP

$$A_{CP}(t) = \frac{A^{dir}\cos(\Delta m_q t) + A^{mix}\sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) - A^{\Delta}\sinh(\Delta\Gamma_q t/2)}$$

channel	Yield ($2fb^{-1}$)	B/S
$B_s \rightarrow \phi\gamma$	11 k	<0.55bb 90% CL

SM: $A^{dir} \approx 0$, $A^{mix} \approx \sin 2\psi \sin 2\phi$, $A^{\Delta} \approx \cos 2\psi \cos\phi$

$\tan\psi = |b\rightarrow s\,\gamma_R| \,/\, |b\rightarrow s\,\gamma_L| \sim 0$ $\quad \cos\phi \approx 1$

– A^{Δ} & A^{mix} probe the γ polarization

- SM $\tan\psi \sim 0$ can be increased by NP
- with $\Delta\Gamma_s \neq 0$ ➔ A^{Δ} can be measured – no tagging required

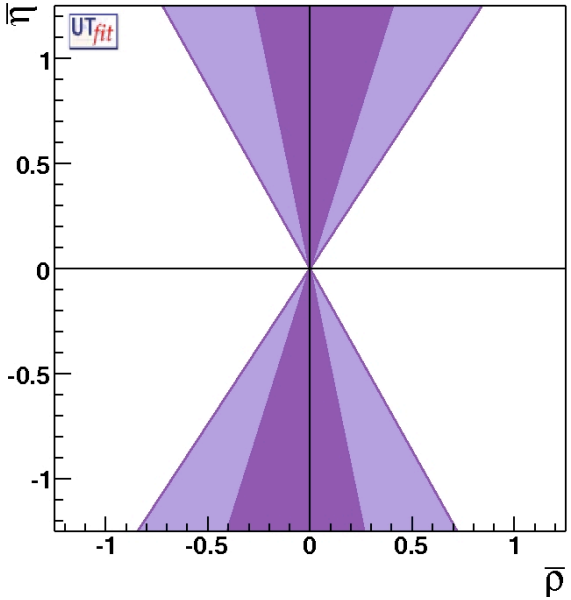
Some systematics considered

CP asymm	$2\ fb^{-1}$
$\sigma(A^{dir})$	0.11
$\sigma(A^{mix})$	0.11
$\sigma(A^{\Delta})$	0.22 (*)

(*) No tagging required

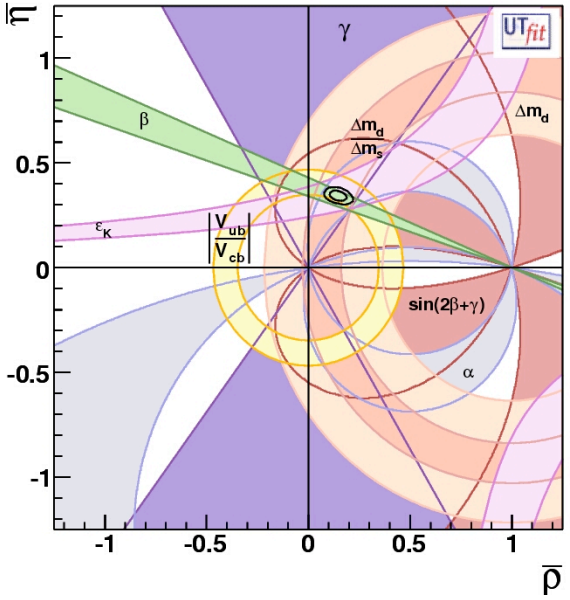
Motivations for a precise measurement of γ

Direct measurements
(from tree processes)



UT-fit $\gamma = (88 \pm 16)°$

Overall constraints



UT-fit $\gamma = (66.7 \pm 6.4)°$

LHCb-2007-041
LHCb-2007-017

γ from trees: $B^0_s \rightarrow D^-_s K^+$

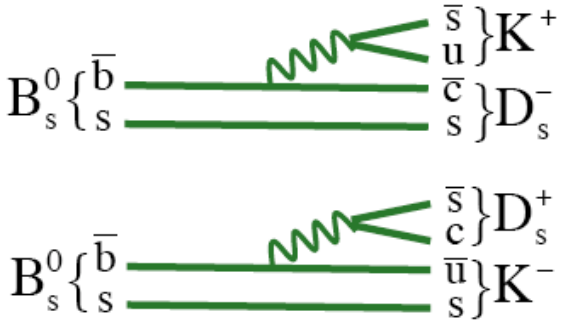
- Two tree ampl. ($b \rightarrow c$ & $b \rightarrow u$) interfere via B_s mixing

  Measure $\gamma+\phi_s$ in a very clean way

  8-fold ambiguity in γ reduced to 2 with a sizable $\Delta\Gamma_s$

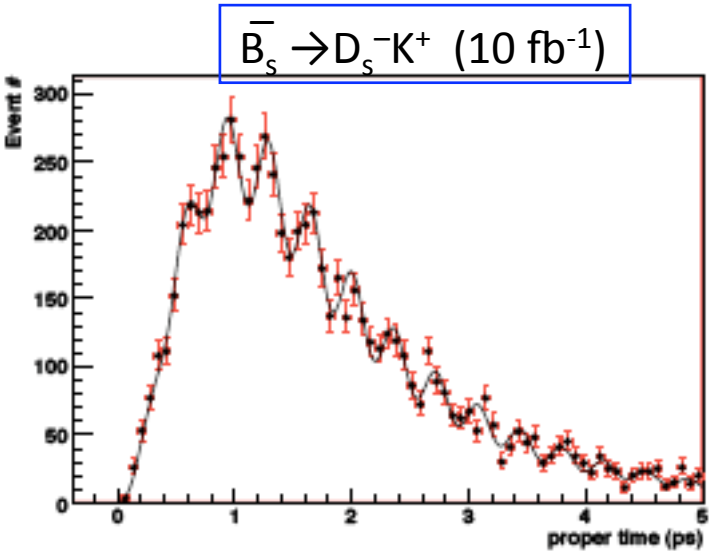
  Simultaneous fit $B_s \rightarrow D_s K$ and $B_s \rightarrow D_s \pi$ channels
  (tagged& untagged) to constrain common parameters $\Delta\Gamma_s$, ΔM_s, tagging

  K-π discrimination crucial to suppress specific bkg



decay	Yield ($2fb^{-1}$)	B/S 90%CL	Sensitivity In $2fb^{-1}$
$B_s \rightarrow D_s K$	6.2k	<0.18 bb [0.08-3]	**$\sigma(\gamma+\phi_s)$=9-12°** (*)
$B_s \rightarrow D_s \pi$	140k	<0.05 bb <0.4	**$\sigma(\Delta M_s)$=0.007ps^{-1}**

(*) $\sigma(\phi_s)$~1.2°



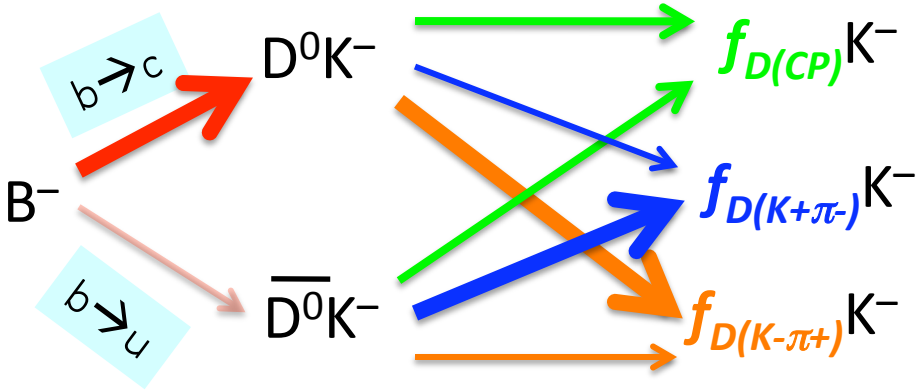
γ from trees: B→DK

LHCb-2008-011
LHCb-2006-066
LHCb-2007-043

- Two tree amplitudes (b→c & b→u) interfere in decays to a common D^0 and $\bar{D}^0$ state f_D

$$\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i\delta_B} e^{-i\gamma}$$

- Measure the **time independent asymmetries** (no tagging or time measurement required / PID crucial)



- **GLW method:** f_D is a CP eigenstate: K^+K^-, $\pi^+\pi^-$, $K_S\pi^+\pi^-$
  Large rate / small asymmetries

- **ADS method:** f_D is a common flavour state Kπ, K3π
  Favoured mode: Large event rate / tiny asymmetry
  Suppressed mode: Lower event rate / large asymmetry

(*) depending on strong phases

decay	Yield ($2fb^{-1}$)	B/S	σ(γ) In $2fb^{-1}$
GLW: $B^\pm \to D_{hh} K^\pm$	8.6k	1.7	**8.2-9.6°** (*)
ADS: $B^\pm \to D_{K\pi} K^\pm$ favo.	56k	0.6	
ADS: $B^\pm \to D_{K\pi} K^\pm$ suppr.	(*)	B~O(1.5k)	

γ from trees: B→DK

LHCb-2007-050
LHCb-2007-043
LHCb-2007-048
LHCb-2007-098
LHCb-2007-141

(*) depending on strong phases (#) depending on the bkg assumptions

decay	method	Yield ($2fb^{-1}$)	B/S	σ(γ) In $2fb^{-1}$
$B^{\pm} \to D^0(K3\pi)\ K^{\pm}$	ADS	61k	1.5	
$B^{\pm} \to D^{0*}(D^0\pi^0/D^0\gamma)\ K^{\pm}$	GLW+ADS	42k		High bkg
$B^0 \to D^0(K\pi/hh)K^{*0}$ + cc	GLW+ADS	4.5k	0.5	**6-25°**(*)
$B^{\pm} \to D^0(K^0_s\pi^+\pi^-)\ K^{\pm}$	GGSZ Dalitz Model indep	5k	0.24 (spec) <0.7 (bbar)	**7-12°(#)+10° 9-13°+3°**
$B^{\pm} \to D^0(K^+K^-\pi^+\pi^-)\ K^{\pm}$	GLW-Dalitz	1.7k	0.9	18°

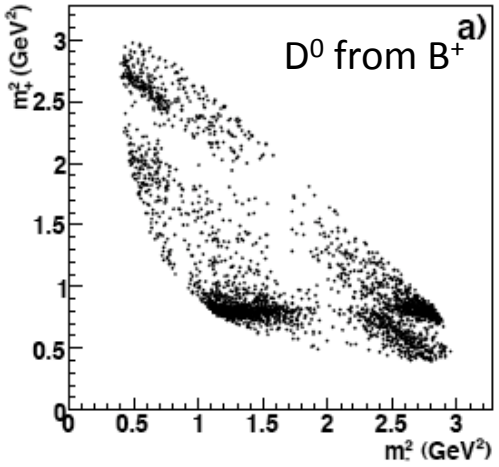
mass resolution & PID crucial to suppress bkg

Difference in the $K^0_s\pi\pi/K^+K^-\pi^+\pi^-$ Dalitz plots from B^+ and B^- are due to γ

$$\left|f_D^{B^{\pm}}\right|^2 = \left|f_D + r_B e^{i\cdot(\delta \pm \gamma)} f_{\overline{D}}\right|^2$$

Clean extraction of γ, r_B and δ but need to assume the D^0 (f_D) decay model.
For $D^0(K^0_s\pi\pi)$ main systematic error: 10° (model)/ 3° (CLEO-c data)

Global fit of all the channels **σ(γ) = 4.3-6.2° in $2fb^{-1}$** (range->syst.)



LHCb-2007-059

γ from loops: $B^0_{d/s} \rightarrow h^+h^-$

- Interference of b→u tree & b→d(s) penguin diagrams leads to CP violation depending on γ (Sensitive to NP)

$$A_f^{CP}(t) = \frac{A_f^{dir}\cos(\Delta m_q t) + A_f^{mix}\sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) - A_f^{\Delta}\sinh(\Delta\Gamma_q t/2)}$$

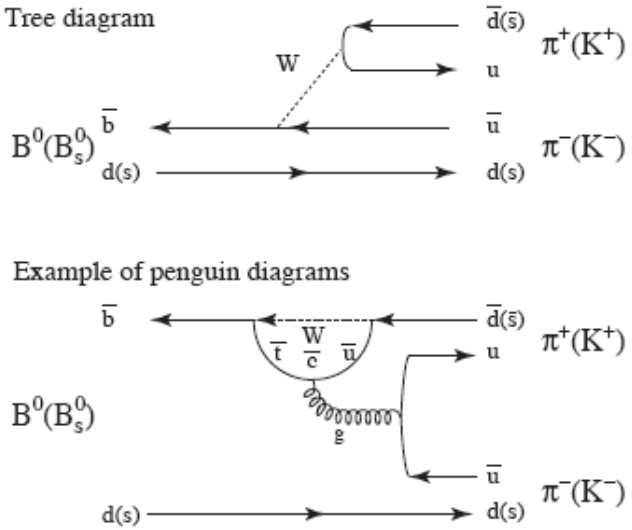
- In each mode A^{dir} & A^{mix} depend on mixing phase $2\beta_{d/s}$, γ, and ratio of penguin to tree amplitudes = $d\, e^{i\theta}$

$$A^{dir}_{\pi\pi} = f_1(d,\theta,\gamma) \qquad A^{mix}_{\pi\pi} = f_2(d,\theta,\beta_d,\gamma)$$
$$A^{dir}_{KK} = f_3(d',\theta',\gamma) \qquad A^{mix}_{KK} = f_4(d',\theta',\beta_s,\gamma)$$

- $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ are ruled by ~same diagrams by d→s exchange (exchange and annihilation diagrams neglected) **U-spin symmetry**.

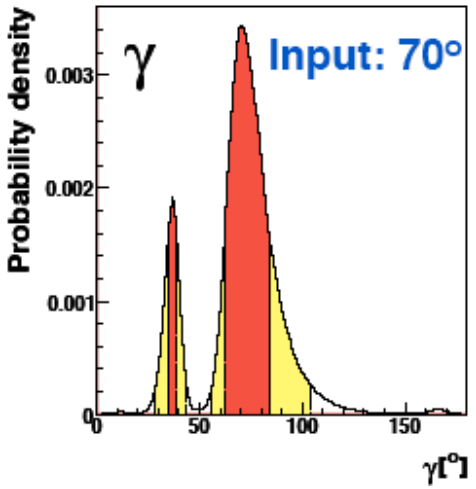
Weak assumption: d = d' ± 20% θ, θ' independent

$\beta_{d/s}$ known (measured)



decay	Yield ($2fb^{-1}$)	B/S
$B^0 \rightarrow \pi^+\pi^-$	36k	0.5
$B_s^0 \rightarrow K^+K^-$	36k	1.5

$\sigma(\gamma)$ In $2fb^{-1}$
10°



Compare to γ from trees to get hints of NP in penguins

LHCb-2007-049

Charm physics

- Dedicated HLT trigger D* stream ~300 Hz of bandwidth
  - Huge sample of $D^0 \to h^+h^-$ on tape (100 M in 2fb^{-1})
- **Calibration of RICH** K/π PID
- **Charm Physics studies**

$\bar{D}^0/D^0$ tag with pions from $D^{*\pm} \to D^0\pi^\pm$

D^0 mixing tiny in the SM / experimental evidence by BaBar&Belle (NP) ?

Study time dependence of wrong sign (DCS) Kπ decays

$$r(t) \approx e^{-\Gamma t}\left(R_D + \sqrt{R_D}\,y' \cdot \Gamma t + \frac{x'^2 + y'^2}{4} \cdot (\Gamma t)^2\right)$$

Lifetime ratio of D^0 to CP(K^+K^-) and non-CP($K^-\pi^+$) eigenstates => $\mathbf{y_{CP}}$ (= y' if noCPV)

CP Violation in $D^0 \to K^+K^-$ and $\pi^+\pi^-$ (≤10^{-3} SM up to 1% NP)

channel	Yield (2fb^{-1})	B/S
$D^0 \to K^-\pi^+$ +cc RS	12.4M	0.21
$D^0 \to K^+\pi^-$ +cc WS	46.5k	2.6
$D^0 \to K^+K^-$ +cc	1.6M	0.21
$D^0 \to \pi^+\pi^-$ +cc	0.6M	0.38

D^0 lifetime "improved" measurement σ(t)=45 fs

$$x = \frac{\Delta M}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

x', y' rotated resp. x, y by a strong phase

→ σ x10^3	x'^{2}	y'	y_{CP}	A_{CP}
LHCb 2 fb^{-1} (*)	0.14	1.95	1.1	1.1
LHCb 10fb^{-1}(*)	0.064	0.87	0.5	0.48
B-fact.2008	R_M=0.13±0.27		11.3±2.7	1.2±2.5

(*) Statistical error only

Conclusions

LHCb is a heavy flavour precision experiment searching for New Physics in **CP Violation** and **Rare Decays**

Already with 0.5fb^{-1} (2009) interesting results can be obtained on

$B_s \rightarrow J/\psi\phi$ $\quad \sigma(\phi_s) \sim 0.042$

$B_s \rightarrow \mu\mu$ $\quad$ BR limit down to SM value

$B \rightarrow K^*\mu\mu$ $\quad$ Study A_{FB} with ~1800 events $\sigma(s_0) \sim 0.9$ GeV^2/c^4

CP Violation: 2 fb^{-1}

γ from trees: 5^o - 10^o

γ from penguins: $\approx 10^o$

B_s mixing phase: 0.021

Rare Decays: 2 fb^{-1}

$B \rightarrow K^*\mu\mu$ s_0 : 0.5 GeV^2/c^4

$B \rightarrow s\gamma$ A_{dir} , A_{mix} : 0.11

A_Δ : 0.22

$B_s \rightarrow \mu\mu$: 3σ obs. of the SM BR

Charm Physics: 2 fb^{-1}

x'^2: 0.14x10^{-3}

y': 2.x10^{-3}

CP violation: 1.1x10^{-3}

Aim: collect ~10fb^{-1} by 2013

We are getting ready to run and analyse real data!!