PROSPECTS FOR CHARM MIXING AND CPV AT THE LHCb UPGRADE

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on behalf of the LHCb collaboration

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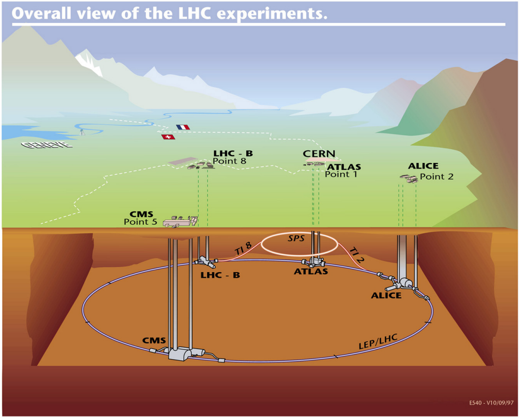
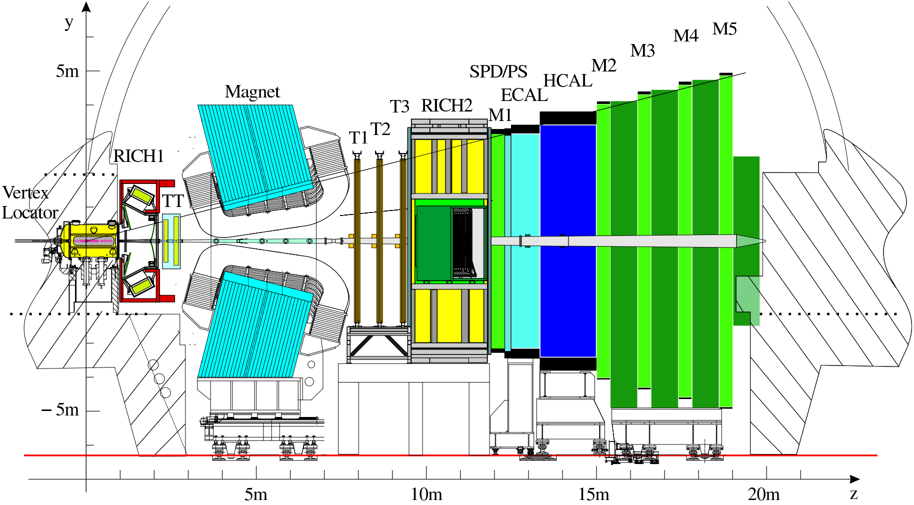
LARGE HADRON COLLIDER



CURRENT LHCb detector



An(other) introduction to LHCb

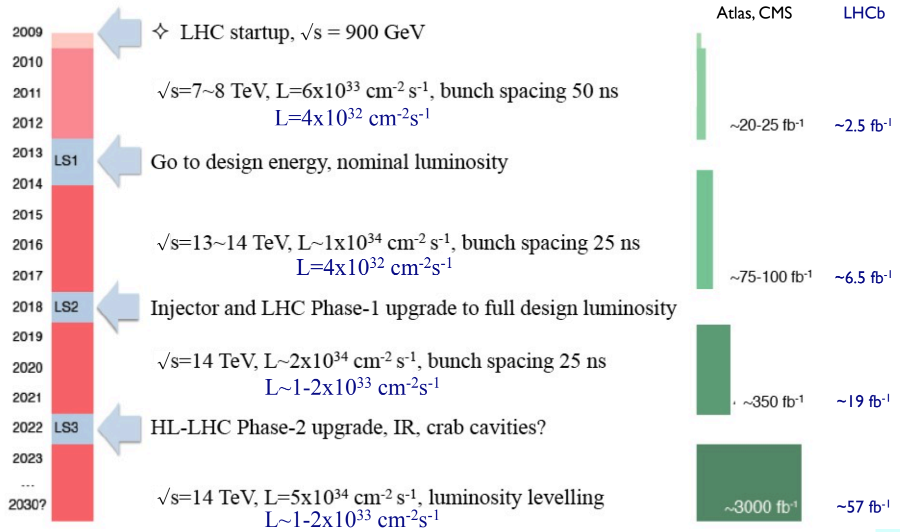
LHCb: a forward-arm spectrometer at the LHC

- Optimized for heavy flavor physics with LHC proton-proton collisions,
- Forward acceptance, $2 < \eta < 5$,
- Large production cross-sections for heavy hadrons,
- Precise vertexing,
- Excellent charged hadron identification,

Flexible two-stage trigger,

- L0 hardware trigger — high p_t particles,
- High Level Trigger (HLT) in software
  - Software trigger running in event farm,
  - Full event reconstruction,
  - Deferred trigger stores events on farm to be triggered inter-fill.

LHC SCHEDULE



Adapted from M. Nessi, Chamonix 2012 by way of M. Gersabeck, CHARM2012

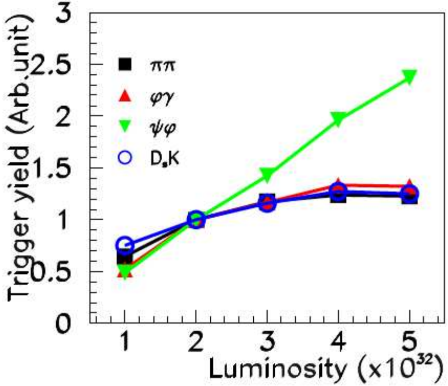
LHCb trigger: pushing limits

Exceeding design specifications to maximize physics reach

	Design	2012
Instantaneous luminosity, $\mathcal{L}_{\text{inst}}$ ($\text{cm}^{-2}\,\text{s}^{-1}$)	2×10^{32}	4×10^{32}
Mean visible p-p interactions/crossing, μ	0.4	1.6
HLT output rate to tape (kHz)	2	4

Current luminosity limits:

- L0 readout limit: 1 MHz,
- Increasing luminosity requires increasing pile-up,
- $\hookrightarrow$increased L0 p_T cuts,
- Effective gain in yield linear for leptonic final states, plateaus for hadronic final states.



LHCb upgrade: transcending limits

LHCb Upgrade goal (simplified version): Collect $5\,\mathrm{fb}^{-1}$ per year for a total of $50\,\mathrm{fb}^{-1}$ with a more efficient and flexible trigger without sacrificing detector performance.

For more information, see the plenary talk by Marie-Hélène Schune

At $\sqrt{s} = 14\,\mathrm{TeV}$, the LHC will create more than $1\,\mathrm{MHz}$ of charm into the LHCb acceptance.

- We will saturate with the current p_T-triggered hardware readout

The key upgrade is removing this $1\,\mathrm{MHz}$ L0 readout bottleneck

- Upgrade detector electronics and DAQ to readout at $40\,\mathrm{MHz}$,
- Full software trigger.

Upgrade detector elements to take advantage of hardware advances.

Implemented during the LHC 2018-2019 LS2 long shutdown.

CHARM COLLECTION IN THE LHCb upgrade

	Affect on charm yield
$c\bar{c}$ cross-section increases with collision energy $\sqrt{s} = 8\,\text{TeV} \rightarrow 14\,\text{TeV}$ *Much of this benefit will already be visible in 2014.*	1.8×
Increase in trigger efficiency by going to an all-software trigger *Final states with higher particle multiplicities may benefit event more*	2×
Luminosity / year increase with respect to 2012	2-3×

Yield / fb^{-1} expected to increase by a factor 3.5-4.

Yield / year to increase by about an order of magnitude.

That's billions, with a 'b'

LHCb-PUB-2012-006

Mode	2011 yield (kilo events)	$50\,\text{fb}^{-1}$ yield (mega events)
untagged $D^0 \to K^- K^+$	25 000	4 600
untagged $D^0 \to \pi^- \pi^+$	6 500	1 200
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^- \pi^+$	40 000	7 000
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^+ \pi^-$	130	20
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^- K^+$	4 300	775
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^0_s \pi^- \pi^+$	300	180
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^0_s K^- K^+$	45	30
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^- K^+ \pi^- \pi^+$	120	20
$D^{*+} \to D^0 \pi^+;\, D^0 \to K^+ \mu^- X$	–	0.1
$D^+ \to K^- \pi^+ \pi^+$	60 000	11 000
$D^+ \to K^- K^+ \pi^+$	6 500	1 200
$D^+ \to \pi^- \pi^+ \pi^+$	3 200	575
$D^+ \to K^0_s K^+$	525	330
$D^+_s \to \phi \pi^+,\, (\phi \to K^- K^+)$	5 350	1 000

Dealing with systematic uncertainties

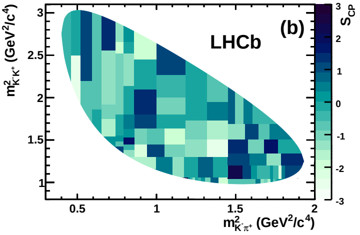
Construct observables that are ratios or differences, *e.g.*

$$y_{CP} \equiv \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to (K^+K^-, \pi^+\pi^-)} - 1 \approx y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \sin\phi$$

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = [a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\text{ind}}.$$

Model-independent measurements with multibody decays,

- Phase-space comparison for *CPV* searches,
- Binned multibody mixing measurements



Distribution of normalized yield asymmetries in $D^+ \to K^-K^+\pi^+$, Phys.Rev. D84 (2011) 112008

Most of our limiting systematic uncertainties scale with statistics,

- Data-driven methods of measuring detector and production asymmetries.

UPGRADE SENSITIVITY TO MIXING PARAMETERS
LHCb-PUB-2012-006

First LHCb mixing measurement on 2010 data set, JHEP 04 (2012) 129,

$$y_{CP} = (5.5 \pm 6.3(\text{stat}) \pm 4.1(\text{syst})) \times 10^{-3}$$

with a statistical uncertainty on the order of current best measurements.

Systematic uncertainties limited by sample size and will scale.

More mixing measurements in preparation.

Extrapolating to the statistical sensitivity of the LHCb upgrade

Mode	Parameter(s)	Precision
$D^{*+} \to D^0\pi^+$; $D^0 \to K^-K^+, (\pi^-\pi^+)$	y_{CP}	0.004% (0.008%)
$D^{*+} \to D^0\pi^+$; $D^0 \to K^-K^+, (\pi^-\pi^+)$	A_Γ	0.004% (0.008%)
WS/RS $K\pi$	(x'^2, y')	$\mathcal{O}[(10^{-5}, 10^{-4})]$
WS/RS $K\mu\nu$	R_M	$\mathcal{O}(5 \times 10^{-7})$
$D^{*+} \to D^0\pi^+$; $D^0 \to K^0_s\pi^-\pi^+$	(x, y)	(0.015%, 0.010%)

UPGRADE SENSITIVITY TO CPV PARAMETERS
LHCb-PUB-2012-006

Indirect *CP* violation in SM is predicted precisely and very small,

- A_Γ is an almost-clean measurement of indirect *CPV*

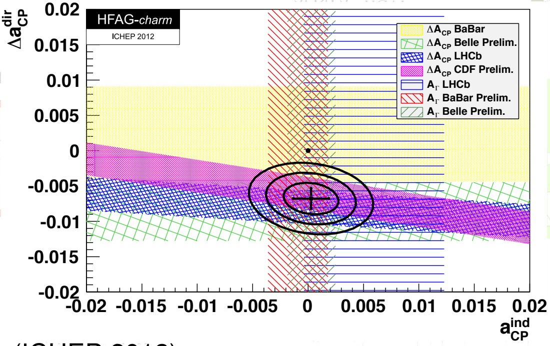
Direct *CP* violation searches in as many modes as possible to fully understand its source and properties.

Extrapolating to the statistical sensitivity of the LHCb upgrade

Mode	Parameter(s)	Precision
$D^{*+} \to D^0\pi^+;\ D^0 \to K^-K^+, (\pi^-\pi^+)$	A_Γ	0.004% (0.008%)
$D^{*+} \to D^0\pi^+;\ D^0 \to K^-K^+, \pi^-\pi^+$	ΔA_{CP}	0.015%
$D^+ \to K^0_S K^+$	A_{CP}	10^{-4}
$D^+ \to K^-K^+\pi^+$	A_{CP}	5×10^{-5}
$D^+ \to \pi^-\pi^+\pi^+$	A_{CP}	8×10^{-5}
$D^+ \to h^-h'^+\pi^+$	CPV in phases	$(0.01 - 0.10)^\circ$
$D^+ \to h^-h'^+\pi^+$	CPV in fractions	$(0.01 - 0.10)\%$

COMBINING A_Γ AND A_{CP}

Combining time-dependent and time-independent *CP* asymmetry measurements in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$

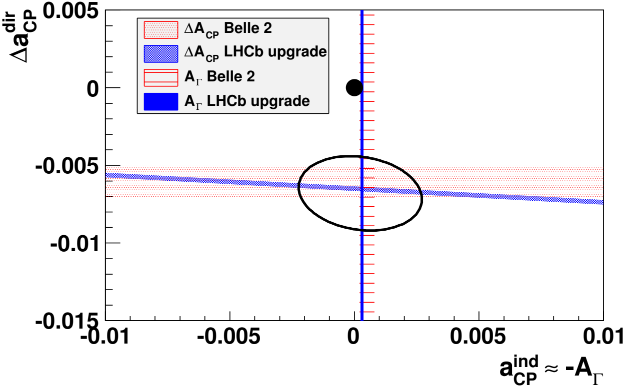


HFAG averages (ICHEP 2012):

$$a_{CP}^{\rm ind} = (0.027 \pm 0.163)\%$$
$$\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\%$$

UPGRADED CHARM CPV

Combining expected statistical sensitivities from Belle 2 and the LHCb Upgrade for time-dependent and time-independent *CP* asymmetry measurements in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$



M. Gersabeck, CHARM 2012

OUTLOOK

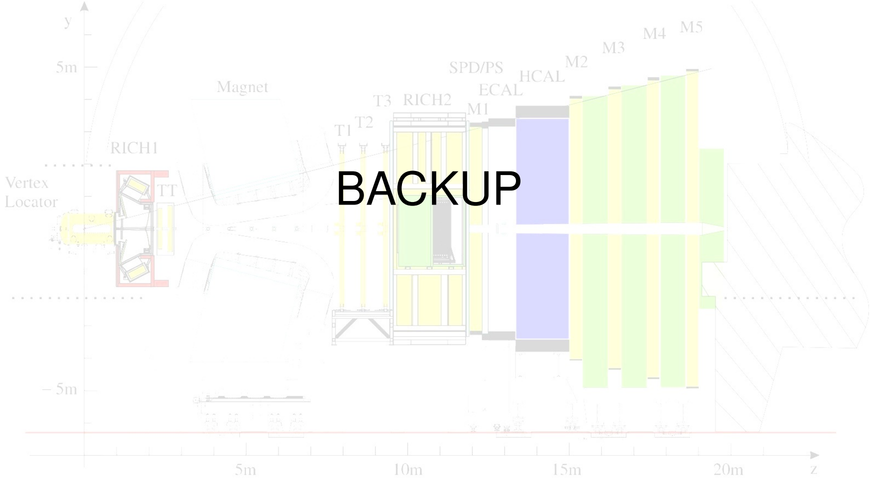
LHCb already producing sub-% precision charm *CPV* measurements

Data-driven methods to estimate systematic uncertainties scale with size of data set

The LHCb upgrade will have the precision to discover *CP* violation and determine its origin.

The LHCb upgrade is capable of even more!

- Precise *CPV* searches in charm baryons,
- Multiple $c\bar{c}$ production and multiply-charmed baryon studies,
- Great reach for rare decay measurements and lepton flavor violation searches.


y
5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
− 5m
5m
10m
15m
20m
z

BACKUP

UPGRADE TIMELINE

Letter of Intent submitted to the LHCC March 2011

- Physics case fully endorsed by the LHCC.

Framework TDR submitted to LHCC May 2012

- Defines schedule, cost, and participating institutes,
- Now under review.

Technological choices will be made before mid-2013

- Sub-system TDRs submitted by end of 2013.

Production and QA in 2014-17.

Installation and commissioning in 2018.