Charm Mixing and CP Violation at LHCb

PHENO Symposium, University of Pittsburgh, PA, USA
6-8 May 2013

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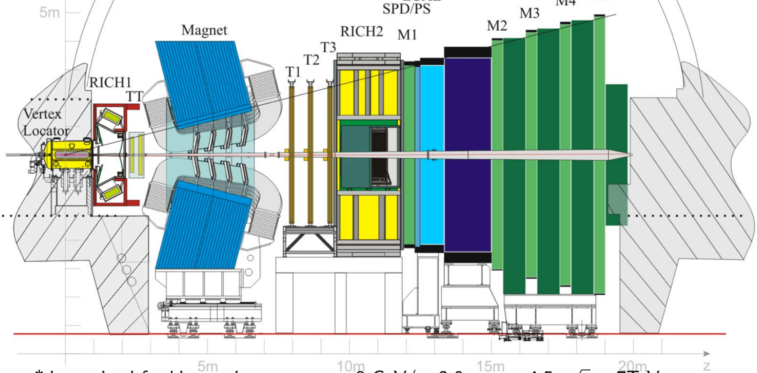
University of Oxford

LHCb

- Single arm spectrometer at the LHC
- Pseudorapidity coverage $2 < \eta < 5$
- Designed to study heavy flavour physics
- Large charm cross section:
  $\sigma(c\bar{c}) = 1419 \pm 12(stat.) \pm 116(syst.) \pm 65(frag.)\mu b$*

Every 10th event is a charm event!

[Nucl. Phys. B **871**, (2013), pp. 1 - 20]



*determined for kinematic range $p_T < 8$ GeV/c, $2.0 < \eta < 4.5$, $\sqrt{s} = 7$TeV

CP violation in SCS charm decays

- Singly Cabbibo suppressed (SCS) charm decays $\rightarrow$ theatre for studying *CPV*
- Manifests due to interference between tree and penguin processes
- Direct *CPV* predicted to be small in SM [Phys. Rev. D75:036008, 2007]
- Large signals could be a sign of new physics in loop diagrams
- Can access direct *CPV* through asymmetry measurements

$$A_{CP} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}$$

- Detection and production effects can induce fake asymmetries to measured value
- Difference of A_{raw} can be approximated to,

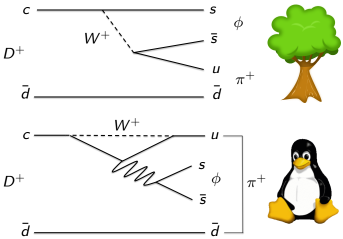
$$\Delta A_{CP} = A_{CP}(D \rightarrow f_1) - A_{CP}(D \rightarrow f_2) \approx A_{raw}(D \rightarrow f_1) - A_{raw}(D \rightarrow f_2)$$

- Cancels production/detection asymmetries common to both final states

Today I will present 3 analyses:
2 direct *CPV* searches in SCS decays, 1 mixing measurement

CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

- Quasi 2-body decay with large $\mathcal{BF} \approx 2.65 \times 10^{-3}$
- ϕ dominates narrow region of $D^+ \to K^+K^-\pi^+$ Dalitz plot
- Contributions from S-wave and other resonances
- Theoretical predictions are challenging pseudoscaler $\to$ vector decay



- Measure ΔA_{CP} from difference in A_{raw} for $D^+ \to \phi\pi^+$ and $D^+ \to K_S^0\pi^+$

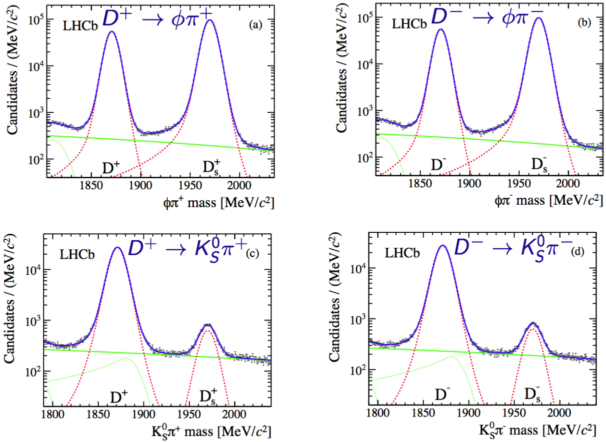
$$\Delta A_{CP}(D^+ \to \phi\pi^+) = A_{raw}(D^+ \to \phi\pi^+) - A_{raw}(D^+ \to K_S^0\pi^+) + A_{CP}(K^0/\bar{K}^0)$$

- Also extract ΔA_{CP} from SCS $D_s^+ \to K_S^0\pi^+$ and CF $D_s^+ \to \phi\pi^+$

$$\Delta A_{CP}(D_s^+ \to K_S^0\pi^+) = A_{raw}(D_s^+ \to K_S^0\pi^+) - A_{raw}(D_s^+ \to \phi\pi^+) + A_{CP}(K^0/\bar{K}^0)$$

- Small effect of CPV in K_S^0 decay accounted for in $A_{CP}(K^0/\bar{K}^0)$ term
- Assume CPV in D^+ from CF/DCS interference negligible

CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$



- Results from 1.0 fb^{-1} recorded in 2011:

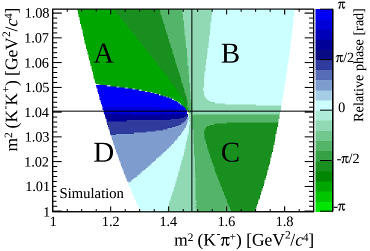
$$\Delta A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14(stat.) \pm 0.13(sys.))\%$$

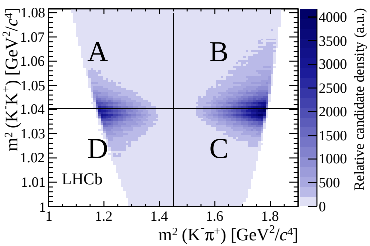
$$\Delta A_{CP}(D_s^+ \to K_S^0\pi^+) = (-0.61 \pm 0.83(stat.) \pm 0.13(sys.))\%$$

[arXiv:1303.4906v1] submitted to JHEP

CP violation in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

- Improve sensitivity to of *CPV* in $D^+ \to \phi\pi^+$ region
- Average out asymmetry from variation in strong phase about ϕ resonance





$$A_{CP|S} = \frac{1}{2}[(A^{A}_{raw} + A^{C}_{raw}) - (A^{B}_{raw} + A^{D}_{raw})]$$

- No need to account for D^+ production asymmetry
- Cancels affects that change sign across ϕ band

$$A_{CP|S} = (-0.18 \pm 0.17(stat.) \pm 0.18(sys.))\%$$

- No evidence for *CP* violation is seen [arXiv:1303.4906v1]

ΔA_{CP} from $D^0 \to h^+h^-$ decays

- Measure ΔA_{CP} between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays
- Decay time dependent asymmetry for D^0 decays to a CP eigenstate

$$A_{CP}(f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = a_{CP}^{\mathrm{dir}}(f) + \frac{t}{\tau} a_{CP}^{\mathrm{ind}}$$

- Assuming equal decay time acceptance for K^+K^- and $\pi^+\pi^-$

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

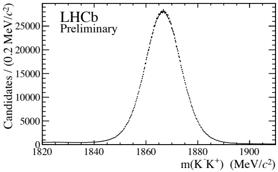
- Insensitive to indirect CP violation $\to$ universal to both final states
- Two datasets:
  - Prompt: $D^{*+} \to (D^0 \to h^+h^-)\pi^+_{\mathrm{soft}}$ Update
  - Secondary: $B \to (D^0 \to h^+h^-)\mu X$ New result!
- In both cases assume:

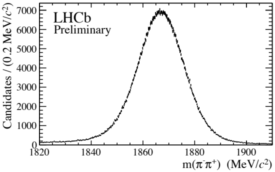
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

- But, treatment of production and detection asymmetries different for each
- Both use 1.0 fb^{-1} of data collected in 2011
- Little overlap between prompt and secondary data (statistics and systematics)

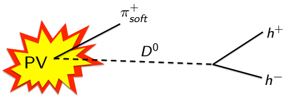
ΔA_{CP} from $D^0 \rightarrow h^+h^-$ decays: Prompt

- Previous result from LHC*b*, $\Delta A_{CP} = (-0.82 \pm 0.21(stat.) \pm 0.11(sys.))\%$
  [Phys. Rev. Lett. 108 (2012) 111602]
- Sparked a flurry of work by you guys - we like to keep you on your toes!
- Update now includes full 1.0 fb^{-1} from 2011





[CERN-LHCb-CONF-2013-003]



- Tag flavour of D from charge of π^+_{soft}

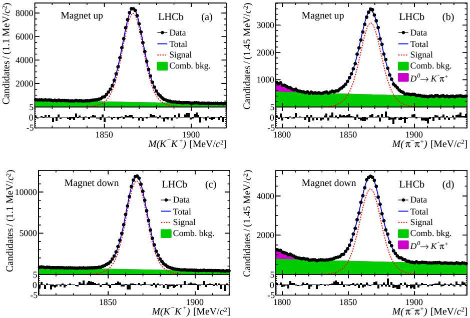
- Raw asymmetry given by,

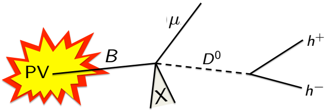
$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi^+_{soft}) + A_P(D^{*+})$$

- Detection asymmetry of spin-0 decay to self-conjugate state, $A_D(f) = 0$
- $A_D(\pi^+_{soft})$ and $A_P(D^{*+})$ depend on D^{*+} kinematics and therefore selection
- Re-weight $|p|$, p_T and ϕ distributions to account for difference in decay kinematics and selection criteria of $\pi\pi$ and KK final states

$\Delta A_{\rm CP}$ from $D^0 \to h^+h^-$ decays: Secondary

- All previous measurements of ΔA_{CP} are from D^{*+} decays
- Previous result strongly motivated a cross-check $\to$ use secondary charm





Flavour of D tagged from charge of μ

[LHCb-PAPER-2013-003]
submitted to Phys. Lett. B

- Raw asymmetry can be approximated to,

$$A_{raw} = A_{CP} + A_D^{\mu} + A_P^{B}$$

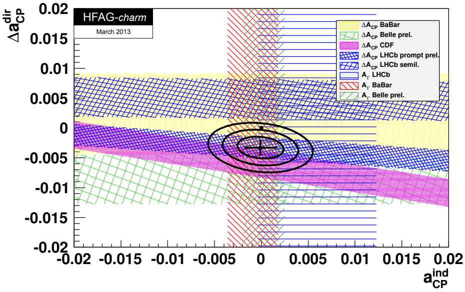
- A_P^B is the $b/\bar{b}$ production asymmetry, independent of the final state particles
- Re-weight D^0 (p_T, η) distributions to account for differences in A_D^{μ} (muon detection asymmetry) between the $\pi\pi$ and KK final states

$\Delta A_{\rm CP}$ from $D^0 \to h^+h^-$ decays

Prompt: $\Delta A_{CP} = (-0.34 \pm 0.15(stat.) \pm 0.10(sys.))\%$
[CERN-LHCb-CONF-2013-003]

Secondary: $\Delta A_{CP} = (+0.49 \pm 0.30(stat.) \pm 0.14(sys.))\%$
[LHCb-PAPER-2013-003]

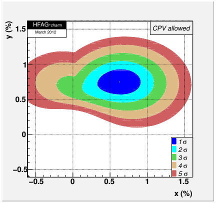
- Both consistent with no CP violation hypothesis



World average: $\Delta A^{dir}_{CP} = (-0.329 \pm 0.121)\%$
[Heavy Flavour Averaging Group]

Mixing from WS/RS $D^0 \to K^{\mp}\pi^{\pm}$ decays

- Mixing is well established in the Standard Model (K, $B(B_s)$ and D)
- Charm mixing is known to be small ($x \approx y \approx 1\%$)
- Previous evidence from accumulation of many results [Link to HFAG references]



- Mixing characterised by dimensionless parameters

$$x = \frac{\Delta m}{\Gamma} = \frac{M_1 - M_2}{\Gamma}, \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Measure time-dependent ratio of $D^0 \to K^+\pi^-$ (WS) to $D^0 \to K^-\pi^+$ (RS)
  - RS: Cabbibo favoured (CF) amplitude only
  - WS: Doubly Cabbibo suppressed (DCS) amplitude, mixing + CF decay
- Assuming small mixing and negligible CP violation,

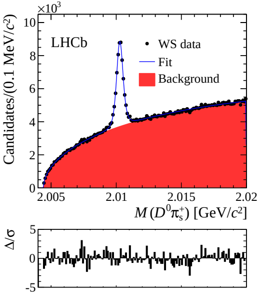
$$R(t) \approx R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

- Mixing parameters rotated by strong phase difference between CF and DCS

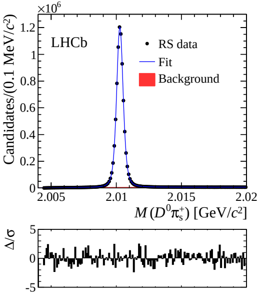
$$x' = x\cos(\delta) + y\sin(\delta) \qquad y' = y\cos(\delta) - x\sin(\delta)$$

Mixing from WS/RS $D^0 \to K^{\mp}\pi^{\pm}$ decays

WS data



RS data

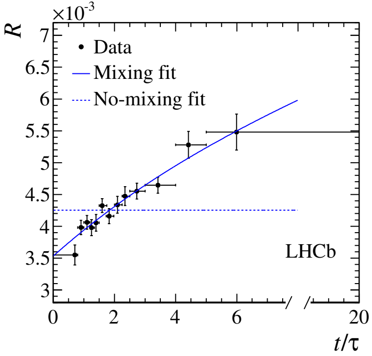


[Phys. Rev. Lett. 110, 101802 (2013)]

- Use 1.0 fb^{-1} of data collected in 2011
- Prompt $D^{*+} \to (D^0 \to K^{\mp}\pi^{\pm})\pi^+_{soft}$, π^+_{soft} tags flavour of D
- Mis-reconstructed charm from secondary B decays can cause bias in decay time
- Systematic effect on x' and y' found to be smaller than statistical error

Observation of $D^0 - \bar{D}^0$ mixing

- Limit of no mixing expect ratio of WS/RS to be a flat line as a function of time
- Clear deviation from no-mixing fit
- Observation of $D^0 - \bar{D}^0$ mixing!
  [Phys. Rev. Lett. 110, 101802 (2013)]
- No mixing excluded to 9.1 σ
- CDF has 6.1 σ observation
  [Paolo Maestro's slides from Beauty 2013]
- Both observations of D mixing!



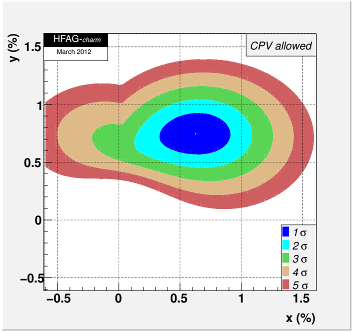
$$x'^2 = (-0.9 \pm 1.3(stat. + sys.)) \times 10^{-4} \qquad y'^2 = (7.2 \pm 2.4(stat. + sys.)) \times 10^{-3}$$

$$R_D = (3.52 \pm 0.15(stat. + sys.)) \times 10^{-3}$$

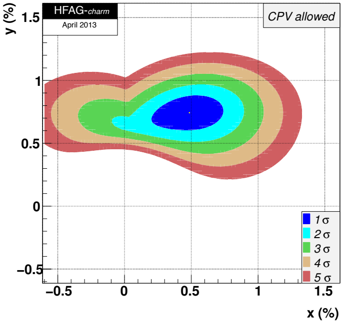
[Phys. Rev. Lett. 110, 101802 (2013)]

World averages

Where we were:



Where we are:



HFAG averages March 2012

HFAG averages April 2013

- Future results from LHCb will improve our understanding even more

Summary

Results from time-integrated CP violation measurements:

- $\Delta A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14(stat.) \pm 0.13(sys.))\%$
- $A_{CP|S}(D^+ \to \phi\pi^+) = (-0.18 \pm 0.17(stat.) \pm 0.18(sys.))\%$
- $\Delta A_{CP}(D_s^+ \to K_S^0\pi^+) = (-0.61 \pm 0.83(stat.) \pm 0.13(sys.))\%$
- ΔA_{CP} from $D^0 \to K^+K^-, \pi^+\pi^-$ decays:

Prompt: $\Delta A_{CP} = (-0.34 \pm 0.15(stat.) \pm 0.10(sys.))\%$

Secondary: $\Delta A_{CP} = (0.49 \pm 0.30(stat.) \pm 0.14(sys.))\%$

Results from charm mixing:

$$x'^2 = (-0.9 \pm 1.3(stat. + sys.)) \times 10^{-4} \qquad y'^2 = (7.2 \pm 2.4(stat. + sys.)) \times 10^{-3}$$
$$R_D = (3.52 \pm 0.15(stat. + sys.)) \times 10^{-3}$$

- No evidence for CP violation from 1.0 fb^{-1} at LHCb
- Another 2 fb^{-1} on tape!
- 9.1 σ observation of mixing in charm!
- Even more charm coming after 2015

Expect many more charm results from LHCb in the future!

Backup

Interpretation of ΔA_{CP}

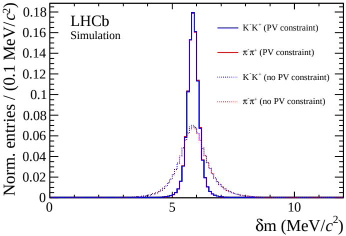
- Central value is considerably closer to zero than previous result
- Series of 1-2 σ changes that had a large cumulative effect e.g.
  - (1) Larger dataset
  - (2) Improvements to the detector calibration and reconstruction software
  - (3) Difference between the analysis techniques
  - (4) Constrain π^+_{soft} to originate from PV
- (1) + (2):
  - 15% K^+K^- and 14% $\pi^+\pi^-$ events no longer selected with new redo
  - Remaining 85%:
    $\Delta A_{CP,old} = (-0.80 \pm (stat.)0.23)\% : \Delta A_{CP,new} = (-0.78 \pm (stat.)0.23)\%$
  - Additional 17% K^+K^- and 34% $\pi^+\pi^-$ events selected with new reco
    $\Delta A_{CP} = (-0.55 \pm (stat.)0.21)\%$
  - Disjoint samples were found to be consistent with a statistical fluctuation
  - Additional 400 pb^{-1} with old technique $\Delta A_{CP} = (-0.28 \pm (stat.)0.26)\%$
- (3) + (4):
  - Kinematic binning $\rightarrow$ re-weighting = no effect on ΔA_{CP}
  - Constrain π^+_{soft} to PV:
    $\Delta A_{CP,no} = (-0.45 \pm (stat.)0.17)\% : \Delta A_{CP,yes} = (-0.34 \pm (stat.)0.15)\%$
  - Resolution affect alone = 0.05%
  - Correlation with events where π^+_{soft} has large IP = 0.08%

Constraining π_{soft} to the Primary Vertex

- Useful variable in suppressing many types of background is δm,

$$\delta m = m(D^{*+}) - m(D^0) - m(\pi^+_{soft})$$

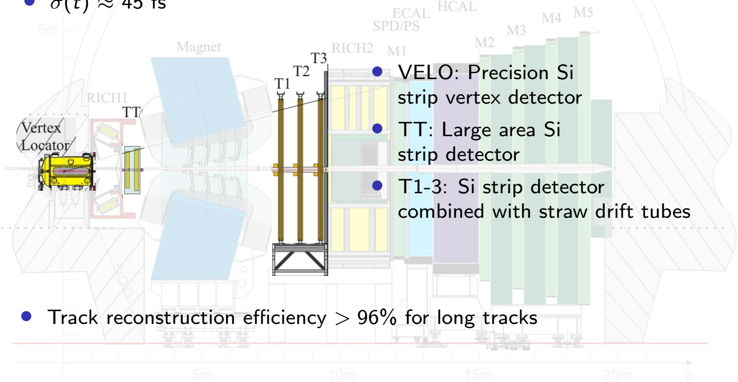
- LHCb has a extremely powerful decay tree re-fitting tool, DecayTreeFitter [Nucl.Instrum.Meth. A552 (2005) 566-575]
- Can use this to constrain π^+_{soft} to originate from the PV
- Improves δm resolution by a factor ≈ 2.5



δm distributions for $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ from simulated events before and after applying the π^+_{soft} conatraint

LHCb

- Excellent track reconstruction from VELO, TT and T stations
- $\frac{\Delta p}{p} = 0.4\%$ @ 5 GeV/c to 0.6% @ 100 GeV/c
- $\sigma(\text{IP}) = 20\ \mu$m for high p_T tracks
- $\sigma(t) \approx 45$ fs



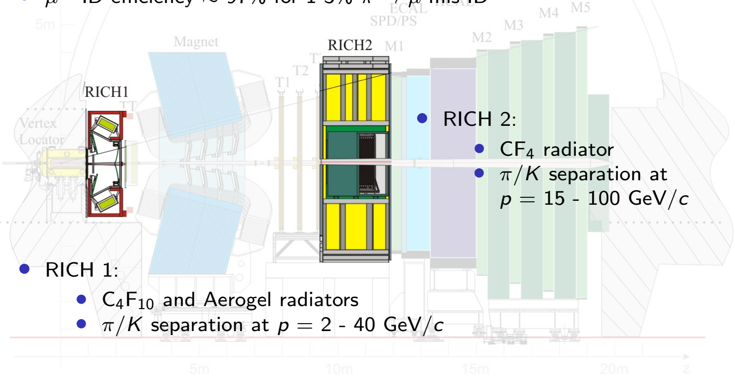
- VELO: Precision Si strip vertex detector
- TT: Large area Si strip detector
- T1-3: Si strip detector combined with straw drift tubes

- Track reconstruction efficiency $> 96\%$ for long tracks

LHCb

Excellent particle identification from RICH detectors:

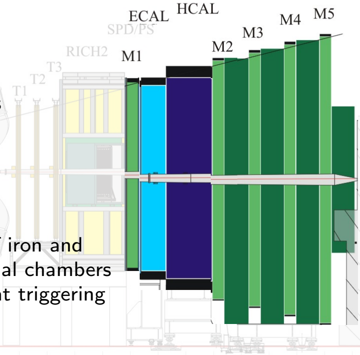
- $e^{\pm}$ ID efficiency $\approx$ 90% for 5% $e \to h$ mis-ID
- $K^{\pm}$ ID efficiency $\approx$ 95% for 5% $\pi \to K$ mis-ID
- $\mu^{\pm}$ ID efficiency $\approx$ 97% for 1-3% $\pi \to \mu$ mis-ID



- RICH 2:
  - CF_4 radiator
  - π/K separation at p = 15 - 100 GeV/c
- RICH 1:
  - C_4F_{10} and Aerogel radiators
  - π/K separation at p = 2 - 40 GeV/c

LHCb

- Calorimeter system consists of ECAL and HCAL
- $\sigma(\text{ECAL}) = 1\% + 10\%/\sqrt{E(\text{GeV})}$
- Invariant mass resolution:
  - ≈ 8 MeV$/c^2$ for $B \to J/\Psi X$
  - ≈ 22 MeV$/c^2$ for 2-body B decays
  - ≈ 100 MeV$/c^2$ for $B_s \to \phi\gamma$



- Muon stations:
  - Alternating layers of iron and multiwire proportional chambers
  - Extremely efficient at triggering on μ particles