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The Performance of the LHCb Pixel Hybrid Photon Detectors in a 25ns Structured Test-Beam

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on behalf of the LHCb RICH Collaboration

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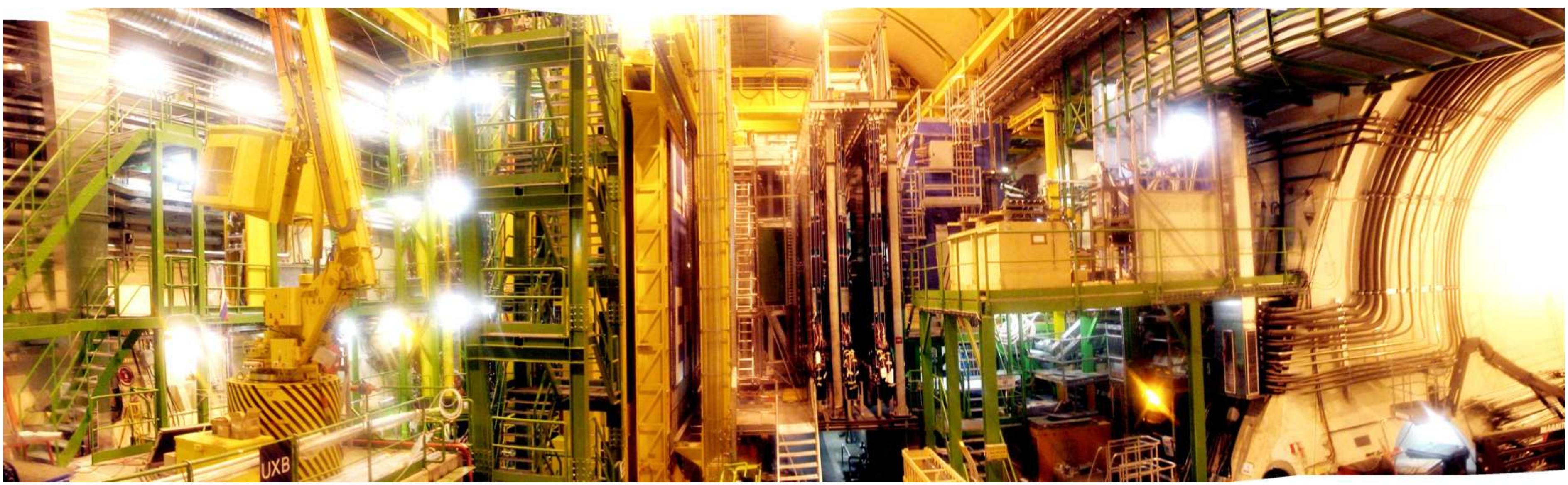
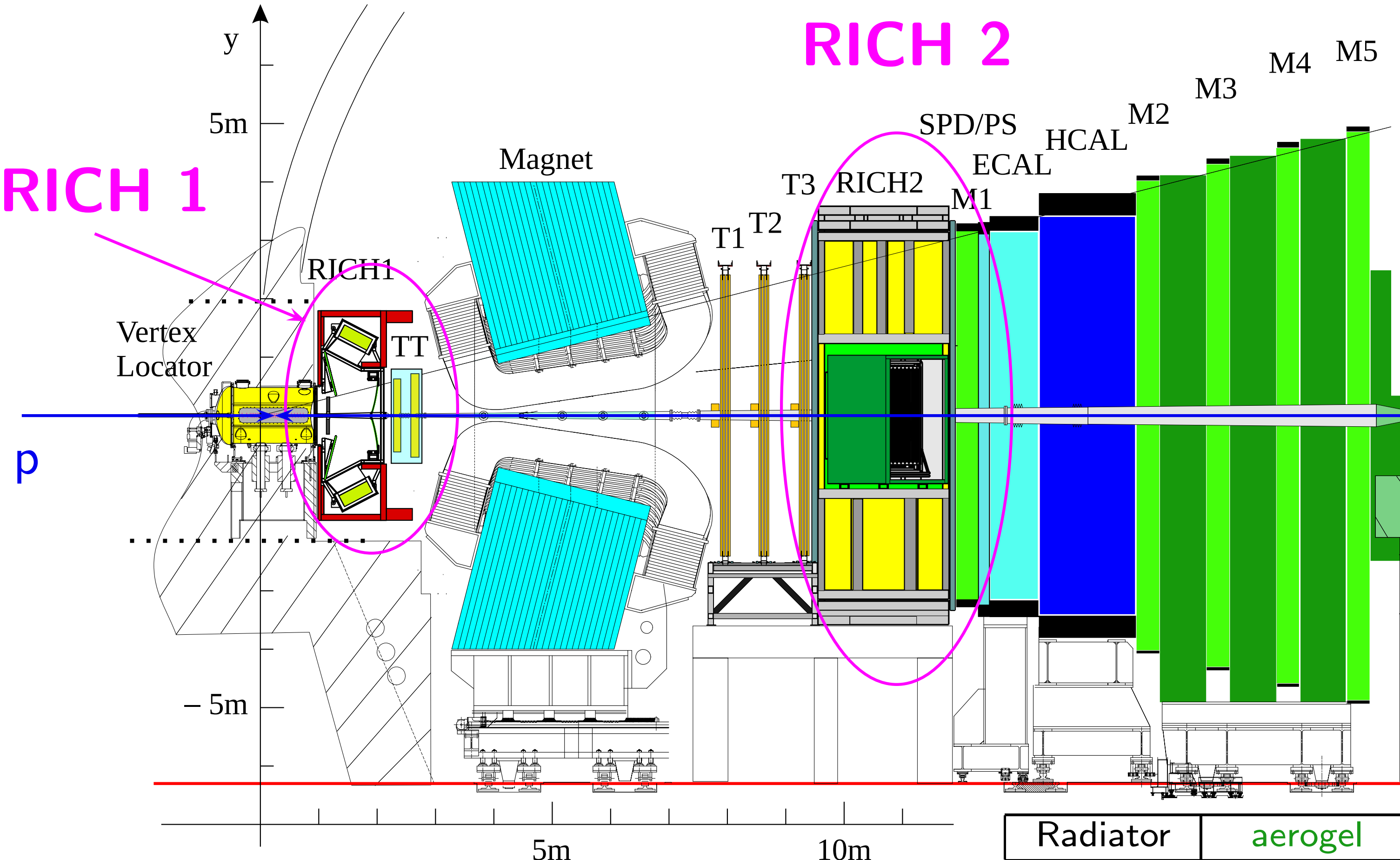
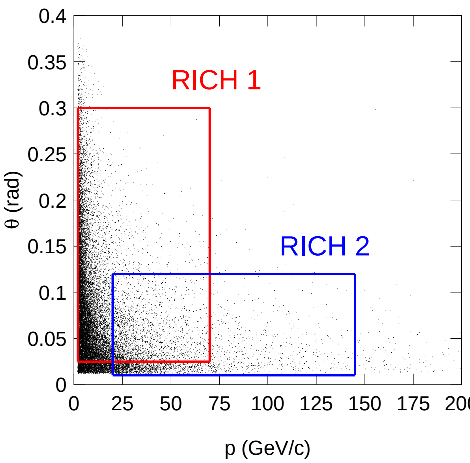
Outline

1. introduction
   - the LHCb experiment at the LHC
   - RICH detectors
   - Pixel Hybrid Photon Detectors (HPD)
2. September 2006 Test Beam
3. photoelectron yield analysis
   - the model
   - N_2 and C_4F_{10} photoelectron yields
4. Cherenkov angle resolution (early study)
5. conclusions



The LHCb Experiment





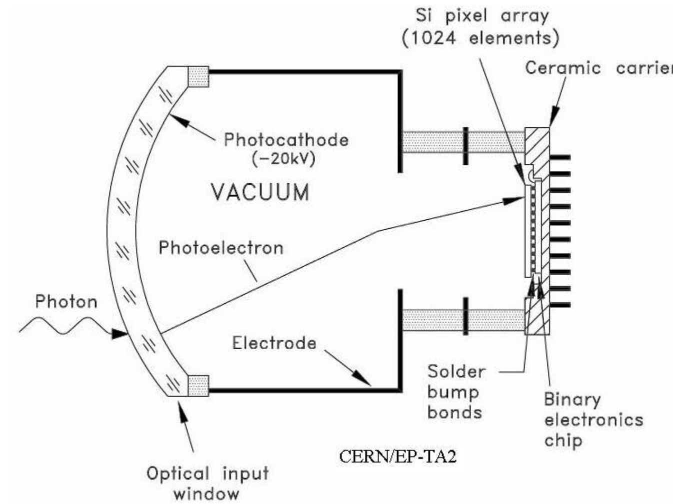
Radiator	aerogel	C_4F_{10}	CF_4
L	5 cm	85 cm	167 cm
n	1.03	1.0014	1.0005
θ_C^{max}	242 mrad	53 mrad	32 mrad
$\sigma^{tot}(\theta_C)$	2.5 mrad	1.4 mrad	0.7 mrad
$\mathcal{N}_{pe}$	5.3	24.0	18.4

1. detector construction nearing completion
2. detector commissioning in progress
3. LHCb ready to collect data at the LHC start–up

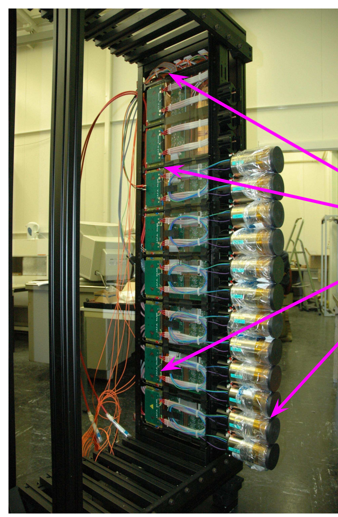
The Pixel Hybrid Photon Detectors (HPD)

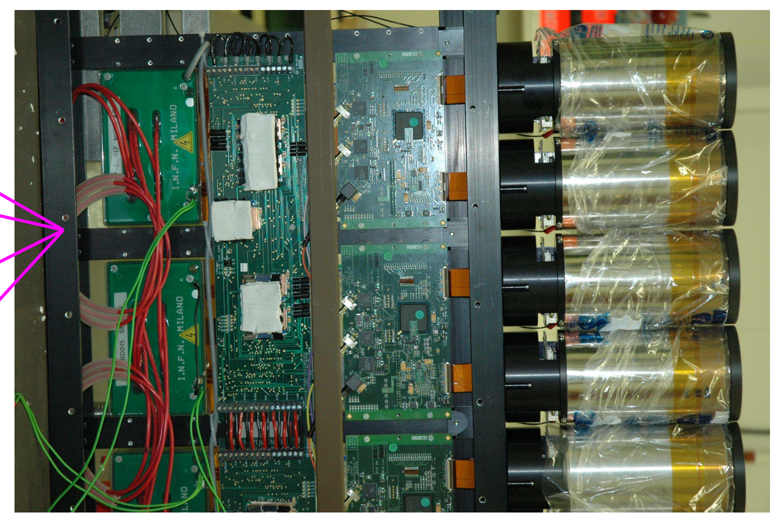
A total of 484 pixel HPDs produced to detect Cherenkov photons

1. vacuum tube, diameter 83 mm, height 120 mm
2. S20 multi–alkali photocathode
3. 200 – 600 nm sensitive wavelength range
4. average QE improved during production up to $\sim 35\%$
5. cross focusing optics ($\Delta V = 20$kV), demag factor ~ 5
6. photoelectrons focused on the pixelized silicon anode
7. $\sim$ 500k pixels over total active area $\sim 3.3\text{m}^2$



Further details by T. Blake (N53–1)

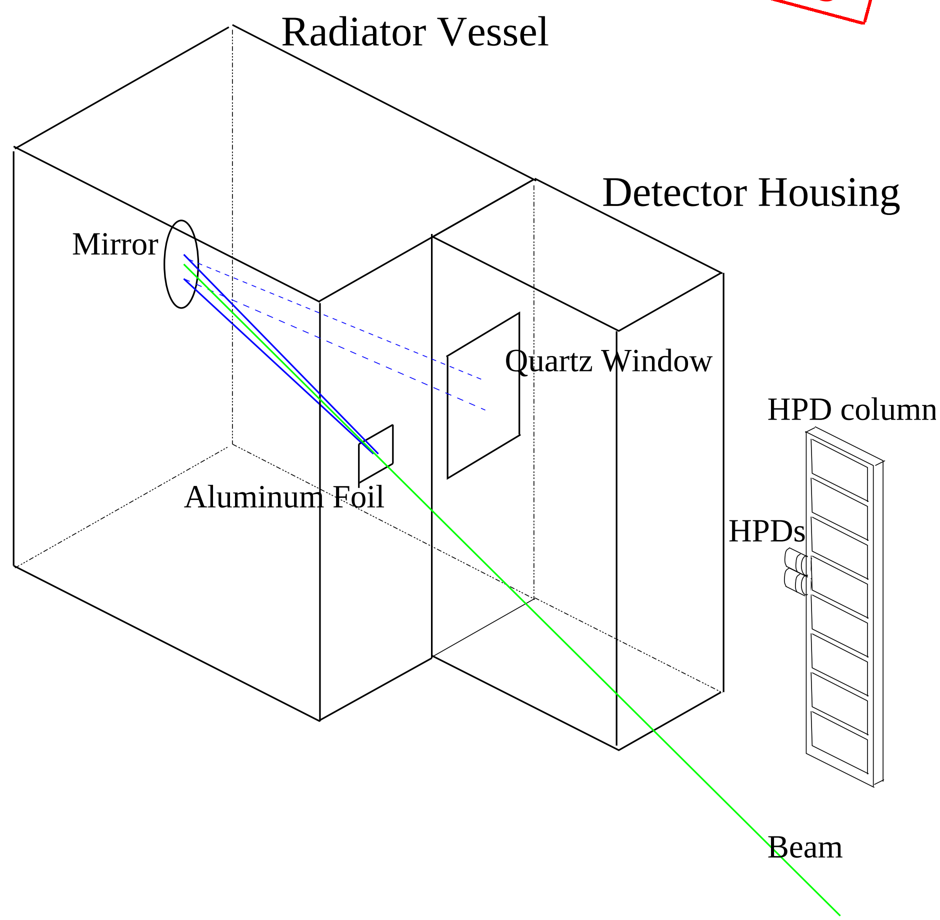




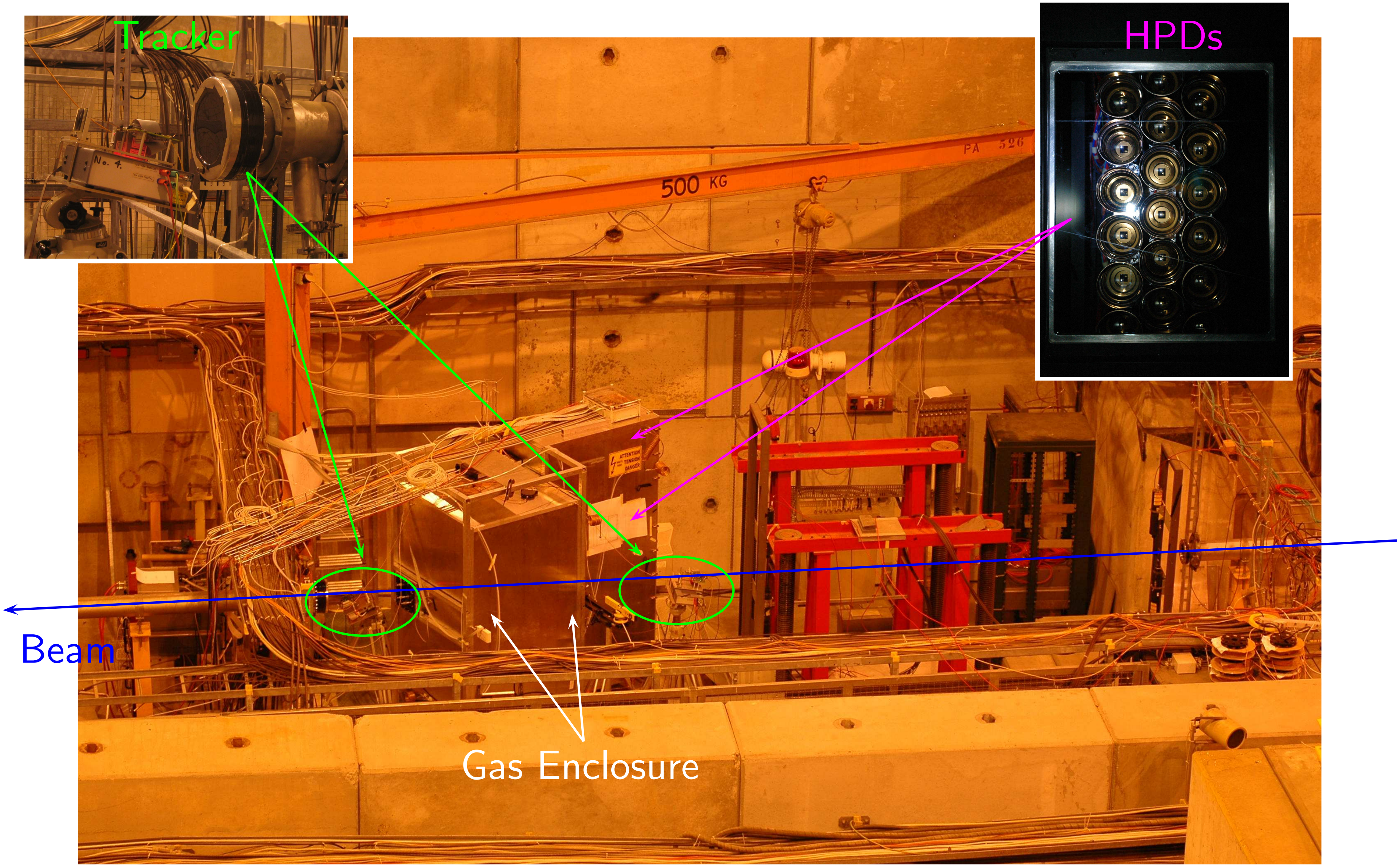
September 2006 Test Beam (1)

1. first test with LHC time structure
   - complete RICH detector, prototype placed at SPS Hall H6 (CERN)
   - final versions of the read–out electronics and DAQ
   - analysis using LHCb software
2. tilted parabolic mirror to focus Cherenkov photons
3. three RICH2 columns with 48 HPDs in total
4. N_2 and C_4F_{10} gas as Cherenkov radiators
   - L $\sim$ 1 m
5. beam properties
   - 25 ns bunch spacing
   - 80 GeV/c beam from CERN–SPS
   - mixture of π (80%), e (10%), K (7%), p (3%)
   - average < 1 particle per bunch train
6. trigger
   - two scintillators in coincidence
   - no veto on event with more than one particle
7. tracking
   - two HPD silicon sensors as tracking stations

First test with LHC bunch spacing



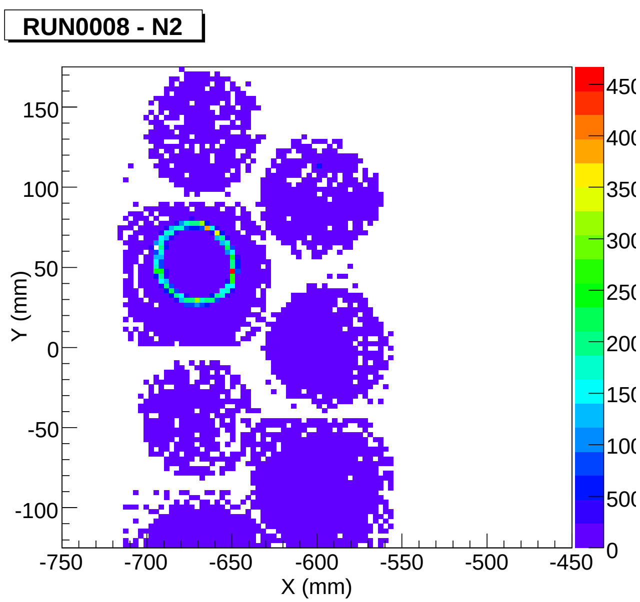
September 2006 Test Beam (2)

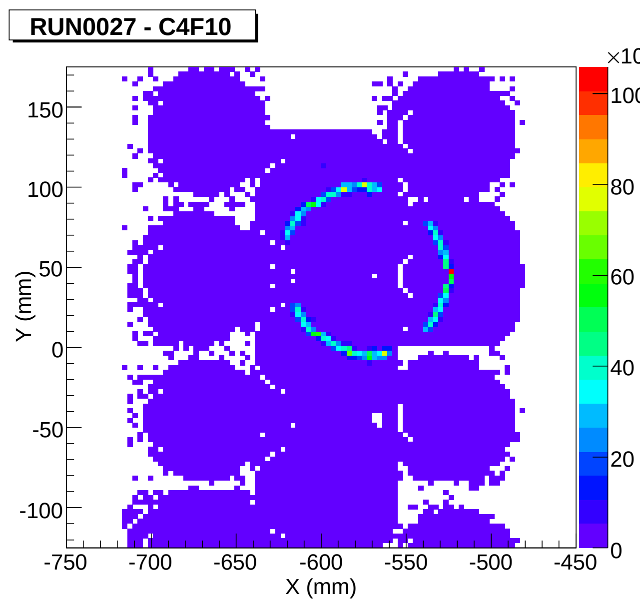


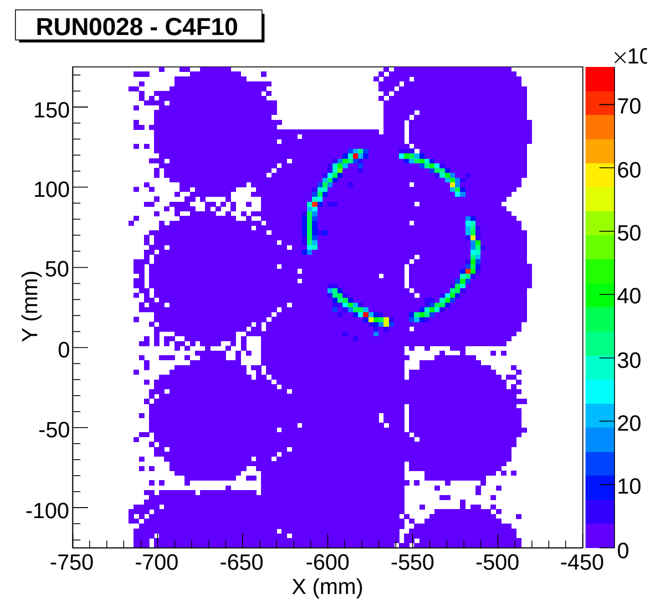
Radiators and Data Taking

1. N_2 and C_4F_{10} gas radiator used
   - N_2 data: $n = 1.000297 \Longrightarrow$ Cherenkov ring on single HPD
   - C_4F_{10} data: $n = 1.0014 \Longrightarrow$ Cherenkov ring on 3 or 4 HPD

   test the full electronic chain at the same time
2. LED and dark count runs ($\longrightarrow$ noise studies)
3. goals of this test beam
   - both hardware and software global tests
   - data acquisition and analysis checks
   - photoelectron yield studies (N_2 and C_4F_{10} data)
   - Cherenkov angle resolution evaluation



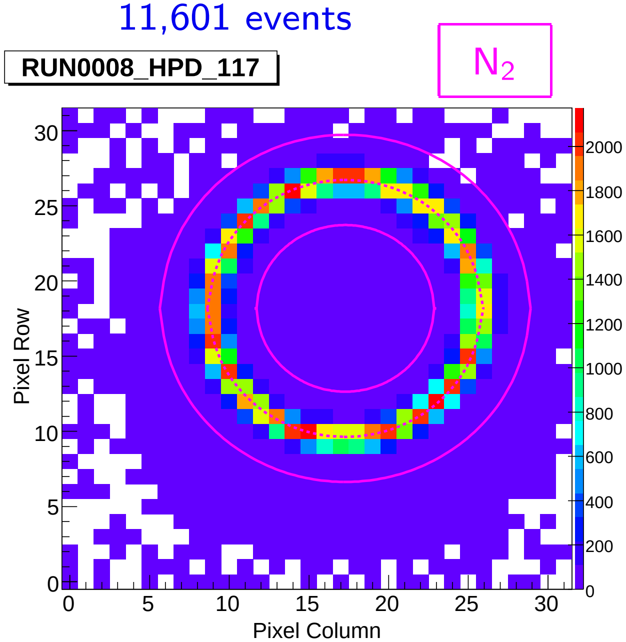




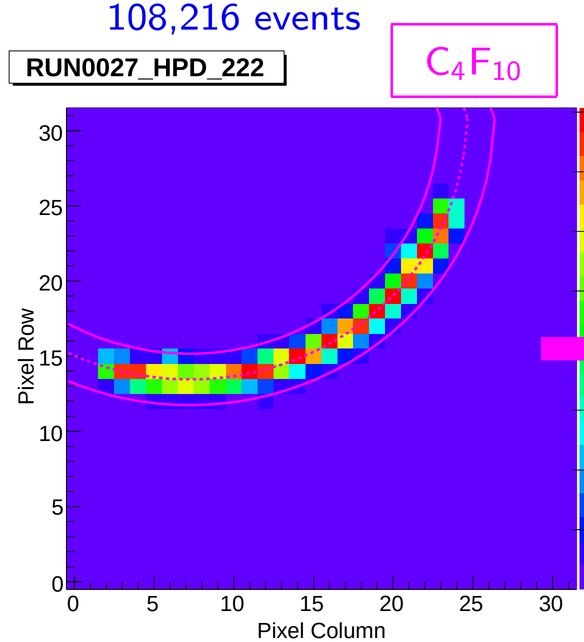
Photoelectron Yield Analysis

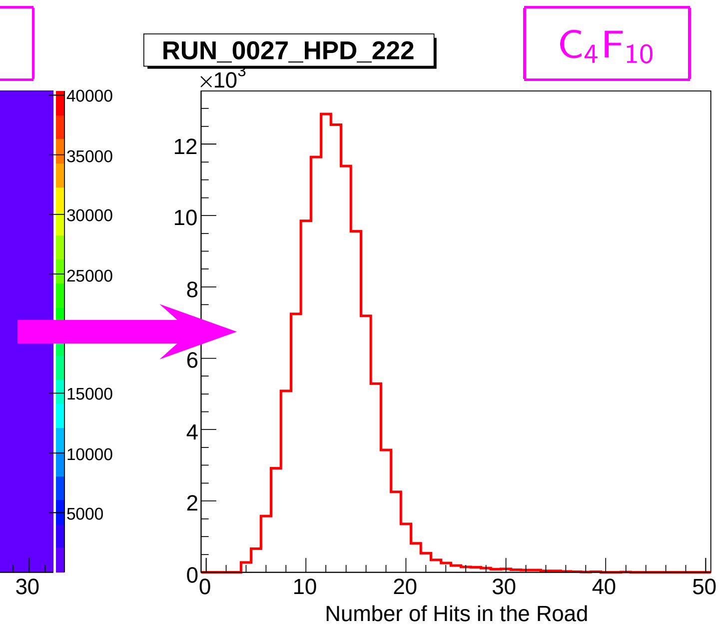
1. fit N_2 and C_4F_{10} rings on an event–by–event basis
   - require at least 5 hits in each event
   - fit a circle (3 free parameters)
2. determine a road around the average ring centre
   - select signal and reject background events with large number of fired hits outside the signal region
   - road defined as $R \pm \Delta R$ ($\Delta R = 3$ pixels for N_2; $\Delta R \sim 1.7$ pixels for C_4F_{10})
3. selection of events with 4 or more hits inside the road and less than 3 outside
4. histogram the number of hits in the road for selected events

11,601 events



108,216 events

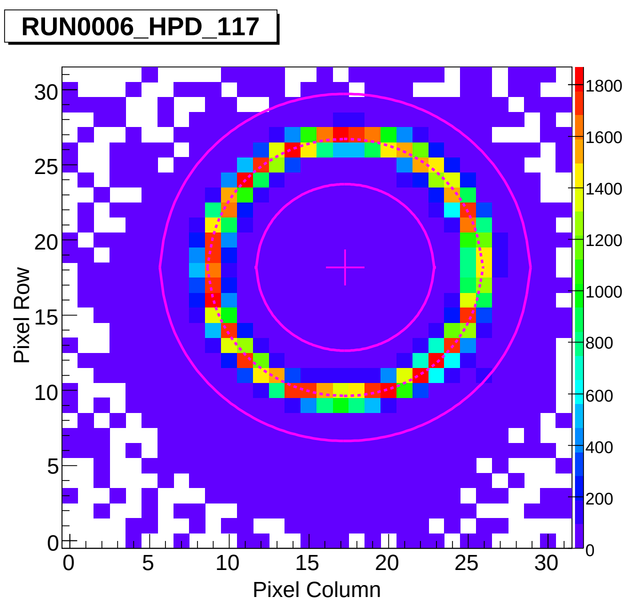


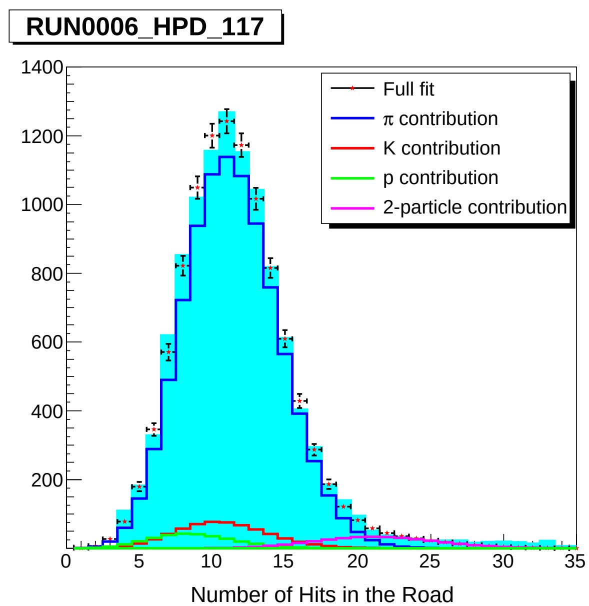


Modelling the Photoelectron Yield

1. photoelectron yield from a constrained fit to the N(n) hit distribution
2. fit model
   - sum of Poisson contributions modelling Cherenkov emission
   - beam composition: 80% π and 10% e (saturated), 7% K and 3% p (relevant for N_2 only)
   - describe one, two (and three) particle contributions in the beam
3. HPD effects (measured in dedicated LED and dark count runs)
   - account for pixel–to–pixel charge sharing ($\sim$ 3% on average)
   - double hits contamination
4. vary the μ parameter in the fit model

Preliminary Results

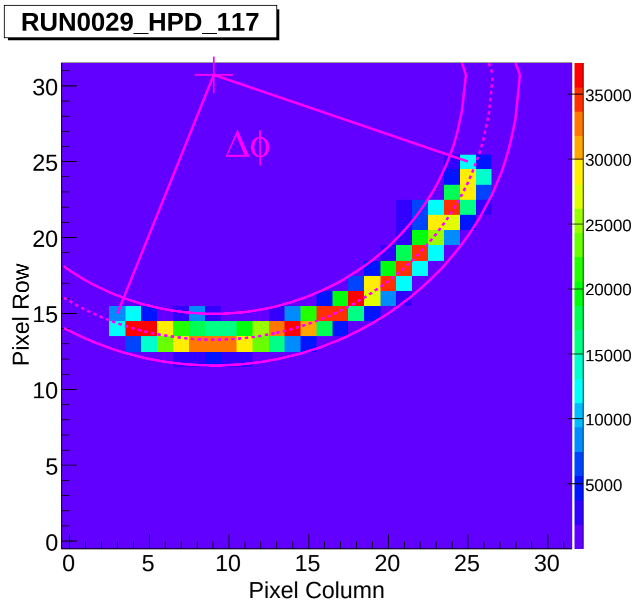


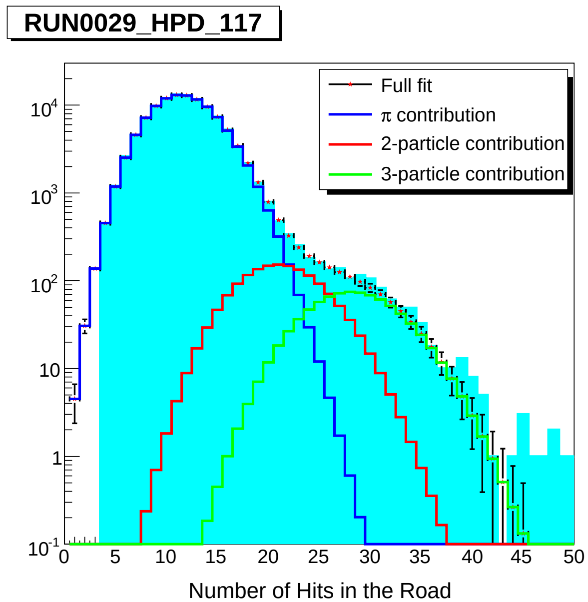


$$N_1 = 14880 \pm 124$$
$$N_2 = 351 \pm 29$$
$$\mu = 12.42 \pm 0.04$$
$$s = 0.016 \text{ (fixed)}$$
$$\chi^2/NDF = 31.52/23$$
$$\mu_{\text{expected}} \sim 13$$

HPD	Measured	Expected
117	12.32±0.12	12.20±0.62
264	13.14±0.13	14.09±0.70
265	12.56±0.12	12.81±0.65

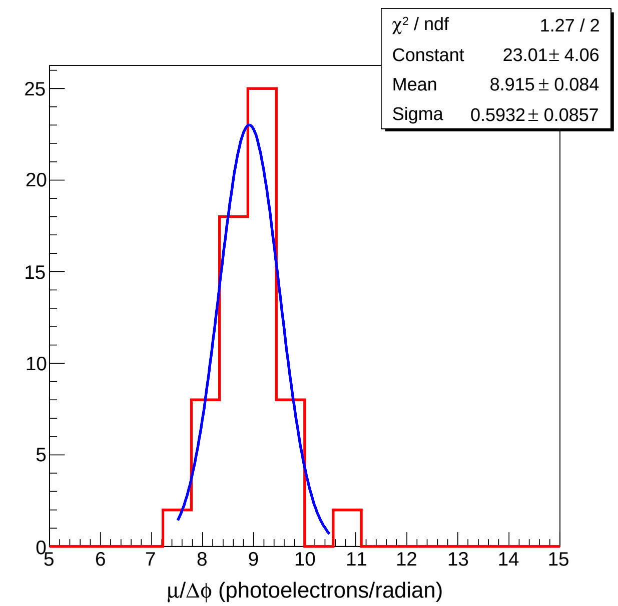
C_4F_{10} Photoelectron Yield





Preliminary Results

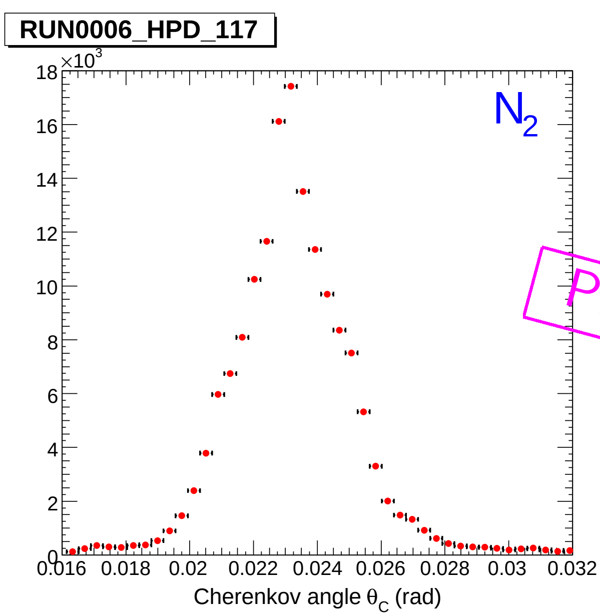
$$N_1 = 105401.6 \pm 336.0$$
$$N_2 = 1395.1 \pm 104.6$$
$$N_3 = 1008.3 \pm 72.1$$
$$\mu = 12.72 \pm 0.04$$
$$s = 0.016 \text{ (fixed)}$$
$$\chi^2/\text{NDF} = 19.0/21$$



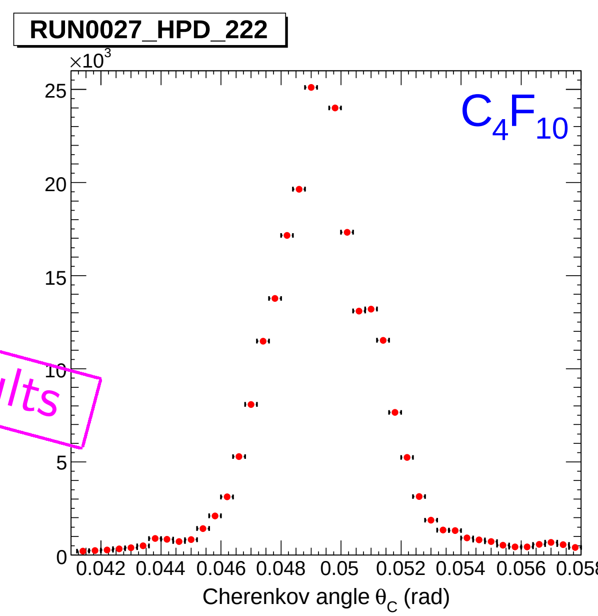
1. include and fit 1, 2 and 3 particle contributions
2. only one–particle species assumed (saturated π)
3. reasonable χ^2/NDF $\Longrightarrow$ N(n) accurate model of data
4. 2 and 3 particle fraction $\sim$2% of the total
5. stability of the dμ/d$\Delta\phi$ ratio checked: flattish distribution along ϕ
6. 10% spread of $\mu/\Delta\phi$ in agreement with the QE of the HPDs involved
7. expected yield in good agreement with full Monte–Carlo simulation
8. systematic uncertainties contribute at 5% level

Cherenkov Angle Resolutions

1. Cherenkov angle, single photon resolution studies started recently
2. encouraging results using ray tracing procedure
3. N_2 data
   - $\sigma(\theta_C) \sim 1.6$ mrad
   - work ongoing to better understand the various contributions to the resolution
4. C_4F_{10} data
   - $\sigma(\theta_C) \sim 1.6$ mrad
   - excellent resolution reached due to iterative alignment procedure
   - shift in absolute θ_C: refractive index not calibrated ($5 - 10\%$ N_2 contamination)



Preliminary Results



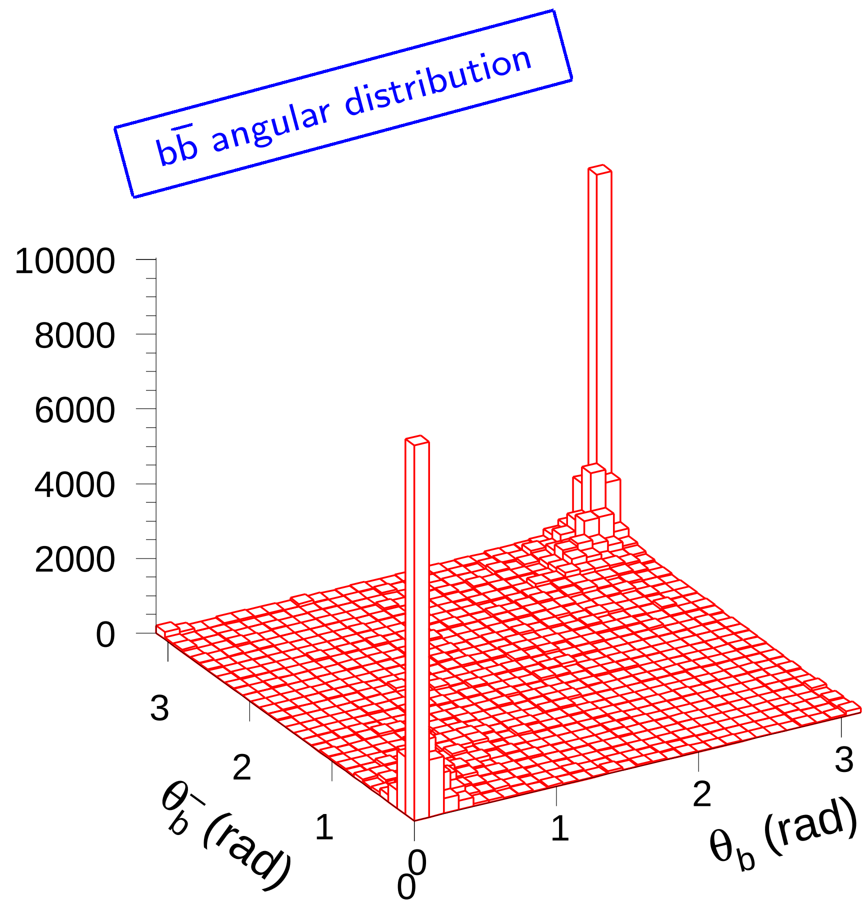
Conclusions

1. September 2006 Test Beam
   - first test with 25 ns LHC time structure
   - electronics and DAQ working at 40 MHz
   - three RICH2 columns with 48 HPDs in total
   - N_2 and C_4F_{10} Cherenkov radiators
   - 80 GeV/c mixed beam from CERN–SPS
2. data collected using an early version of the official LHCb online framework
3. analysis done using the official LHCb reconstruction software
   - photoelectron yield analysis
   - Cherenkov angle resolutions
4. LHCb photon detection system successfully tested

Back–up slides

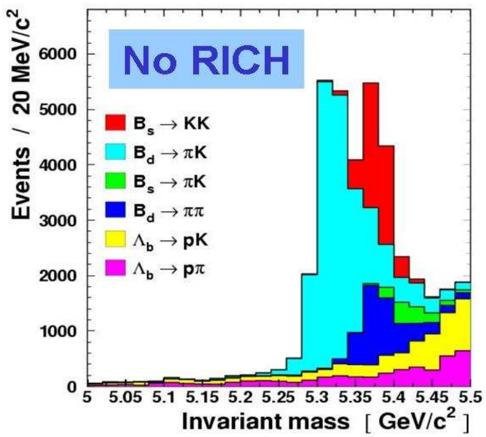
B Physics at LHC

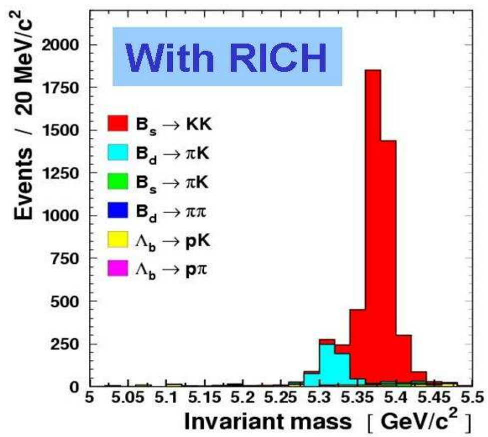
1. the aim of the LHCb experiment
   - study CP Violation in B decays through precise measurement of the CKM parameters
   - hints of New Physics in rare B–decays
2. the Large Hadron Collider
   - start–up in fall 2008
   - proton–proton at $\sqrt{s} = 14$ TeV
   - 40 MHz frequency
   - $\mathcal{L} = 2 \times 10^{32}$ cm^{-2}s^{-1} – mostly single interaction
   - $\sigma_{b\bar{b}} \simeq 500\ \mu$b
3. $\mathcal{N}_{b\bar{b}} \simeq 10^{12}$/year expected
4. all b–hadron species produced: B_d, B_s, B_c and b–baryons
5. very high statistics available for several decay channels
6. $b\bar{b}$ pairs correlated in the forward/backward cones
   - LHCb: single arm forward spectrometer
   - acceptance: 300 mrad (H) and 250 mrad (V)
   - $1.9 \leq \eta \leq 4.9$ region

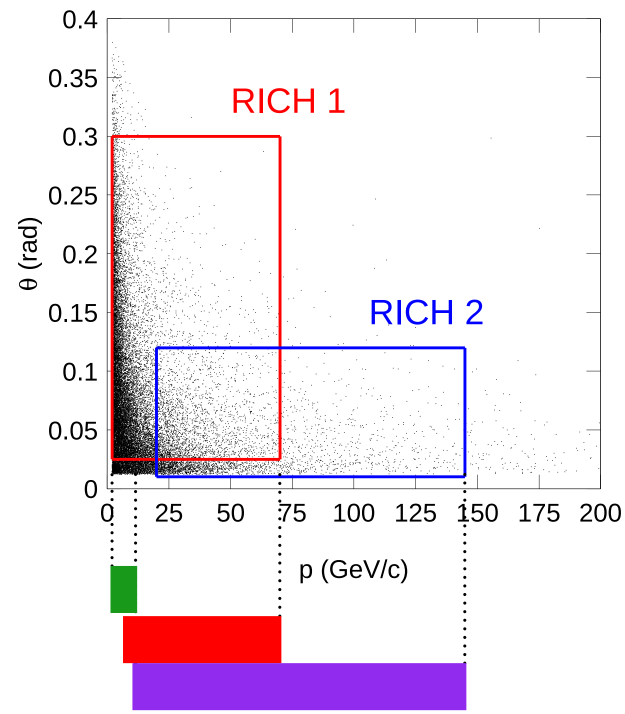


RICH Detectors

Particle identification and $B_s^0 \rightarrow K^+K^-$ decay channel (as an example)

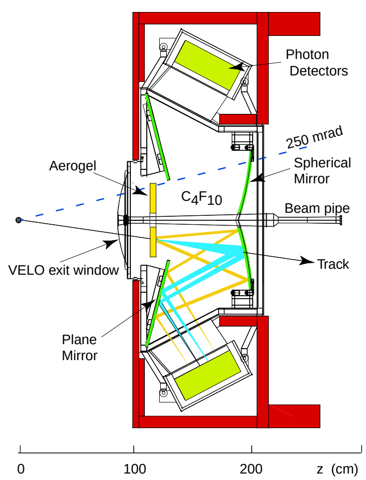


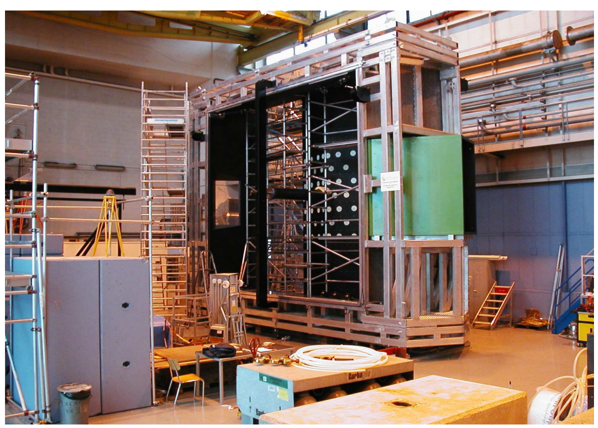




Clear correlation between momentum and polar angle of particles to be identified

- 2 RICH detectors
- 3 radiators, one solid (aerogel) and two gaseous (C_4F_{10} and CF_4)





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Modelling the Photoelectron Yield

1. photoelectron yield: constrained fit to the N(n) hit distribution
2. properties of the fit function
   - account for pixel–to–pixel charge sharing (s) and double hits (d)
   - describe one, two (and three) particle contributions in the beam
   - beam composition: 80% π and 10% e (saturated), 7% K and 3% p (relevant for N_2 only)
3. measured values of charge sharing (from dedicated LED and dark count runs) fixed in the minimization
4. vary the parameter in the fit model

$$\mathrm{N}(n) = \overbrace{N_\pi \times P\left(n; \mu_\pi, s, d\right)}^{\text{pion/electron term}} + \overbrace{N_K \times P\left(n; \mu_K, s, d\right)}^{\text{kaon term}} + \overbrace{N_p \times P\left(n; \mu_p, s, d\right)}^{\text{proton term}} + \overbrace{N_{2\pi} \times P\left(n; 2\mu_\pi, s, d\right)}^{\text{two}-\text{particle term}}$$

5. probability to observe n fired pixel hits given a photoelectron yield μ as product of Poisson distributions

$$\mathrm{P}\left(n; \mu, s, d\right) = \sum_{\mathrm{i}=0}^{n} \sum_{\mathrm{j}=0}^{\infty} \underbrace{P\left(n-i+j; \mu\right)}_{\text{number of hits}} \underbrace{P\left(i; (n-i)s\right)}_{\text{charge sharing}} \underbrace{P\left(j; (n-i+j)(n-i+j-1)d\right)}_{\text{double hits}}$$

Charge Sharing Studies

1. photoelectron signal optimally contained in a single pixel
2. signal over threshold in two or more adjacent pixels, probability around 3% $\Longrightarrow$ charge sharing
3. important to know its fraction for each HPD to control the photoelectron yield
4. dedicated LED data and toy model
   - estimate number of photoelectrons $\neq$ number of hits due to charge sharing
   - estimate number of adjacent hits due to two genuine photoelectrons
5. ion feedback and micro discharges, main background contributions of this study
   - account for 5% of hits in the HPDs
   - clustered in large groups of adjacent pixels
   - ion feedback: shower of photoelectrons created by residual ion inside the vacuum tube colliding with the photocathode
   - micro discharge: spark from near the photocathode due to electrical breakdown of the gas around the tube
6. charge sharing fraction measured for each HPD
   - 0.1% precision
   - main inaccuracy still from ion feedback
   - numbers to be used in the N_2 and C_4F_{10} photoelectron analyses