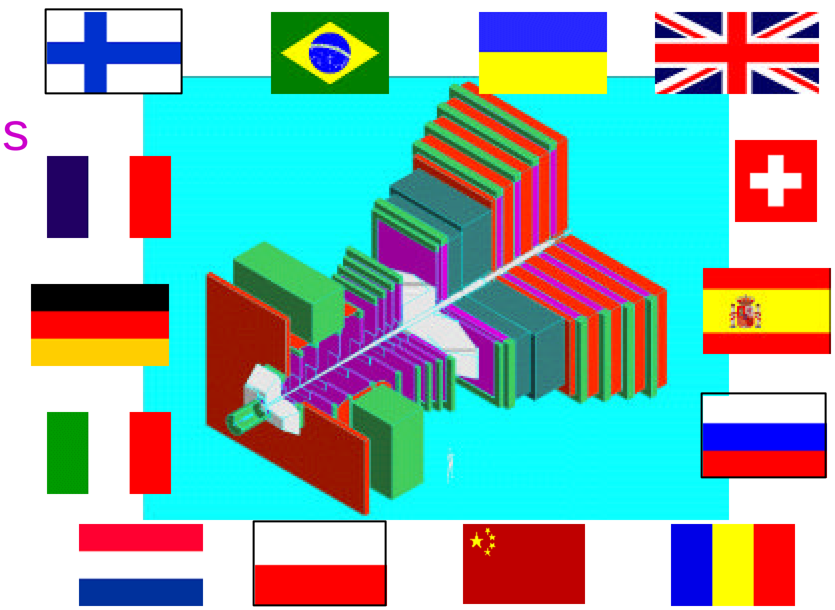
Status of the LHCb Experiment

- Introduction
- Detector Status
  - VELO
  - RICH
  - ECAL
  - Trigger
- Physics
- Conclusions

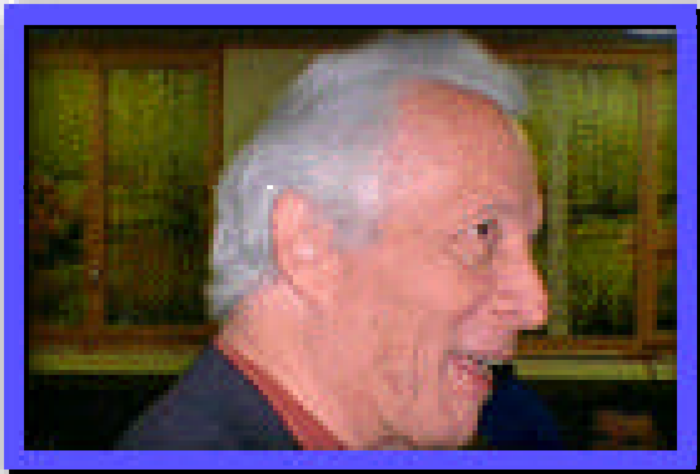


Beauty 2000
Sea of Galilee
13. 9. 2000

Franz Muheim
University of Edinburgh

Dedication

Tom Ypsilantis
1928 - 2000



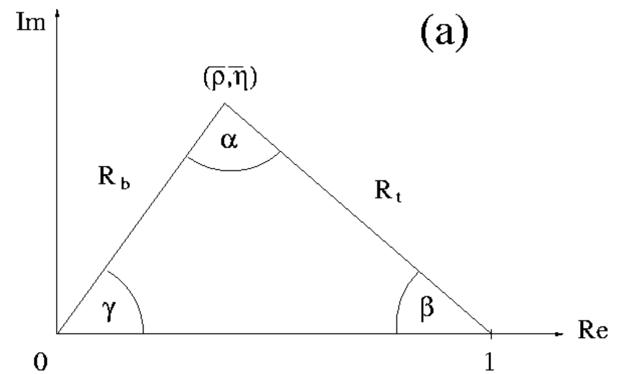
- conceived RICH detectors in 1977 (with J. Seguinot)
- a founding member of LHCb, totally dedicated to the RICH project
- a colleague always eager to discuss new ideas
- was a good friend for many of us
- He will be missed

Introduction

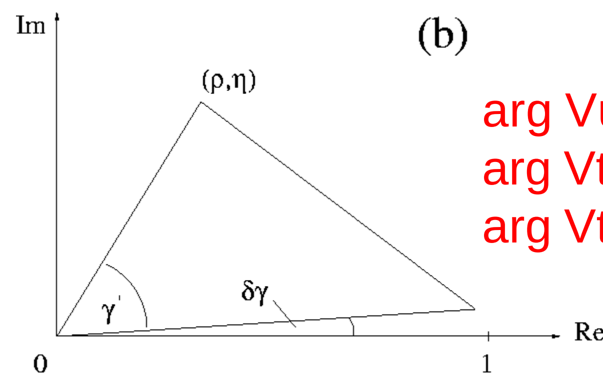
- ~~CP~~′ only observed in neutral kaon system
  - theoretical uncertainties
- Standard Model
  - 3 generation CKM matrix allows for ~~CP~~ if $\eta \neq 0$
  - predicts large ~~CP~~ asymmetries for B mesons
- No real understanding
  - Baryogenesis: additional source of ~~CP~~ needed
  - why is strong ~~CP~~ small?
  - ➔ New physics around the corner?

UnitarityTriangles

$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$



$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$

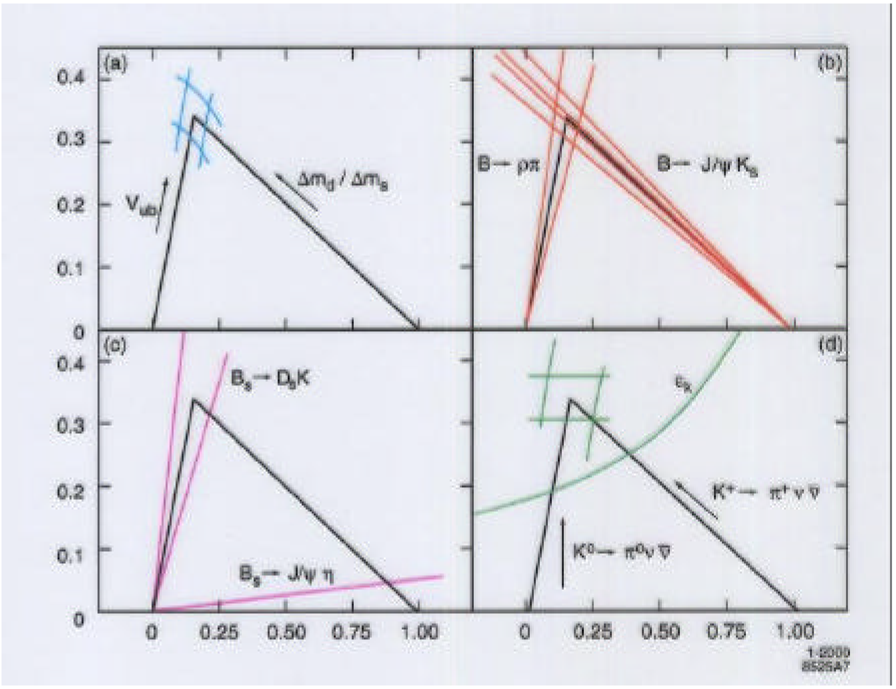


arg $V_{ub} = -\gamma$
arg $V_{td} = -\beta$
arg $V_{ts} = \pi + \delta\gamma$

~~CP~~ in B Meson System

- Ideal to search for new physics
- SM makes accurate predictions
  - precision tests
- ~~CP~~ in many decays
  - consistency
- Examples
  - Vub & $B\bar{B}$-mixing
  - sin 2β & sin 2α
  - γ & $\delta\gamma$ with B_s mesons
  - compare to kaon sector ε_K & K-> $\pi\nu\bar{\nu}$
- Can extract parameters of SM and new physics

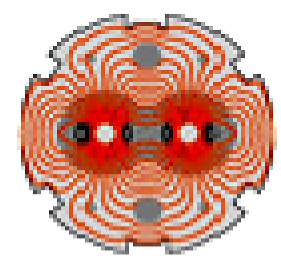
Peskin, EPS 1999



Large Hadron Collider

- By 2005: BABAR, BELLE, CLEO-III, CDF, D0, HERA-B
  - ➔ 1st test of CKM matrix $(\bar{\rho},\bar{\eta})$ vs $\sin 2\beta$
- ***LHCb*** is a 2nd generation experiment
  - ➔ precision measurements of ~~CP~~
    overconstrain CKM elements
  - ➔ large statistics, B_s mesons
- LHC is the most intensive source of B mesons (B_d, B_u, B_s, B_c)
  - – $\sigma_{b\bar{b}}$ = 500 μb $\sigma_{inelastic}$ = 80 mb
  - – Luminosity $\langle L \rangle_{LHCb} = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$
    $\langle L \rangle_{LHC} = 10^{34}\ cm^{-2}\ s^{-1}$
  - ➔ $10^{12}\ b\bar{b}\ /\ 10^{7}$ s

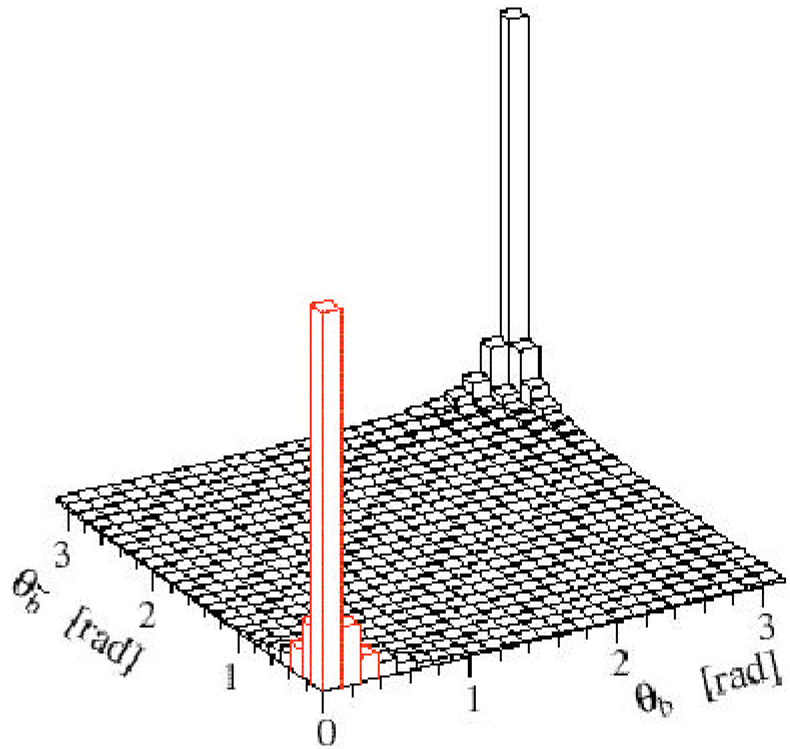
LHC



LHCb Experiment

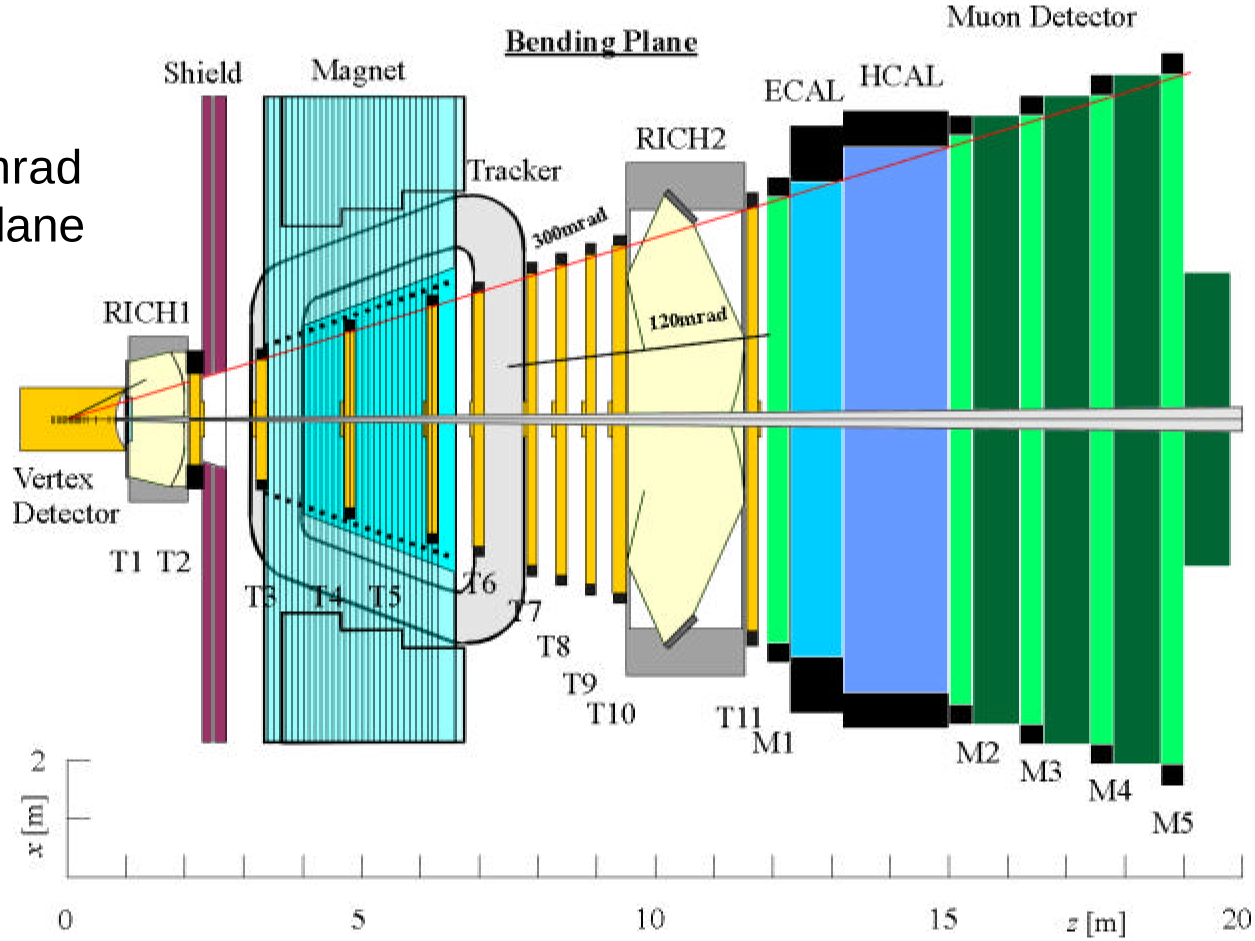
- Detector
  - forward single arm spectrometer
- Challenges
  - Trigger: leptonic and hadronic final states (eg $B_d \to \pi\pi$)
  - Particle Identification: π-K separation $1\ \text{GeV} < p < 150\ \text{GeV}$
  - Vertexing: proper time resolution
    43 fs $B_s \to D_s\pi(K)$
    30 fs $B_s \to J/\psi\ \phi$

bb angular production



LHCb Experiment

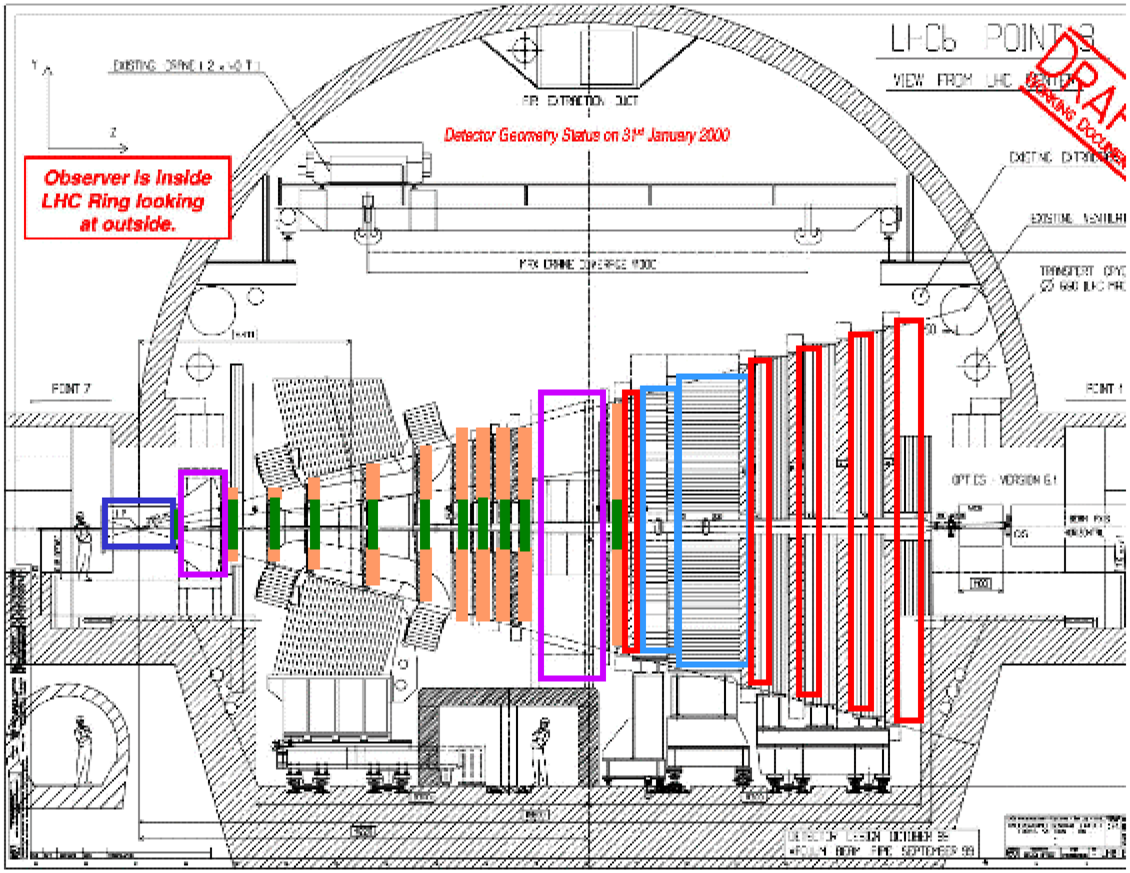
- Acceptance
  10 - 300 (250) mrad
  (non)-bending plane



- Open geometry
  easy access

LHCb Experiment

- Vertex
- Inner Tracker
- Outer Tracker
- RICH1
- RICH2
- Calorimeters
  ECAL
  HCAL
- Muon Detector



LHCb Subsystems

System	Technology
Magnet	warm
Vertex Locator	r-phi Si strip detectos
Inner Tracker	All Si strips or Si / Triple GEM
Outer Tracker[1]	Straw tube drift chambers
RICH	HPD baseline/ MaPMT backup
Calorimeters	Preshower: Scintillator/Pb/scint. ECAL: Shashlik, HCAL: Fe-scint. tile
Muons[2]	MWPC & RPC - single or double gap
Trigger	L0 (hardware), L1 (vertex), L2, L3
Computing[3]	OO & GAUDI, LHC GRID

See separate talks by 1) B. Hommels, 2) E. Santovetti, 3) G. Corti

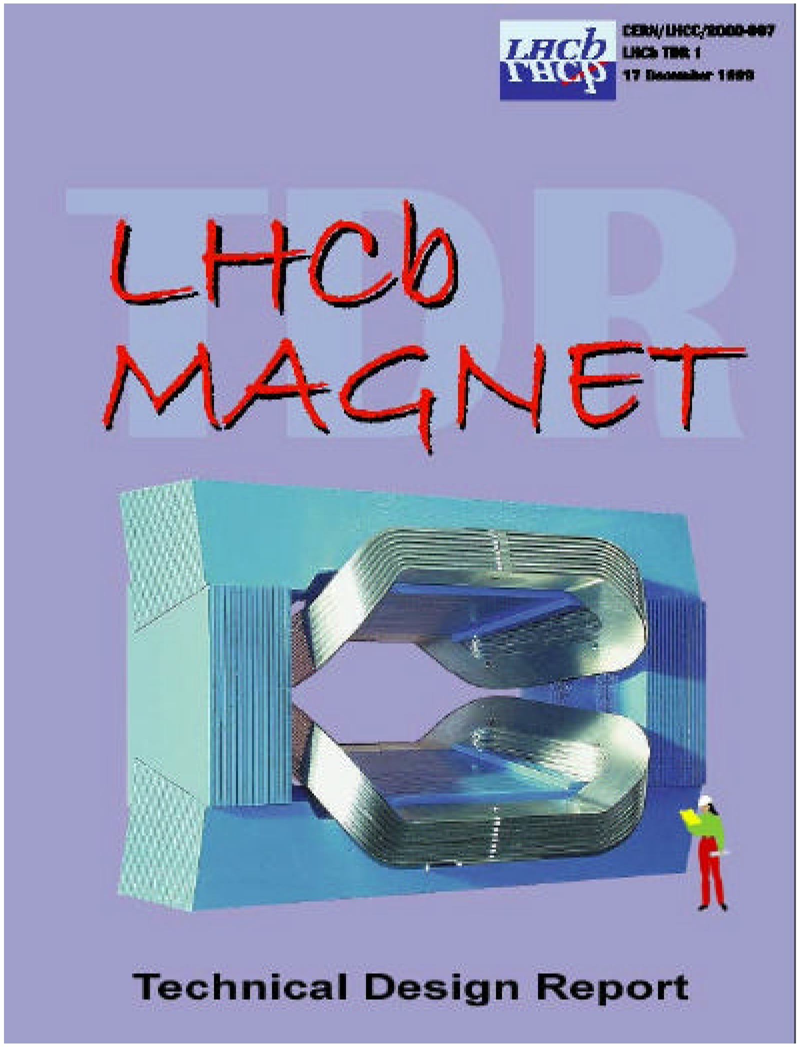
LHCb Milestones

- Aug 1995: *LHCb* Letter of Intent
- Feb 1998: Technical Proposal
- Sep 1998: Approval of TP
- 1999 - 2001: Technology choices
- Jan 2000: 1st Technical Design Report (TDR) - Magnet
- 2000 - 2002 remaining TDRs
- now - July 2004: Construction phase
- July 2005: 1st beam

LHCb TDR Summary

❑ Magnet	TDR approved April 2000
❑ Vertex Locator	TDR April 2001
❑ Inner Tracker	TDR Sept 2001
❑ Outer Tracker	TDR March 2001
❑ RICH	TDR submitted 7. Sep 2000
❑ Calorimeters	TDR submitted 6. Sep 2000
❑ Muons	TDR Jan 2001
❑ Trigger	TDR Jan 2002
❑ Computing	TDR July 2002

Magnet

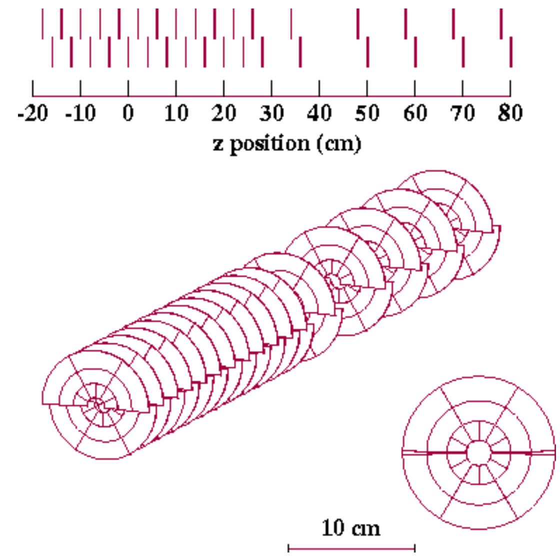


- Properties:
  - Normal conducting (Al)
  - ∫Bdl = 4Tm
  - Power 4.2 MW
  - Yoke 1450 t
- TDR
  - submitted: Jan 2000
  - recommended (LHCC) approved: April 2000 (Research Board)
- Call for tender
  - now

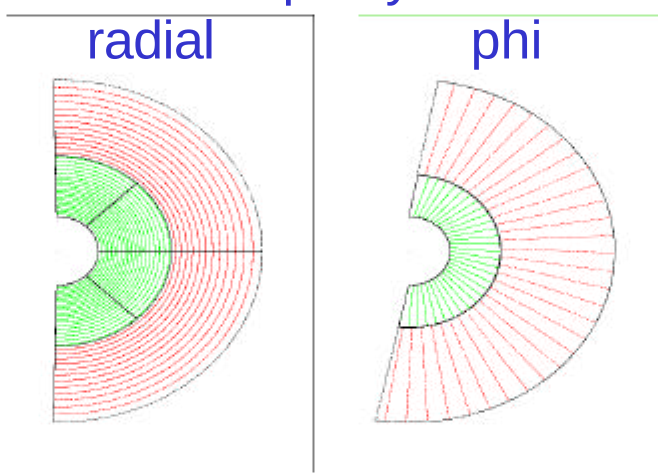
Vertex Locator

VELO Design

- Si strip detectors p-n, n-n,
  single sided, double metal read-out
  220 μm thick, 180^0 wedges
- Optimized for Level 1 trigger (L1)
- ➔ Alternate r and phi strip detectors
  varying strip pitch 20 - 40 μm in r
- Detector halves retracted by
  $\pm$ 30 mm in y during injection
- ➔ 8 mm from beam during physics
- Radiation damage
- ➔ may replace detectors after a few years



Si Strip Layout



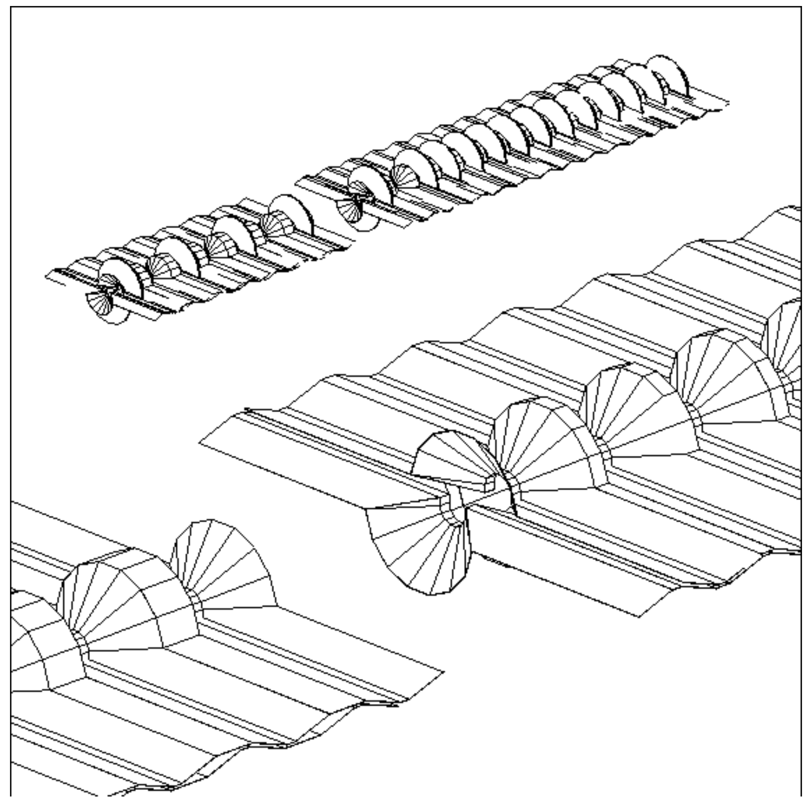
VELO Design

Optimisation

Toblerone RF shield

- Use Liverpool MAP farm (300 Linux PCs)
  - 3.5 Million events
  - optimize # of stations, positions, outer & inner radii
- 25 stations, mounted in "toblerone" RF shields
  - 220 k channels
  - 9.5 hits/ track
- Proper time resolution

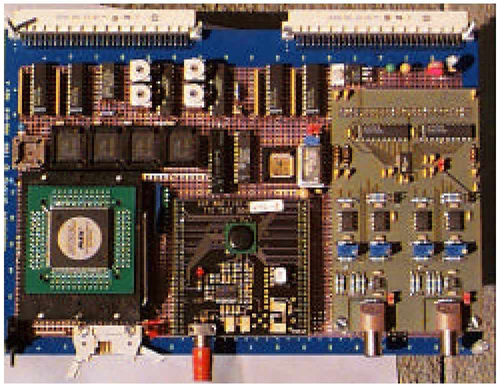
  σ_t = 43 fs $\quad$ $B_s \to D_s\pi$
  - sensitive up to $x_s \sim 75$ (1 year)



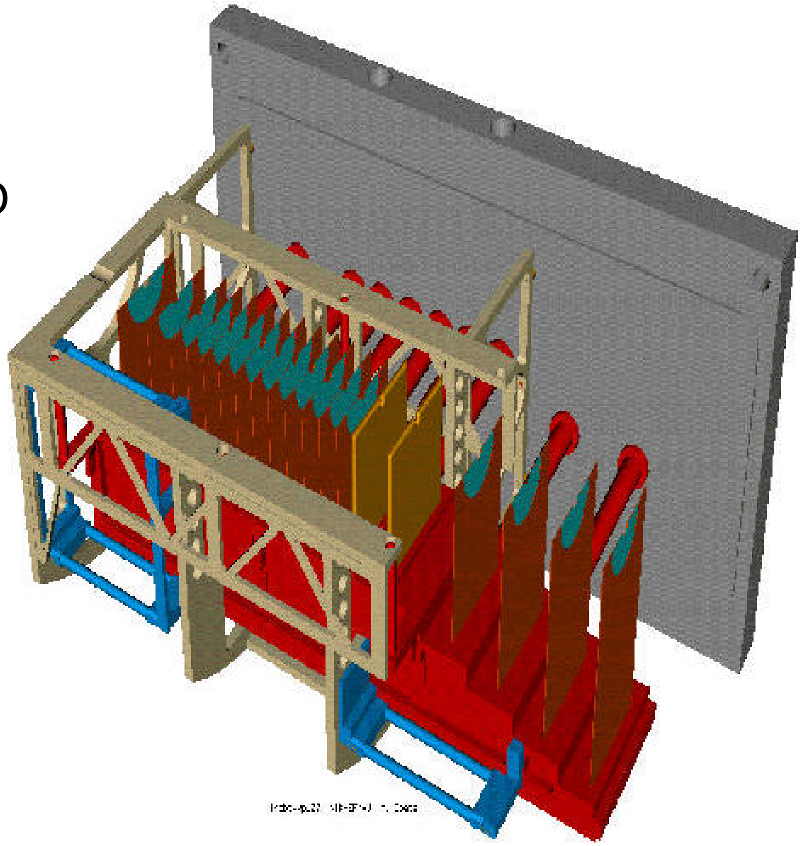
Electronics & Mechanics

Electronics

- Analogue read-out
- Front-end chip design
  - sub micron - BEETLE
  - DMILL - SCTA128_VELO
- ODE prototype
  - Testbeam



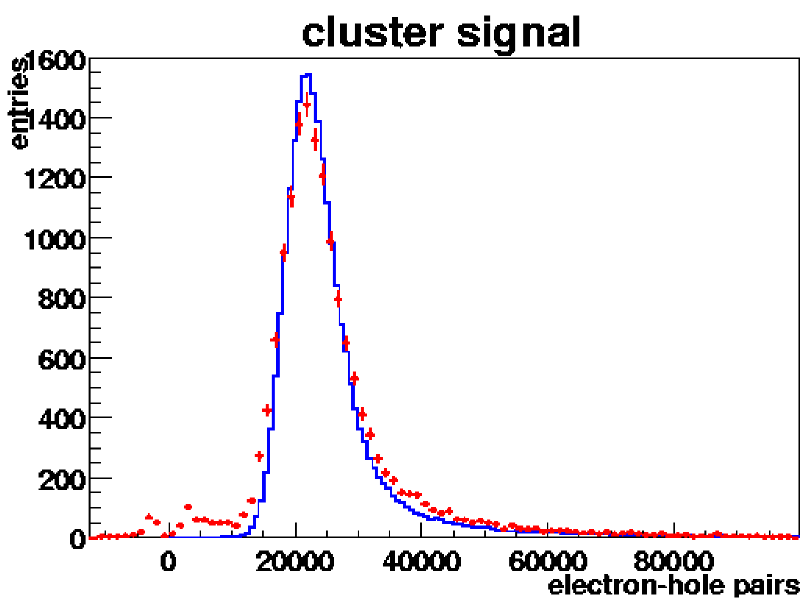
Vertex tank

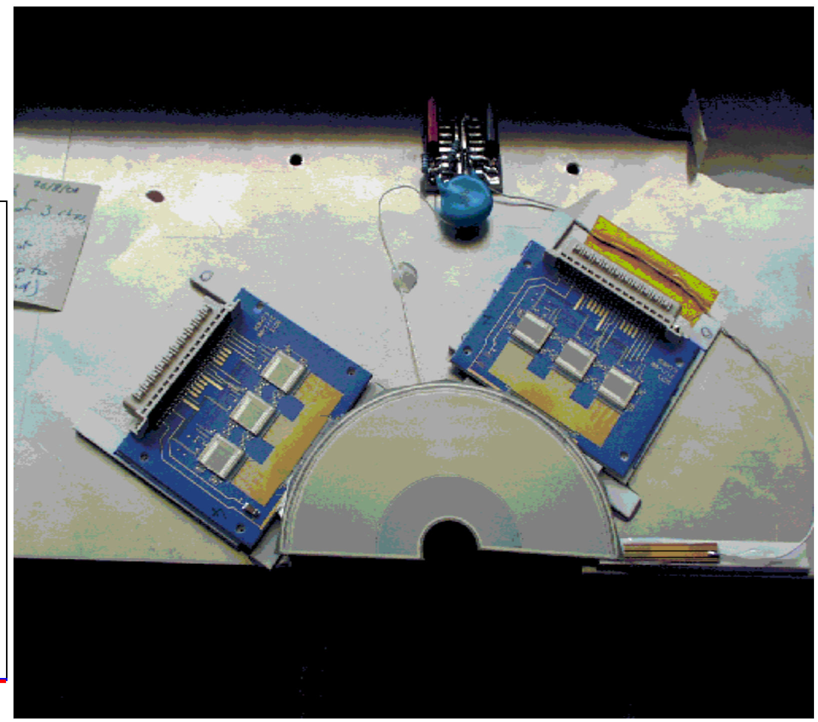


VELO Tests

- Testbeam
  - irradiated prototypes
  - cluster finding efficiency
  - resolution
  - signal shape

Setup
200 µm p-n “Micron”





VELO Summary

- Geometry
  - smallest pitch where most important for impact parameter resolution, at inner radius: “pixels” of 20 x 6300 μm^2
  - optimum for L1 trigger
  - constant occupancy < 5 x 10^{-3}
- Thin detectors
  - read out at outer rim
  - minimize multiple scattering
  - S/N ~ 15 sufficient for L1 trigger
- Number of readout channels
  - 220 k reflects in cost

→ **Design Criteria** optimum for vertexing in LHCb

Particle Identification

- LHCb needs excellent charged particle identification
- e.g. $B_s^0 \rightarrow D_s^{\mu} K^{\pm}$ sensitive to ~~CP~~ angle γ

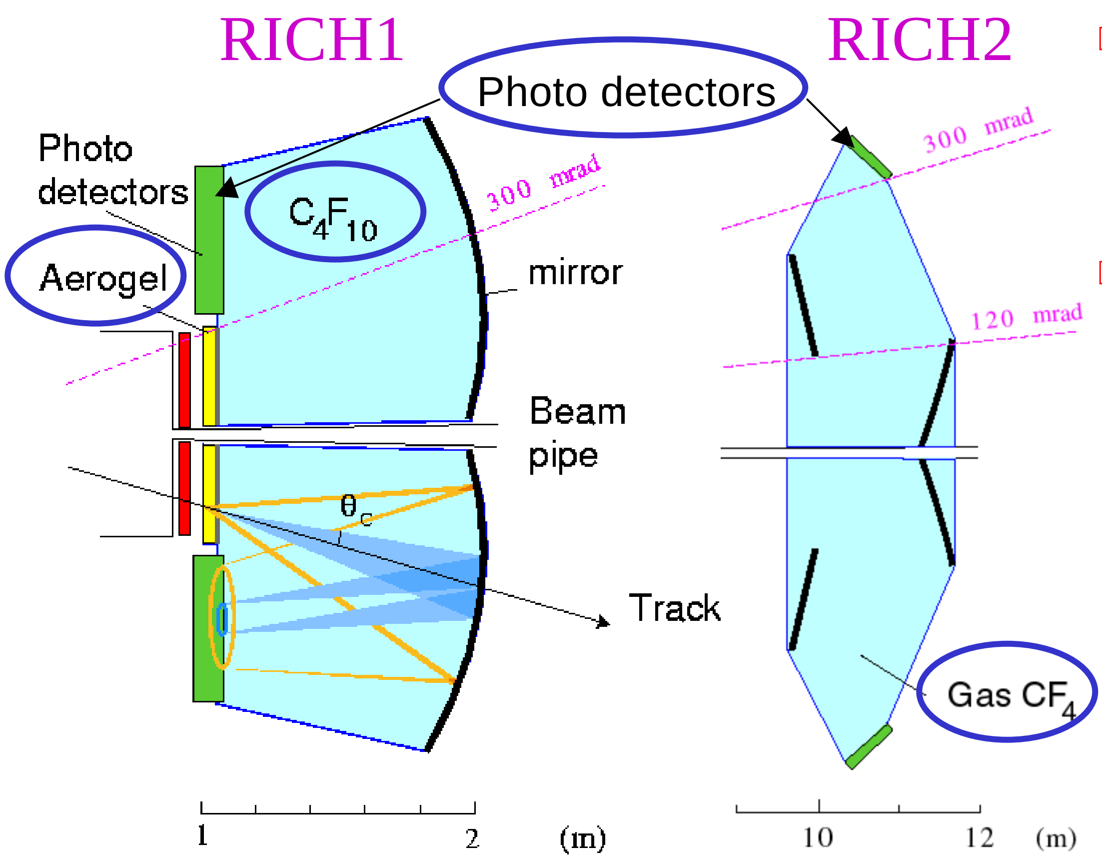
  $\hookrightarrow \phi\pi^-$

  $\hookrightarrow K^+K^-$

  Cabibbo suppressed wrt to $B_s^0 \rightarrow D_s^{\mu}\pi^{\pm}$
  final state: 3 kaons
- Kaon tagging for b production flavour
- Large momentum range $1 < p < 150$ GeV

→ **RICH**

Ring Imaging Cherenkov Detectors



- Acceptance
  - 300 mrad RICH 1
  - 120 mrad RICH 2
- Radiators / thresholds
  - Aerogel C4F10 CF4

π	0.6	2.6	4.4	GeV
K	2.0	9.3	15.6	GeV

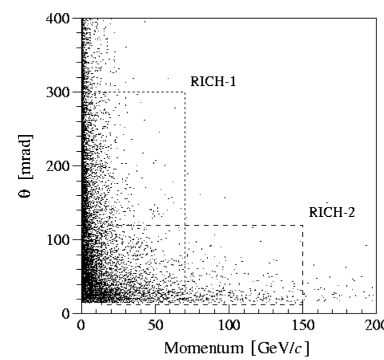
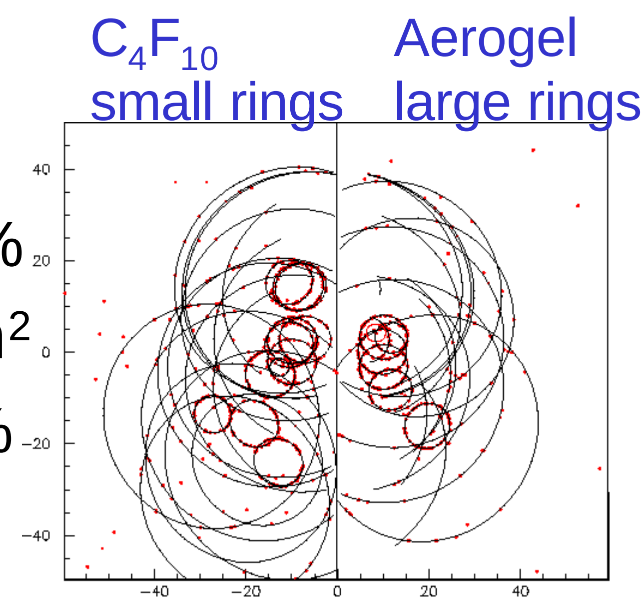
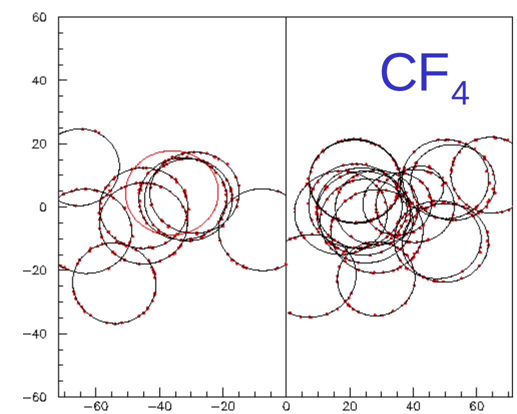


Photo Detectors

- Photo detector area: 2.9 m^2
- Single photon sensitivity: 200 - 600 nm, quantum efficiency>20%
- Good granularity: ~ 2.5 x 2.5 mm^2
- Large active area fraction: ≥ 73%
- LHC speed read-out electronics: 40 MHz
- LHCb environment: magnetic fields, charged particles

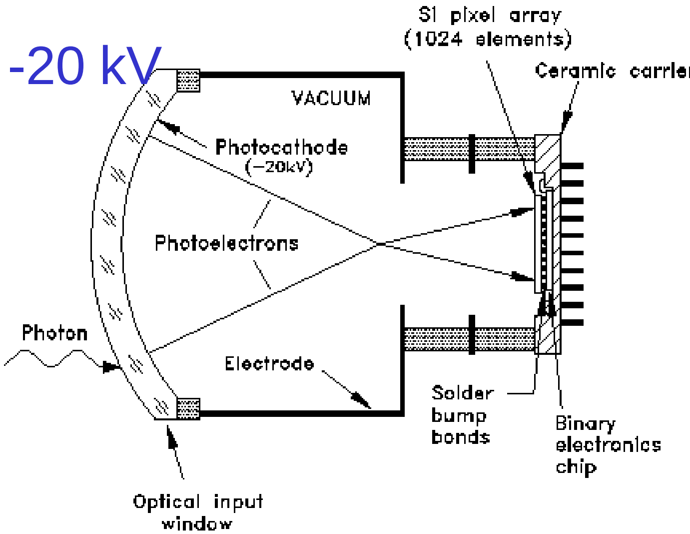
→ **HPD or MAPMT**





Hybrid Photo Diodes

Pixel HPD (baseline)



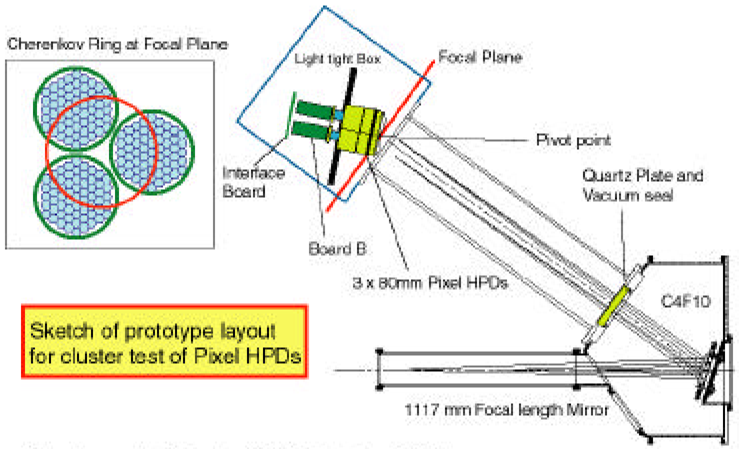
- Quartz window, thin S20 photo cathode ∫QE dE = 0.77 eV
- 32 x 32 Si pixel array: 500 μm
- Cross-focusing optics
  - demagnification ~ 5
  - 50 μm point-spread function
  - 20 kV operating voltage
- Encapsulated binary electronics
- Tube, encapsulation: DEP
- Pixel sensor: CERN

61 pixel HPD

- Existing prototype external read-out

Φ = 80 mm

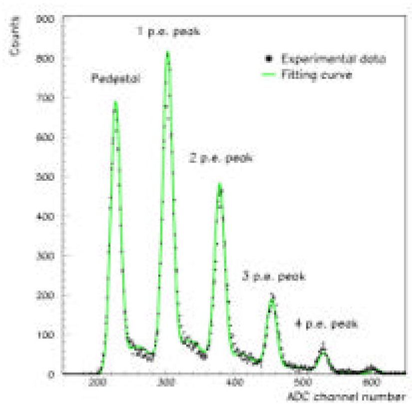
Testbeam



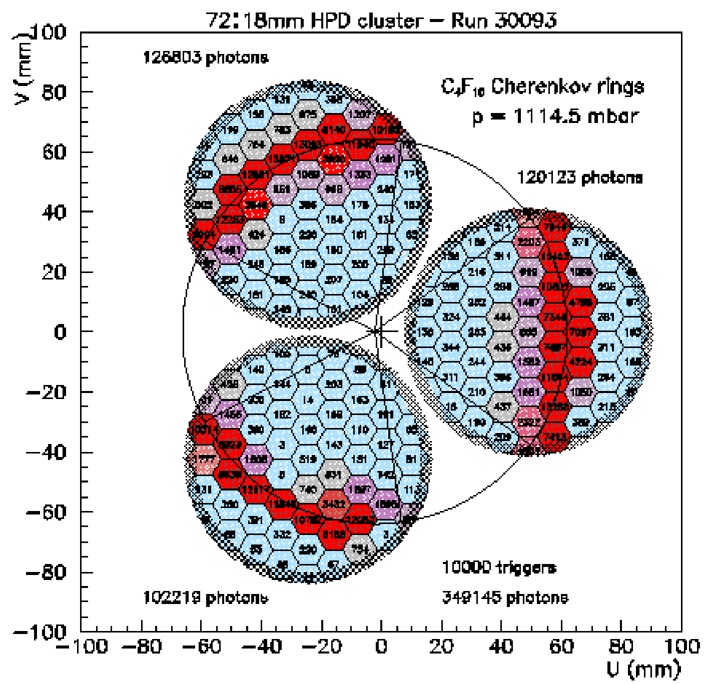
d with C4F10 radiator at 1000mbar

LED

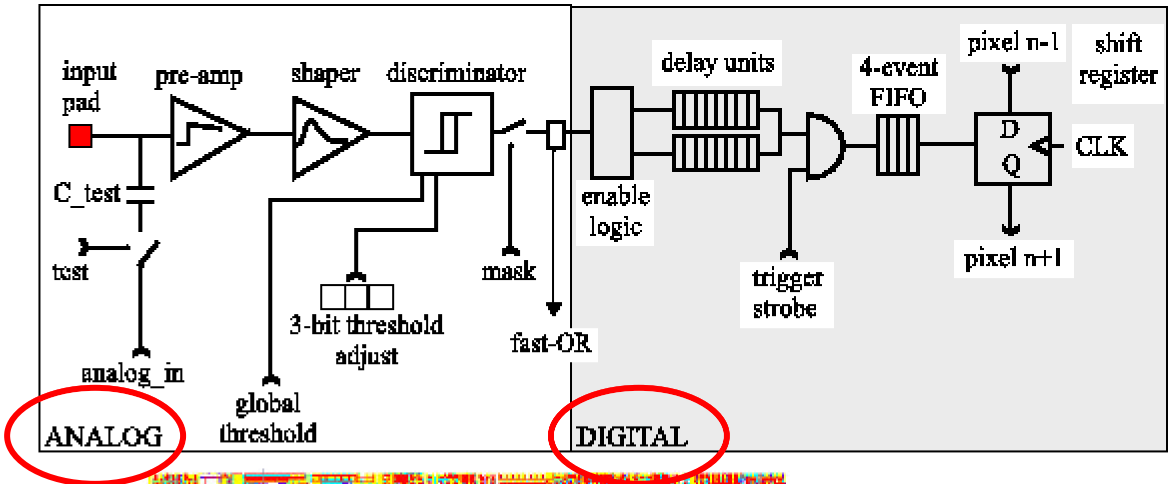
Spectrum



- ❑ Testbeam Setup
  - RICH 1 prototype
  - 3 HPDs
- ❑ Figure of merit
  - $N_0 \approx 225 - 250 \text{ cm}^{-1}$

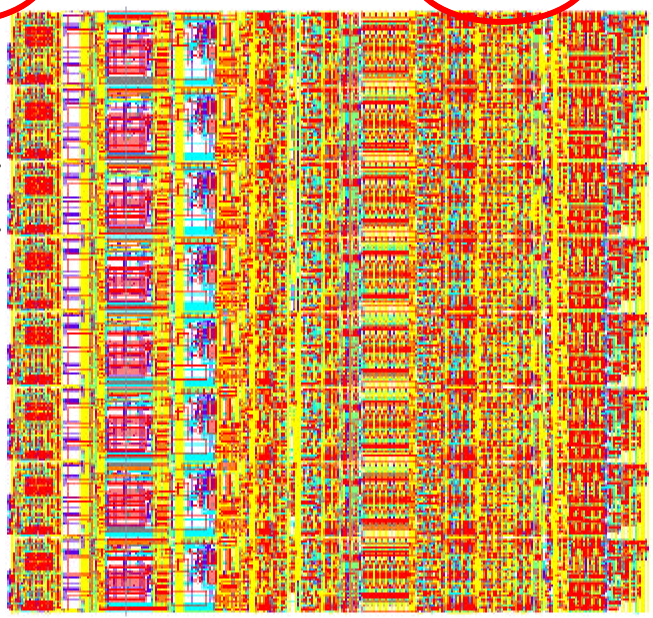


HPD Electronics



Pixel chip

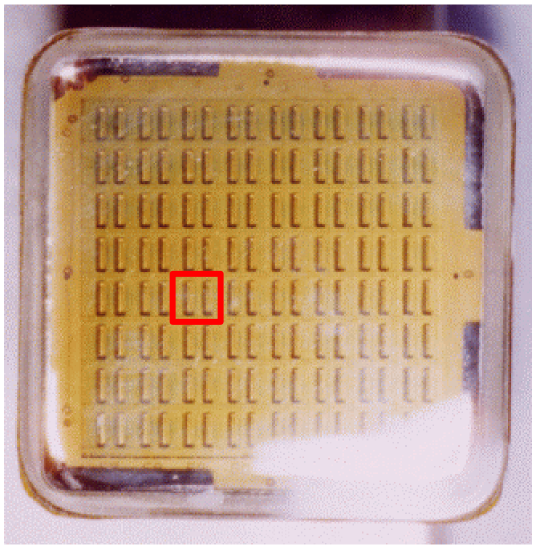
Occupancy
~3 % RICH 1
< 1% RICH 2

50 µm


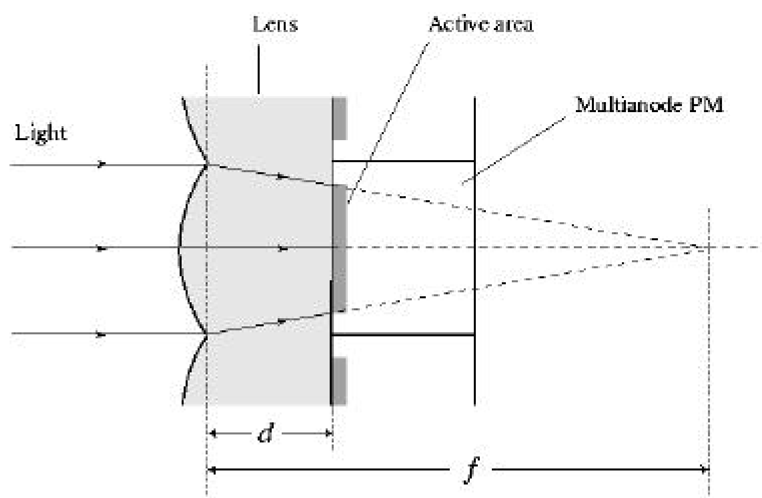
- ALICE / LHCb
- pixel size 50 µm x 425 µm
- 8 pixels = 1 LHCb unit
- 40 MHz read-out clock
- in production (IBM)
- Bump bonding: chip-sensor

MAPMT (backup)

Multianode Photo Multiplier Tube



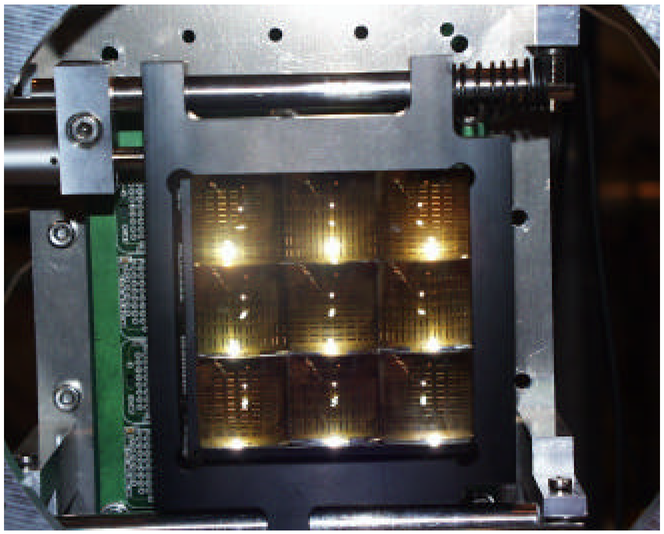
- 8x8 dynode chains, pixel 2x2 mm^2
- Gain: $3 \cdot 10^5$ at 800 V
- UV glass window
  Bialkali photo cathode,
  QE = 22% at λ = 380 nm

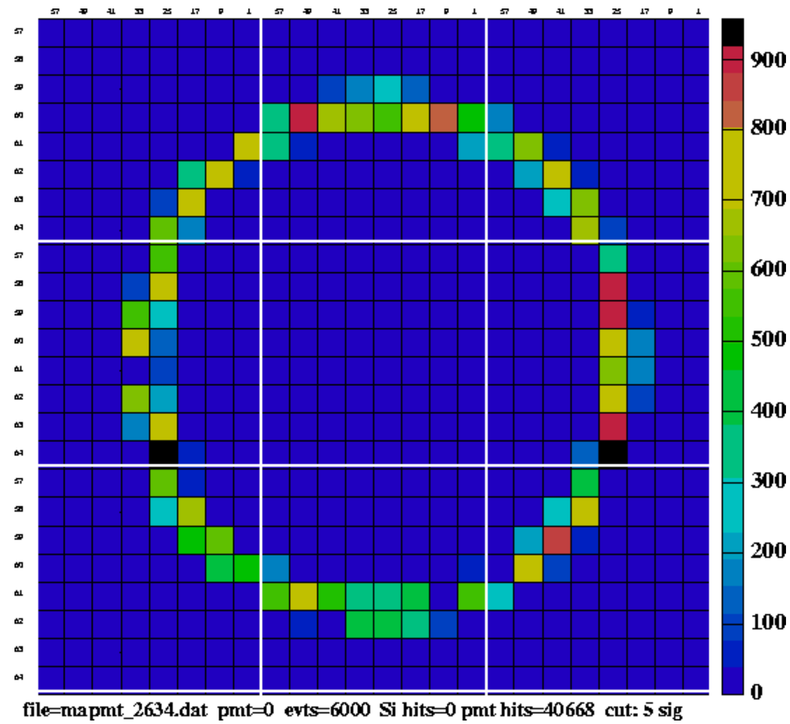


- MAPMT active area fraction:
  38% (includes pixel gap)
- Increase with quartz lens
  with one flat and one curved
  surface to 85%

MAPMT R&D Results

3x3 Cluster Test





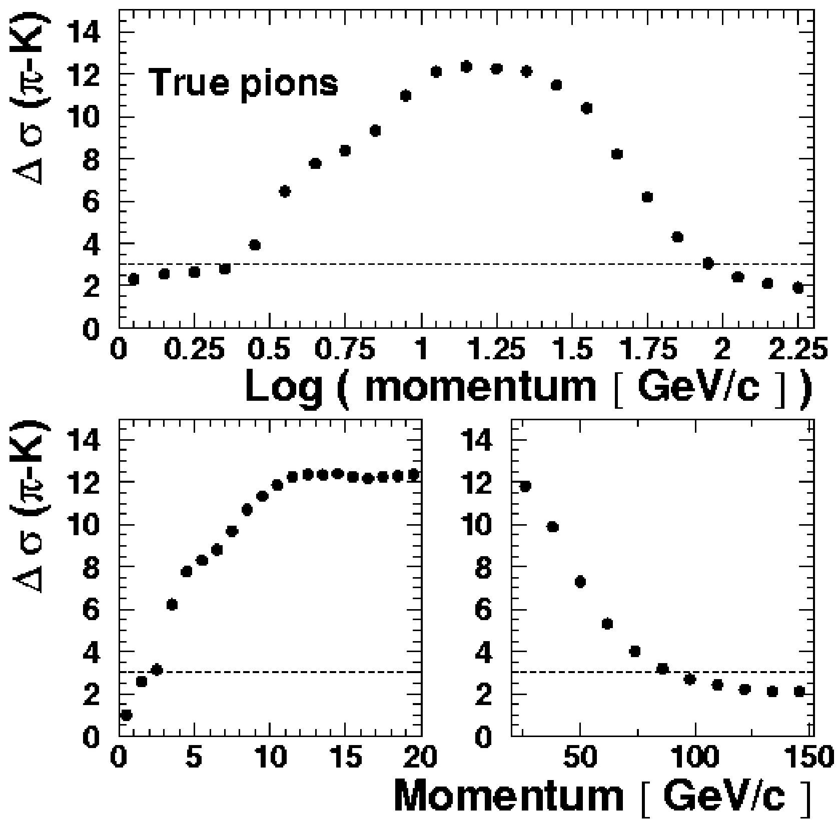
- Beam test
  - RICH 1 Prototype
  - CF4 @ 700 mbar
- 40 MHz Read-out: APVm chip

- Observe in data
  6.51 ± 0.34 p.e.
- Expect from simulation
  6.21 p.e.

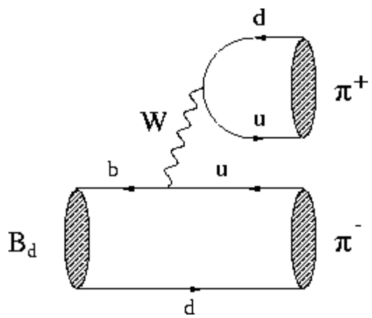
RICH Performance

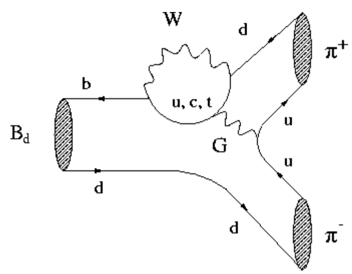
- Simulation
  - based on measured test beam HPD data
  - global pattern recognition
  - background photons included
- # of detected photons
  - 7 Aerogel
    33 C4F10
    18 CF4
- Angular resolution [mrad]
  - 2.00 Aerogel
    1.45 C4F10
    0.58 CF4

π-K separation



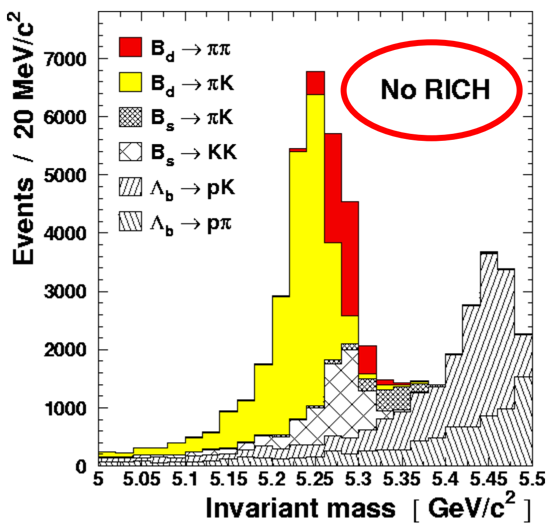
$B_d \rightarrow \pi^- \pi^+$

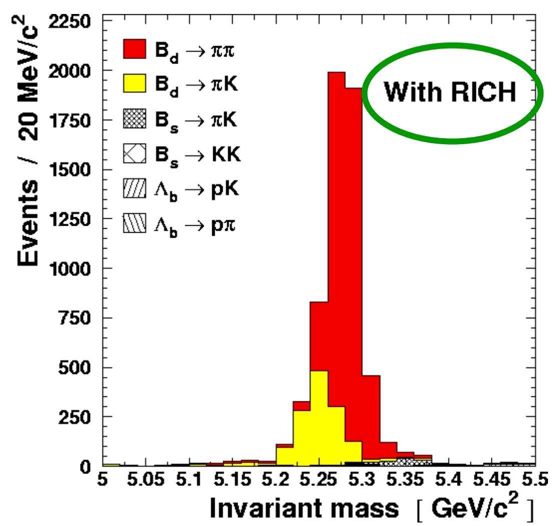




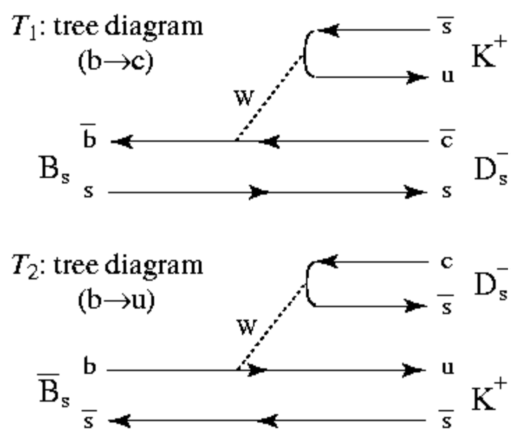
Tree T   Penguin P

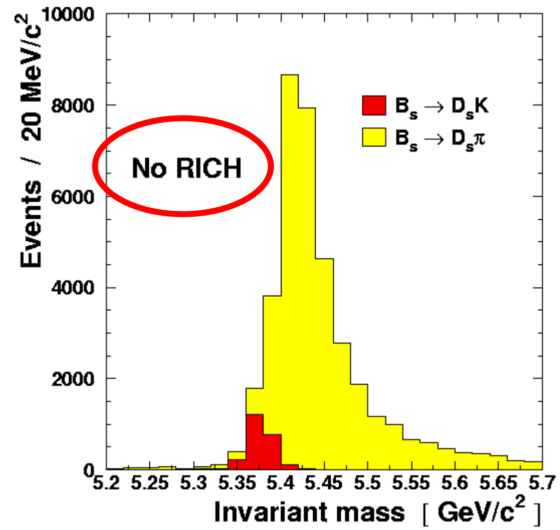
- sensitive to CP angle α
- A_{dir} and A_{mix} depend also on |P/T| and strong phase δ
- $\sigma_\alpha \sim 2^0 - 5^0$ in 1 year
  - α dependent
  - if |P/T| from elsewhere
- Backgrounds have CP

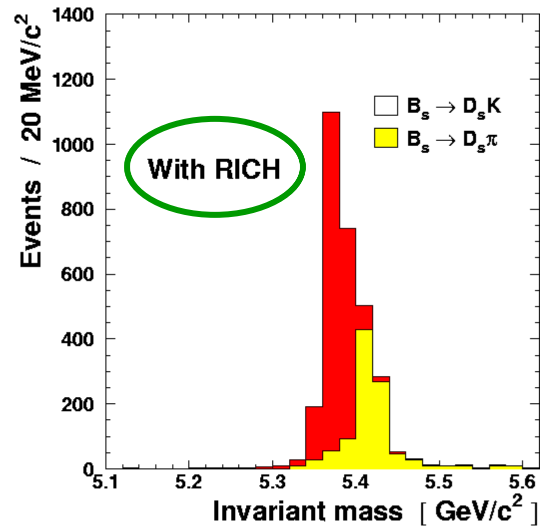




B_s -> $D_s^{\mu}K^{\pm}$







- Both diagrams of O(λ^3)
- ➔ expect large ~~CP~~
- Rate asymmetries measure angle $\gamma-2\delta\gamma$
- Expect 2400 events in 1 year of data taking
- ➔ s(g-2dg) = 6^0 .. 14^0

RICH Construction

RICH 1

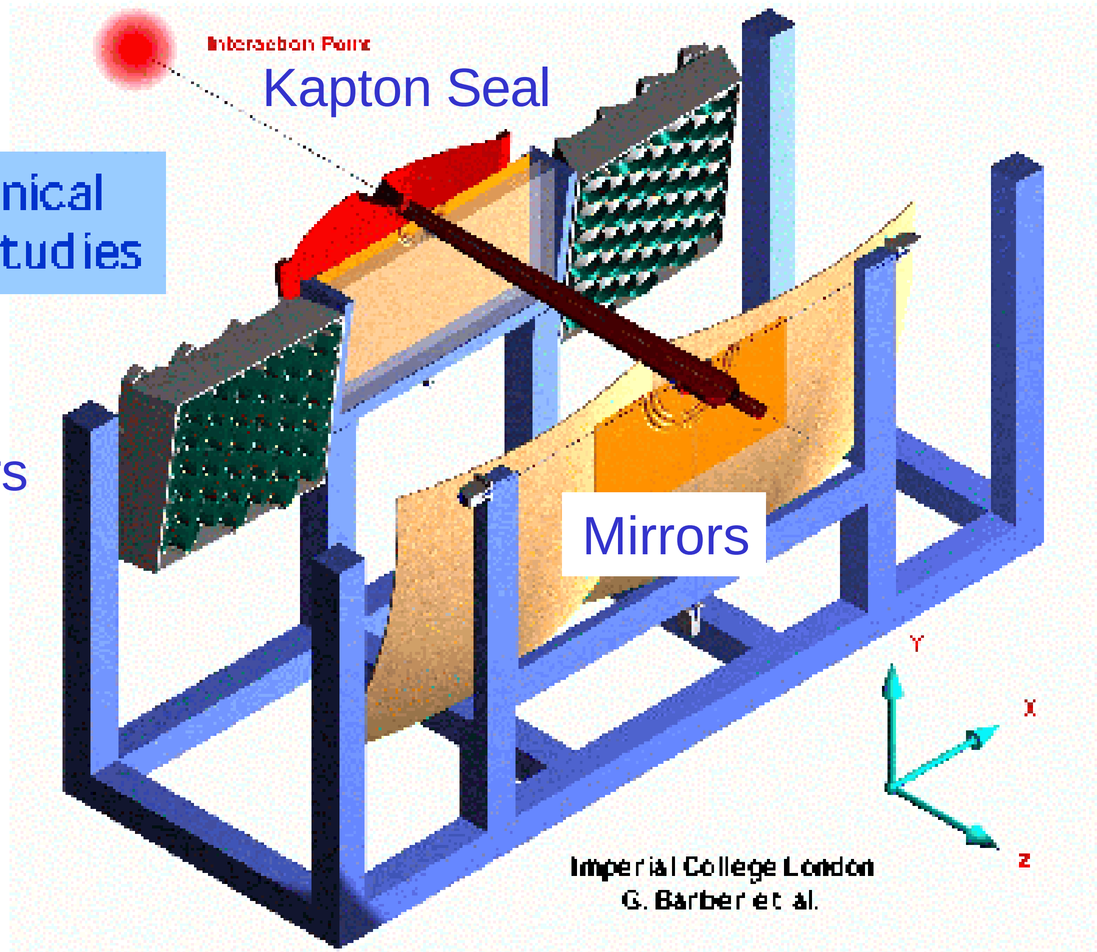
14% X_0

Mechanical design studies

Kapton Seal

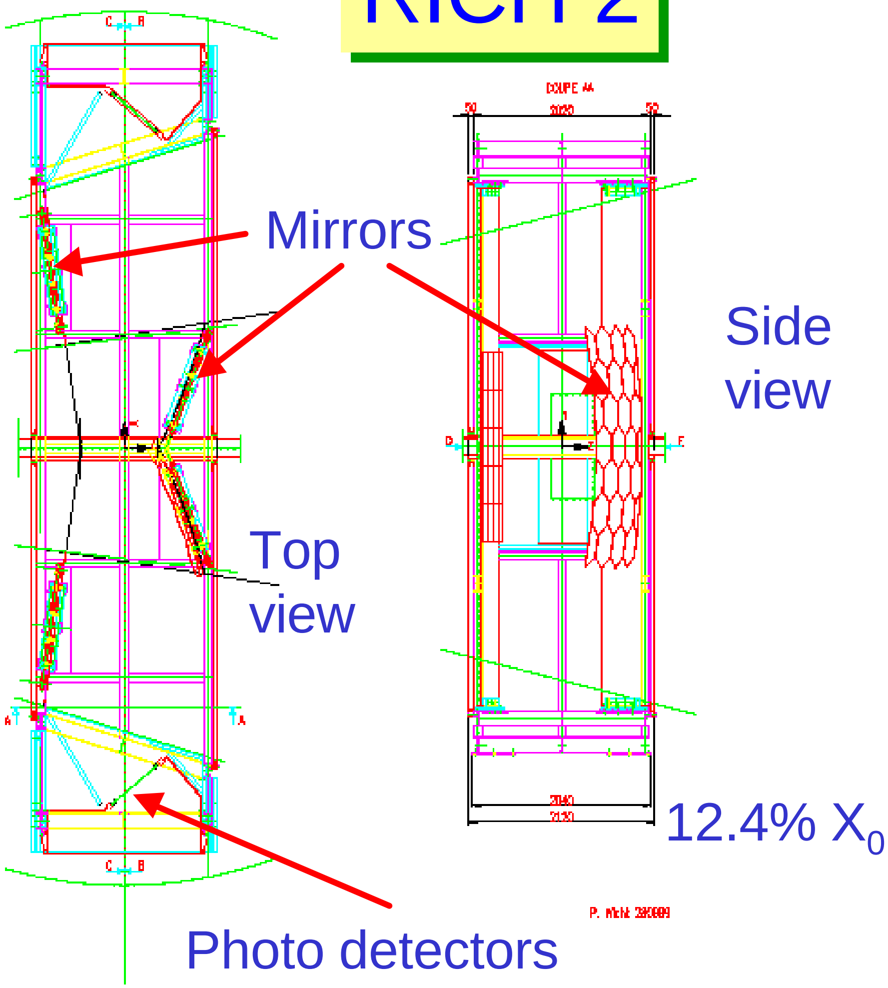
Photo detectors

Mirrors



RICH Construction II

RICH 2



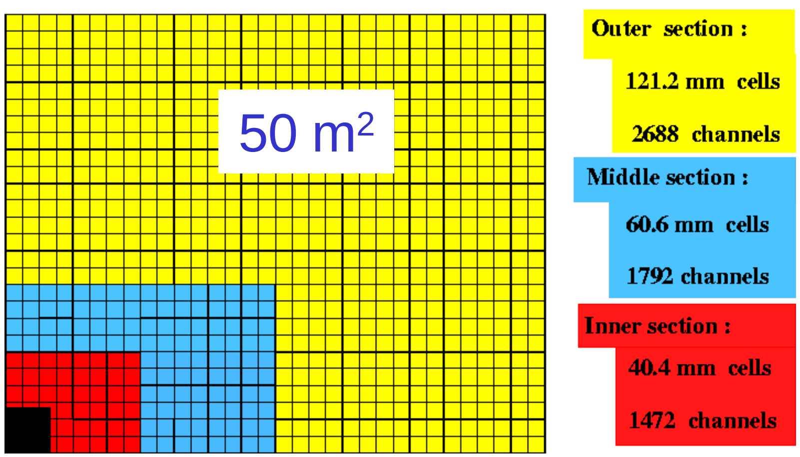
- Submitted 7.9. 2000

Calorimeters

- L0 trigger - high p_T hadrons, electrons, photons, π^0
- electron, photon, π^0 particle identification

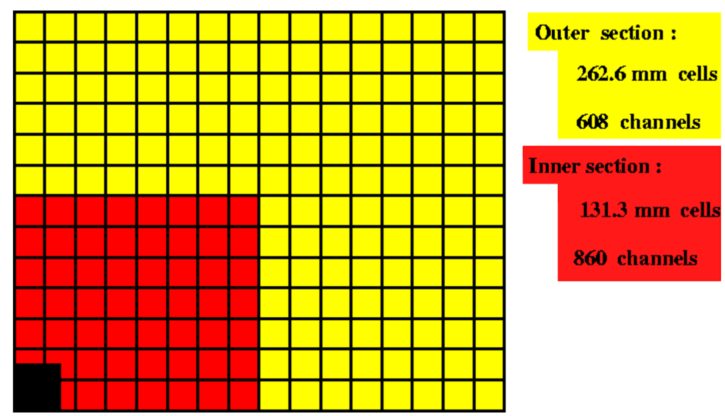
ECAL

- Shashlik Pb/scintillator tiles, λ shifting fibres, PMT, 25 X_0



HCAL

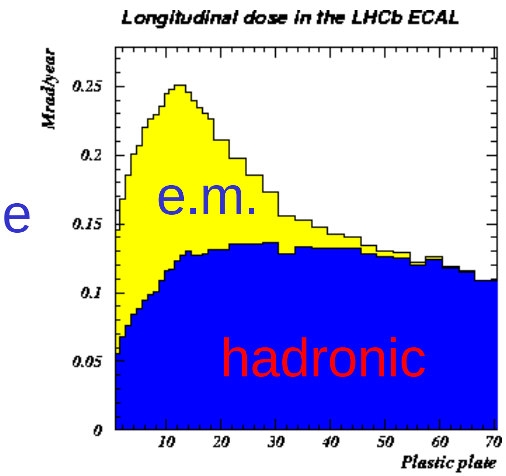
- Fe/ scintillator tiles, λ-shifting fibres, PMT, 5.6 λ



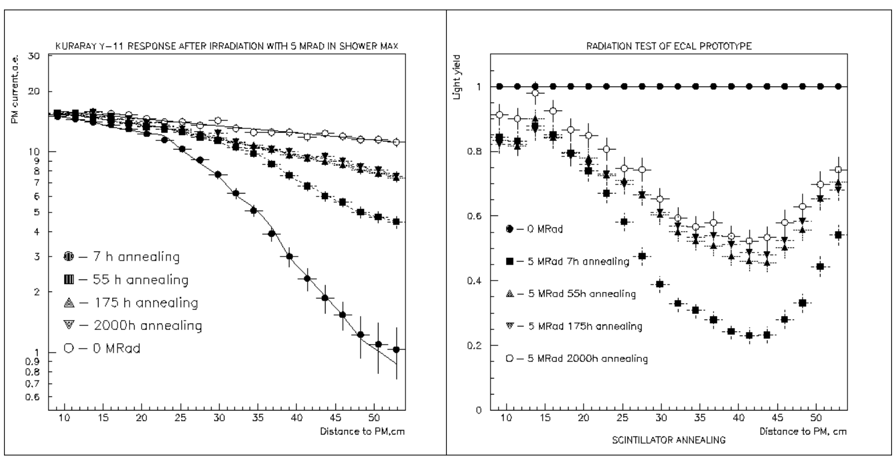
Scintillator / λ-Shifter

- Radiation
  - Inner most module 0.25 Mrad/year
- Extensive R&D
  - irradiation up to 5 Mrad
  - annealing for 175 h

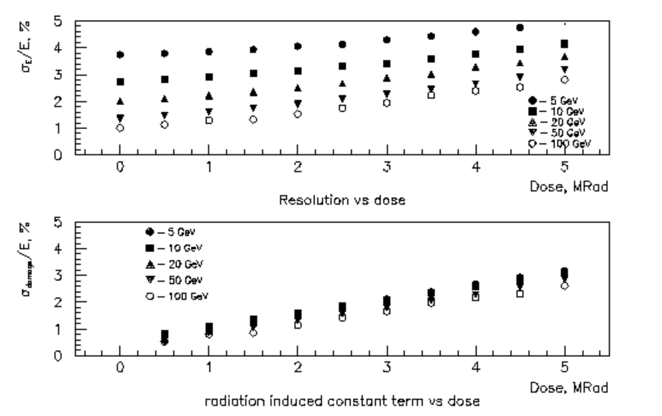
Dose



Scintillator λ - shifter



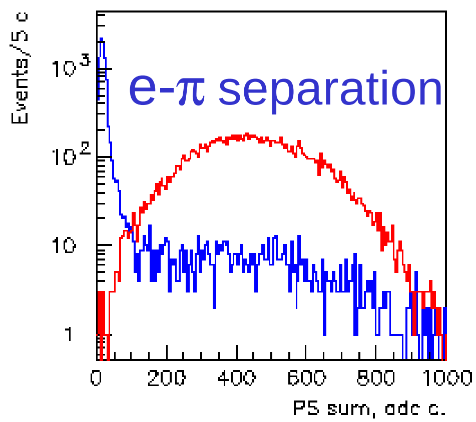
Resolution



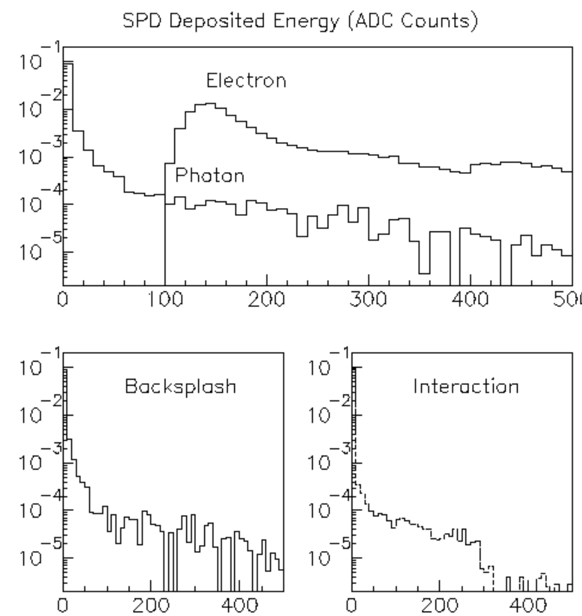
SPD / Preshower

- Scintillator Pads/ Pb 2X0 / PS Scintillator
- improved ECAL E resolution
- λ-shifting fibres read-out by MAPMTS

Preshower

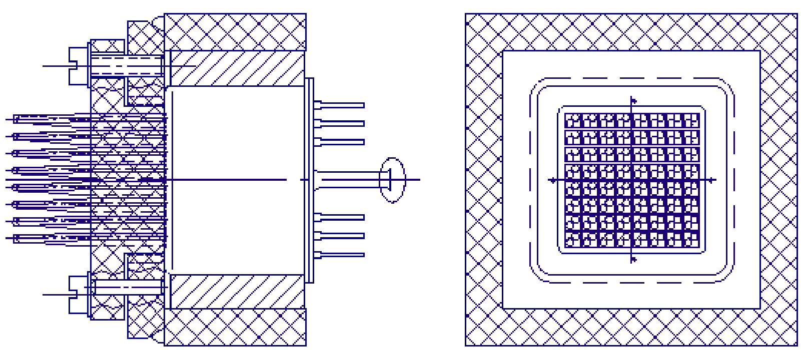


Scintillator Pad Detector



- electron - photon separation, L0 trigger

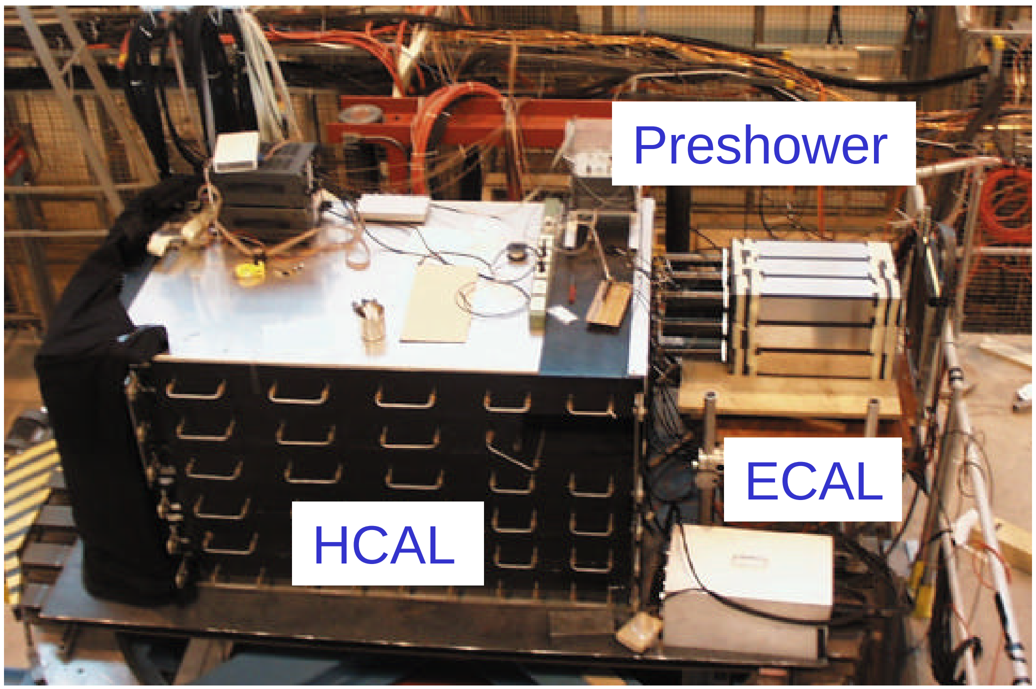
Fibre/MAPMT optical coupling



ECAL Performance

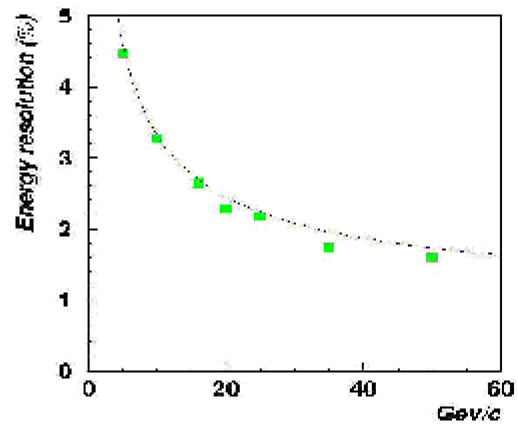
Joint Calorimeter Test

$$\frac{s(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 1.5\%$$



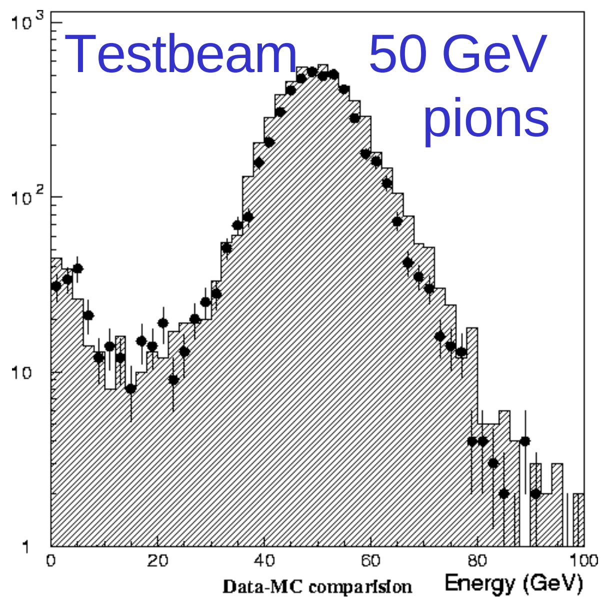
Energy resolution

Testbeam



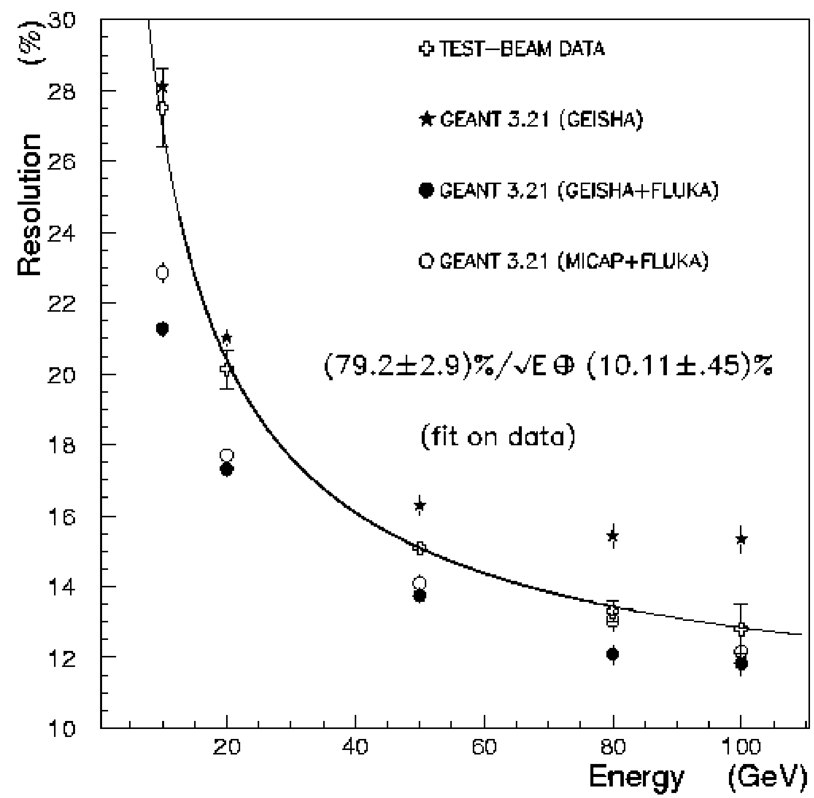
- HERA-B ECAL with similar design works well: π^0 and η peak

HCAL Performance



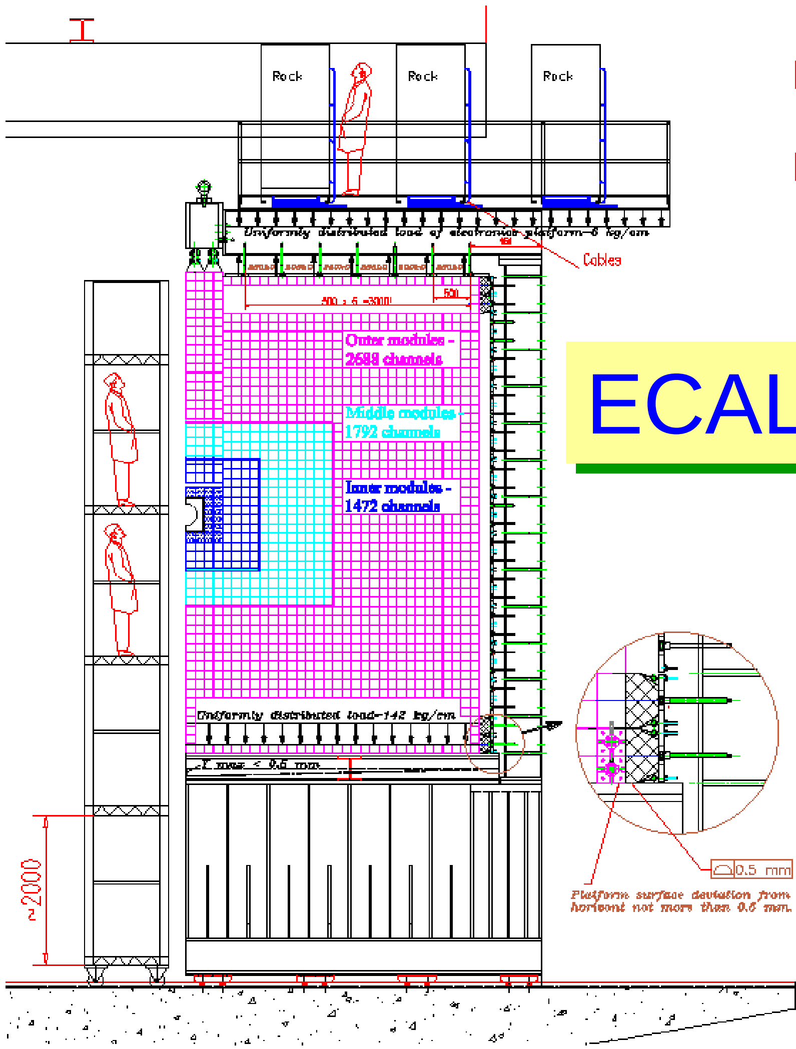
Energy resolution

$$\frac{s(E)}{E} = \frac{80\%}{\sqrt{E}} \oplus 5\%$$



- Since TP: HCAL length shortened 7.3 λ to 5.6 λ
  - tiny effect on resolution
- HCAL design- similar to ATLAS tile calorimeter

Calorimeter Construction



ECAL

- TDR submitted
- Construction starts 2001

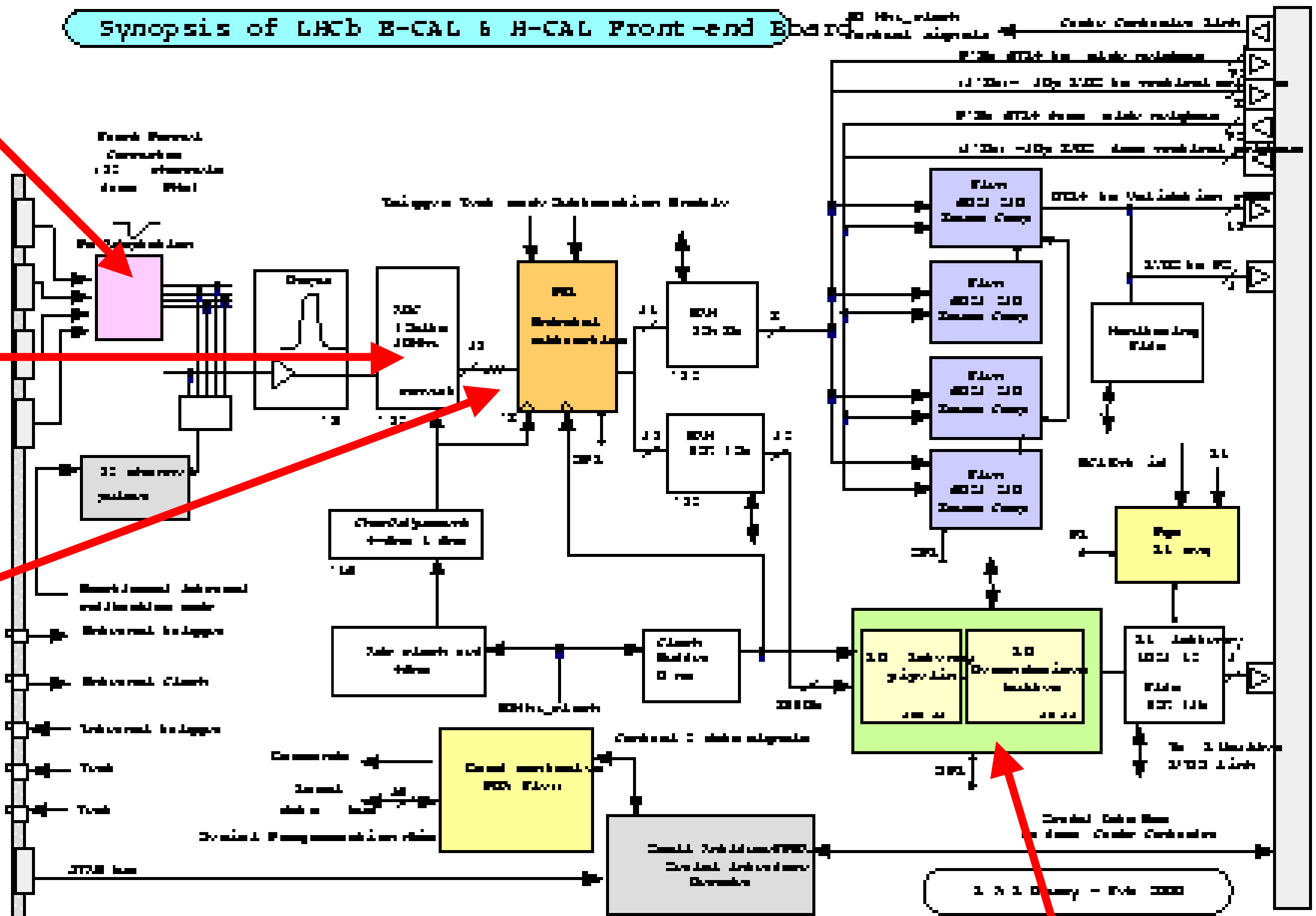
HCAL module

Front-End Electronics

F/E chip
amplifier
integrator

12 bit ADC

FPGA
pedestal
subtraction

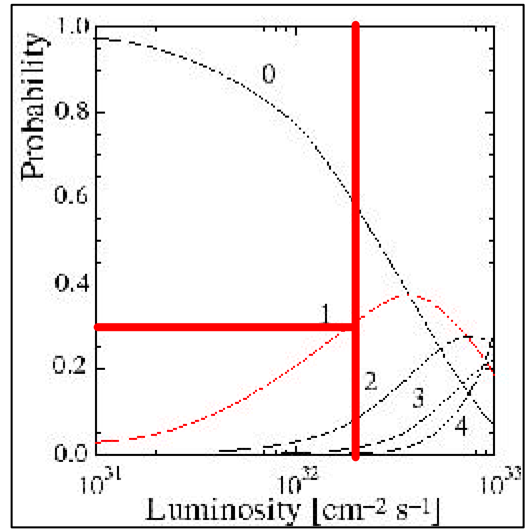


L0 pipeline,
derandomizer

- Radiation hard: single event upsets

Trigger System

- Luminosity
  - bunch crossings with one pp interaction
  - radiation damage, occupancy, pile-up
  - $\langle L \rangle_{LHCb} = 2 \times 10^{32}$ cm^{-2} s^{-1}, low, 1st year LHC, tunable



- Trigger is very challenging
  - 40 MHz interaction rate, $\sigma_{inel} / \sigma_{b\bar{b}}$ =160
  - bb rate 10^5 s^{-1}, low interesting branching fractions, eg. B($B \to \pi\pi$) = 5×10^{-6}
- Multilevel

  L0: Hardware L1: Vertex L2 & L3: Full event

Triggers

Level 0

1 MHz

- suppression x 40 — latency: 4 μs
- high p_T muons — Muon
- high p_T electrons, photons, π^0 — ECAL — Hardware
- high p_T hadrons — E&HCAL
- Pile-up veto, Interaction rate 12.3 MHz

L1 Vertex trigger

40 kHz

- suppression x 25, latency: 500 μs
- 1) track finding with r strips
  2) primary vertex
  3) secondary tracks
  4) use phi strips - 3d vertices
  5) secondary vertices

Level 2 & 3

- L2: vertexing with all tracking systems
- L3: full event information

DAQ: 200 Hz

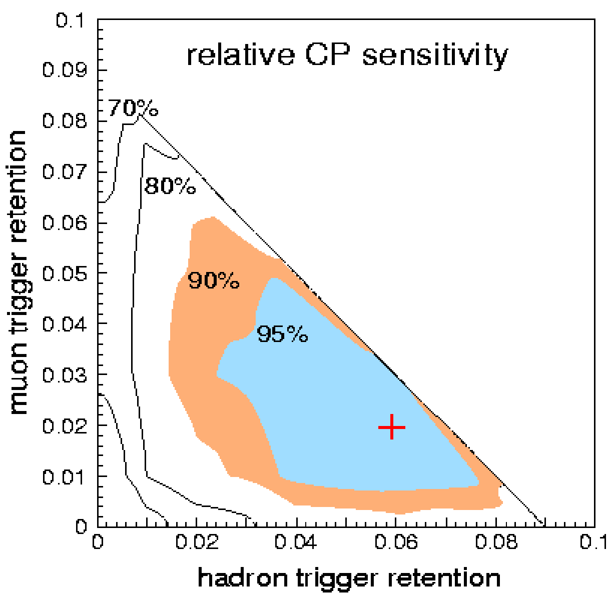
Trigger Efficiencies

	L0(%) m	e	h	all	L1(%)	L2(%)	Total(%)
$B_d \to J/\psi(ee)K_S$ + tag	17	**63**	17	**72**	42	81	**24**
$B_d \to J/\psi(\mu\mu)K_S$ + tag	**87**	6	16	**88**	50	81	**36**
$B_s \to D_s K$ + tag	15	9	**45**	**54**	56	92	**28**
$B_d \to DK^*$ + tag	8	3	**31**	**37**	59	95	**21**
$B_d \to \pi^+\pi^-$ + tag	14	8	**70**	**76**	48	83	**30**

- Trigger efficiencies are ~ 30 %
- hadron trigger is important
- Tagging: efficiency 40 %, mistag rate: 30 %
  - muon or electron from other B
  - charge kaon from other B

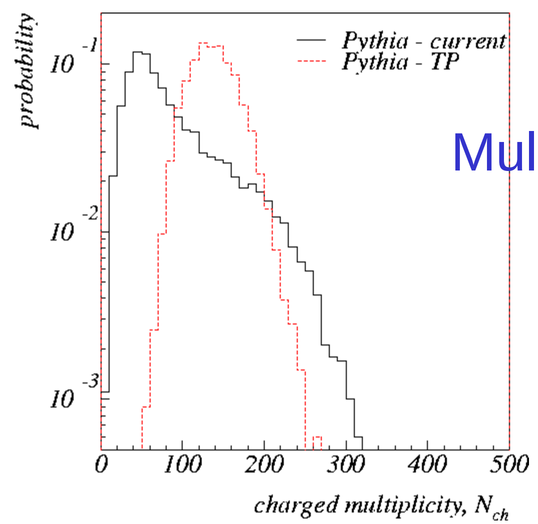
Trigger Strategy

- Multi level, Flexibility
  - not rely on single detector
- Stability, Robustness
  - running conditions



Vary L0 thresholds

- Event Generator
  - Updated Pythia model and structure functions
- Large change for charged multiplicities compared to TP

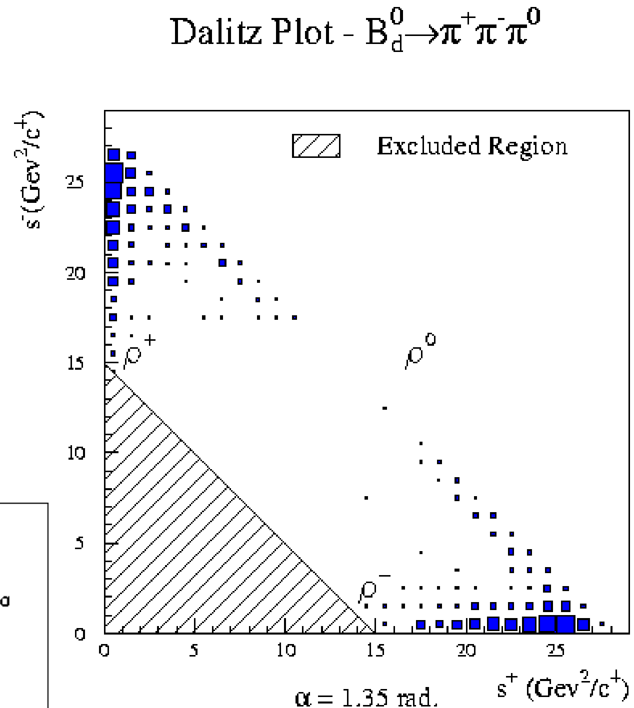


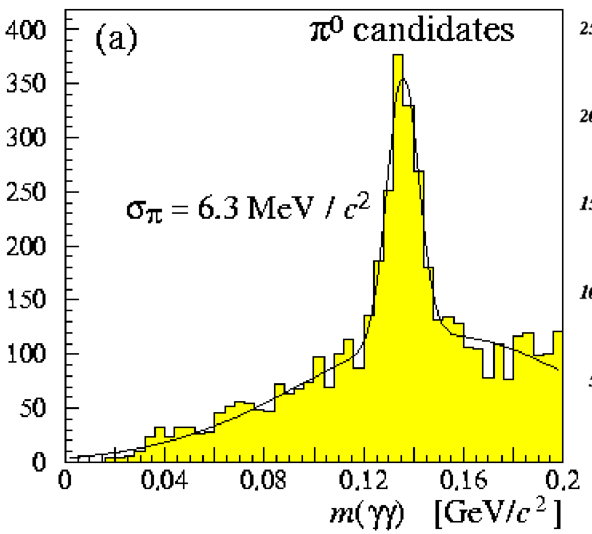
Multiplicity

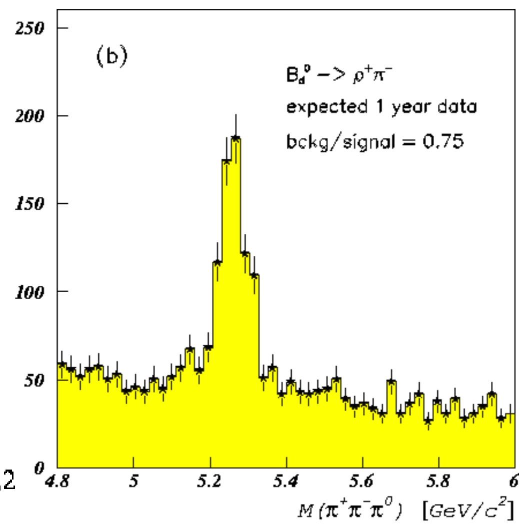
- Small effect on L0 performance

$B_d \to \rho^- \pi^+$

- Sensitive to angle α
- 1300 events / year
- Time dependent analysis of Dalitz plot allows measure
  - α, tree and penguin amplitudes



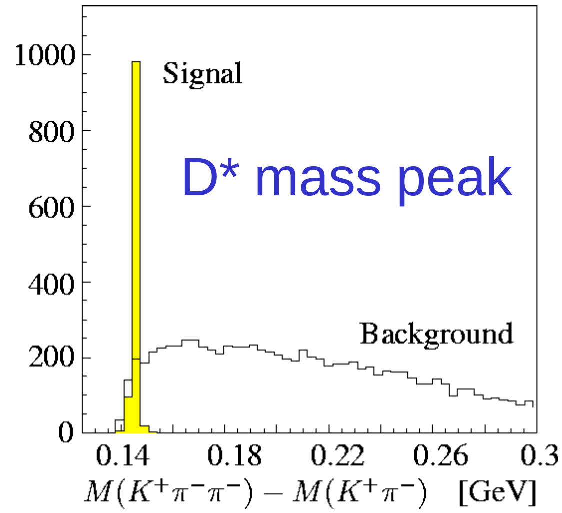


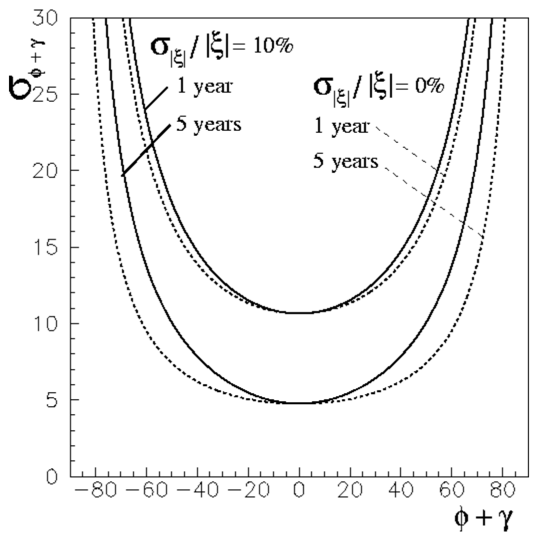


$\sigma_\alpha \sim 3^0 - 6^0$ in 1 year

B_d -> $D^{*\mu}\ \pi^{\pm}$

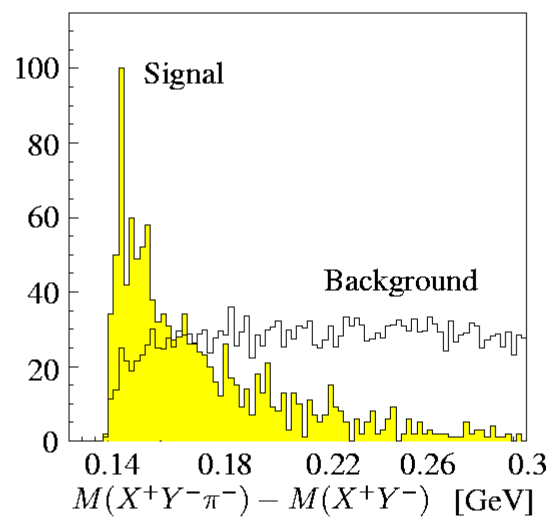
- Sensitive to angle $-2\beta-\gamma$ theoretically clean
- Asymmetry tiny, but large BR
- hadron trigger
- 80 k exclusive events
  260 k inclusive $D^*\pi$ events





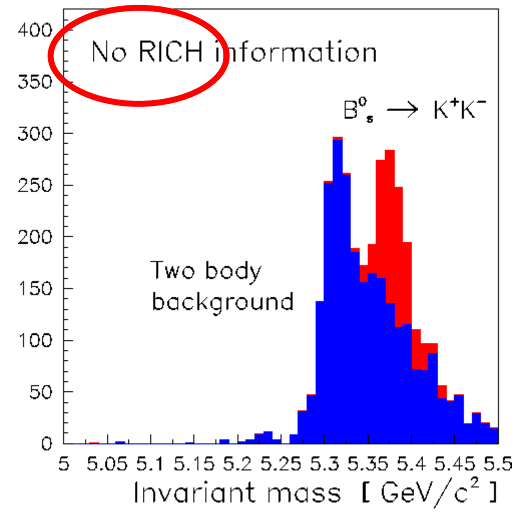
Sensitivity $\sigma_{2\beta+\gamma}$

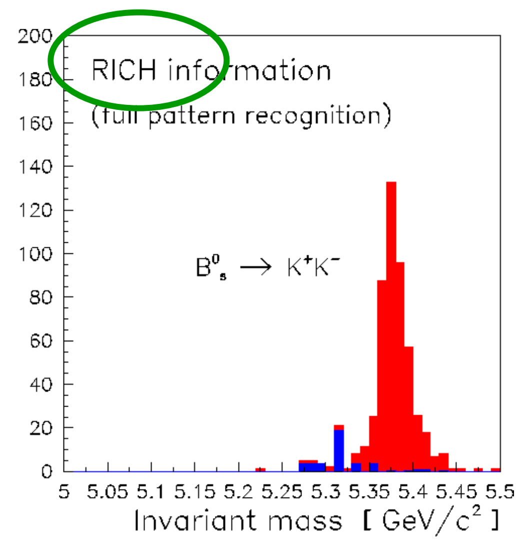
Will add
B_d -> $D^{*\mu}\ a_1^{\pm}$
360 k events



New Methods

- New strategies for measuring CKM angles - direct CP
- combine $B_d \to \pi K$ - charged and neutral B to extract γ
  - $s_g \sim 2^0 - 7^0$ ambiguous solutions
- combine $B_s \to KK$ and $B_d \to \pi\pi$
  - $s_g \sim 4^0$ β known, U-spin
  - LHCb RICH at its best
- combine $B_{d,s} \to D^+_{d,s} D^-_{d,s}$
  - O(100k) events per year
  - $s_g \sim$ a few ^{0}
- Overconstrain CP angles α, β, γ, and $\delta\gamma$





Rare Decays

- $B_s \to \mu^+\mu^-$
  - Standard Model branching ratio: 3.7×10^{-9}
    ideal to search for new physics - FCNC
  - Expected signal (bkgd) : 11 (3.3) 1 year
- $B_d \to K^*\mu^+\mu^-$
  - Standard Model branching ratio: 1.5×10^{-6}
    dimuon mass spectrum, forward-backward asymmetry
  - combine with $B_d \to \rho\, \mu^+\mu^-$ $|V_{ts}/V_{td}|$
  - Expected signal (bkgd): 22400 (1400) 1 year
- $B_d \to K^*\gamma$
  - Standard Model branching ratio: 5×10^{-5}
    search for new physics in ~~CP~~ asymmetry O(1%) in SM
  - Expected signal: 26000 1 year

LHCb CP Sensitivities

Parameter	Channels	Evts/year	σ(1 year)	LHCb feature
$2(\beta+\gamma)$	$B_d \to \pi\pi$	4900		
	$\Delta\lvert P/T\rvert = 0$		2°-5°	PID, hadron trigger
	$B_d \to \rho\pi$	~1300	3°-6°	PID, hadron trigger
$2\beta+\gamma$	$B_d \to D^*\pi$	340000	> 11°	PID, hadron trigger
β	$B_d \to J/\psi K_s$	37000	0.6°	
$\gamma-2\delta\gamma$	$B_s \to D_s K$	2400	6°-14°	PID, hadron trigger, σ_t
γ	$B_d \to DK^*$	400	10°	PID, hadron trigger
$\delta\gamma$	$B_s \to J/\psi\phi$	44000	0.6°	σ_t
Bs oscillations				
x_s	$B_s \to D_s\pi$	120000	up to 75	hadron trigger, σ_t
Rare Decays				
BR	$B_s \to \mu\mu$		$<2\times10^{-9}$	σ_t
	$B_d \to K^* \mu\mu$	22400		PID

Conclusions

- ***LHCb*** is progressing rapidly since Technical Proposal
  - Major technology choices made, e.g.
  - Magnet normal conductive coil
  - RICH pixel HPD baseline
- Technical Design Reports
  - Magnet approved, RICH & ECAL submitted
  - other subsystems on track in this talk: Vertex
- Trigger
  - robustness demonstrated, optimum luminosity, tuneable
  - ➔ take data from start of LHC & long physics programme
- Physics performance studies extended
- Construction phase starts now