LHCb Plan

- **LHCb is a special case among the experiments in which I participated: I did not take part in the initial conception, because of ALEPH first and then my lab directorship (It was the first time for me, that I joined an expt at a later time, old age!)**
- **So I will give an introduction on LHCb initial ideas taken from Tatsuya Nakada presentation at the workshop 50year of CP violation 2014**
- **I will then present some of the main parts of the LHCb detector**
- **With a special emphasis on two parts in which LAL was involved: the calorimeter (for which I was project leader with Andreas Schopper from 1998 to 2006) and the calorimeter trigger**
- **I will then present a discussion on "unexpected problems discovered at commissioning time" giving some examples**
- **Finally I will not try to review the vast LHCb physics program, but I will present the recent results on an analysis of B=>K*e+e- angular distribution: this has been the analysis on which I have worked from 2008 up to now with**
  M. Borsato, Jibo He, M. Nicol, C. Prouve, and M-H Schune.

B physics at LHC?

The discussion on the possibility to do B physics at LHC with a specially designed experiment started around 1990's . A key date was the EVIAN workshop in March 1992 where physicists interested in using a hadron collider at CERN to do experiments submitted "Expression Of Interest" EOI

One should remember that the SSC collider in the U.S. had started its construction in 1991 (it was stopped in October 93)

At CERN as you have seen the LEP experiments had barely started their physics at the Z. The CERN management was pushing a high luminosity LHC (compared to SSC) which was announced to start rapidly (before 2000!) and could even run in // with LEP !!!!!

Many ideas were expressed at the EVIAN workshop

Meanwhile B factories where approved at SLAC and KEK in 1993. They started to take data in 2000

EoI's presentation, 1992

ECFA
European Committee for Future Accelerators

CERN
European Organization for Nuclear Research

Towards the LHC Experimental Programme

5-8 March 1992
Evian-les-Bains, France

LHC

Proceedings
of the General Meeting
on LHC Physics & Detectors

4 General purpose high p_T experiments

3 B experiments

Evian workshop on EoI's presentation, 1992

Four high p_T experiments

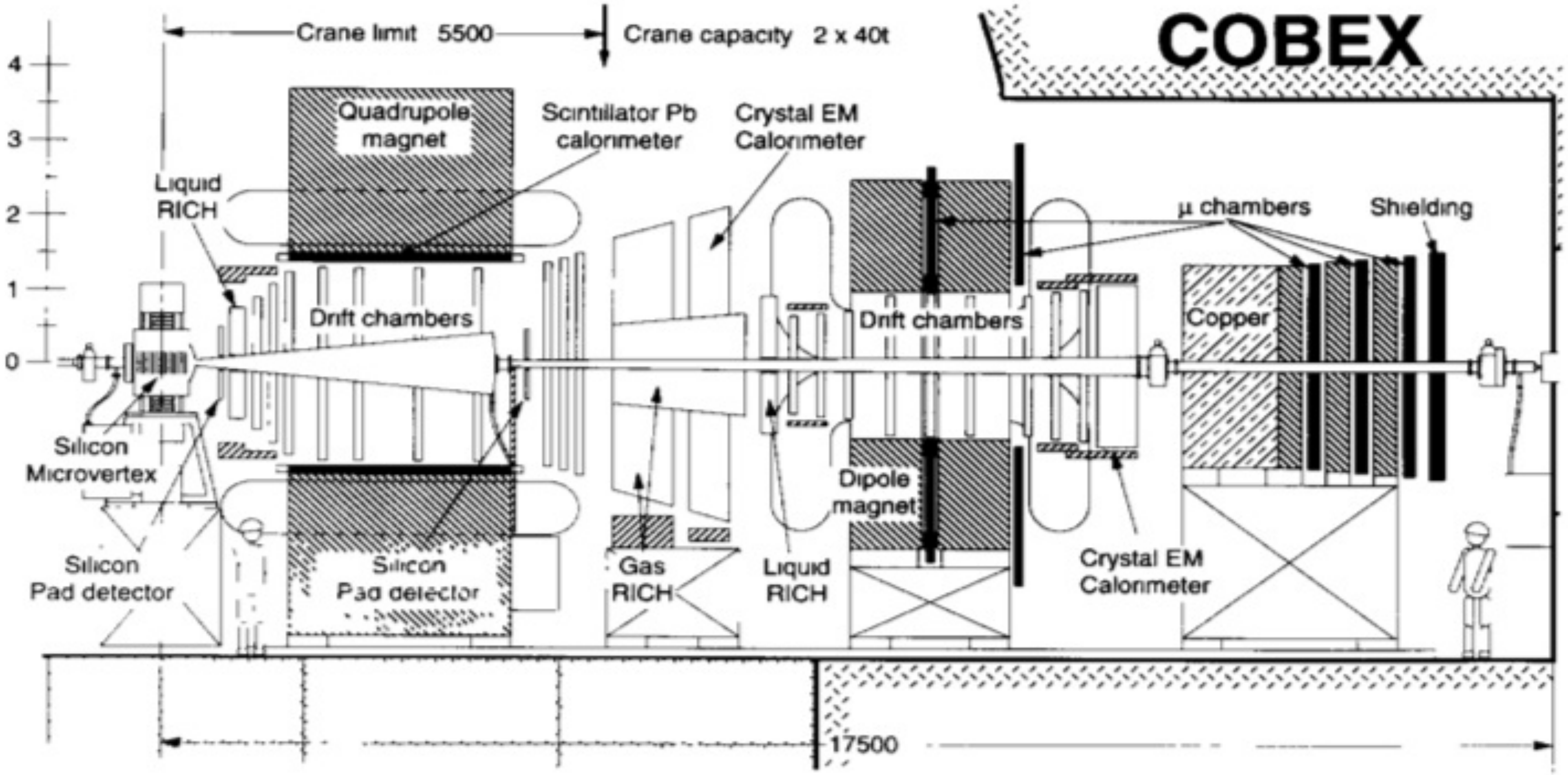
Neutrino and Heavy Ion experiments

Three B physics experiments

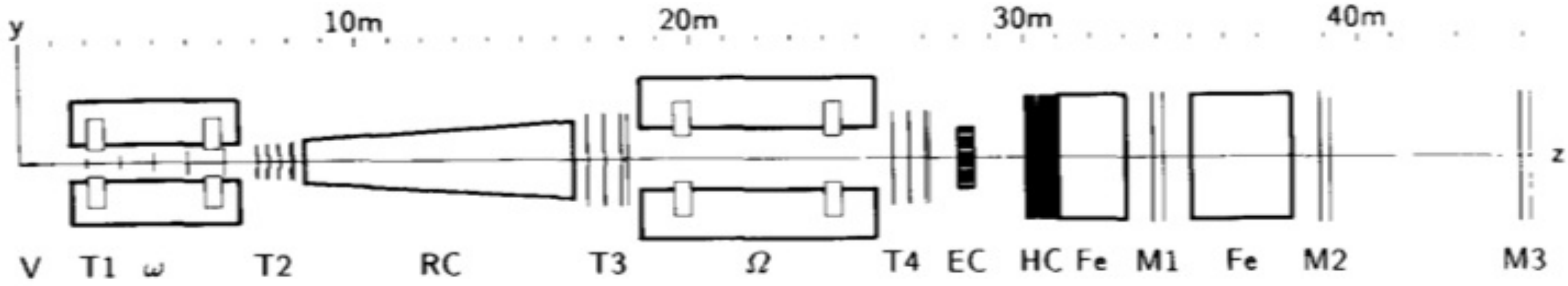
- SM was not quantitatively tested for CPV
  - main goals were
    - CPV in →J/ψK_S, B_s oscillations
- three different approaches
  - 1) pp colliding mode in the forward direction
    - COBEX
  - 2) extraction of p to a fixed target
    - LHB
  - 3) internal gas jet as a fixed target
    - GAJET

Followed by three LoI's in 1993

COBEX : collider mode (14 TeV)
vertex and tracking detector, two magnets, RICH, E-cal, muon
first level topology trigger at low L and μ p_T trigger at high L
☺large √s → large bb cross section



LHB p on target => sqrt(s) = 120 GeV
vertex and tracking detector, two magnets, RICH, E+H-cal, muon
first level lepton (μ and e) p_T trigger
☺large boost → charged Bs are visible in the vertex detector ($B^+ \to \tau\nu$)



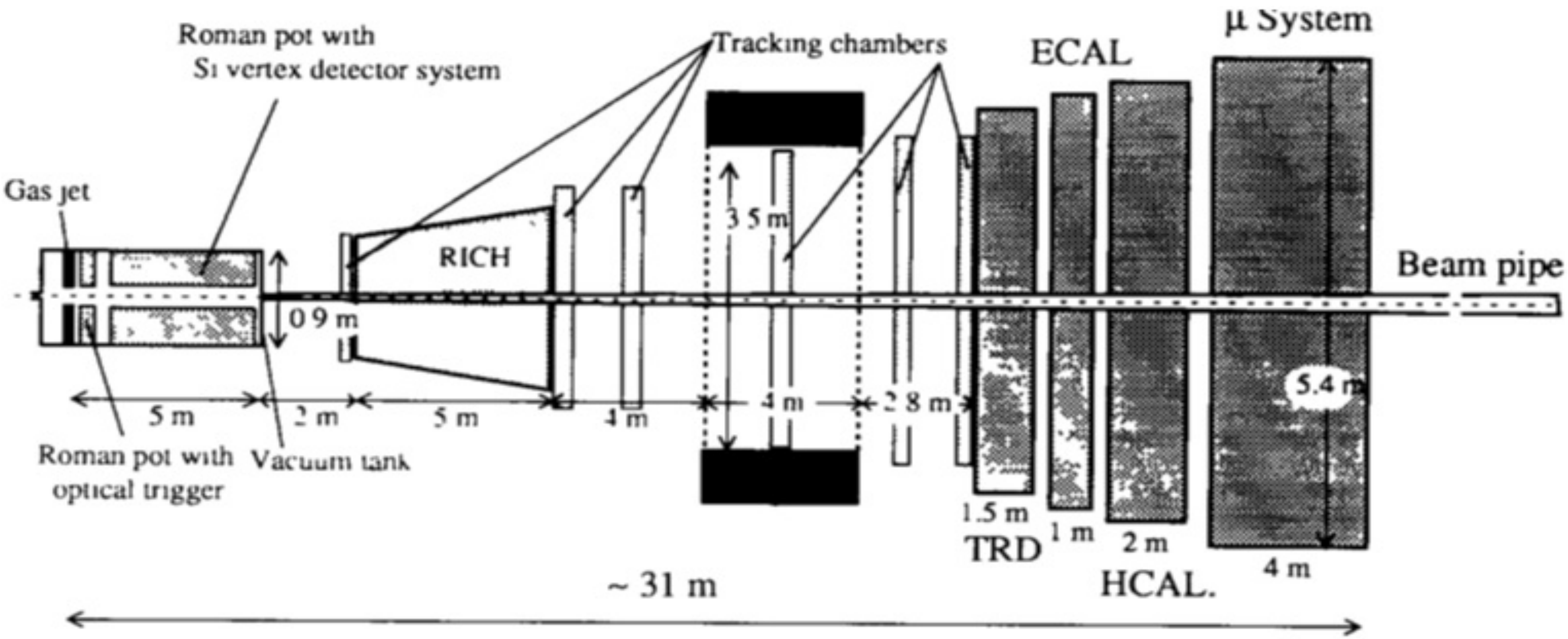
protons are extracted from the beam halo using a bent crystal
dedicated experimental area, i.e. more flexibility

GAJET p+gas => sqrt(s) = 120 GeV

vertex and tracking detector, single magnet, RICH, TRD, E+H-cal, muon

first level impact parameter and hadron+lepton p_T trigger

☺small dimension of gas target → B production vertex a priori known



LHCC decisions

January 1994

In the subsequent discussion on B physics, the LHCC considered the case for a dedicated B experiment at the LHC, and agreed on a recommendation to be sent to the Director General for consideration by the Research Board.

June 1994

Decided not to approve any of the three experiments but to form one new collaboration to propose a new experiment based on the collider mode to exploit its large $b\bar{b}$ cross section with a convincing trigger strategy.

This appears to have been a correct decision, given the fact

1) B-factories and Tevatron did very well

2) LHC came (much) later than originally thought

Advantage of the LHC collider mode

Large b cross section (~250μb)

Large $\sigma_{bbar} / \sigma_{inelastic}$ ($>10^{-3}$)

at fixed target energies 10^{-6}

Different b-hadrons (B_u, B_d, B_s, B_c, L_b, Λ_b, Ξ_b etc.)

Many primary particles => well defined b production vertex

To fight against combinatorial backgrounds:

vertexing, PID, and mass resolution

Open trigger a la charm fixed-target experiment

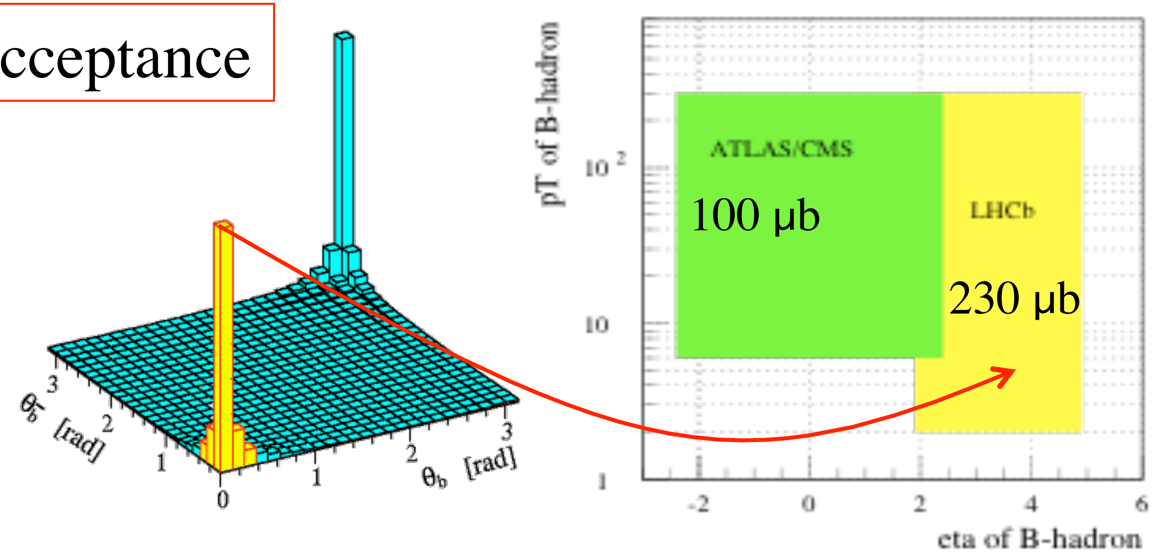
- was not an option at LHC
  - too high inelastic event rate
  - interesting decay modes are restricted

Trigger is crucial

- At the first level
  - inclusive signature: p_{T} and displaced tracks/vertices
- At the intermediate level
  - semi-exclusive partial reconstruction
- Finally
  - exclusive reconstruction

A reminder of the forward geometry

Acceptance



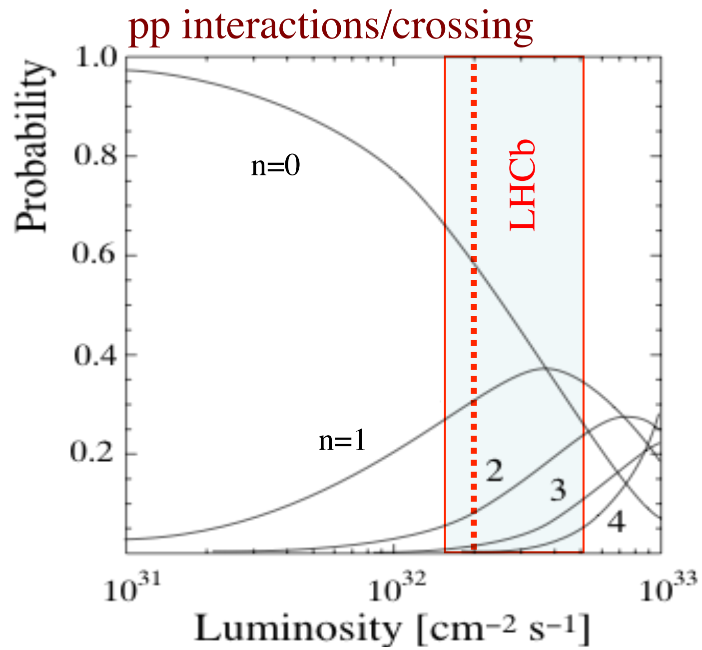
p_T threshold for calo- and m-trigger can be set to few GeV/*c* for high b efficiency

Luminosity requirements

L tuneable by adjusting final beam focusing

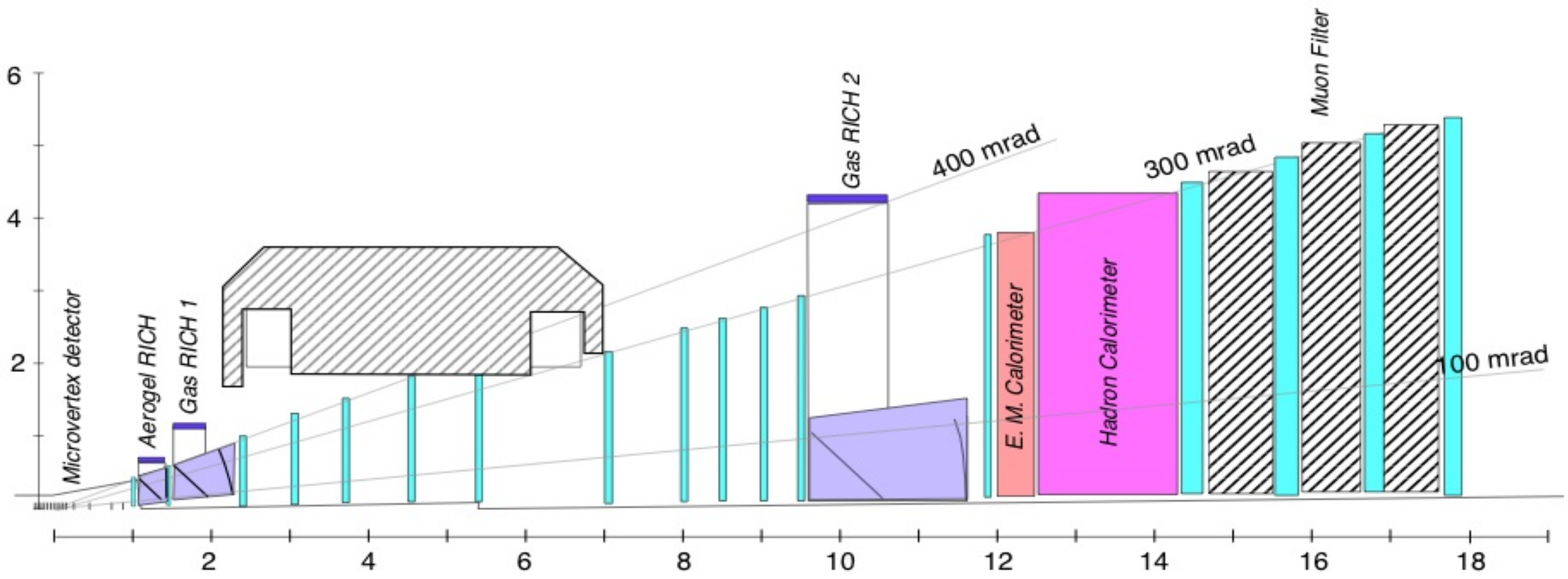
Choose <*L*> ~ 2*10^{32} cm^{-2}s^{-1} (max. ~5*10^{32})

- Clean environment: <*n*> ≈ 0.5
- Less radiation damage
- Will be available from "first" physics run



LHCb Evolution

Letter of Intent for LHC-B, August 1995



x-*y* Si micro-strip detector
warm magnet
three RICH's (aerogel + 2-gas) with HPD's
HERA-B tracking system
Pre-shower, Shashlik+$PbWO_4$, Fe-Tilecal+Quarz-W
CSC or Honeycomb or drift tube muon system

L-1 p_T	200 KHz
L-2 tracking + vertex	10 kHz
L-3 full reconstruction	

RICH and HPD design
T. Ypsilantis

Approval in 1998 was non-trivial

- Some of the things said were
  - B factory experiments would do everything. If not, Tevatron experiments would do the rest. Thus, nothing important would be left.
  - Steal precious LHC luminosity from the general purpose experiments
  - Resources are limited
  - General purpose experiments can do the same physics as well
  - etc…
- But, finally we got it!

1998 LAL Arrival in LHCb

Toward the end of 1997 some senior LAL physicists were contacted by collaborators of LHCb: we formed a group with physicist from ALEPH DELPHI H1 and started to think of a contribution to the apparatus. A part needing reinforcement in LHCb at the time was the Calorimeter group.

We started to work (mainly on the electronics), then around mid 98 Tatsuya Nakada asked me to take the responsibility for the calo system which I accepted if I could form a team with Andreas Schopper of CERN.

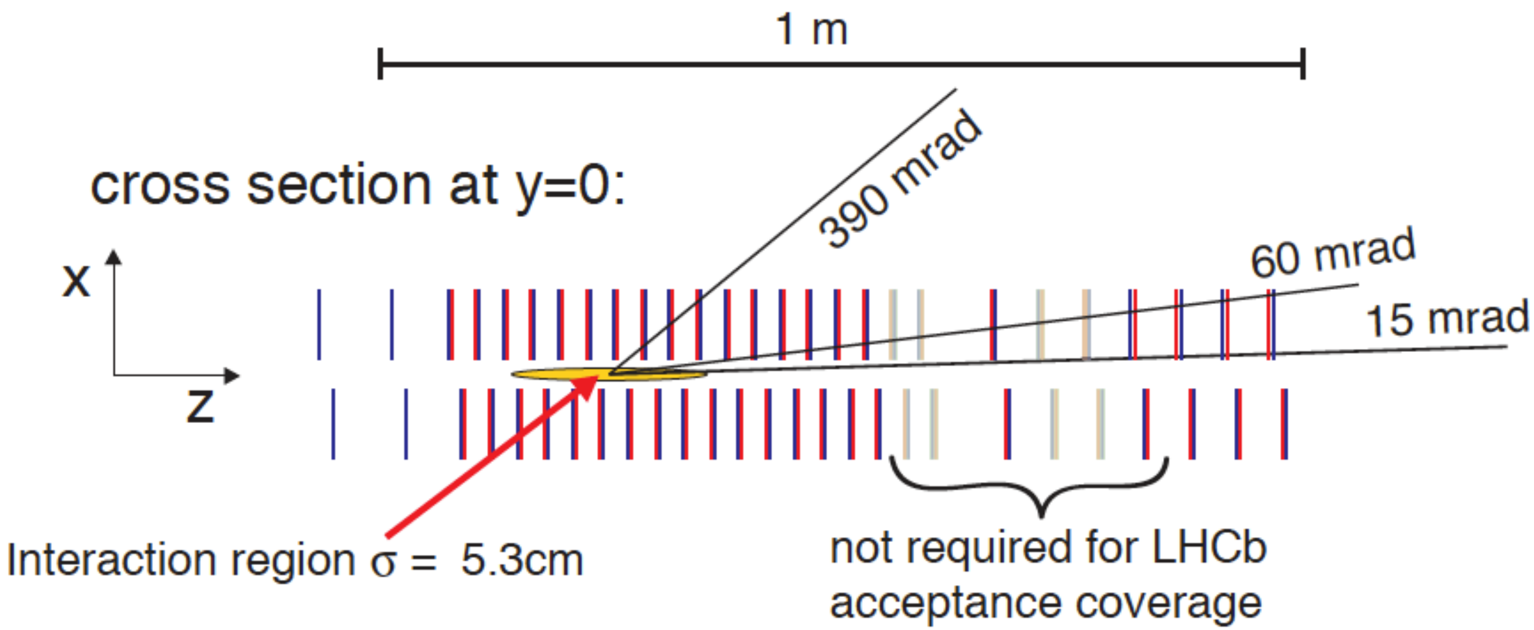
LAL-Orsay also had an important role in the calorimeter trigger under the impulse and responsibility of O. Callot

Some main apparatus choice for LHCb:VELO(I)

The key element for a sucessful B (or charm) experiment at a hadron machine is the vertex detector. This is because, compared to a B e+e- factory, the combinatorial background would naturally be much larger because of the large multiplicity of tracks from the primary vertex (PV)

The way out as discovered already at SPS and FNAL around 1980 is the use of an accurate vertex detector; then only charged particles consistent with the B vertex contribute to combinatorial background

This was achieved by the LHCb VELO using R-φ Silicon strip sensors: typical impact parameter accuracy vs the PV are about 40 μ while B tracks have typical IP of 400 μ

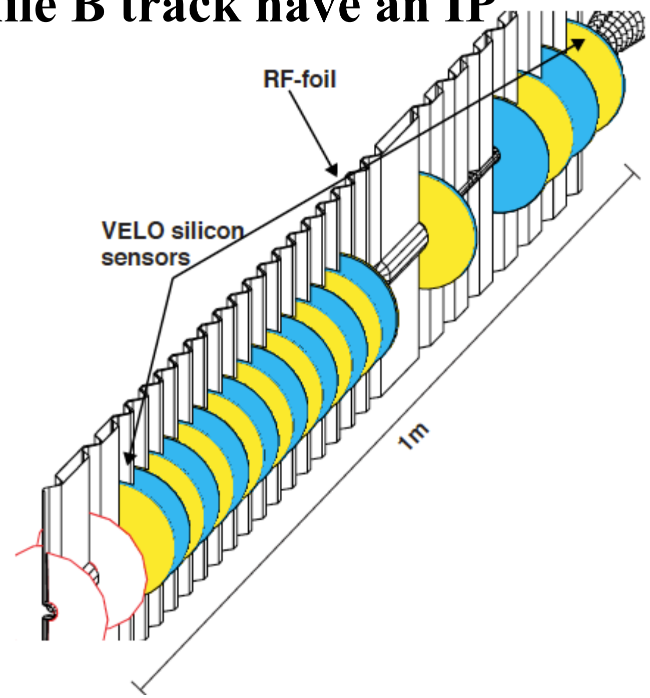


Some main apparatus choice for LHCb:VELO(II)

The VELO sensors go very close to the beam (at r= 8.2mm). But they have to be separated by a thin RF foil to separate detector vacuum and LHC vacuum and to protect the VELO from induced pulses from bunches passage

It was decided to use r-φ geometry of strips because with a beam at r=0 primary track can be found by straight lines in r-z coming from the same Z , while B track have an IP in r-Z.

This was estimated to speed up the HLT1 trigger recognising IP of B tracks



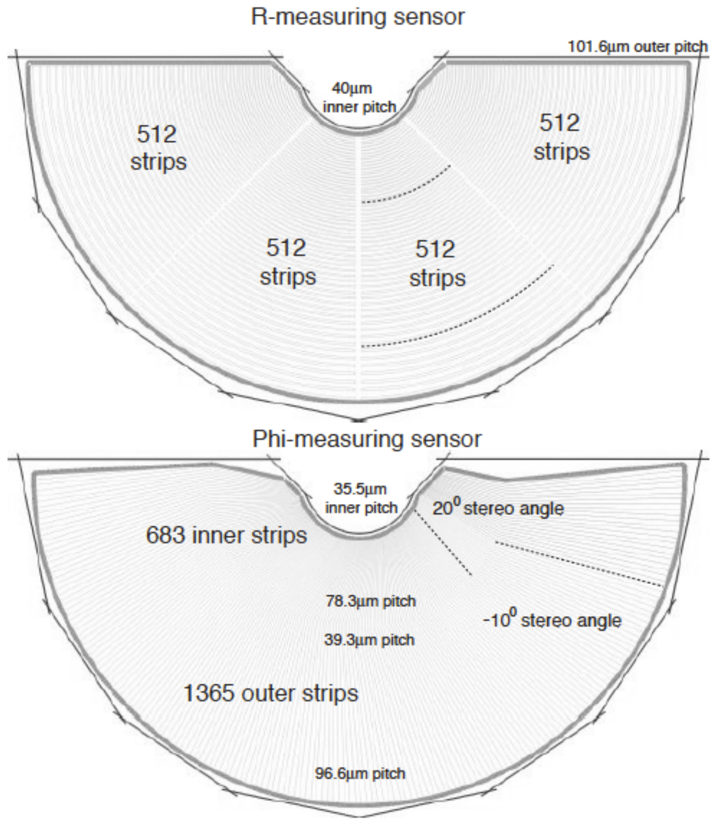
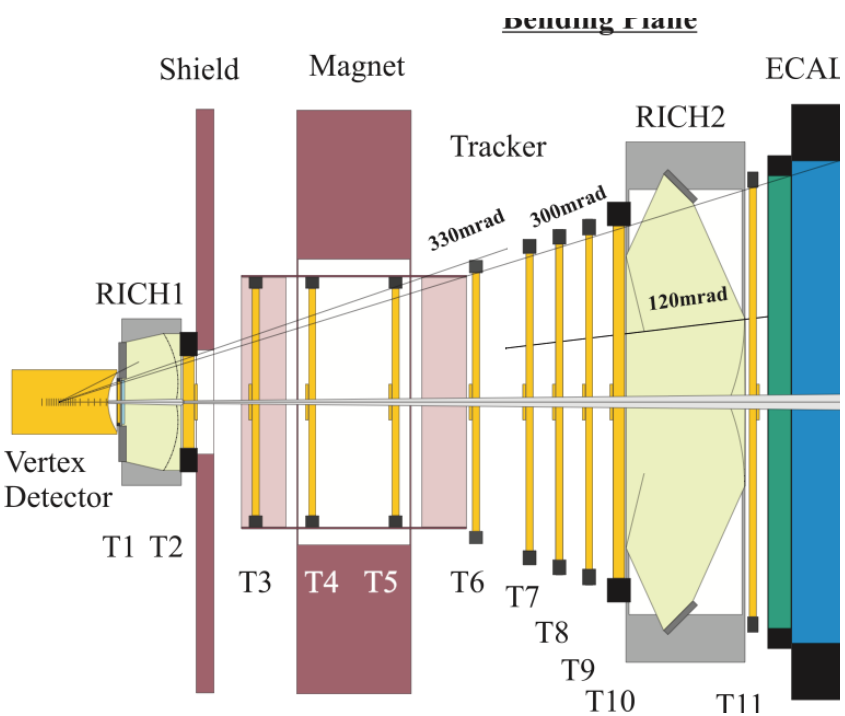


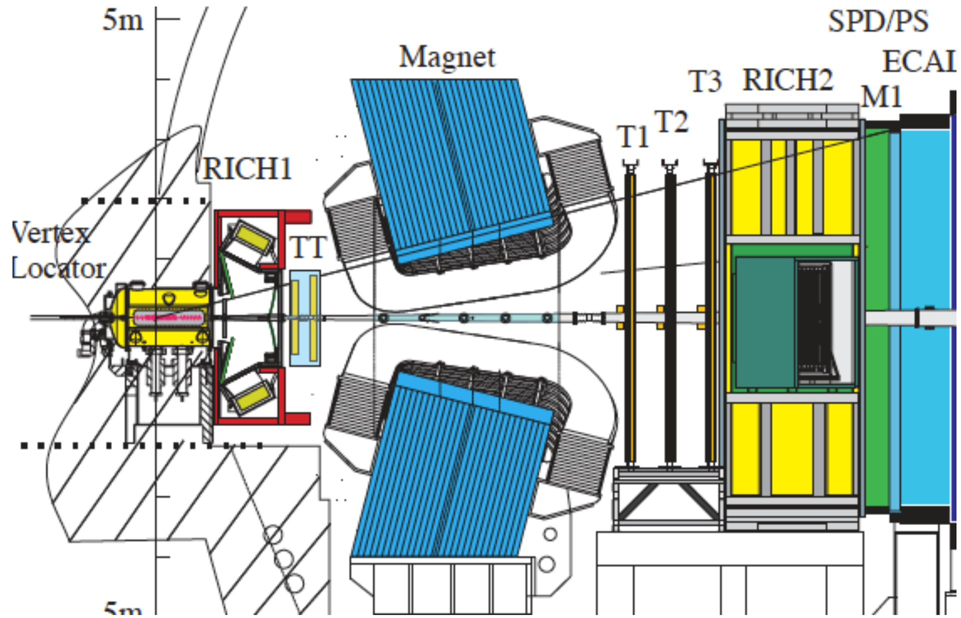
Figure 3.11: Sensor layout. Some strips are indicated with dotted lines for illustration.

Some main apparatus choice for LHCb-tracker(I)

The main choice for the tracking detector was made before 1998. The elements were tracking stations using straw tubes with stereo construction XUVX for the outer part, and silicon strip detectors for the part closest to the beam.

A very important evolution happened from mid 2001 to a new TDR Sept 2003: the detector had evolved to a larger amount of X/X0 and interaction length, it was decided to go from 11 tracking station to 4 stations! This was a very good move=> less X/X0 + simpler & faster reconstruction software



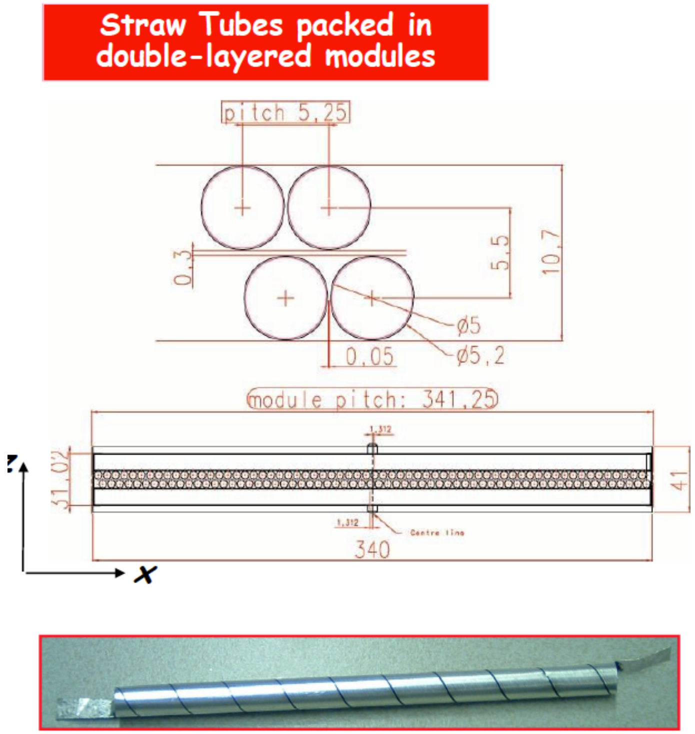


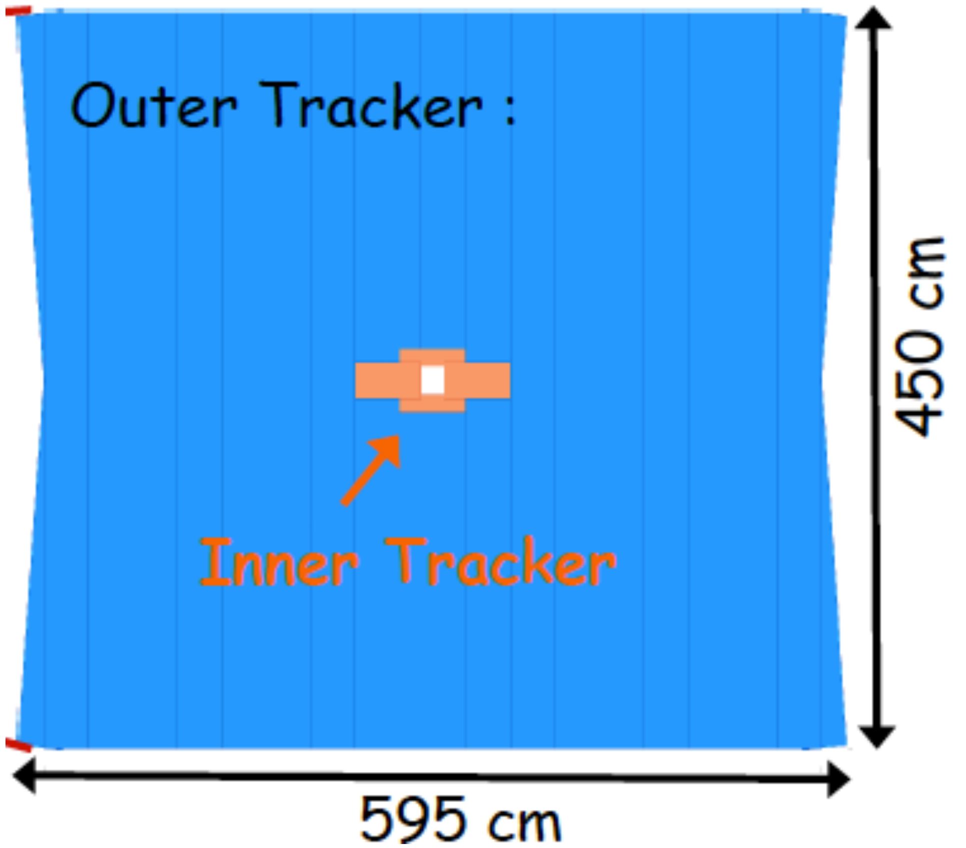
Some main apparatus choice for LHCb-tracker (II)

Outer Tracker uses 3 stations : each station has 4 modules (XUVX (U,V=+-5°)) of 2 layer-straw-tubes. Drift time in straws (0-50ns) => accuracy about 200µ. Advantage of straw : reasonable price (about 56K channels) , small X/X0 0.37% but occupancy 4.5%-9%

Inner tracker made of "classical" silicon strip

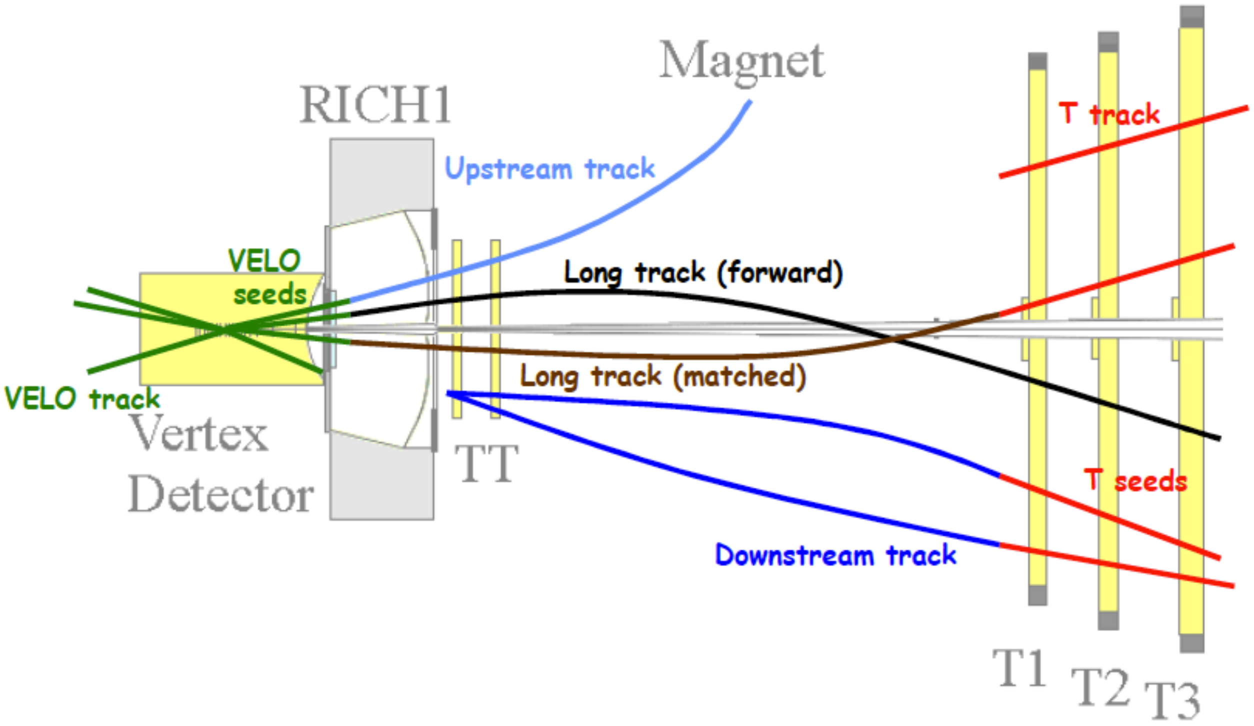
Upgrade 2018 => Scintillating Fiber tracker





Some main apparatus choice for LHCb-tracking

Tracking at LHCb



Long tracks ⇒ highest quality for physics (good IP & p resolution)
Downstream tracks ⇒ needed for efficient K_S finding (good p resolution)
Upstream tracks ⇒ lower p, worse p resolution, but useful for RICH1 pattern recognition
T tracks ⇒ useful for RICH2 pattern recognition
VELO tracks ⇒ useful for primary vertex reconstruction (good IP resolution)

Some main apparatus choice for LHCb-RICH(I)

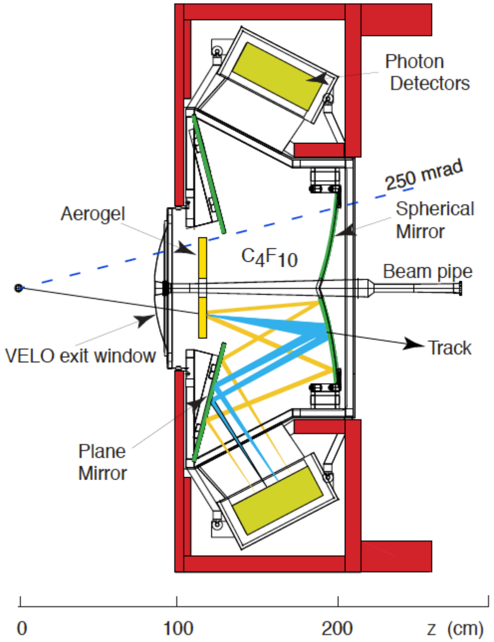
One of the advantage of LHCb forward geometry is that typical B momenta are in the 50-100 GeV range => typical decay products 15-60 GeV . This is a very good range to identify particles using gas Čerenkov measuring the Čerenkov angle => cone

Identification of beam particle by Čerenkov angle is an old practice (remember DISC, CEDAR) but use in spectrometers more recent (before use of threshold Č) . Ypsilantis advocated use of RICH => construction for DELPHI => very complicated design => not convincing. But for LHCb situation better (above) and better than in general purpose detectors like ATLAS, CMS, CDF, D0

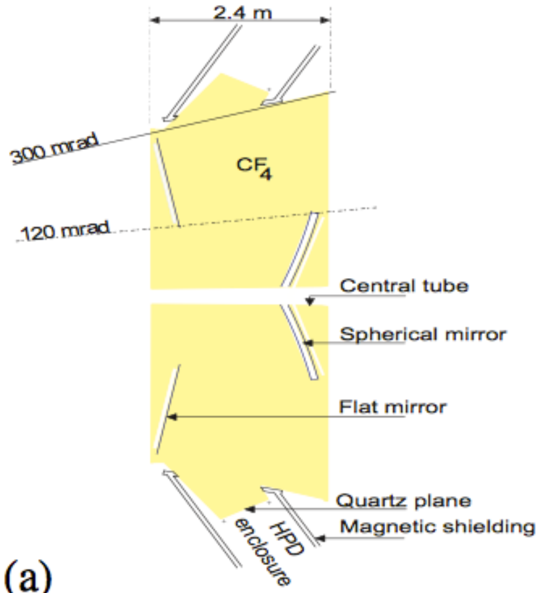
Motivation was also very strong there are very often K in decays of D or B and combinatorial is quite reduced with correct PID. Very often essential to separate correctly B=>KPI from B=>PIPI for example. => decided to invest (about 12% of LHCb)

Some main apparatus choice for LHCb-RICH (II)

Below=> optics of RICH2 and RICH1 and the circles produced by photons on detectors



(a)



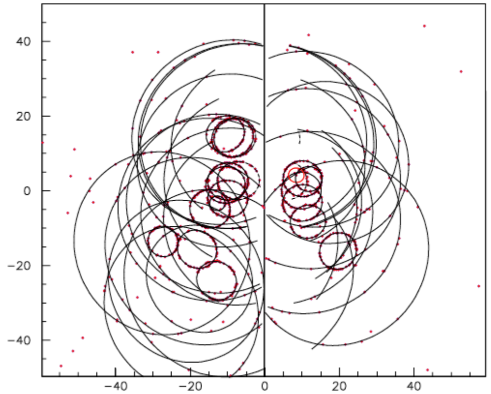


Figure 11: Event display of a simulated $B_d^0 \to \pi^+\pi^-$ event, with the photodetector planes of RICH 1 drawn side by side (scale in cm), and the Cherenkov rings superimposed.

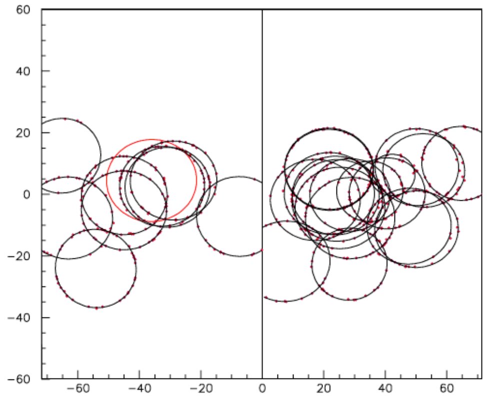
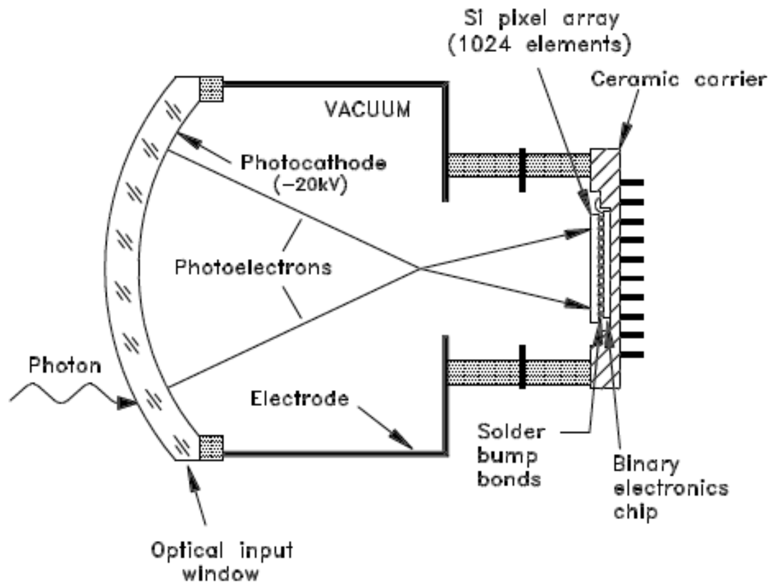


Figure 12: Event display of the same event as Fig. 11, for RICH 2.

May 14th 2015

Some main apparatus choice for LHCb-RICH (III)

The delicate question was the choice of the photon detector=>
Either a 64 channel multi-anode PMT (Hamamatsu) pro: commercial+ electronics accessible, against expensive (3500 tubes, 224K channels!)
Or, custom made HPD finally chosen , very nice idea but delicate construction.
Excellent results achieved: big plus for LHCb



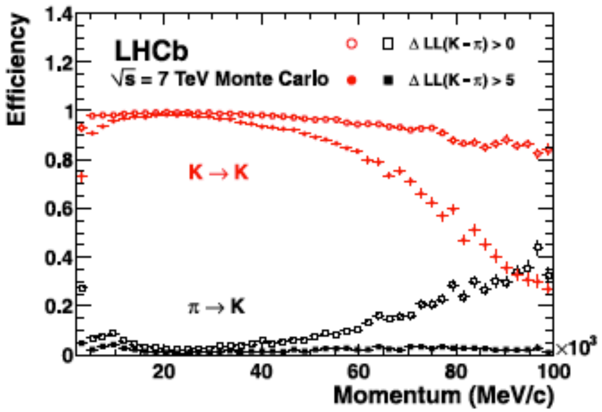


Fig. 18 Kaon identification efficiency and pion misidentification rate measured using simulated events as a function of track momentum. Two different $\Delta \log \mathcal{L}(K-\pi)$ requirements have been imposed on the samples, resulting in the open and filled marker distributions, respectively

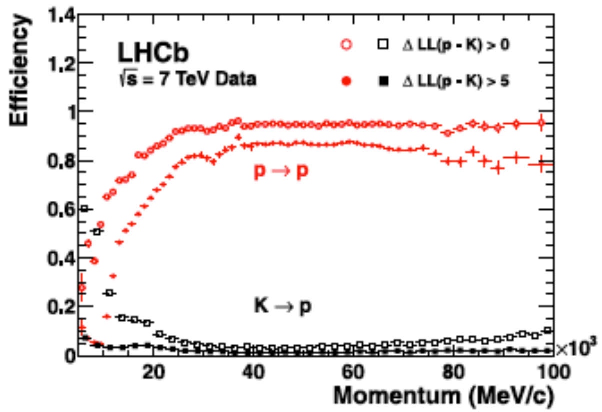


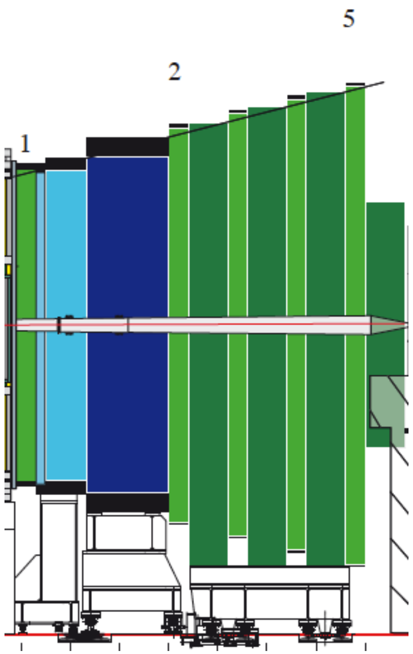
Fig. 20 Proton identification efficiency and kaon misidentification rate measured on data as a function of track momentum. Two different $\Delta \log \mathcal{L}(p-K)$ requirements have been imposed on the samples, resulting in the open and filled marker distributions, respectively

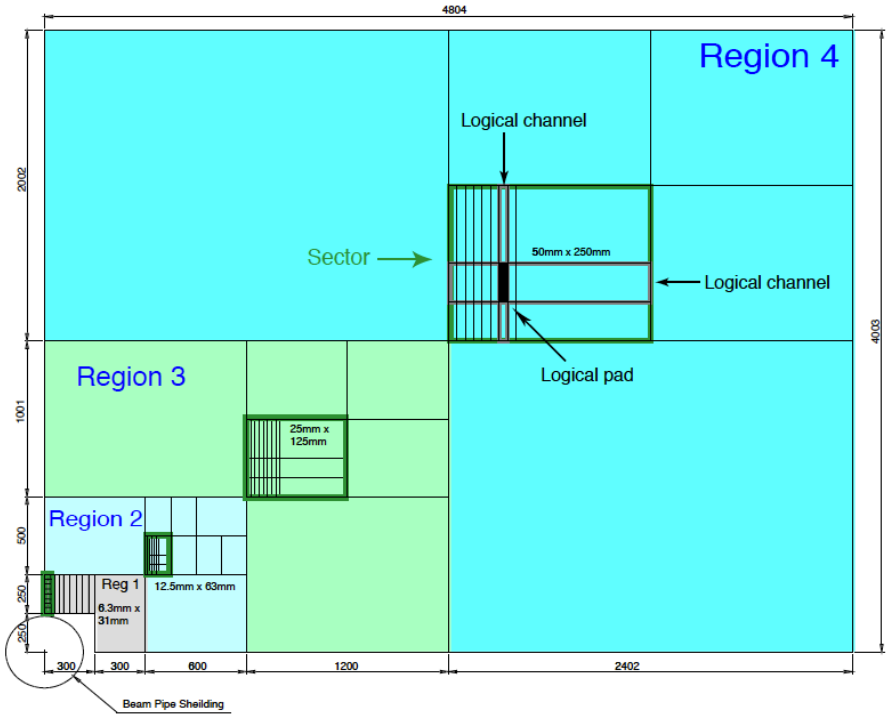
Some main apparatus choice for LHCb-Muon

The muon detector was constructed of 5 chamber layers with cathode readout. The size of the "logical pads" and the chambers were adjusted as function of distance from the beam, since for a given Pt P decreases as 1/θ. The hadron filter is the ECAL,HCAL+3 iron walls of 80cm thickness

A key decision was to choose MWPC as detector(end of 2002), initially RPC were foreseen for most regions but the risk of aging and performance degradation was too large (1344 chambers (2gap) = big project but ALEPH ECAL had 1620! (1gap))

Double gap => redundancy + good efficiency. Good timing was obtained ε=99% in 20ns window. The use of M1 was debated useless for PID but a safety for trigger=> remove in 2018





Some main apparatus choice for LHCb-Calo

The main design choices were guided by the uses

1. **Most important was the calorimeter use in the trigger system to reduce rate of input data to the computer farm from a pp interaction rate of ≈ 40 MHz to < 1MHz**
2. **The HCAL had also a role in μ and e identification but << than the μ chambers and ECAL**
3. **ECAL system (ECAL + Preshower+SPD) allowed to select at the trigger level e , γ**
4. **The ECAL system was also used to identify offline e and γ**
5. **Finally the γ energy and angles had to be reconstructed to see decays of the B like B=>K*γ or $B \Rightarrow \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^-\gamma\gamma$**

On the other hand the constraints were very severe

1. **It is impossible for a photon detector to reconstruct the direction well enough to separate photons from primary or B vertex => much higher combinatorial background for low Pt photons => decrease the incentive to invest in γ detector**
2. **The detector had to be fast (<25ns) which eliminates most photon detectors using scintillators as in BABAR, BELLE**
3. **The detector had to be radiation resistant: the radiation level is higher than in OT or RICH since particles shower in calo and higher than in muon since most particle stop before muon detector => about 2.5 Mrad for $20fb^{-1}$ waouh!**

Calorimeter system(I)

4. A very serious constraint was the investment : because of the large distance from the interaction point, the size (surface) of the calo system was about 2/3 of the size of similar detector for ATLAS or CMS … but their overall budget was > 6 times bigger! And because of point 1 => unreasonable to spend 50% of LHCb in calo system => So we had to compromise compared to ATLAS CMS BABAR BELLE

A first compromise was to adapt the granularity to the density of particles => we had lower luminosity than ATLAS CMS and further away so can use bigger cells. However we are interested in lower Pt photons so the compromise hurts somewhat!

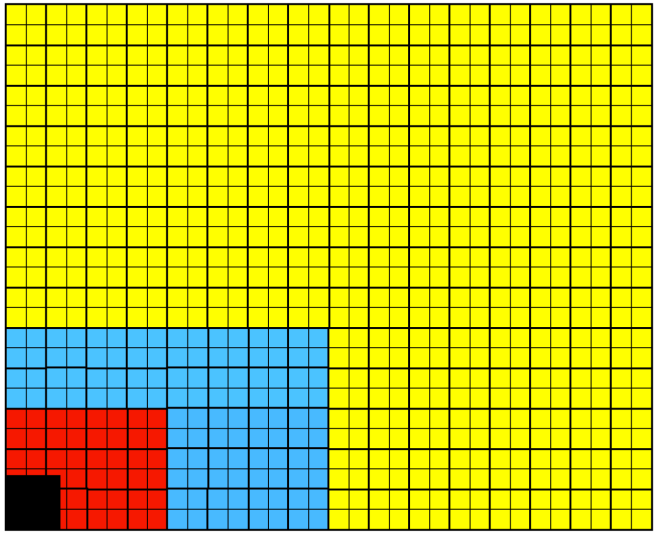
A second compromise was to focus on c,b physics to adapt the range of the electronics to the expected Pt (0-10 GeV/c vs 0-Few Tev for Atlas CMS) =>Hurts somewhat: some physicist wanted to study W,Z => saturation of calo

A 3rd saving was to use same PMT and electronics for ECAL and HCAL

Finally because of the importance of trigger the ECAL was preceded by a preshower with same cell size (helping γ,π separation) + in front a scintillating pad detector to separate e from γ

The ECAL is made of Pb scintillator sandwiches HCAL iron scintillator. In all cases the scintillator tiles are read by Wave length Shifting Fibers (WLS)

Calorimeter system(II)

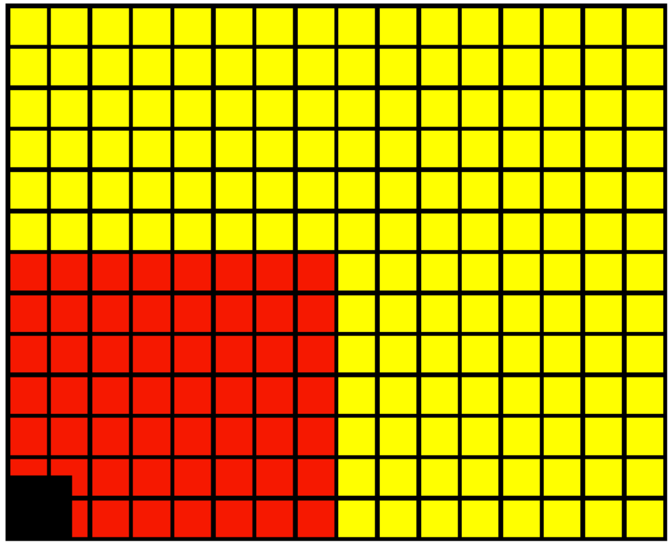


Outer section :
121.2 mm cells
2688 channels

Middle section :
60.6 mm cells
1792 channels

Inner section :
40.4 mm cells
1472 channels

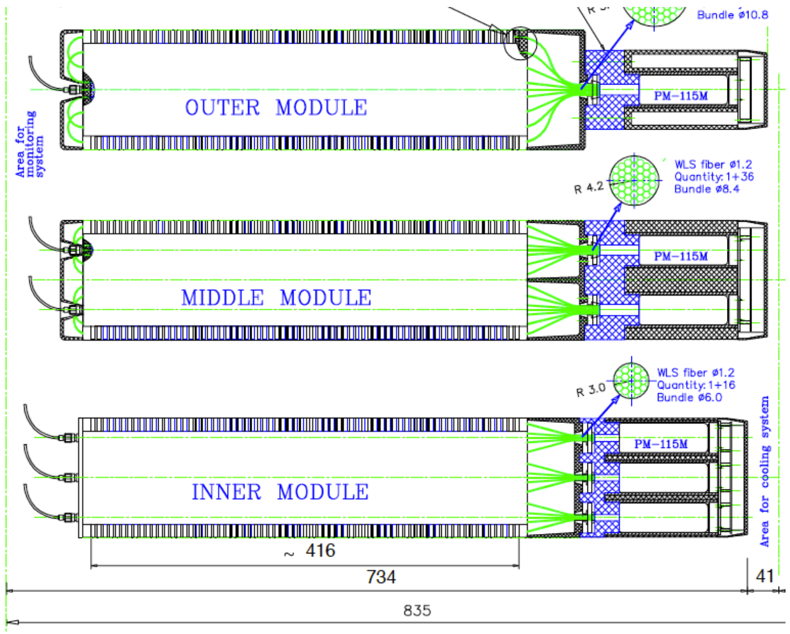
Figure 2.1: *Lateral segmentation of the SPD/PS and ECAL. One quarter of the detector front face is shown. The cells dimensions are given for ECAL and reduce by ≈1.5% for SPD/PS.*

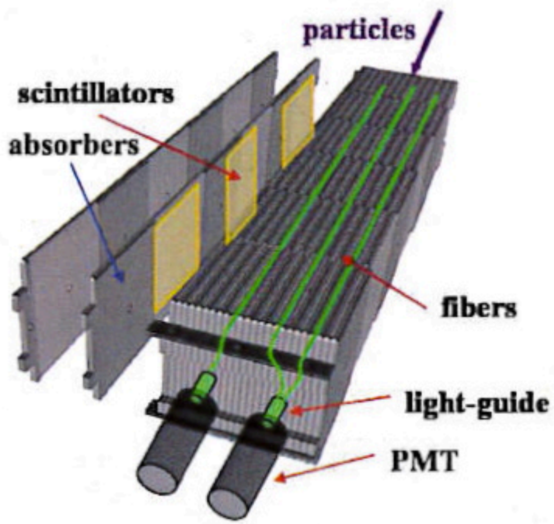


Outer section :
262.6 mm cells
608 channels

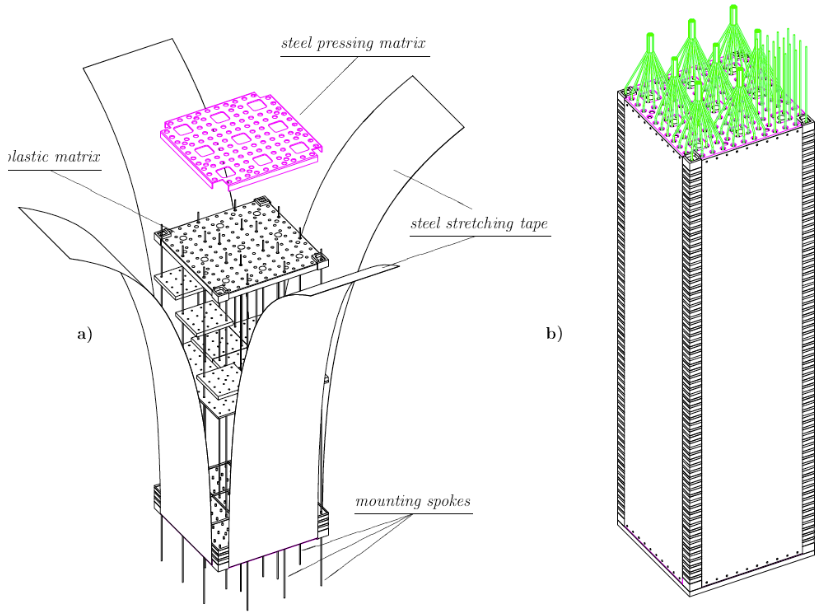
Inner section :
131.3 mm cells
860 channels

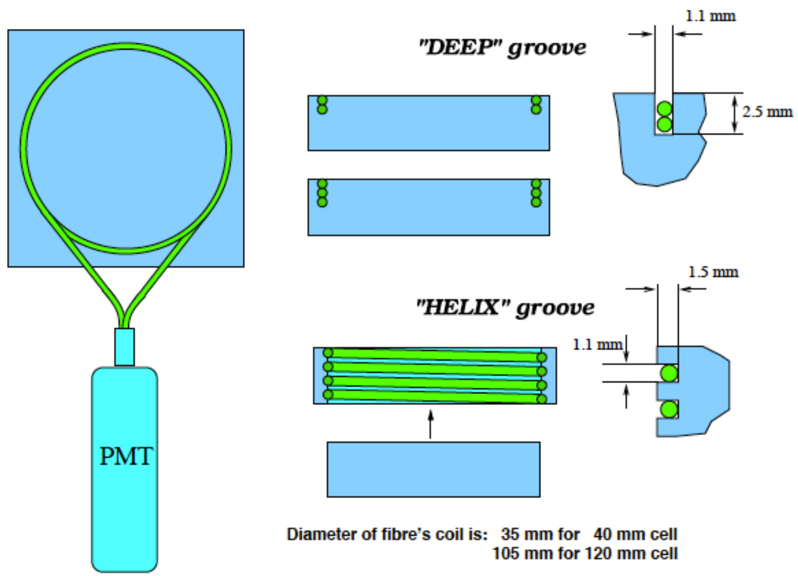
Figure 2.2: *Lateral segmentation of HCAL. One quarter of the detector front face is shown.*





Calorimeter system(III)

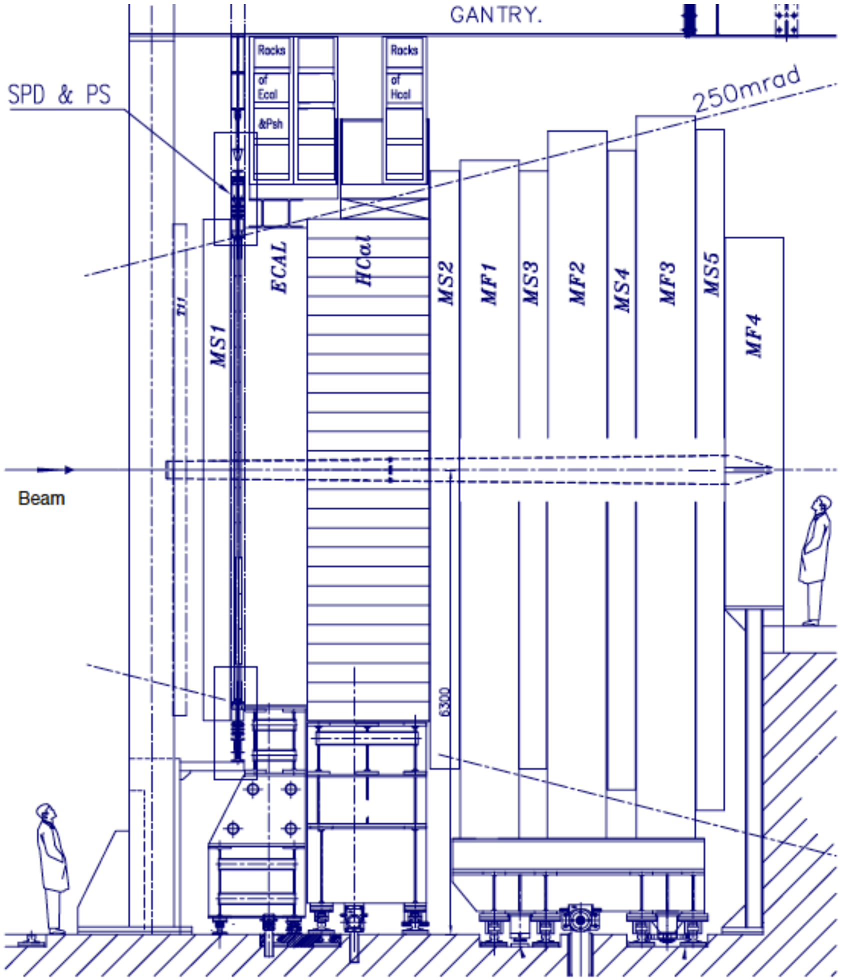




Detail of an ECAL module for the inner part (cells of 4cmX4cm)
Fibers are grouped on PMT placed behind the modules.
About 6000 channels=PMT
Accuracy of Shaslik ECAL modules => 10%/sqrt(E) + 1%
HCAL accuracy about 80%/sqrt(E)

Details of the WLS readout of PS/ SPD tiles. As shown next slide, fibers are grouped+ connected to clear fibers + read by 64 anode PMT (only 10$/ channel vs 100$/ PMT for ECAL/ HCAL

Calorimeter system(IV)



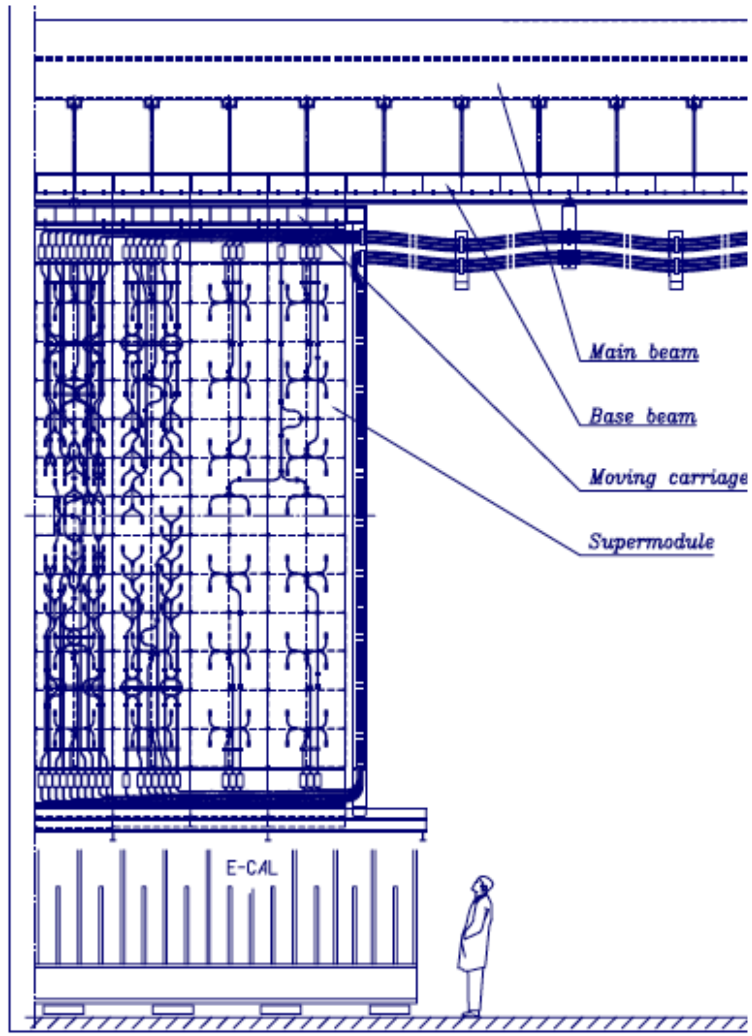
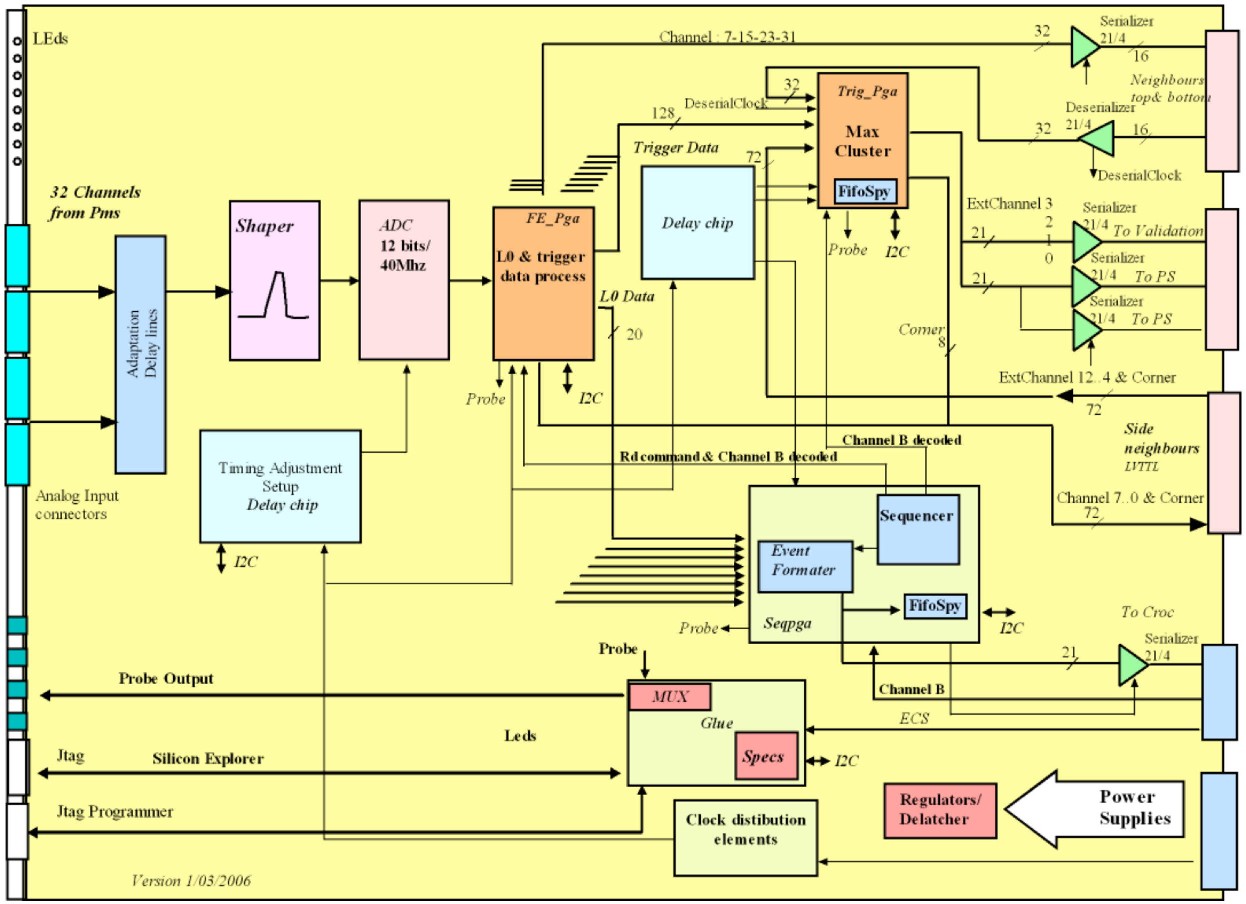


Figure 5.2: *The layout of one half of the SPD/PS detector.*

ECAL/HCAL electronics

Coax PMT=>Front End Board (FEB) 192 cards for ECAL, 54 for HCAL (identical) Each FEB 32 input.

First amplifier integrator (ASIC) => commercial 12 bit 40 MHz ADC => FPGA (pedestal subtraction, calibration for trigger, store data in memory for 4 µs until trigger, then store in 16 deep derandomiser, then readout in serie => 16 cards in one crate connected by backplane for trigger and readout.
PS/SPD similar (64 channels/ cards, 10 bits ADC)



LHCb trigger system (L0 (I))

For 2008, the foreseen speed at which data can be multiplexed from the various detectors and send successively to different PC computers of the FARM was << smaller than 40 MHz (LHCb event size about 50 Kbytes) => decide in 2000 that for each FE card all data at 40 MHz will be stored in a pipeline for 4μs => during this time a L0 is calculated if the answer is L0 yes (maximum average rate 1MHz) the data is passed to a 16 events memory (the derandomiser) and then readout to the computer farm at the rate of 1MHz. For 2018 => upgrade data readout at 40 MHz.

L0 choice of events; use a B signature. It was made by the muon detectors (high Pt muon(s)) and calorimeter system (high Pt hadron or e or γ)

A key choice for the L0 implementation was made in 1997-98. An american group advocated a specific computer (advantage flexibility) While French groups (Marseille Orsay Clermont) advocated an FPGA based system (big advantage system synchronous: all events take exactly the same time to select):

I am sure it was the right choice: It would have been very difficult, if not impossible, to operate a computer with a fixed time budget (2μs + 2μs in cables) while an FPGA works by construction as a pipeline system with a fixed latency!

LHCb trigger system (L0 -Mu)

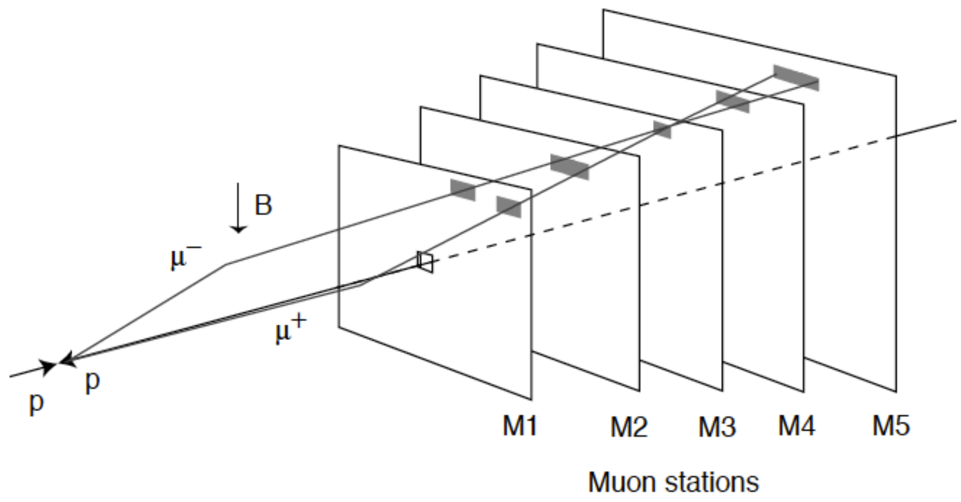
The size of the cells in the muon chambers are such that an infinite momentum traverse cells with the same "number" in M1…M5

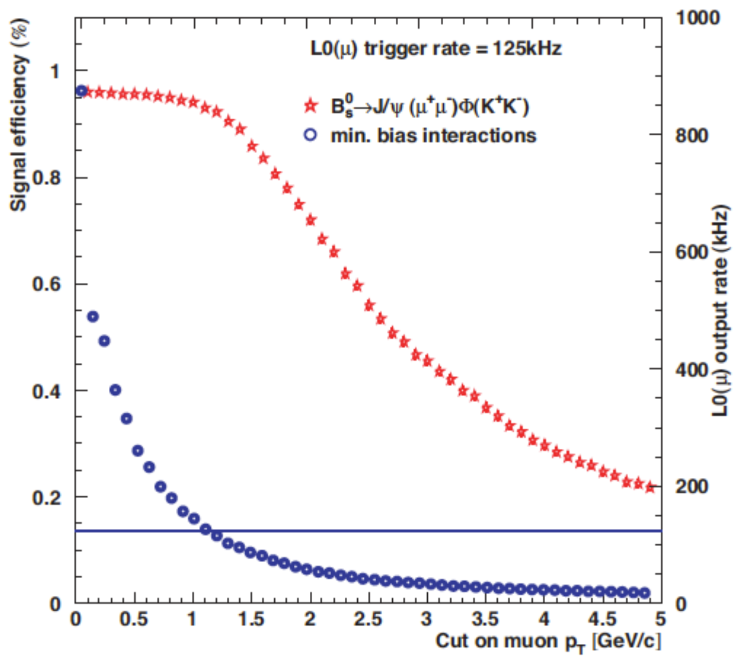
The trigger consist of asking that for a cell in M3 one has the same cell numbers in other Mi ±3 (the exact number gives the Pt)

There is one crate of 16 cards per ¼ of chambers

A delicate problem is the exchange of information between regions using the back-plane of crate. (Trigger is mainly a communication problem!) The needed time is 42 clock cycles (1.05 µs)

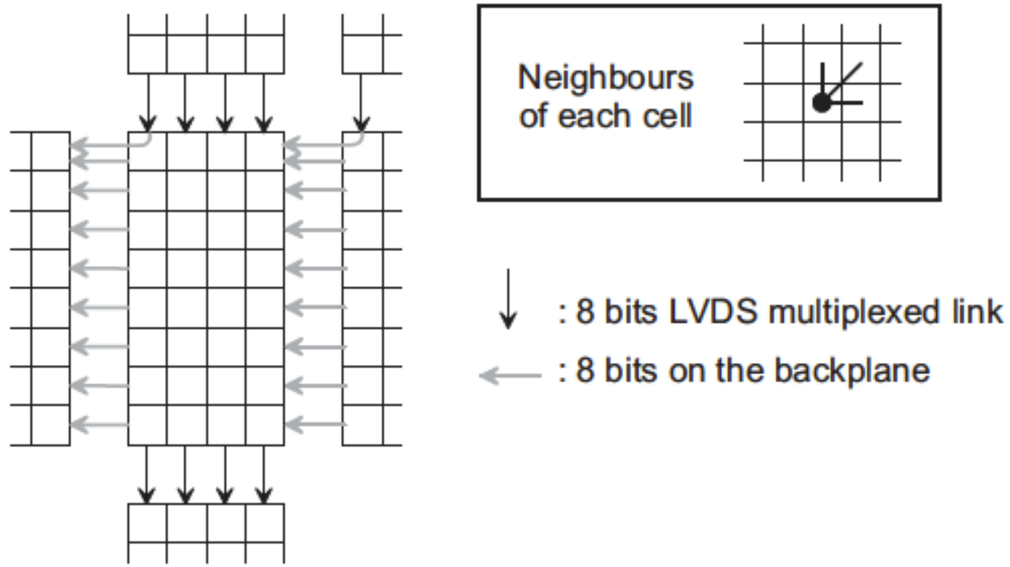
The efficiency and rejection is shown ,typical settings for L0 muon was Pt>1. GeV for one muon or 2 muons Pt>0.5





LHCb trigger system (L0 - Calo)

Since the ECAL, HCAL cells are calibrated in Et to obtain the Et of a particle it is sufficient to form a 2X2 cluster. i.e. for each position add 4 8-bits numbers (using FPGA=> 25ns)
Easy in one card :As for muon the delicate point is to get neighbour as shown (done using 280 MHz serialiser)
Then get for each card highest Et cluster its Et and address => associate information from PS SPD, then choose biggest Et for e,γ, h in a crate then in whole calo.
L0 for example asks e or γ with Et> 2.5 or summing ECAL+HCAL Et>3.5 for h



LHCb trigger system (HLT(I))

After reduction at 1 MHz further selection in the computer farm is needed to select about <few KHz of b, c, candidates. This is done in 2 steps a “simple” first rejection, fast to calculate, is needed to reduce rate to about 50KHz (HLT1) then there is more time to do the full reconstruction => few KHz (HLT2)

Before first data, the “official idea” for HLT1 was to examine the track which had caused the L0 (μ, h, e, γ(?)) reconstruct this track in VELO and OT recalculate the L0 selection criteria more accurately and ask for an IP in the VELO for this track => procedure took too much CPU for an incomplete farm (2010) and was not ideal for efficiency&rejection. => Crisis!

Luckily there was a young Post Doc (V. Gligorov “Vava”) who invented a simpler, faster, more efficient way (remember first lecture about a PhD changing the rotating condenser at Harvard cyclotron => I said I would give example of young physicist impact.)

Basic idea is simple : what is common to all b decays? => at least one track with high IP and high Pt => sufficient for HLT1

Show next copies of 3 of Vava 2010 slides

LHCb trigger system (HLT(II))

The claim

In any B decay to charged tracks, you can always find one track with

PT	> 1 GeV
P	> 10 GeV
IP	> 100 μm
Track Chi2	< 2

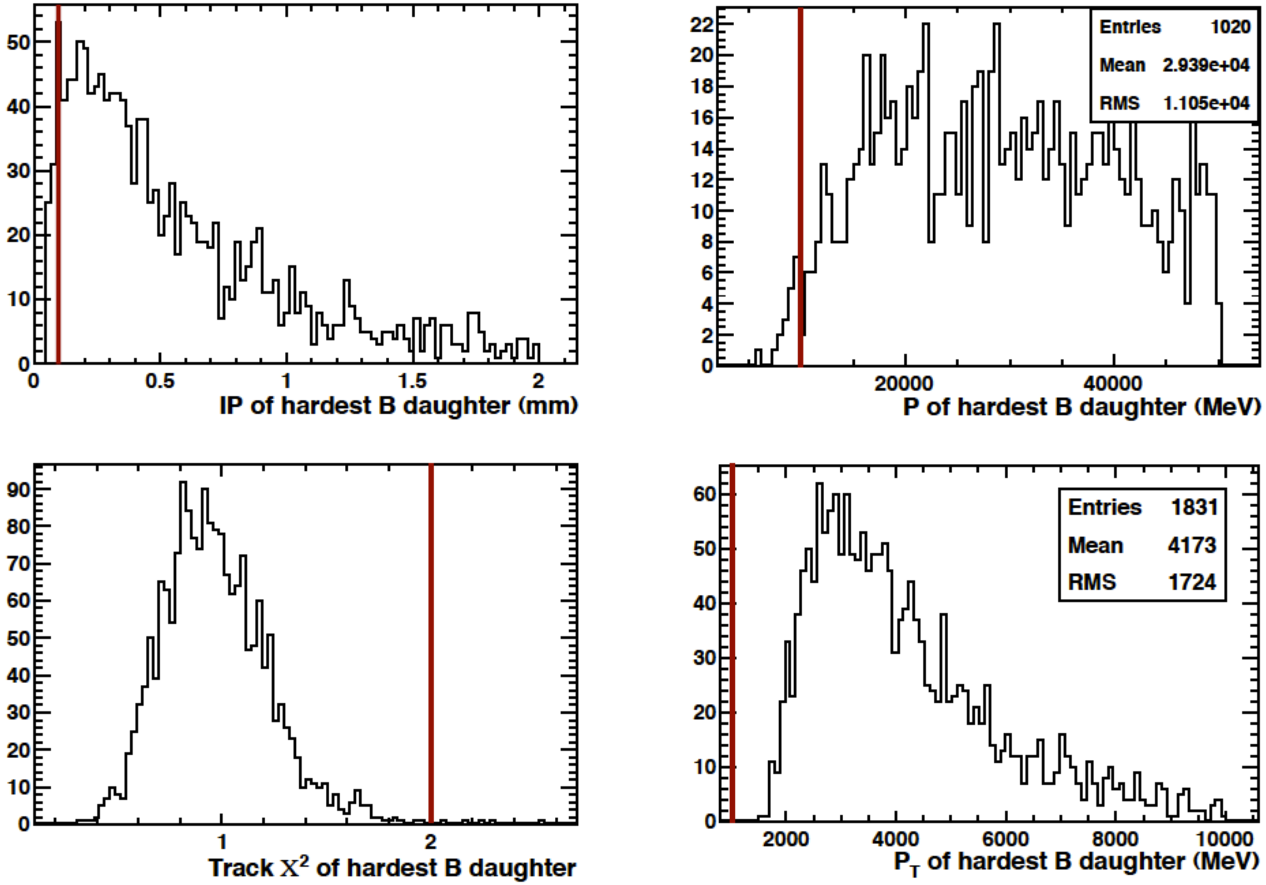
This kind of track is almost never present in a minimum bias event

Use B->hhh as the "guinea pig"

LHCb Trigger and Stripping meeting, 16th August 2010

LHCb trigger system (HLT(III))

Signal distributions



LHCb Trigger and Stripping meeting, 16th August 2010

LHCb trigger system (HLT(IV))

Efficiencies

Channel	L0 1F Global eff. (±3%)	Efficiency wrt. L0 (±3%)
B->hh	92%	89%
B->hhh	86%	93%
$B_s \to \mu\mu$	98%	91%
$B \to K^*\mu\mu$	93%	83%
$B \to D\mu\nu X$	93%	80%
$B \to DK$, $D \to 4h$	83%	90%
$B_s \to D_s K1$	90%	87%
$B \to DK$, $D \to K\pi\pi^0$	90%	84%
$B \to DK$, $D \to K_S\pi\pi$ (DD)	85%	78%
$B \to K^*ee$	92%	77%
$B_s \to \varphi\varphi$	76%	74%
$B \to K_S\pi\pi$, DD K_S	84%	71%
$B \to X\gamma$	95%	53%
$D \to \mu\mu$	97%	37%
$D \to hh$ (Real Data)	53%	50%
$D \to hhh$ (Real Data)	68%	50%

LHCb Trigger and Stripping meeting, 16th August 2010 9

LHCb trigger system (conclusion)

This HLT1 idea stayed at the core of the HLT1 for 2012-13

HLT2 relied also on ideas of common features of b, c hadron decays (topological features b=> n tracks)) but is also more specific (PID)

L0 nevertheless is an important cause of inefficiency =>2018 no L0 =>

read 40 MHz of data in computer farm

Unforeseen problems in commissioning(I)

Experienced physicists know that starting an apparatus is not simple. But published articles on apparatus and their performance talk about successes, almost never mention problems.

And I realise I have done about the same for ACO, NA3, ALEPH… I could have recalled some problems on those but the mind tend also to slowly forget problems and remember the best. So I will give a few examples for LHCb.

Actually it might even be useful to have some lectures in physics-schools on problems , because of longer periods between experiments the occasions to learn by experiences are smaller now for PhD’s and postdocs.

Of course everybody knows and expects that during the R&D period before construction there are difficulties… trial and errors… until the decision is made for construction.

What is less known is that there are ALWAYS problems even at the commissioning time, the role of the experienced physicist is then to diagnostic the problem (like a detective problem ☺) and then find how to repair or how to minimize the impact, I will give a few examples:

Unforeseen problems in commissioning(II)

Malfunctioning of serialisers in the ECAL/HCAL cards (found Dec2007):

First I should explain that as a precaution we had switches on power (+3V) for FE cards, (MAXIM, MAX869 =>Web) they are like intelligent fuse. If the current exceeds the (adjustable) limit the voltage =>off state for a few ms. Can also be turned off permanently by control line, information on turn-off is stored : much more flexible than a fuse => It was a very good decision to have these MAX869.

For exchange of the large amount of information used for triggers+readout we used multiplexers (DS90CR215): 21 information at 40 MHz =>3lines at 280MHz+1clock

When commissioning we found that at low trigger threshold (triggering on noise => many pulses) the MAX869 switch went off on a few boards => bring a board back to Orsay => reproduce the problem => increase the current limit=>saw a current increase of 500ma => touch circuits on cards =>I burned my finger (low tech device!) on one DS90CR215 (out of 6) since it was receiving 3VX0.6A=>1.8W

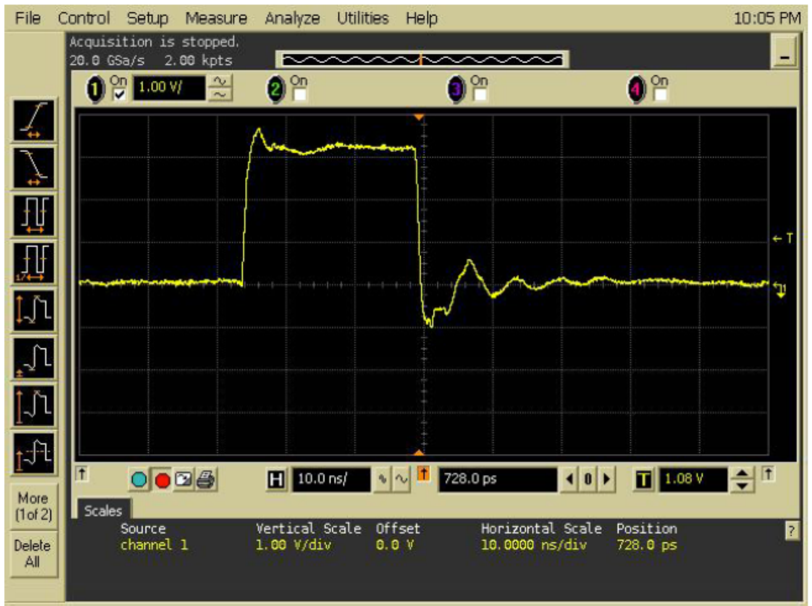
Unforeseen problems in commissioning (III)

It was found that there was a complicated protection on the serialisers' inputs: if there was a negative undershoot <-0.7 volts at a high rate (>0.1 MHz) on more than one input=> chip goes in high current mode: Of course not documented by manufacturer! => replace with same serialiser but another manufacturer =>OK

Conclusion had to test new chip for radiation resistance (old chip had been tested) then replace 2 chips on 256 FE boards!!! Painful (4 persons,few weeks) but problem solved.

Case of no problem

Case of problem

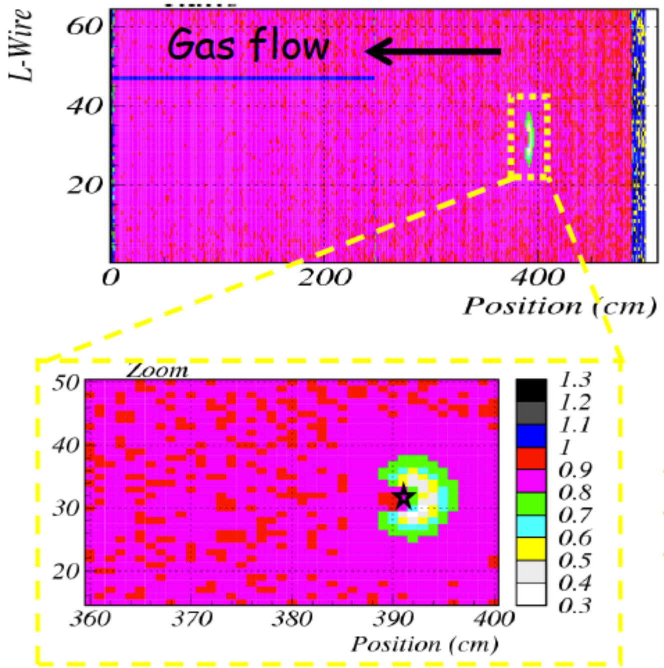


Unforeseen problems in commissioning (IV)

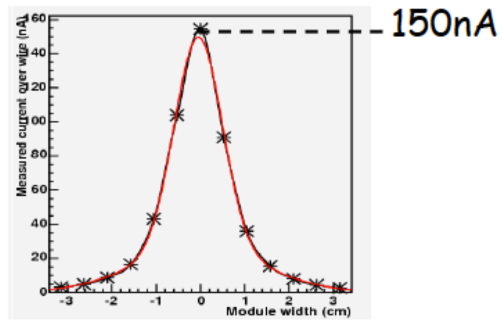
The outer tracker prototypes had been tested as resisting to radiation, but by chance a testing source was left during a week-end

Ageing Surprise!

Ratio Plot: I_{after}/I_{before}



Irradiate with 2 mCi ^{90}Sr source



The ageing of the LHCb OT exhibits **unique features**:

- The ageing rate is large
- No ageing below the source
- No ageing downstream of the radioactive source

A real surprise - this had not been seen in the ageing tests performed with test modules in the R&D phase

Unforeseen problems in commissioning (V)

Huge effort to survive/understand: Flushing and heating seem to decrease the "poison", training with HV, use of 2% O_2 in gas "cures" irradiated chambers => confident no problem until 2018. Then found the culprit!

<u>During our tests, we came to realize that:</u>

For mass production, did not use AY103, but AY103-1

- in 2003 producer switched from AY103 to AY103-1

The new araldite contained methyl Ethyl Naphtalene vs Dibutyl Phtalate before ! => layer deposit on wire. Mass analysis of gas found much larger amount of "heavy hydrocarbon" in OT gas in case of AY103-1

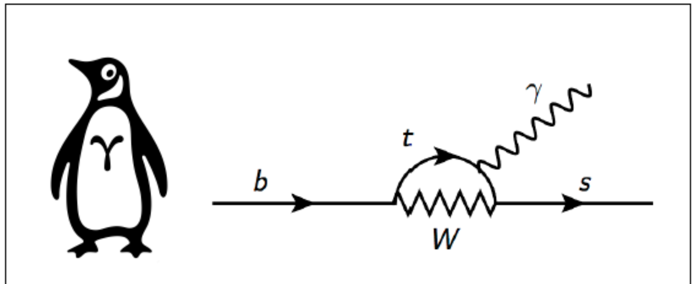
THERE ARE ALWAYS PROBLEMS!

Unforeseen problems in commissioning (VI)

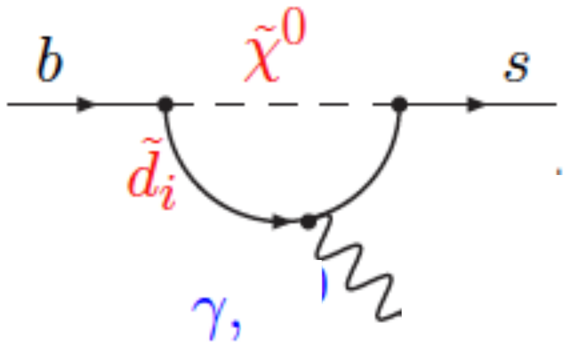
- **Of course there are many other examples: ECAL HV PMT bases should have been like HCAL but were modified (?) => bad regulation => gain instability => extract 6000 PMT base + modify components**
- **RICH ASIC of amplifier + readout after L0 => because of design error does not allow 2 successive L0 (25ns) =>all LHCb limited with $\Delta t \geq 50$ns**
- **VELO+IT ASIC error in derandomiser => cure behaviour emulated by trigger system**
- **+ many others… a useful lecture on problems would need > 10 slides per problem**
- **In conclusion: There will always be unforeseen problems, no miracle recipe =>**
  - **Test beam with use by non-expert sometime useful to find weaknesses**
  - **Should plan long enough commissioning time for good understanding… and repair.**
  - **Should never bypass in commissioning a not-understood problem thinking it is minor… It will probably come back at the worse moment during data taking!**
  - **In design if possible prefer solutions with accessibility and flexibility (for example reprogrammable FPGA better than ASIC (but ASIC sometime essential!))**
  - **Encourage openness and exchange of story of problems : it spreads experience among a bigger number of physicist.**
  - **I really think it would be a good idea to foresee case study in physics school (one full afternoon? More?)**

The angular analysis of $B^0 \Rightarrow K^*ee$

In a "brain-storming" discussion, beginning of 2008, in the LHCb-LAL ORSAY group, on possible future interesting physics analyses, the subject of photon polarisation in b => sγ was raised. The interest is that photon are produced by penguin diagrams (loops) and other particles can circulate in the loop:



"The gamma penguin"



For the main diagram of b => sγ the s quark is left handed (with small right handed contribution of order ms/mb) and therefore the photon in B =>K*γ is also left handed. But in Susy models or Left-Right models there can be sizeable right handed contributions
Decide to start a study M.H.Schune, Jibo He, M.Nicol(2010-2012), C.Prouve(2012-2013) M.Borsato(2013-2015) and J.L.

How to measure the photon polarisation?

There are a few measurements sensitive to the photon helicity (A_R,A_L)

In B=3π γ decays, the normal to the plane of the 3π is an axial vector and the angle between this A.V. and the γ is sensitive to the helicity (done by LHCb Phys Rev 112.161801) however measuring directly the helicity of the photon is prop. to A_R^2/A_L^2 not sensitive for small A_R => need interference measurements sensitive to $2*A_R/A_L$

One such measurement is the interference B,B_{bar} in $\gamma K^0_s\pi^0$ decay (Babar,Belle)

$B \to A_L + \varepsilon A_R$

$\bar{B} \to A_R + \varepsilon A_L$

But $B \to K^*\gamma$ with $K^* \to K^0\pi^0$

$$A_{CP(t)} = \frac{2\mathrm{Re}(A_L A_R^*)\cos\delta}{|A_R|^2 + |A_L|^2}\sin(2\beta)\sin(\Delta m t)$$

δ: strong phase between the 2 amplitudes. A priori only one resonance ⇒ δ=0

Another possibility is B,B_{bar} interference in B => φγ (analysis in progress in LHCb)

2. Study the $B_s \to \Phi\gamma$ decay : the term proportional to $\Delta\Gamma_s$ is sensitive to $A_L A_R$

LHCb-2007-147

$$\Gamma(B_q(\bar{B}_q) \to f^{CP}\gamma) \propto e^{-\Gamma_q t}\left(\cosh\frac{\Delta\Gamma_q t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_q t}{2} \pm \right.$$
$$\left. \pm\mathcal{C}\cos\Delta m_q t \mp \mathcal{S}\sin\Delta m_q t\right). \quad (1)$$

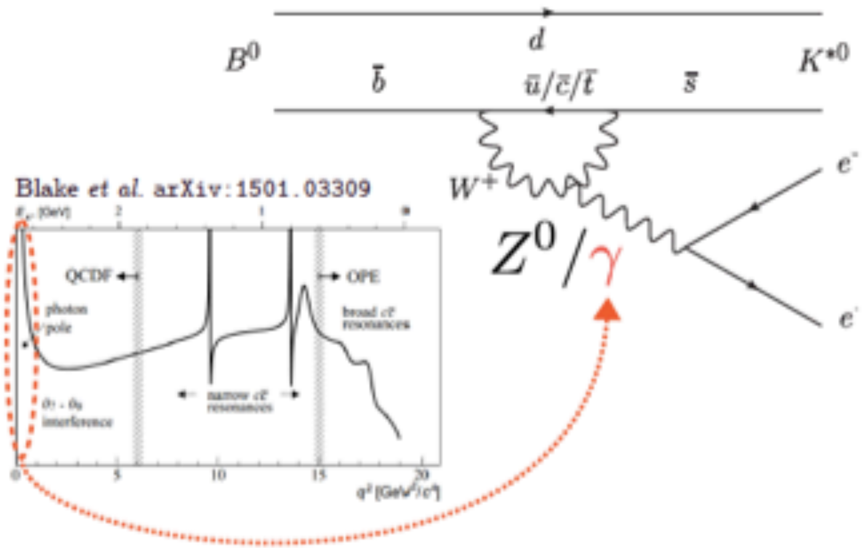
SM : $\mathcal{S} \approx \sin 2\psi \sin\varphi,\ \mathcal{A}^{\Delta} \approx \sin 2\psi\cos\varphi,\ \mathcal{C} \approx 0.$ $\quad \tan\psi \equiv \left|\frac{A(\bar{B}\to f^{CP}\gamma_R)}{A(\bar{B}\to f^{CP}\gamma_L)}\right|$

A measurement of A^{Δ} : sensitive to the fraction of right handed photon

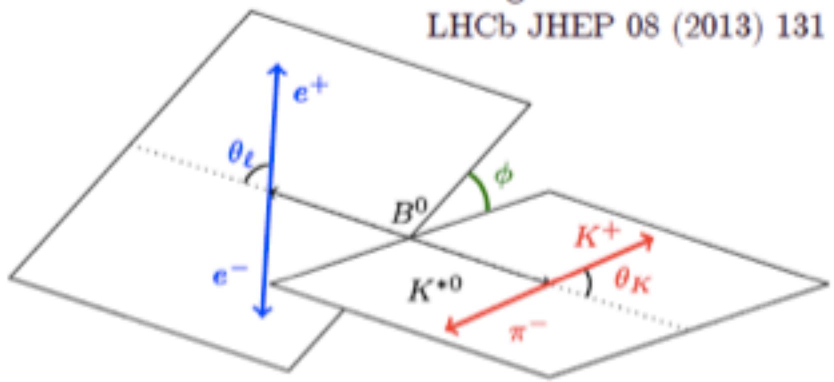
çois

Using B=>K*ee (LHCb arxiv:1501.03038 =>JHEP)

- FCNC via penguin and box diagrams
- Exploit **electronic channel** to go very low in q^2
  $\rightarrow$ analysis in q^2 bin $[0.0004, 1]\ \mathrm{GeV}^2/c^4$
  $\rightarrow$ photon pole largely dominating
  $\Rightarrow$ **disentangle** $b \rightarrow s\gamma$ **contribution**
- Measured BR with $1\,\mathrm{fb}^{-1}$ LHCb: JHEP05 (2013) 159
  $\mathcal{B}(B^0 \rightarrow e^+e^-K^{*0}) = (3.1\ ^{+0.9}_{-0.8}\ ^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$
- $3\,\mathrm{fb}^{-1}$ allow 3D angular analysis on θ_ℓ, θ_K and ϕ
  $\Rightarrow$ assess **photon polarization** in $b \rightarrow s\gamma$
  Grossman *et al.* JHEP06 (2000) 029
  Jäger *et al.* JHEP05 (2013) 043



angle definitions as in
LHCb JHEP 08 (2013) 131



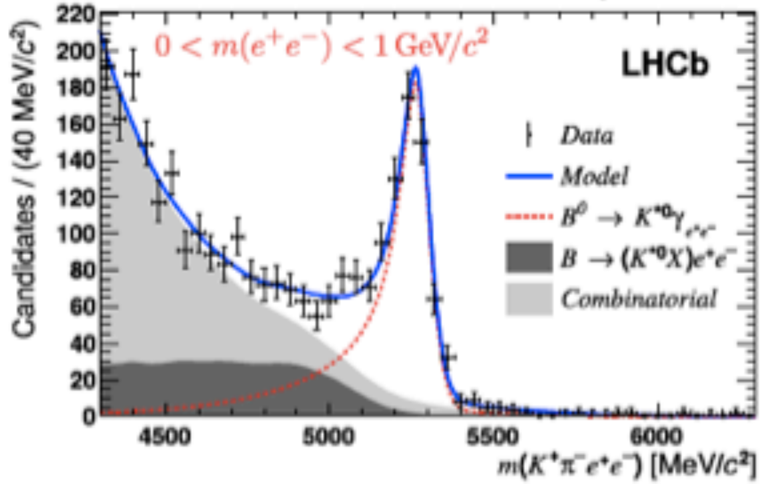
The phi distribution is sensitive to transversity amplitudes squared $A_{//}^2$ and A_{perp}^2 but $A_{//}=A_R+A_L$ and $A_{perp}=A_R-A_L$
We are therefore sensitive to interference effect and to A_R/A_L

for small A_R/A_L , $A_T^{(2)} = (|A_\perp|^2 - |A_{//}|^2) / (|A_\perp|^2 + |A_{//}|^2)$ is $\approx 2\ A_R/A_L$

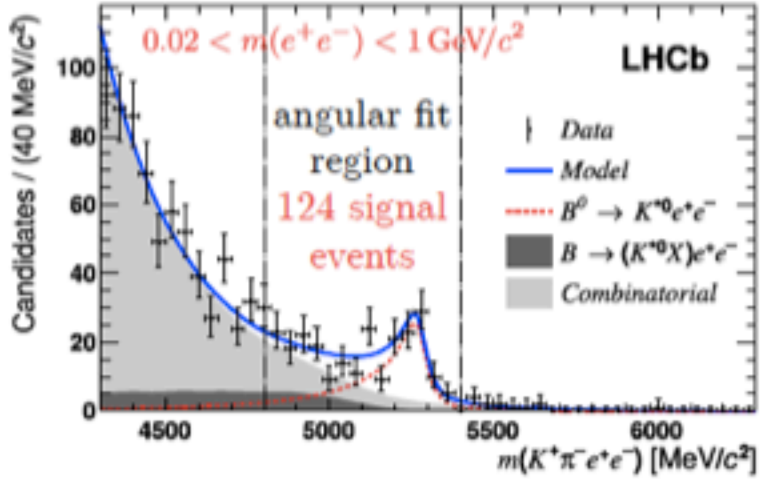
Event selection and background

- Multivariate selection based on kinematic and track isolation
- mass shape affected by bremmstrahlung emission and partial recovery
- main background at low mass from semileptonic $B^0 \to D^- e^+ \nu$
  $\hookrightarrow K^{*0} e^- \overline{\nu}$
- partially reconstructed $B \to (K^{*0}X)e^+e^-$
- $B^0 \to K^{*0}\gamma$ with γ conversion is a good proxy but also a background
  $\to$ after veto: $(3.8 \pm 1.9)\%$ pollution
- angular fit in reduced mass region

validate on $B^0 \to K^{*0}\gamma$



rare $B^0 \to K^{*0}e^+e^-$



Angular analysis

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Bigg[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \left(\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K - F_\mathrm{L}\cos^2\theta_K\right)\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} + (1-F_\mathrm{L})A_\mathrm{T}^\mathrm{Re}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^\mathrm{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Bigg]. \quad (1)$$

$A_T^{(2)}$ at q^2=>0 =$2A_R/A_L$

In Wilson coefficient formulation for the decay mode, the terms are expressed as function of C_7 and C_7' the Wilson coefficients for left-handed photons and right handed photons

$$\mathrm{A}_\mathrm{T}^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7\mathcal{C}_7'^*)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}$$

$$\mathrm{A}_\mathrm{T}^\mathrm{Im}(q^2\to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7\mathcal{C}_7'^*)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}.$$

Accurate at 5% if integrated in our q^2 range

- F_L: longitudinal polarization $\Rightarrow$ small as the quasi-real photon is transversely polarized
- $\mathrm{A}_\mathrm{T}^\mathrm{Re} = \frac{4}{3}A_\mathrm{FB}/(1-F_\mathrm{L})$ related to forward-backward asymmetry

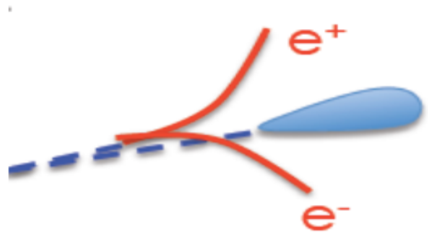
Specific Backgrounds

- $B^0 \to K^{*0}\eta$
  - $\to \gamma\gamma$
    - $\to$ single conversion ⇨ NEGLIGIBLE
    - $\to$ double conversion ⇨ 2.9 evts not peaking
  - $\to \gamma\, e^+e^-$ Dalitz decay ⇨ 4.2 evts above 4.8 GeV/c²
    1.5 evts above 5.1 GeV/c²

(1 evt ≈ corresponds to 0.8% background

- $B^0 \to K^{*0}\pi^0$
  - $\to \gamma\gamma$
    - $\to$ single conversion ⇨ NEGLIGIBLE (even with merging)
    - $\to$ double conversion ⇨ NEGLIGIBLE
  - $\to \gamma\, e^+e^-$ Dalitz decay ⇨ 0.6 evts above 5.1 GeV/c² (merging included)

Bremshtrahlung energy measured in ECAL at the positions extrapolated from the e+,e- angles before the magnet are added to e+,e- momentum measured in magnet (slide 48). For π^0 decay "merging" = one photon is in same cell cluster as Brem photon.

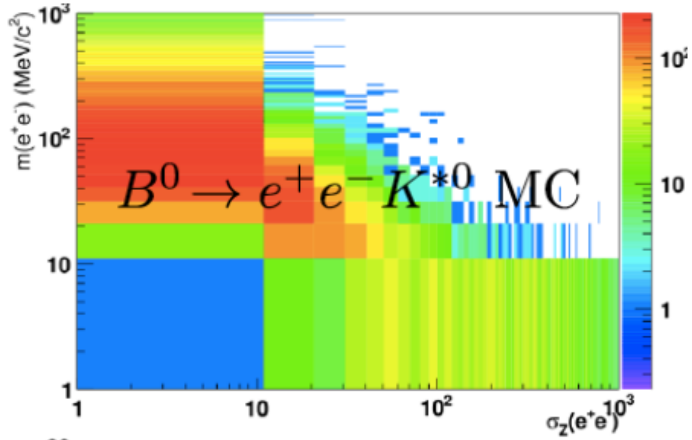


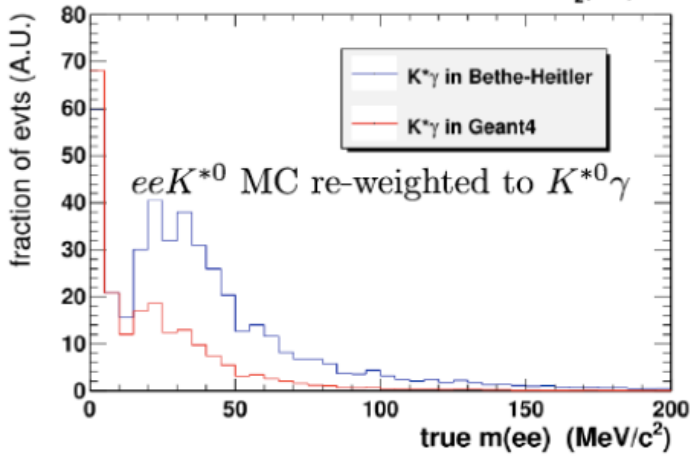
The lower M_{ee} limit and the K*γ background

Because of multiple scattering in the VELO material, the e^+,e^- receive a transverse momentum "kick" of 15 MeV*Sqrt(X/X_0) in x or y => multiplied by sqrt(2) (X and Y) multiplied by sqrt(2) for 2 particles => 5x2 =10 MeV . For M_{ee} <20 MeV, angles are too modified by multiple scattering => cannot measure φ => Use only events with M_{ee} (measured) > 20 MeV. Also ask that Kπee come from same vertex and the σ_Z of the eepair is < 30mm

The Mee>20 MeV and σ_Z cuts removes many events from K*γ with the γ converted to e+e- in the VELO material. Some left because mult. Scatt. increases the mass or because the conversion gives a mass >20 MeV

- Use 6M MC evts → 5 MC evts after veto cut
- Take normalization from bin [0-5] MeV of data sPlot without veto cut (subtract 3% of $K^{*0}ee$)
- But we know Geant4 is wrong
  - di-leptons from photon conversion have smaller masses compared to Bethe-Heitler formula
    → use $K^{*0}ee$ MC and re-weight $m(ee)_{gen}$ to reproduce m(ee) distributions from Geant4 and Bethe-Heitler after all cuts
    → extract a correction factor of 2.0
- This gives a contamination of 6.0 ± 3.0 evts
  → $(\mathbf{3.8 \pm 1.9})$**% of signal yield**
- Bad resolution in ϕ → flat distribution
  → $A_T^{(2)}$ and A_T^{Im} smaller by $\sim 4\%$
  → correct and assign a systematic





The B=> K*V (V=>e+e-) Background

These background are indistinguishable from B=>K*ee (actually the amplitudes can interfere!)

The branching ratio B=>K*ρ, K*ω, K*φ have been measured and V=> e+e- is know (remember the ACO measurements! Lecture 1 and improvements since 1970!)

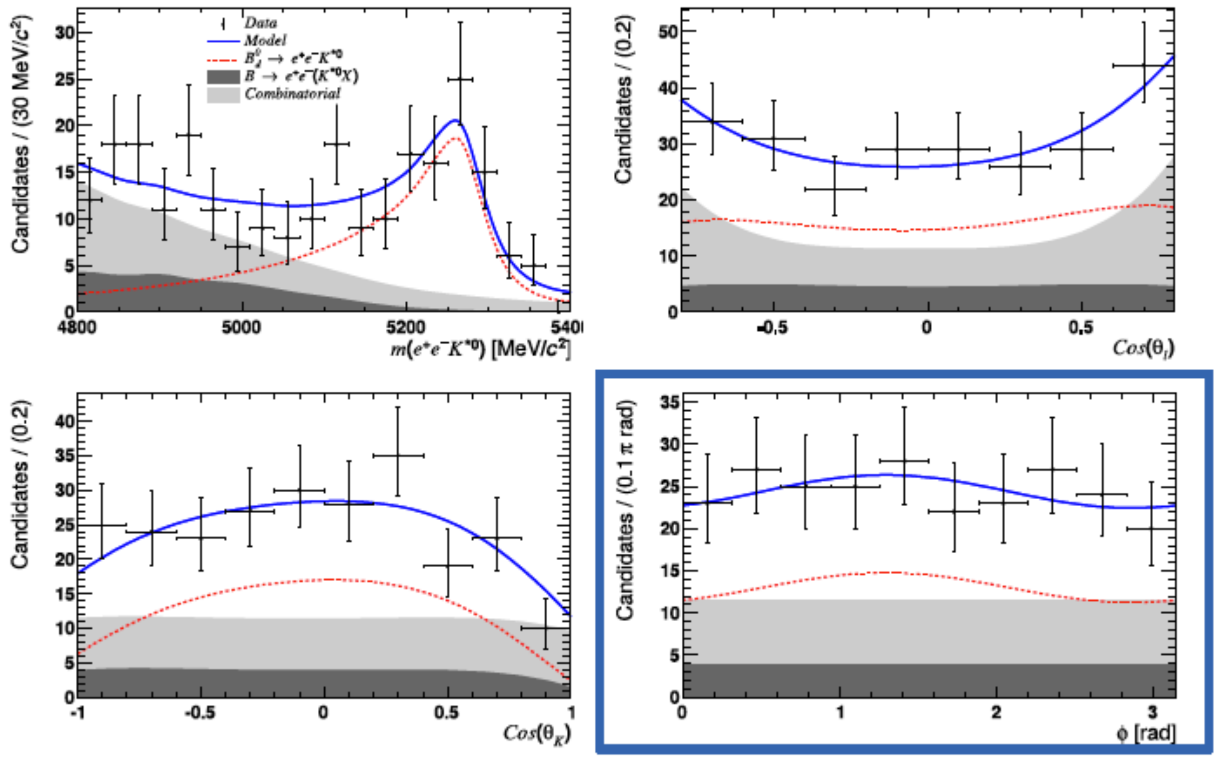
Can calculate the expected number of events the φ is the biggest (1.2%) other much smaller

Interference effects could be bigger (we did a simplified calculation then two theorist evaluations) => negligible once integrated over $20\text{MeV}<M_{ee}<1000\text{MeV}$

Taking into account the acceptance as function of q^2, and event migration in q^2 the effective q^2 range is $0.002<q^2<1.120$ GeV2 Standard model prediction for that range are (Jager &Camalich arxiv:1412.1383)

$$
\begin{aligned}
F_L &= 0.10^{+0.11}_{-0.05} \\
A_T^{Re} &= -0.15^{+0.04}_{-0.03} \\
A_T^{(2)} &= +0.03^{+0.05}_{0.04} \\
A_T^{Im} &= (-0.2^{+1.2}_{-1.2}) \times 10^{-4}
\end{aligned}
$$

Fit results



Data Results

$$
\begin{aligned}
F_L &= 0.16 \pm 0.06 \pm 0.03 \\
A_T^{Re} &= +0.10 \pm 0.18 \pm 0.05 \\
A_T^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\
A_T^{Im} &= +0.14 \pm 0.22 \pm 0.05
\end{aligned}
$$

b→sγ photon polarization

Impact on limit of right handed current(I)

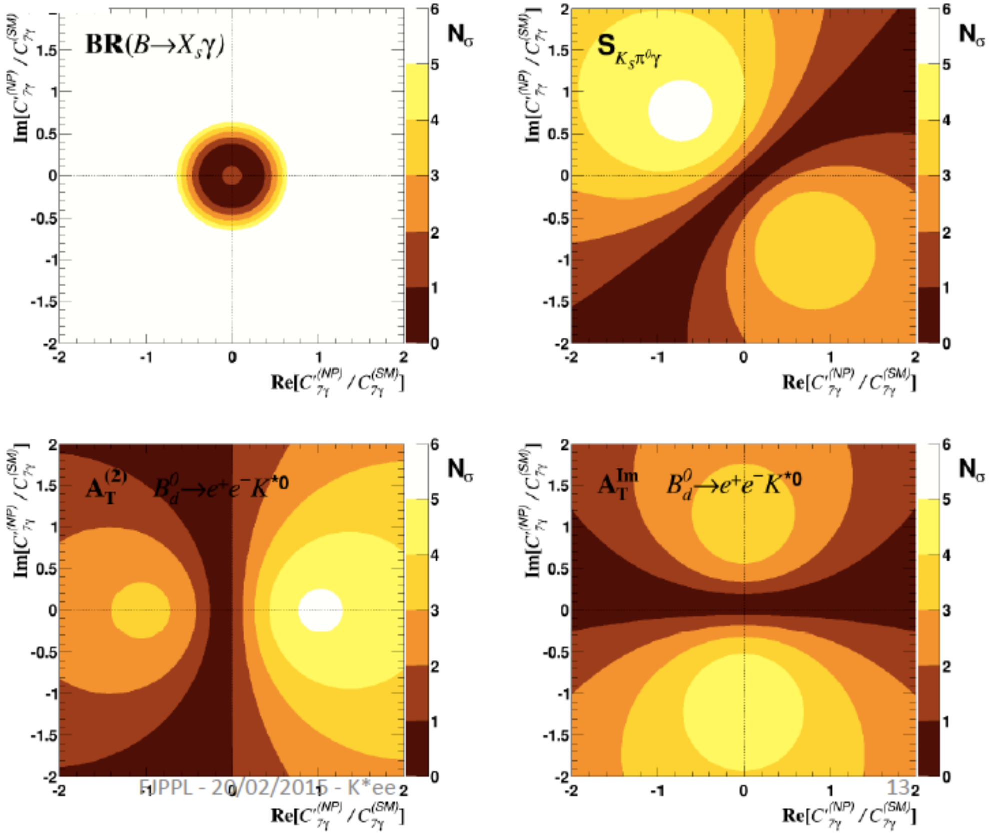
$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7 \mathcal{C}_7'^*)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{\mathrm{Im}}(q^2 \to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7 \mathcal{C}_7'^*)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}.$$

of $[C_7'^{(\mathrm{NP})}/C_7^{(\mathrm{SM})}]$

accurate at 5% level

Based on Becirevic et al
http://arxiv.org/abs/1206.1502



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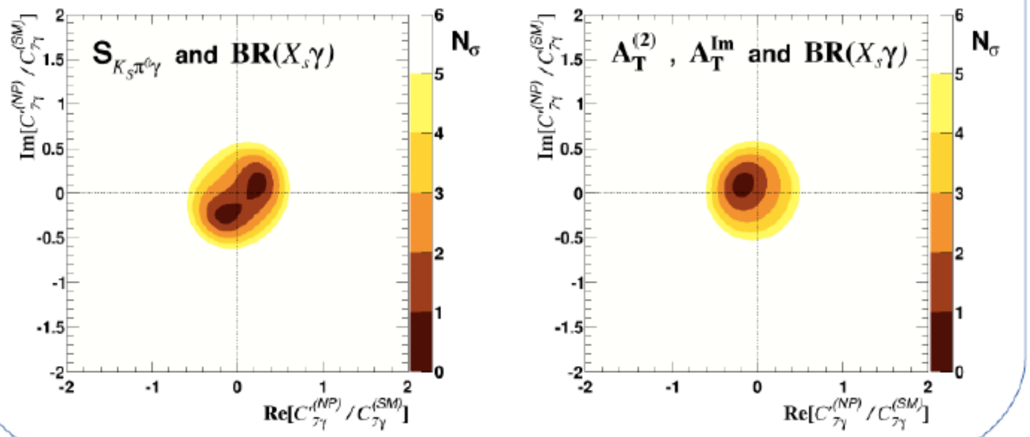
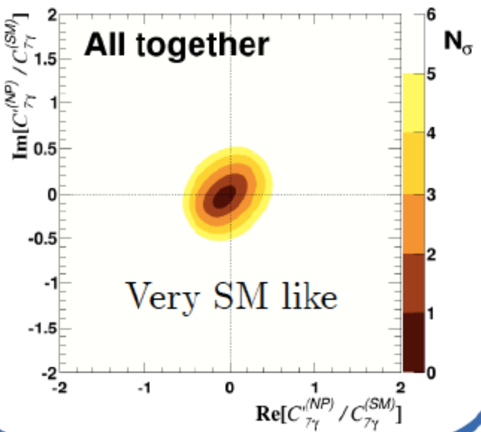
Impact on limit of right handed current(II)

comparison of $S_{K^0_S \pi^0 \gamma}$ and $B^0 \to K^{*0} e^+ e^-$





- **No deviations from SM**
- **New constraint** on C_7'/C_7 complex plane more stringent than the average of time-dependent CP asymmetry in decay $B^0 K^{*0}$ ($\to \pi^0$)γ decays

BaBar PRD78 (2008) 071102, Belle PRD74 (2006) 111104

L - 20/02/2015 - K*ee 14

Conclusions

Conclusion on LHCb:

LHCb has clearly demonstrated the power of hadron collider for b quark and c quark physics

No sure deviation from SM predictions (at the discovery level (5σ)) has been established. An upgrade is planned 2018 allowing a factor of 5-10 in number of events

Will it produce the eagerly awaited signature of "new physics"???

But analysis >2019 not for "ancient physicist" ☺

Remains to thank Yuanning Gao and Tsinghua University for this occasion to plunge back in my past experiments.

It has been a great Pleasure Thank You ALL