LHCb
Search for New Physics at a Hadron B Factory

CERN Colloquium

March 13, 2008

Tatsuya Nakada
CERN and EPFL

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

What is on the moon?

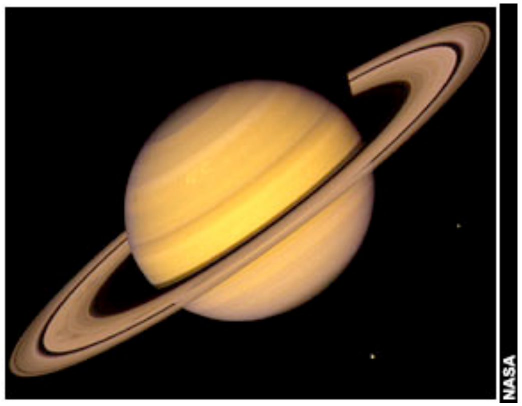
What is on the moon?

Of course going there...

What is on the moon?

Of course going there...

But you can study a lot from here before

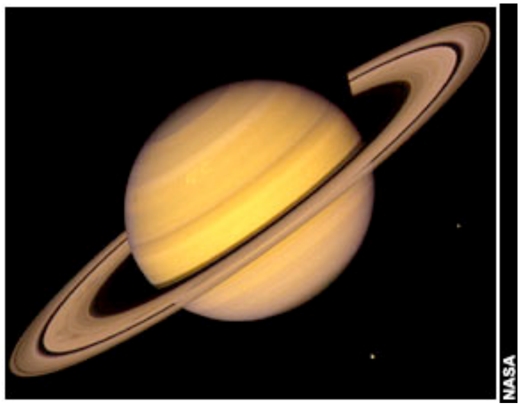


And may be finding something new?

What is on the moon?

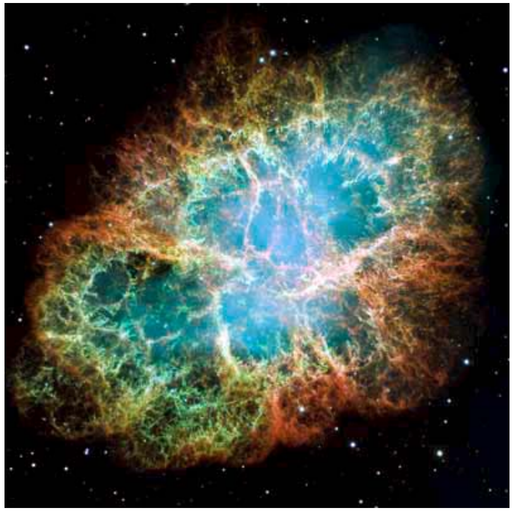
Of course going there...

But you can study a lot from here before



And may be finding something new?

Instruments can be improved and

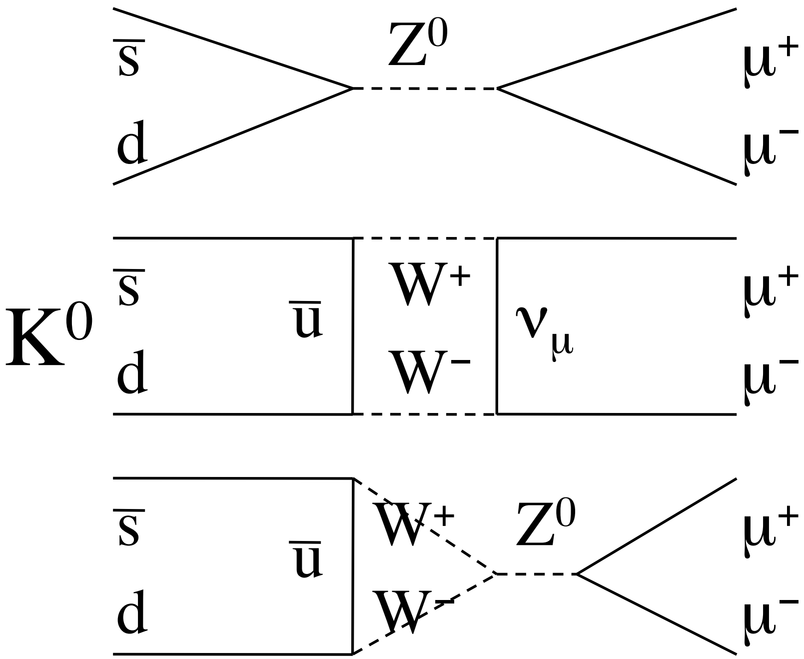


We see far beyond the direct reach...

Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+\mu^-$

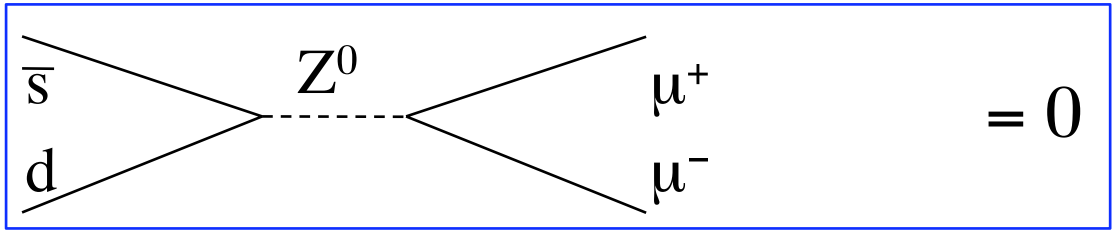


?

Flavour Physics

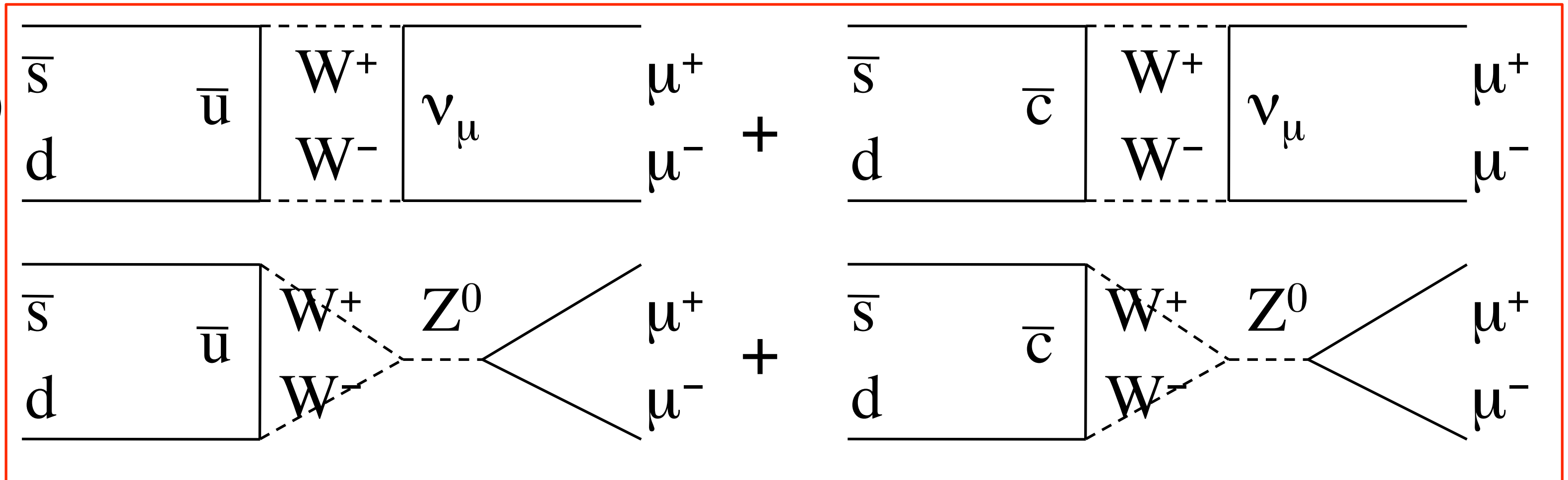
Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)



$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

K^0



$= 0$ if $m_u = m_c$

Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

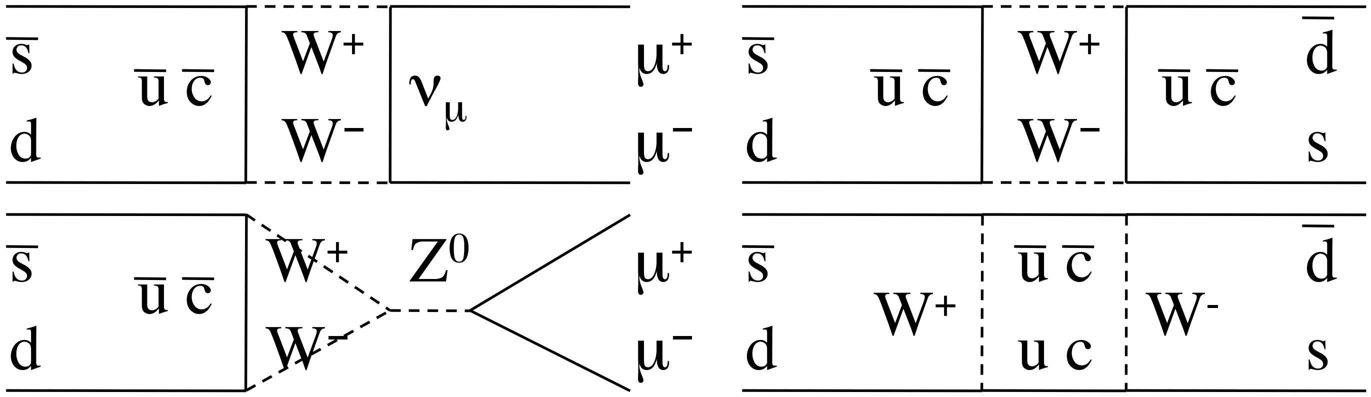
Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$

Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass ~1.5 GeV/c^2



$Br(K^0 \rightarrow \mu^+\mu^-) = F(m_c,\ldots)$ $\Delta m_K = G(m_c,\ldots)$

Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \to \mu^+\mu^-$ ⇒ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \to \mu^+\mu^-)$ ⇒ charm mass

CPV and very suppressed $B \to \mu^+\mu^-$ ⇒ third family

Δm_B ⇒ top mass

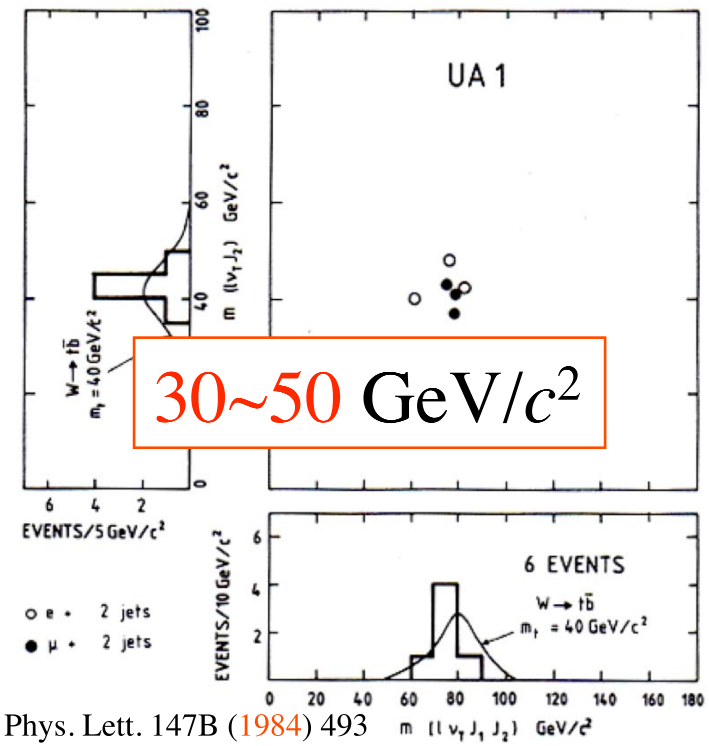
before observing directly c, b or t

History of m_t

UA1, 1984

$W^+ \rightarrow t\,\bar{b}$ → jet

$t \rightarrow b l \nu$, b → jet



30~50 GeV/c^2

Phys. Lett. 147B (1984) 493

History of m_t

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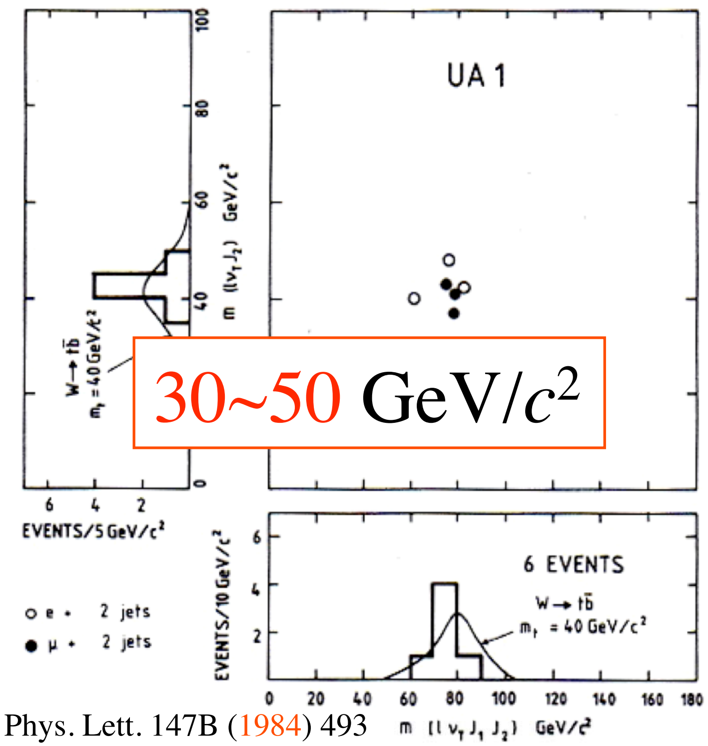


30~50 GeV/c^2

Phys. Lett. 147B (1984) 493

ARGUS, 1987

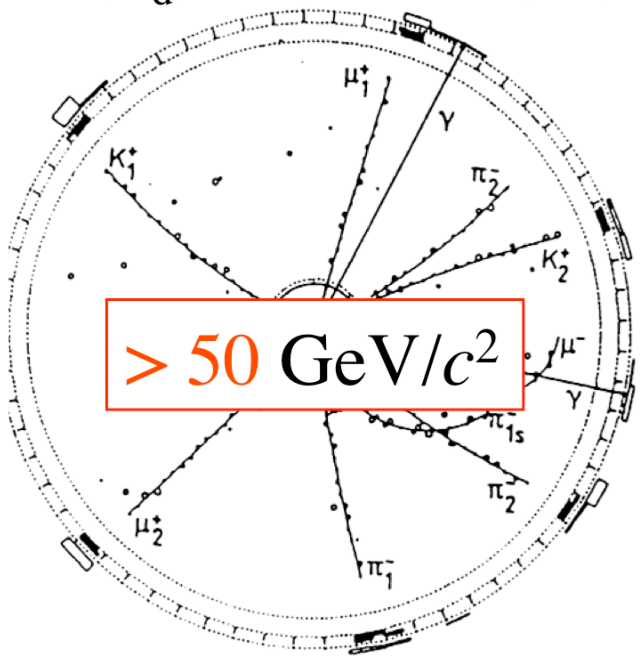
$$\Upsilon(4S) \to B_d^0 \overline{B}_d^0$$

$$\to B_d^0 B_d^0 \text{ or } \overline{B}_d^0 \overline{B}_d^0$$

$$\to \ell^+\ell^+ \text{ or } \ell^-\ell^-$$

24.8±7.6±3.8

$$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$$



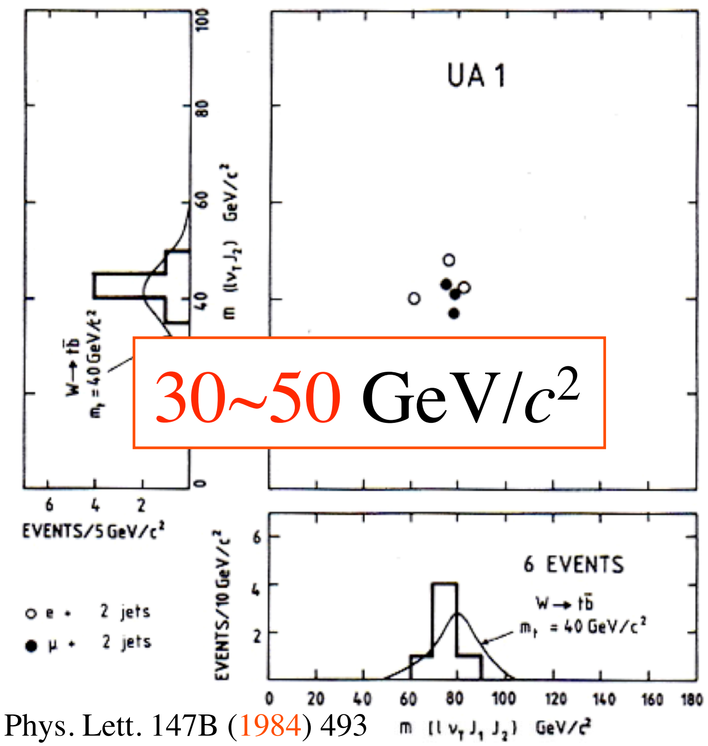
> 50 GeV/c^2

Phys. Lett. B 192 (1987) 245

History of m_t

UA1, 1984

$W^+ \to t\bar{b}$, $\bar{b} \to$ jet, $t \to b l \nu$, $b \to$ jet



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$\Upsilon(4S) \to B_d^0 \overline{B}_d^0$

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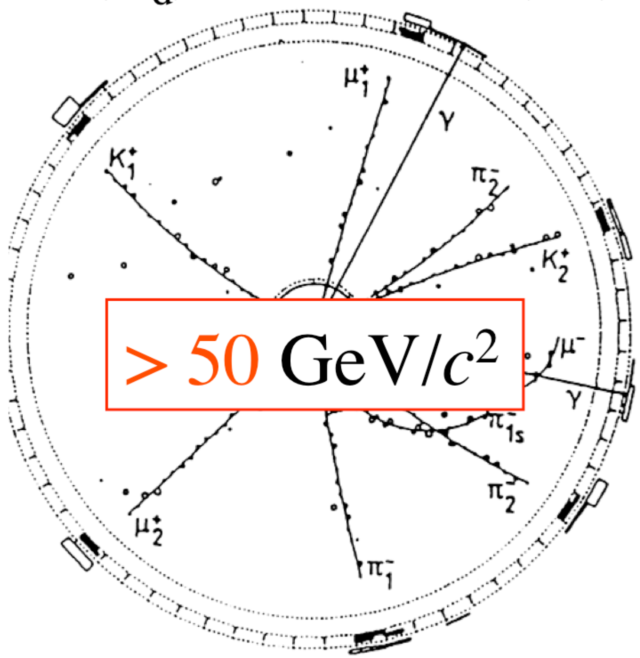


> 50 GeV/c^2

Phys. Lett. B 192 (1987) 245

LEP

electroweak fit

150~210 GeV/c^2

1995

CDF

175±8±10 GeV/c^2

D0

199^{+19}_{-21}±22 GeV/c^2

Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \to \mu^+\mu^-$	$\Rightarrow$ SU(2) doublet structure (GIM)
Δm_K and $Br(K_L \to \mu^+\mu^-)$	$\Rightarrow$ charm mass
CPV and very suppressed $B \to \mu^+\mu^-$	$\Rightarrow$ third family
Δm_B	$\Rightarrow$ top mass
and …	
ν-$\bar{\nu}$ oscillation	$\Rightarrow$ may be heavy neutrinos?

Thoughts on Flavour Physics Experiments

General observation

Hadron machines have been "discovery" machines,
e.g. charm, beauty, W, Z, and top

CP violation in the kaon system mainly studied at hadron machines
plus some contribution from KLOE

Charm mesons have been successfully exploited by
both fixed target hadron beams and e^+e^- storage rings.

Fixed target charm experiments

Important breakthrough in the middle of 80's:
large number of fully reconstructed D mesons
from the hadronic decays

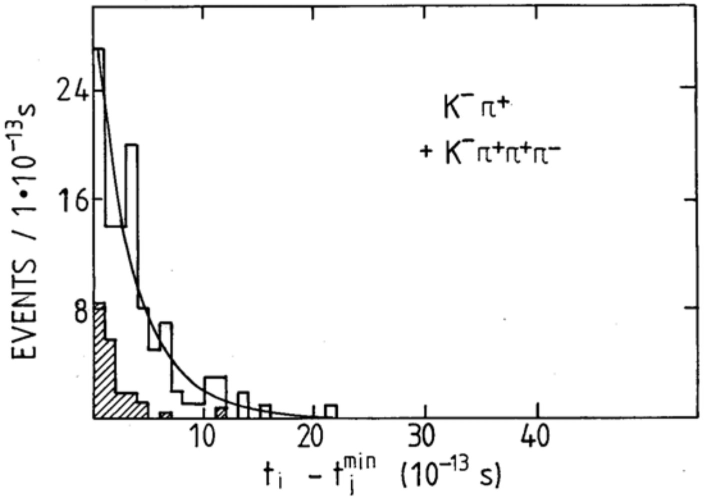
using
Si micro-strip vertex detector and open trigger

$$\frac{\sigma_{c\bar{c}}}{\sigma_{\text{inelastic}}} \approx 10^{-3}$$

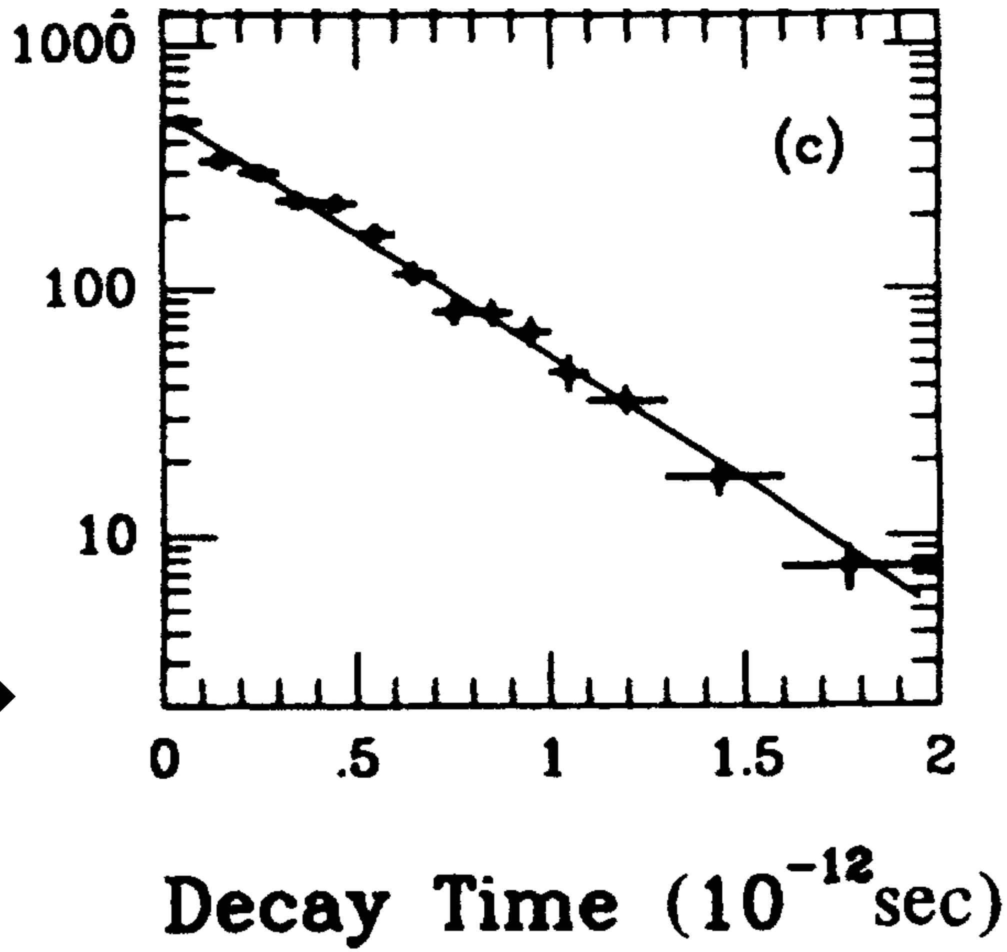
Large amount of data processed by a custom made microprocessor farm

An example: D^0 lifetime

200 GeV/c K and π beam
ACCMOR 1987



Tagged photon beam
E691 1988

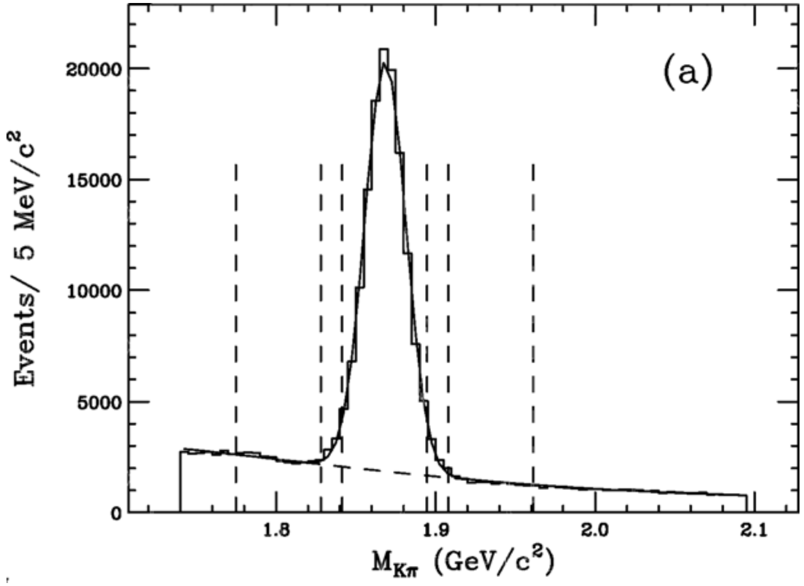


factor ~50 in statistics →

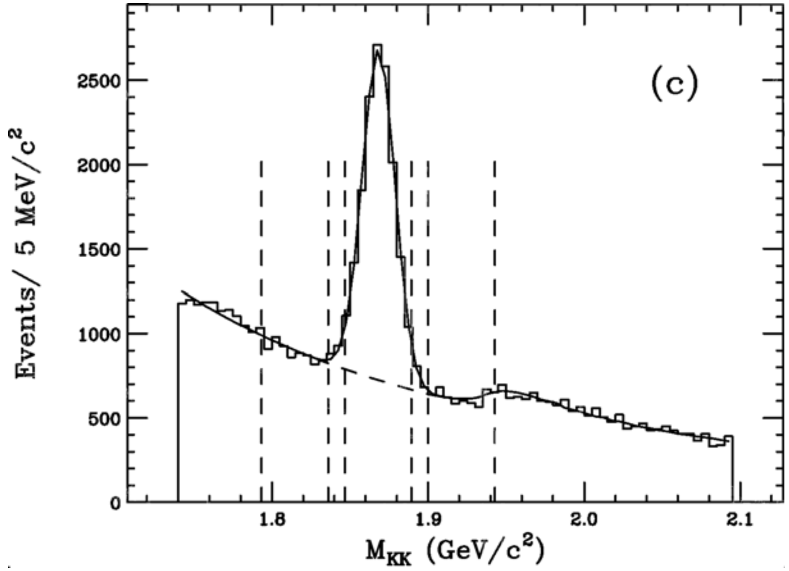
The la(te)st generation of fixed target charm experiments

	beam	statistics	average σ_t
E791	500 GeV π	10^5	40 fs
Focus	up to 300 Gev γ	10^6	30 fs
Selex	600 GeV Σ, π, p	10^4	20 fs

Focus

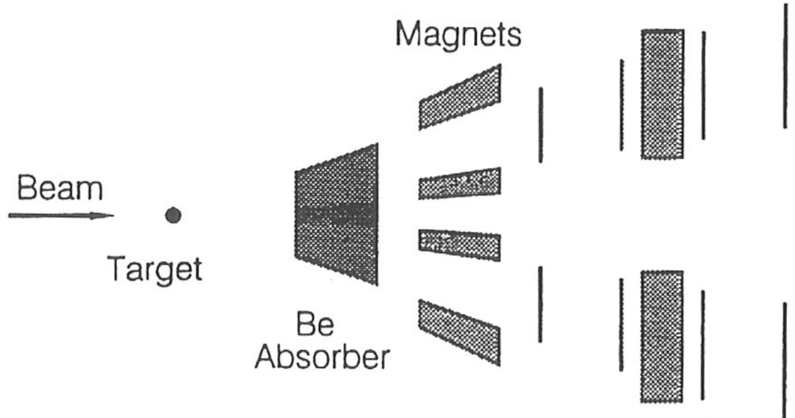


$D^0 \to K^- \pi^-$ 119738 evts

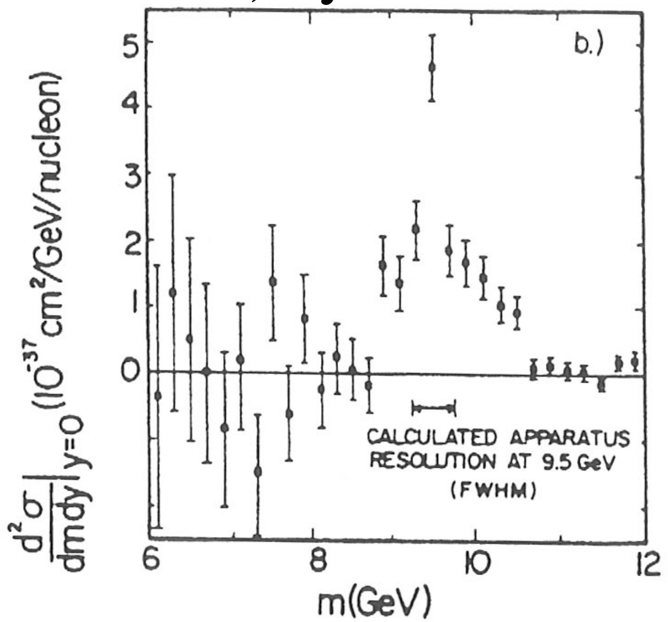


$D^0 \to K^+ K^-$ 10331 evts

After the the discovery of Υ resonances ($\bar{b}b$ S states) by hadron machine



S. Herb et al. in 1977@ FNAL



For many years, B meson study had been dominated by
DORIS, CESR, VEPP and LEP

i.e. at e^+e^- machines

Experiments at hadron machines, fixed target, were "limited"

CERN: Beatrice FNAL:E866/E789/E772, E771

b cross section measurements (with large error bars)

→ simply not enough b's and too small $\sigma_b/\sigma_{inelastic}$

There were some ideas to make B experiments at $p\bar{p}$ colliders

Bjorken at Tevatron

P. Schlein at $Sp\bar{p}S$ and Tevatron

CERN-SPSC/88-33
SPSC/P238
16 January 1989

PROPOSAL to the SPSC

STUDY OF BEAUTY PHYSICS AT THE SPS-COLLIDER
WITH REAL-TIME USE OF SILICON MICROVERTEX INFORMATION

A. Brandt, S. Erhan, D. Lynn, M. Medinnis, P. Schlein*, J. Zweizig
University of California, Los Angeles, U.S.A.

T. Ypsilantis
College de France[1], Paris, France

G. Borreani
University of Ferrara and INFN[2], Italy

M. Calvetti
University of Perugia and INFN[2], Italy

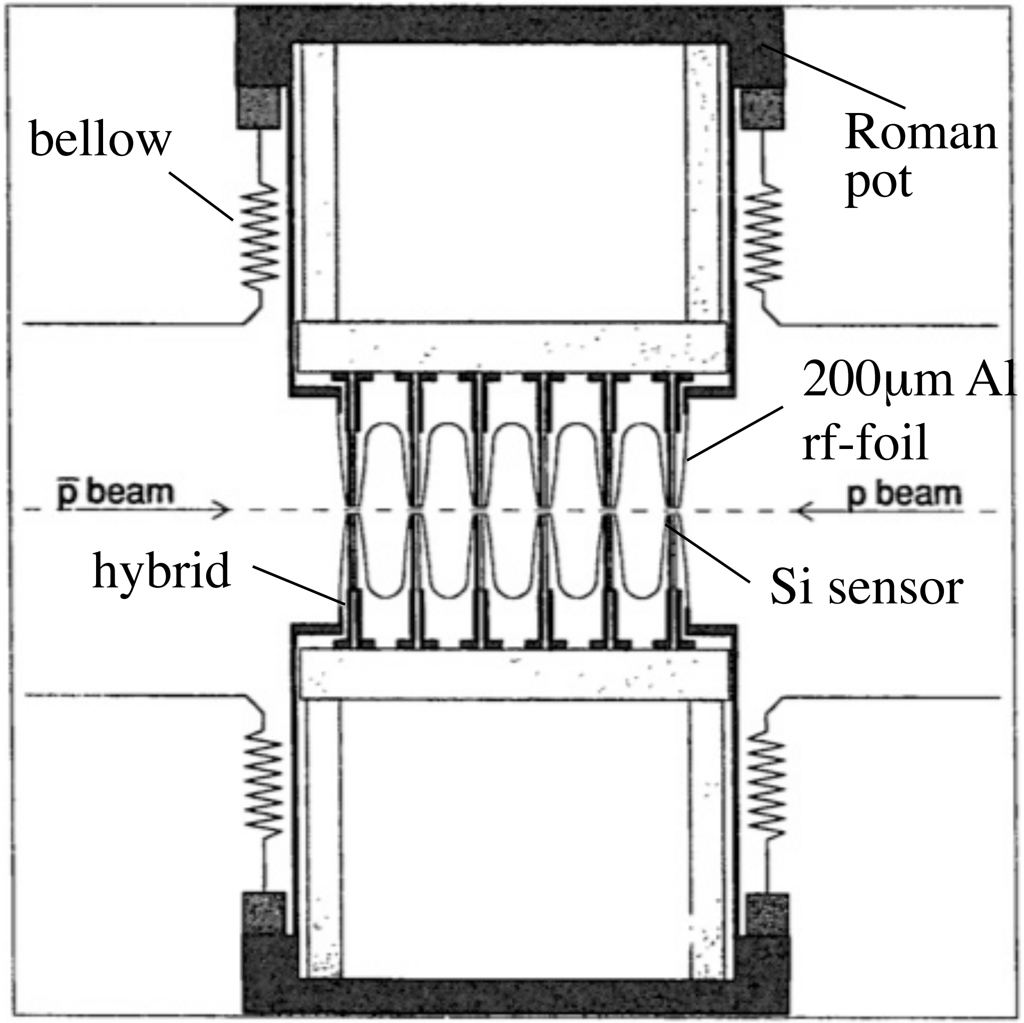
J.B. Cheze, J. Zsembery
Centre d'Etudes Nucleaires – Saclay[3], Gif-sur-Yvette, France

R. Dznelyadin, Y. Guz, V. Kubic, V. Obraztsov, A. Ostankov
IHEP-Serpukhov, Protvino, U.S.S.R.

C. Biino, R. Cester, A. Migliori, R. Mussa, S. Palestini
University of Torino and INFN[2], Italy

Large $b\bar{b}$ cross section
Si vertex detector in
Roman Pot
Forward spectrometer
(forward peaked b production)

Experiment not approved but a test run was made (1990)



NIM A317 (1991)28

rf-foil 1.5 mm from
the beam (15 r.m.s.)
Si sensitive point 3.1 mm

DELPHI single sided
silicon μ-strip
detector + SVX chip

Beam position fill to fill variation
less than 100μm

Vacuum
5×10^{-4} mb inside the rf-boxes
5×10^{-10} mb in the machine

A very clean running condition was observed, a pioneering work!

at CERN Sp$\overline{\text{p}}$S, 630 GeV, $L = 3\times10^{30}$ cm^{-2}s^{-1}

In the mean time, many ideas to build an e^+e^- B meson "factory" at $\Upsilon(4S)$, starting with SIN in 1986 double ring with $L > 5\times10^{32}\ \mathrm{cm^{-2}s^{-1}}$, symmetric energy
Upgraded to PSI Proposal (1988)
$L > 10^{33}\ \mathrm{cm^{-2}s^{-1}}$
with modest asymmetric energy option

PR-86-13

Motivation and Design Study
for a B-Meson Factory with High Luminosity

R.Eichler[1], T.Nakada[2], K.R.Schubert[3], S.Weseler[3], and K.Wille[4]

1) Institut für Mittelenergiephysik, ETH Zürich
c/o SIN, CH-5234 Villigen, Switzerland
2) Schweizerisches Institut für Nuklearforschung (SIN)
CH-5234 Villigen, Switzerland
3) Institut für Hochenergiephysik, Universität Heidelberg
D-6900 Heidelberg, Germany
4) Institut für Physik, Universität Dortmund
D-4600 Dortmund, Germany

November 24, 1986

Swiss Institute
for Nuclear Research

CH-5234 Villigen
Switzerland

Discovery of B-$\overline{\mathrm{B}}$ mixing in 1887 made it possible to make a SM prediction for CPV for $B\rightarrow J/\psi K_S$ without knowing m_t: ~0.4 i.e. "large" (NB f_B = 110 MeV in those days)

Z. Phys. C 36 (1987) 503

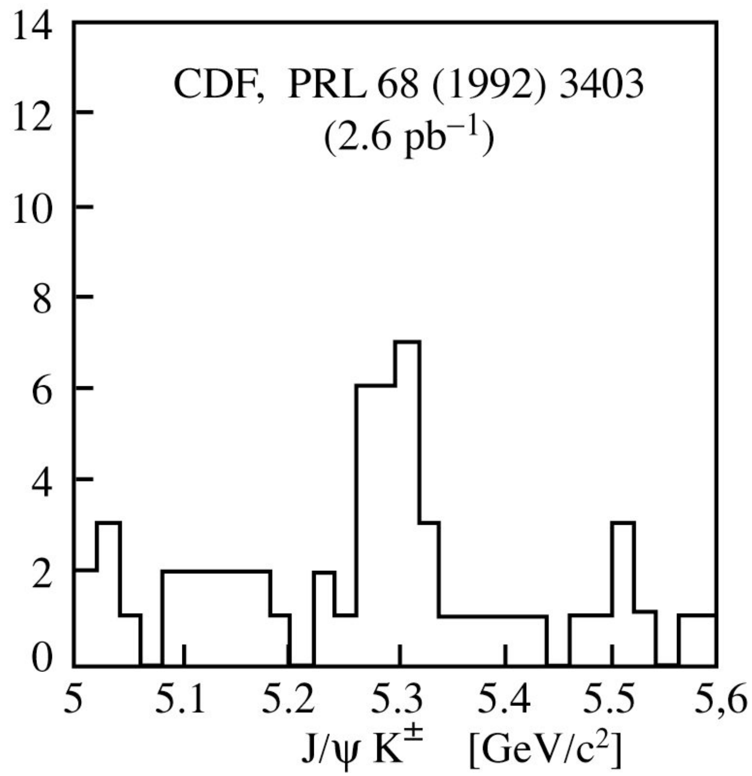
➜a concrete minimum "luminosity requirement"
i.e. $>10^{33}\ \mathrm{cm^{-2}s^{-1}}$

Many B factory ideas emerged:
SLAC, DESY, Cornell, KEK, Novosibirsk, Italy, UCLA and CERN
from standard storage rings with symmetric energy, with different energy asymmetries, linear collider, and to linear against circular…

European option has died with CERN-ISR option in 1990
CERN-YELLOW-90-02
→No European B opportunity except LEP running at Z^0

In US: competition between Cornell and SLAC
In Japan: water was slowly boiling

Then



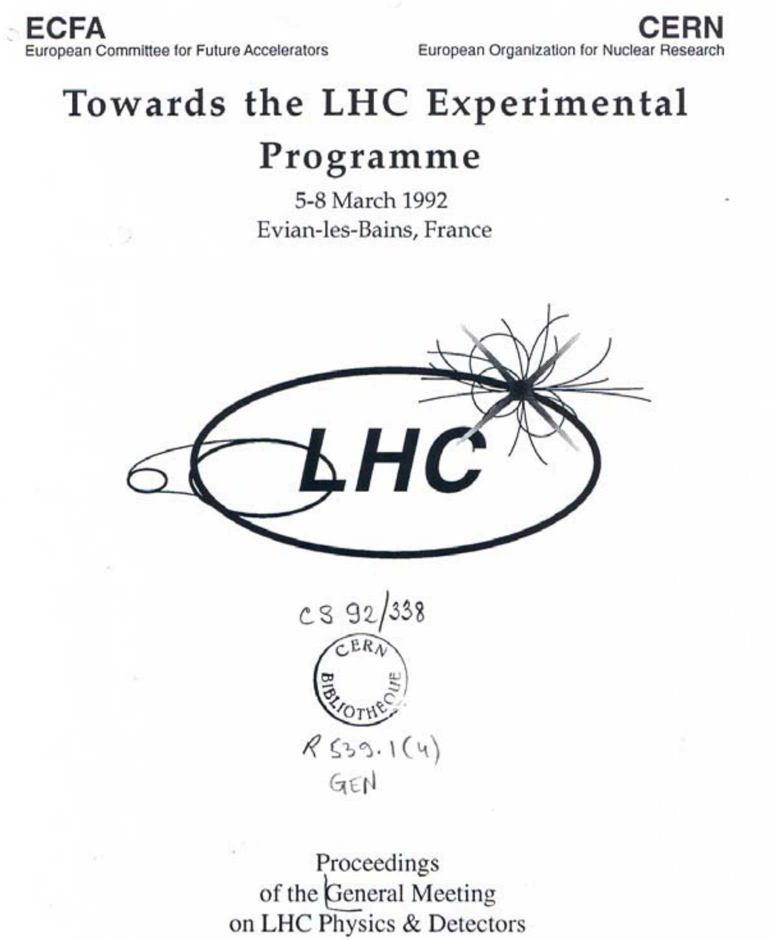
First fully reconstructed B meson at a hadron machine!
(largest number of reconstructed $B^{\pm} \to J/\psi K^{\pm}$ at that time)

B physics with a hadron machine at high energy looks feasible!

D0 and CDF then contributed a lot in lifetimes, CPV, and oscillations. (B_s oscillation measurement is still unique)

Back to the European Front

Evian workshop 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

Proceedings
of the General Meeting
on LHC Physics & Detectors

NB: Approval of B factories at KEK and SLAC in 1993
Starting of data taking in 2000

Table of Contents

General purpose high p_T experiments

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 $\rightarrow J/\psi K_S$, $\rightarrow \pi\pi$, 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

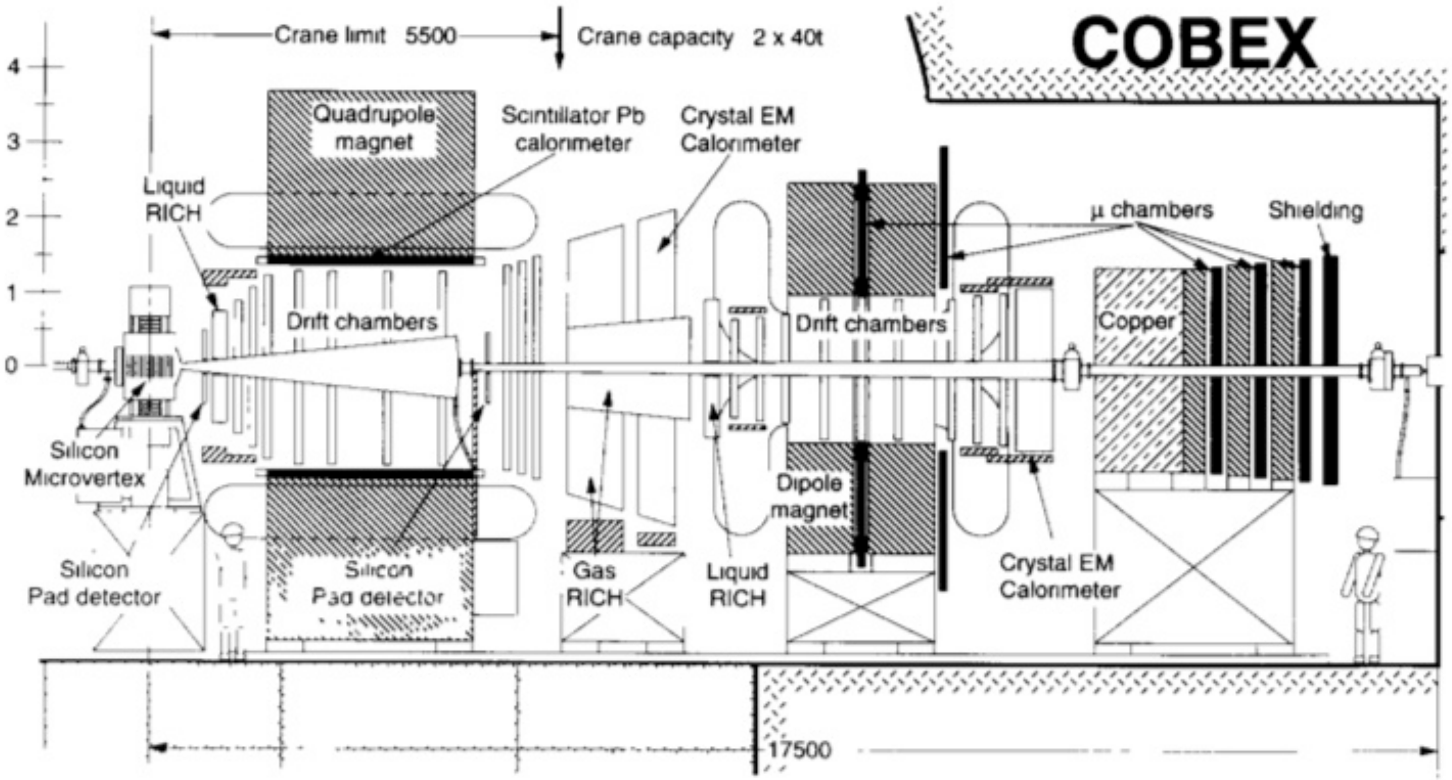
Followed by three LoI's in 1993

COBEX

vertex and tracking detector, two magnets, RICH, E-cal, muon

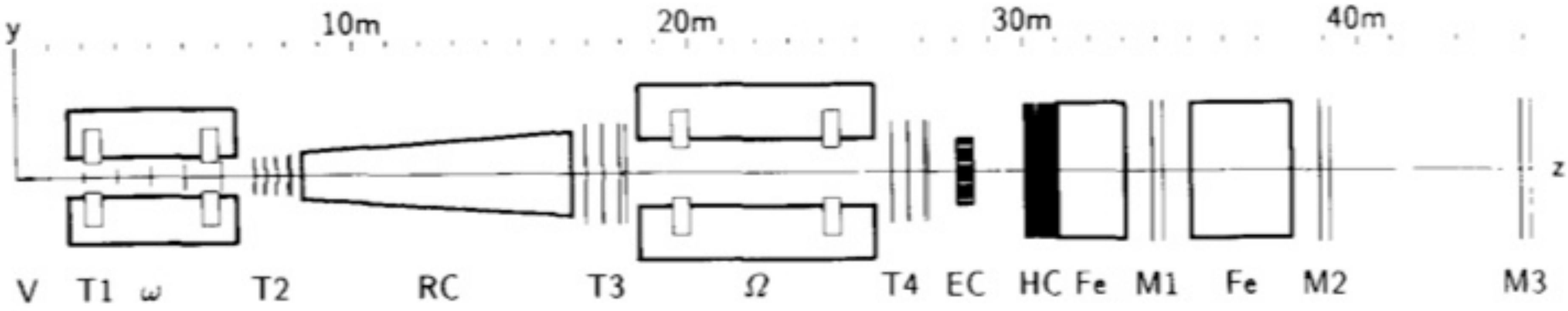
first level topology trigger at low L and μ p_T trigger at high L

☺large √s → large bb cross section



LHB

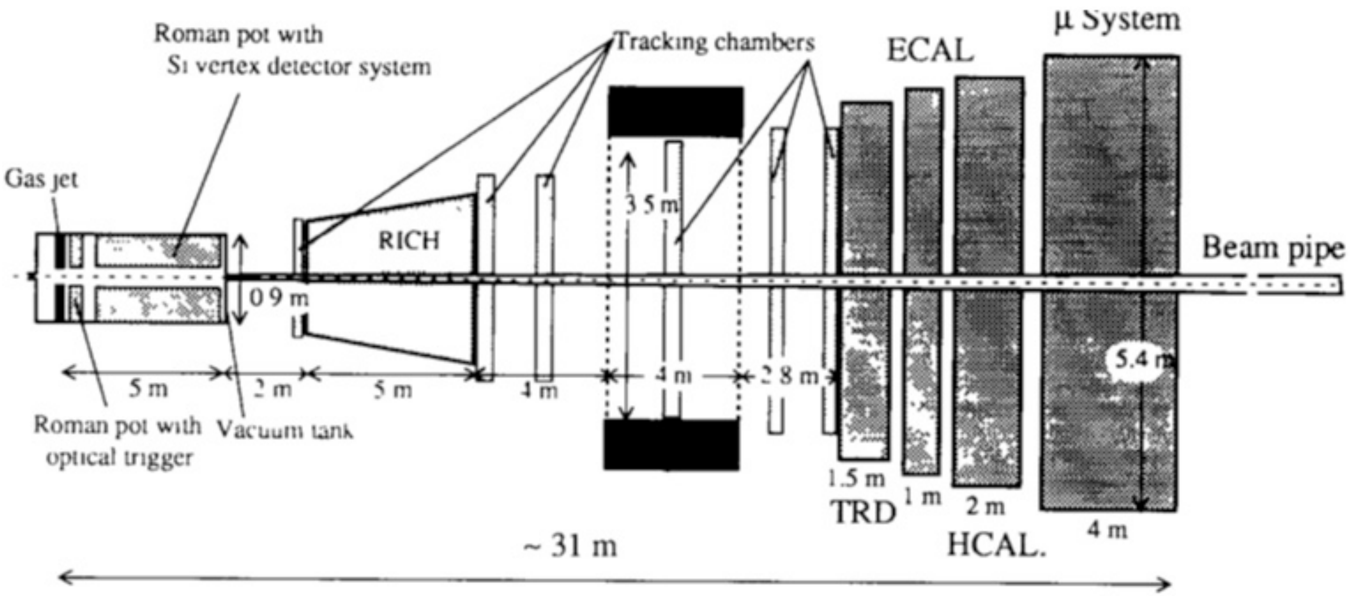
vertex and tracking detector, two magnets, RICH, E+H-cal, muon
first level lepton (μ and e) p_T trigger
☺large boost → charged Bs are visible in the vertex detector ($B^+ \to \tau\nu$)



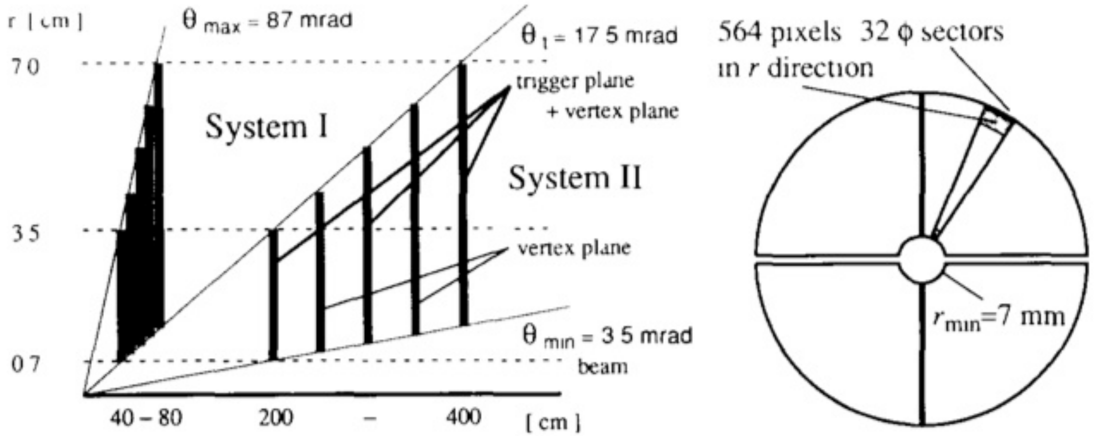
protons are extracted from the beam halo using a bent crystal
dedicated experimental area, i.e. more flexibility

GAJET

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



r-φ striplets
vertex detector



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

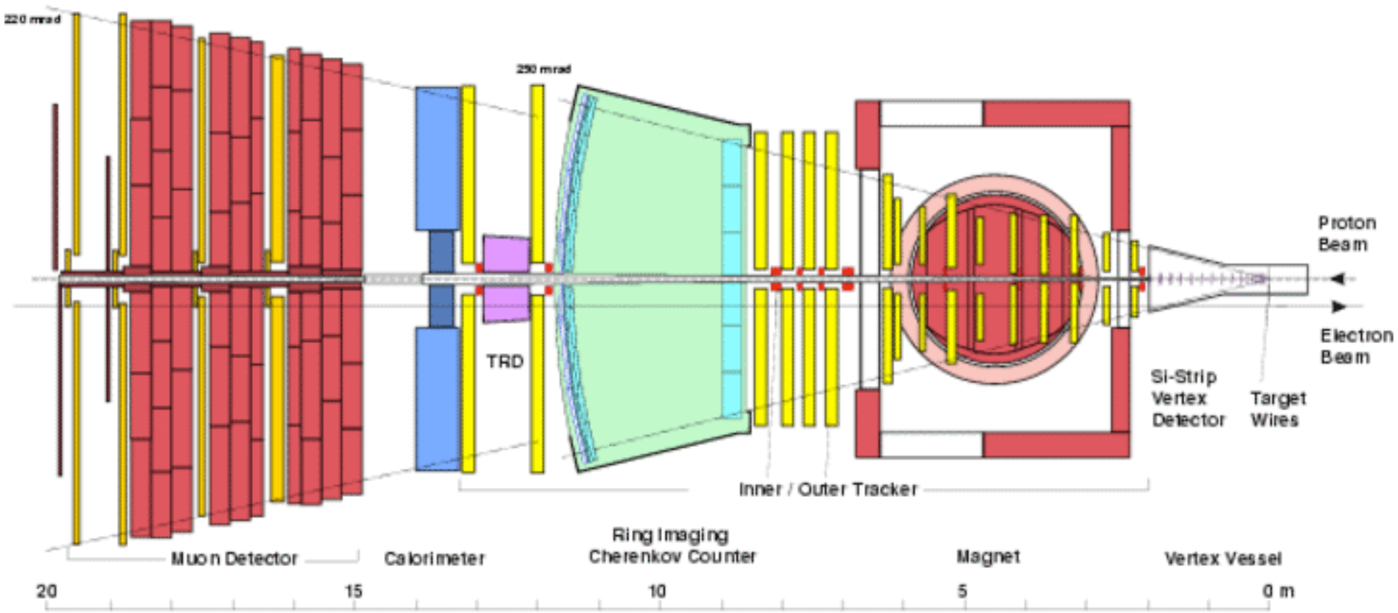
Decided not to approve any of the three experiments but to form one new collaboration to propose a new experiment based on the collider mode to exploit its large $b\bar{b}$ cross section with a convincing trigger strategy.

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

1) B-factories and Tevatron are doing well
2) LHC is (much) later than originally thought

HERA-B remark

ARGUS group at DESY started to think about a fixed target experiment using HERA proton ring (920 GeV/c) and internal wire targets around the time of Evian workshop in 1992.



Approved in 1994 to compete with B-factories with $\sigma(\sin 2\beta) = 0.13\ y^{-1}$
Physics data taking started in 2001. Physics paper on production cross sections, but not CPV…

It was a quite tough job: $\sigma_b / \sigma_{total} \sim 10^{-6}$

Advantage of the LHC collider mode

Large b cross section (~500μb)

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

at fixed target energies 10^{-6}

$\approx \sigma_{c\bar{c}} / \sigma_{inelastic}$ at fixed target energies

Different b-hadrons (B_u, B_d, B_s, B_c, Λ_b, Σ_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

is 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

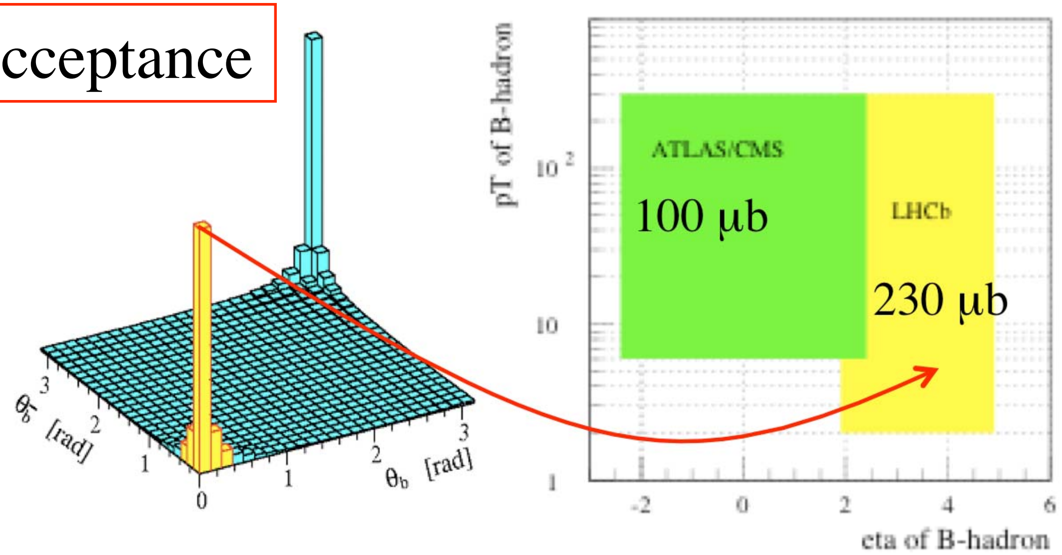
- semi-exclusive partial reconstruction

Finally

- exclusive reconstruction

A reminder of the forward geometry

Acceptance



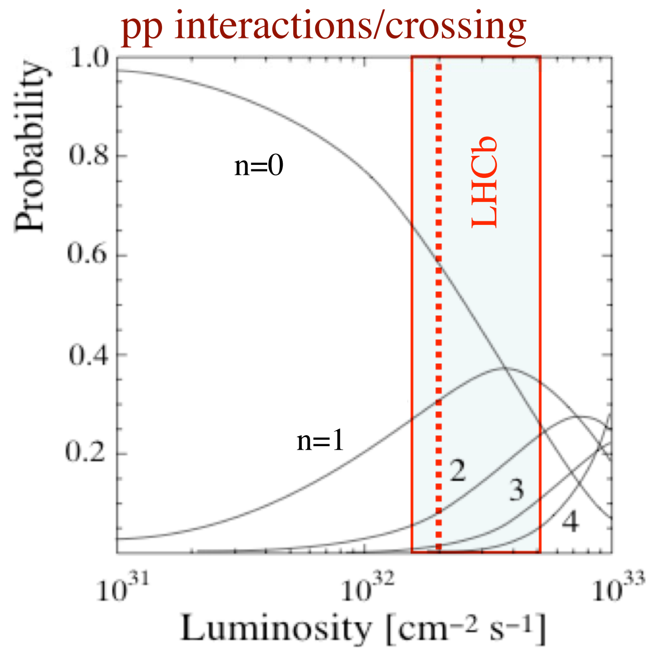
p_T threshold for calo- and μ-trigger can be set to few GeV/c for high b efficiency

Luminosity requirements

L tuneable by adjusting final beam focusing

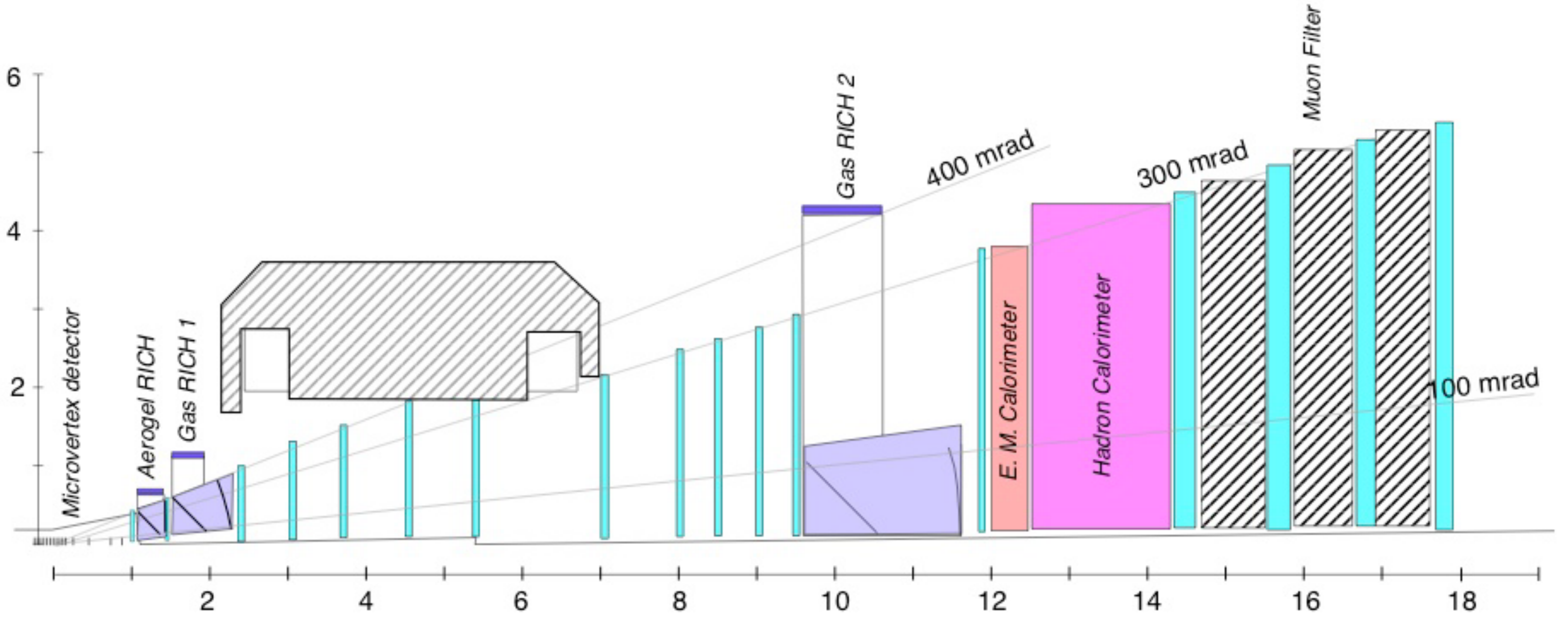
Choose $\langle L \rangle \sim 2\times10^{32}\ \mathrm{cm^{-2}s^{-1}}$ (max. $\sim5\times10^{32}$)

- Clean environment: $\langle n \rangle \approx 0.5$
- 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	L-1 p_T	200 KHz
warm magnet	L-2 tracking + vertex	10 kHz
three RICH's (aerogel + 2-gas) with HPD's	L-3 full reconstruction	

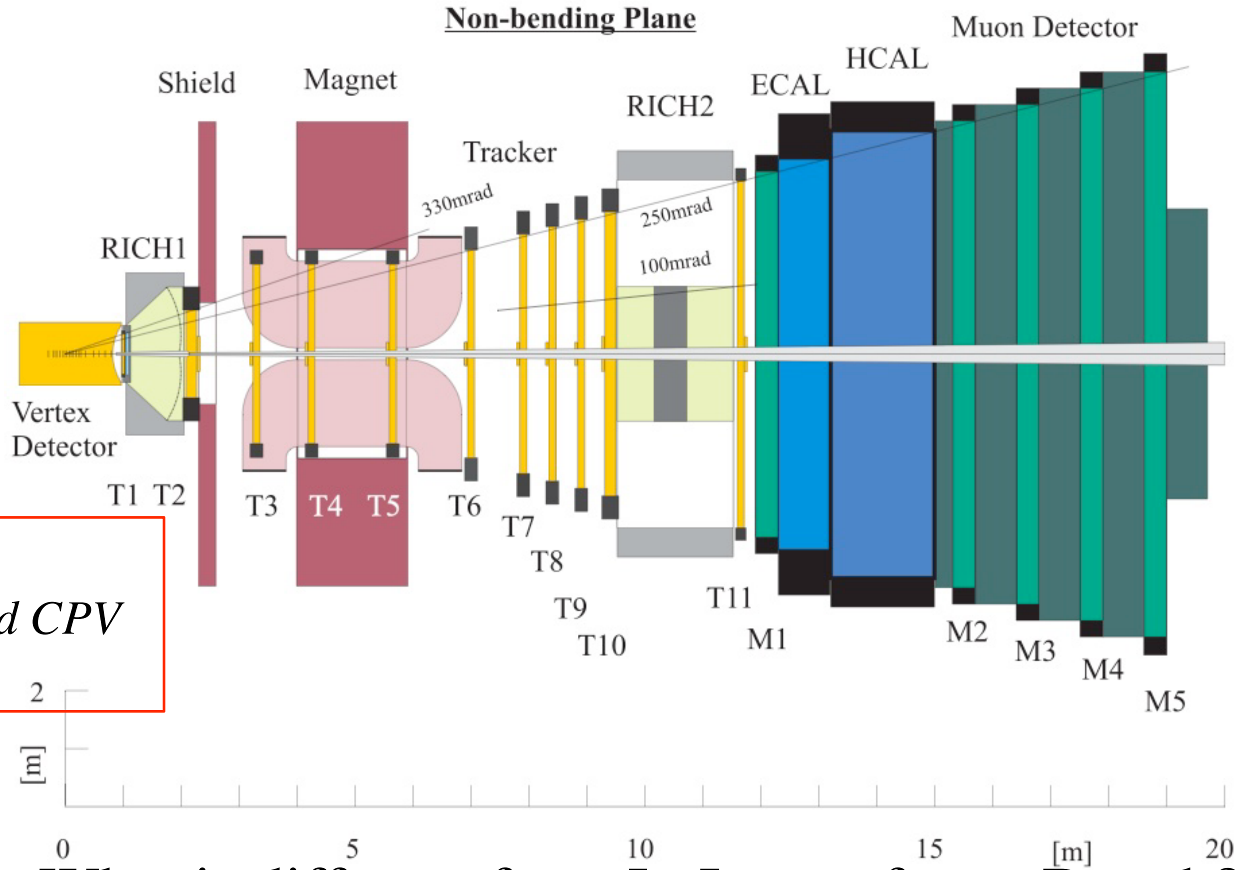
HERA-B tracking system

Pre-shower, Shashlik+$PbWO_4$, Fe-Tilecal+Quarz-W

CSC or Honeycomb or drift tube muon system

RICH and HPD design
T. Ypsilantis

Technical Proposal for LHCb, February 1998



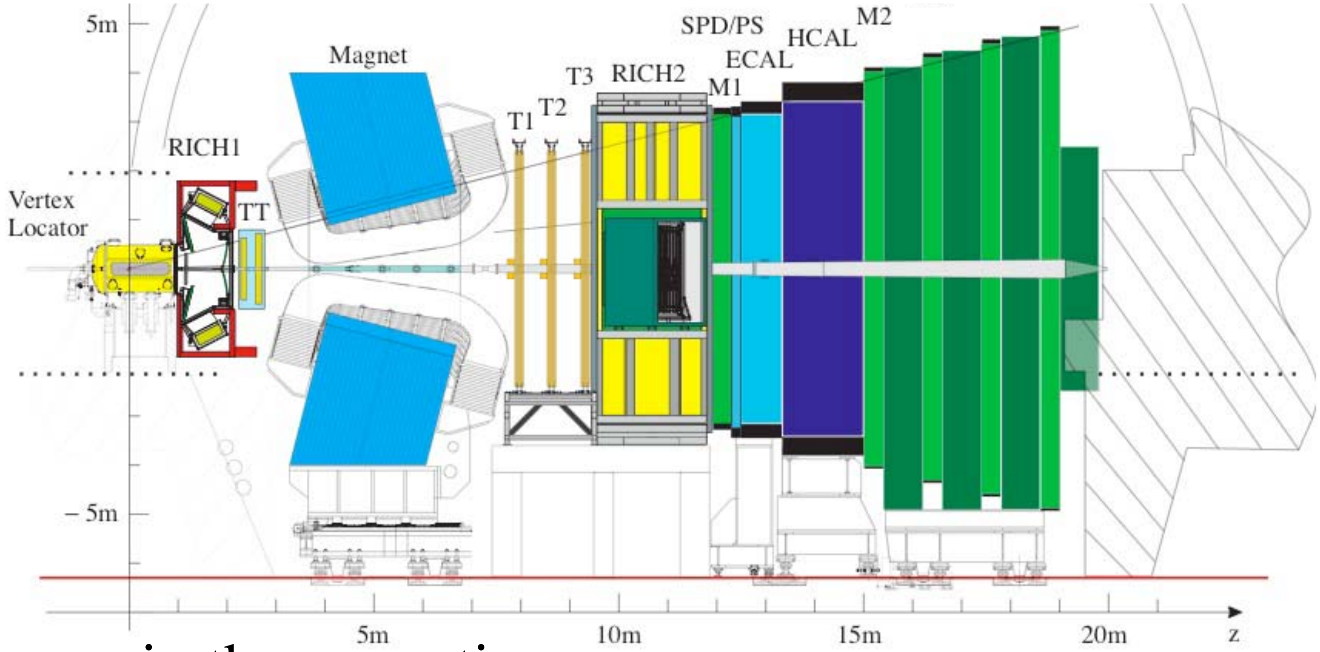
Outer Tracker
B_s oscillations and CPV
W. Ruckstuhl

What is different from LoI apart from -B → b?

Super conductive magnet
r-ϕ strip Si vertex detector
Two RICH's (still three radiators)
No inner-part of calorimeters
MRPC+MWPC muon system

L-0 p_T	1 MHz
L-1 tracking + vertex	40 kHz
L-2 vertex with p	5 kHz
L-3 full reconstruction	200 Hz

Reoptimization TDR for LHCb, September 2003



Many changes in the mean time
Be conical beam pipe
Normal conductive magnet
All MWPC (with a little GEM) muon system
Straw chamber + Si tracking system
Greatly reduced tracking stations (nothing in the magnet)
All Si first tracking station
Two level trigger (1 MHz full readout after the first level to CPU farm)

Changes were motivated by:

budgetary constraint (financial and material)

technical feasibility

physics flexibility

After TP, B physics has evolved a lot: major ones are…

CPV in $B_d \rightarrow J/\psi K_{S,L}$ measured with $\sigma \approx 0.026$

$\gamma(\phi_3)$ measured with $\sigma \approx 25°$

B_s-$\overline{B}_s$ oscillation frequency measured, better than one needs

i.e. KM model for CPV is now quantitatively tested

No major improvement of the B factory results expected from now on

-BABAR end of run in April, Belle in 1~2 years-

Emphasis on the LHCb physics goal is shifting from

Confirmation of CKM → Search for new physics

Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \to \mu^+\mu^-$

CPV in $B_s \to J/\psi\phi$

overtake Tevatron after several months and down to the SM level in ~one year

Probing Flavour Changing Neutral Current $b \to s$: deviation in

Phase = CP violation $B_s \to \phi\phi$ — improvement over B factory ϕK_S

Lorentz structure = angular distribution or γ polarization

$B_d \to K^{*0}\mu^+\mu^-$ — far larger statistics than B factory

CPV in $B_s \to \phi\gamma$ — improvement over B factory $K^*(K_S\pi^0)\gamma$

from Standard Model predictions

FCN current in "up" type quark: NP effect different from "down" type

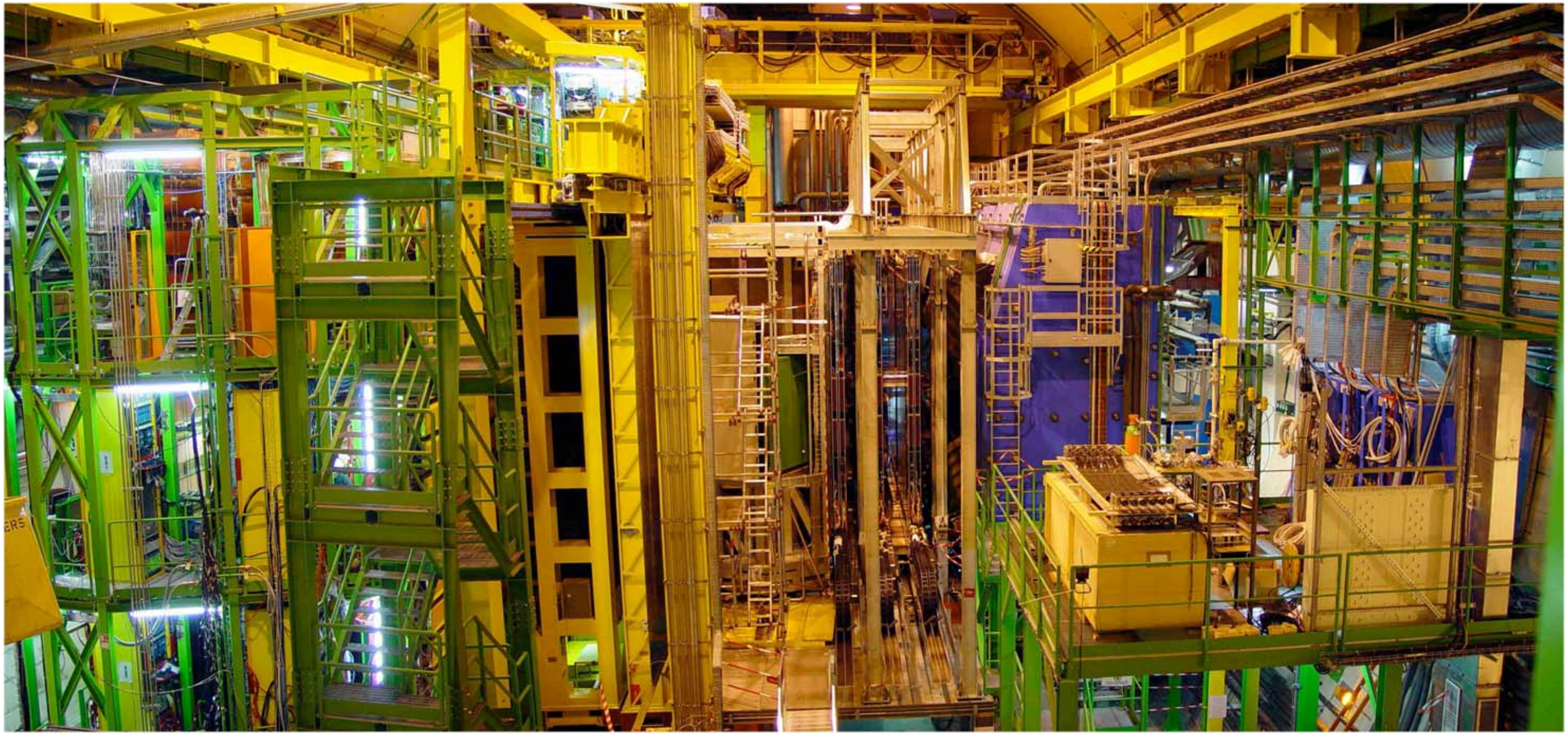
D: oscillations and CP violation down to the level of SM

much larger statistics than B factory

γ from tree (only SM) and from tree + penguin (SM+NP): $\sigma_\gamma \approx 3°$

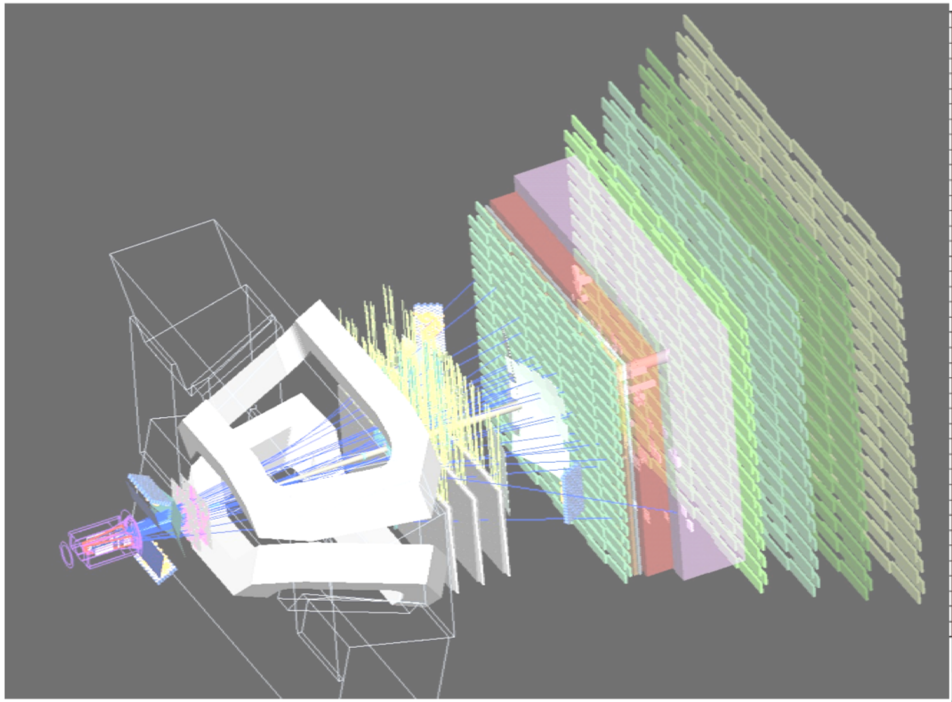
much larger statistics than B factory

LHCb now close to being ready for physics

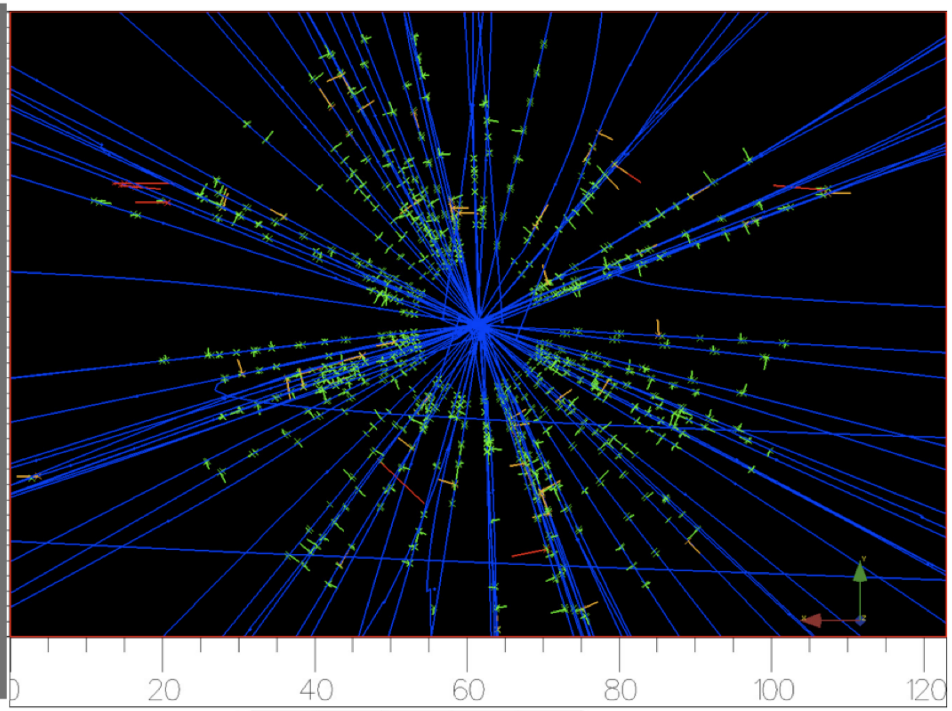


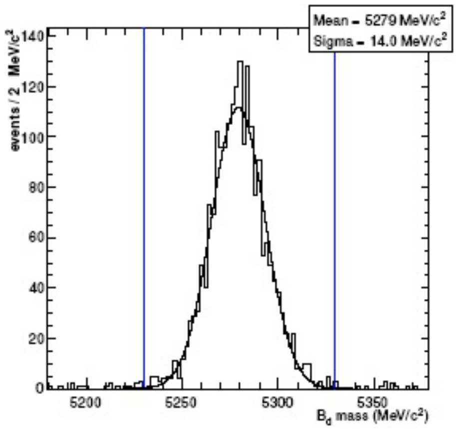
A lot of Monte Carlo events were

generated

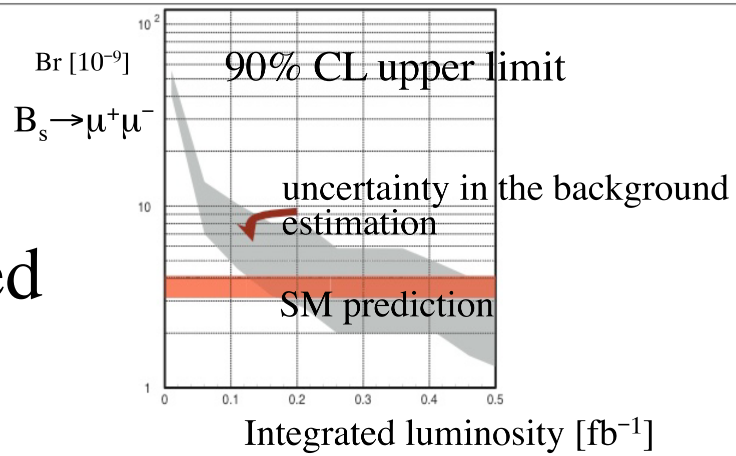


reconstructed

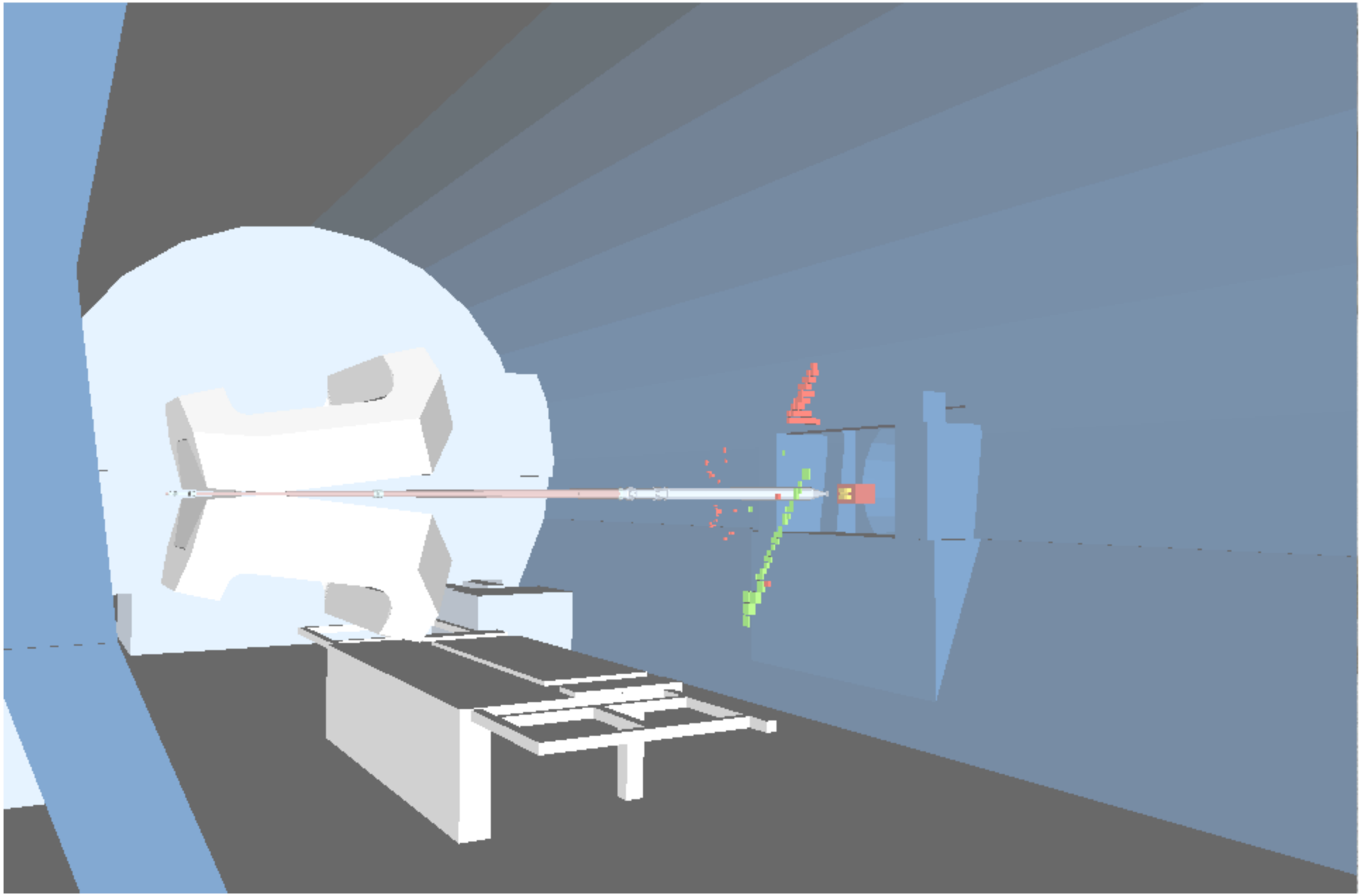




and analysed



Now we also have "properly" triggered cosmic events



going through E-cal and H-cal

We are looking forward to see XX TeV pp collisions in our detector very soon!

Followed by finding out which one of the following excitements we will have:

In 2014 at LHC

ATLAS CMS high p_T physics
LHCb flavour physics
Particle Physics

In 2014 at LHC

ATLAS CMS high p_T physics	BSM
LHCb flavour physics	Only SM
Particle Physics	☺

In 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM
LHCb flavour physics	Only SM	BSM
Particle Physics	☺	☺

In 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

In 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Oh, no more space left…