Heavy Flavors III

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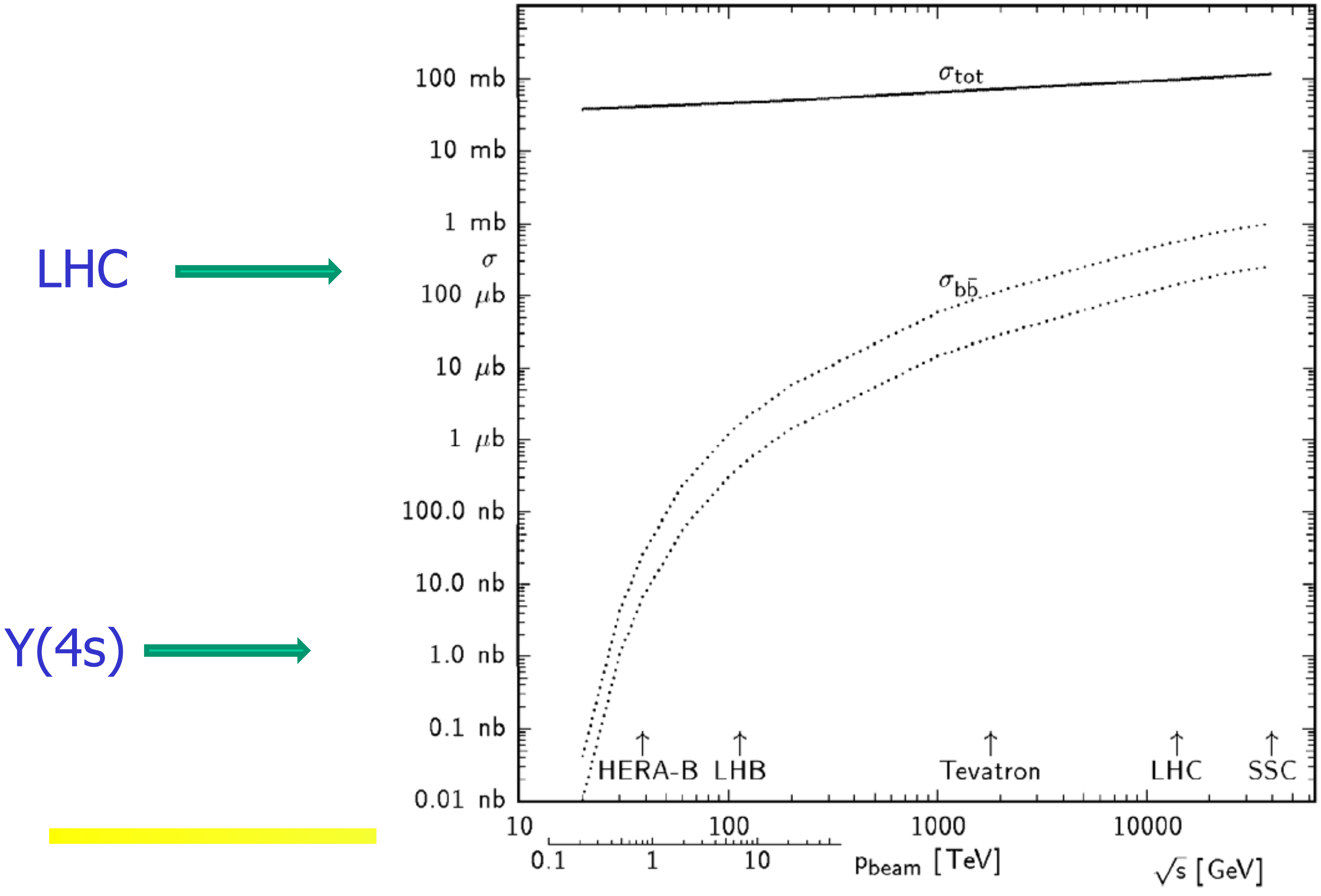
Contents, this lecture

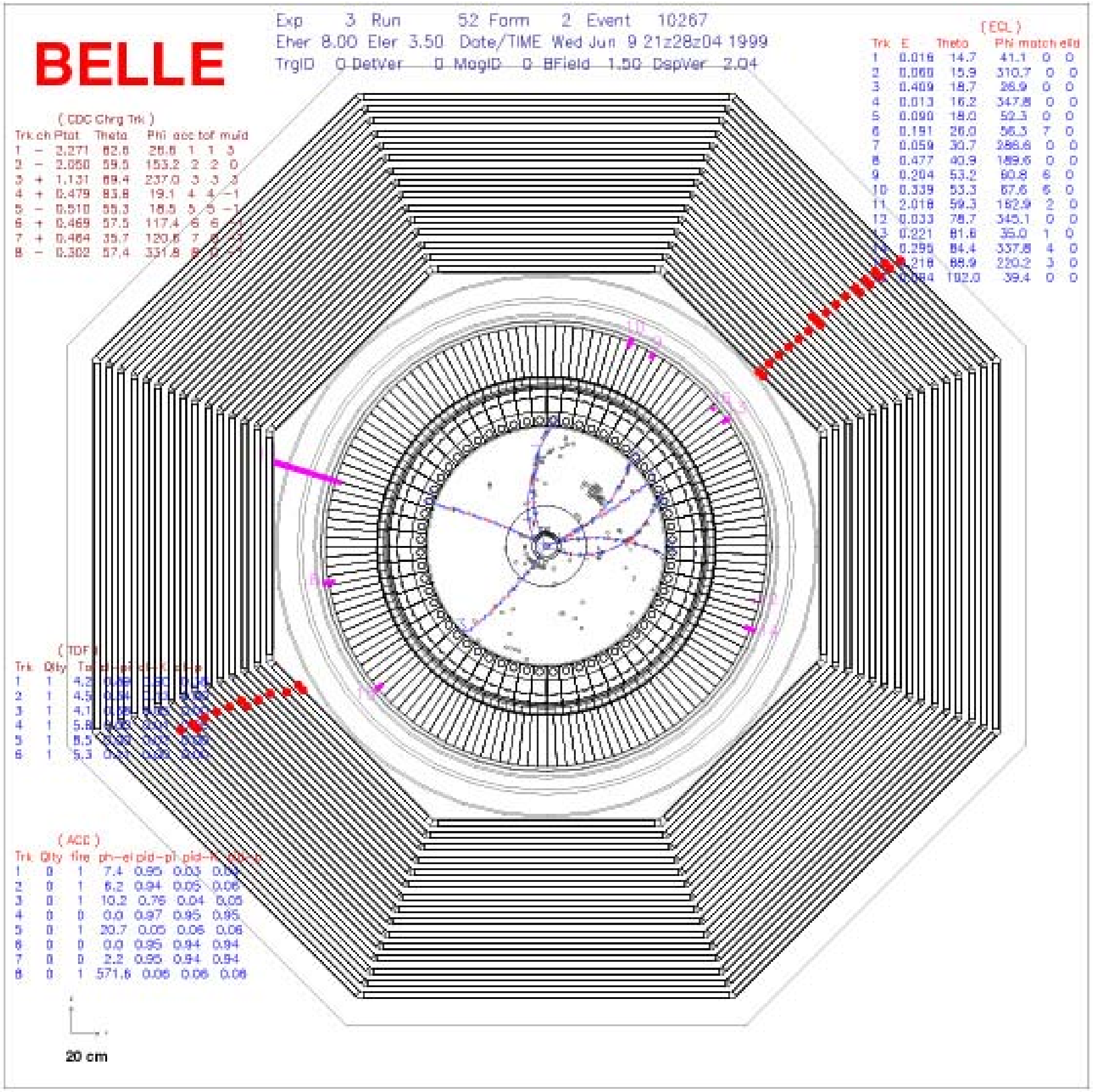
- Flavor physics: introduction, with a little bit of history
- Flavor physics at B factories: CP violation
- Flavor physics at B factories: rare decays and searches for NP effects
- Super B factory
- **Flavor physics at hadron machines: history, LHCb and LHCb upgrade**

Why hadron machines?

- large bb production rates - compare to 1.1nb at Y(4s)
- large boosts → $\langle L \rangle = \langle \beta\gamma \rangle$ 480 μm
- in addition to B^0/B^{+-} also B_s, B_c, Λ_b,..



bb events at e^+e^- machines: BELLE



Exp 3 Run 52 Form 2 Event 10267
Eher 8.00 Eler 3.50 Date/TIME Wed Jun 9 21z28z04 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 2.04

(CDC Chrg Trk)

Trk	ch	Ptot	Theta	Phi	acc	tof	muid
1	−	2.271	82.8	28.8	1	1	3
2	−	2.050	59.5	153.2	2	2	0
3	+	1.131	89.4	237.0	3	3	3
4	+	0.479	83.8	19.1	4	4	−1
5	−	0.510	55.3	18.5	5	5	−1
6	+	0.469	57.5	117.4	6	6	[illegible]
7	+	0.464	35.7	120.6	7	[illegible]	[illegible]
8	−	0.302	57.4	331.8	8	[illegible]	[illegible]

(ECL)

Trk	E	Theta	Phi	match	eid
1	0.016	14.7	41.1	0	0
2	0.060	15.9	310.7	0	0
3	0.409	18.7	26.9	0	0
4	0.013	16.2	347.8	0	0
5	0.090	18.0	52.3	0	0
6	0.191	26.0	56.3	7	0
7	0.059	30.7	286.6	0	0
8	0.477	40.9	189.6	0	0
9	0.204	53.2	60.8	6	0
10	0.339	53.3	67.6	6	0
11	2.018	59.3	182.9	2	0
12	0.033	78.7	345.1	0	0
13	0.221	81.6	35.0	1	0
[illegible]	0.295	84.4	337.8	4	0
[illegible]	[illegible]	88.9	220.2	3	0
[illegible]	[illegible]	102.0	39.4	0	0

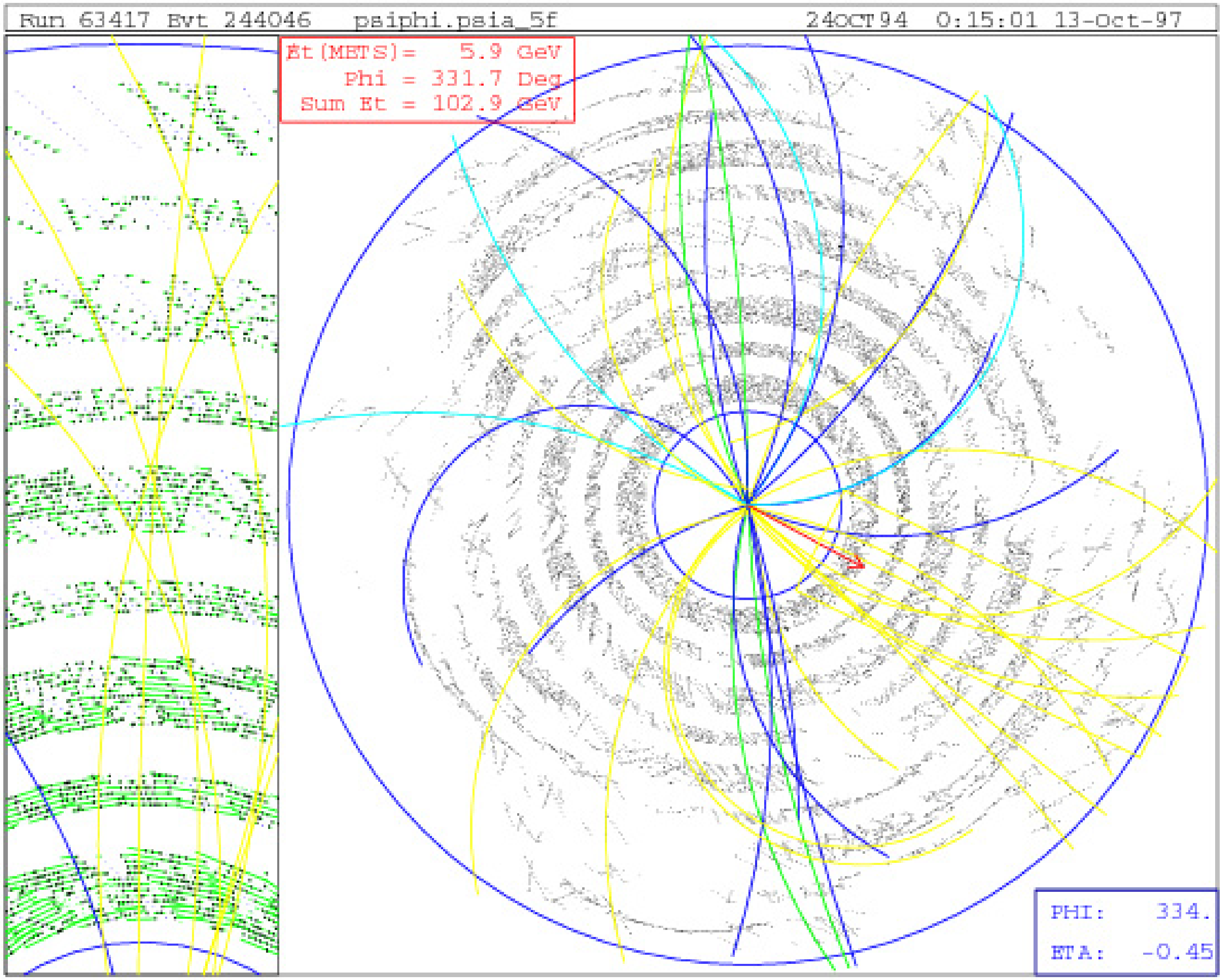
(TOF)

Trk	Qlty	[illegible]	[illegible]	[illegible]	[illegible]
1	1	4.2	[illegible]	[illegible]	[illegible]
2	1	4.5	[illegible]	[illegible]	[illegible]
3	1	4.1	[illegible]	[illegible]	[illegible]
4	1	5.8	[illegible]	[illegible]	[illegible]
5	1	6.5	[illegible]	[illegible]	[illegible]
6	1	5.3	[illegible]	[illegible]	[illegible]

(ACC)

Trk	Qlty	fire	ph-el	pid-pi	pid-K	[illegible]
1	0	1	7.4	0.95	0.03	0.04
2	0	1	6.2	0.94	0.05	0.06
3	0	1	10.2	0.76	0.04	0.05
4	0	0	0.0	0.97	0.95	0.95
5	0	1	20.7	0.05	0.06	0.06
6	0	0	0.0	0.95	0.94	0.94
7	0	0	2.2	0.95	0.94	0.94
8	0	1	571.6	0.06	0.06	0.06

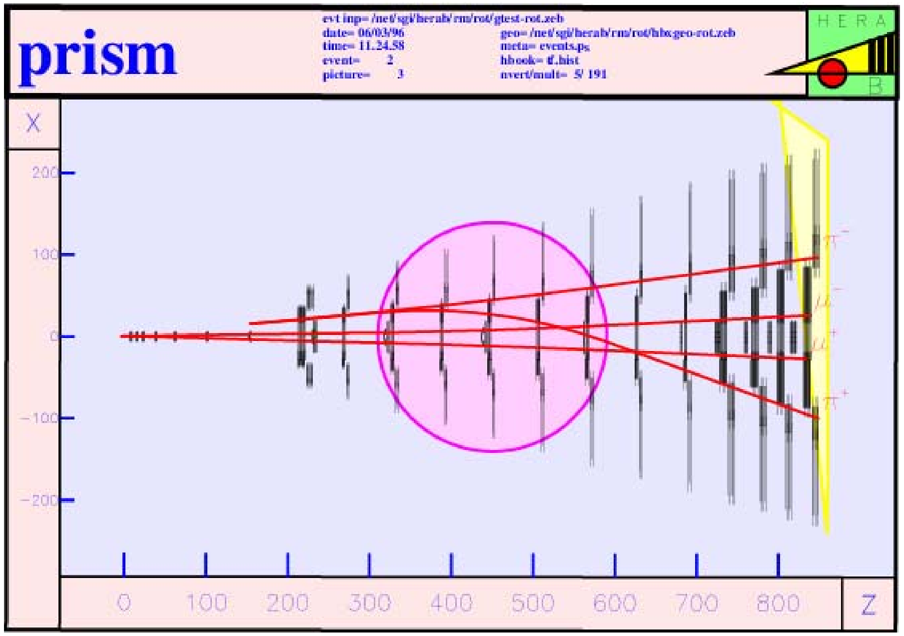
bb event at CDF



bb event at HERA-B:

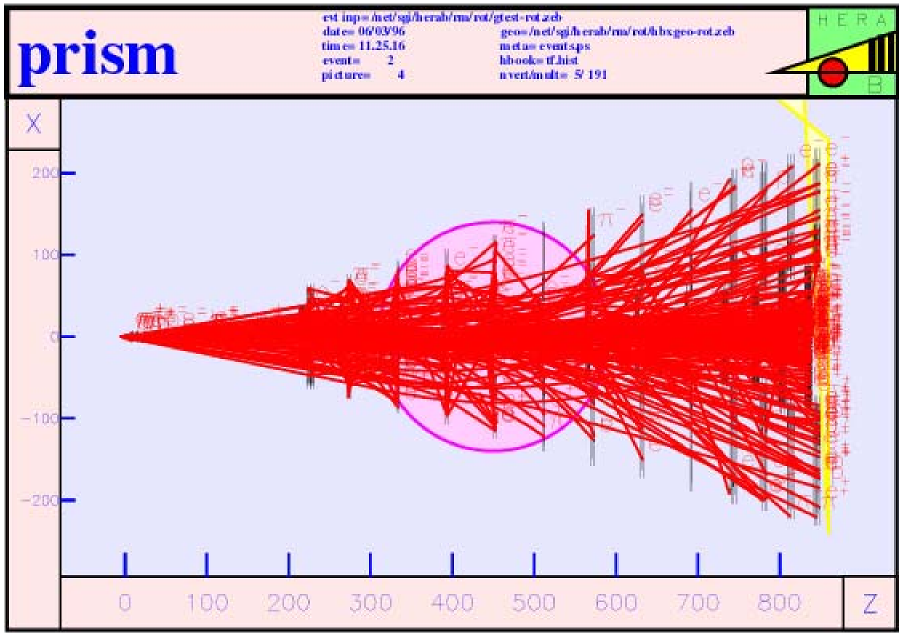
Needle

in haystack...



```
evt inp= /net/sgi/herab/rm/rot/gtest-rot.zeb
date= 06/03/96              geo= /net/sgi/herab/rm/rot/hbxgeo-rot.zeb
time= 11.24.58              meta= events.ps
event=      2               hbook= tf.hist
picture=      3             nvert/mult=  5/ 191
```

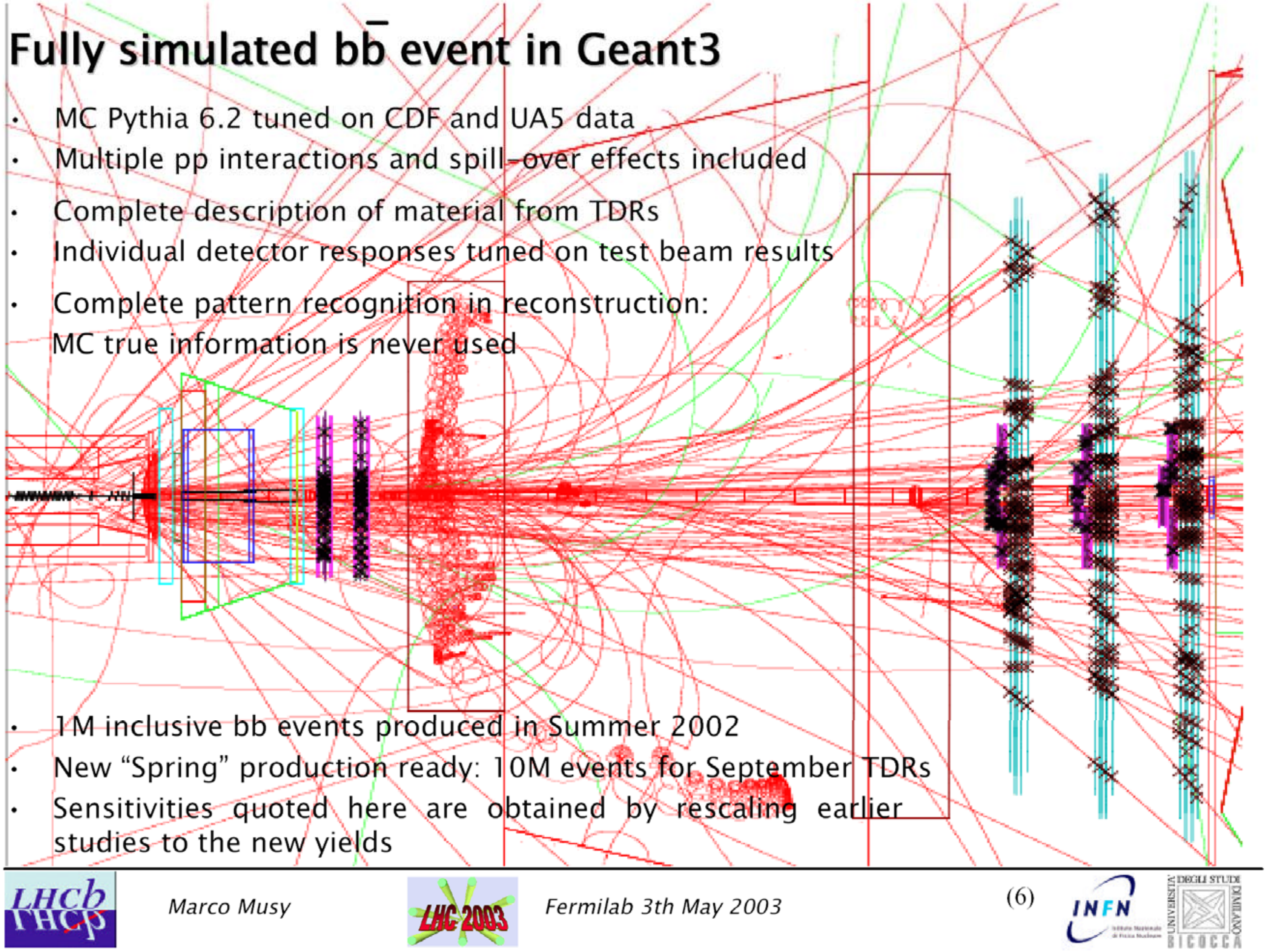
B → J/ψ Ks



```
evt inp= /net/sgi/herab/rm/rot/gtest-rot.zeb
date= 06/03/96              geo= /net/sgi/herab/rm/rot/hbxgeo-rot.zeb
time= 11.25.16              meta= events.ps
event=      2               hbook= tf.hist
picture=      4             nvert/mult=  5/ 191
```

and the rest

bb event at LHCb:



Fully simulated $b\bar{b}$ event in Geant3

- MC Pythia 6.2 tuned on CDF and UA5 data
- Multiple pp interactions and spill-over effects included
- Complete description of material from TDRs
- Individual detector responses tuned on test beam results
- Complete pattern recognition in reconstruction: MC true information is never used

- 1M inclusive bb events produced in Summer 2002
- New “Spring” production ready: 10M events for September TDRs
- Sensitivities quoted here are obtained by rescaling earlier studies to the new yields

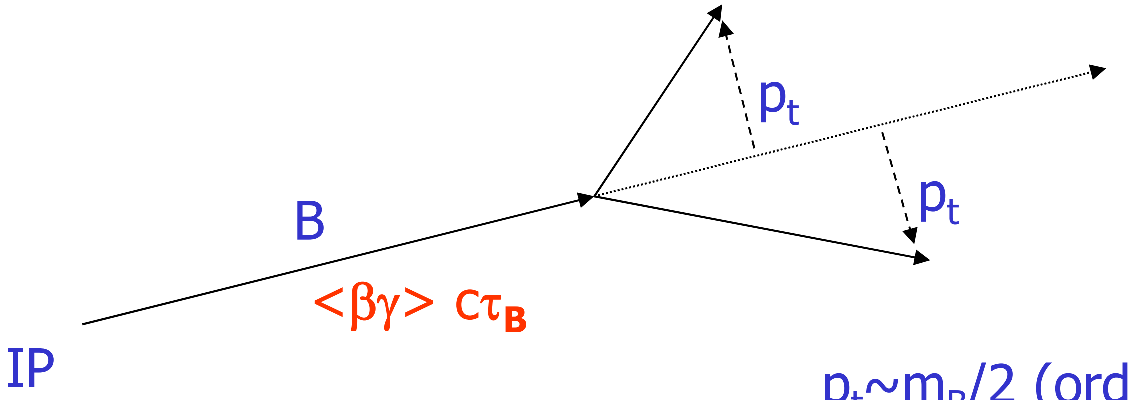
B detection in hadron collisions

What do we have to consider when designing a detector for b mesons and baryons at a hadron machine?

High particle fluxes → radiation hard detectors

Early selection of interesting events → selective triggers

Use the characteristic features of a B decay



$p_t \sim m_B/2$ (order of magnitude)

B detection in hadron collisions

Early selection of interesting events → selective triggers:

- high p_t decay products: $B \to \mu\nu X$, $B \to J/\psi\ Ks \to \mu^+\mu^-\ \pi^+\pi^-$, $B \to \pi^+\pi^-$ →helps because decay products carry a lot of momentum - typically ~1-2 GeV/c - perpendicularly to the flight direction (p_t), while backgrounds have low p_t

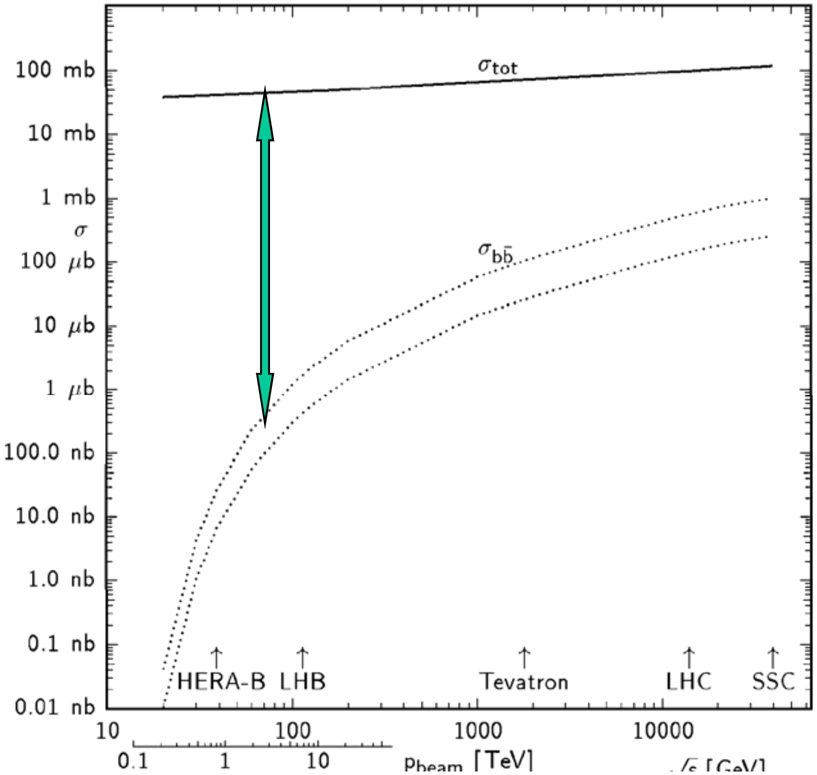
- displaced vertex: $\langle L \rangle = \langle \beta\gamma \rangle c\tau_{\mathbf{B}} = \langle \beta\gamma \rangle\ 480\ \mu m$ → helps because other decay products are promt = originate directly in the interaction point

Proof of principle: CDF, D0 at the Tevatron collider. Most importnat measurement: Observation of B_s mixing.

HERA-B

First attempt to make a precision flavour physics measurement at a hardon machine.

Fixed target B - Factory at HERA (DESY): parasitic use of the proton beam with an adaptable target in the beam halo



Originally designed for measurement of CP violation in $B \rightarrow J/\psi K_S^0$

920 GeV prootons, sqrt(s)=42 GeV

σ(b bar-b) ~ 12 nb -> σ(b bar-b)/ σ(inel) ~10^{-6}

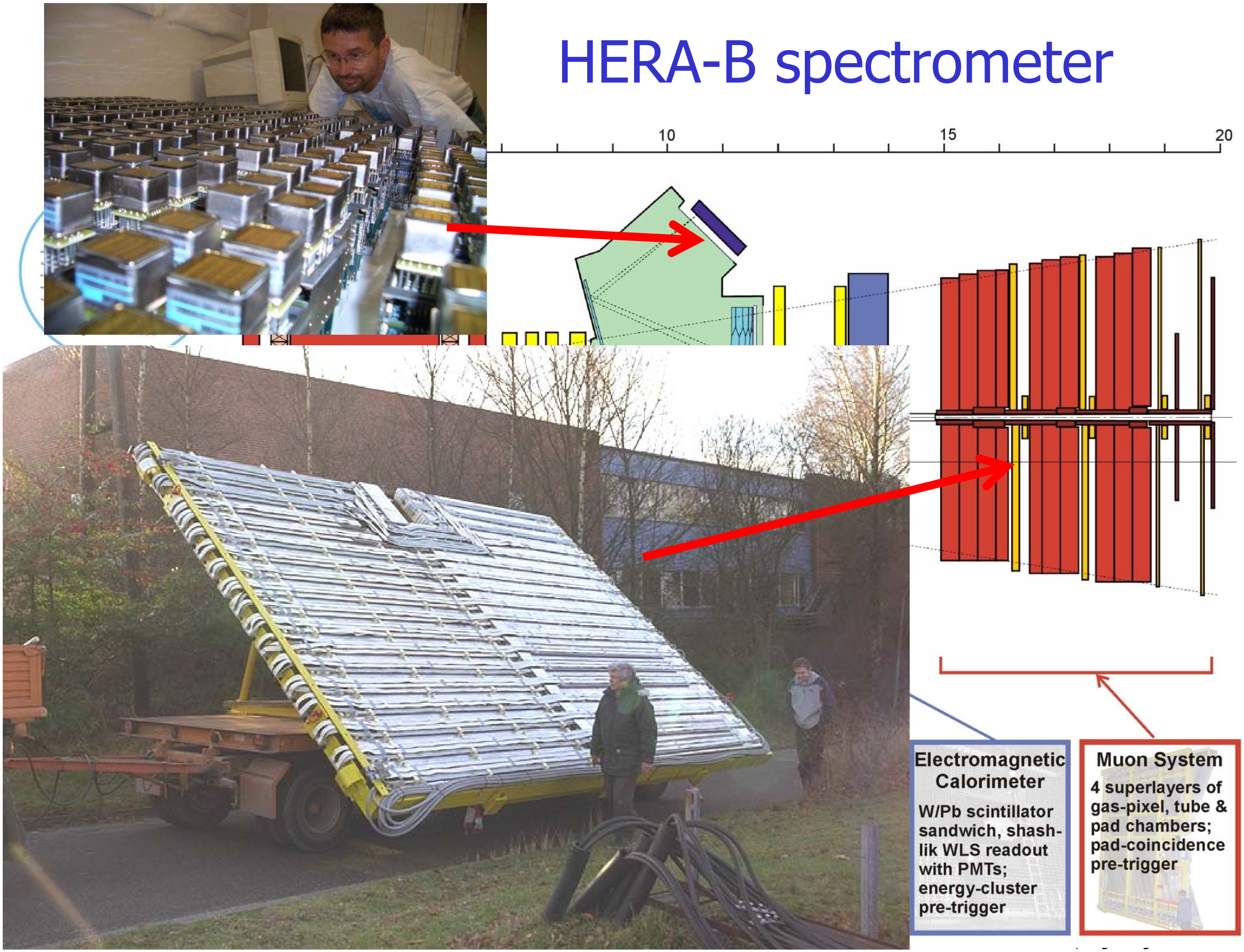
BR for interesting decays of ~ 10^{-5}-10^{-4}

→ 11 orders of magnitude

→ Need multiple events for 40 MHz interaction rate (=0.4 10^8 s^{-1})

→LHC like experiment 10 years before LHC

HERA-B spectrometer



Electromagnetic Calorimeter

W/Pb scintillator sandwich, shashlik WLS readout with PMTs; energy-cluster pre-trigger

Muon System

4 superlayers of gas-pixel, tube & pad chambers; pad-coincidence pre-trigger

HERA-B Summary

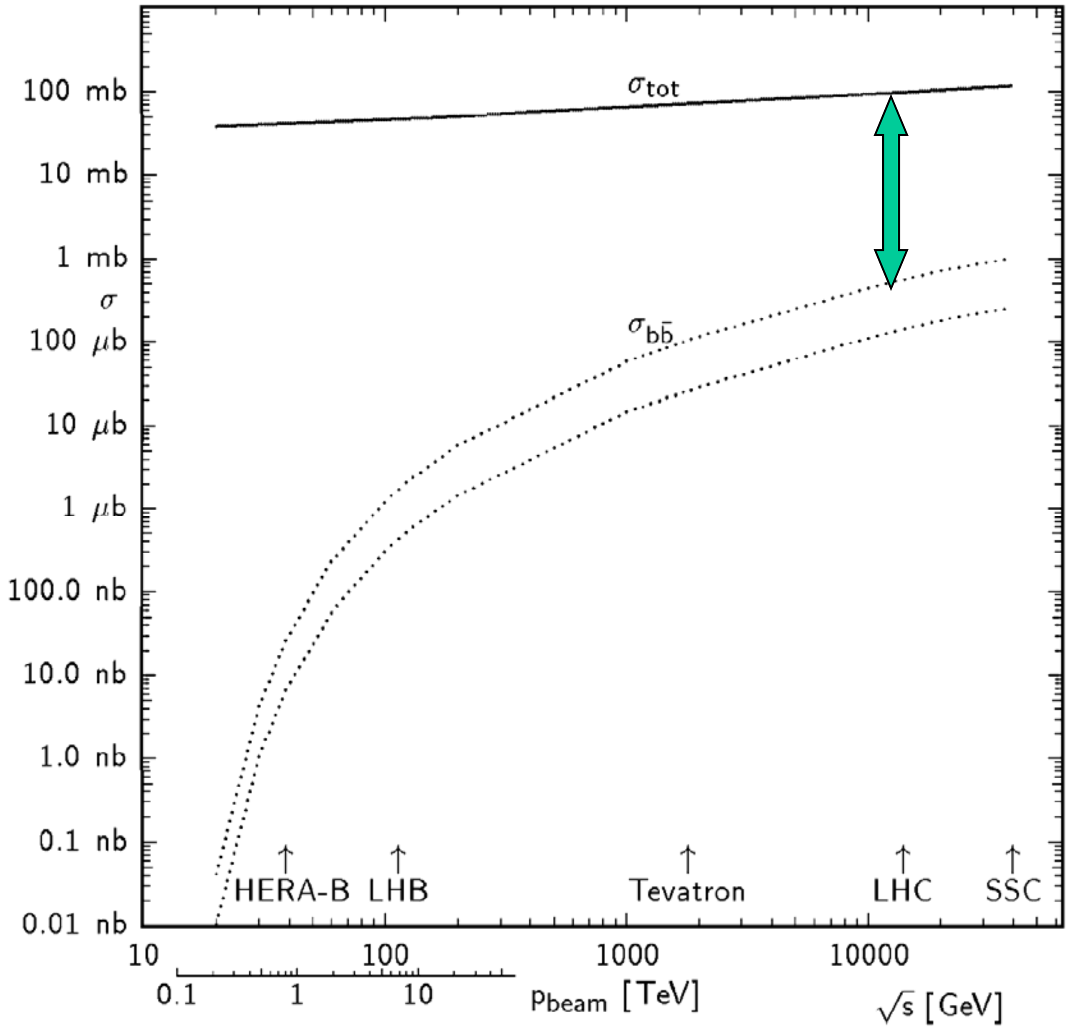
- First LHC like experiment before the LHC
- Designed with a very ambitious goal
- Many components behaved very well (e.g. SVD, RICH, calorimeter and muon system)
- Several critical components were less successful (tracking)
- Trigger efficiency (which heavily relied on the tracking system efficiency) was >10x lower than expected

→No precision tests in B physics were possible

- Still: a solid physics program could be carried out (i.e. bb and cc production cross sections, a limit on D->$\mu\mu$, pentaquark searches)
- HERA-B experience: An important input for LHC experiments

b-production in pp collisions at LHC

Cross section for bb pair production much higher at LHC



b-production in pp collisions

- Pairs of $b\bar{b}$ quarks are mostly produced in the forward/backward direction:

$$\boxed{\sigma_{b\bar{b}} = 500\mu b}$$

$10^{12} b\bar{b}$ produced per year

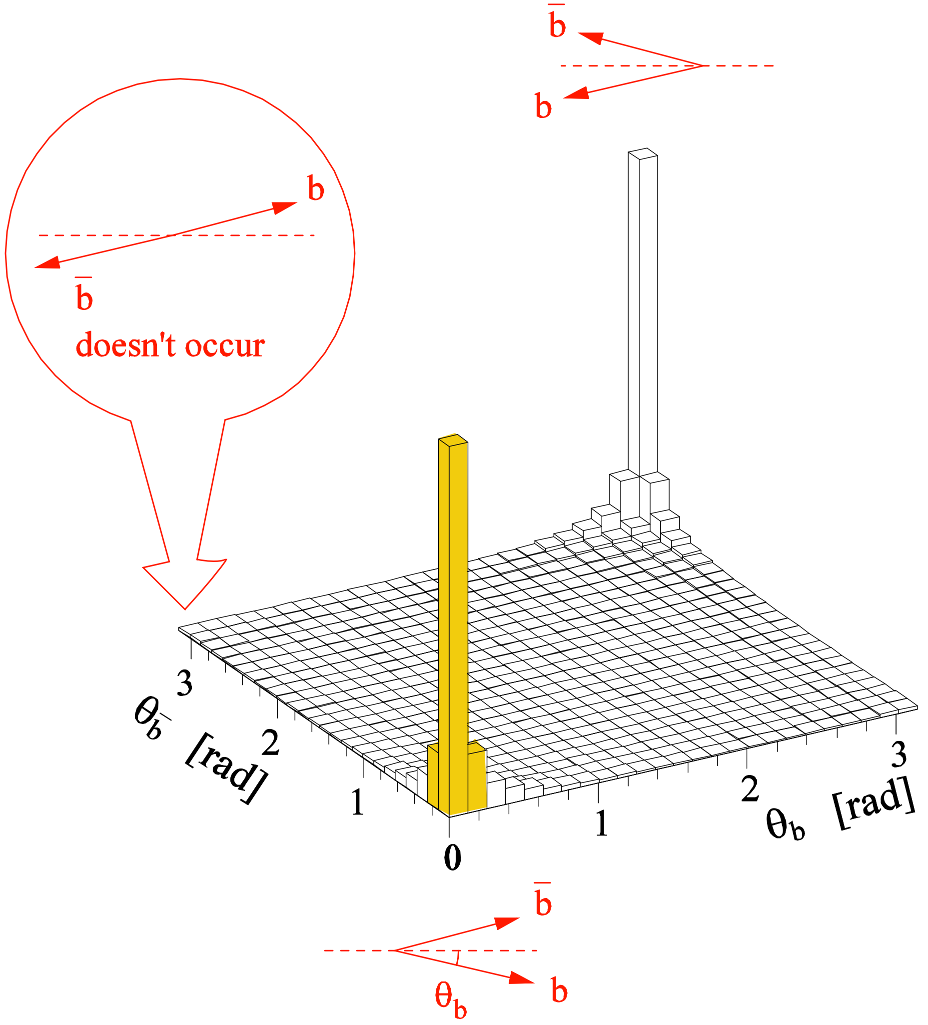
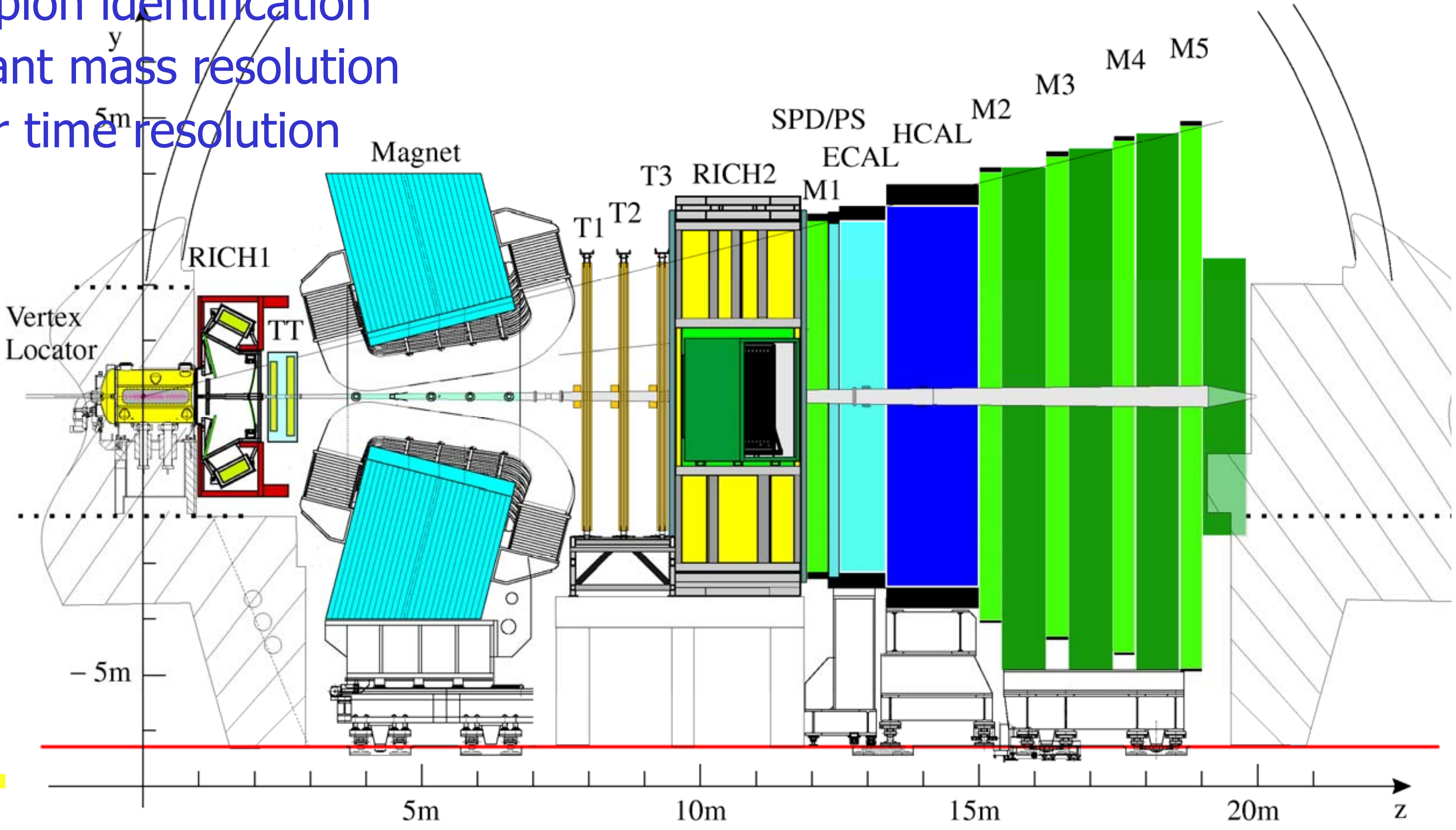


Figure 2.1: Polar angles of the b- and $\bar{b}$-hadrons calculated by the PYTHIA event generator.

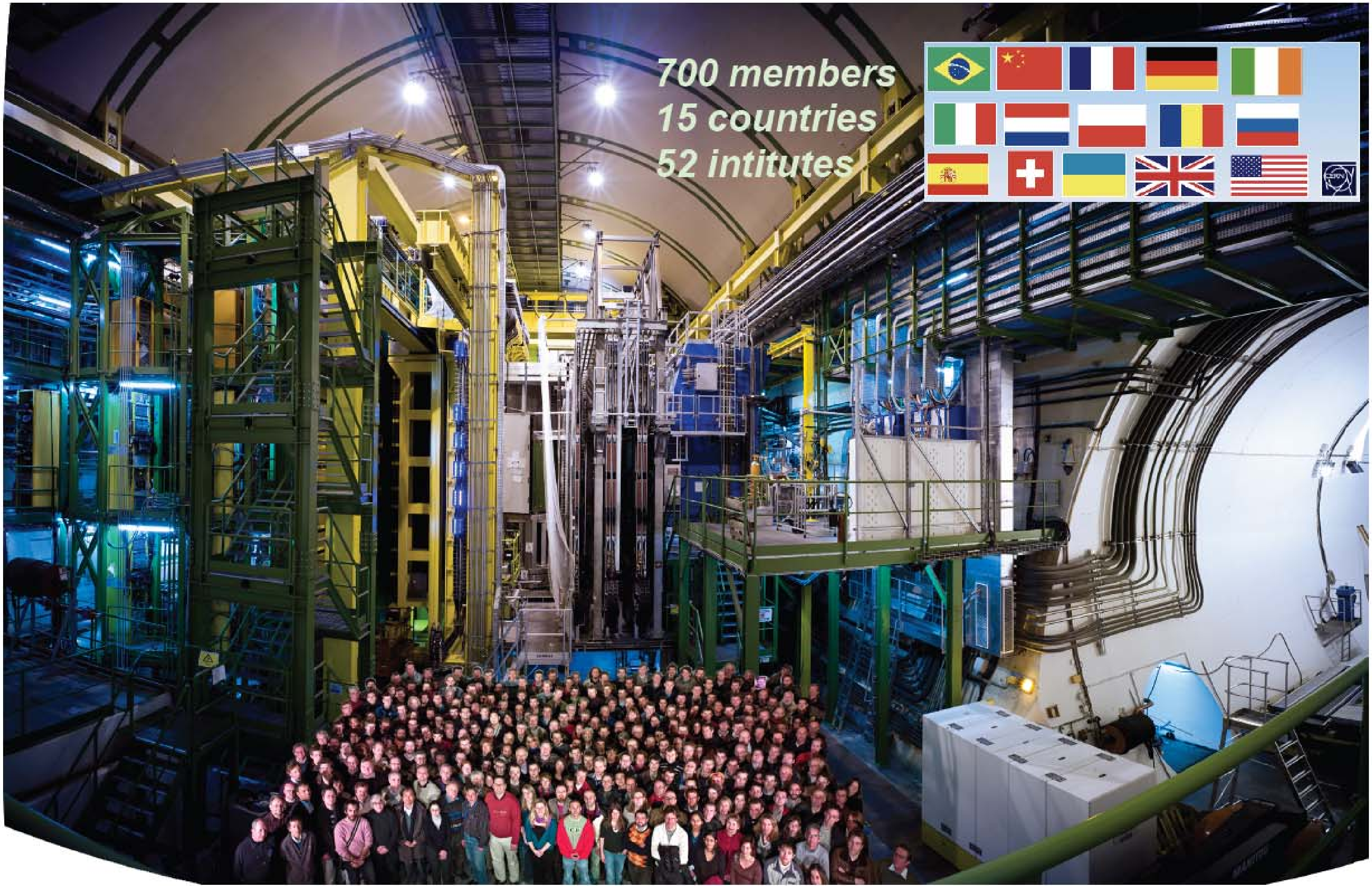
LHCb

LHCb is a forward spectrometer:

- Acceptance 10-300 mrad
- Efficient B-mesons trigger
- Good Kaon/pion identification
- Good invariant mass resolution
- Good proper time resolution

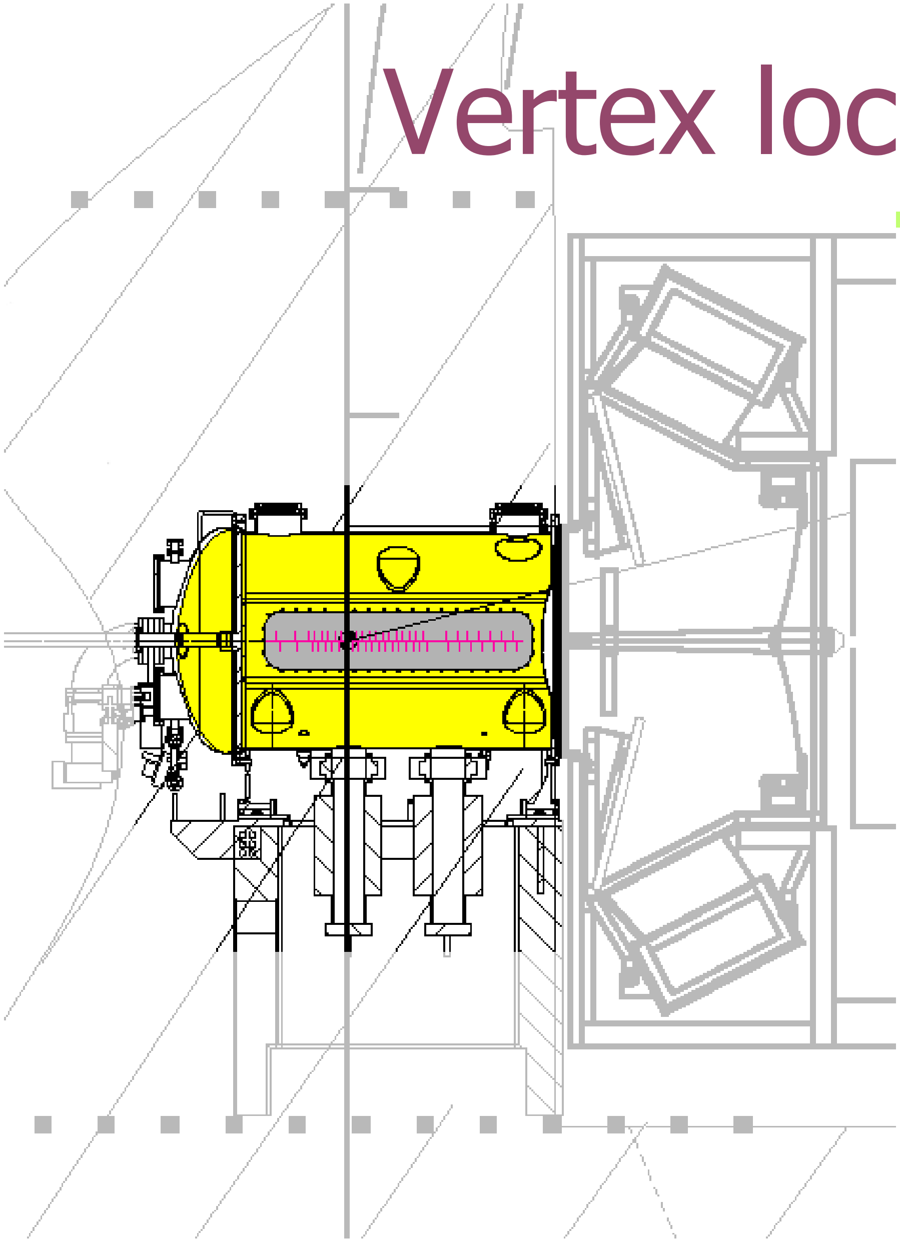


LHCb Collaboration



700 members
15 countries
52 intitutes

Vertex locator - VELO



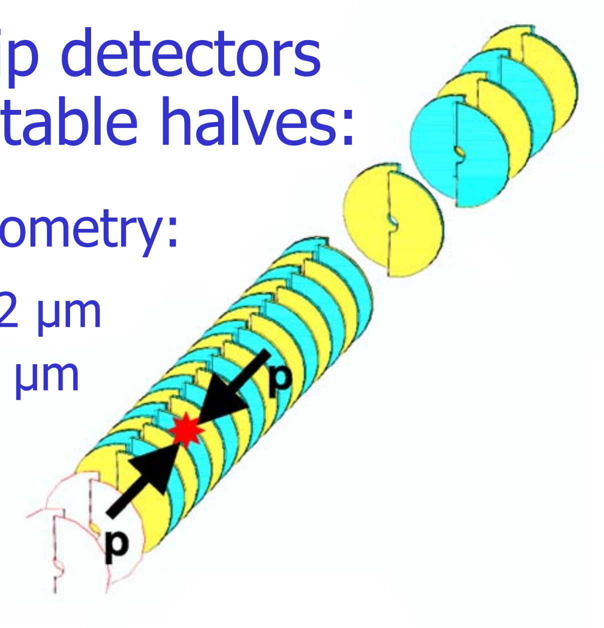
Vertex detector

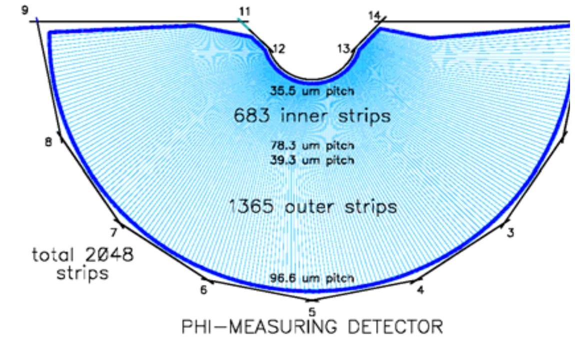
Key element surrounding the IP:

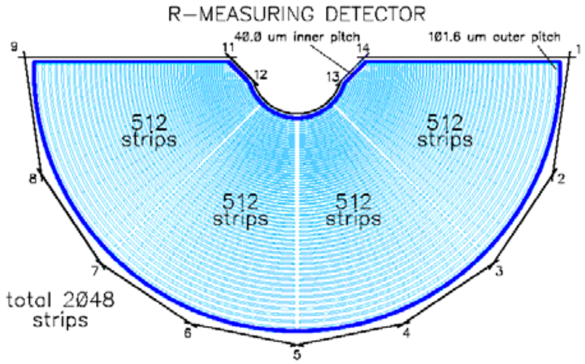
- Measure the position of the primary and the $B_{d,s}$ vertices
- Used in L1 trigger.

Vertex locator

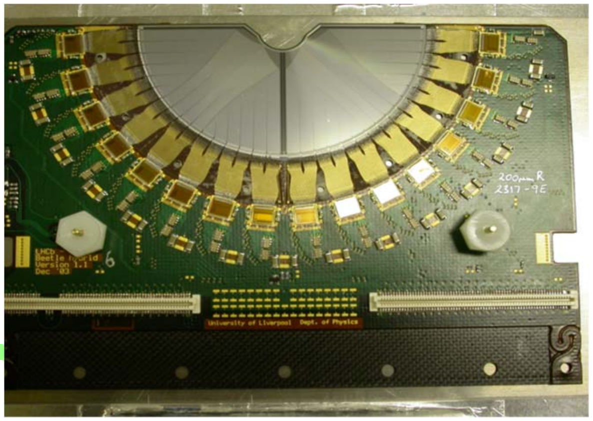
- 21 pairs of silicon strip detectors arrange in two retractable halves:
  - Strips with an R-φ geometry:
    - R strip pitch: 40-102 μm
    - φ strip pitch: 36-97 μm
  - 172k channels.



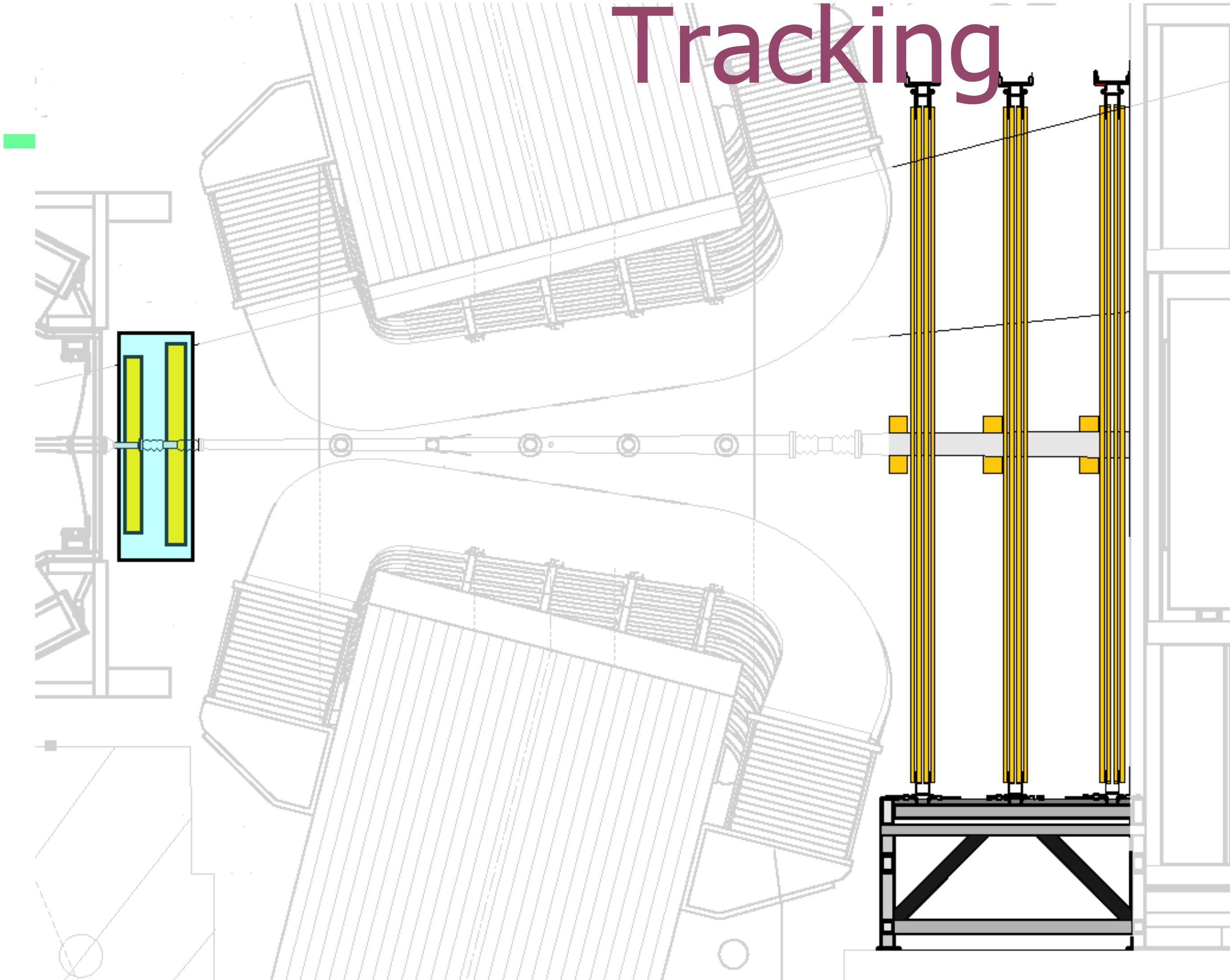




- Operated:
  - In vacuum, separated from beam vacuum by an Al foil
  - Close to the beam line (7 mm)
  - Radiation ≤ 1.5×10^{14} n_{eq}/cm² per year
  - Cooled at -5 °C

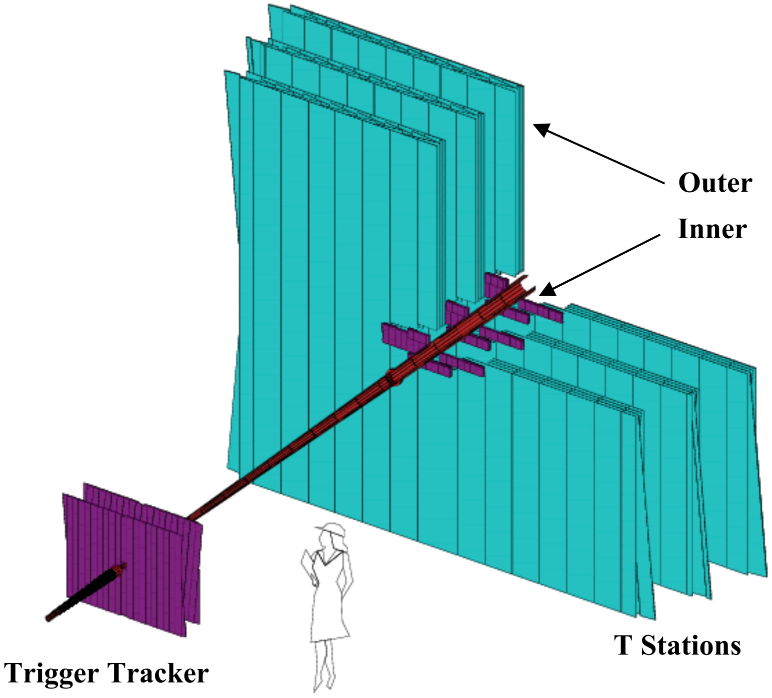


Tracking



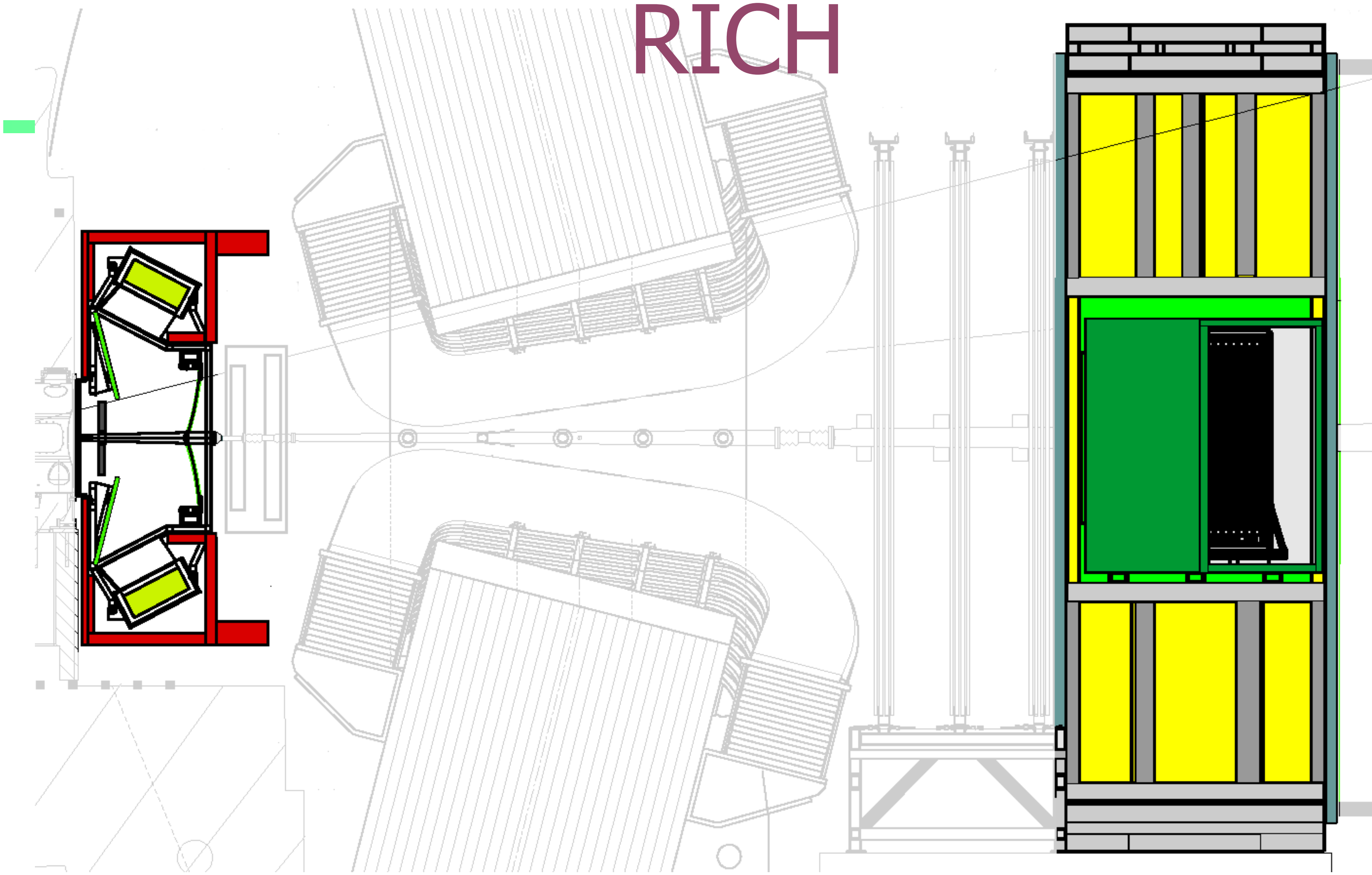
Key elements to find tracks and to measure their momentum.

Tracking system



- Trigger Tracker:
  - Microstrip silicon detector
  - 144k channels
- Three T stations:
  - Inner tracker:
    - Microstrip Silicon detector
    - 130k channels
  - Outer tracker:
    - Straw tubes (5 mm)
    - 56k channels

RICH



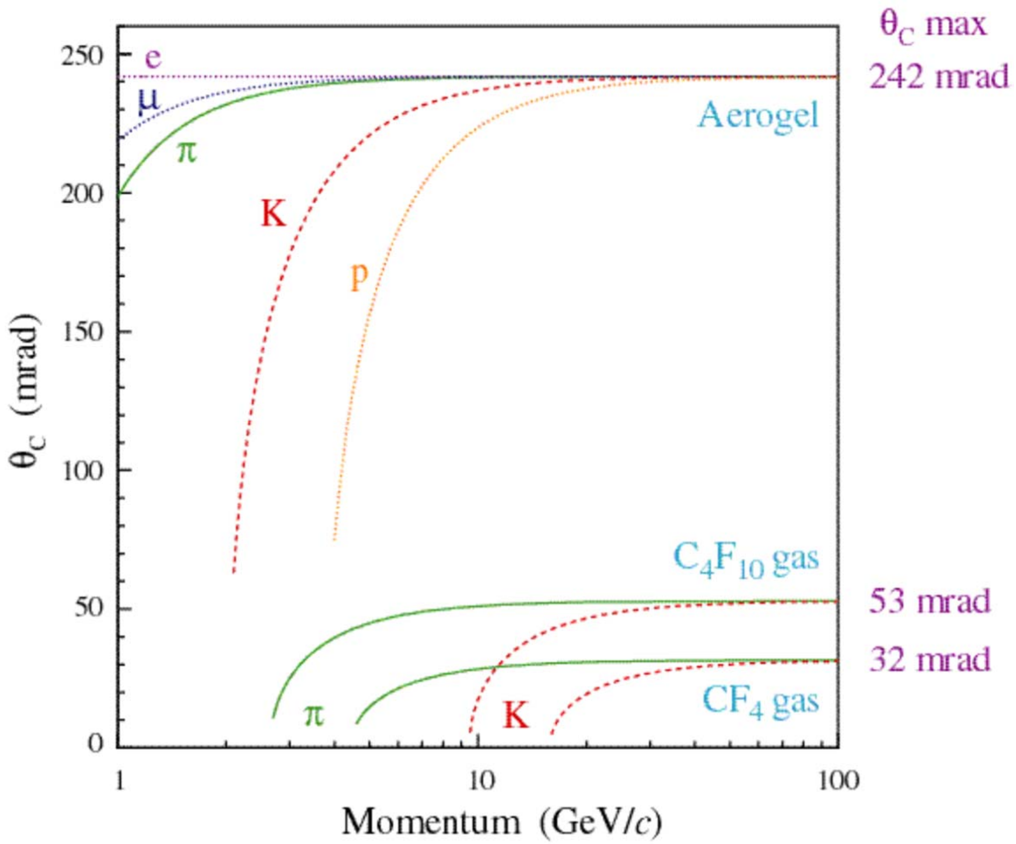
Key elements to identify pions and kaons in the momentum range $p \in [2,100]\,\mathrm{GeV}/c$

LHCb RICHes

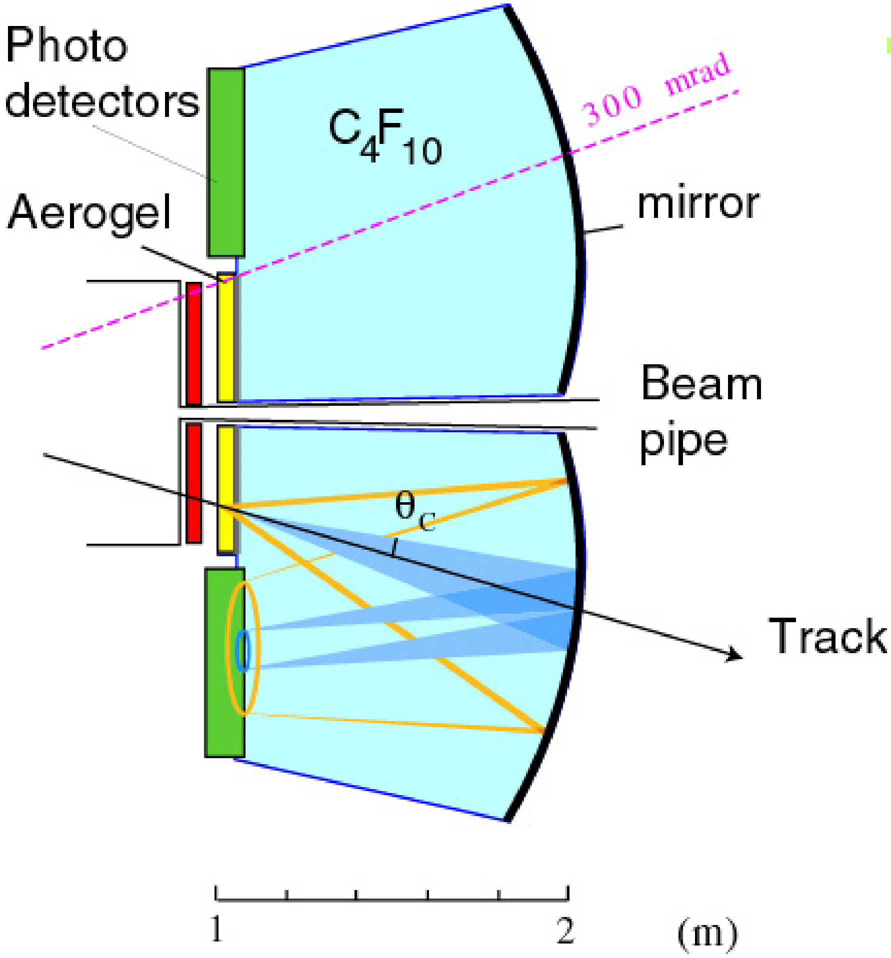
RICH system divided in two detectors equipped with 3 radiators to cover the full acceptance and momentum range:

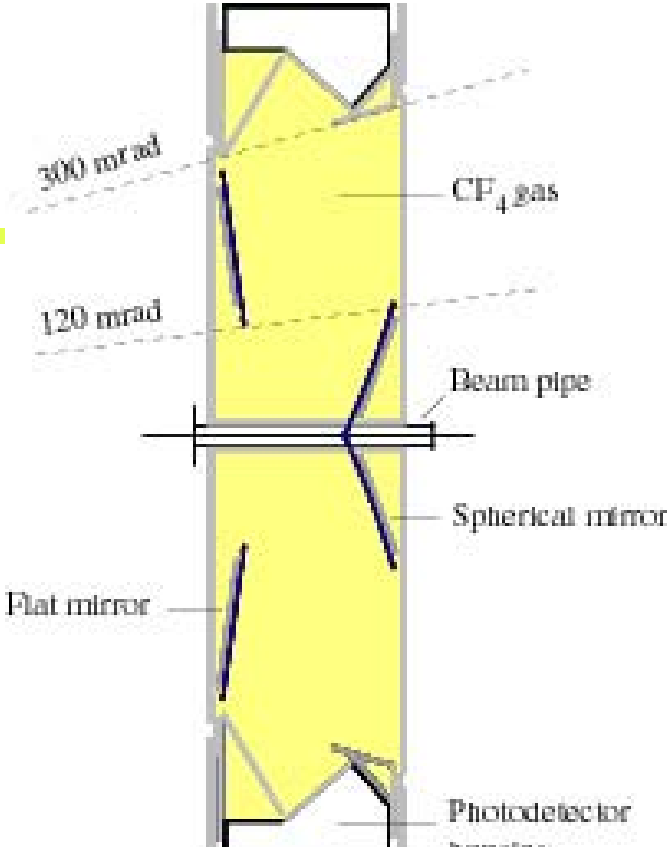
- from a few GeV (tagging kaons)
- up to 100 GeV: two body B decays

General rule: for 3σ separation, a RICH with a single radiator can cover a factor of 4-7 in momentum from threshold to the max. p. Larger region → more radiators!



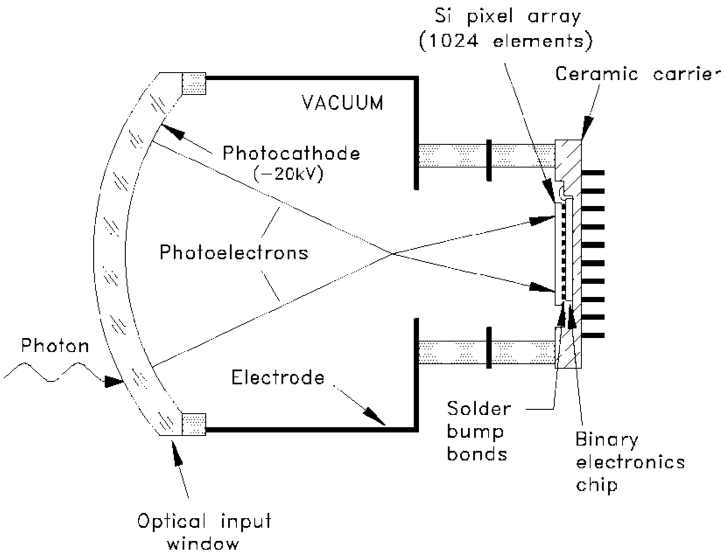
RICH with three radiators



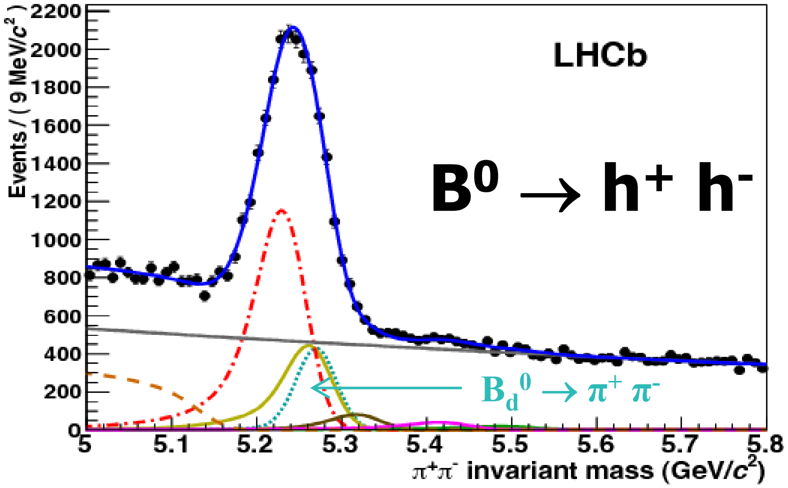


Hybrid photodetector:

32×32 pixel sensor array (500×500 μm²), 20 kV operation voltage, demagnification factor ~5



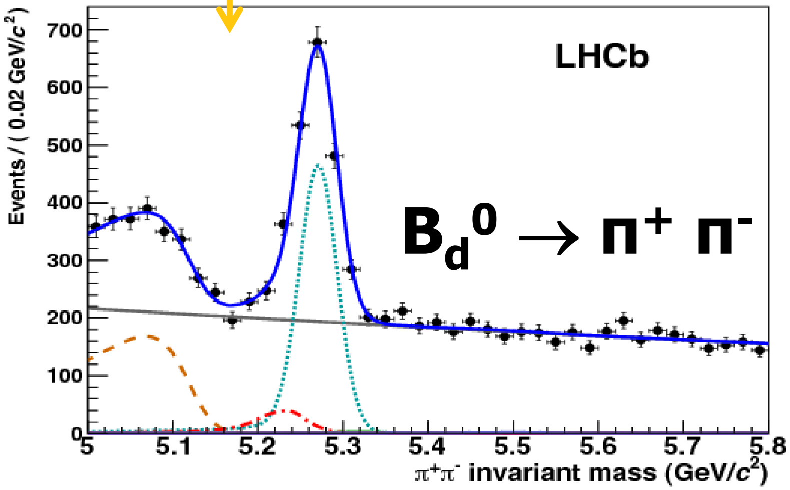
Particle ID with RICH



Efficient particle ID of π, K, p essential for selecting rare beauty and charm decays

K-identification and π-misidentification efficiencies vs. particle momentum

particle identification of 2 pions



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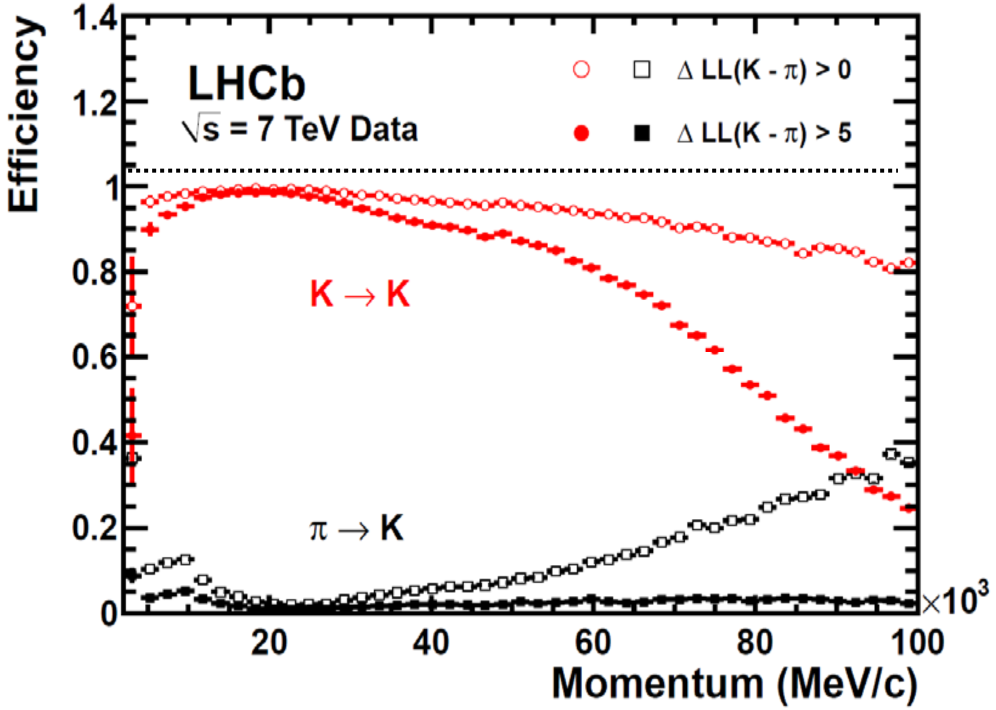
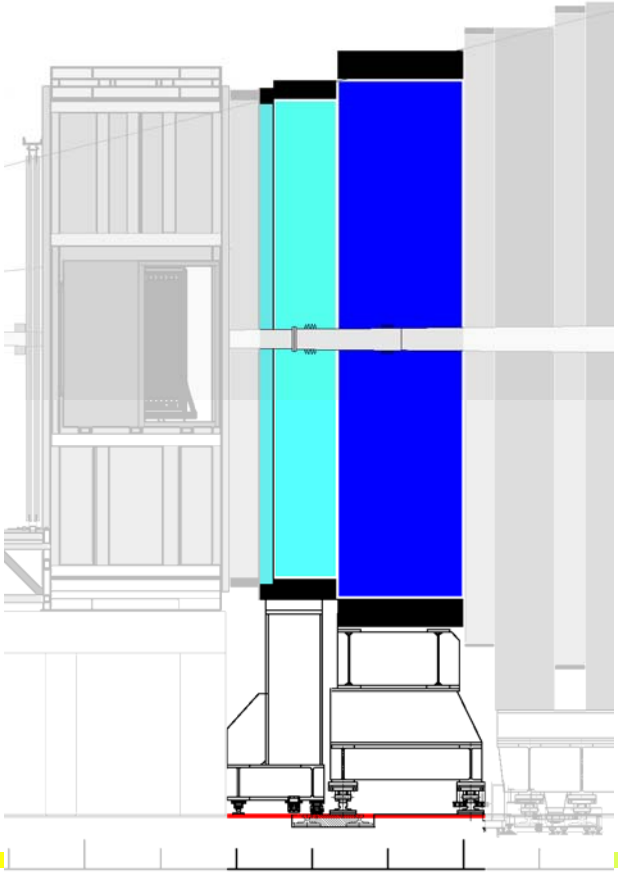
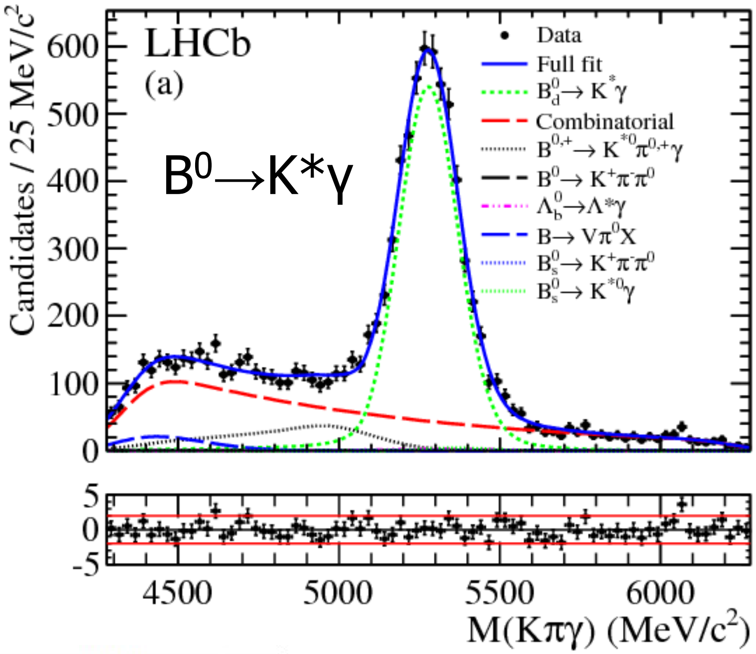


Calorimeters

Key element to identify γ, π^0 and to measure their energy.

Used in L0 trigger.





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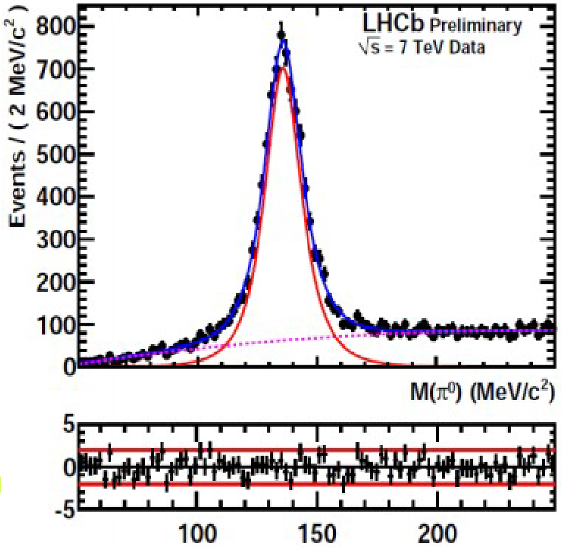


$\pi^0 \to \gamma\gamma$

LHCb calorimeters

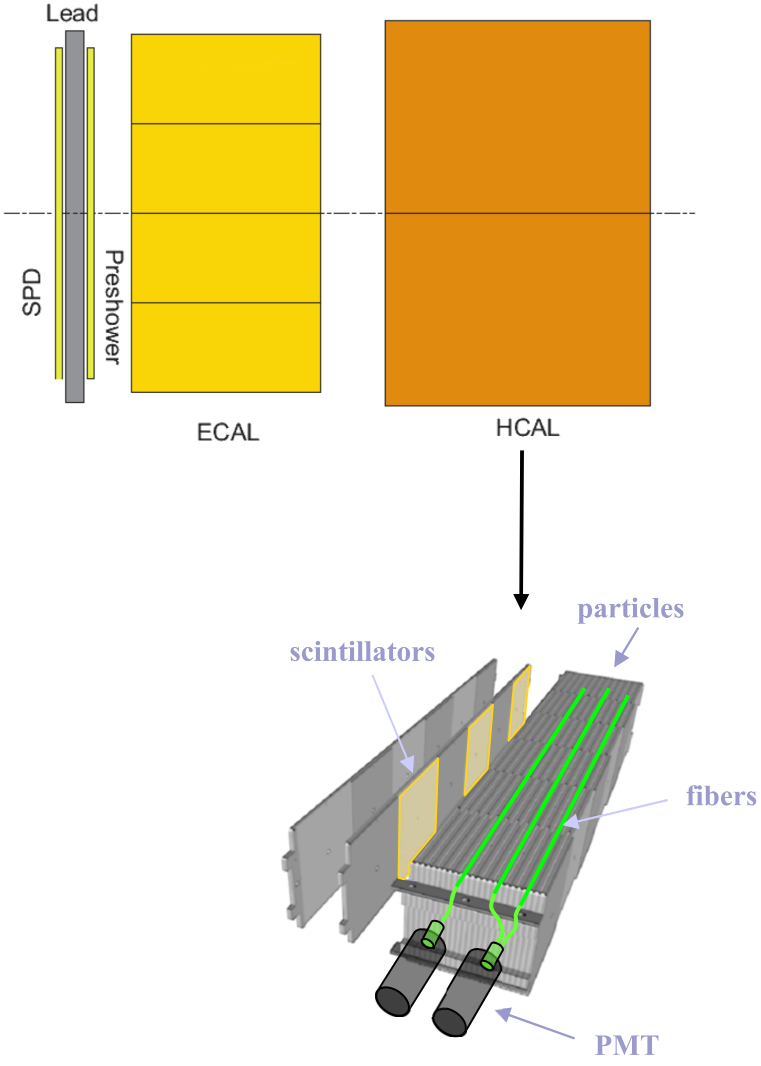
- System subdivided in 3 parts:

  Scintillating Pad Detector (SPD) and Preshower:
    - Two layers of scintillator pads separated by a 1.5cm lead converter

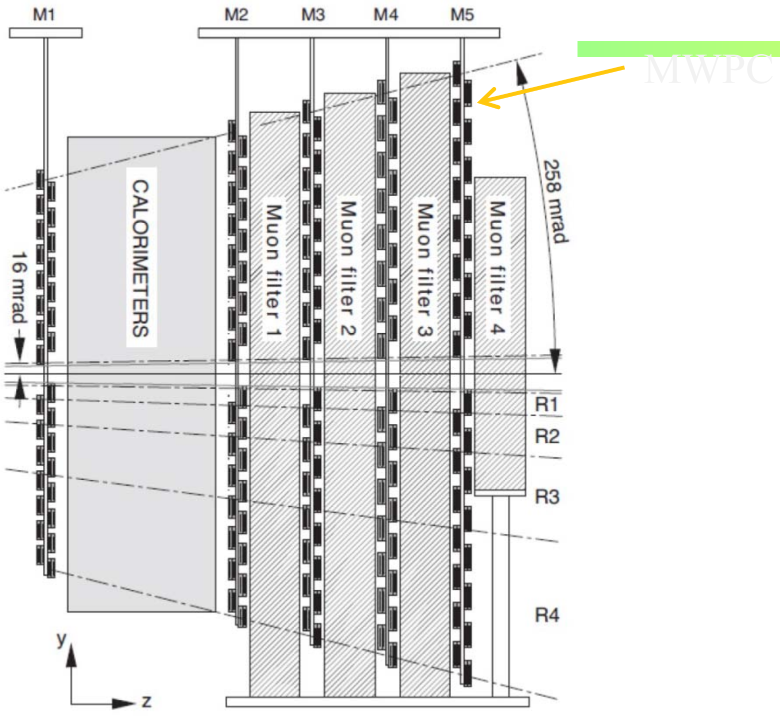
  Electromagnetic Calorimeter (ECAL):
    - Shashlik types,
    - Lead+ scintillator tiles
    - 25 X_0

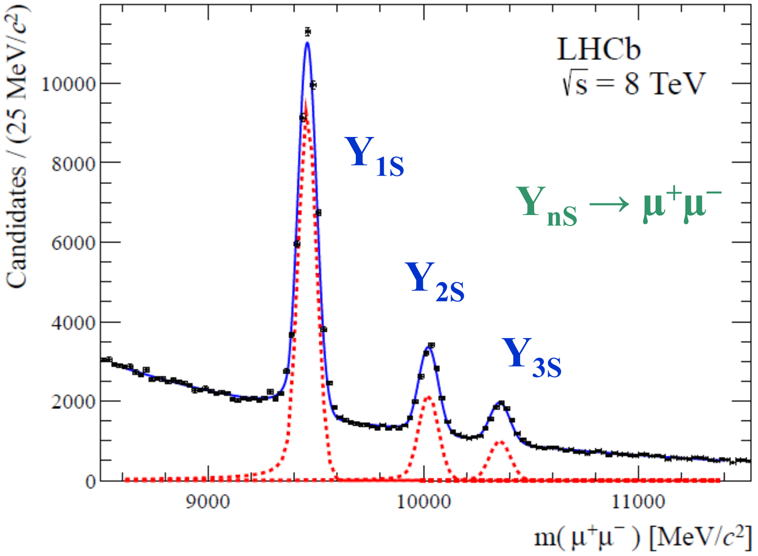
- Hadronic calorimeter (HCAL):
  - Iron + scintillator tiles
  - 5.6 λ_I

- A total of 19k channels readout by Wave Length Shifter fibres connected to PMs or MaPMTs.



Particle ID with the Muon System

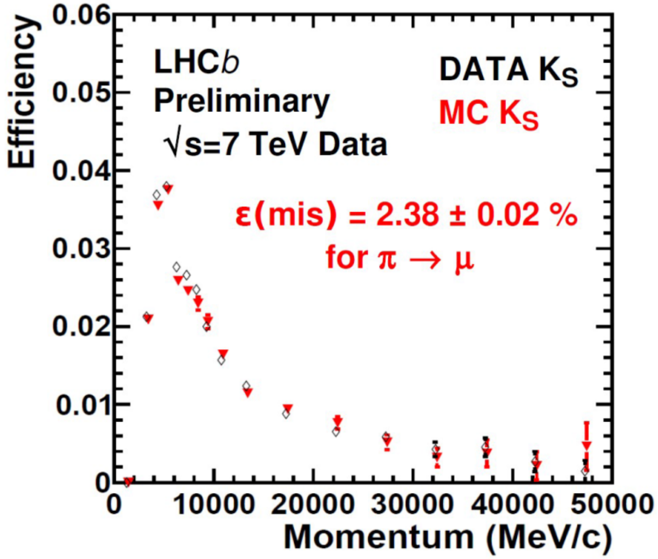




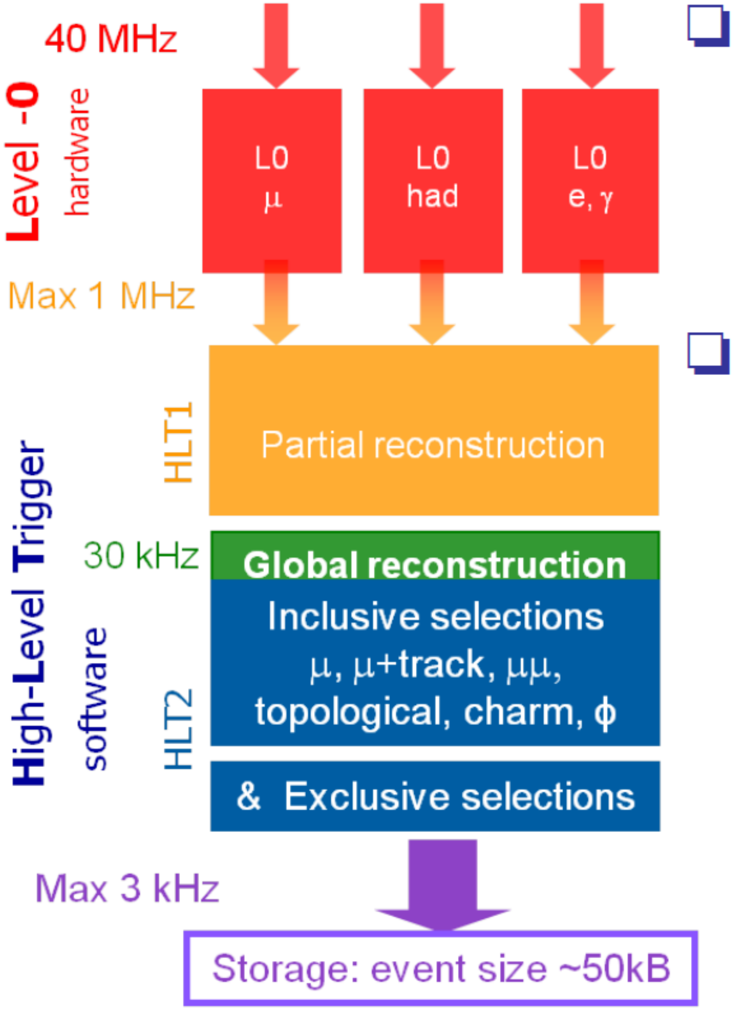
High detection efficiency: $\varepsilon(\mu) = (97.3\pm1.2)\%$

Low misidentification rates:

$\varepsilon(p \rightarrow \mu) = (0.21 \pm 0.05)\%$
$\varepsilon(\pi \rightarrow \mu) = (2.38 \pm 0.02)\%$
$\varepsilon(K \rightarrow \mu) = (1.67 \pm 0.06)\%$



Triggers



40 MHz

Level -0 hardware

L0 μ

L0 had

L0 e, γ

Max 1 MHz

HLT1

Partial reconstruction

High-Level Trigger software

30 kHz

Global reconstruction

HLT2

Inclusive selections μ, μ+track, $\mu\mu$, topological, charm, ϕ

& Exclusive selections

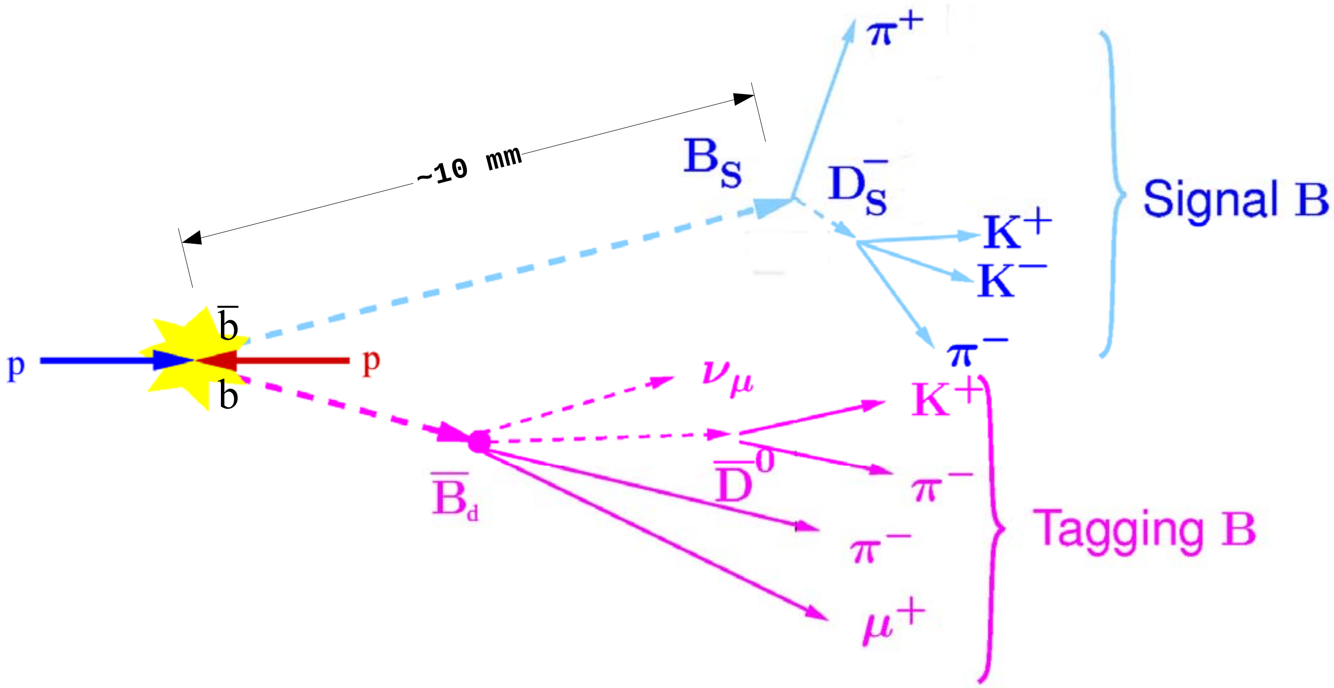
Max 3 kHz

Storage: event size ~50kB

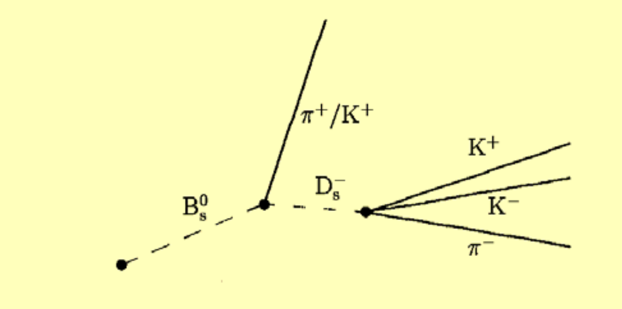
- ❑ Level-0:
  - — fully synchronous custom electronics at 40 MHz
    - 11 MHz of visible interactions reduced to max. 1 MHz
    - select single objects with large p_T (E_T), typically $p_T(\mu) > 1$ GeV/c and $E_T(h,e,\gamma,\pi^0) > 3$–4 GeV
- ❑ High-level trigger
  - — Farm of 1500 multi-processor boxes
  - — Stage 1: add tracking info, impact parameter cuts
  - — Stage 2: full reconstruction + selections
  - — Output:
    - ~1 kHz charm, ~ 1 kHz B, ~1 kHz others

	Typical efficiencies
B decays with $\mu\mu$	70–90%
Fully hadronic B decays	20–45%
Fully hadronic charm decays	10–20%

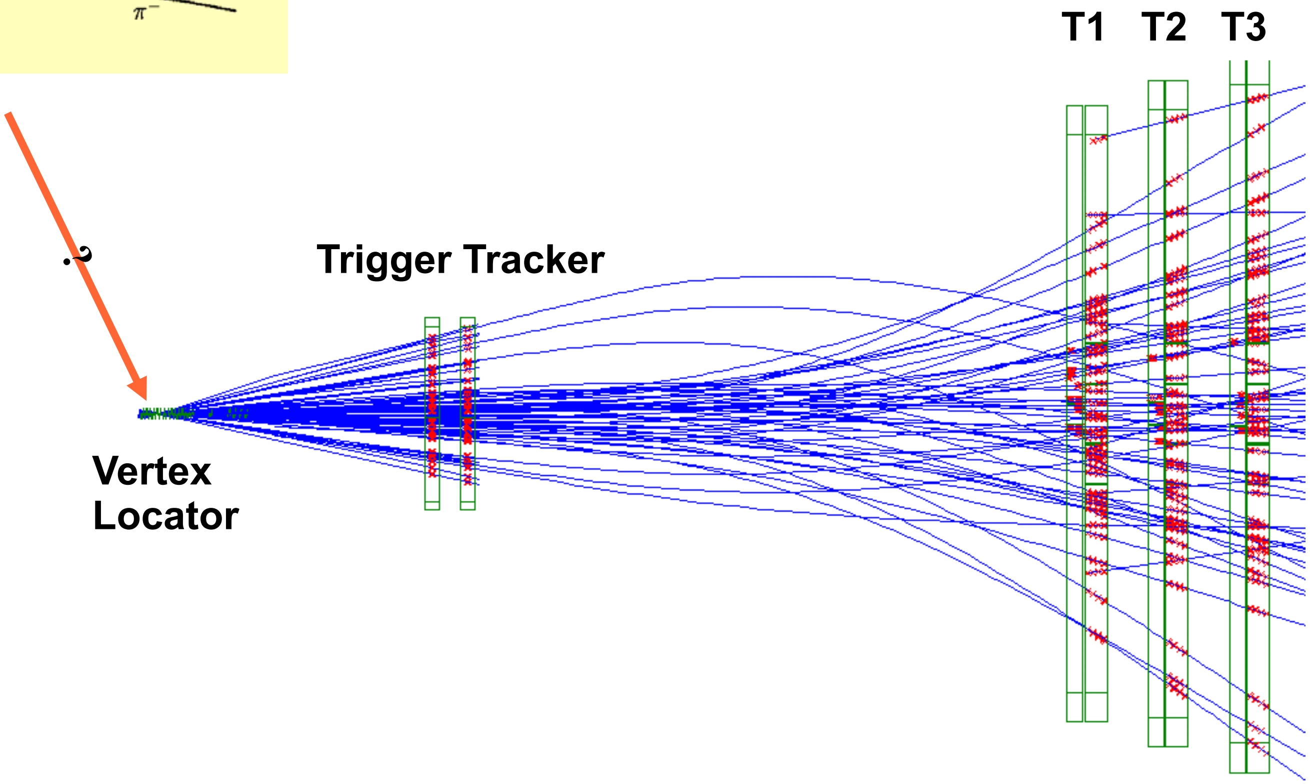
Time dependent measurements at LHCb



- The proper time of the signal B decay is measured via:
  - the position of the primary and secondary vertexes;
  - the momentum of the signal B state from its decay products.

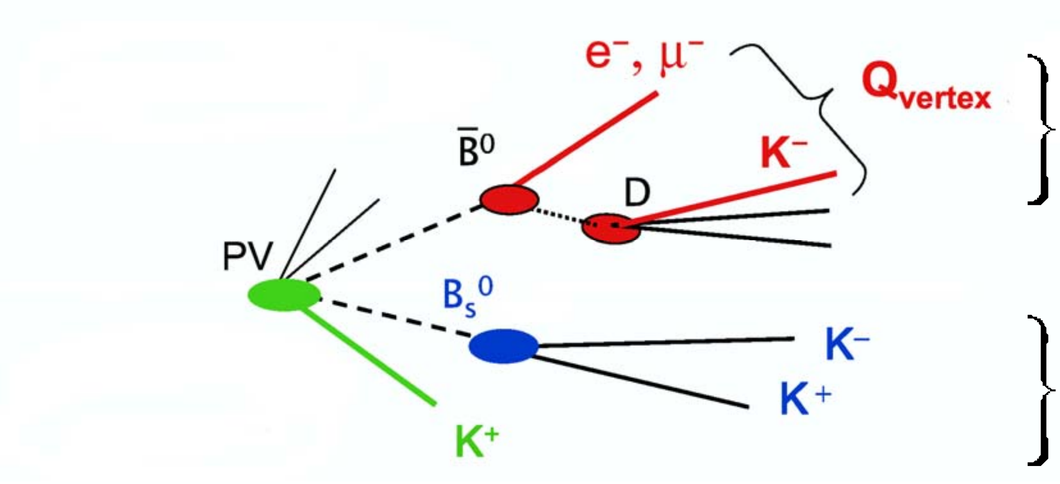


$$B_s \to D_s^{\pm} K^{\mp} \to \left(K^+ K^- \pi^{\pm}\right) K^{\mp}$$



Reconstructed event: ~72 tracks

Flavour Tagging



Tagging B
<u>Opposite side</u>

Signal $B_{d,s}$
<u>Same side</u>

Opposite side:

- e, μ from semileptonic b decays;
- K± from b decays chain;
- Inclusive vertex charge.

Same side:

- K± from fragmentation accompanying B_s meson.

Effective tagging efficiencies vary between 3% and 9% depending on the final state.

N.B. Effective tagging efficiencies is **>30%** at B factories, ~2% at CDF/D0

LHCb results – a selection

- B_s system parameters
- Angle of the unitarity triangle: precise measurements
- FCNC processes

Measurement of Δm_s

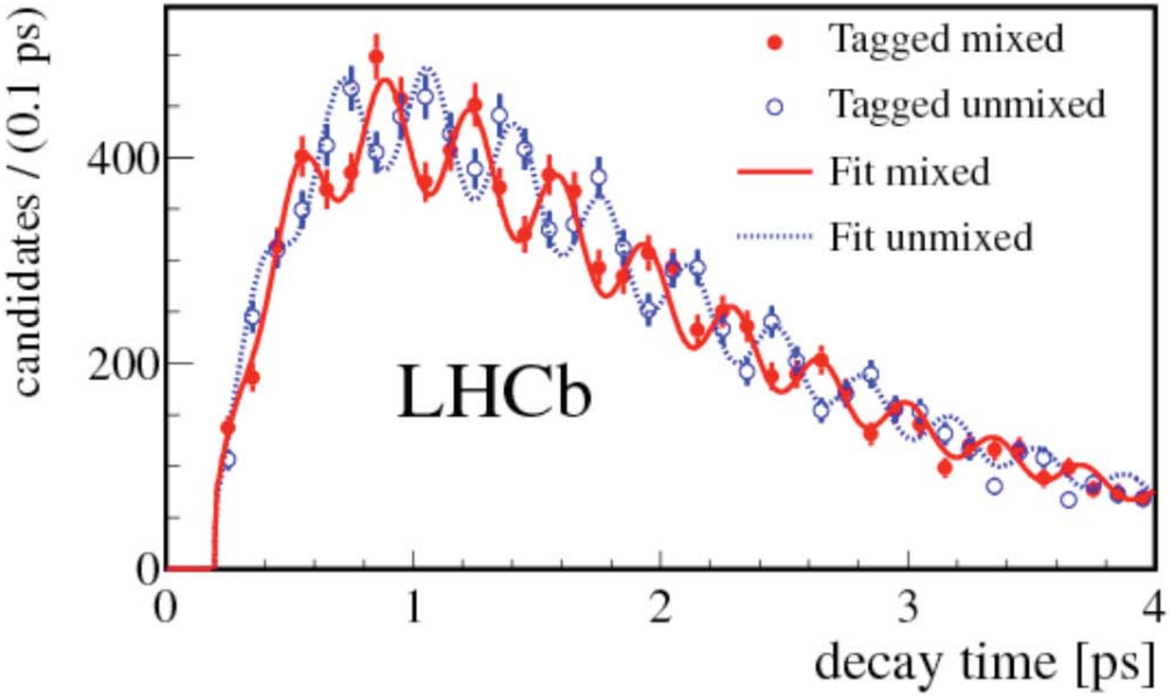
B_s mix much faster the B_d mesons!

First observed at CDF in 2005: $\Delta m_s = 17.33 \,^{+0.42}_{-0.21}$ (stat) +- 0.07 (syst) ps^{-1}

LHCb: Precision measurement

New J.Phys. 15 (2013) 053201

Uses 34,000 $B_s \rightarrow D_s\pi$ decays from 1/fb of 2011 data

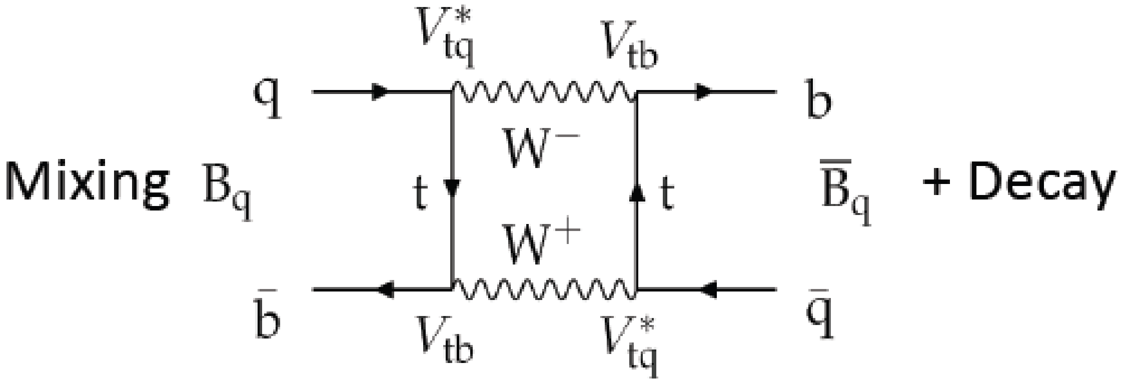


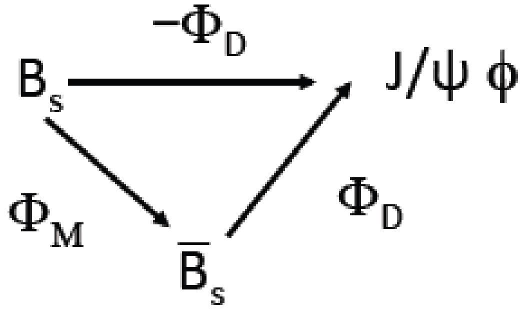
Timing resolution makes fast oscillations visible

Δm_s = 17.768 +- 0.023 (stat) +- 0.006 (syst) ps^{-1}

CP violation in $B_s \to J/\psi\ \phi$ decays

Similar as B → J/ψ K decays, but now measuring one of the smaller unitary triangles.





Tag initial flavour and measure decay time distributions.
Then essentially the measurement is of:

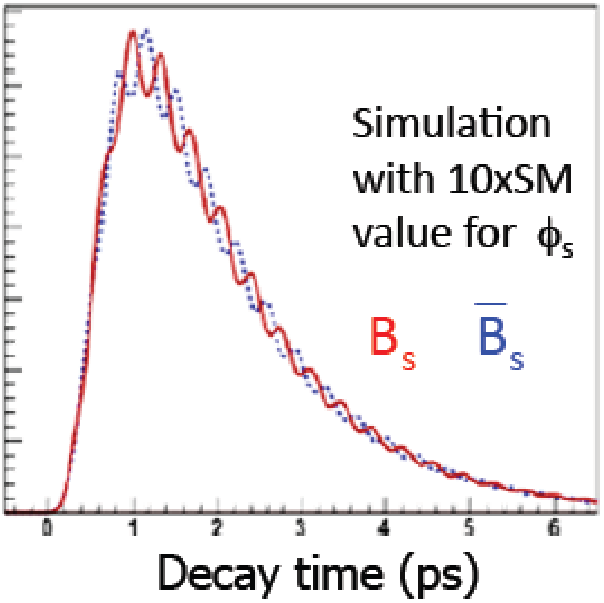
$$\boxed{\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)}$$

CPV phase $\phi_s = \Phi_M - 2\,\Phi_D$

Decay time resolution

Mistag rate

B_s mixing frequency



In Standard Model CPV phase is small $\phi_s \sim -0.04$

S. Playfer, 50 years of CP violation, London, 2014

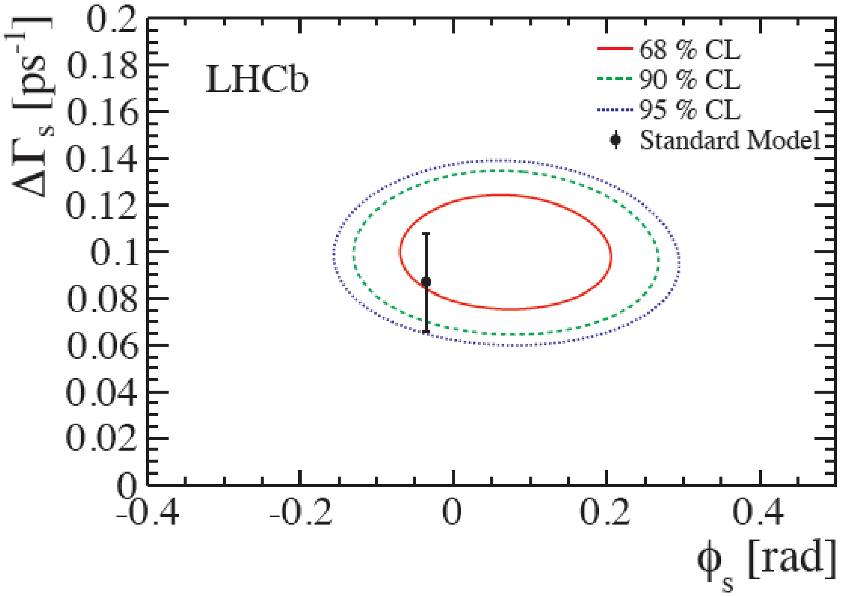
CP violation in $B_s \rightarrow J/\psi\ \phi$ decays

Measuring one of the thinner unitary triangles – angle ~2^0 (instead of 21^0)
→small and therefore sensitive to possible New Physics effects

CP violating phase

$$\phi_s = 0.07 \pm 0.09(\text{stat.}) \pm 0.01(\text{syst.})$$

In good agreement with SM expectations.
In the same measurement it is also possible to measure the (large) decay width difference in the B_s system.

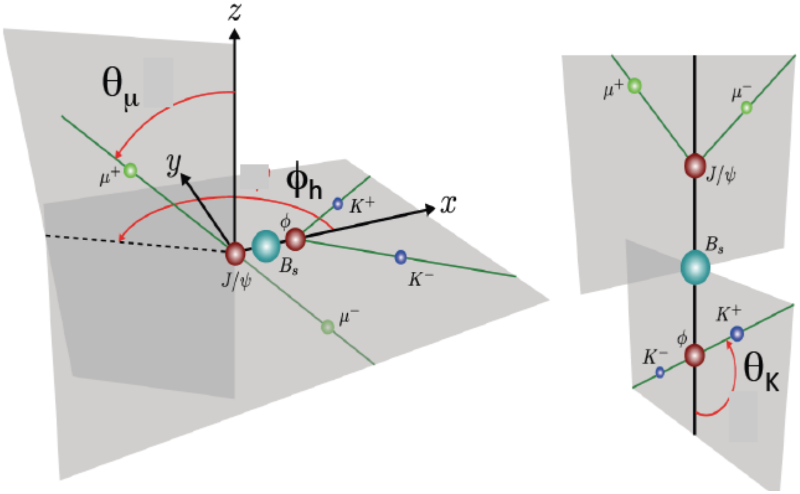


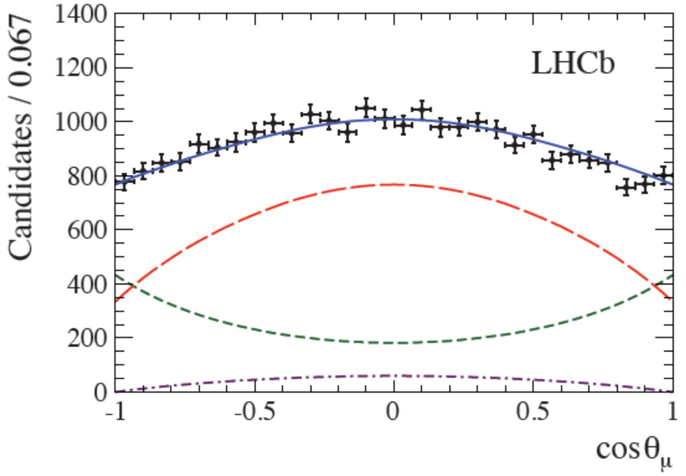
Decay width difference

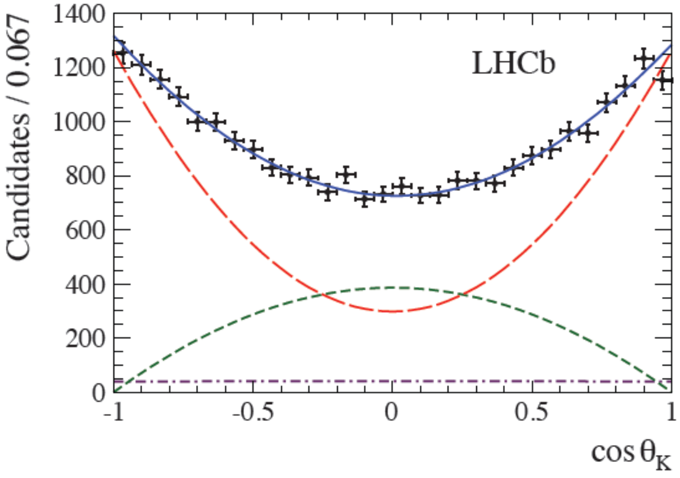
$$\Delta\Gamma_s = (\Gamma_L - \Gamma_H)$$
$$= 0.100 \pm 0.016(\text{stat.}) \pm 0.003(\text{syst.})/\text{ps}$$

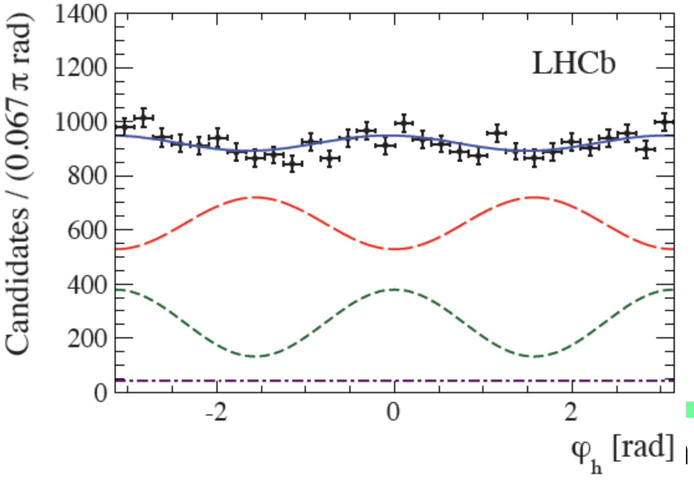
CP violation in $B_s \rightarrow J/\psi\ \phi$ decays

Two vector mesons in the final state (+ a non-resonant KK component): odd and even angular momenta → CP odd and even parity possible → have to combine CP violation measurement with an angular analysis





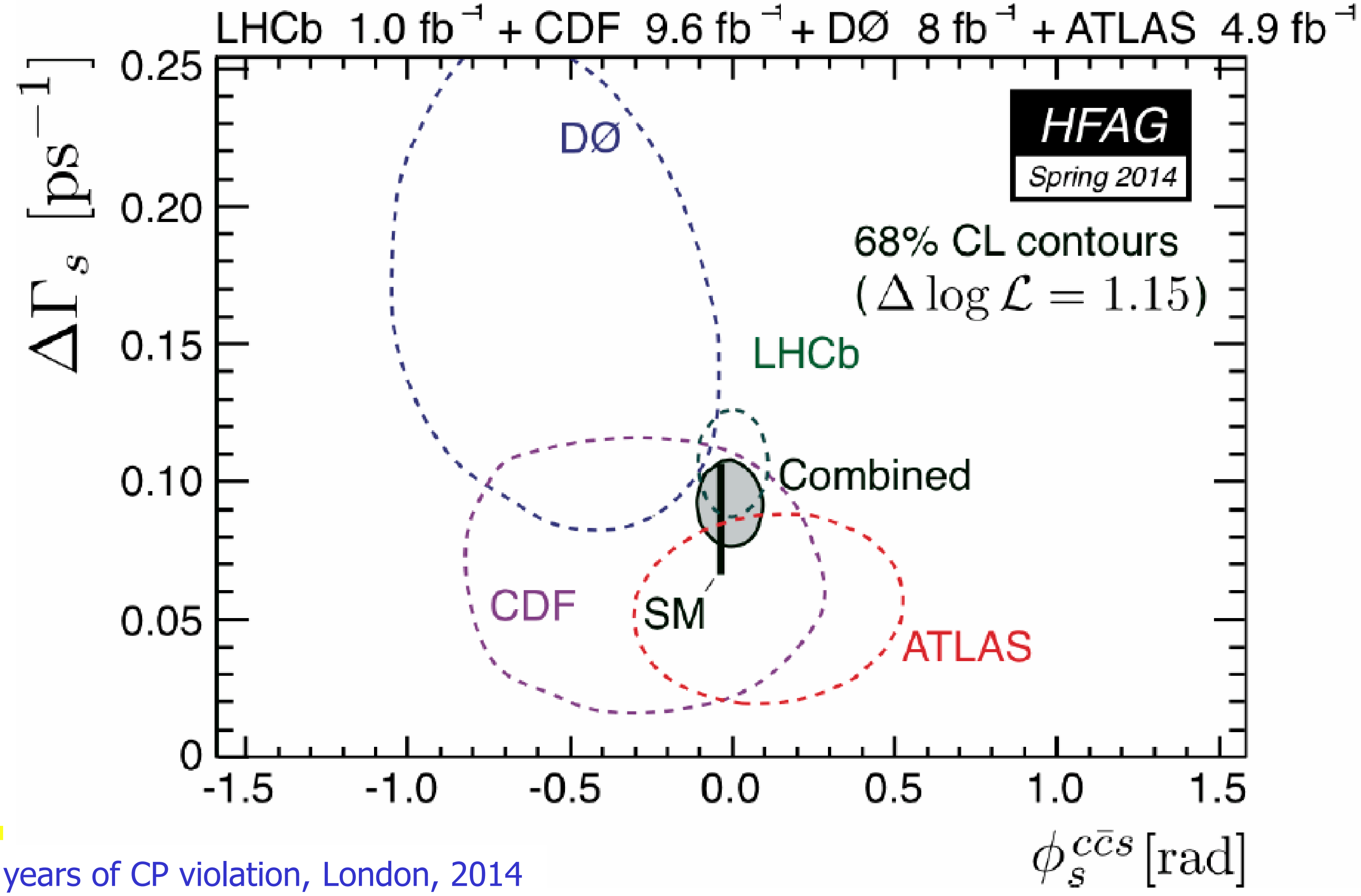




CP Even
CP Odd
S-wave (KK)

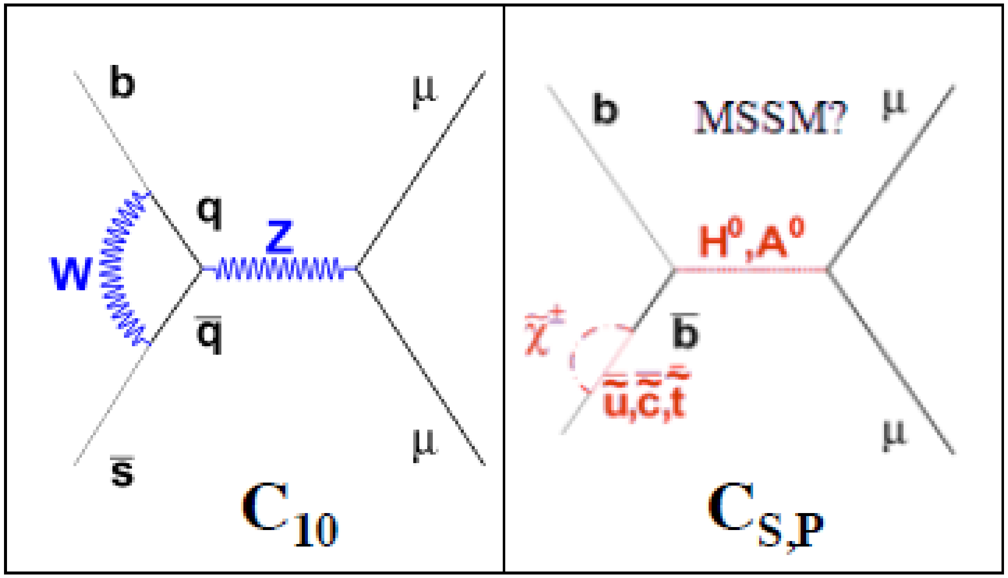
CP violation in $B_s \rightarrow J/\psi\ \phi$ decays

The power of a dedicated experiment: comparison of LHCb to the results from general purpose detectors.



New physics search in the decay $B_s \to \mu^+\mu^-$

Decay, very sensitive to the presence of New Physics (remember the role of K_L → μμ in getting an indication of the charm quark)



Standard Model prediction

$$BR_{SM} = (3.2 \pm 0.2) \times 10^{-9}$$

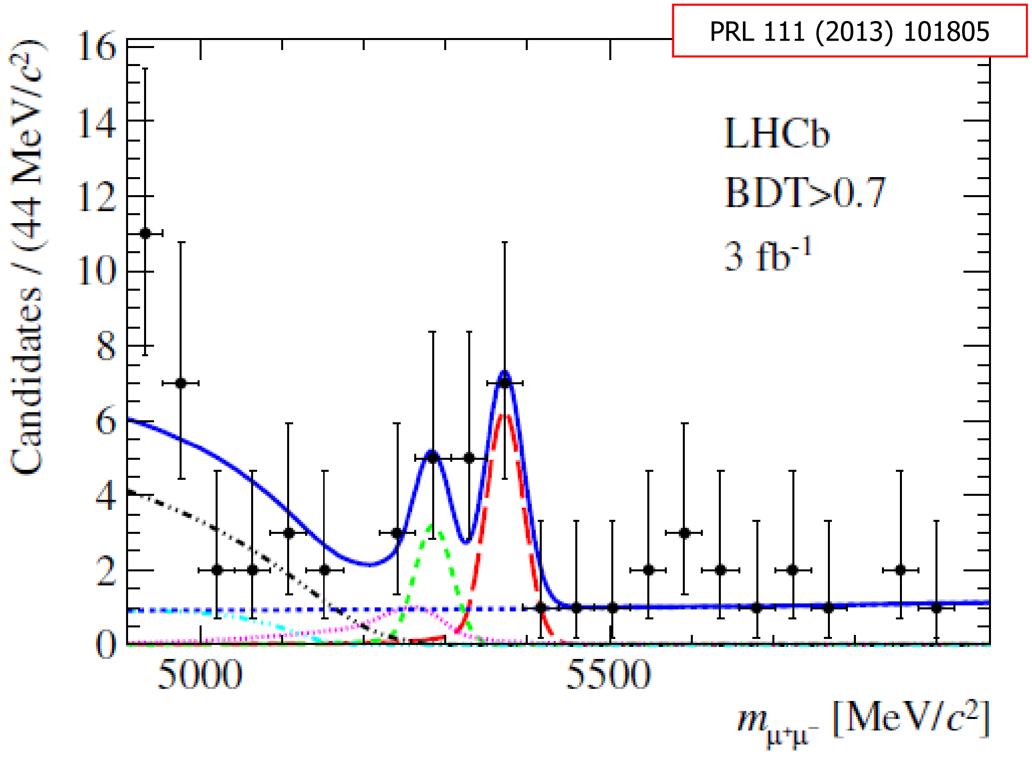
Buras et al., JHEP 10 (2010) 009

New physics search in the decay $\mathrm{B_s} \to \mu^+\mu^-$

Challenge: very very rare in SM

Advantage: extremly clear signature, two high transverse momentum muons

PRL 111 (2013) 101805



Result

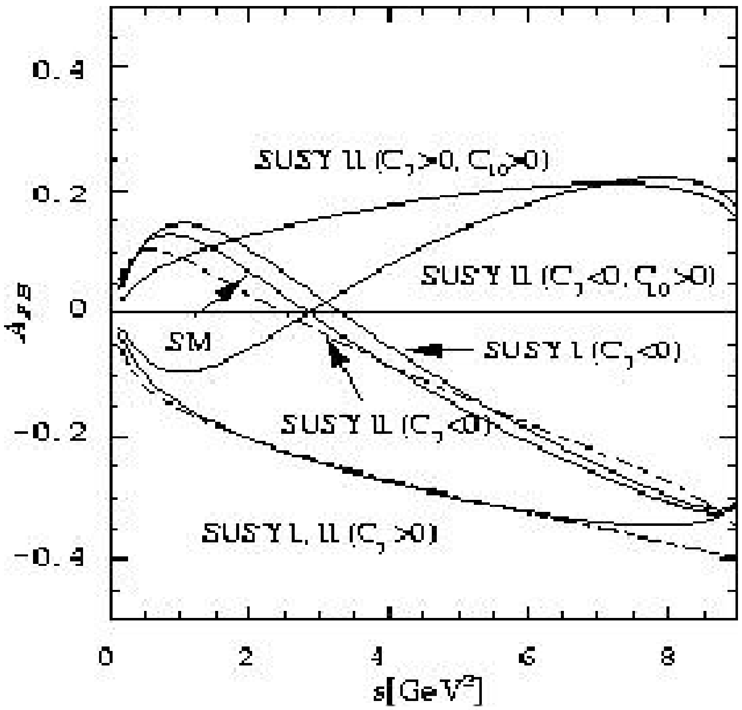
$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

In excellent agreement with SM prediction $\mathrm{BR_{SM}} = (3.2 \pm 0.2) \times 10^{-9}$

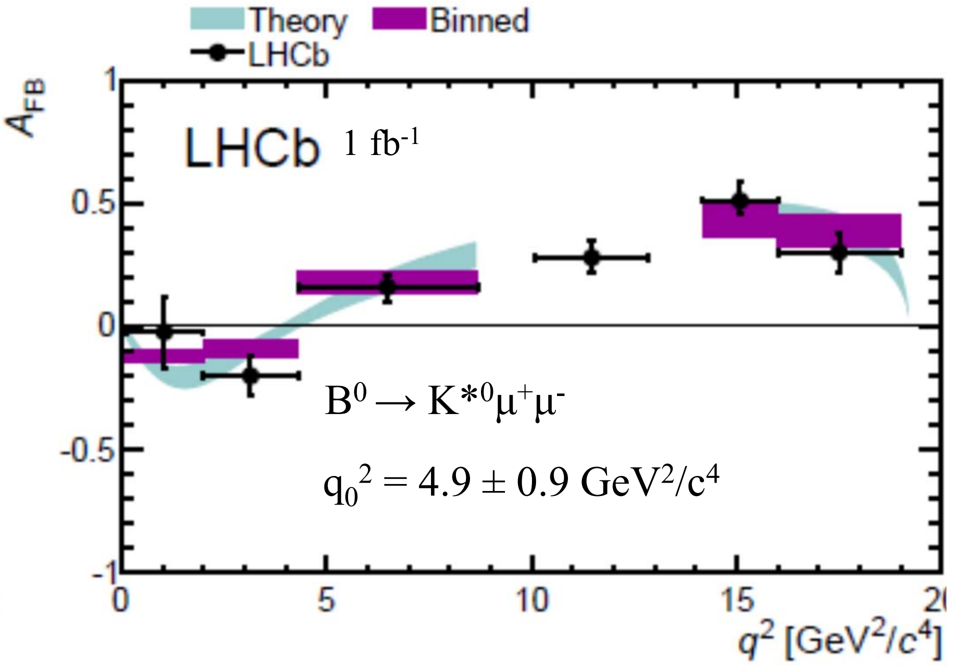
Buras et al., JHEP 10 (2010) 009

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

- Forward-backward asymmetry in the μμ rest frame $\boxed{A_{FB}(s)}$ is a sensitive probe of new physics
- SM: proceeds through a box diagram



- Sensitivity at 1 fb^{-1}: zero point crossing location to +-0.9 GeV^2

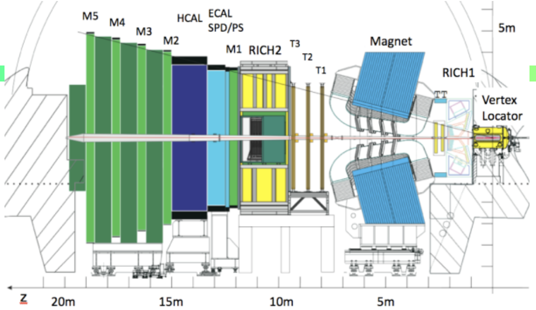


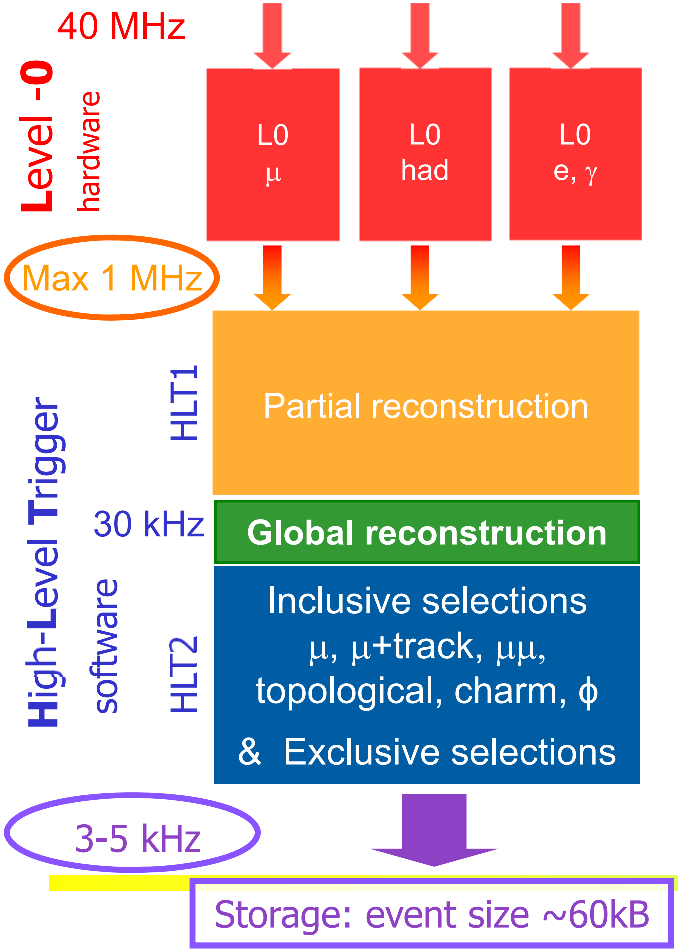
$B^0 \to K^{*0}\mu^+\mu^-$

$q_0^2 = 4.9 \pm 0.9\ GeV^2/c^4$

JHEP 1308 (2013) 131

LHCb Trigger – Limitations




40 MHz

Level -0 hardware

L0 μ

L0 had

L0 e, γ

Max 1 MHz

High-Level Trigger software

HLT1

Partial reconstruction

30 kHz

Global reconstruction

HLT2

Inclusive selections
μ, μ+track, $\mu\mu$,
topological, charm, ϕ
& Exclusive selections

3-5 kHz

Storage: event size ~60kB

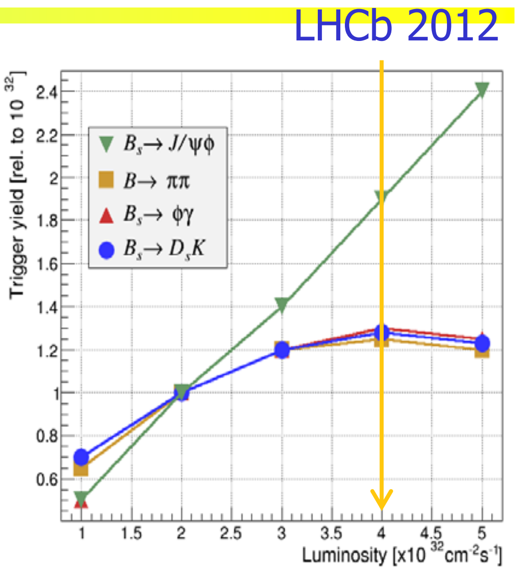
- Final states with muons

→ Linear gain

- Hadronic final states

→ Yield flattens out

→ Must raise p_T cut to stay within 1 MHz readout limit

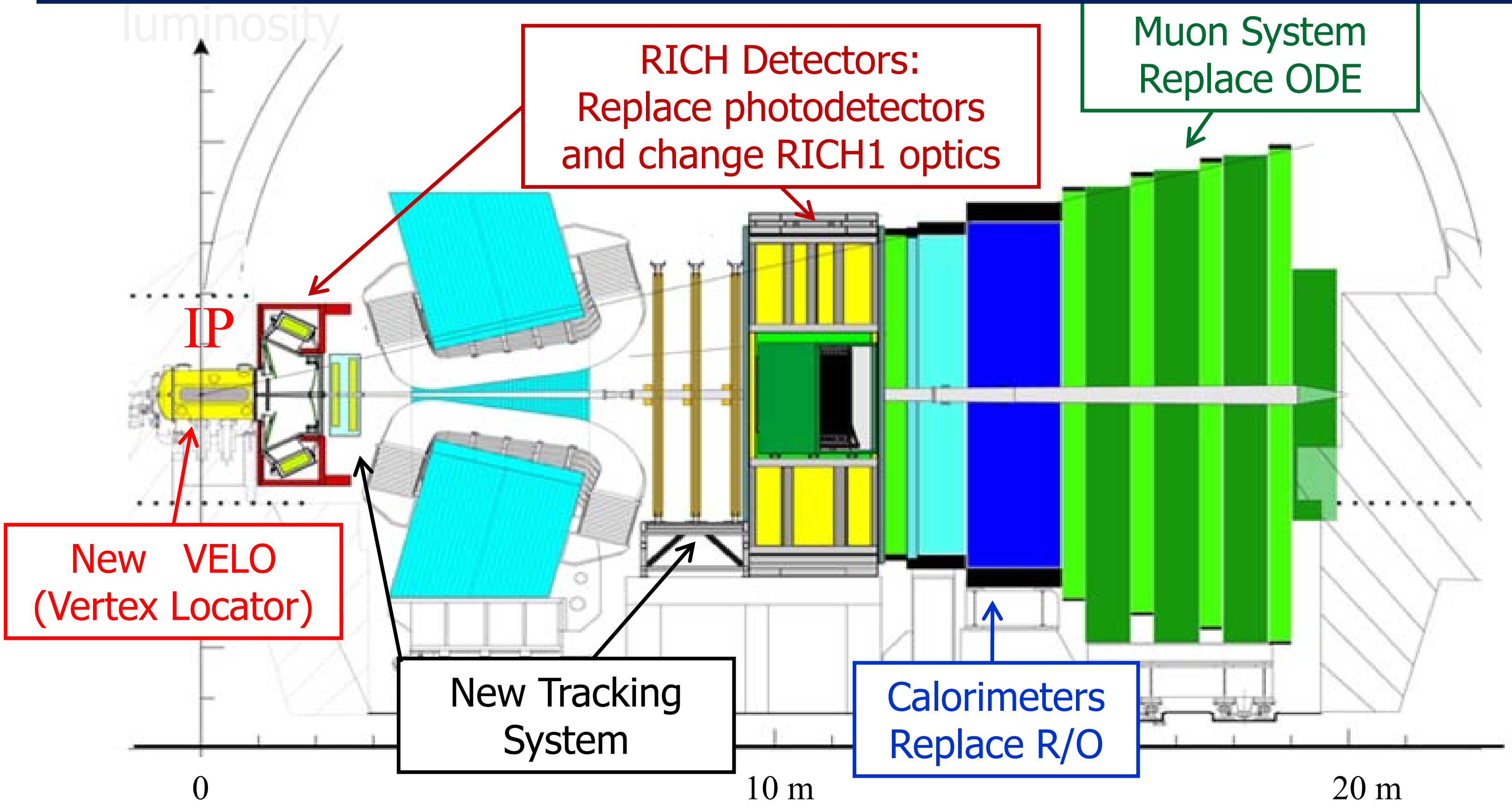


- To profit of a luminosity of 10^{33}cm^{-2}s^{-1}, information has to be introduced that is more discriminating than E_T.

Upgrade strategy:
40MHz readout rate
Fully software trigger
20kHz output rate

Detector upgrade to 40 MHz R/O

- upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- replace complete sub-systems with embedded FE electronics
- adapt sub-systems to increased occupancies due to higher luminosity
- keep excellent performance of sub-systems with 5 times higher luminosity



RICH Detectors:
Replace photodetectors
and change RICH1 optics

Muon System
Replace ODE

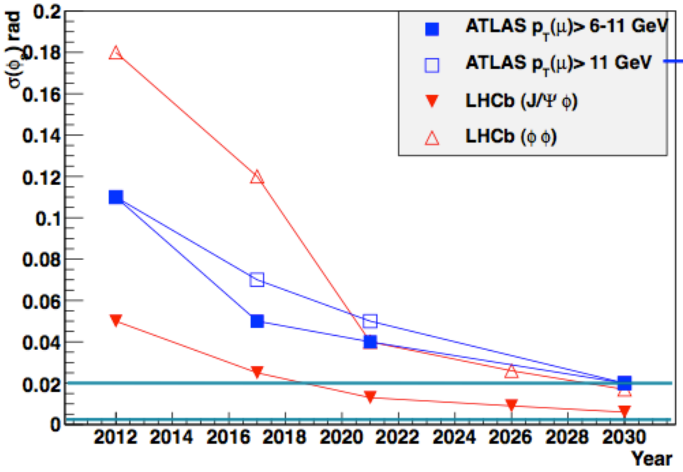
New VELO
(Vertex Locator)

New Tracking
System

Calorimeters
Replace R/O

LHCb upgrade - expected precision

B_s mixing phase ϕ_s

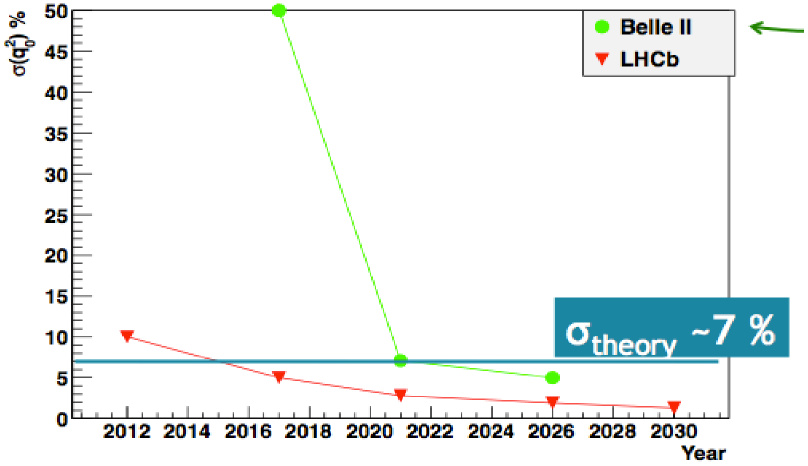


conservative

$\sigma^{\Phi\Phi}_{th}$ ~0.02

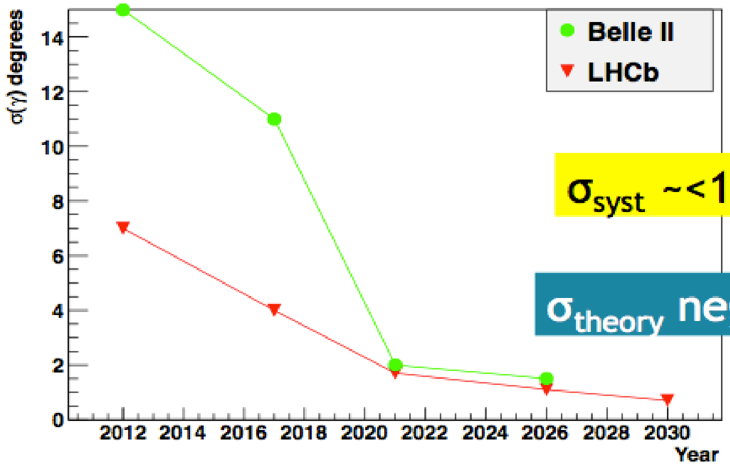
$\sigma^{J/\psi\Phi}_{th}$ ~0.003

q_0 from $B \to K^* ll$



σ_{theory} ~7 %

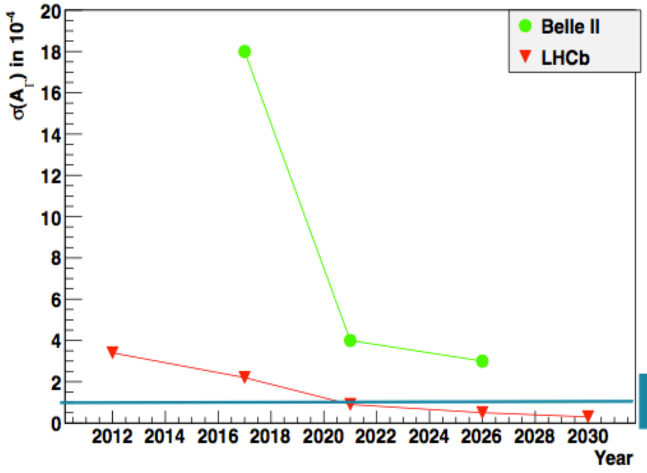
CKM angle γ from trees



σ_{syst} ~<1 °

σ_{theory} negligible

A_Γ: CPV in charm



SM ~10^{-4}

From M.H. Schune, ECFA HL-LHC 2013 workshop

Flavor physics at hadron machines -summary

- CDF and D0 at Tevatron: excellent B physics is possible even in the hostile environment of a hadorn collider
- HERA-B: first attempt to do precision physics at a hadron machine
- In the last four years, LHCb has contributed significantly to the progress in flavour physics, a number of very important results, some selected measurements also with ATLAS and CMS
- LHCb is ready for data taking in Run 2
- Preparations for the upgrade of LHCb well underway

Backup slides

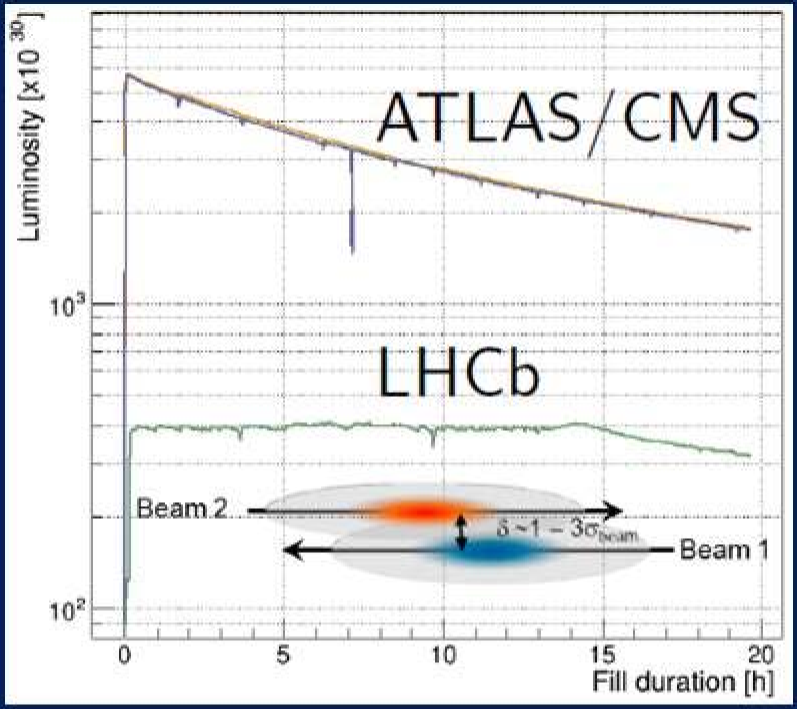
Why hadron machines?

Production	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$	$e^+e^- \to Z^0 \to b\bar{b}$	$pA \to b\bar{b}X$	$p\bar{p} \to b\bar{b}X$	$p\bar{p}(p) \to b\bar{b}X$ forward
Accelerator	CESR, DORIS PEPII, KEKB	LEP, SLD	HERA p	Tevatron	Tevatron, LHC
Spectrometer	CLEO, ARGUS BaBar, BELLE	ALEPH, DELPHI, L3, OPAL, SLD	HERA-B	CDF, D0	BTeV, LHCb
$\sigma(b\bar{b})$	≈ 1 nb	≈ 6 nb	≈ 12 nb	$\approx 50\ \mu$b	$\approx 100\ \mu$b ($\approx 500\ \mu$b)
$\sigma(b\bar{b}):\sigma(had)$	0.26	0.22	10^{-6}	10^{-3}	$2 \cdot 10^{-3}$ $(6 \cdot 10^{-3})$
B^0, B^+	yes	yes	yes	yes	yes
$B_s^0, B_c^+, \Lambda_b^0$	no	yes	yes	yes	yes
boost $< \beta\gamma >$	0.06 (0.5)	6	≈ 20	$\approx 2 - 4$	$\approx 4 - 20$
$b\bar{b}$ production	B's at rest (in c.m.s)	$b\bar{b}$ back-to-back	$b\bar{b}$ not back-to-back	$b\bar{b}$ not back-to-back	$b\bar{b}$ not back-to-back
multiple events	no	no	yes, 4	yes	yes, 2
trigger	inclusive	inclusive	lepton pairs (high p_t hadrons)	leptons only (high p_t hadrons)	displaced vertex

Expected luminosity evolution

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

LHC Run I	LS1	LHC Run II	LS 2	LHC Run III	LS3	LHC Run IV
pp runs with - 50ns bunch spacing - E_{CM} 7TeV and 8 TeV LHCb $\mathcal{L}$~$4x10^{32}/cm^2/s$ LHCb $\int\mathcal{L}$ ~3/fb	LHC splice consoli-dation	pp runs with - 25ns bunch spacing, - E_{CM} 13 TeV LHCb $\mathcal{L}$>$4x10^{32}/cm^2/s$ LHCb $\int\mathcal{L}$ >5/fb	LHC injector upgrade LHCb upgrade	pp runs with - 25ns b.spacing - E_{CM} 14 TeV $\mathcal{L} > 1x10^{33}/cm^2/s$ LHCb $\int\mathcal{L}$ > 15/fb	HL-LHC prep GPD phase 2 upgrades	$\mathcal{L}$=$2x10^{33}/cm^2/s$ $\int\mathcal{L}$ > 23/fb



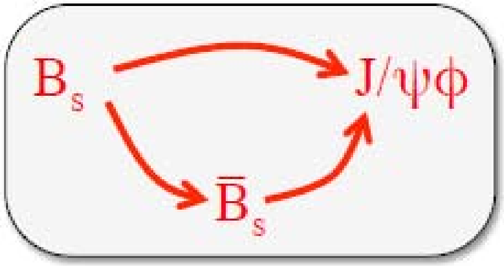
LHCb up to 2018 → ~ 8 fb^{-1}:

- find or rule-out large sources of flavour symmetry breaking at the TeV scale

LHCb upgrade → ≥ 50 fb^{-1}:

- increase precision on quark flavour physics observables
- aim at experimental sensitivities comparable to theoretical uncertainties

Mixing-induced CPV in $B_s \to J/\psi\phi$



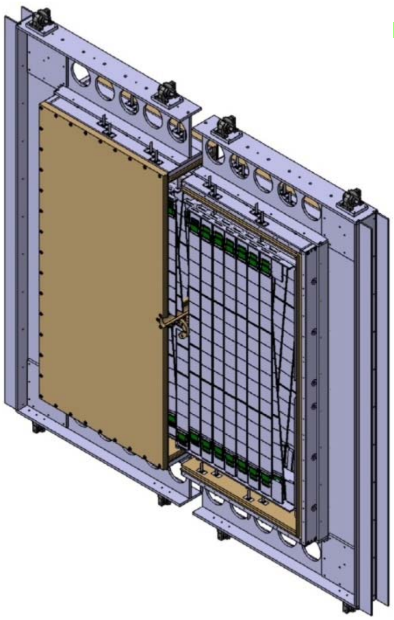
- ❑ $B_s \to J/\psi\phi$ is strange counterpart of $B^0 \to J/\psi K^0$
  - — ϕ_s = phase difference between the $B_s \to J/\psi\phi$ decay amplitudes without or with oscillation
  - — ϕ_s is the equivalent of the phase 2β for $B^0 \to J/\psi K_S$
- ❑ ϕ_s is small in SM, hence very sensitive to New Physics contributions to B_s mixing:

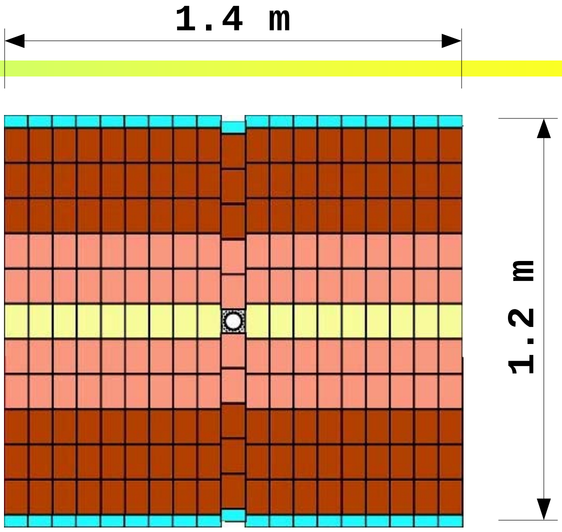
$$\boxed{\phi_s = \phi_s^{SM} + \phi_s^{NP}} \quad \text{with} \quad \phi_s^{SM} \cong -2\beta_s \equiv -2\arg\left(-\frac{\overbrace{V_{ts}V_{tb}^*}^{\text{mixing}}}{\underbrace{V_{cs}V_{cb}^*}_{\text{decay}}}\right) = -0.036 \pm 0.002$$

J. Charles et al.
PRD 84 (2011) 033005

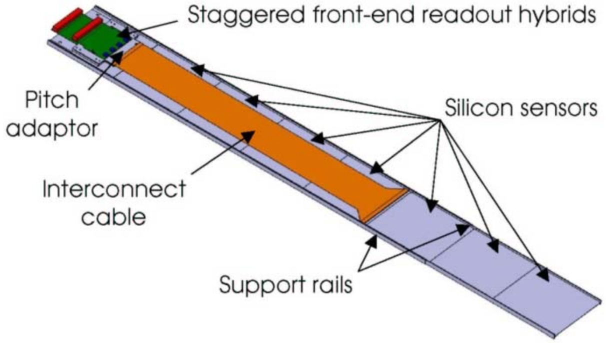
- ❑ Important differences between B_s and B^0 cases:
  - — $\Delta m_s >> \Delta m_d$ → need excellent proper time resolution to resolve oscillations
  - — $\Delta\Gamma_s >> \Delta\Gamma_d$ → access to $\cos\phi_s$ in addition to $\sin\phi_s$
  - — $B_s \to J/\psi\, KK$ final state is a mixture of CP-even and CP-odd eigenstates, with 4 contributing transversity amplitudes → need angular analysis
    - KK in P-wave state: amplitudes $A_\perp(t)$, $A_{//}(t)$, $A_0(t)$ → final state is CP-odd or CP-even
    - KK in S-wave state: amplitude $A_S(t)$ → final state is CP-odd

Trigger Tracker



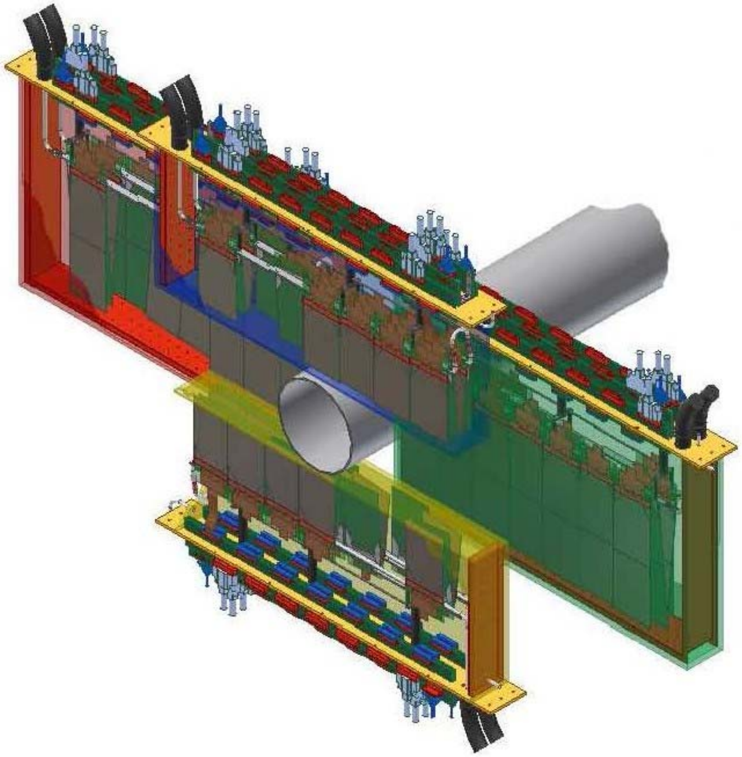


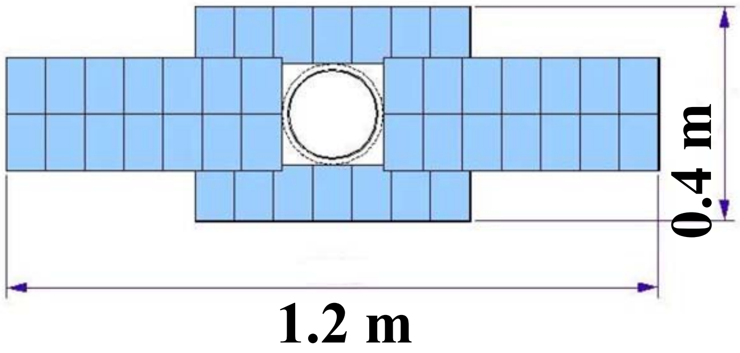
0° layer



- Microstrips silicon detector
  - Two groups of two layers (0°, +5°, -5°, 0°) separated by 30 cm
  - Strip pitch 198 μm
    Strip length 11, 22 and 33 cm
  - Radiation ≤ 9×10^{12} n_{eq}/cm^2 over 10 years
  - Cooled at -5 °C

T Station: inner tracker part

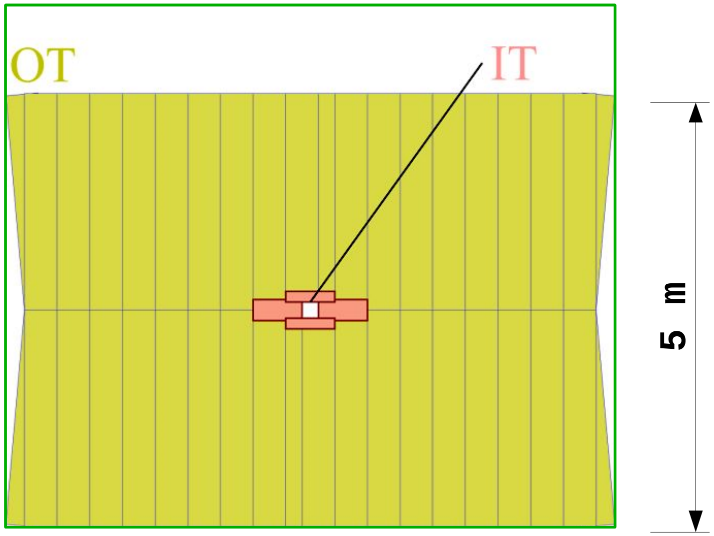


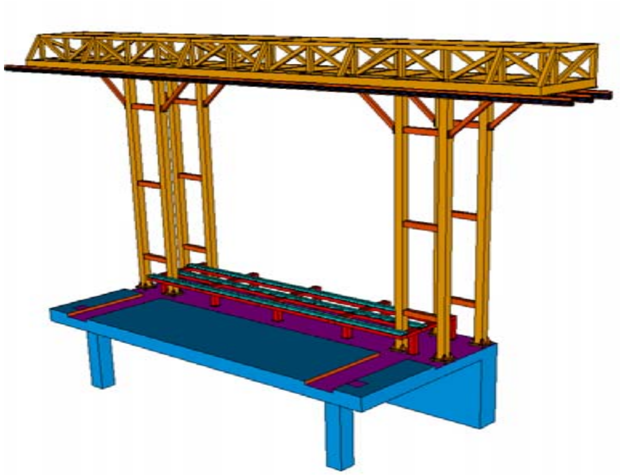


Microstrips silicon detector:

- Same sensors as Trigger Tracker
- Four layers (0°, +5°, -5°, 0°)
- Strip length 11, 22 cm
- Radiation ≤ 9×10^{12} n_{eq}/cm^2 over 10 years
- Cooled -5 °C

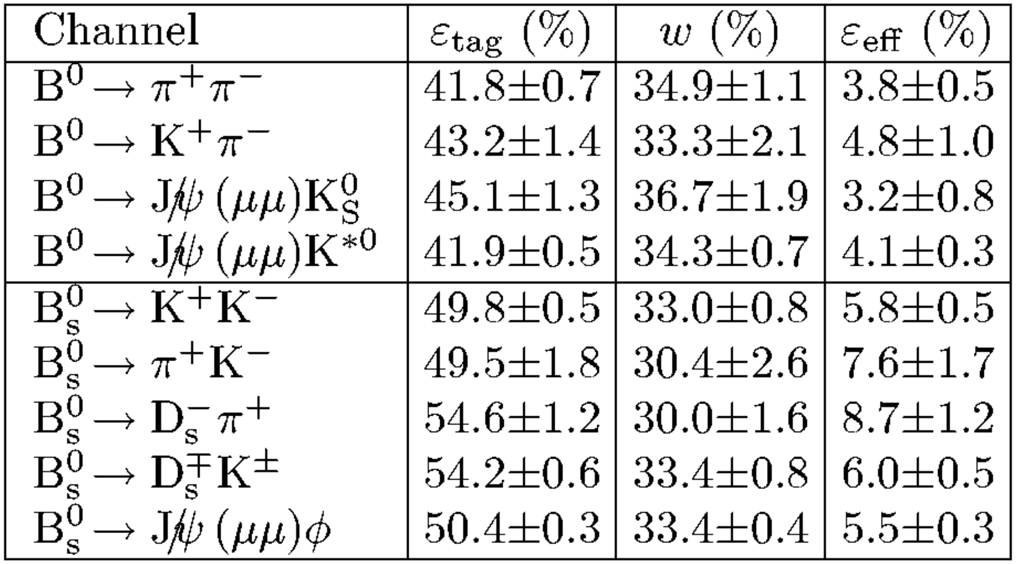
T station: outer tracker part





- Straw tubes:
  - Four double layers (0°,+5°,-5°,0°)
  - Staw length 5 m read on both sides
  - $Ar/CF_4/CO_2$

Performance of Flavour Tagging



Channel	$\varepsilon_{\rm tag}$ (%)	w (%)	$\varepsilon_{\rm eff}$ (%)
$B^0 \to \pi^+\pi^-$	41.8±0.7	34.9±1.1	3.8±0.5
$B^0 \to K^+\pi^-$	43.2±1.4	33.3±2.1	4.8±1.0
$B^0 \to J/\psi\,(\mu\mu)K^0_S$	45.1±1.3	36.7±1.9	3.2±0.8
$B^0 \to J/\psi\,(\mu\mu)K^{*0}$	41.9±0.5	34.3±0.7	4.1±0.3
$B^0_s \to K^+K^-$	49.8±0.5	33.0±0.8	5.8±0.5
$B^0_s \to \pi^+K^-$	49.5±1.8	30.4±2.6	7.6±1.7
$B^0_s \to D_s^-\pi^+$	54.6±1.2	30.0±1.6	8.7±1.2
$B^0_s \to D_s^\mp K^\pm$	54.2±0.6	33.4±0.8	6.0±0.5
$B^0_s \to J/\psi\,(\mu\mu)\phi$	50.4±0.3	33.4±0.4	5.5±0.3

- Effective tagging efficiencies vary between 3 and 9% depending on the final state.
- The wrong tag fraction is measured using control channels with similar topology, e.g.

$$B_d \to J/\psi K^{*0} \text{ for } B_d \to J/\psi K_S$$

N.B. Effective tagging efficiencies is **>30%** at B factories, ~2% at CDF/D0

HERA-B Summary 2

First LHC like experiment before the LHC → messages for the LHC experiments

-do not use micro-strip gas chambers (MSGC)

-large area trackers are not easy

-trigger processors can get saturated by high occupancy events which are not necessarily interesting

-RICH counters are more robust than anticipated

-retractable SVD works reliably