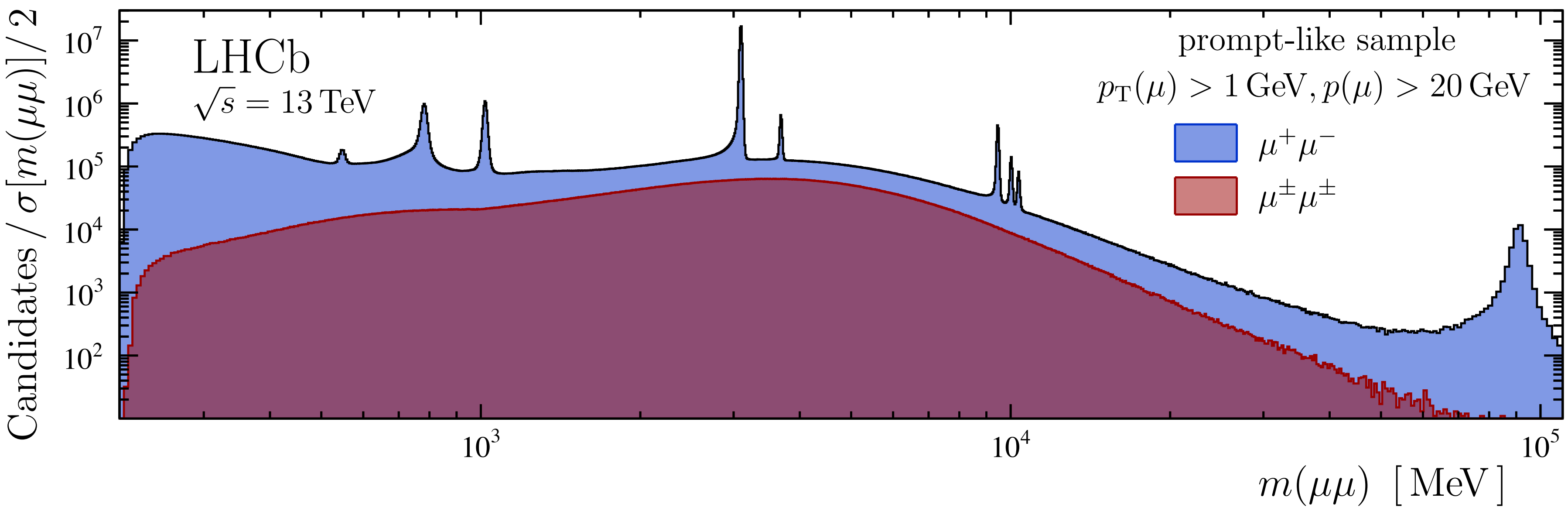


Physics at the LHC - WS 2021-2022

Flavour physics at the LHC

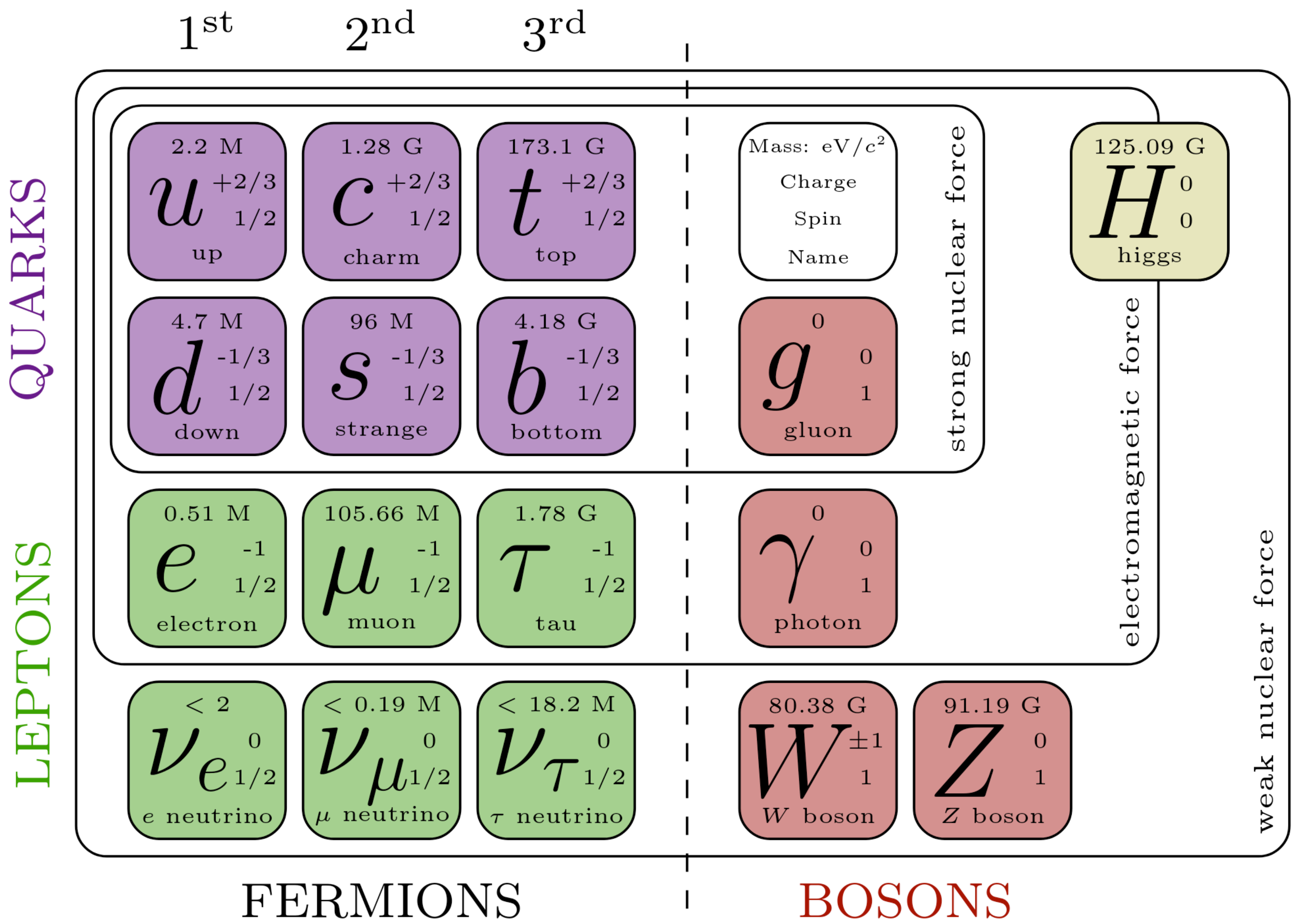
Martino Borsato

Credits/references

- **P.Owen lecture at HCPSS2021**
- **M.Williams LHCb StarterTalk**
- **LHCb detector performance paper**

Lecture 1/4 - Monday Jan 10th 2022

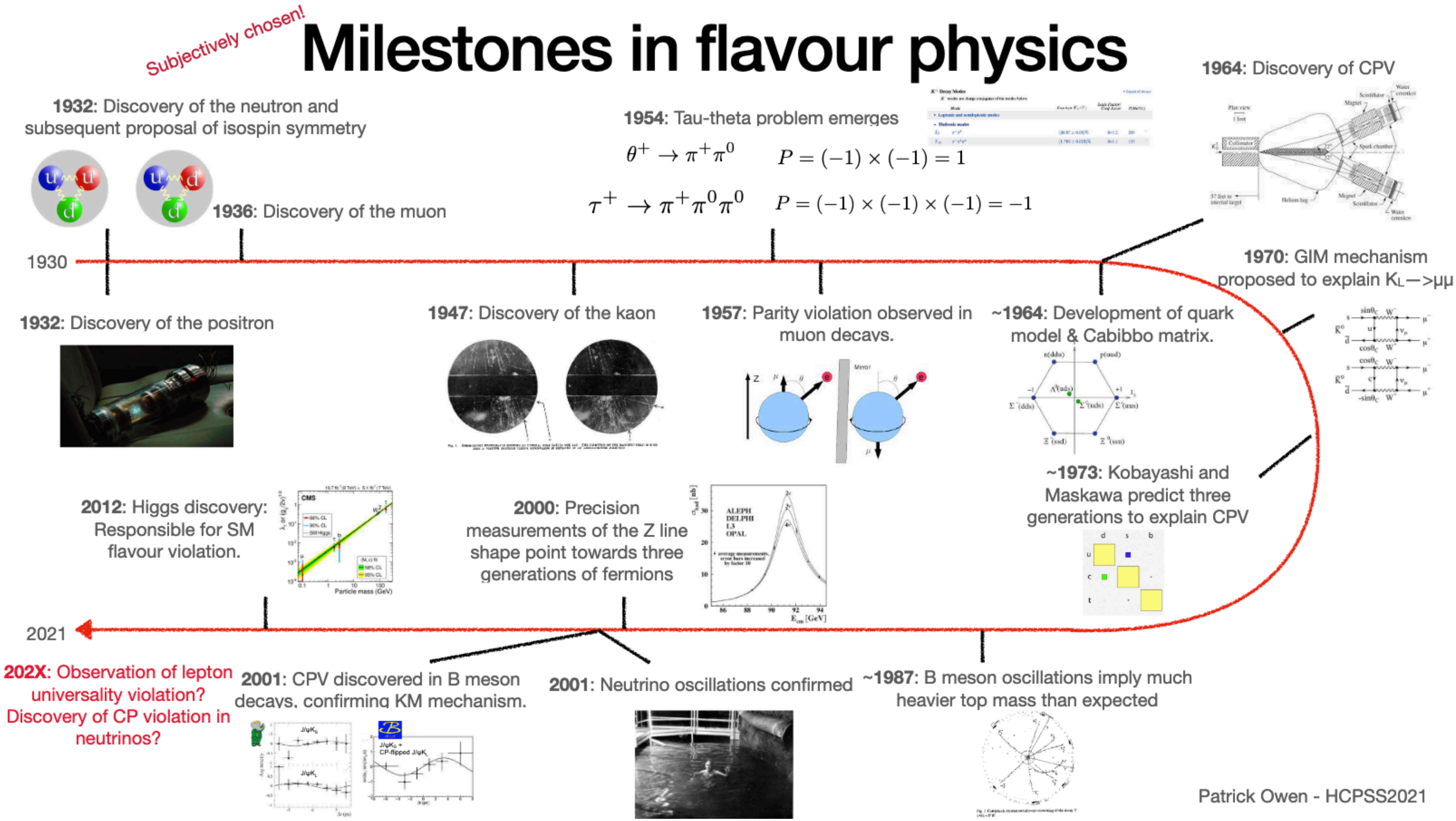
Flavour physics



Flavour physics

- Try to answer questions such as:
  - How often does a beauty quark transition into an up quark?
  - Does a charm meson behave similarly to its anti-particle?
  - How many flavours are there?
  - Are the charged leptons just heavier copies of each other?
  - What are the mass eigenstates of the neutrinos?
- …but also hadron spectroscopy
  - Mesons, baryons, tetraquarks, pentaquarks

The history of flavour physics



Flavour physics nowadays

- Flavour is ugly (unnatural?)
  - Gauge sector has 3 couplings of O(1)
  - Higgs sector has 15 parameters parameters with values spanning 6 orders of magnitude
- Where did the antimatter go?
  - Quark mizing only source of CP violation
  - Connection with baryogenesis?
- Reach high energy indirectly
  - Precision frontier vs energy frontier
  - Physics at high energy might have different flavour structure

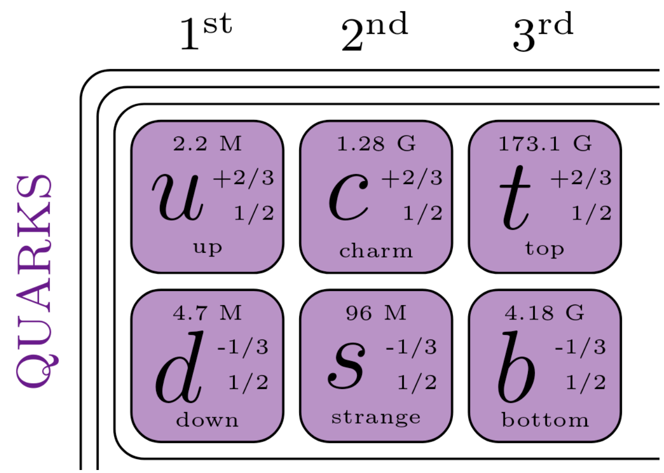
Flavour

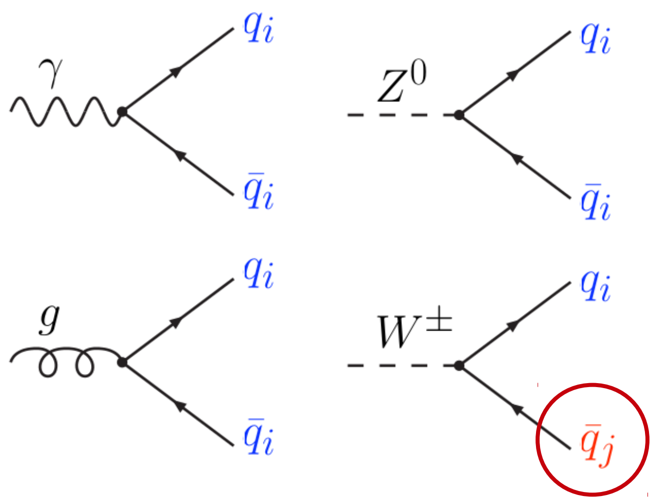
Parameters of the Standard Model

#	Symbol	Description	Renormalization scheme (point)	Value
1	m_e	Electron mass		0.511 MeV
2	m_μ	Muon mass		105.7 MeV
3	m_τ	Tau mass		1.78 GeV
4	m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
5	m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
6	m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
7	m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
8	m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
9	m_t	Top quark mass	On shell scheme	173.5 GeV
10	θ_{12}	CKM 12-mixing angle		13.1°
11	θ_{23}	CKM 23-mixing angle		2.4°
12	θ_{13}	CKM 13-mixing angle		0.2°
13	δ	CKM CP violation Phase		0.995
14	g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
15	g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
16	g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
17	θ_{QCD}	QCD vacuum angle		~0
18	v	Higgs vacuum expectation value		246 GeV
19	m_H	Higgs mass		125.09 ±0.24 GeV

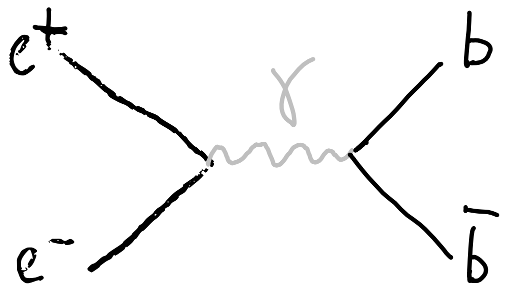
Flavour physics nowadays

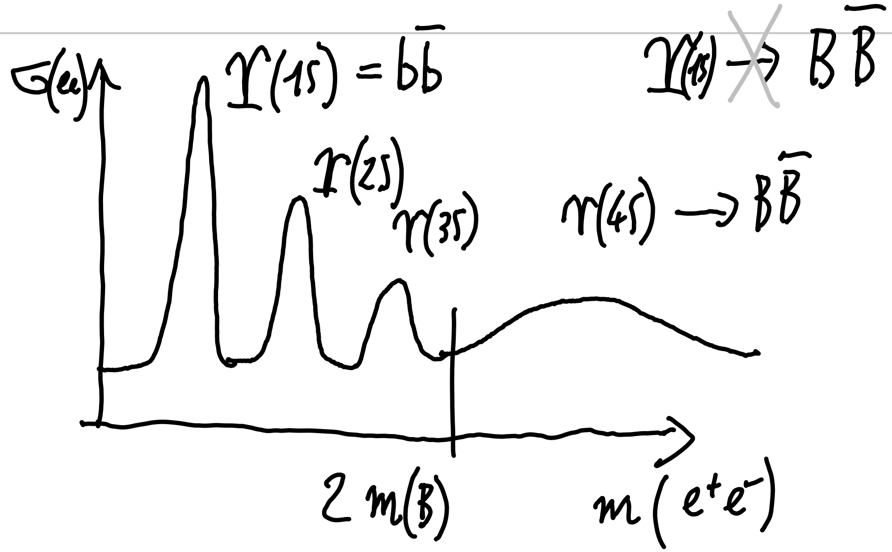
- Beauty hadrons
  - b-quark heaviest that hadronises
  - Far from QCD scale
    → perturbative calculations
  - Heavy enough to decay in a lot of different final states
  - Decays by changing flavour
    → involves virtual heavy W
- How do we study B physics?





The B factories



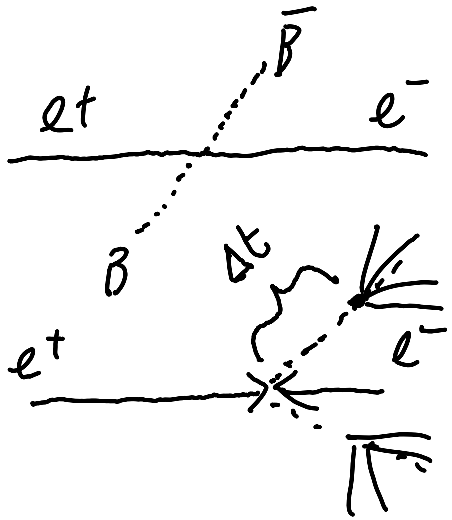


$$\sigma(ee \to B\bar{B}) = 10^{-3}\,\mu b$$

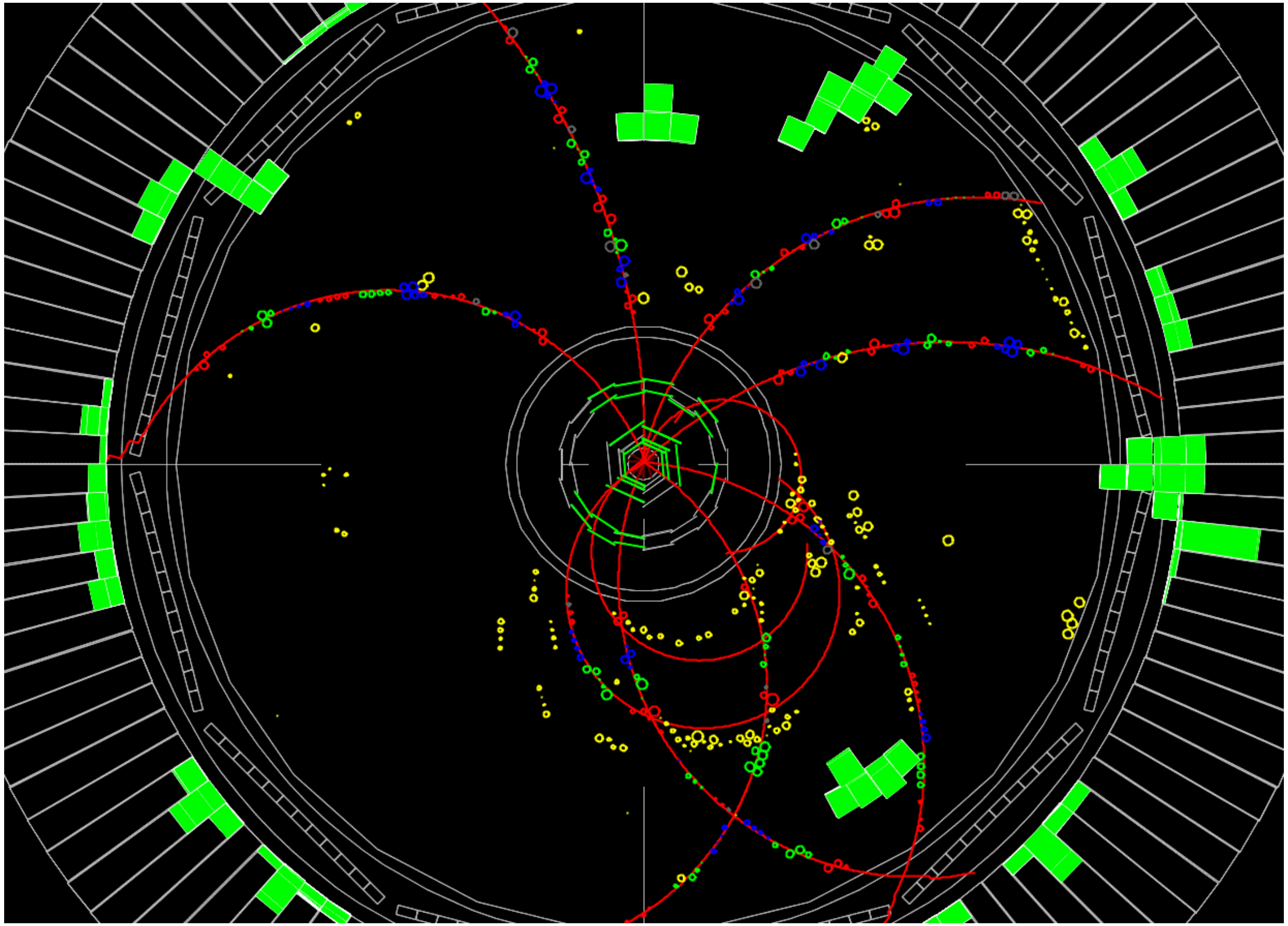
$$\mathcal{L} = 2 \cdot 10^{34}\ cm^2/s$$

$$\frac{N_{B\bar{B}}}{s} = \sigma \cdot \mathcal{L} = 20/s$$

$$\tau(B) = 1.5\ ps$$

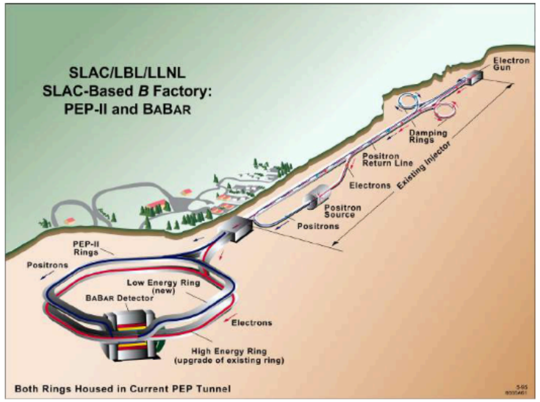


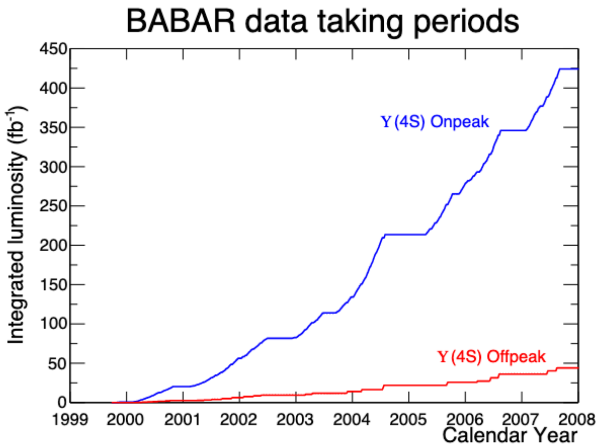
The B factories



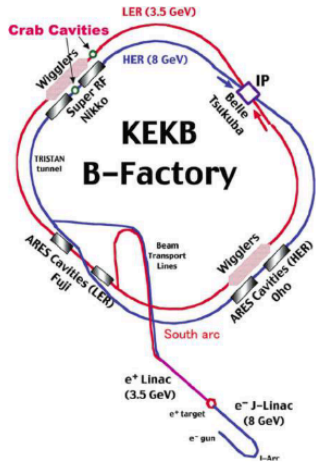
The B factories

BABAR 1999-2008

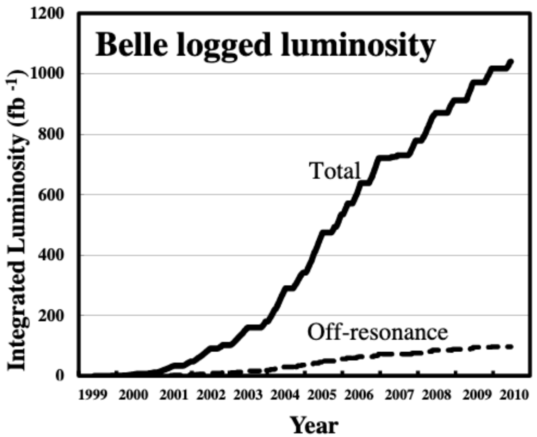




BELLE 1999-2010



[1406.6311]



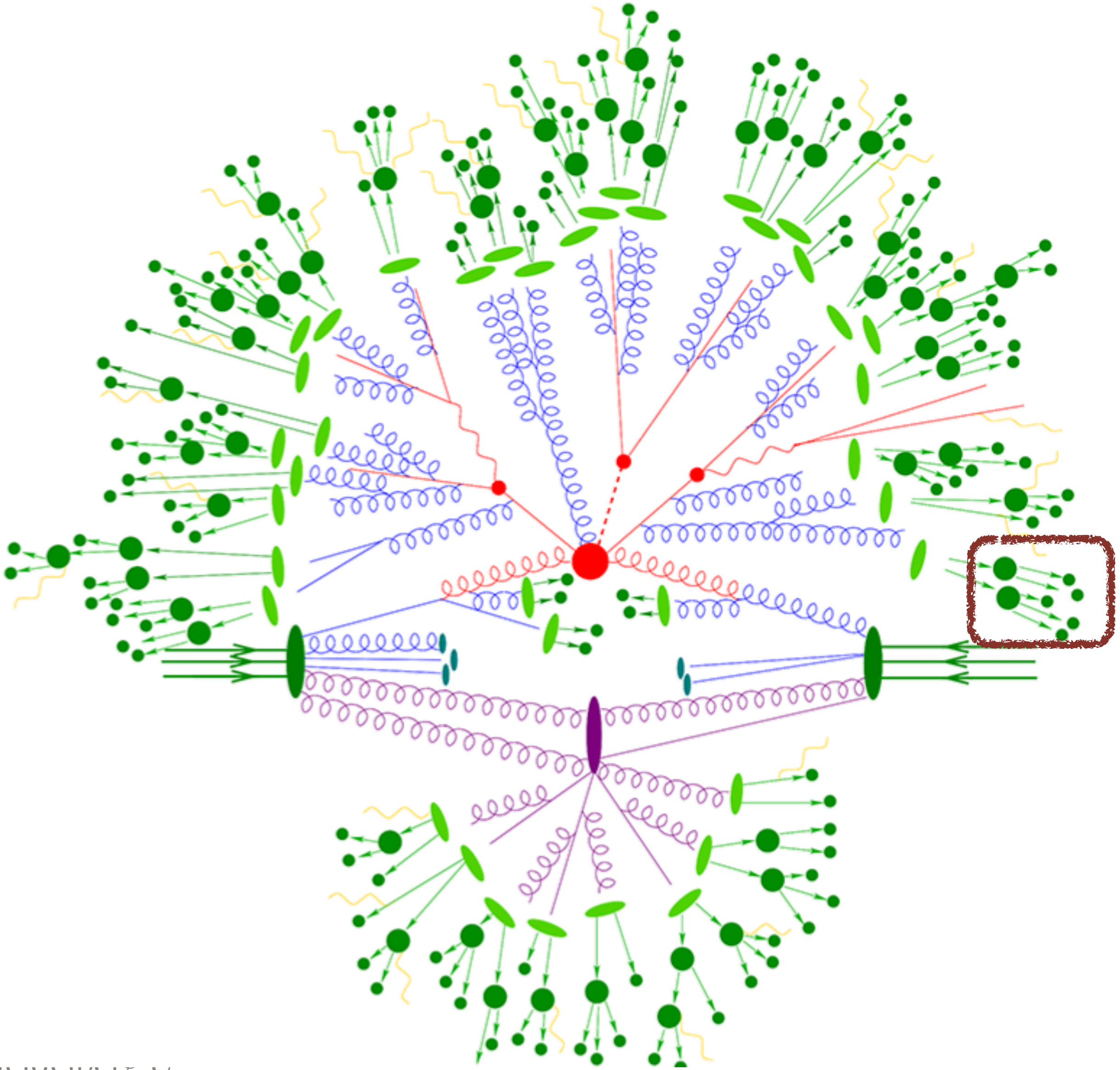
b production at the LHC

$$\sigma(pp \to b\bar{b}X) \approx 500\ \mu b \quad @\ 13\,\text{TeV}$$

$$\mathcal{L} = 10^{34}\ \text{cm}^2/s$$

$$\frac{N_{b\bar{b}}}{s} = \sigma \cdot \mathcal{L} = \frac{500 \cdot 10^4}{s} = \frac{5M}{s}$$

b production at the LHC

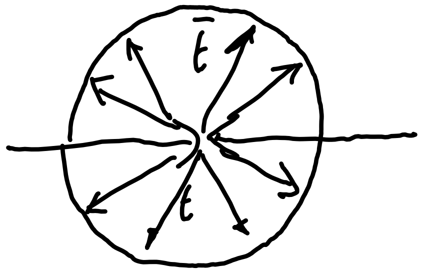


What LHCb is interested on

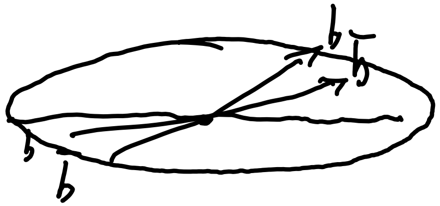
$b\bar{b}$ forward production

- PARTONS CARRY A FRACTION OF ENERGY

- $pp \to t\bar{t}X$



- $pp \to b\bar{b}X$

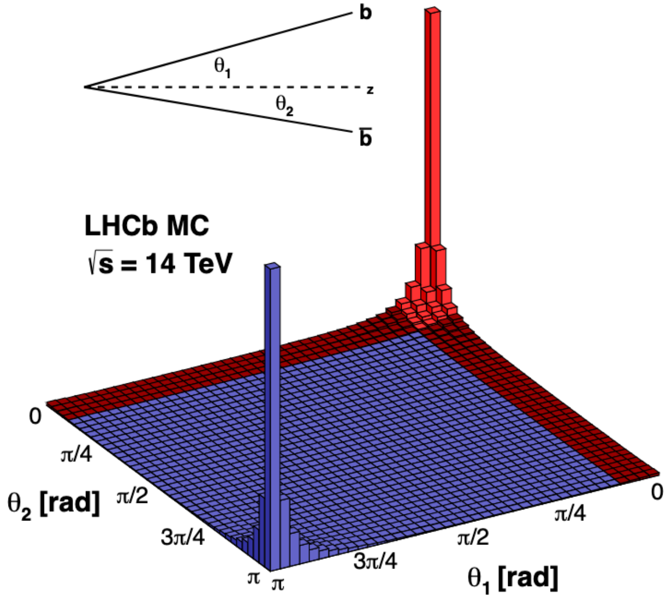


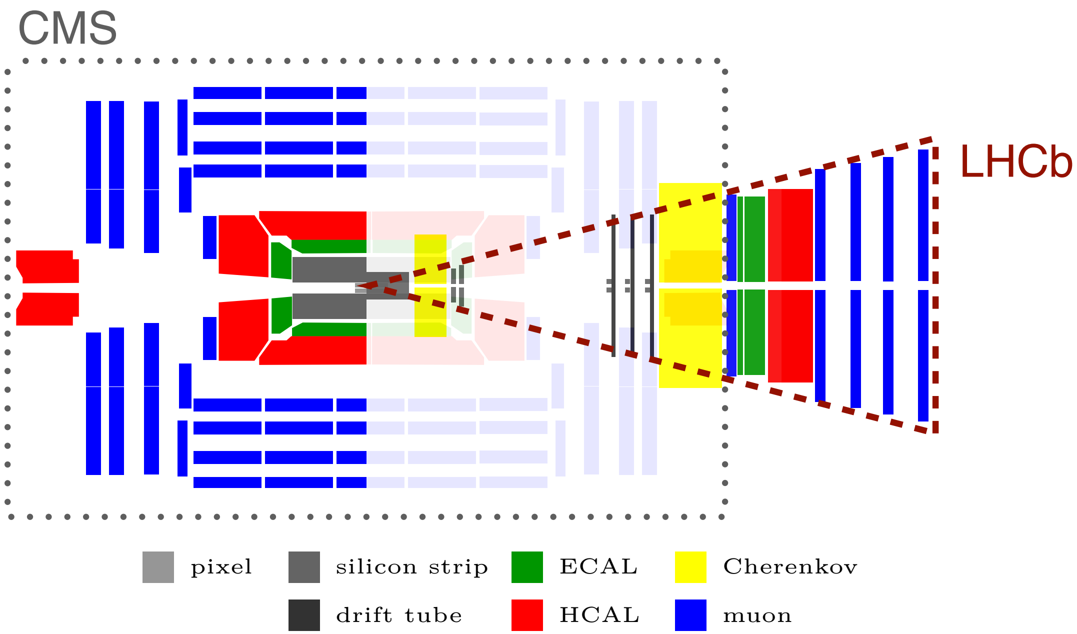
$\beta\gamma \sim 20 \qquad \tau(B) \sim 1.5\,ps$

$$c = 0.3\ \frac{mm}{ps}$$

$$\Delta z = c\tau\beta\gamma = 9\ mm$$

LHCb forward geometry

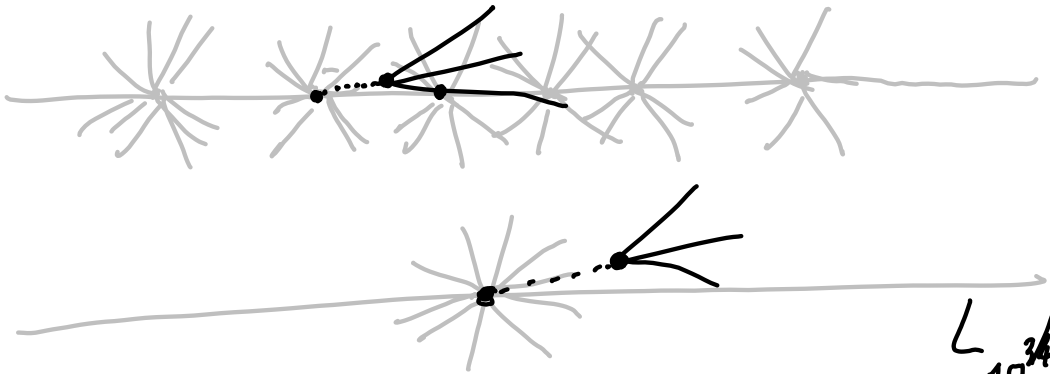




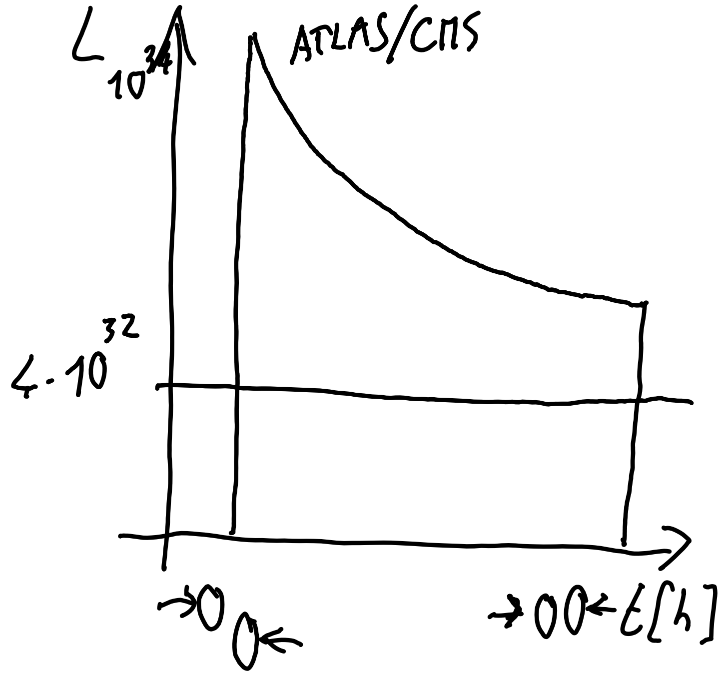
- LHCb covers $2 < \eta < 5$ (forward only)
  - 3% of 4π solid angle $\propto$ price
  - 25% of $b\bar{b}$ production $\propto$ physics

LHCb forward geometry

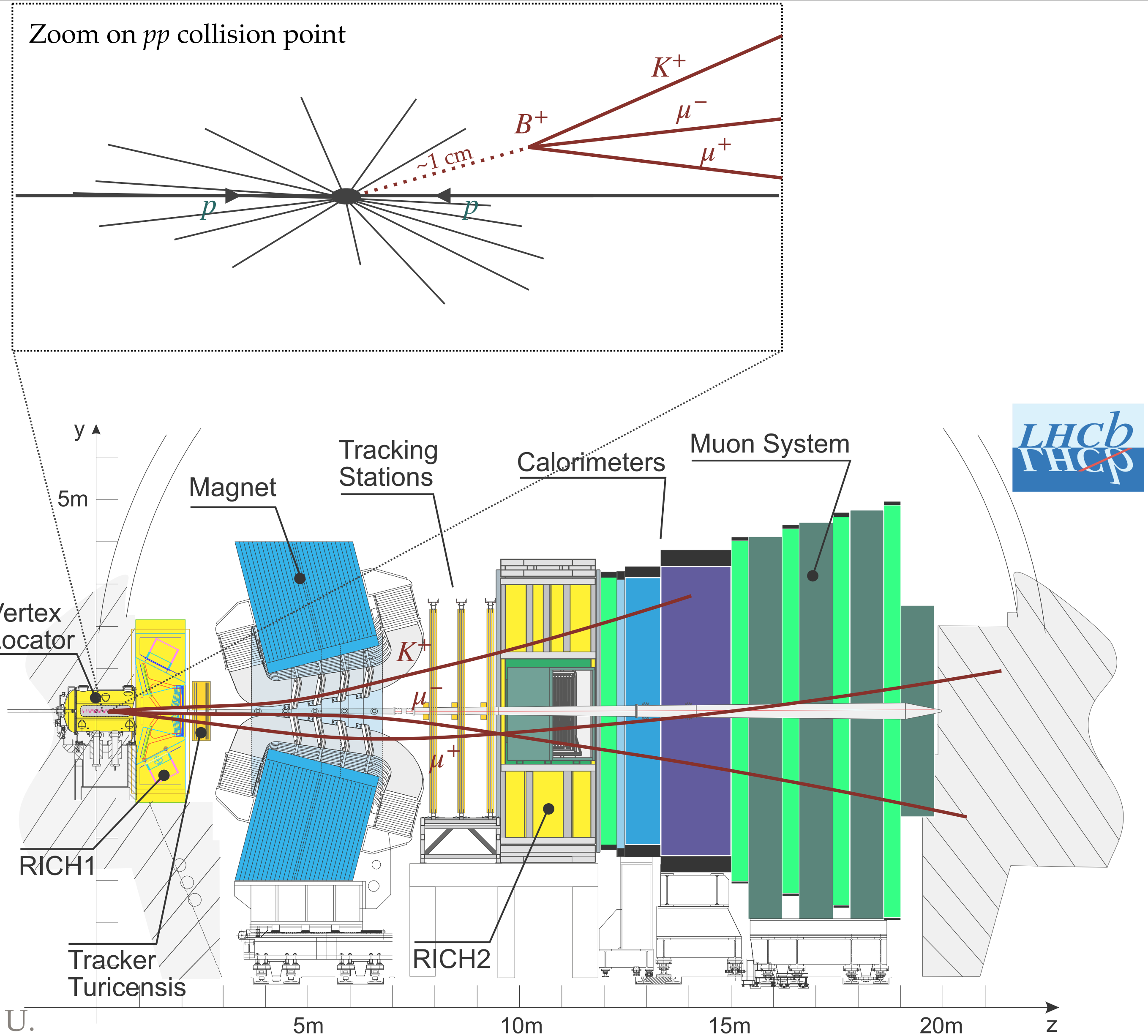
Pile up



→ LUMINOSITY LEVELLING



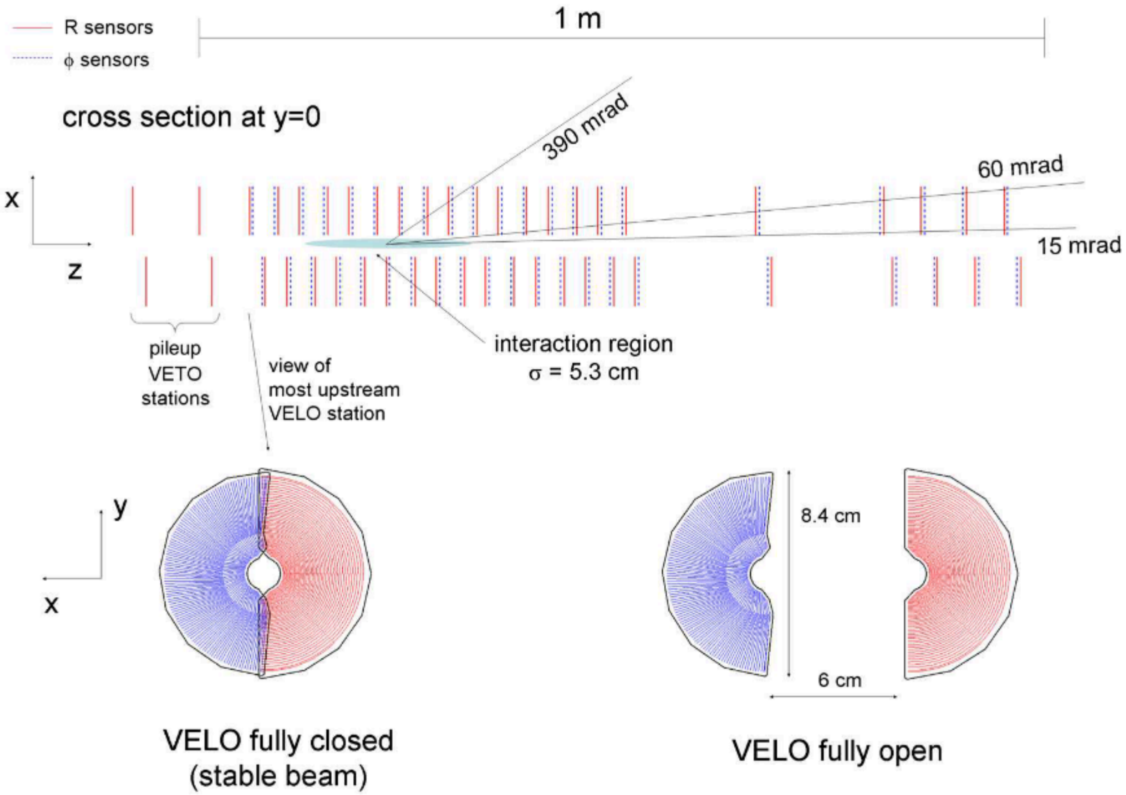
LHCb subdetectors



Vertexing

- Displaced vertex is signature of weak decay of heavy-flavour
  - Key to separate *B* decay products from rest of the event
- Displacement (and momentum) is a measurement of decay time
  - Key to measure fast meson oscillations
- Precise vertexing obtained by placing tracker modules as close as possible to *pp* collision point
  - Dangerous high-multiplicity region

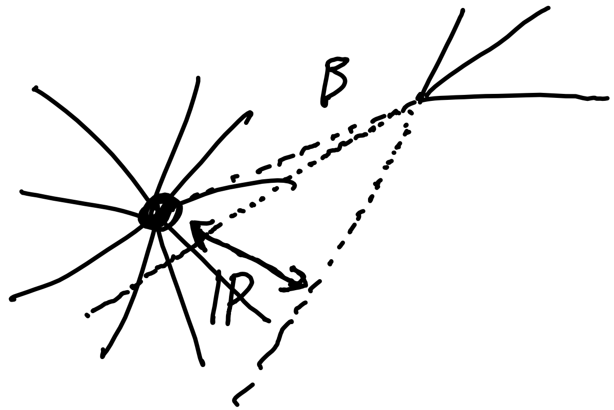
The LHCb Vertex Locator (VELO)



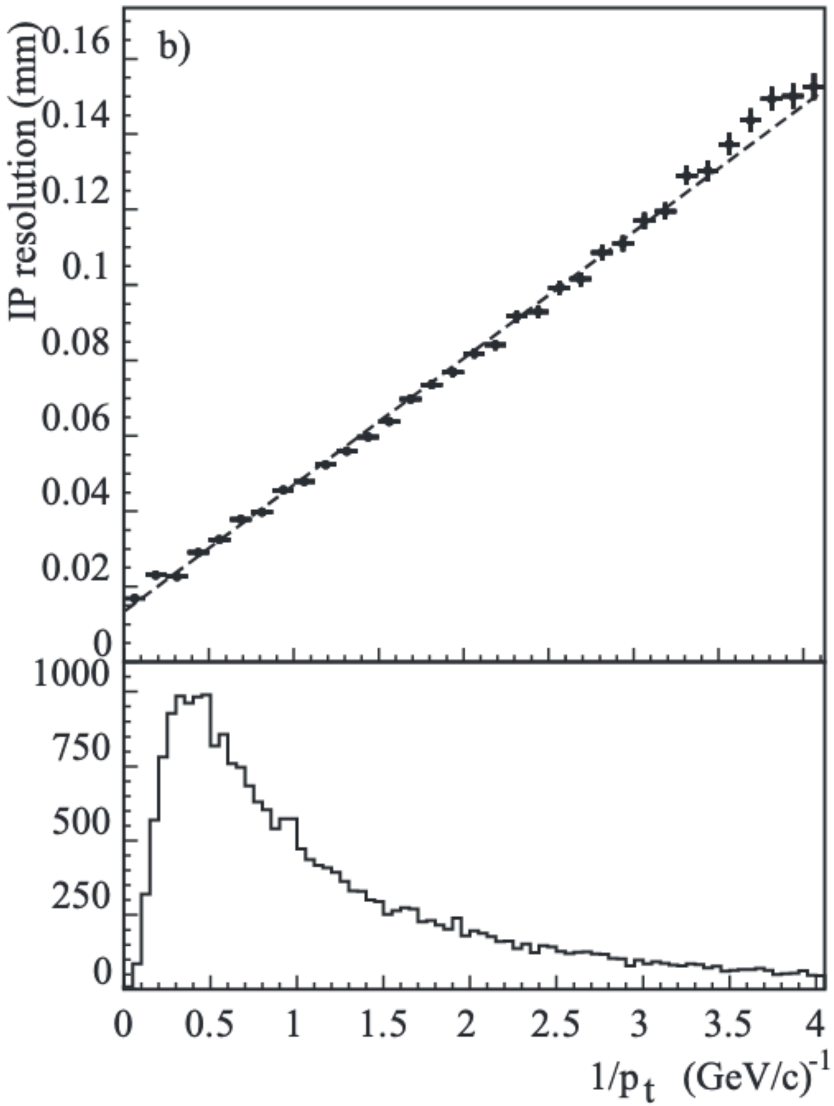
Vertexing: impact parameter

IP

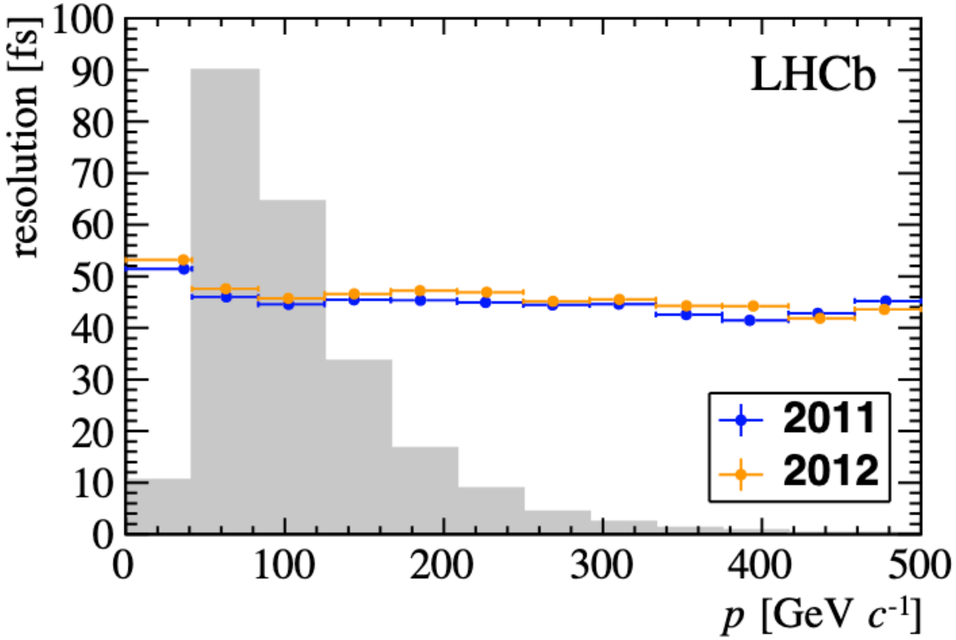
1) multiple scattering
2) hit resolution
3) track extrapolation



Vertexing

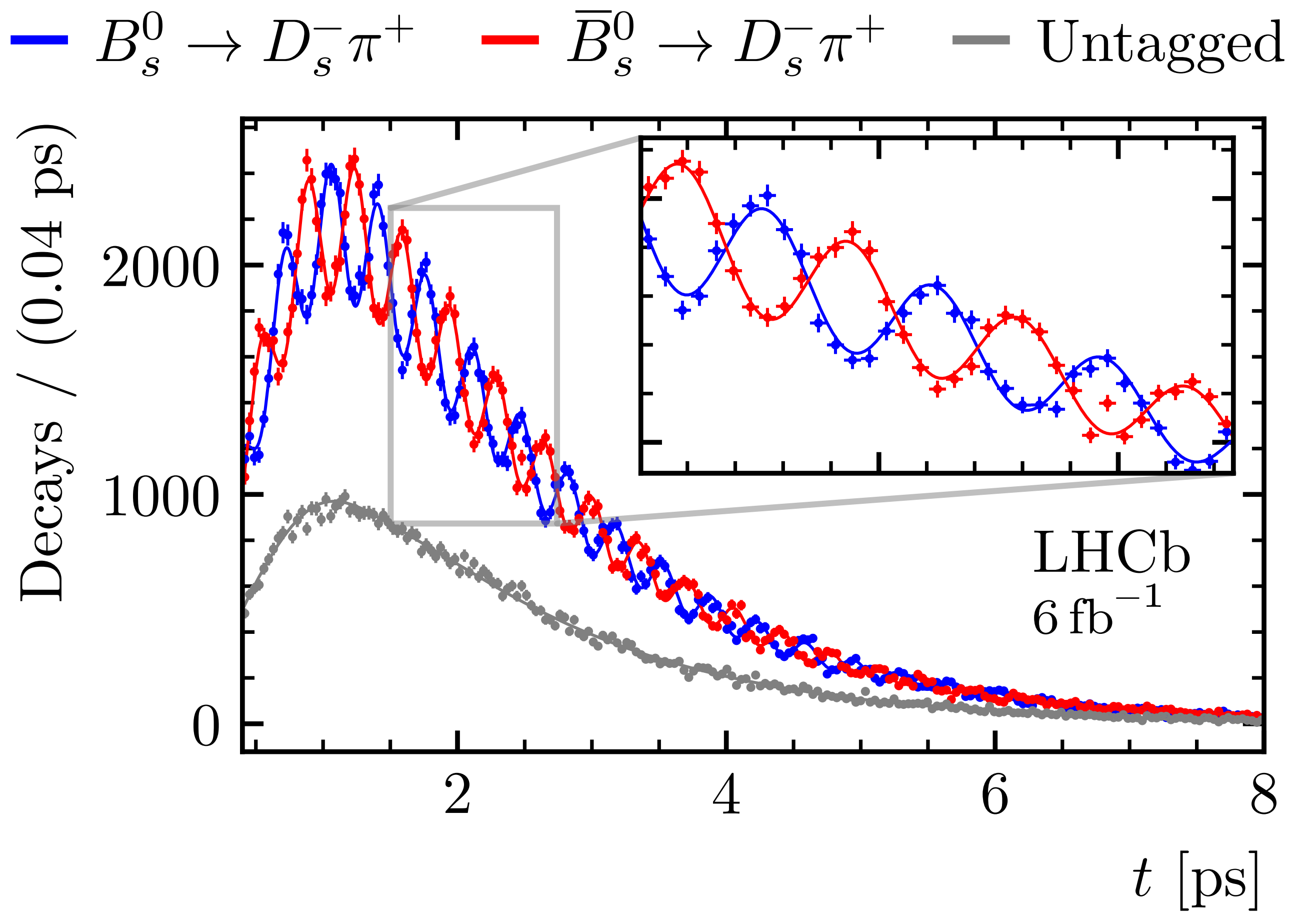


b)
IP resolution (mm)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1000
750
500
250
0
0 0.5 1 1.5 2 2.5 3 3.5 4
1/pt (GeV/c)-1



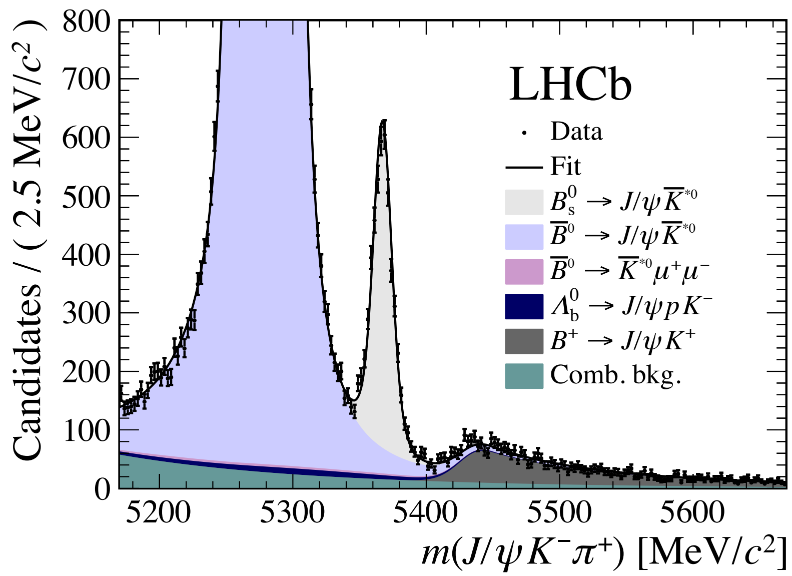
LHCb
resolution [fs]
100
90
80
70
60
50
40
30
20
10
0
0 100 200 300 400 500
p [GeV c-1]
2011
2012

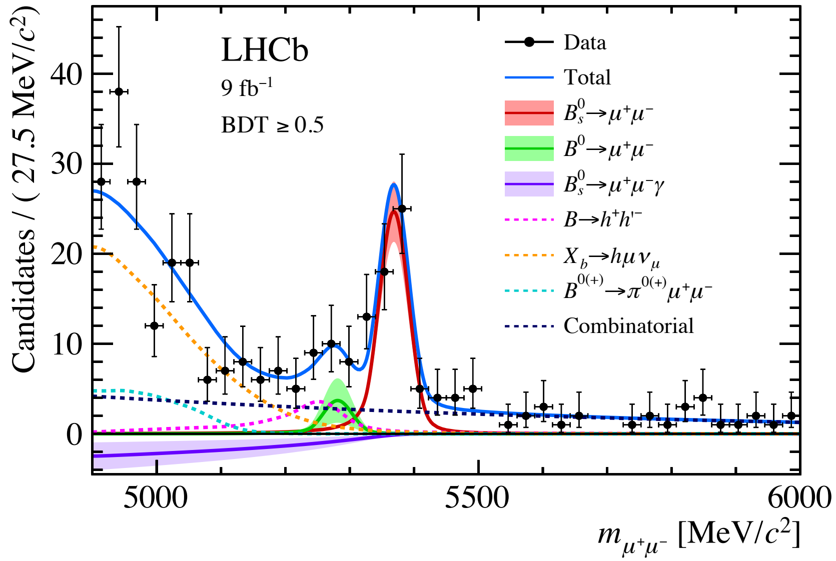
Vertexing: oscillations



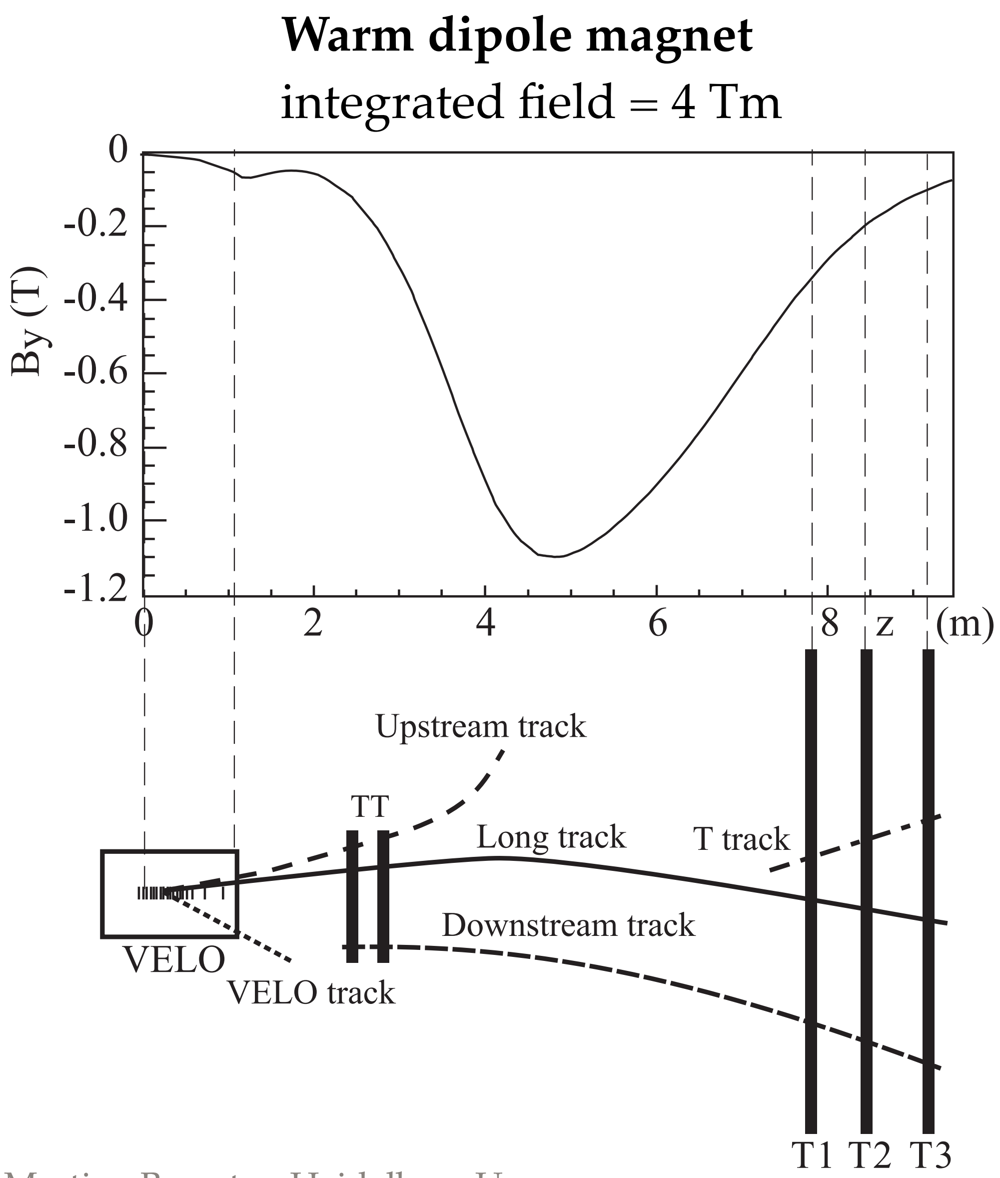
Spectrometer

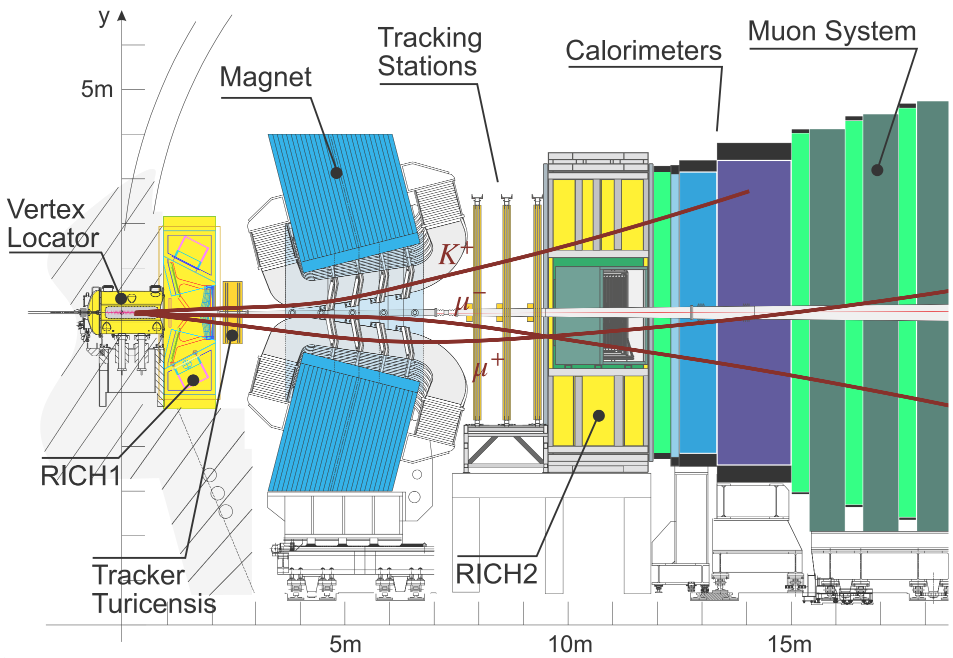
- Invariant mass is key in B physics
  - Separate B^0 and B_s → 1.6% difference in mass = 90 MeV
- Cover relevant range of momenta for B decays
  - Well below p = 100 GeV
  - Keep tracks in acceptance down to p = 3 GeV

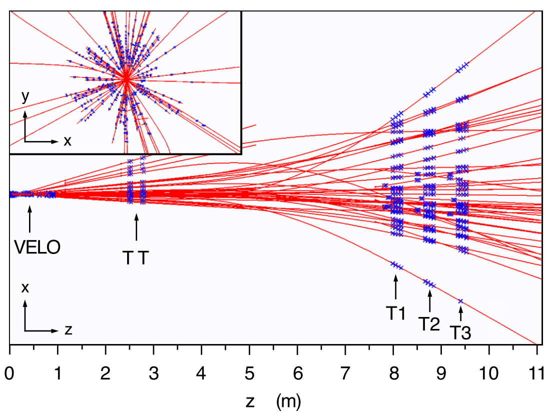




Spectrometer



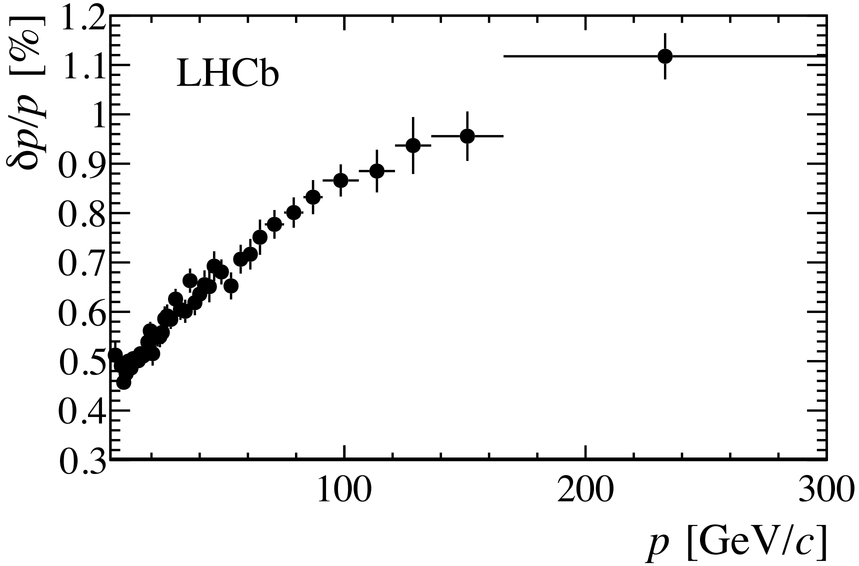


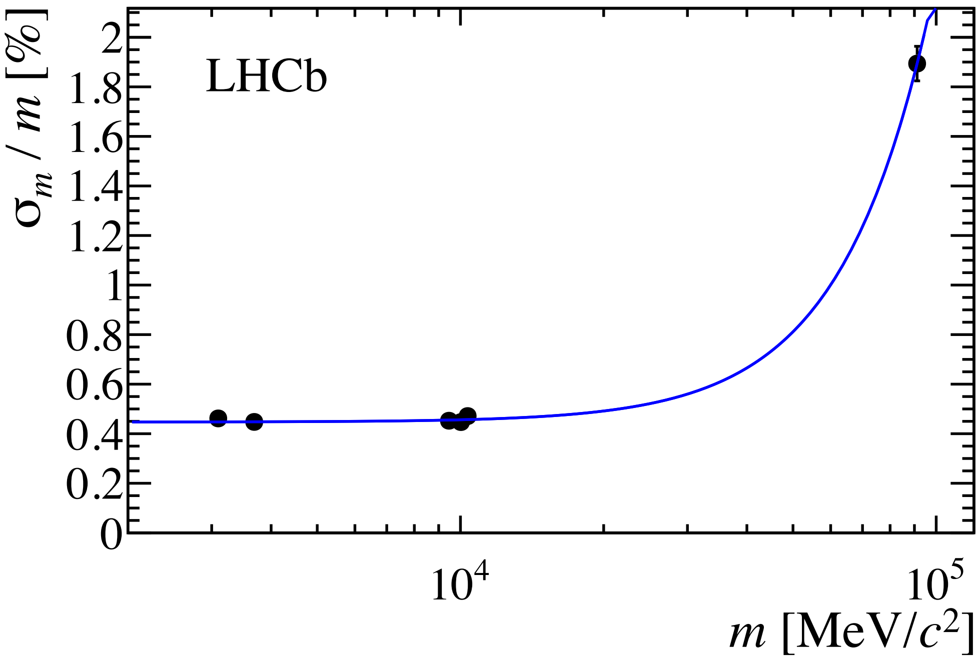


Spectrometer

Resonance	Mass resolution (MeV/c^2)
J/ψ	14.3 ± 0.1
$\psi(2S)$	16.5 ± 0.4
$\Upsilon(1S)$	42.8 ± 0.1
$\Upsilon(2S)$	44.8 ± 0.1
$\Upsilon(3S)$	48.8 ± 0.2
Z^0	1727 ± 64

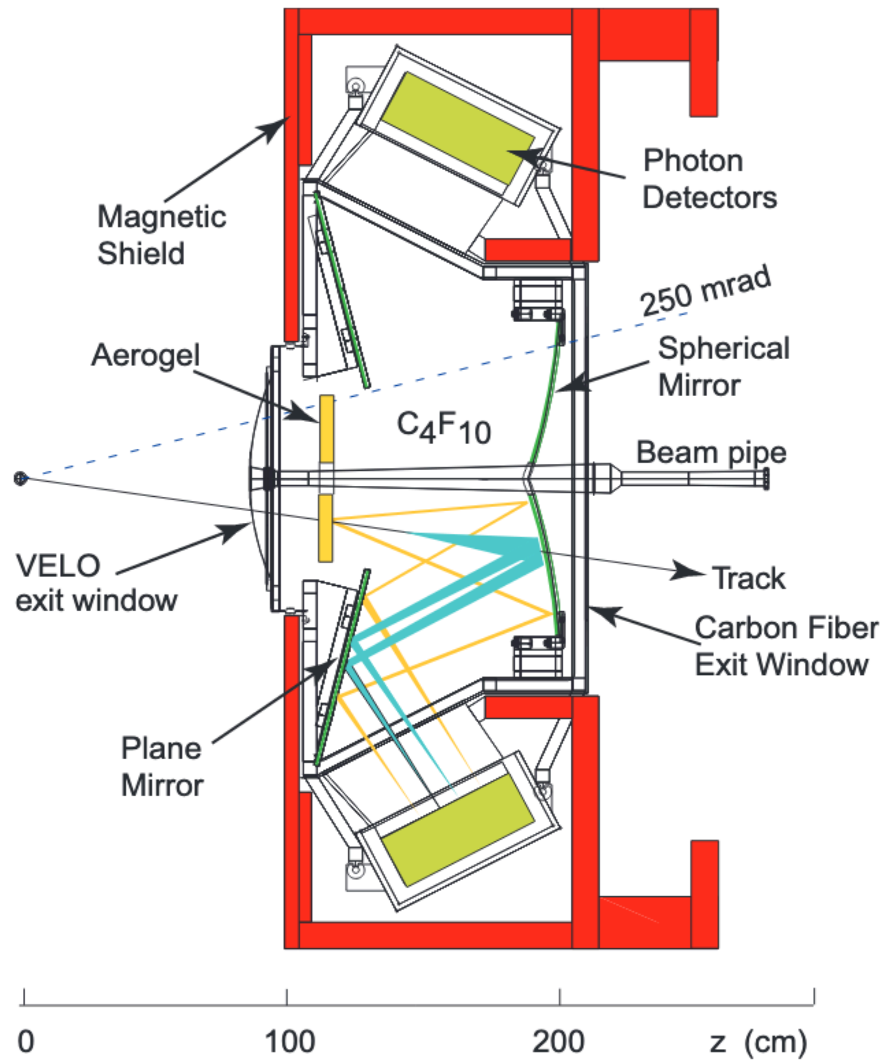
$\delta p/p \sim 0.5\,\%$ for $p < 20$ GeV





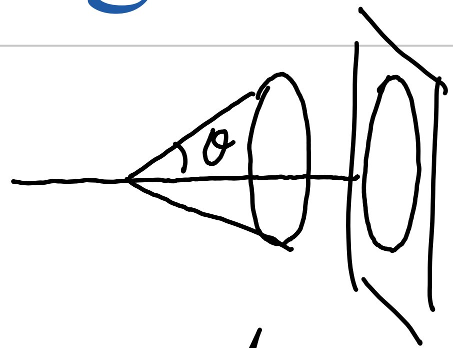
PID of charged hadrons

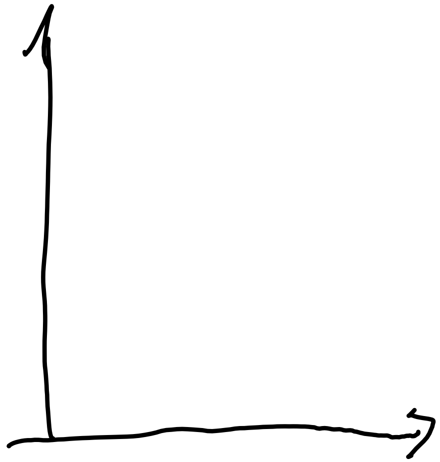
- Special requirement of flavour physics:
  Distinguish $K^{\pm}$ from $\pi^{\pm}$
  - $m(K^{\pm}) \simeq 500$ MeV,
    $m(\pi^{\pm}) \simeq 140$ MeV
  - Same signature in tracking and calorimeter
- Different β for same p
  - Time of flight hard to separate
  - Measure β with Cherenkov radiation!
- LHCb uses two RICH detectors
  - RICH = Ring Imaging Cherenkov
  - Faint light → photon detector out of acceptance



PID of charged hadrons

$$\cos\theta = \frac{1}{n\beta}$$





threshold at $\frac{1}{n\beta} < 1 \Rightarrow \beta > \frac{1}{n}$

$$\beta = \frac{p}{E}$$

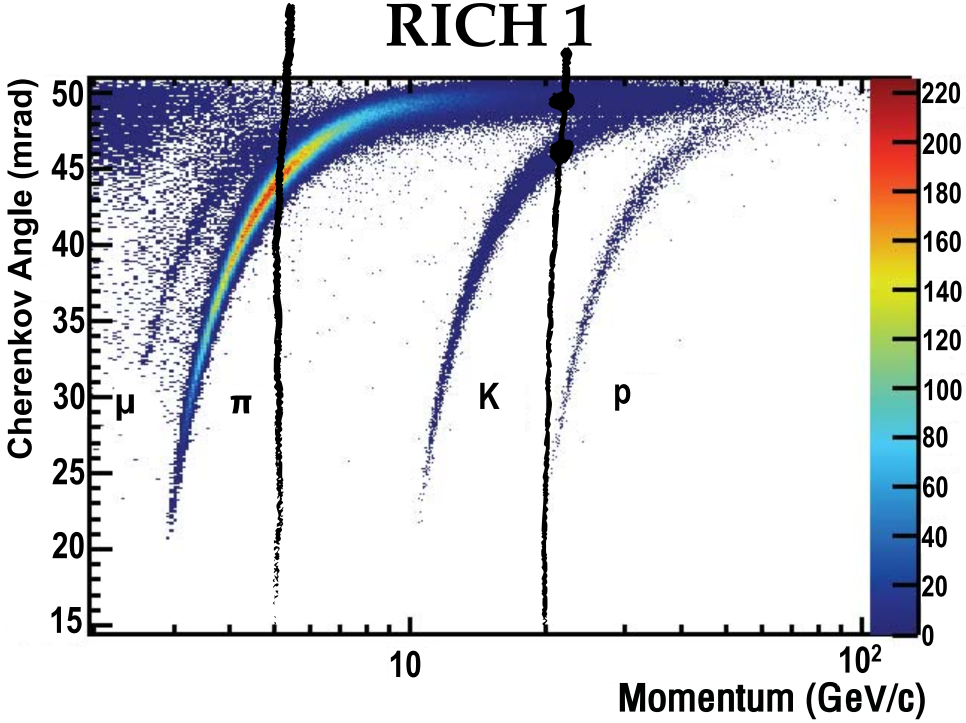
$$p \gtrsim m\sqrt{\frac{1}{2(n-1)}}$$

$$\gamma = \frac{m}{E}$$

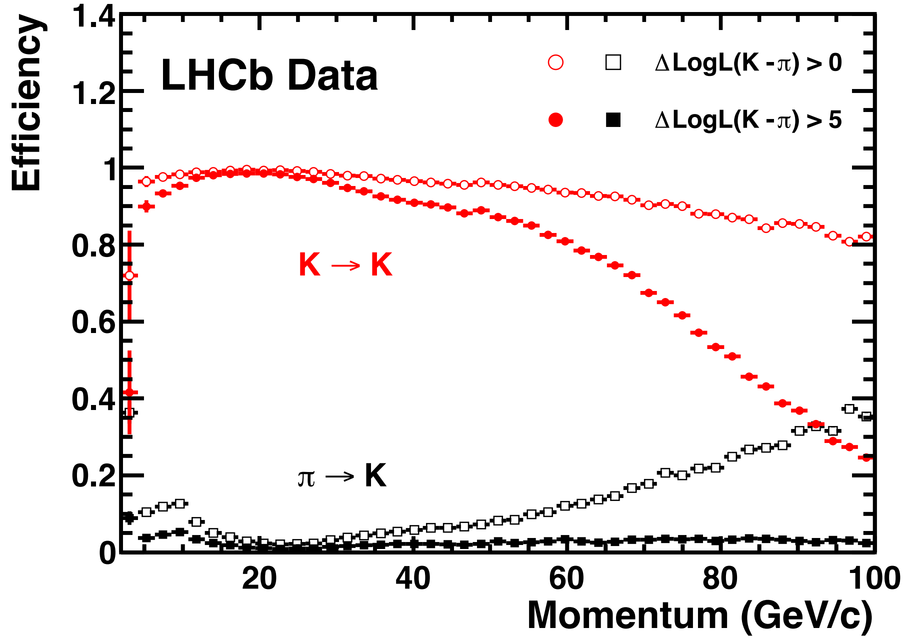
	n	$p(\pi) >$	$p(K)$
RICH 1	1.0014	2.6 GeV	9.3 GeV
RICH 2	1.0005	4.4 GeV	15.6 GeV

PID of charged hadrons

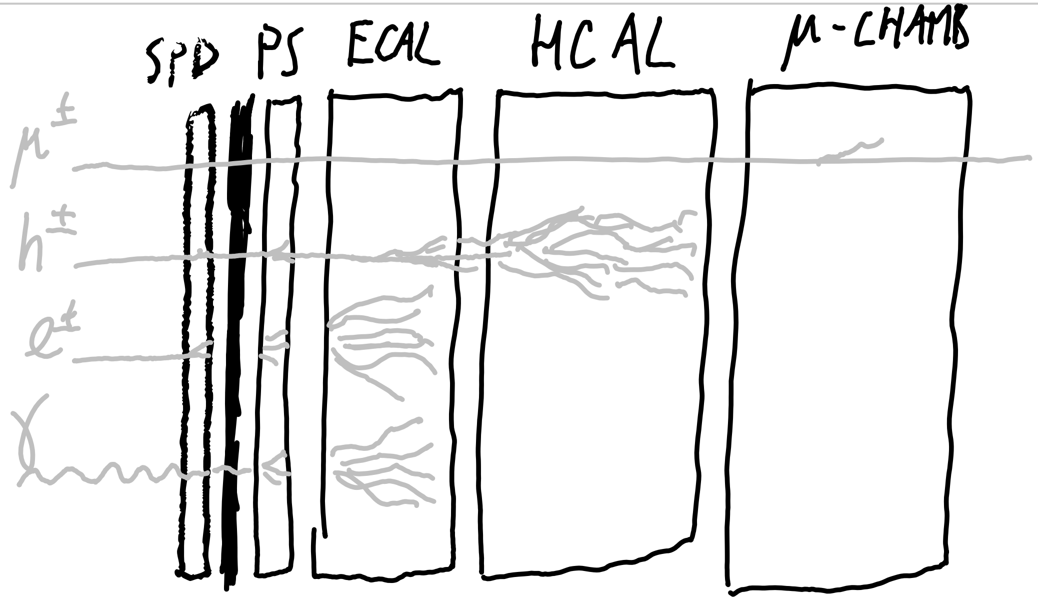
RICH 1

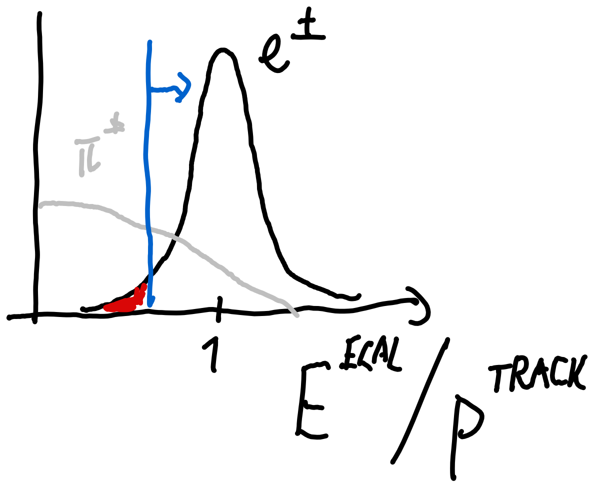


RICH 1+2 performance

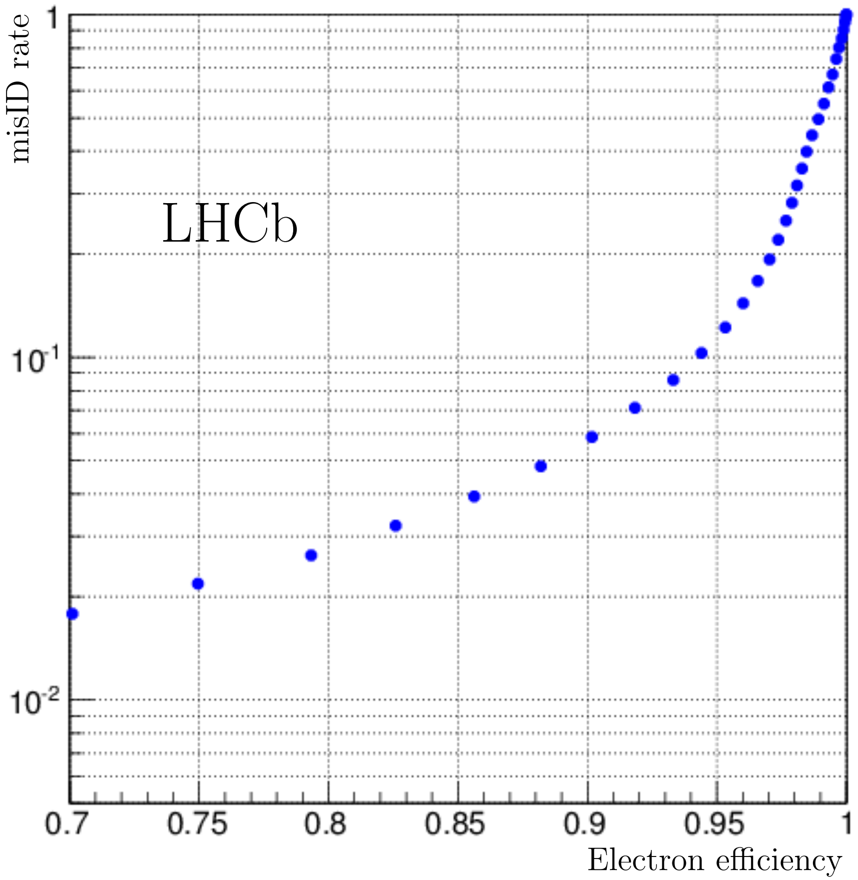


Calorimeters + muon chambers

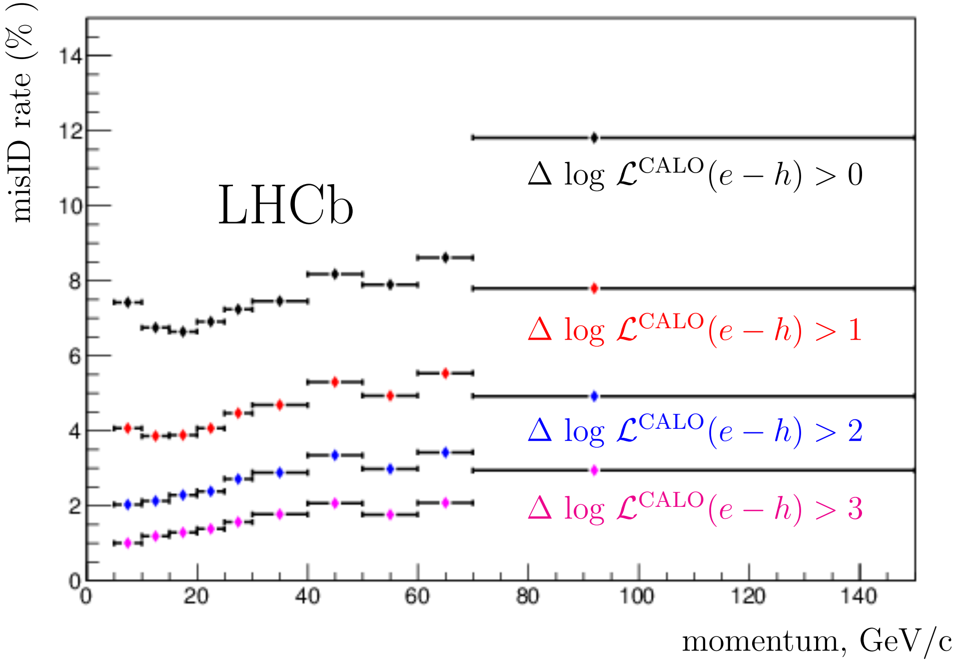




Electron ID



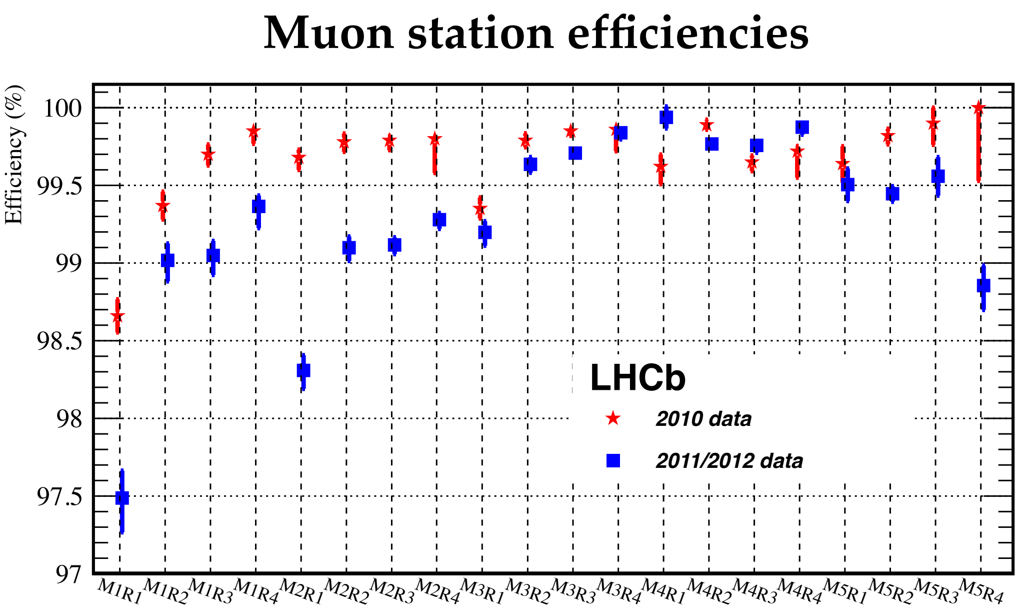
misID rate
LHCb
1
10^{-1}
10^{-2}
0.7
0.75
0.8
0.85
0.9
0.95
1
Electron efficiency



misID rate (%)
LHCb
Δ log $\mathcal{L}^{\mathrm{CALO}}(e-h) > 0$
Δ log $\mathcal{L}^{\mathrm{CALO}}(e-h) > 1$
Δ log $\mathcal{L}^{\mathrm{CALO}}(e-h) > 2$
Δ log $\mathcal{L}^{\mathrm{CALO}}(e-h) > 3$
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
momentum, GeV/c

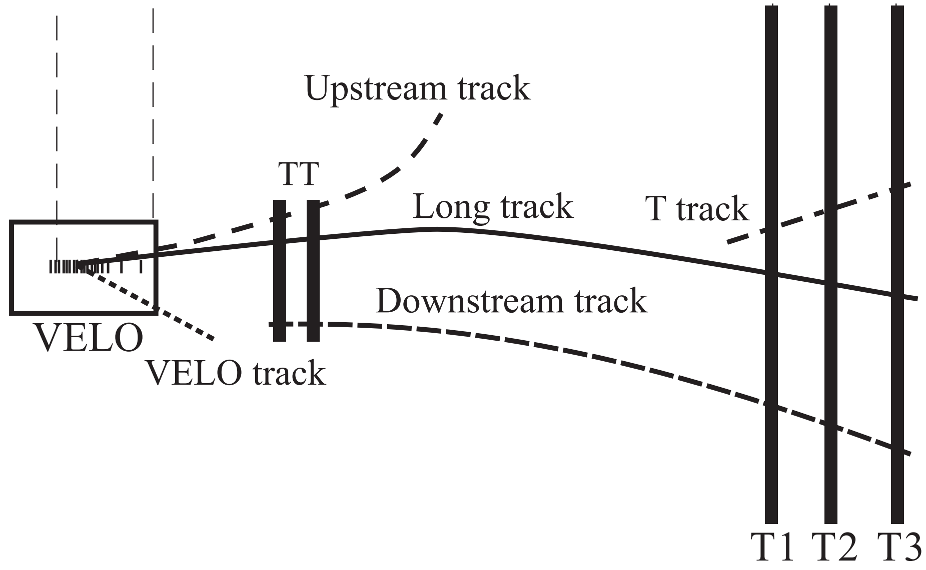
Hit efficiencies

- Calculated using $J/\psi \to \mu^+\mu^-$ tracks with $p > 10$ GeV (to avoid multiple scattering)
- Hit efficiency in silicon trackers (IT / TT) is above 99.7%
- In the Straw tubes (Outer tracker) it is 99.2%
- Efficiency in muon station >99%
  - thanks to redundancy
  - Despite dead time of 50-100 ns

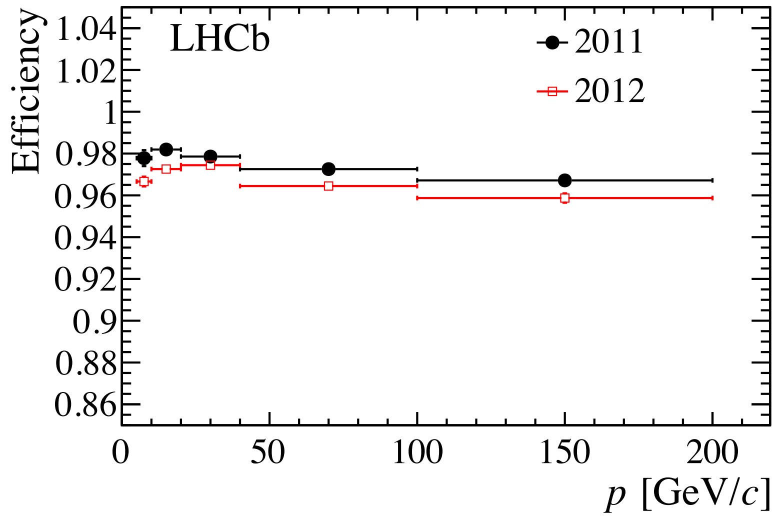


Long-track reconstruction

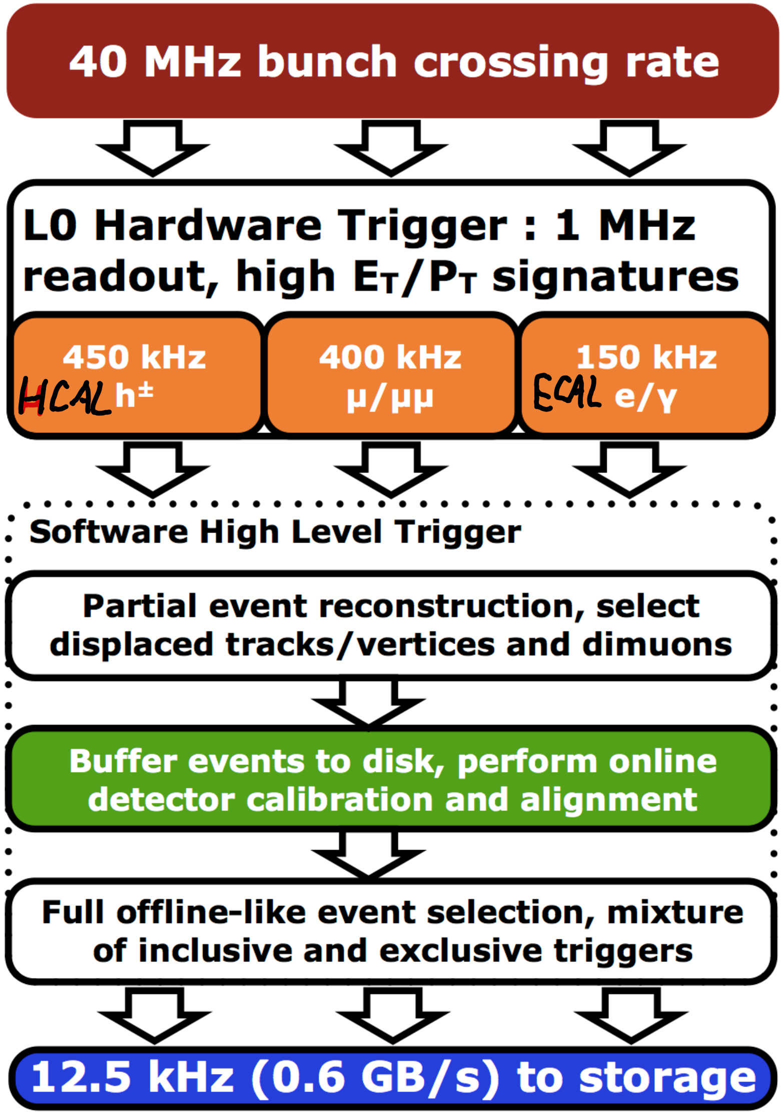
1. Reconstruct VELO track (straight)
2. Add T stations with Forward tracking or Track matching
3. Add TT hits to improve momentum resolution
4. Fit taking into account multiple scattering and energy losses
5. Remove fake tracks (best using NN classifier)



Tracking efficiencies

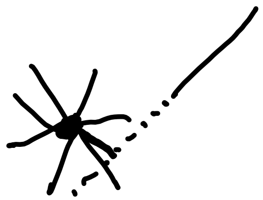


Trigger



HLT1 :

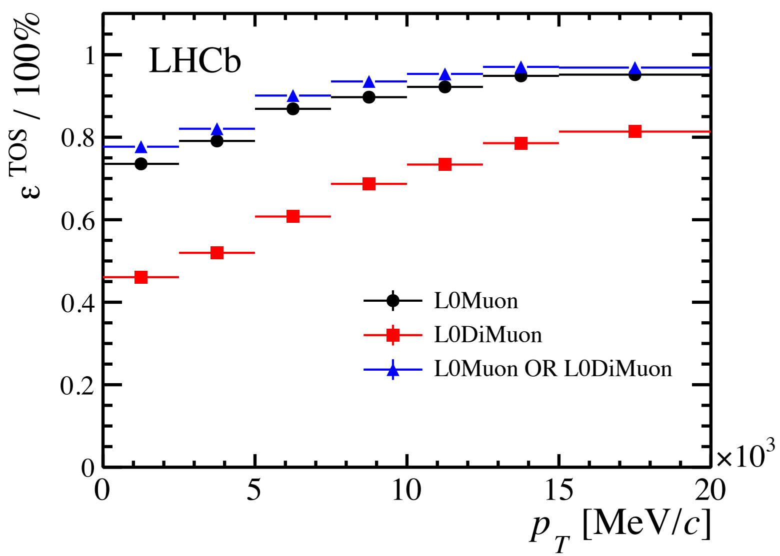
HLT2

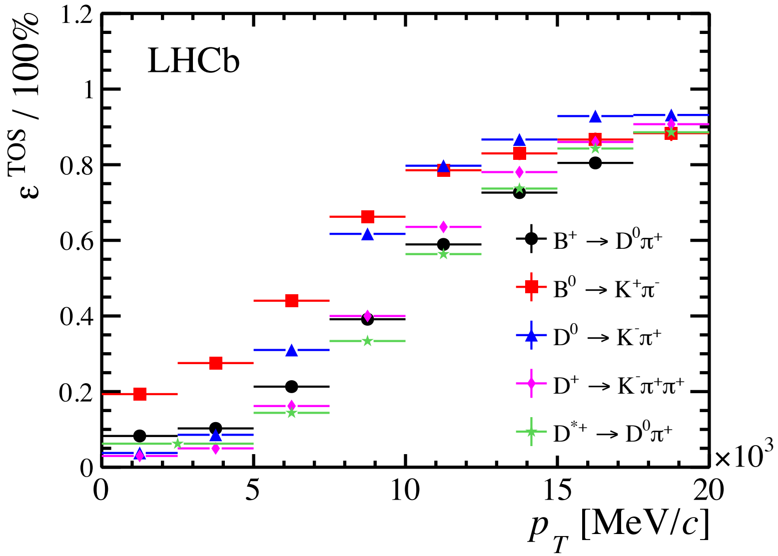


Trigger

Table 4: Typical L0 thresholds used in Run I [85].

	p_T or E_T 2011	p_T or E_T 2012	SPD 2011 and 2012
single muon	1.48 GeV/c	1.76 GeV/c	600
dimuon $p_{T1} \times p_{T2}$	$(1.30\ \text{GeV}/c)^2$	$(1.60\ \text{GeV}/c)^2$	900
hadron	3.50 GeV	3.70 GeV	600
electron	2.50 GeV	3.00 GeV	600
photon	2.50 GeV	3.00 GeV	600

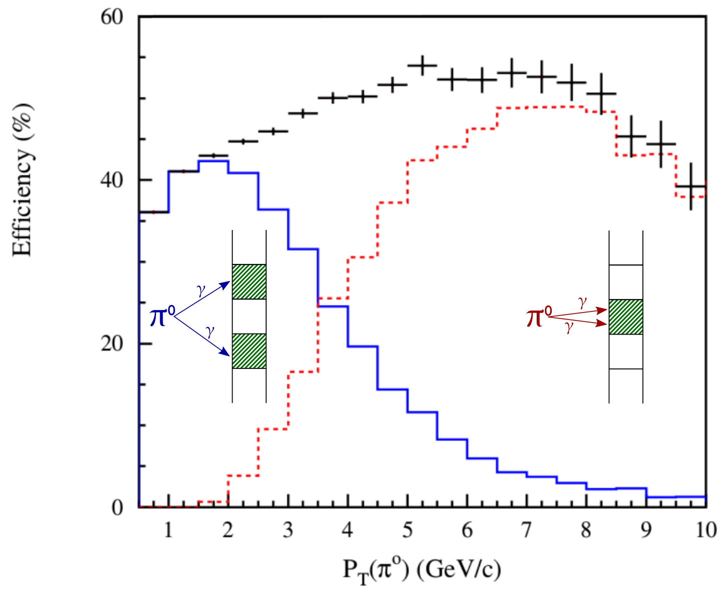


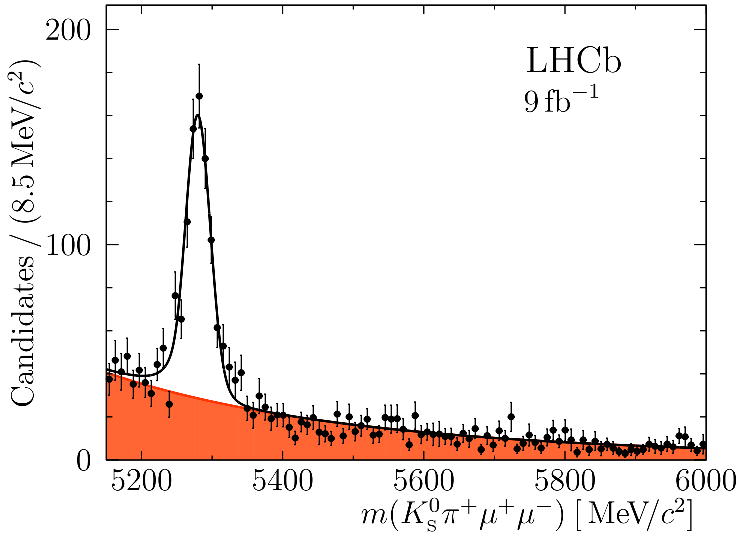


Bremsstrahlung

Neutral hadrons

- π^0 has lifetime 8.5×10^{-5} ps
  - If $p = 10$ GeV then it flies 2 μm
  - Decays ~100% in $\pi^0 \to \gamma\gamma$
  - Hard to distinguish from γ if too energetic
- K_L has lifetime 5×10^4 ps
  - If $p = 10$ GeV then it flies 300 m
  - Decays out of LHCb
- K_S has lifetime 90 ps
  - If $p = 10$ GeV then it flies 50 cm
  - Can be reconstructed as $K_S \to \pi^+\pi^-$ if it decays soon enough
  - Overall an order of magnitude less efficient than K^+ reconstruction

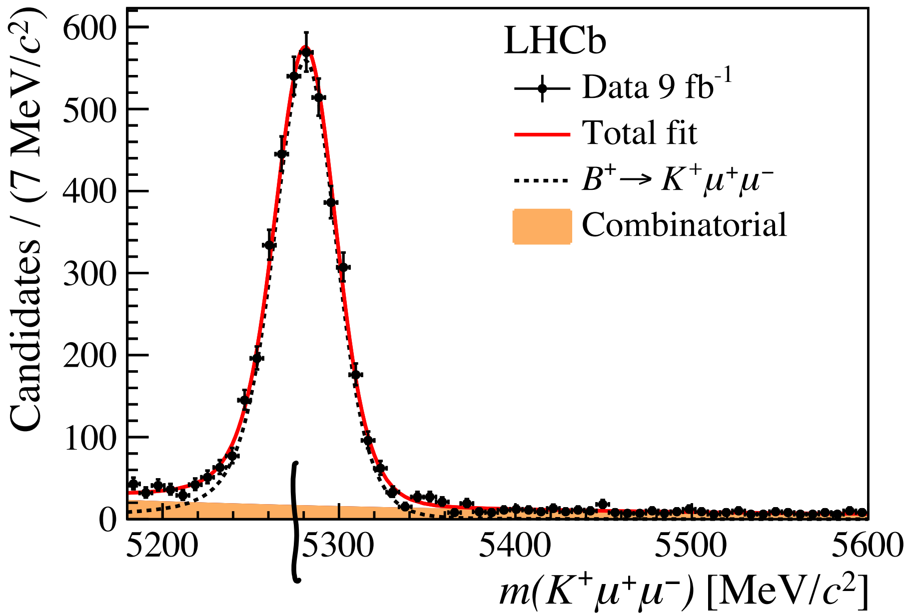




World-leading samples

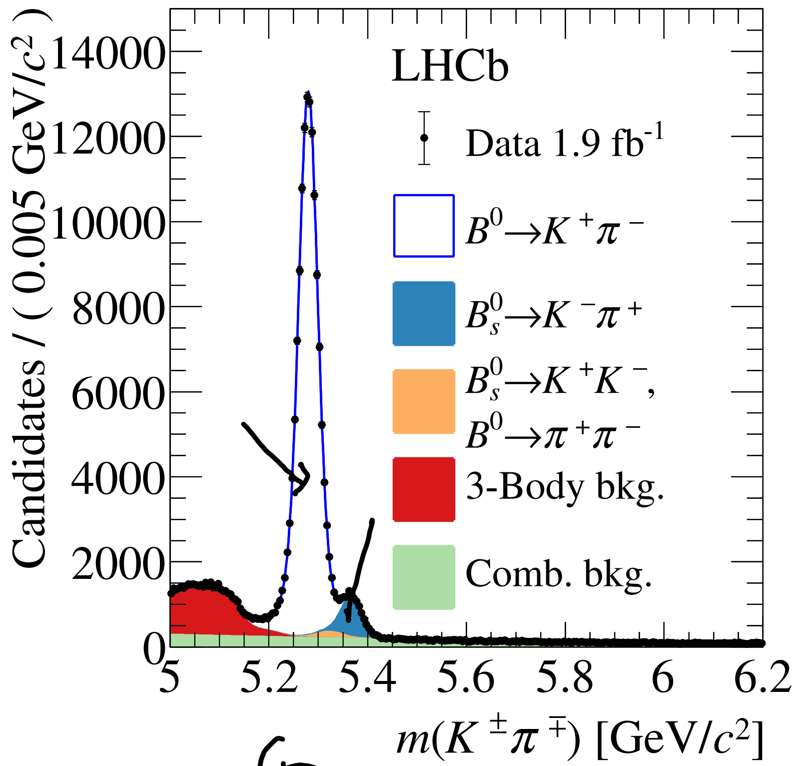
~4k $B^+ \to K^+\mu^+\mu^-$

BR of about 1.2×10^{-7}



~140k $B^0 \to K^+\pi^-$

BR of about 2×10^{-5}



$B_d^0 \begin{cases} \bar{b} \\ d \end{cases}$ $B_s^0 \begin{cases} \bar{b} \\ s \end{cases}$