Introduction to flavour experiments

In memoriam of Sheldon Stone (Feb. 14, 1946 – Oct. 6, 2021)

https://cerncourier.com/a/sheldon-stone-1946-2021/

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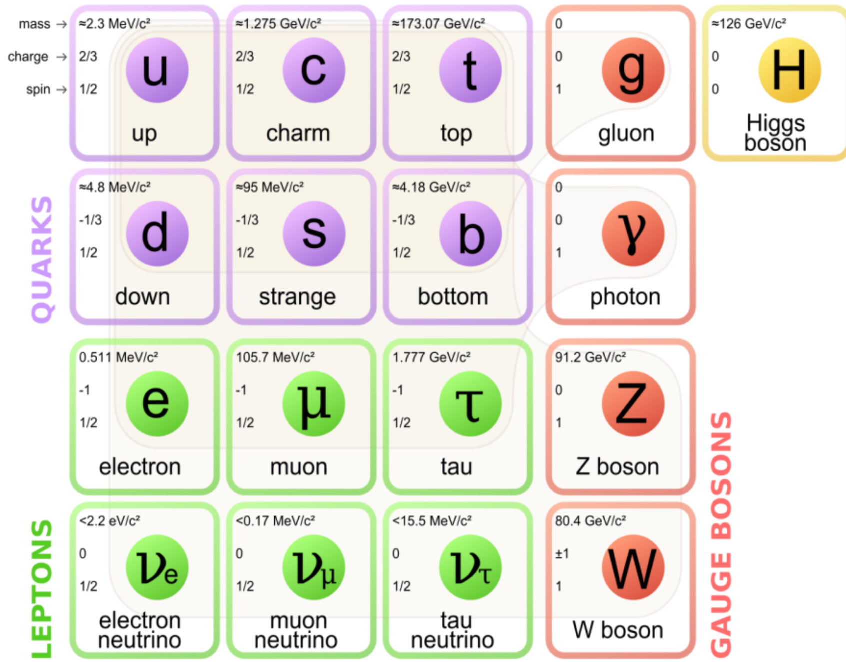
Outline

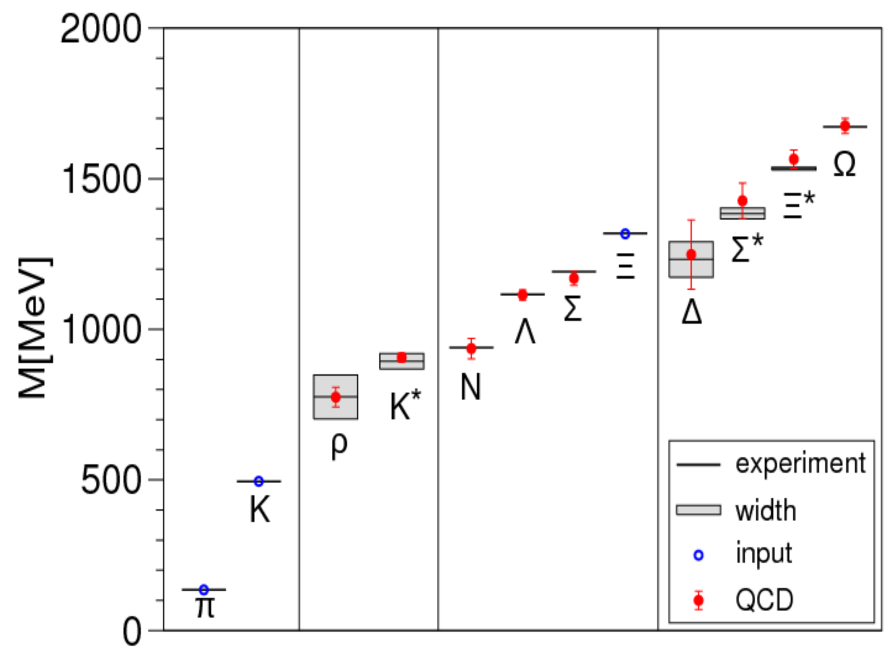
- Lesson 1: Introduction to flavour physics
- Lesson 2: The CKM matrix
- Lesson 3: Rare decays of heavy hadrons
- Lesson 4: Mixing and CP violation

Introduction

The Standard Model of Particle Physics:



+ antiparticles (ex: e- ↔ e^+)



Hadron spectrum

Flavour Physics: study of the transitions between different types of particles (**quarks** and leptons), governed by the weak interaction (Z,W)

Introduction

The Standard Model of Particle Physics:

Free parameters:

3 gauge couplings: α_{em}, α_{weak}, α_{strong}

2 Higgs parameters m_H, v

6 quark masses

3 quark mixing angles + 1 phase (CKM matrix)

3 (+3) lepton masses

(3 lepton mixing angles + 1 phase) (PMNS matrix)

→ **Related to flavour**

To be measured by experiments !

() = with Dirac neutrino masses

Introduction

Unknown in the Standard Model:

- Quantum Theory of Gravity
- Inflation
- **Quark/lepton generation masses: compositeness?**

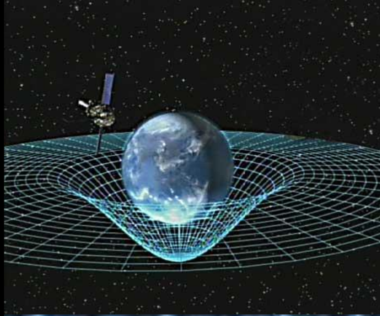
  Substructure? Strings?

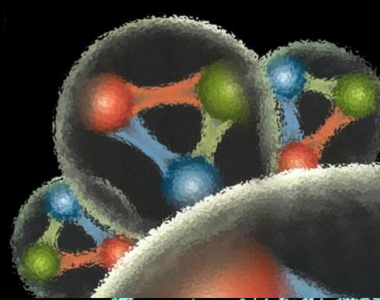
  Common sub-elements quarks and leptons?

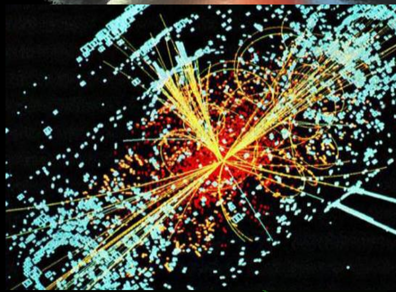
  Why three families?
- **Matter-Antimatter asymmetry**

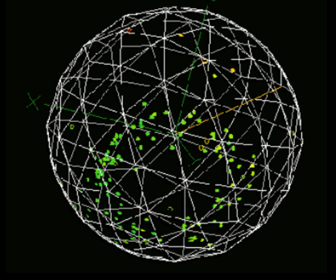
  CPV in SM (K, B) + Big Bang ?
- Cosmological constant (dark energy …)
- Dark matter
- **EW symmetry breaking, Higgs? Forces Unification?**
- **Neutrinos (mass?, hierarchy?**...)

Many of them are related to flavour!





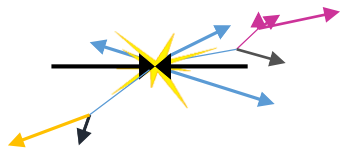




Introduction

Looking for New Physics…

Direct searches:

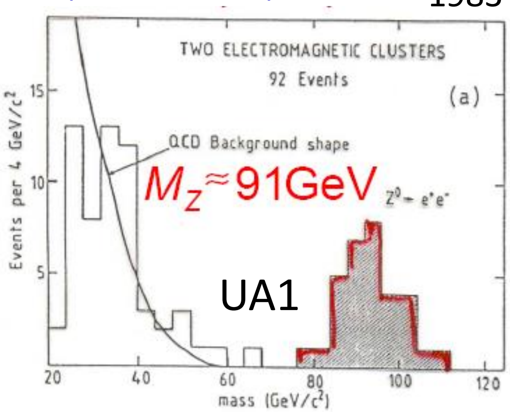


$$E^2 = m^2c^4 + p^2c^2$$

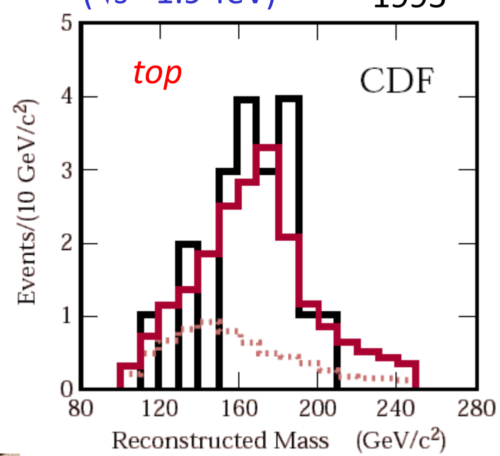
High energy

$\rightarrow$ **particles created *on-shell*: *Evidence in mass plots***

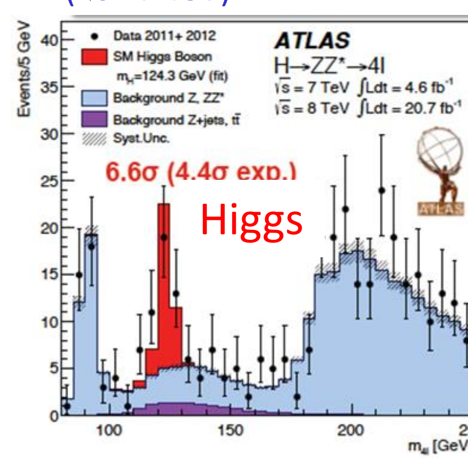
(√s= 546 GeV) 1983



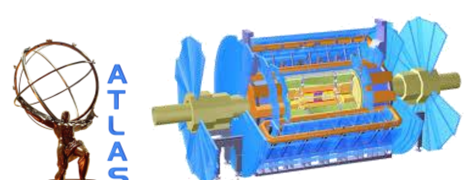
(√s= 1.9 TeV) 1995

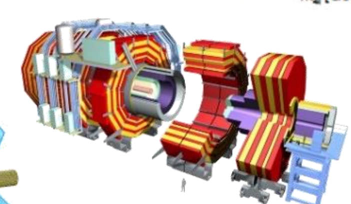


(√s= 7 TeV) 2012



Higgs discovery, 2012

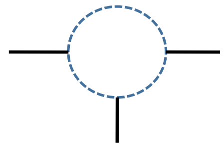




CMS

Introduction

Looking for New Physics…

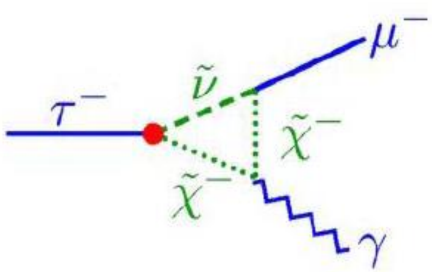


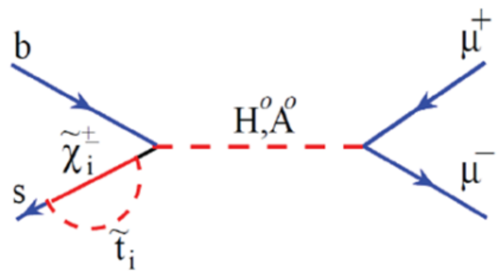
Indirect searches:

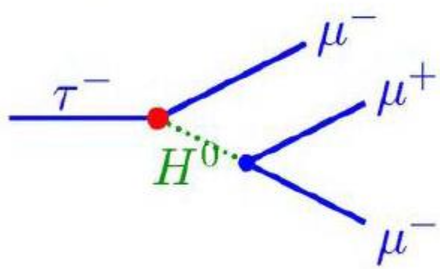
High precision

→ **particles created *off-Shell: Evidence in quantum effects (loops)***

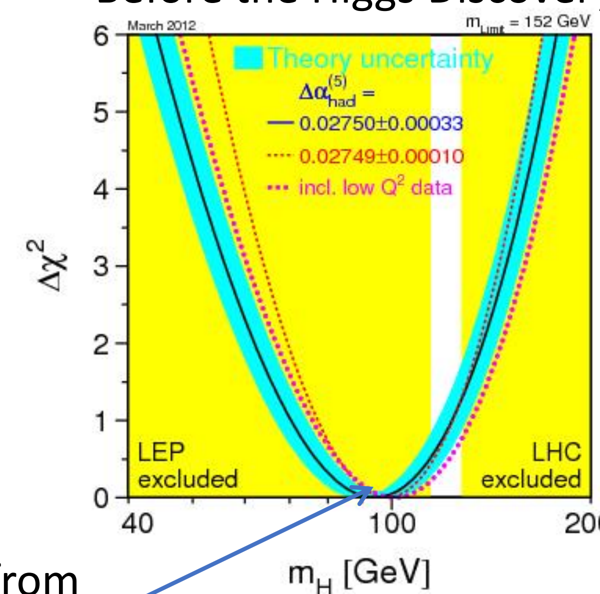
(BR's, asymmetries…)



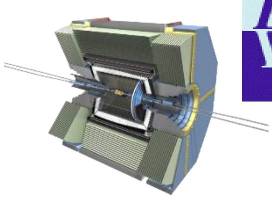


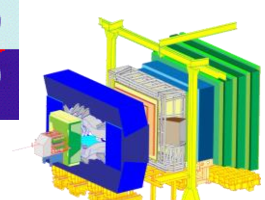


Before the Higgs Discovery…

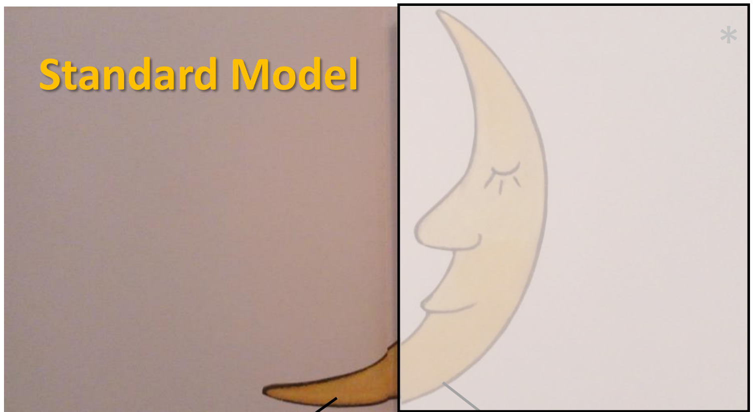


Predicted from electroweak measurements





Introduction

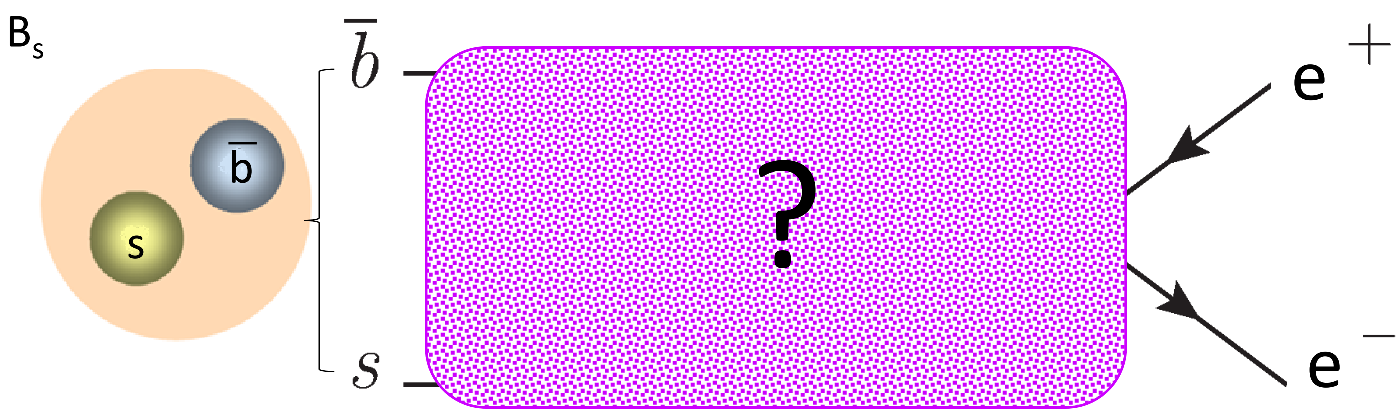


What we see

What we think it is

What it is in reality

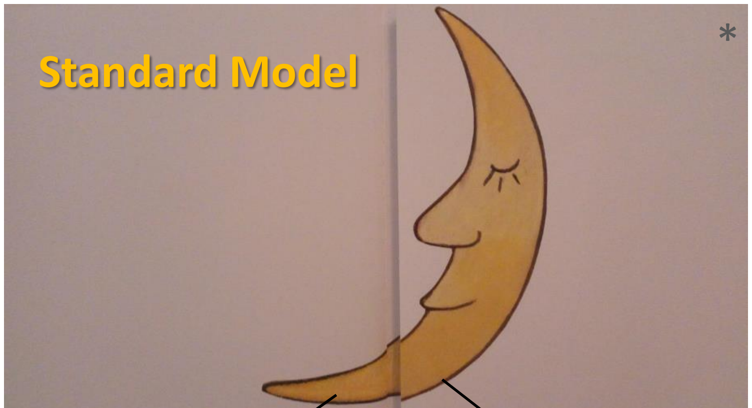
It can be tested by studying quantum effects:



Number of particles produced, angular distributions, origin point in the detector…

* ¡Oh!, Josse Goffin

Introduction



What we see

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What it is

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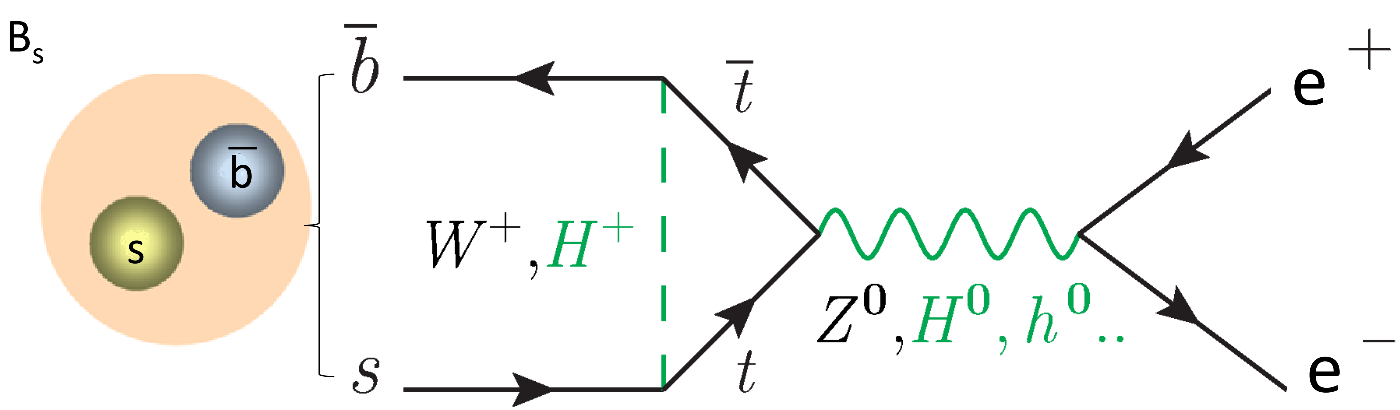
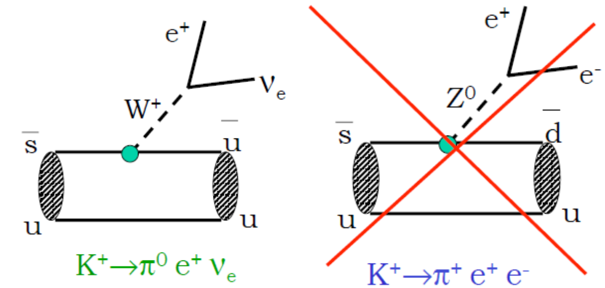


Number of particles produced,
angular distributions,
origin point in the detector…

New Particles

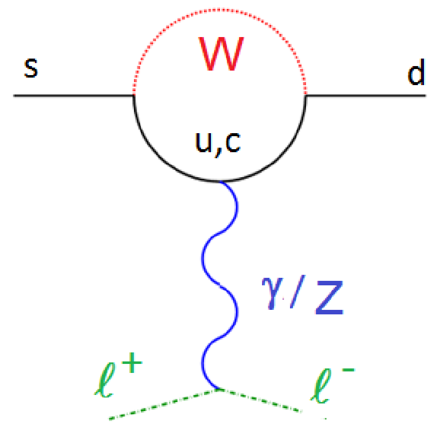
* ¡Oh!, Josse Goffin

Introduction

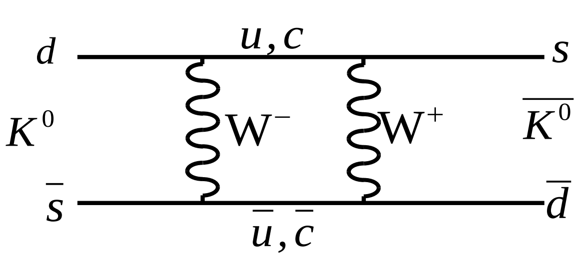


- The GIM mechanism:

In 1970's Glashow, Iliopoulos and Maini described the mechanism by which flavour-changing neutral currents (FCNCs) were suppressed, and predicted the existence of the c quark



- Gaillard, Lee and Rosner : $m_c \sim 1.5$ GeV from kaon mixing



$$\Delta m_K = \frac{G_F^2}{4\pi} m_K f_K^2 m_c^2 \cos^2\theta_c \sin^2\theta_c$$

- 1974 c quark discovered (B. Richter at SLAC and S. Ting at BNL)

2 December 1974
EW LETTERS

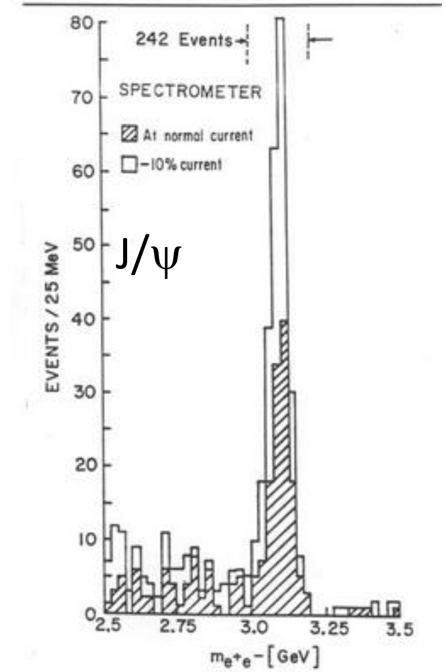
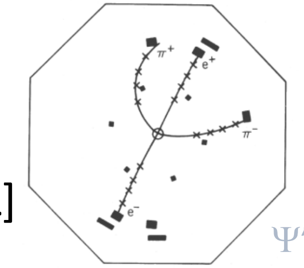


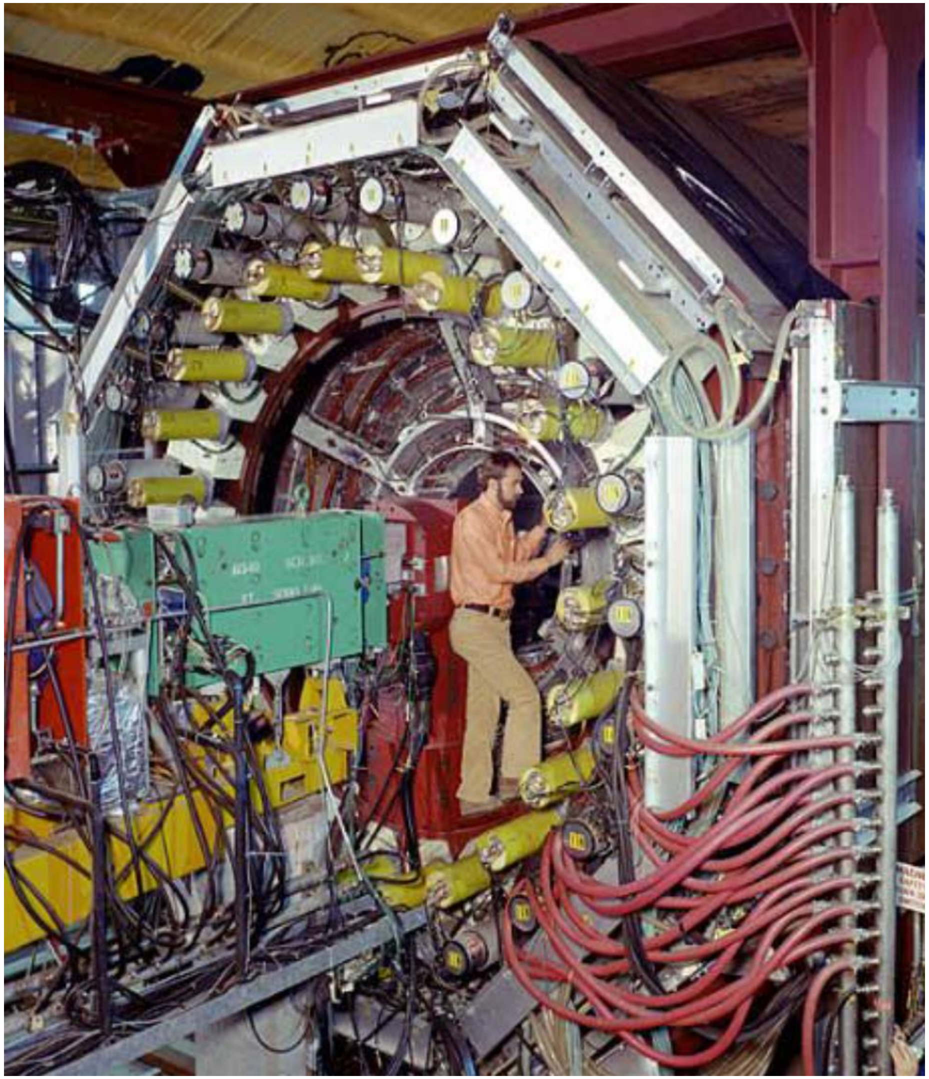
FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

https://cerncourier.com/a/50-years-of-the-gim-mechanism/

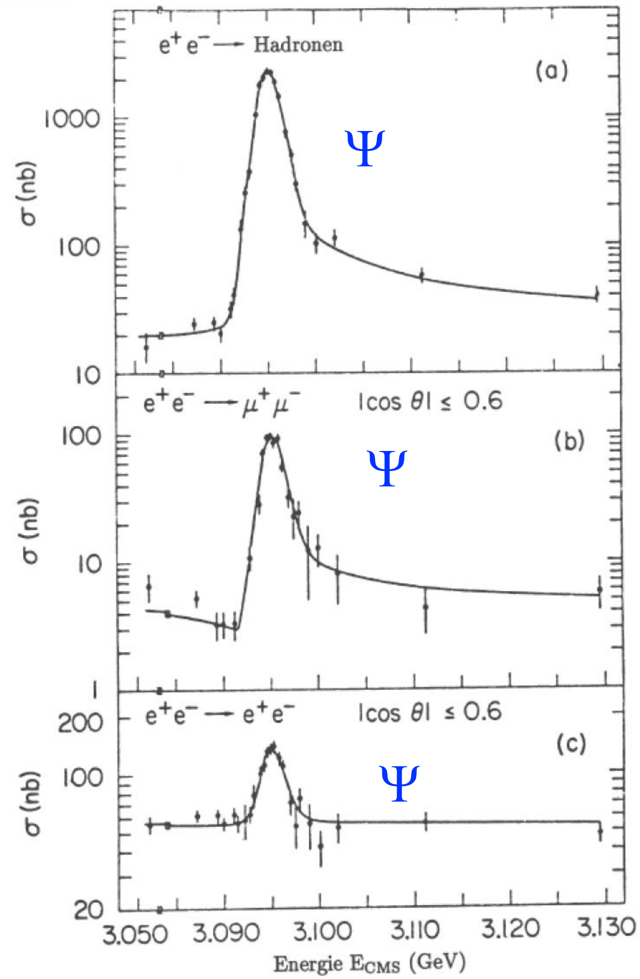
Introduction



The MARK 1 detector at the e^+e^- storage ring SPEAR (1973-1976) [SLAC-LBL]



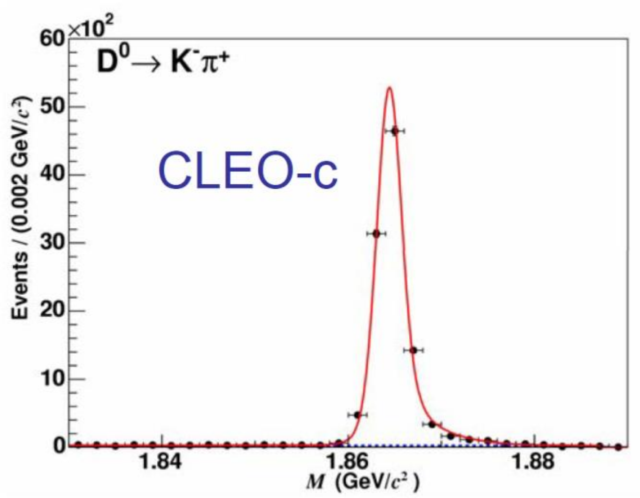
$M_{J/\Psi}$ $[c\bar{c}]$ ~ 3097 MeV

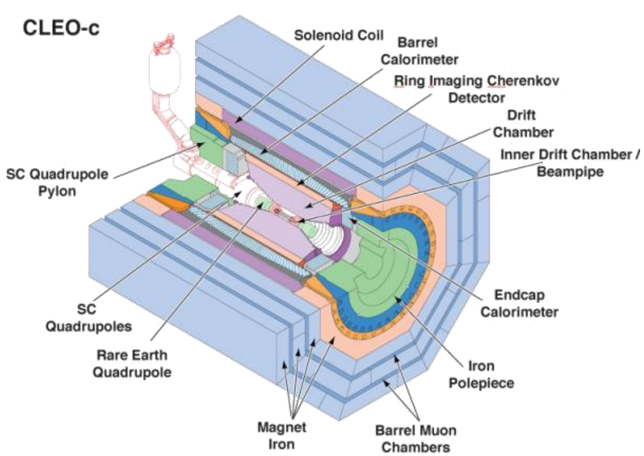


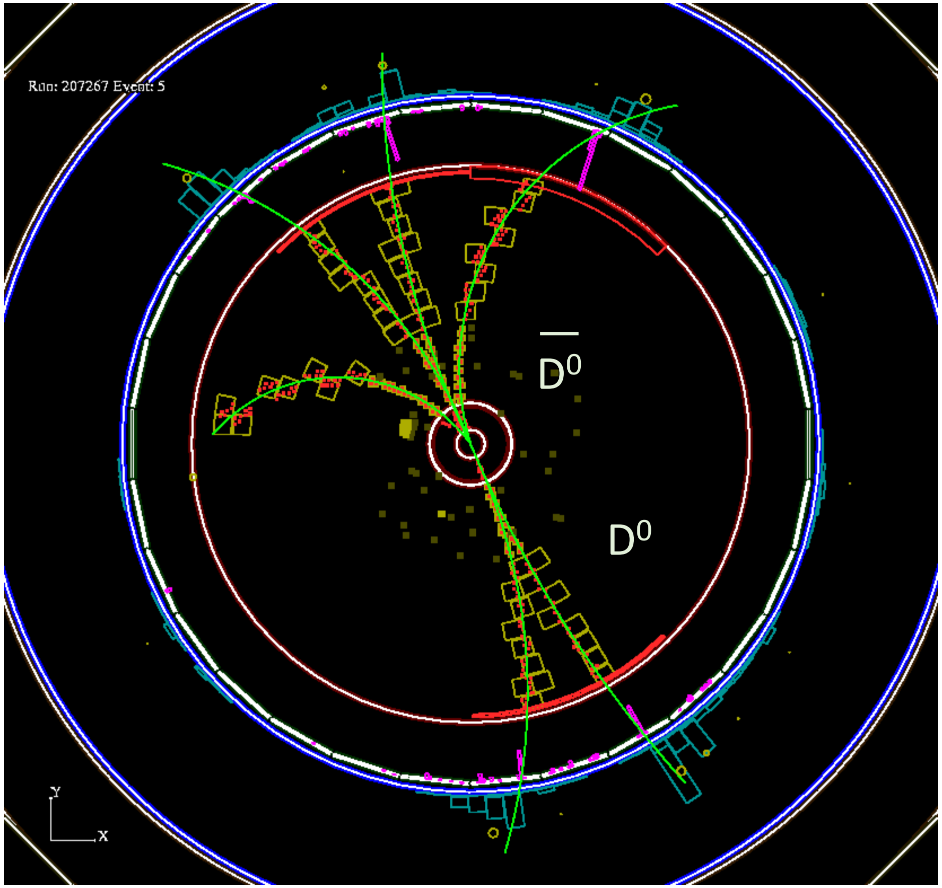
Introduction

Charm physics has been studied in e^+e^- experiments working at the $\Psi(3770)$ resonance (charm threshold: production of $D\bar{D}$ mesons)

Ex: CLEO-c at CESR and BES III at BEPC



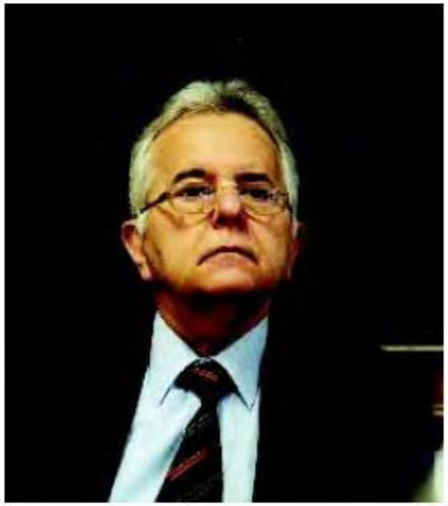




$\psi(3770)$

Introduction

- The CKM mechanism:

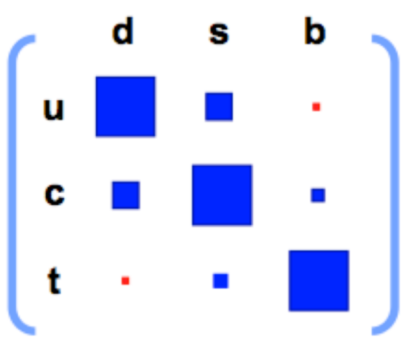


Cabibbo

Kobayashi

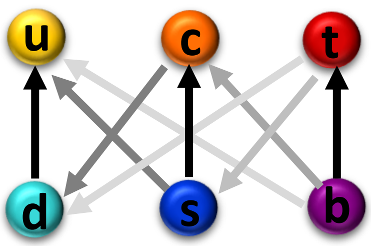
Maskawa

$V_{CKM} =$

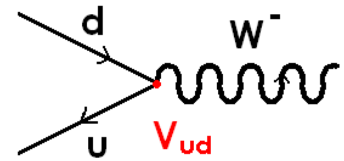


Introduction

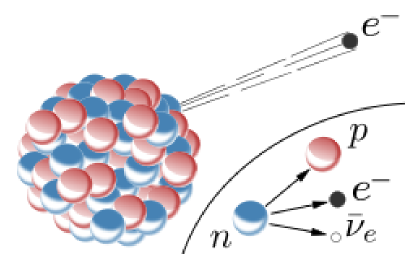
• In the Standard Model of Particle Physics, transitions between different quarks are governed by the CKM mechanism:



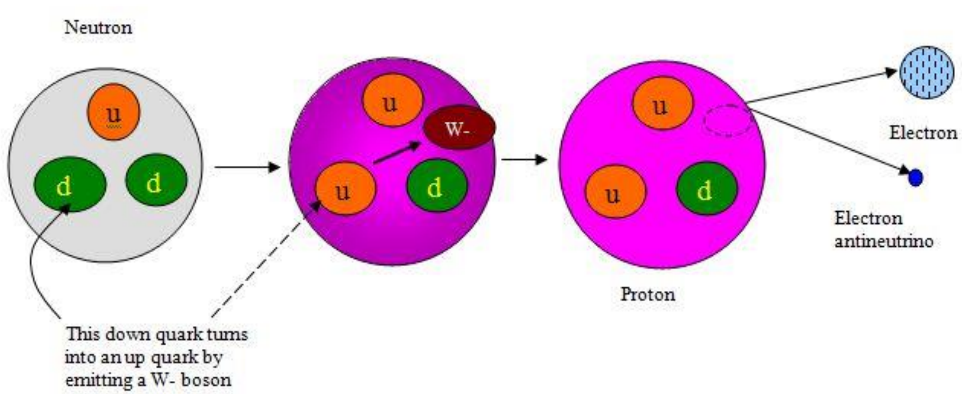
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

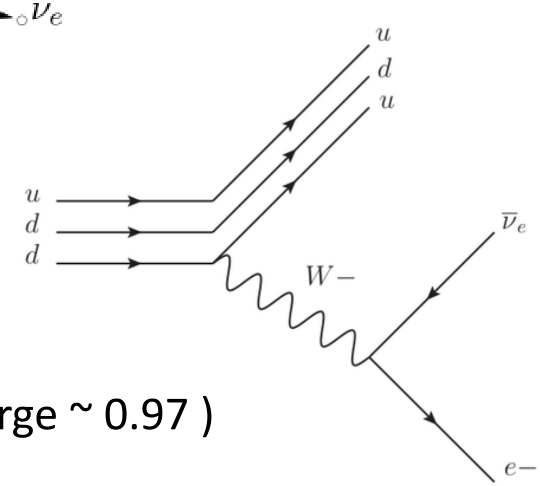


Example: β -decay (very well known)



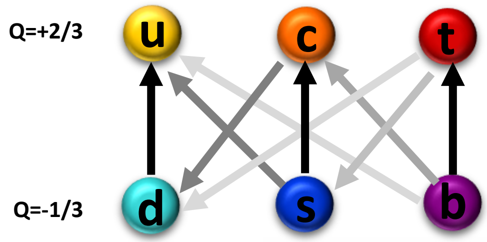
$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \overline{\nu_e}$$



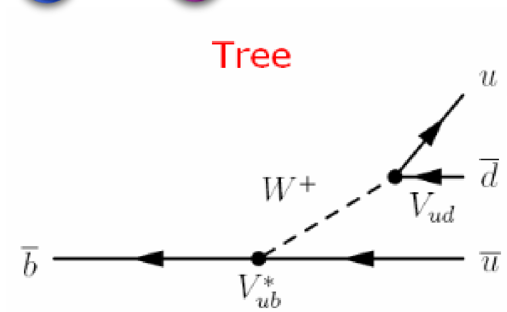


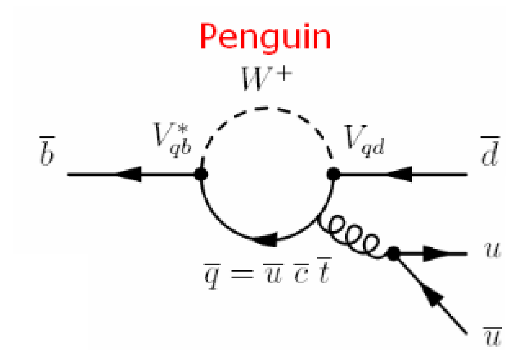
(V_{ud} is large ~ 0.97)

Introduction



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix},$$





- Transitions between the same family are favoured
- Some of the processes are rare (ex: V_{ub})
- Need to change charge: FCNC not allowed at tree level, need to proceed via loop diagrams (CKM suppressed)
- Matrix elements have to be determined by experiments
- Transition probabilities can be thus calculated in this framework
- If a transition occurs with larger probability than expected
  $\rightarrow$ **New Particle** (i.e. New Physics)

Introduction

In summary:

- We understand that the Standard Model cannot be the ultimate theory

  It should be a low-energy effective theory of a more fundamental theory at a higher energy scale (TeV range or even higher)
  $\rightarrow$ *it could happen than one cannot access it by direct searches at LHC*

- New Physics requires to keep the predictions from the SM unaltered, since they are quite successful (hundreds of observables!)

- Flavour mechanism in the SM:
  $\rightarrow$ provide the suppression mechanism for FCNC processes already observed
  $\rightarrow$ In the recent years several ***anomalies*** in different observables have been found
  $\rightarrow$ we need to measure the flavour structure to distinguish between possible new physics scenarios

- The physics performed at LHCb and Belle II (flavour physics) goes hand-in-hand with direct searches (ATLAS and CMS) but have larger range of accessibility to new physics

Introduction

Why *b*-hadrons ?

- The *b*-quark is the heaviest quark forming hadronic bound states (m~4.7 GeV)
- Must decay outside the 3rd family
  - $\rightarrow$ Long lifetime (~1.6 ps)
  - $\rightarrow$ Many accessible decay channels (small BR's)

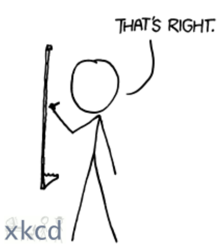
Good for experimentalists!

- Type of processes:

Dominant: $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed)

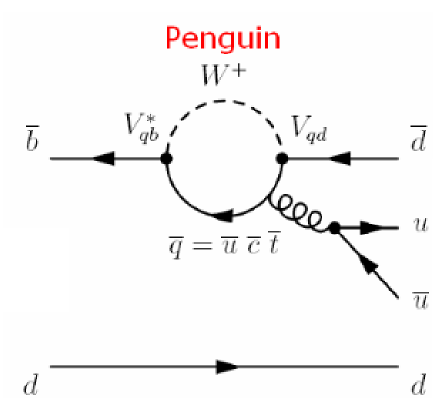
Rare: Flavour Changing Neutral Current (FCNC): $b \rightarrow s,d$

Flavour oscillations and CP violation



Ideal place to probe New Physics effects!

Good for theorists!

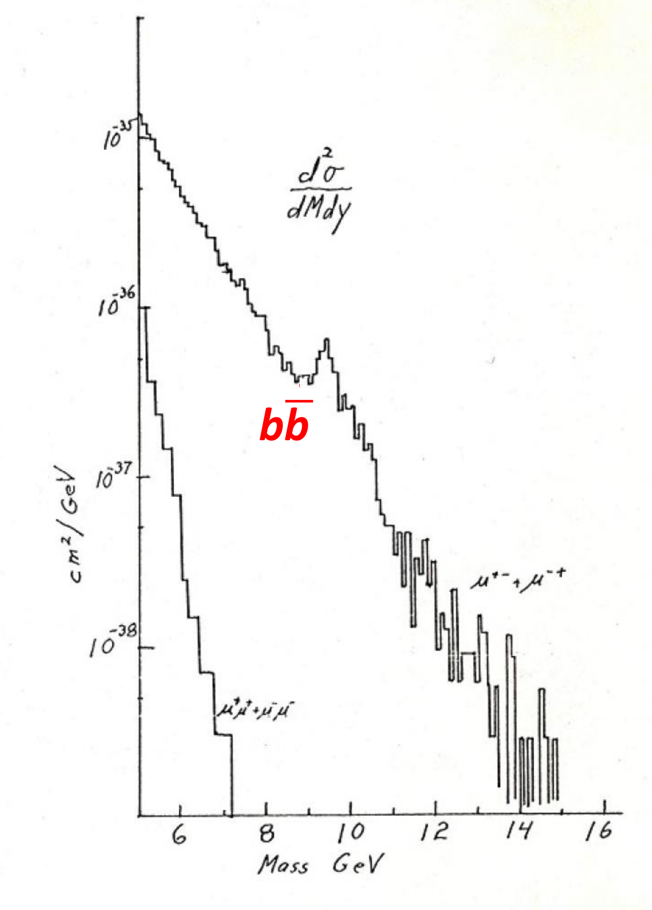


Introduction

☆ The *b* quark was discovered by the E288 experiment at Fermilab (fixed targed p (400 GeV) + Be):

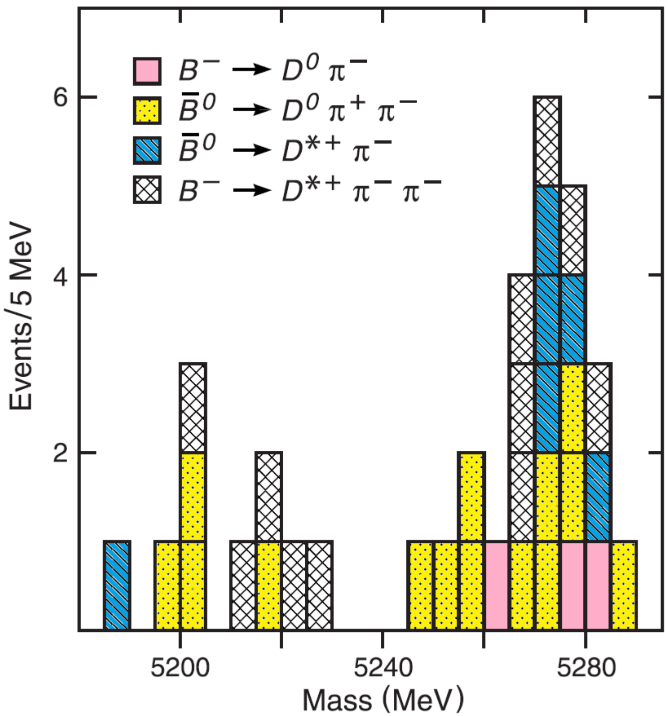
Phys.Rev.Lett. 39 (1977) 252-255

Υ(1S) resonance m ~ 9.5 GeV



☆ The first measurements of *B* meson decays were performed by the CLEO experiment at CESR (e^+e^- collider ring) *Phys.Rev.Lett.* 50 (1983) 881

B mesons were coming from decays of the Υ(4S)



$m[\bar{B}^0]$ $5274.2 \pm 1.9 \pm 2.0$ MeV

$m[B^-]$ $5270.8 \pm 2.3 \pm 2.0$ MeV

Introduction

Some basic definitions:

E_{CM} = center-of-mass energy. Available energy for particle creation

Fixed target experiment: $E_{\rm cm}^2 = (m_1^2 + m_2^2 + 2m_2E_{1,\rm lab})$

Collider: $E_{\rm cm}^2 = (E_1 + E_2)^2$

Luminosity = a measurement of the number of collisions that can be produced in a detector per cm^2 and per second

$$\mathcal{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y} \quad [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

n_1, n_2: the number of particles per bunch
σ_x, σ_y : beam transverse size at the interaction point
f: collision rate

Rate $R = \mathcal{L}\,\sigma$ $[s^{-1}]$

σ: cross section of the physics process
["barn" – 1 b = 10^{-24} cm^2 **]**

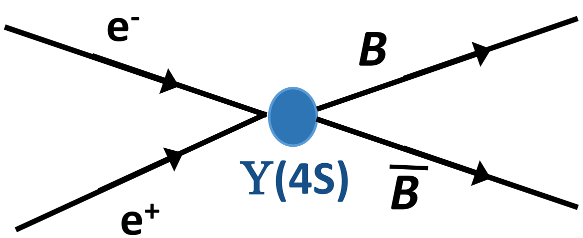
Ex: for $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1} and σ = 1 nb $\rightarrow$ R = 10 Hz

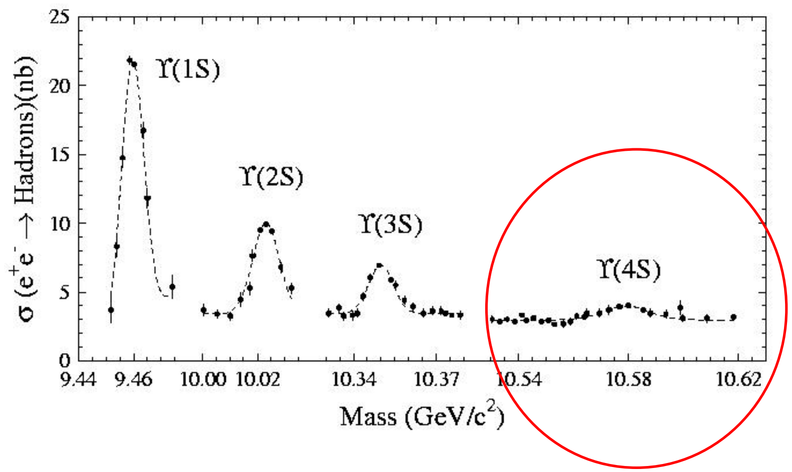
Introduction

CLEO, ARGUS,
BaBar, **BELLE (II)**

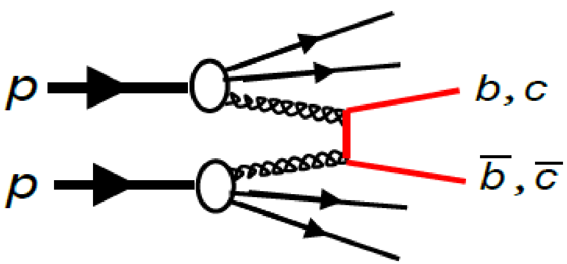
How *b*-hadrons are produced?

- From the decay of the $\Upsilon(4S)$ resonance, produced in e^+e^- collisions:



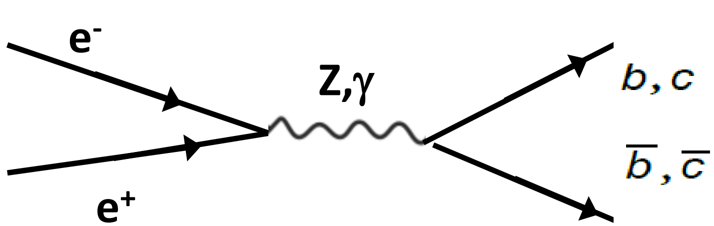


- From the hadronization of b quarks produced in p-p (or antiproton) collisions:



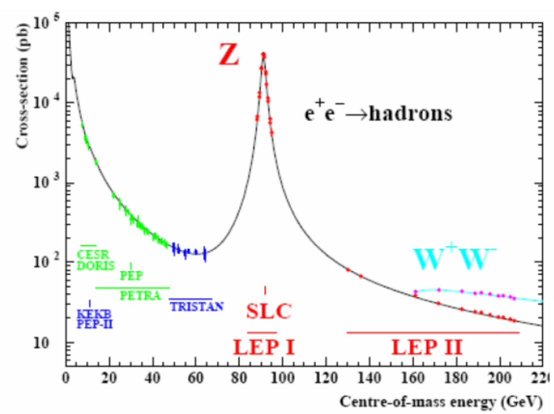
CDF, D0
LHCb, ATLAS, CMS

- From the decay of the Z resonance, produced in e^+e^- collisions:



DELPHI, L3,
ALEPH, OPAL

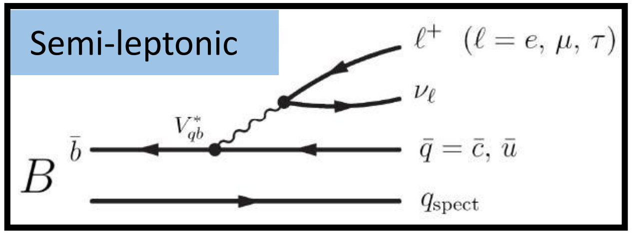
SLD

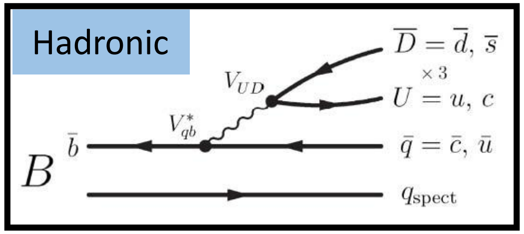


Introduction

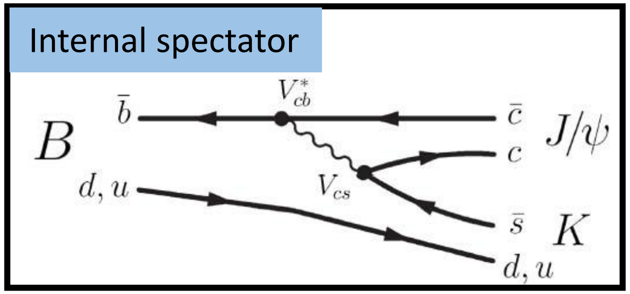
How b-hadrons decay?

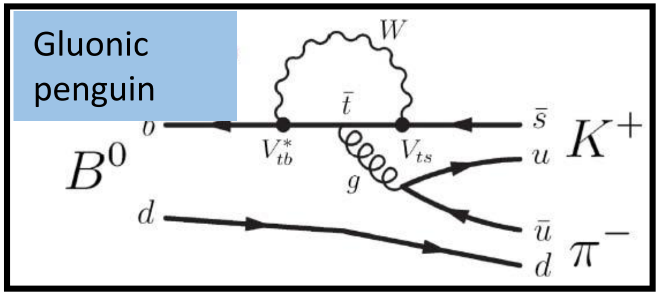
Dominant tree decays:

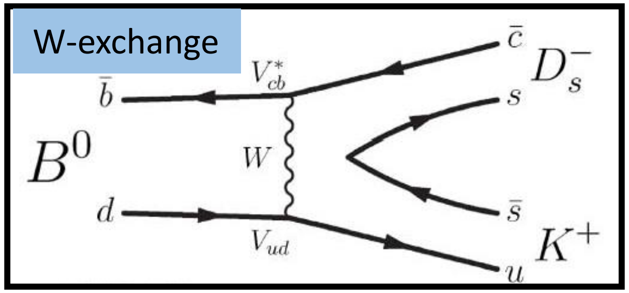




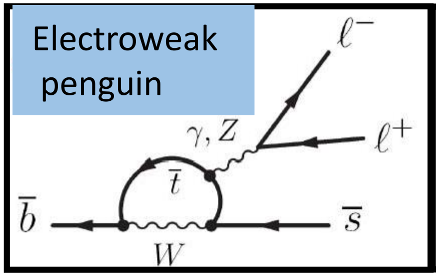
Rare hadronic decays

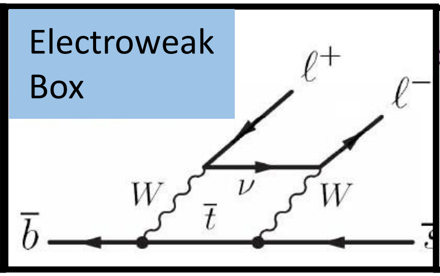


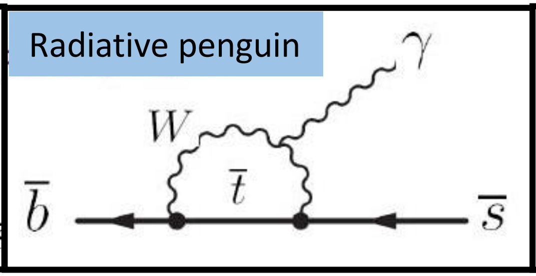


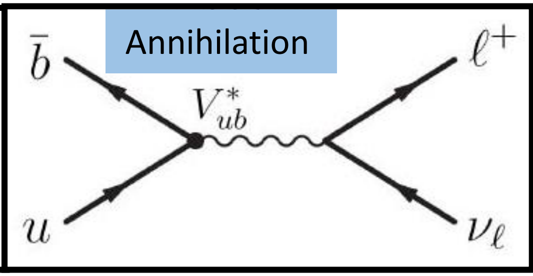


Radiative and leptonic decays



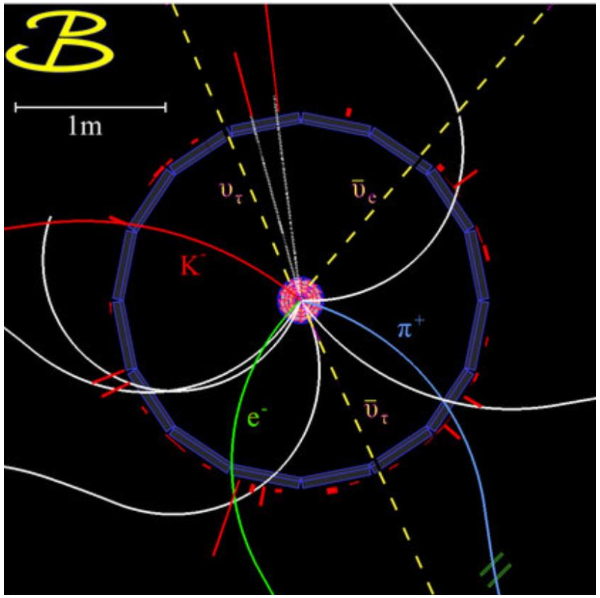


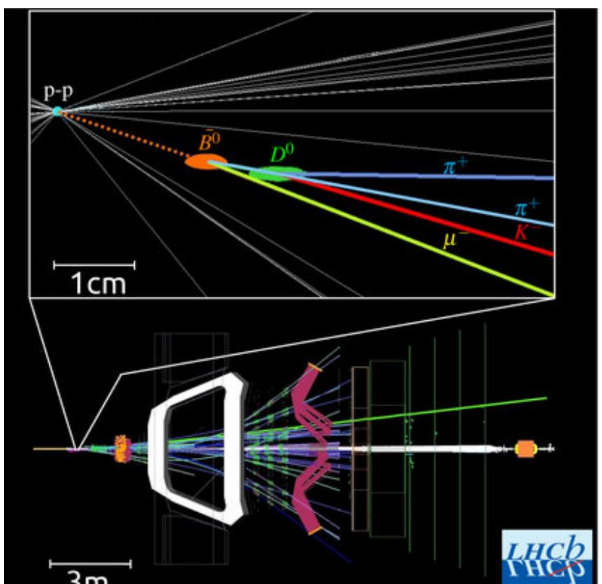




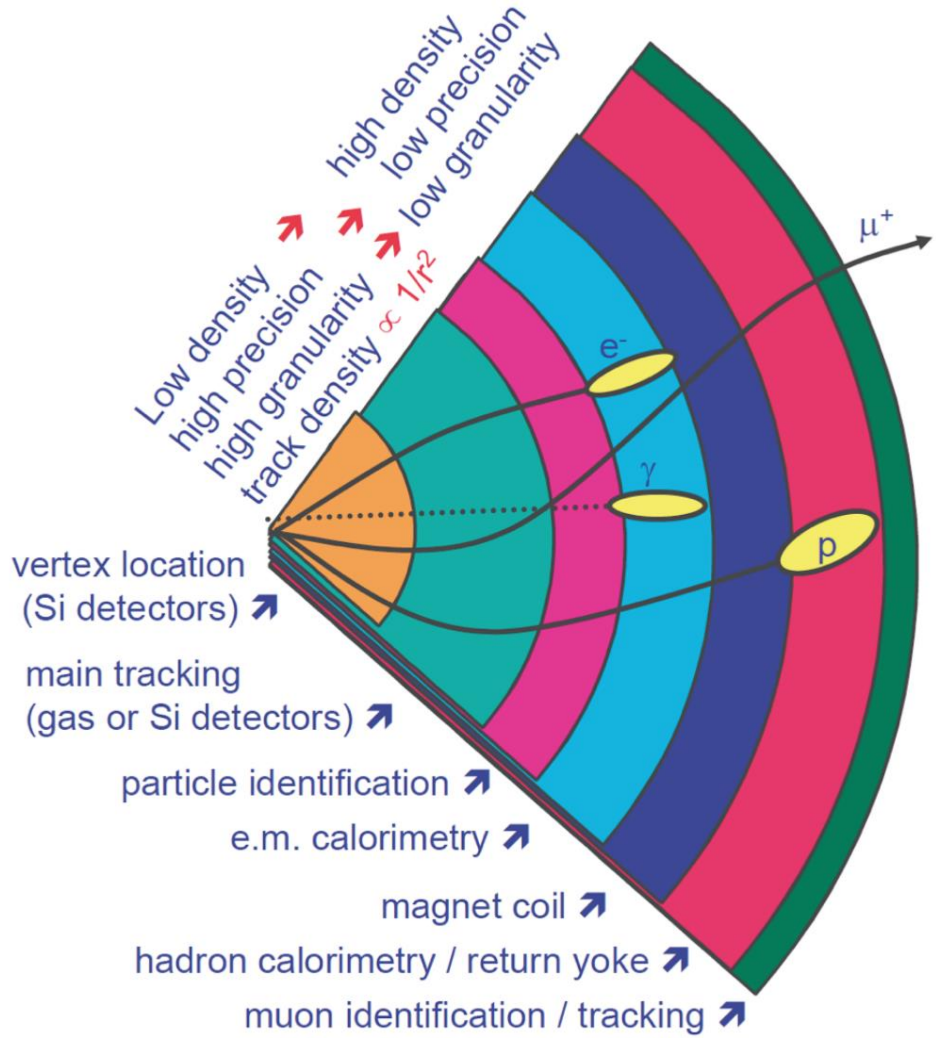
How we detect them?

Introduction





Typical structure of a HEP detector:



(1999 - 2008 / 2010)

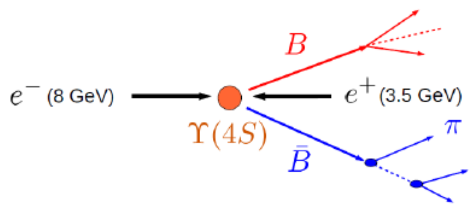
The flavour experiments

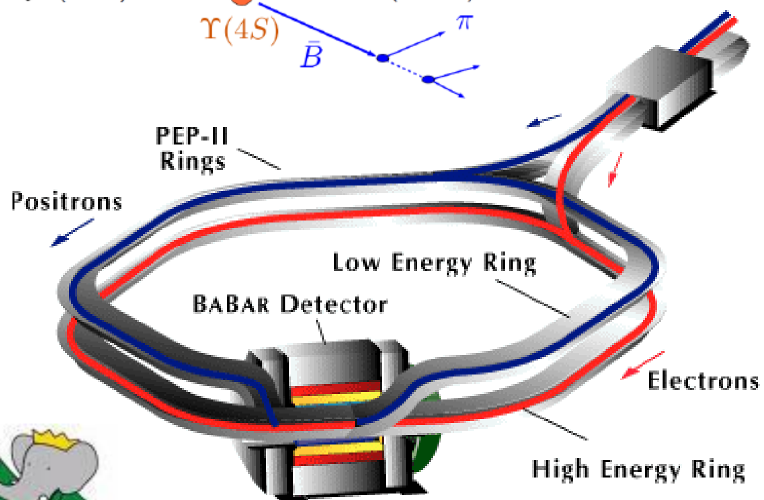
* First measurement of CPV in the B system
* High precision CKM matrix
* Discovery of η_b

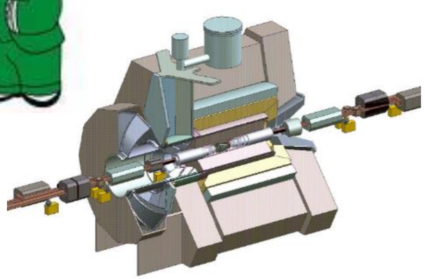
The precessors, key in flavour physics:

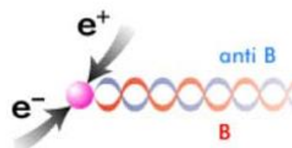
The b-factories: Belle at KEK (Japan) and BaBar at PEP-II (California)

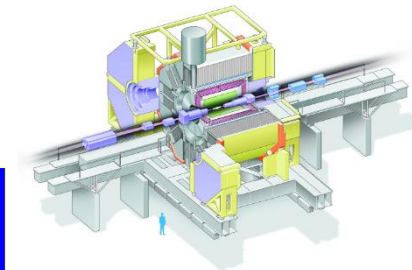
Asymmetric e^+e^- colliders working at the Υ(4S) energy (10.54 GeV).

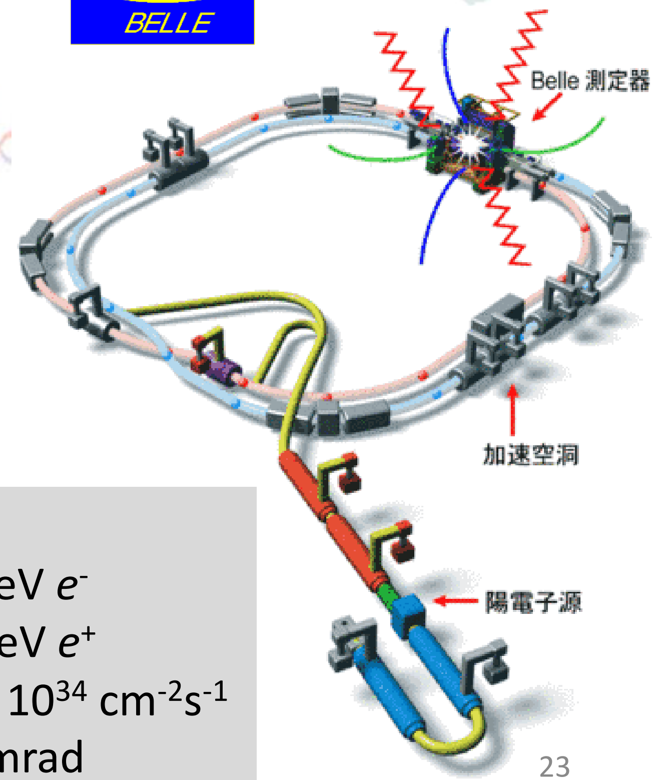












PEP-II / KEK-B

High Energy Ring : 9.0 / 8.0 GeV e^-

Low Energy Ring : 3.1 / 3.5 GeV e^+

Design luminosity : 3 x 10^{33} / 10^{34} $cm^{-2}s^{-1}$

Beam crossing angle : 0 / 22 mrad

The flavour experiments

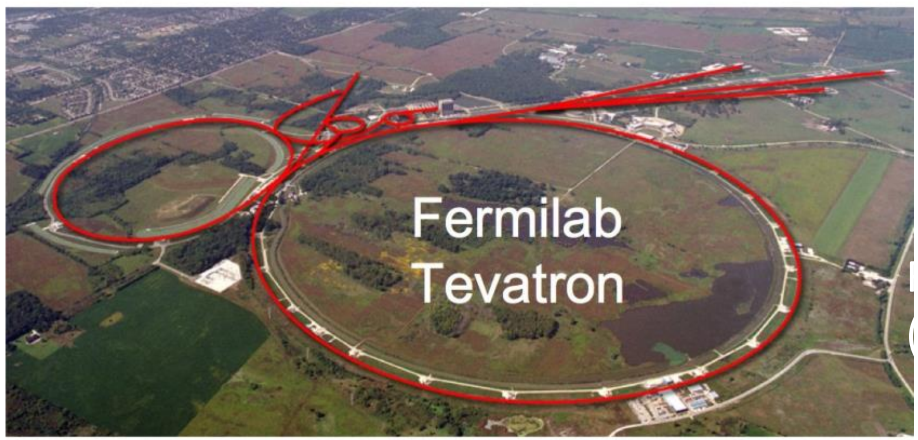
(1987- 2011)

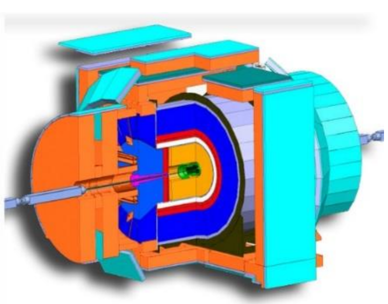
* Discovery of the top quark
* First measurement of B_s oscillations
* Discovery of the Ξ_b baryon

The precessors, key in flavour physics:

The Tevatron at Fermilab (Illinois): CDF and D0

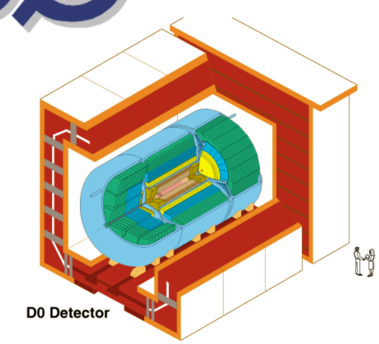
$p\bar{p}$ collider working at cm of mass energy of 1.96 TeV.





TEVATRON

Superconducting $p\bar{p}$ ring
Energy : 1 TeV/beam
Detectors: CDF, D0
Luminosity: 10^{32} $cm^{-2}s^{-1}$
Physics: W, Z, Top Production
Higgs searches
B physics



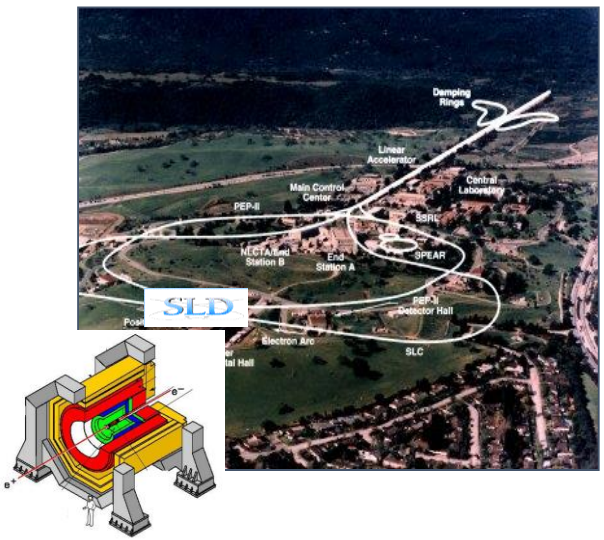
The flavour experiments

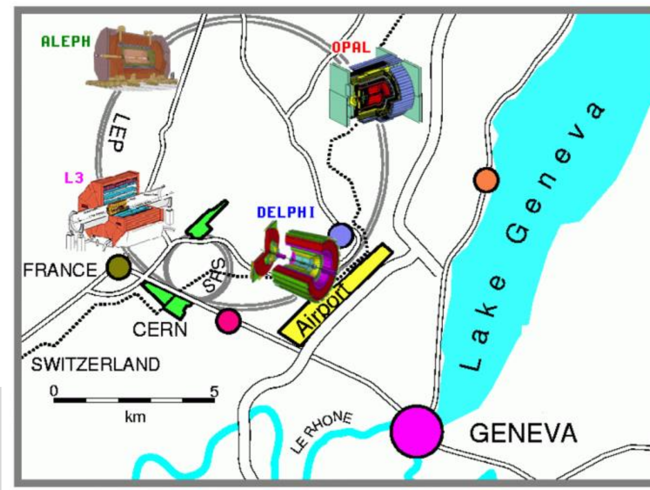
(1989-2000)

* R_b, R_c
* b-hadron lifetimes
* B oscillations
* The CKM matrix
* Discovery of B_s and Λ_b

The precessors, key in flavour physics:

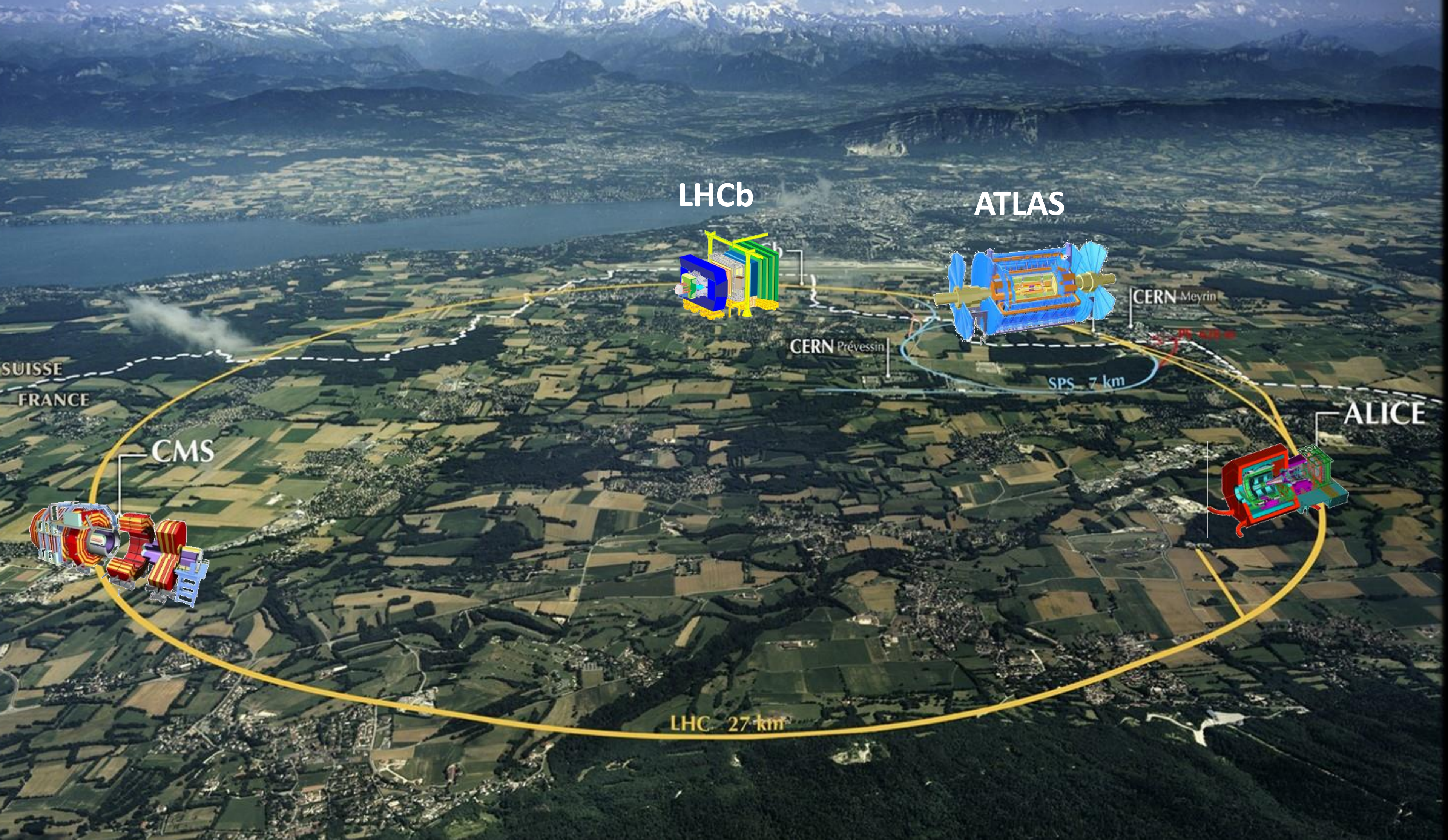
The SLC (California): SLD
The LEP (CERN): ALEPH, DELPHI, L3 and OPAL
e^+e^- colliders working at cm of mass energy of the Z





SLC / LEP
e+e- linear collider / ring
Energy : ~50 / 45 -104 GeV /beam
Detectors: SLD / ALEPH, DELPHI, L3, OPAL
Luminosity: 2 / ~ 20 x 10^{30} $cm^{-2}s^{-1}$
Physics: Z / W, Z
B physics
Higgs searches

The LHC experiments



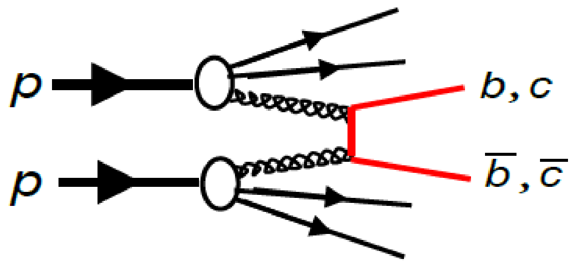
LHC: the proton-proton collider at CERN with an energy of 13TeV

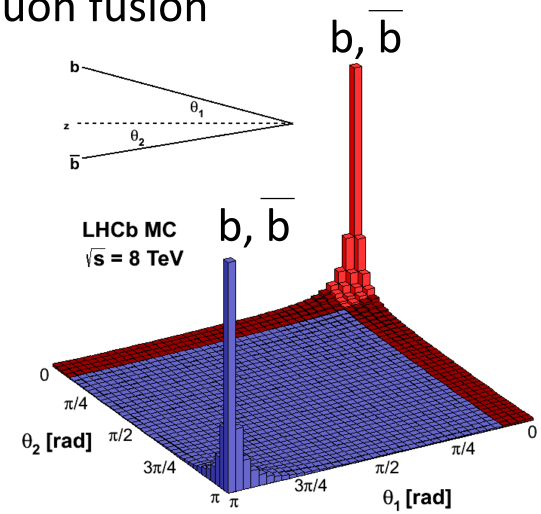
The LHCb experiment

The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion
  ~ 300 μb @ √s=7 TeV
  ~ 600 μb @ √s=13 TeV

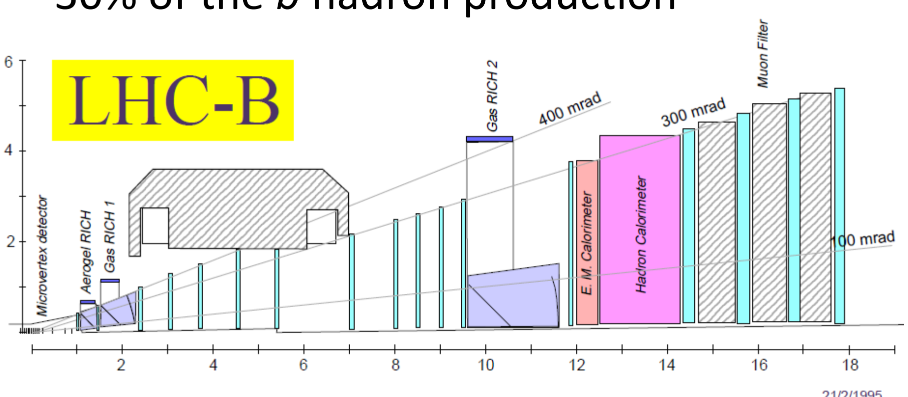
  [PRL 118 (2017) 052002]
  [JHEP 02 (2021) 023]



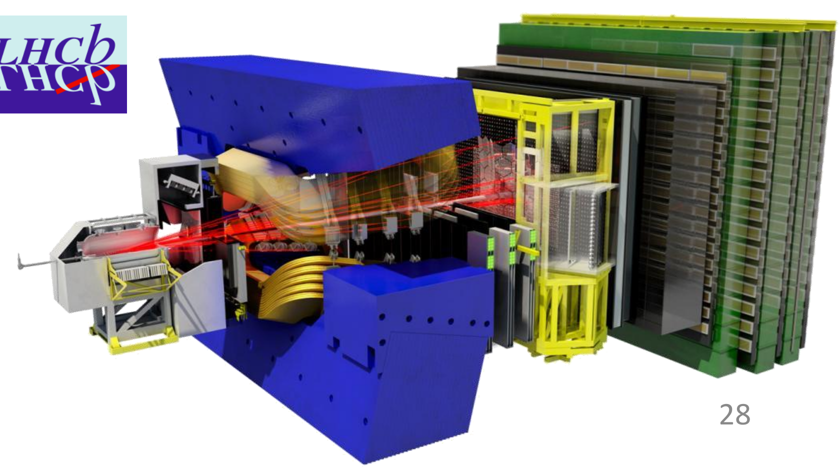


The *b* quarks hadronize in B, B_s, $B^*_{(s)}$, *b*-baryons…
→ average B meson momentum ~ 80 GeV

- The LHCb idea: to build a single-arm forward spectrometer:
 ~ 4% of the solid angle (2 < η < 5),
 ~30% of the *b* hadron production

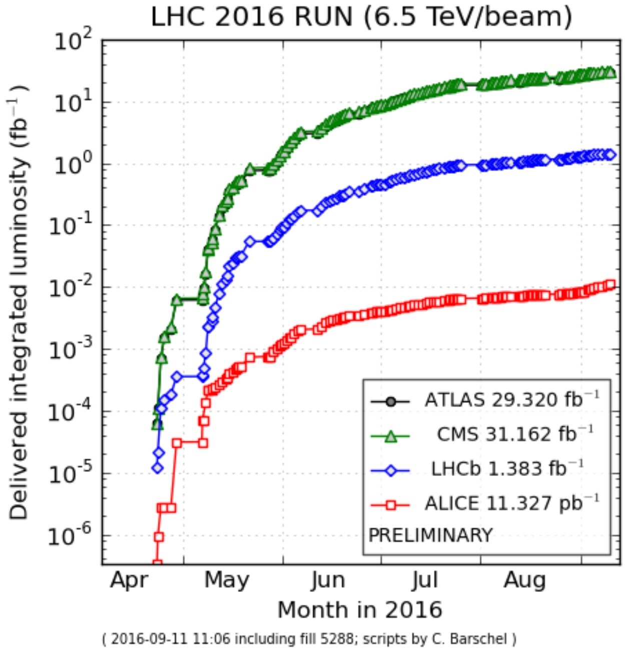


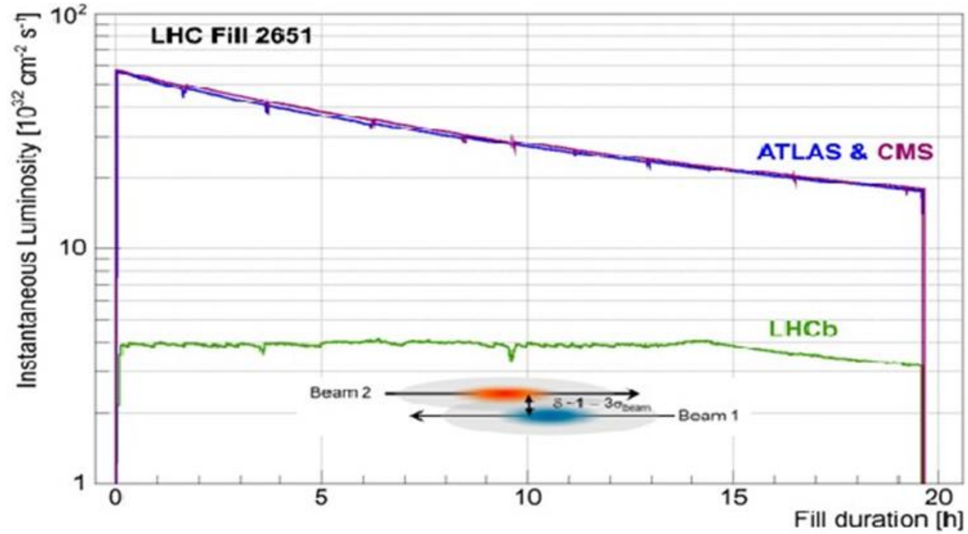
Letter of Intent, 1995

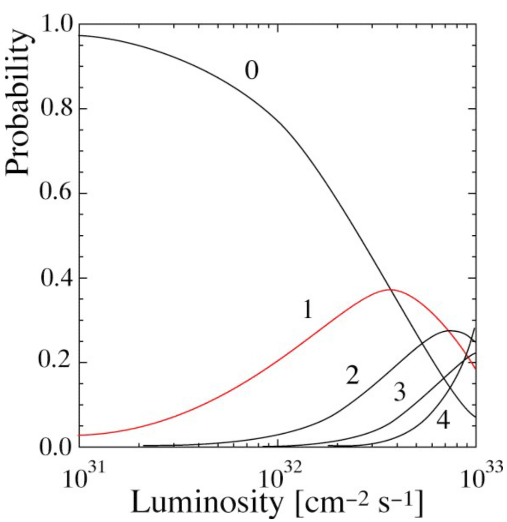


$N = \int \mathcal{L} \sigma$

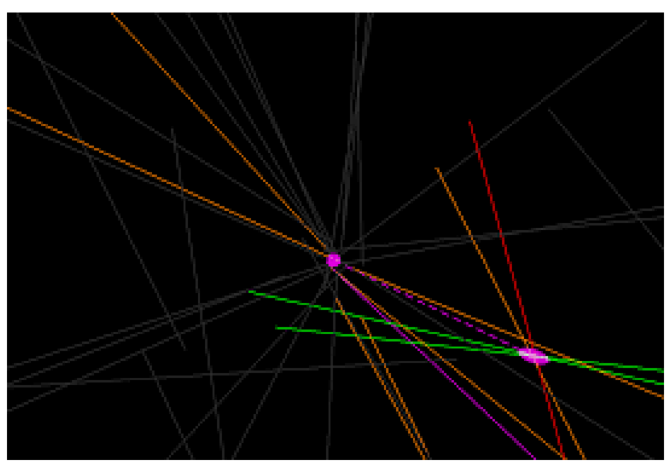
The LHCb experiment



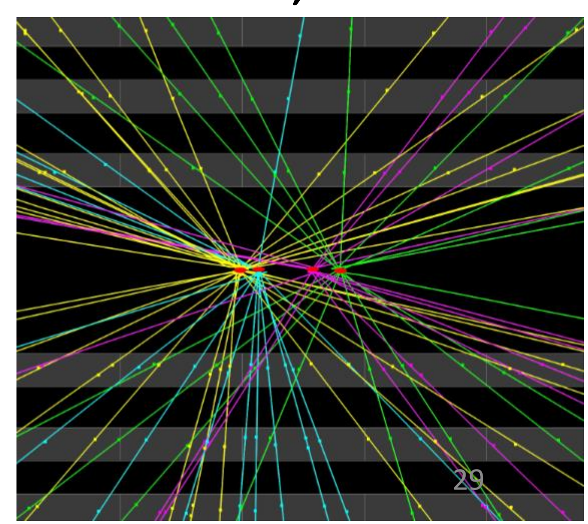




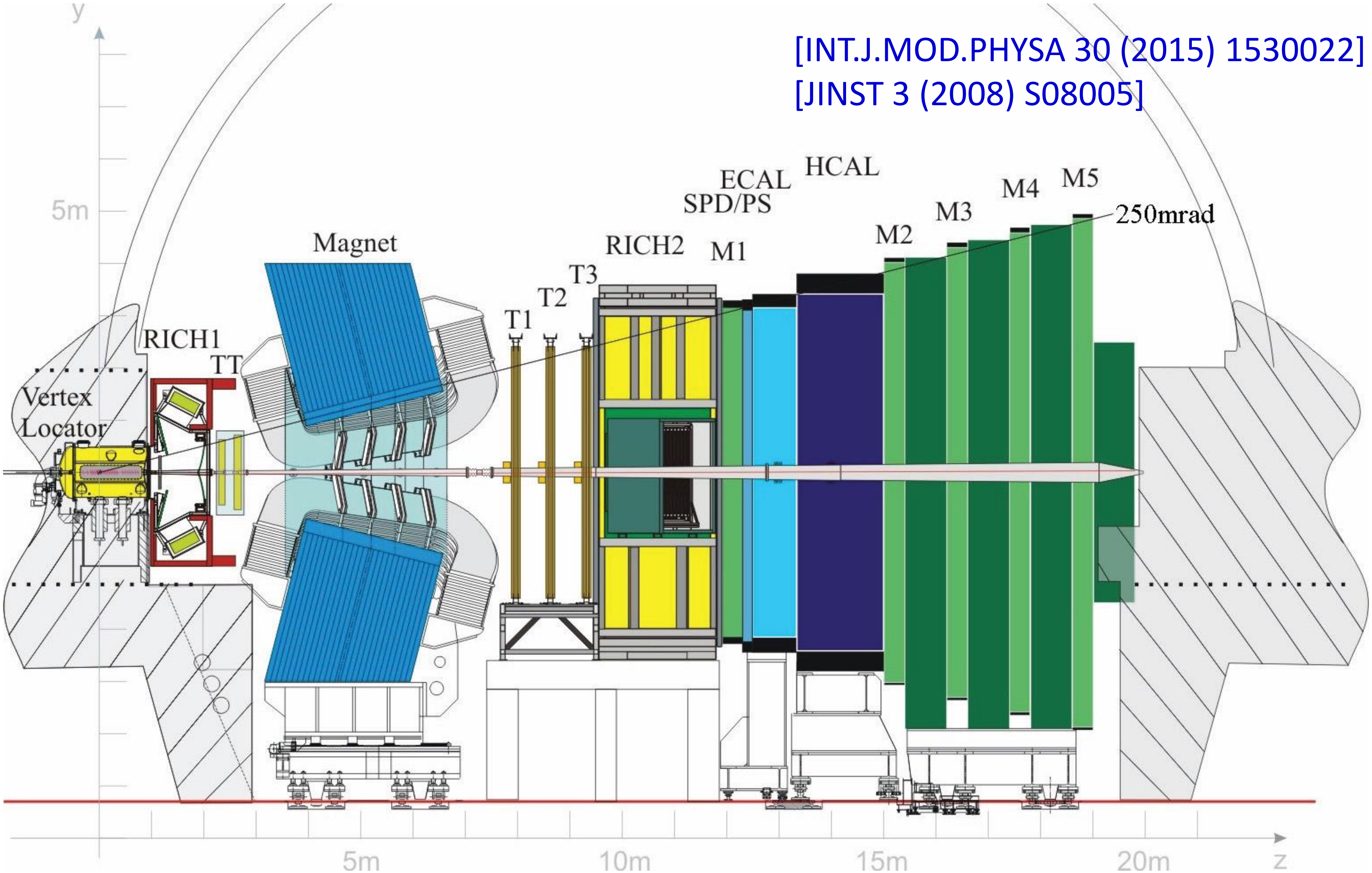
LHCb



ATLAS, CMS

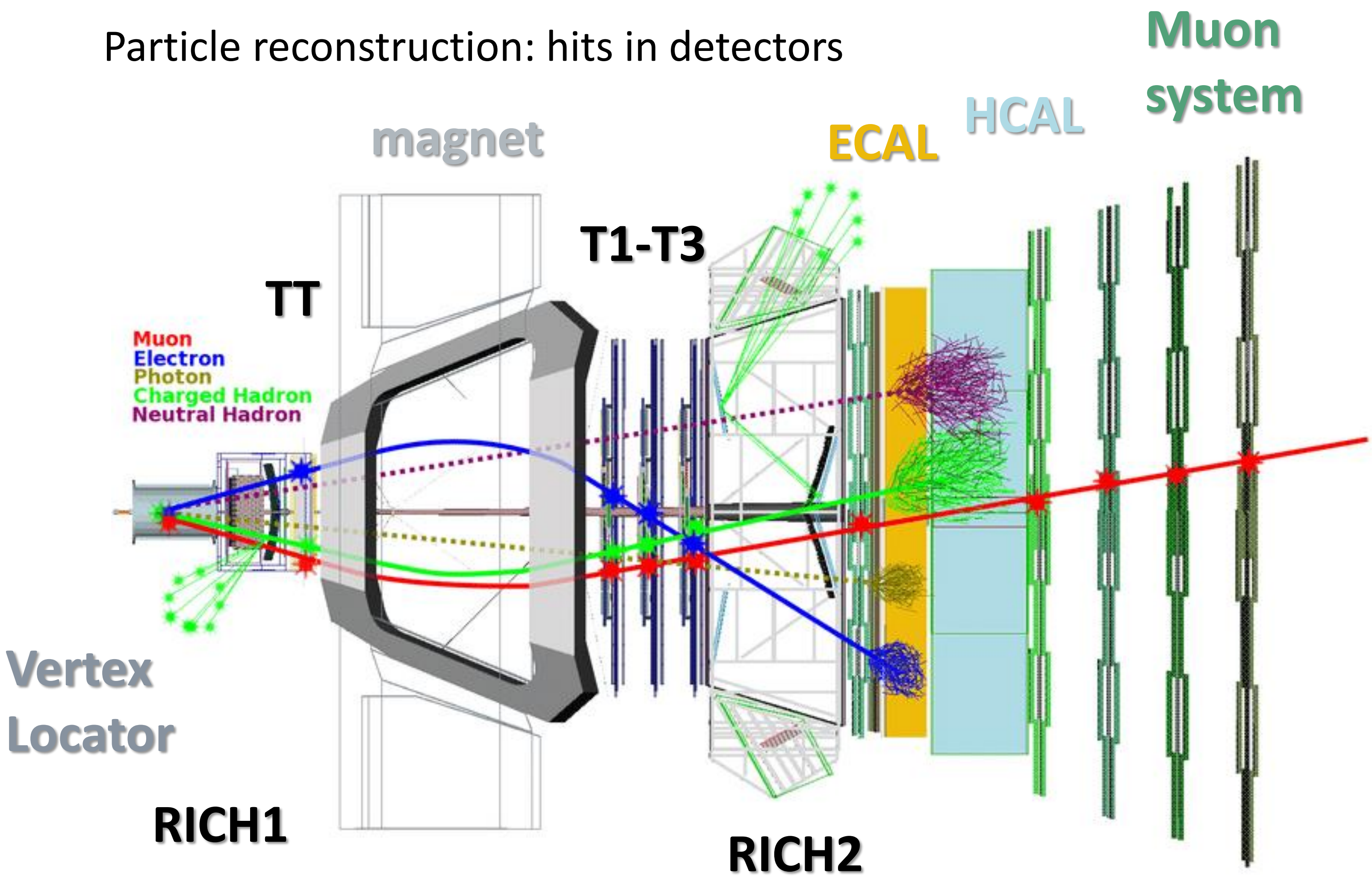


The LHCb experiment



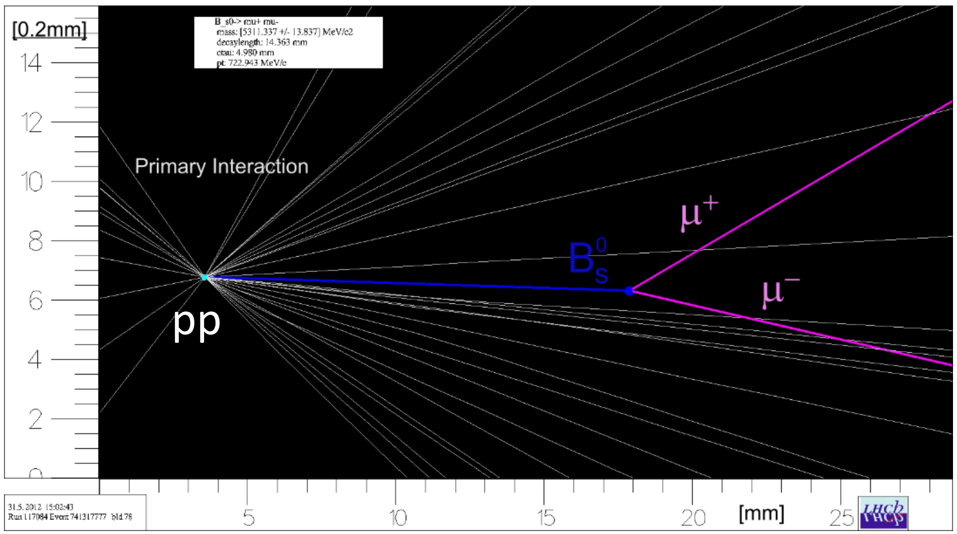
The LHCb experiment

Particle reconstruction: hits in detectors



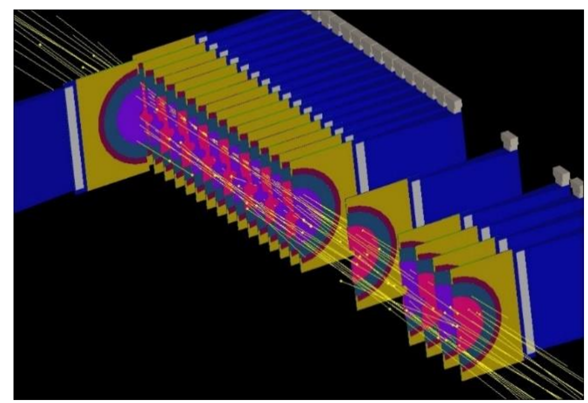
The LHCb experiment

What do we need?



- To reconstruct the production and decay vertices
  - → Good decay vertex resolution
  - → Good impact parameter resolution
- To reconstruct the particle trajectory
  - → Good momentum resolution

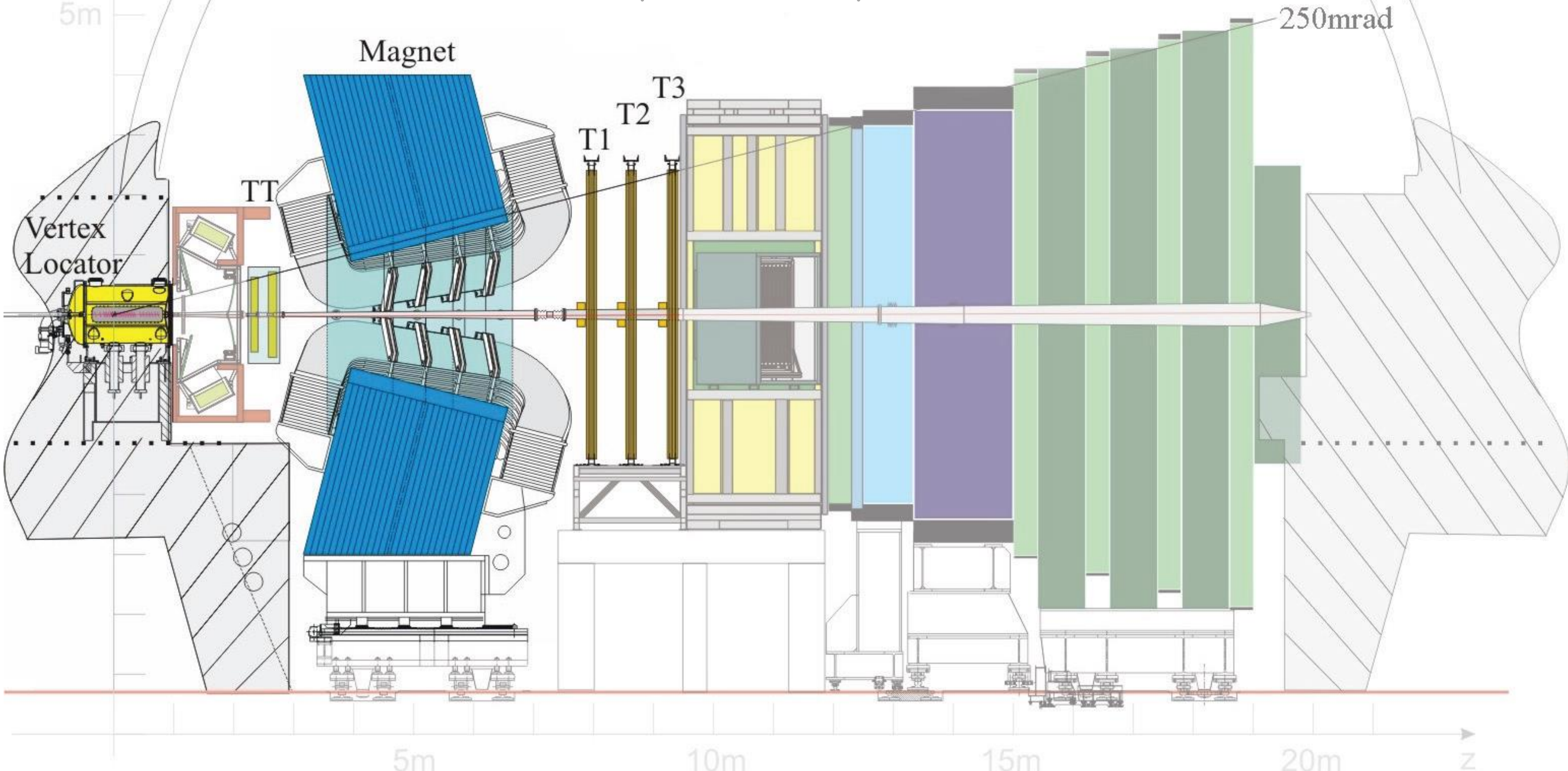
Vertex detector (VELO)



How long will a Λ_b baryon be travelling in the detector before decaying? ($p_{\Lambda b}$~80 GeV)

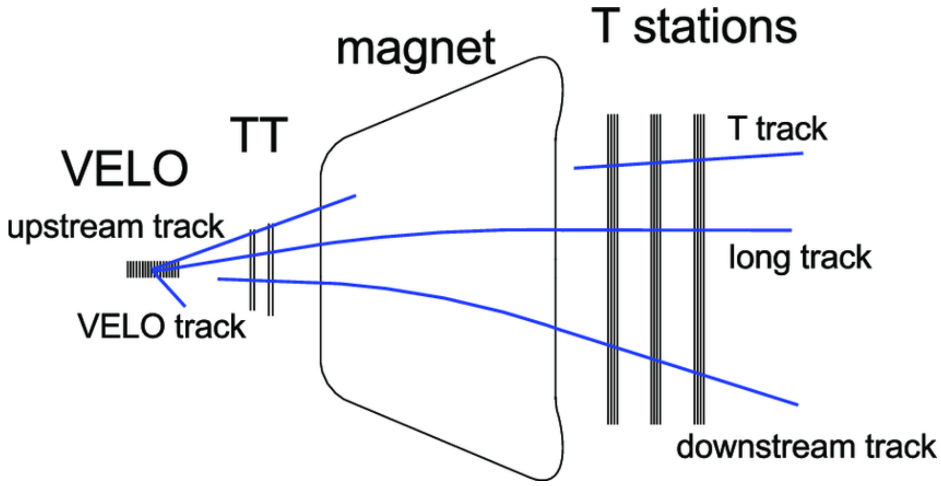
The LHCb experiment

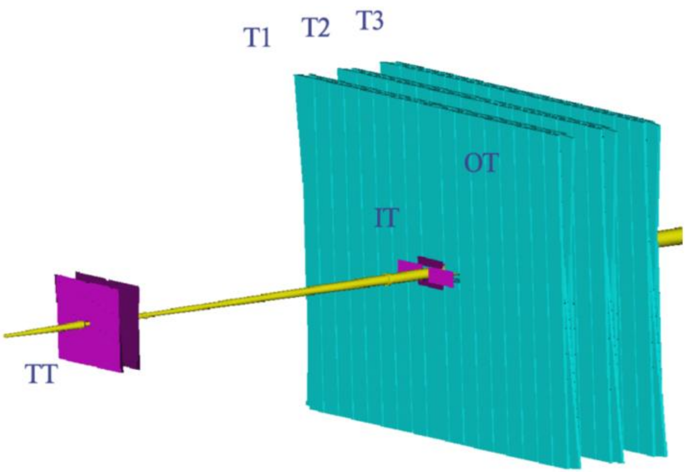
Precise tracking (p∈0 GeV/c –200 GeV/c, Δp/p = 0.5%–1%)
Good Impact Parameter (IP) resolution (20 μm)
Good vertex resolution (15μm (x,y) - 70μm(z))

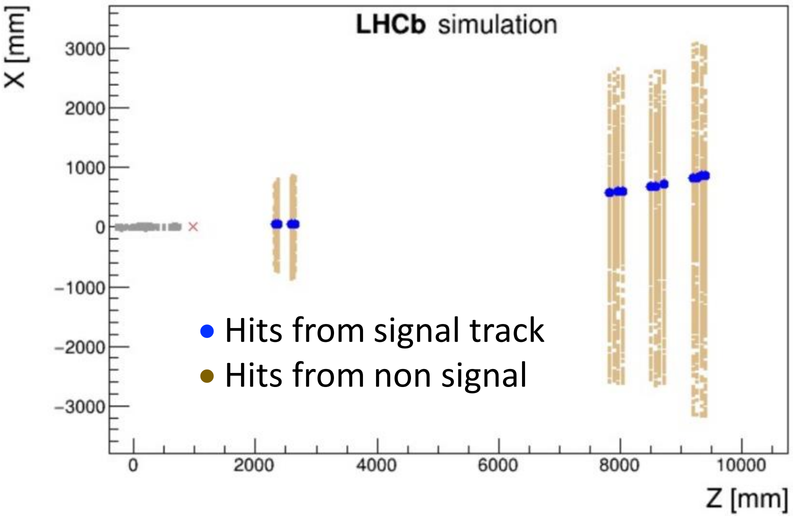


The LHCb experiment

Tracking at LHCb:



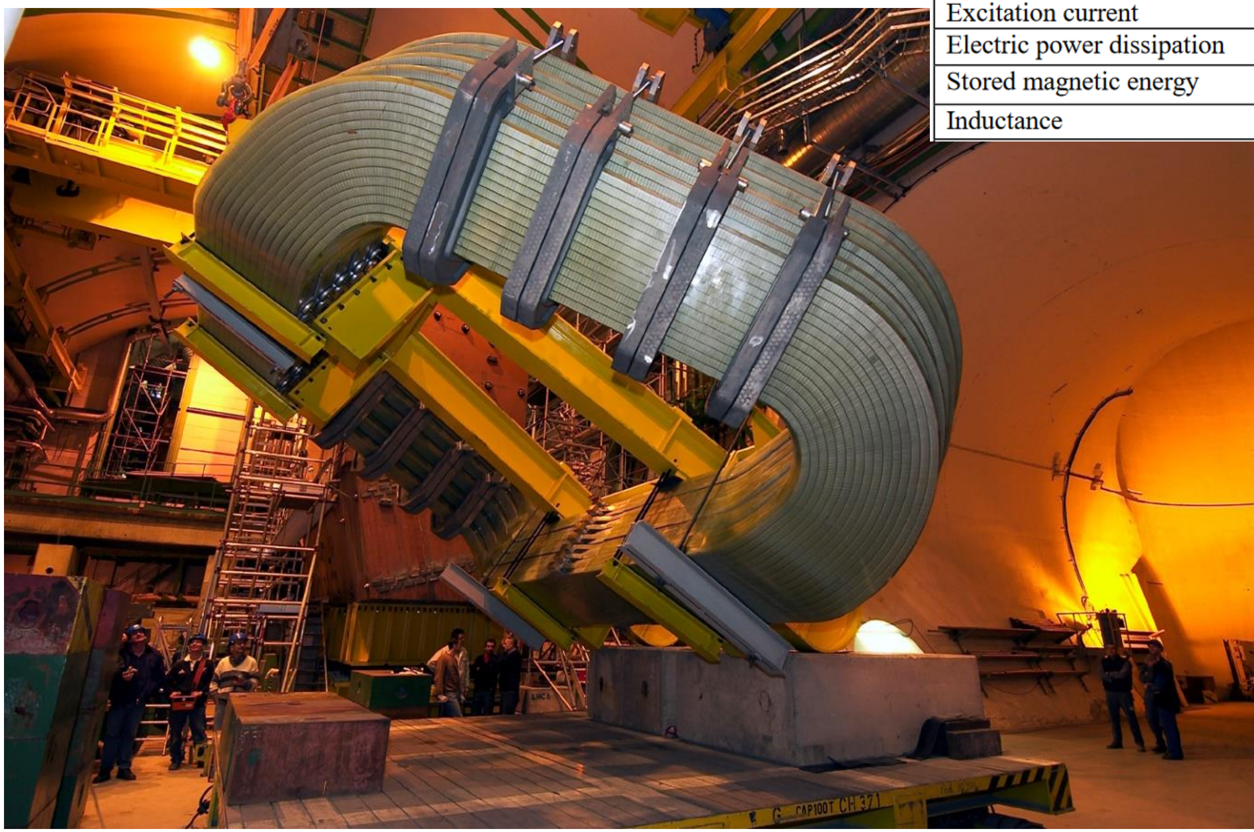


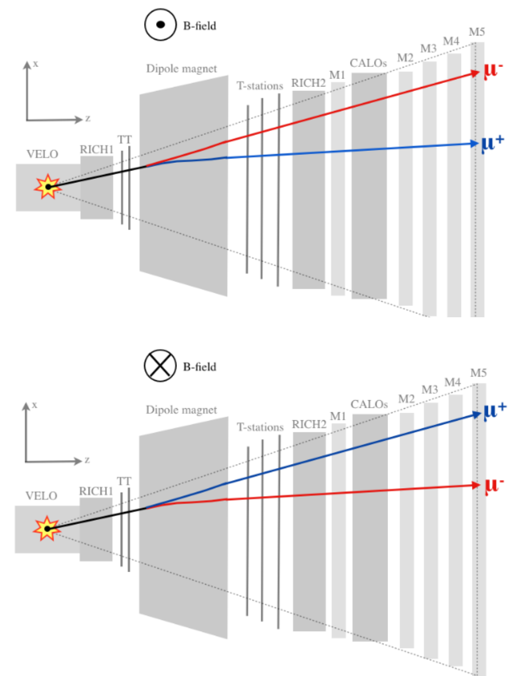


The LHCb experiment

The LHCb magnet:

Magnetic Parameters	
Bending power	$\int B\,dl = 4$ Tm (10 m track length)
Non-uniformity of $\int B\,dl$	$\leq \pm$ 5% in acceptance (hor.: ±300 mrad, vert.: ±250 mrad)
Excitation current	NI = 2 x 1.3 MA
Electric power dissipation	P_e = 4.2 MW
Stored magnetic energy	$W_m \approx$ 32 MJ
Inductance	L ≈ 2 H



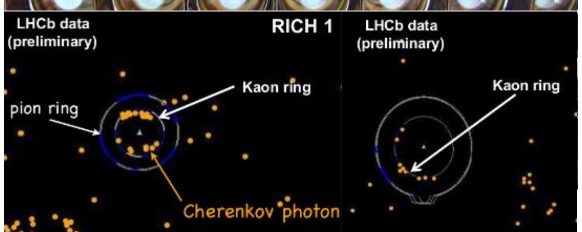


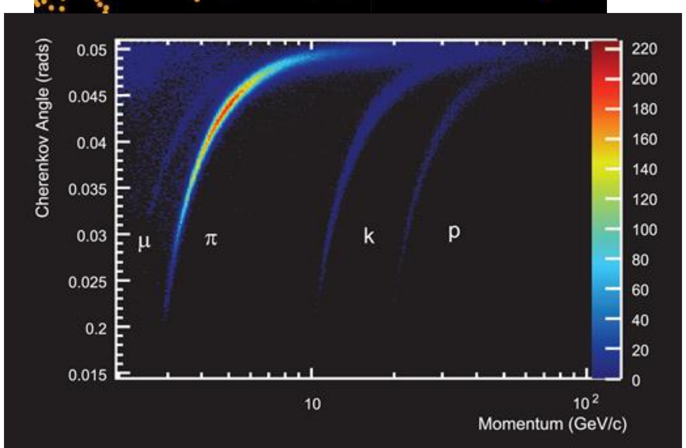
→ Inversion of polarity to study detector asymmetries

The LHCb experiment

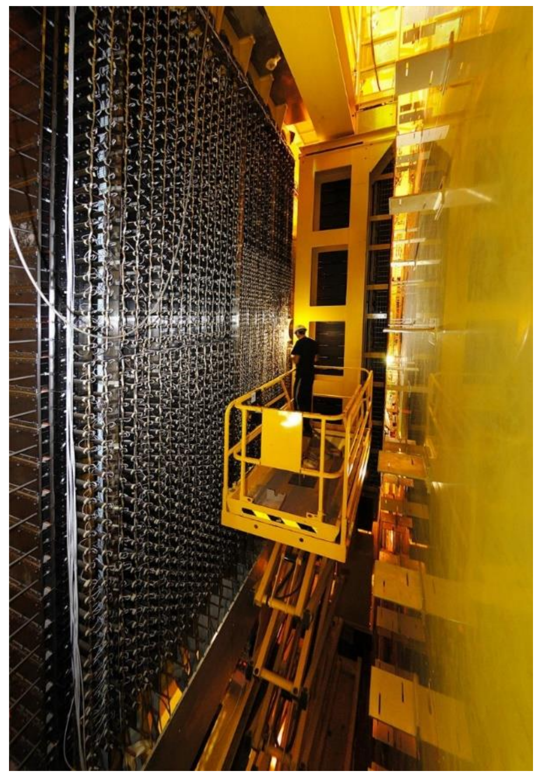
- To recognize the type of particles
  → Good particle identification systems (PID)

Cherenkov detectors (RICH)

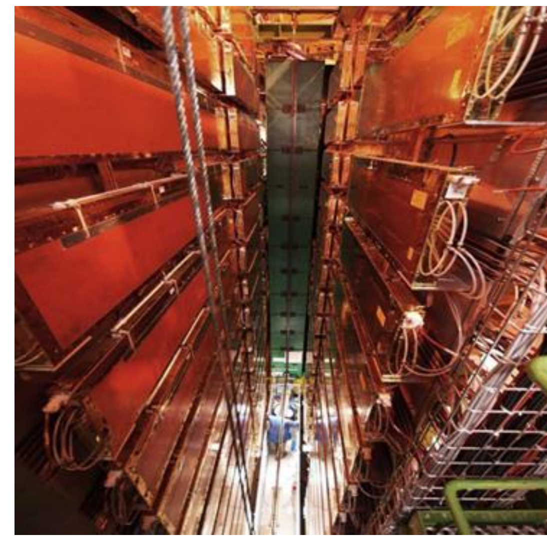


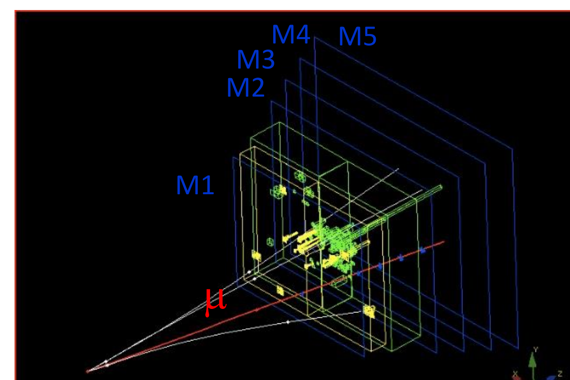


Calorimeters (ECAL, HCAL)



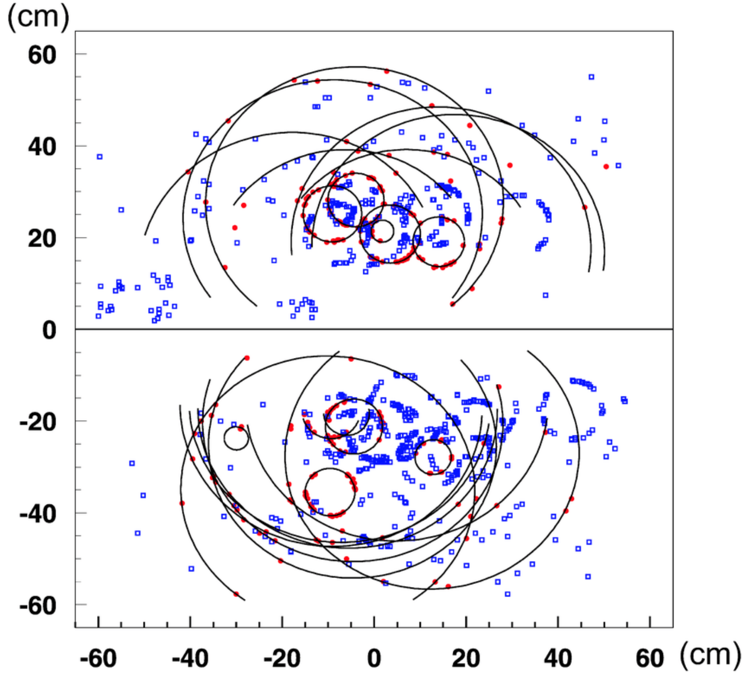
Muon chambers





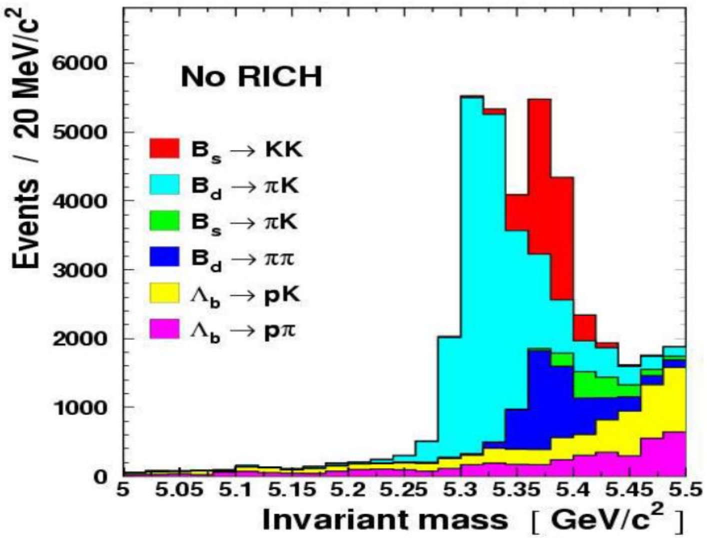
The LHCb experiment

Reconstruction of $B_s \rightarrow K^+K^-$ decays:

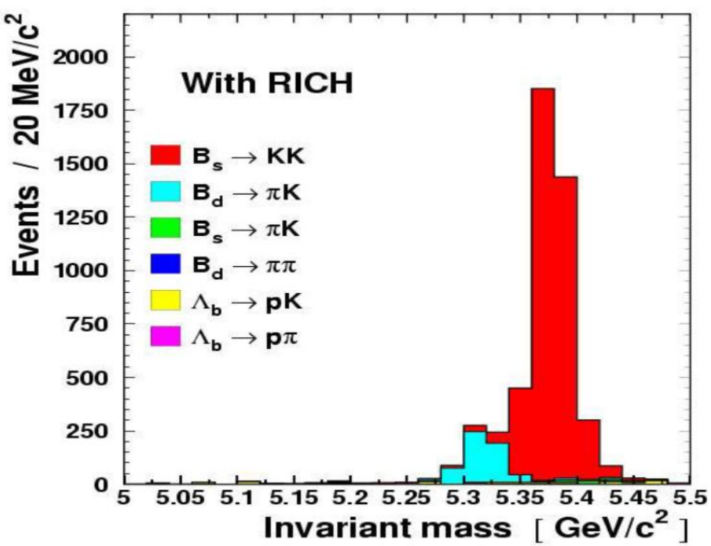


RICH rings are from particle tracks passing through aerogel and C4F10 radiators

Without PID



With PID

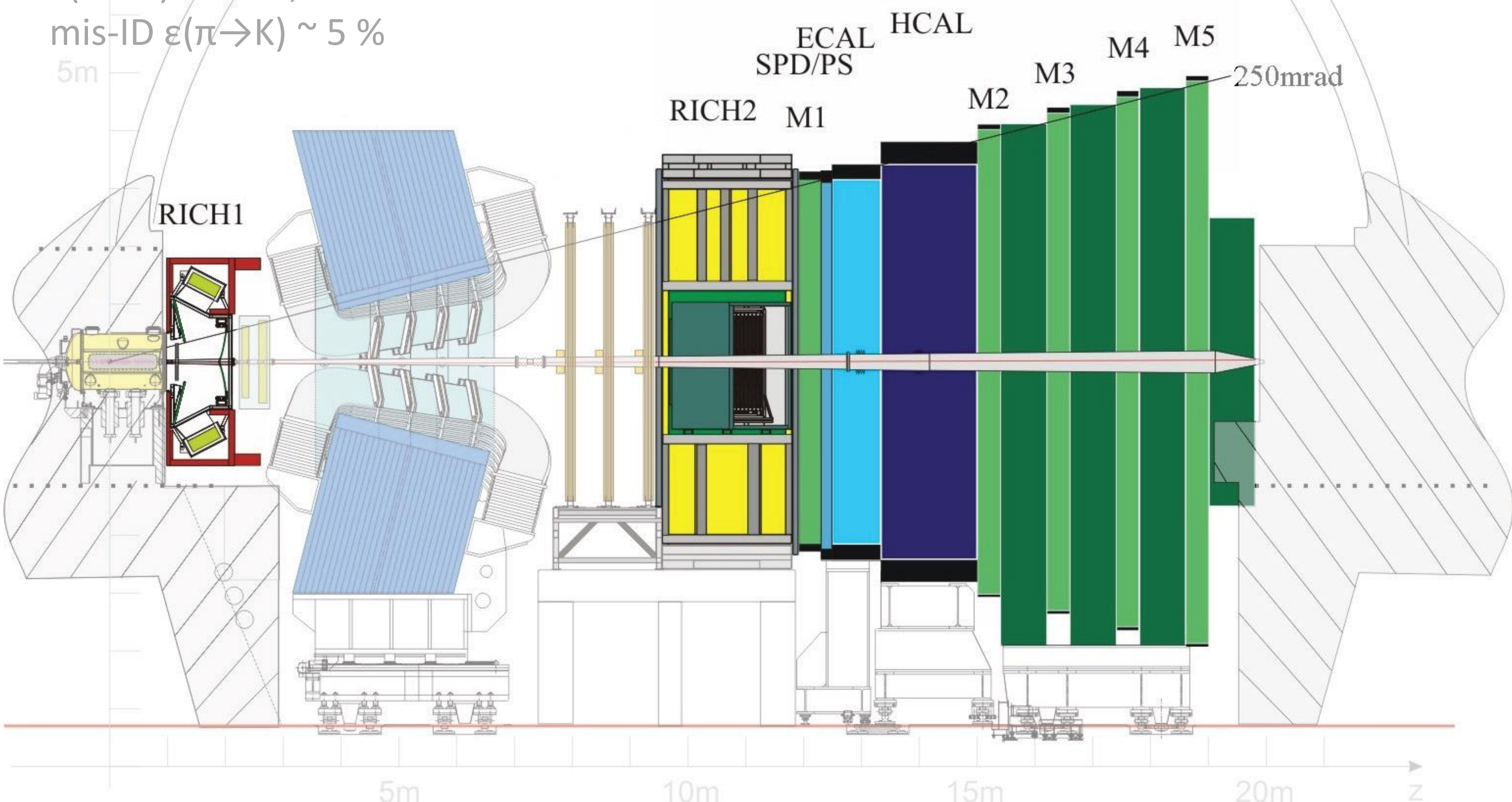


The LHCb experiment

Excellent particle identication
π/K separation over 2-100 GeV
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

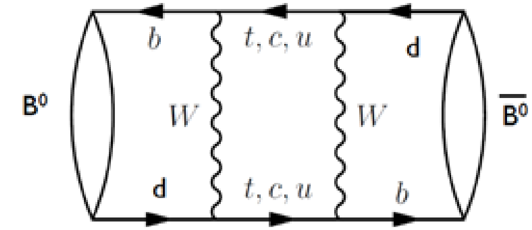
Calorimeter system
ΔE/E = 1 % ⊕10 %/√E (GeV)

Powerful μ identification
ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %

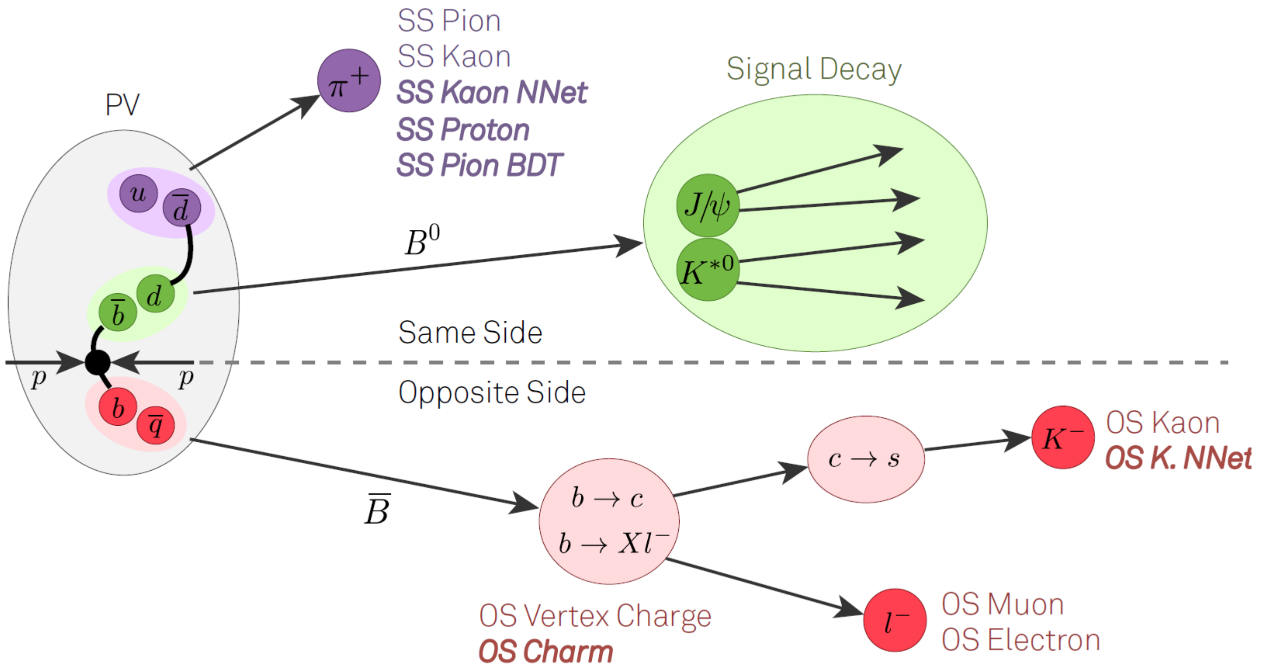


The LHCb experiment

→ B mesons oscillates between particle and antiparticle
→ We need to know the flavour of the particle at the production point



Flavour tagging Use different algorithms that make use of the characteristics of the fragmentation of the b quark, the charge of the decay products or the charge related to the other b hadron produced in pp → X b$\overline{\text{b}}$

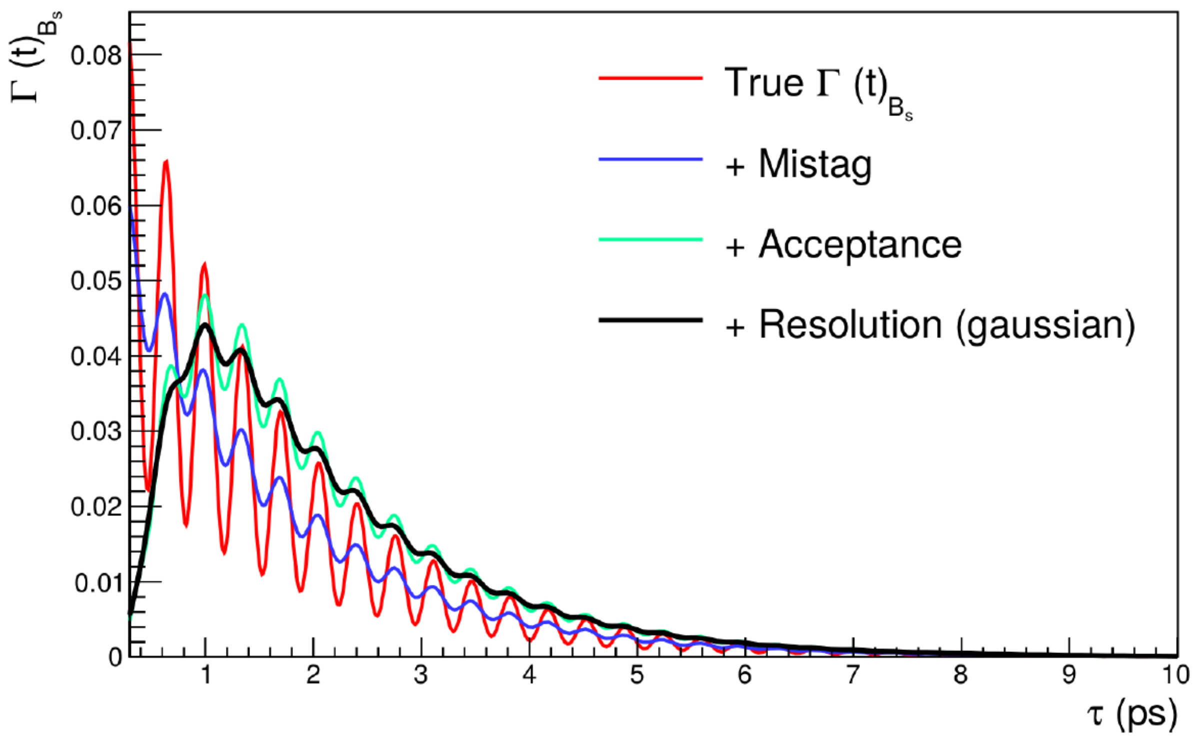


The LHCb experiment

Tagging efficiency ε_{tag} : fraction of events with a flavour tag decision
Wrong-tag fraction ω: fraction of tagged events for which tagging decision is wrong
→ Figure of merit: ***effective tagging power*** $\boldsymbol{\varepsilon_{eff} = \varepsilon_{tag} D^2 = \varepsilon_{tag} (1 - 2\omega)^2}$

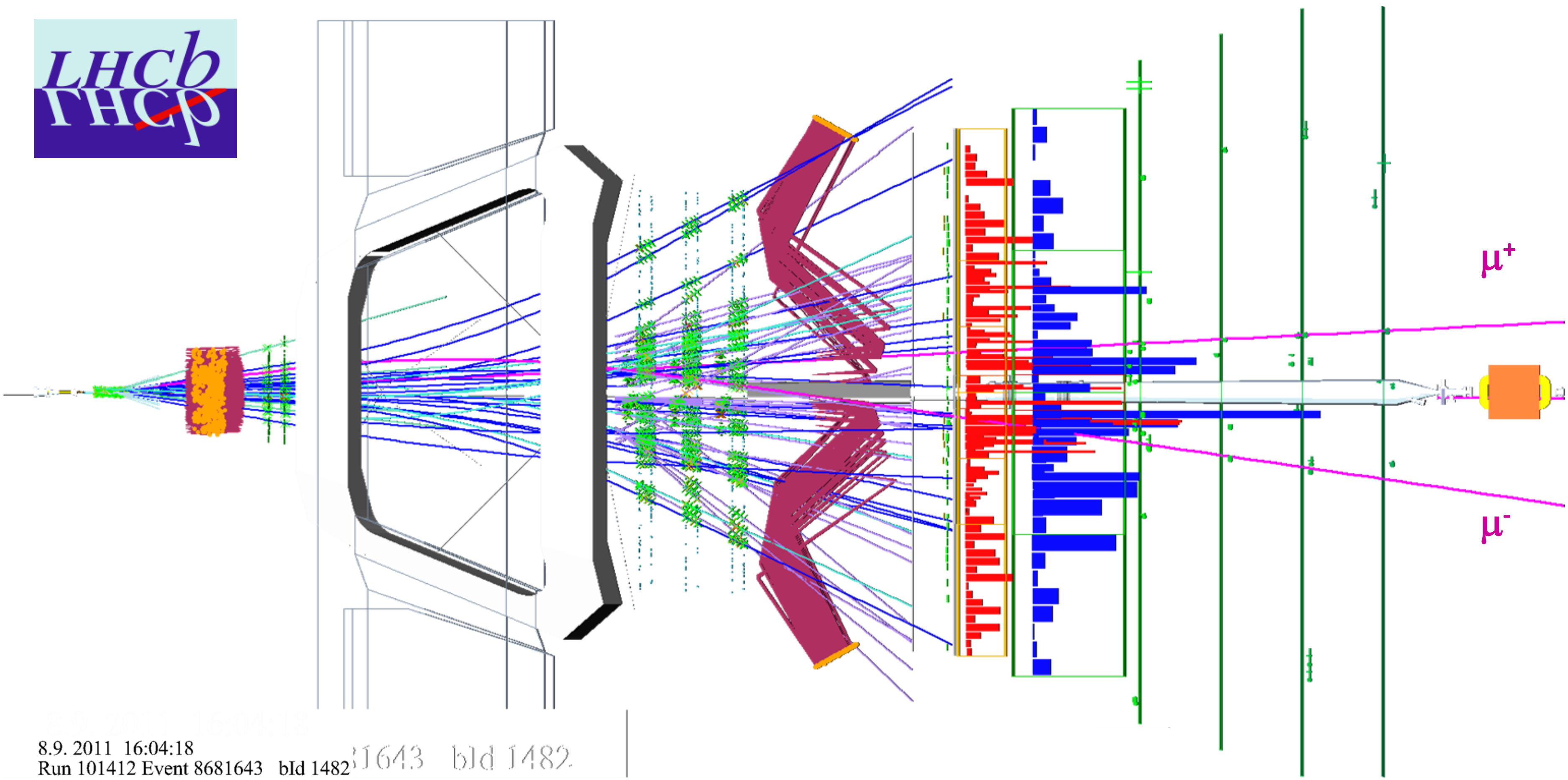
$D^2 \equiv$ dilution factor

$\mathbf{N_{evts} \times \varepsilon_{tag}(1\text{-}2\omega)^2}$



The LHCb experiment

$B_s \rightarrow \mu^+\mu^-$ event



The other LHC experiments

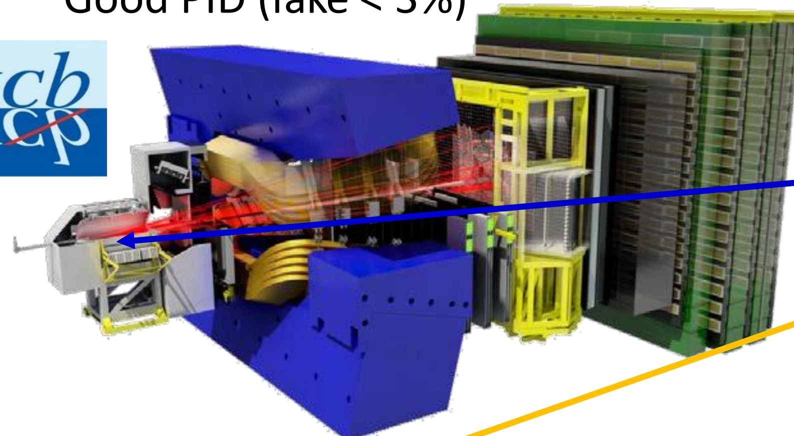
LHCb,
ATLAS & CMS

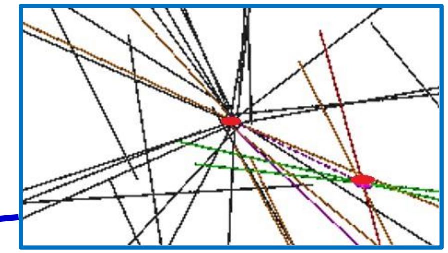
$2<\eta<5$

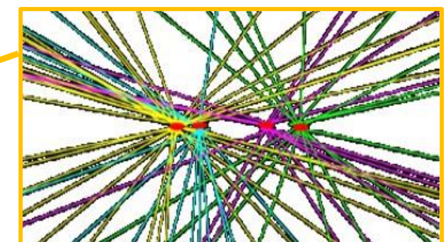
$\sigma_P \sim 0.5\text{-}1\%$

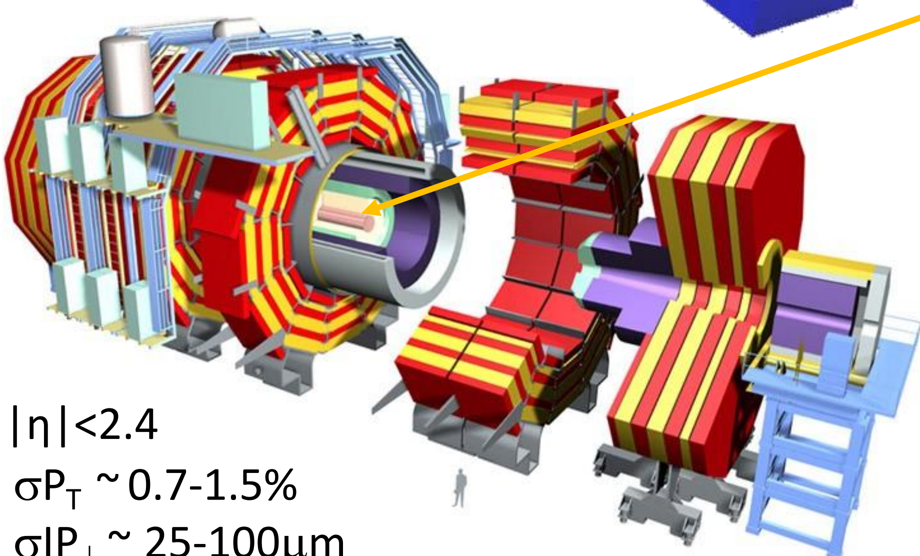
$\sigma IP_\perp \sim 15\text{-}50\ \mu m$

Good PID (fake < 3%)







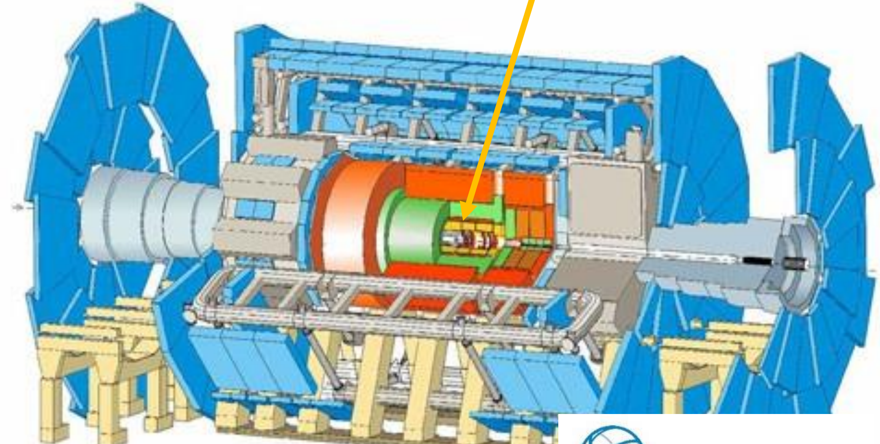


$|\eta|<2.4$

$\sigma P_T \sim 0.7\text{-}1.5\%$

$\sigma IP_\perp \sim 25\text{-}100\mu m$

Very good PID (fake < 0.1%)



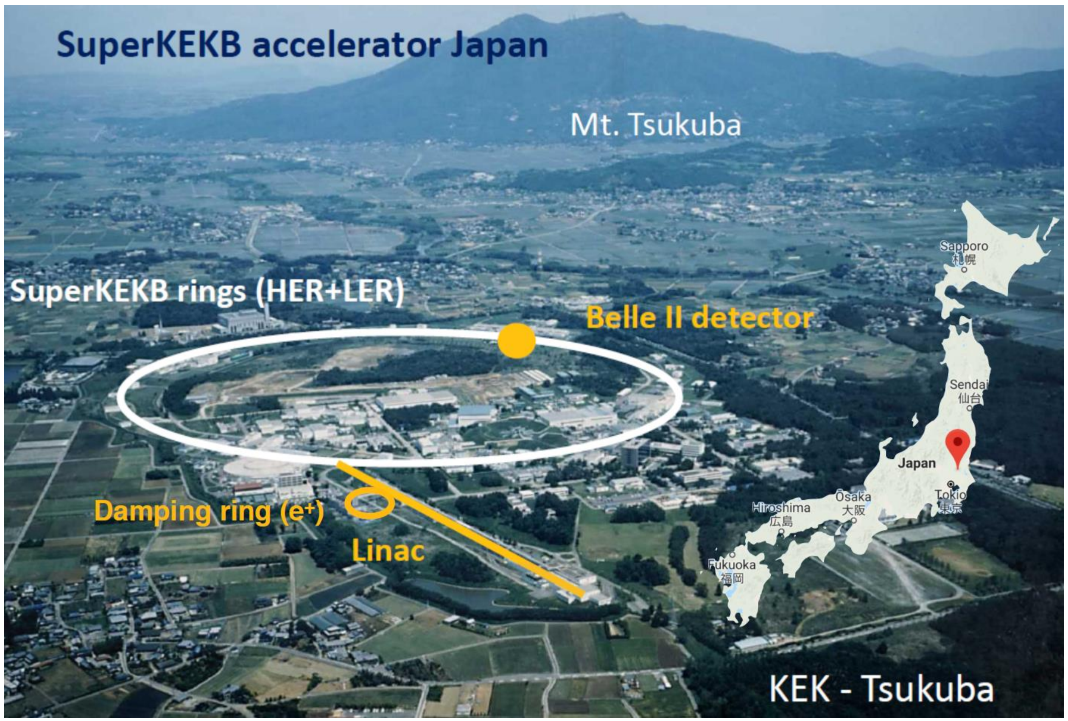
$|\eta|<2.5$

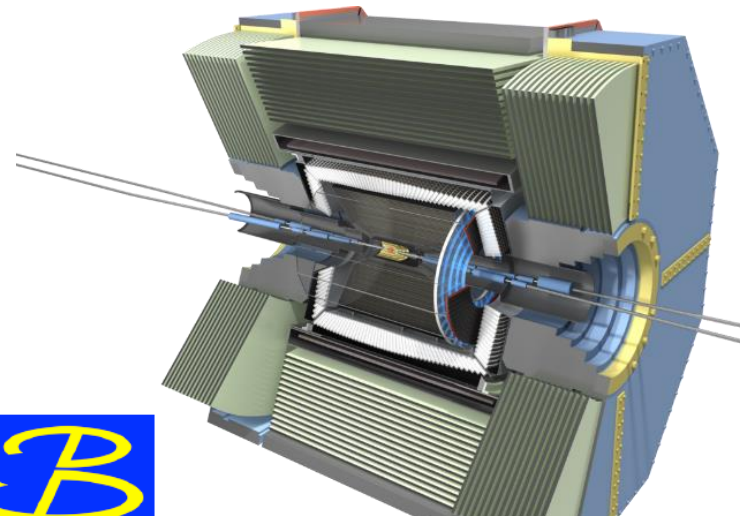
$\sigma P_T \sim 1.3\text{-}3.8\%$

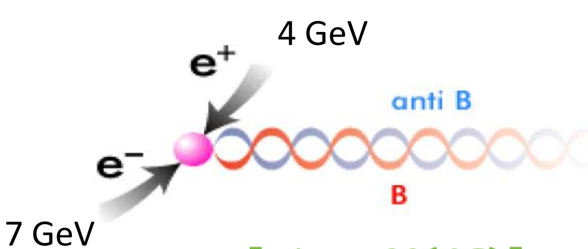
$\sigma IP_\perp \sim 25\text{-}100\mu m$

The Belle II experiment

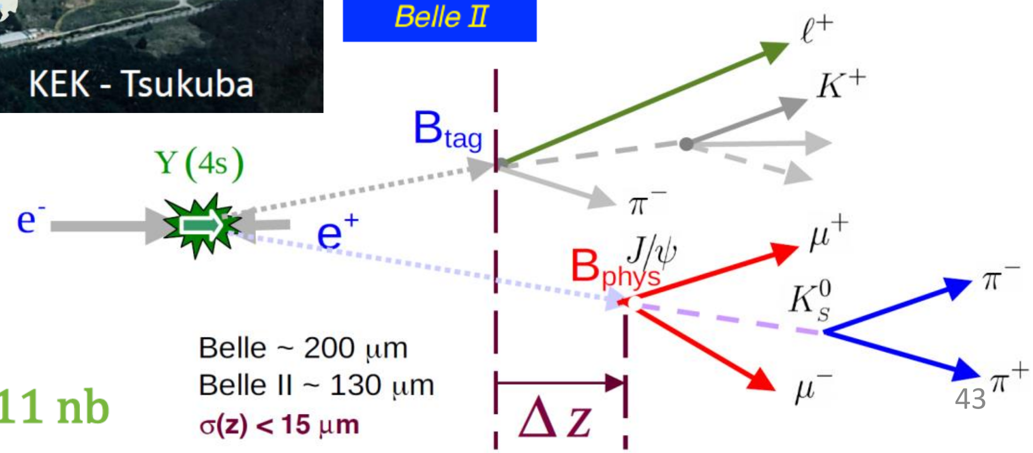
- Upgrade of the KEK e^+e^- asymmetric accelerator and the Belle experiment, working at the $\Upsilon(4S)$ (10.54 GeV). It is taking data since 2019.







$\sigma\,[e^+e^- \to \Upsilon(4S)] = 1.11$ nb

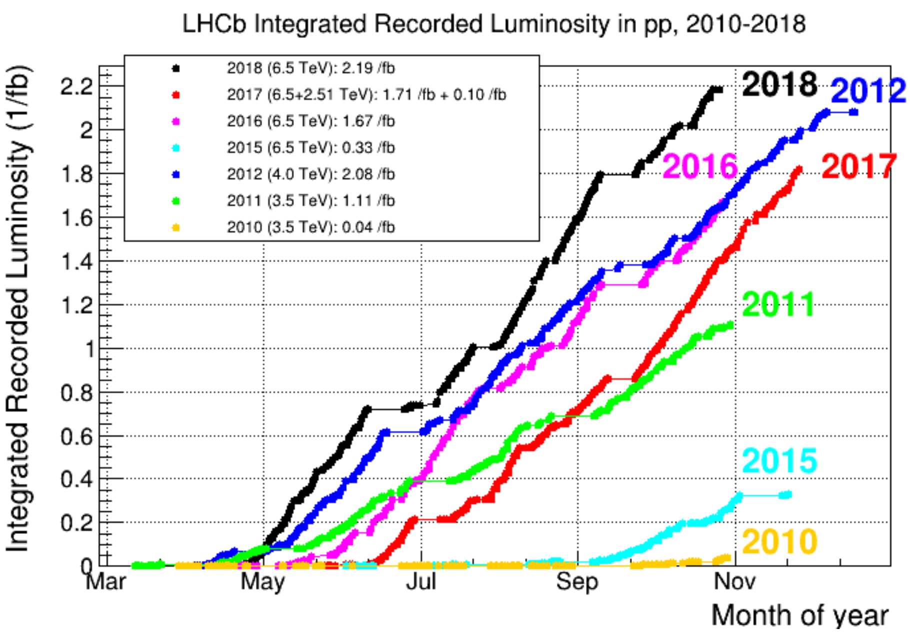


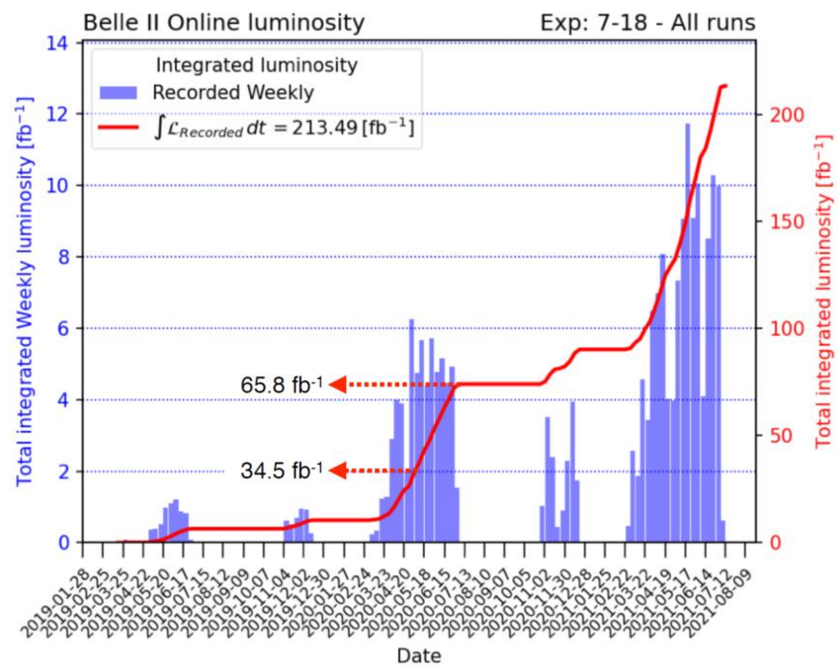
The flavour experiments

The data:

3 (Run1) + 6 (Run2) fb^{-1} (2011 - 2018)

213 fb^{-1} (2019 - 2021)





In terms of *b*-hadrons: $N=\int \mathcal{L}\sigma$ at LHCb:

→ σ ~ 600 μb at 13TeV, x 30% (due to the acceptance) = 180 μb

→ $b\bar{b}$ pairs produced in *1 inverse femtobarn* (N/fb^{-1}) = 10^{15} * 180 x 10^{-6}

~ 1.8 x 10^{11}

The flavour experiments

- Comparison between facilities:

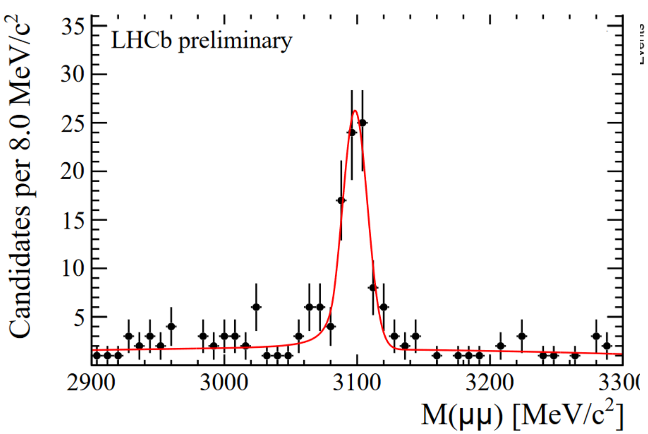
	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2$ TeV) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14$ TeV) LHC
Production cross-section	1 nb	$\sim 100\ \mu$b	$\sim 500\ \mu$b
Typical $b\bar{b}$ rate	10 Hz	~ 100 kHz	~ 500 kHz
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s^0 (10%), Λ_b^0 (10%), others (< 1%)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

Q : Which is the maximum momentum of the pion in the B $\to \pi\ell\nu$ decay in the lab frame in Belle II at (SuperKEK) and LHCb (at LHC) experiments ?

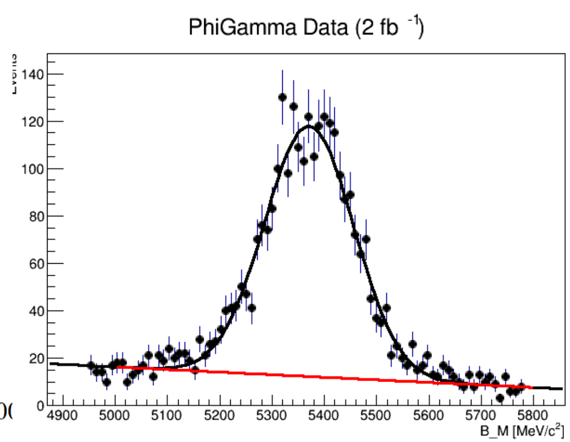
The flavour experiments

What do we measure? Examples of observables:

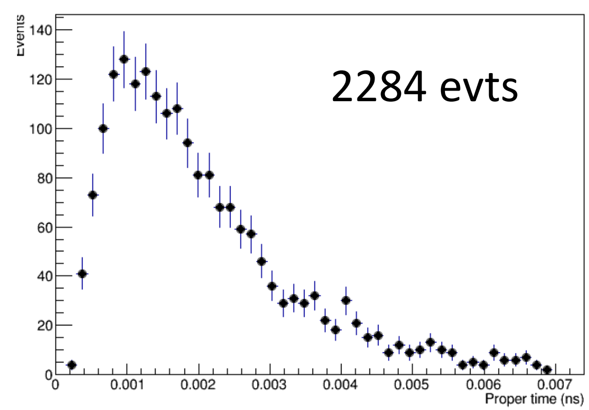
- ***Invariant masses:*** from momentum and PID hypothesis of the detected particles
- ***Decay time distributions:*** from distance between the origin and decay vertices (and using information of the particle momentum)
- ***Angular distributions:*** from directions of the decay products (momentum, vertices)
- ***Branching fractions:*** from the mass distributions, counting the number of events
- ***Differential decay widths:*** as function of q^2, for instance, the 4-momentum transfer
- ***Time-dependent asymmetries*** (needed flavour tagging!)
- ***Ratios of observables:*** cancellation of experimental or theoretica uncertainties



$M_{J/\psi}$ (MeV)



M_{Bs}(MeV) ($\phi\gamma$)

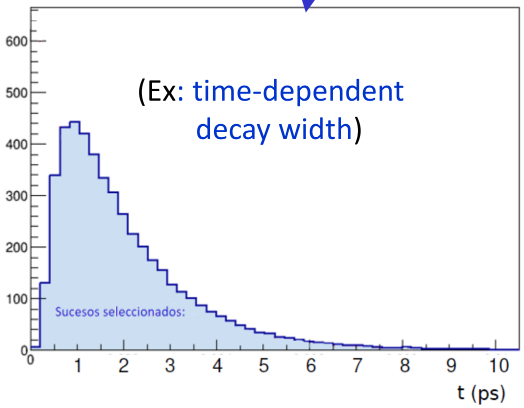


t(ns)

The flavour experiments

Including experimental effects:

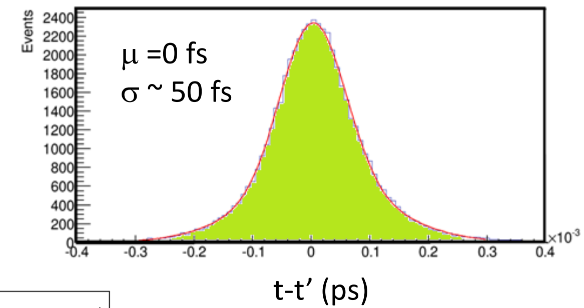
Observable(X’) = Physics (X, P) · Acceptance(X) x Resolution (X,X’)

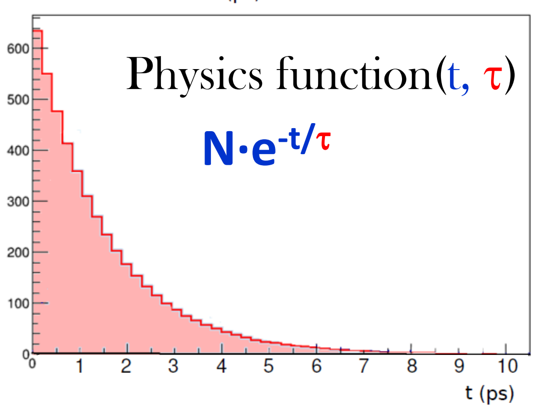


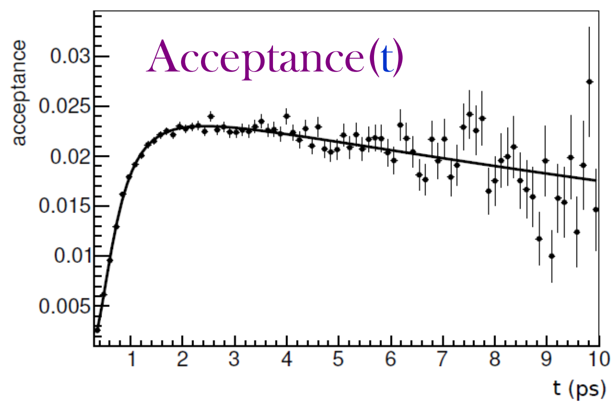
Efficiency dependent of X

$$\frac{\#\ \text{detected}\ (X)}{\#\ \text{produced}\ (X)}$$

R(t,t’)







- One can use MC simulations to study the acceptance and resolution functions
- Better: use control samples from data (similar to the signal channel) to extract them

The flavour experiments

Some key references:

The Physics of B factories
https://arxiv.org/abs/1406.6311

PDG (reviews)
https://pdg.lbl.gov/

Heavy Flavour Averaging Group:
https://hflav.web.cern.ch/