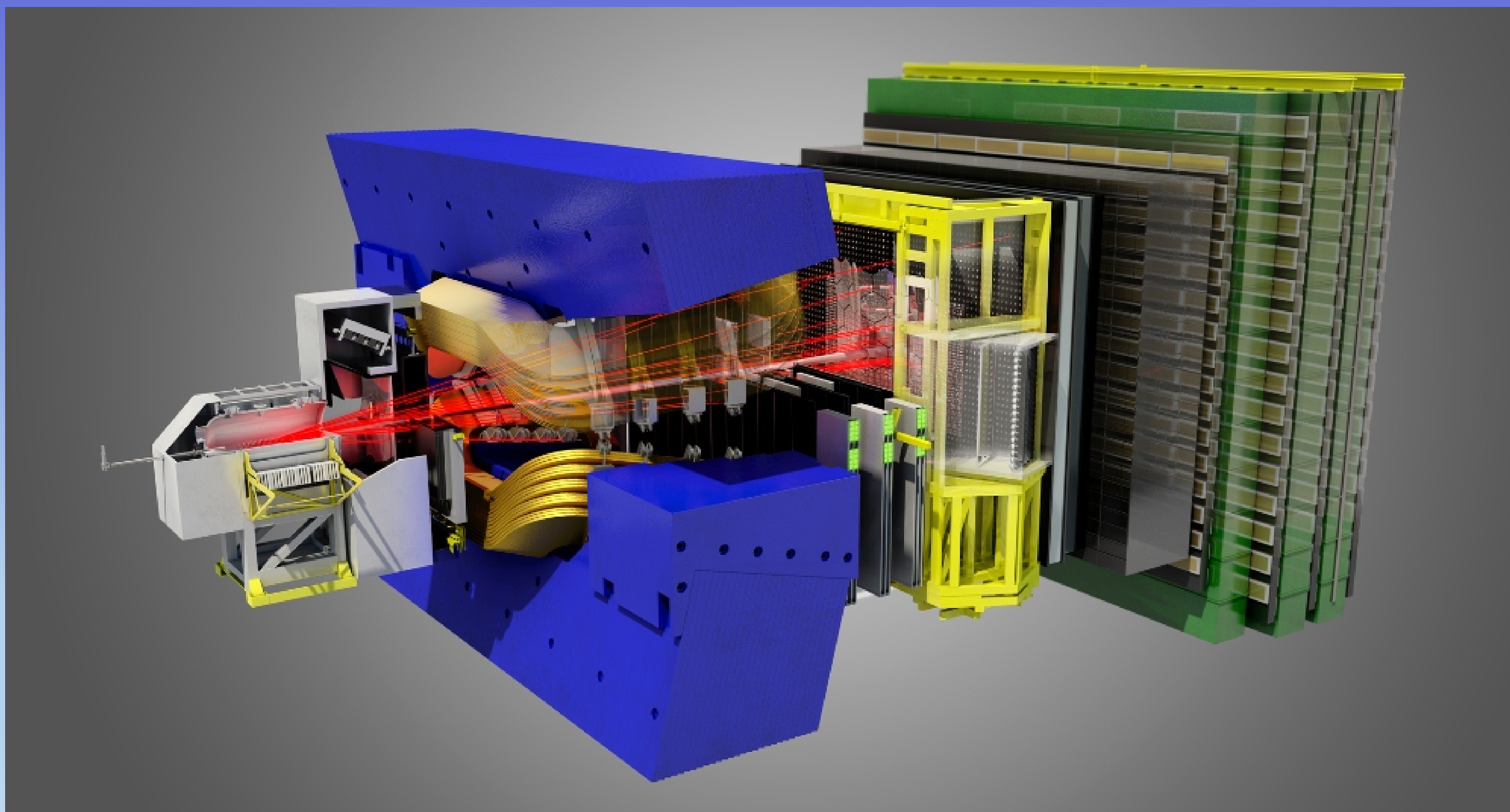
IDPASC 2018, 21st-31st May, Valencia, Spain

Experimental Flavour Physics



Arantza Oyanguren (IFIC – CSIC/UV)

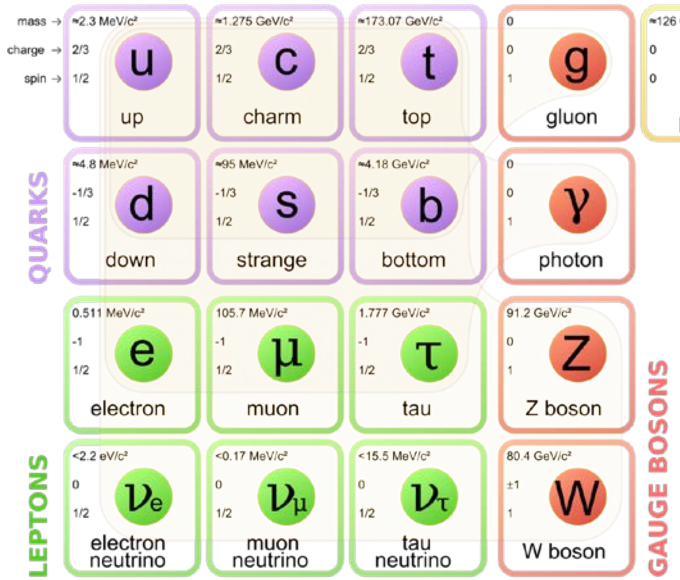

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Outline

- Introduction
- The LHCb experiment
- The CKM matrix
- B mixing and CP violation
- Rare decays of B mesons
- Future plans

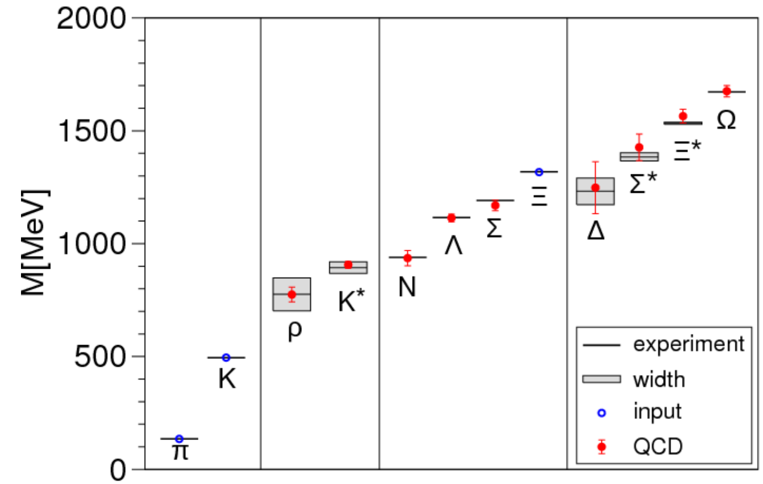
Introduction

Our Standard Model of Particle Physics:

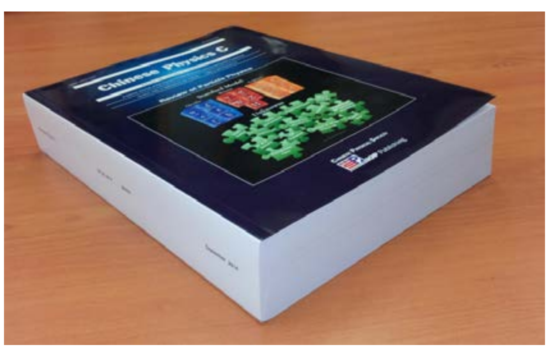


+ antiparticles

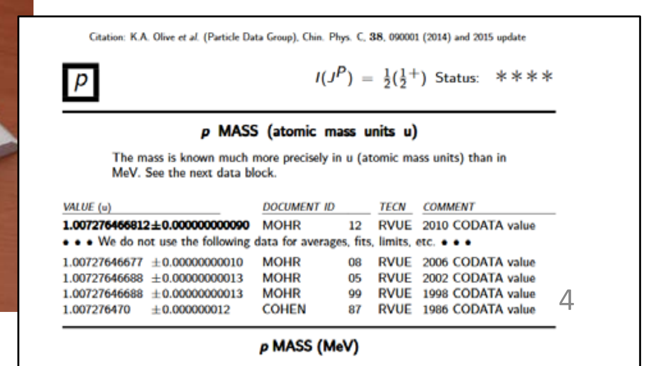
Hadrons:



Particle Data Book (PDG):



1675 pages!!



Citation: K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update

p $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS (atomic mass units u)

The mass is known much more precisely in u (atomic mass units) than in MeV. See the next data block.

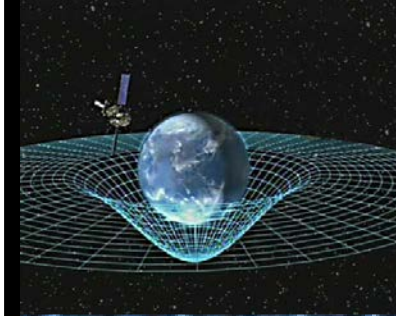
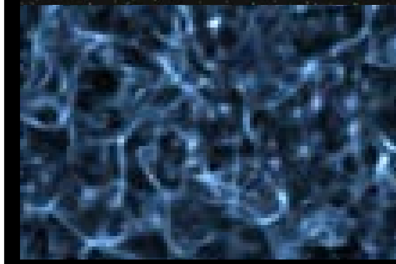
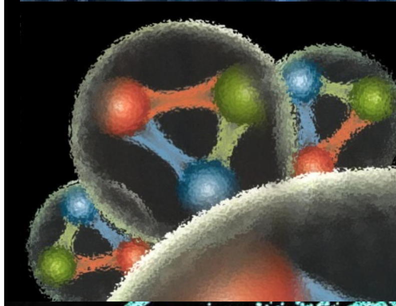
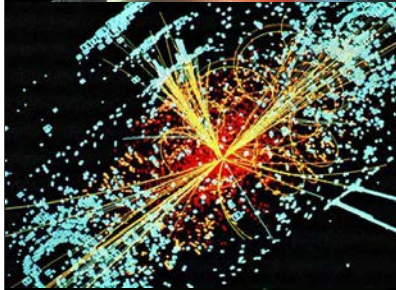
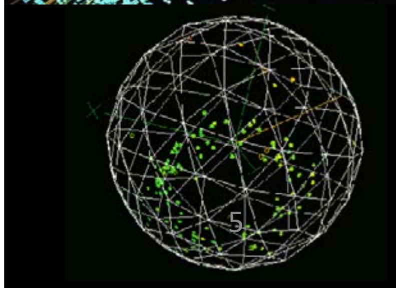
VALUE (u)	DOCUMENT ID		TECN	COMMENT
1.007276466812±0.000000000090	MOHR	12	RVUE	2010 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.00727646677 ±0.00000000010	MOHR	08	RVUE	2006 CODATA value
1.00727646688 ±0.00000000013	MOHR	05	RVUE	2002 CODATA value
1.00727646688 ±0.00000000013	MOHR	99	RVUE	1998 CODATA value
1.007276470 ±0.000000012	COHEN	87	RVUE	1986 CODATA value

p MASS (MeV)

Introduction

The problems of our Standard Model …

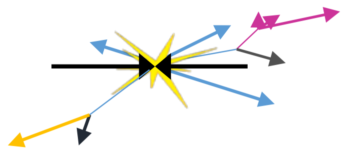
- Quantum Theory of Gravity
- Inflation?
- Quark/lepton generation masses: compositeness?
  Substructure? Strings?
  Common sub-elements quarks and leptons?
  Why three families?
- Matter-Antimatter asymmetry
  CPV in SM (K, B) + Big Bang ?
- Cosmological constant (dark energy …)
- Dark matter
- Higgs & EW symmetry breaking? Forces Unification?
- Neutrinos (mass?, hierarchy?...)

Introduction

Looking for New Physics…

Direct searches:

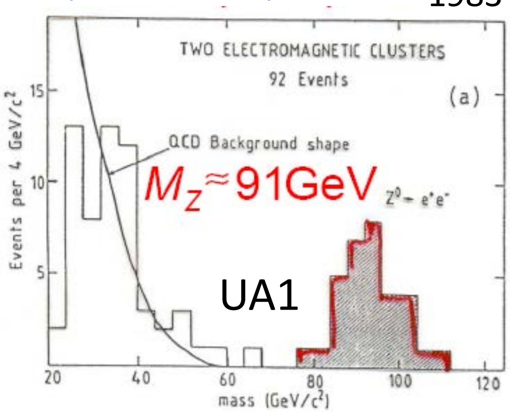


$$E^2 = m^2c^4 + p^2c^2$$

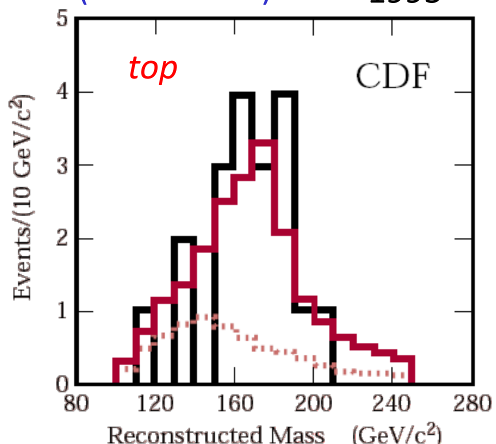
High energy

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

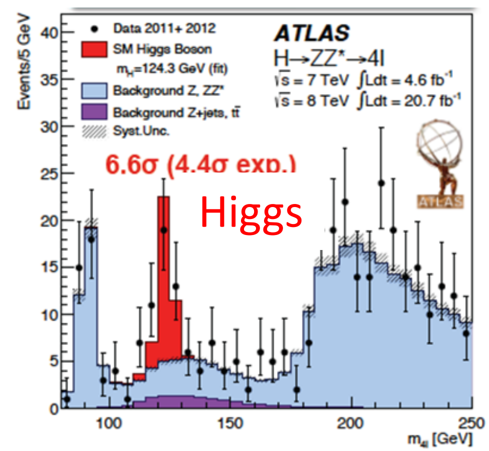
(√s= 546 GeV) 1983



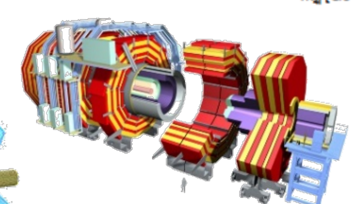
(√s= 1.9 TeV) 1995



(√s= 7 TeV) 2012



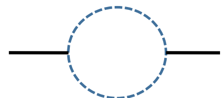
Higgs discovery, 2012



Introduction

Looking for New Physics…

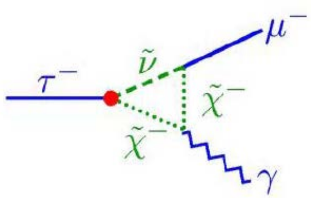
<u>Indirect searches</u>**:**

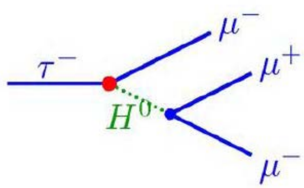


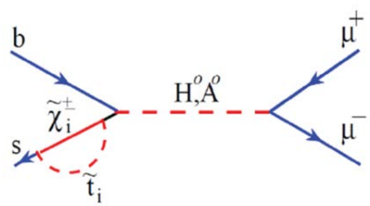
High precision

$\rightarrow$ **particles created *off-Shell:* *Evidence in quantum effects (loops)***

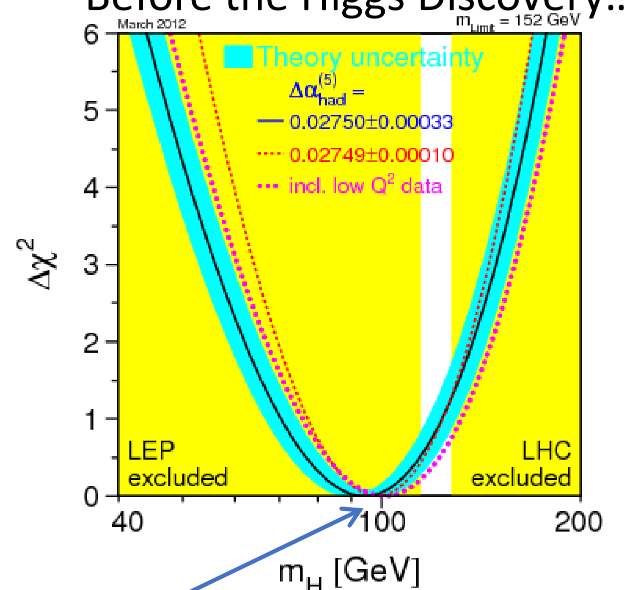
(BR's, asymmetries…)



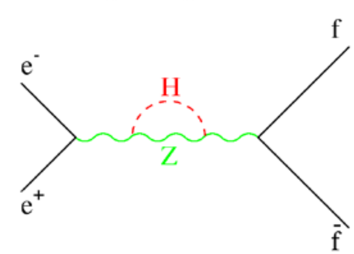


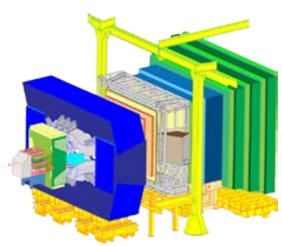


Before the Higgs Discovery…

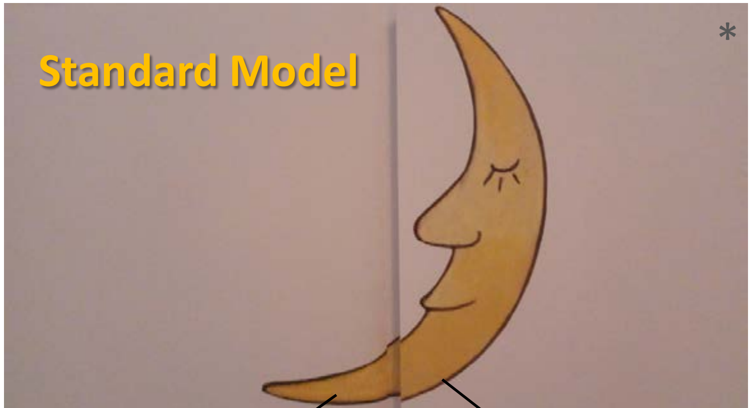


Predicted from electroweak measurements





Introduction

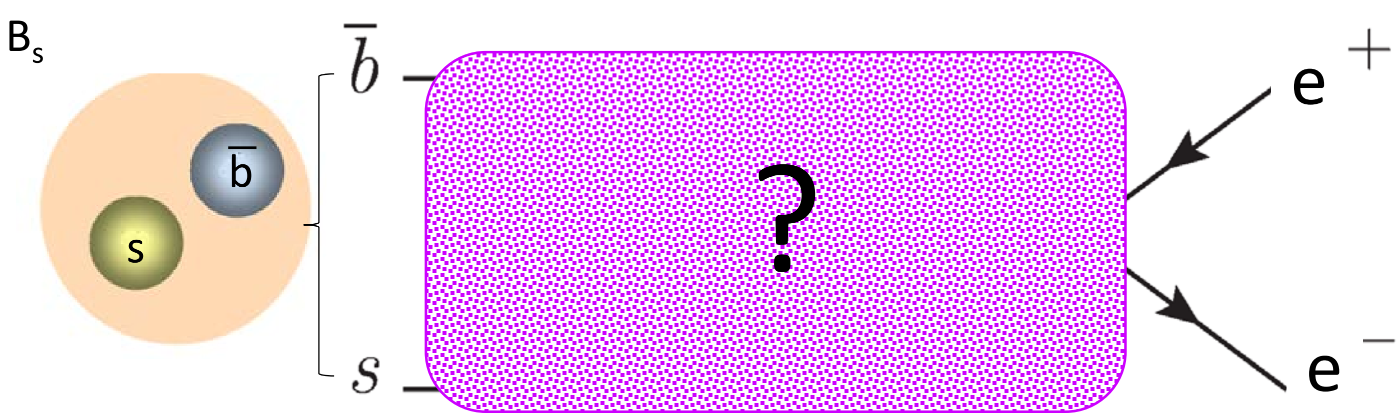


What we see

What we think it is

What it is

It can be tested by studying quantum effects:



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

* ¡Oh!, Josse Goffin

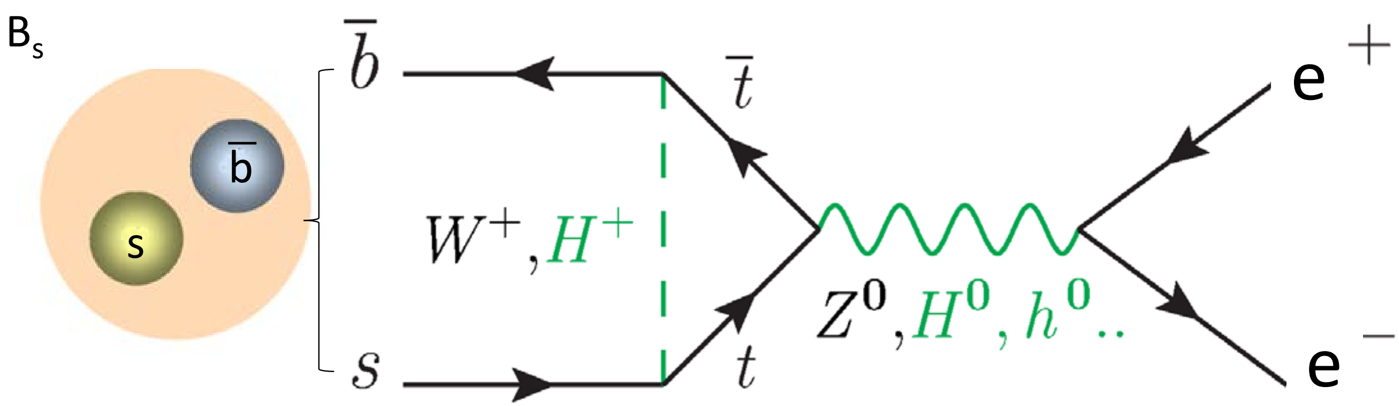
Introduction

What we see

What we think it is

What it is

It can be tested by studying quantum effects:



Number of particles produced,
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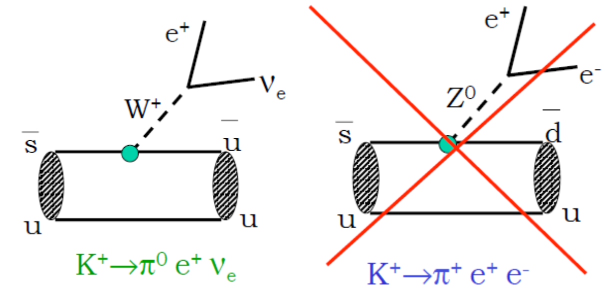
the detector…

New Particles

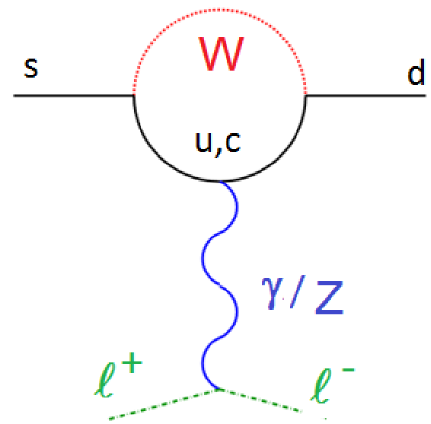
* ¡Oh!, Josse Goffin

Introduction

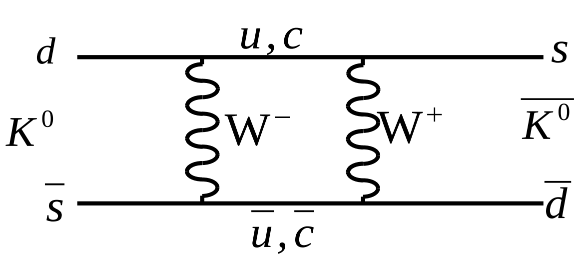
- The GIM mechanism:



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



- Gaillard, Lee and Rosner :
m_c~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)

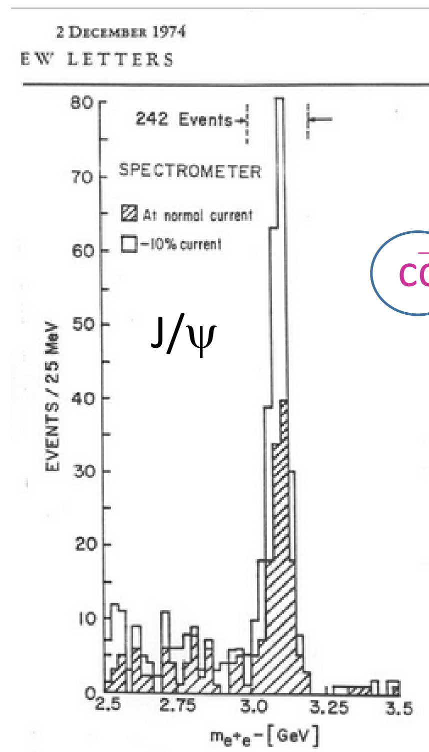
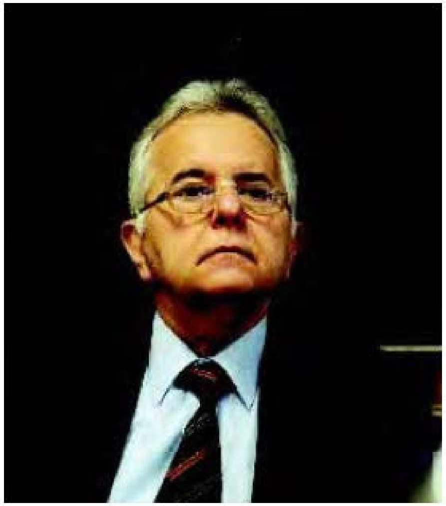


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

$c\bar{c}$

Introduction

- The CKM mechanism:

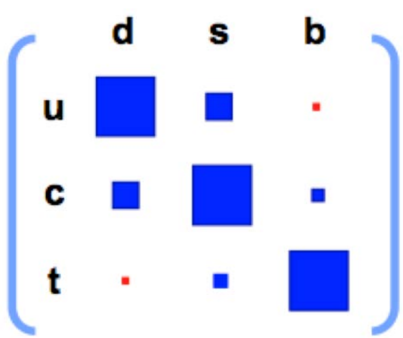


Cabibbo

Kobayashi

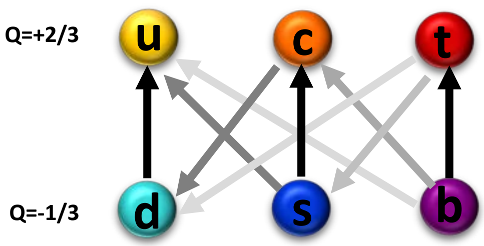
Maskawa

$V_{CKM} =$

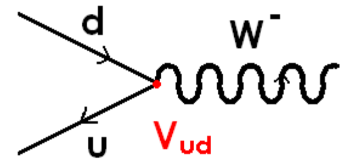


Introduction

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

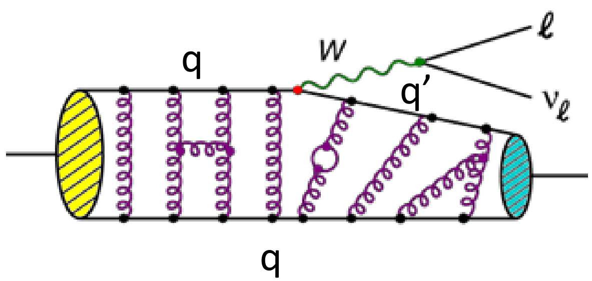


$$V_{\rm CKM} = \begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{pmatrix}$$



• The amplitude of a hadron decay process can be described using Effective Field Theories: Operator Product Expansion (OPE)

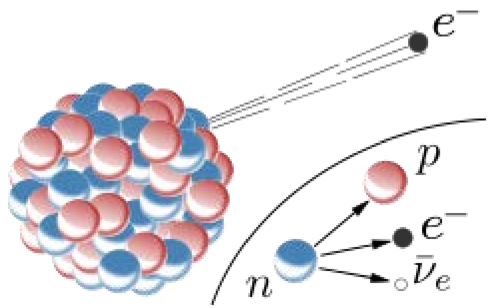
$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|Q_i(\mu)|M\rangle$$



CKM couplings

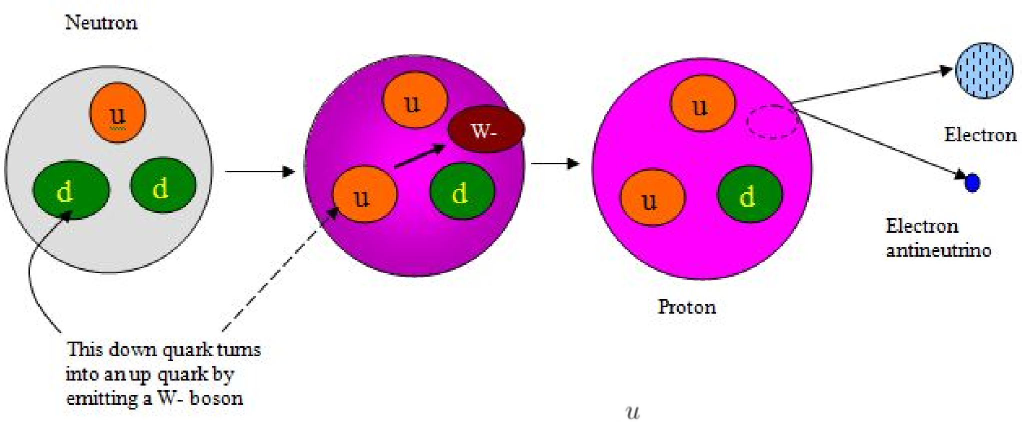
Wilson Coefficients (μ = scale)

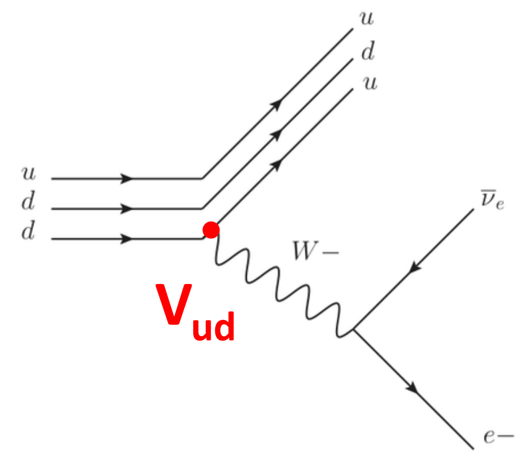
Introduction



Example: β -decay (very well known)

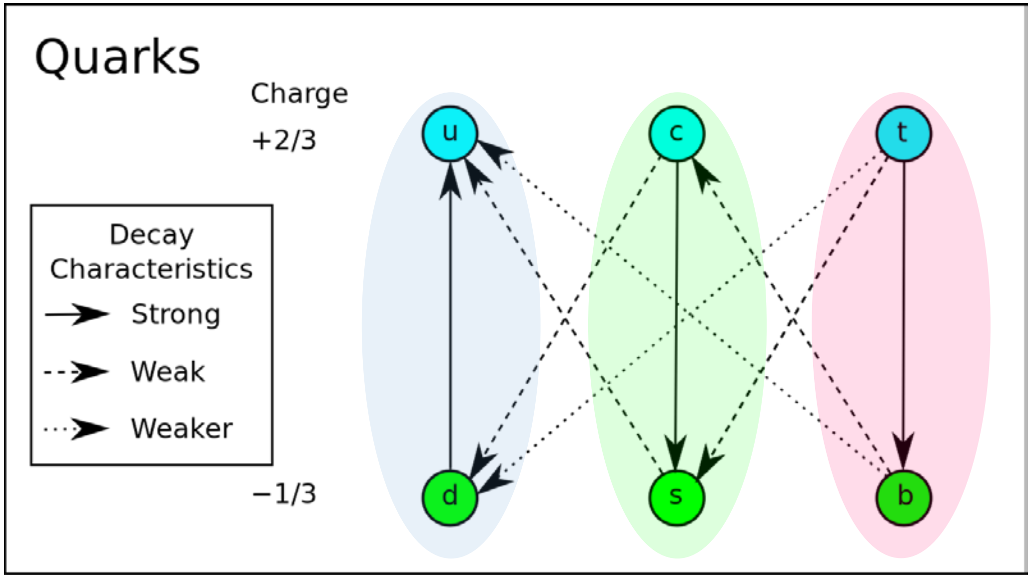
$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \overline{\nu}_e$$

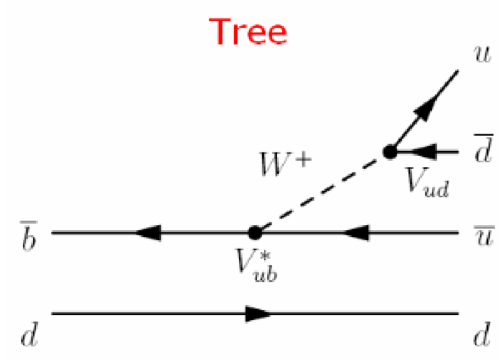




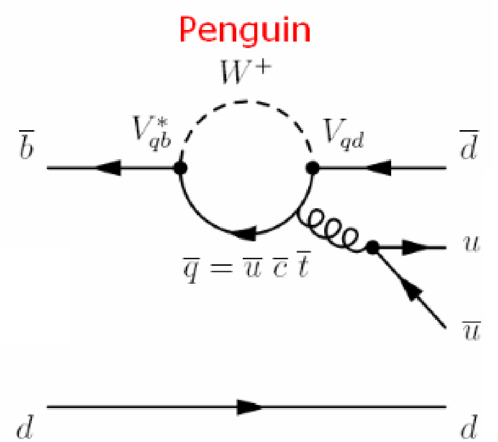
(V_{ud} is large ~ 0.97)

Introduction





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



- Transitions between the same family are favored
- Some of them are very rare (ex: V_{ub})
- Need to change charge: FCNC not allowed at tree level, need to proceed via loop diagrams (CKM suppressed)
- If a transition occurs with larger probability than expected
  → **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), but no new particles have been found so far at LHC by ATLAS and CMS!

- Flavour structure of the SM:
  $\rightarrow$ provide the suppression mechanism for FCNC processes already observed.
  $\rightarrow$ need to measure the flavour structure to distinguish between the NP models.

- The physics performed at LHCb (flavour physics) goes hand-in-hand with direct searches (ATLAS and CMS).

Introduction

Why the b of LHCb?

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

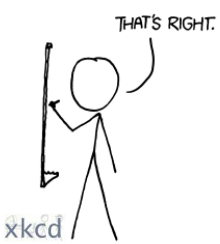
Good for experimentalists!

- Type of processes:

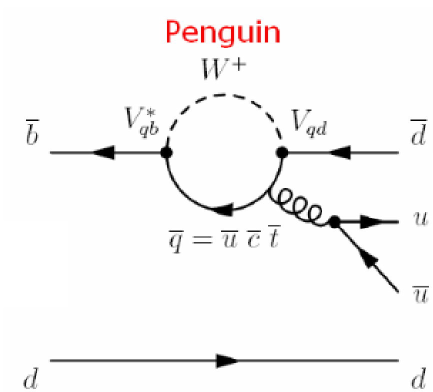
 Dominant: $b \to c$ (favoured) and $b \to u$ (suppressed)

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

 Flavour oscillations and CP violation

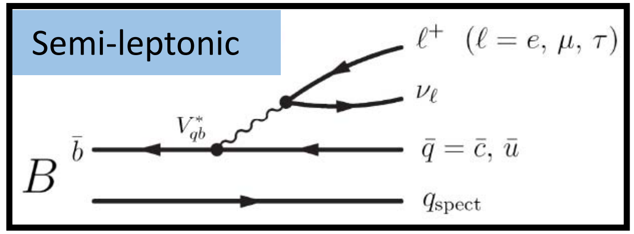


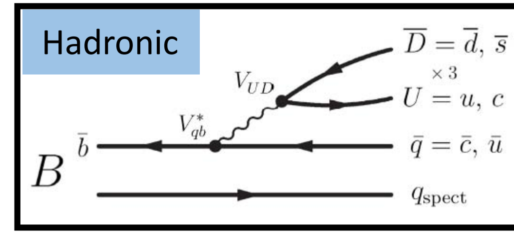
Ideal place to probe New Physics effects!



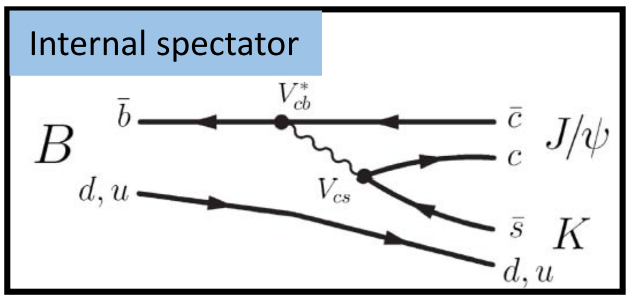
Introduction

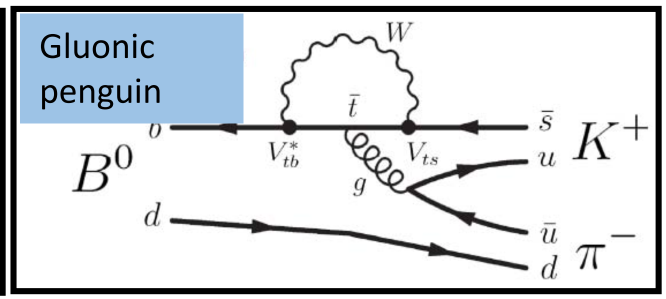
Dominant tree decays:

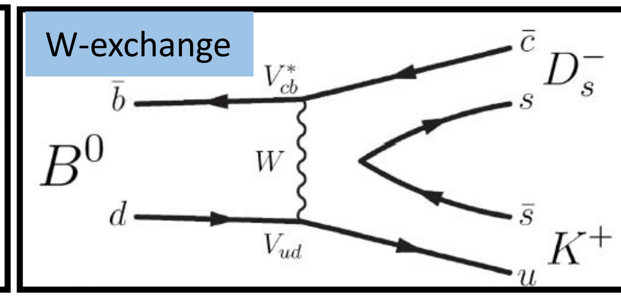




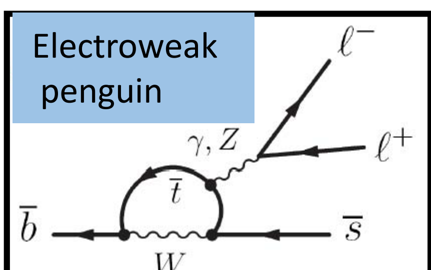
Rare hadronic decays

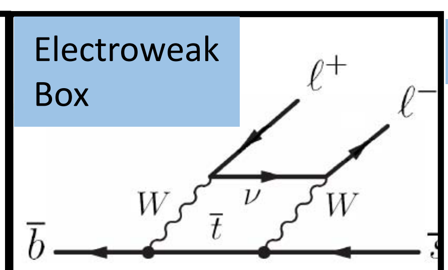


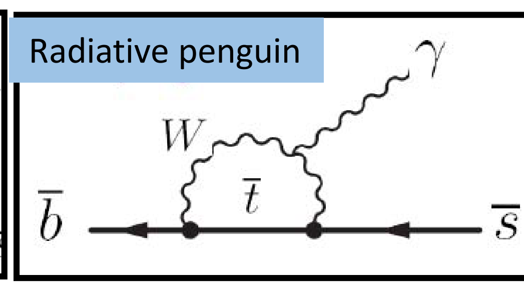


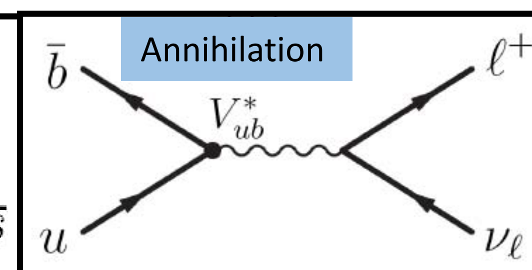


Radiative and leptonic decays









(1999 - 2008 / 2010)

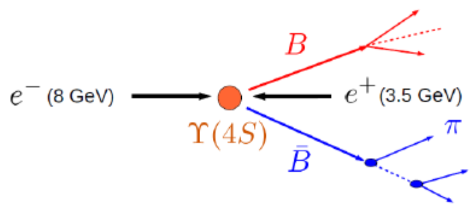
Introduction

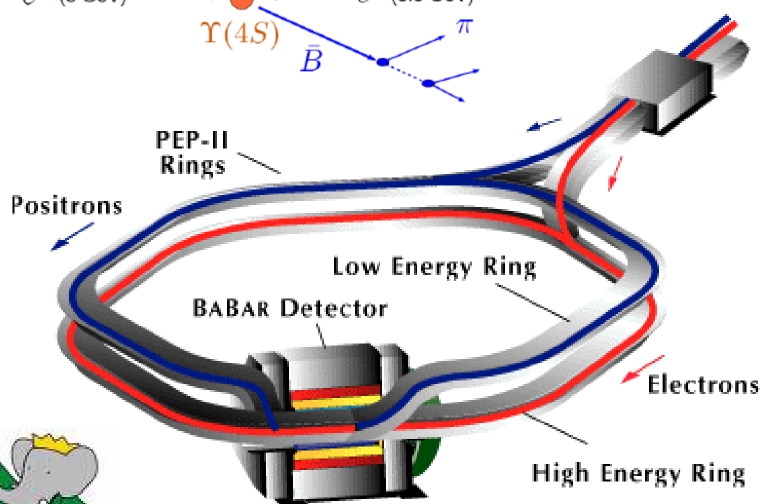
* First measurement of CPV in the B system
* High precision CKM matrix
* Discovery of η_b

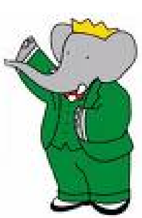
The precesors of LHCb, key in flavour physics:

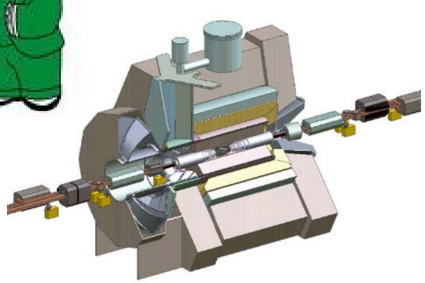
The b-factories: Belle at KEK (Japan) and BaBar at PEP-II (California)

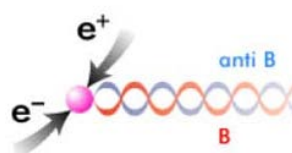
Asymmetric e+ e- colliders working at the Υ(4S) energy.

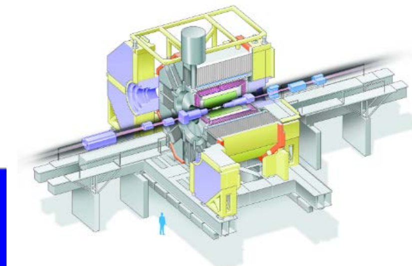


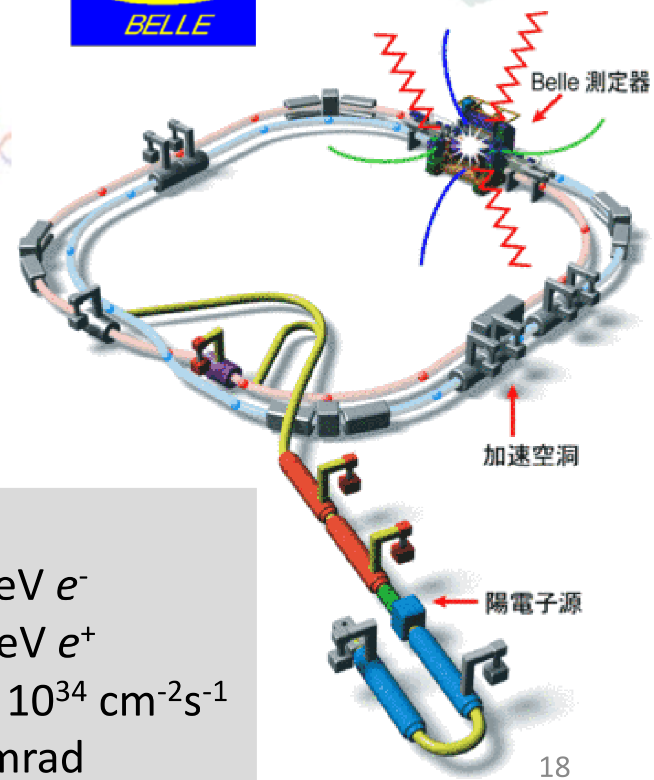












PEP-II /KEK-B

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

Introduction

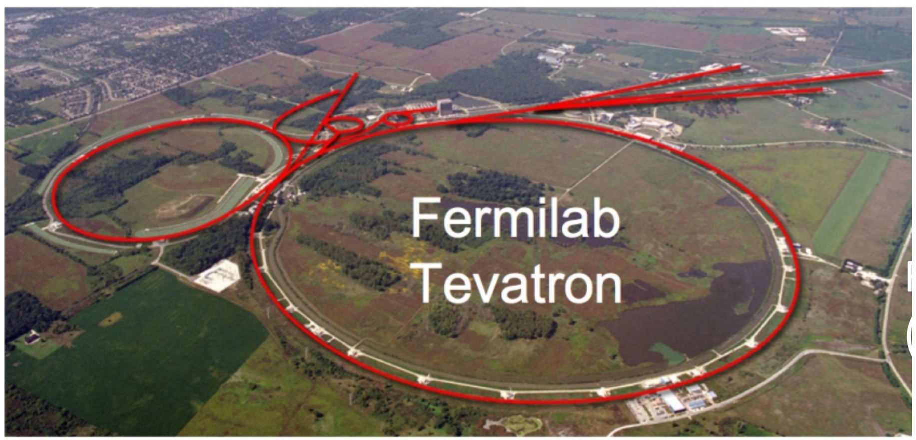
(1987- 2011)

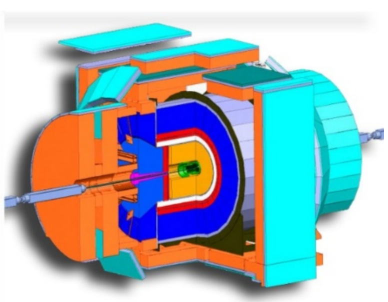
* Discovery of the top quark
* First measurement of B_s oscillations
* Discovery of the Ξ_b baryon

The precesors of LHCb, key in flavour physics

The Tevatron at Fermilab (Illinois): CDF and D0

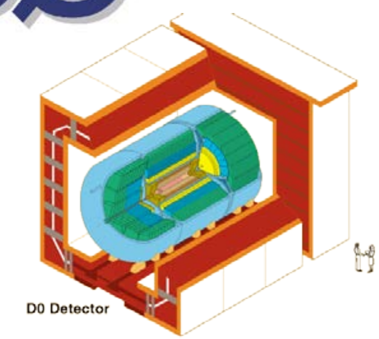
$p\bar{p}$ collider working at center of mass energy (c.m.) of 1.96 TeV.





TEVATRON

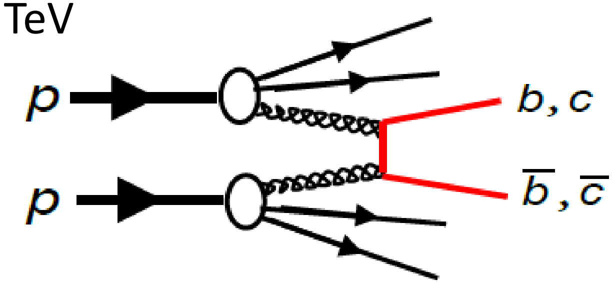
Superconducting $p\bar{p}$ ring
Energy : 1 TeV/beam
Detectors: CDF, D0
Luminosity: 10^{32} $cm^{-2}s^{-1}$
Physics: W, Z,Top Production
Higgs searches
B physics

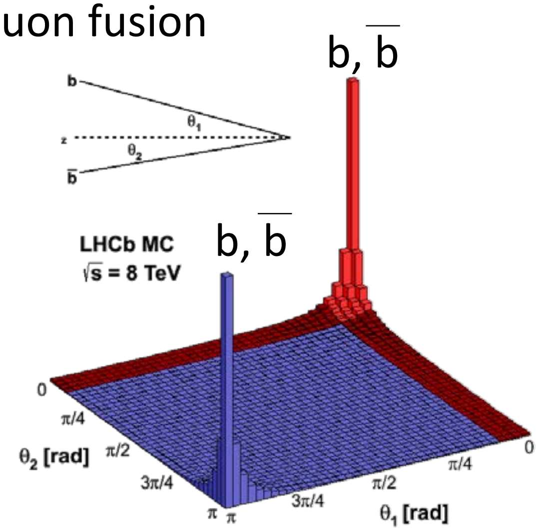


The LHCb experiment

The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion
  ~250 μb @ $\sqrt{s}$=7 TeV
  ~500 μb @ $\sqrt{s}$=14 TeV

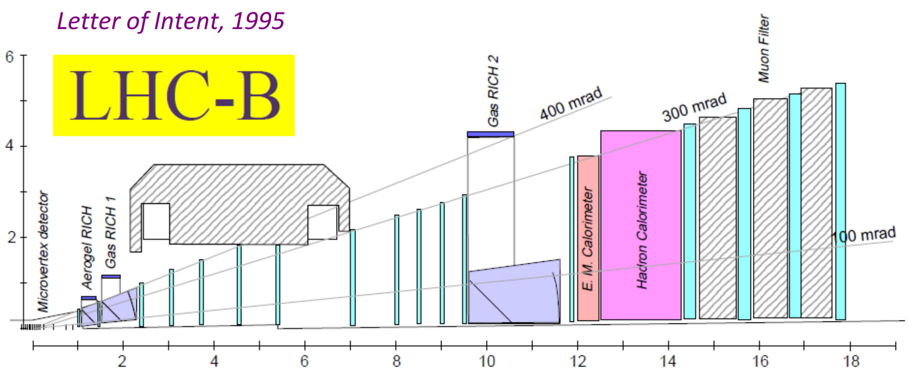


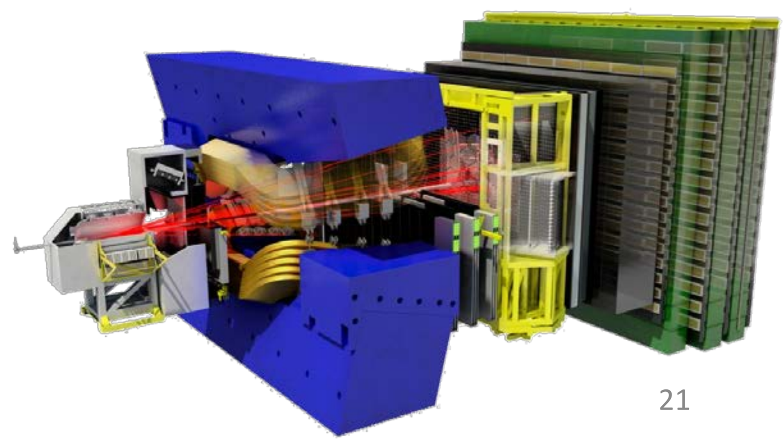


The b quarks hadronize in B, B_s, $B^*_{(s)}$, b-baryons…
→ average B meson momentum ~ 80 GeV

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

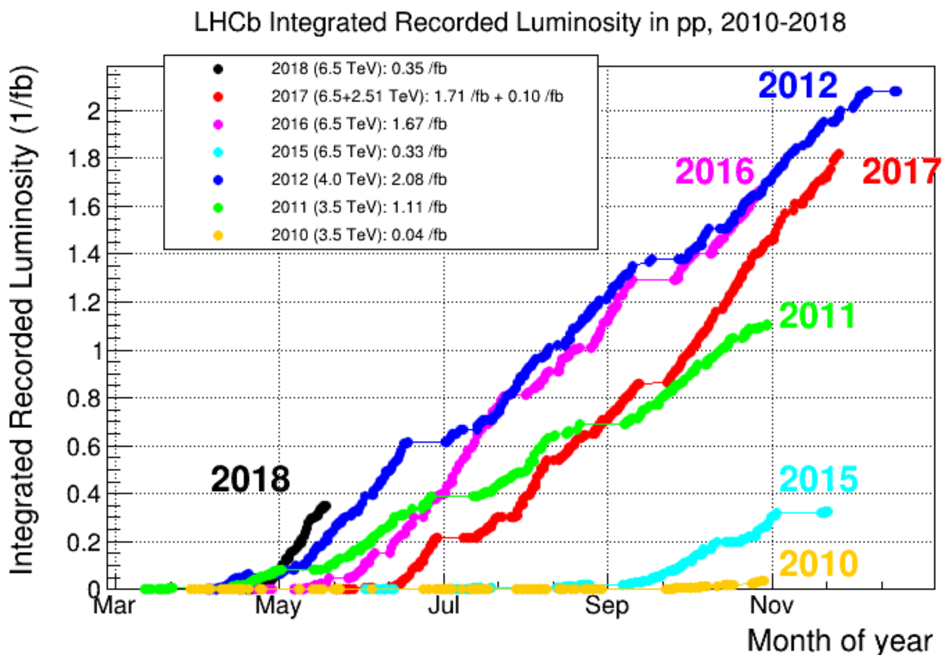
Letter of Intent, 1995





The LHCb experiment

- Very good performance: **3 fb^{-1}** accumulated in Run1 at 7 TeV, working well for Run2 at 13TeV, aiming at **5 fb^{-1}**

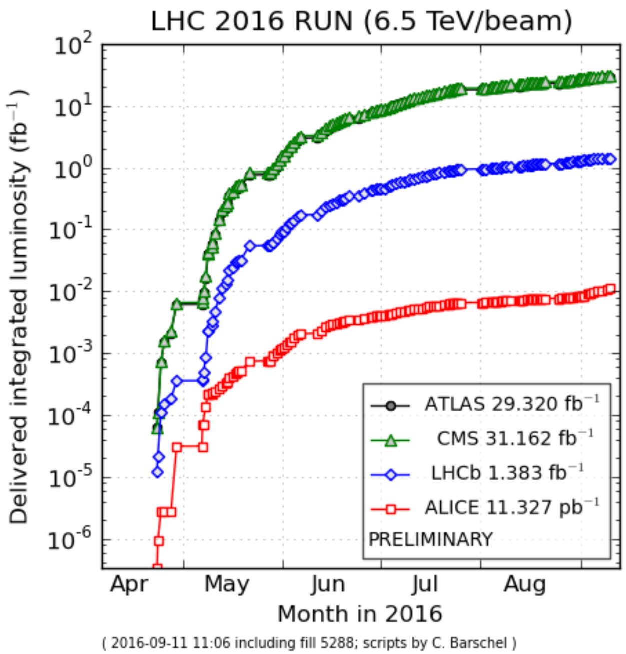


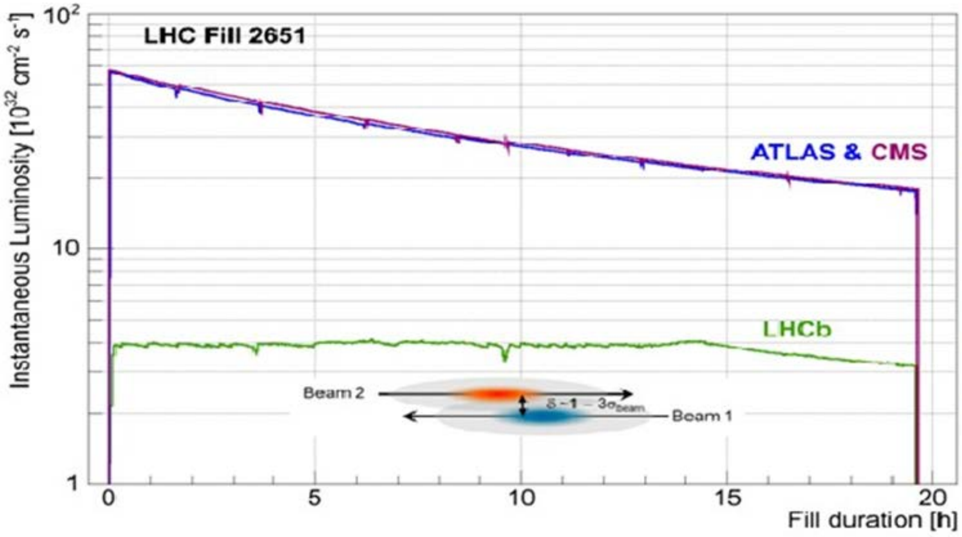
In terms of b-hadrons: $N=\int \mathcal{L}\sigma$

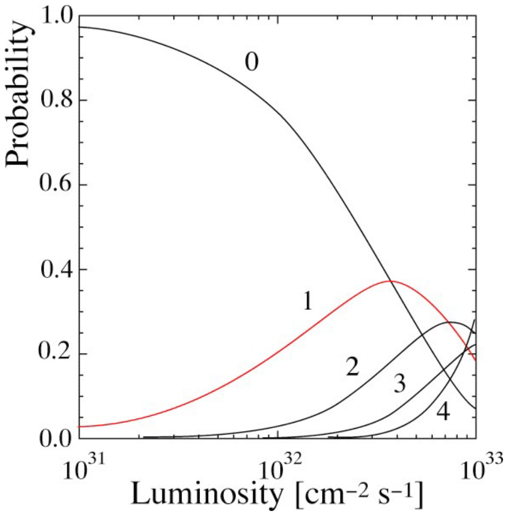
$\rightarrow$ σ ~ 500 μb at 13TeV, x 30% (due to the acceptance) = 150 μb
$\rightarrow$ $b\bar{b}$ pairs produced in *1 inverse femtobarn* (N/fb^{-1}) = 10^{15} * 150 x 10^{-6}

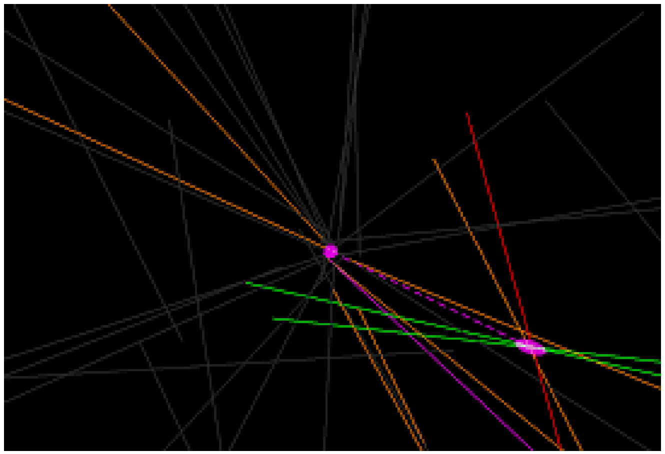
~ 1.5 x 10^{11}

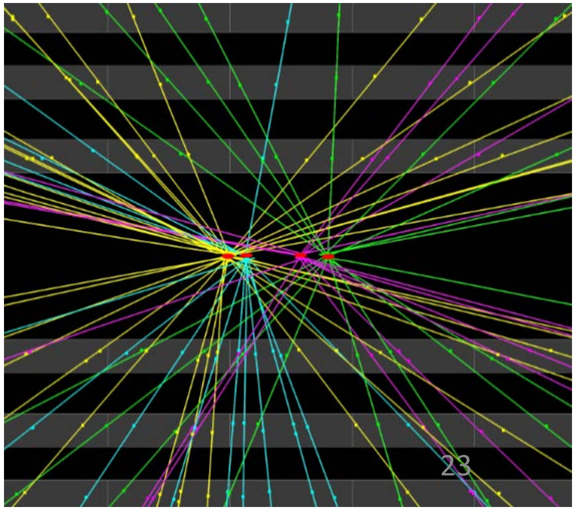
The LHCb experiment



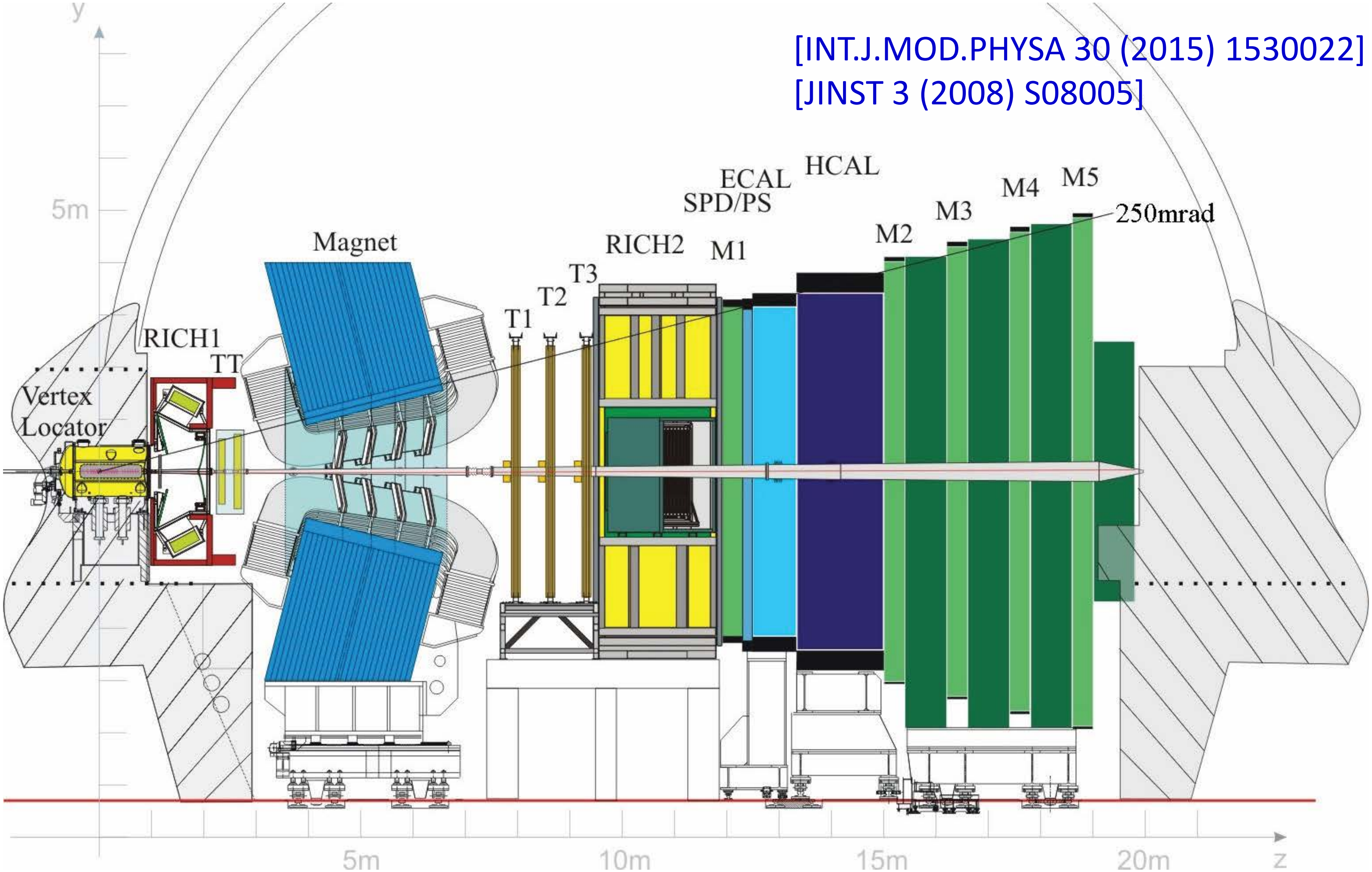








The LHCb experiment



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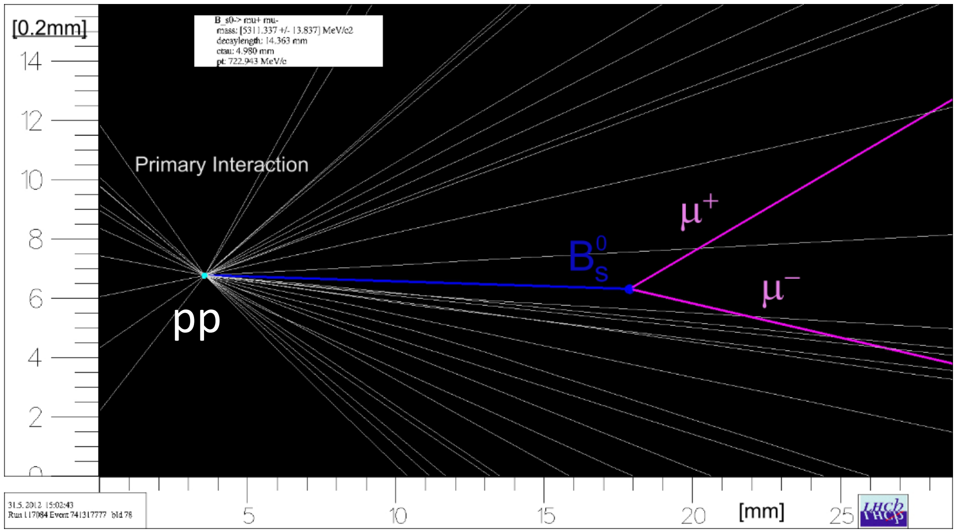
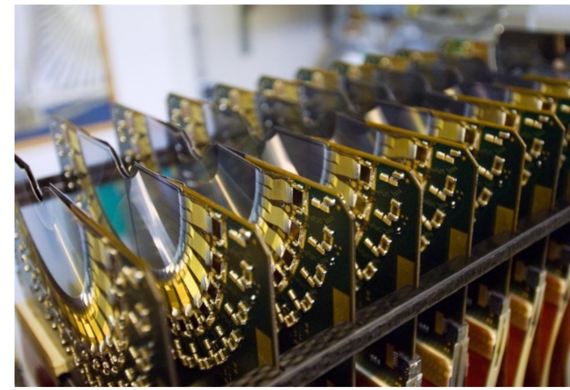
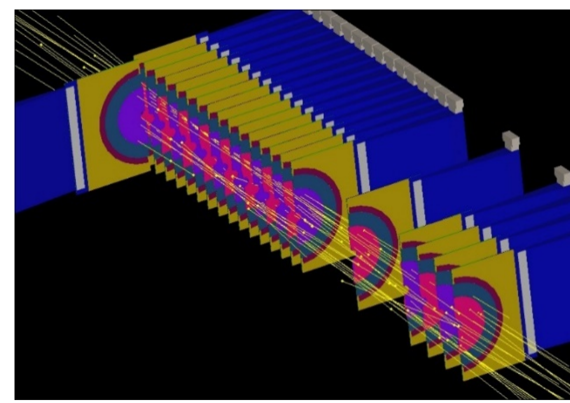
The LHCb experiment

What do we need?



Vertex detector (VELO)





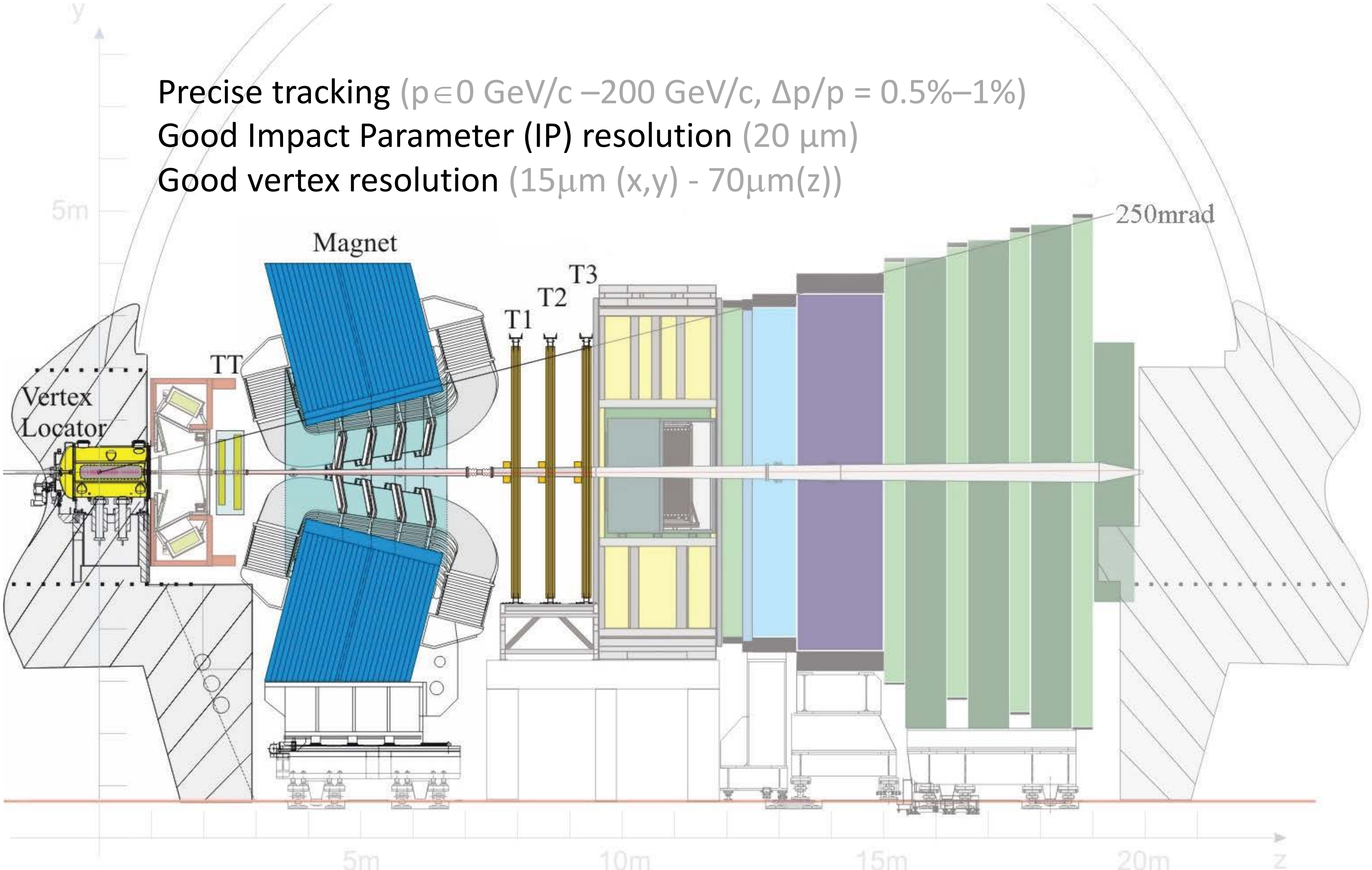
- To reconstruct production and decay vertices
  - $\rightarrow$ Good decay vertex resolution
  - $\rightarrow$ Good impact parameter resolution
- To reconstruct the particle trajectory
  - $\rightarrow$ Good momentum resolution

$\langle L \rangle = c\tau\beta\gamma$

Q : How long will a Λ_b baryon be travelling in the detector before decaying? ($\beta\gamma$ ~100)

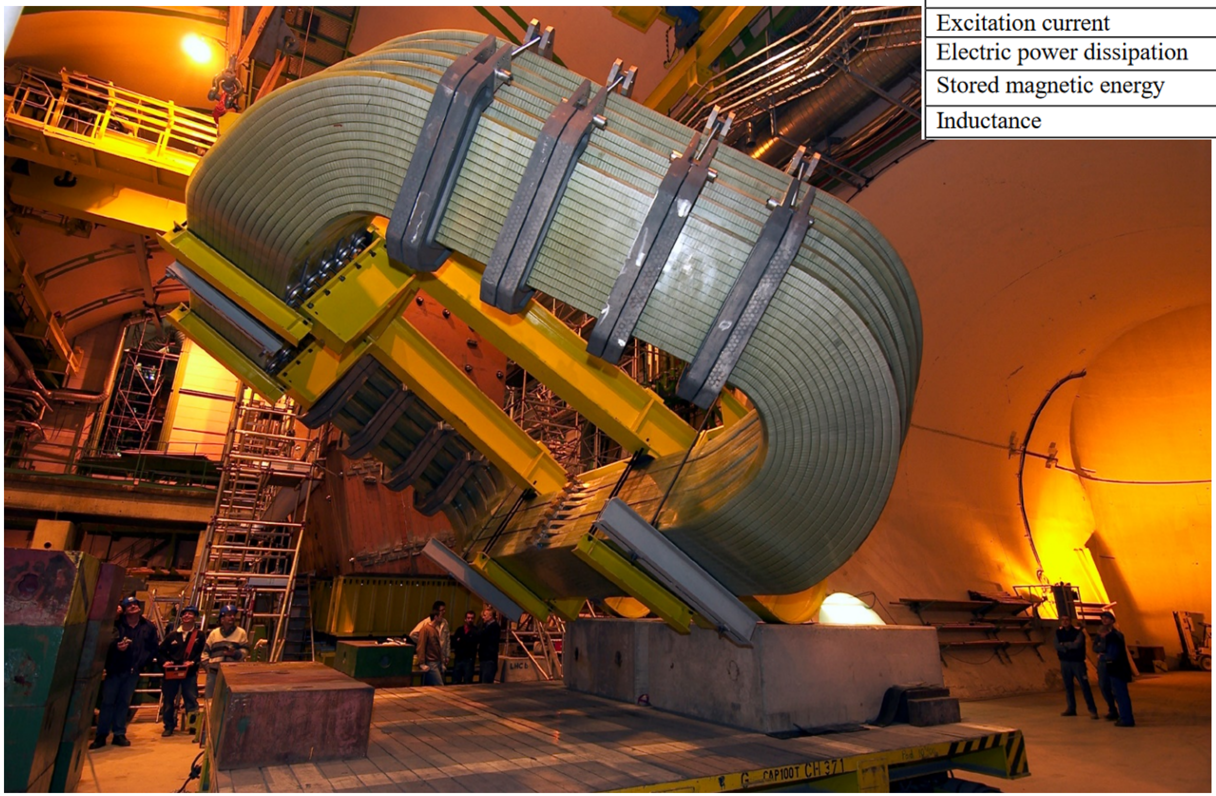
The LHCb experiment

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))

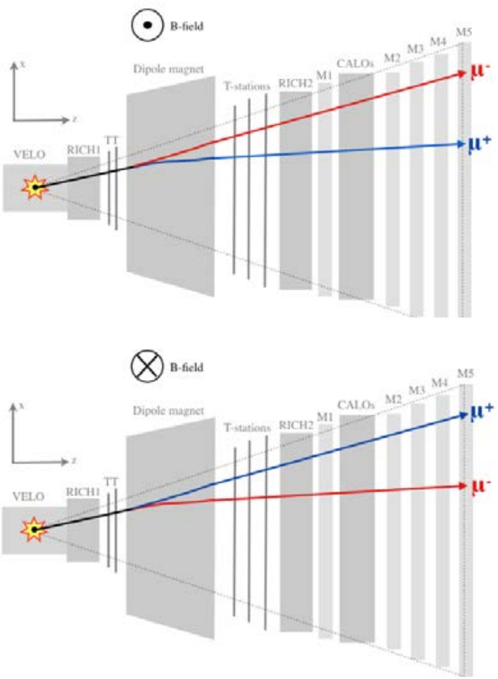


The LHCb experiment

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	$L \approx 2$ H



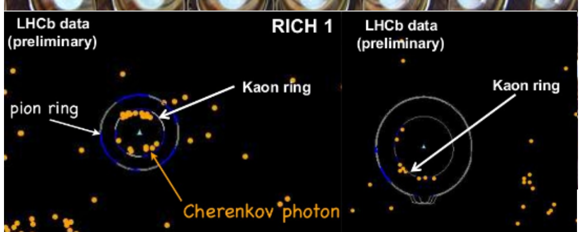
→ Inversion of polarity to study detector asymmetries

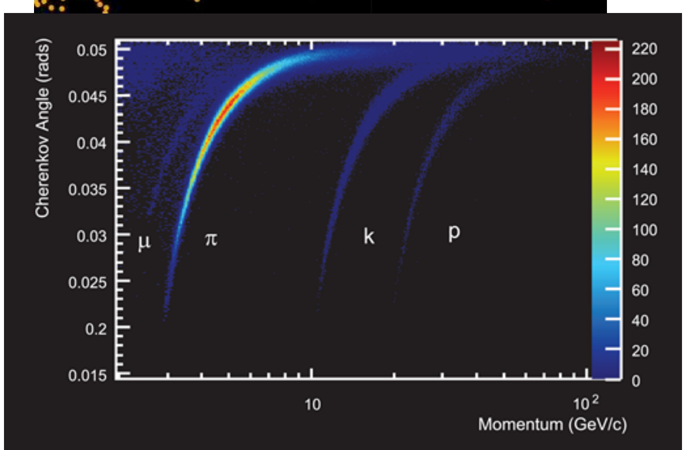
The LHCb experiment

- To recognize the type of particles

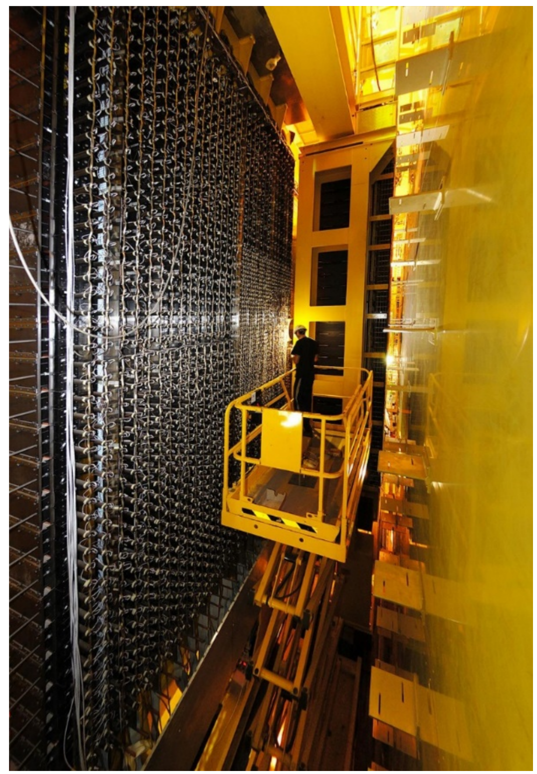
  → Good particle identification systems (PID)

Cherenkov detectors (RICH)

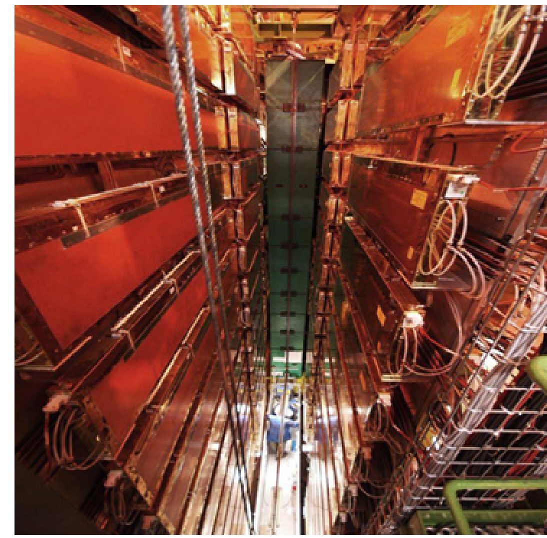


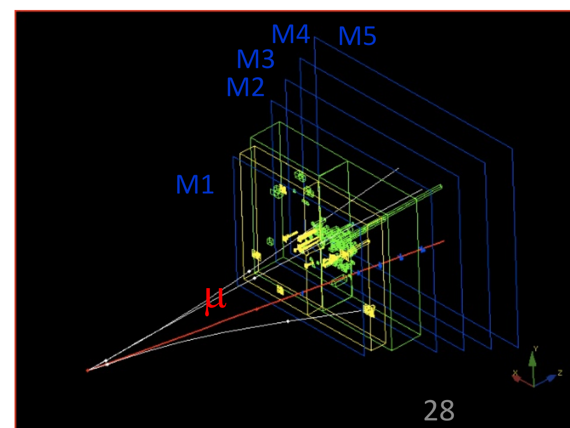


Calorimeters (ECAL, HCAL)



Muon chambers



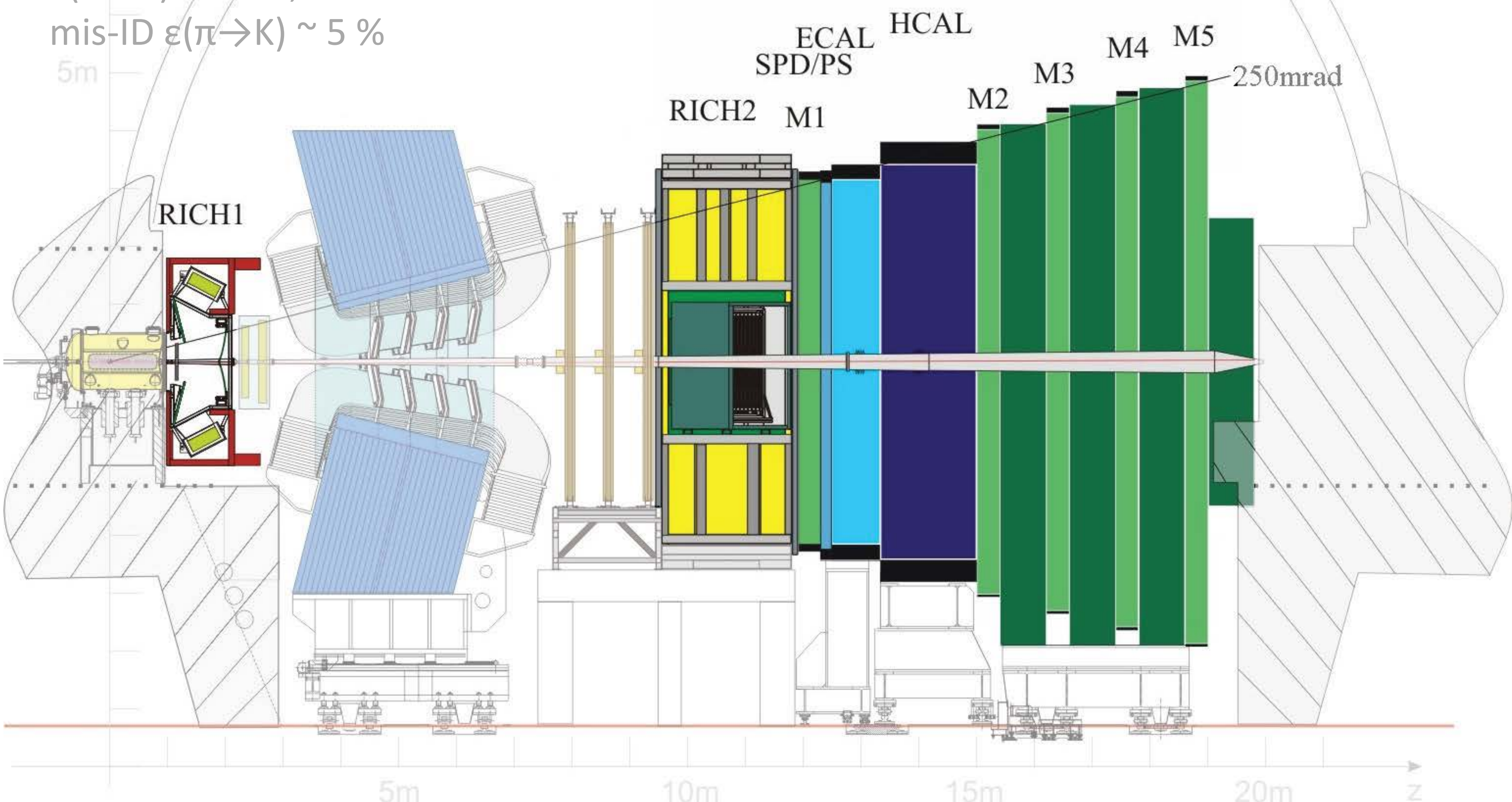


The LHCb experiment

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 %

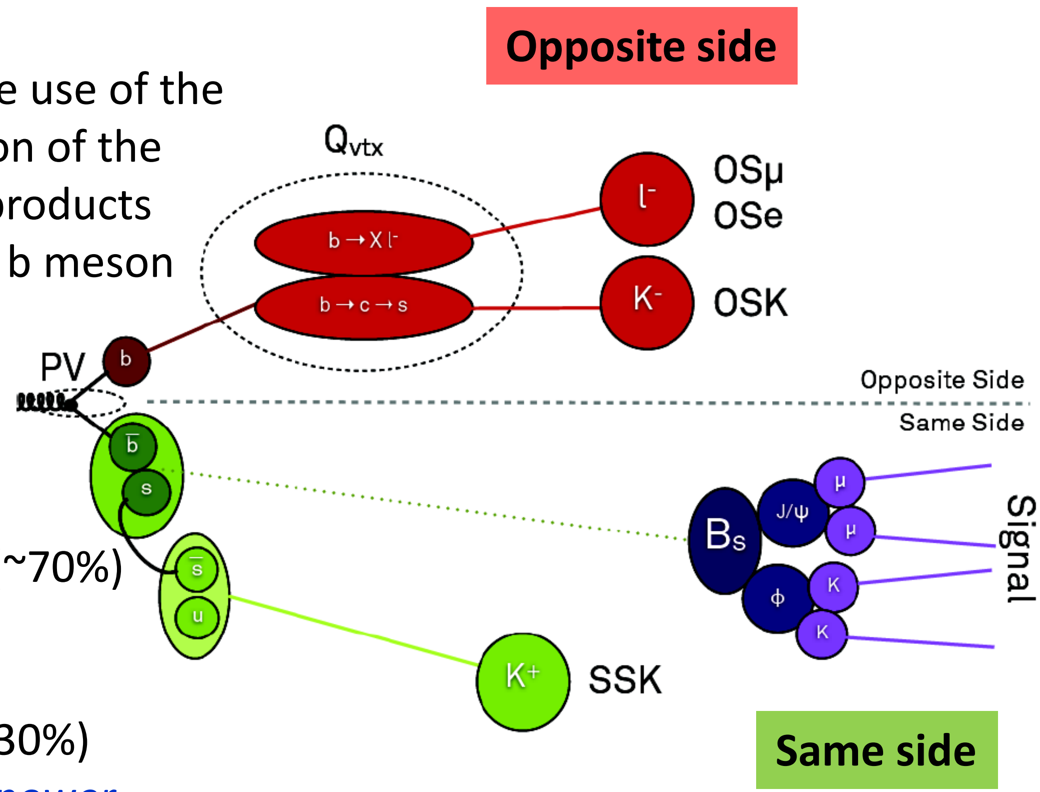


The LHCb experiment

- B mesons oscillates between particle and antiparticle $B^0 \rightarrow \overline{B}^0$
- 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 meson produced in pp $\rightarrow$ X $b\overline{b}$



Tagging efficiency ε_{tag} : fraction of events with a flavour tag decision (~70%)
Wrong-tag fraction ω:
fraction of tagged events for which tagging decision is wrong (~30%)
Figure of merit: *effective tagging power*

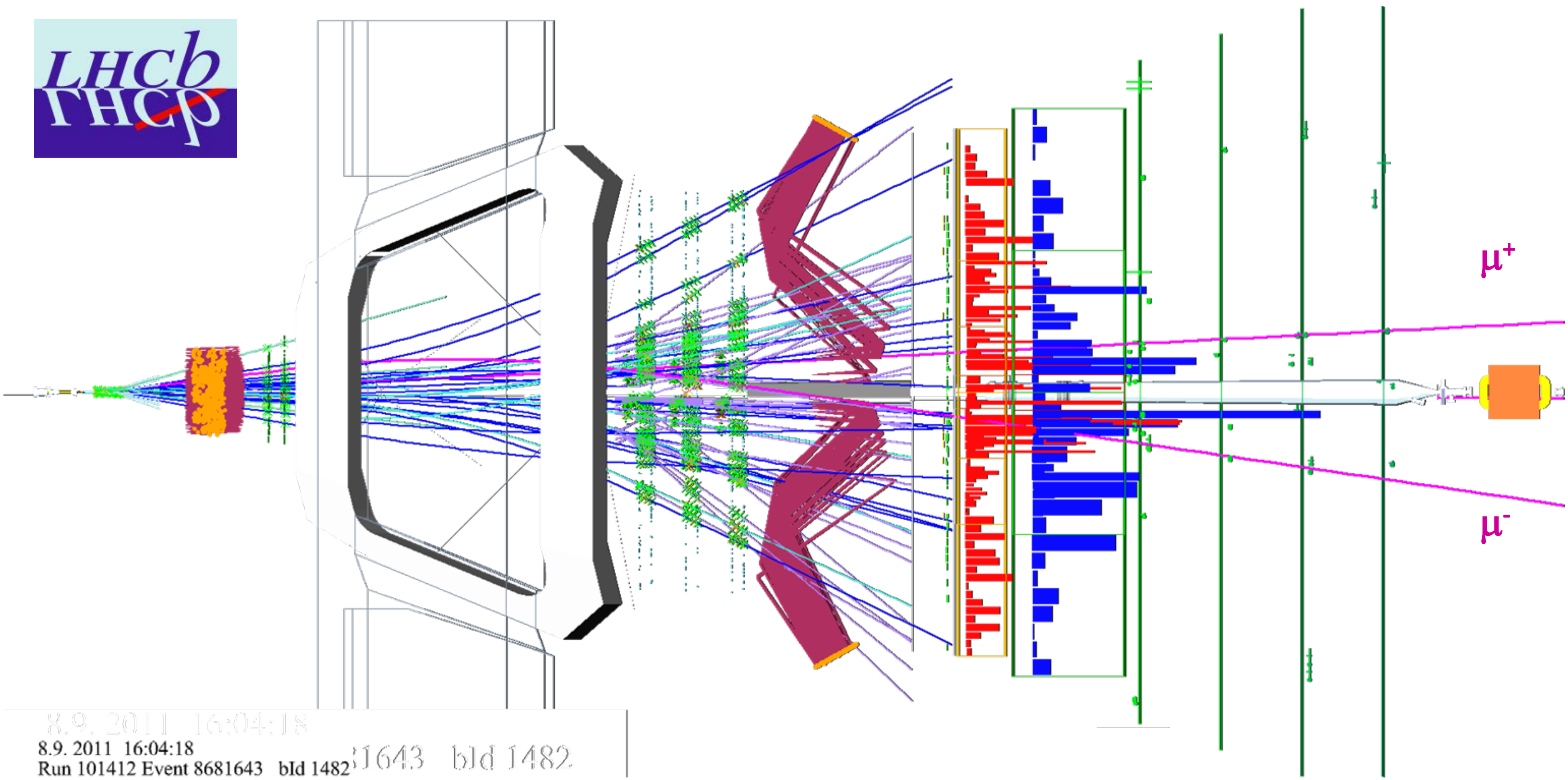
$$\varepsilon_{eff} = \varepsilon_{tag} D^2 = \varepsilon_{tag} (1 - 2\omega)^2$$

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

$D^2 \equiv$ dilution factor

The LHCb experiment

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



The LHCb experiment

- Comparison between facilities:

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\text{TeV}$) LHC
Production cross-section	1 nb	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\text{kHz}$	$\sim 500\,\text{kHz}$
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^0_s (10%), Λ^0_b (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	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

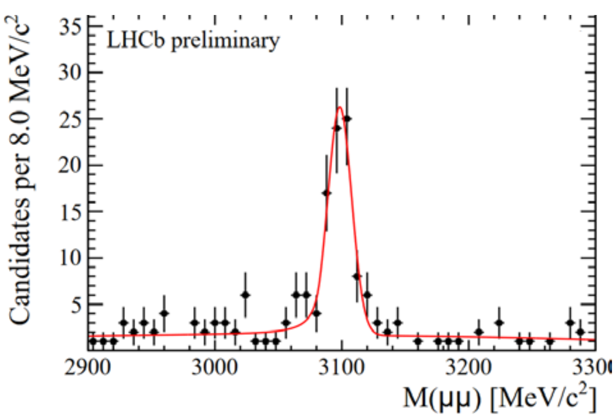
Q : Which is the maximum momentum of the pion in the B $\to \pi\ell\nu$ decay in the lab frame in BaBar at PEP-II and LHCb at LHC experiments ? Which will be easier to measure?

The LHCb experiment

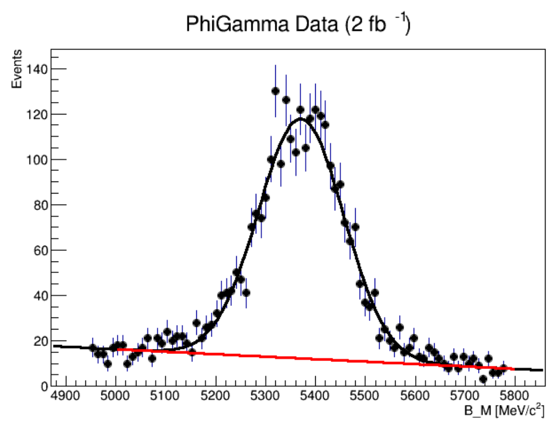
What do we measure?

Examples of observables:

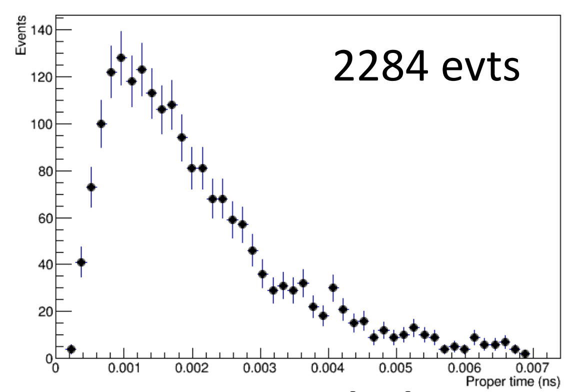
- Invariant masses: from momentum and PID hypothesis of the detected particles
- Decay times: from distance between the origin and decay vertices (and using information of the particle momentum)
- Angular distributions: from directions of the decay products (momentum, vertices)
- Branching fractions: from the mass distributions, counting the number of events
- Time dependent asymmetries (needed flavour tagging!)
- Ratios of observables: cancellation of systematic uncertainties



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



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

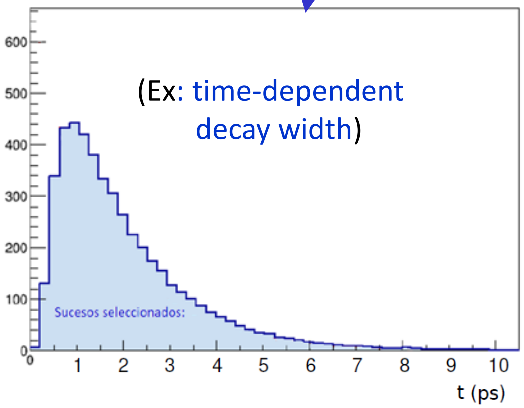


t_{Bs} (ns)

The LHCb experiment

Including experimental effects:

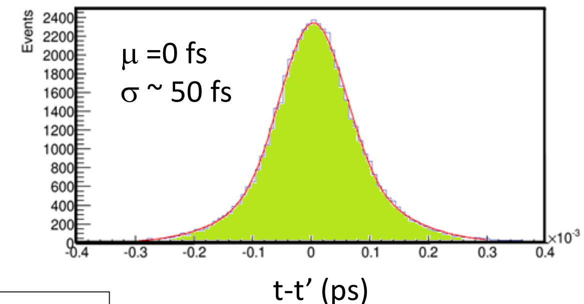
Observable(X') = Physics (X, P) · Acceptance(X) x Resolution (X,X')

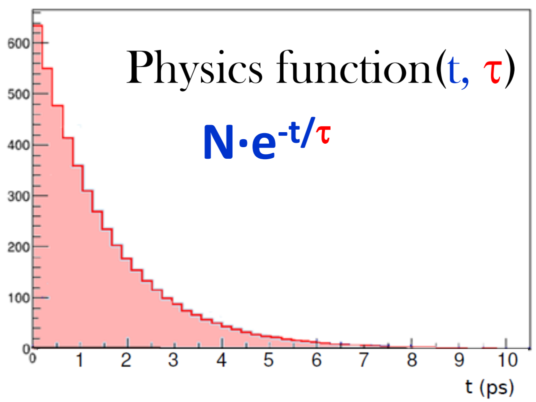


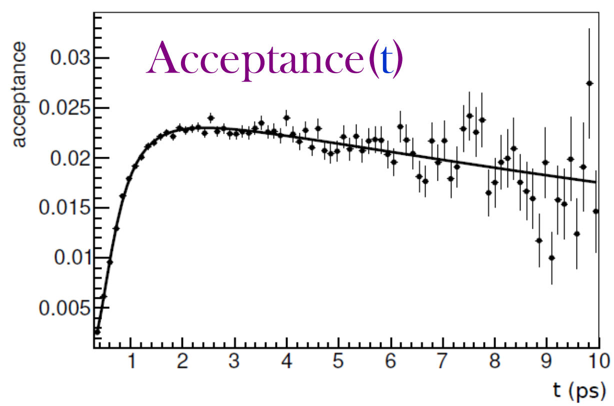
Efficiency dependent of X

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

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 CKM matrix

The CKM matrix V_{CKM} describes rotation for quarks between the weak eigenstates (d',s',b') and mass eigenstates (d,s,b)

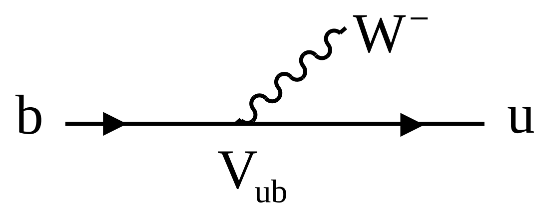
Quarks

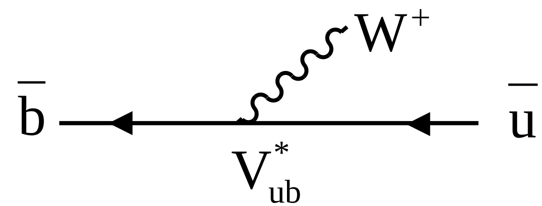
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Antiquarks

$$\begin{pmatrix} \overline{d}' \\ \overline{s}' \\ \overline{b}' \end{pmatrix} = \begin{pmatrix} V_{ud}^* & V_{us}^* & V_{ub}^* \\ V_{cd}^* & V_{cs}^* & V_{cb}^* \\ V_{td}^* & V_{ts}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} \overline{d} \\ \overline{s} \\ \overline{b} \end{pmatrix}$$

V_{ij} governs the transition from quark j to quark i





CP violation due to complex phases of CKM matrix elements

The CKM matrix

- The CKM matrix is complex and unitary $\hat{V}^{+}_{CKM}\hat{V}_{CKM} = 1$
- 4 independent parameters
  - $\rightarrow$ Fundamental constants of the Standard Model
  - $\rightarrow$ Must be determined from experiment

- **Standard parametrization (PDG):**
  - 3 angles: $\theta_{12}, \theta_{23}, \theta_{13}$ and 1 phase δ

$$V_{CKM} = R_{23} \times R_{13} \times R_{12}$$

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$$

The CKM matrix

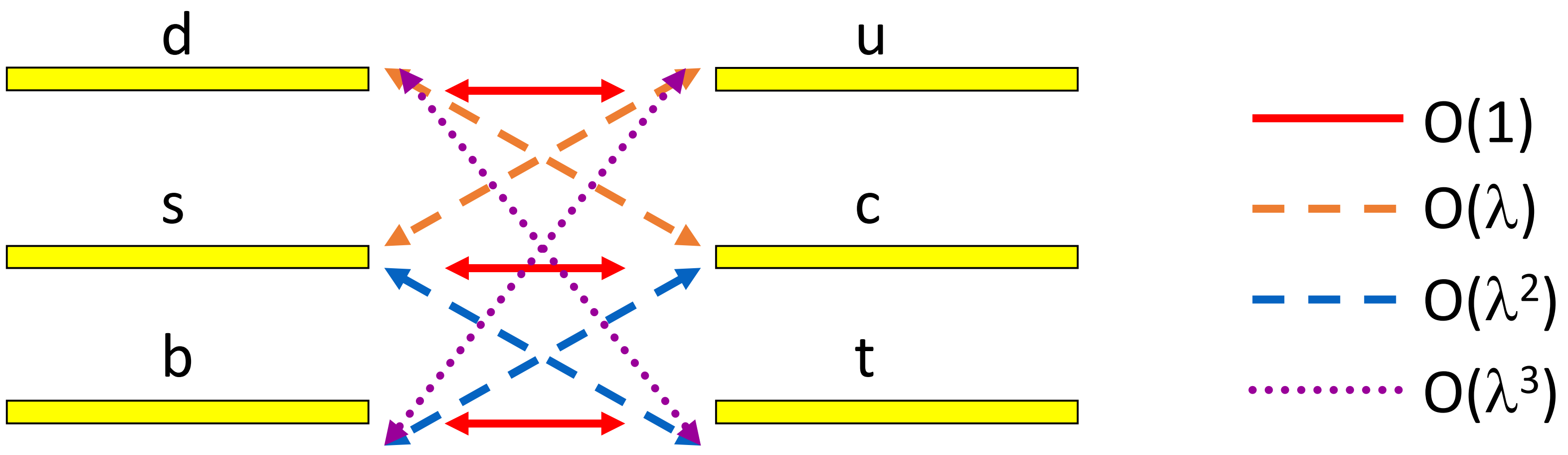
- **Wolfenstein parameterization:** $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{23} \sim 0.004$

- Perturbative, reflects the hierarchy of the matrix elements in terms of λ

$$\lambda = sin\,\theta_{12} \approx 0.23$$

- The four parameters are defined as:

$$\lambda = s_{12} \quad A = \frac{s_{23}}{s_{12}^2} \quad \rho = \frac{s_{13}\cos\delta}{s_{12}s_{23}} \quad \eta = \frac{s_{13}\sin\delta}{s_{12}s_{23}}$$



The CKM matrix

Wolfenstein parameterization to O(λ^3):

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

(but next-to leading order corrections in λ may be important at LHC)

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5\left(1/2-\rho-i\eta\right) & 1-\lambda^2/2-\lambda^4/8\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 + A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$$(\bar{\rho},\bar{\eta}) \equiv \left(1-\lambda^2/2\right)(\rho,\eta)$$

The CKM matrix

- CP Violation in the Standard Model:

  - Requirements for CP violation

$$\left(m_t^2 - m_c^2\right)\left(m_t^2 - m_u^2\right)\left(m_c^2 - m_u^2\right)$$
$$\times\left(m_b^2 - m_s^2\right)\left(m_b^2 - m_d^2\right)\left(m_s^2 - m_d^2\right) \times J_{CP} \neq 0$$

$$J_{CP} = \left| \mathrm{Im}\left\{ V_{i\alpha} V_{j\beta} V_{i\beta}^{*} V_{j\alpha}^{*} \right\} \right| \quad (i \neq j, \alpha \neq \beta)$$

  - *Jarlskog* invariant:

$$J_{CP} = s_{12} s_{13} s_{23} c_{12} c_{23} c_{13} \sin\delta = \lambda^6 A^2 \eta = O\left(10^{-5}\right)$$

$\rightarrow$ CP violation is small in the Standard Model

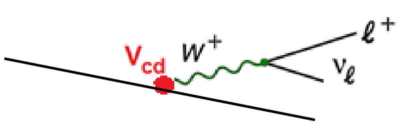
(and cannot explain the observed baryon asymmetry of the Universe)

The CKM matrix

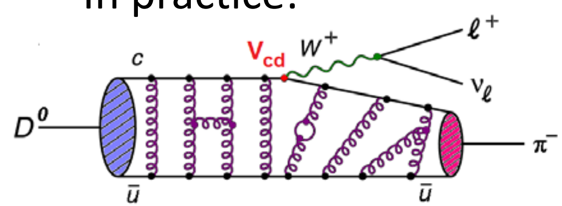
- PDG 2016:

0.97434 ± 0.00012 superallowed $0^+ \to 0^+$ β decays	0.22506 ± 0.00050 semileptonic / leptonic kaon decays hadronic tau decays	$(3.57 \pm 0.15) \times 10^{-3}$ semileptonic / leptonic B decays
0.22492 ± 0.00050 semileptonic charm decays charm production in neutrino beams	0.97351 ± 0.00013 semileptonic / leptonic charm decays	$(41.1 \pm 1.3) \times 10^{-3}$ semileptonic B decays
$(8.75 \pm 0.33) \times 10^{-3}$ B_d oscillations	$(40.3 \pm 1.3) \times 10^{-3}$ B_s oscillations	0.99915 ± 0.00005 single top production

In theory:



In practice:



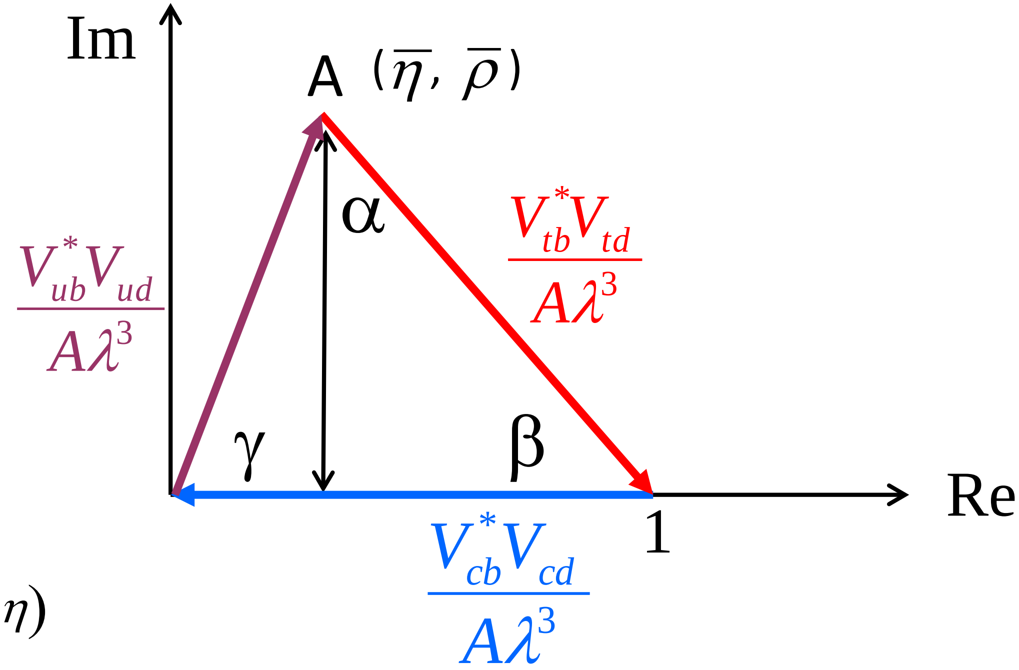
→ Need theory to describe QCD effects (lattice QCD)

The CKM matrix

The Unitarity Triangle → CKM is unitary:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{cd} & V_{td} \\ V_{us} & V_{cs} & V_{ts} \\ V_{ub} & V_{cb} & V_{tb} \end{pmatrix}^* = I$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$(\bar{\rho}, \bar{\eta}) \equiv (1 - \lambda^2/2)(\rho, \eta)$$

$$\gamma \equiv \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right] = \tan^{-1}\frac{\eta}{\rho} \sim 70^o$$

$$\beta \equiv \arg\left[-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right] = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}} \sim 21^o$$

$$\alpha \equiv \pi - \beta - \gamma$$

The CKM matrix

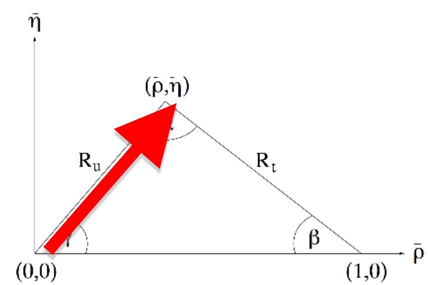
The Unitarity Triangle

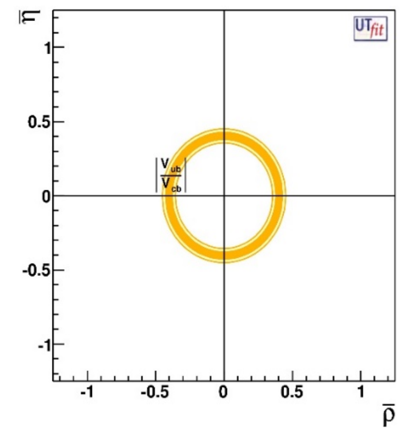
The idea: try to measure as many flavour observables as possible
overconstraint the unitarity triangle

Ex: Measuring the b→ u ℓν vs the b→ c ℓν transition

$$\frac{\Gamma(b \to u \ell \nu)}{\Gamma(b \to c \ell \nu)} \sim \left| \frac{V_{ub}}{V_{cb}} \right|^2 \sim \frac{1}{50}$$

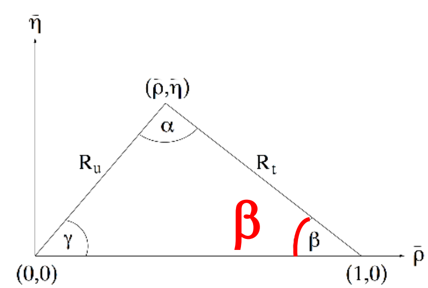
$$\left| \frac{V_{ub}}{V_{cb}} \right| = \frac{\lambda}{1-\lambda^2/2} \sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

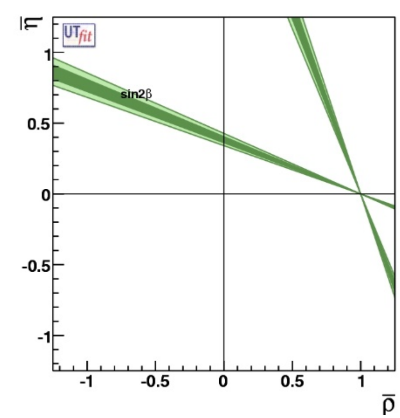




Ex: Measuring time-dependent asymmetries in b→c$\bar{c}$ s decays
(effect from interference of mixing and decay)

$$\beta = \tan^{-1} \frac{\bar{\eta}}{1-\bar{\rho}}$$

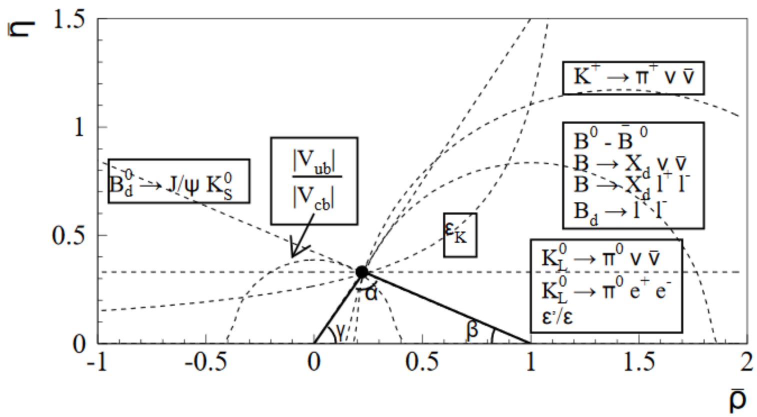




The CKM matrix

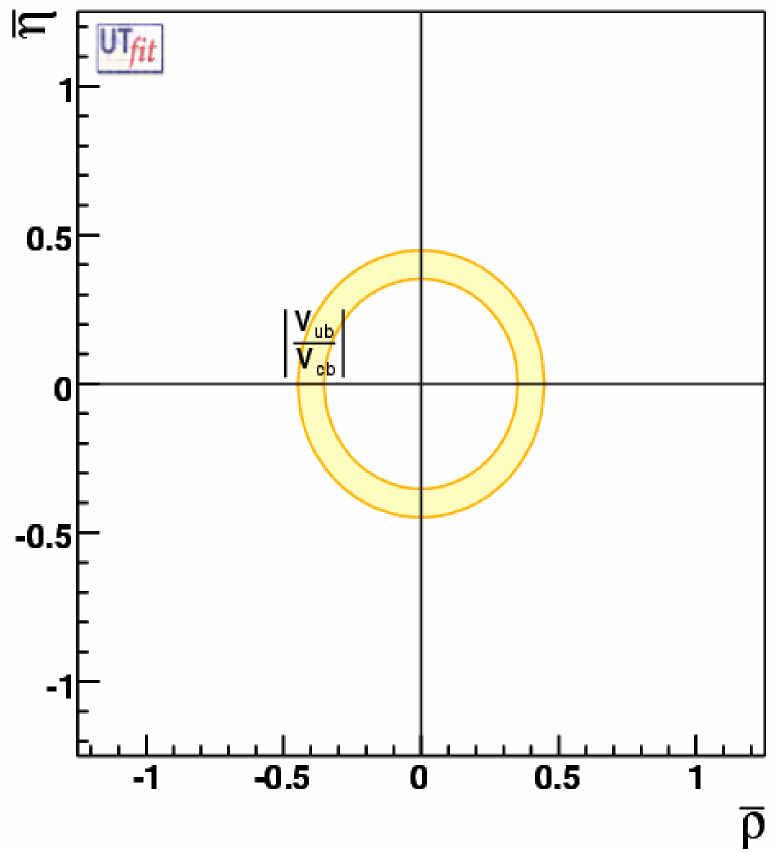
The Unitarity Triangle

The idea: try to measure as many flavour observables as possible
overconstraint the unitarity triangle



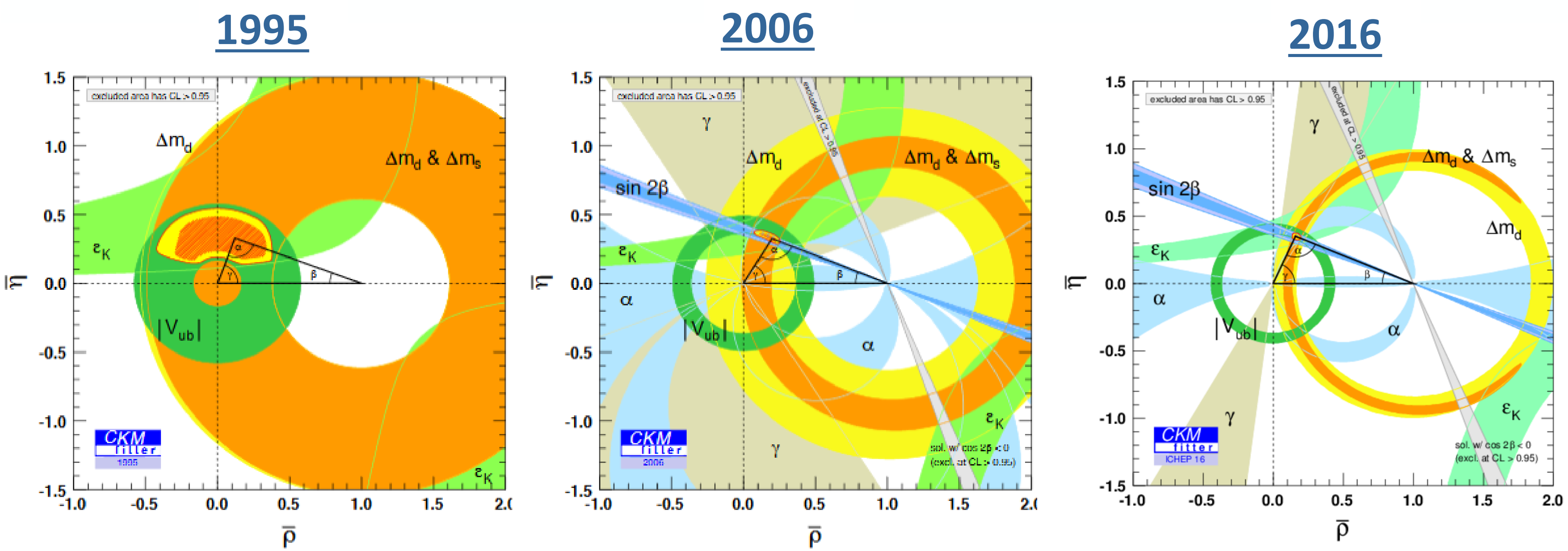
- If all measurements meet in the same apex$\rightarrow$ good understanding of the flavour structure of the SM

- If not $\rightarrow$ New Physics



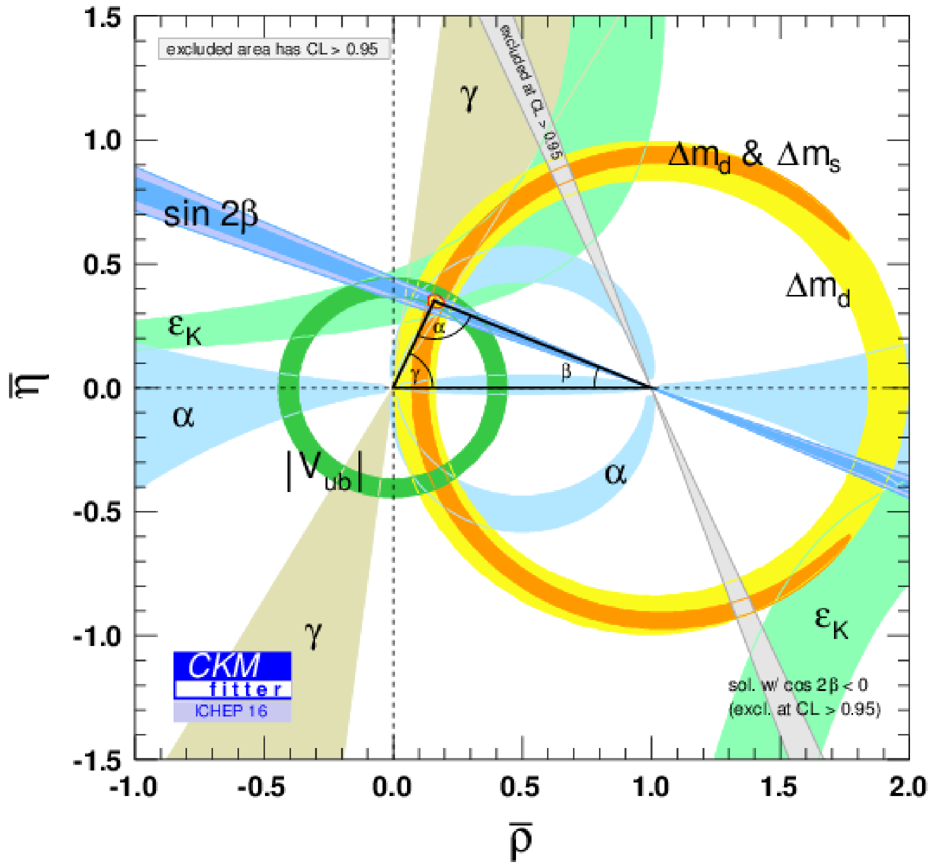
The CKM matrix

The Unitarity Triangle



- Precision measurements of CKM elements (fundamental parameters!)
- Measure all angles and sides in many different ways and look for inconsistencies → quantum effects from new particles
- Compare tree level processes (new physics is not expected) with loop processes sensitive to new particles
- With more precision the new physics scale has to be higher.

The CKM matrix



- Good agreement between experimental measurements

- Validation of Standard Model in the flavour sector

- Few discrepancies (“tensions”)

- Understanding from QCD is crucial

- Still room for New Physics, need more precision!

$$\bar{\rho} = 0.1598 \pm 0.0076$$
$$\bar{\eta} = 0.3499 \pm 0.0063$$

http://ckmfitter.in2p3.fr/

http://www.utfit.org/UTfit/