Findings in a heartbeat

Vladimir V. Gligorov LPNHE, February 12th 2015



Research career summary

2003-2008 : PhD, University of Oxford, LHCb experiment

- -- Measurement of the CKM angle γ in B>DX decays
- -- Emulation of the L1 displaced vertex hardware trigger and measurement of B meson lifetimes

2007-2009 : Research Associate, University of Glasgow, LHCb

- -- Implemented first inclusive software triggers and offline selections for the $B \rightarrow DX$ family of decays
- -- Data-Driven approach to correction of trigger lifetime biases in time-dependent B/D measurements fully commissioned within the LHCb simulation framework

2009-2012 : CERN Marie Curie Fellow, LHCb

- -- Deputy convener of Gamma-With-Trees WG of LHCb
- -- Responsible for Hadronic/Radiative LHCb software triggers
- -- Co-author of trigger section of LHCb upgrade LOI
- -- Analysis : measurement of B-hadron fractions
- -- Analysis : measurement of $B_s \rightarrow KK$ lifetime
- -- Analysis : mixing and CPV in $D^0 \rightarrow hh$ decays

2012-2017 : CERN Staff, LHCb

- -- Co-convener, B2OpenCharm WG of LHCb
- -- HLT project leader
- -- Analysis : first observations of $X_b \rightarrow X_c X_c$ decay modes
- -- Analysis : measurement of CKM angle γ in $B_s {\rightarrow} D_S K$
- -- Analysis : precise measurements of excited B hadrons



Shift leader & Trigger Piquet >150 shifts/piquet days in Run I

Finding antimatter

Afterglow Light Pattern 400,000 yrs.

Inflation

Quantum Fluctuations

> 1st Stars about 400 million yrs.

Dark Ages

Equal amount of matter and antimatter created



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The standard model...



Very predictive, wonderfully accurate, and wholly incompatible with cosmology!



Electromagnetic force

Strong force

Weak force



...ptolemaic model?



A sometimes forgotten property of the Ptolomeic model : it was very predictive and accurate. One just had to some epicycles (particles?)...





Indirect detection



Particles which are too heavy to produce can affect processes virtually

Indirect detection



Particles which are too heavy to produce can affect processes virtually



t,c,uhad the SM. models and predictions or der diagrams for neutral meson mixing in the SM.

SM respects the SM gauge symmetry, as we expected from general argunitients, be found in extbooks, recent reviews of and lecture notes. An up-to-date review of $(\bar{q}_i Q_j)$ be we ittent in the following general forme PDG The fol-

 $\mathcal{A}(f_i \to f_j + X) = \mathcal{A}_0 \sqrt{\frac{\mathcal{C}SMestimat}{M_W}} + \frac{\mathcal{C}SMestimat}{\Lambda^2}$ apply to \mathcal{B}_s^0 and \mathcal{B}_d^0 . u, c, t

e of the new degrees of freedom $\operatorname{Consider}_{flavour eigenstates}^{\operatorname{Consider}_{and}}$ the superposition of the nclude appropriate CKM factors and eventually a Sobrölinger (and pression if $(b \rightarrow s)$ (c
ightarrow u)ated. Given our ignorance about the $c_{\rm NP}$, the $d_{\rm NP}$ and $d_{\rm NP}$ and d_{\rm NP} and $d_{\rm NP}$ and d_{\rm NP} and d_{\rm $\Delta m_s, A^s_{S(b)}$ $D-\bar{D}$ ver a wide range. However, the general result in Eq. (3.1) allows us to precipet Oscillations Since the meson decays and we do not consider the property ave funct CPV of final stades PV he Oscillations prove with future experiments: the insensitivity homitian. scale in assignment the inclusion of the inclusio in D system used to measure the observable. This implies that is not easy to increase M and Γ , ct the symmetries and the symmetry $B_{B}^{for the moment}$ is arbitrary such we can choose either the phase of M_{12} or Γ_{12} and Flayour physics constrains naw their phase difference matters? Consequently, the mixing lame parametrizeect detection!









Quark mixing in the Standard Model



Transformations between up and down type quarks can be arranged in a 3x3 matrix



Quark mixing in the Standard Model



These transitions are very hierarchical, quarks in the same column mix almost maximally



Quark mixing in the Standard Model



$$\mathbf{V}_{\mathbf{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \sum_{n=4}^N O(\lambda^n)$$

Imaginary component gives rise to matter-antimatter asymmetry (CP violation)

The unitarity triangle



Unitary matrix => 6 triangles in imaginary plane, one experimentally convenient



The apex of the triangle



Overconstraining the apex tests the consistency of the SM picture of CP Violation

http://ckmfitter.in2p3.fr Similar plots with Bayesian treatment available at www.utfit.org



Overconstraining the epicycles



Any New Physics model must also exibit consistency in the triangle : a powerful experimental protection against further epicycles!



y and matter-antimatter asymmetries



Because γ is the argument of this term which contains the imaginary V_{ub} , we measure it by observing matter-antimatter asymmetries





t, c, une SME models and predictions order

2. Beauty mixing phenomenology in a nutshell

pects the SM gauge symmetry, as we expected firting general margunitients, be found in textbooks, recent reviews and lecture notes. An up-to-date review of exper (QiQj) or-violating amplitudes canibe avaittent in the following general former PDGV The fol-

 $f_i \to f_j + X) = \mathcal{A}_0$ $\frac{1}{W_2} \frac{1}{1} \int_{ime-evolution of the B^0-\overline{B}^0}^{ime-evolution of the B^0-\overline{B}^0} system$ e new degrees of freedom $\widehat{\operatorname{Figure}}_{\operatorname{flavour}}$ is the wave function $B^0(t)$ for a neutral meson that is the superposition of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the superposed of $B^0(t)$ for a neutral meson that is the appropriate CKM factors and eventually a Sobrölinger Gration suppression if iven our ignorance about the $c_{\rm NP}$, the dyale of the scale of th ide range. However, the general result in Eq. (3.1) allows us to precipiet Oscillations Since the meson decays and we do not consplored average function of the final strates Pulse with future experiments: the hisensitivity hon itia. Scale in a system the incomparent of the second states of the to measure the observable. This implies that is not easy to increase M and Γ , h indirect NP searches only. Moreover, from Eq. (9.1) It is also chear Rev. Nucl. Part. Sci. 60 Since M and Γ are hermitian, their 2000 al 31 strents are real ord 200 $M_{21} = P$ scales well above the TeN₁₂ for models where are M_{12} by M_{21} and Γ_{22} . Ignoring ymmetries and the symmetry-breaking pattern of the SM side in the interference with the symmetry breaking pattern of the SM side in the phase of M_{12} or Γ_{12} and M_{12} or Γ_{13} and M_{12} or Γ_{13} and M_{12} or Γ_{12} and M_{12} or Γ_{12} and M_{12} or Γ_{13} and M_{12} or Γ_{12} and M_{12} or Γ_{13} and M_{13} or Γ_{13} and A = 2 operators have all their phase difference matters: Consequently, the mixing can be parametrized





Dramatis personae



LHCb : forward spectrometer for flavour physics at LHC

Finding CPV in oscillations





The physics of $B_s \rightarrow D_s K$

FD





Interference in mixing and decay => CPV



We in fact have four decay rates

Each decay rate is a function of the decay-time of the B_s (anti)meson, and the parameters of that function depend on Y

1. $B^0_S \rightarrow D^+_s K^-$ 2. anti- $B^0_S \rightarrow D^+_s K^-$ 3. $B_{S}^{0} \rightarrow D_{s}^{-}K^{+}$ 4. anti- $B^0_S \rightarrow D^-_s K^+$



















 $\frac{1}{2}$ $\frac{1$

4







24



















 $m(K^{+}K^{-}\pi^{\pm}, \pi^{+}\pi^{-}\pi^{\pm}, K^{\pm}\pi^{-}\pi^{+}) [MeV/c^{2}]$







Event type	$\varepsilon_{\mathrm{tag}}$ [%]	$\varepsilon_{\mathrm{eff}}$ [%]
OS-only	19.80 ± 0.23	$1.61 \pm 0.03 \pm 0.03$
SSK-only	28.85 ± 0.27	$1.31 \pm 0.22 \pm 0.021$
OS-SSK	18.88 ± 0.23	$2.15 \pm 0.05 \pm 0.05$
Total	67.53	5.07

Time fit to D_sK





28

Time fit to D_sK



LHCb-PAPER-2014-038









The measurement of y



About 2.8 sigma away from no CP violation point...

LHCb-PAPER-2014-038



The impact of LHCb on y



Combining all channels, LHCb has the world's most precise measurement of Y. The world average is now approximately $\pm 6.5^{\circ}$, so we still have a way to go to catch up with α/β .

 $\gamma = (72.9^{+9.2}_{-9.9})^{\circ}$ @68% CL, $\gamma \in [63.0, 82.1]^{\circ}$ @68% CL, @95% CL. $\gamma \in [52.0, 90.5]^{\circ}$



LHCb-CONF-2014-014





Finding particles at 40 MHz







The heartbeat of the LHC



P. Sphicas Triggering

Collisions at the LHC: summary

Proton - Proton2804 bunch/beamProtons/bunch1011Beam energy7 TeV (7x1012 eV)Luminosity1034cm-2s-1

Crossing rate 40 MHz

Collision rate \approx 10⁷-10⁹

New physics rate ≈ .00001 Hz

Event selection: 1 in 10,000,000,000,000

A good approach in Run1





In Run I, this was a good approach : only 0.5% of bunch crossings contain bbar, so we can use simple inclusive criteria to distinguish bbar from the rest and save them







1.

Information gathering
("reconstruction") stage



Information gathering ("reconstruction") stage



















Displaced track trigger 15









A topological decision tree trigger





A topological decision tree trigger





HLT2 3-Body 1

measure

corrected

Optimal performance : real-time MVA



See also LHCb-PUB-2011-002,003,016 http://arxiv.org/abs/1310.8544 http://arxiv.org/abs/1211.3055

Gligorov&Williams <u>http://arxiv.org/abs/1210.6861</u>



Optimal performance : real-time MVA



See also LHCb-PUB-2011-002,003,016 http://arxiv.org/abs/1310.8544 http://arxiv.org/abs/1211.3055



Gligorov&Williams <u>http://arxiv.org/abs/1210.6861</u>



Triggers today

www.jolyon.co.uk





Input data rate of the LHCb experiment = 1.5 TB/second

NB : ATLAS/CMS about a bit more than one order of magnitude above LHCb

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Input data rate of the LHCb experiment = 1.5 TB/second





Facebook 180 PB/yr

Facebook 180 PB/yr

LHCb 15000 PB/yr



Facebook 180 PB/yr

Facebook Computing O(500) M\$/yr

LHCb 15000 PB/yr

LHCb Computing O(10) M\$/yr



Facebook 180 PB/yr

Facebook Computing O(500) M\$/yr

LHCb 15000 PB/yr

Storing data costs more than processing => real time analysis!

LHCb Computing O(10) M\$/yr/



Back to our traditional outreach slide...





P. Sphicas Triggering

Collisions at the LHC: summary

Proton - Proton	2804 bunch/beam
Protons/bunch	10 ¹¹
Beam energy _uminosity	7 TeV (7x10 ¹² eV) 10 ³⁴ cm ⁻² s ⁻¹

Crossing rate 40 MHz

Collision rate ≈ **10⁷-10⁹**

New physics rate ≈ .00001 Hz

Event selection: 1 in 10,000,000,000,000

Enter the MHz signal era



Fitzpatrick&Gligorov LHCb-PUB-2014-027



In the HL-LHC era triggers will discriminate between different signal classes!



Triggers today

www.jolyon.co.uk



Triggers in the future





More precision \Rightarrow real time analysis

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate



Software High Level Trigger Partial event reconstruction, select displaced tracks/vertices and dimuons

detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

More precision \Rightarrow real time analysis LHCb 2015 Trigger Diagram 40 MHz bunch crossing rate L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures 450 kHz 400 kHz 150 kHz h± **н/н** e/y Software High Level Trigger Partial event reconstruction, select displaced tracks/vertices and dimuons Buffer events to disk, perform online detector calibration and alignment Full offline-like event selection, mixture of inclusive and exclusive triggers **12.5 kHz Rate to storage**



Calibrate particle identification run-by-run





Real time data analysis...



...at 10⁻⁵ precision?



...at 10⁻⁵ precision?



The future is sub-permille measurements in real time. I hope you are scared.

CKM angle γ

Charm CPV





A few key observables

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

K⁰→π⁰VV, KOTO⁺⁺, NA62⁺⁺ (?)

Flavourv

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160

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60

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30⊢

25

20

15

10⊟

0<u>↓</u> 2016

2018

-0.5 -1.0 Probe $\sim 10^3$ TeV for non-hierarchical NP

Probe ~10-20 TeV for hierarchical tree-level NP

Probe ~1-2 TeV for hierarchical loop-level NP

Competitive/complementary with direct searches! 1.0 0.5 0.0

2012 2014 2016 2018 2020 2022 2024

-1.0

 $\overline{\rho}$

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

 $K^0 \rightarrow \pi^0 VV$ KOTO⁺⁺, NA62⁺⁺ (?)

Need to measure flavour structure to differentiate NP models

FLAVOUR STUDIES REQUIRED

Flavour sets scale of NP and guides design of future direct searches

