Flavour Physics at LHCb: now and next

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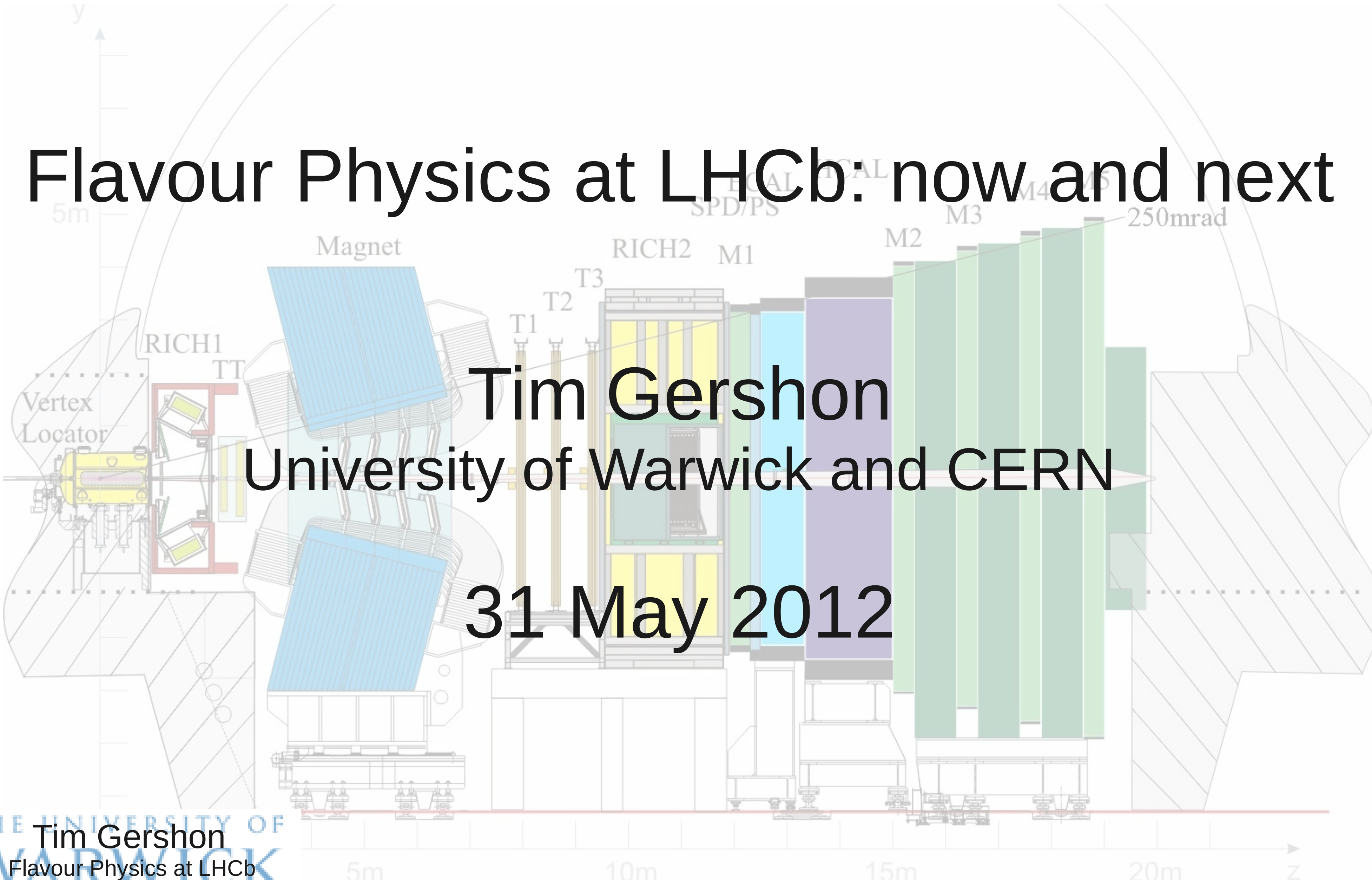
University of Warwick and CERN

31 May 2012



Outline

- Flavour physics – what and why?
  - CP violation and the CKM matrix
- The LHC and the LHCb detector
  - Data taking performance in 2011 and 2012
- Selected highlights of results so far
  - Rare decays
  - CP violation
- The LHCb upgrade

Flavour physics – What and why?

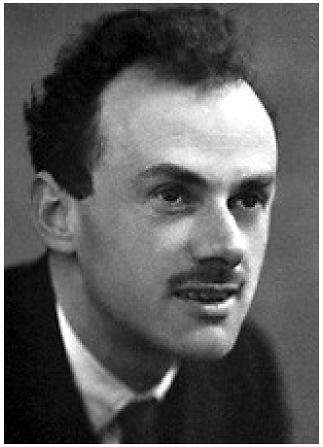
What is flavour physics?

Fermions ("matter")		Bosons ("forces")
Quarks: uuu ccc ttt / ddd sss bbb	$\times$ { MATTER / ANTIMATTER }	$gggggggg$
		γ
		W^+
		W^-
Leptons: e μ τ / ν_e ν_μ ν_τ		Z
		H

Mysteries of flavour physics

- Why are there so many different fermions?
- What is responsible for their organisation into generations / families?
- Why are there 3 generations / families each of quarks and leptons?
- Why are there flavour symmetries?
- What breaks the flavour symmetries?
- What causes matter–antimatter asymmetry?

Dirac's prescience



Concluding words of 1933 Nobel lecture

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

Matter-antimatter asymmetry

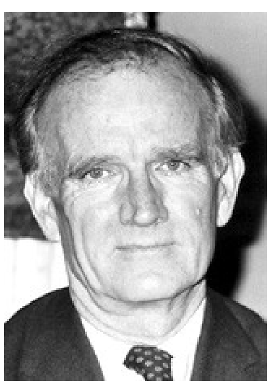
- Consider violation of the
  "complete symmetry between positive and negative electric charge"
- In particle physics, the charge conjugation (C) operator inverts all internal quantum numbers
- It is usually discussed together with other discrete symmetries
  - parity (P) : inversion of all spatial coordinates
  - time-reversal (T) : as the name suggests ...

(will not discuss T today)

- Require CP violation to distinguish absolutely between matter and antimatter

Discovery of CP violation

- 1964: J.W.Cronin,V.L.Fitch *et al.* discover $K_L^0 \rightarrow \pi^+\pi^-$
  - K_L^0 was previously thought to be CP-odd state (K_2^0)



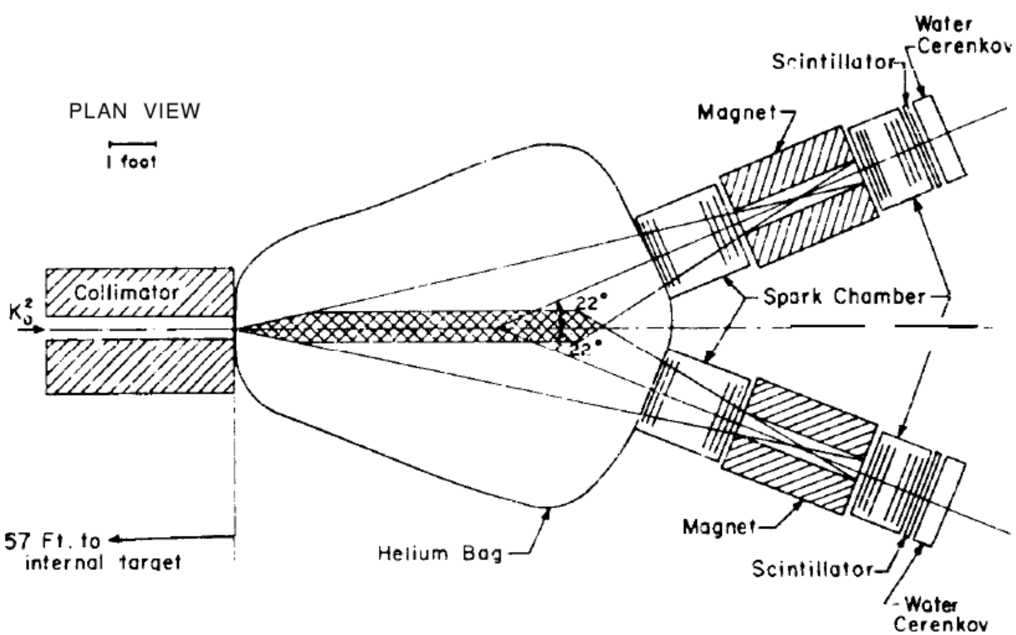


Fig. I. Plan view of the apparatus as located at the A. G. S.

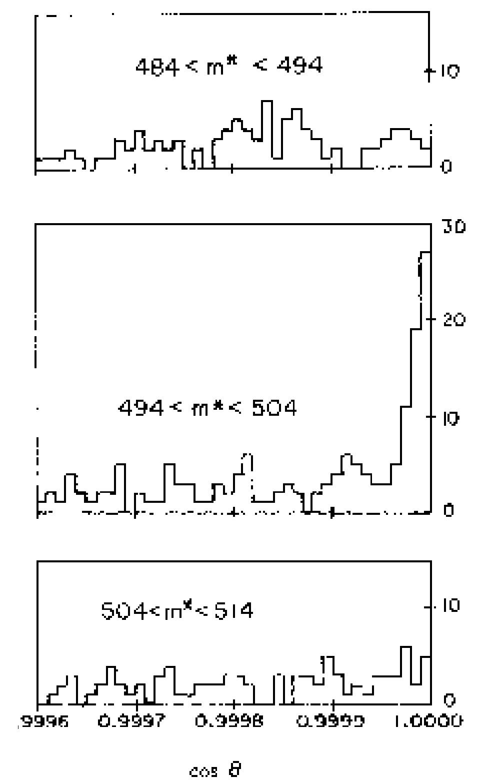


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

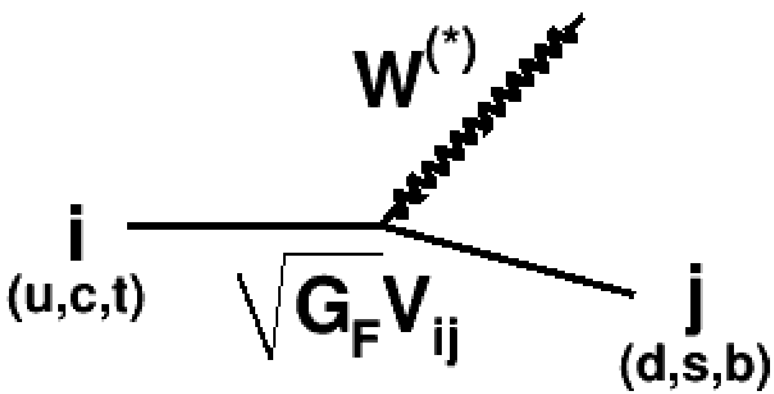
The need for more quarks

- In 1973, Kobayashi & Maskawa showed that CP violation could not be accommodated in a theory with only four quark fields
  - At that time only up, down & strange were known
  - Quarks largely considered as a mathematical model,
    not as real physical entities
  - Existence of charm hypothesised (GIM mechanism)
    ... but discovery not until the next year
- Among possible extensions, KM considered
  - Introduction of a third family (bottom and top) of quarks
  - Quark mixing following the scheme introduced by Cabibbo

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

Dirac medal 2010

Nobel prize 2008

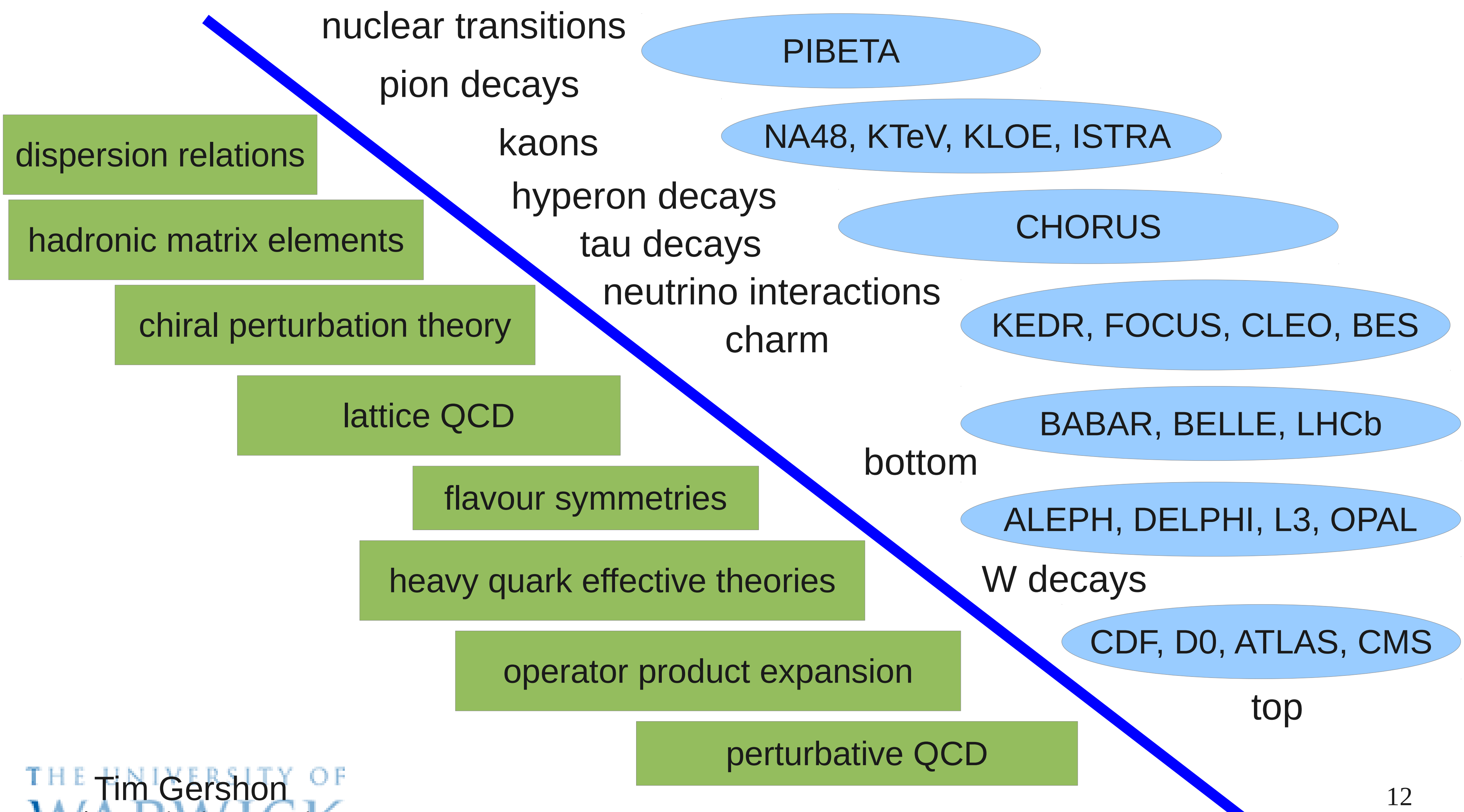


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM phenomenology

- CKM theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters
- CKM matrix is hierarchical
  - theorised connections to quark mass hierarchies, or (dis-)similar patterns in the lepton sector
    - origin of CKM matrix from diagonalisation of Yukuwa (mass) matrices after electroweak symmetry breaking
  - distinctive flavour sector of Standard Model not necessarily replicated in extended theories → strong constraints on models
- CKM mechanism introduces CP violation
  - only source of CP violation in the Standard Model ($m_\nu = \theta_{QCD} = 0$)

Range of CKM phenomena



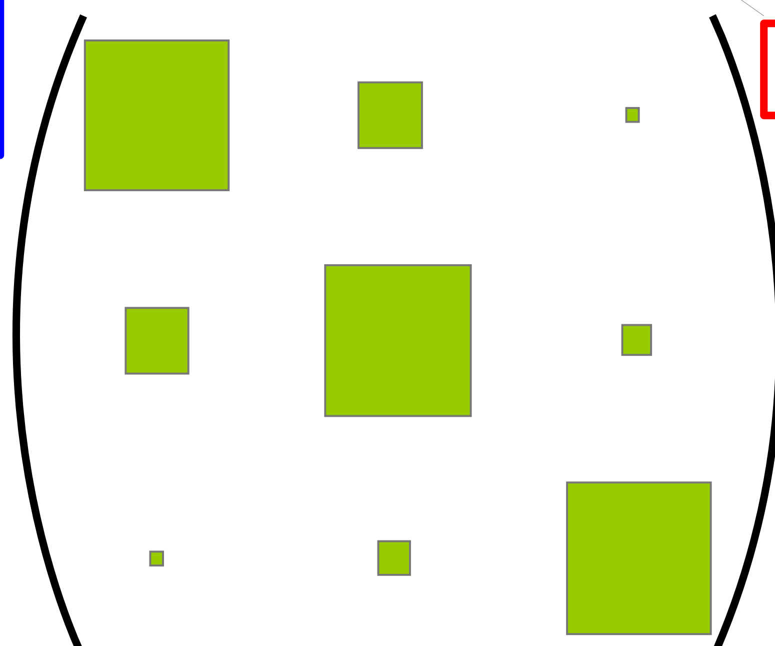
Hierarchy of CKM matrix elements

Wolfenstein parametrisation of the four free parameters

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

Expansion parameter
$\lambda = \sin(\theta_c) \sim 0.22$

Source of CP violation



What breaks the flavour symmetries?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking m_ν=0)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks
- Consequently, the only flavour-changing interactions are the charged current weak interactions
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests

The Sakharov conditions

- Proposed by A.Sakharov, 1967
- Necessary for evolution of matter dominated universe, from symmetric initial state
  - (i) baryon number violation; (ii) C & CP violation; (iii) thermal inequilibrium
- Widely accepted that SM CPV insufficient to explain observed baryon asymmetry of the Universe
- To create a larger asymmetry, require
  - new sources of CP violation that occur at high energy scales
- Where might we find it?
  - lepton sector: CP violation in neutrino oscillations
  - quark sector: discrepancies with KM predictions
  - gauge sector, extra dimensions, other new physics: precision measurements of flavour observables are generically sensitive to additions to the Standard Model

Flavour physics at LHCb

- LHCb is an experiment designed to study (mainly)
  - flavour-changing interactions of charm and beauty quarks
- But quarks feel the strong interaction and hence hadronise
  - various different charmed and beauty hadrons
  - many, many possible decays to different final states
- Hadronic uncertainties can obscure interpretation
- On the other hand, hadronisation greatly increases the observability of CP violation effects
  - the strong interaction can be seen either as the "unsung hero" or the "villain" in the story of quark flavour physics

I. Bigi, hep-ph/0509153

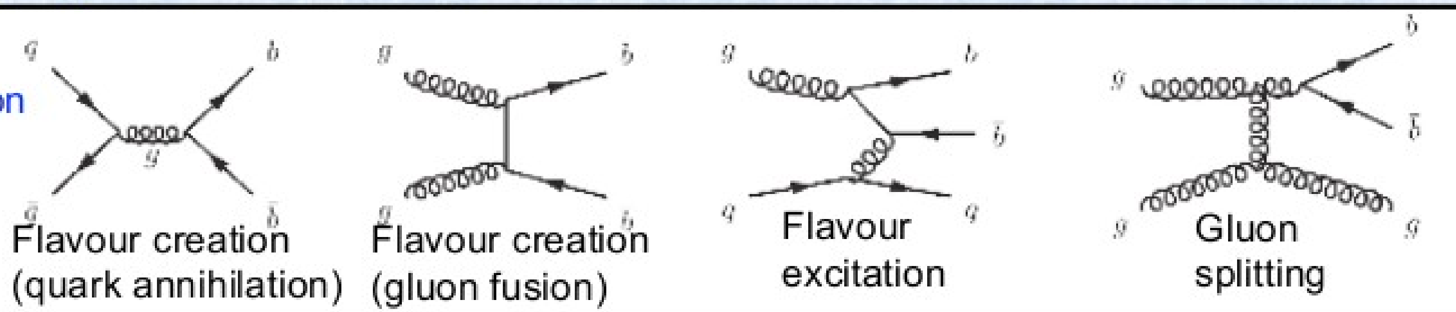
The LHC and the LHCb detector

Data taking performance in 2011 and 2012

Flavour physics at hadron colliders

	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$ **PEP-II, KEK-B**	$p\bar{p} \to b\bar{b}X \quad (\sqrt{s} = 2\ \mathrm{TeV})$ **TeVatron**	$pp \to b\bar{b}X \quad (\sqrt{s} = 14\ \mathrm{TeV})$ **LHC**
prod	1 nb	~100 μb	~500 μb
typ. $b\bar{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~1/4	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\bar{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%),\ \mathrm{b-baryons}(10\%)$	
B boost	small, βγ~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\bar{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\bar{B}^0$ mixing	coherent	incoherent→ flavour tagging dilution	

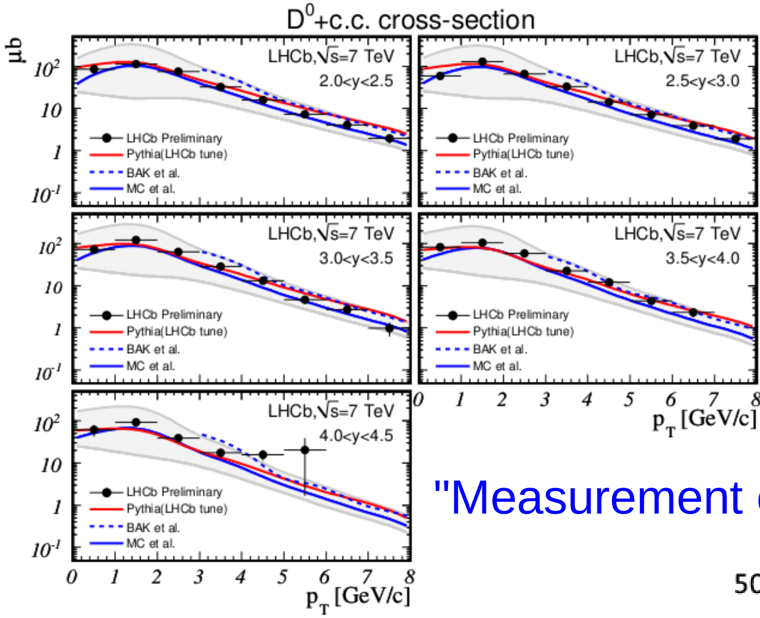
bb production at hadron colliders



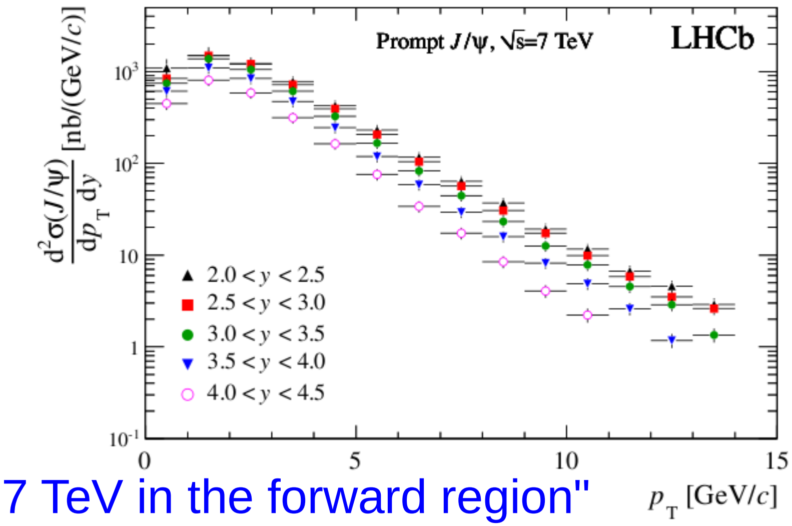
from Val Gibson HCPSS 2009

Heavy flavour production @ LHCb

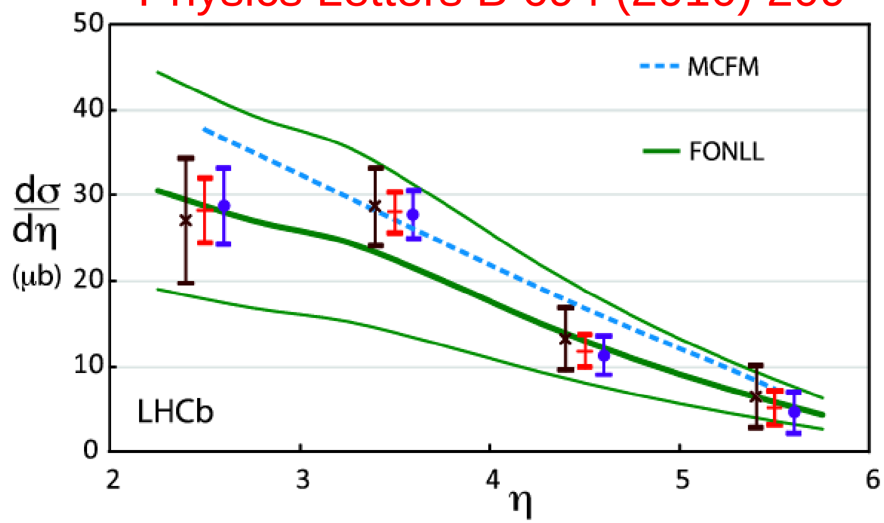
"Prompt charm production in pp collisions at √s = 7 TeV"
LHCb-CONF-2010-013



"Measurement of J/ψ production in pp collisions at √s = 7 TeV"
Eur. Phys. J. C 71 (2011) 1645

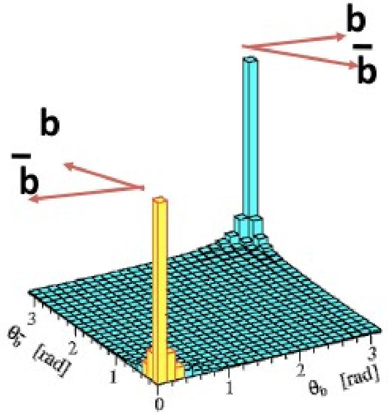


"Measurement of $\sigma(pp \rightarrow b\bar{b}X)$ at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209

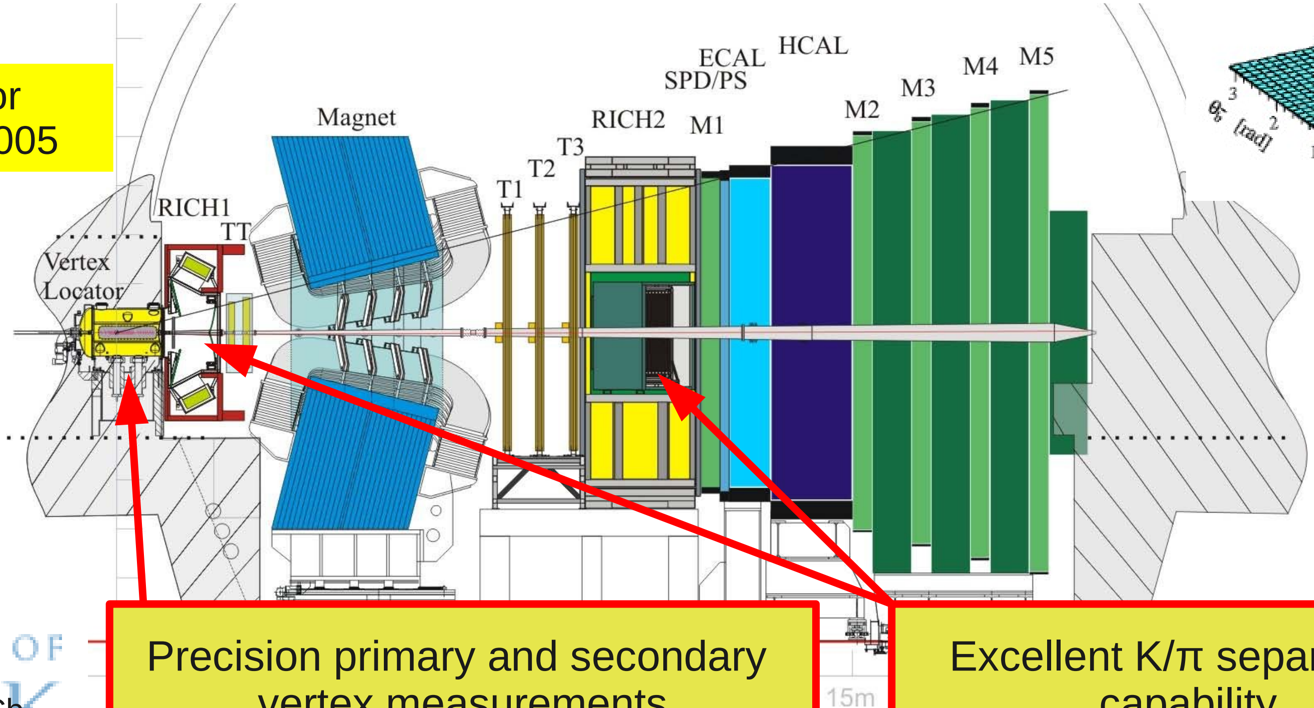


Geometry

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer
  - a new concept for HEP experiments



The LHCb Detector
JINST 3 (2008) S08005

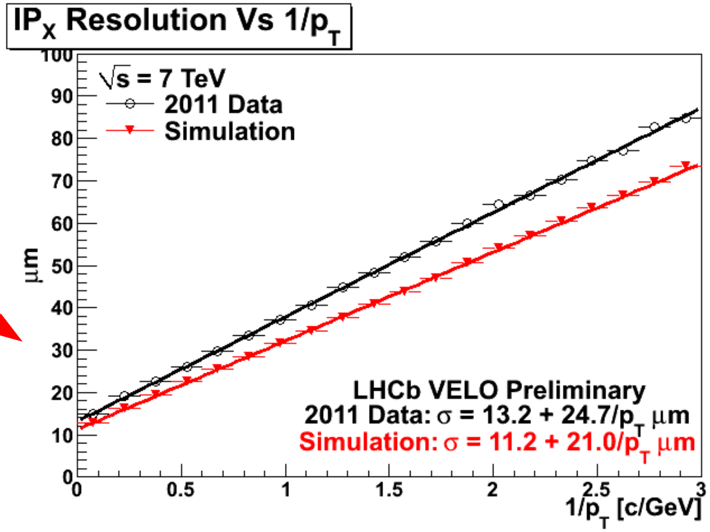


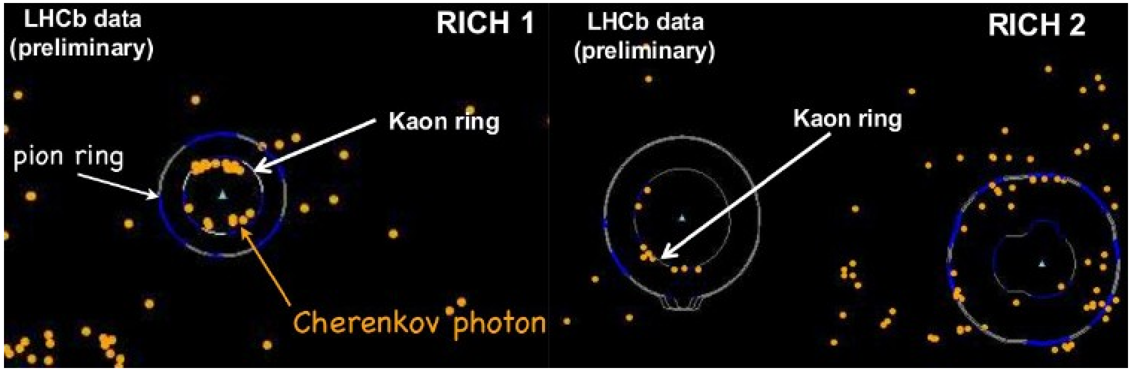
Precision primary and secondary vertex measurements

Excellent K/π separation capability

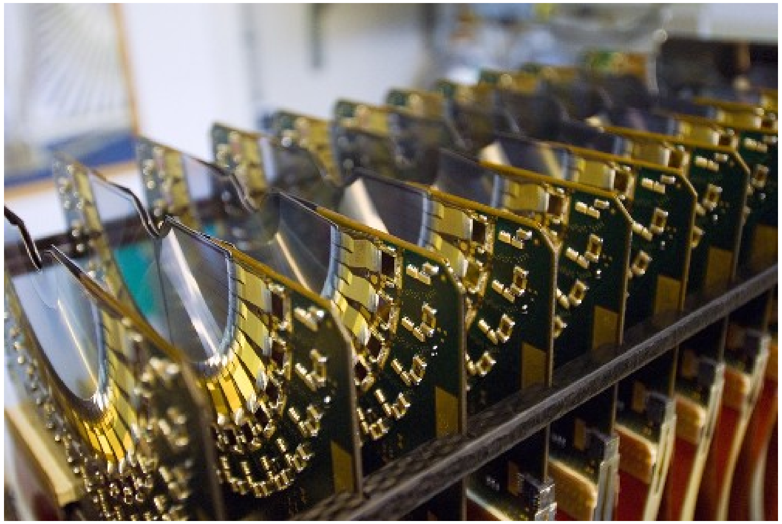
LHCb detector features

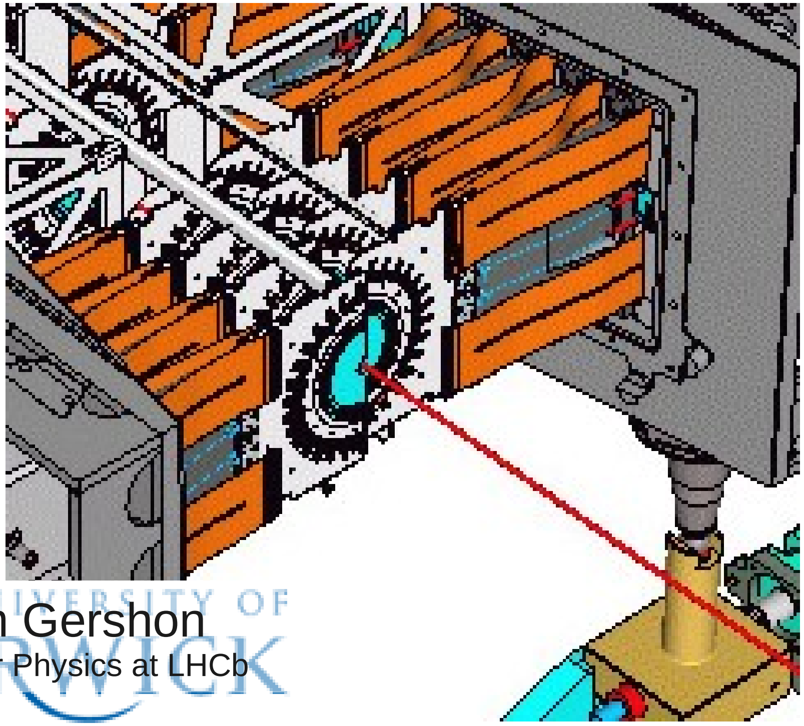
- Tracking and calorimetry
  - basic essentials of any collider experiment!
  - muon chambers
- VELO
  - reconstruct displaced vertices
- RICH
  - particle ID (K/π separation)
- Trigger
  - fast and efficient



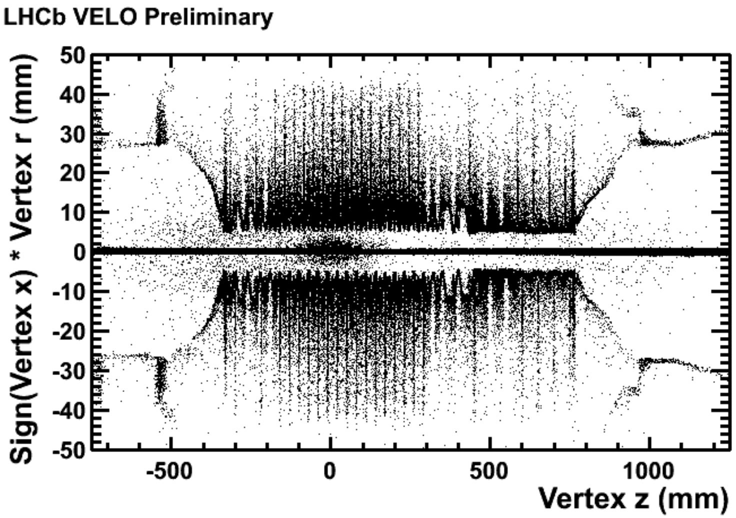


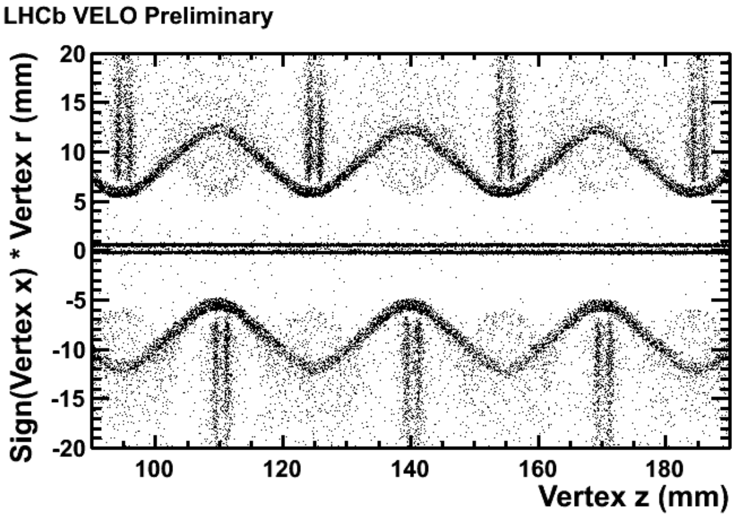
VELO



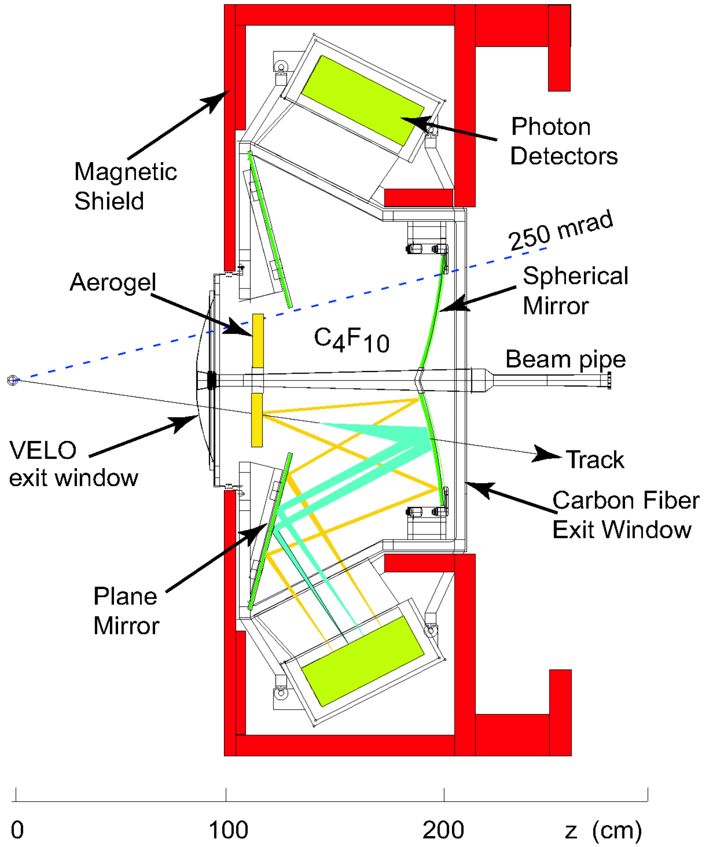


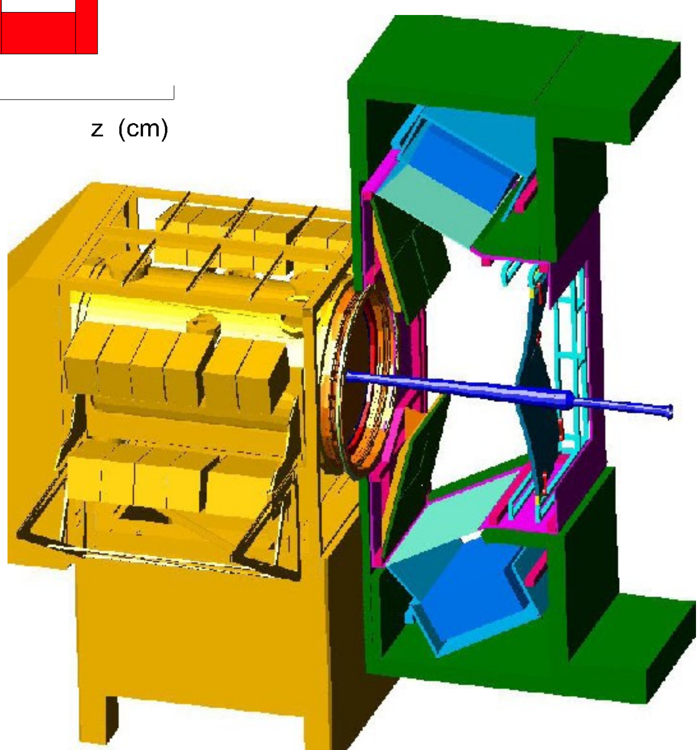
Material imaged used beam gas collisions





RICH


Magnetic
Shield
Photon
Detectors
250 mrad
Aerogel
Spherical
Mirror
C_4F_{10}
Beam pipe
VELO
exit window
Track
Carbon Fiber
Exit Window
Plane
Mirror
0
100
200
z (cm)



e^+e^- vs. pp collisions

	$e^+e^- \to \Upsilon(4s) \to B\overline{B}$ PEP-II, KEK-B	$p\overline{p} \to b\overline{b}X \quad (\sqrt{s} = 2\ \text{TeV})$ TeVatron	$pp \to b\overline{b}X \quad (\sqrt{s} = 14\ \text{TeV})$ LHC
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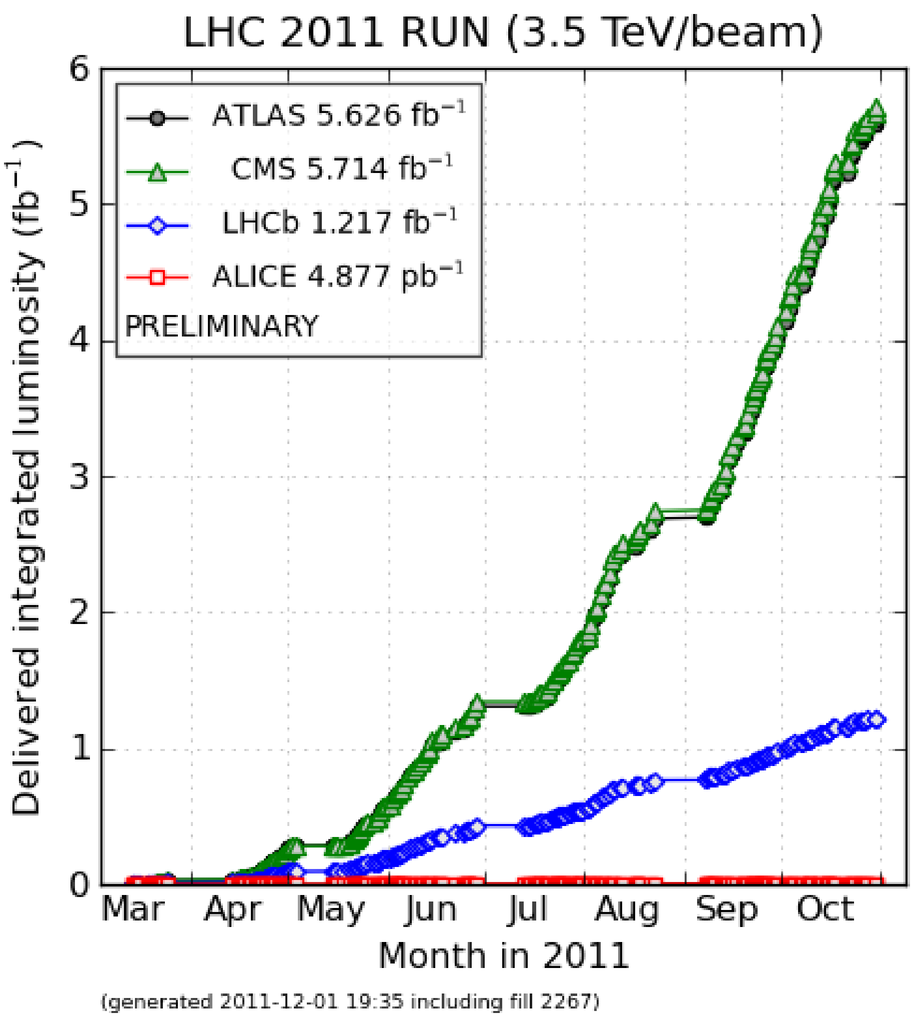
typ. $b\overline{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~1/4	$\sigma_{b\overline{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\overline{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\overline{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%)$, b – baryons(10%)	
B boost	small, βγ~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\overline{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\overline{B}^0$ mixing	coherent	incoherent→ flavour tagging dilution	

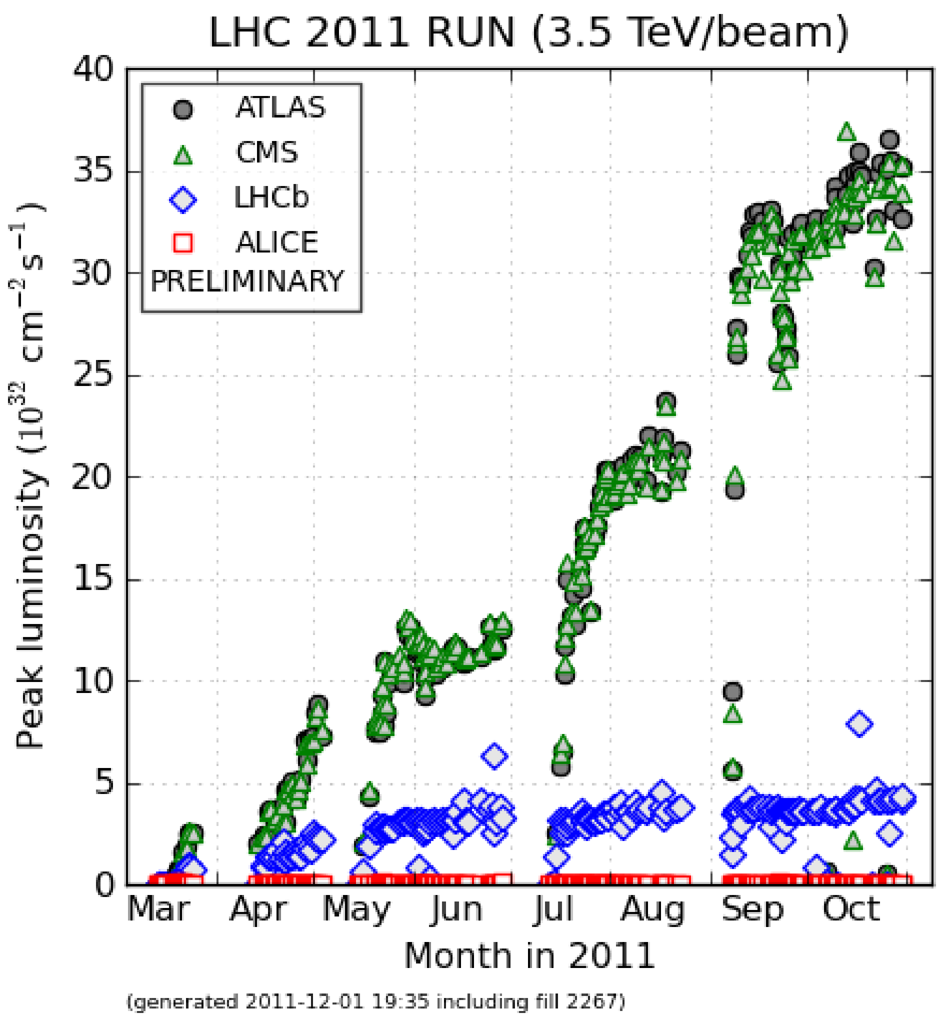
Main relative strengths:

- e^+e^- facilities allow to “reconstruct everything in the event”
  - excellent for modes with missing particles (e.g. ν) and inclusive measurements
- hadron colliders provide enormous cross-section and distinctive displaced vertex
  - high yields and low backgrounds in modes with high trigger efficiencies

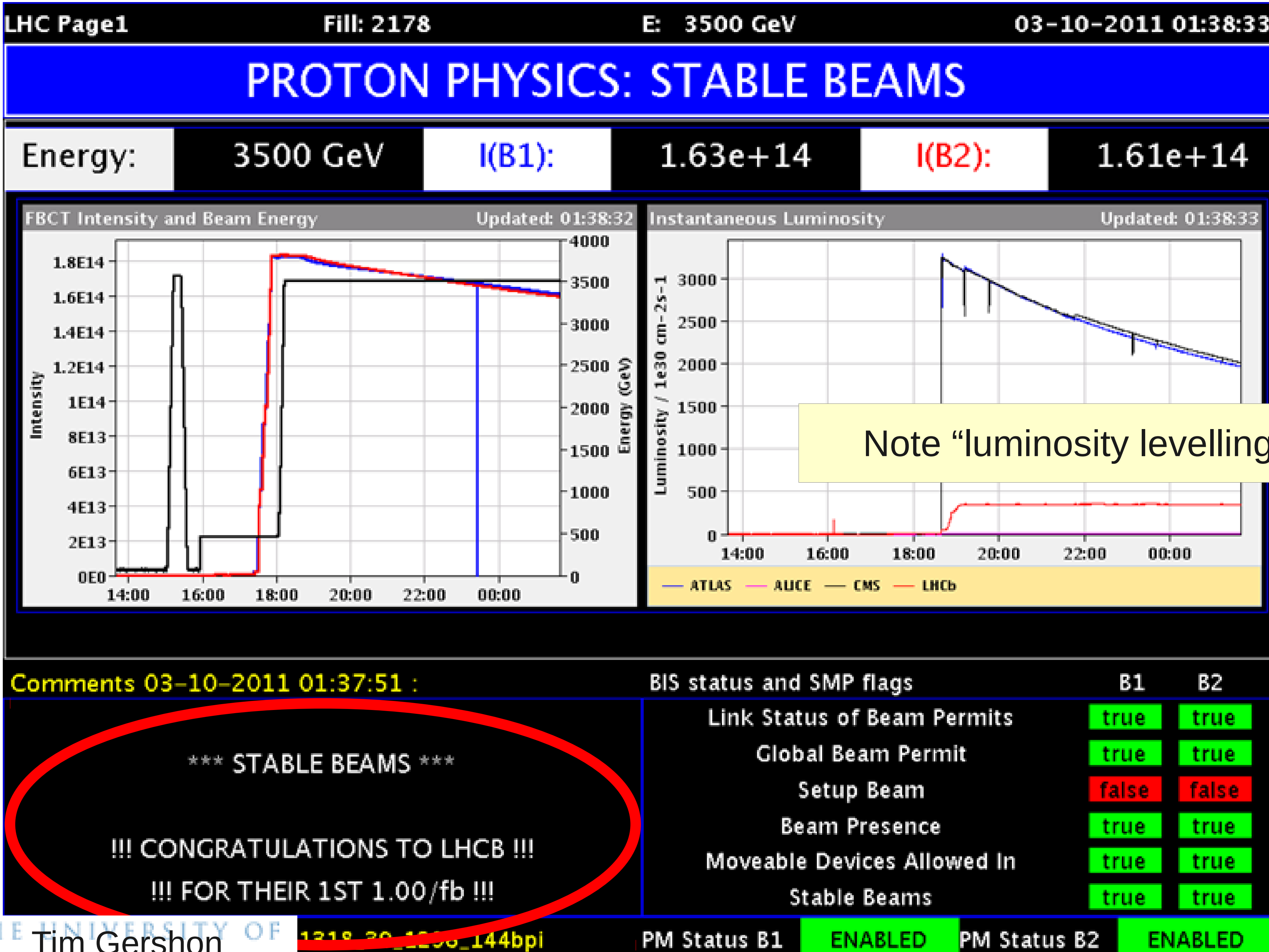
The LHC

LHC performance 2011



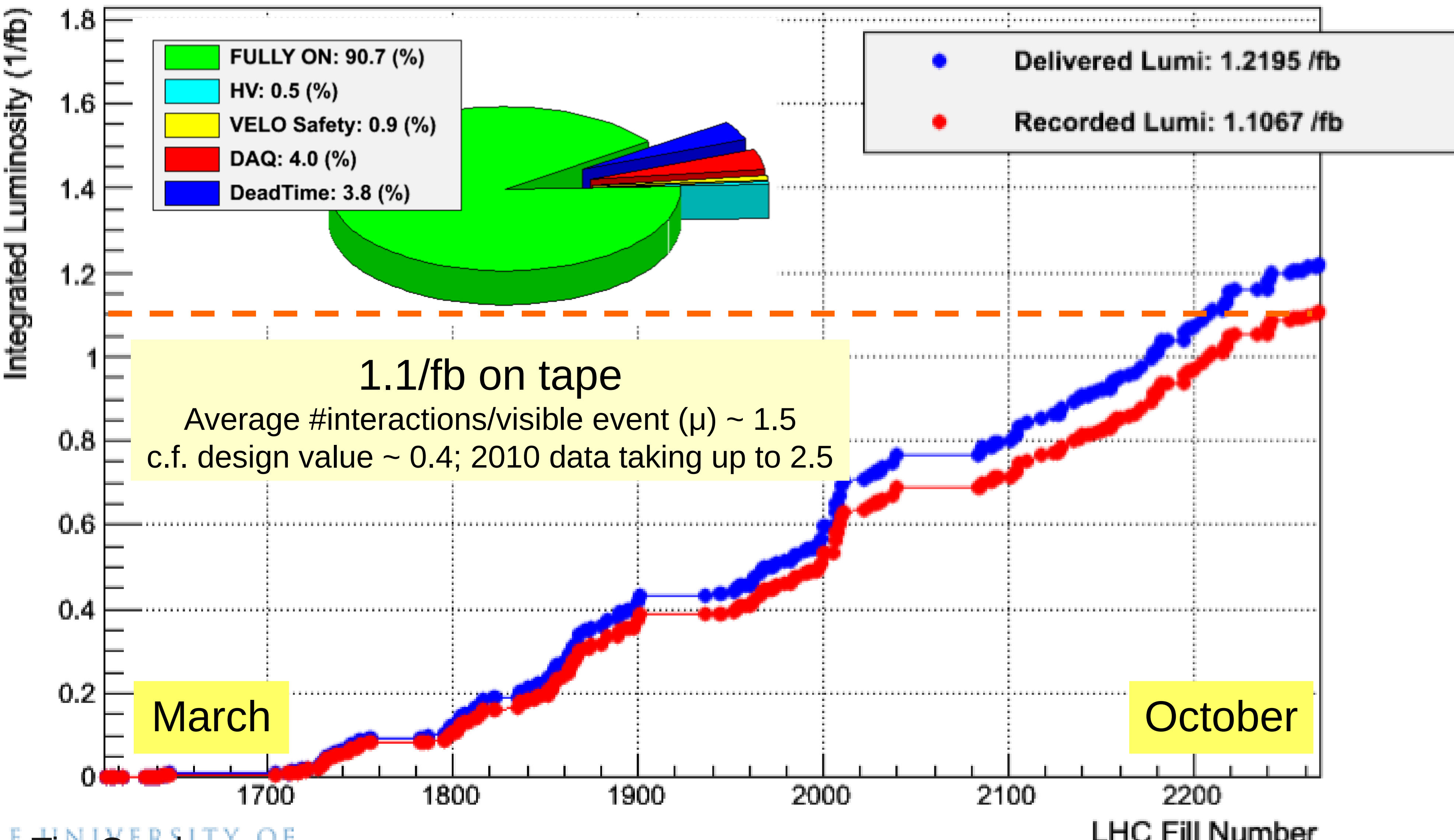


LHCb design luminosity: 2 10^{32}/cm^2/s



Note “luminosity levelling”

2011 data taking



Data taking efficiency close to 91 %

What does $\int L\,dt$ = 1/fb mean?

- Measured cross-section, in LHCb acceptance

$$\sigma(pp \to b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

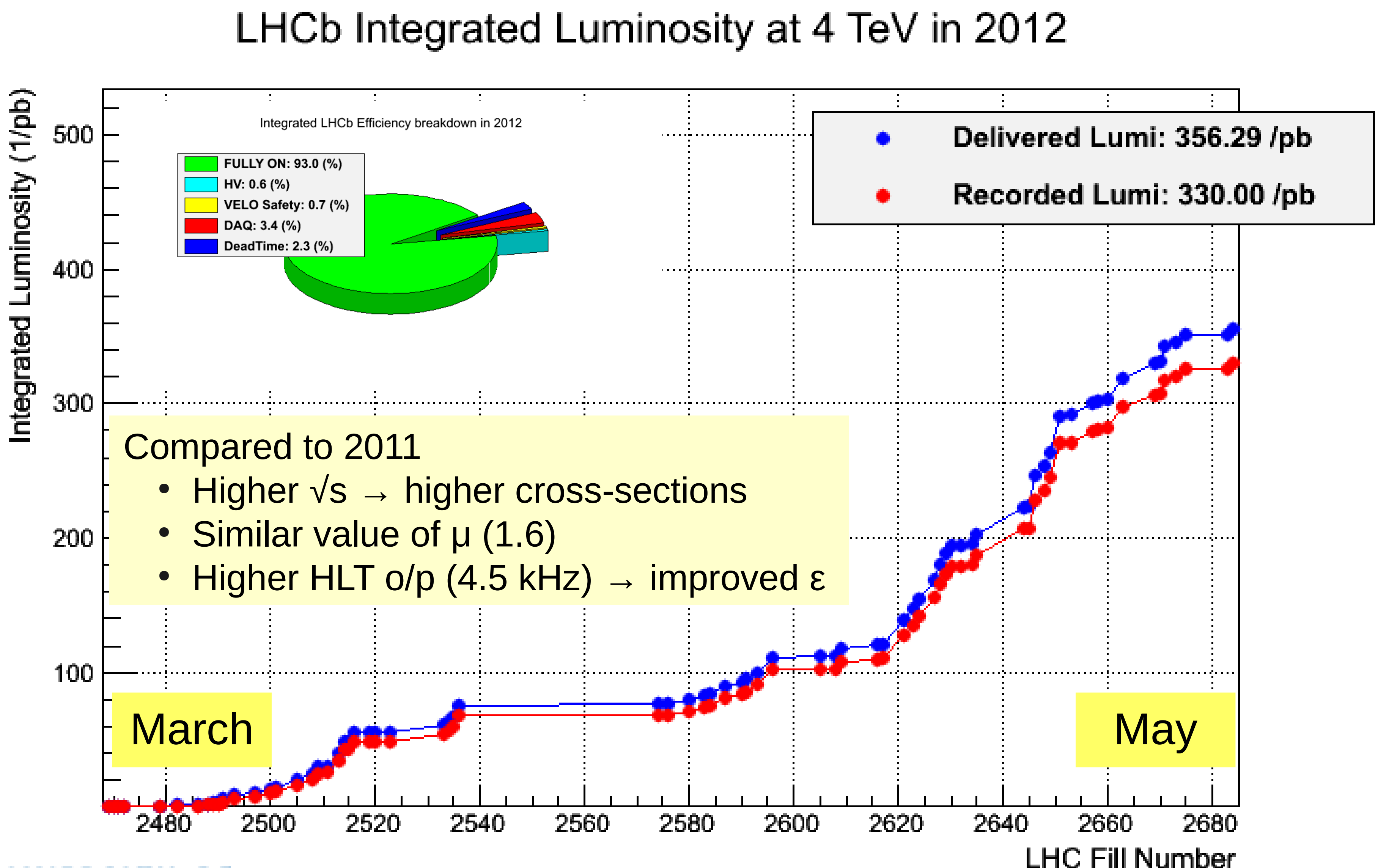
- Compare to combined data sample of e^+e^- "B factories" BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \to c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

2012 data taking (so far)



Compared to 2011
- Higher √s → higher cross-sections
- Similar value of μ (1.6)
- Higher HLT o/p (4.5 kHz) → improved ε

Target of 1.5/fb recorded in 2012

The all important trigger

Challenge is

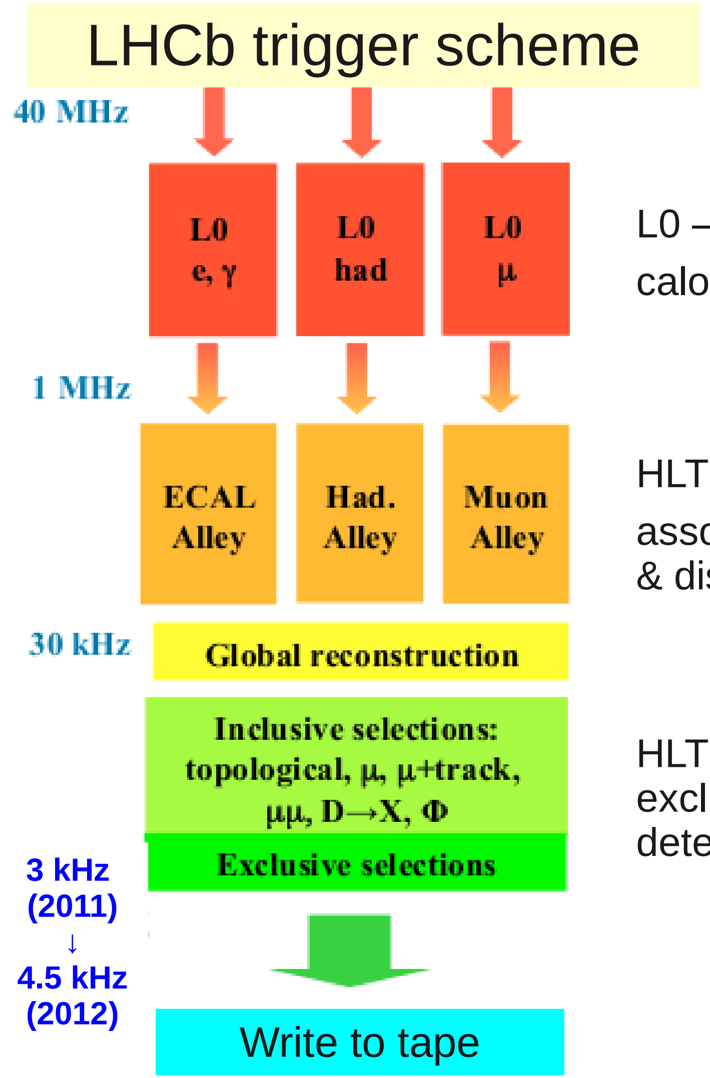
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



L0 – high p_T signals in calorimeters & muon chambers

HLT1 – find high p_T tracks; associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

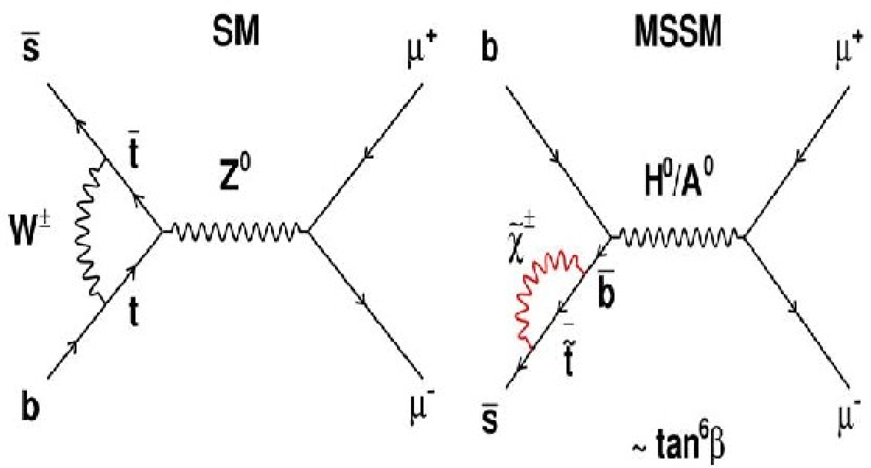
Selected highlights of results so far
Rare Decays

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

Killer app. for new physics discovery

Very rare in Standard Model due to
- absence of tree-level FCNC
- helicity suppression
- CKM suppression

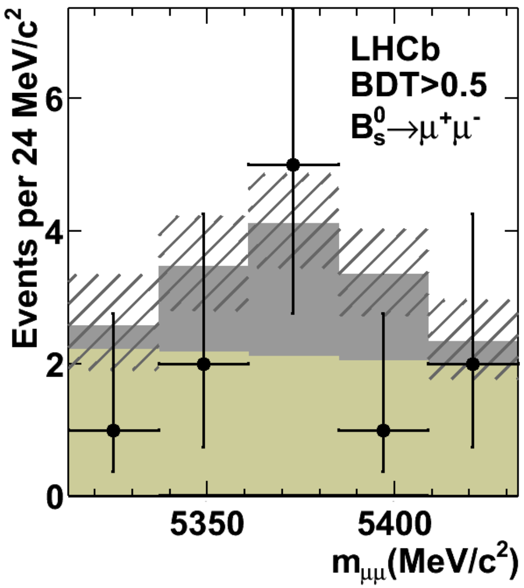
… all features which are not necessarily reproduced in extended models

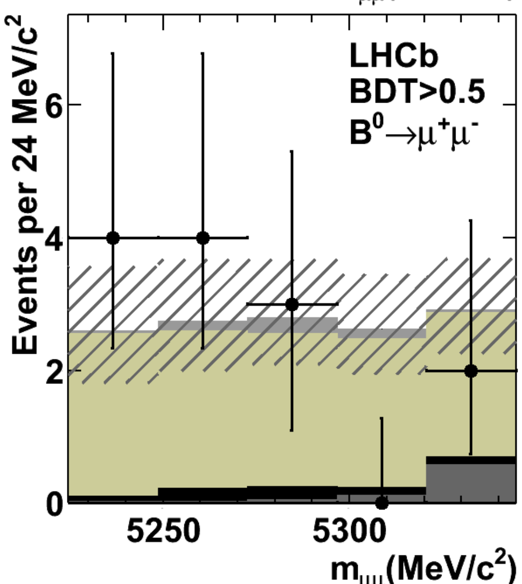


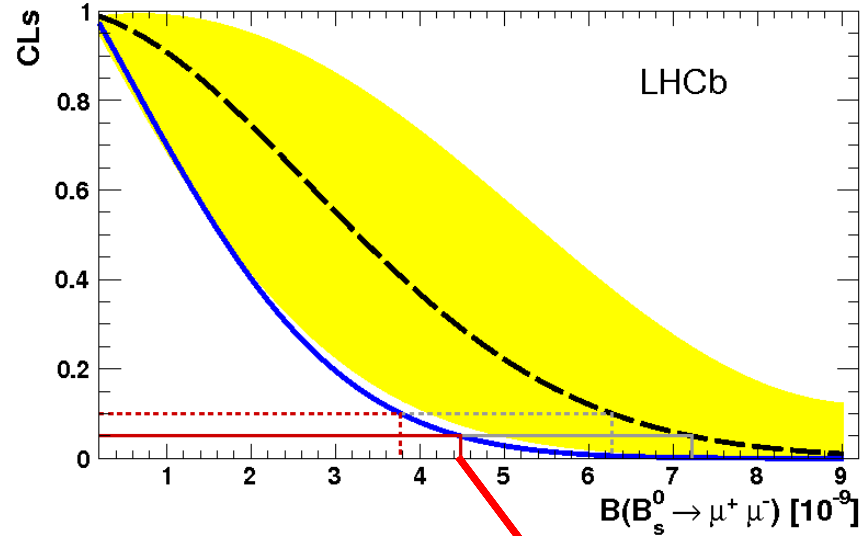
$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-8} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

Latest results on $B_s \to \mu^+\mu^-$

LHCb (1/fb) arXiv:1203.4493







Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

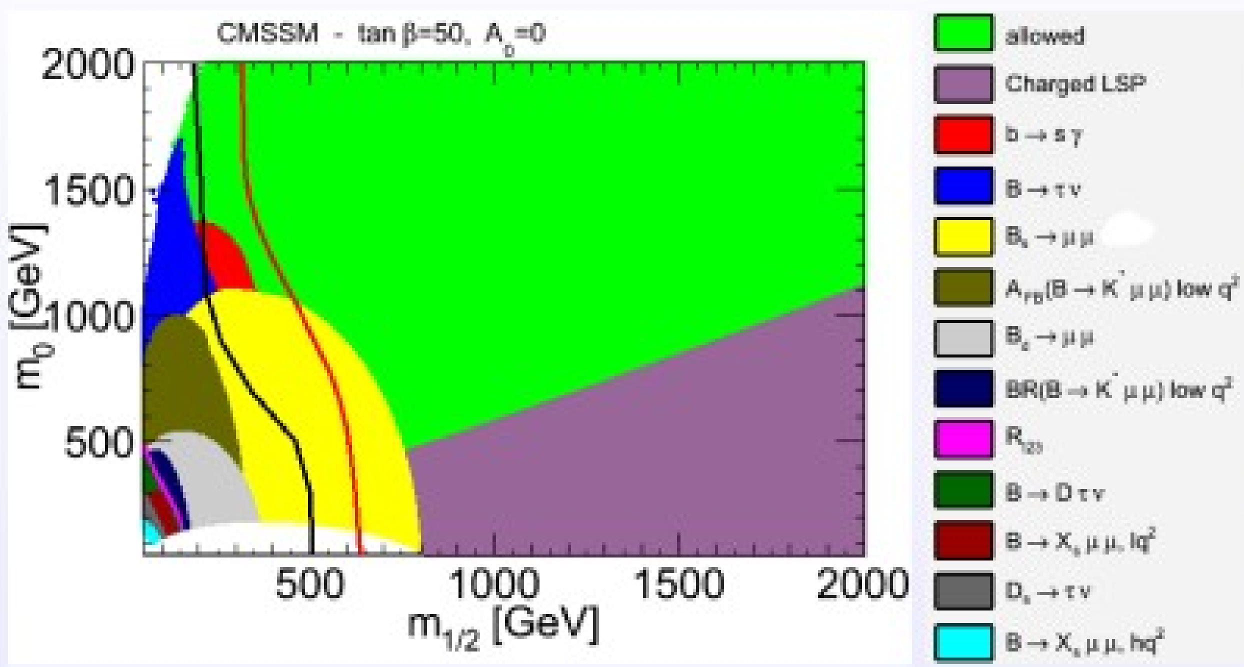
Standard Model expectation, e.g. $(3.2 \pm 0.2) \times 10^{-9}$
Buras, arXiv:1012.1447

N.B. Should be corrected up by 9% since time-integrated branching fraction is measured (arXiv:1204.1737)

Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2×10^{-9} and 125"



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

… before ...

Superiso v3.2+

N. Mahmoudi at Moriond

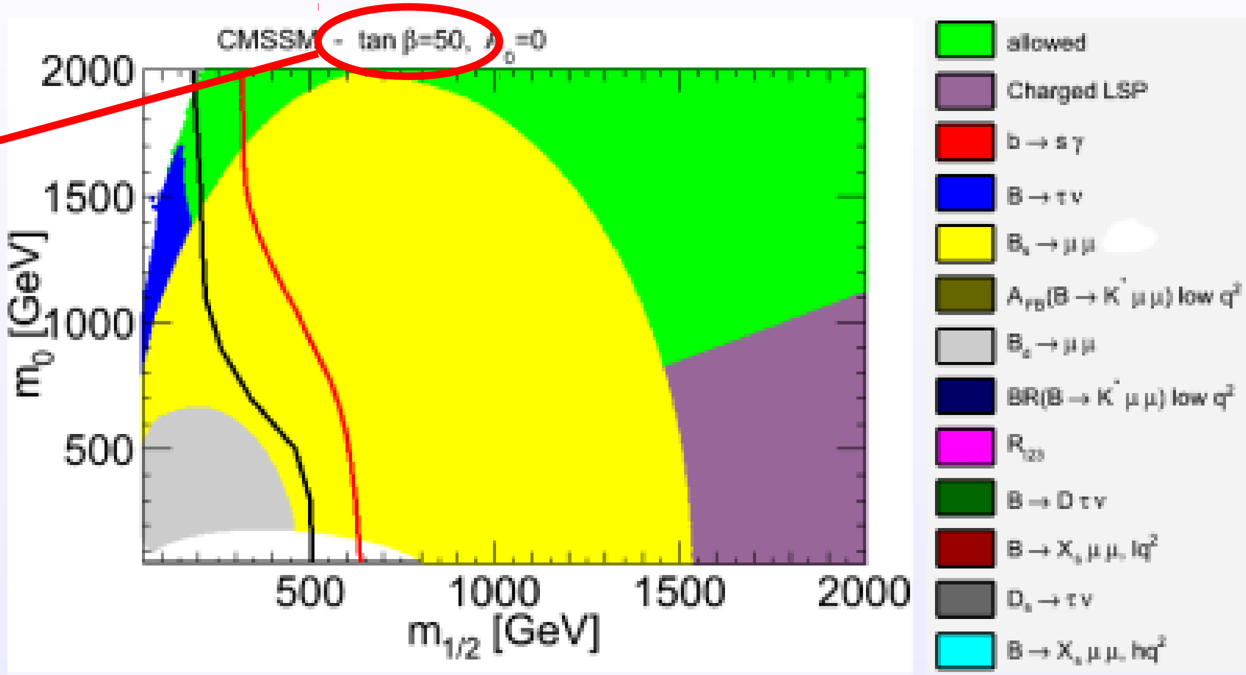
Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2 x 10^{-9} and 125"

"the wow plot"

Simple TeV-scale models with large tan β ~ ruled out



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

New LHCb limits for $BR(B_s \to \mu^+\mu^-)$ and $BR(B_d \to \mu^+\mu^-)$

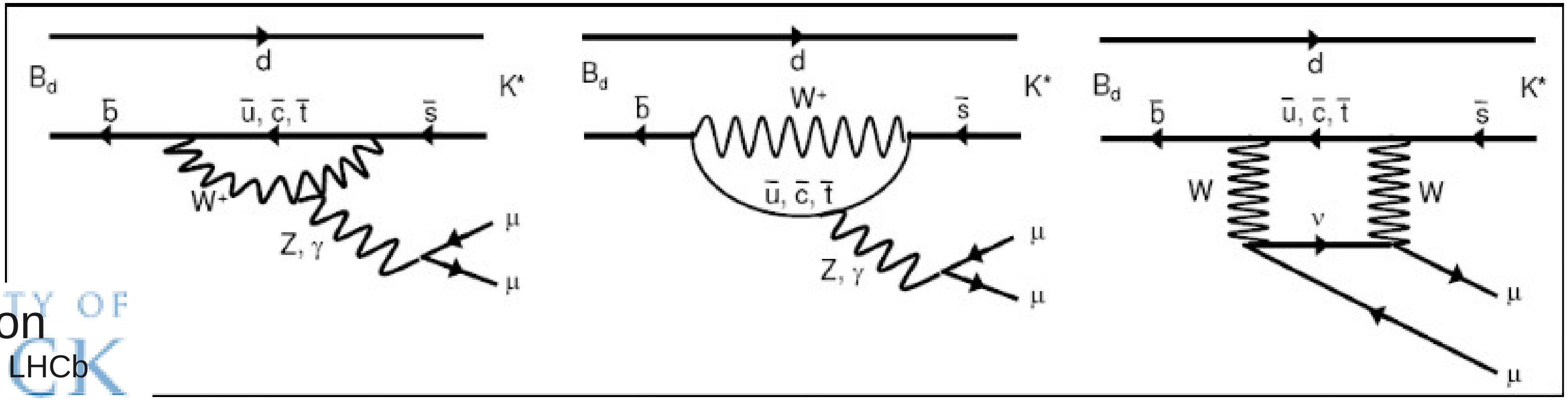
… after …

Superiso v3.2+

N. Mahmoudi at Moriond

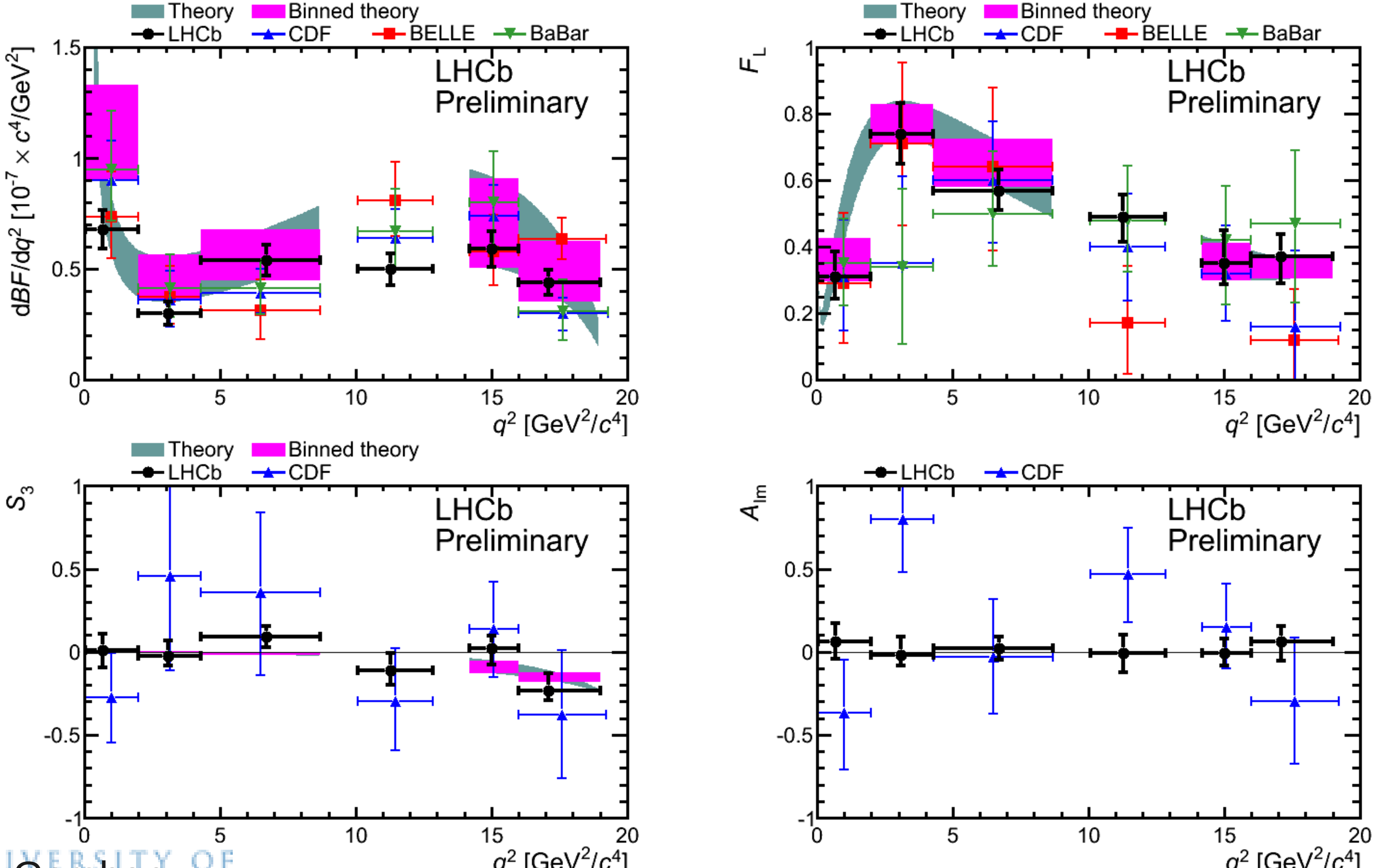
$B \to K^* \mu^+ \mu^-$

- $b \to s l^+ l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is $B_d \to K^{*0} \mu^+ \mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)



Differential branching fraction and angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb-CONF-2012-008



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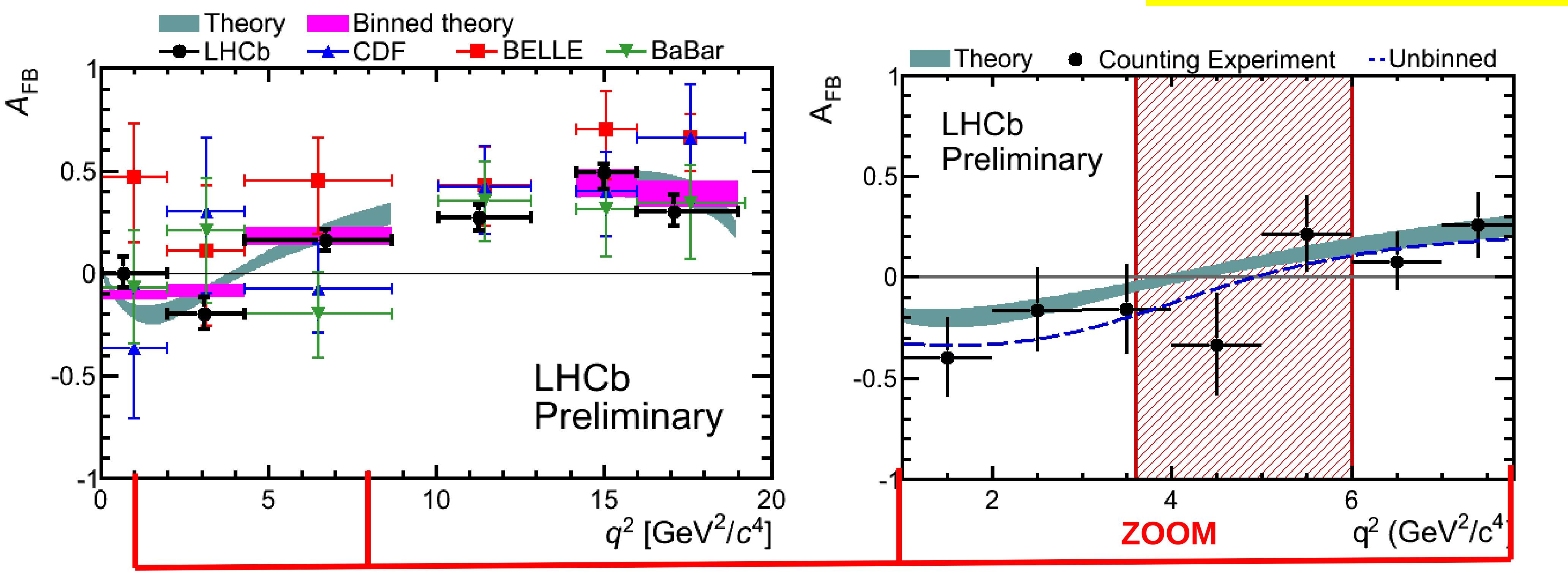


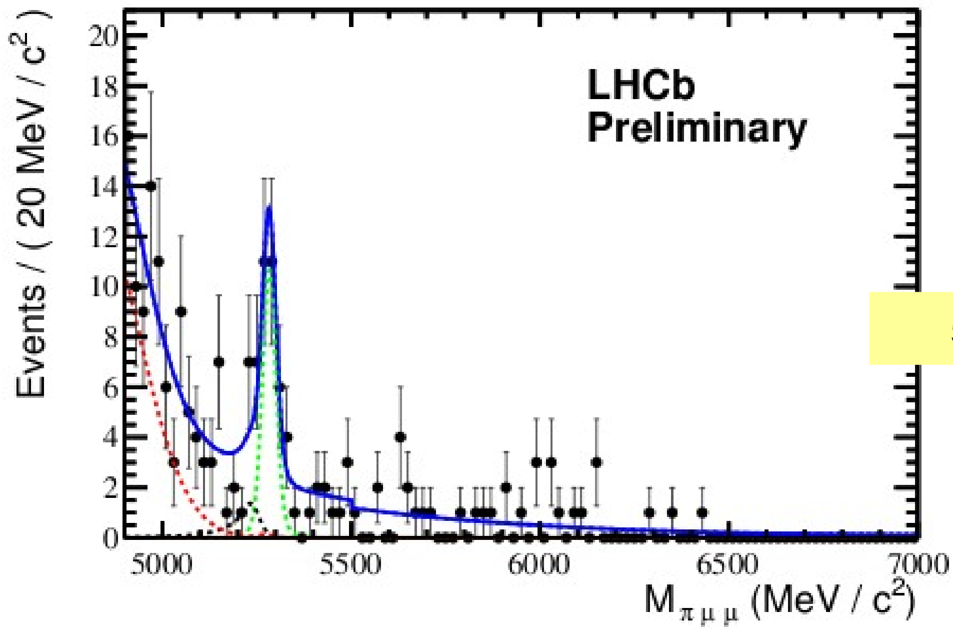
First measurement of the zero-crossing point of the forward-backward asymmetry

$q^2_0 = (4.9^{+1.1}_{-1.3})$ GeV^2

(SM predictions in the range 4.0 – 4.3 GeV^2)

First observation of $B^+ \to \pi^+\mu^+\mu^-$

LHCb-CONF-2012-006
1/fb



5.2σ

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6\ (\text{stat}) \pm 0.2\ (\text{syst})) \times 10^{-8}.$$

Previous best < 6.9 10^{-8}
(Belle, 90% CL, full dataset)
Rarest B decay observed to date!

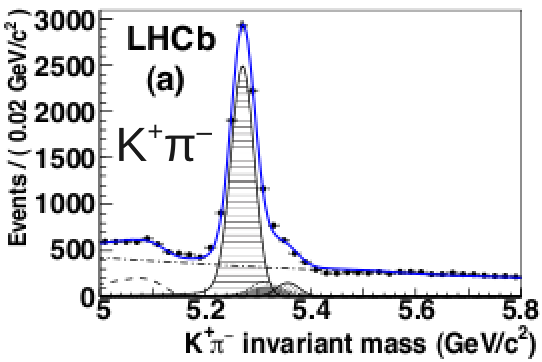
Selected highlights of results so far
CP violation

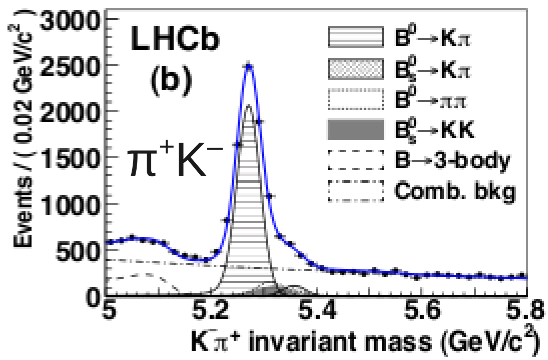
Charmless two-body decays

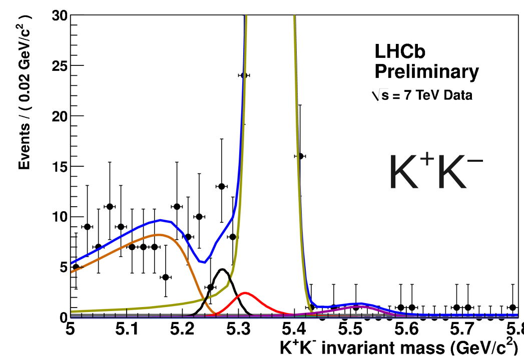
- Excellent channel to profit from displaced vertex trigger
- Particle ID extremely important

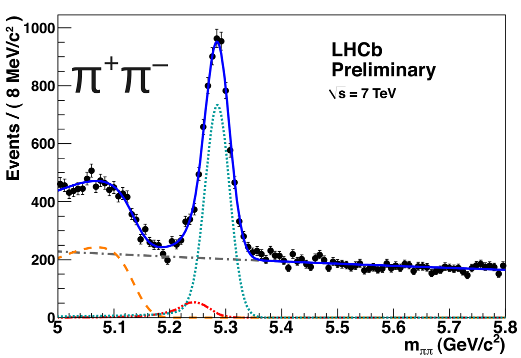
LHCb arXiv:1202.6251

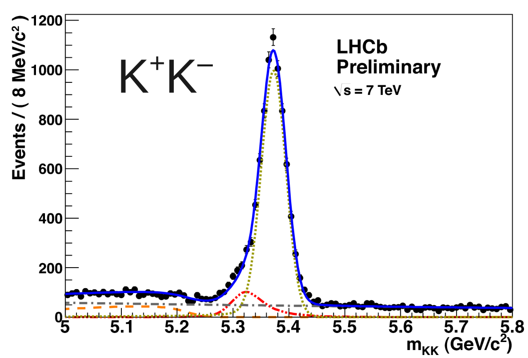
also now see suppressed decays

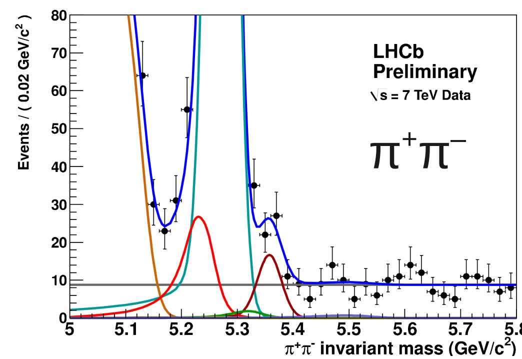










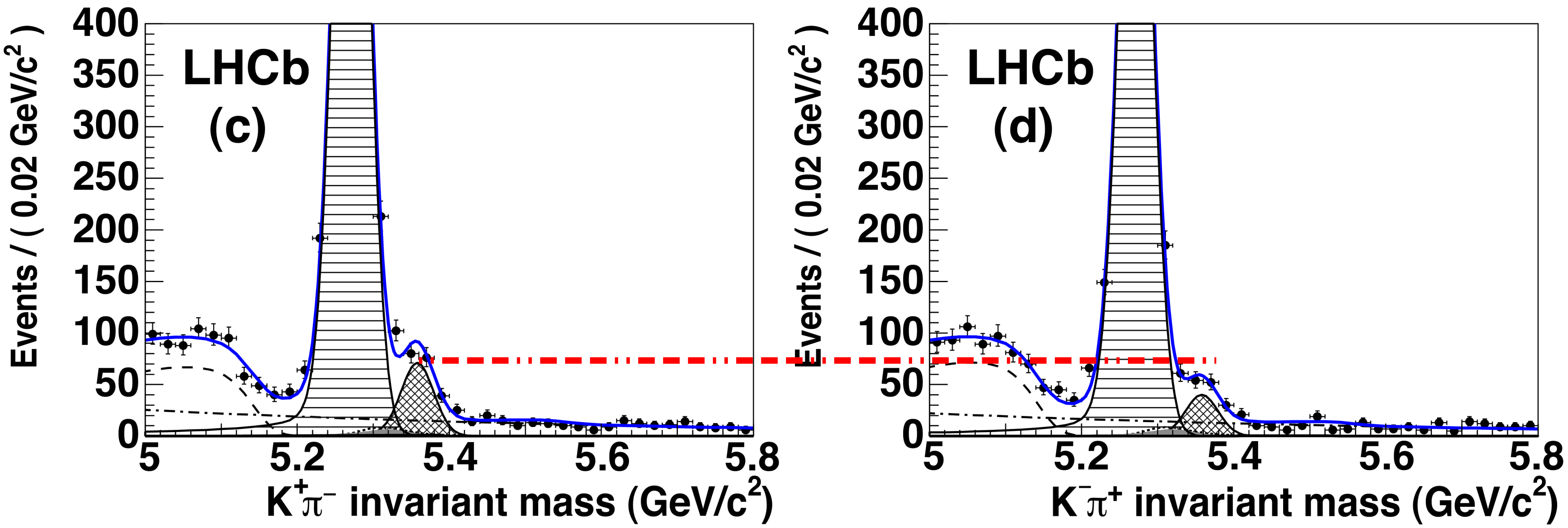


LHCb-CONF-2012-007

LHCb-CONF-2011-042

First evidence for CP violation in the B_s sector

LHCb arXiv:1202.6251



$A_{CP}(B_s \to K\pi) = 0.27 \pm 0.08\ (\text{stat}) \pm 0.02\ (\text{syst})$

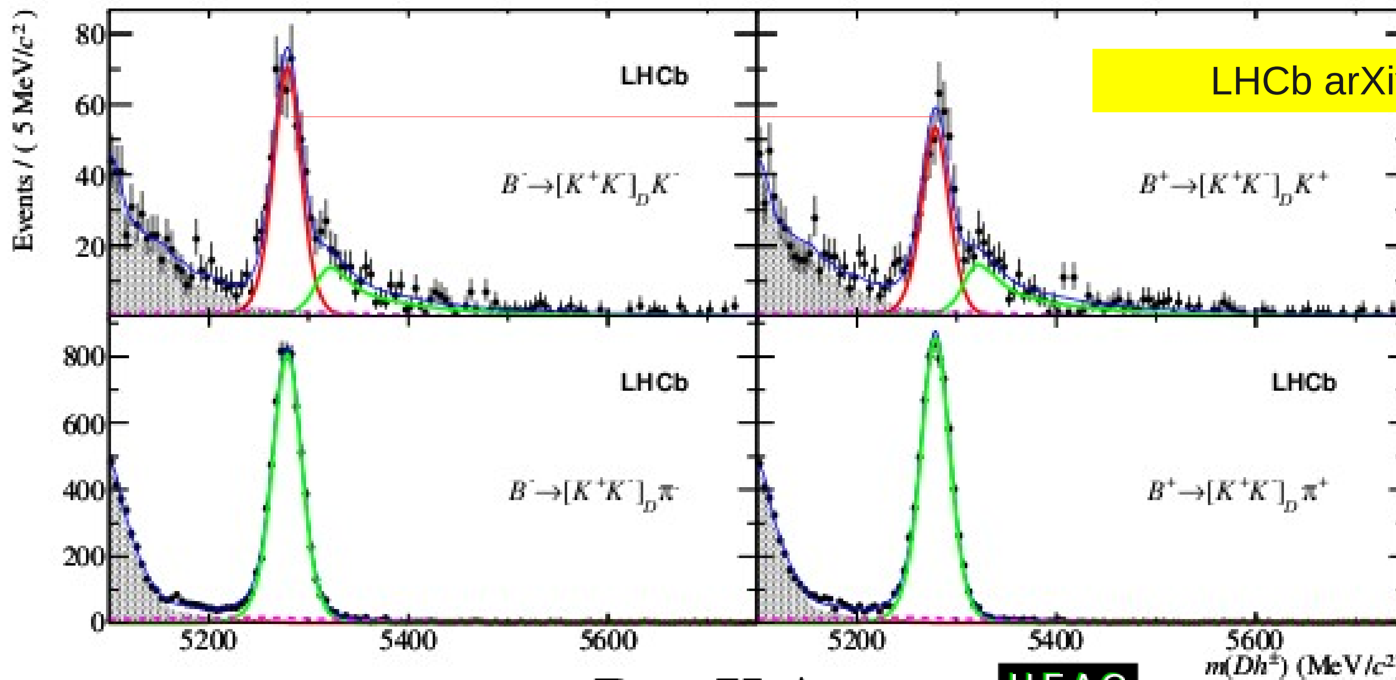
[NB. Also $A_{CP}(B_d \to K\pi) = -0.088 \pm 0.011\ (\text{stat}) \pm 0.008\ (\text{syst})$]

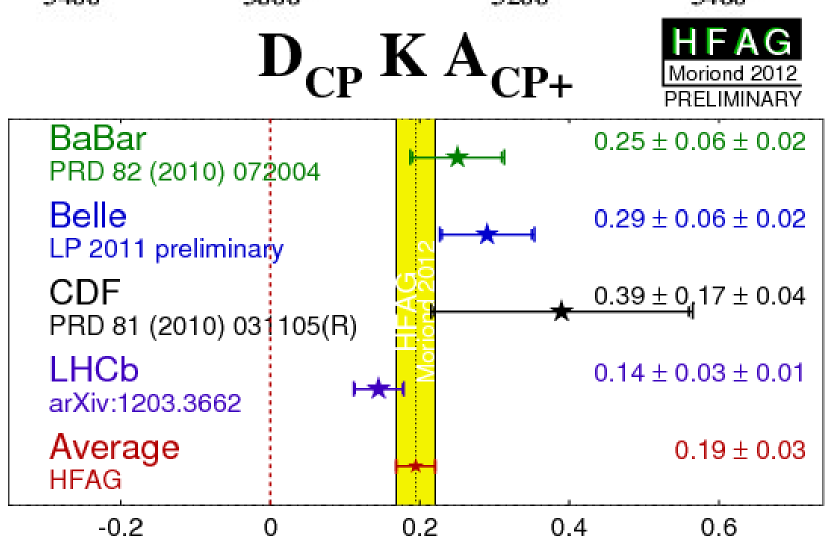
consistent with, and more precise than, previous measurements

B → DK decays
"GLW" method (D → CP eigenstates)

Evidence for direct CP violation (γ≠0)

LHCb arXiv:1203.3662



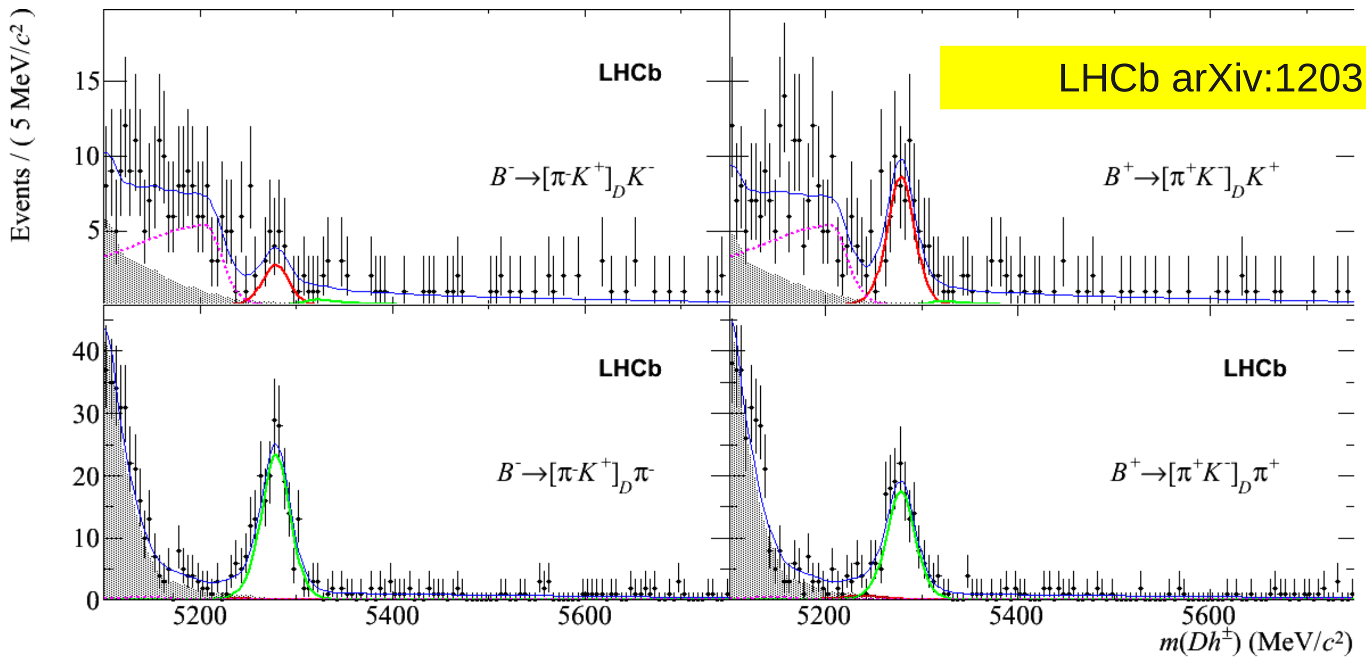


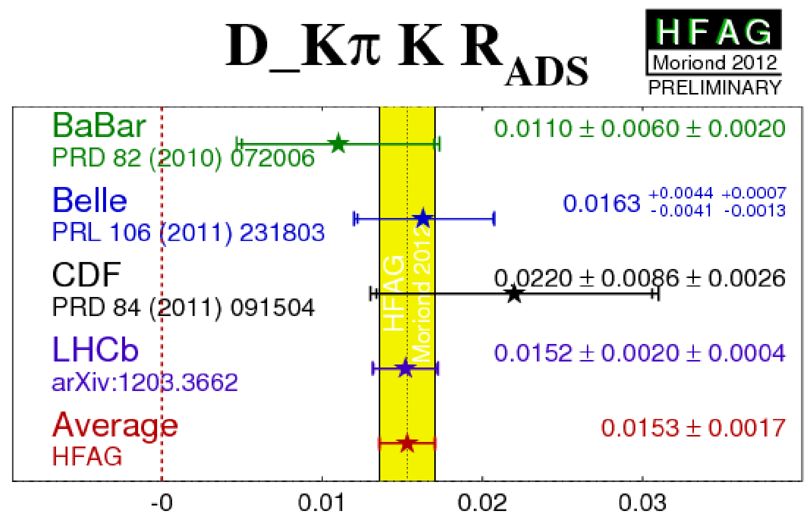
B → DK decays give theoretically clean way to measure CKM phase

B → DK decays
"ADS" method (suppressed D decays)

Observation of suppressed mode
Evidence for direct CP violation (γ≠0)

LHCb arXiv:1203.3662





B → DK decays give theoretically clean way to measure CKM phase

Evidence for CP violation in $D \to h^+h^-$ decays

LHCb PRL 108 (2012) 111602

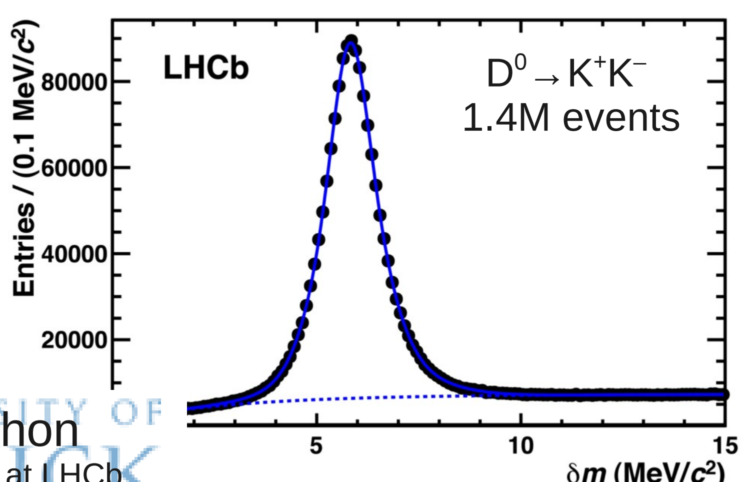
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \to f$, where D meson flavour is tagged by $D^{*+} \to D^0\pi^+$ decay

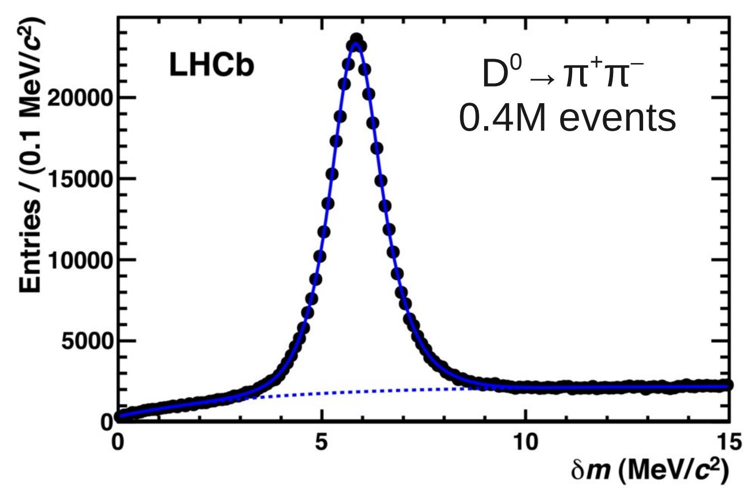
$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}^+) + A_{\rm P}(D^{*+}).$$

final state detection asymmetry vanishes for CP eigenstate

Cancel asymmetries by taking difference of raw asymmetries in two different final states (Since A_D and A_P depend on kinematics, must bin or reweight to ensure cancellation)

$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+).$$



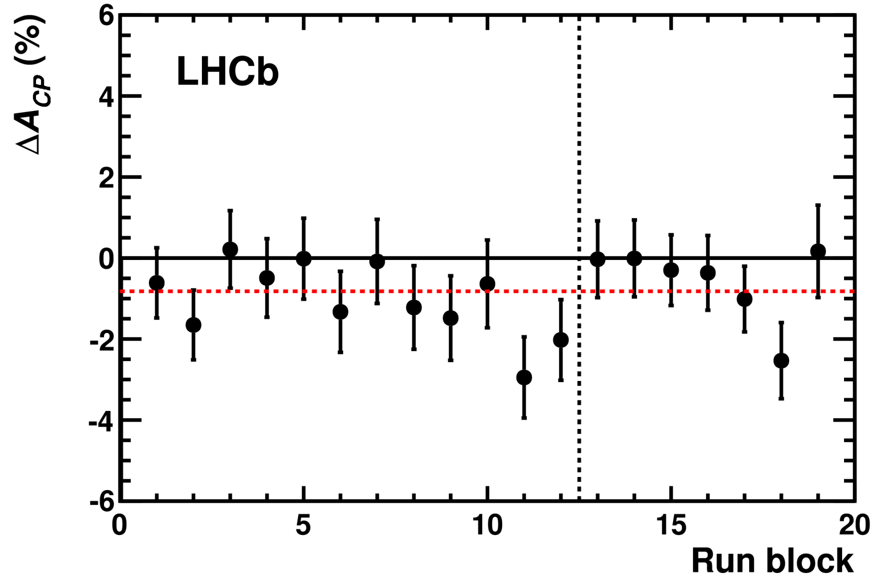


Evidence for CP violation in D → h^+h^- decays

LHCb PRL 108 (2012) 111602

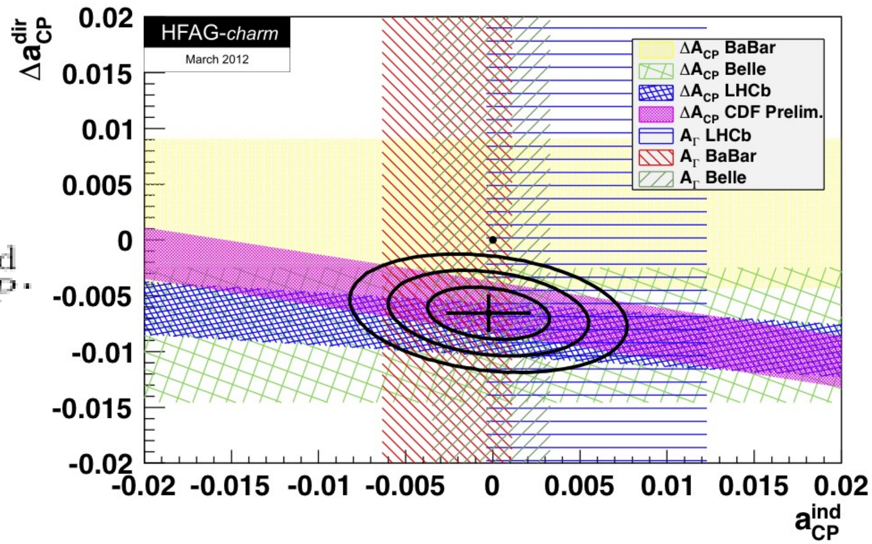
Result, based on 0.62/fb of 2011 data
ΔA_{CP} = [−0.82 ± 0.21(stat.) ± 0.11(syst.)]%

Naively expected to be much smaller in the Standard Model

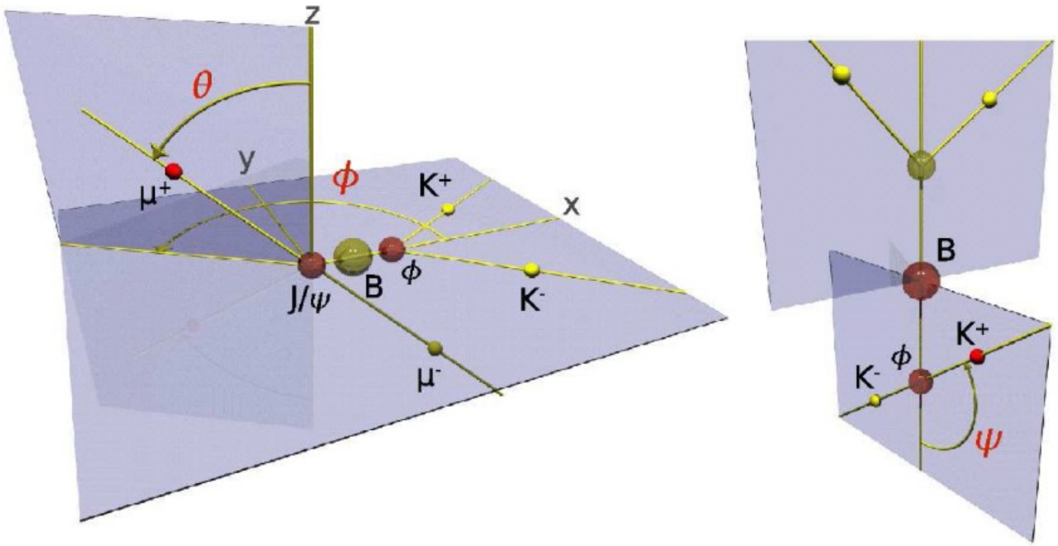


ΔA_{CP} related mainly to direct CP violation
(contribution from indirect CPV suppressed by difference in mean decay time)

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$= \left[a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind}.$$



$\Phi_s = -2\beta_s$ ($B_s \rightarrow J/\psi\varphi$)



- VV final state

  three helicity amplitudes

  → mixture of CP-even and CP-odd

  disentangled using angular & time-dependent distributions

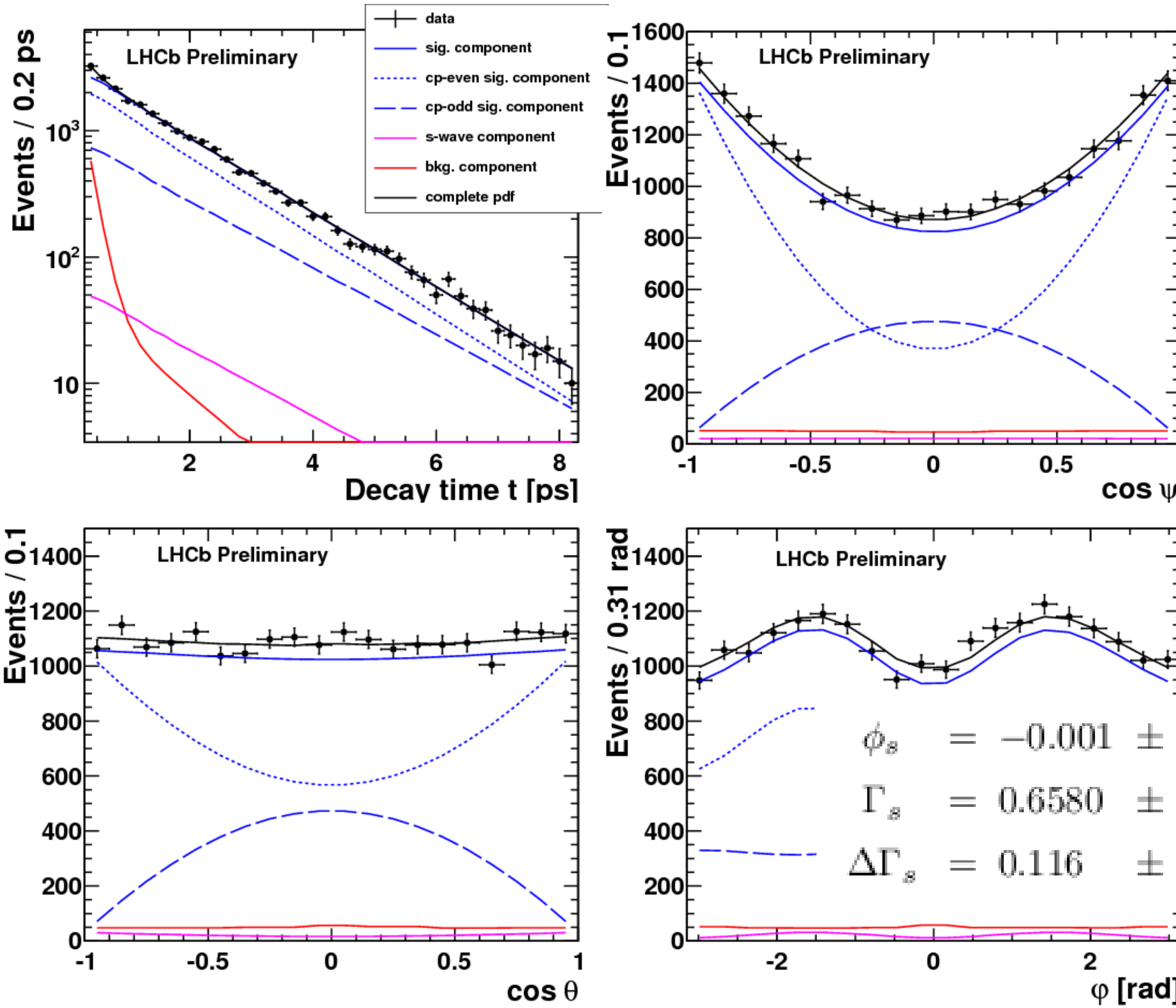
  → additional sensitivity

  many correlated variables

  → complicated analysis

- LHCb also uses $B_s \rightarrow J/\psi f_0$ ($f_0 \rightarrow \pi^+\pi^-$)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from $J/\psi\varphi$ analysis (Γ_s, $\Delta\Gamma_s$)

CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$



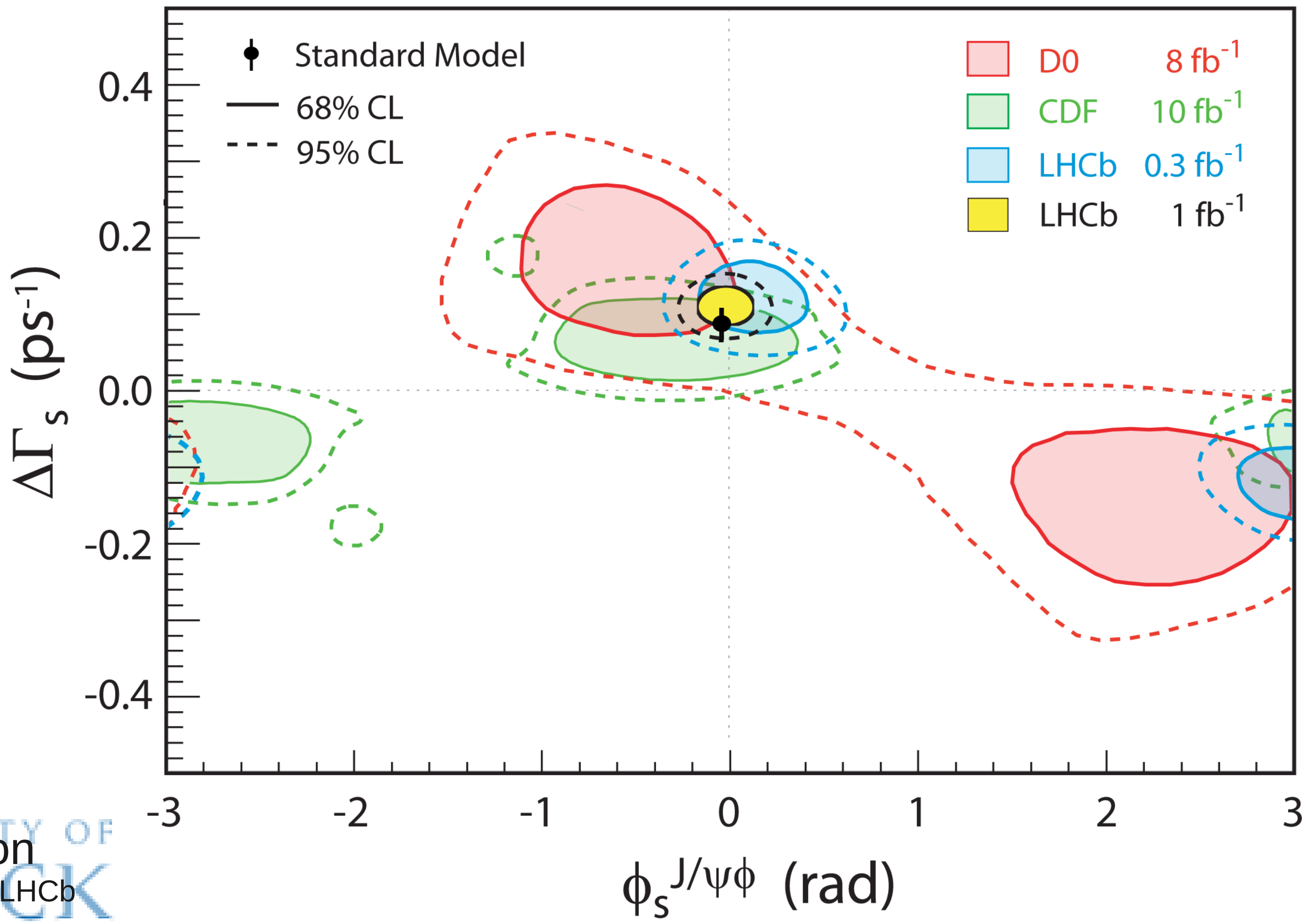
LHCb-PAPER-2011-028
0.37/fb
LHCb-CONF-2012-002
LHCb-PAPER-2012-005
LHCb-PAPER-2012-006
All 1/fb

LHCb-CONF-2012-002

$$\phi_s = -0.001 \pm 0.101 \;(\text{stat}) \pm 0.027 \;(\text{syst})\;\text{rad},$$
$$\Gamma_s = 0.6580 \pm 0.0054 \;(\text{stat}) \pm 0.0066 \;(\text{syst})\;\text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.116 \pm 0.018 \;(\text{stat}) \pm 0.006 \;(\text{syst})\;\text{ps}^{-1}.$$

CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

- Ambiguity resolution ↔ LHCb-PAPER-2011-028
- Tagged time-dependent angular analysis of $J/\psi\phi$ with 1/fb ↔ LHCb-CONF-2012-002
- Amplitude analysis to determine CP content of $J/\psi\pi\pi$ ↔ LHCb-PAPER-2012-005
- Tagged time-dependent analysis of $J/\psi\pi\pi$ ↔ LHCb-PAPER-2012-006



The LHCb upgrade

LHCb upgrade

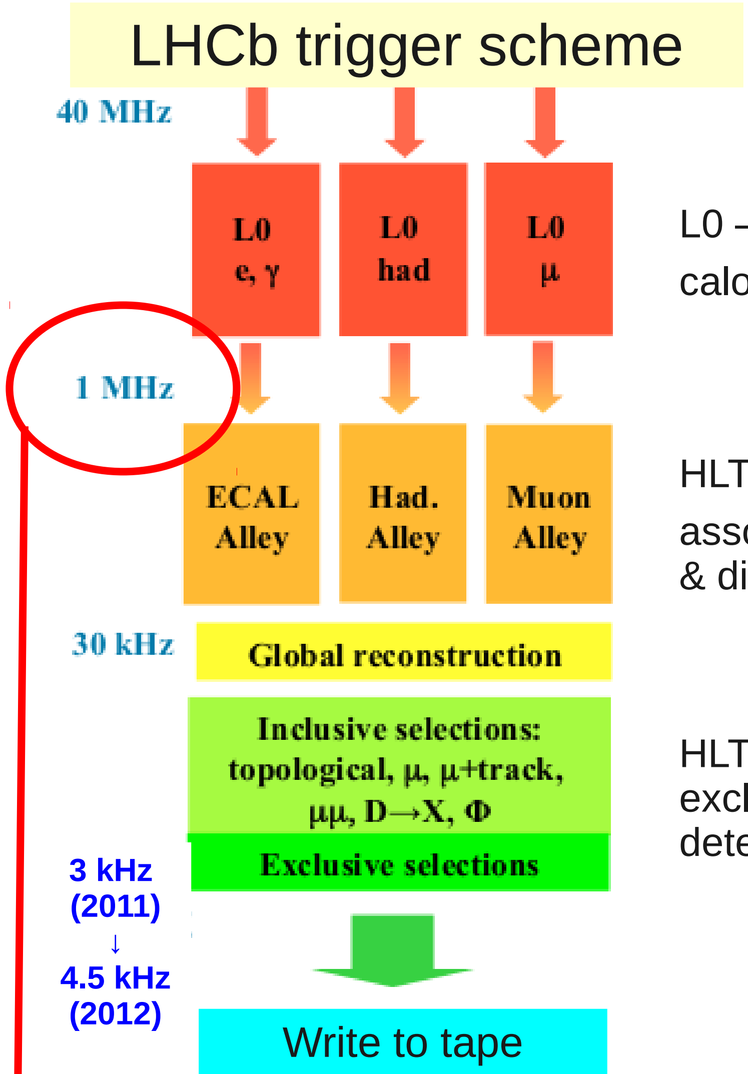
- To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  - full readout & trigger at 40 MHz to enable high L running
  - "high L" = $10^{33}/cm^2/s$ (so independent of machine upgrade)
  - planned for 2018 shutdown
- With full software trigger, LHCb upgrade will be a general purpose detector in the forward region
  - physics case extends far beyond flavour physics
  - (e.g. search for long-lived exotic particles)

The all important trigger

Challenge is
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds
- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles
- high p_T signals (muons)
- displaced vertices



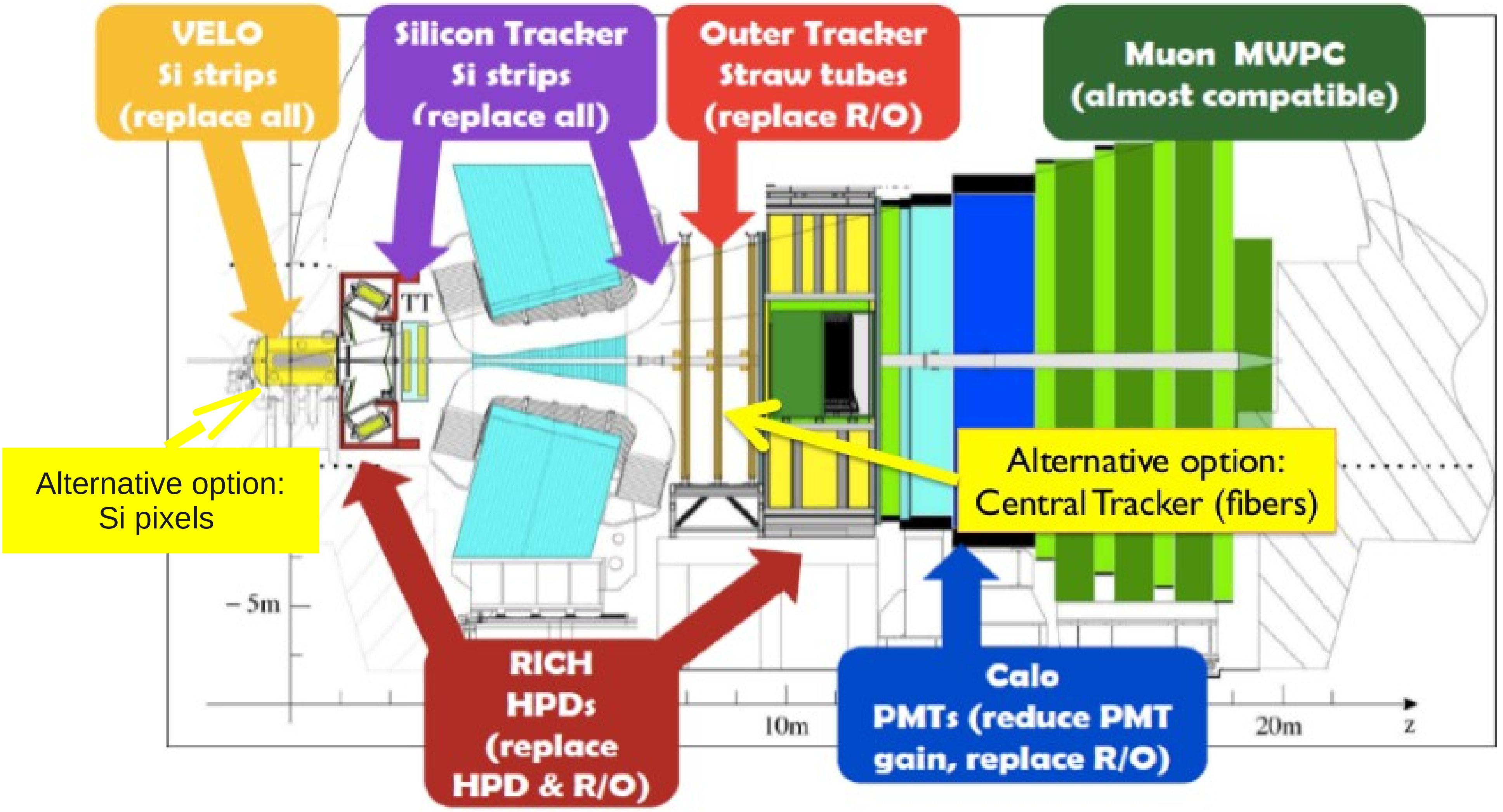
L0 – high p_T signals in calorimeters & muon chambers

HLT1 – find high p_T tracks; associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

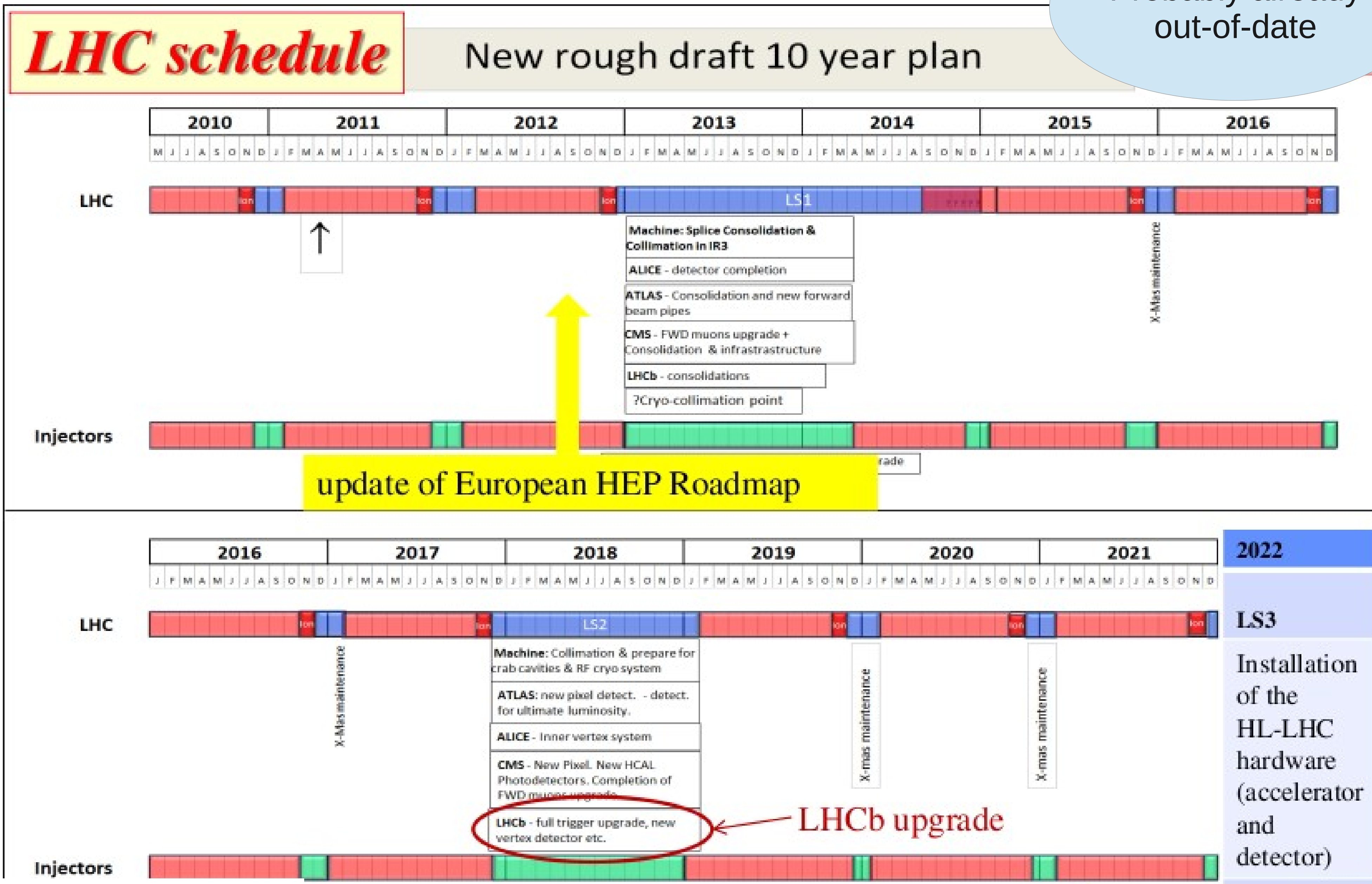
Limitation is at 1 MHz L0 o/p

LHCb detector upgrade



Timescale

Probably already out-of-date



Upgrade – expected sensitivities

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s$ ($B^0_s \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B^0_s \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\mathrm{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B^0_s \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K^0_S$)	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

- sample sizes in most exclusive B and D final states far larger than those collected elsewhere
- no serious competition in study of B_s decays and CP violation

Steps towards the LHCb upgrade

- *March 2011, "Letter of Intent for the LHCb Upgrade" submitted to LHCC*
  → Endorsement of physics case. Review of proposed trigger concept (40 MHz)
- *June 2011, Positive peer review of trigger concept*
  → LHCC endorses the LOI, green light for TDR preparation
- *June 2012, Submission of "Framework TDR for the LHCb Upgrade" to LHCC*
  (intermediate document describing the plan, cost and resources needed for the upgrade)
- *September 2012, Approval of "Framework TDR" expected*
- *October 2012, Presentation of "Framework TDR" to RRB and to Funding Agencies*
  → Start of negotiations for signing the "Addenda to MoU for the LHCb Upgrade"
- *Fall 2013, Submission of LHCb subsystems TDRs to LHCC*

The "*Framework TDR*" will address the schedule, a first (reasonably accurate) evaluation of CORE costs and of interests of institutes
→ working document to the FA for R&D funding and for "cost envelopes" definition

The need for more precision

- “Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

Summary

- Concept of LHCb definitely proved
  - Dedicated experiment for heavy flavour physics (forward spectrometer) at a hadron collider
- Many world leading results already with 2011 data … and many more to come
  - Significant increase in available samples with 2012 data
- Standard Model still survives
  - Not a cause for depression! Now probing regions where “realistic” new physics effects might appear
- LHCb upgrade to be installed in 2018
  - Essential next step forward for flavour physics

BACK UP

What is flavour physics?

Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

Flavour in particle physics

Flavour quantum numbers:

- Baryon number: B
- Lepton number: L
- Strangeness: S
- Charm: C
- Bottomness: B'
- Topness: T
- Isospin: **I** or I_3
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations:

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

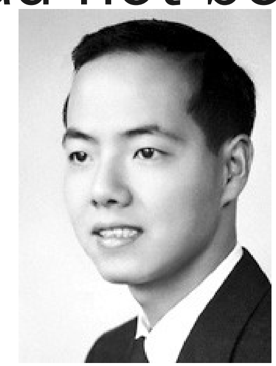
- CKM matrix
- PMNS matrix
- Flavour complementarity

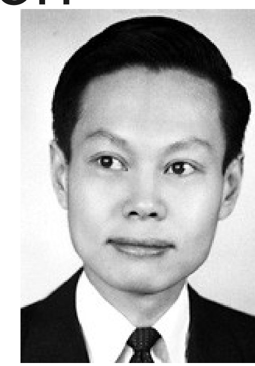
"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887

Discovery of parity violation

- In 1956, T.D.Lee and C.N.Yang (Nobel prize 1957) pointed out that parity conservation had not been tested in the weak interaction





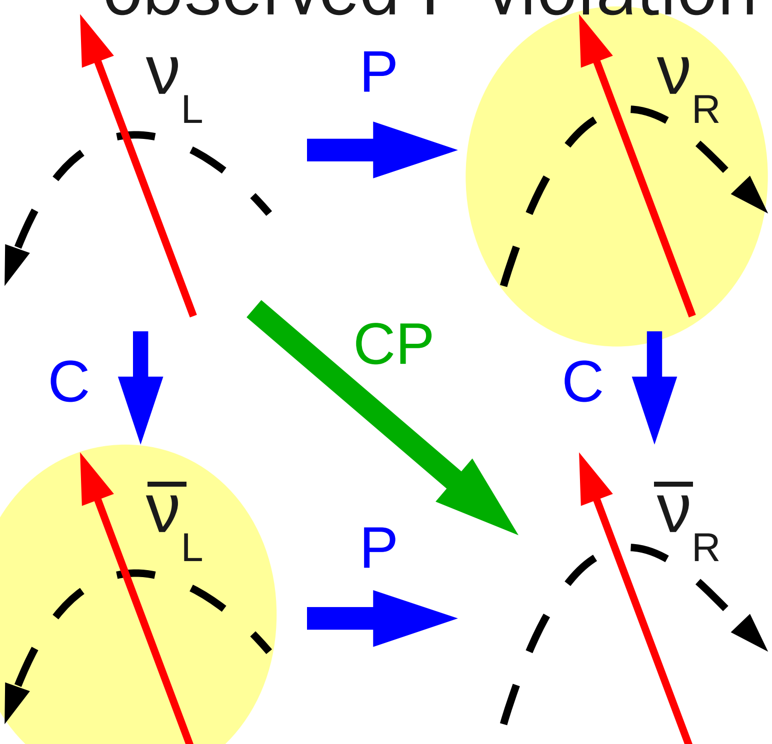
- C.S.Wu *et al.* were the first to make such a test, using β decays of ^{60}Co
  - Other immediate confirmations:

    (π → μ → e) decay (L.M.Lederman *et al.*),

    (K → μ → e) decay, Λ^0 decay, ...

P & C violation but CP conservation

- L.Landau proposed CP as the true matter-antimatter symmetry
  - observed P violation is also C violation



Only left-handed neutrinos and right-handed antineutrinos take part in weak interactions

ν_R and $\bar{\nu}_L$ are unphysical

C violation vs CP violation

- C violation allows one to say

"Nuclei are orbited by electrons, which are emitted together with right-handed antineutrinos in beta decay"

- This does not provide an absolute distinction between matter and antimatter
- CP violation allows one to say

"Nuclei are orbited by electrons, which are emitted less often in semileptonic decays of the long-lived neutral kaon"

Unitarity Triangles

PLB 680 (2009) 328

Build matrix of phases between pairs of CKM matrix elements

Φ_{ij} = phase between remaining elements when row i and column j removed

unitarity implies sum of phases in any row or column = 180° → 6 unitarity triangles

$$\Phi = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} \Phi_{ud} & \Phi_{us} & \Phi_{ub} \\ \Phi_{cd} & \Phi_{cs} & \Phi_{cb} \\ \Phi_{td} & \Phi_{ts} & \Phi_{tb} \end{pmatrix} \end{array} \simeq \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1^o & 22^o & 157^o \\ 67^o & 90^o & 23^o \\ 112^o & 68^o & 0^o \end{pmatrix} \end{array}$$

β_s (1°)

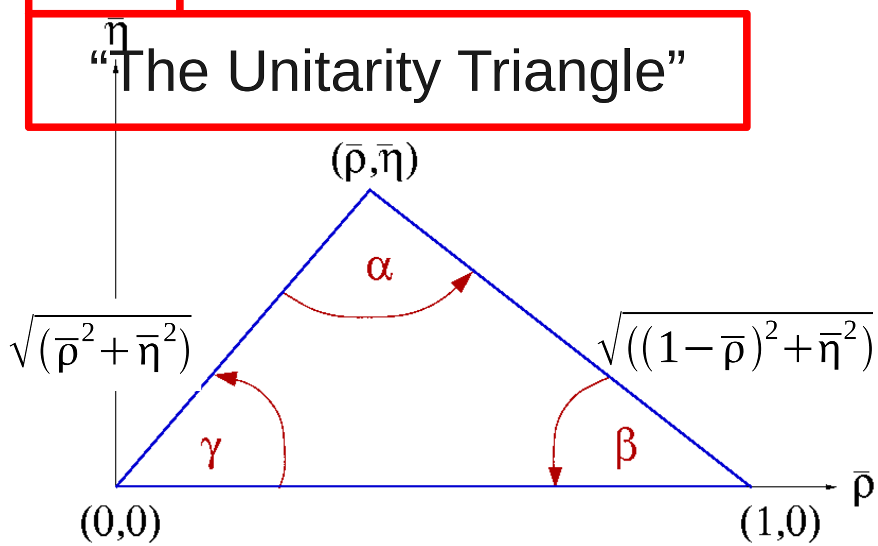
$\beta \equiv \varphi_1$ (22°)

$\alpha \equiv \varphi_2$ (90°)

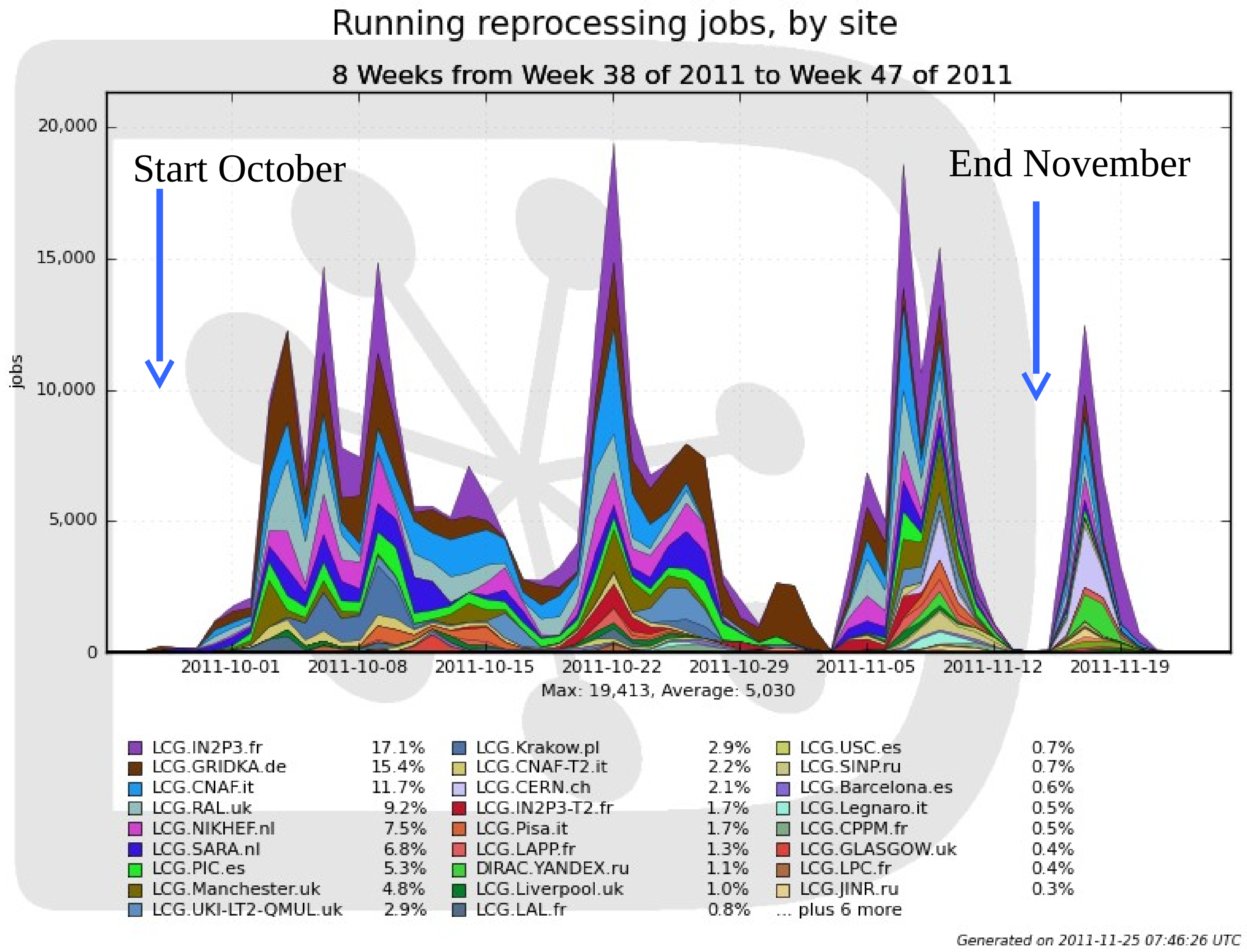
$\gamma \equiv \varphi_3$ (68°)

$\varphi_D/2$ (0°)

"The Unitarity Triangle"



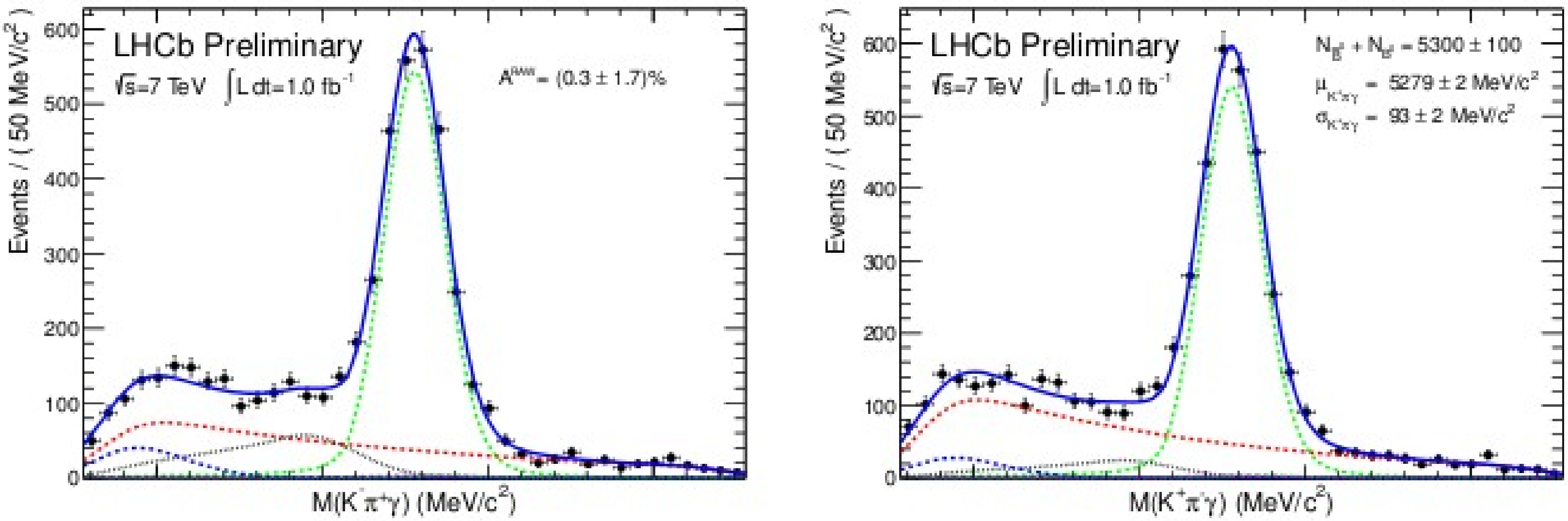
2011 data reprocessing



2011 data reprocessing completed in 8 weeks

Radiative B decays

LHCb-CONF-2012-004
1/fb



$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = 0.008 \pm 0.017(\mathrm{stat}) \pm 0.009(\mathrm{syst}),$$

SM prediction: (–0.7 ± 0.5)% hep-ph/0406055
"The error to the direct CP asymmetry must get smaller than 1%. …
This is not possible without the super B factory."

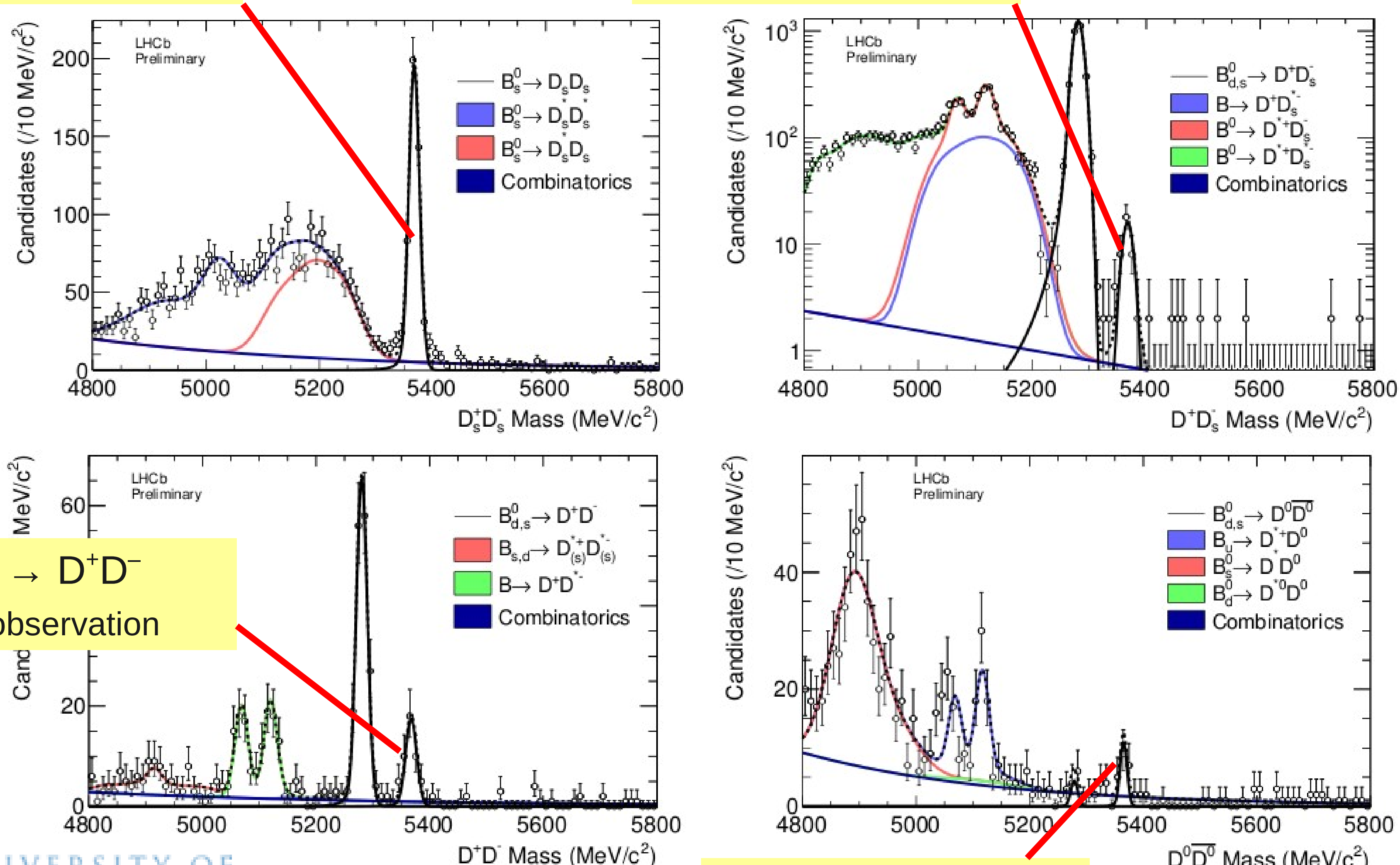
… in fact also possible with LHCb

$B_{(s)}^0 \to D_{(s)}^+ D_{(s)}^-$ & $D^0\bar{D}^0$

$B_s^0 \to D_s^+ D_s^-$
477 ± 23 signal events

$B_s^0 \to D^+ D_s^-$
first observation

LHCb-CONF-2012-009
1/fb



$B_s^0 \to D^+ D^-$
first observation

$B_s^0 \to D^0 \bar{D}^0$
first observation

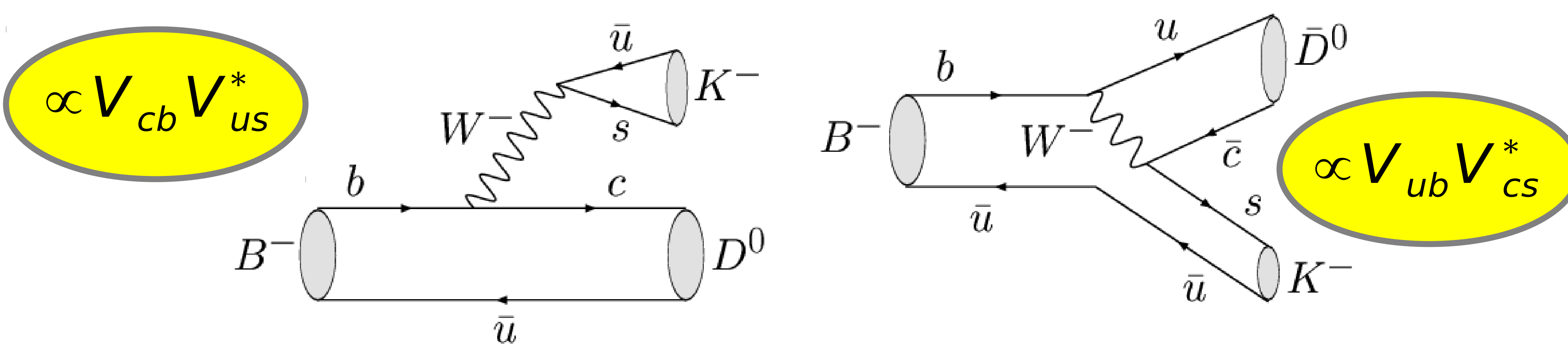
Importance of γ from B→DK

- γ plays a unique role in flavour physics

the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

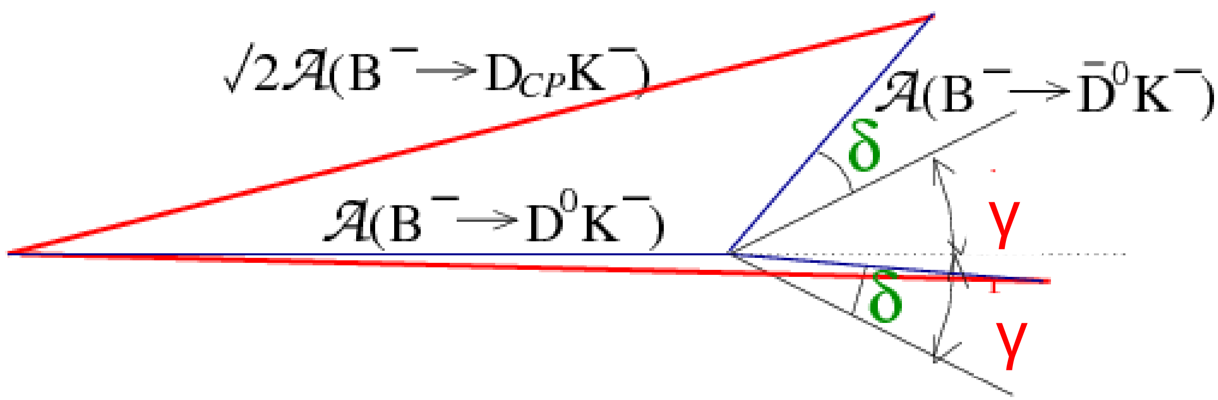
- A benchmark Standard Model reference point
  - doubly important after New Physics is observed



Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

Why is B→DK so nice?

- For theorists:
  - theoretically clean: no penguins; factorisation works
  - all parameters can be determined from data
- For experimentalists:
  - many different observables (different final states)
  - all parameters can be determined from data
  - γ & δ_B (weak & strong phase differences), r_B (ratio of amplitudes)



The other Unitarity Triangles

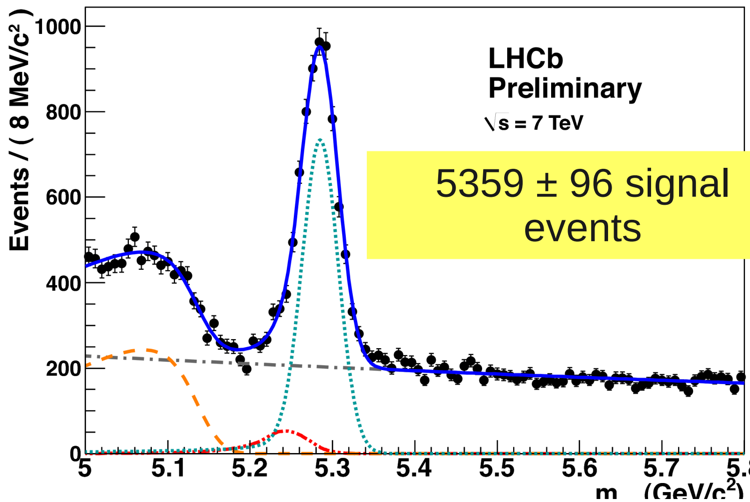
- High statistics available at LHCb will allow sensitivity to smaller CP violating effects
  - CP violating phase in B_s oscillations ($O(\lambda^4)$)
    - B_s oscillations (Δm_s) measured 2006 (CDF)
  - CP violating phase in D^0 oscillations ($O(\lambda^5)$)
    - D^0 oscillations ($x_D = \Delta m_D/\Gamma_D$ & $y_D = 2\Delta\Gamma_D/\Gamma_D$) measured 2007 (Babar, Belle, later CDF)

- Observations of CP violation in both K^0 and B^0 systems won Nobel prizes!

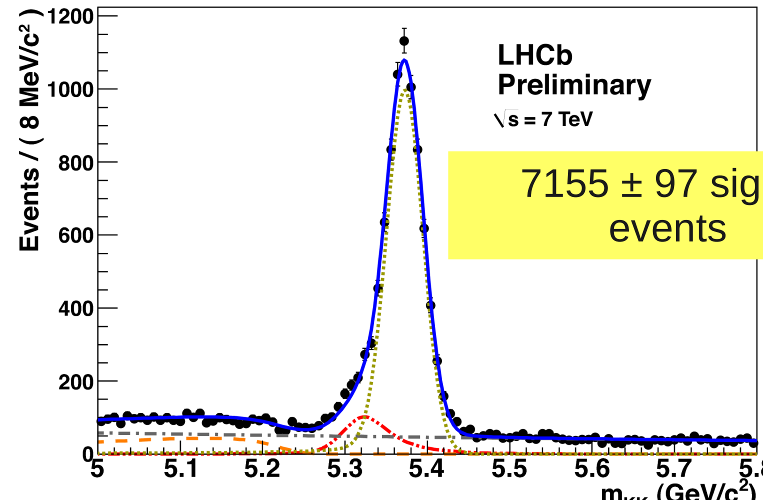
$B^0 \to \pi^+\pi^-$ & $B_s^0 \to K^+K^-$

First CP violation measurements in these channels at a hadron collider ($B^0 \to \pi^+\pi^-$) / ever ($B_s^0 \to K^+K^-$)

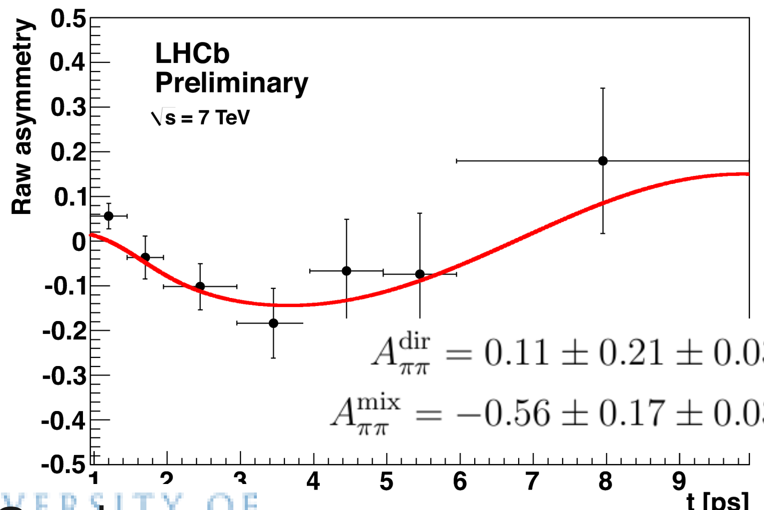
LHCb-CONF-2012-007



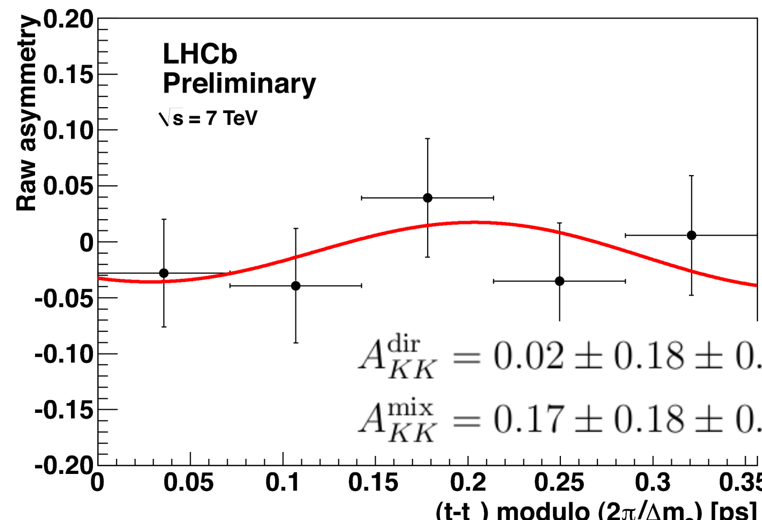
5359 ± 96 signal events



7155 ± 97 signal events



$$A^{\rm dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03,$$
$$A^{\rm mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03,$$



$$A^{\rm dir}_{KK} = 0.02 \pm 0.18 \pm 0.04,$$
$$A^{\rm mix}_{KK} = 0.17 \pm 0.18 \pm 0.05,$$

Evidence for CP violation in $D \to h^+h^-$ decays

- Naive SM expectation is for decays to be tree-dominated
- Penguin contributions are possible for singly-Cabibbo-suppressed decays but CKM suppression is severe
- So CP violation effects should be $O(10^{-4})$ … or should they?
  - Implications of the LHCb Evidence for Charm CP Violation arXiv:1111.4987
  - Direct CP violation in two-body hadronic charmed meson decays arXiv:1201.0785
  - CP asymmetries in singly-Cabibbo-suppressed D decays to two pseudoscalar mesons arXiv:1201.2351
  - Direct CP violation in charm and flavor mixing beyond the SM arXiv:1201.6204
  - New Physics Models of Direct CP Violation in Charm Decays arXiv:1202.2866
  - Repercussions of Flavour Symmetry Breaking on CP Violation in D-Meson Decays arXiv:1202.3795
  - On the Universality of CP Violation in Delta F = 1 Processes arXiv:1202.5038
  - The Standard Model confronts CP violation in $D0 \to \pi+\pi-$ and $D0 \to K+K-$ arXiv:1203.3131
  - A consistent picture for large penguins in $D \to$ pi+pi-, K+K- arXiv:1203.6659
  - ...

… and many others! Further experimental input needed to clarify whether CPV is SM or NP

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin\left(\Delta m \, t\right) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right] .$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t} \times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right].$$

CP violating asymmetries

CP conserving parameter

$$A_{CP}^{dir} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2} \qquad A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2} \qquad A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

$B_s \rightarrow J/\psi\varphi$ formalism

Differential decay rate:

$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t)\, f_k(\Omega)$$

$A_0(0) \rightarrow$ CP even
$A_\parallel(0) \rightarrow$ CP even
$A_\perp(0) \rightarrow$ CP odd

Bs | $\overline{\text{Bs}}$

k	$h_k(t)$	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert\bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\lvert\bar{A}_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert\bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

± signs differ for B_s and $\bar{B}_s$

$$|\bar{A}_0(t)|^2 = |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],$$

$$|\bar{A}_\parallel(t)|^2 = |\bar{A}_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],$$

$$|\bar{A}_\perp(t)|^2 = |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right],$$

$$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\} = |\bar{A}_\parallel(0)||\bar{A}_\perp(0)| e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\right],$$

$$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\} = |\bar{A}_0(0)||\bar{A}_\parallel(0)| e^{-\Gamma_s t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right] \text{ and}$$

$$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\} = |\bar{A}_0(0)||\bar{A}_\perp(0)| e^{-\Gamma_s t}\left[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\right].$$