Flavour Physics at LHCb: now and next

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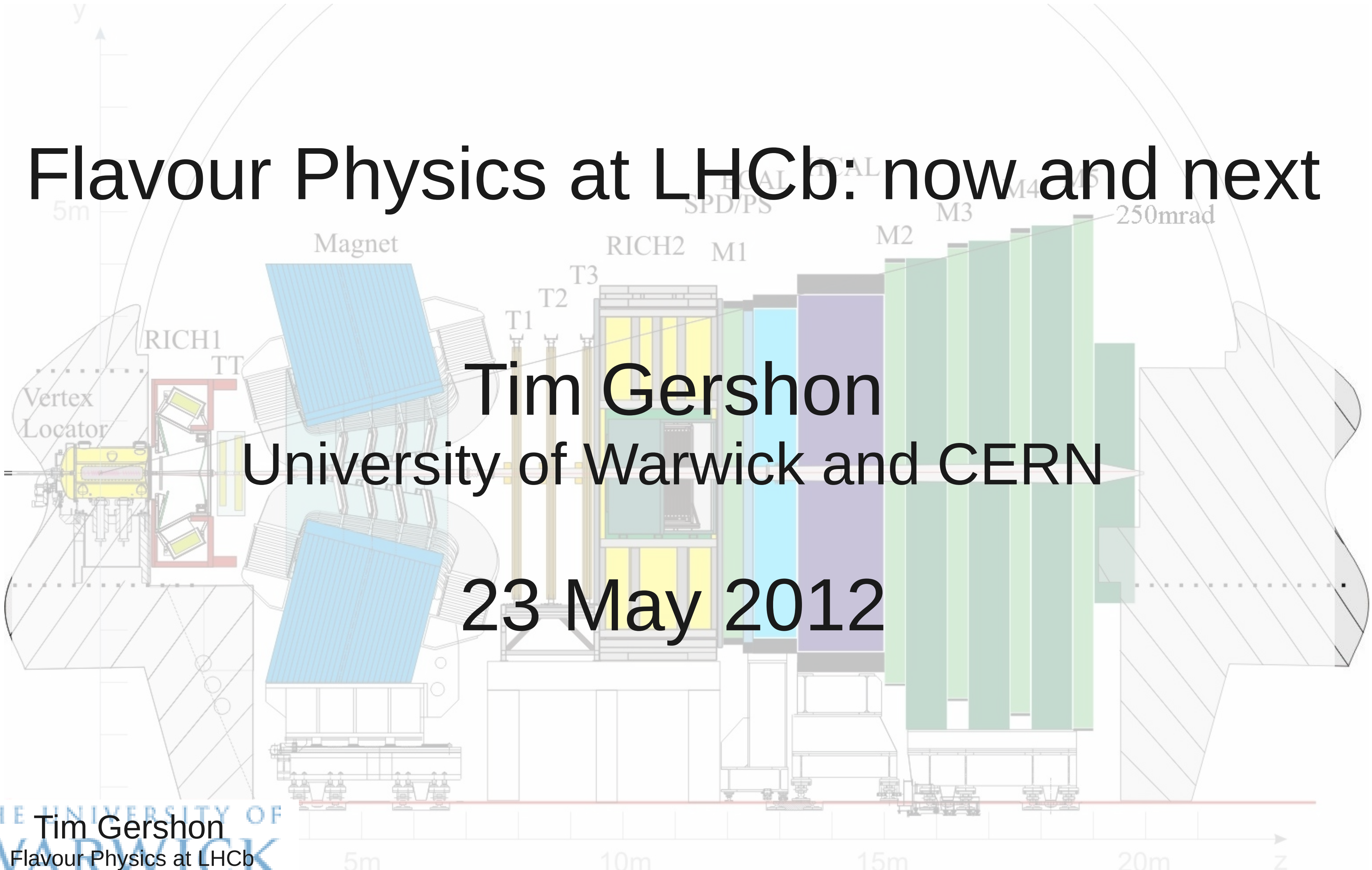
23 May 2012



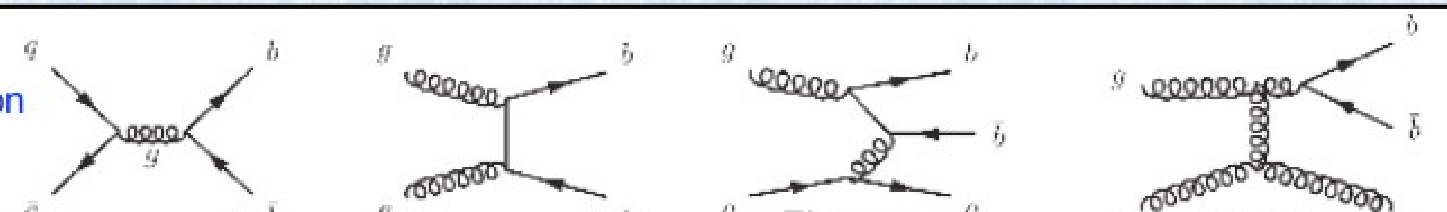
Outline

- The LHCb detector
- Data taking performance in 2011 and 2012
- Heavy flavour physics phenomenology
- Selected highlights of results so far
  - Rare decays
  - CP violation
- The LHCb upgrade

Flavour physics at hadron colliders

	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$ **PEP-II, KEK-B**	$p\bar{p} \to b\bar{b}X \quad (\sqrt{s}=2\ \text{TeV})$ **TeVatron**	$pp \to b\bar{b}X \quad (\sqrt{s}=14\ \text{TeV})$ **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	$B^+B^-(50\%), B^0\bar{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%),\ \text{b-baryons}(10\%)$	
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

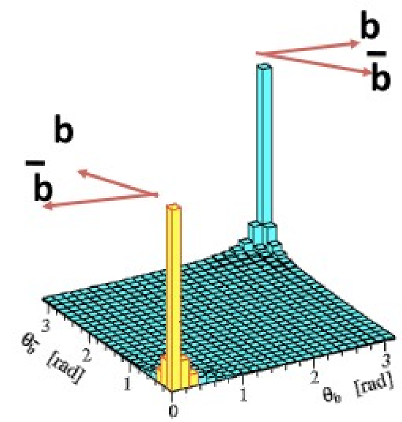


Flavour creation (quark annihilation) | Flavour creation (gluon fusion) | Flavour excitation | Gluon splitting

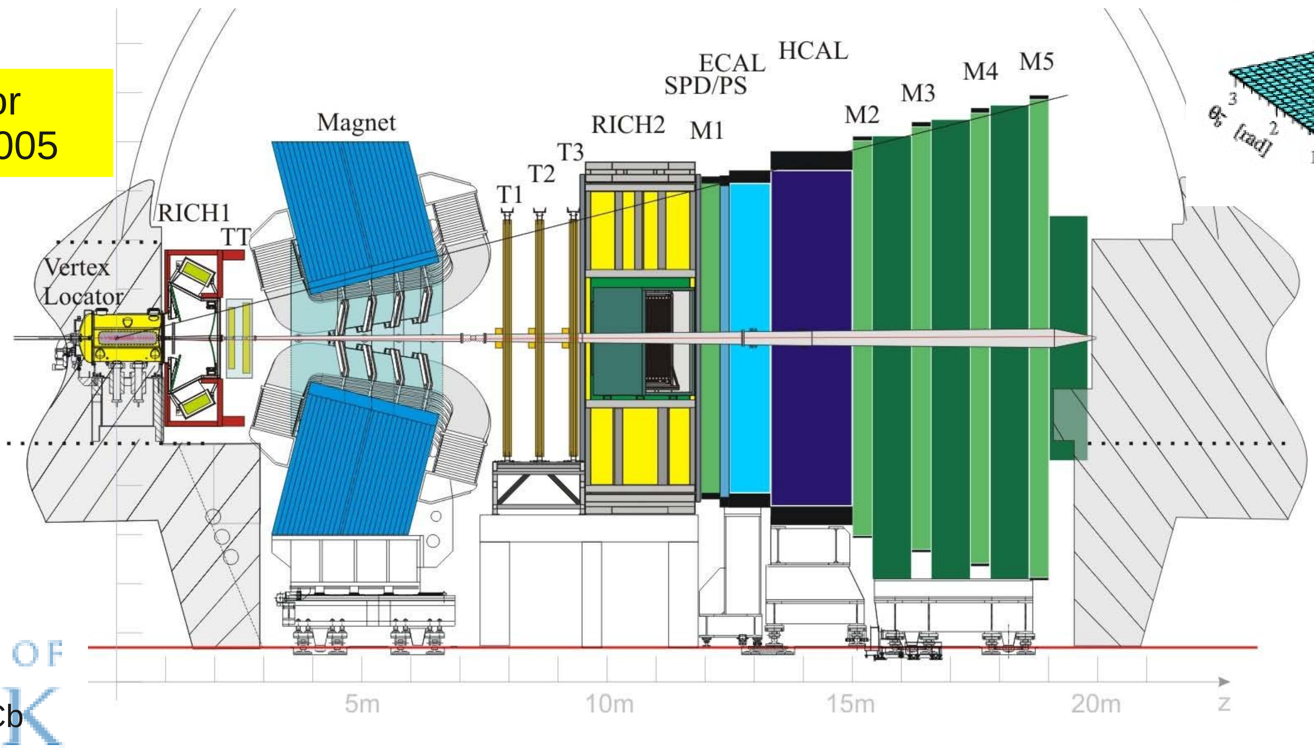
from Val Gibson HCPSS 2009

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

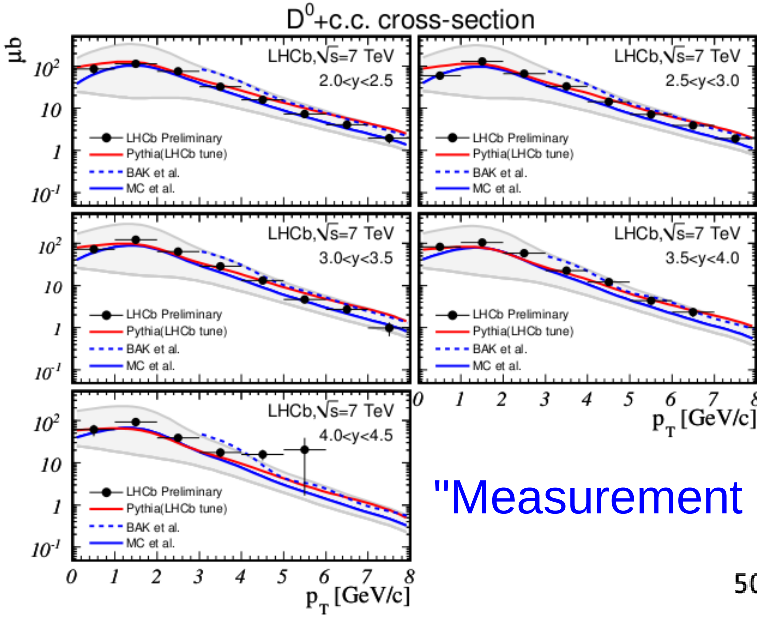


The LHCb Detector
JINST 3 (2008) S08005

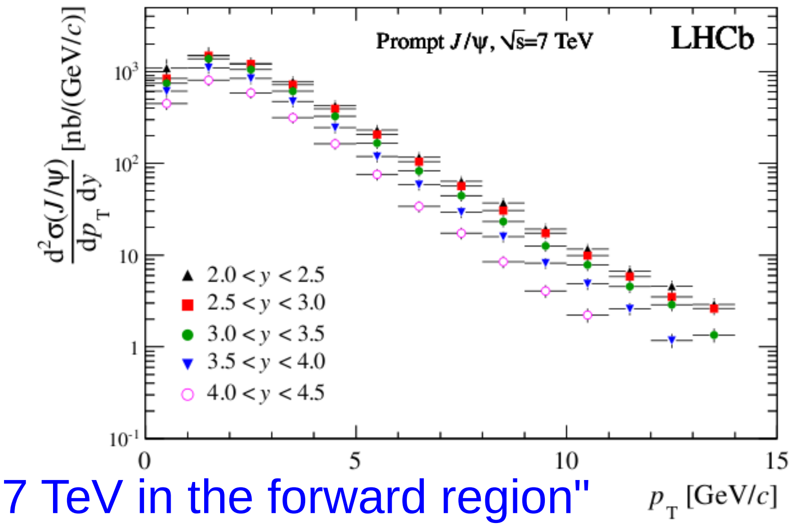


Heavy flavour production @ LHCb

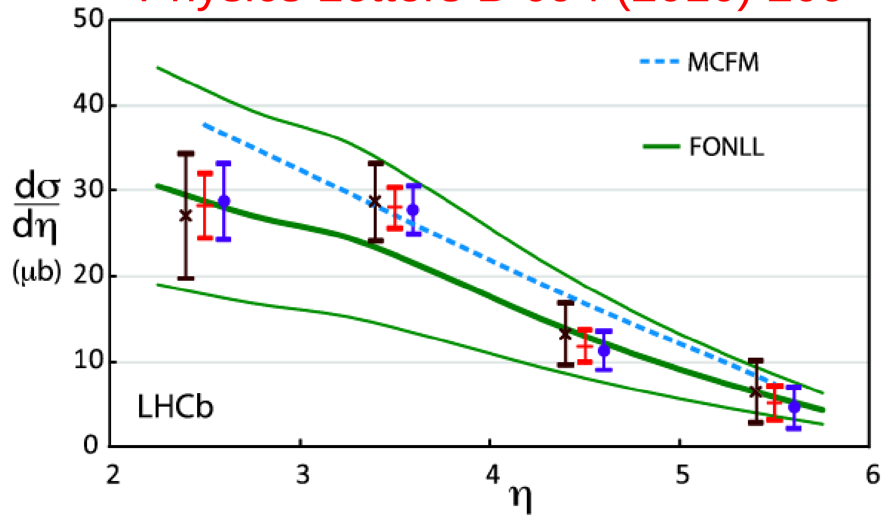
“Prompt charm production in pp collisions at √s = 7 TeV”
LHCb-CONF-2010-013



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

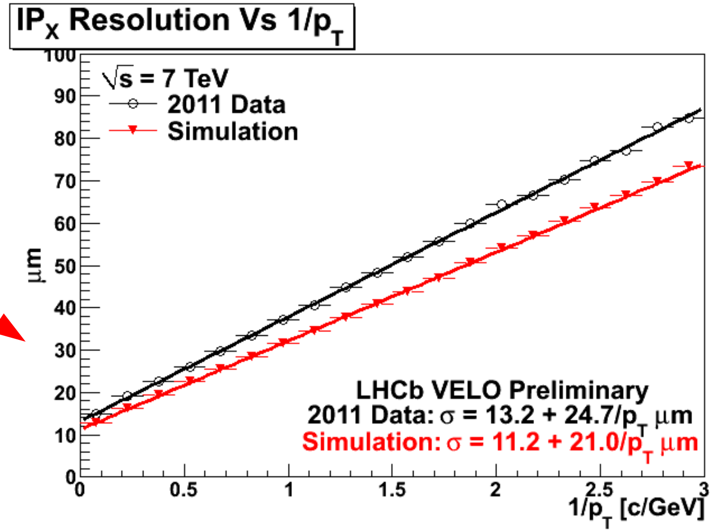


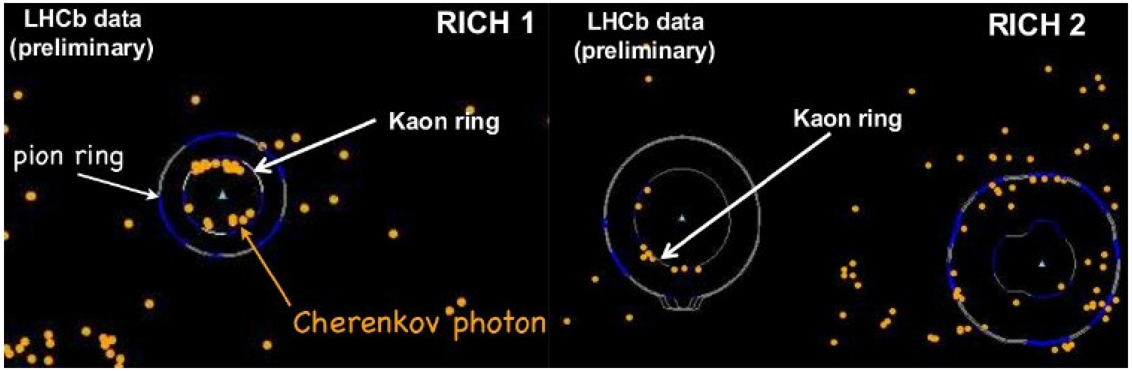
"Measurement of $\sigma(pp \to b\bar{b}X)$ at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



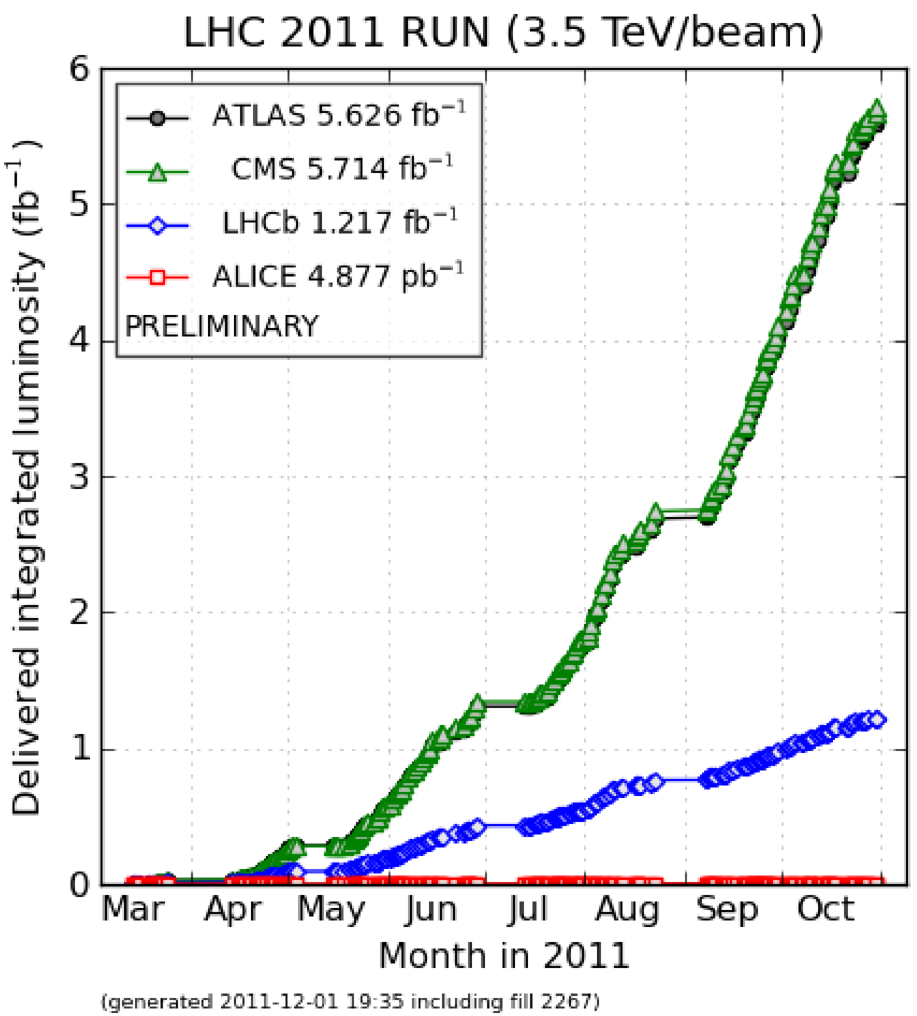
LHCb detector features

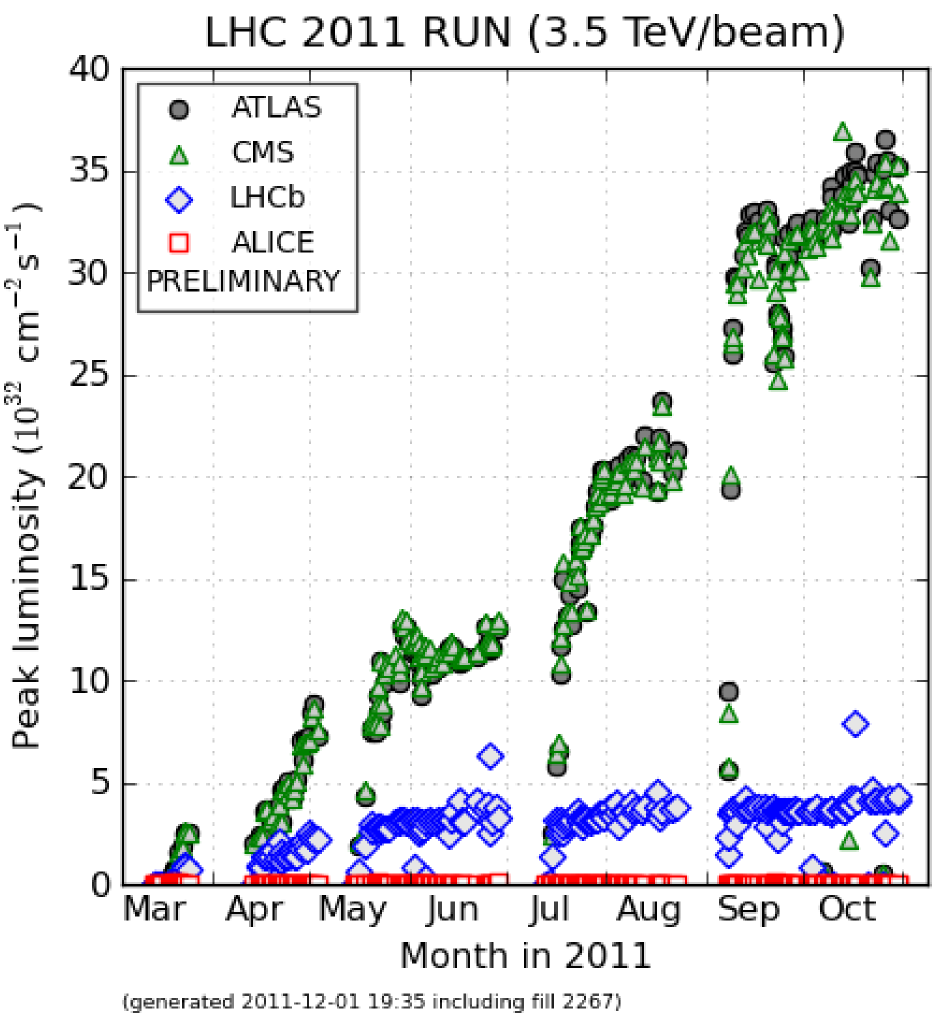
- Tracking and calorimetry
  - basic essentials of any collider experiment!
  - muon chambers
- VELO
  - reconstruct displaced vertices
- RICH
  - particle ID (K/π separation)
- Trigger
  - fast and efficient



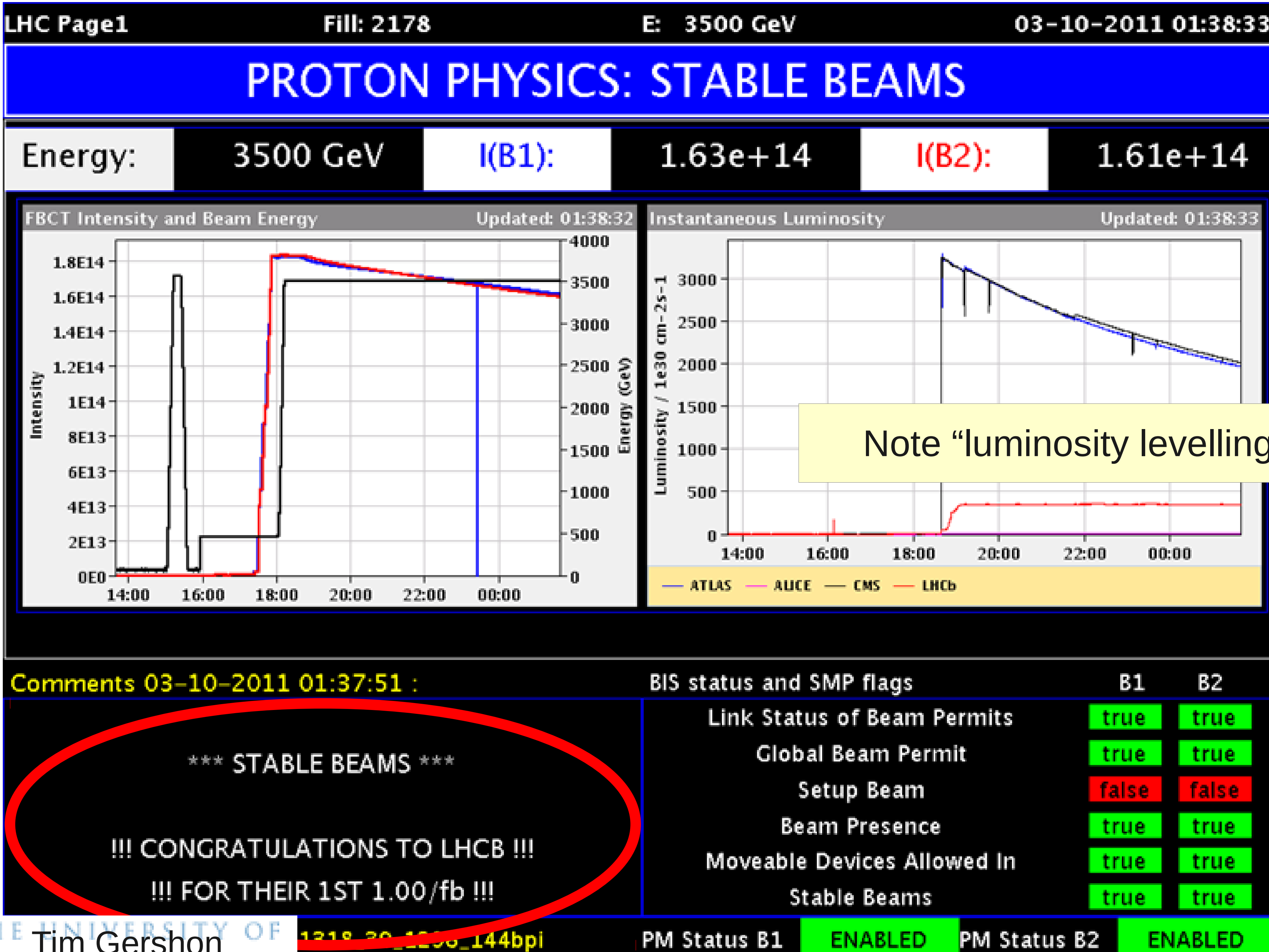


LHC performance 2011



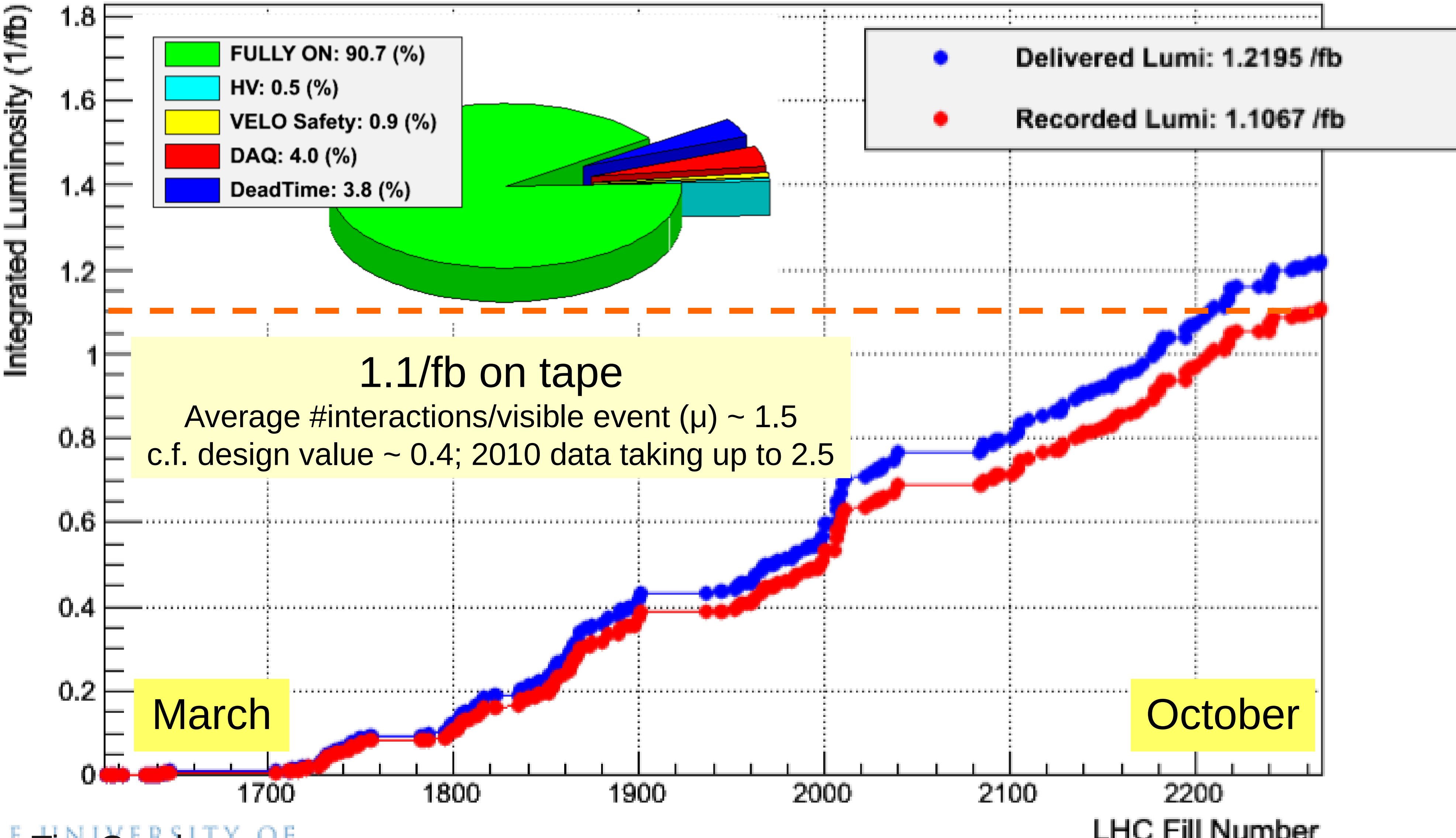


LHCb design luminosity: $2\ 10^{32}/cm^2/s$



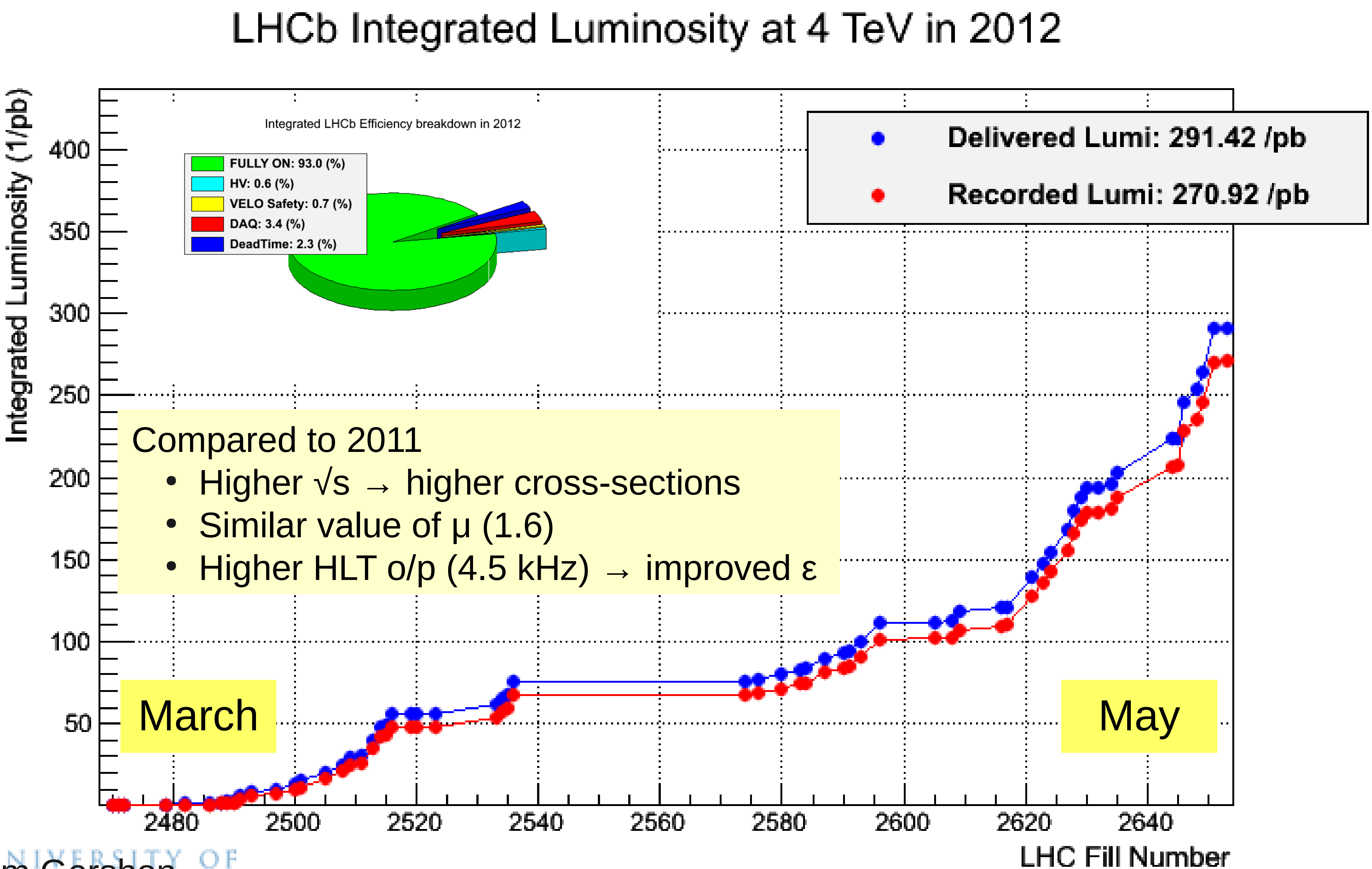
Note “luminosity levelling”

2011 data taking



Data taking efficiency close to 91 %

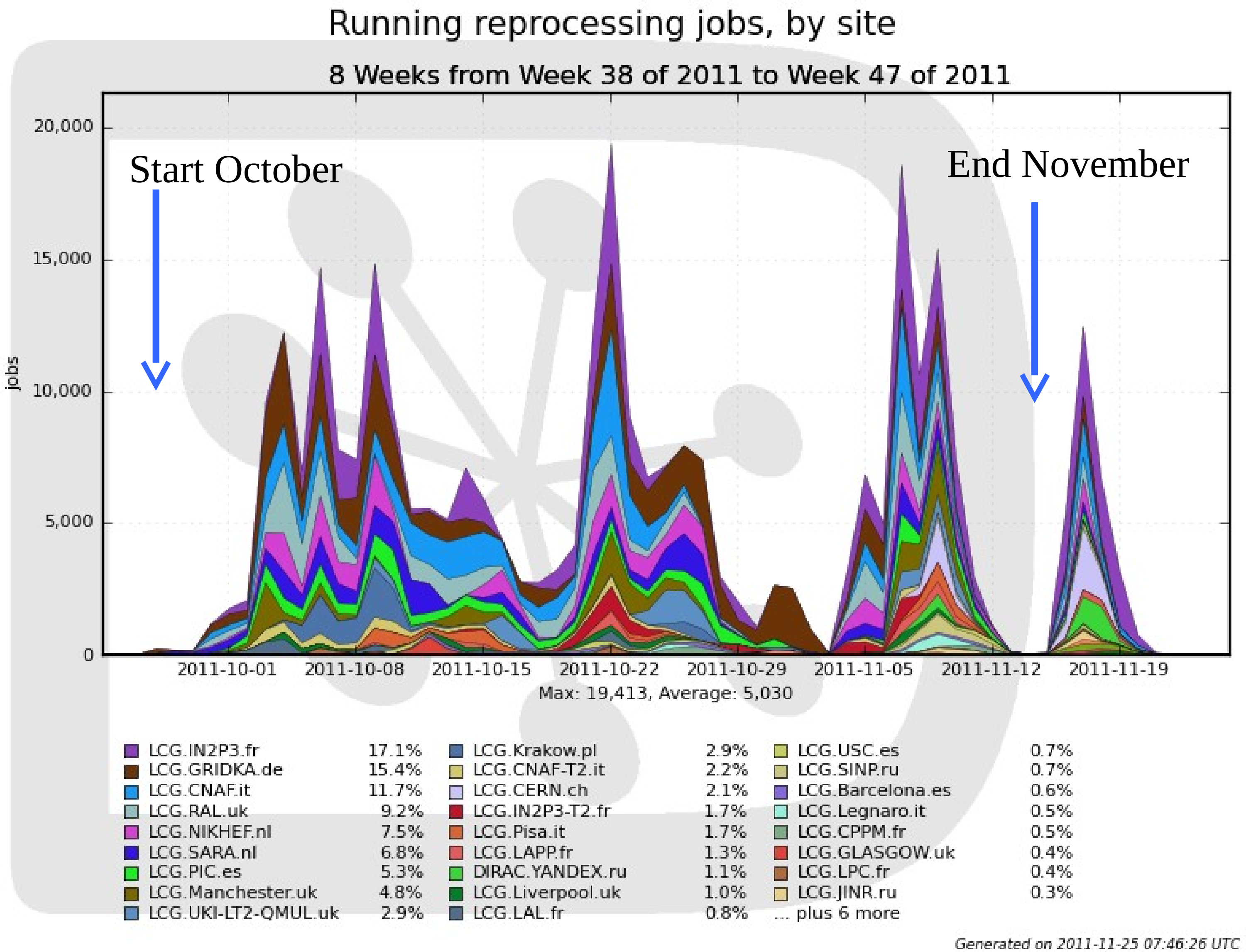
2012 data taking (so far)



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

2011 data reprocessing



2011 data reprocessing completed in 8 weeks

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

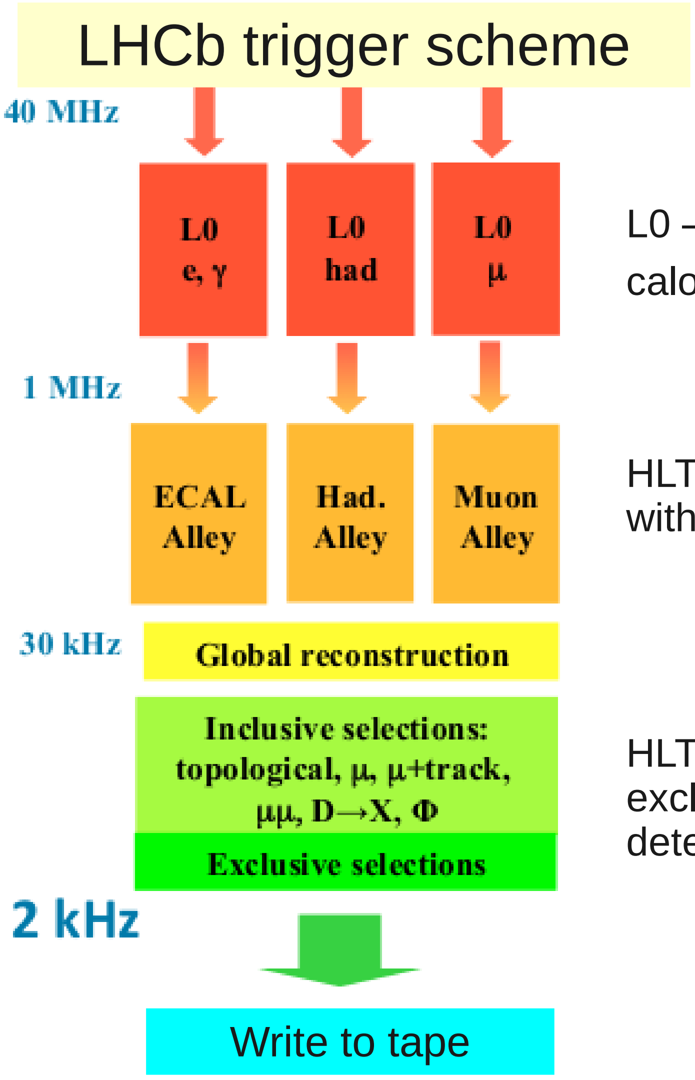
LHCb-CONF-2010-013

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 – associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

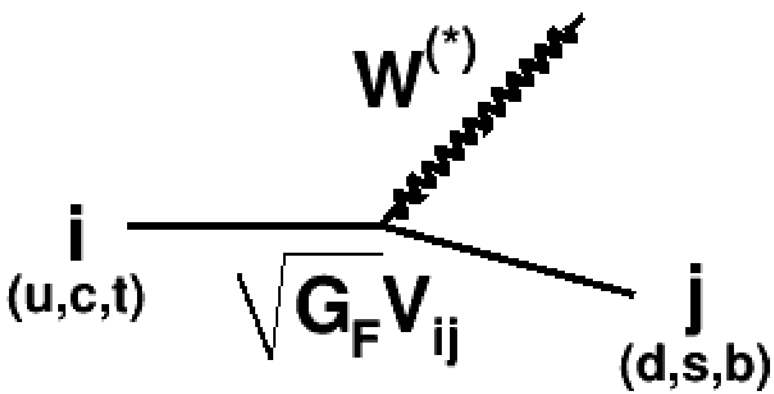
Heavy flavour physics phenomenology

(a very brief reminder)

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

Dirac medal 2010

Nobel prize 2008



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

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

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

- A 3x3 unitary matrix
- Described by 4 parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ
  - Wolfenstein parametrisation: λ, A, ρ, η
- Highly predictive

CKM phenomenology

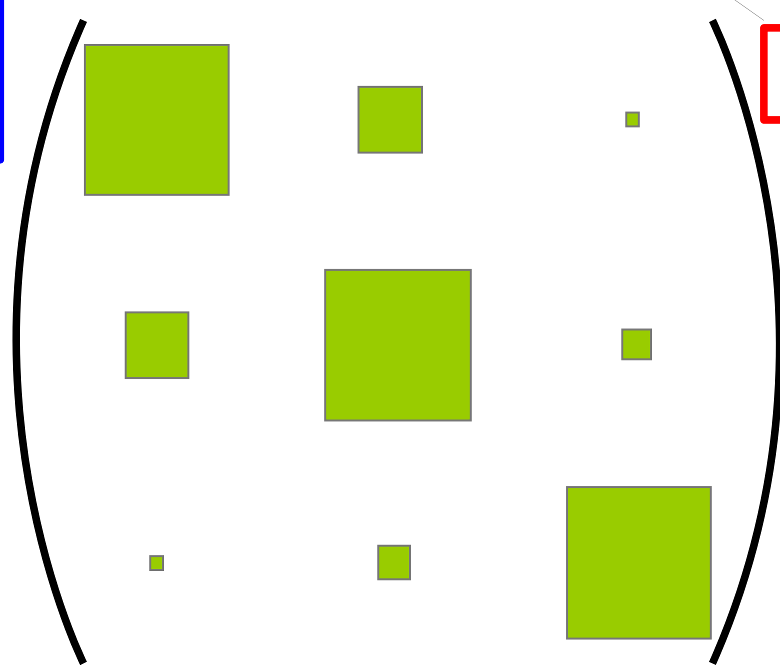
- CKM theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters
- CKM matrix is hierarchical
  - theorised connections to quark mass hierarchies, or (dis-)similar patterns in the lepton sector
    - origin of CKM matrix from diagonalisation 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 ($m_\nu = \theta_{QCD} = 0$)

Wolfenstein parametrisation

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

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

Source of CP violation



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

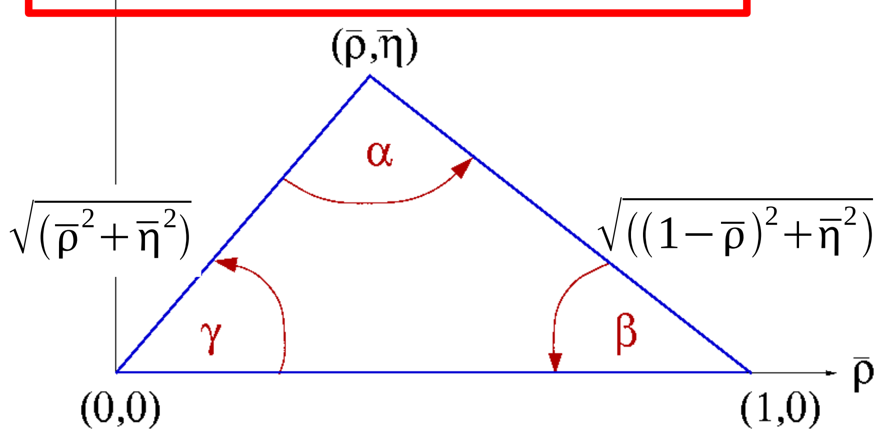
$\beta \equiv \varphi_1$

$\alpha \equiv \varphi_2$

$\varphi_D/2$

$\gamma \equiv \varphi_3$

"The Unitarity Triangle"

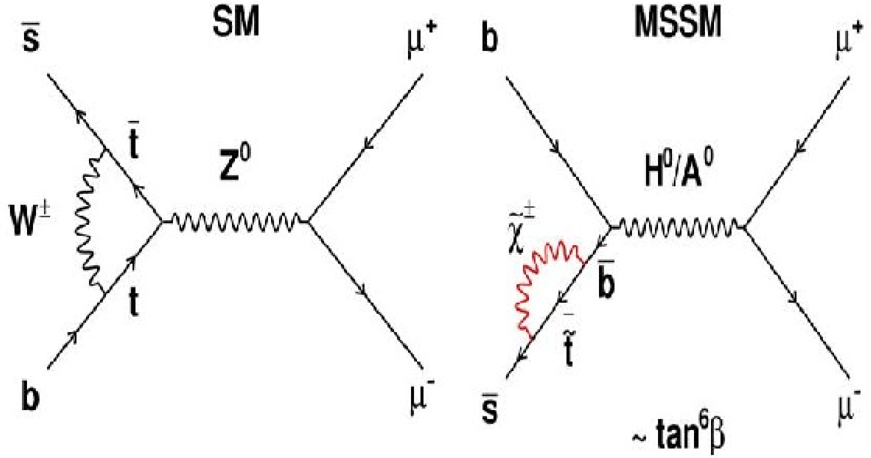


Rare Decays

$B_s \to \mu^+\mu^-$
Killer app. for new physics discovery

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

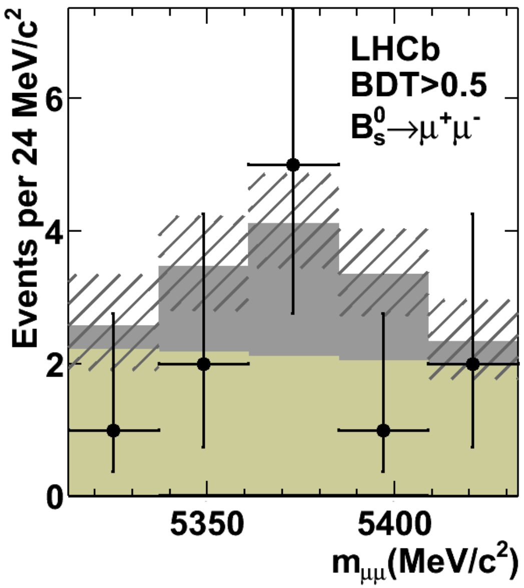
… all features which are not necessarily reproduced in extended models

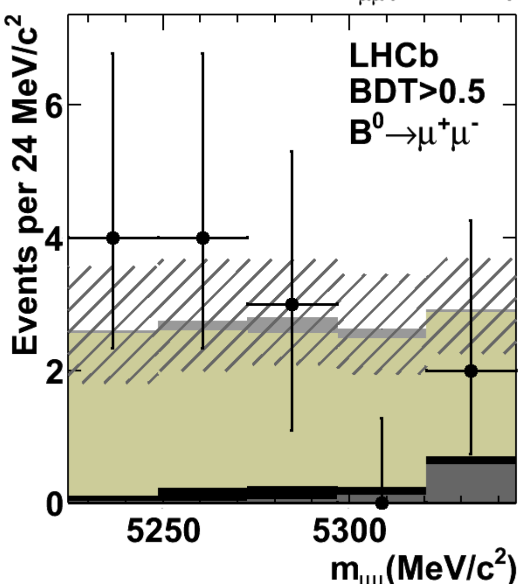


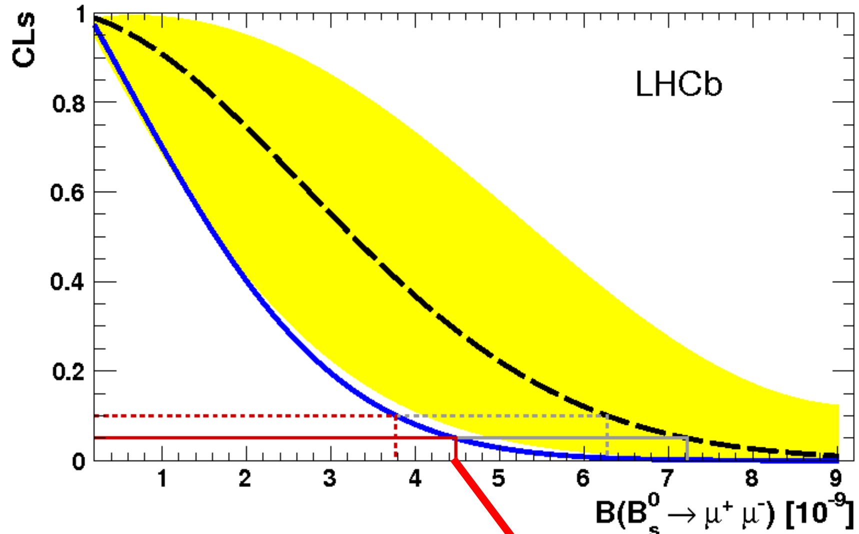
$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-8} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

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

LHCb (1/fb) arXiv:1203.4493







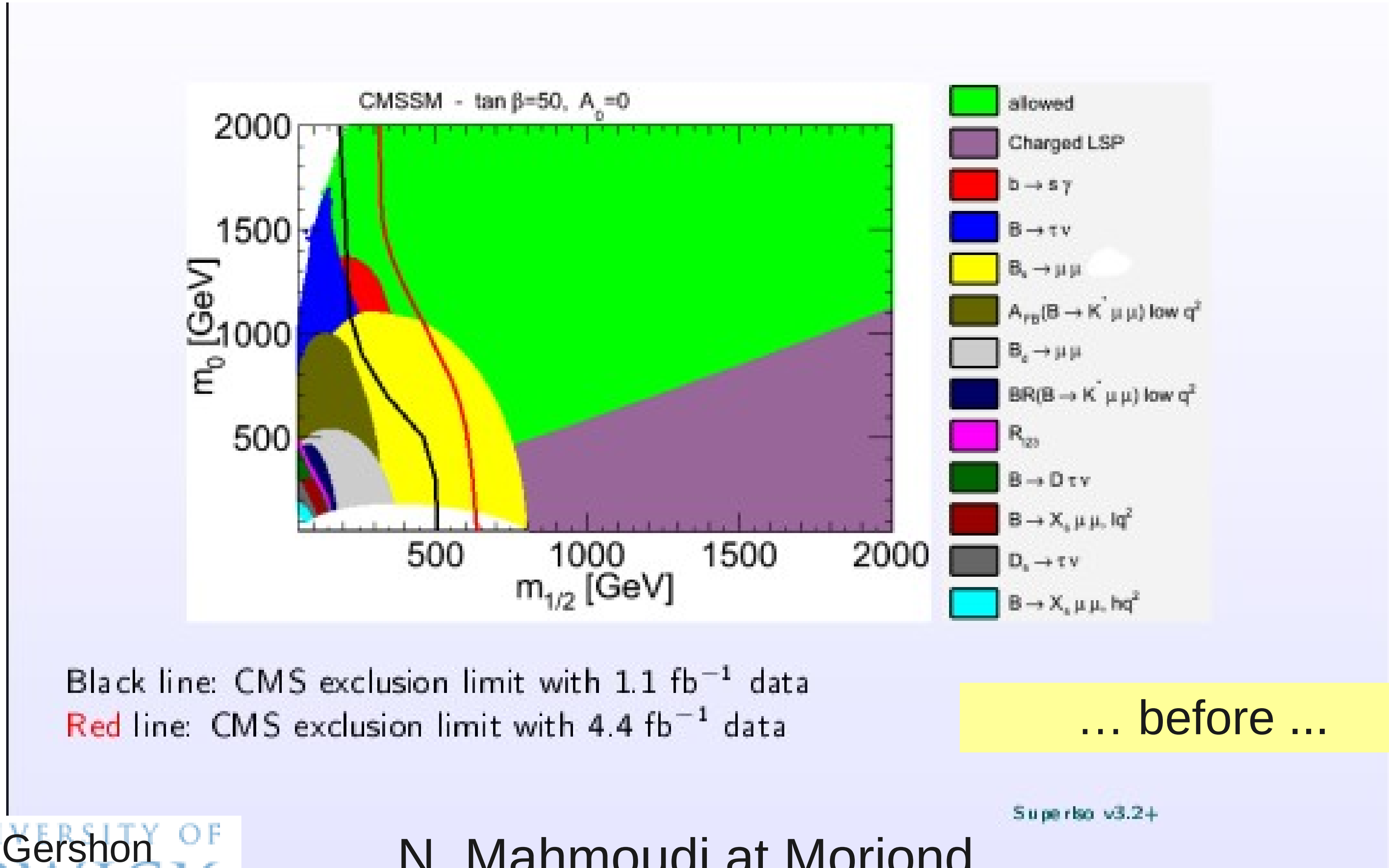
Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

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

Implications

G.Dissertori Moriond QCD summary talk:

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



… before ...

N. Mahmoudi at Moriond

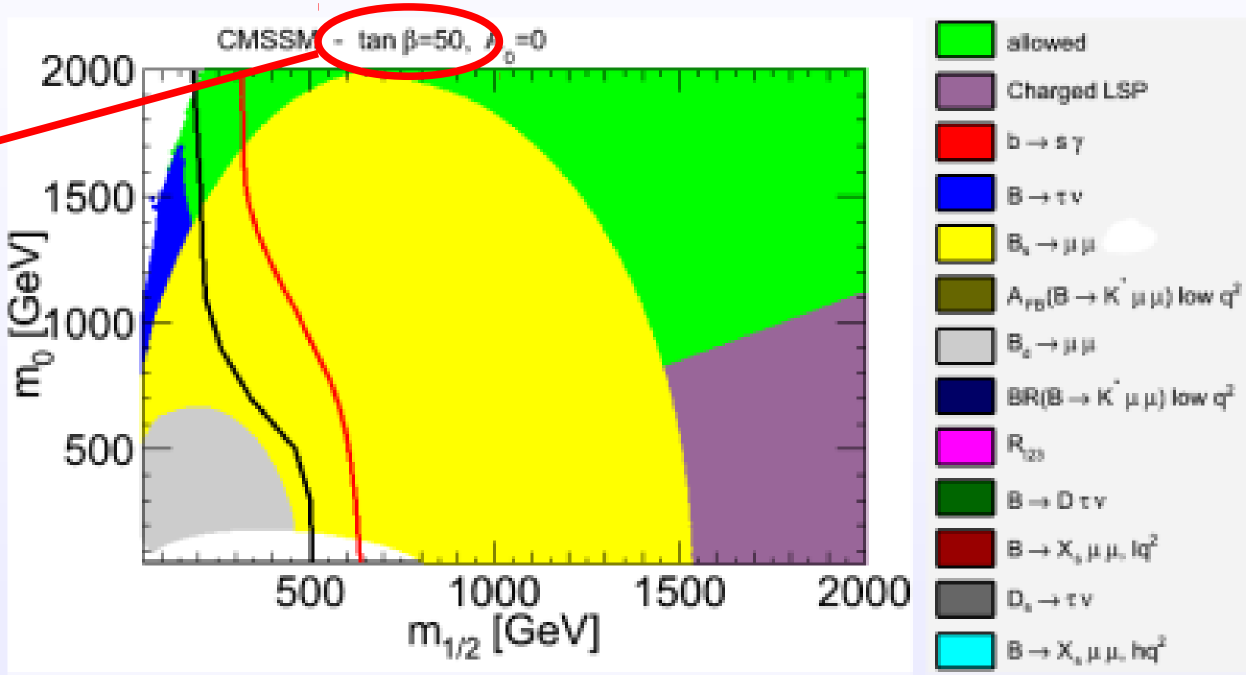
Implications

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 $BR(B_d \to \mu^+\mu^-)$

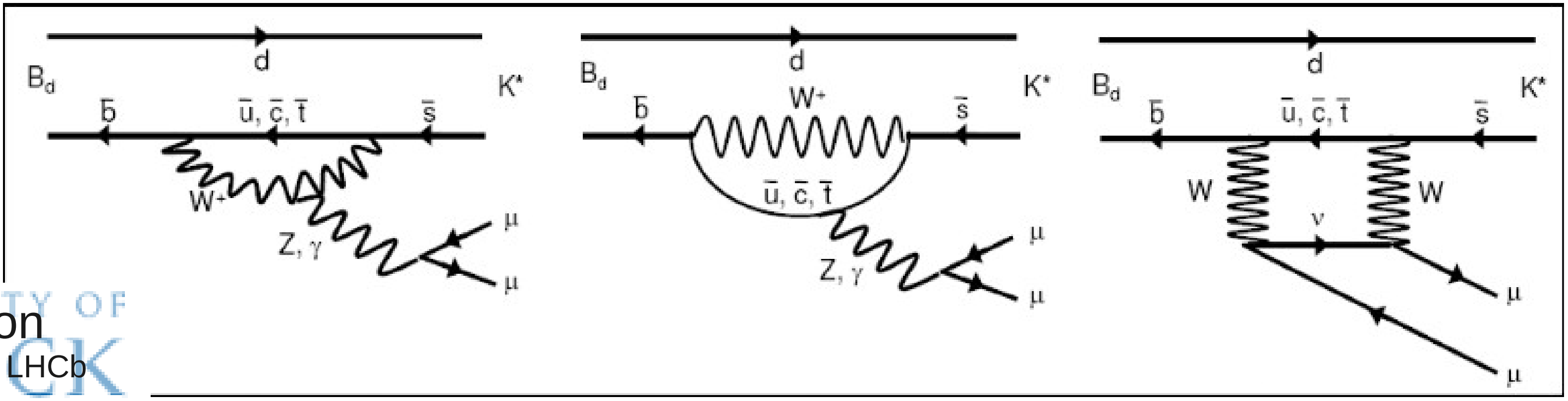
… after ...

SuperIso v3.2+

N. Mahmoudi at Moriond

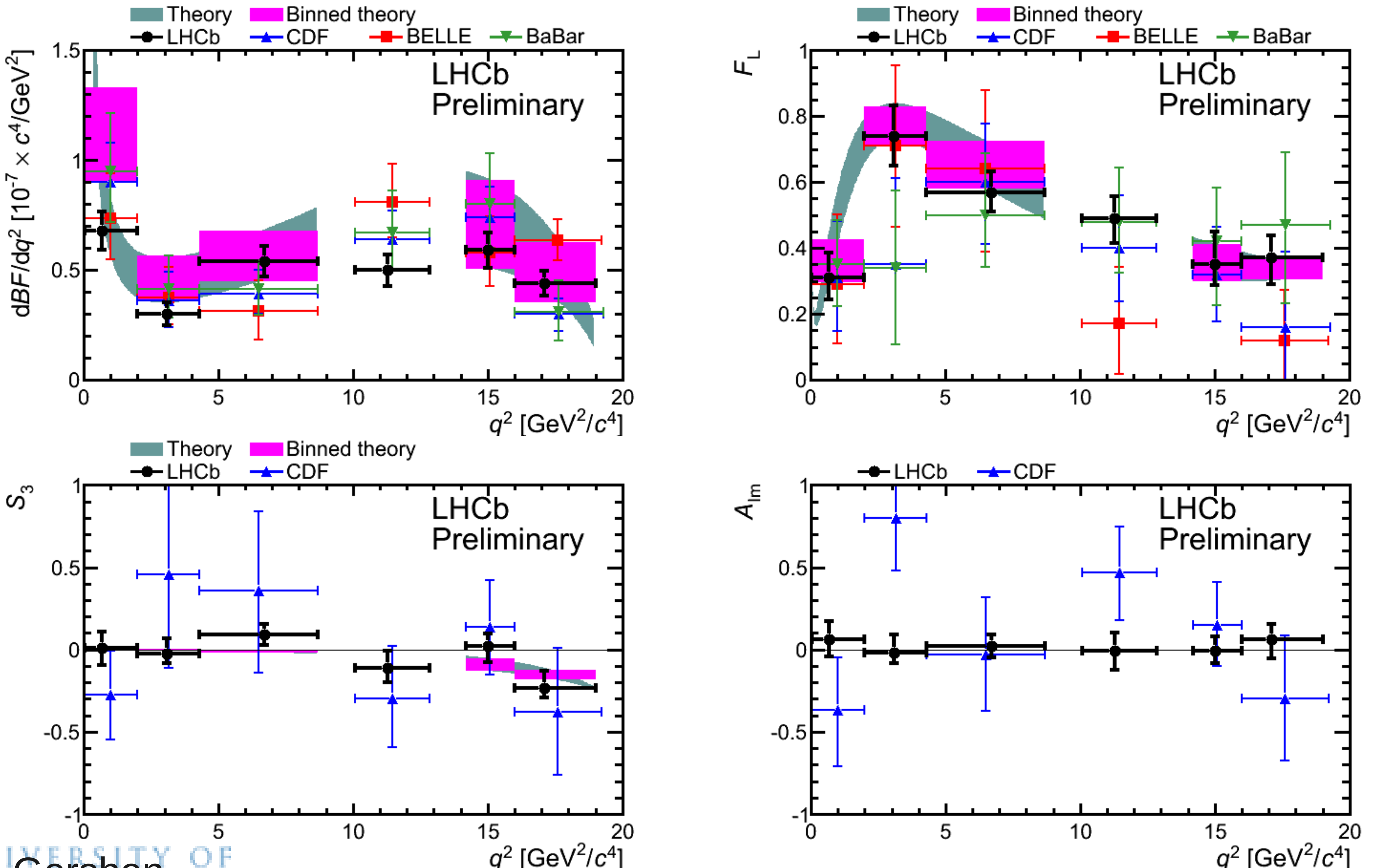
$B \to K^* \mu^+ \mu^-$

- $b \to s l^+ l^-$ 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)



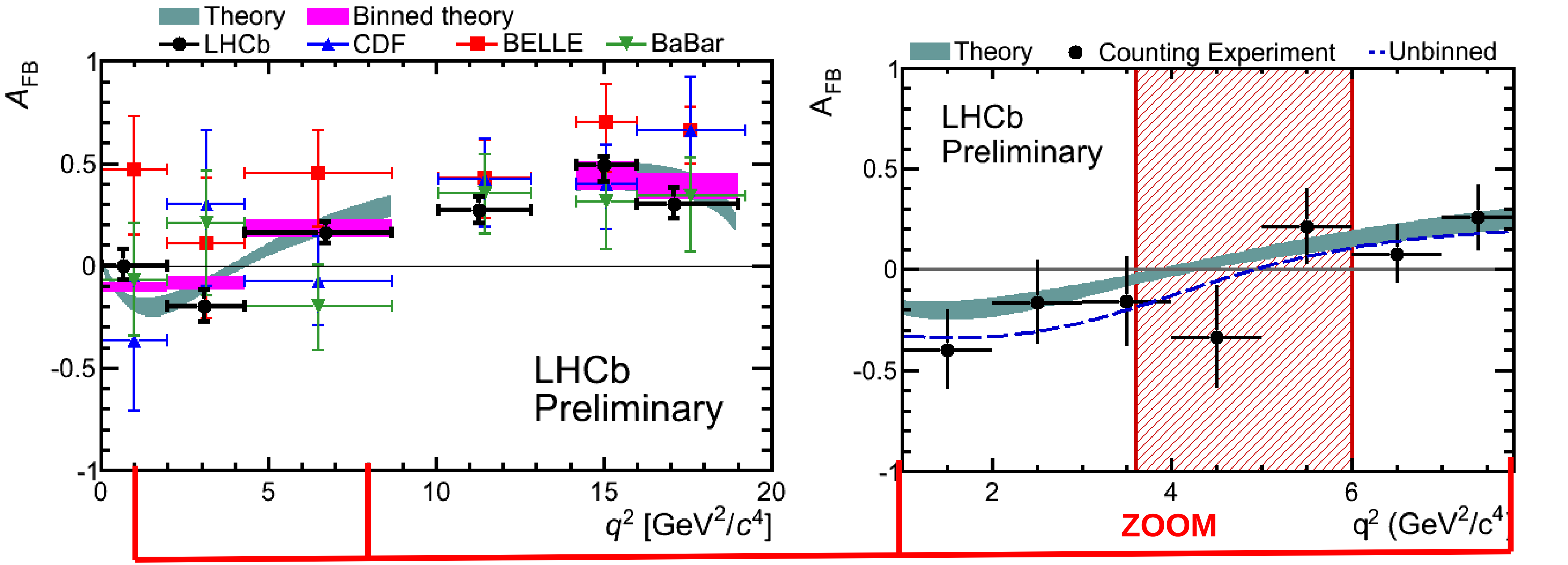
Differential branching fraction and angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb-CONF-2012-008



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

LHCb-CONF-2012-008



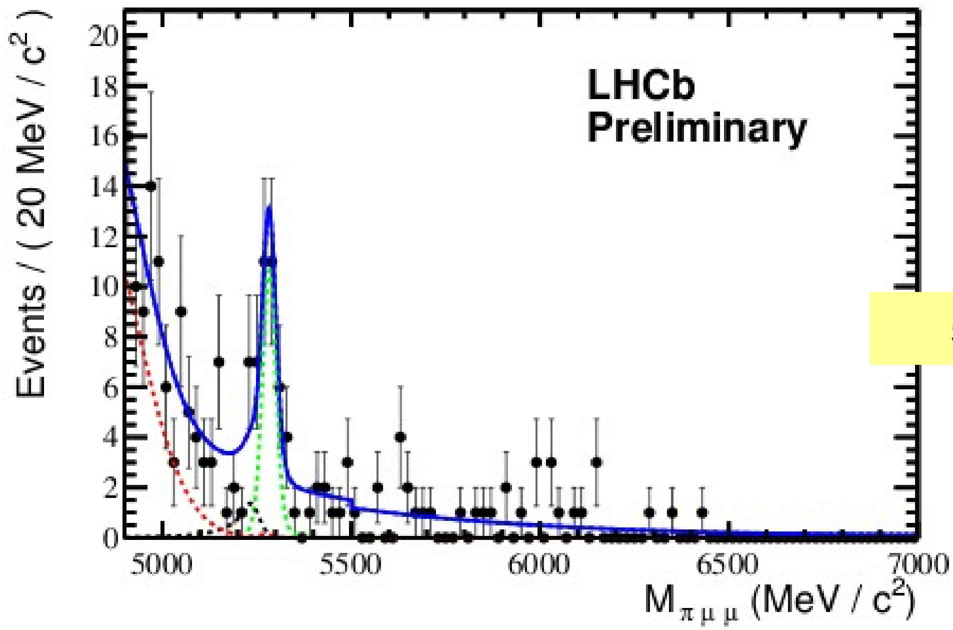
First measurement of the zero-crossing point of the forward-backward asymmetry

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



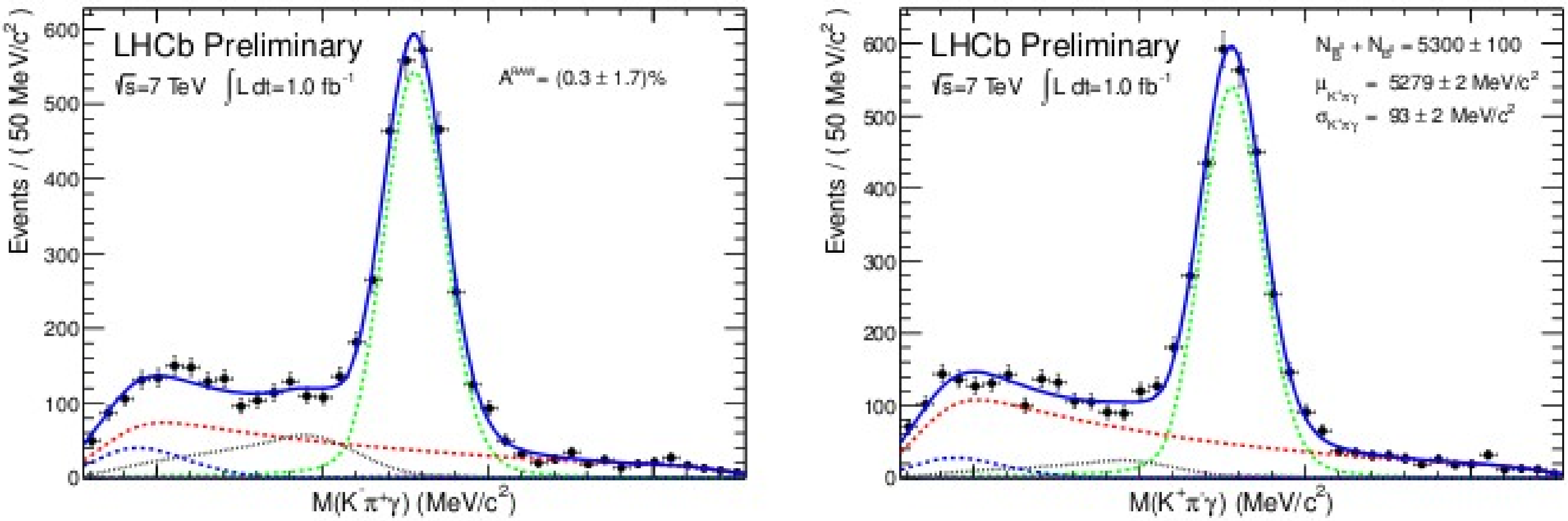
5.2σ

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

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

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

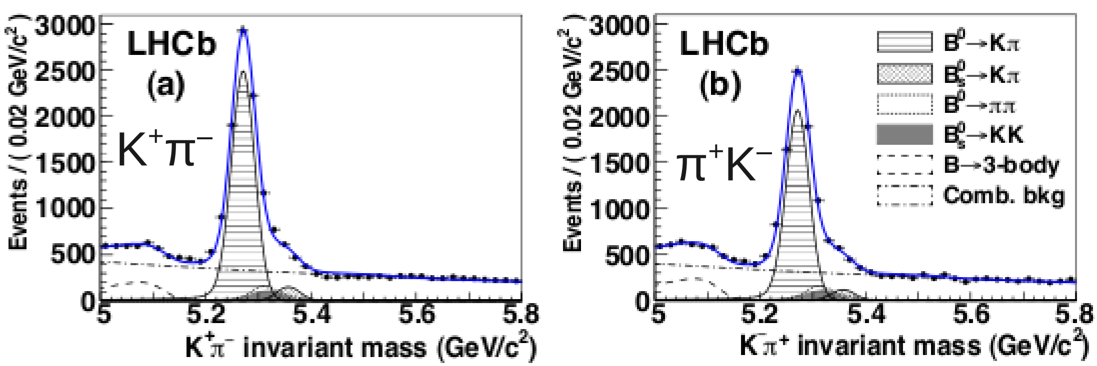
CP violation

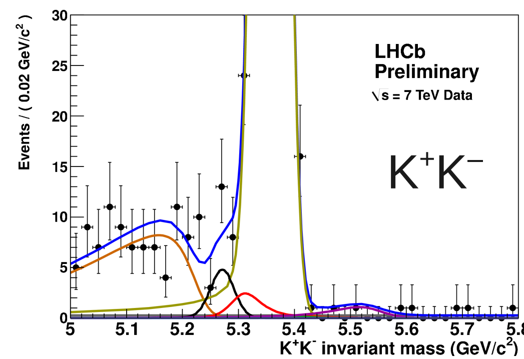
Charmless two-body decays

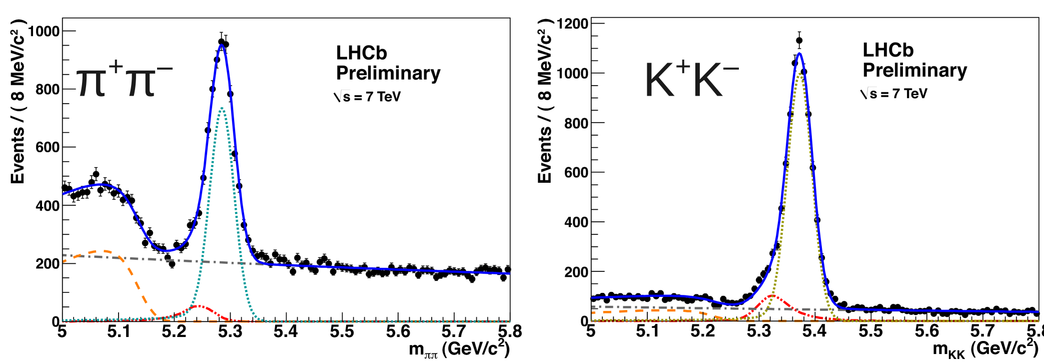
- Excellent channel to profit from displaced vertex trigger
- Particle ID extremely important

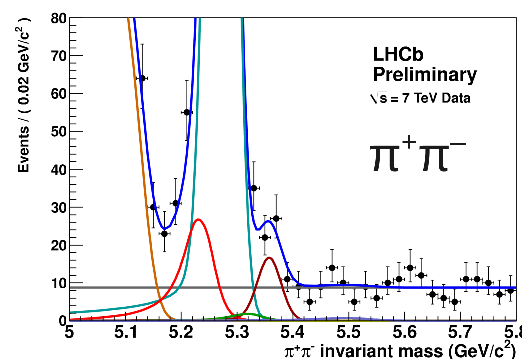
LHCb arXiv:1202.6251

also now see suppressed decays









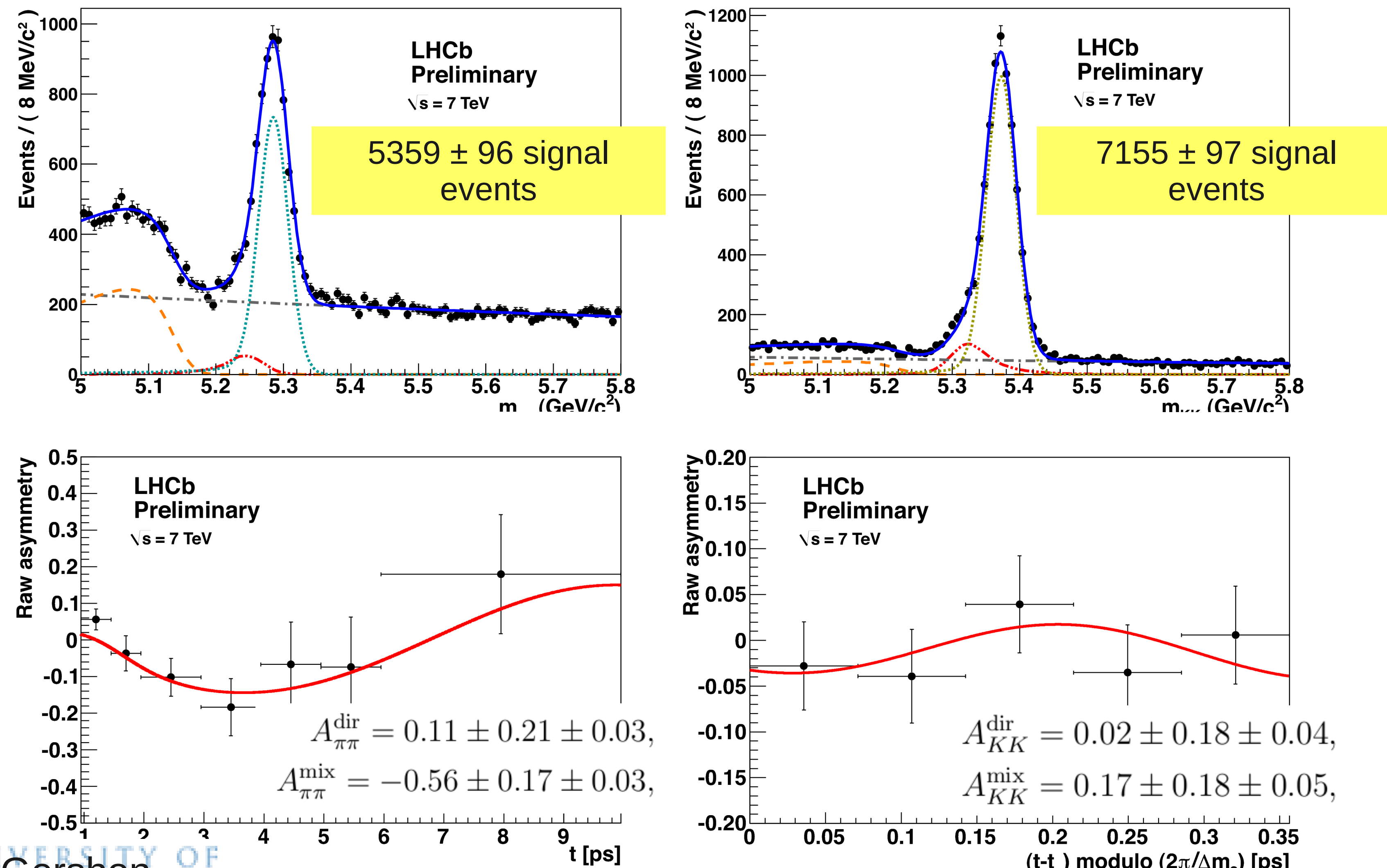
LHCb-CONF-2012-007

LHCb-CONF-2011-042

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

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



$B_{(s)}^0 \rightarrow D_{(s)}^+ D_{(s)}^-$ & $D^0\overline{D}^0$

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

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

LHCb-CONF-2012-009
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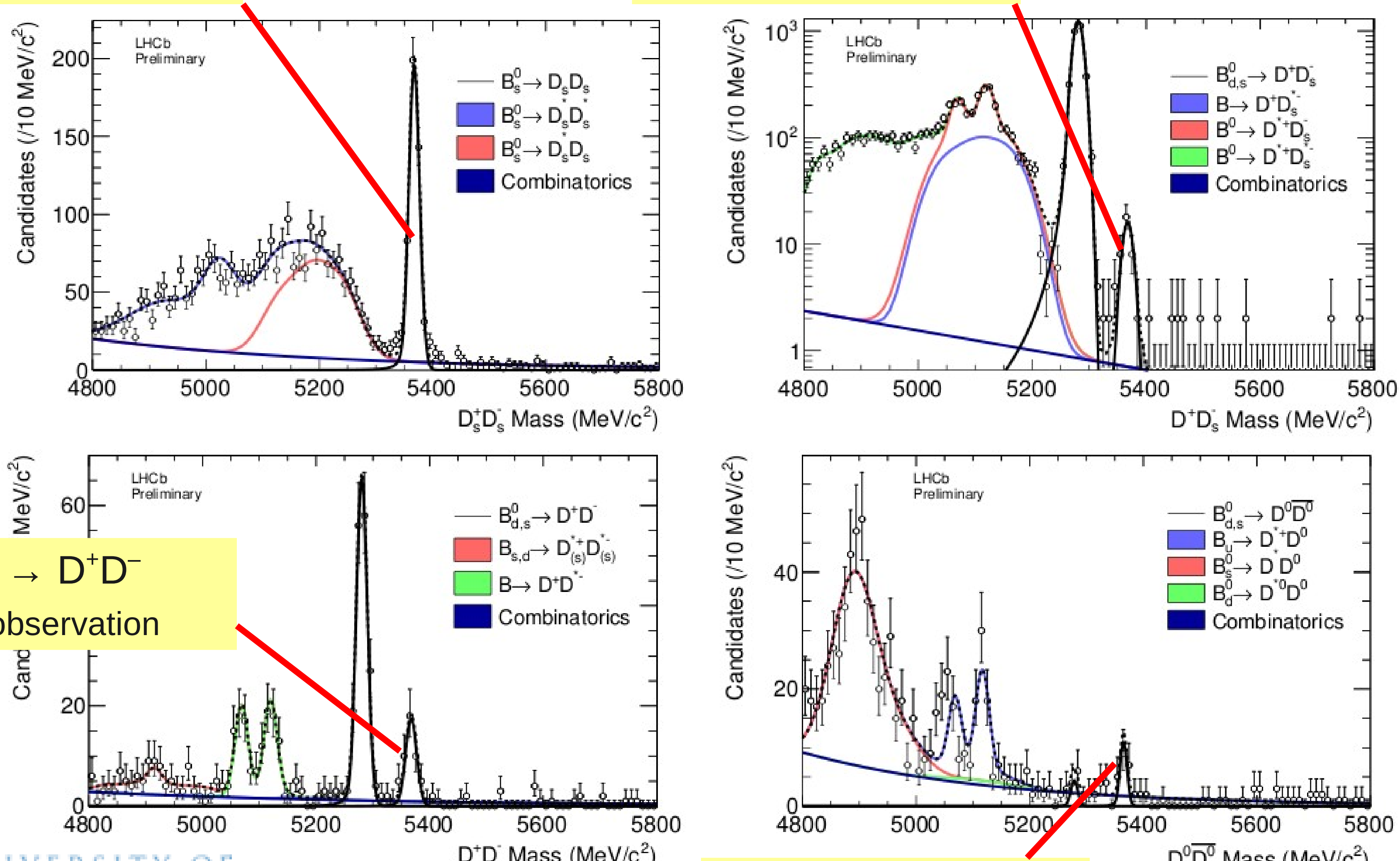


$B_s^0 \rightarrow D^+ D^-$
first observation

$B_s^0 \rightarrow D^0\overline{D}^0$
first observation

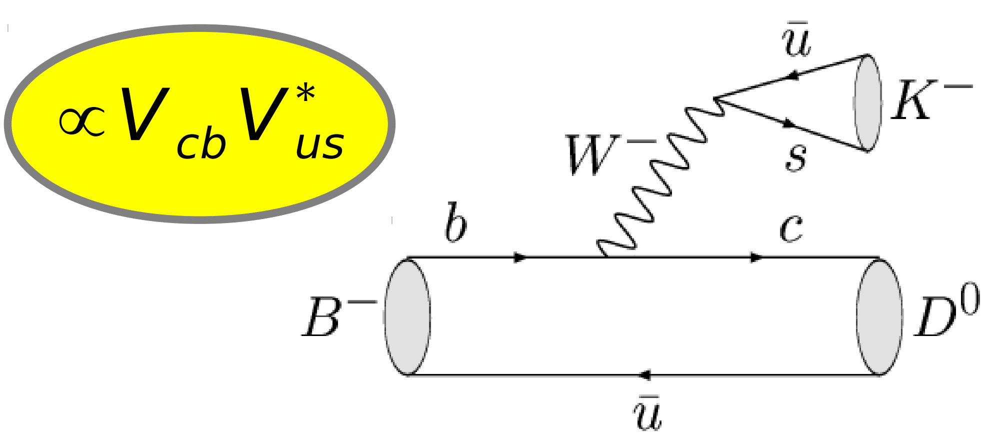
Importance of γ from B→DK

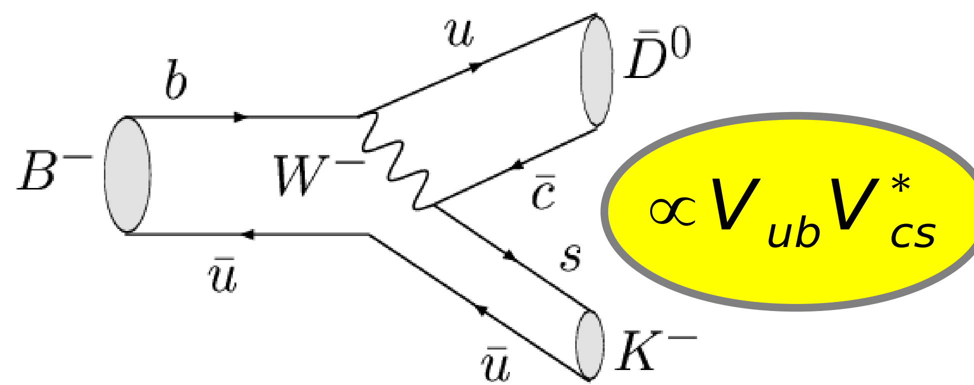
- γ plays a unique role in flavour physics

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

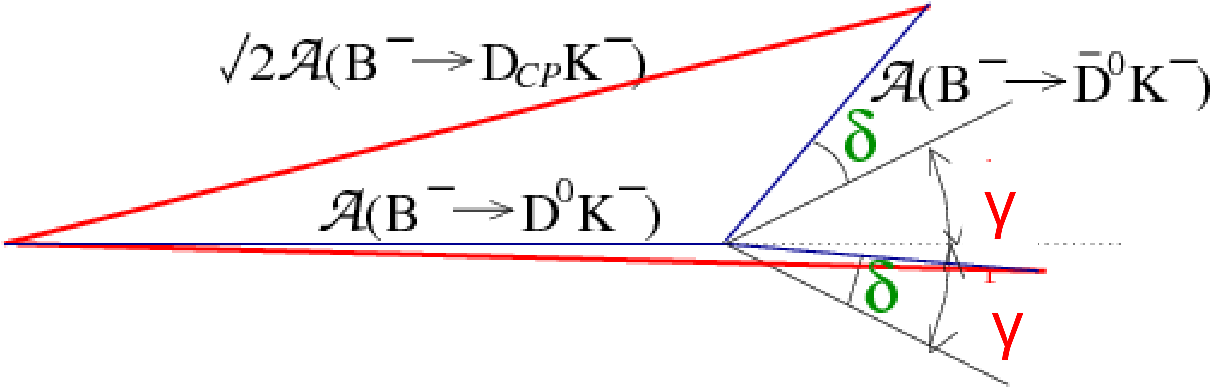




Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

Why is B → DK so nice?

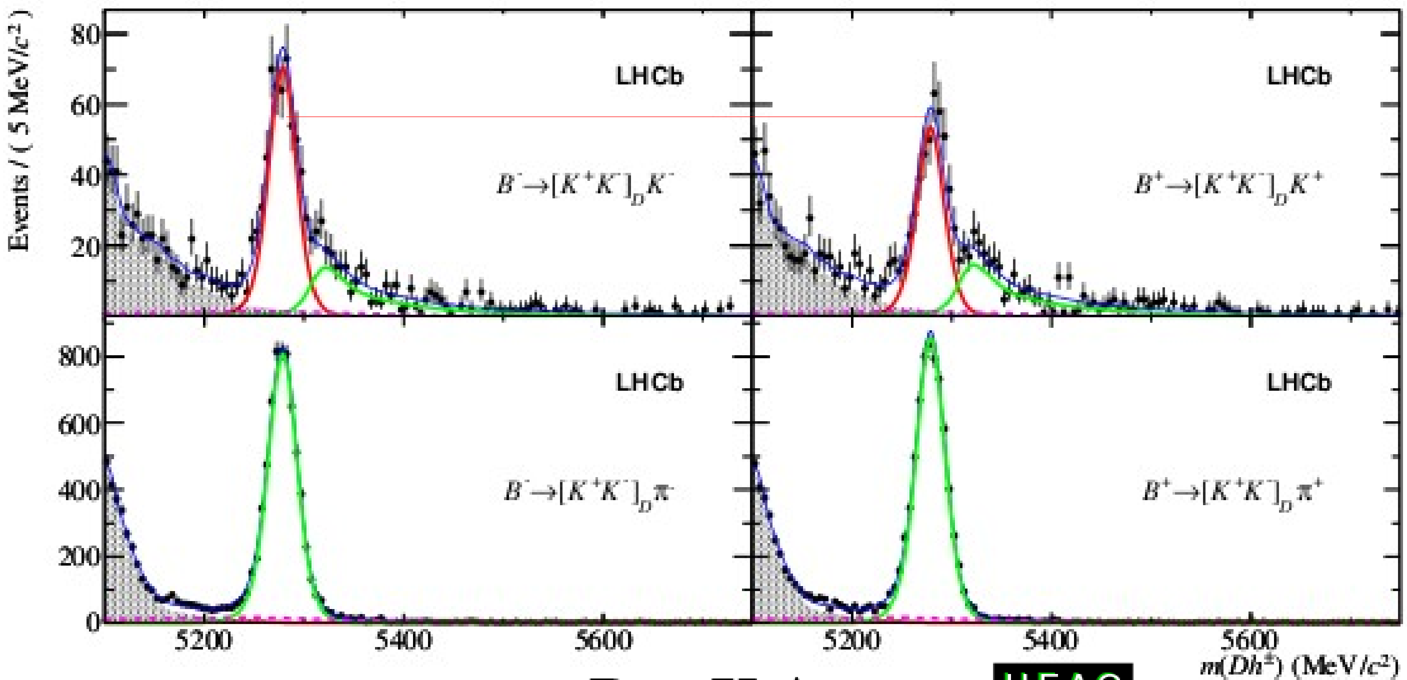
- For theorists:
  - theoretically clean: no penguins; factorisation works
  - all parameters can be determined from data
- For experimentalists:
  - many different observables (different final states)
  - all parameters can be determined from data
  - γ & δ_B (weak & strong phase differences), r_B (ratio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

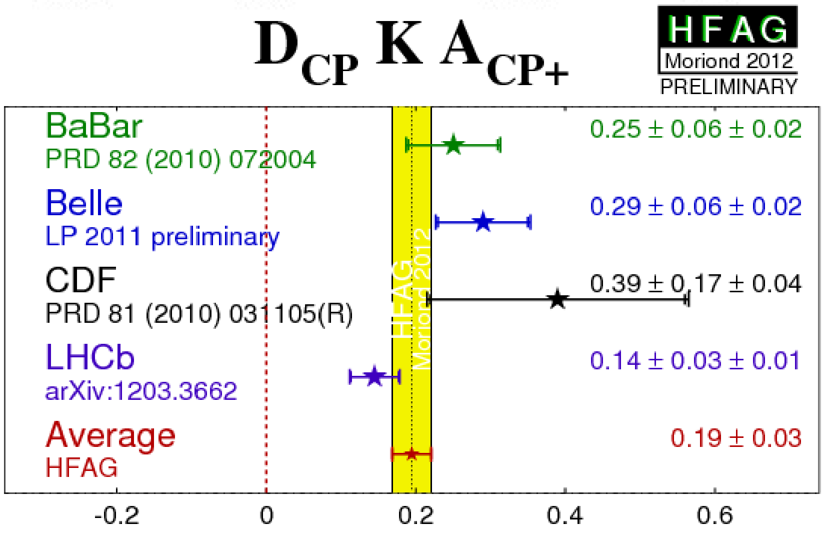


Latest results on B→DK : GLW

LHCb arXiv:1203.3662

Evidence for direct CP violation (γ≠0)

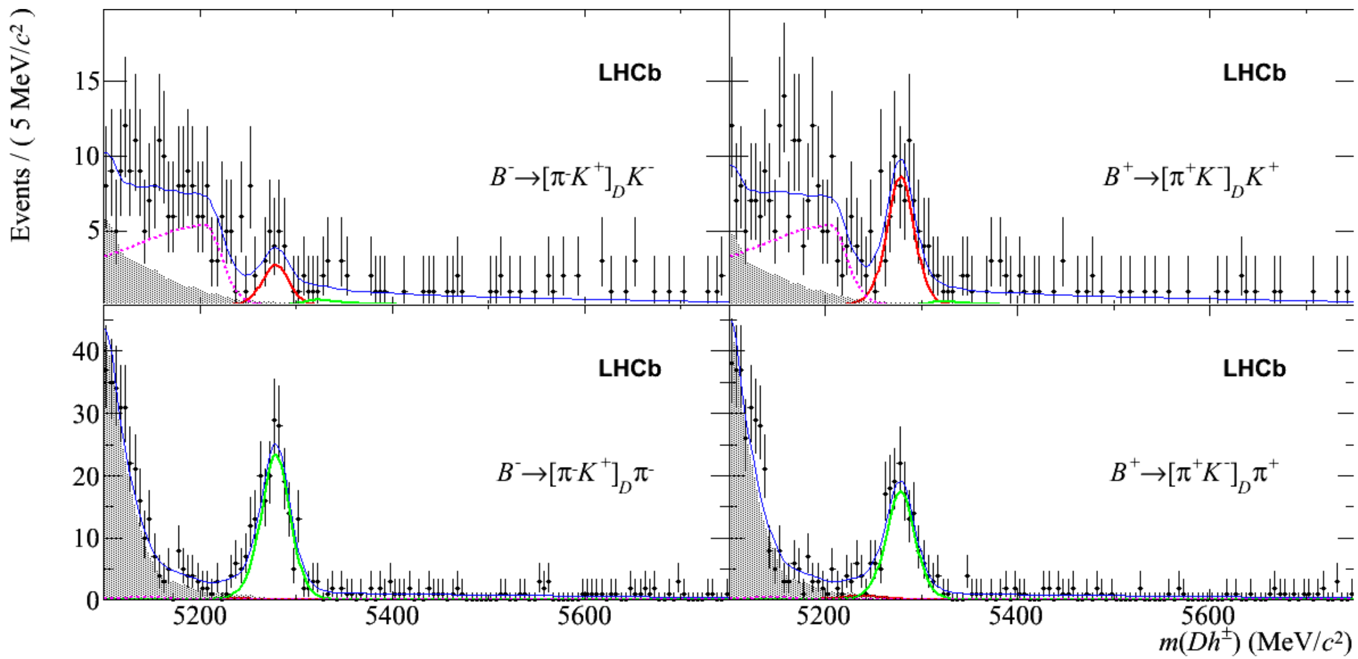


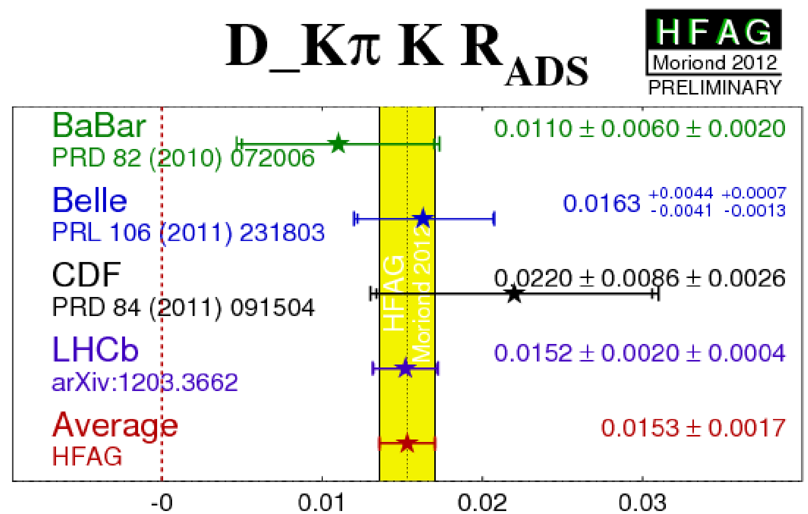


Latest results on B → DK : ADS

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

LHCb arXiv:1203.3662





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!

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

LHCb PRL 108 (2012) 111602

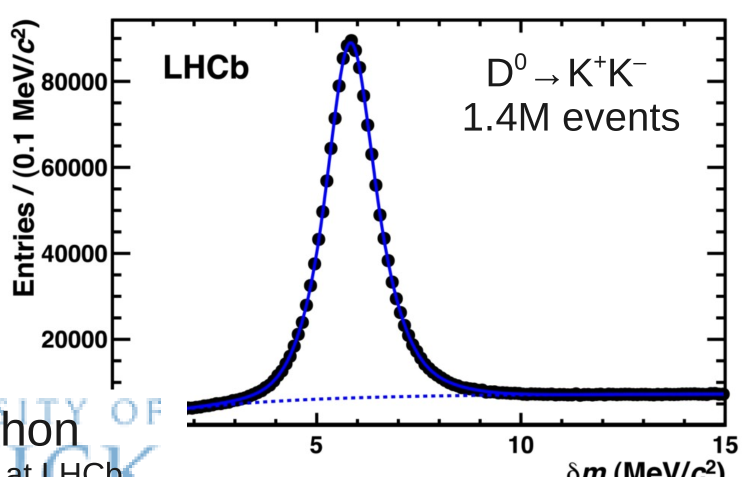
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \to f$, where D meson flavour is tagged by $D^{*+} \to D^0\pi^+$ decay

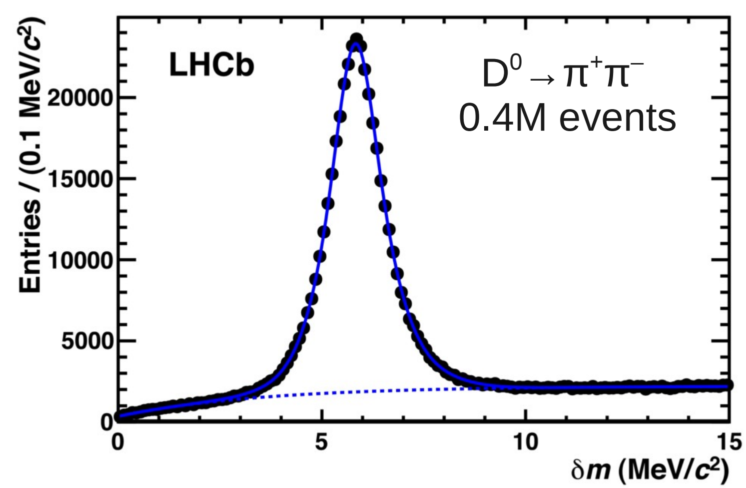
$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}^+) + A_{\rm P}(D^{*+}).$$

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)

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

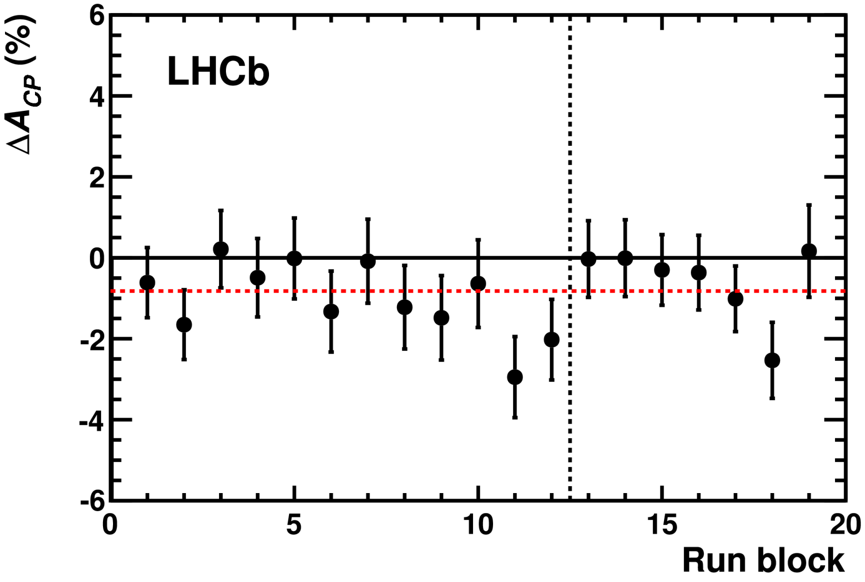




Evidence for CP violation in $D \to h^+h^-$ decays

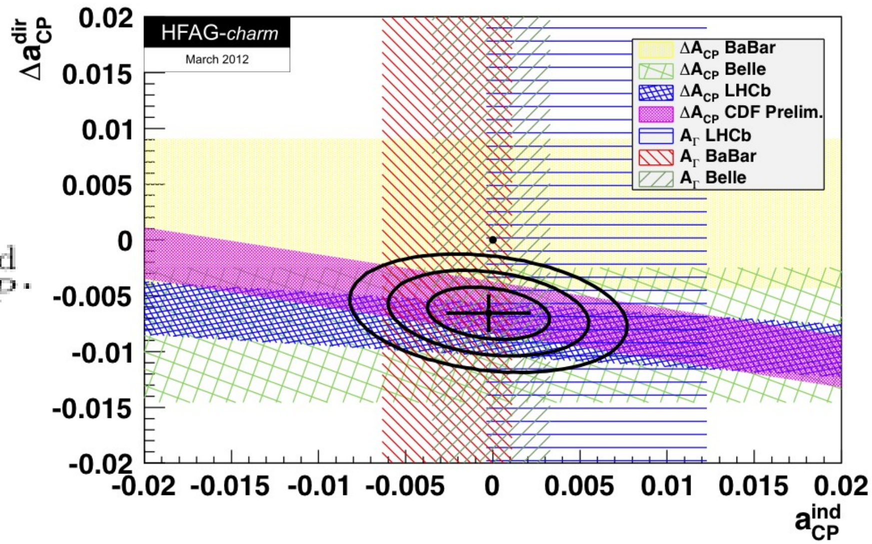
LHCb PRL 108 (2012) 111602

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



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

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

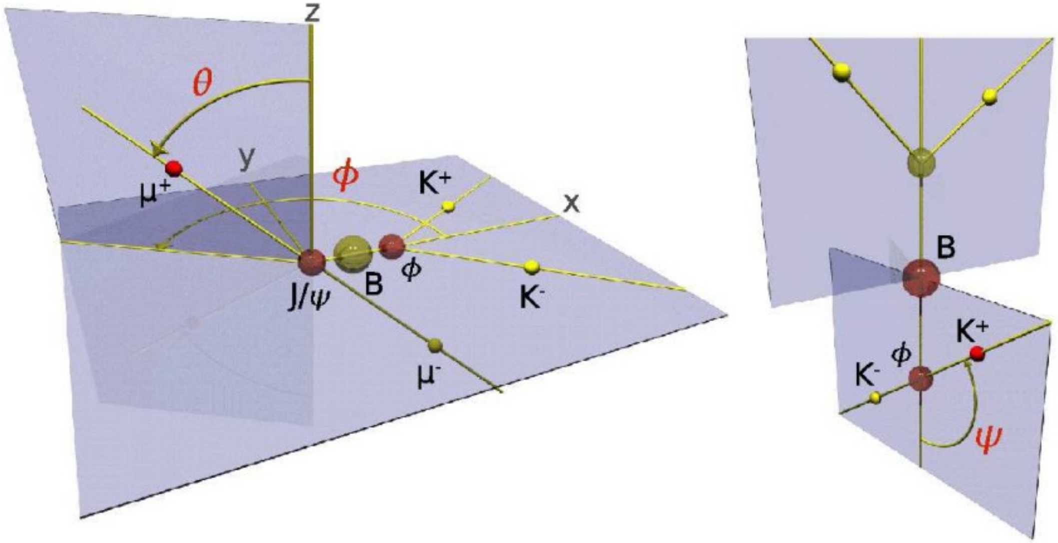


Evidence for CP violation in D $\rightarrow$ h^+h^- decays

- 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 $D0 \rightarrow \pi+\pi-$ and $D0 \rightarrow K+K-$ arXiv:1203.3131
  - A consistent picture for large penguins in D $\rightarrow$ pi+pi-, K+K- arXiv:1203.6659

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

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



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

Time-dependent CP Violation Formalism

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

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, (1 + a) \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right] .$$

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CP violating asymmetries

CP conserving parameter

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

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

$B_s \to J/\psi\phi$ formalism

Differential decay rate:

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

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

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta,\psi,\varphi)$
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	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

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

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

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

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

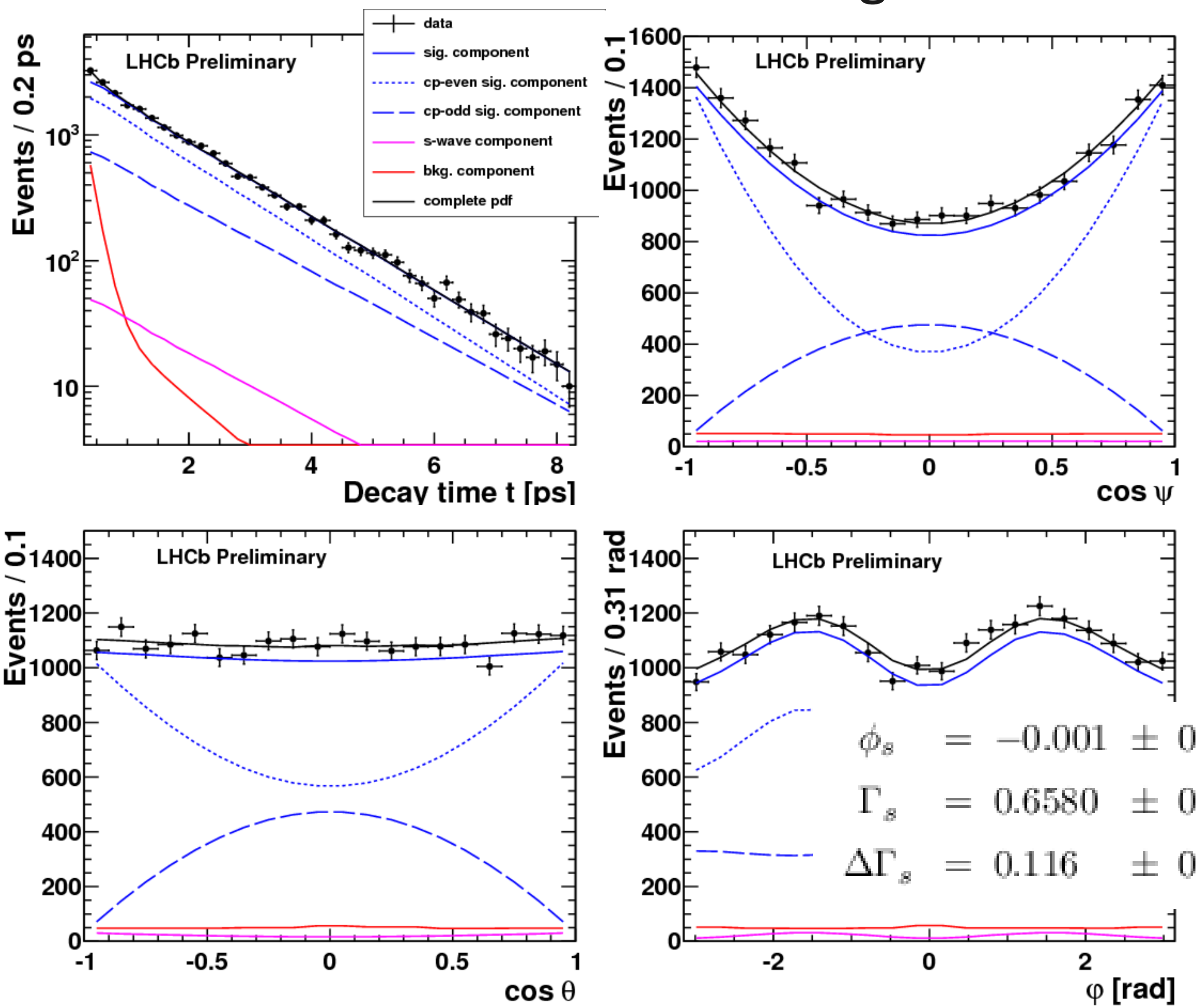
$$|\bar{A}_\perp(t)|^2 = |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right],$$

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

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

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

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



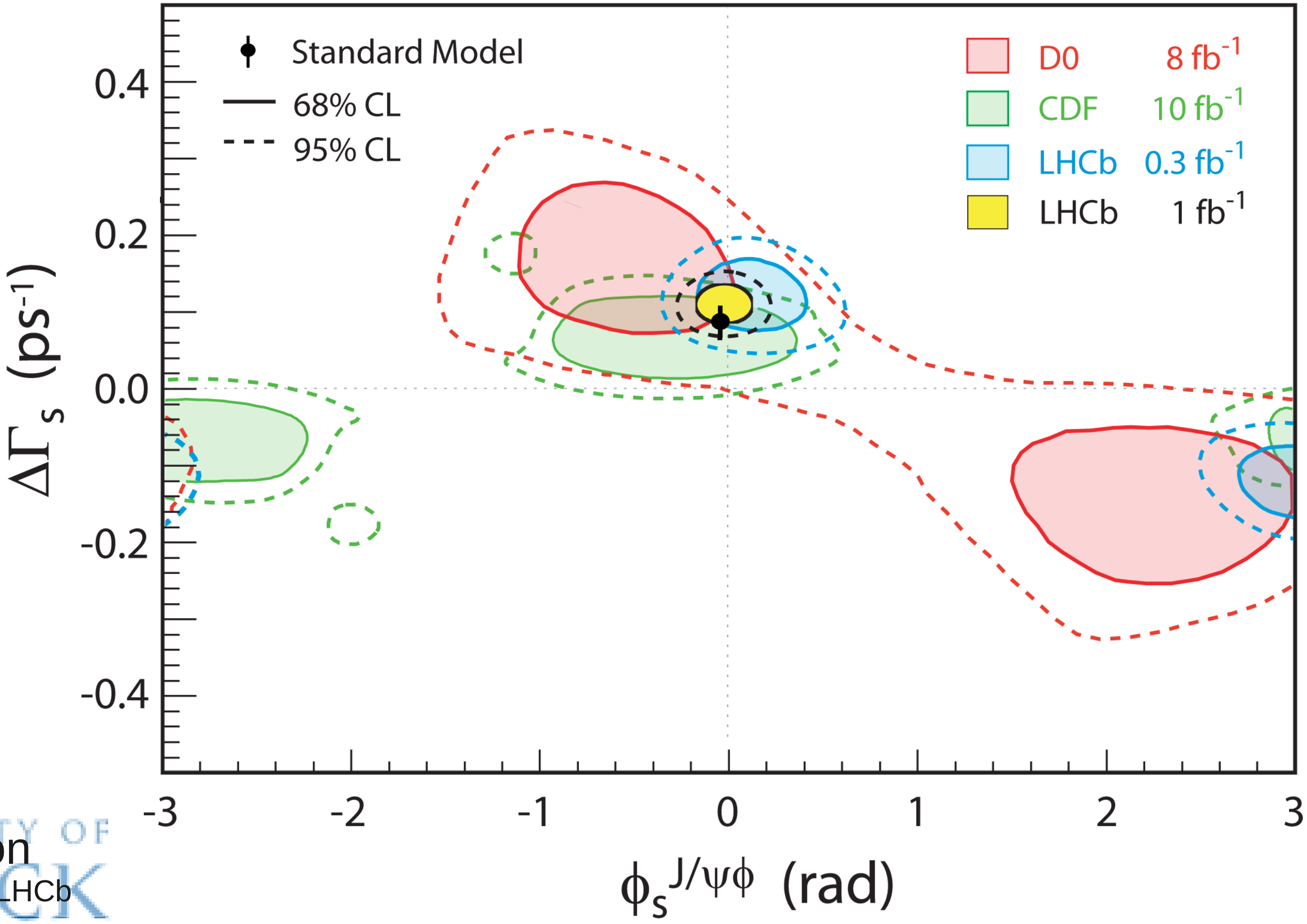
LHCb-PAPER-2011-028
0.37/fb
LHCb-CONF-2012-002
LHCb-PAPER-2012-005
LHCb-PAPER-2012-006
All 1/fb

LHCb-CONF-2012-002

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

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

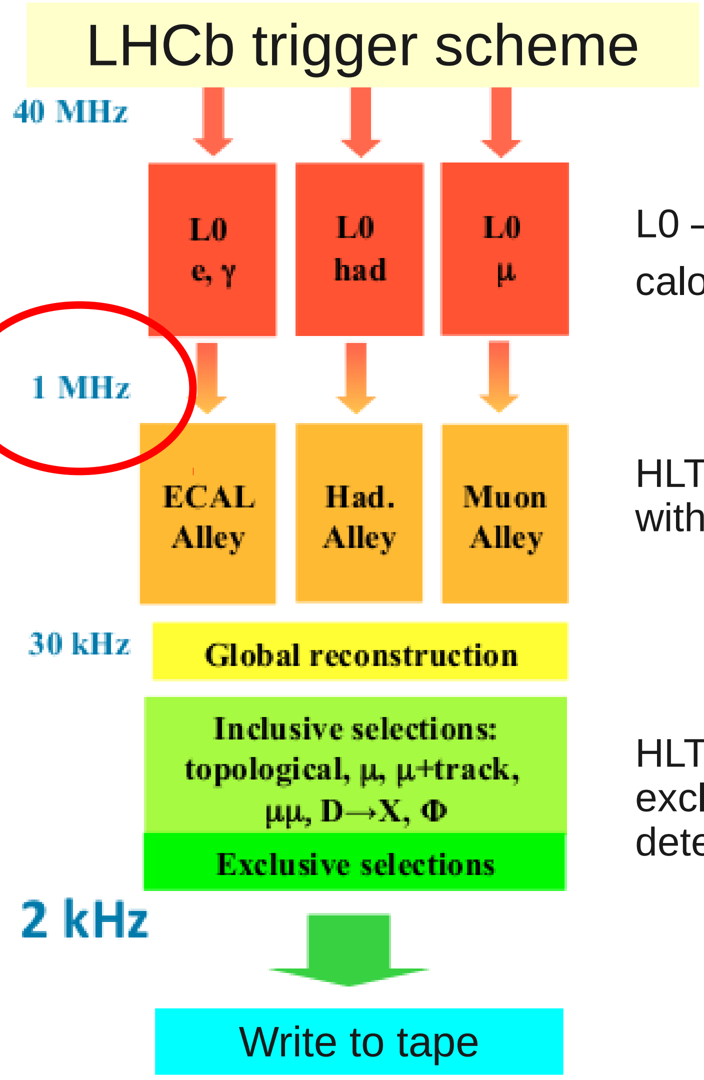
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

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

Handles

- high p_T signals (muons)
- displaced vertices



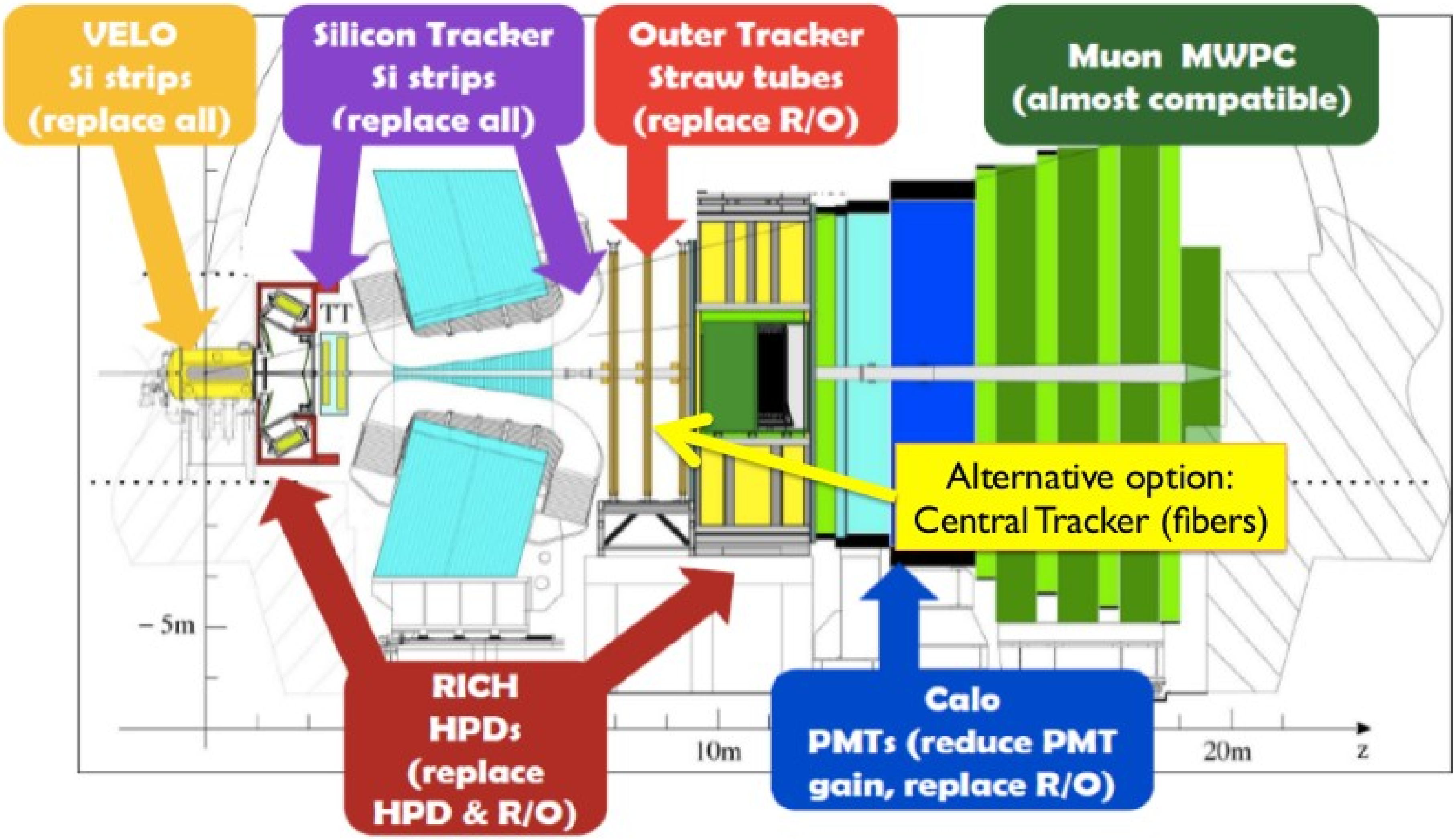
L0 – high p_T signals in calorimeters & muon chambers

HLT1 – associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

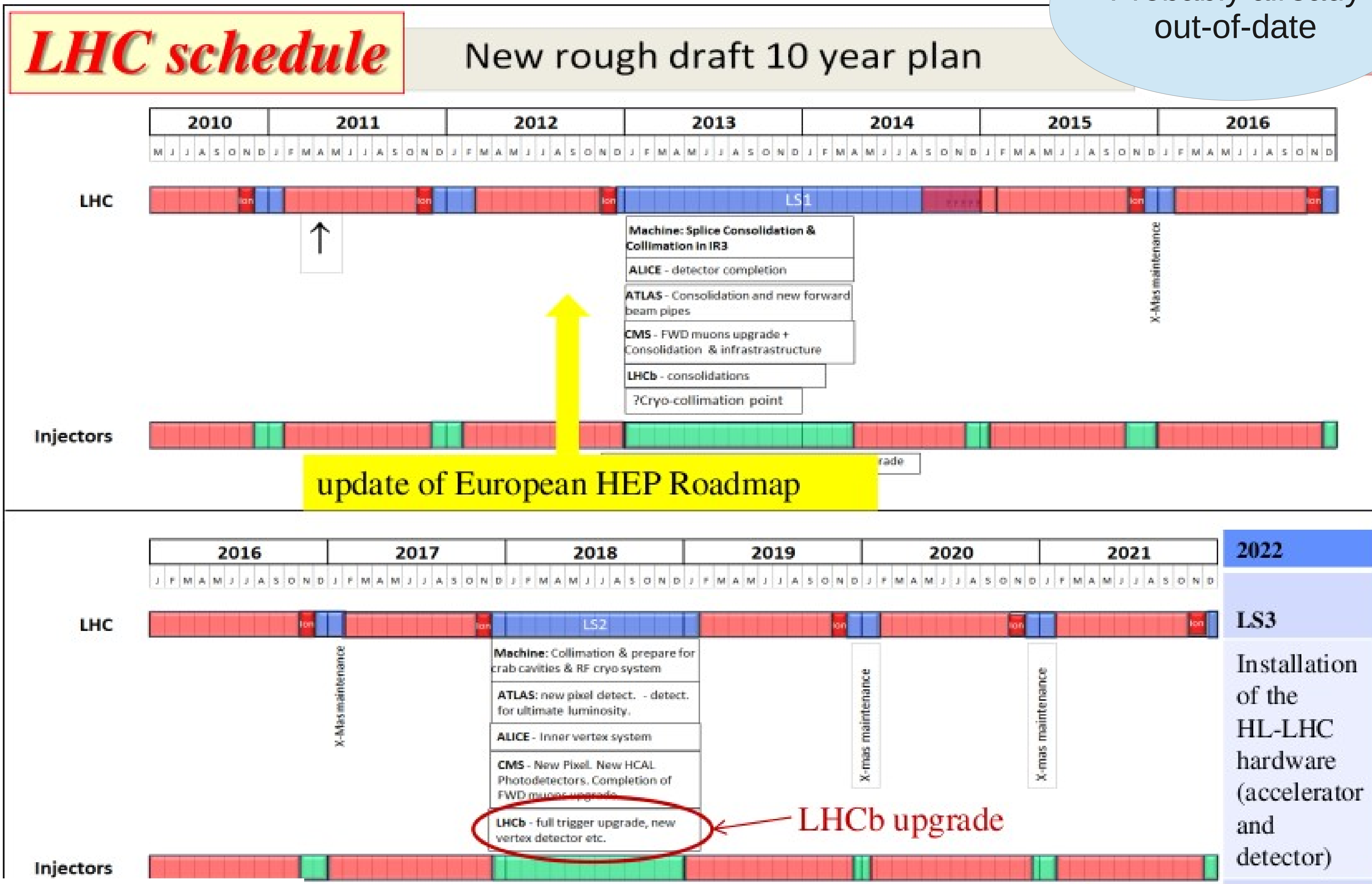
Limitation is at 1 MHz L0 o/p

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_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	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	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	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

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