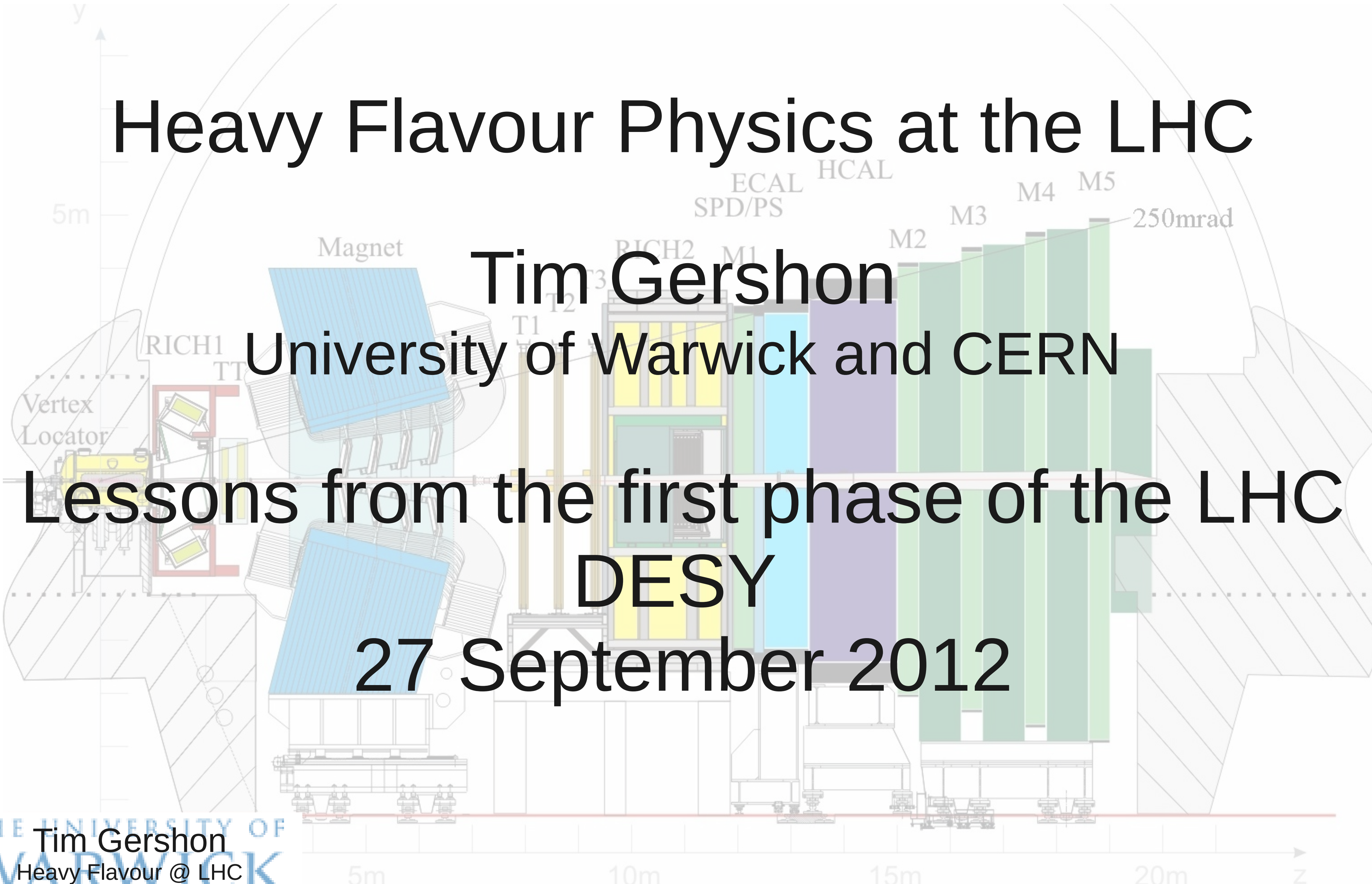
Heavy Flavour Physics at the LHC

Tim Gershon
University of Warwick and CERN

Lessons from the first phase of the LHC

DESY

27 September 2012



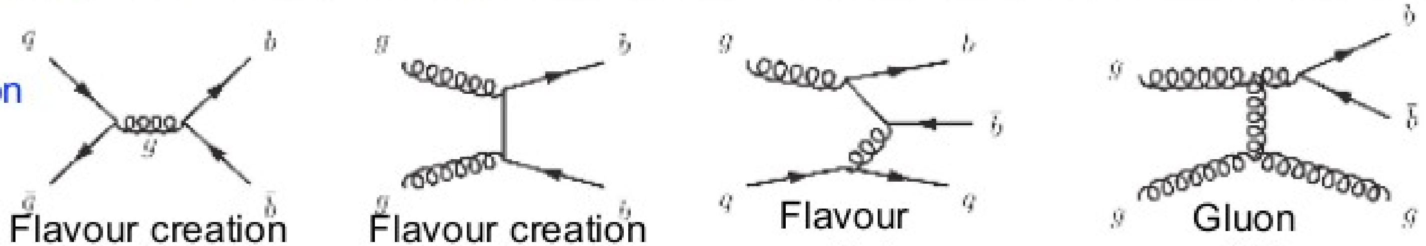
Outline

- Heavy flavour production at the LHC
- The LHCb experiment
- Selected highlights of results in rare decays
- Selected highlights of results in CP violation
- The LHCb upgrade

Flavour physics at hadron colliders

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

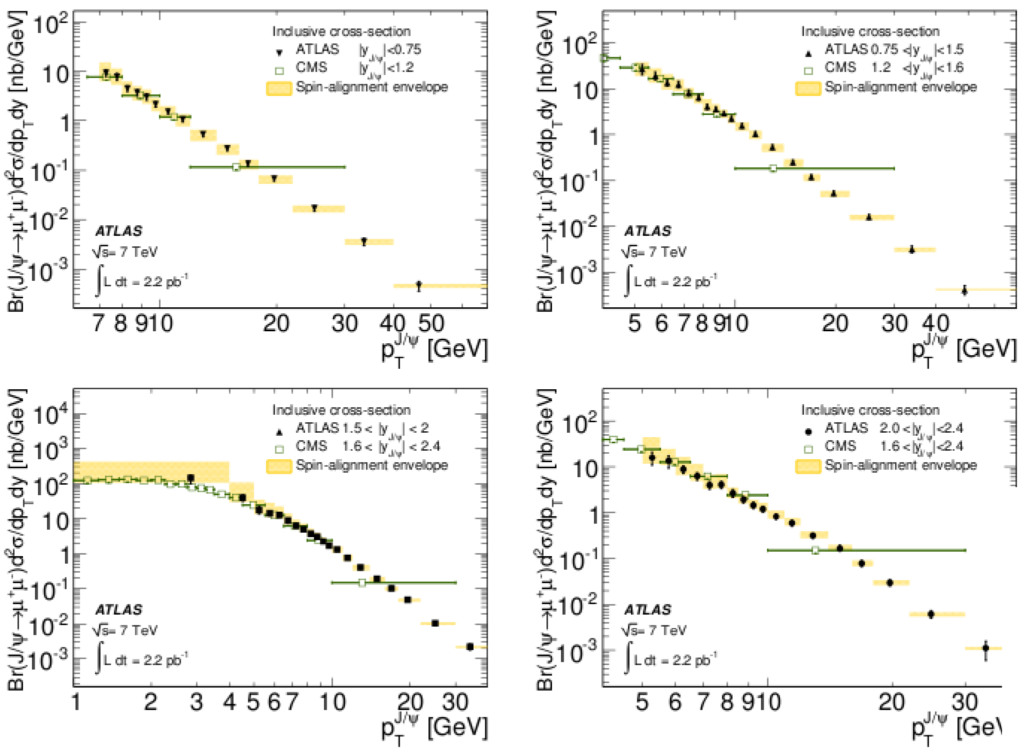
Flavour excitation

Gluon splitting

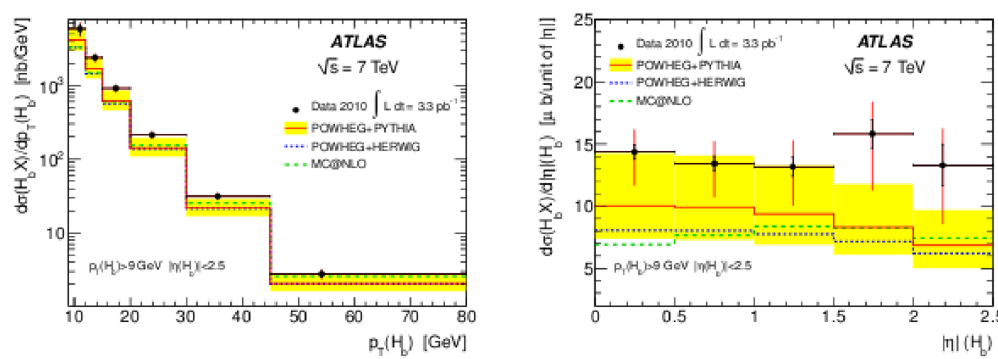
from Val Gibson HCPSS 2009

Heavy flavour production @ ATLAS

"Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton-proton collisions at √s = 7 TeV"
Nucl. Phys. B 850 (2011) 387



"Measurement of the b-hadron production cross section using decays to D*+ μ- X final states in pp collisions at √s = 7 TeV with the ATLAS detector"
Nucl. Phys. B 864 (2012) 341

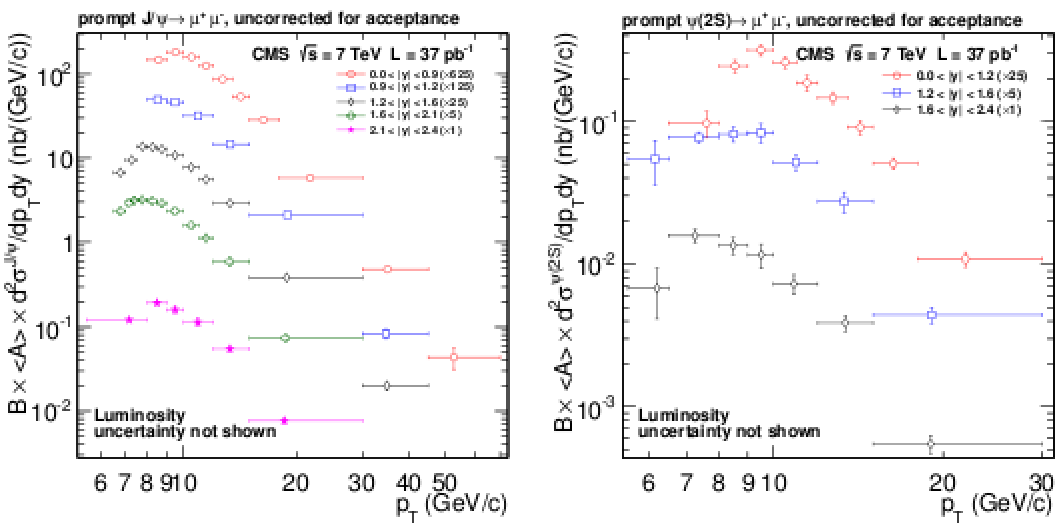


(a) (b)

Heavy flavour production @ CMS

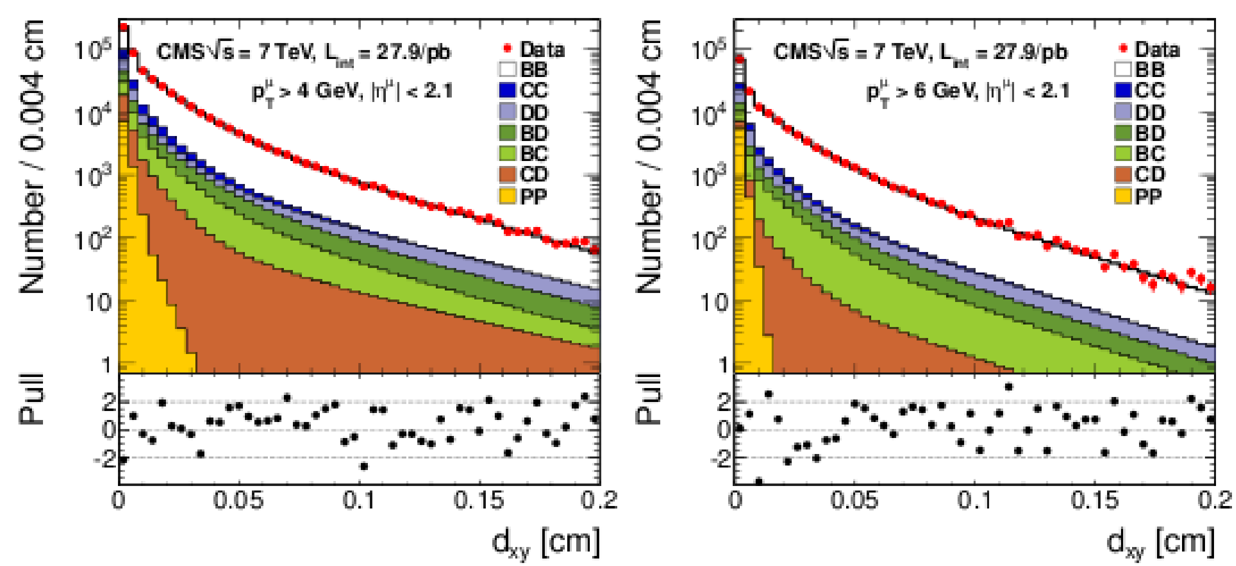
"J/ψ and ψ(2S) production in pp collisions at $\sqrt{s}$ = 7 TeV "

J. High Energy Phys. 02 (2012) 011



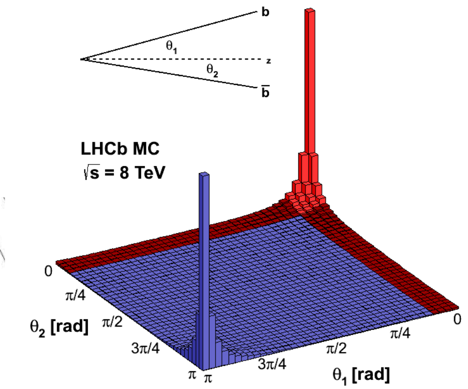
"Measurement of the cross section for production of b b-bar X, decaying to muons in pp collisions at s√=7 TeV"

J. High Energy Phys. 06 (2012) 110

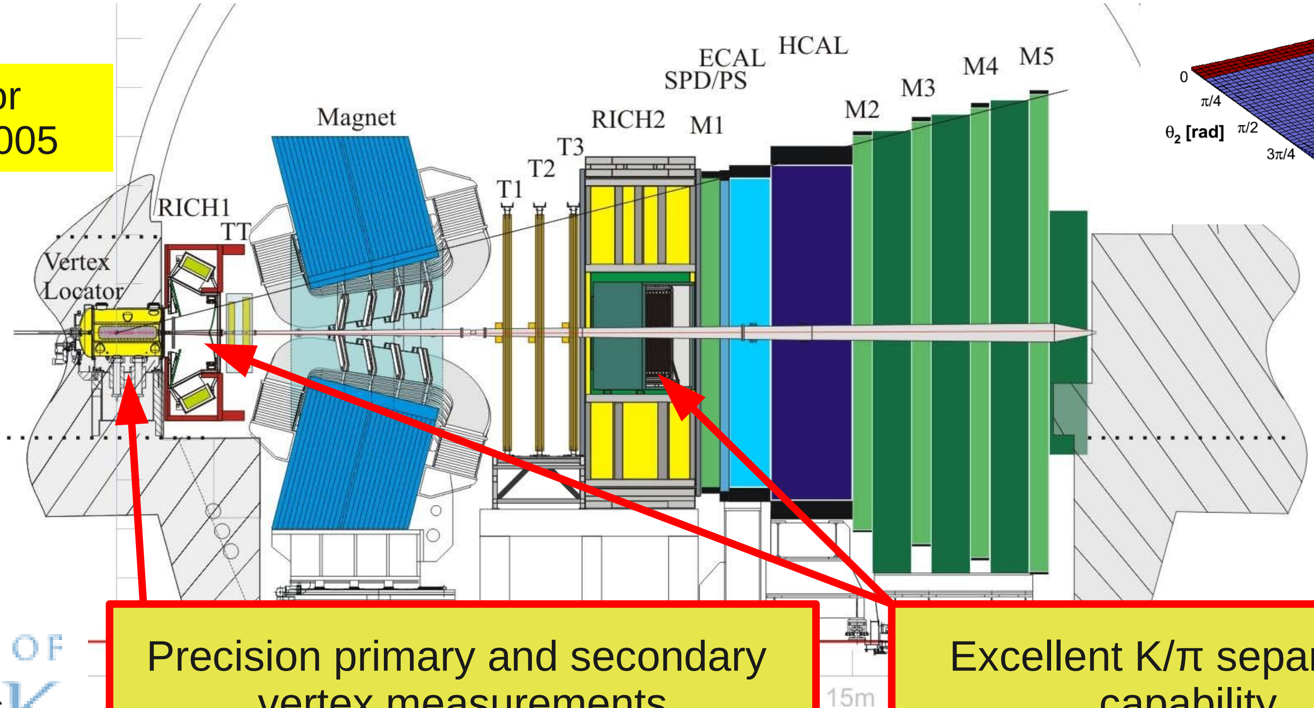


Geometry

- 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



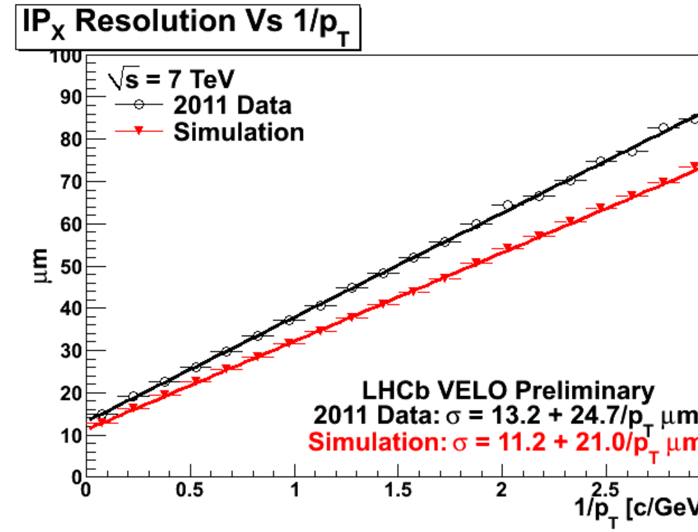
The LHCb Detector
JINST 3 (2008) S08005

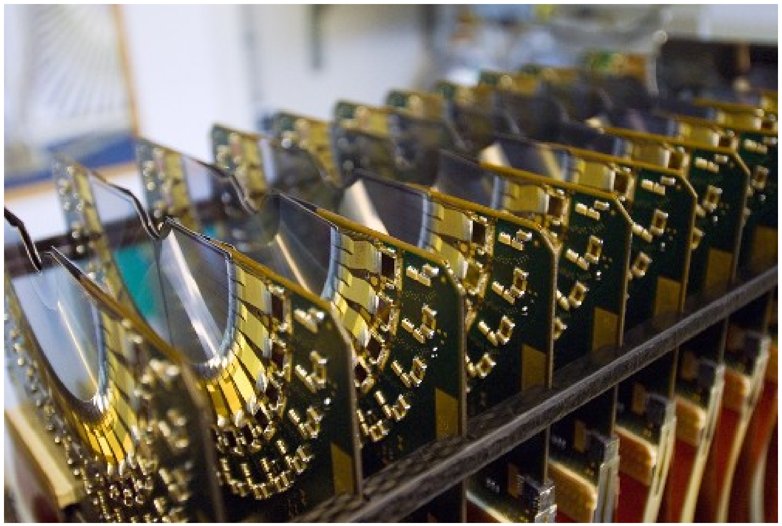


Precision primary and secondary vertex measurements

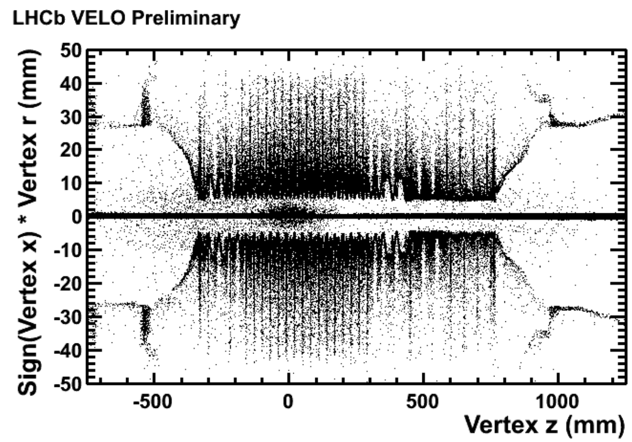
Excellent K/π separation capability

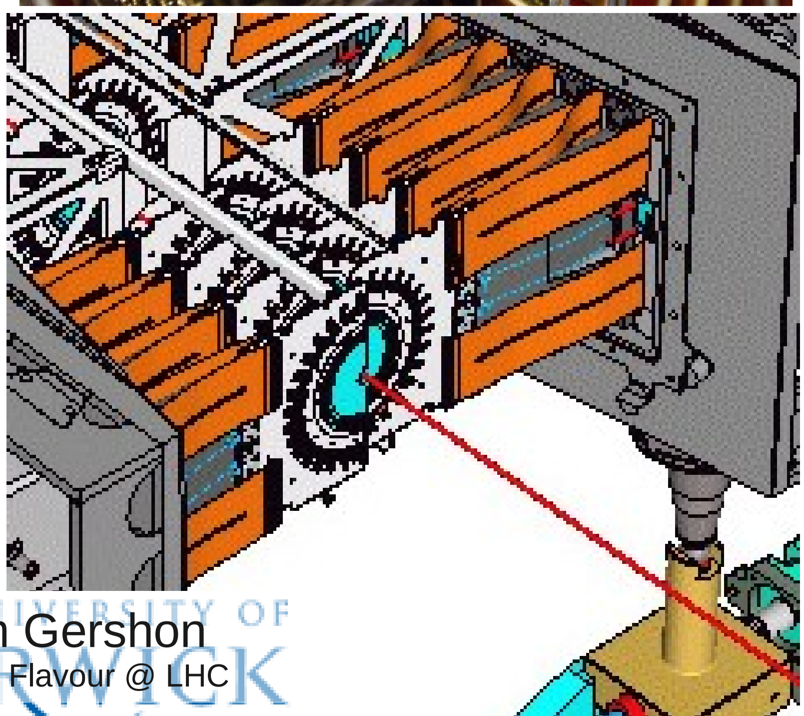
VELO

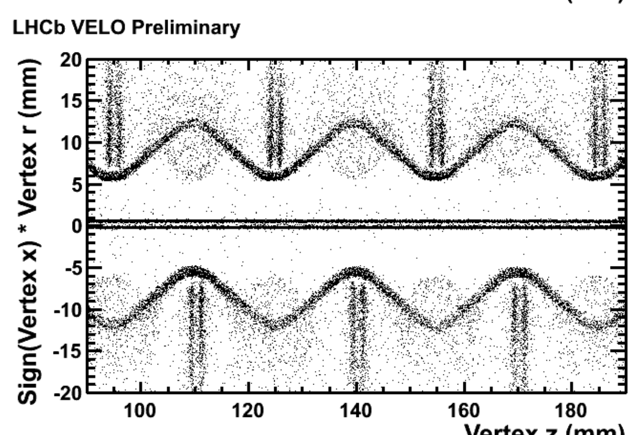




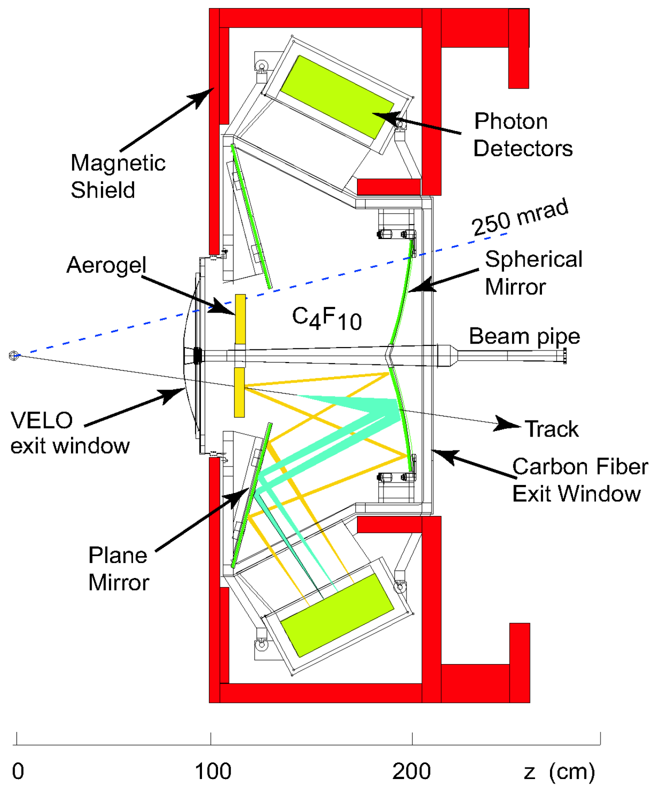
Material imaged used beam gas collisions



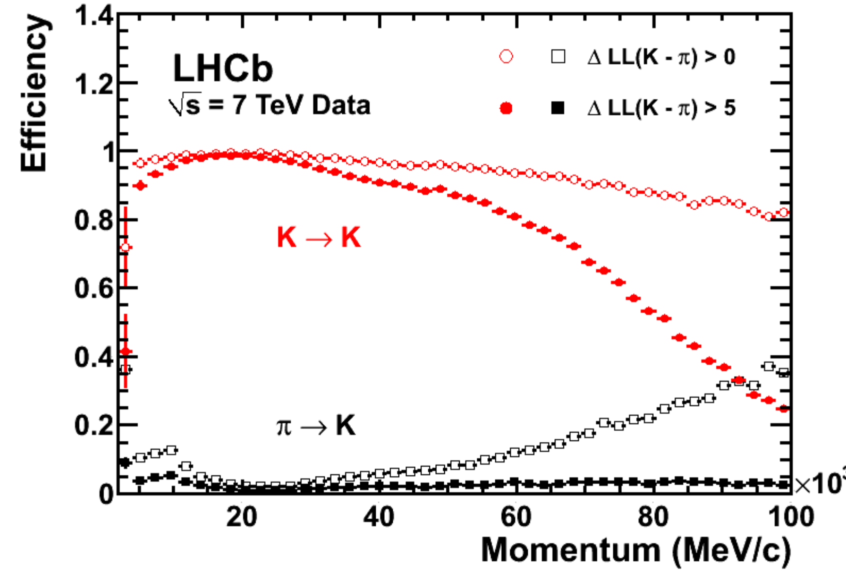




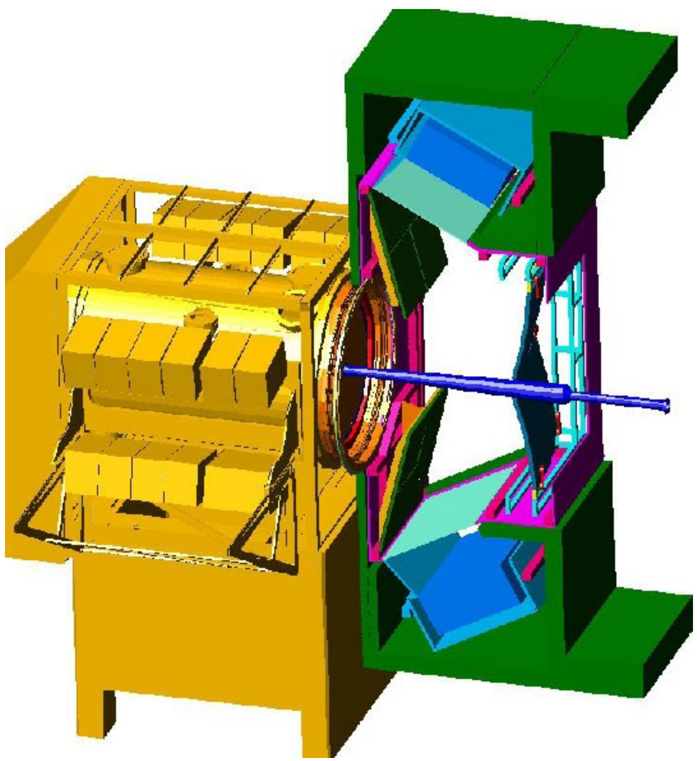
RICH



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)



Efficiency
LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
Momentum (MeV/c)
×10³

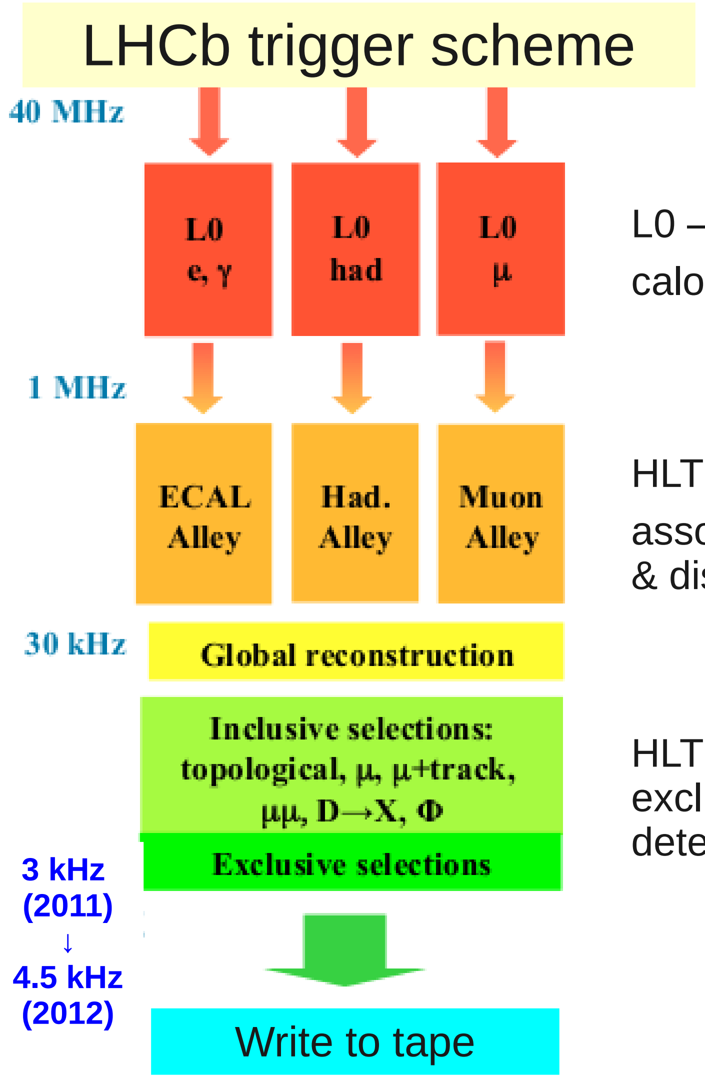


The all important trigger

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



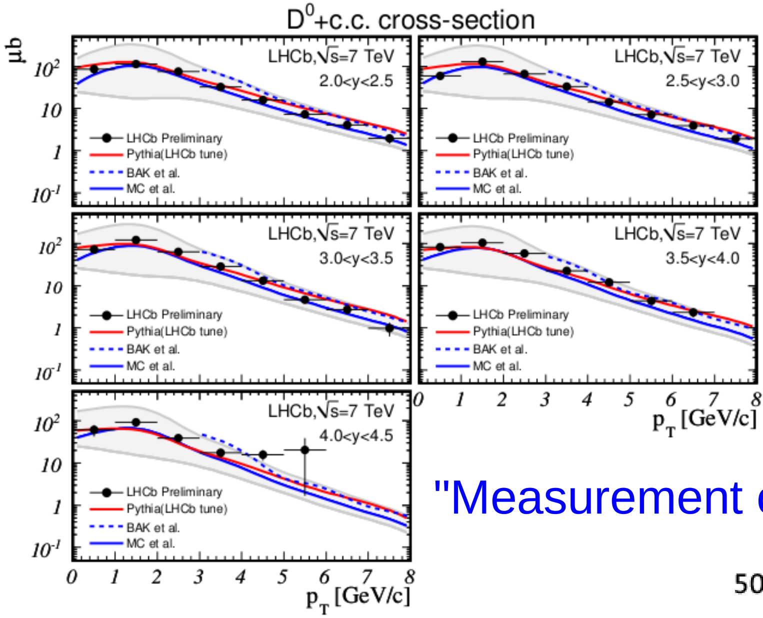
L0 – high p_T signals in calorimeters & muon chambers

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

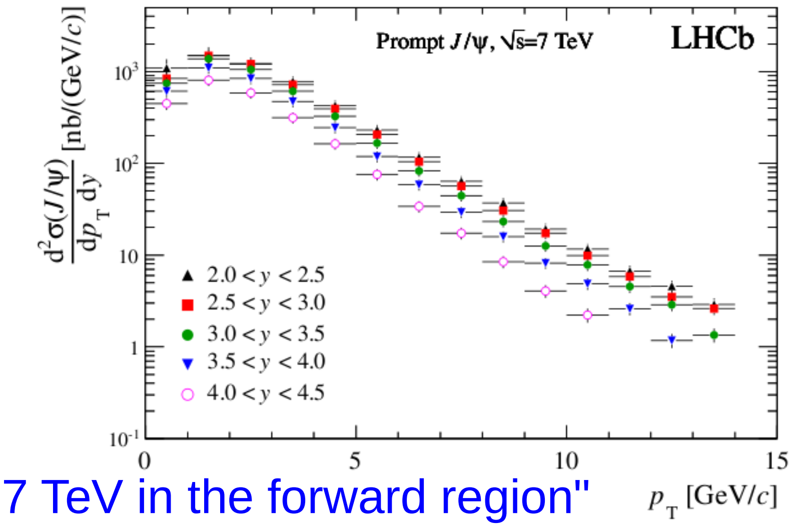
HLT2 – inclusive signatures + exclusive selections using full detector information

Heavy flavour production @ LHCb

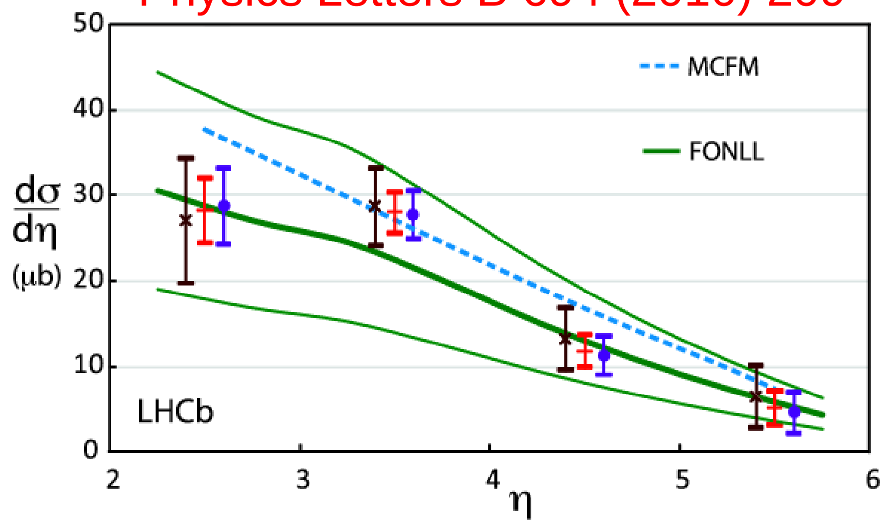
"Prompt charm production in pp collisions at √s = 7 TeV"
LHCb-CONF-2010-013



"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

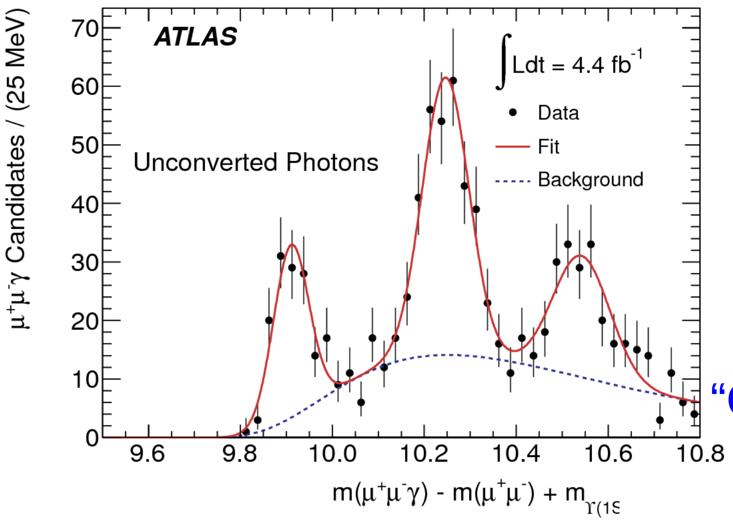


Observations of new states

(no, not the Higgs)

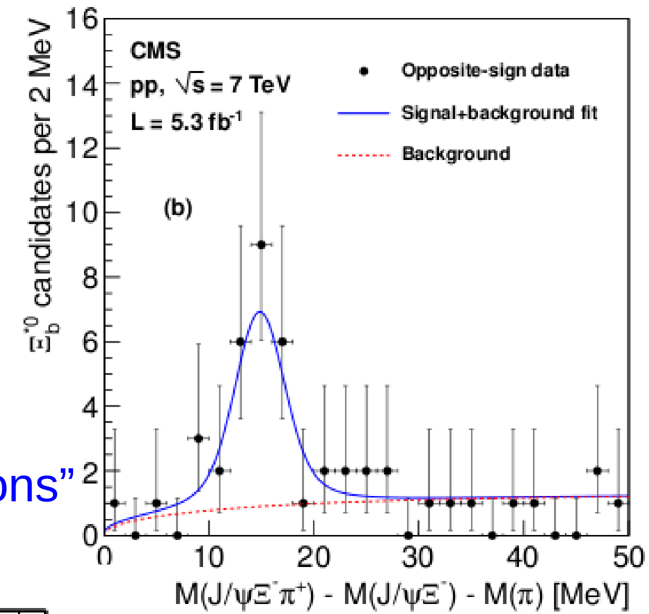
"Observation of a New χ_b State in Radiative Transitions to Υ(1S) and Υ(2S) at ATLAS"

Phys. Rev. Lett. 108 (2012) 152001



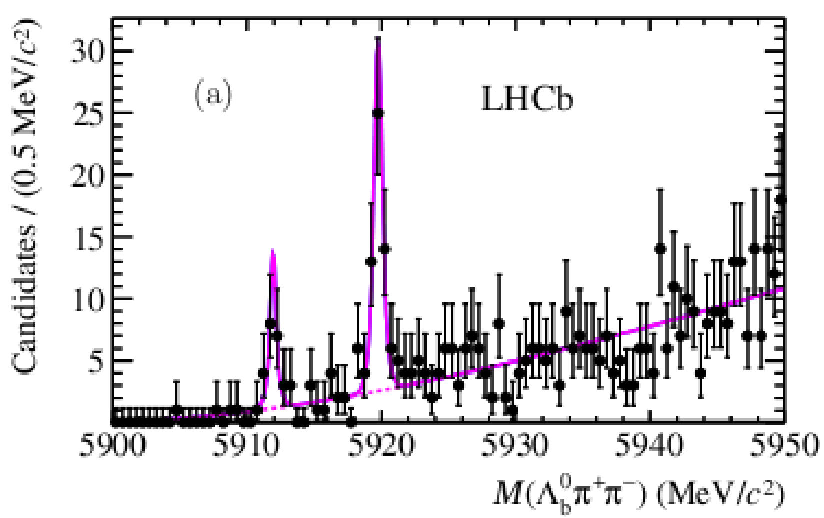
"Observation of a New Ξ_b Baryon"

Phys. Rev. Lett. 108 (2012) 252002



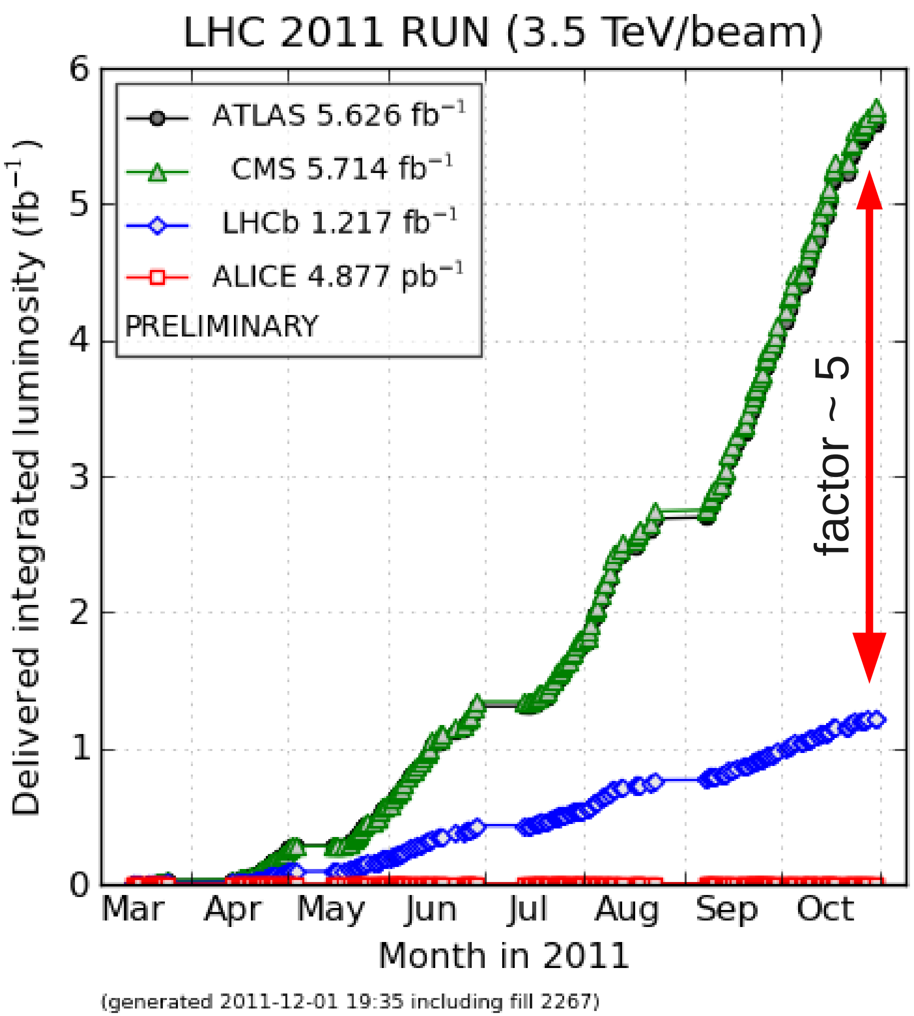
"Observation of excited Λ^0_b baryons"

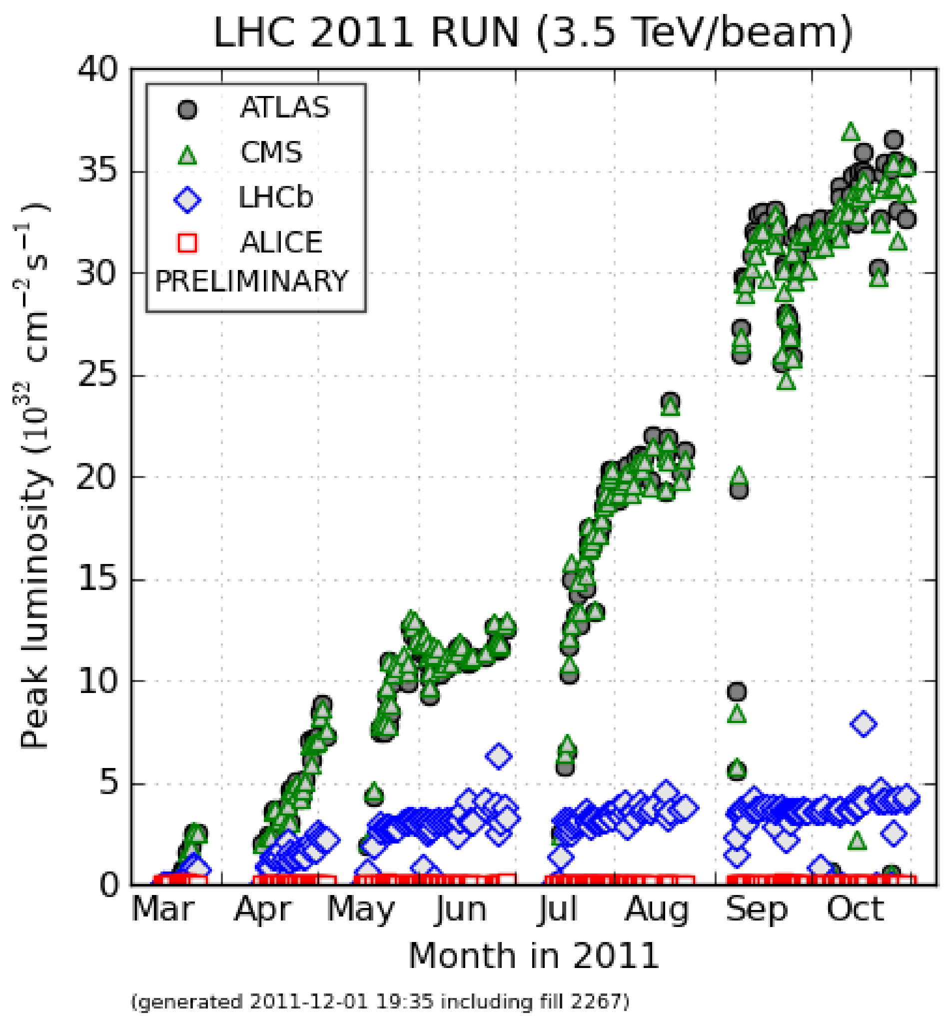
arXiv:1205.3452



The LHC

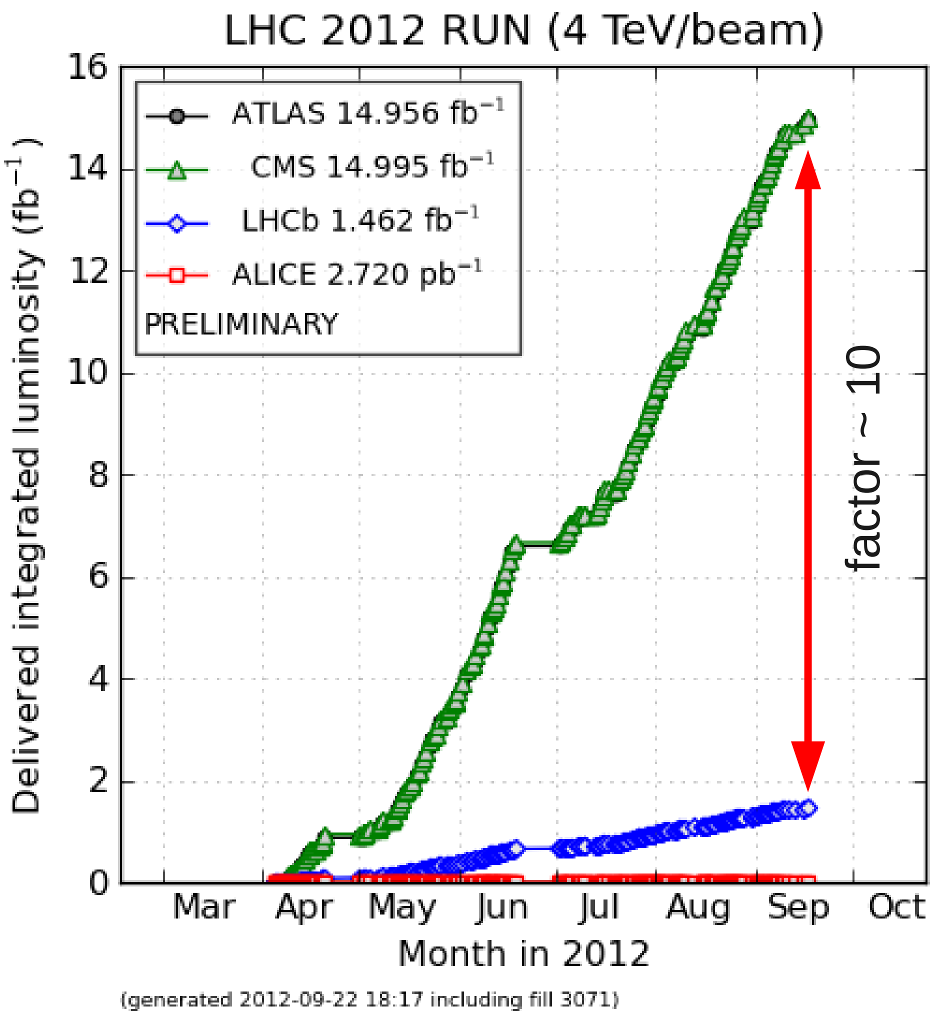
LHC performance 2011

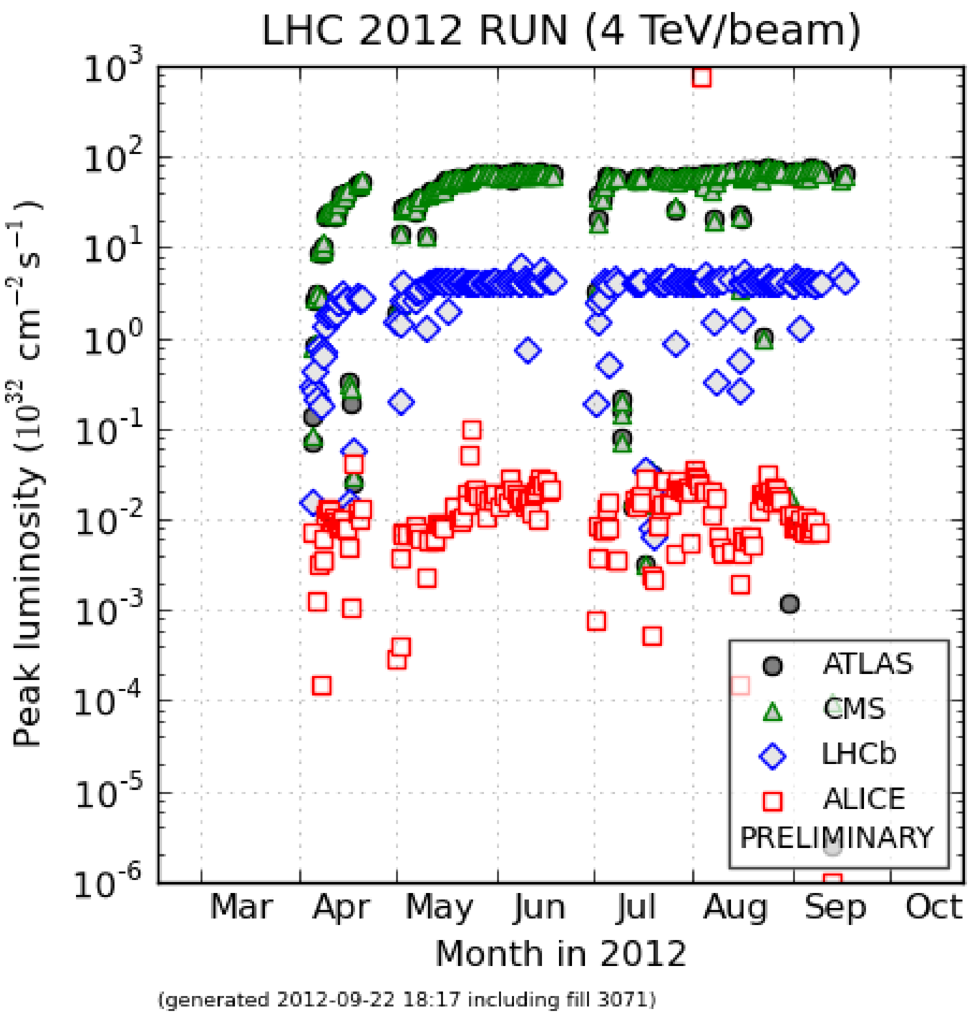




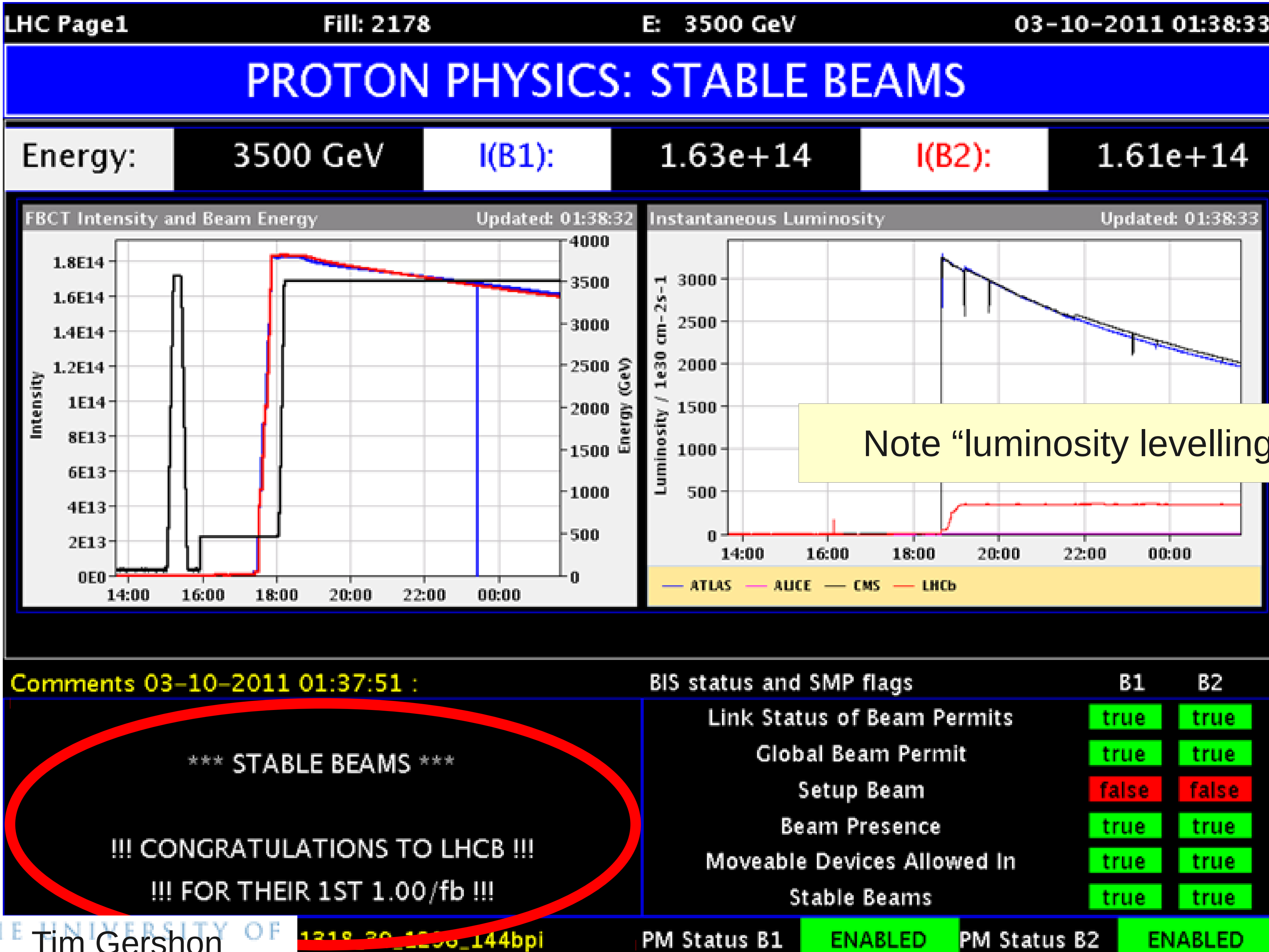
LHCb design luminosity: 2 10^{32}/cm^2/s

LHC performance 2012





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



Note “luminosity levelling”

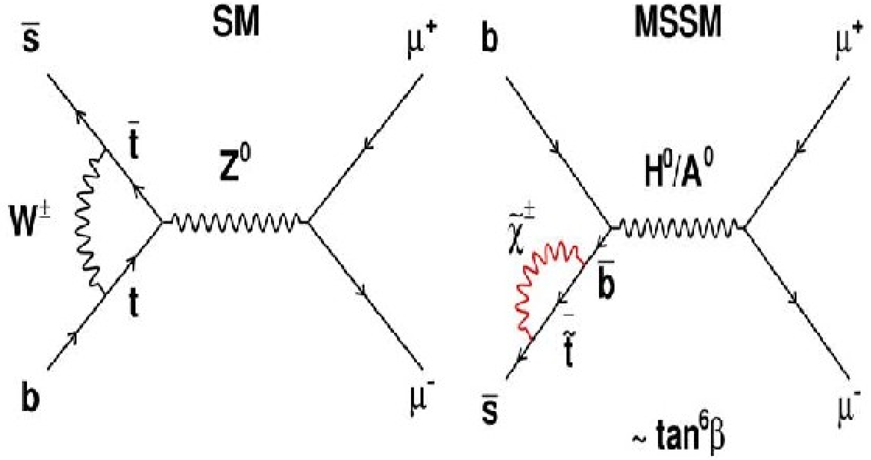
Selected highlights of results
Rare Decays

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

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

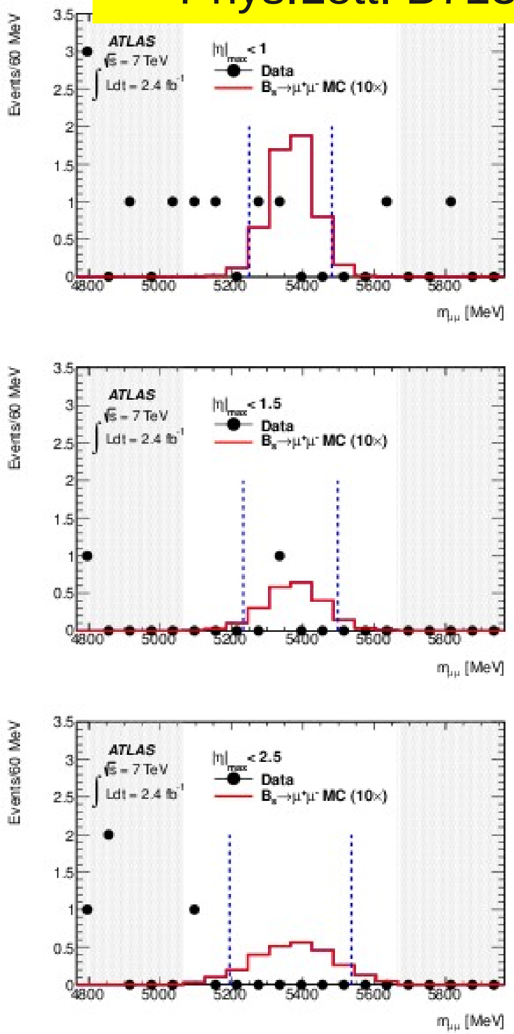


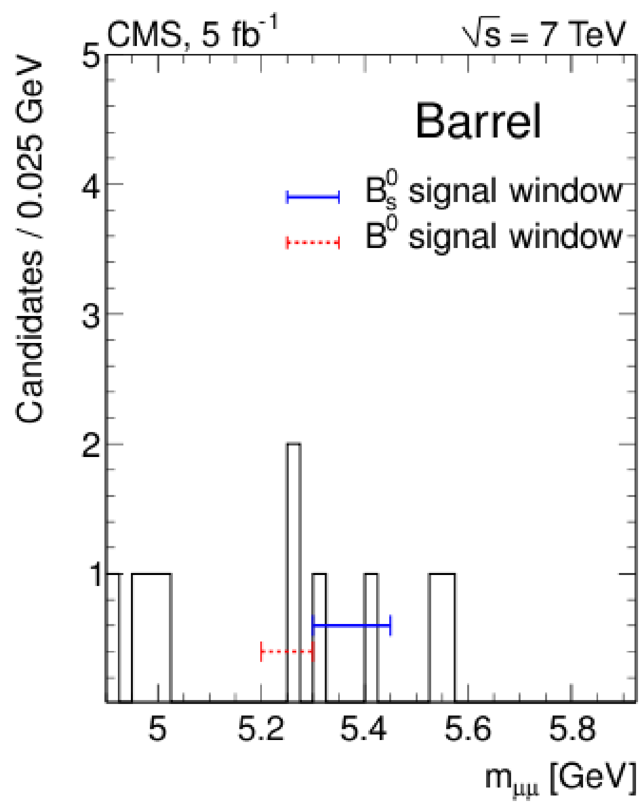
$B(B_s \to \mu^+\mu^-)^{SM} = (3.2 \pm 0.3) \times 10^{-9}$ $\quad$ $B(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta/M^4_{A0}$

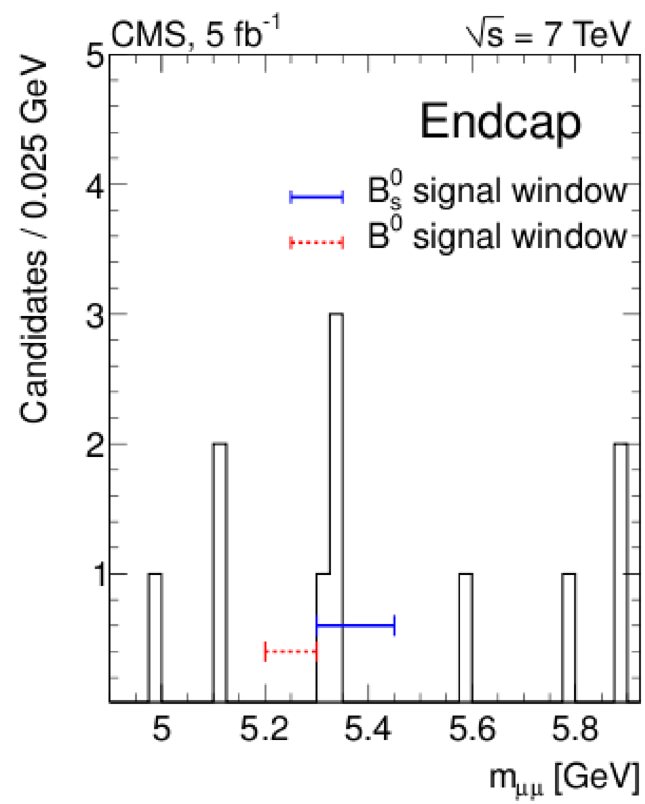
Latest results on $B_s \to \mu^+\mu^-$

ATLAS (2.4/fb)
Phys.Lett. B713 (2012) 387

CMS (5/fb)
J. High Energy Phys. 04 (2012) 033



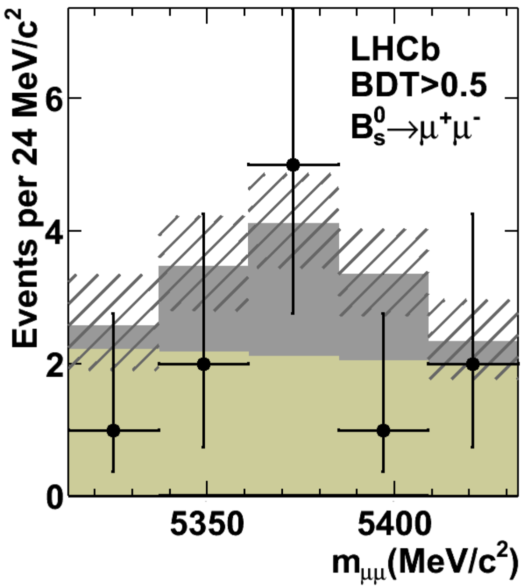


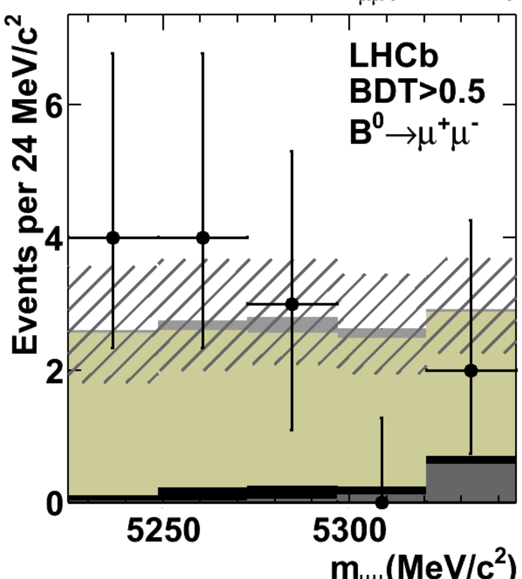


ATLAS $B(B_s \to \mu^+\mu^-) < 2.2\ (1.9) \times 10^{-8}$ @ 95% (90%) CL

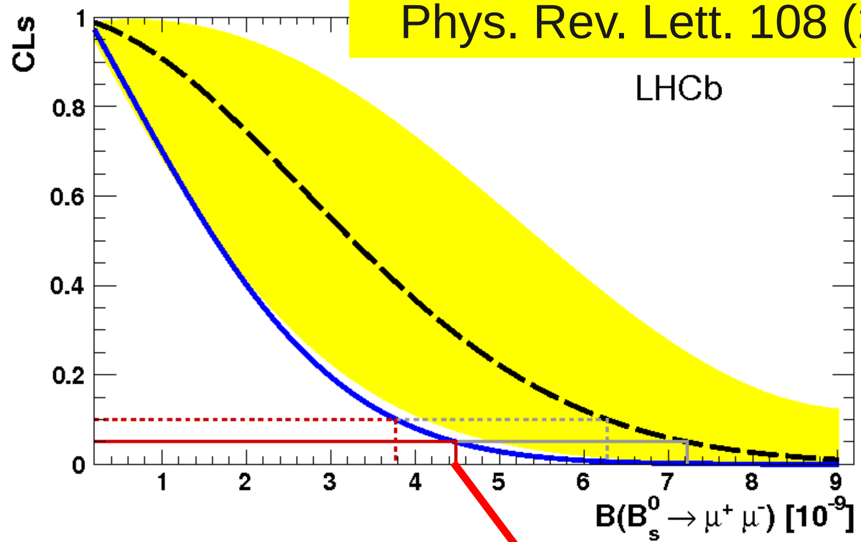
CMS $B(B_s \to \mu^+\mu^-) < 7.7\ (6.4) \times 10^{-9}$ @ 95% (90%) CL

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





LHCb (1/fb)
Phys. Rev. Lett. 108 (2012) 231801



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}

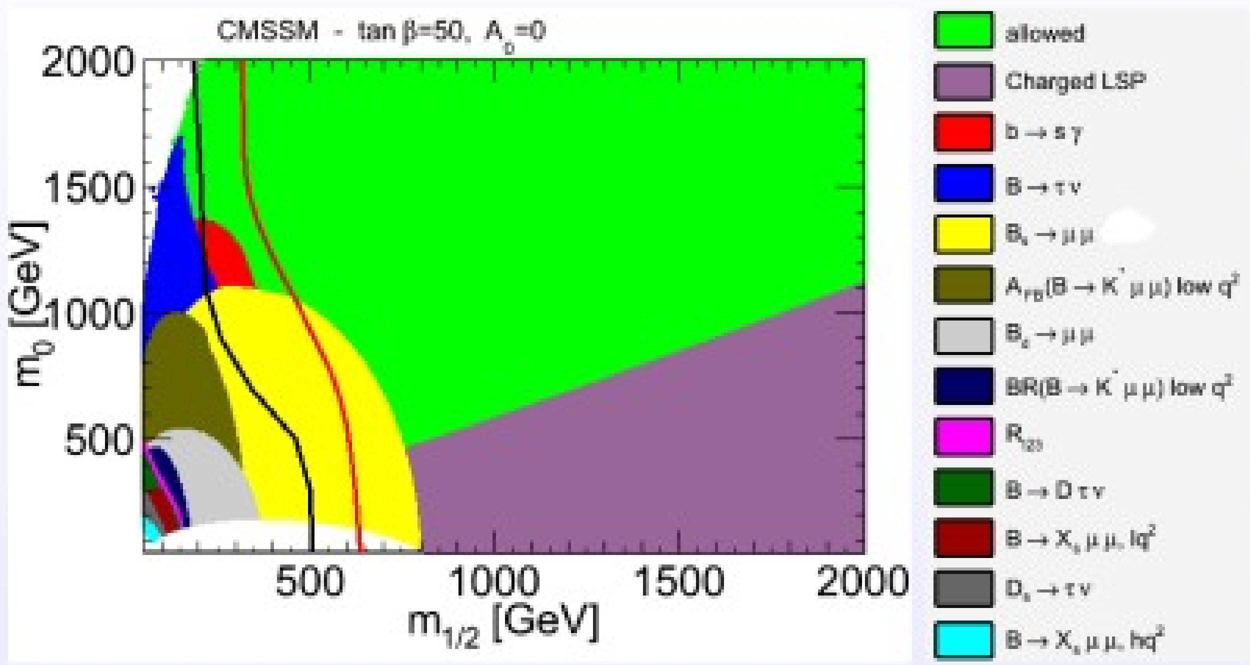
Standard Model expectation, e.g. $(3.2 \pm 0.3) \times 10^{-9}$
Buras et al, arXiv:1208.0934

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

Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2 x 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+

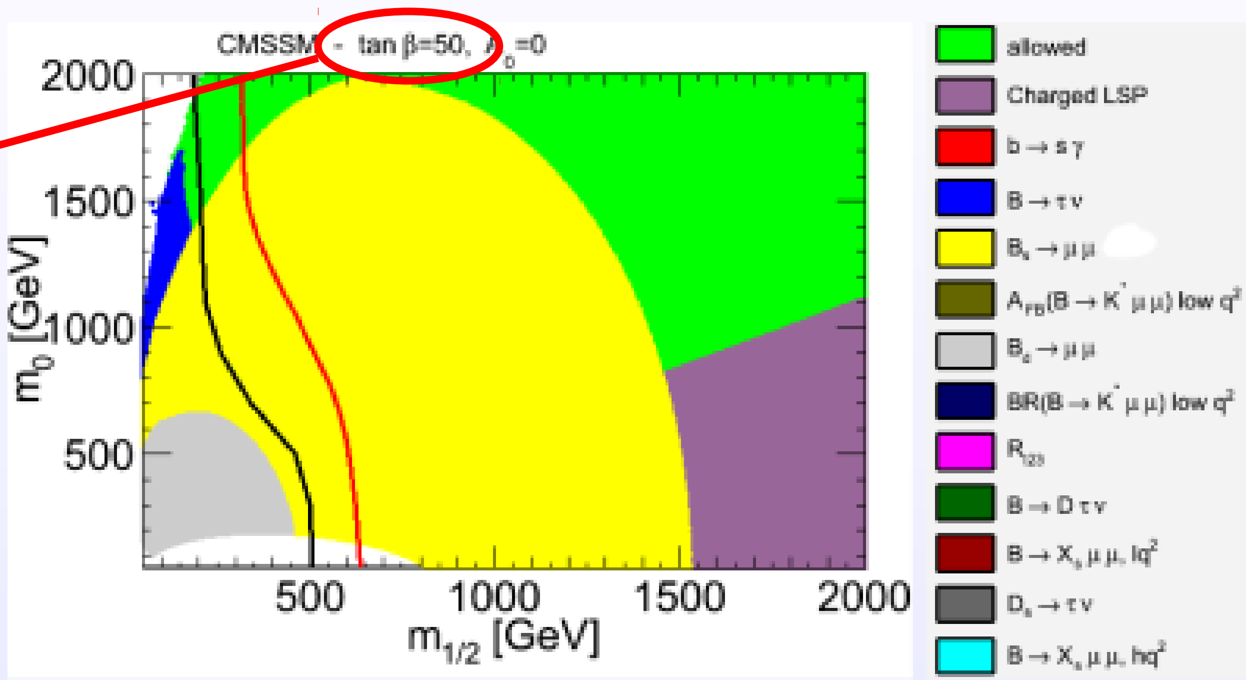
N. Mahmoudi at Moriond

Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2×10^{-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 $BR(B_d \to \mu^+\mu^-)$

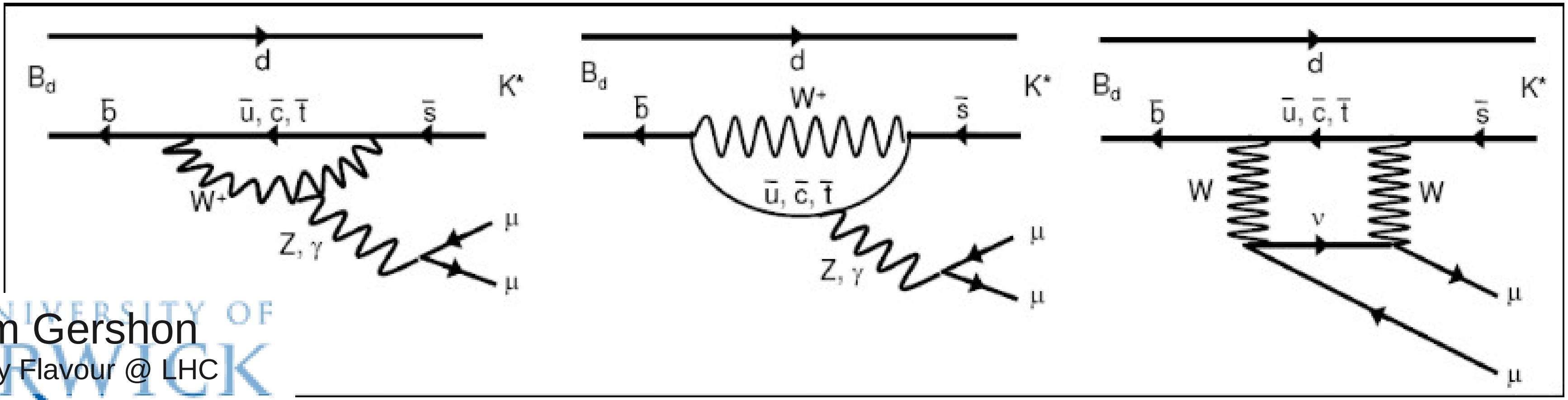
… after …

Superlso v3.2+

N. Mahmoudi at Moriond

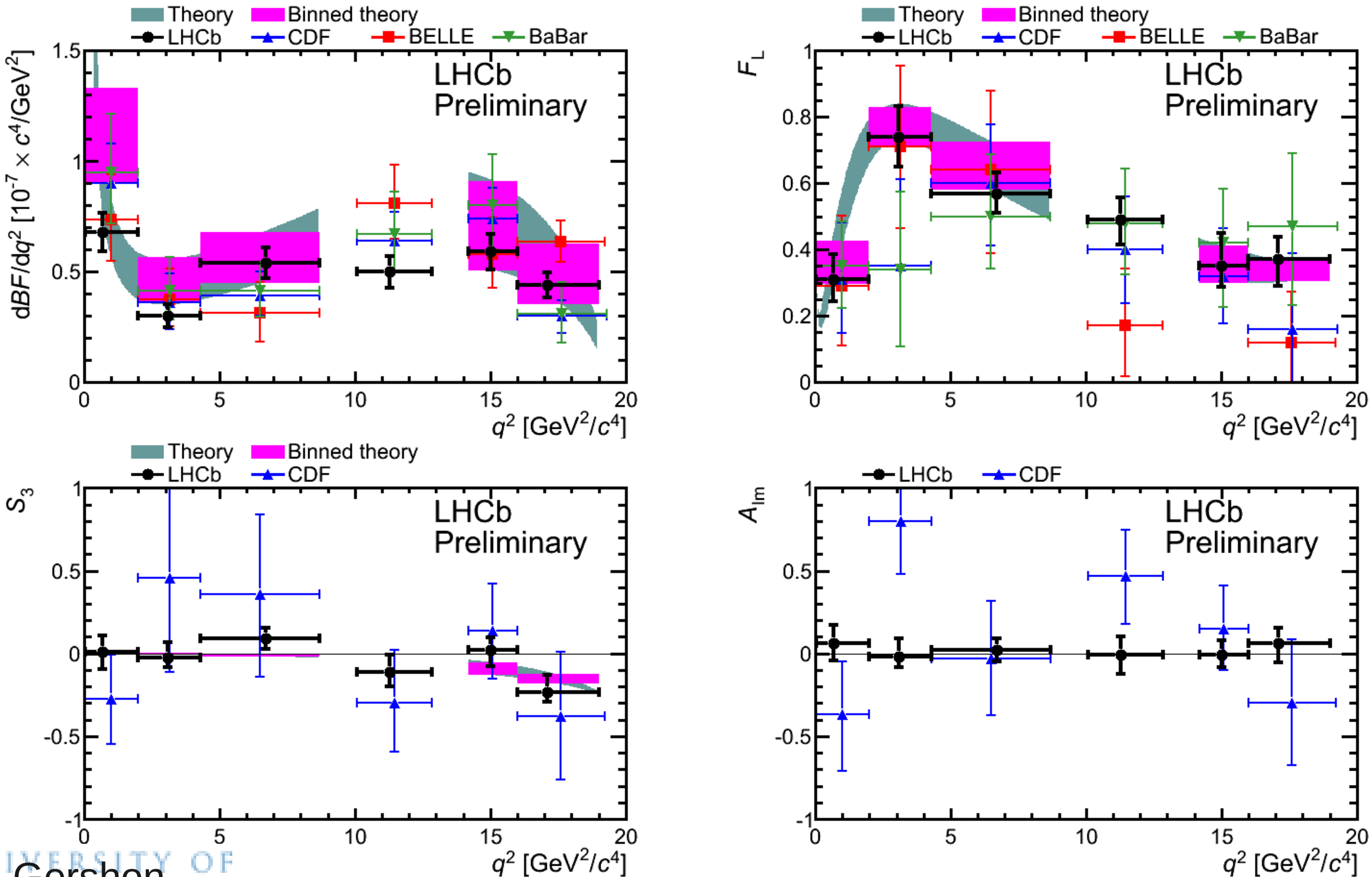
$B \to K^{*}\mu^{+}\mu^{-}$

- $B_d \to K^{*0}\mu^{+}\mu^{-}$ provides complementary approach to search for new physics in $b \to sl^{+}l^{-}$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions



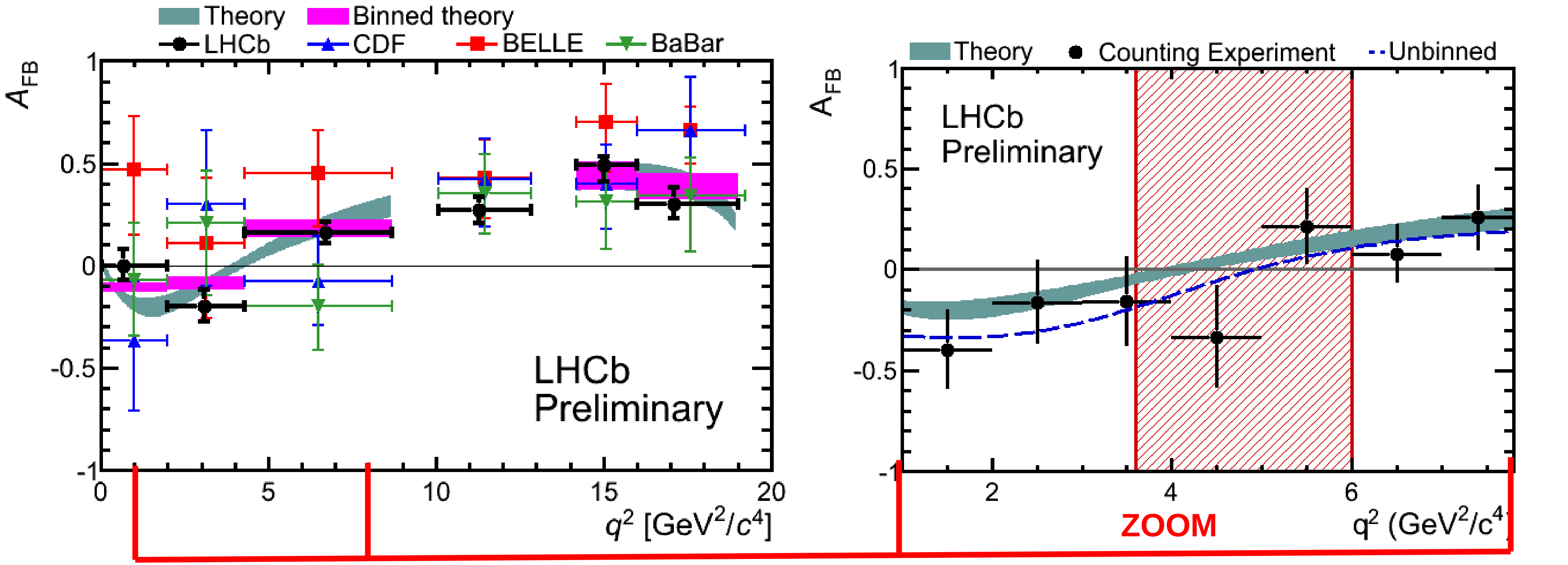
Differential branching fraction and angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb-CONF-2012-008



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

LHCb-CONF-2012-008



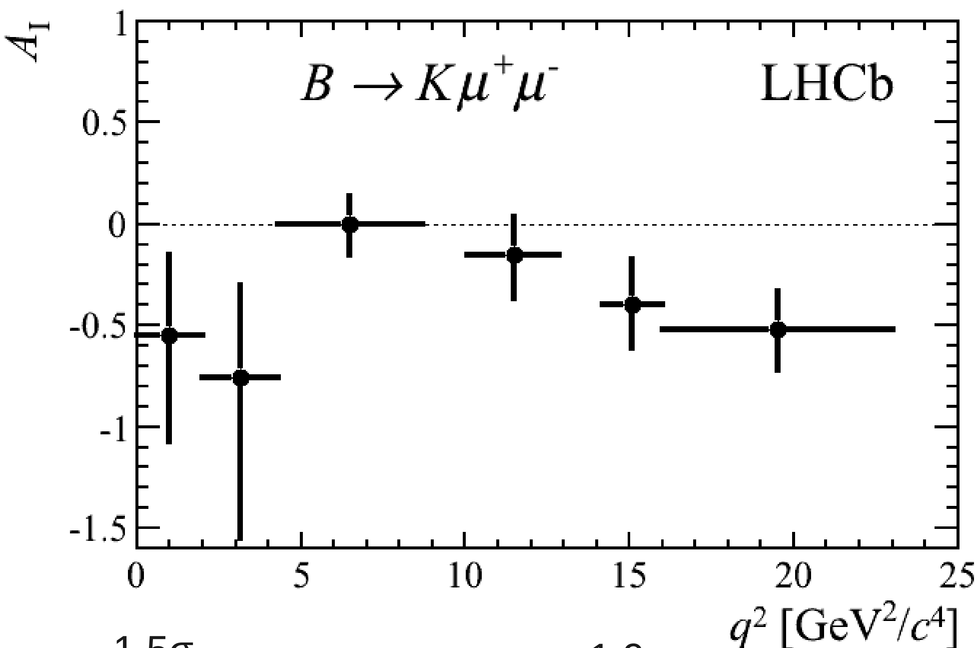
First measurement of the zero-crossing point of the forward-backward asymmetry

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

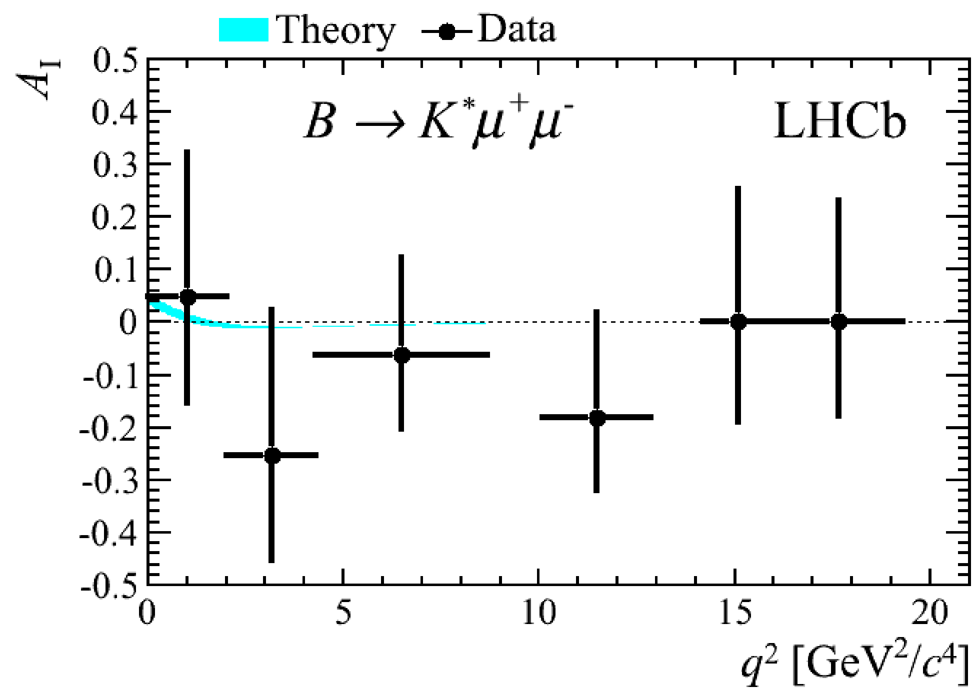
(SM predictions in the range 4.0 – 4.3 GeV^2)

Isospin asymmetry in B → K(*)μμ

LHCb
J. High Energy Phys. 07 (2012) 133



1.5σ
1.9σ
1.9σ
3.0σ



Deviation from zero integrated over q^2 ~ 4.4σ
Consistent with previous measurements
(BaBar, Belle, CDF)

Consistent with zero & with SM prediction
Consistent with previous measurements
(BaBar, Belle, CDF)

Food for thought ...

Selected highlights of results
CP violation

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

LHCb PRL 108 (2012) 111602

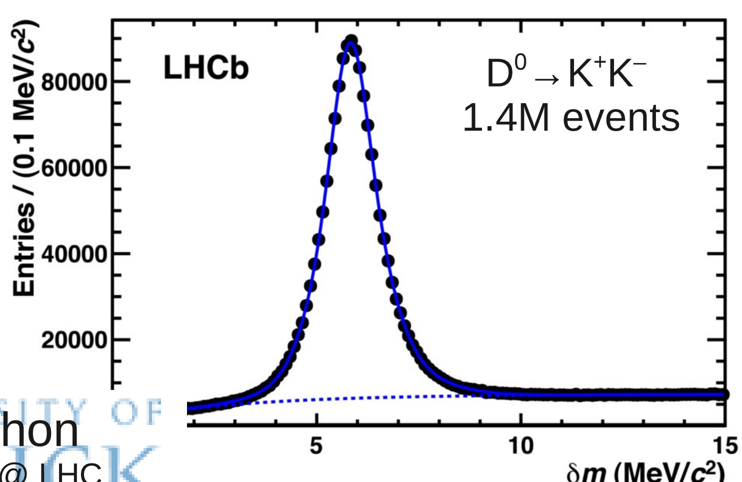
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \rightarrow f$, where D meson flavour is tagged by $D^{*+} \rightarrow D^0\pi^+$ decay

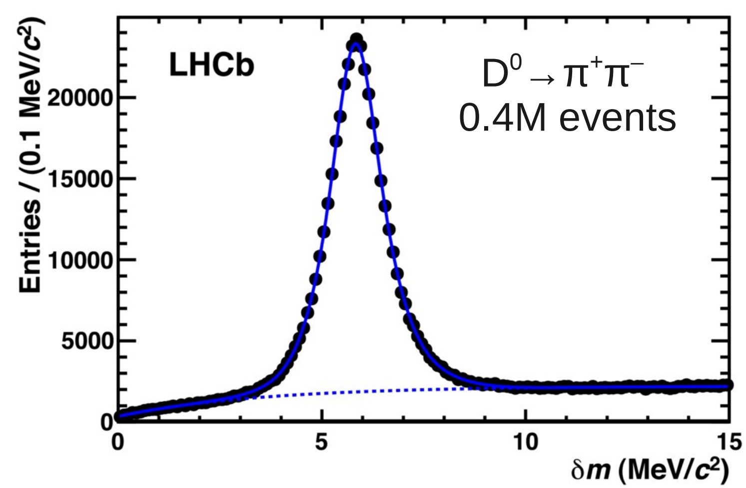
$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_s^+) + A_{\rm P}(D^{*+}).$$

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)

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



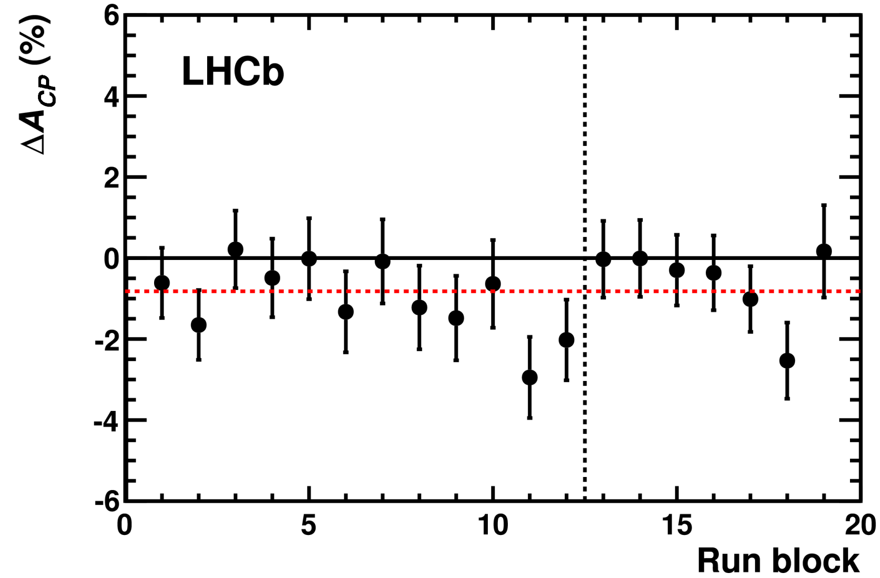


Evidence for CP violation in D → h⁺h⁻ decays

LHCb PRL 108 (2012) 111602

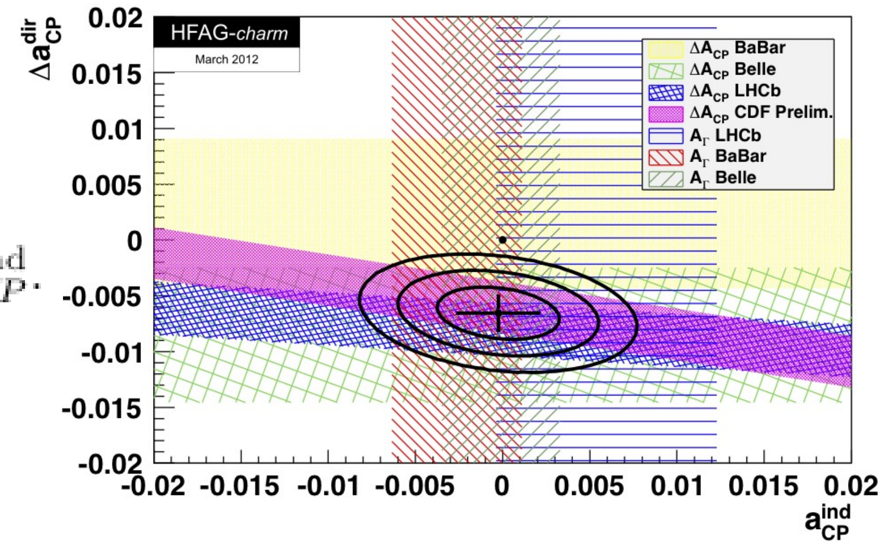
Result, based on 0.62/fb of 2011 data
ΔA_{CP} = [−0.82 ± 0.21(stat.) ± 0.11(syst.)]%

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)

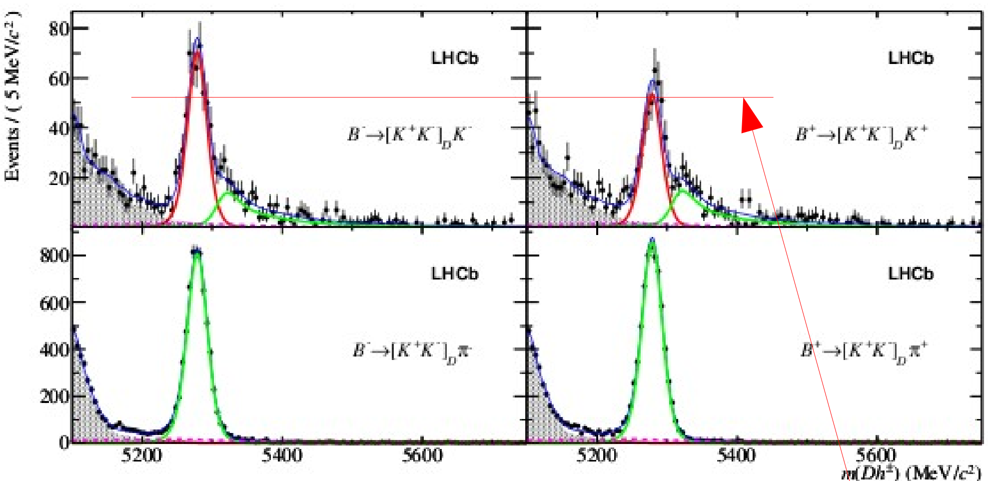
$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$= \left[a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind}.$$

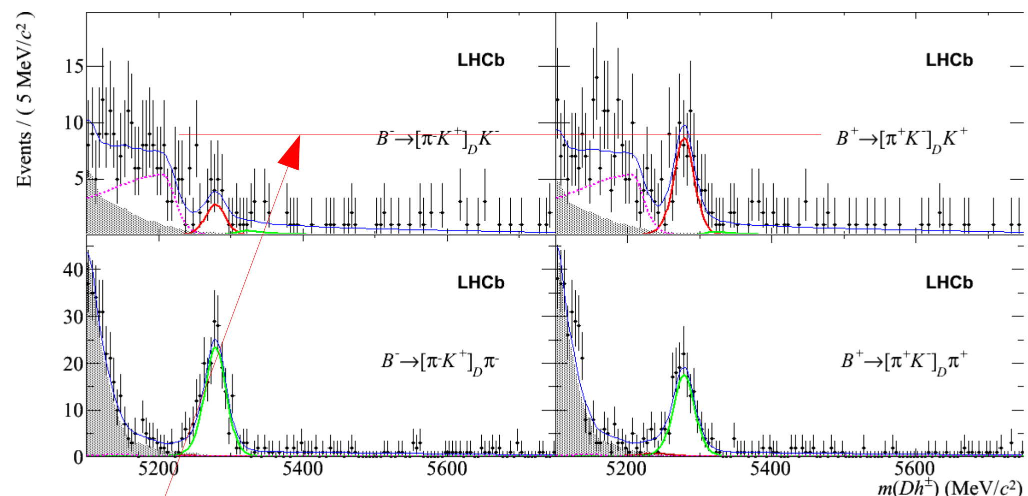


B → DK decays
give theoretically clean
way to measure
CKM phase γ

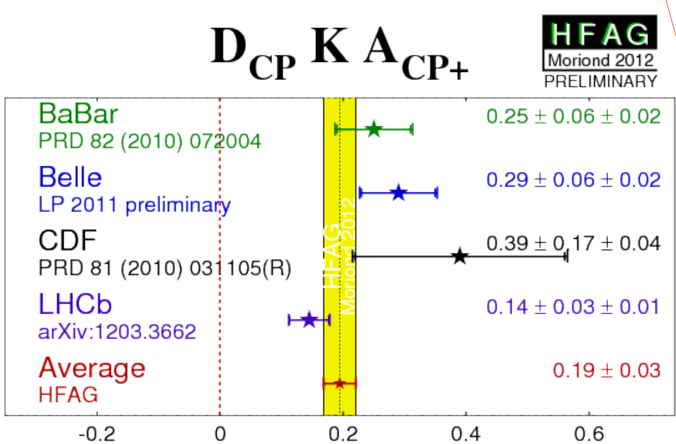
B → DK decays
"GLW" and "ADS" methods

LHCb
Phys. Lett. B 712 (2012) 203

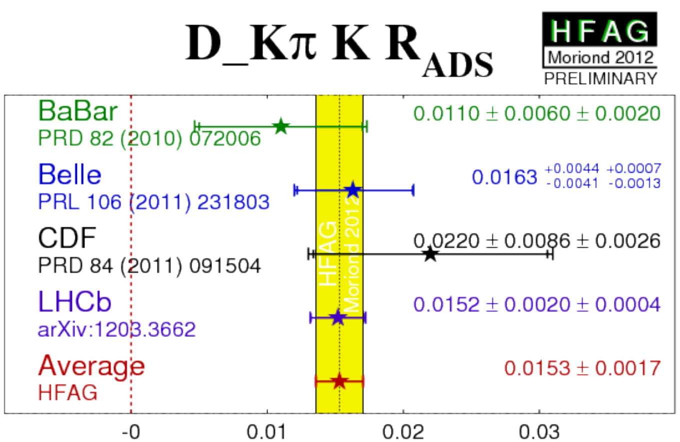




D_{CP} K A_{CP+}

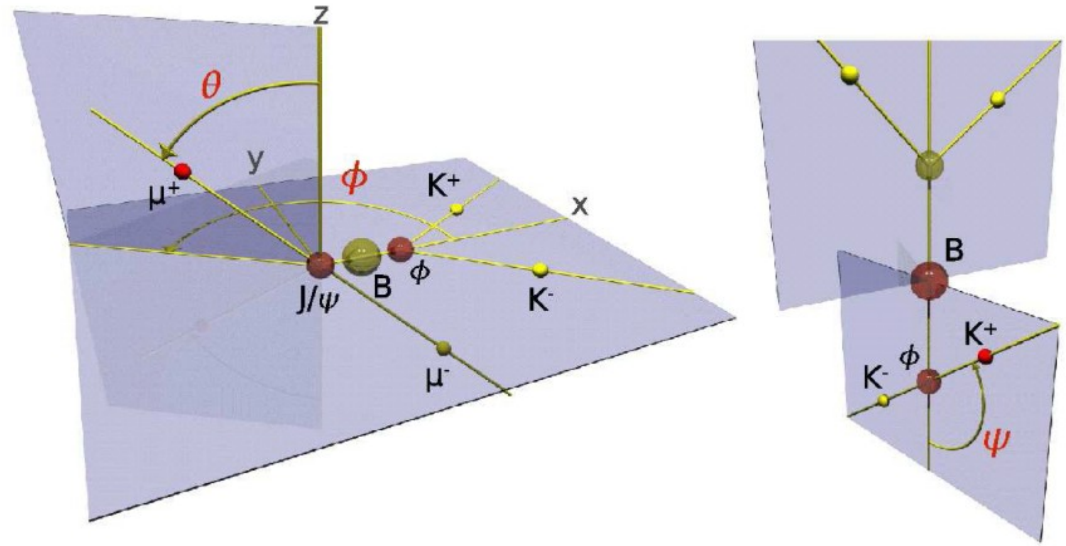


D_Kπ K R_{ADS}



Observation of CP violation in B → DK decays

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



- VV final state

  three helicity amplitudes

  → mixture of CP-even and CP-odd

  disentangled using angular & time-dependent distributions

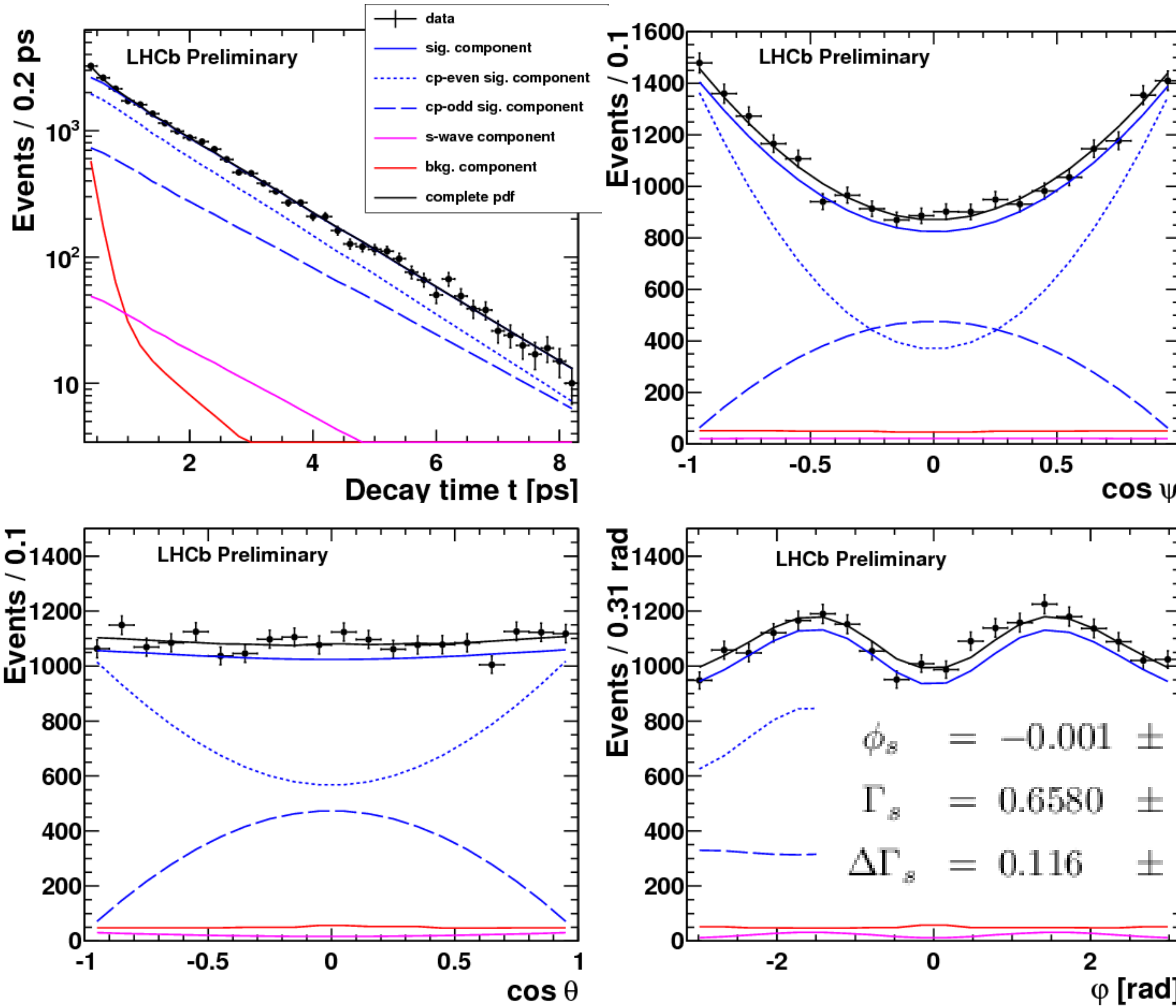
  → additional sensitivity

  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 $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

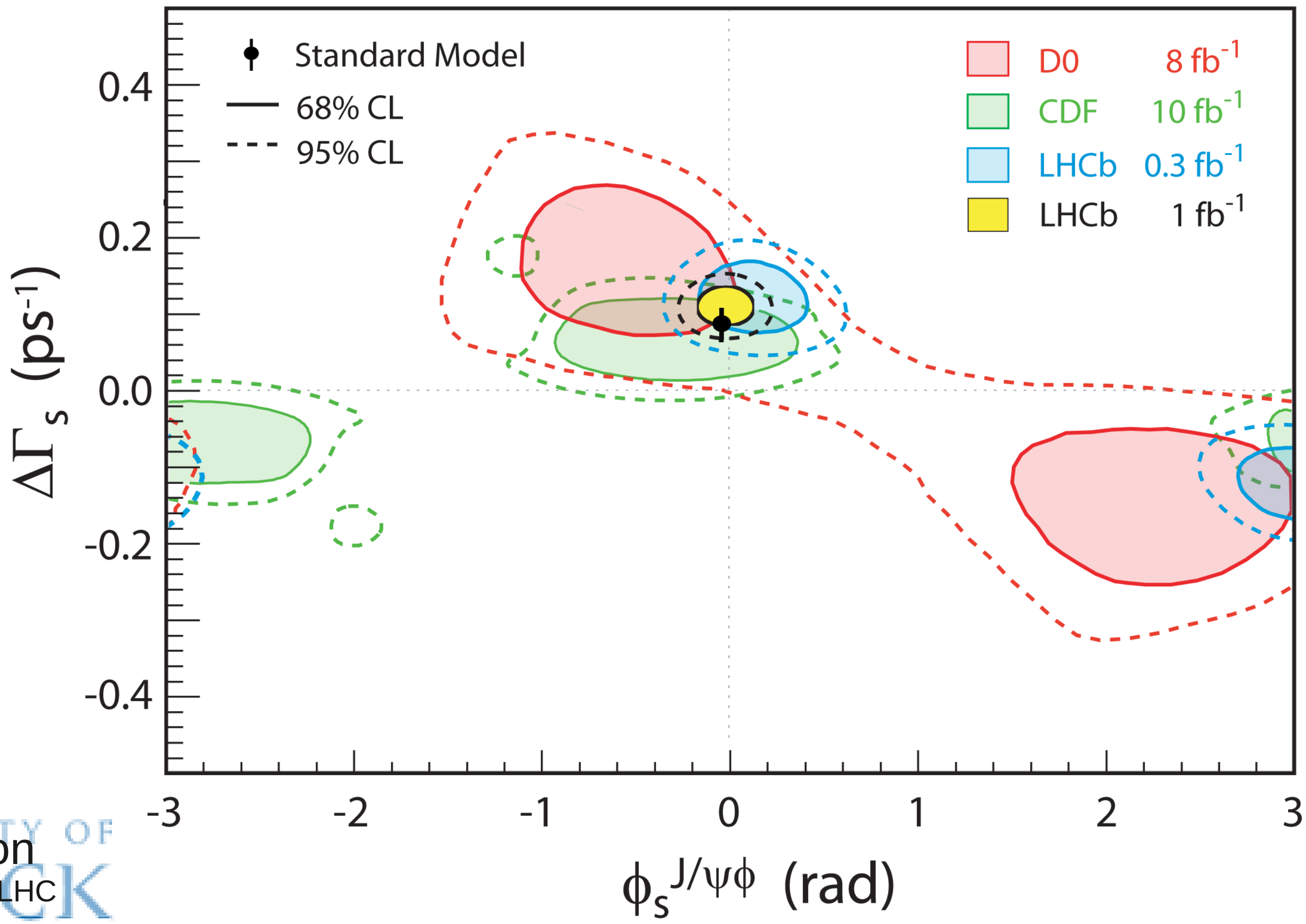


LHCb-CONF-2012-002

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

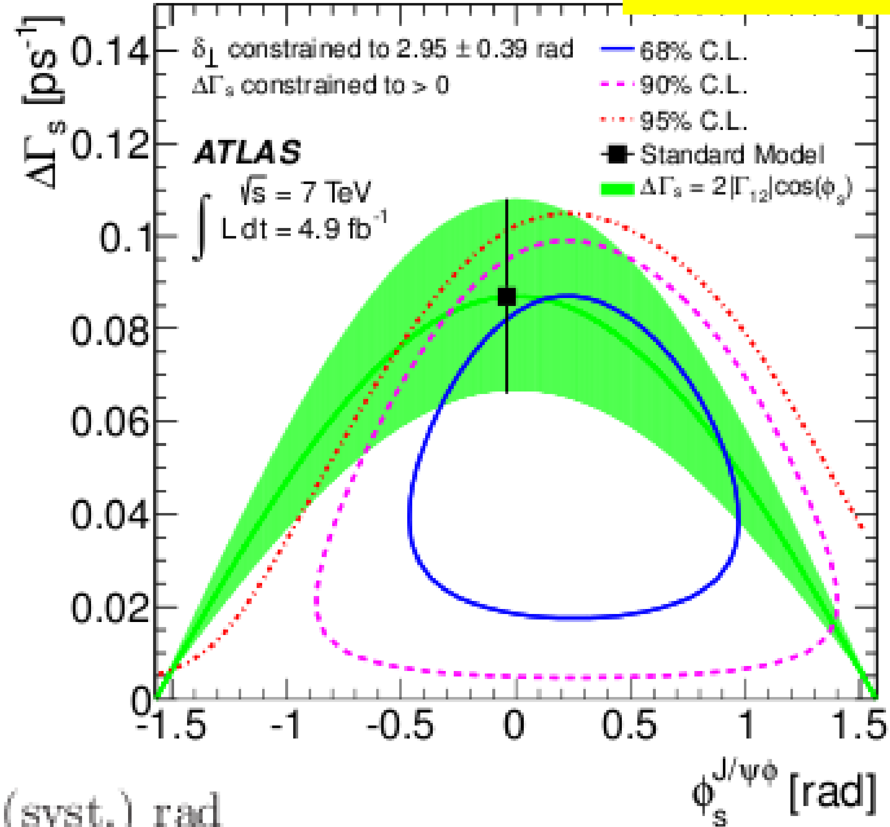
CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

- Ambiguity resolution ↔ PRL 108 (2012) 241801
- Tagged time-dependent angular analysis of $J/\psi\phi$ with 1/fb ↔ LHCb-CONF-2012-002
- Amplitude analysis to determine CP content of $J/\psi\pi\pi$ ↔ PRD 86 (2012) 052006
- Tagged time-dependent analysis of $J/\psi\pi\pi$ ↔ PLB 713 (2012) 378



ATLAS results on $B_s \to J/\psi\phi$

arXiv:1208.0572



$$\phi_s = 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.) rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.008 \text{ (syst.) ps}^{-1}$$

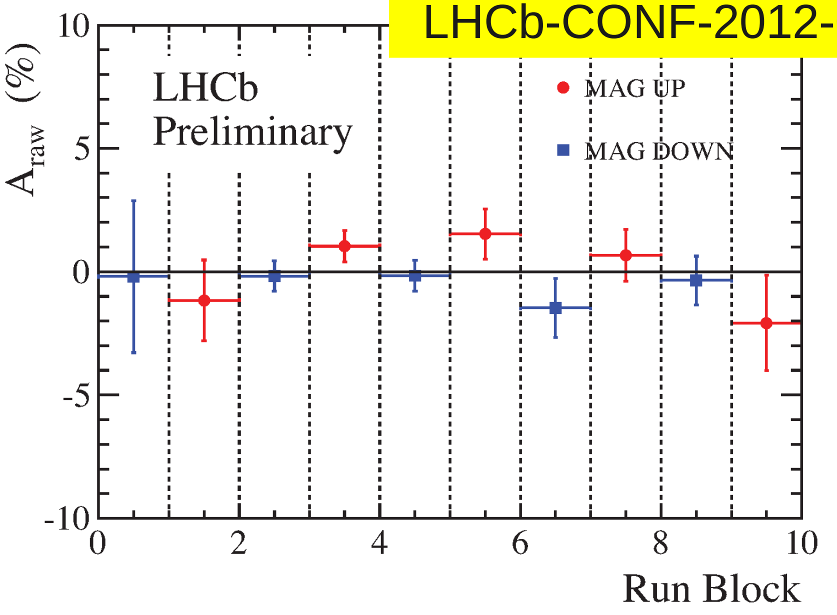
$$\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.) ps}^{-1}$$

untagged, hence reduced sensitivity

high statistics measurements with 4.9/fb

Semileptonic asymmetries

LHCb-CONF-2012-002

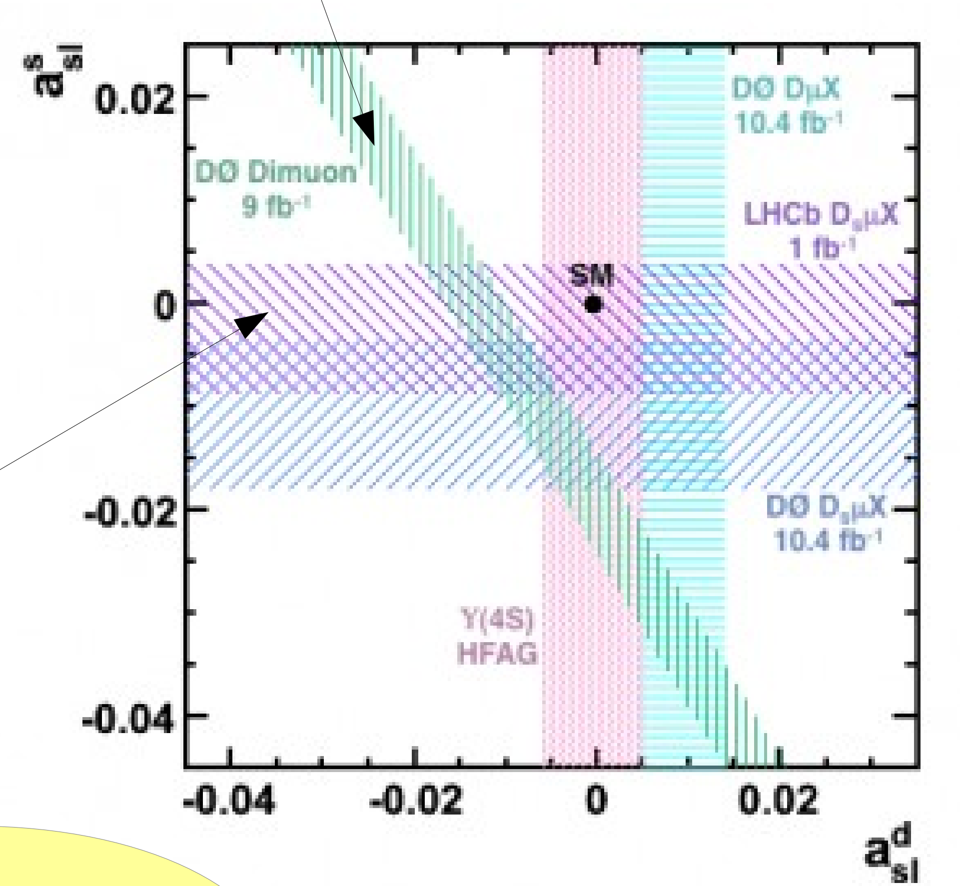


$$a_{\rm sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%.$$

Based on $B_s \rightarrow D_s \mu\nu X$ with $D_s \rightarrow \phi\pi$

D0 inclusive dimuon result 3.9σ from SM

PRD 84 (2011) 052007



Situation unclear – improved measurements needed

Tim Gershon
Heavy Flavour @ LHC

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

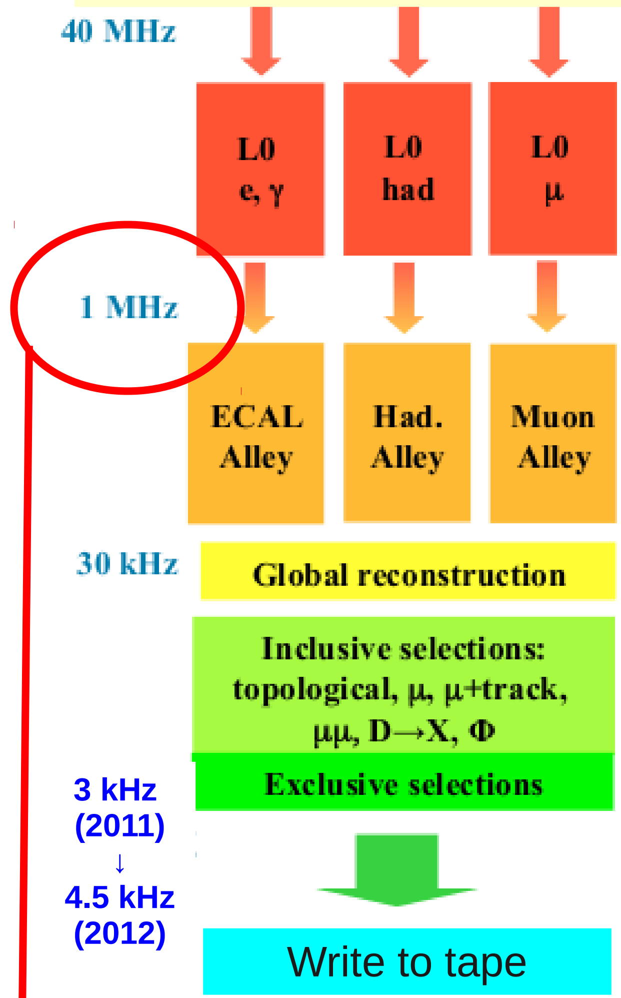
Main backgrounds

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

Handles

- high p_T signals (muons)
- displaced vertices

LHCb trigger scheme



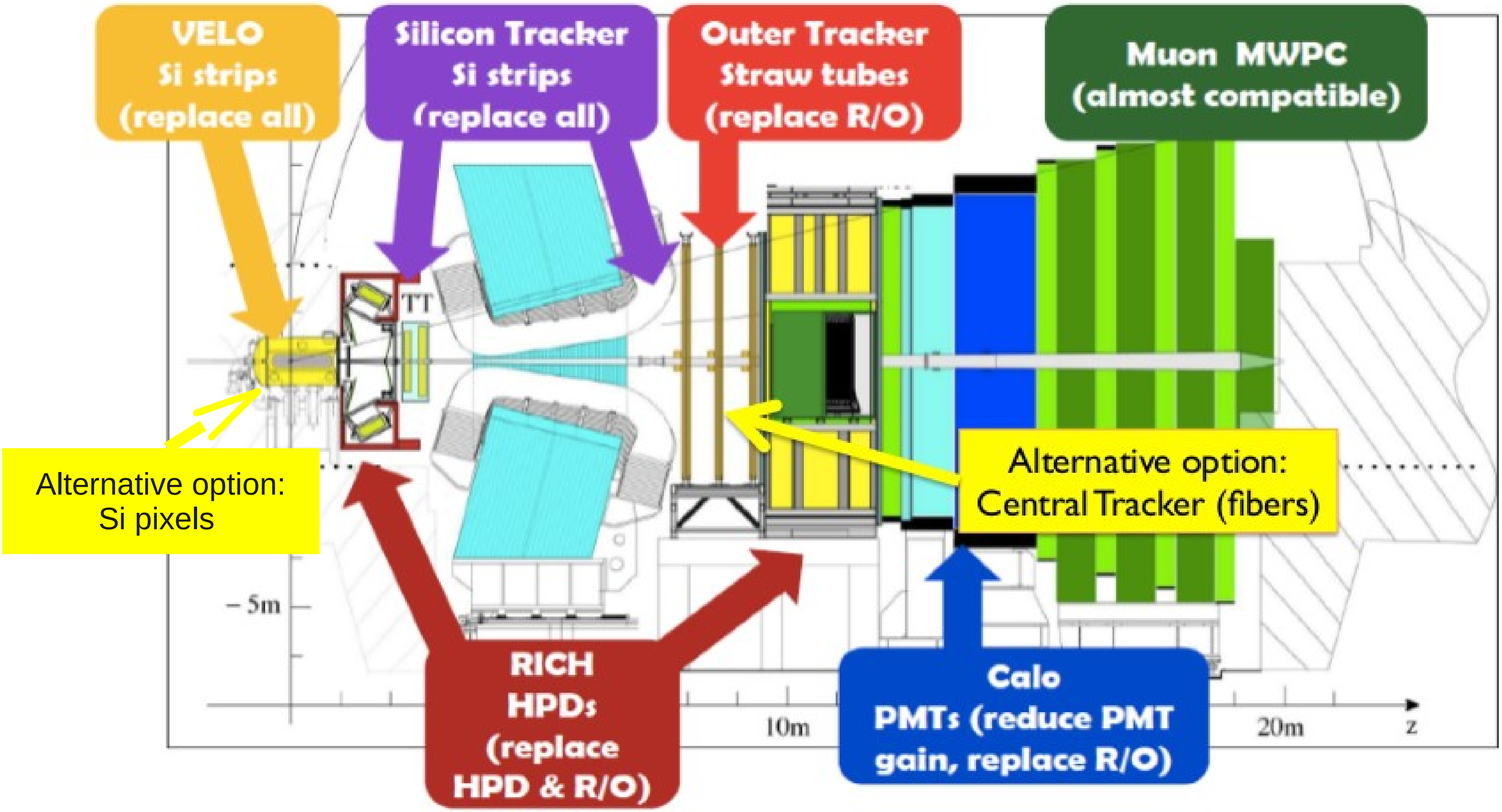
L0 – high p_T signals in calorimeters & muon chambers

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



Upgrade – expected sensitivities

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	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
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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 ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	$4°$	$0.9°$	negligible
	γ ($B_s^0 \to D_sK$)	–	$11°$	$2.0°$	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 $50\,\text{fb}^{-1}$ 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

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

Summary

- Concept of LHCb definitively 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
  - Several new results to be presented at CKM2012 next week
  - 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
  - A core component of LHC exploitation