Results from LHCb

Tim Gershon
University of Warwick & CERN

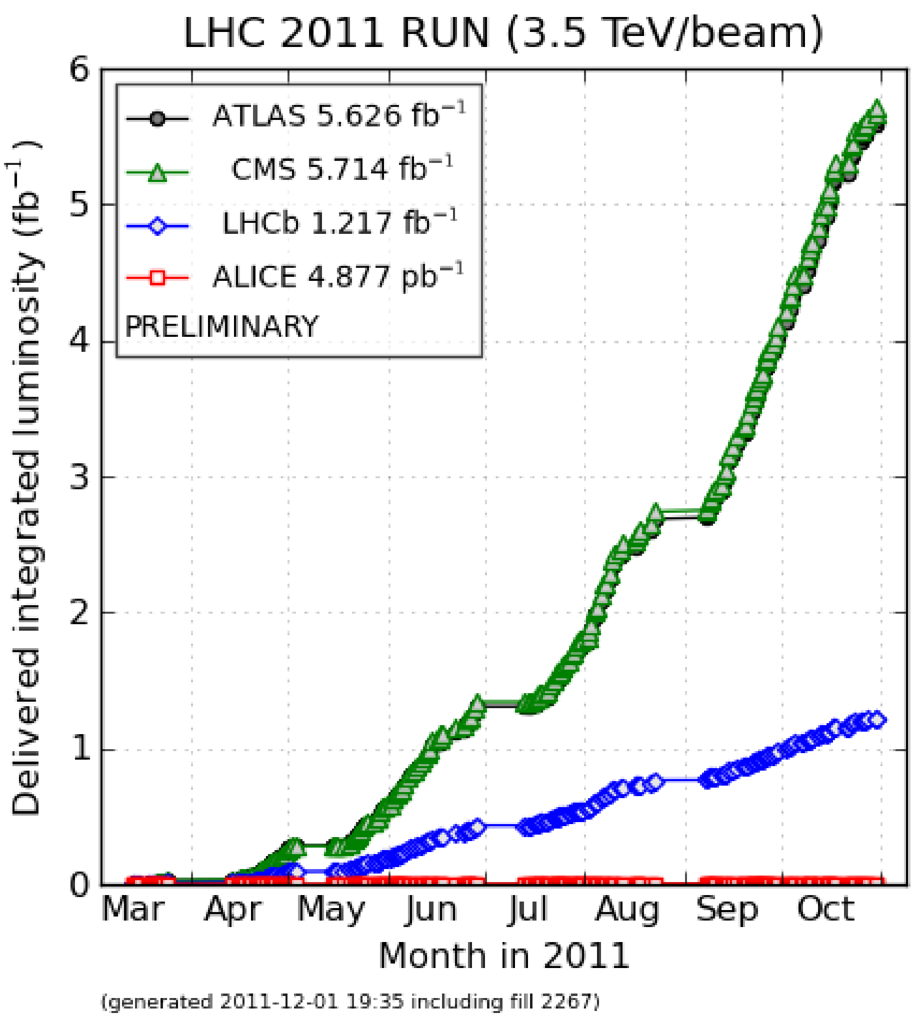
SuperB Physics Workshop
INFN-LNF
12th December 2011

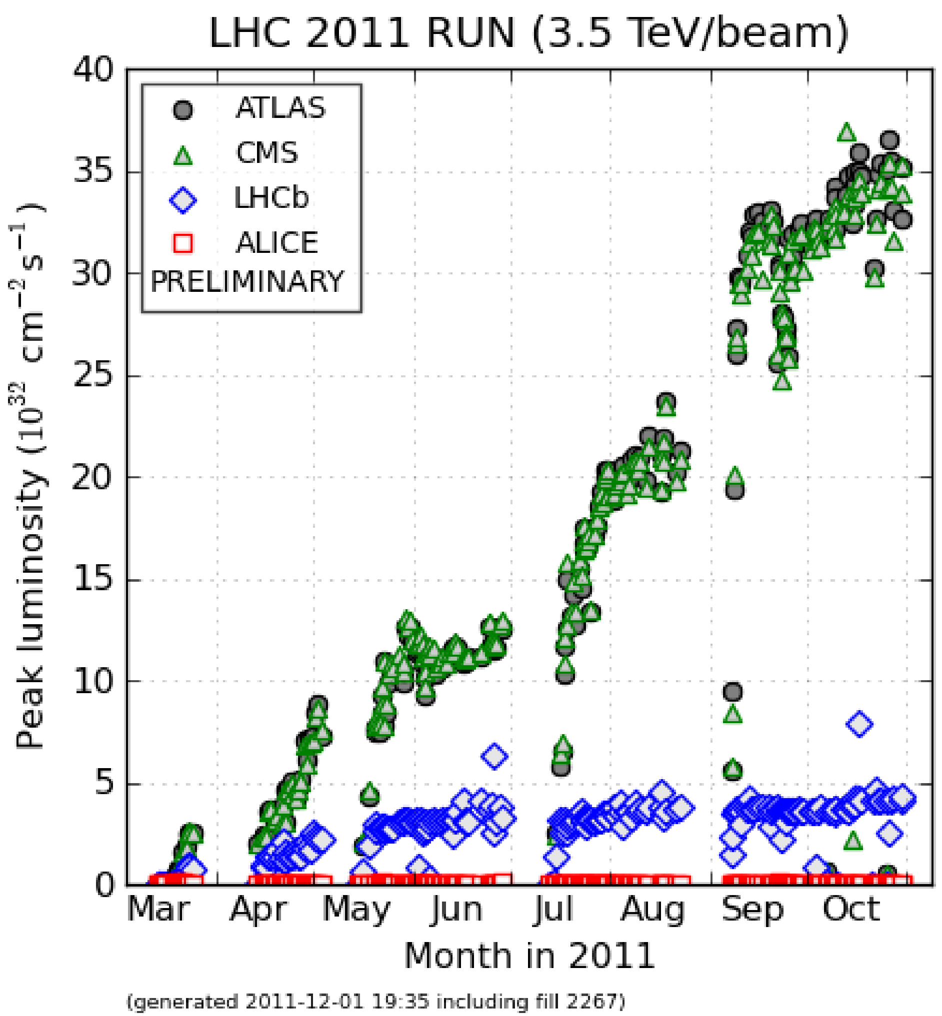
Contents

- Introduction to LHCb
- Highlights of recent results
  - Production of (new and old) particles
  - Rare decays
  - CP violation
  - (for charm physics, see Walter Bonivento's talk)
- Looking to the future

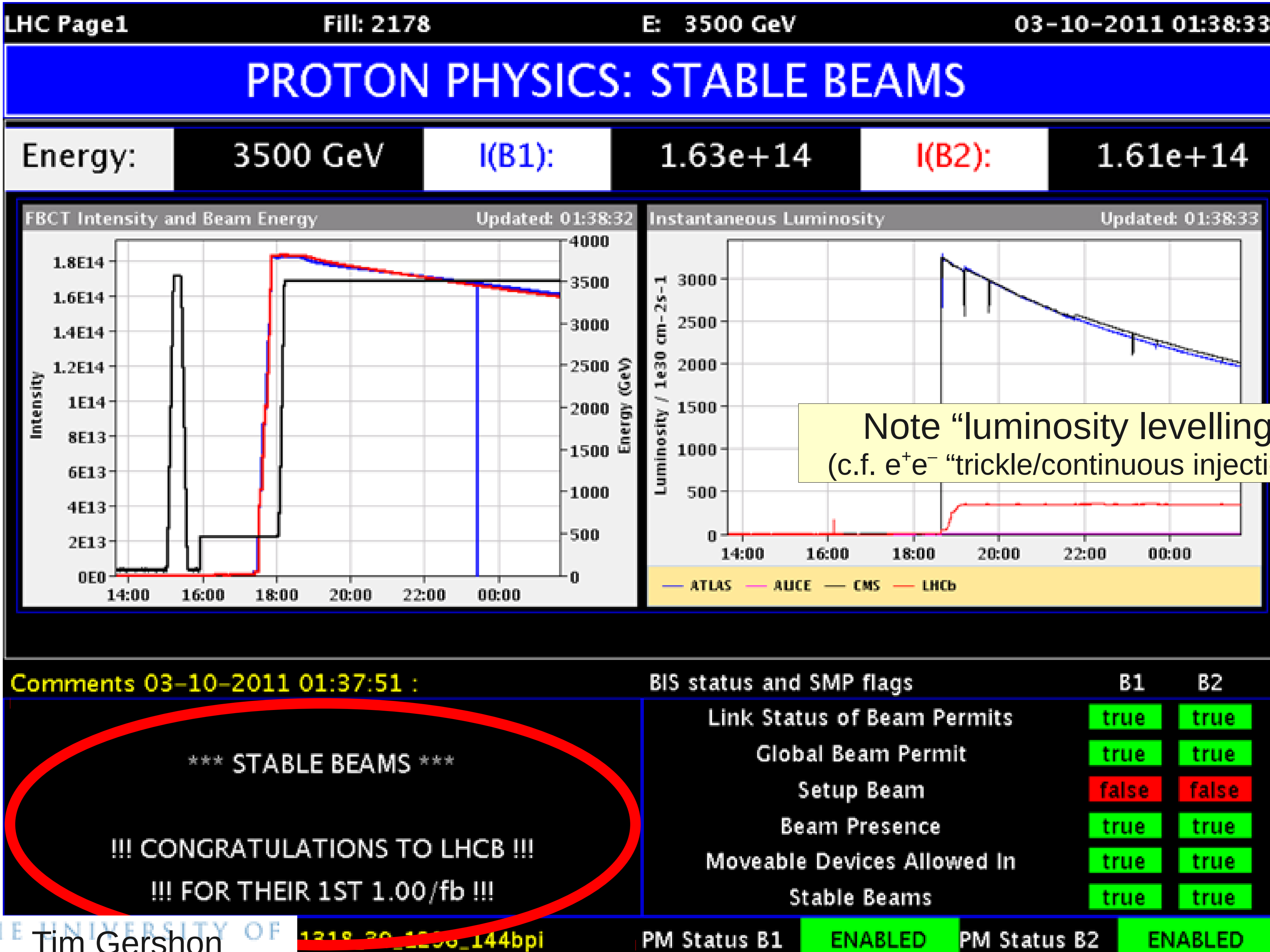
The LHC & LHCb

LHC performance 2011



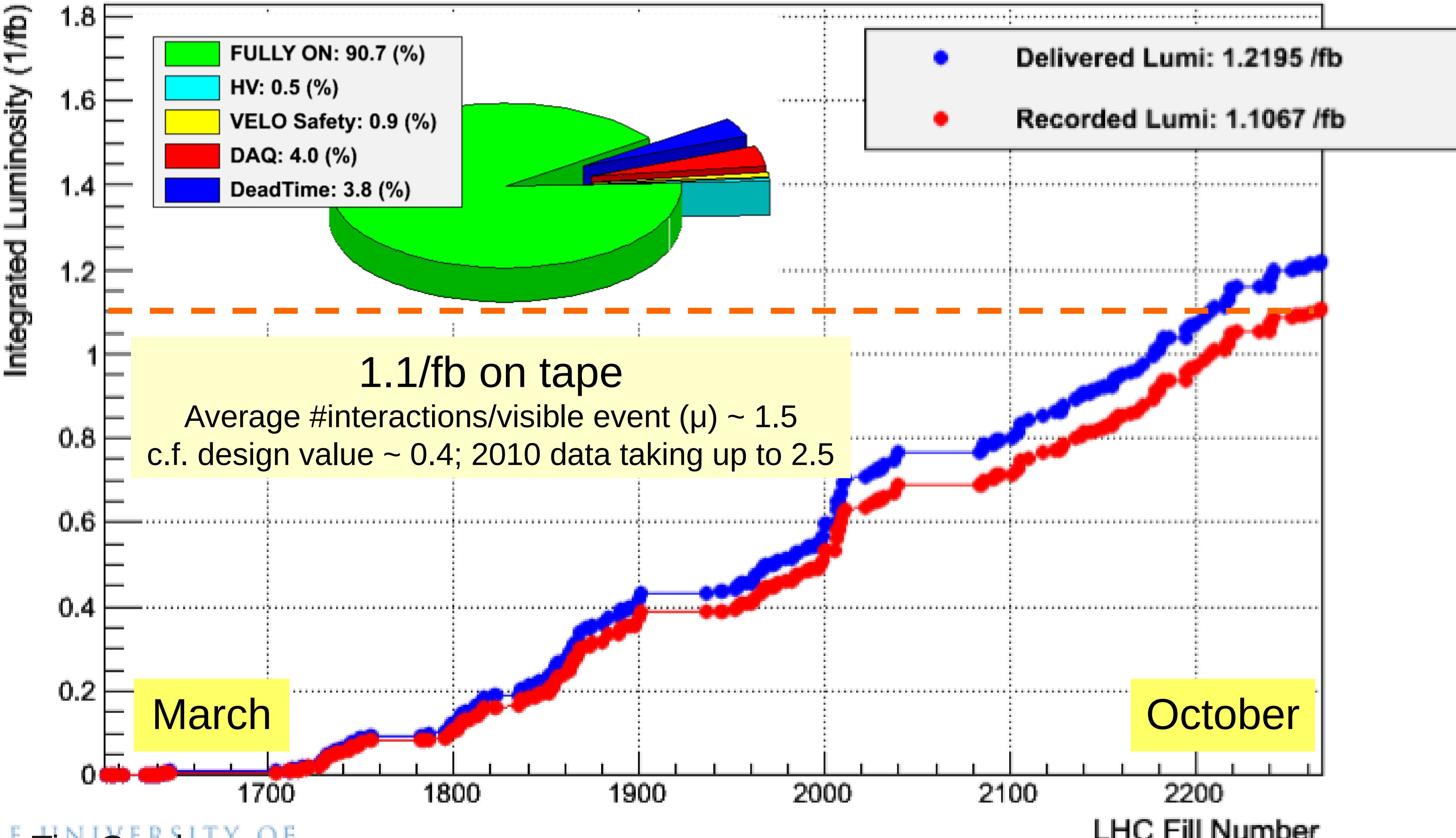


LHCb design luminosity: 2 10^{32}/cm^2/s



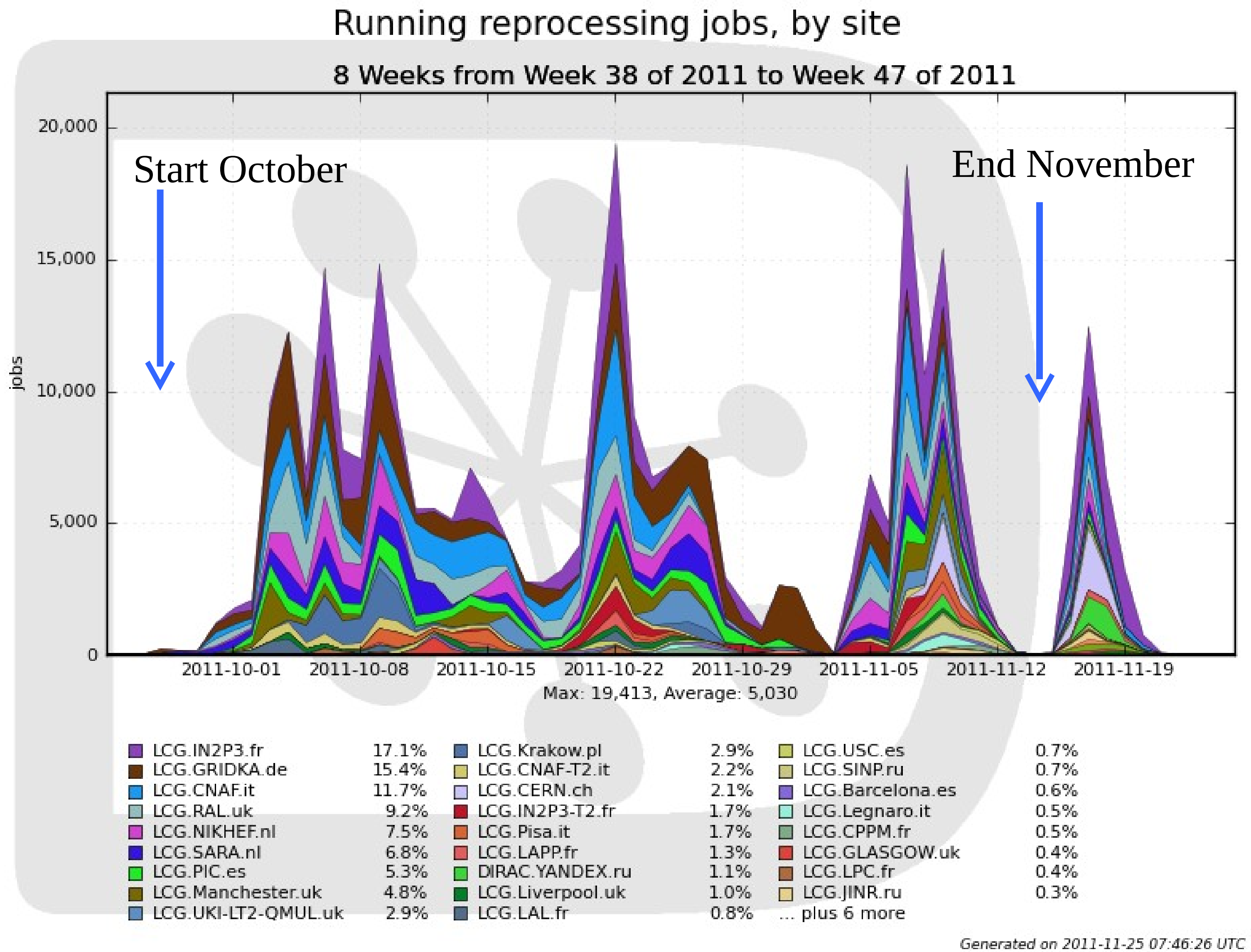
Note “luminosity levelling”
(c.f. e^+e^- “trickle/continuous injection”)

2011 data taking



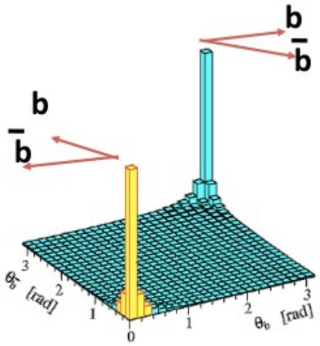
Data taking efficiency close to 91 %

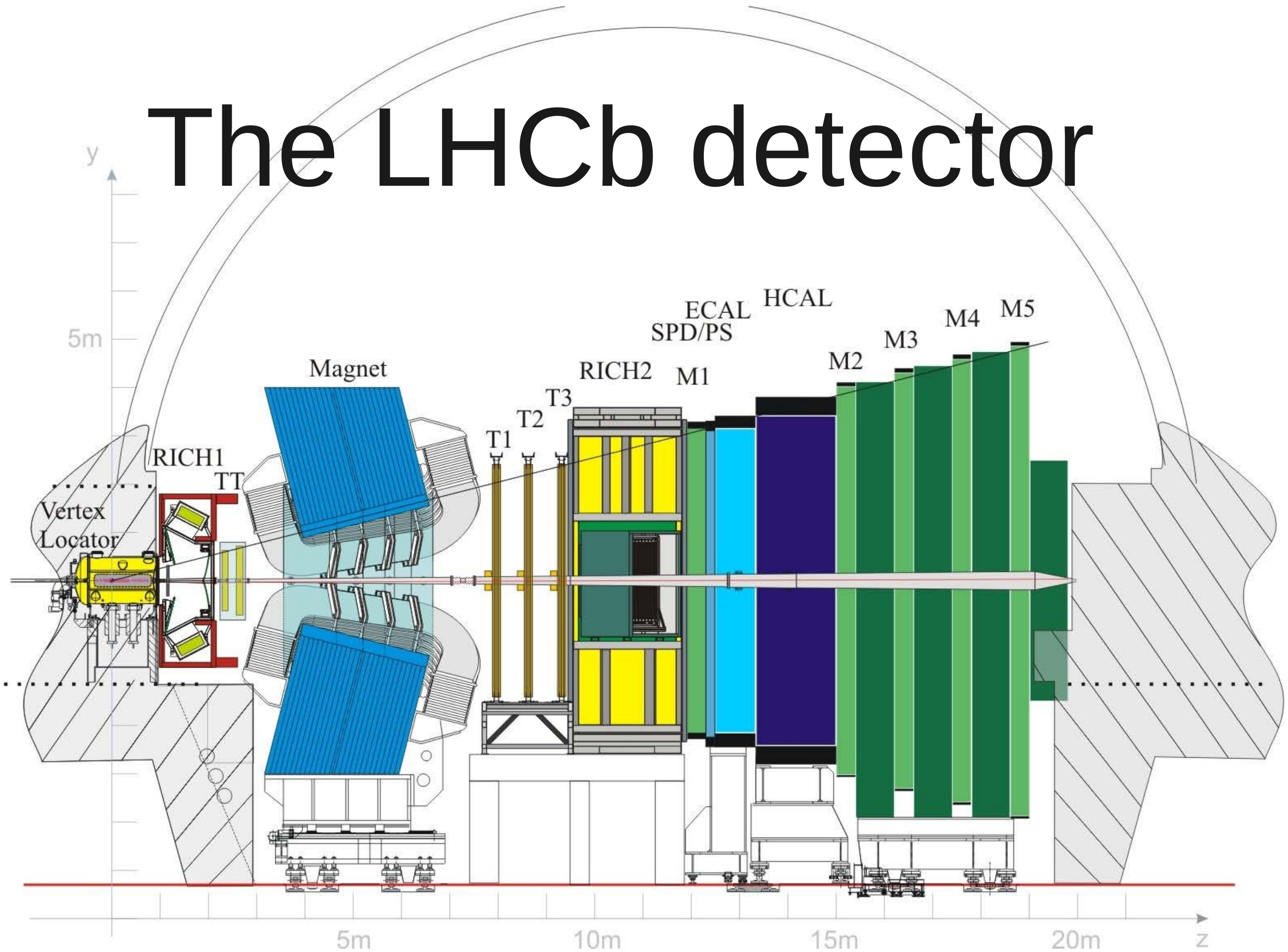
2011 data reprocessing



2011 data reprocessing completed in 8 weeks

The LHCb detector



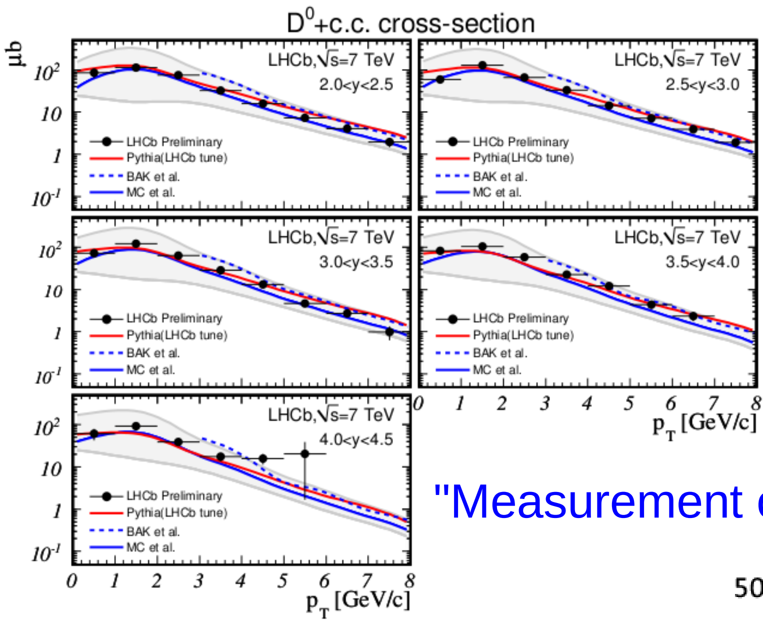


Designed to study production and decay of heavy flavoured particles

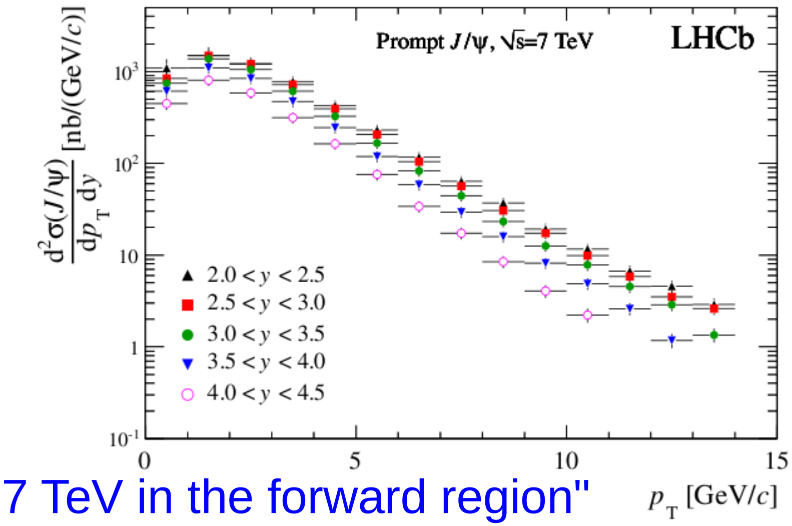
- forward spectrometer: pseudorapidity region $2 < \eta < 5$ (roughly $1° < \theta < 15°$)
- MUON detectors & CALO system select high-p_T decay products
- VELO silicon detector identifies displaced vertices
- RICH particle identification device separates kaons from pions

Heavy flavour production @ LHCb

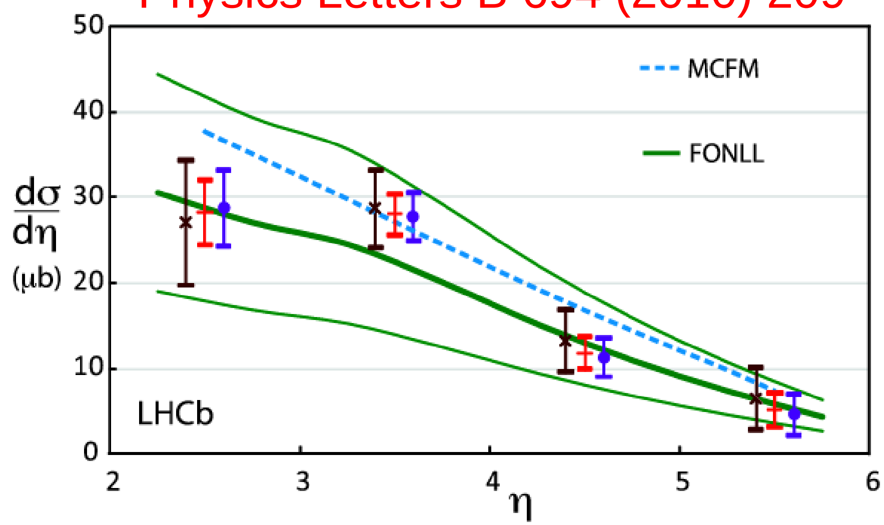
"Prompt charm production in pp collisions at √s = 7 TeV"
LHCb-CONF-2010-013



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



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



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 $B^0\bar{B}^0$ pairs
  - for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, we have the 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

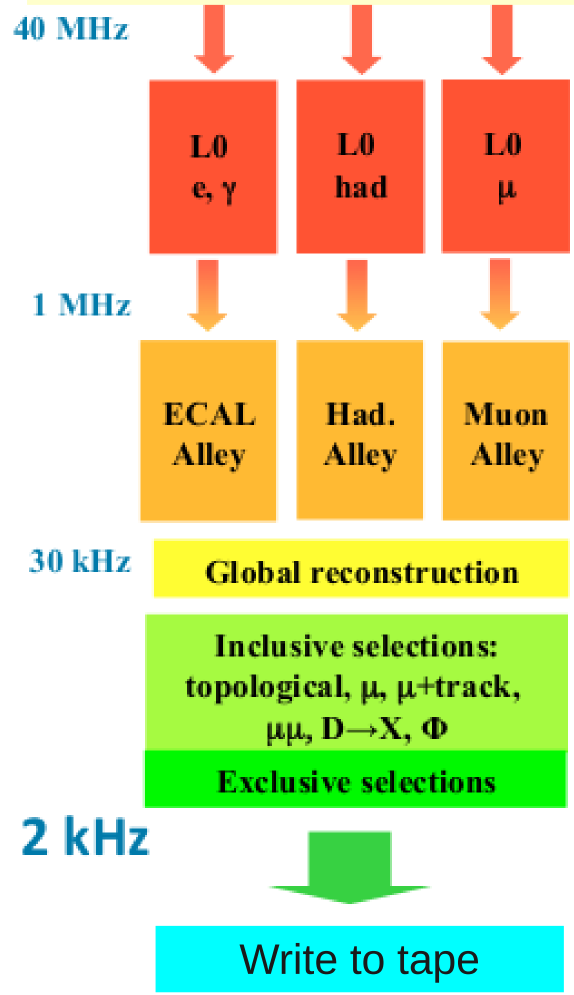
Main backgrounds

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

Handles

- high p_T signals (muons)
- displaced vertices

LHCb trigger scheme



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

LHCb-PUB-2011-002
LHCb-PUB-2011-003
LHCb-PUB-2011-016

Trigger considerations

- Main limitation is at L0
  - reduction from LHC bunch crossing rate (currently ~10 MHz) to maximum HLT input rate of ~ 1 MHz
- HLT provides various output streams
  - "topological trigger" – almost pure inclusive sample of b hadron decays
  - exclusive charm selections – almost pure, especially for 2-body decays
  - since b quarks produced in pairs, two types of event samples
    - triggered on signal (TOS)
    - triggered independent of signal (TIS)
    - provides data-driven evaluation of trigger efficiencies
- HLT limitations: CPU power, CPU time, disk space
    - "brute force" approach to improve: buy more CPU
    - code improvements still possible
    - output rate (3 kHz) limited by offline considerations

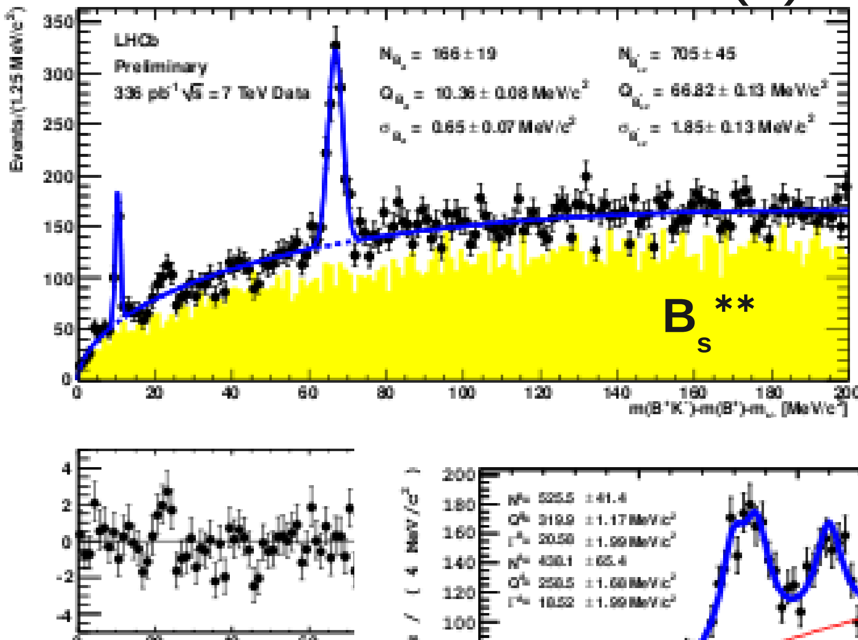
LHCb-PUB-2011-002
LHCb-PUB-2011-003
LHCb-PUB-2011-016

Highlights of recent results

Production of (new and old) particles

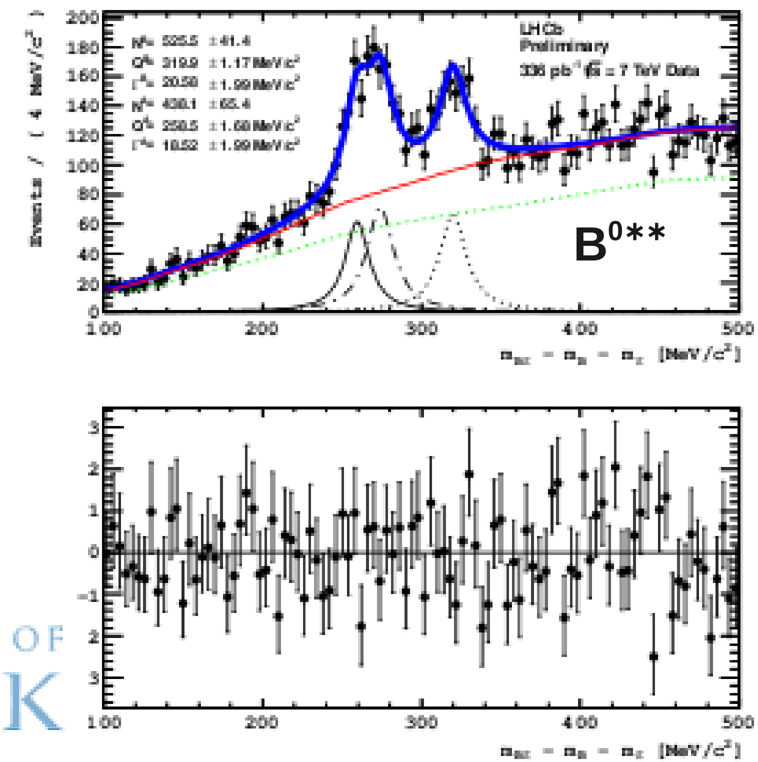
Observations of Orbitally Excited $B_{(s)}$** Mesons

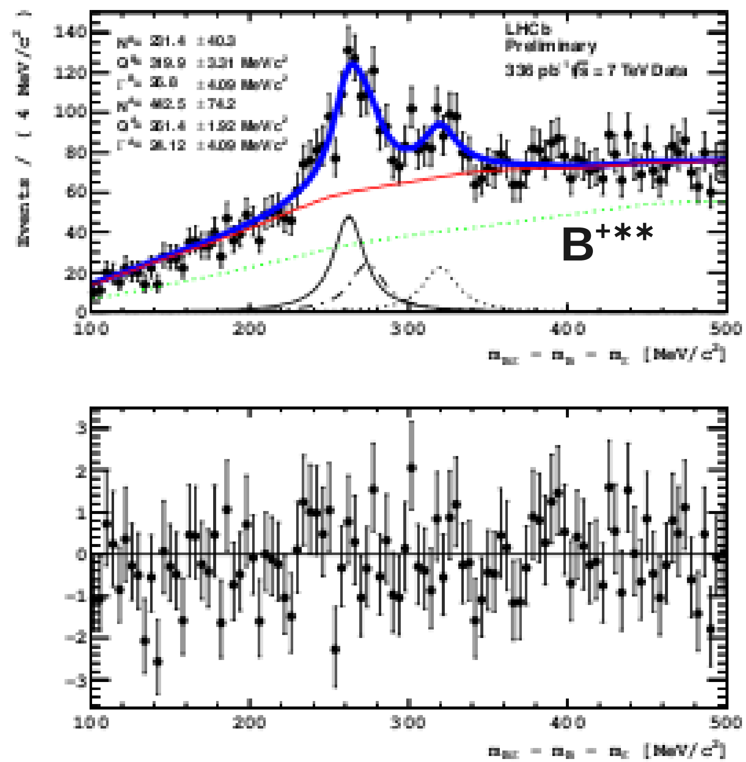
LHCb-CONF-2011-053



First observations of the B^{+}** states!

(to my knowledge, the first new particle discovered at the LHC)





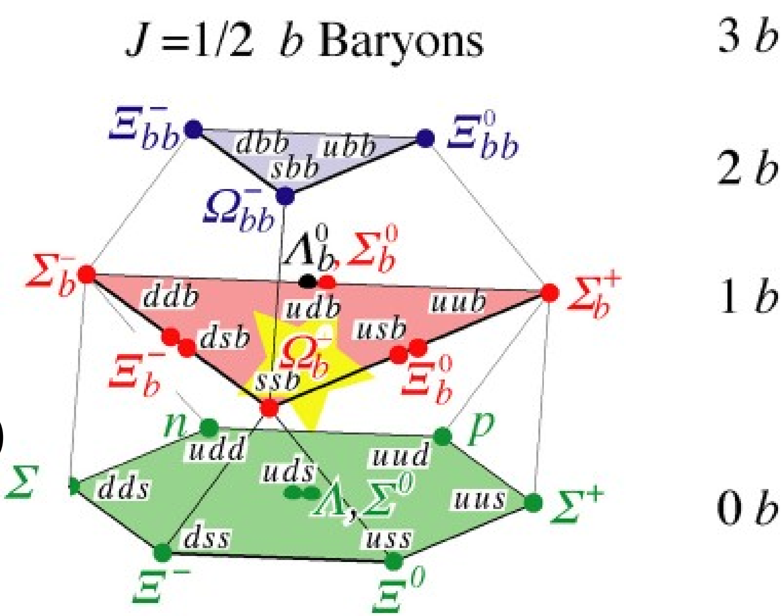
b baryons

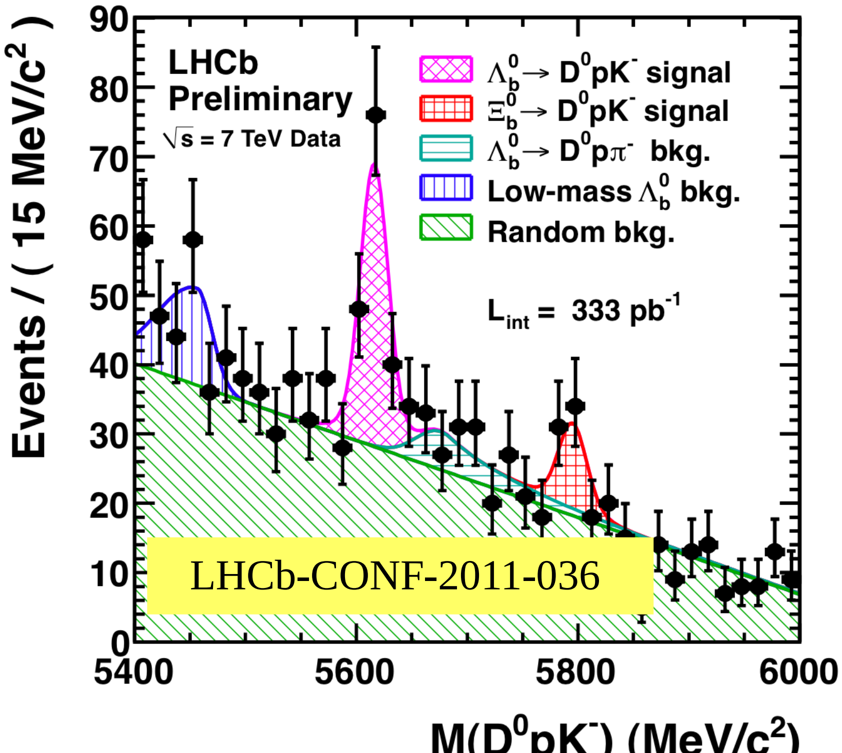
Dataset contains large samples of b baryons

- Λ_b, Ξ_b, Ω_b, etc.

Very little existing experimental information

Wealth of measurements (masses, lifetimes, branching ratios, CP asymmetries, …)





Example: Λ_b and $\Xi_b^0 \rightarrow D^0pK$

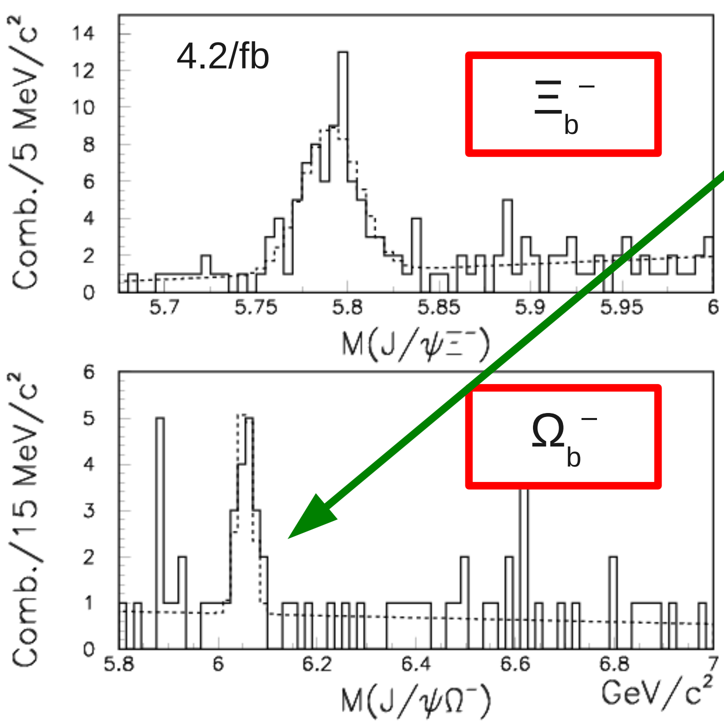
$$R_{D^0pK^-} = \frac{\mathcal{B}(\Lambda_b^0 \to D^0pK^-)}{\mathcal{B}(\Lambda_b^0 \to D^0p\pi^-)} = 0.112 \pm 0.019\,^{+0.011}_{-0.014}$$

$$m(\Xi_b^0) - m(\Lambda_b^0) = (181.8 \pm 5.5 \pm 0.5)\ MeV/c^2$$

(CDF scooped us with first observation of Ξ_b^0 – in a completely different final state – but this remains a demonstration of LHCb's potential)

Ω_b status since 2009

CDF PRD 80 (2009) 72003

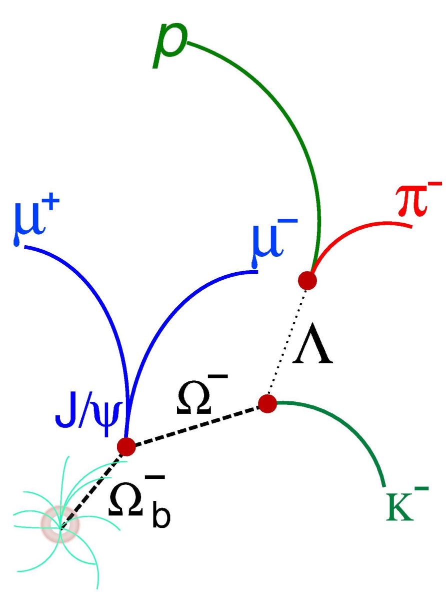


$m(\Omega_b)$ =

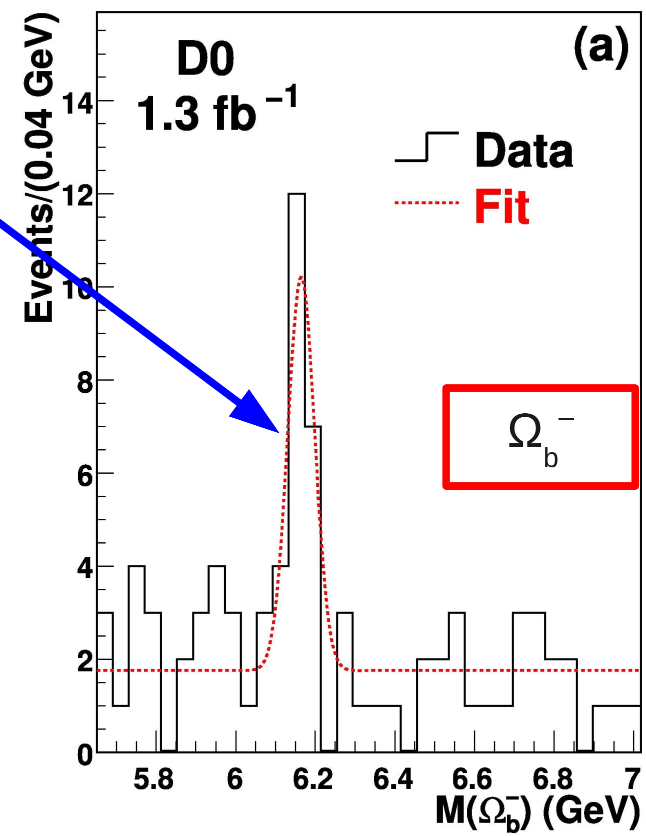
6054.4 ± 6.8 (stat.) ± 0.9 (syst.) MeV

6165 ± 10 (stat) ± 13(syst.) MeV

significant discrepancy
to be understood

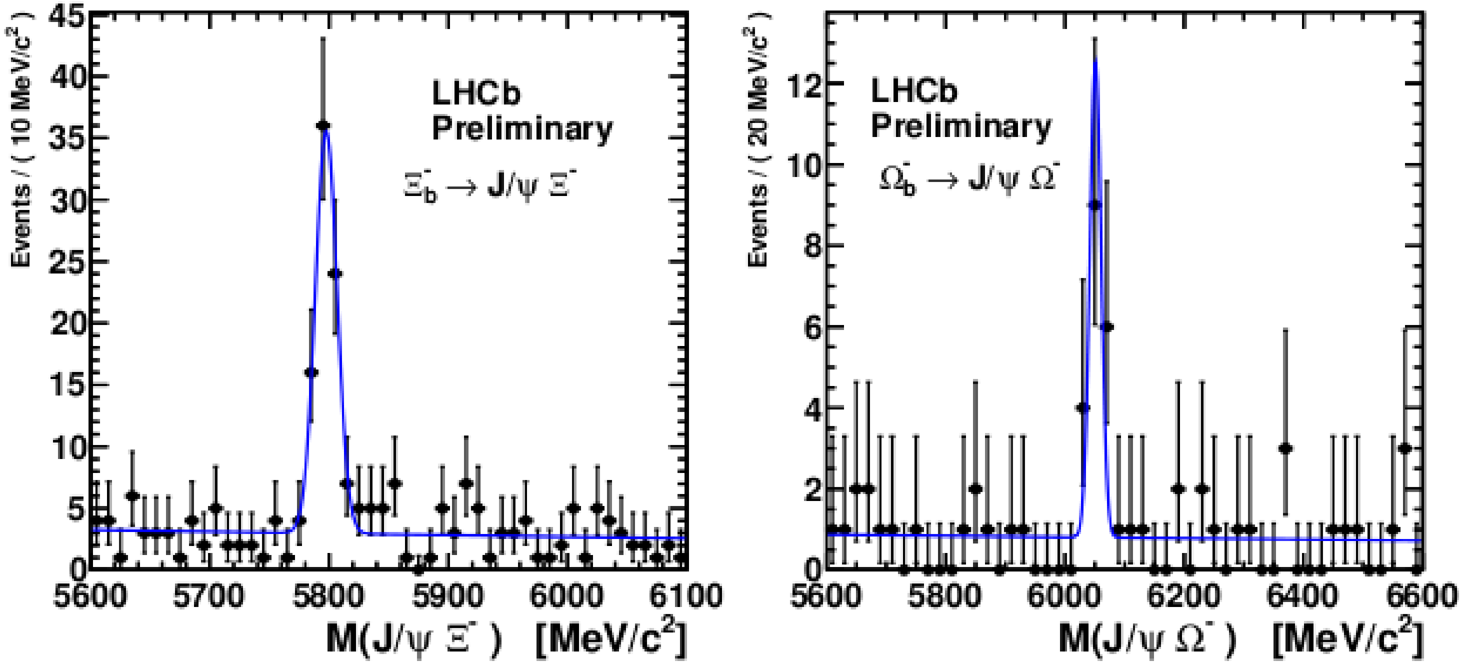


D0 PRL 101 (2008) 232002



LHCb results on Ξ_b and Ω_b

LHCb-CONF-2011-060



$$M(\Xi_b^-) = 5796.5 \pm 1.2 \pm 1.2 \text{ MeV}/c^2;$$
$$M(\Omega_b^-) = 6050.3 \pm 4.5 \pm 2.2 \text{ MeV}/c^2.$$

… which agrees well with CDF

Search for X(4140) in $B^+ \to J/\psi\phi K^+$

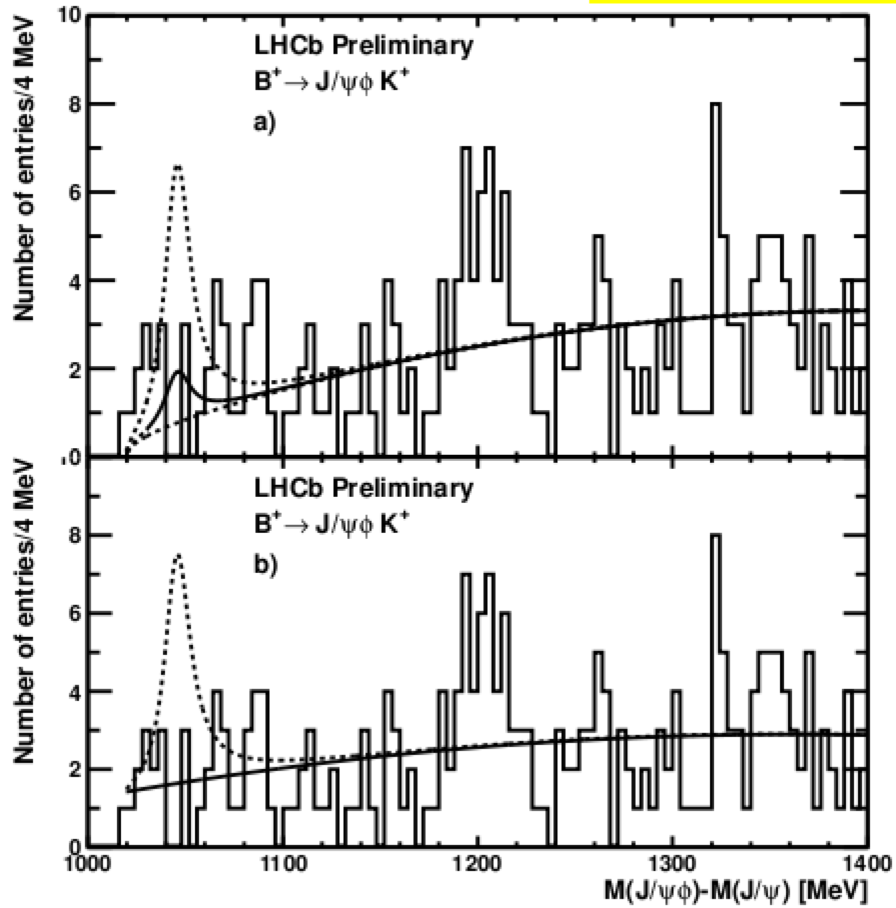
LHCb-CONF-2011-045

CDF claimed a narrow state in $J/\psi\phi$ spectrum at 4140

- PRL 102 (2009) 242002 and arXiv:1101.6058

Not seen in LHCb data

- (dotted lines, expectation based on CDF central value)

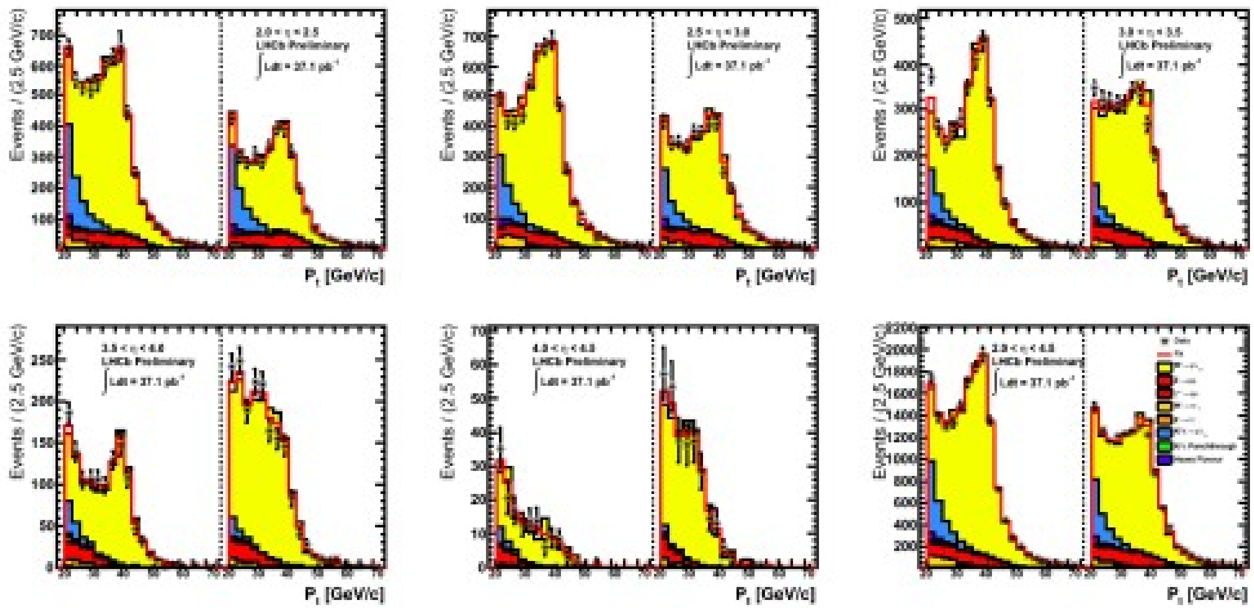


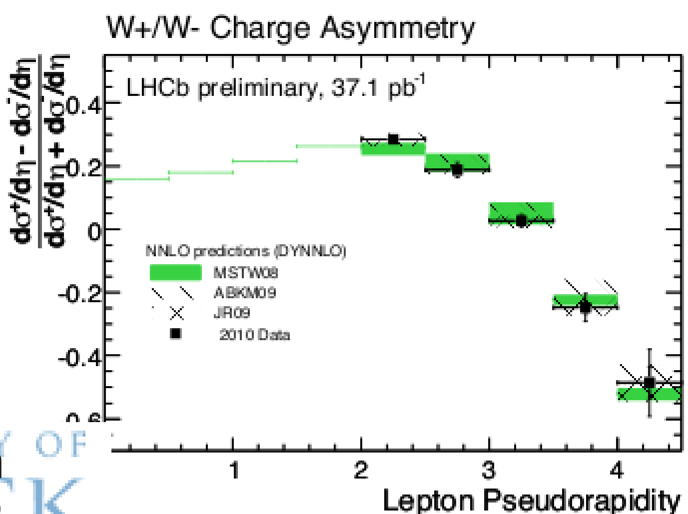
$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.07 \quad \text{at } 90\% \text{ CL.}$$

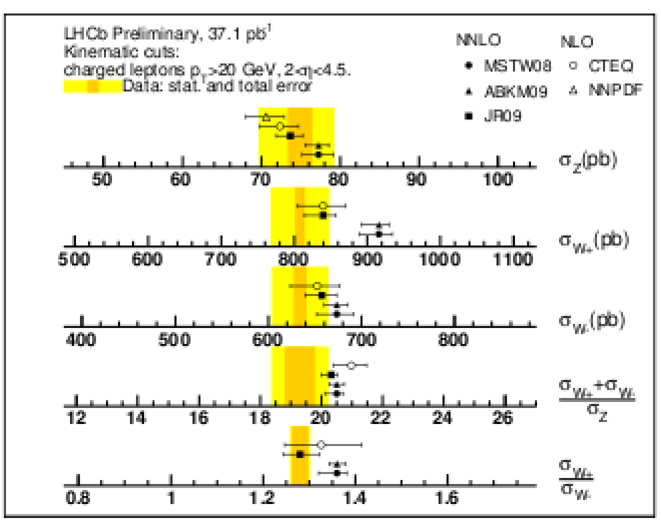
W and Z production

LHCb-CONF-2011-039

Unique forward geometry essential to probe proton structure functions







Highlights of recent results

Rare Decays

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

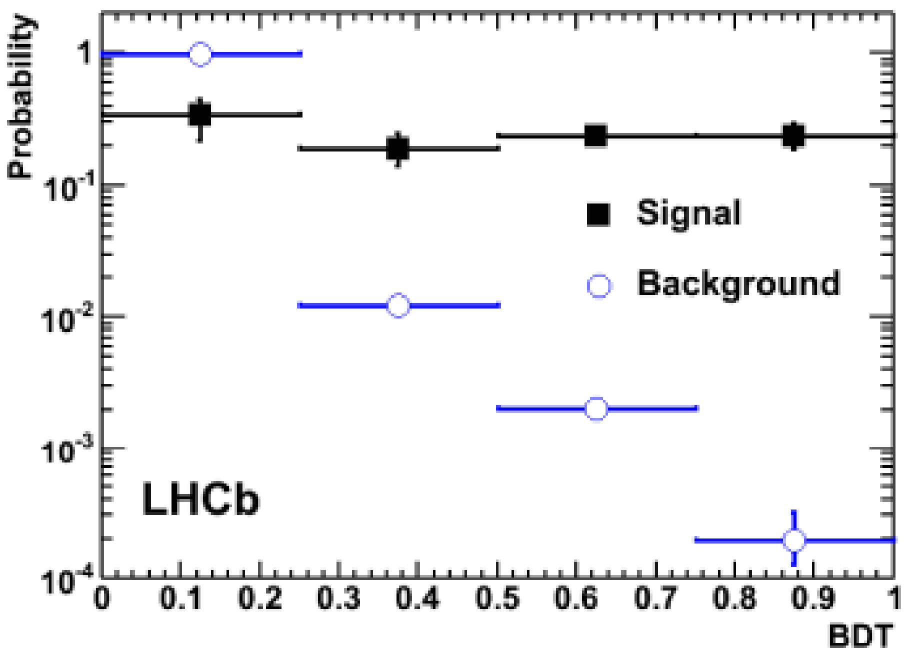
- FCNC with additional SM helicity suppression
  - highly sensitive to contributions from BSM particles
  - e.g. in MSSM

$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.2 \pm 0.2) \times 10^{-8} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

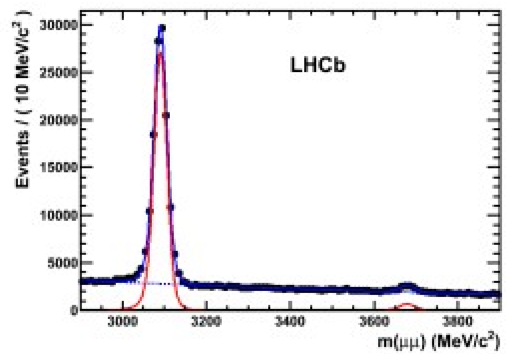
  - provides strongest constraints at high tan β
- Yield obtained from plane of (BDT,mass)
  - BDT is a multivariate discriminant; signal shape obtained from $B \to h^+h'^-$ decays
  - mass resolution extrapolated from J/ψ & Υ $\to \mu^+\mu'^-$
  - normalisation to several channels, e.g. $B^+ \to J/\psi K^+$

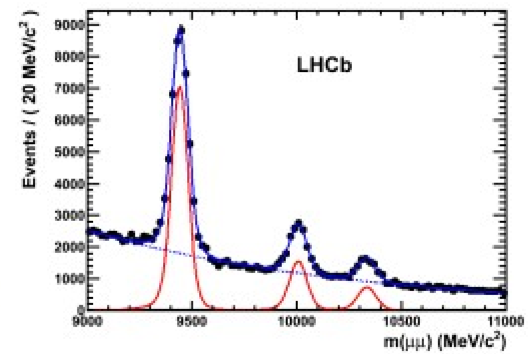
$B_s \to \mu^+\mu^-$ – ingredients of the analysis

LHCb-PAPER-2011-025
arXiv:1112.1600

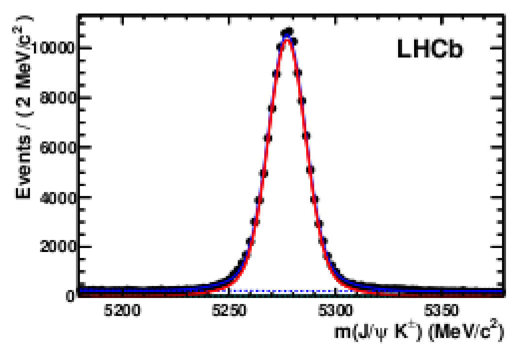


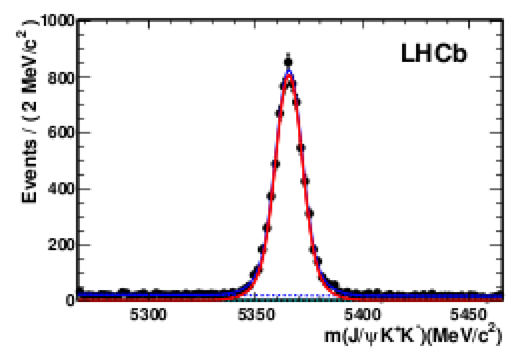
signal shape obtained from $B \to h^+h'^-$ decays





mass resolution extrapolated from J/ψ & $\Upsilon \to \mu^+\mu^-$





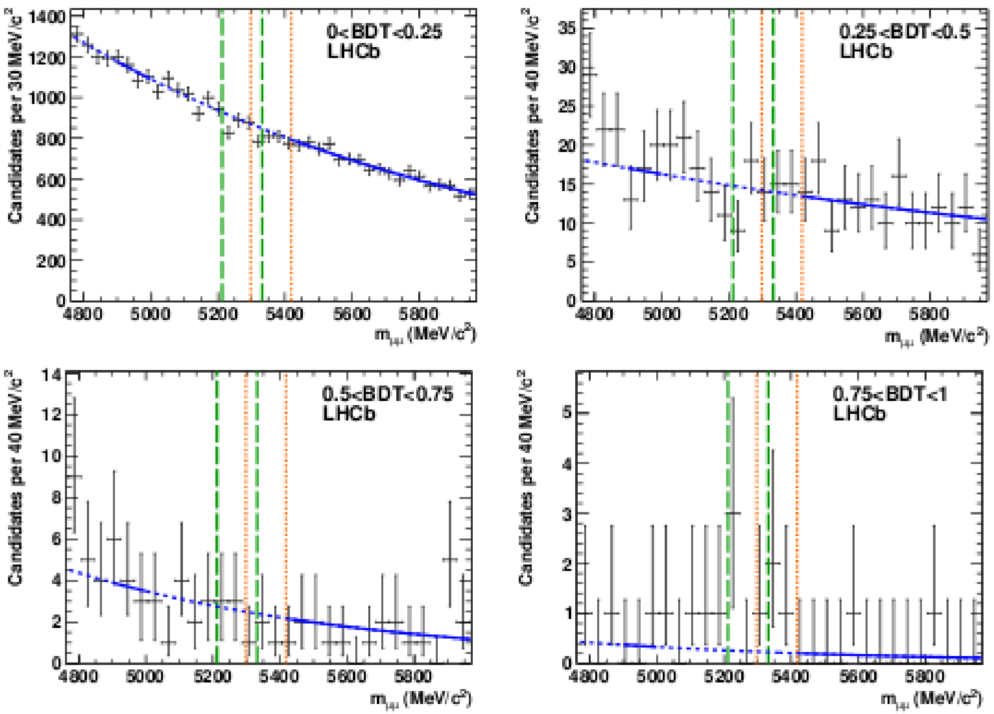
normalisation to several channels, e.g. $B^+ \to J/\psi K^+$

N.B. $f_s/f_d = 0.267^{+0.021}_{-0.020}$

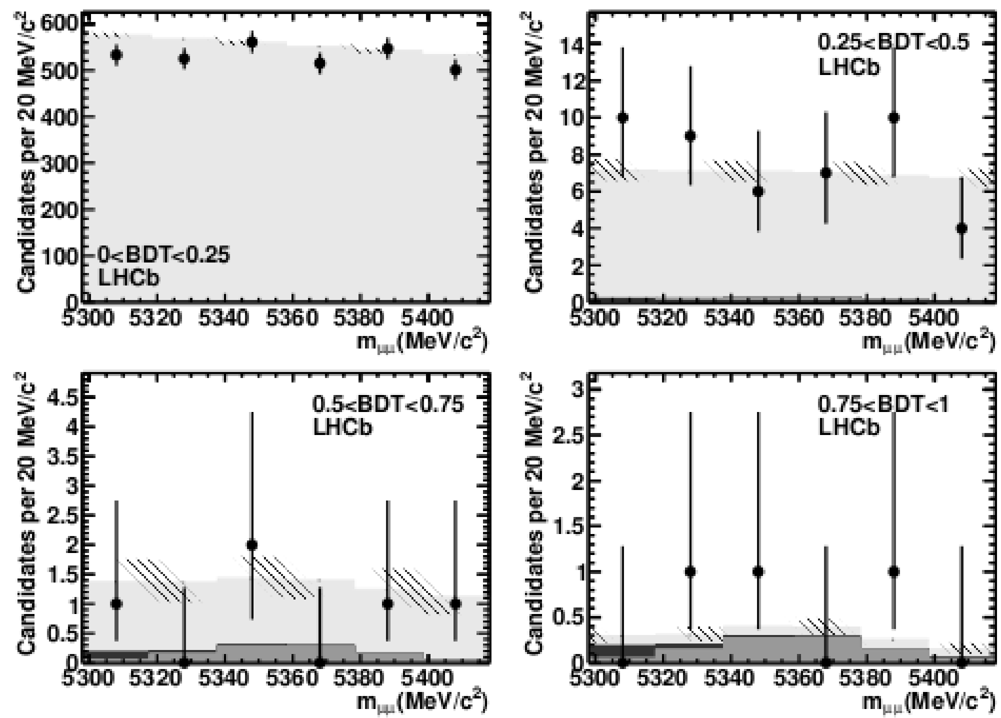
LHCB-PAPER-2011-018 arXiv:1111.2357

$B_s \to \mu^+\mu^-$ – results (0.37/fb)

LHCb-PAPER-2011-025
arXiv:1112.1600



wide mass region



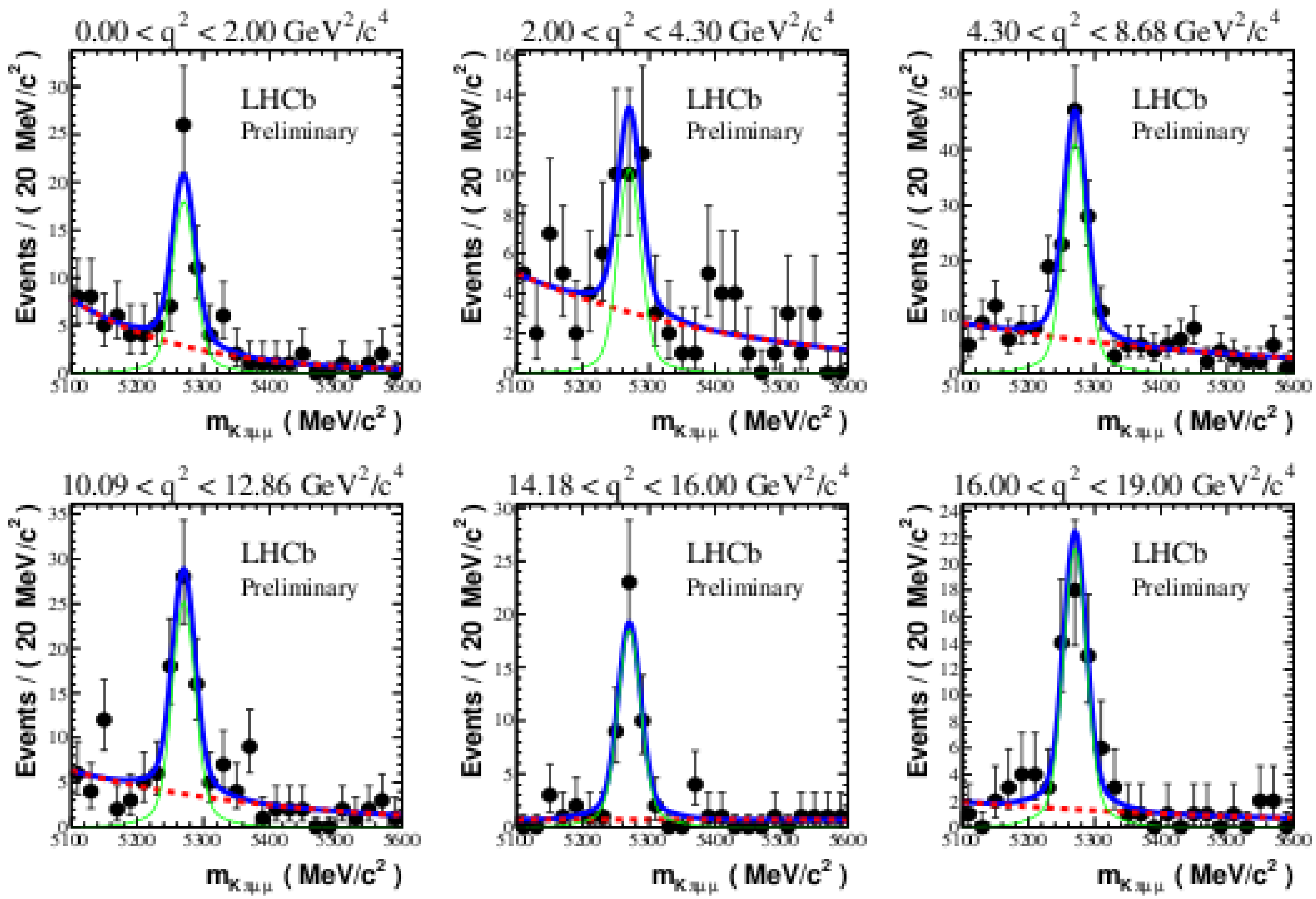
signal mass region

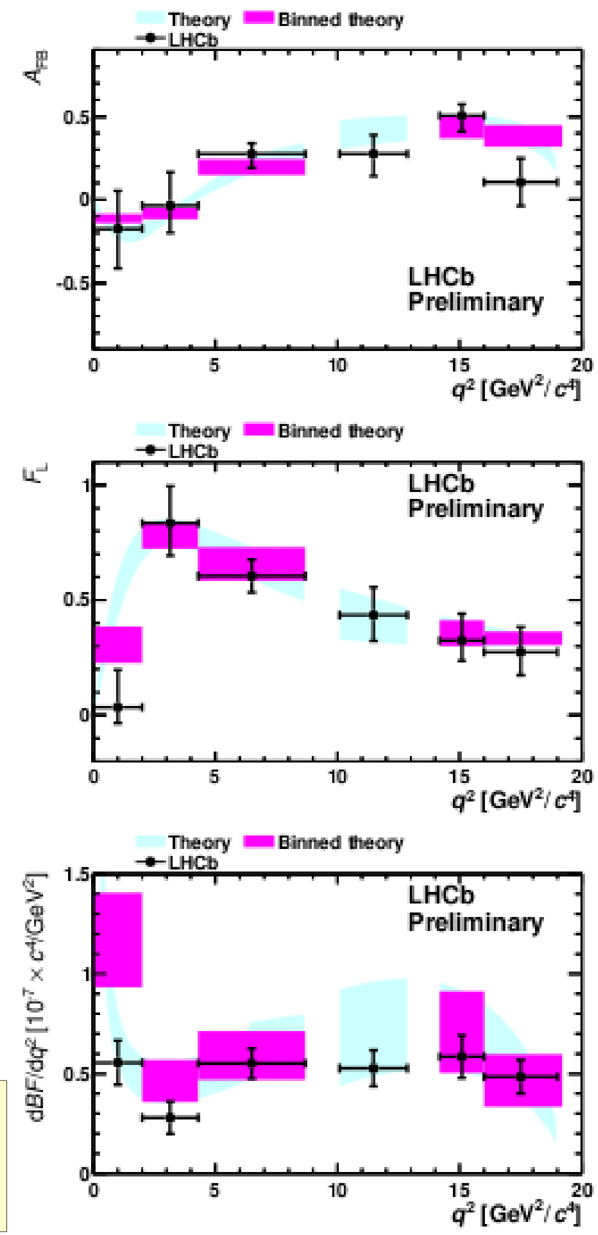
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)(2010+2011) \;<\; 1.2\,(1.4) \times 10^{-8} \text{ at } 90\,\%\,(95\,\%) \text{ CL},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)(2010+2011) \;<\; 2.6\,(3.2) \times 10^{-9} \text{ at } 90\,\%\,(95\,\%) \text{ CL}.$$

starting to approach SM sensitivity

Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

LHCb-CONF-2011-038
(paper to be submitted)

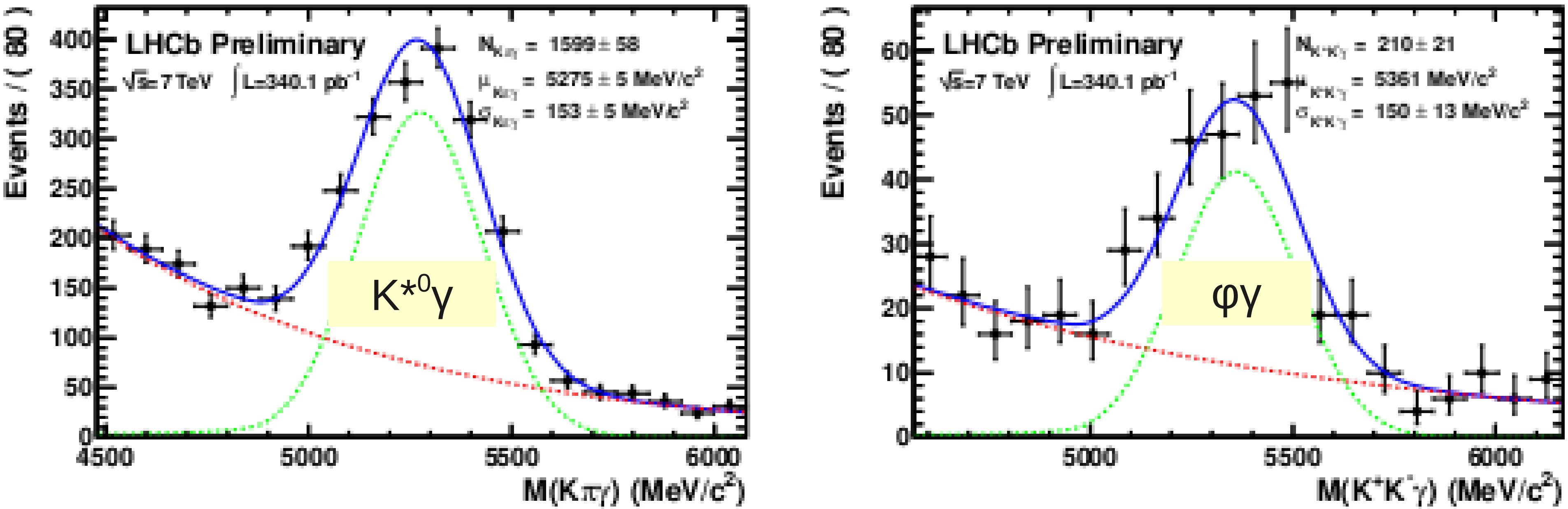




Signal yields already exceed those of previous experiments

Radiative B decays

LHCb-CONF-2011-055



$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.52 \pm 0.14(\mathrm{stat}) \pm 0.10(\mathrm{syst}) \pm 0.12(f_s/f_d)$$

Next steps in programme of measurements

- studies of CP violation
- tests of photon polarisation

Highlights of recent results

CP violation

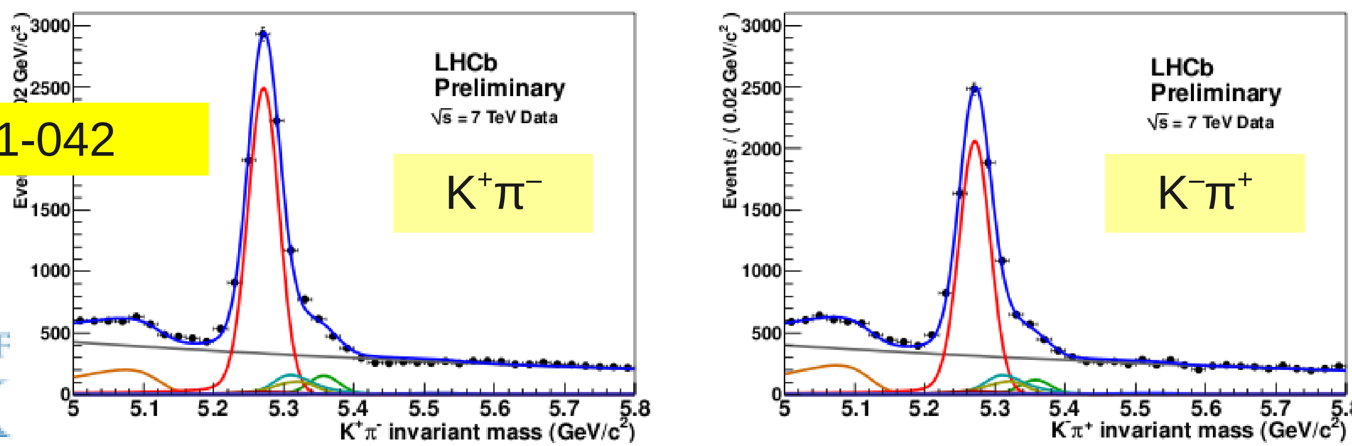
Observations of CP violation

- In B system, only 5σ observations of CPV
  - $\sin(2\beta)$ in $B^0 \to J/\psi K_{S,L}$ (etc.) – BaBar & Belle
  - $S(B^0 \to \eta' K_{S,L})$ (etc.) – BaBar & Belle
  - $S(B^0 \to \pi^+\pi^-)$ – BaBar & Belle
  - $C(B^0 \to \pi^+\pi^-)$ – Belle
  - $A_{CP}(B^0 \to K^+\pi^-)$ – BaBar, Belle & LHCb

$A_{CP}(B^0 \to K^+\pi^-) = -0.088 \pm 0.011 \pm 0.008$

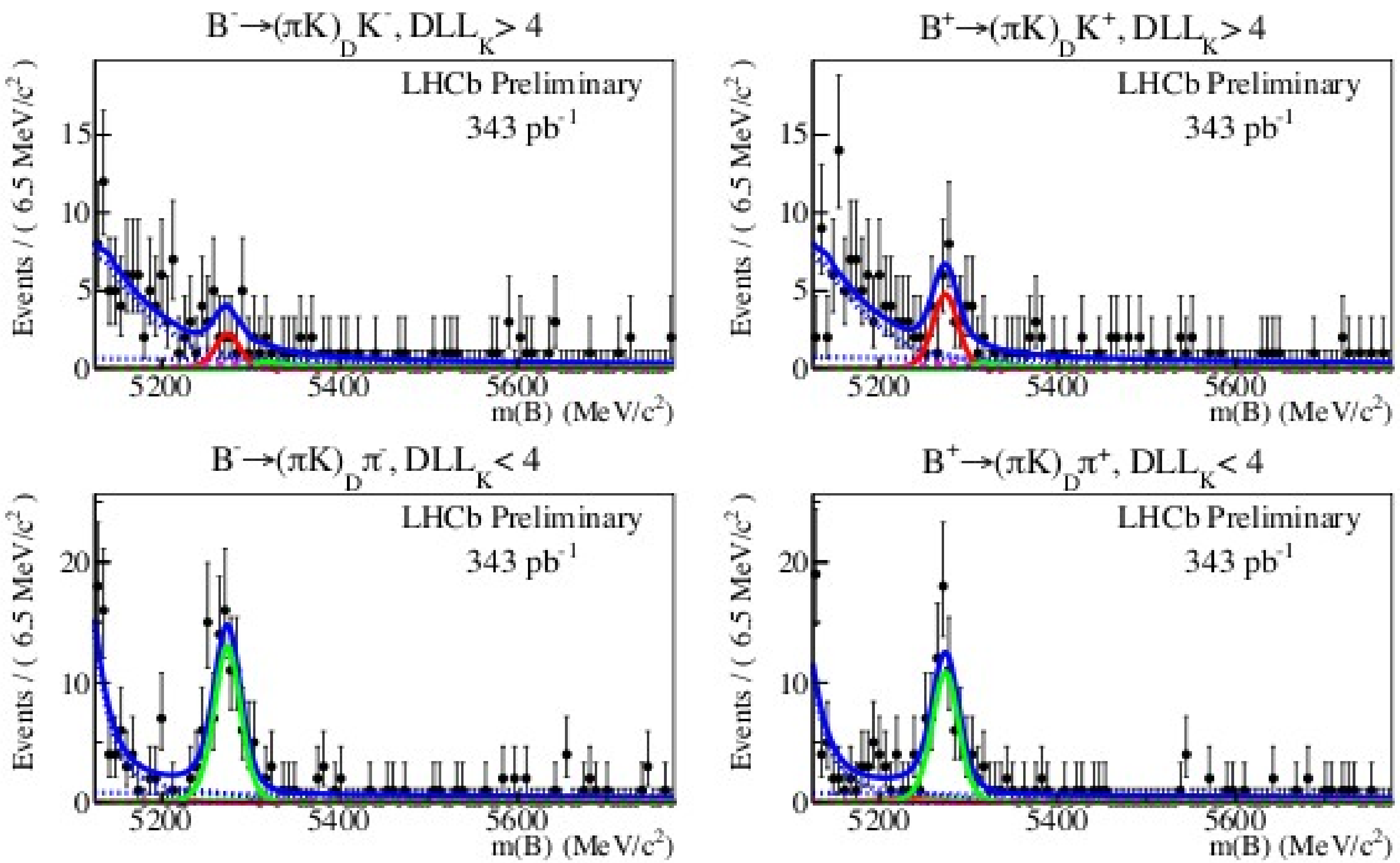
(single most precise measurement)

LHCB-CONF-2011-042



γ from B→DK, D→suppressed states (ADS)

LHCb-CONF-2011-044

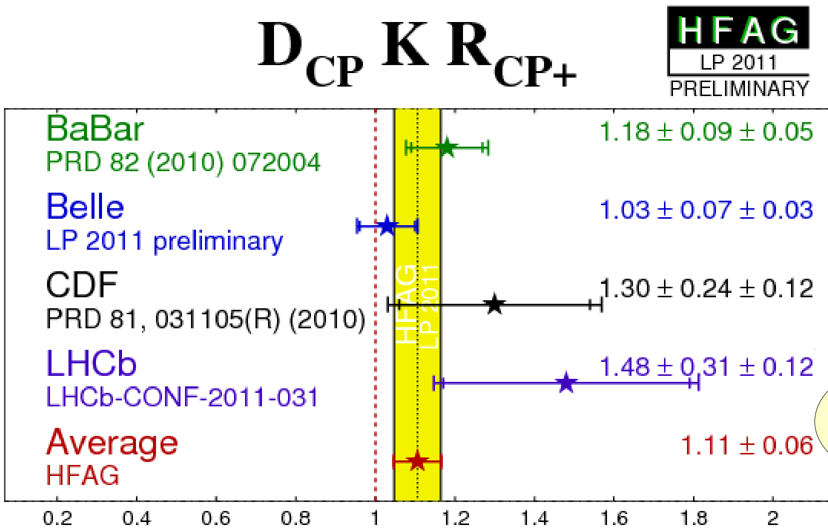


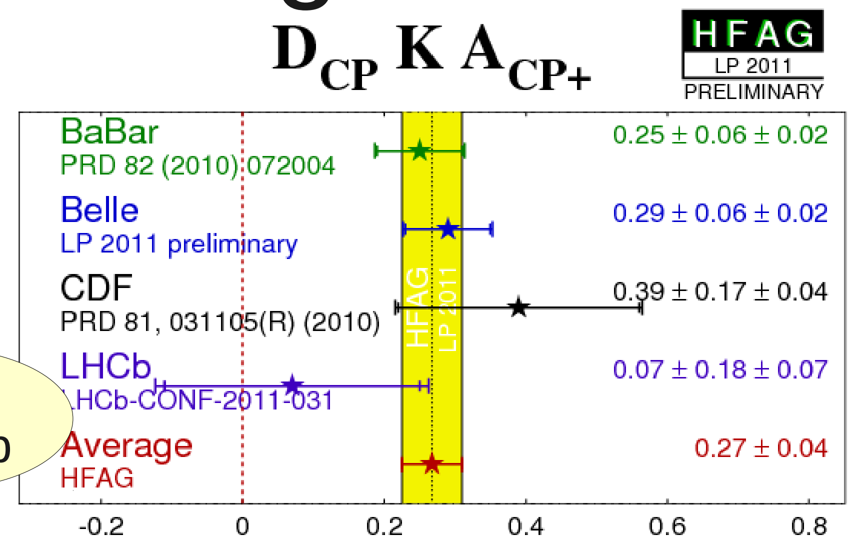
$$R_{ADS} = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2}$$

$$A_{ADS} = -0.39 \pm 0.17 \pm 0.02$$

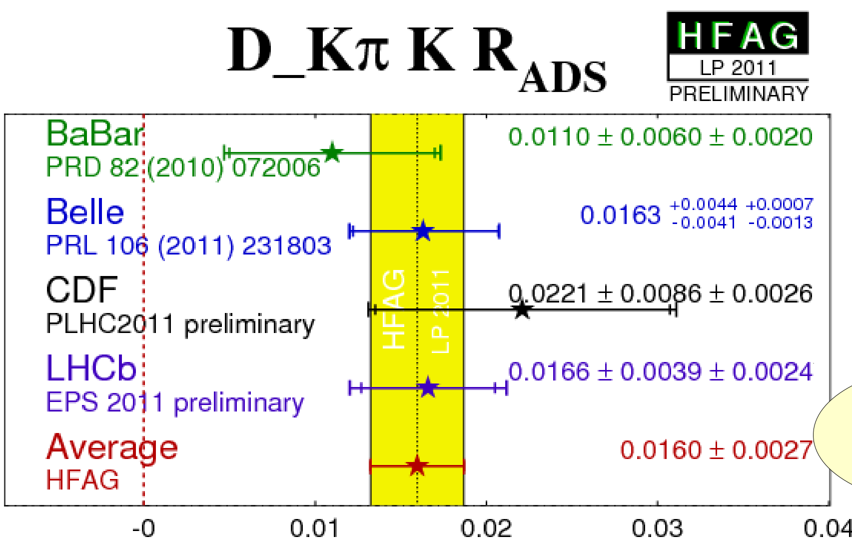
(single most precise measurements)

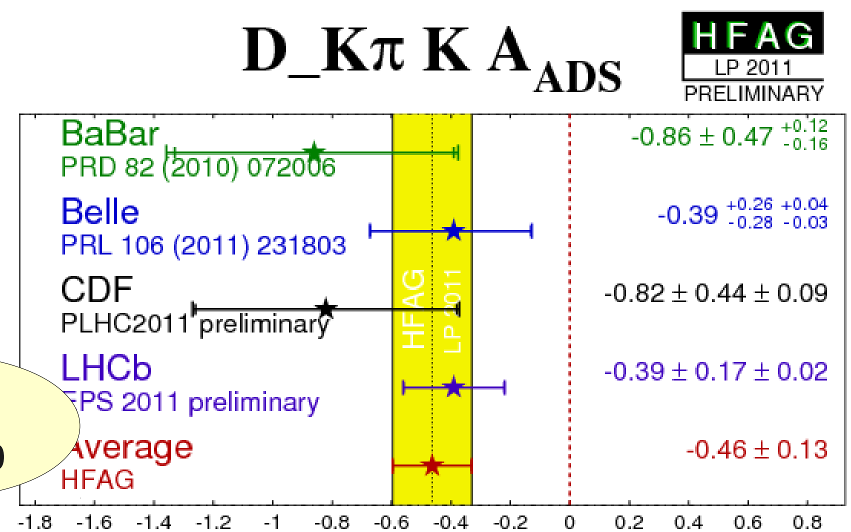
ADS world averages





LHCb
0.037/fb





LHCb
0.34/fb

A_{CP+} and R_{ADS} now clearly established ...
… very promising for γ determination

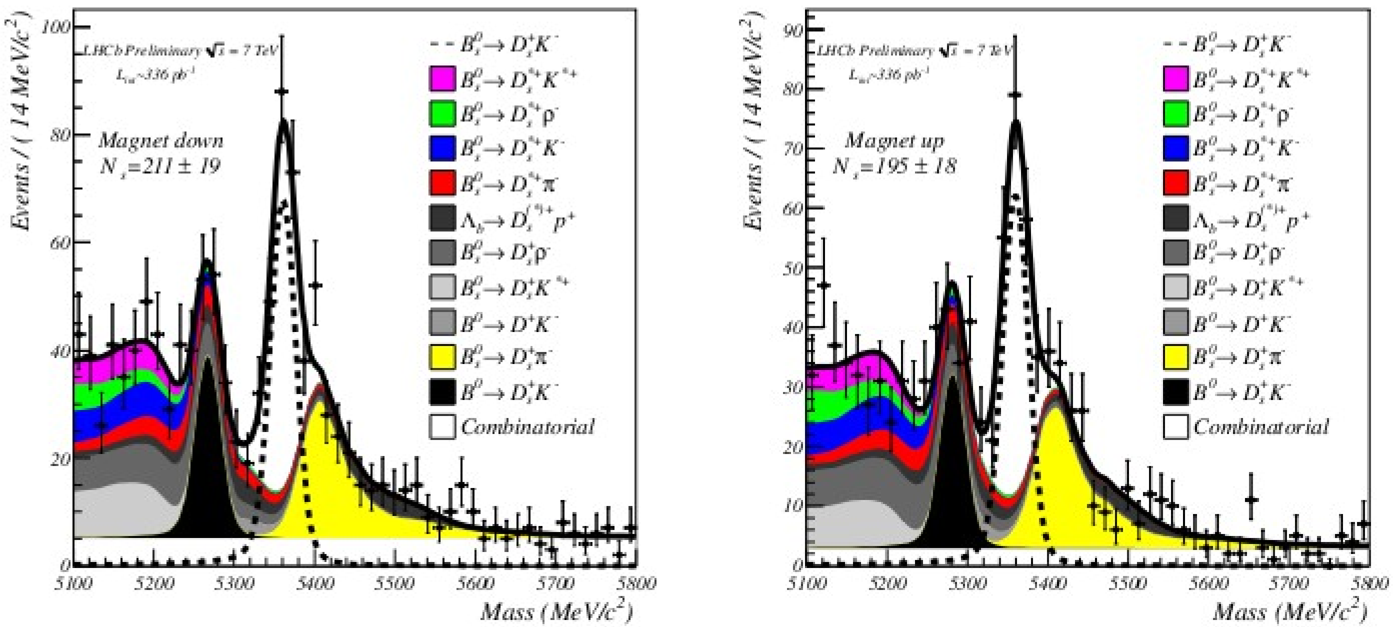
γ from $B_s \to D_s K$

LHCb-CONF-2011-057

γ can be extracted from time-evolution of $B_s \to D_s K$ decays

first stage: establish signals & measure branching fraction

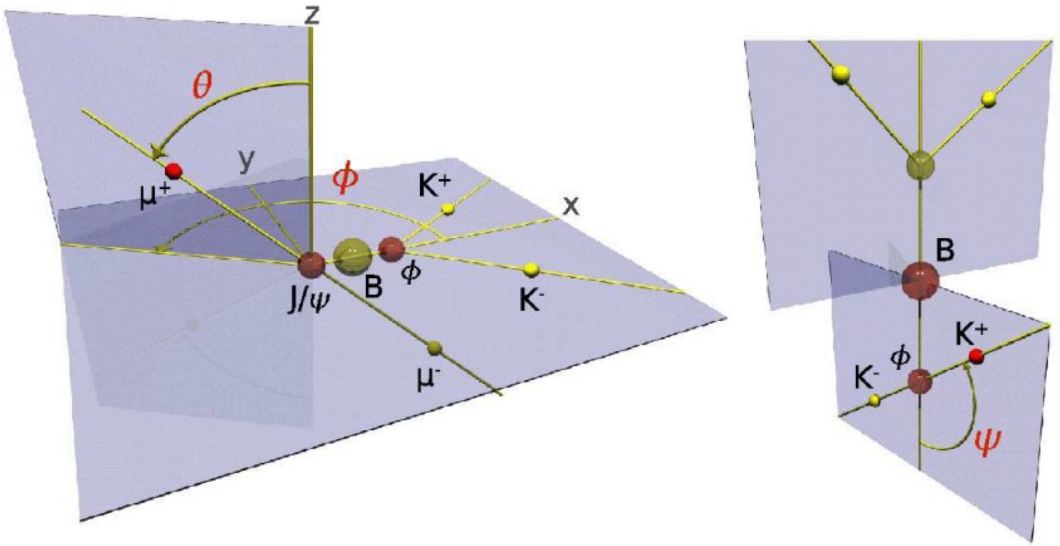
yields split by magnet polarity



$$B\left(B_s \to D_s^{\mp} K^{\pm}\right) = \left(1.97 \pm 0.18\,(stat)\,^{+0.19}_{-0.20}(syst)\,^{+0.11}_{-0.10}(f_s/f_d)\right) \times 10^{-4}$$

Promising for future γ measurement

β_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 $J/\psi f_0$ analysis (Γ_s, $\Delta\Gamma_s$)

$B_s \to J/\psi\phi$ 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 → $h_k(t)$; $\overline{\text{Bs}}$ → $\bar{h}_k(t)$

- $A_0(0)$ → CP even
- $A_{\|}(0)$ → CP even
- $A_\perp(0)$ → CP odd

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	$\lvert A_{\|}(t)\rvert^2$	$\lvert \bar{A}_{\|}(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert \bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_{\|}^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_{\|}^*(t)\bar{A}_\perp(t)\}$	$\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_{\|}(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_{\|}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
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 $\bar{B}_s$

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

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

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

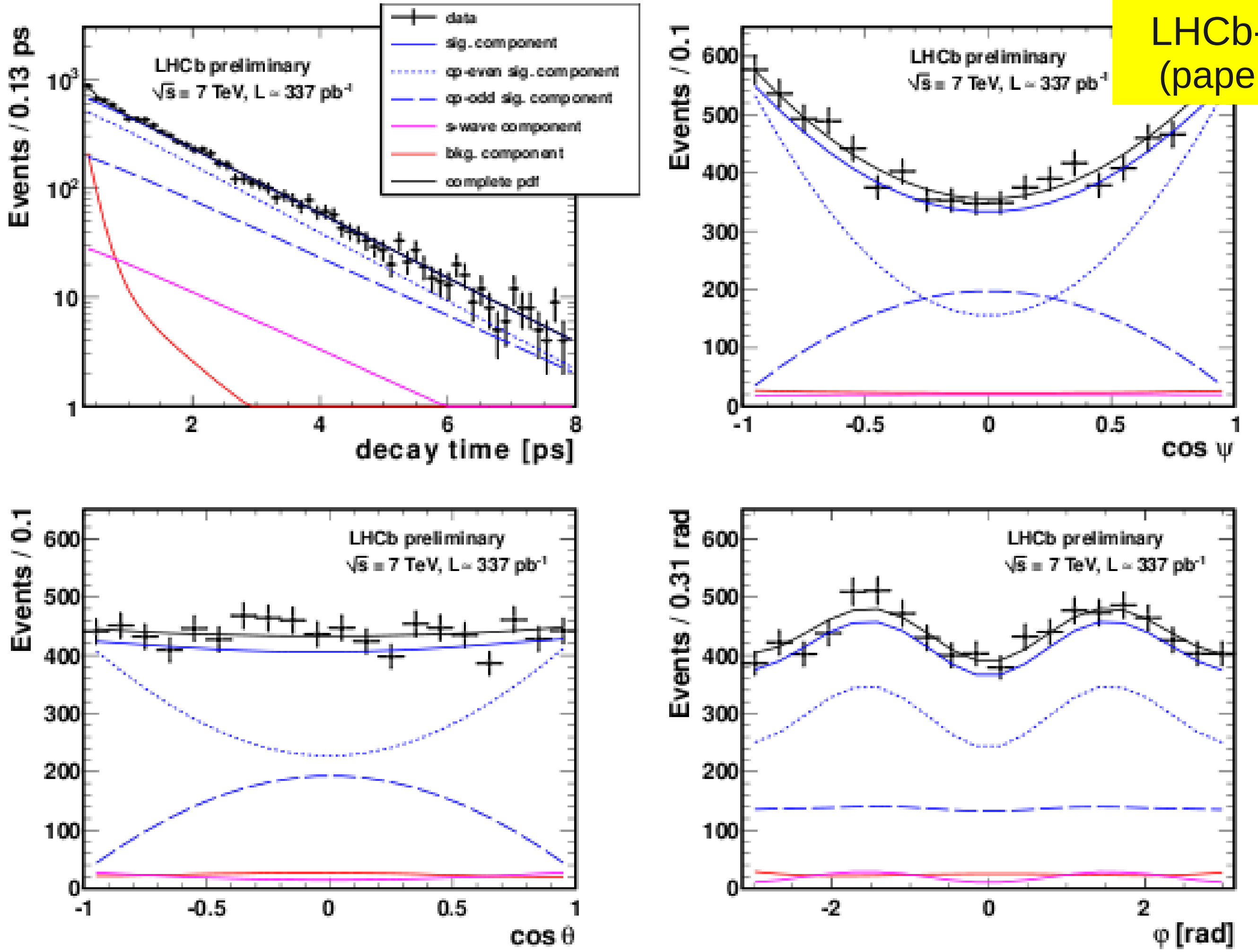
$$\Im\{\bar{A}_{\|}^*(t)\bar{A}_\perp(t)\} = |\bar{A}_{\|}(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_{\|})\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\delta_\perp-\delta_{\|})\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_{\|})\cos\Phi\sin(\Delta m_s t)\right],$$

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

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

Results from $B_s \to J/\psi\phi$ (0.34/fb)

LHCb-CONF-2011-049
(paper to be submitted)



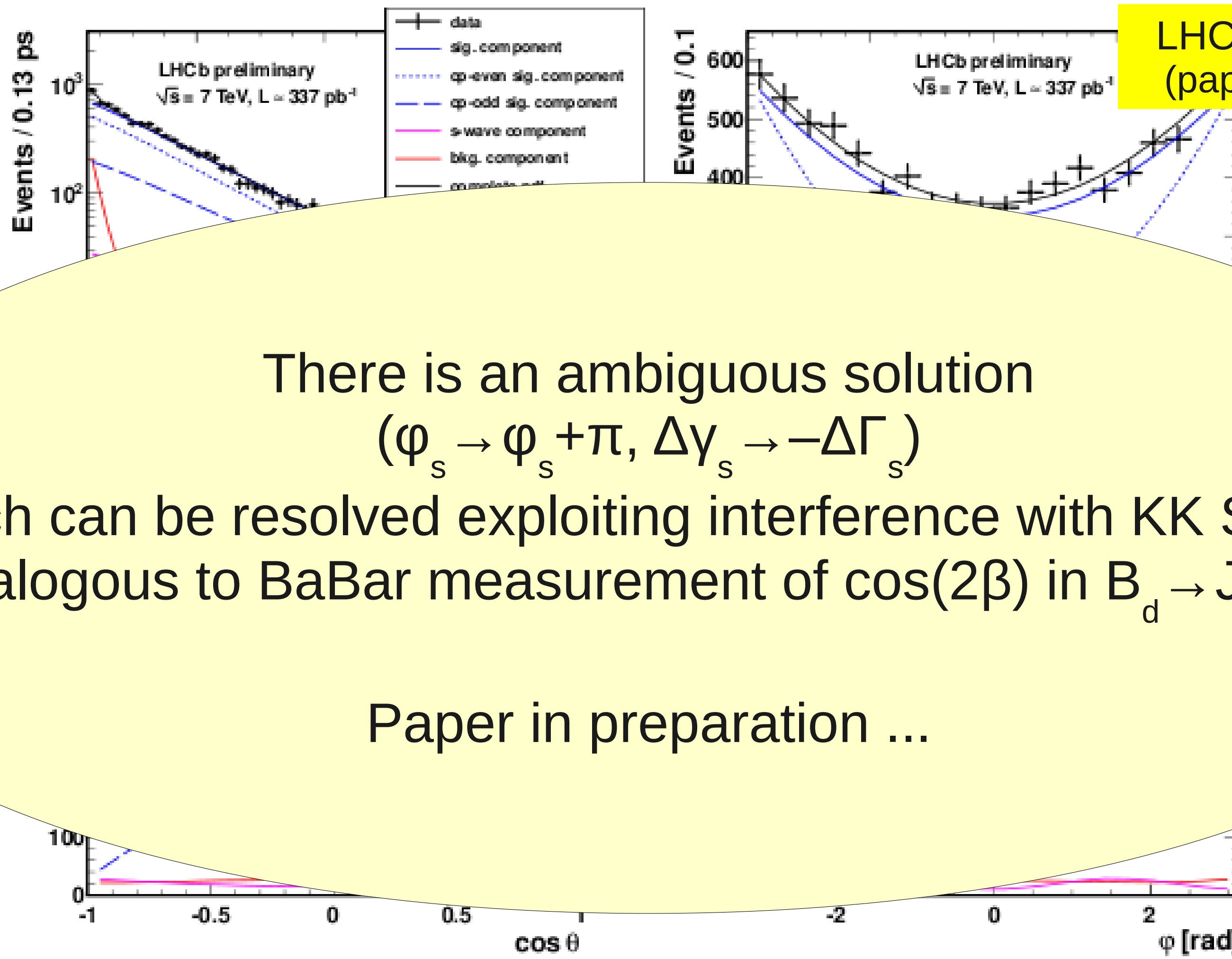
$$\phi_s^{J/\psi\phi} = 0.13 \pm 0.18\ \text{(stat)} \pm 0.07\ \text{(syst)}\ \text{rad},$$

$$\Gamma_s = 0.656 \pm 0.009\ \text{(stat)} \pm 0.008\ \text{(syst)}\ \text{ps}^{-1},$$

$$\Delta\Gamma_s = 0.123 \pm 0.029\ \text{(stat)} \pm 0.011\ \text{(syst)}\ \text{ps}^{-1},$$

Results from $B_s \to J/\psi\phi$ (0.34/fb)

LHCb-CONF-2011-049
(paper to be submitted)



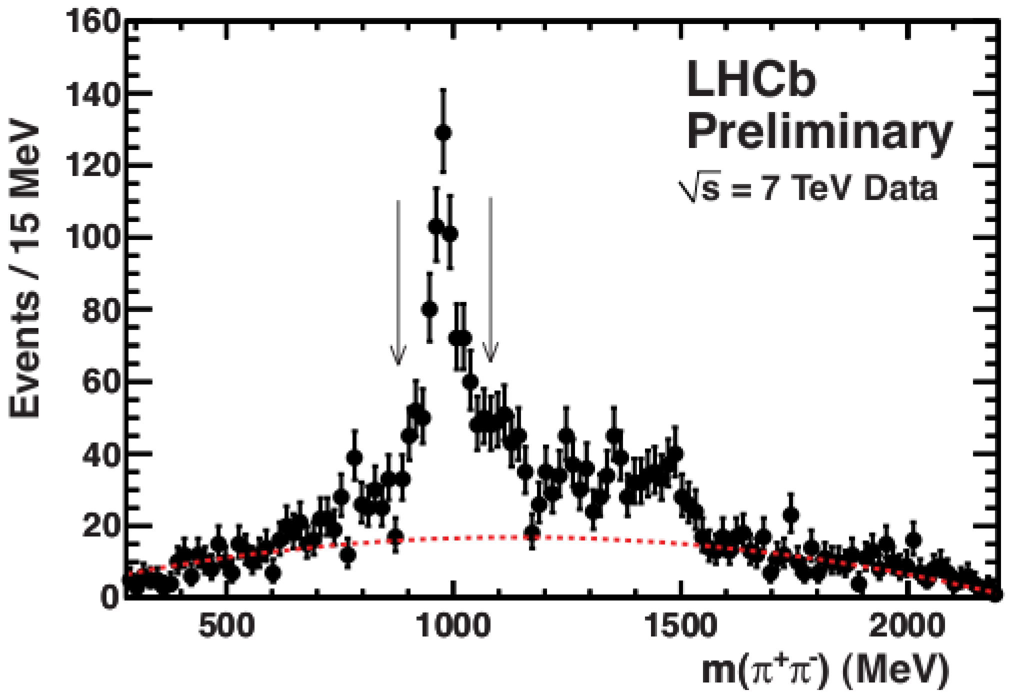
There is an ambiguous solution
($\varphi_s \to \varphi_s + \pi$, $\Delta\gamma_s \to -\Delta\Gamma_s$)
which can be resolved exploiting interference with KK S-wave
(analogous to BaBar measurement of cos(2β) in $B_d \to J/\psi K^{*0}$)

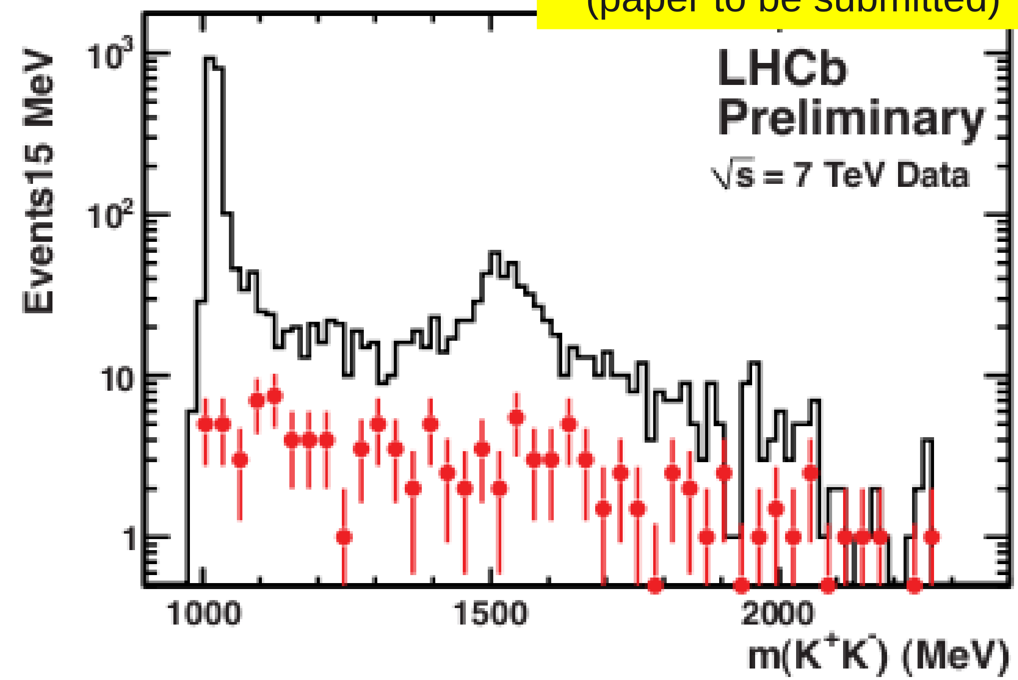
Paper in preparation ...

$$\phi_s^{J/\psi\,\phi} = 0.13 \pm 0.18 \text{ (stat)} \pm 0.07 \text{ (syst) rad},$$
$$\Gamma_s = 0.656 \pm 0.009 \text{ (stat)} \pm 0.008 \text{ (syst) ps}^{-1},$$
$$\Delta\Gamma_s = 0.123 \pm 0.029 \text{ (stat)} \pm 0.011 \text{ (syst) ps}^{-1},$$

Studies of structures in $B_s^0 \to J/\psi\pi^+\pi^-$ and $J/\psi K^+K^-$ including first observation of $B_s^0 \to J/\psi f_2'(1525)$

LHCb-CONF-2011-035
(paper to be submitted)





$$R^{f_0}_{\rm effective} \equiv \frac{\mathcal{B}(B_s^0 \to J/\psi f_0,\ f_0 \to \pi^+\pi^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi,\ \phi \to K^+K^-)} = (21.7 \pm 1.1 \pm 0.7)\%$$

$$\text{for } \left| m(\pi^+\pi^-) - 980 \text{ MeV} \right| < 90 \text{ MeV}.$$

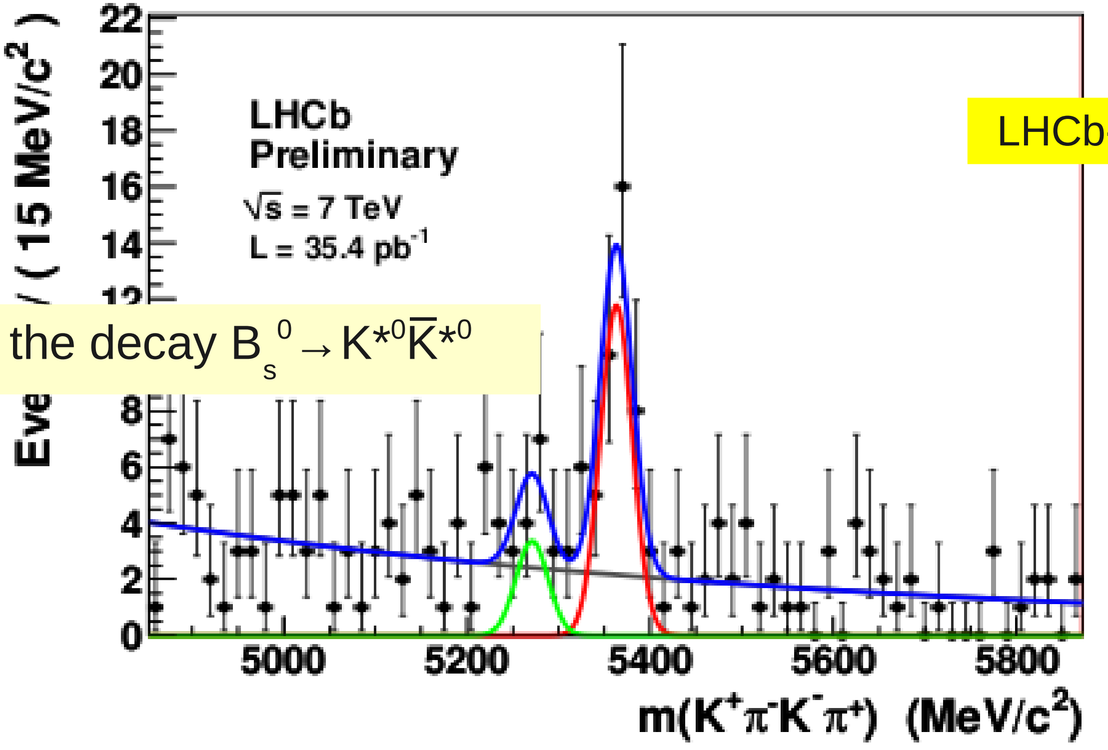
$$R^{f_2'}_{\rm effective} \equiv \frac{\mathcal{B}(B_s^0 \to J/\psi f_2'(1525),\ f_2'(1525) \to K^+K^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi,\ \phi \to K^+K^-)} = (19.4 \pm 1.8 \pm 1.1)\%$$

$$\text{for } \left| m(K^+K^-) - 1525 \text{ MeV} \right| < 125 \text{ MeV}.$$

Studies of hadronic b→s penguins

Decays like $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$ are loop dominated processes

- VV final states; well suited to study at LHCb
- analysis of modes with K_S, f_0, $\eta^{(\prime)}$ are also under study



LHCb-PAPER-2011-012

First observation of the decay $B_s^0 \to K^{*0}\overline{K}^{*0}$

$$\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) = (1.95 \pm 0.47(\text{stat.}) \pm 0.51(\text{syst.}) \pm 0.29\,(f_d/f_s)) \times 10^{-5}$$

Looking to the future

LHCb short-term & upgrade

- 2012
  - record as much data as possible (aim for >1.5/fb)
  - for analysis during "LS0" (2013/14)
- 2015/6
  - profit from increased cross-sections at higher √s
- 2017/8
  - during "LS1", upgrade detector electronics (plus necessary detector components) to allow readout at 40 MHz
    - escape current limitation from L0 trigger
  - then run at luminosity of few $10^{33}/cm^2/s$
    - accumulate total 50/fb (a factor >100 compared to results shown today)

Summary

- First data from LHCb has provided results surpassing those from previous experiments
- Total 1.1/fb recorded during 2011
  - now reprocessed and being analysed
  - expect a wide range of exciting results in winter conferences
- Aim to record >1.5/fb in 2012
  - striving to increase trigger efficiencies and maximise both quantity and quality of physics data on tape
- Upgraded LHCb detector will be installed in 2018
  - allows full flavour physics potential of the LHC to be exploited throughout the high luminosity era