Flavour at the LHC

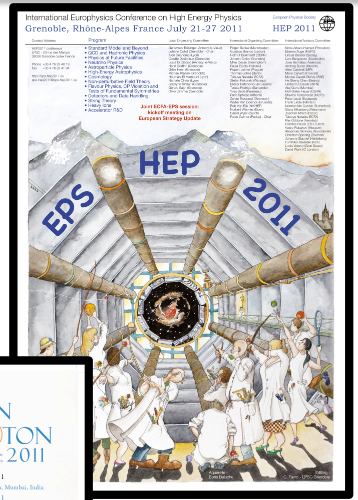
Valerie Gibson, University of Cambridge

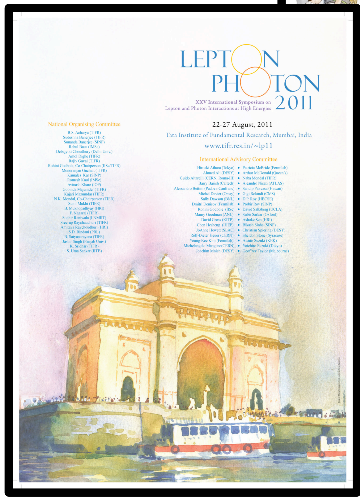
Outline

The Summer of 2011 has seen a giant leap in the flavour sector.

Many new results presented by LHCb (& CMS/ATLAS) at EPS, Lepton-Photon & other conferences.

It is a privilege to summarise some highlights here…





- Introduction
- The LHC(b) Experiments
- Flavour production
- Direct CP violation in B decays
- Mixing and CP violation in B decays
- Rare B decays
- Summary

… at the expense of others e.g. EW physics, charm mixing and CPV etc

Flavour physics

Flavour physics is highly successful. It has led the way to

- The 3 generation Standard Model (SM)
- The CKM picture of flavour
- CP violation (CPV)

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EPS 2011 Prize: Glashow, Iliopolous, Maiani
"For their crucial contribution to the theory of flavour."

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Many open questions in SM found in the flavour sector

- Why are there 3 generations ? (and is it only 3?)
- What determines the hierarchy of the quark and lepton masses ?
- What determines the elements of the CKM matrix ?
- What is the relationship between the CKM matrix and the ν mixing matrix ?
- What is the origin of CP violation ?

Precision studies of flavour observables are an excellent way to look for New Physics.

Progress in flavour physics may help to understand open questions in cosmology – SM CPV insufficient to explain matter/antimatter asymmetry

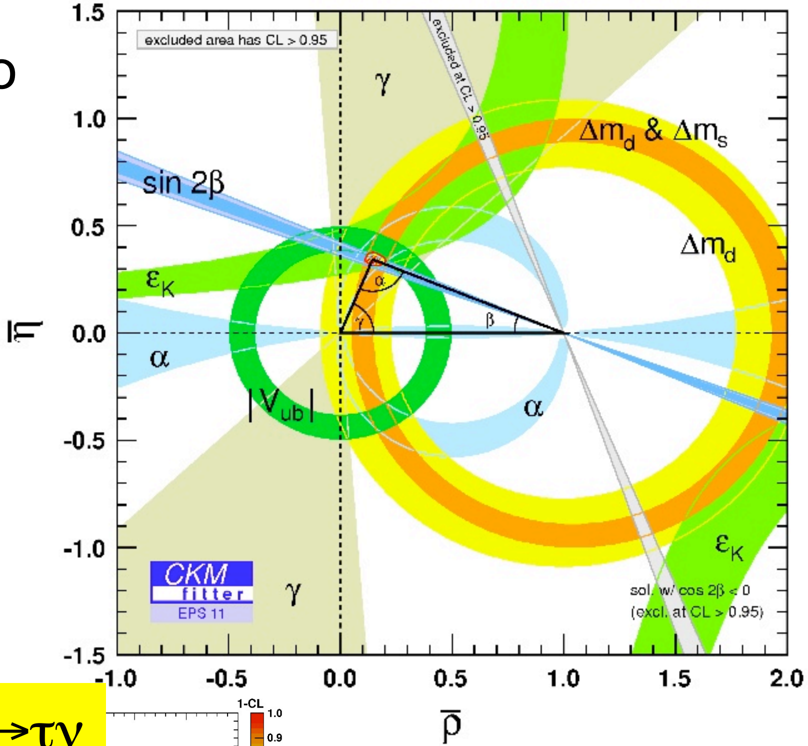
The legacy of the B-factories & CDF/D0

Fantastic achievement over the last decade to test the SM picture of quark couplings, especially CP Violation.

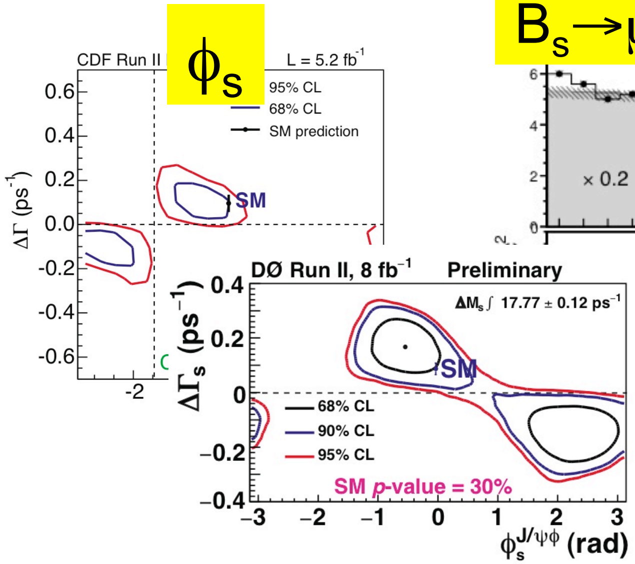
The state of the art is encapsulated in the Unitarity Triangle.

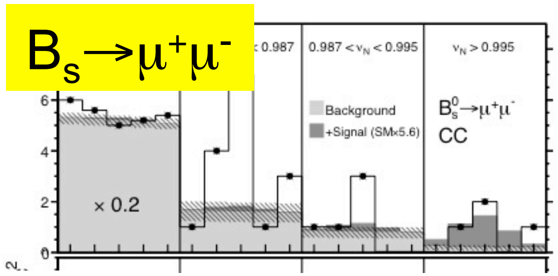
$$\bar{\rho} = 0.144^{+0.027}_{-0.018} \qquad \bar{\eta} = 0.343^{+0.014}_{-0.014}$$

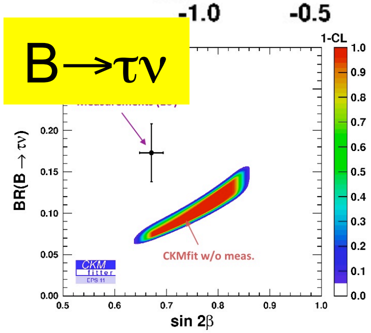
CKMfitter group EPS 2011

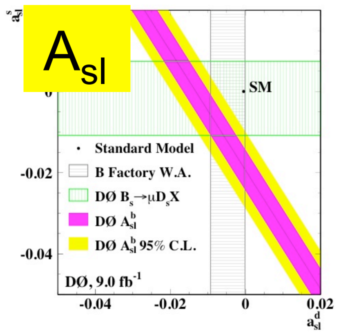


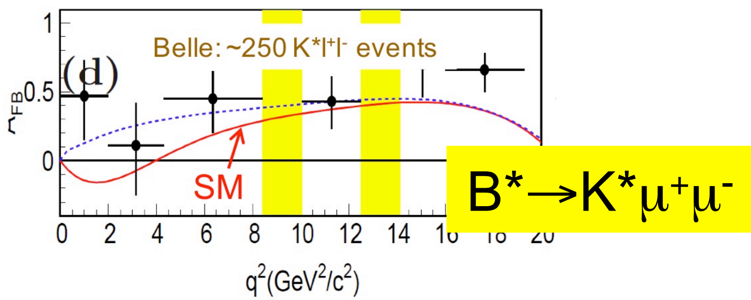
But there are some intriguing signs of NP?











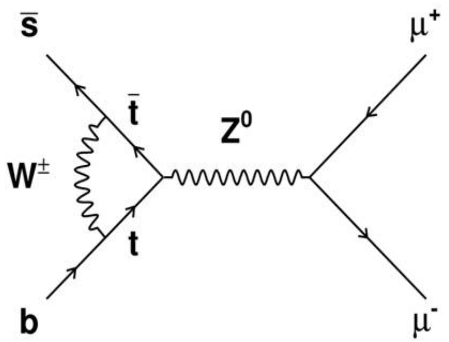
Eagerly await updated results & LHC & SuperB

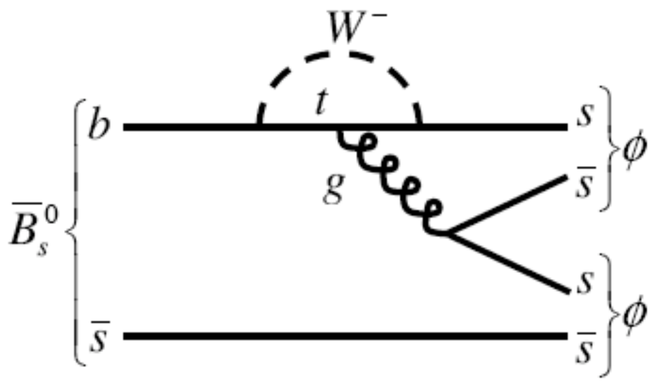
LHC flavour physics program

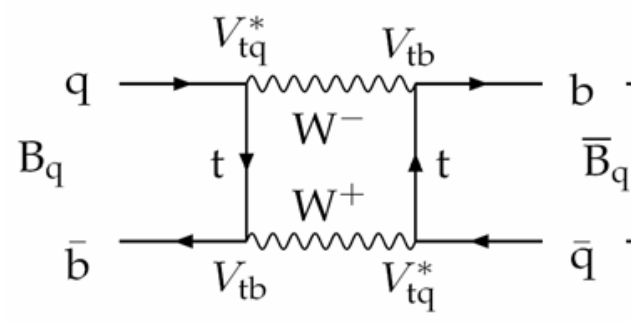
Flavour physics is sensitive to New Physics through the indirect effects that the new degrees of freedom may have on flavour observables.

The search is complimentary to direct searches and provides information on the masses, couplings, spins and CP phases.

Standard Model processes







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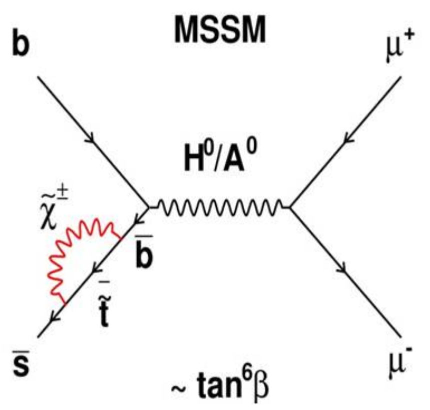
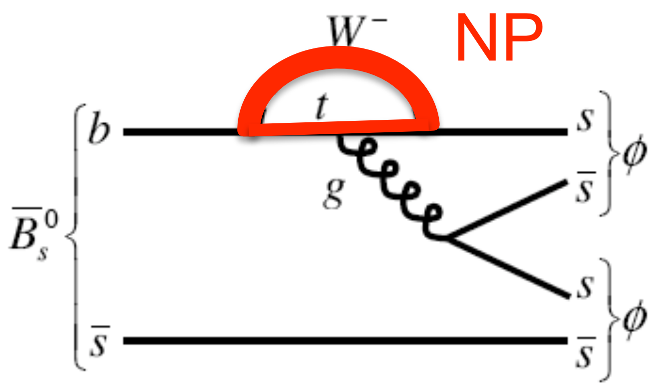
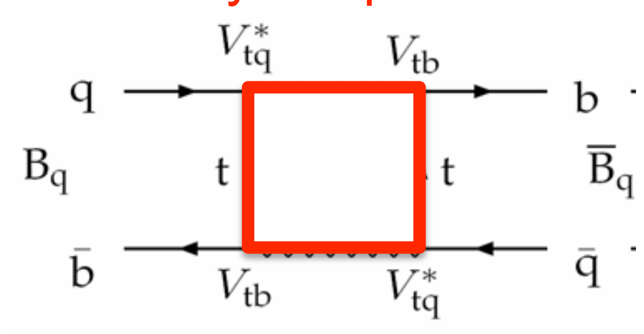




New Physics processes



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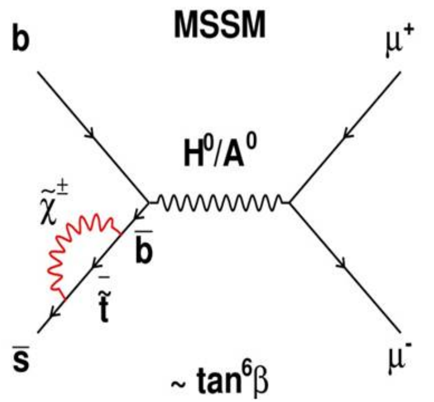
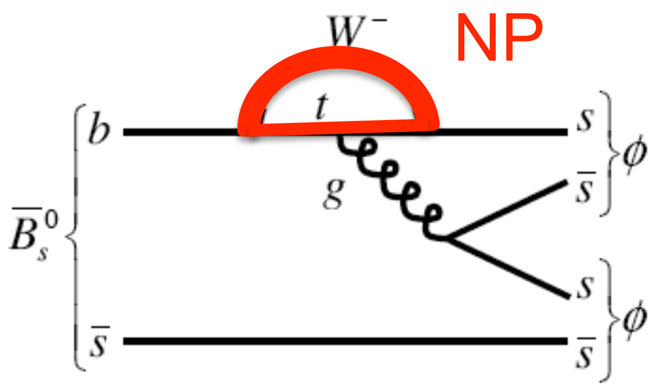
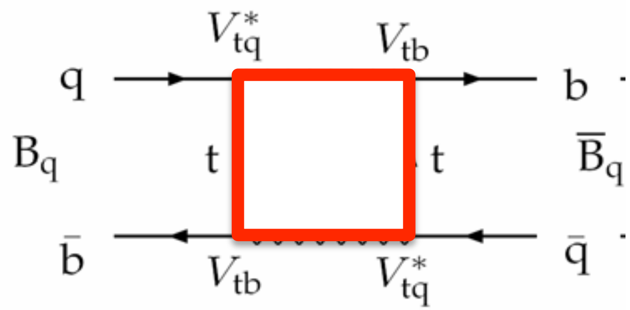




New Physics processes

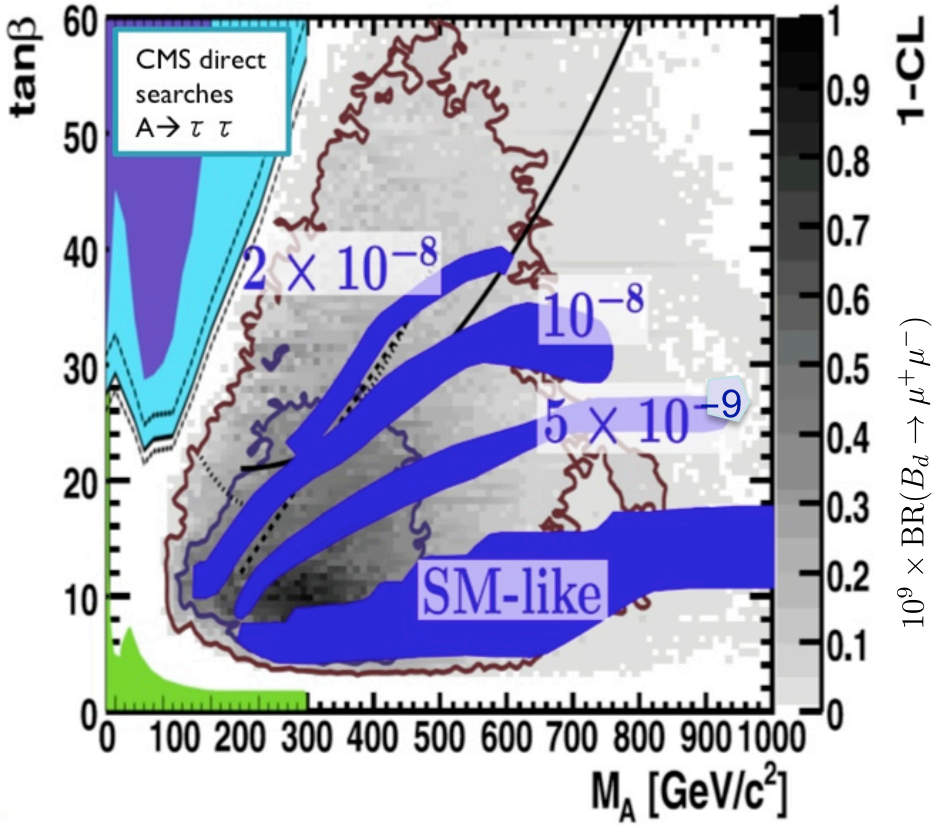


New Physics needs to have a special flavour structure

- to provide the suppression mechanism for FCNC processes already observed.
- It may be too "special"… Minimal Flavour Violation (MFV) models in which the flavour structure of the NP is governed by the CKM matrix.

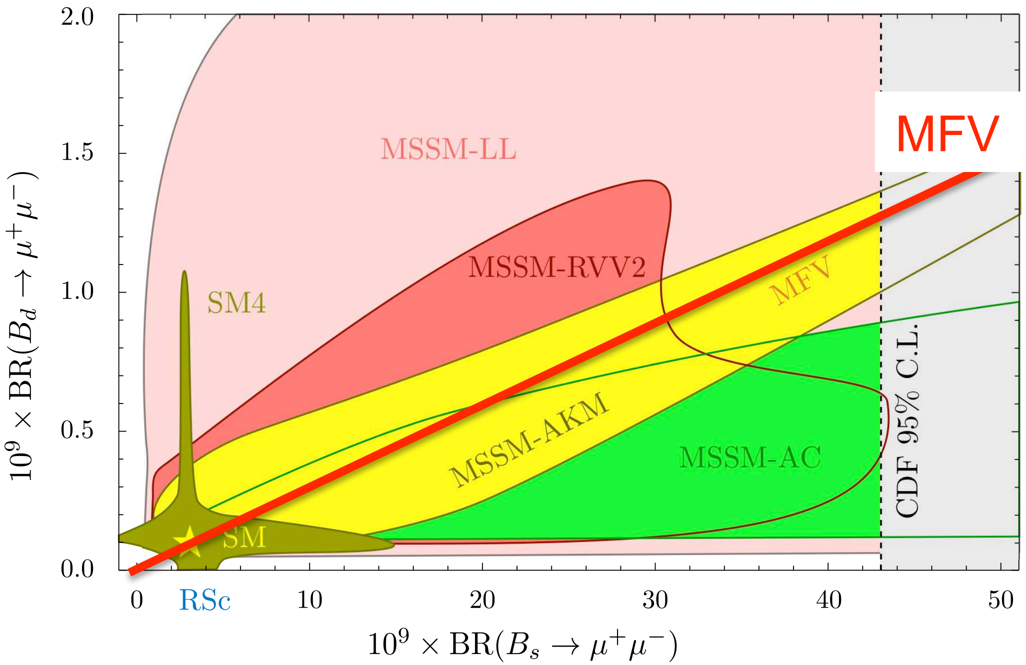
Example: the discovery power of $B_{d,s} \to \mu^+\mu^-$

Large $Br(B_s \to \mu^+\mu^-)$ possible in NP models



MFV would retain flavour universality

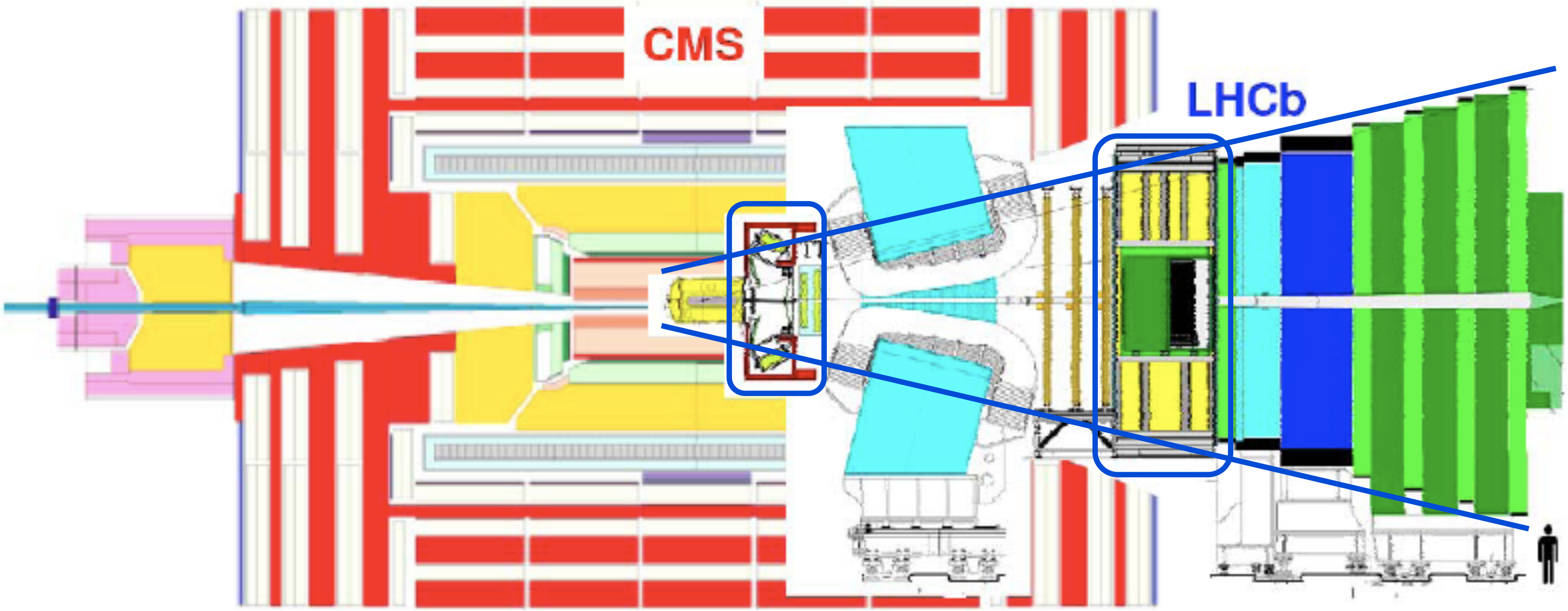
$$\frac{Br\left(B_d \to \mu^+\mu^-\right)}{Br\left(B_s \to \mu^+\mu^-\right)} = \left|\frac{V_{td}}{V_{ts}}\right|^2$$



Background contours : O.Buchmuller et al arXiv:0907.5568
Blue regions : allowed regions for given measurement
SuperIso (F.Mahmoudi, arXiv:08083144) and
SoftSusy (B.C.Allanach, Comp. Phys. Comm 143 (2002) 305-331)

The LHC(b) Experiments

The LHC Experiments



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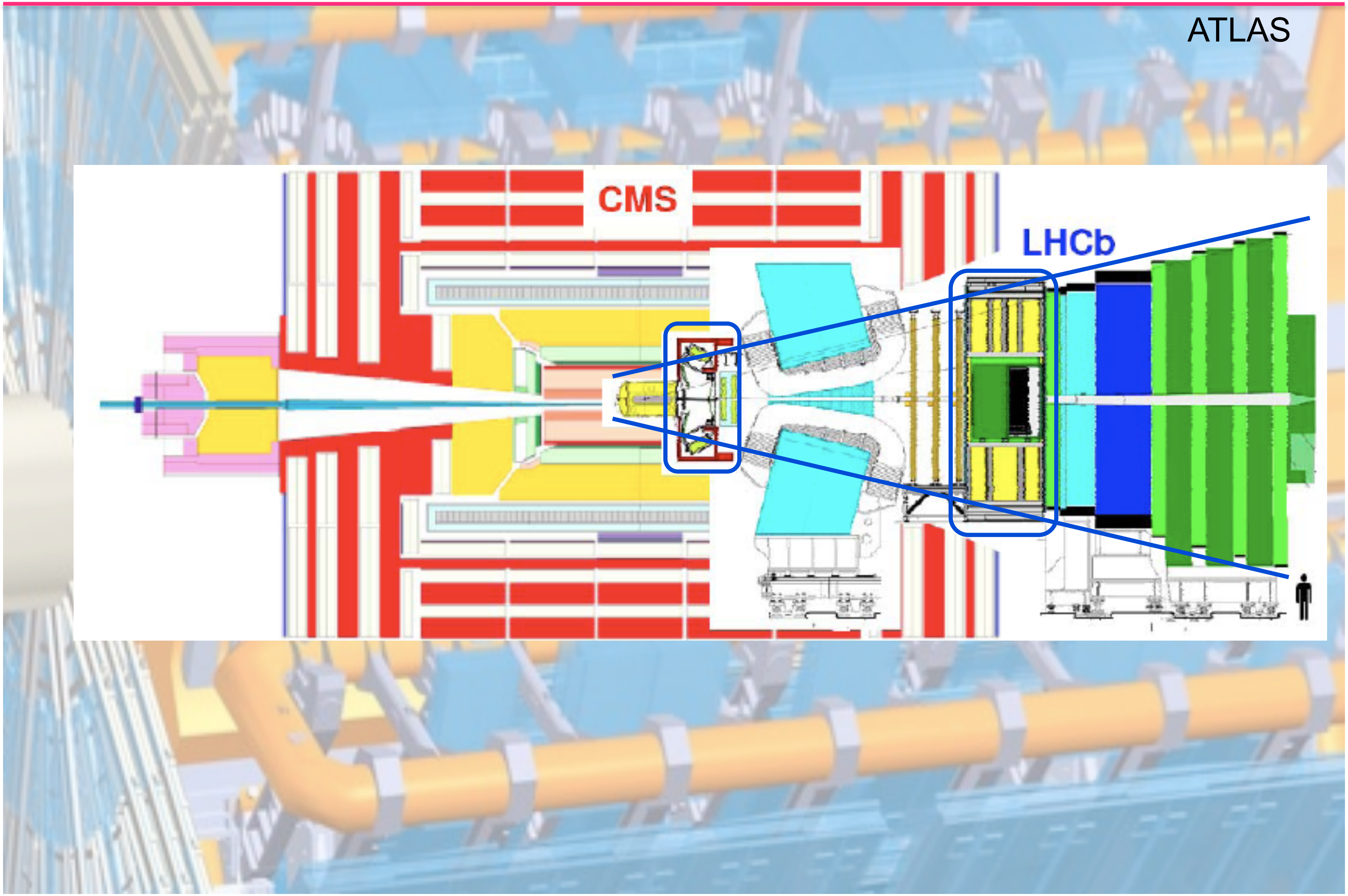
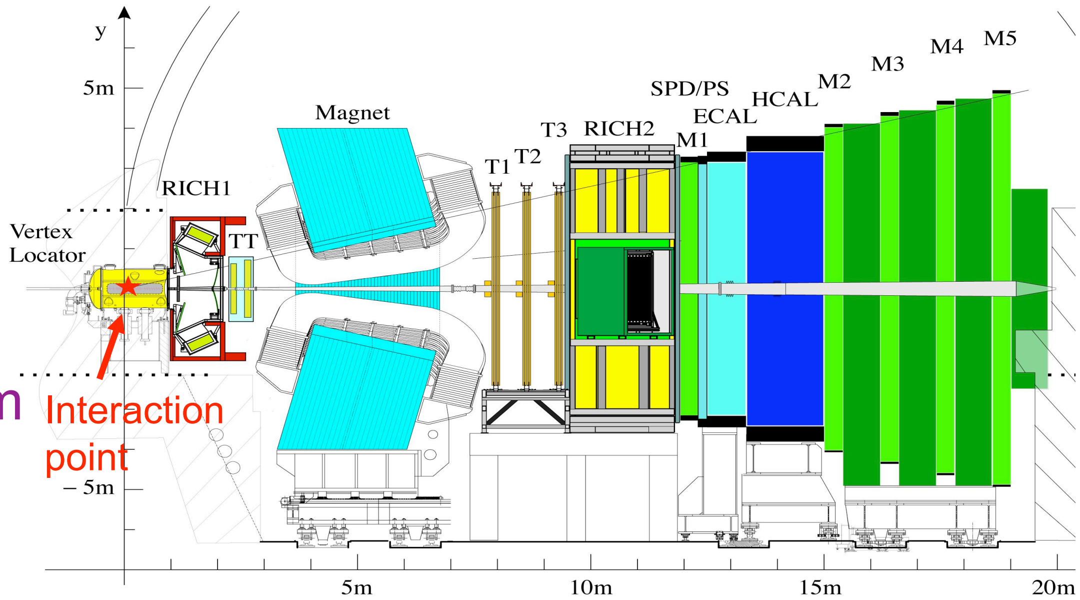


The LHCb experiment

Forward single arm spectrometer

4% solid angle, 40% cross-section.



Excellent tracking

precision silicon detector (VELO)

PV resolution $\sigma_{x,y}$=15 μm, σ_z=75 μm

Excellent particle identification

2 Ring-Imaging Cherenkov (RICH) detectors

π-K separation over ~2-100 GeV/c

Efficient Trigger

low p_T lepton, γ/π^0 & hadron thresholds

All B species produced : $B^-, B_d^0, B_s^0, B_c^-, \Lambda_b, \ldots, + c.c.$

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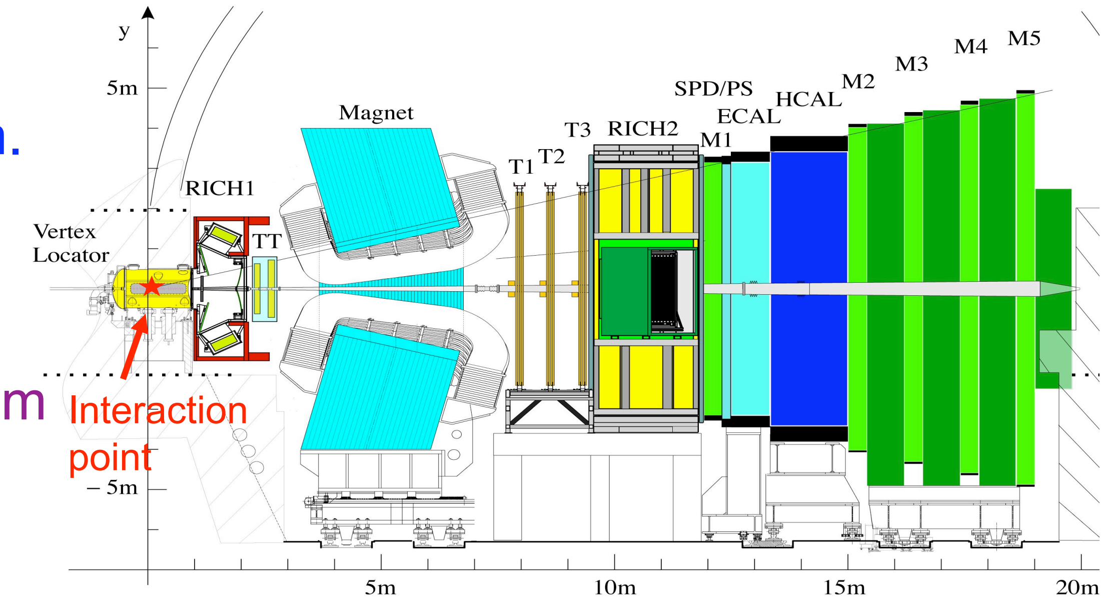

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The UK is the main stakeholder:

Birmingham, Bristol, Cambridge, Edinburgh, Glasgow, Imperial, Liverpool, Manchester, Oxford, STFC/RAL, Warwick

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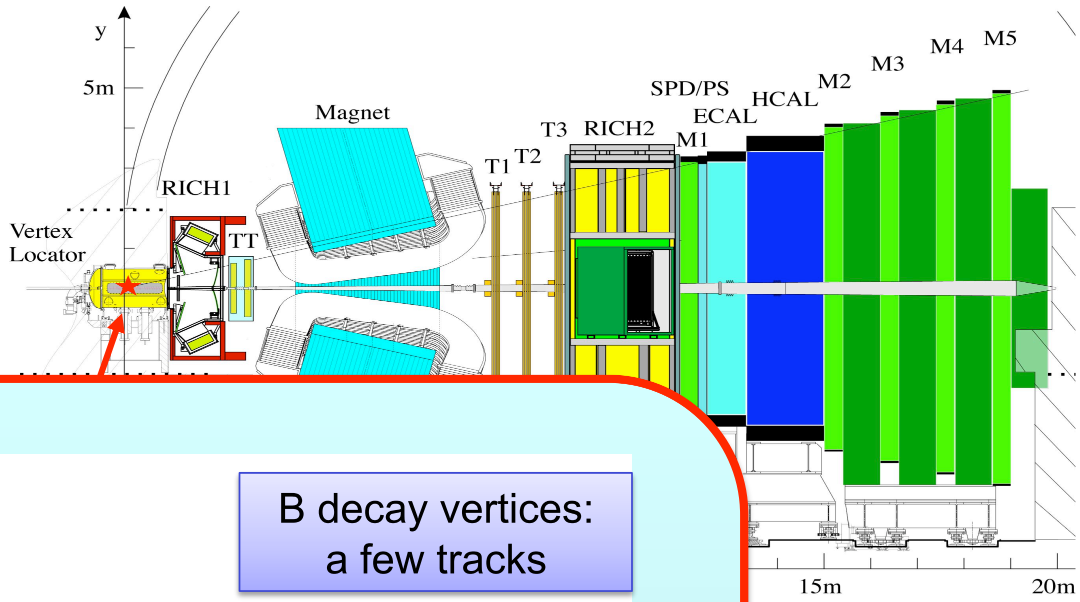

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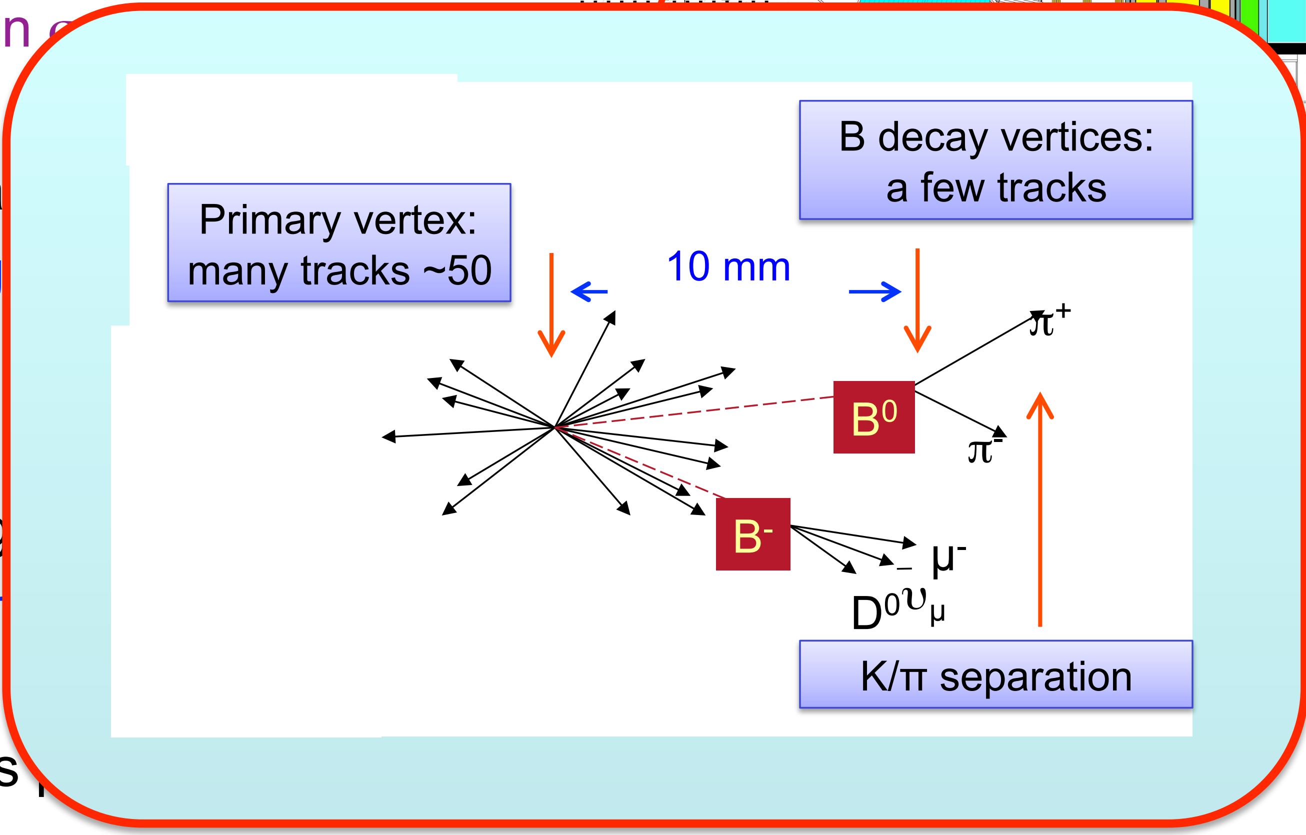


stakeholder:

Cambridge,

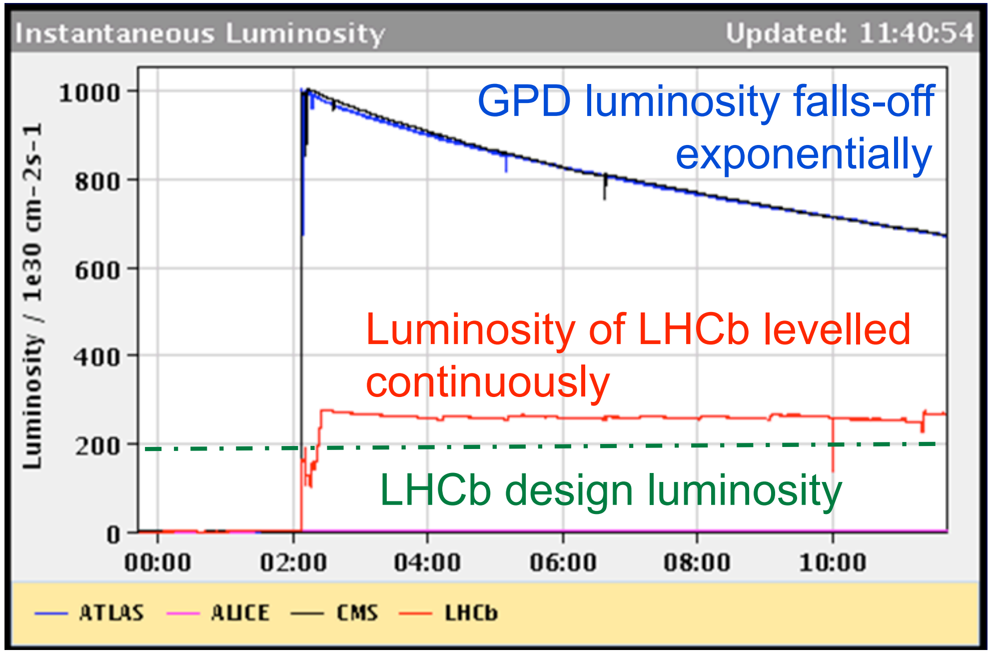
Imperial,

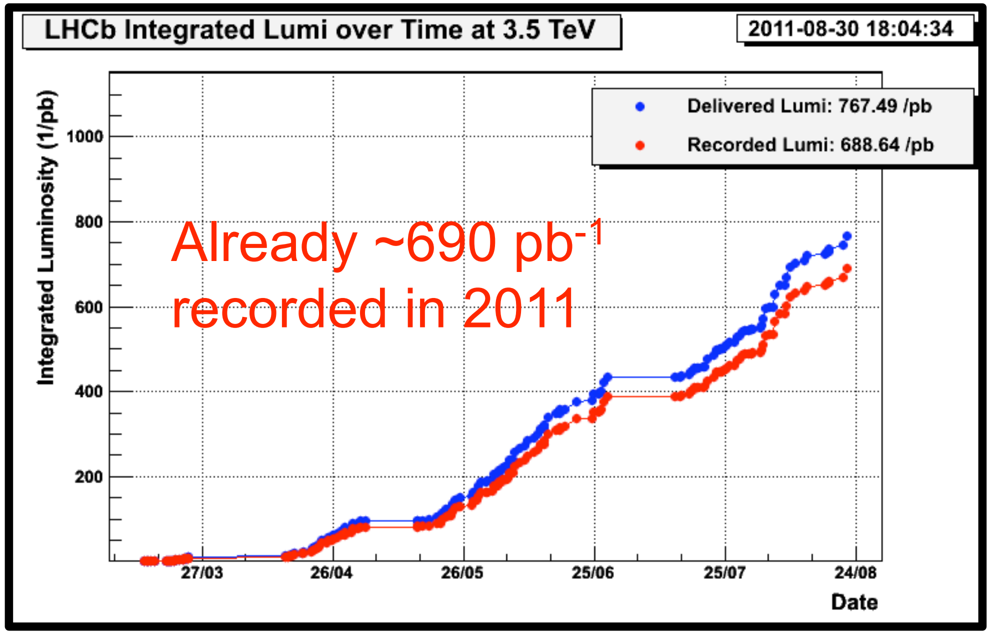
er, Oxford,

Luminosity

LHCb collected ~37 pb^{-1} integrated luminosity in 2010.

Luminosity leveling introduced in 2011 to run at an optimal maximum luminosity of ~3-3.5x10^{32} $cm^{-2}s^{-1}$ and ~1.5 interactions per bunch crossing.



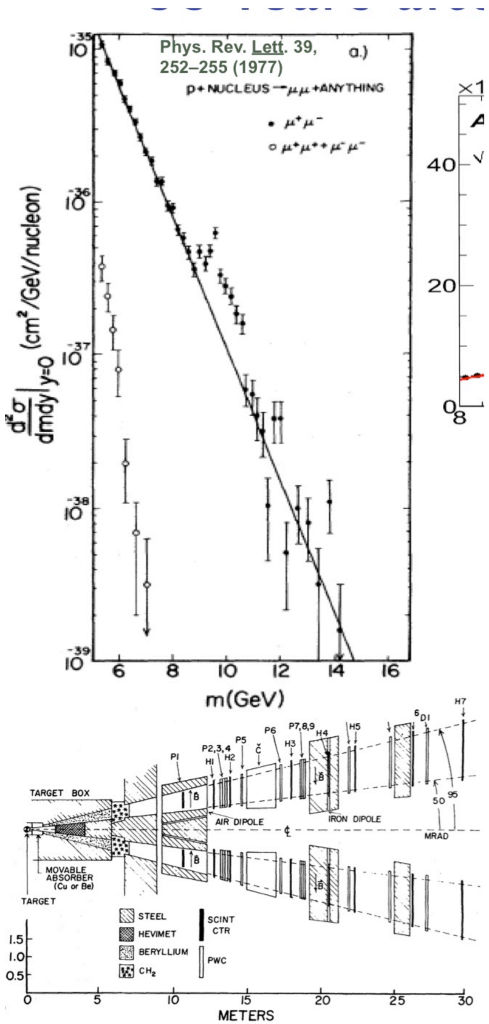


LHCb expects to collect ~1 fb^{-1} in 2011 (and ≥ same in 2012)

Many new results for EPS and Lepton-photon conferences with ~ 330 pb^{-1}

LHC re-discovers the b quark

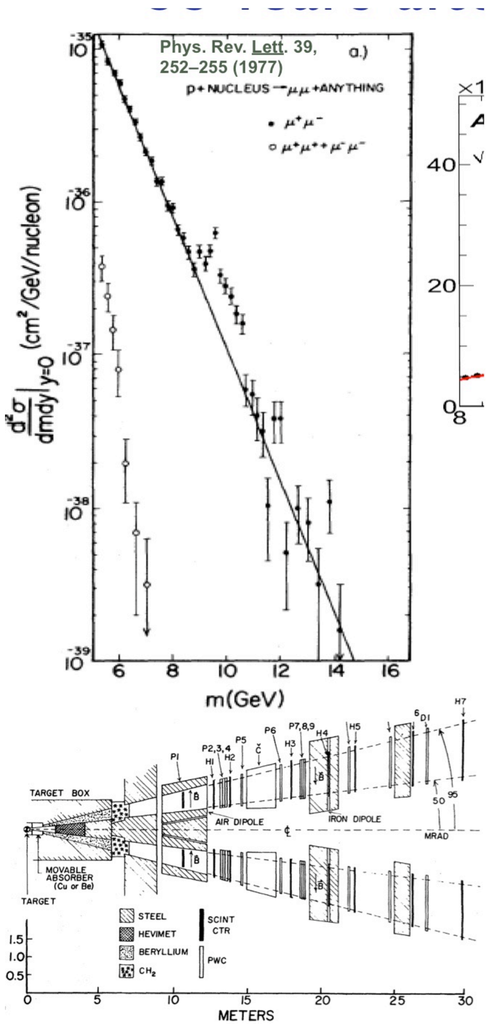
33 years after its initial discovery….

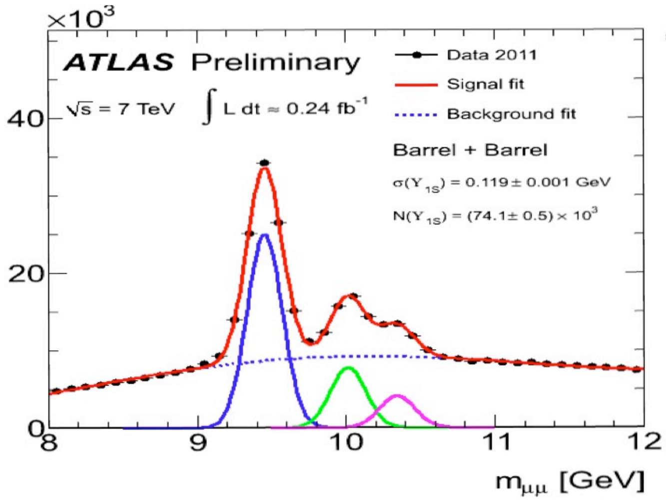


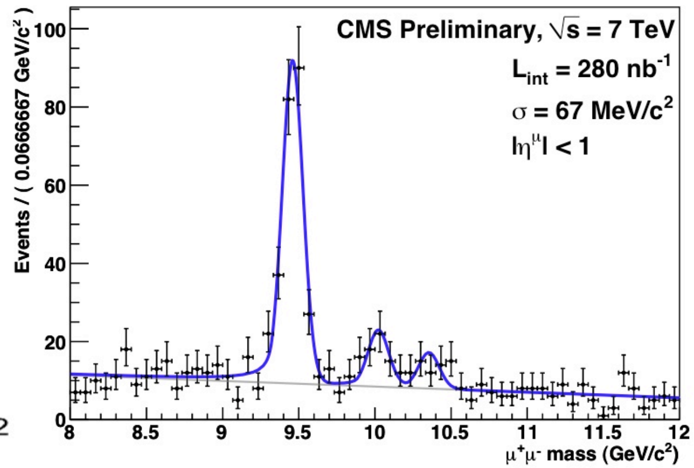
LHC re-discovers the b quark

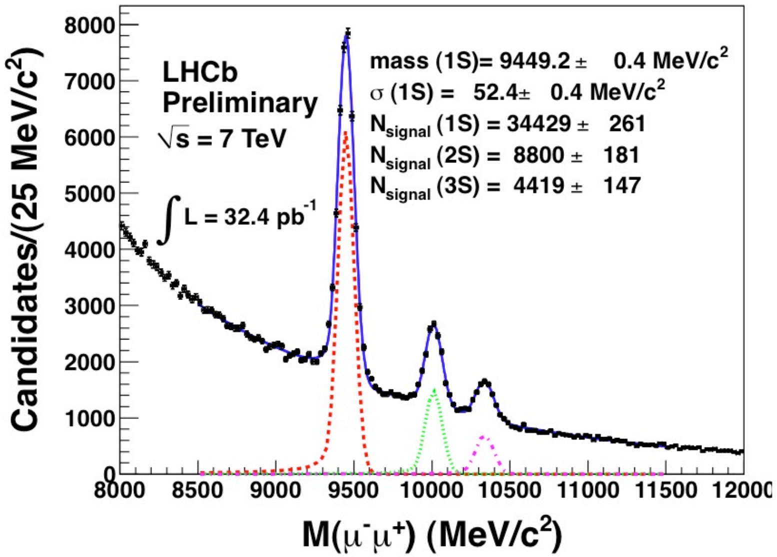
33 years after its initial discovery…. the b quark is still there…..

ϒ states









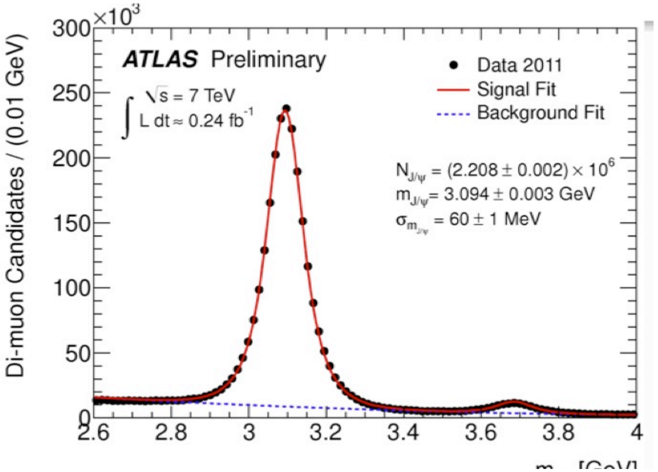
Flavour Production

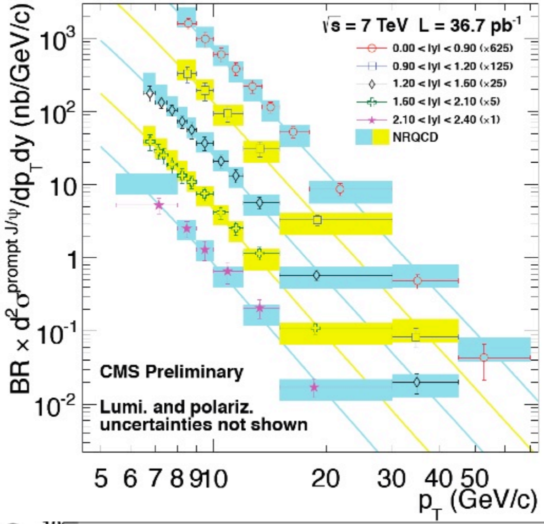
Charmonium

CMS PAS BPH-10-014
LHCb-CONF-2011-026

An important challenge is to understand the mechanism for onia production: colour singlet model, octet model, evaporation model…?

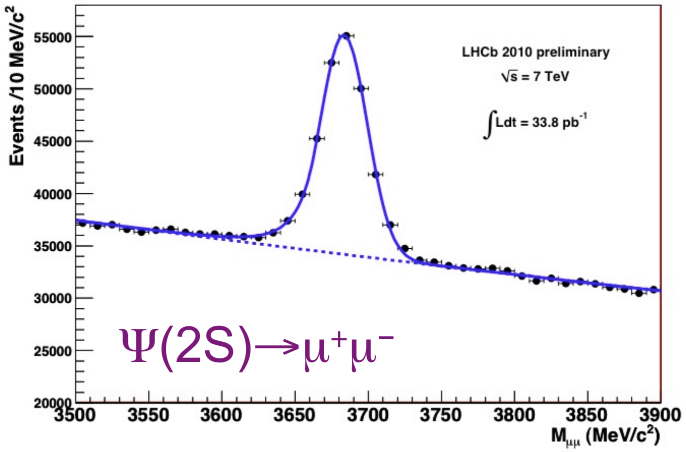
J/ψ

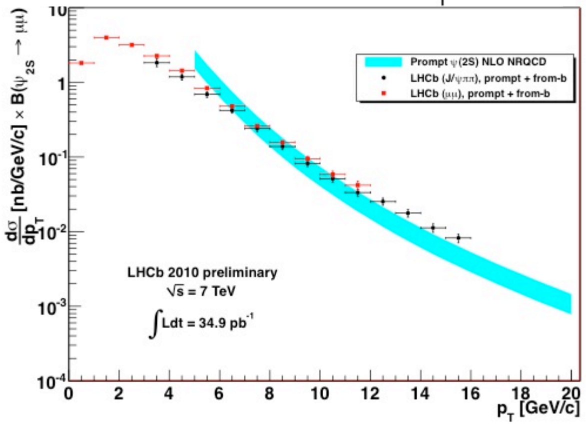




Good agreement with NRQCD

ψ(2S)





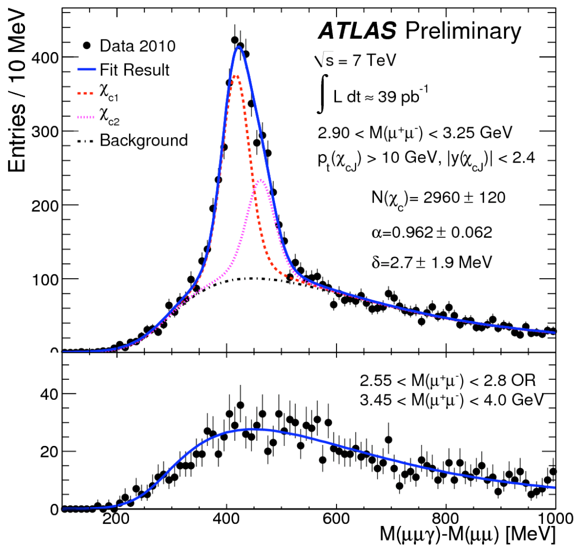
Data more precise than theory (modulo polarization)! Need new observables: more studies of higher states, e.g. ψ(2S) & χ_c, and polarization measurements.

Radiative decays of χ_c states

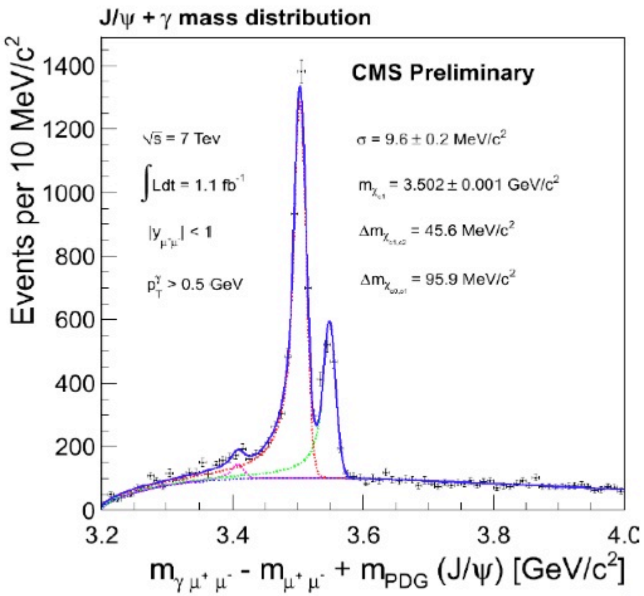
ATLAS-CONF-2011-136
LHCb-CONF-2011-020
CMS DPS-2011/011

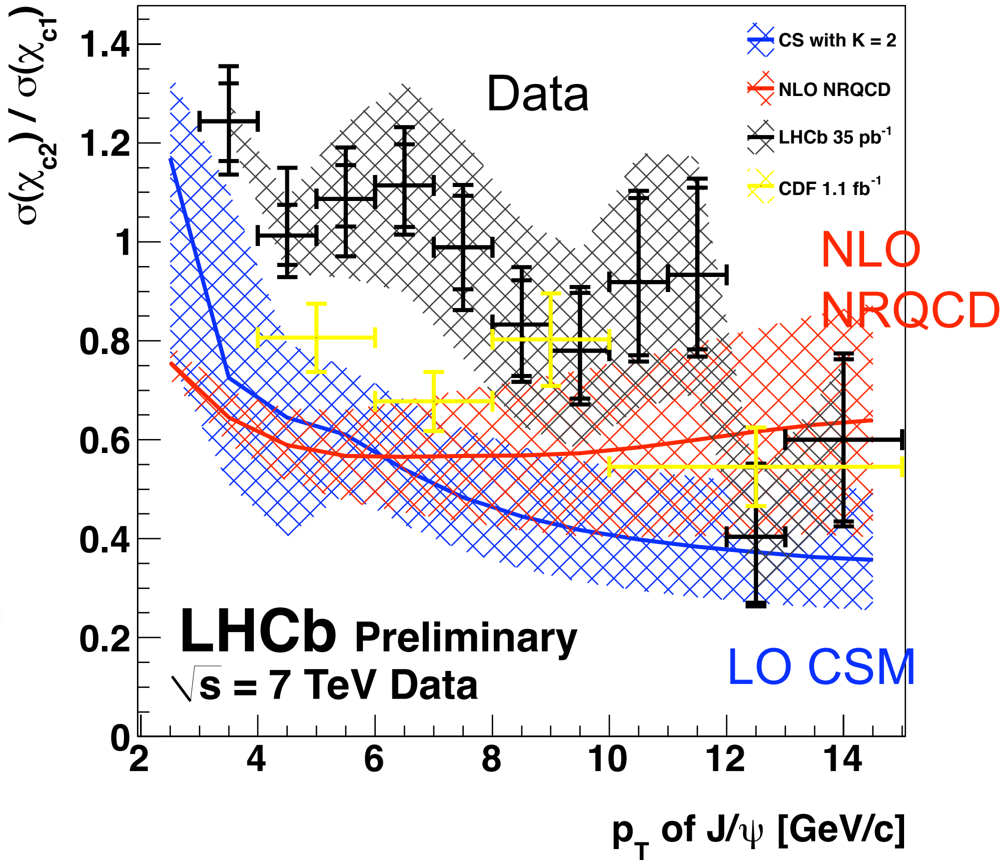
First studies of radiative decays $\chi_c \rightarrow J/\psi\gamma$. Challenge is to resolve χ_{c1} and χ_{c2}

ECAL based approach



Using tracks from $\gamma \rightarrow e^+e^-$



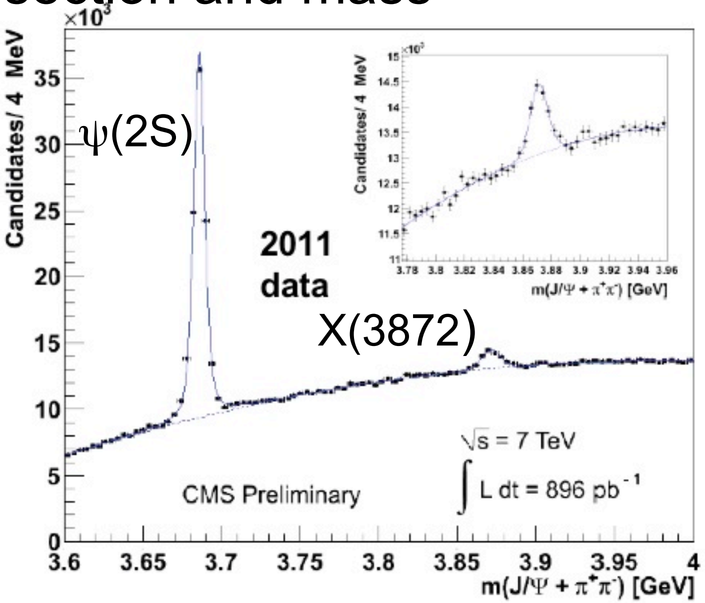


First results for relative production of χ_{c2} vs χ_{c1} are not in good agreement with NLO NRQCD predictions

Studies of exotics : X(3872)

LHCb-CONF-2011-021
LHCb-CONF-2011-043
CMS DPS-2011-009

The LHC experiments are starting to study the X(3872) – observation, cross-section and mass



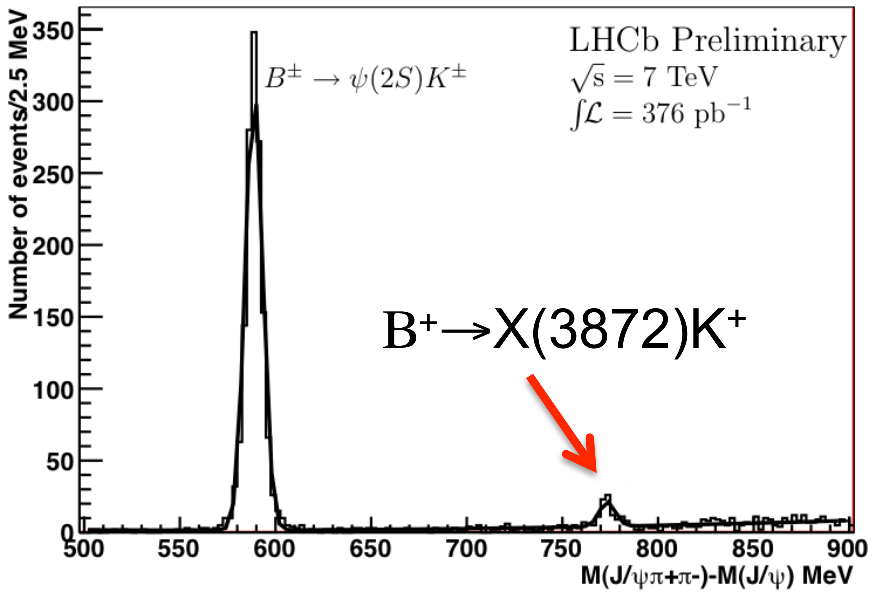
LHCb inclusive 2010 measurements

$$M_{X(3872)} = 3871.96 \pm 0.46\,(stat) \pm 0.10\,(syst)\ \ \mathrm{MeV}/c^2$$

$$\sigma_{X(3872)} \times B\left(X \to J/\psi\,\pi^+\pi^-\right) = 4.74 \pm 1.10 \pm 1.01\,\mathrm{nb}$$

CMS 2010 production analysis

$$R = \frac{\sigma_{X(3872)} \times B\left(X \to J/\psi\,\pi^+\pi^-\right)}{\sigma_{\psi(2S)} \times B\left(\psi \to J/\psi\,\pi^+\pi^-\right)} = 0.087 \pm 0.017 \pm 0.009$$



Perform precise mass and angular measurements (in $B^+ \to X(3872)K^+$) with 2011 data. Determine J^{PC} of the X(3872).

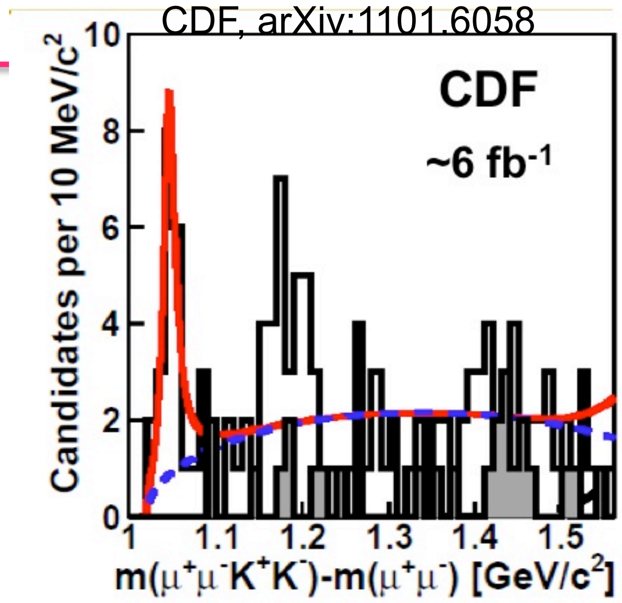
LHCb-CONF-2011-045

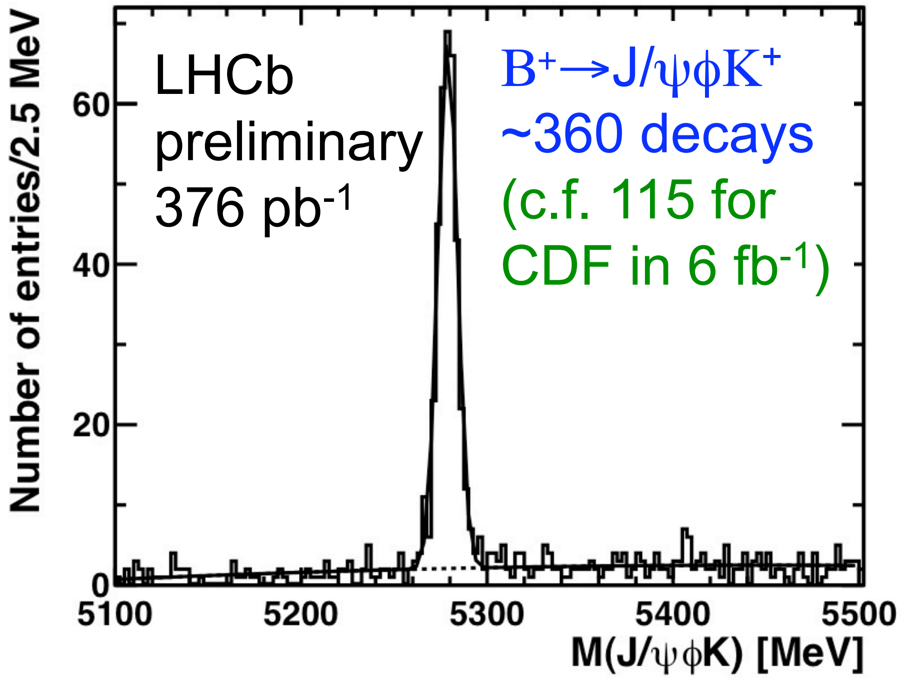
Search for the X(4140)

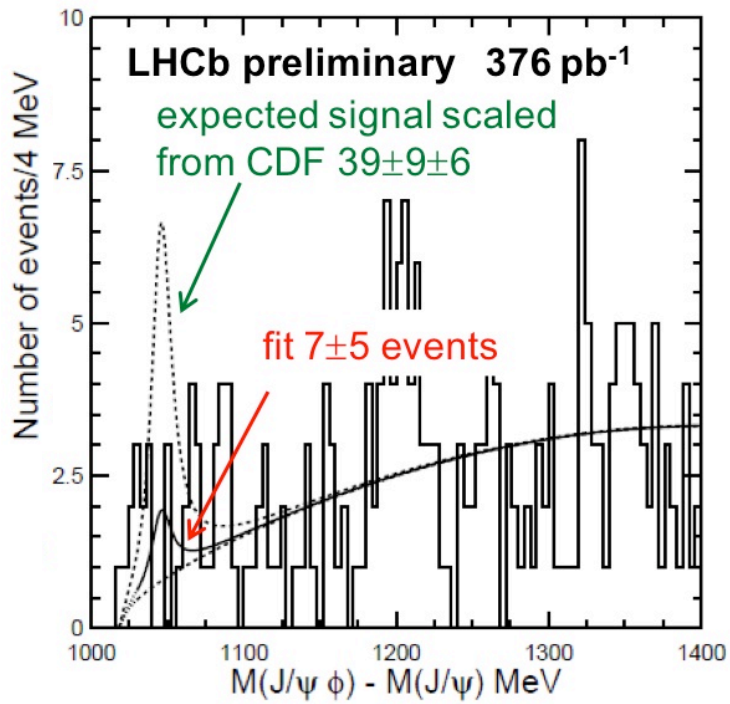
Studies of other possible exotics are underway

CDF reported observation of narrow structure, X(4140), in the $m(J/\psi K^+K^-)-m(J/\psi)$ spectrum in $B^+ \to J/\psi\phi K^+$ events.

LHCb now has a large sample of these decays.







LHCb does not confirm presence of X(4140).

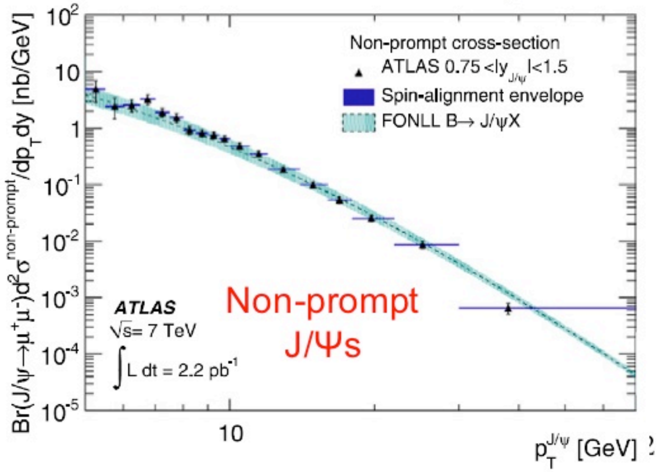
2.4σ tension with CDF

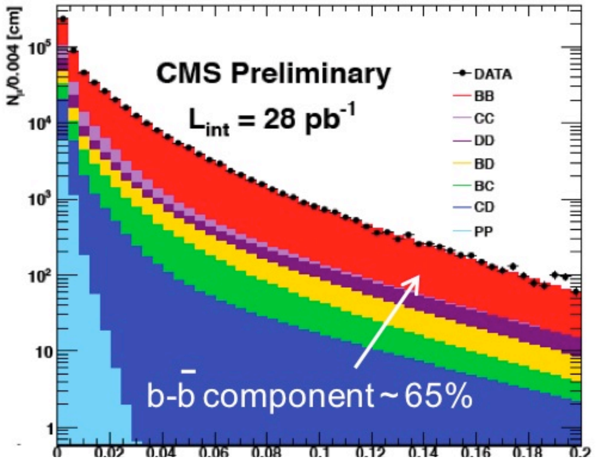
B production

ATLAS NPB 850 (2011) 387
CMS PAS BPH-10-015, arXiv:1106.4048
LHCb-CONF-2011-033

B production studied with detached J/ψ (ATLAS, CMS, LHCb), D+μ tag (LHCb), fully reconstructed J/ψX states (CMS, LHCb) and (di)lepton tags (CMS).

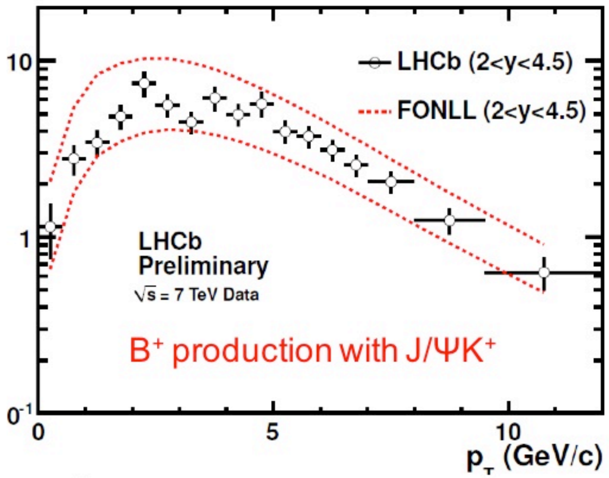
Non prompt J/ψs

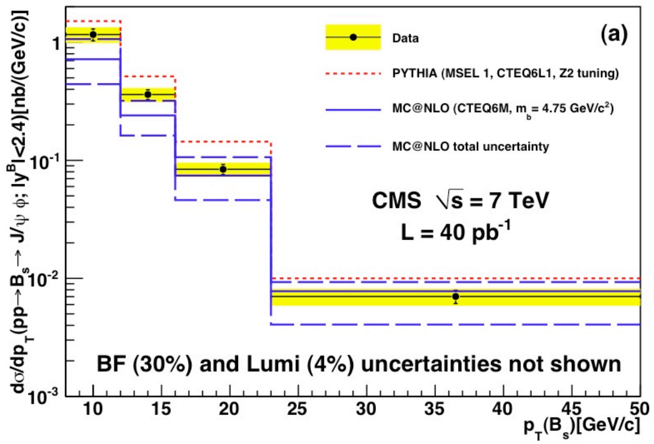




Dimuon tag

B^+ production with $B^+ \to J/\psi K^+$





B_s production with $B_s \to J/\psi\phi$

All measurements reasonably described by theory (FONLL, MC@NLO).

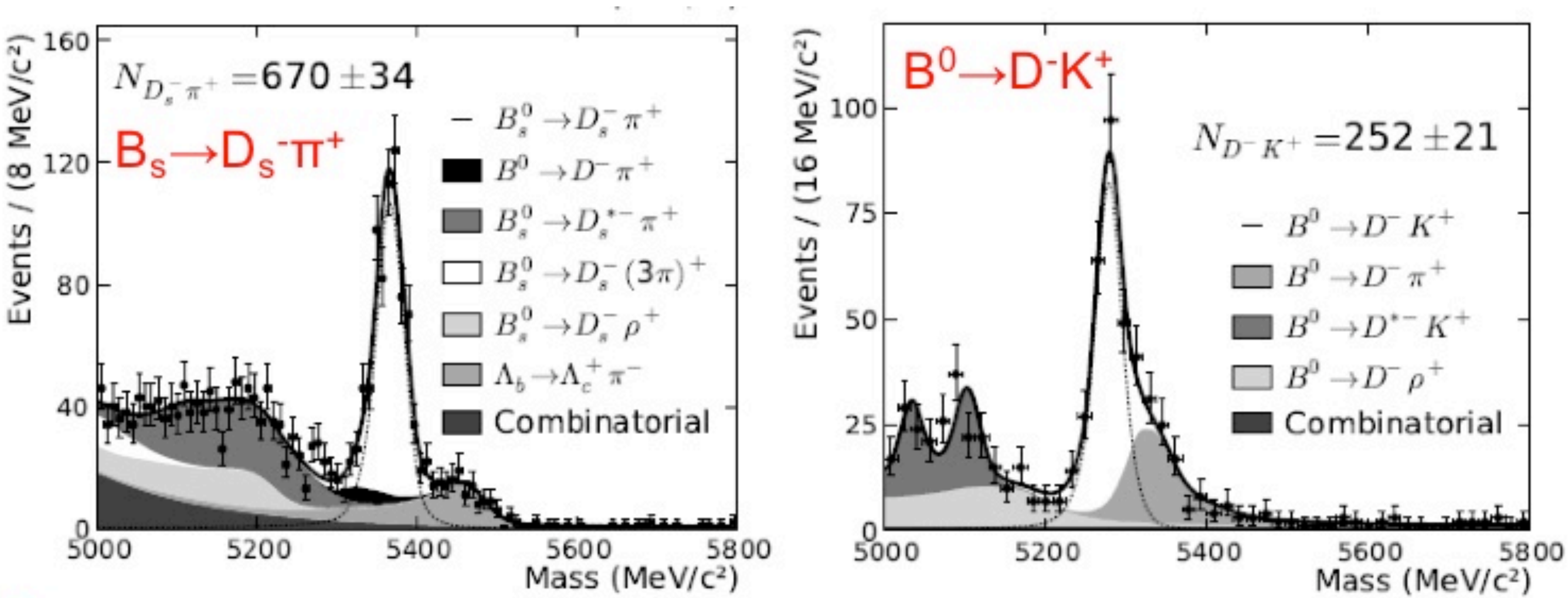
Quite an achievement !

B fragmentation

LHCb-CONF-2011-028
LHCb arXiv:1106.4436
LHCb-CONF-2011-034

LHCb has measured the relative rates of B^+, B_d, B_s, Λ_b… using two approaches:

- Semi-leptonic analysis with $D^0\mu X$, $D^+\mu X$, $D_s\mu X$, $\Lambda\mu X$
- Ratio of related hadronic modes e.g. $B_d \to D^- K^+$, $B_s \to D_s^- \pi^+$



Consistent results for B_s/B_d fragmentation ratio, f_s/f_d, therefore combine

$$\langle f_s / f_d \rangle_{\text{LHCb}} = 0.267^{+0.021}_{-0.020}$$

Necessary input for B_s branching ratio measurements, e.g. $B_s \to \mu\mu$

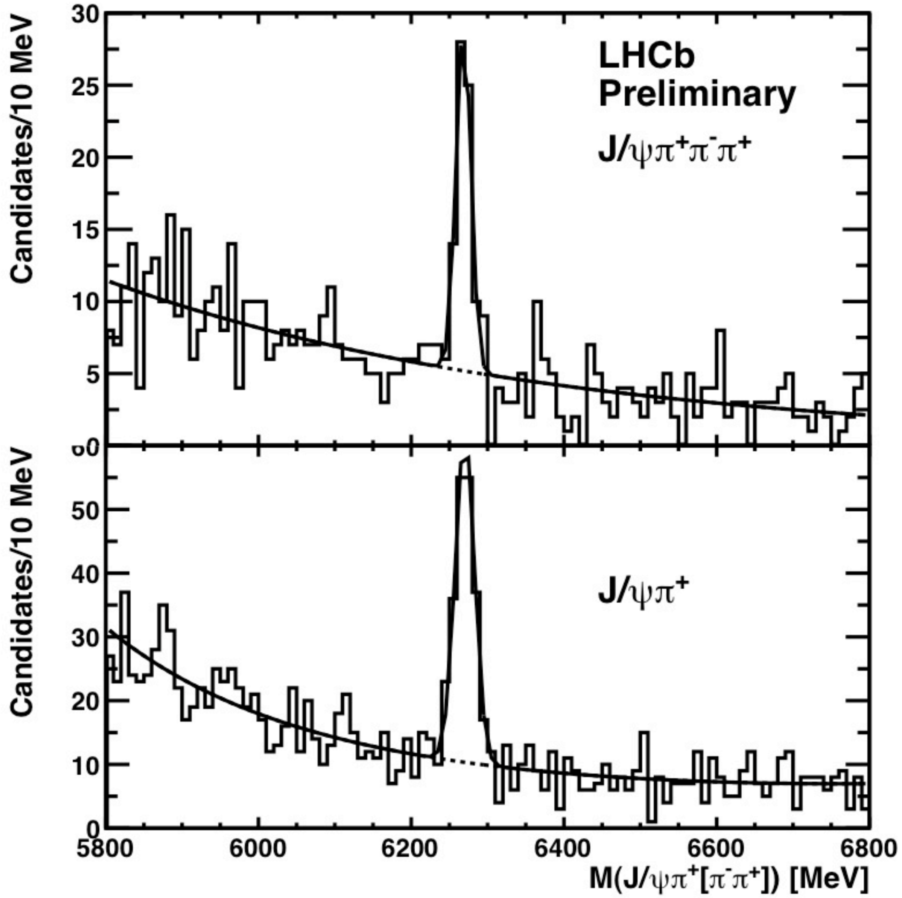
LHCb-CONF-2011-040

Enter the heavies… B_c …

LHCb has observed the decay $B_c \to J/\psi\pi^+\pi^-\pi^+$ for the first time

$B_c \to J/\psi\pi^+\pi^-\pi^+$

$B_c \to J/\psi\pi^+$

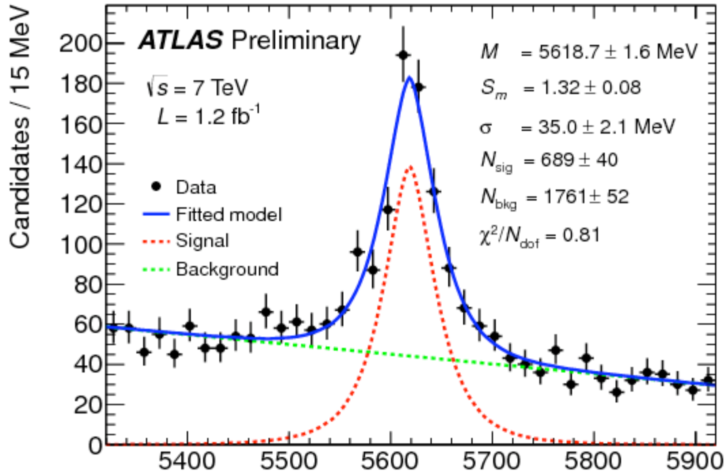


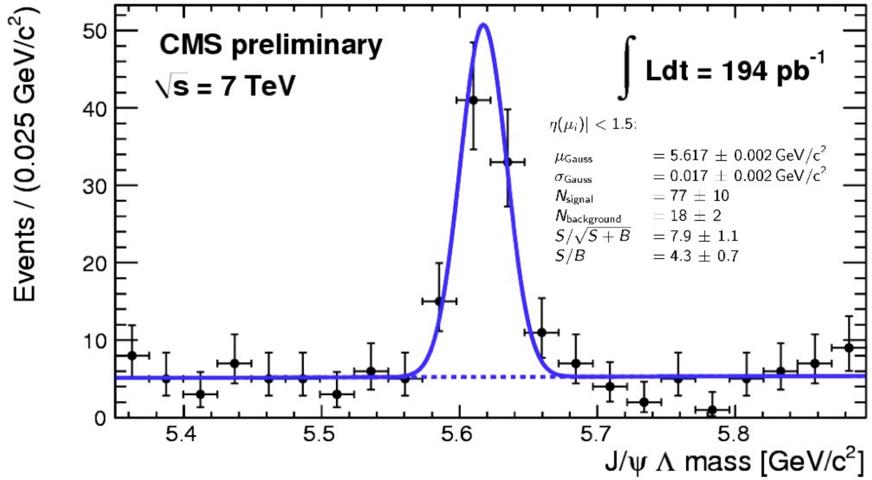
$$\mathcal{B}(B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\,\pi^+) = 3.0 \pm 0.6 \pm 0.4,$$

Enter the heavies… Λ_b…

ATLAS-CONF-2011-124
CMS DP-2011-007
LHCb-CONF-2011-036

$\Lambda_b \rightarrow J/\psi\Lambda$



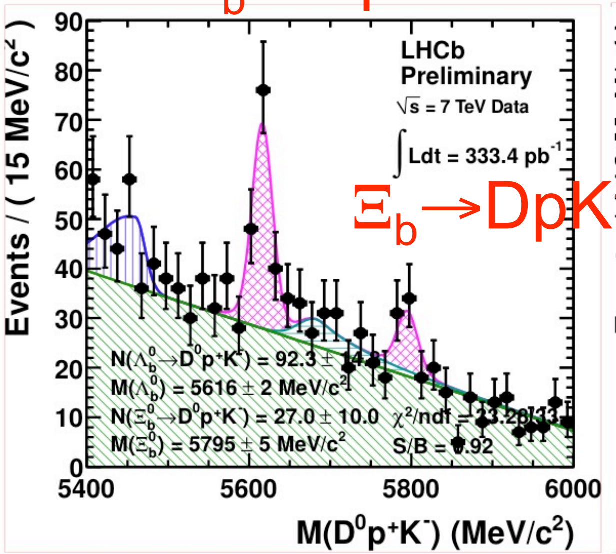


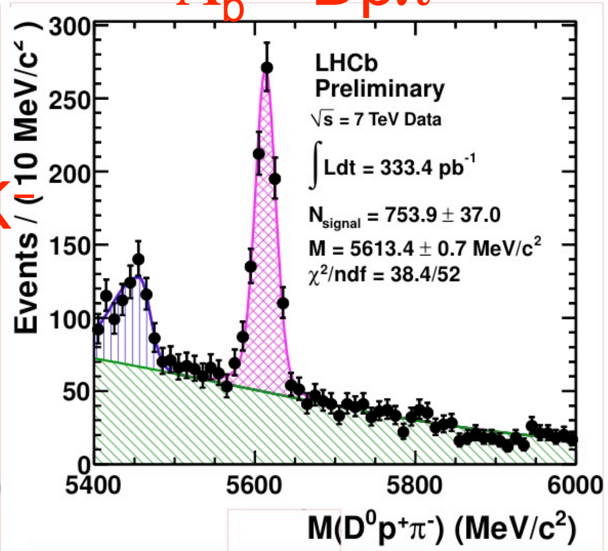
$\Lambda_b \rightarrow DpK^-$

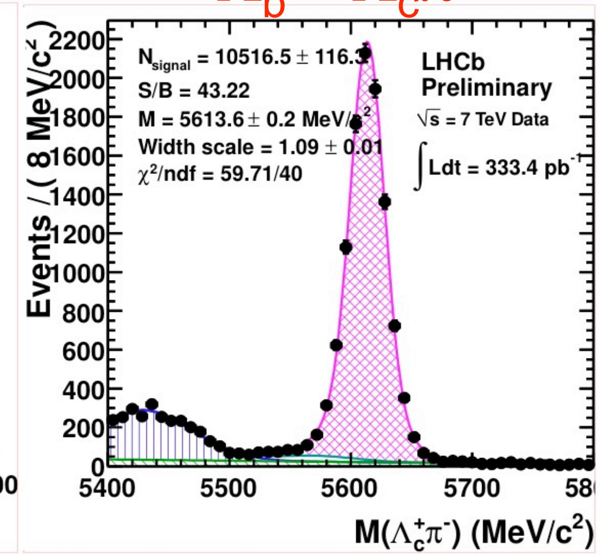
$\Lambda_b \rightarrow Dp\pi^-$

$\Lambda_b \rightarrow \Lambda_c\pi^-$

$\Xi_b \rightarrow DpK^-$

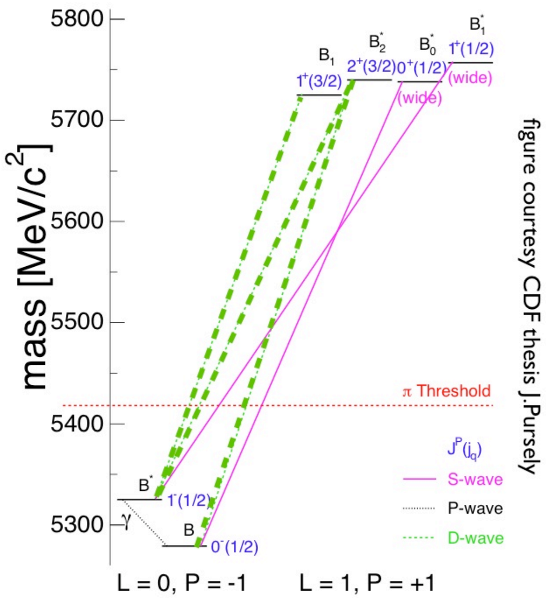






LHCb-CONF-2011-053

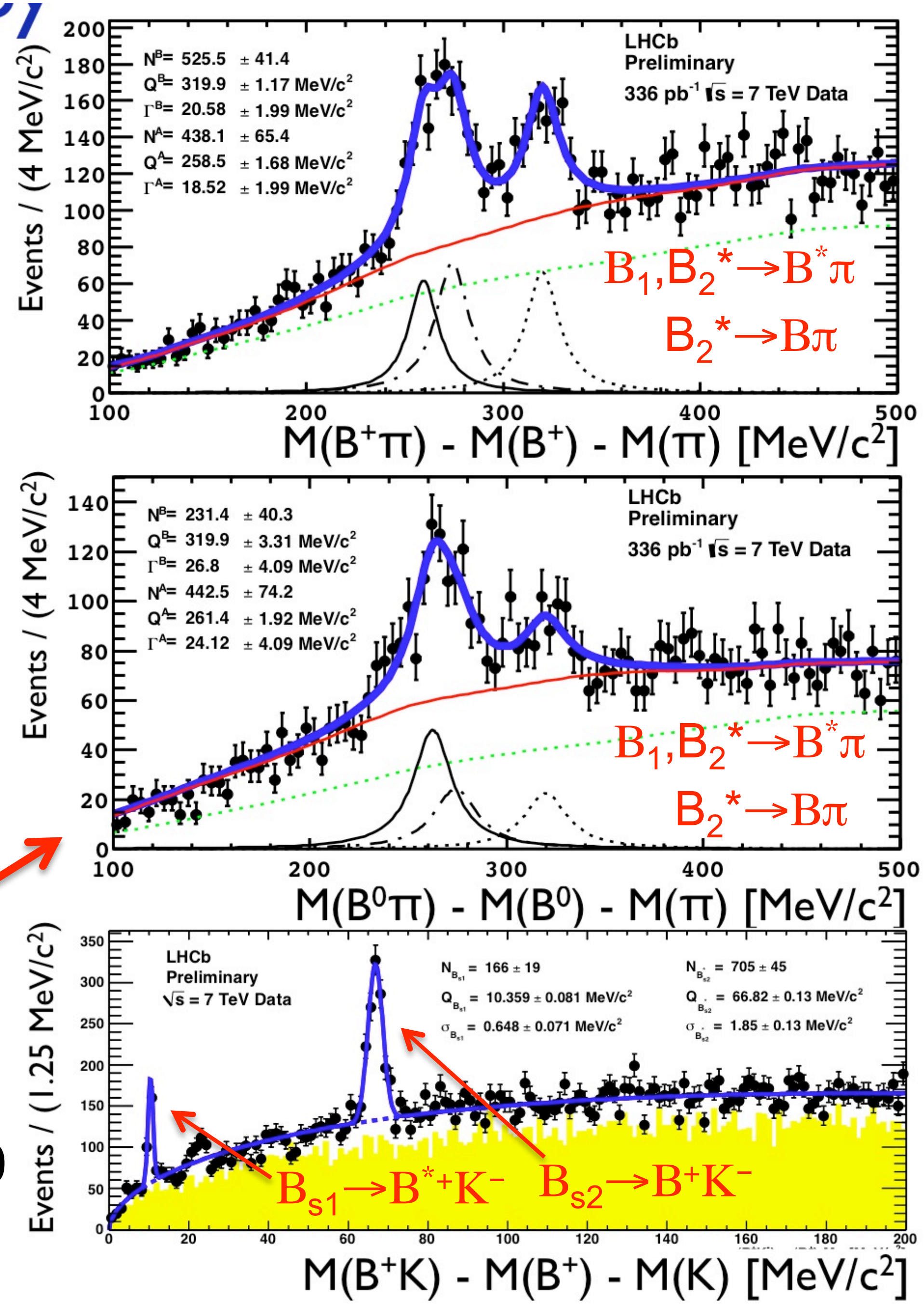
…and excited B states



LHCb takes exclusive $B_d \rightarrow J/\psi K^*$, $D\pi$, $D3\pi$ and combines them with a π or K from the same primary vertex.

First observation of B^{**+} modes.

Other modes already seen by CDF & D0



Direct CP Violation in B decays

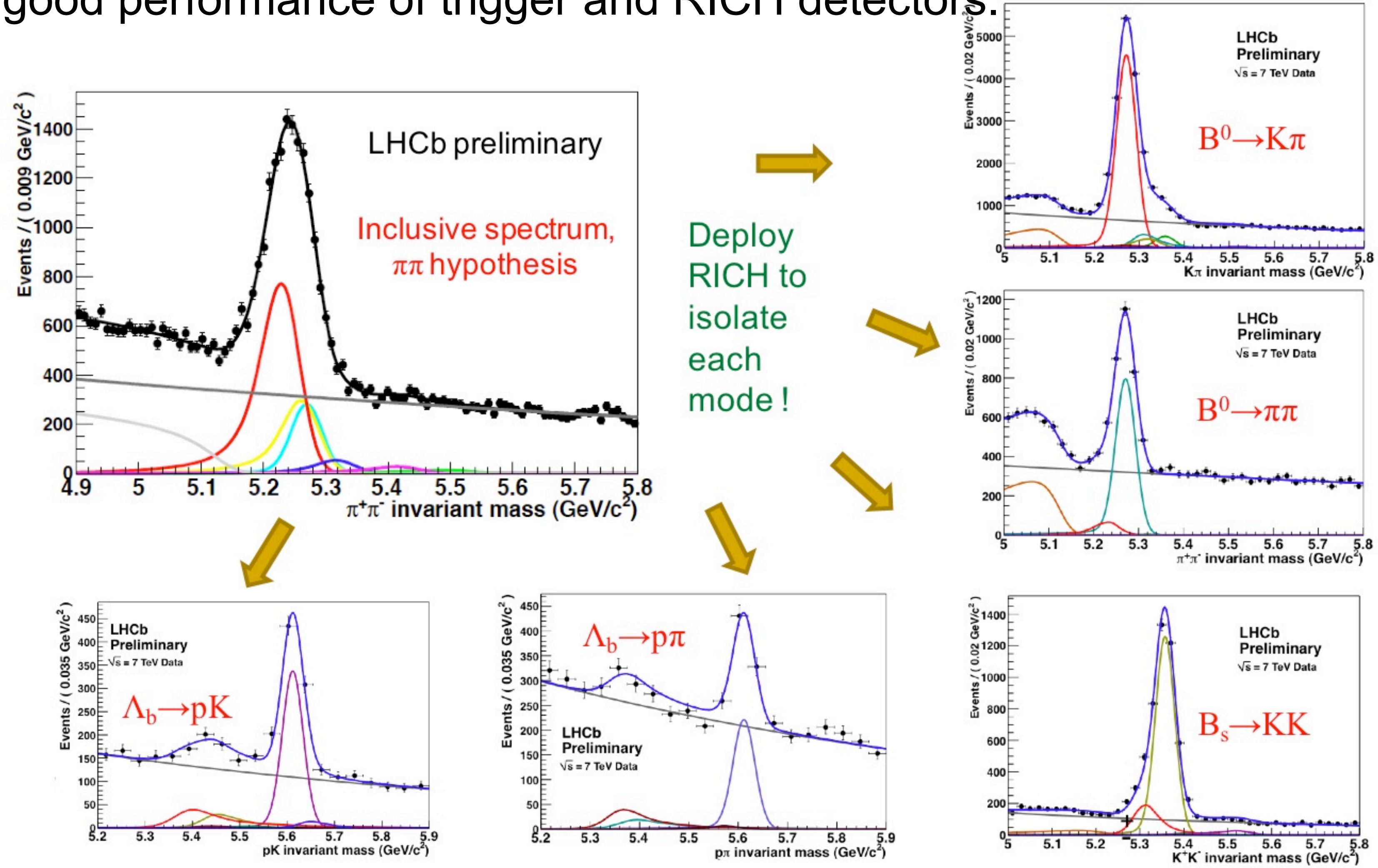
LHCb-CONF-2011-042

The RICHness of "B→hh" (h=π, K, p)

Two-body charmless B decays are a central goal of LHCb physics.

Significant penguin diagrams provide an entry point for New Physics.

Rely on good performance of trigger and RICH detectors.

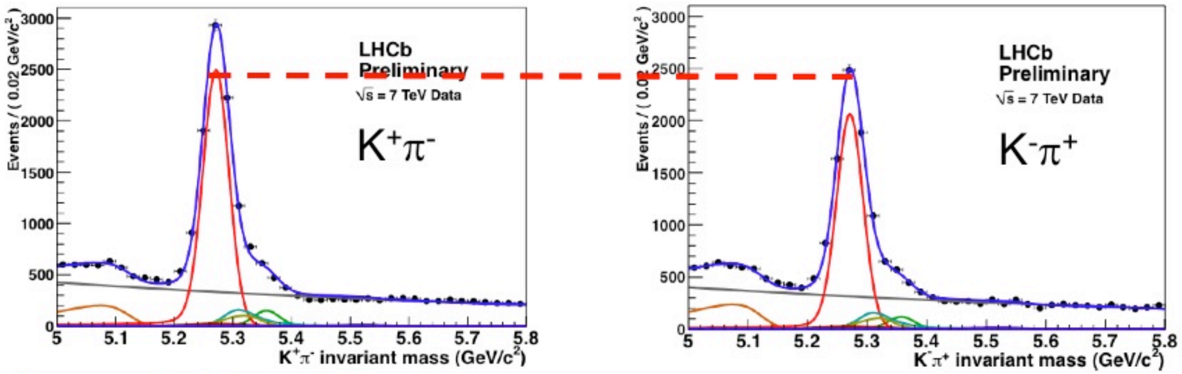


Direct CPV in B→Kπ Decays

LHCb-CONF-2011-042

Ultimate goal is to perform time-dependent study, particularly $B_s \to KK$: this will enable New Physics sensitive measurement of γ [e.g. Fleischer, PLB 459 (1999) 306]

First step: look for direct CPV in flavour specific final states

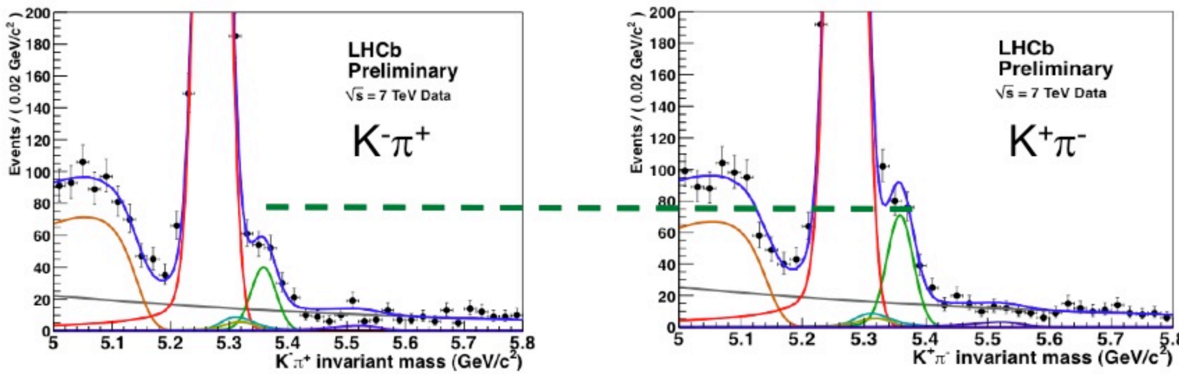


$$A_{CP}\left(B_d \to K^+\pi^-\right) = -0.088 \pm 0.011\left(stat.\right) \pm 0.008\left(syst.\right)$$

Existing world average

$$A_{CP}\left(B_d \to K^+\pi^-\right) = -0.098^{+0.012}_{-0.011}$$

Most precise single measurement and first 5σ observation of CPV at a hadron machine !



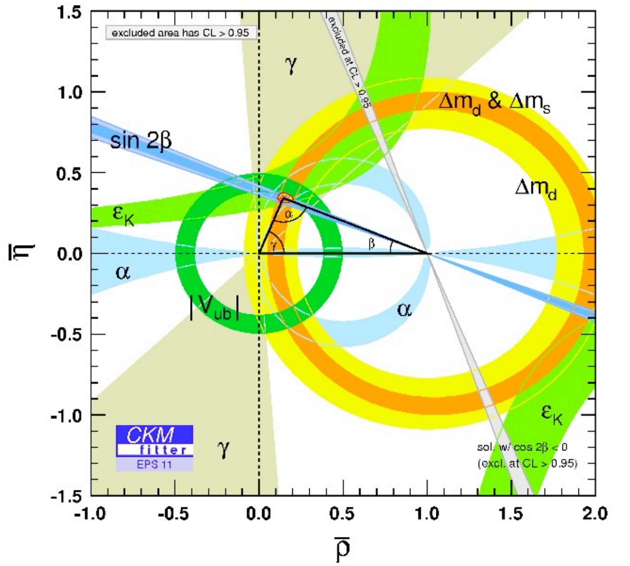
$$A_{CP}\left(B_s \to \pi^+K^-\right) = 0.27 \pm 0.08\left(stat.\right) \pm 0.02\left(syst.\right)$$

CDF result:

$$A_{CP}\left(B_s \to \pi^+K^-\right) = 0.39 \pm 0.17$$

First evidence for CPV in B_s decays !

The next challenge: the measurement of γ



CKM is a tour de force…progress needs improved knowledge of angle γ (a.k.a. ϕ_3).

$$\gamma = \left(68^{+13}_{-14}\right)^{\circ}$$

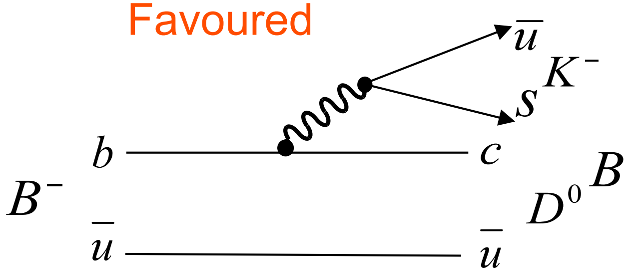
EPS 2011
CKMfitter group

Look in $B^{\pm} \to DK^{\pm}$ decays using common mode for D^0 and $\overline{D^0}$.

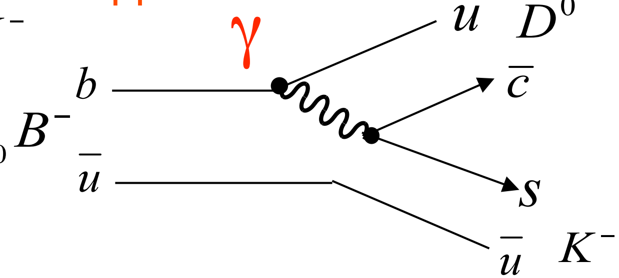
→ γ via interference.

→ different rates for B^+ & B^- (CPV!)

Favoured



Suppressed



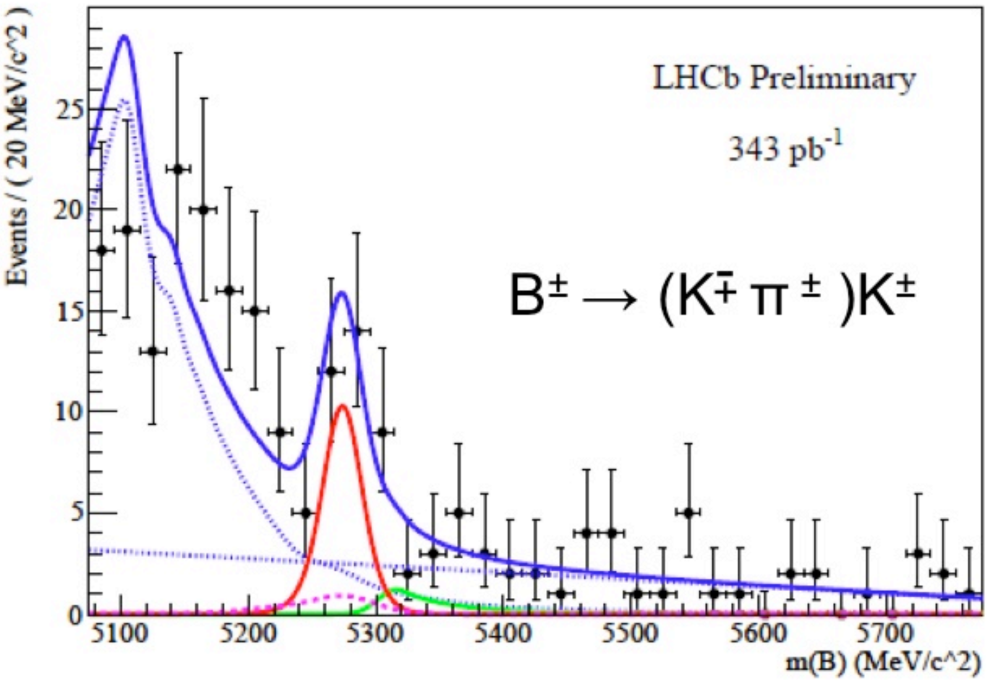
Time integrated methods:

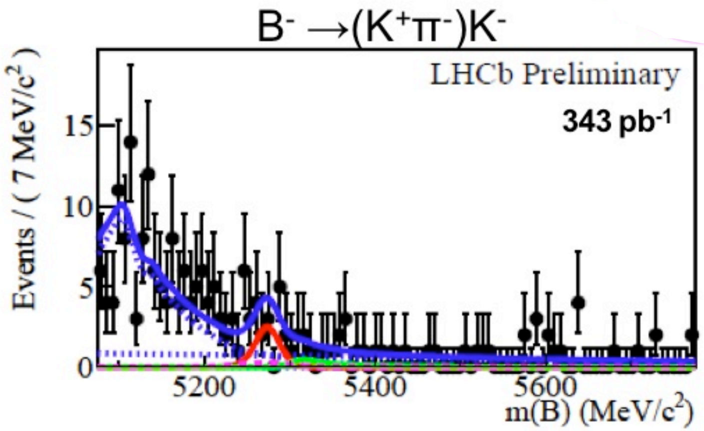
$D^0 \to K^+K^-$	CP eigenstate	"GLW"
$D^0 \to K^+\pi^-$	suppressed D^0 & favoured $\overline{D^0}$	"ADS"
$D^0 \to K^0_s\pi^+\pi^-$	Dalitz analysis	"GGSZ"

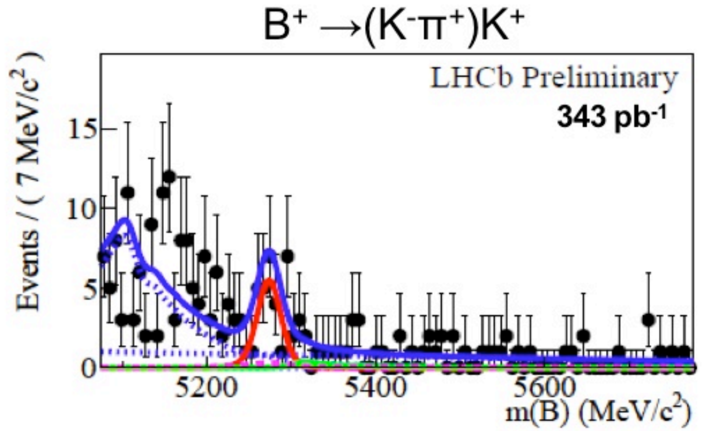
Time dependent analysis: $B^0 \to D^-\pi^+, \quad B_s \to D_s^-K^+$

Evidence for suppressed ADS mode

Signal seen with 4.0σ significance, & hint of asymmetry, consistent with previous results







Ratio to favoured mode:

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

World average (without LHCb) $(1.6 \pm 0.3) \times 10^{-2}$

Asymmetry:

$$A^{DK}_{ADS} = -0.39 \pm 0.17 \pm 0.02$$

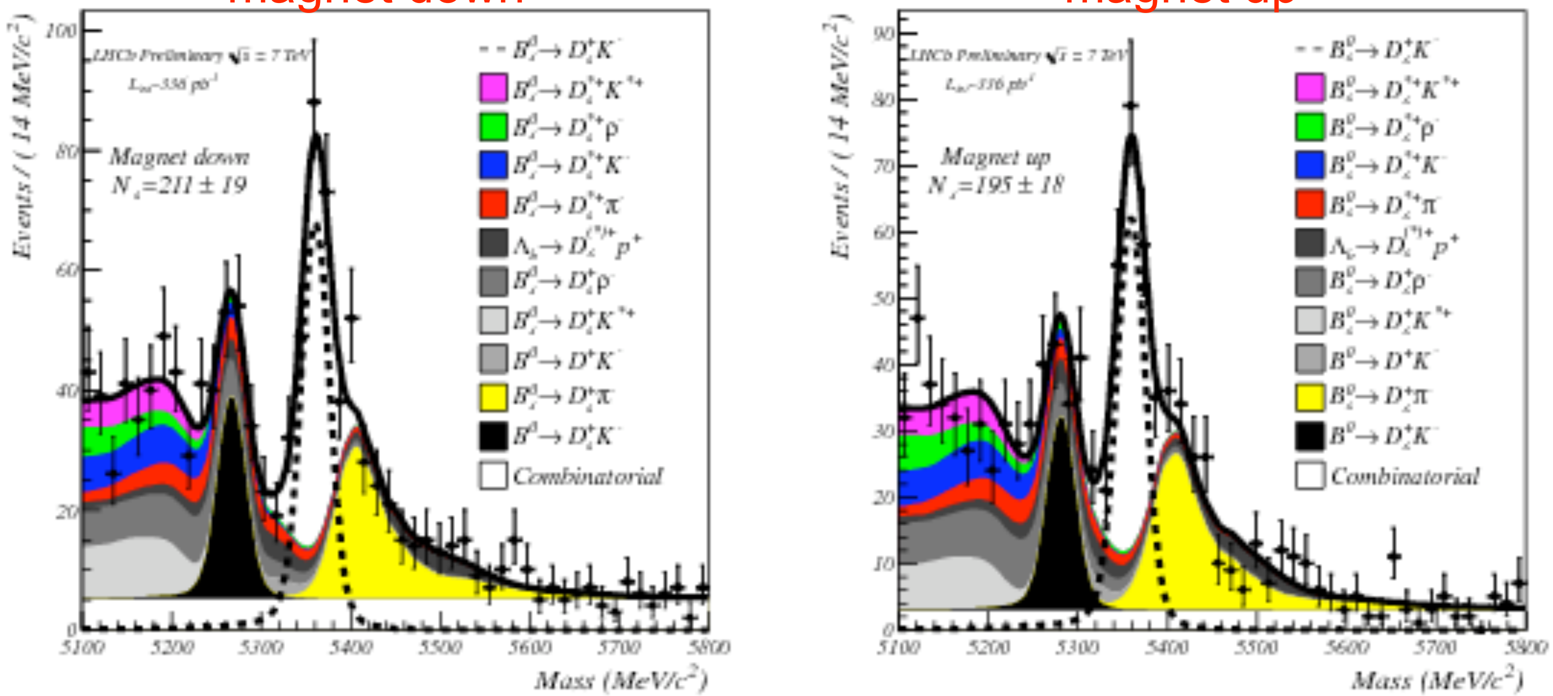
World average (without LHCb) -0.58 ± 0.21

γ from $B_s \to D_s K$

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

First step : establish signals and measure branching fraction

magnet down   magnet up



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

Expect to measure γ with an error of 5° with 2011/2012 data

B Mixing and CP Violation

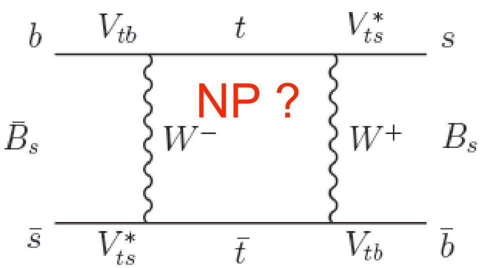
B_s Mixing

Matter-antimatter oscillations are governed by

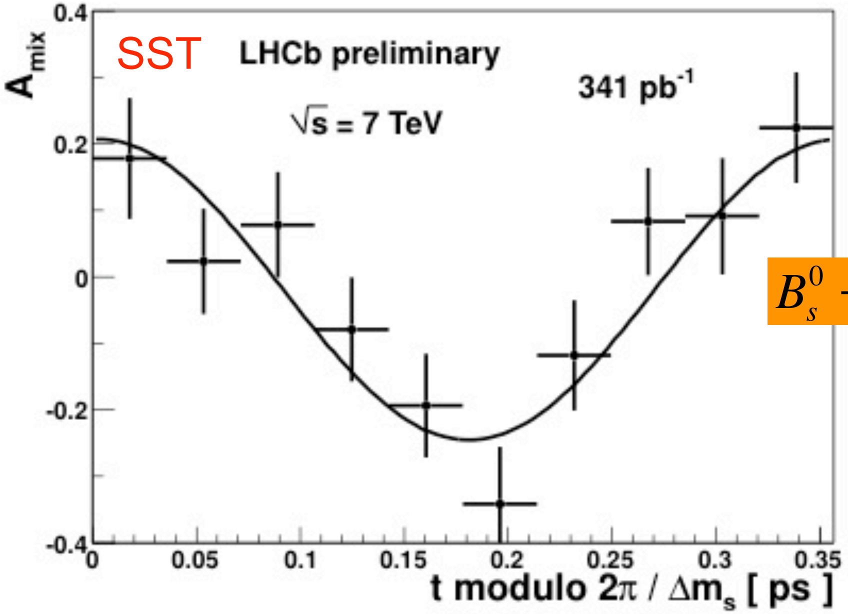
$$i\frac{\partial}{\partial t}\begin{pmatrix}a\\b\end{pmatrix} = H\begin{pmatrix}a\\b\end{pmatrix} = \begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix}$$

$$|B_{L,H}\rangle = p\,|B^0\rangle \pm q\,|\overline{B^0}\rangle$$

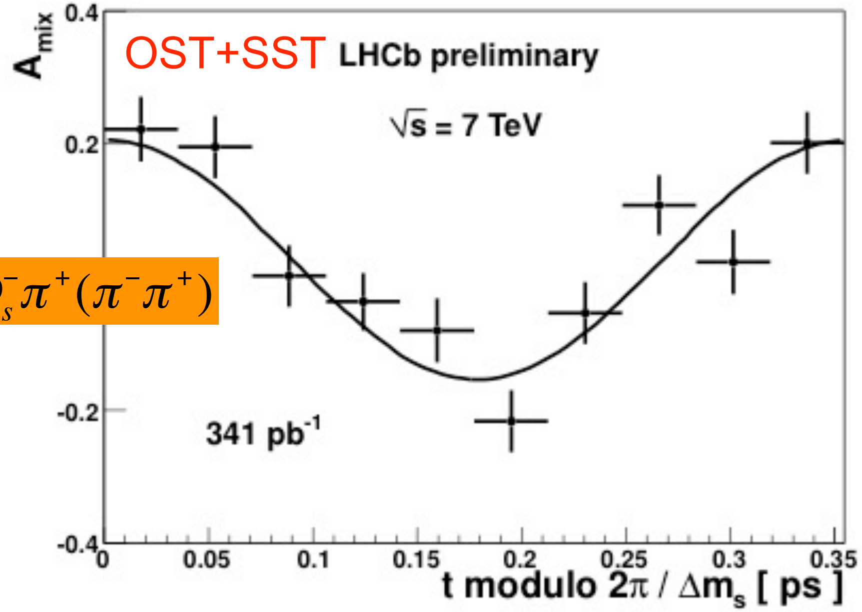
$$\Delta m = m_H - m_L = 2|M_{12}|$$



Flavour of B hadron at production is tagged by sign of μ, e, K and charge of tracks from other B hadron in event (OST) and by K from same side (SST).



$$B_s^0 \to D_s^- \pi^+ (\pi^- \pi^+)$$



Worlds best measurement

$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026 \quad \mathrm{ps}^{-1}$$

CPV in B_d Mixing: Controlling Penguins

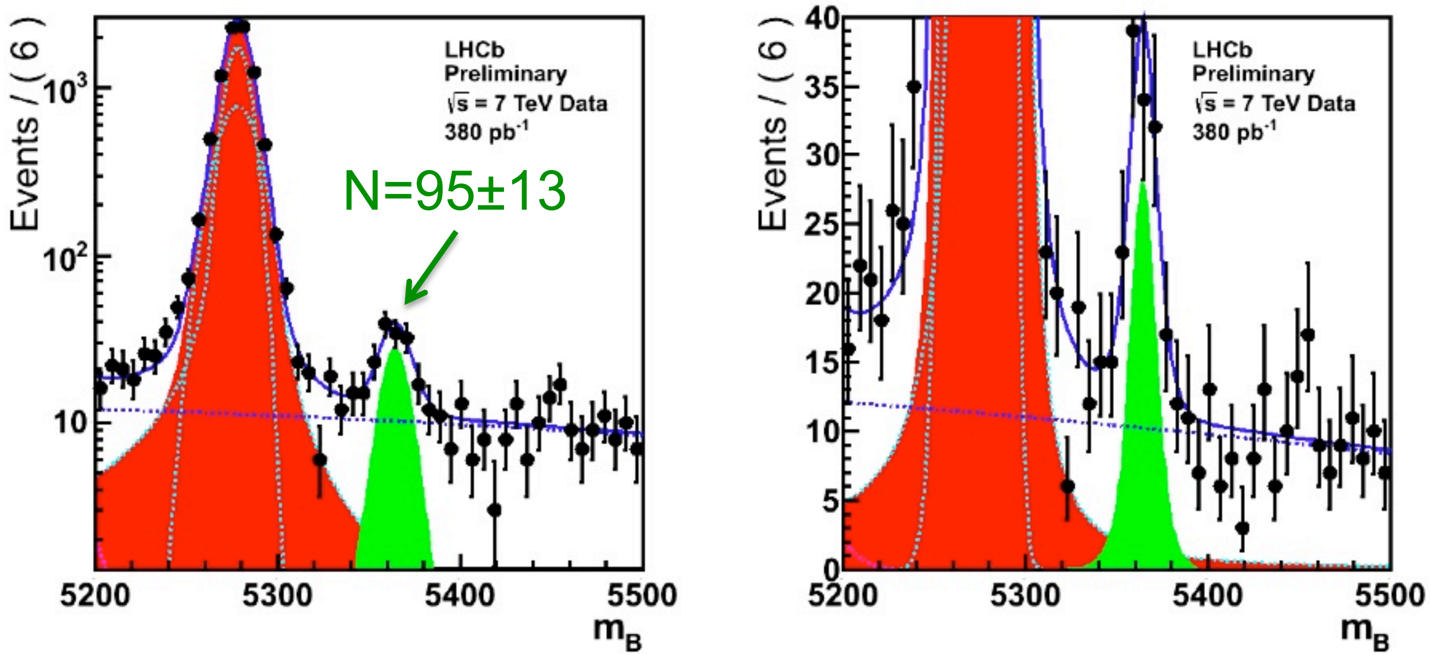
$B_d \rightarrow J/\psi K_s$ is the "golden" mode to measure the B_d mixing phase ϕ_d

NLO+NP : $\phi_d = 2\beta + \Delta\phi_d(a, \theta, \gamma) + \phi_d^{NP}$ Fleischer et al, PRD 79 014030

penguin amplitude, strong phase, weak phase

To search for NP need to control unruly penguins with $B_s \rightarrow J/\psi K_s$ + Uspin.

Also possible to measure angle γ De Bruyn, Fleischer, Koppenburg, EPJ C70 1025.

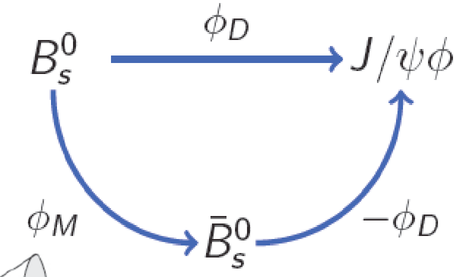


$$\frac{B(B_s \rightarrow J/\psi K_s)}{B(B_d \rightarrow J/\psi K_s)} = 0.0378 \pm 0.0058\,(\text{stat.}) \pm 0.0020\,(\text{syst.}) \pm 0.003\,(\text{f}_s/\text{f}_d)$$

$$CDF:\ 0.0405 \pm 0.0070\,(\text{stat.}) \pm 0.0041\,(\text{syst.}) \pm 0.005\,(\text{f}_s/\text{f}_d)$$

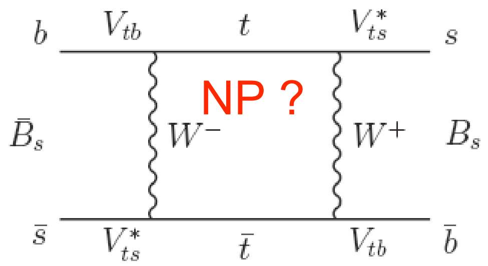
CPV in B_s Mixing : $B_s \to J/\psi\phi$

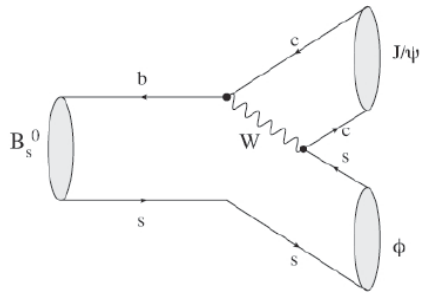
Study the CP violation in interference between mixing and decay in $B_s \to J/\psi\phi$



CP violating phase $\phi_s = \phi_M + 2\phi_D$

In the Standard Model ϕ_s is well determined





$$\phi_M^{SM} = -2\arg\left(V_{ts}V_{tb}^*\right) = -2\beta_s \qquad \phi_D^{SM} = -2\arg\left(V_{cs}V_{cb}^*\right) \approx 0$$

$$\boxed{\phi_s^{SM} = -0.0363 \pm 0.0017 \ \text{rad}}$$

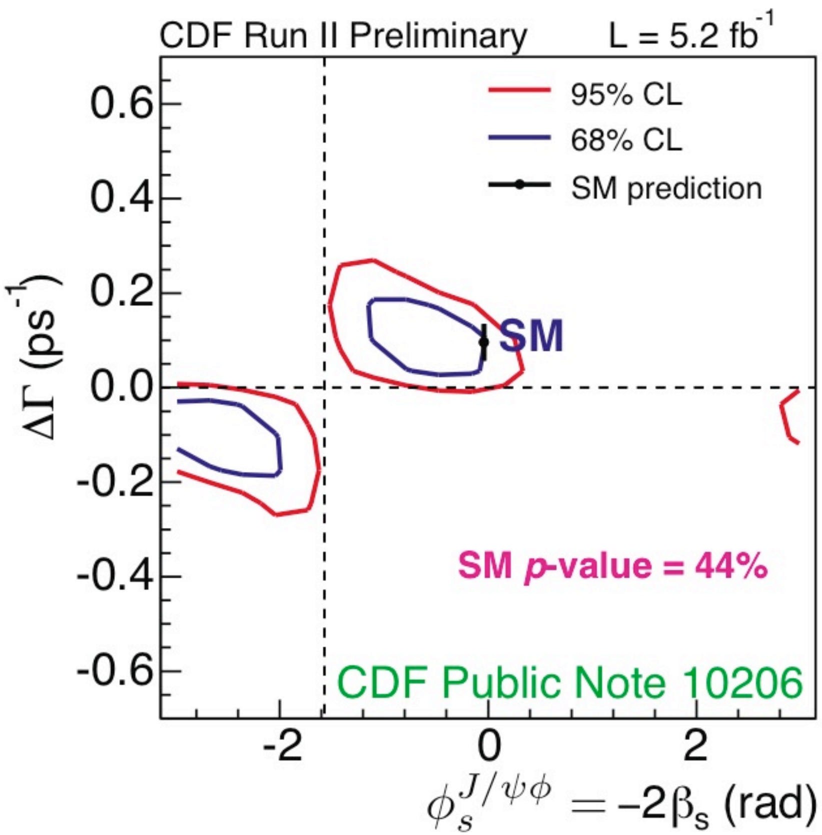
Possible NP can modify the phase $\phi_s = \phi_s^{SM} + \Delta\phi_s^{NP}$

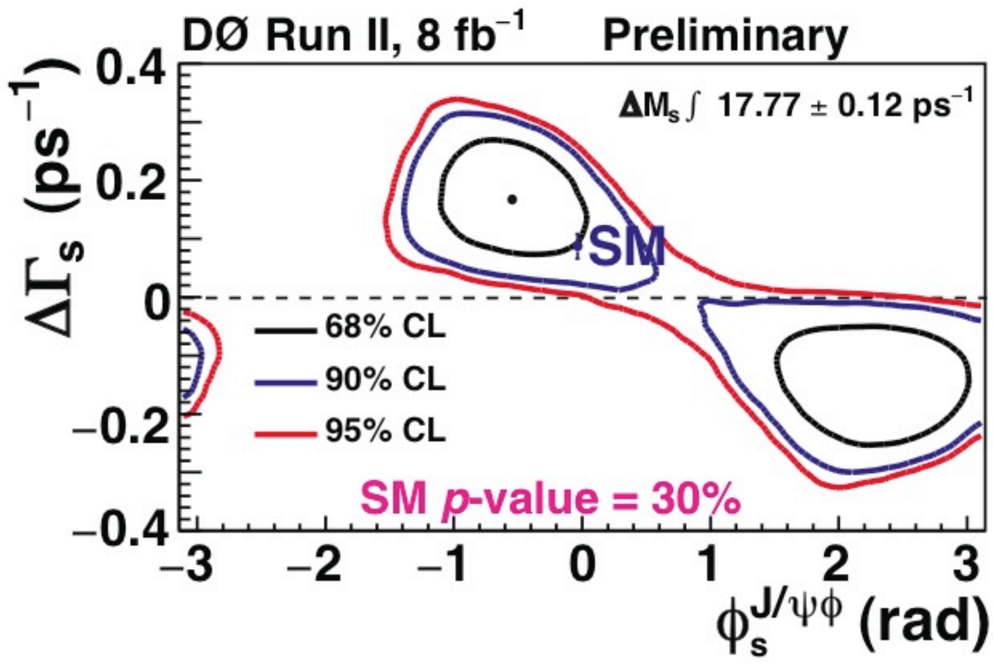
Since the decay is P→VV, the final state is a superposition of different CP states; the measurement requires a complex **tagged, time-dependent, angular analysis.**

Current status of ϕ_s from CDF&D0

Constraints in ($\Delta\Gamma_s$, ϕ_s) plane

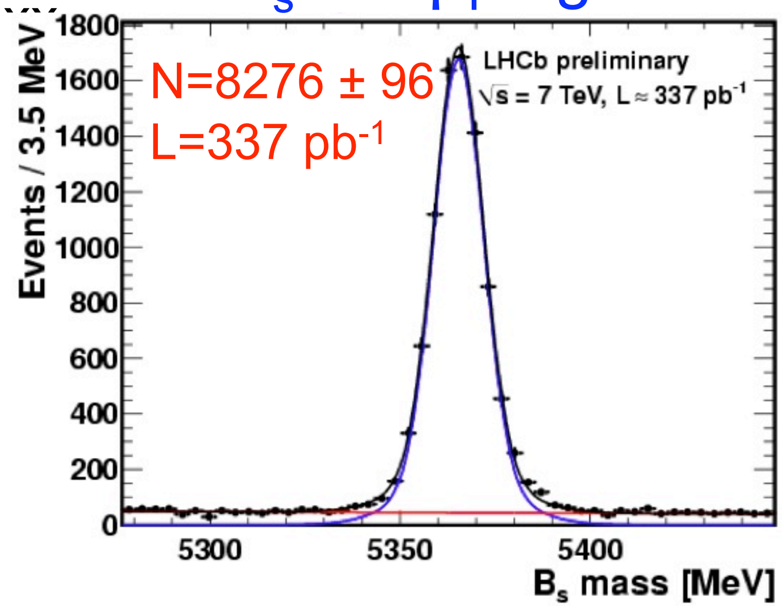
$B_s \to J/\psi\phi$



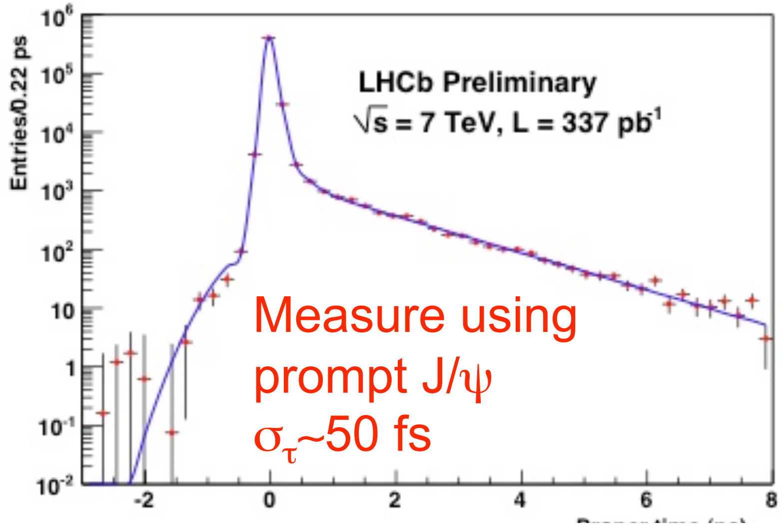


LHCb essential ingredients to measure ϕ_s

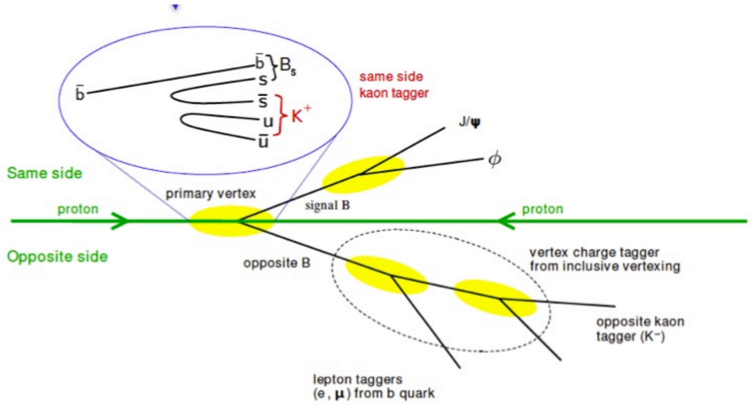
$B_s \to J/\psi\phi$ signal



Excellent proper time resolution

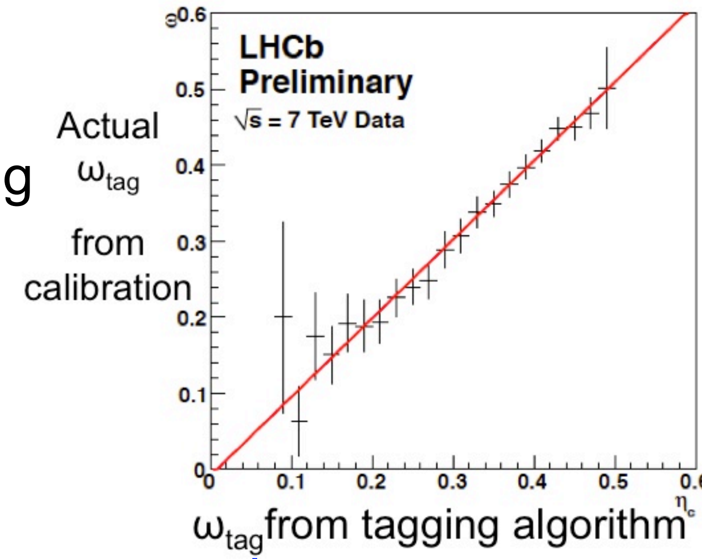


Flavour tagging



OST, calibrate using $B^+ \to J/\psi K^+$

Tagging power $\varepsilon D^2 = (2.08 \pm 0.41)\%$

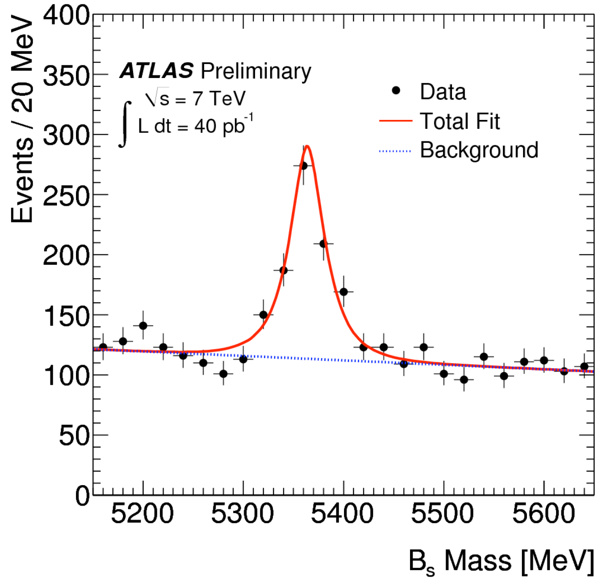


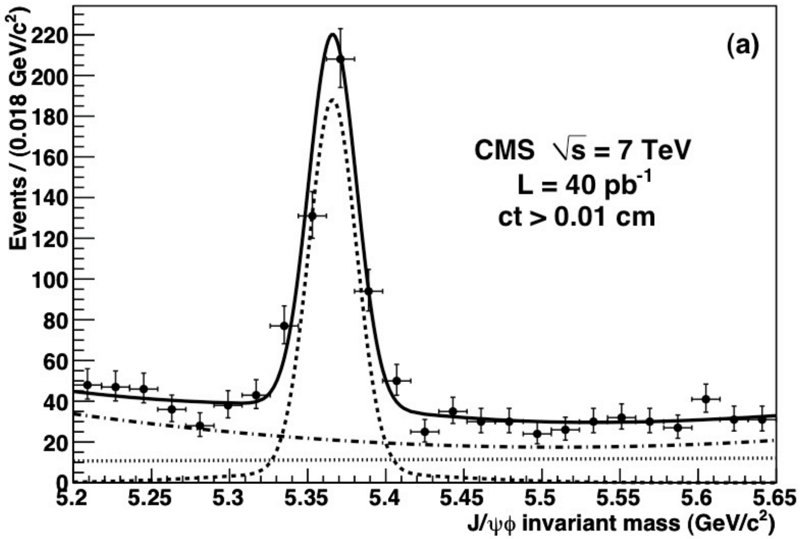
Resolution and tagging included in fit – no systematic

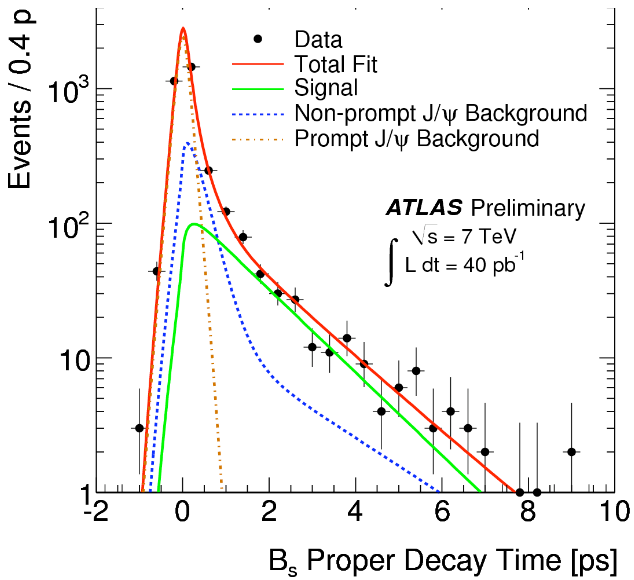
$B_s \rightarrow J/\psi\phi$

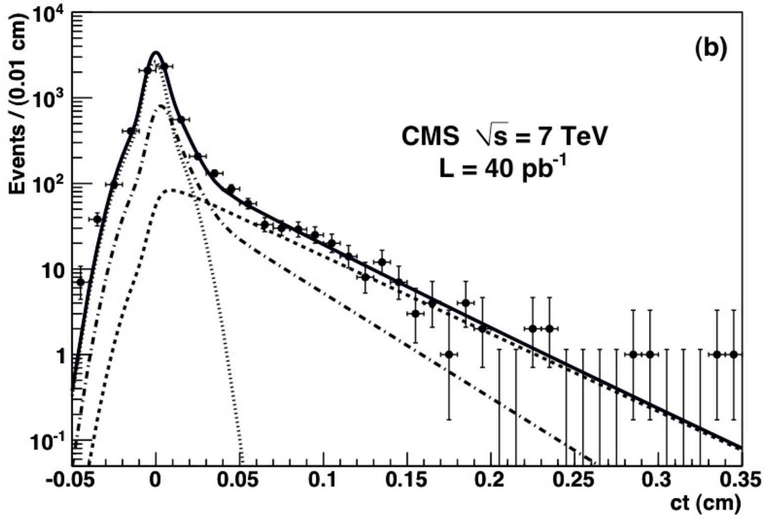
ATLAS-CONF-2011-092
CMS arXiv:1106.4048v1

ATLAS & CMS are also entering the game…





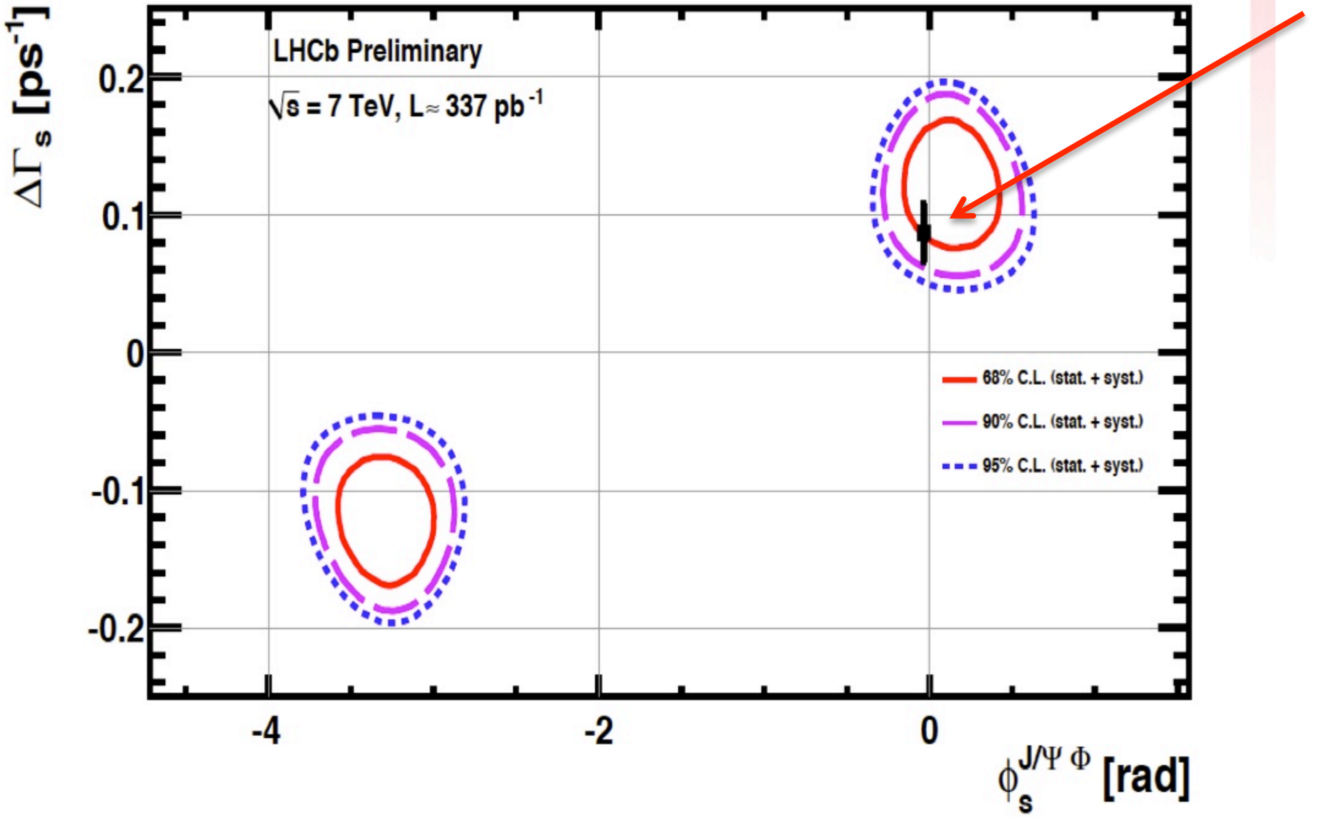




LHCb 2011 measurement of ϕ_s

$B_s \rightarrow J/\psi\phi$

Standard Model
(Lenz, Nierste : arXiv:1102.4274)



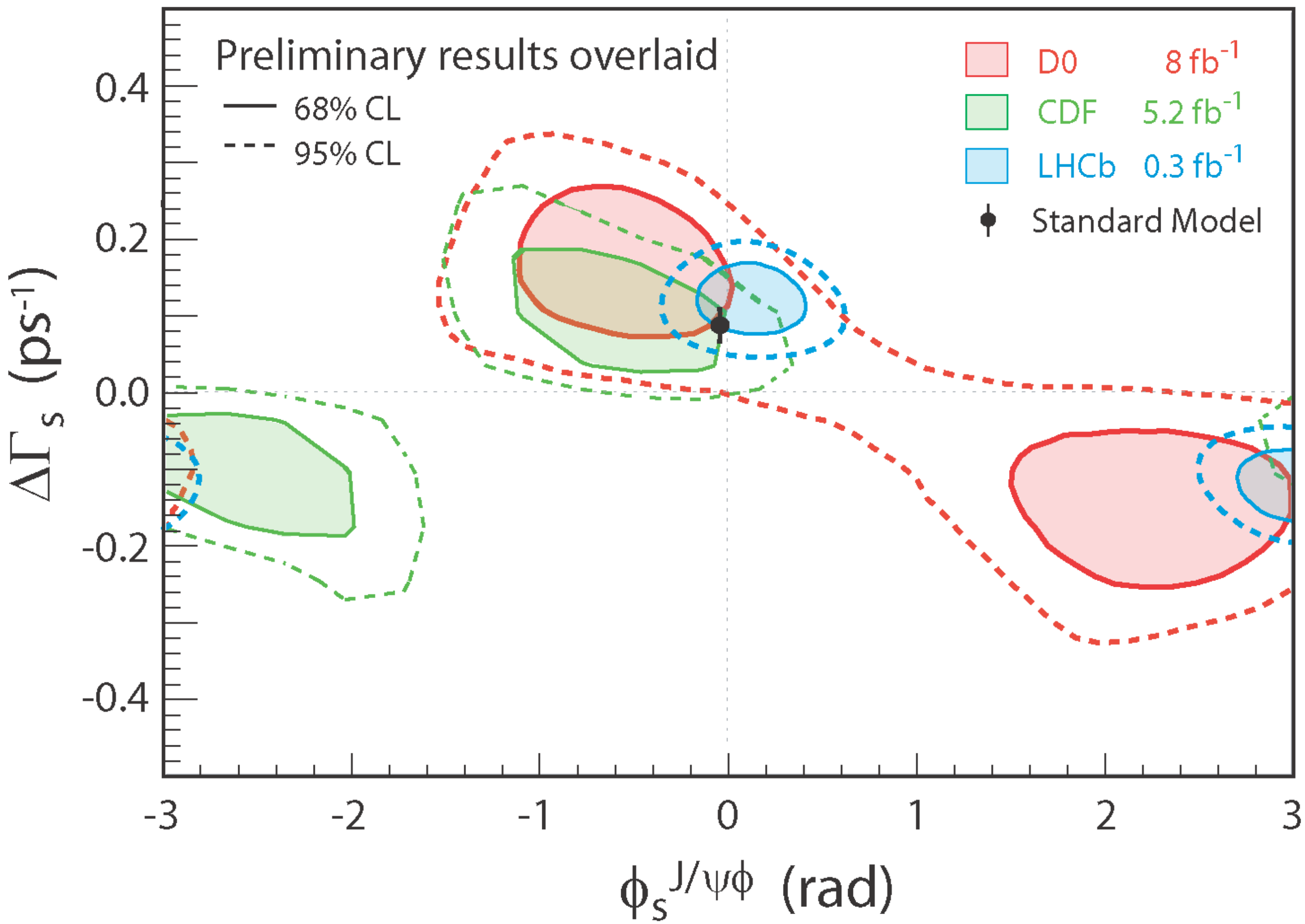
$$\begin{aligned}\phi_s^{J/\psi\phi} &= 0.13 \pm 0.18\ (\text{stat}) \pm 0.07\ (\text{sys})\ \text{rad},\\ \Gamma_s &= 0.656 \pm 0.009\ (\text{stat}) \pm 0.008\ (\text{sys})\ \text{ps}^{-1},\\ \Delta\Gamma_s &= 0.123 \pm 0.029\ (\text{stat}) \pm 0.008\ (\text{sys})\ \text{ps}^{-1},\end{aligned}$$

First point estimate of ϕ_s

First evidence (4σ) for $\Delta\Gamma_s$>0

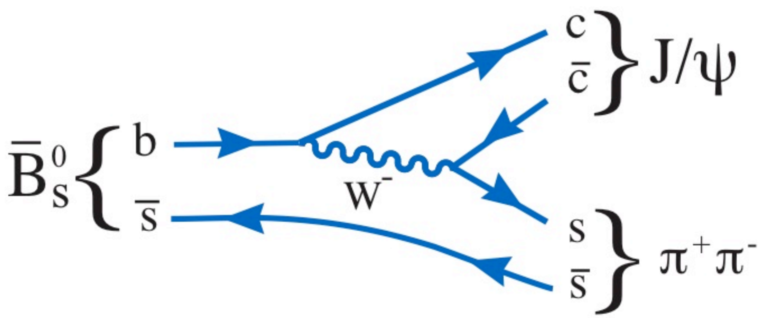
LHCb & CDF & D0 Comparison

$B_s \rightarrow J/\psi\phi$

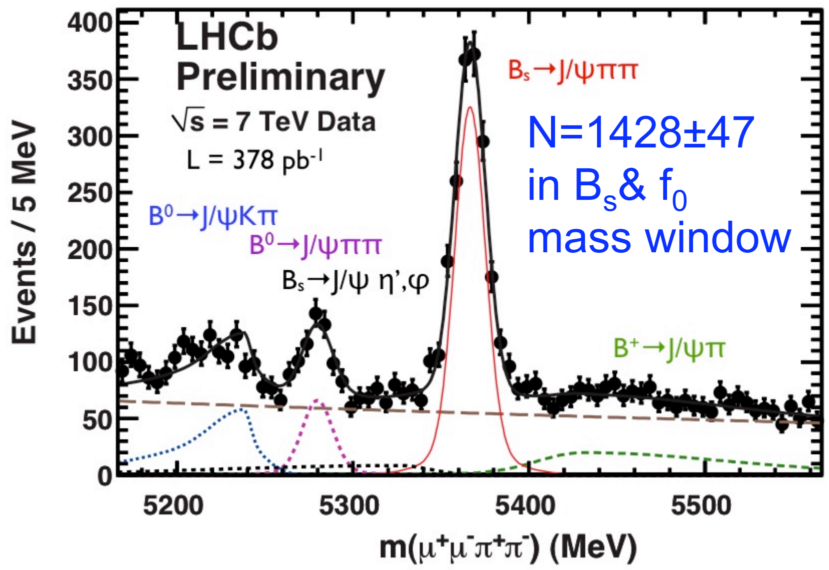


LHCb public web-site

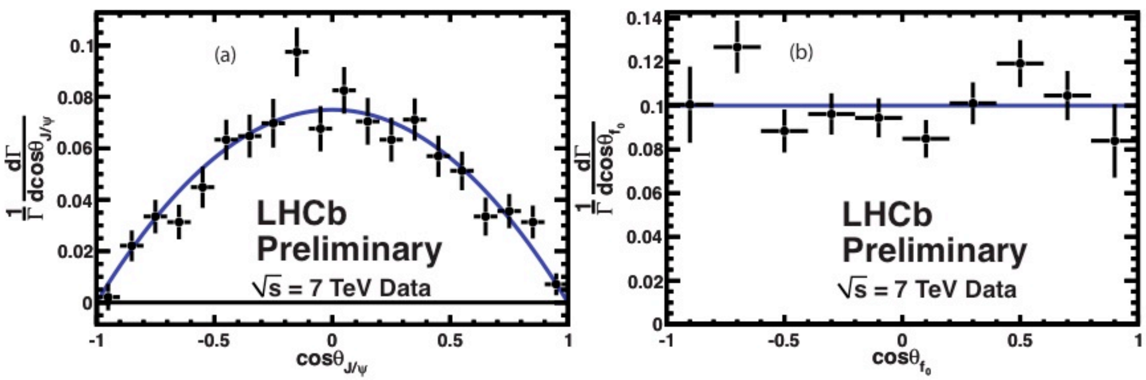
$B_s \to J/\psi f_0$

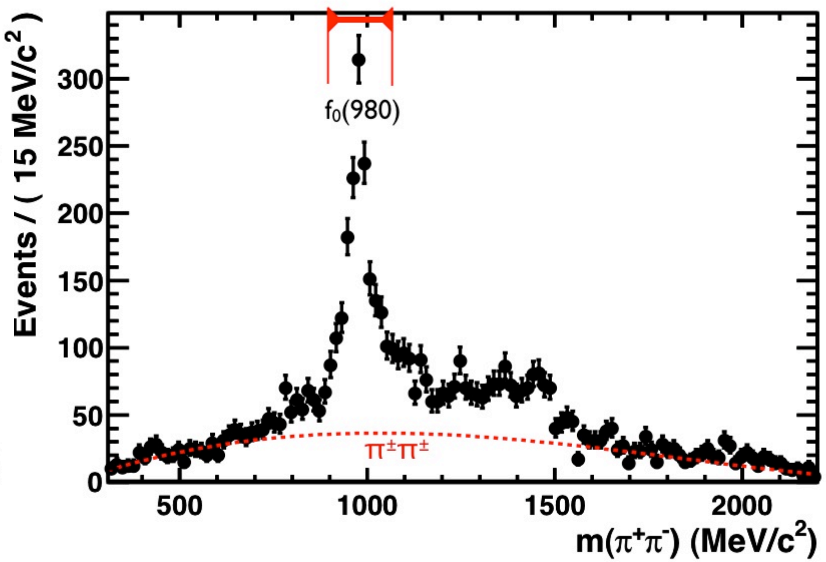


$f_0(980)$ is a scalar with an $s\bar{s}$ component which decays predominantly to $\pi^+\pi^-$



The $f_0(980)$ signal region looks pure scalar→ pure CP odd → no angular analysis needed

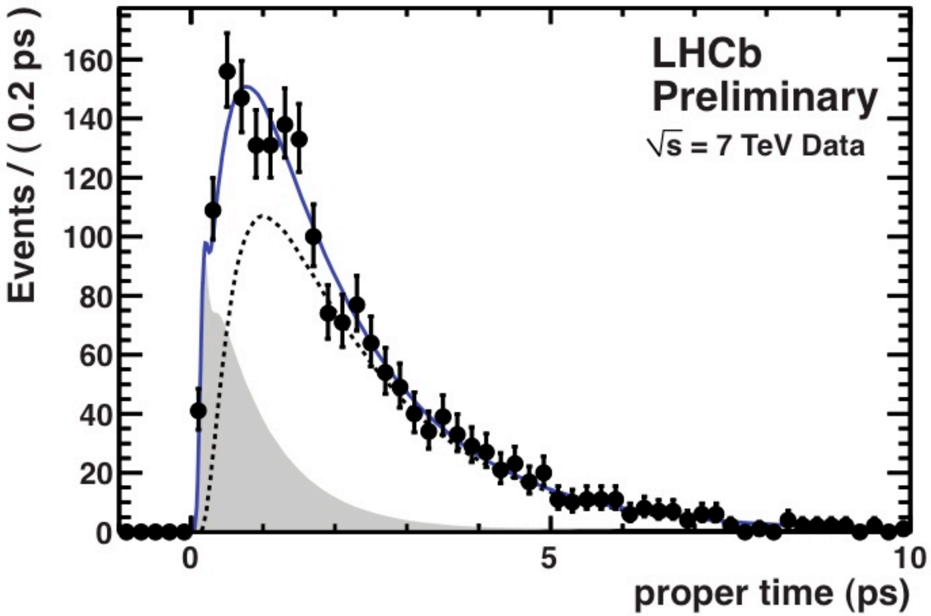


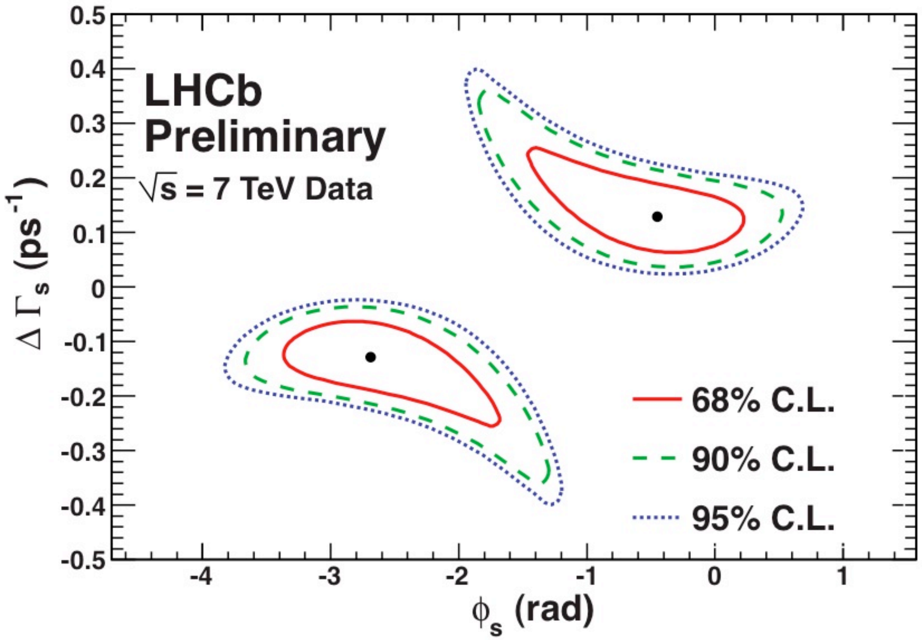


$B_s \to J/\psi f_0$

Maximum likelihood fit to signal+background time+mass distributions

Use Γ_s and $\Delta\Gamma$ (+correlation) from $B_s \to J/\psi\phi$ analysis

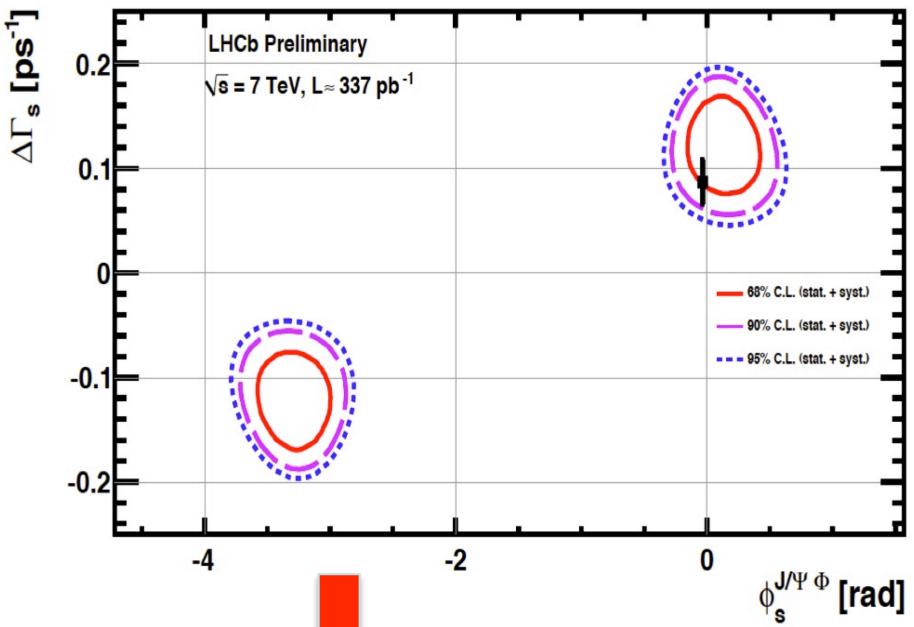


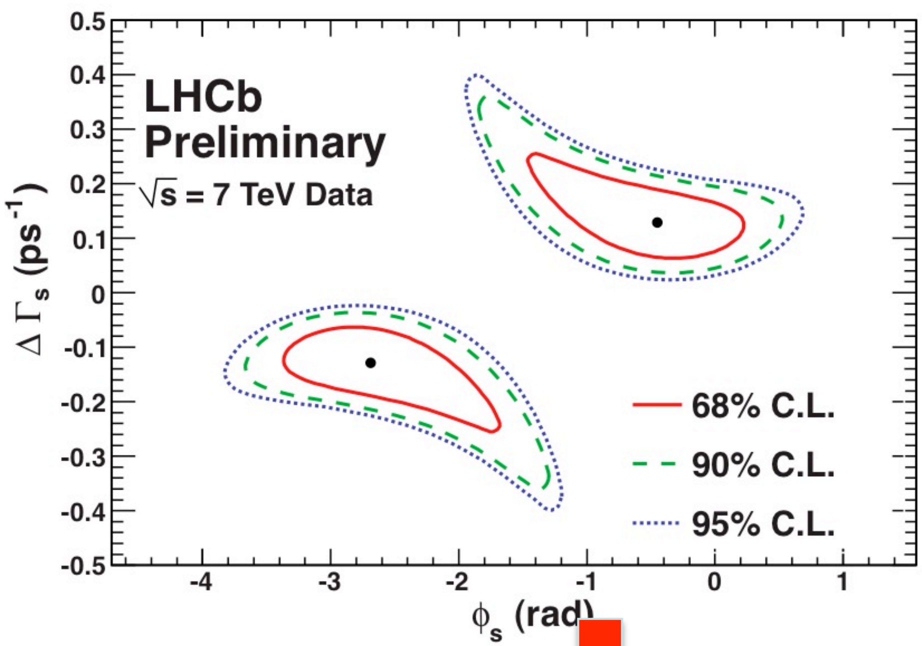


$$\phi_s^{J/\psi f_0} = -0.44 \pm 0.44 \pm 0.2 \text{ rad}$$

LHCb ϕ_s combined prelim. result

Simultaneous fit to both data sets taking all common parameters and correlations into account. Use largest systematic error.





$$\phi_s = 0.03 \pm 0.16 \pm 0.07 \text{ rad}$$

$$\phi_s^{SM} = -0.0363^{+0.0016}_{-0.0015} \text{ rad}$$

CKMFitter group: arXiv:1106.4041

LHCb also has measured CPV in B_s penguins: $B_s \rightarrow \phi\phi$

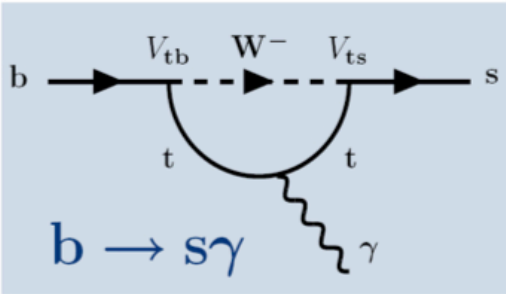
LHCb-CONF-2011-052

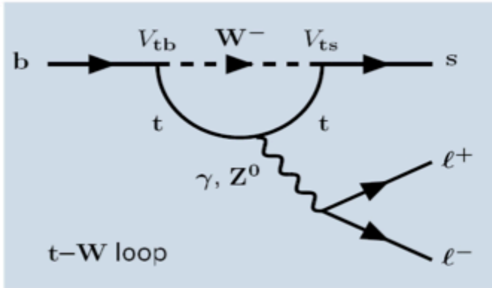
Rare B Decays

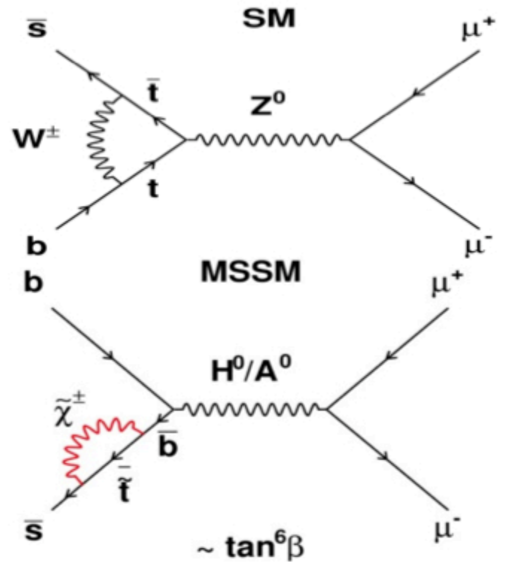
Rare B Decays

Some interesting examples of rare B decays; all $b \to s$ transitions

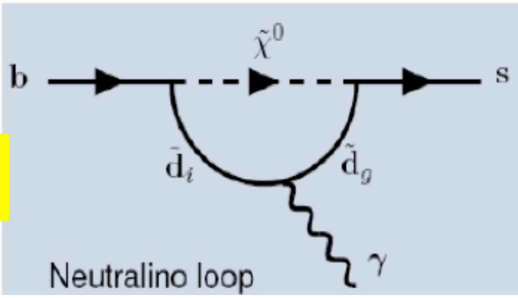
SM

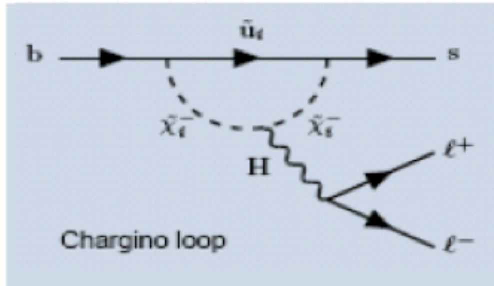






MSSM



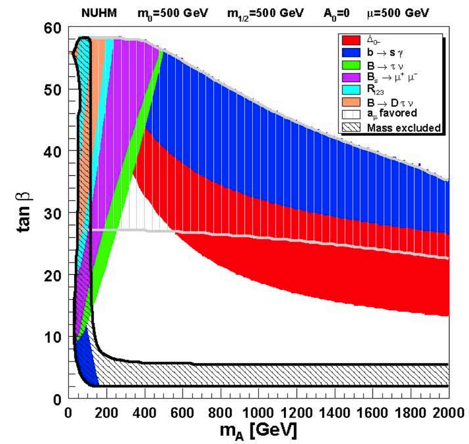


	$B_s \to \phi\gamma$	$B^0 \to K^*\mu^+\mu^-$	$B_s \to \mu^+\mu^-$
Br (SM)	Large theoretical uncertainties		$(3.2 \pm 0.2) \times 10^{-9}$
Br (exp. pre-LHC)	$\left(5.7^{+1.8\,+1.2}_{-1.5\,-1.1}\right) \times 10^{-5}$	$\left(1.05^{+0.16}_{-0.13}\right) \times 10^{-6}$	$< 43 \times 10^{-9} \quad 95\%\ c.l.$
	γ polarization	angular distributions	Branching ratio

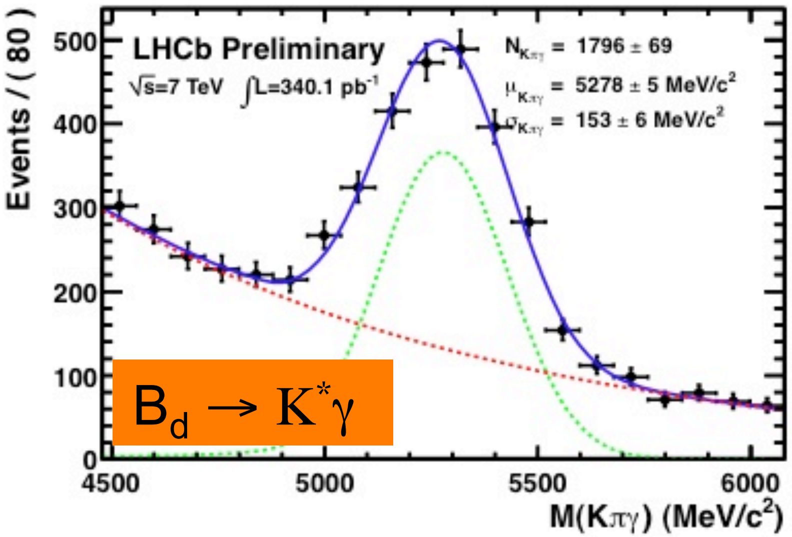
LHCb-CONF-2011-055

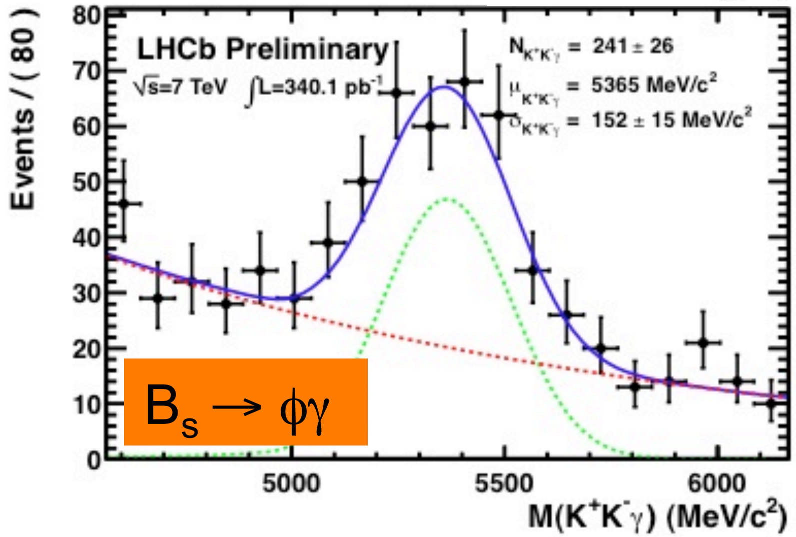
$B_s \to \phi\gamma$ and $B_d \to K^*\gamma$

The measurement of $b \to s\gamma$ provides one of the strongest constraints in MSSM.



LHCb reconstructs exclusive decays with broader signal peak (compared to all-charged final states); implies more work on backgrounds ($B_{d,s} \to K^+\pi^-\pi^0$, $B_d \to K^*e^+e^-$, $B_s \to K^+\pi^-\gamma$ and cross-feed)





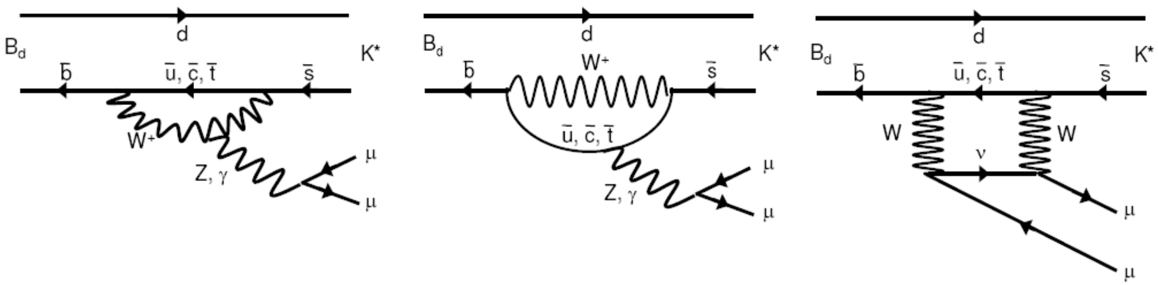
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.52 \pm 0.14(\mathrm{stat}) \pm 0.10(\mathrm{syst}) \pm 0.12(f_s/f_d)$$

Expect 1.0±0.2

Next : Measure CP asymmetries and γ polarization

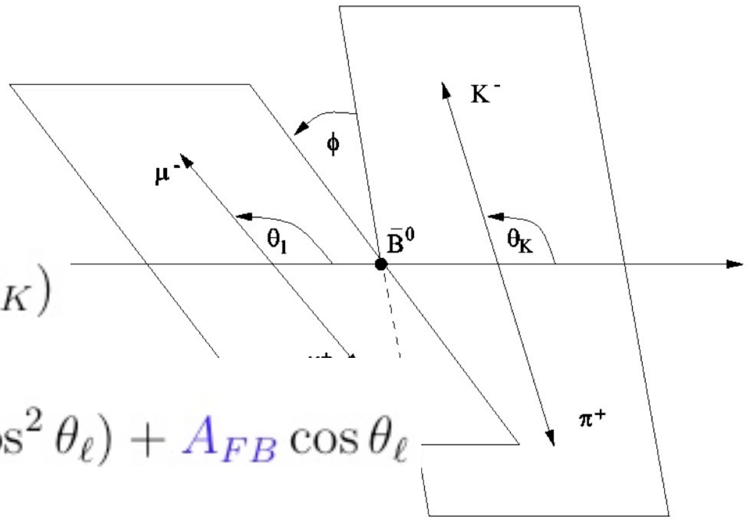
$B_d \to K^*\mu\mu$

$B_d \to K^*\mu\mu$ decays are very sensitive to the presence of NP.



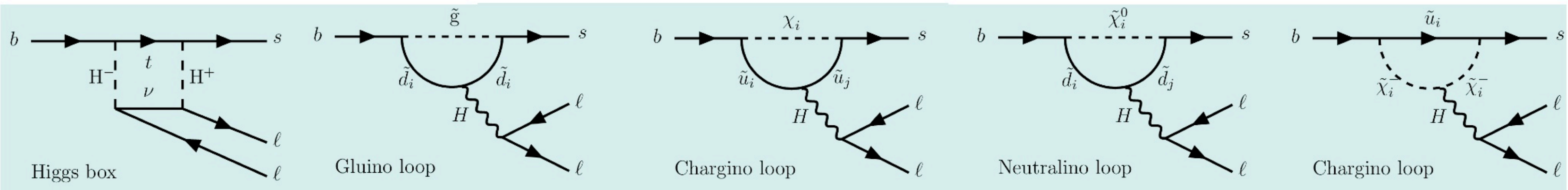
Described by three angles (θ_l, ϕ, θ_K) and $\mu\mu$ invariant mass (q^2)

Angular distributions (1D)



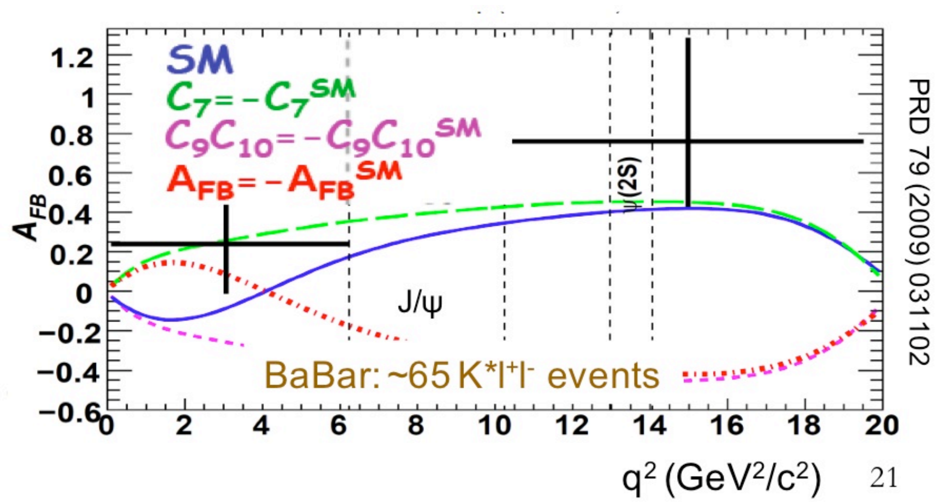
$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_K\,\mathrm{d}q^2} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

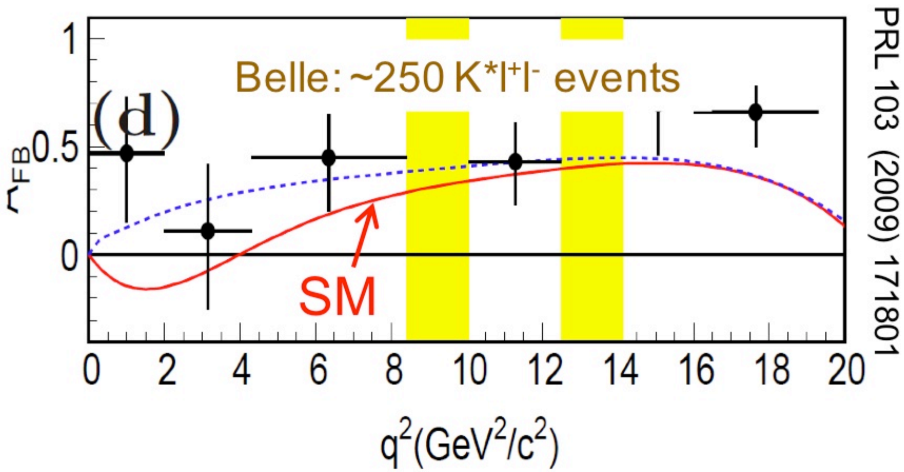
$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}q^2} = \frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$

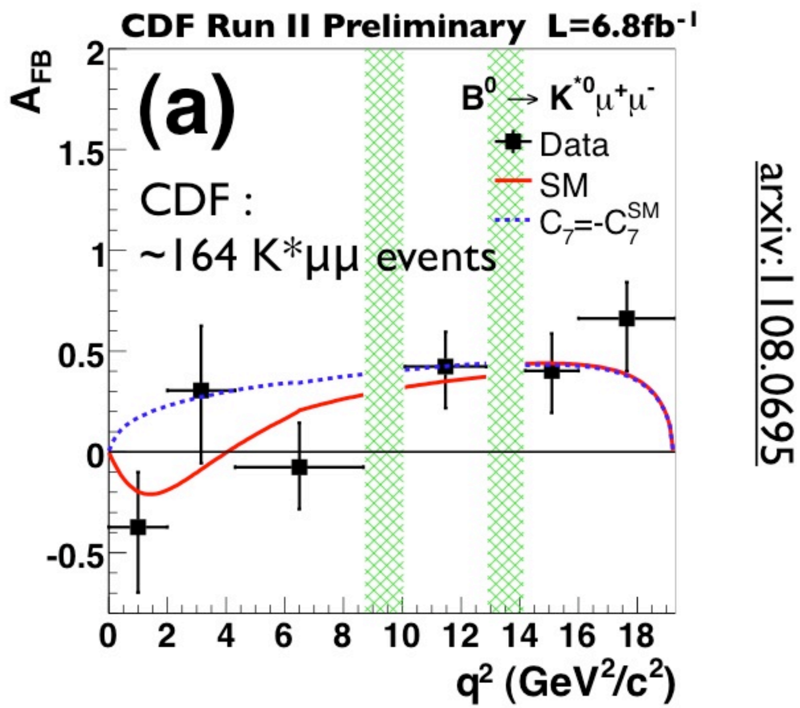


$B_d \rightarrow K^*\mu\mu$

Results from B-factories and CDF show intriguing behaviour in A_{FB} at low q^2







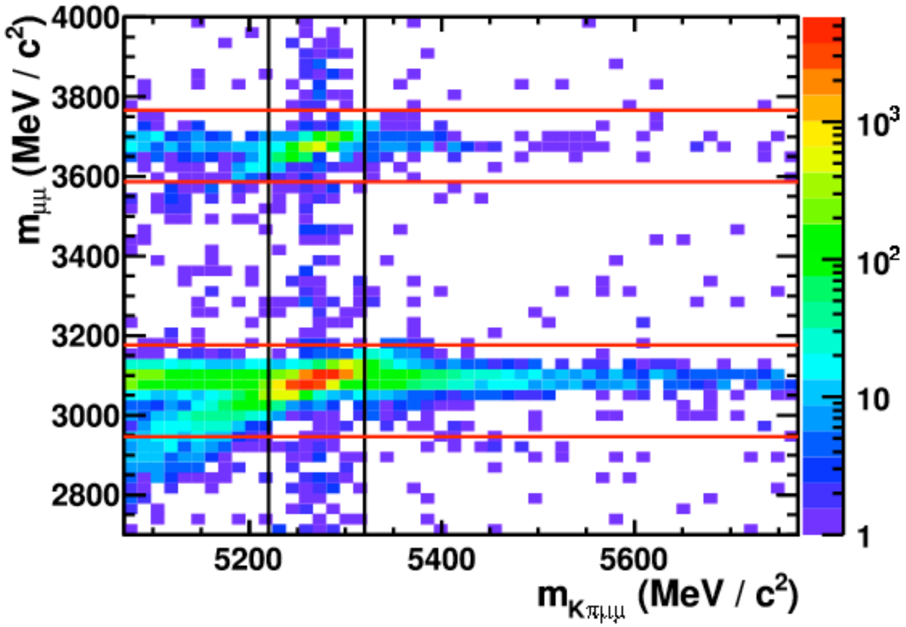
Precision too low yet to speak of an “anomaly”

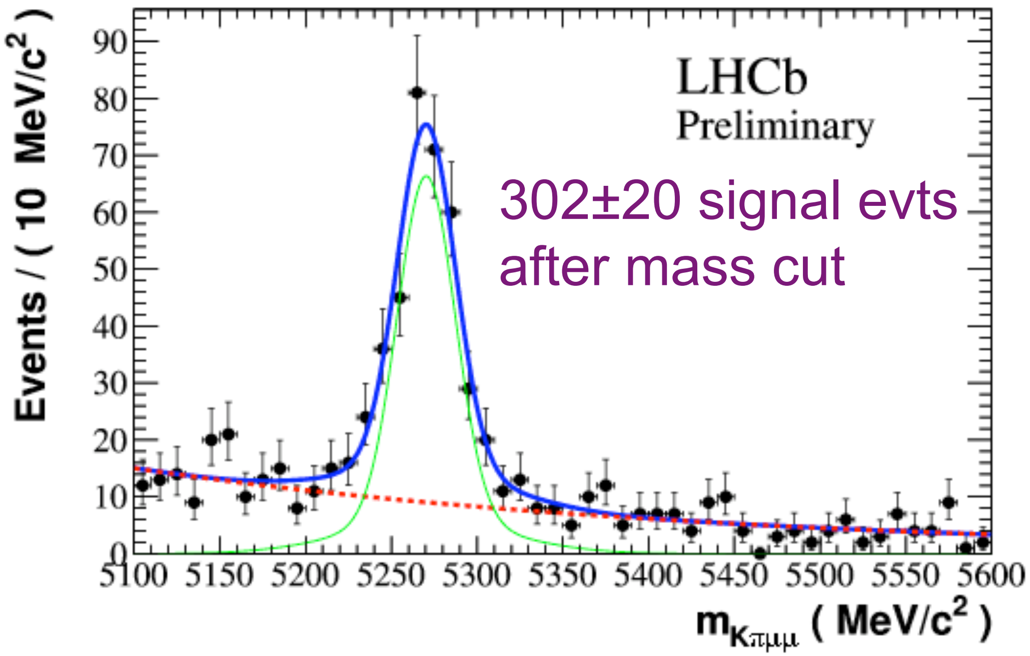
$B_d \to K^*\mu\mu$ at LHCb

LHCb-CONF-2011-038

Select events using a Boosted Decision Tree from a sample of 309 pb^{-1}.

Veto decays in J/ψ and $\psi(2S)$ regions





Measure in 6 q^2 bins

- Differential branching fraction
- Longitudinal polarization, F_L
- Forward-backward asymmetry, A_{FB}

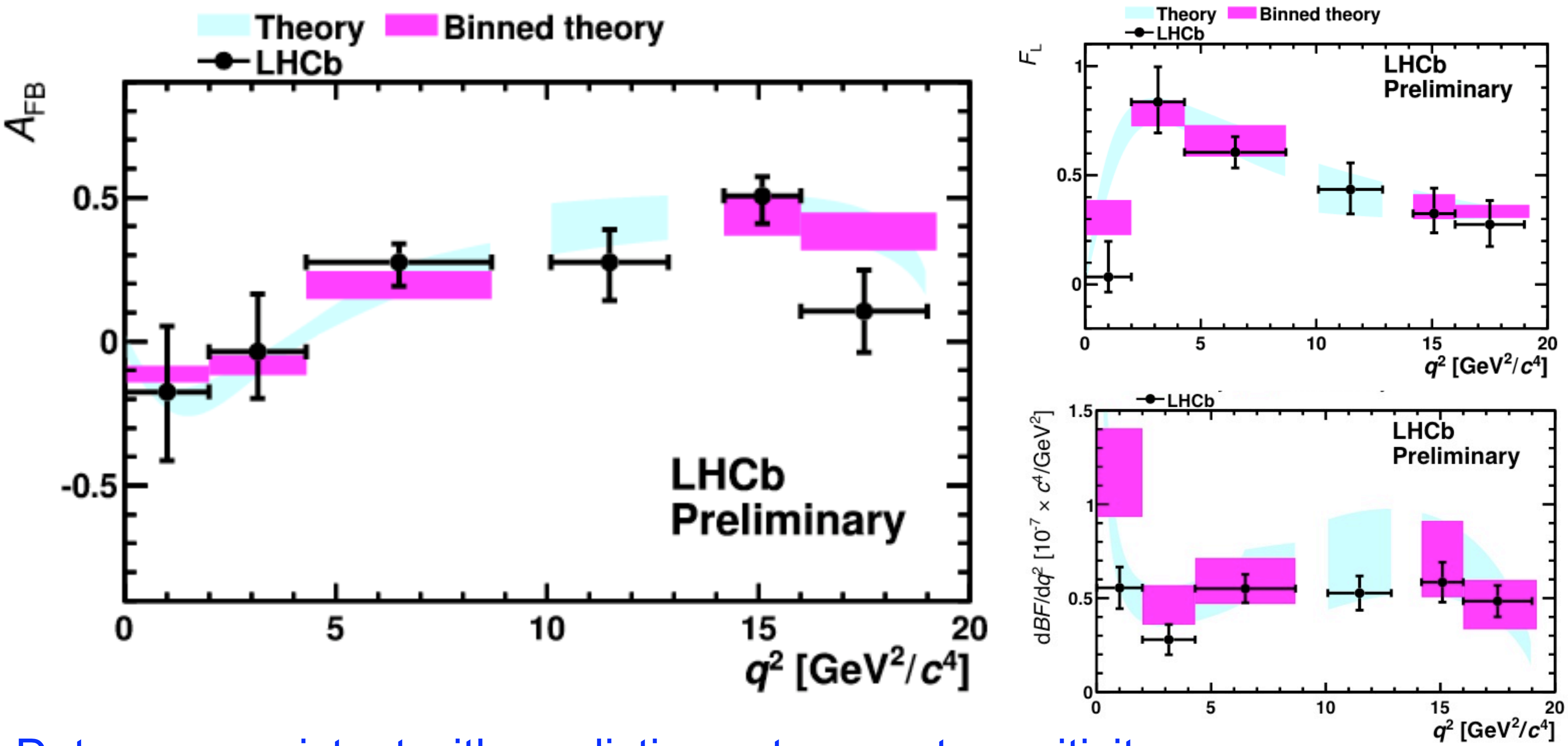
Simultaneous fit of 1D projections of helicity angles of kaon and muon

Performance of fit validated on MC and $B_d \to J/\psi K^*$ decays

LHCb-CONF-2011-038

$B_d \to K^*\mu\mu$ at LHCb

Systematic uncertainties are small and generally statistics limited



Data are consistent with predictions at present sensitivity

Next : Determine A_{FB} crossing-point: sensitive to NP, cleanly predicted in SM

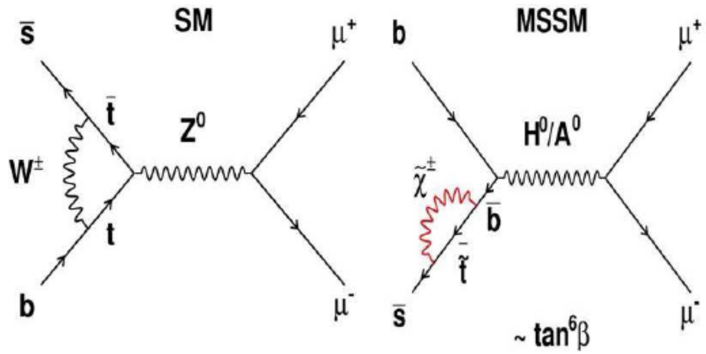
Study other observables, e.g. $A_T^{(2)}$ sensitive to RH currents

$B \rightarrow \mu^+\mu^-$

Very rare and golden FCNC b→d,s transition

Mode	SM
$B_s \rightarrow \mu^+\mu^-$	$3.2 \pm 0.2\ 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$0.10 \pm 0.01\ 10^{-9}$

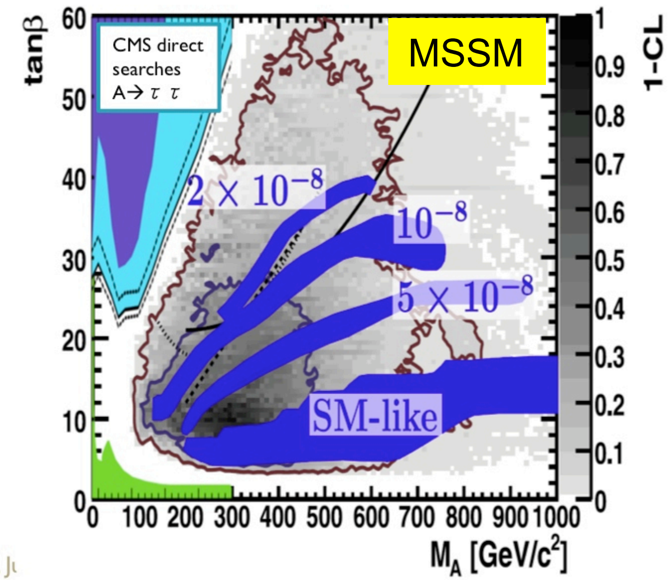
A.J.Buras: arXiv:1012.1447
E. Gamiz et al: Phys.Rev.D 80 (2009) 014503



Strong enhancements in MSSM : $B(B_s \rightarrow \mu^+\mu^-) \propto \frac{\tan^6\beta}{M_A^4}$

$B_s \rightarrow \mu^+\mu^-$
Spring 2011

Experiment	Data	Upper Limit (95% C.L.)
CDF	3.7 fb^{-1}	< 4.3×10^{-8}
D0	6.1 fb^{-1}	< 5.1×10^{-8}
LHCb	36 pb^{-1}	< 5.6×10^{-8}



Recent exciting hint from CDF (7 fb^{-1})

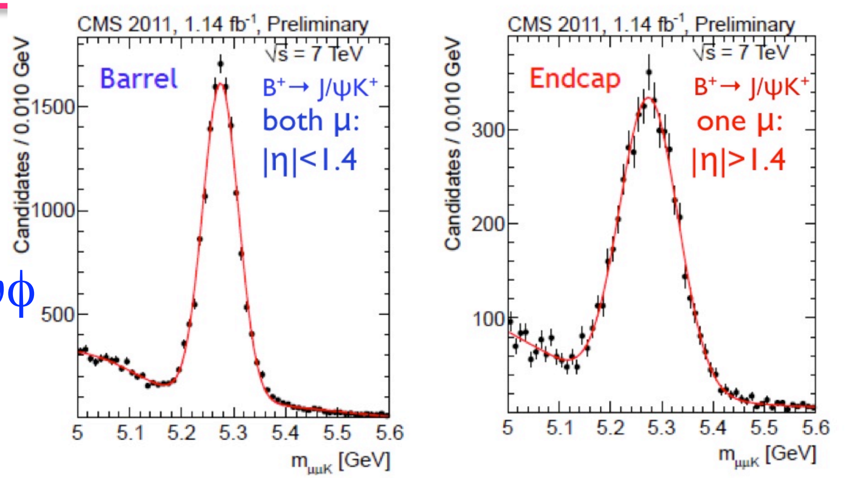
$$B(B_s \rightarrow \mu^+\mu^-) = 1.8^{+1.0}_{-0.9} \times 10^{-8}$$

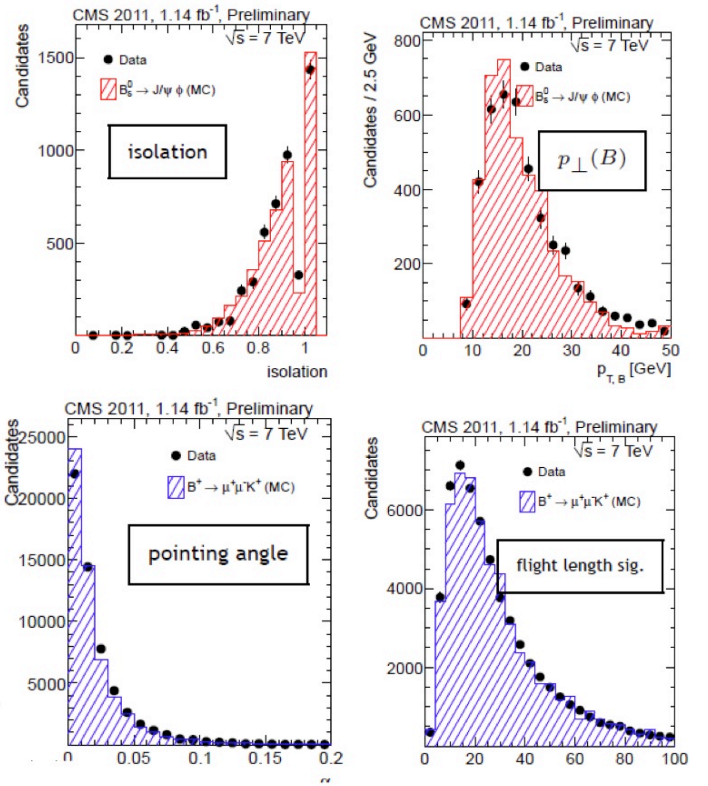
arXiv:1107.2304

CMS search for $B \to \mu^+\mu^-$

Dimuon trigger at L1 & track information added in HLT

Cut based analysis: optimised on MC and verified on data using $B^+ \to J/\psi K^+$ & $B_s \to J/\psi\phi$ prior to unblinding

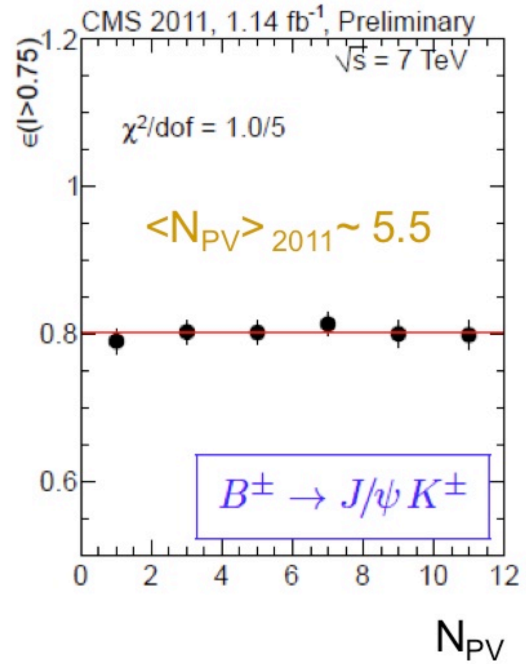




Selection variables well described by simulation

Efficiency of variables potentially sensitive to pile-up (e.g. isolation, flight length) checked on data

Excellent stability observed – good news for higher luminosity !

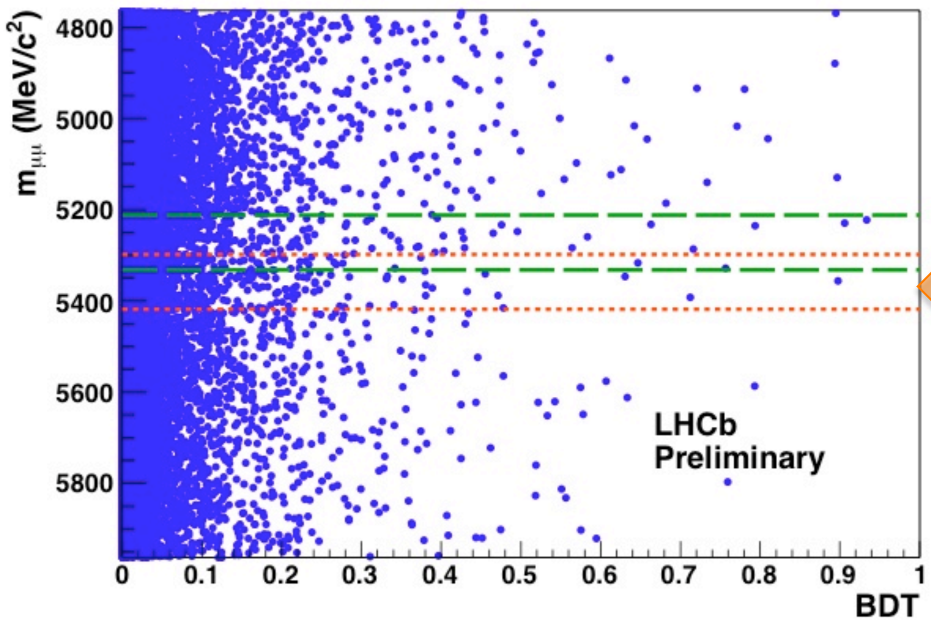


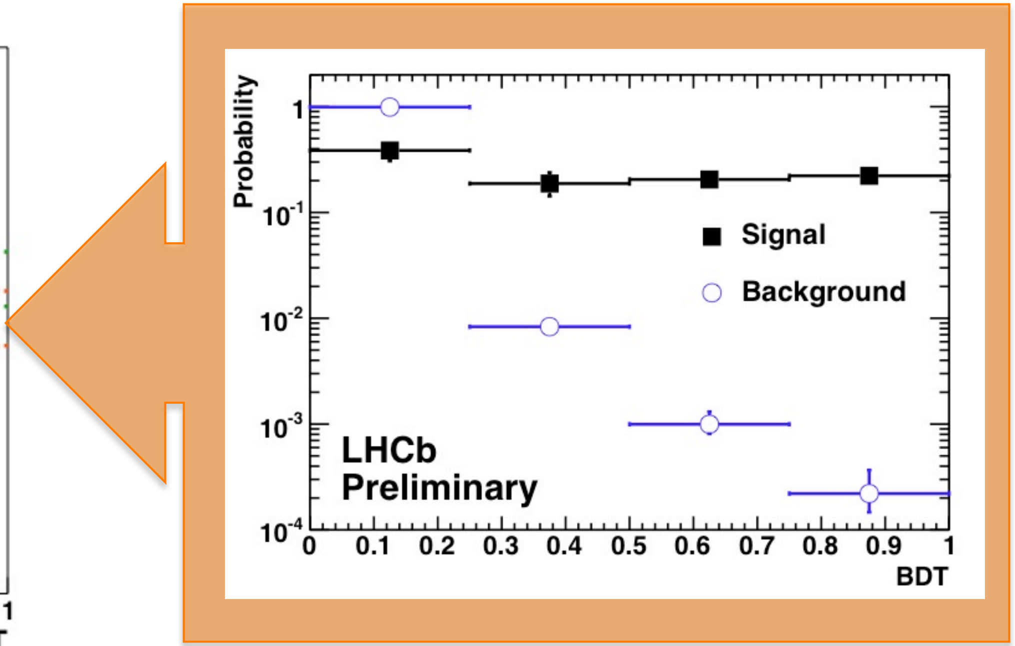
LHCb-CONF-2011-037

LHCb search for $B \to \mu^+\mu^-$

Signal and background events are discriminated using a 2D likelihood: Boosted Decision Tree (BDT) and invariant mass

L=300 pb^{-1}





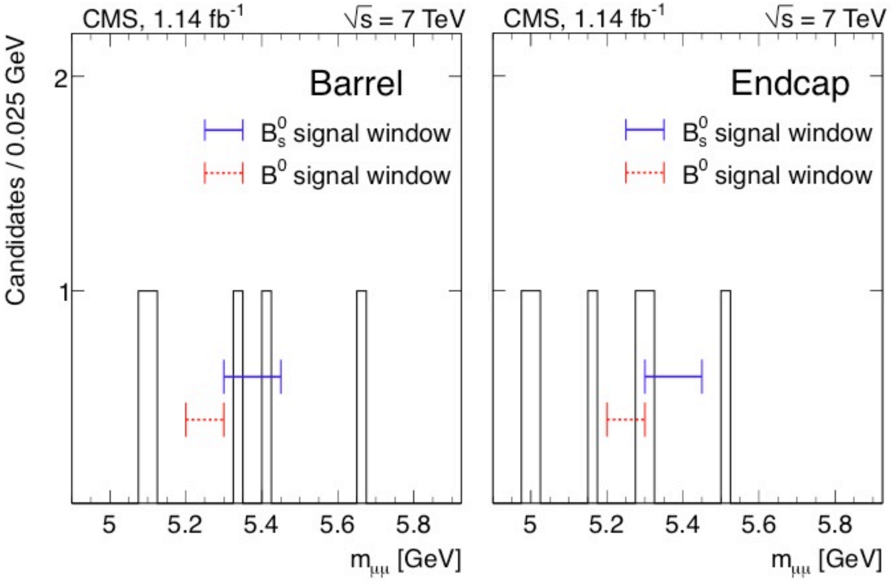
BDT trained on MC and calibrated on $B \to h^+h^-$ (signal) & sidebands (bkgd)

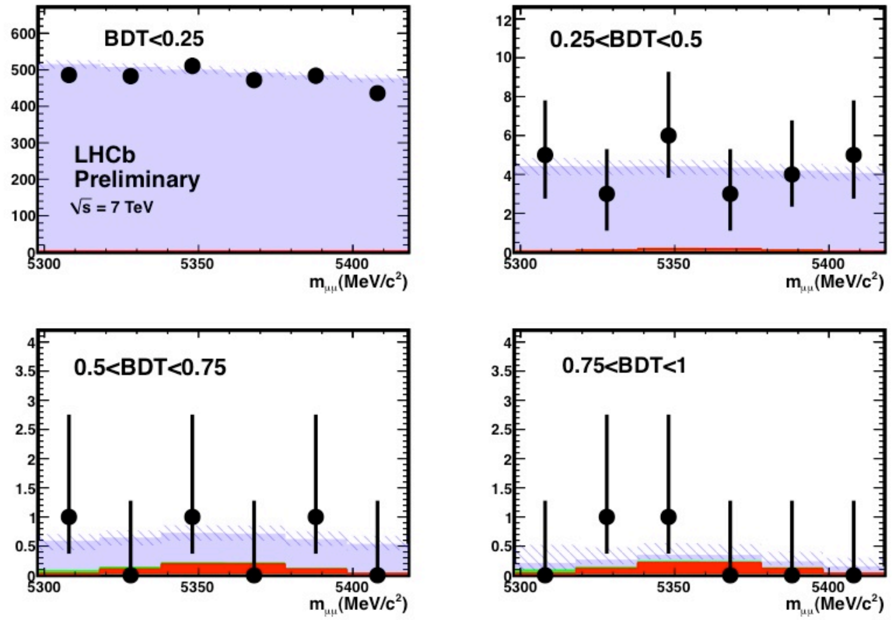
Mass scale and resolution calibrated from data ($\mu\mu$ resonances & $B \to h^+h^-$)

Normalization using $B^+ \to J/\psi K^+$, $B_s \to J/\psi\phi$ & $B_d \to K\pi$ and LHCb result for f_s/f_d

LHC search for $B \to \mu^+\mu^-$

CMS-BPH-11-002
LHCb-CONF-2011-037

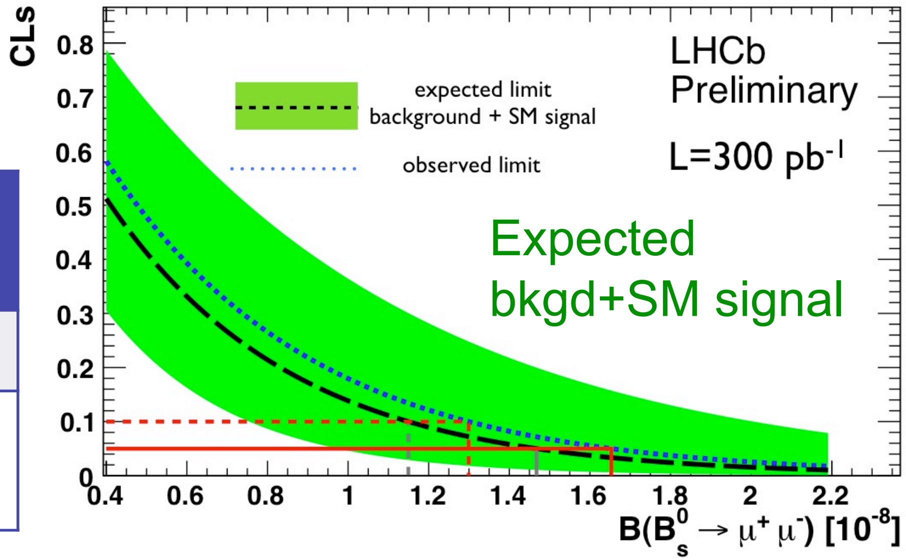




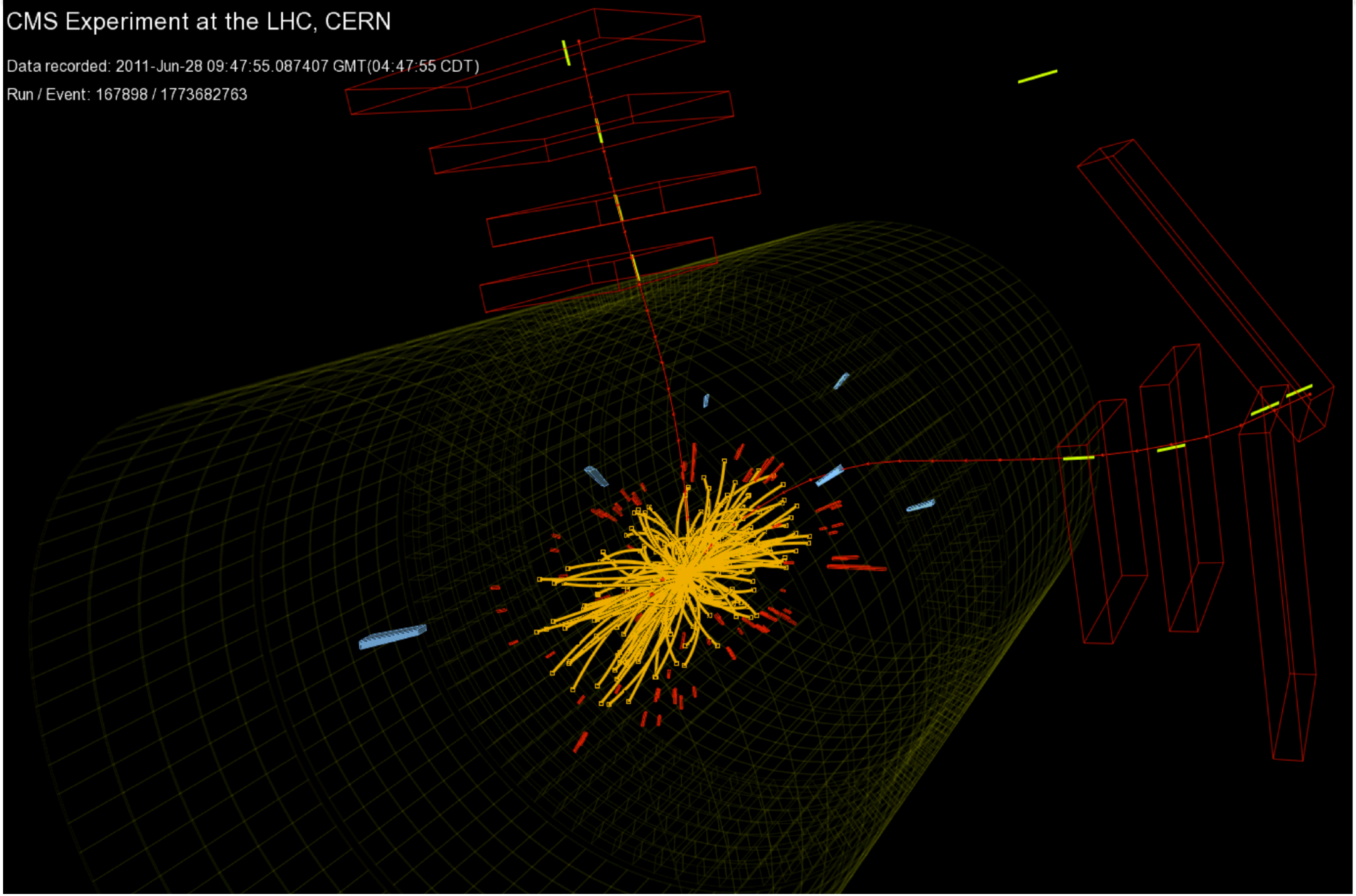
Observations agree with expected bkgd+SM signal.

Calculate upper limits using frequentist CL_S approach.

Experiment	Data	Upper Limit (95% C.L.)
CMS	1.14 fb^{-1}	$<1.9 \times 10^{-8}$
LHCb (2011+2010)	0.34 fb^{-1}	$<1.5 \times 10^{-8}$

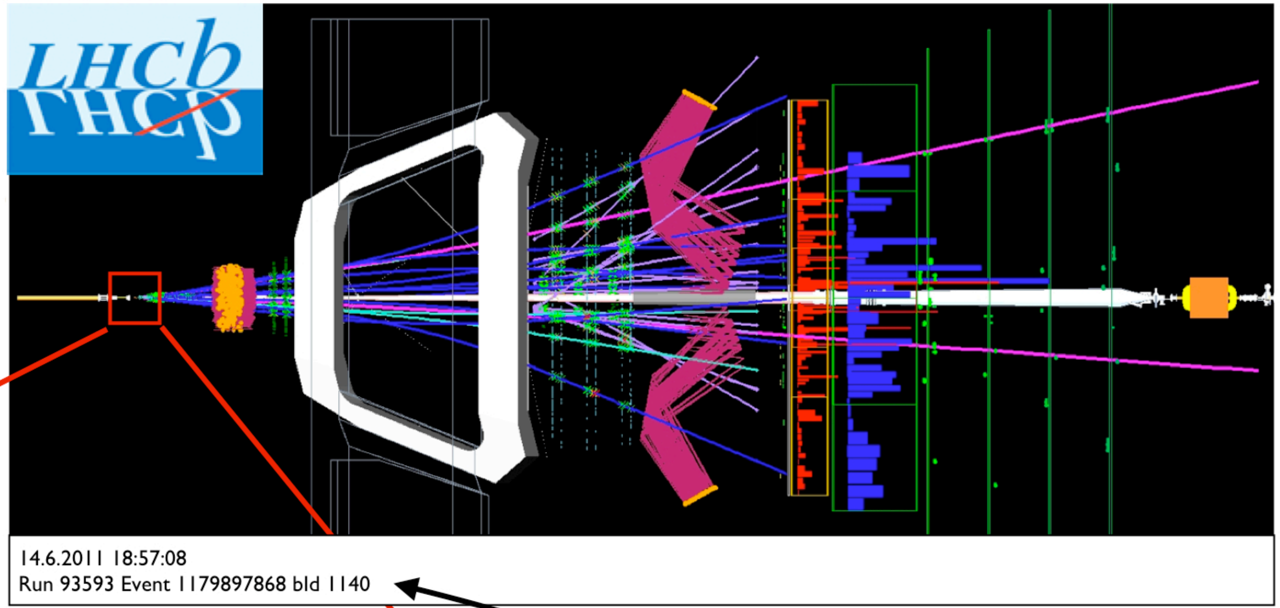


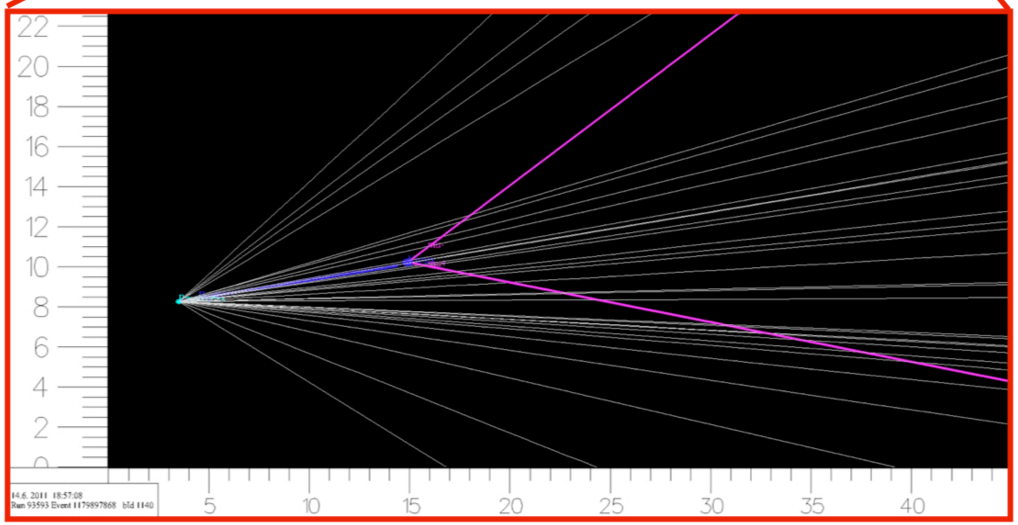
CMS: $B_s \rightarrow \mu\mu$?

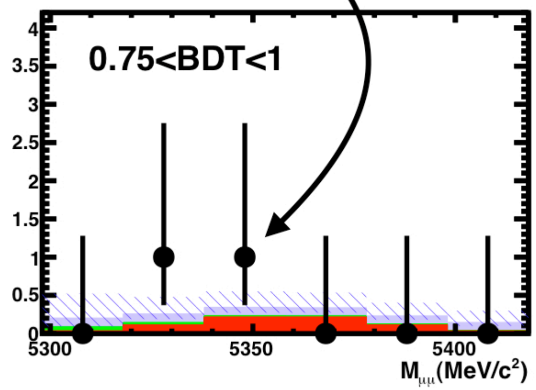


LHCb $B_s \to \mu^+\mu^-$?

$m_{\mu\mu} = 5.357$ GeV
BDT = 0.90
Decay length = 11.5 mm
Tracks shown for $p_T > 0.5$ GeV







13

CMS+LHCb $B \to \mu^+\mu^-$ Combined Limit

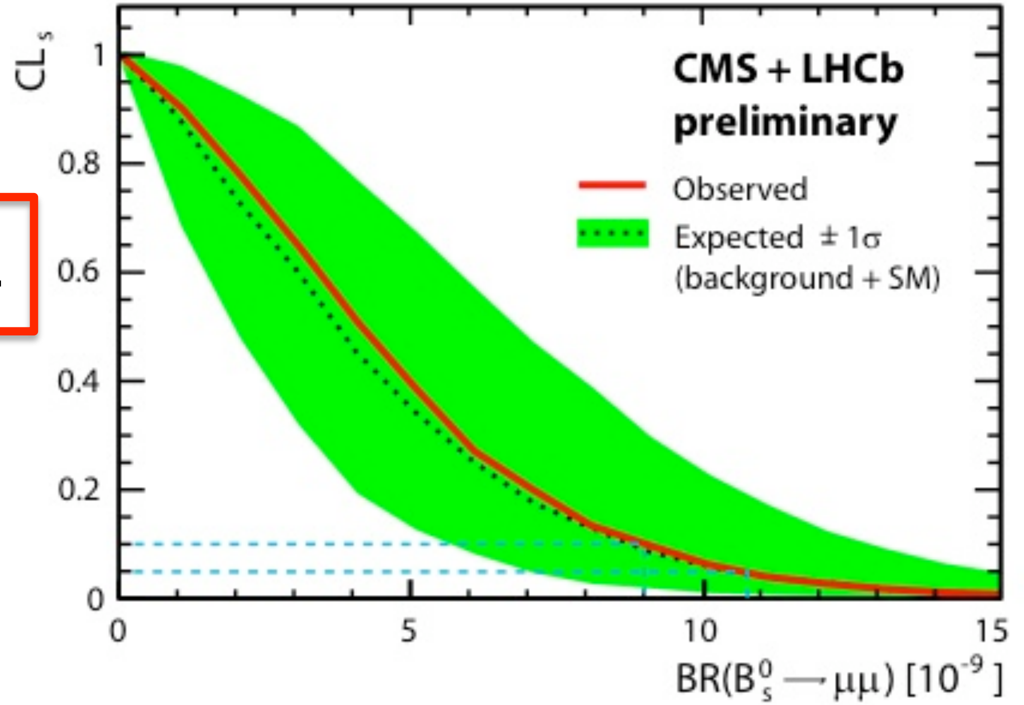
LHCb-CONF-2011-047
CMS PAS BPH-11-019

A preliminary CMS-LHCb combination on $B(B_s \to \mu^+\mu^-)$ has been performed, again using the CL_S approach, & taking the LHCb value of f_s/f_d as common input.

Observed limit

$B(B_s \to \mu^+\mu^-) < 1.08 \times 10^{-8}$ 95% C.L.

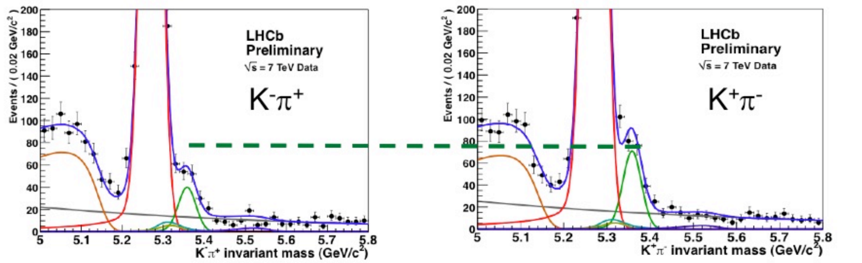
A BR of 1.8×10^{-8} has a CL_S value of ~0.3%

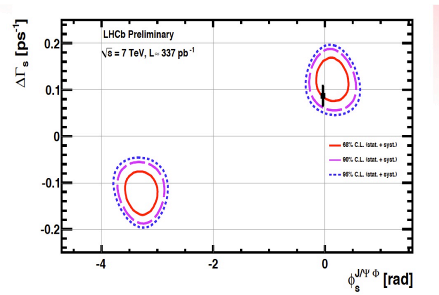


The 95% C.L. limit is still 3.4 times the expected SM value, still plenty of room for New Physics….

Summary

- Flavour physics @ LHC has evolved very quickly in the last 18 months
  - From start of data-taking…
  - … to initial observations of
    well-known modes….
  - … to benchmark measurements.

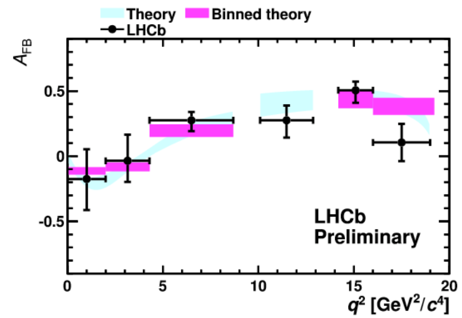




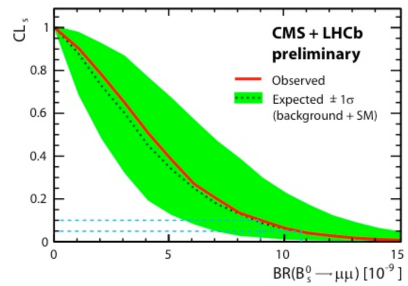
- No signs of New Physics yet…

- … but we have only just started and there is a lot to do.

- In particular, LHCb is expects 1 fb^{-1} by end of 2011 and 5fb^{-1} by 2017, followed by an upgrade to collect 5fb^{-1} per year



Flavour physics is now at the forefront of a new era of discoveries (?) and precision measurements



Exciting times ahead !


Thank you

Questions?

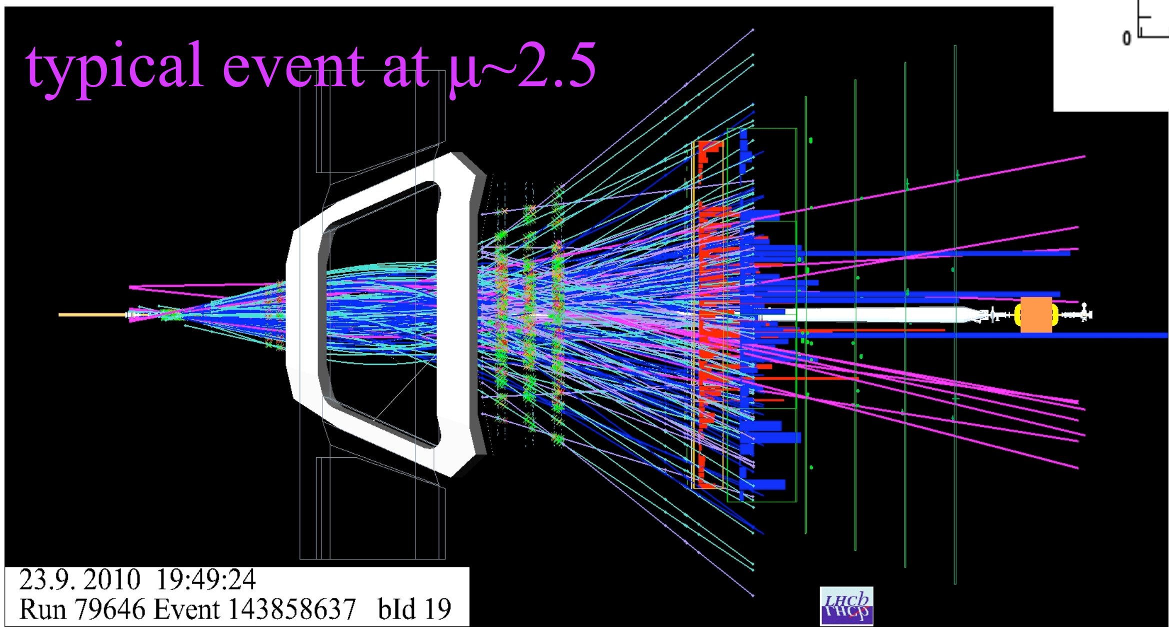
High multiplicity events

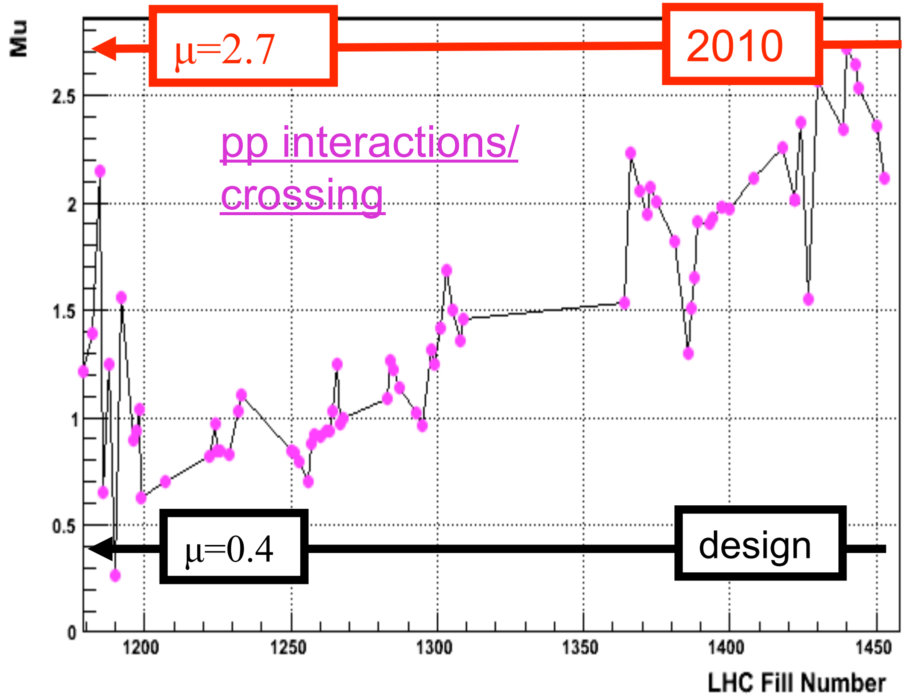
A big challenge for the detector operation, trigger, reconstruction and analysis.

High track multiplicity and many vertices.

Design : L=2x10^{32} cm^{-2} s^{-1},
n_b=2600, <μ>~0.4

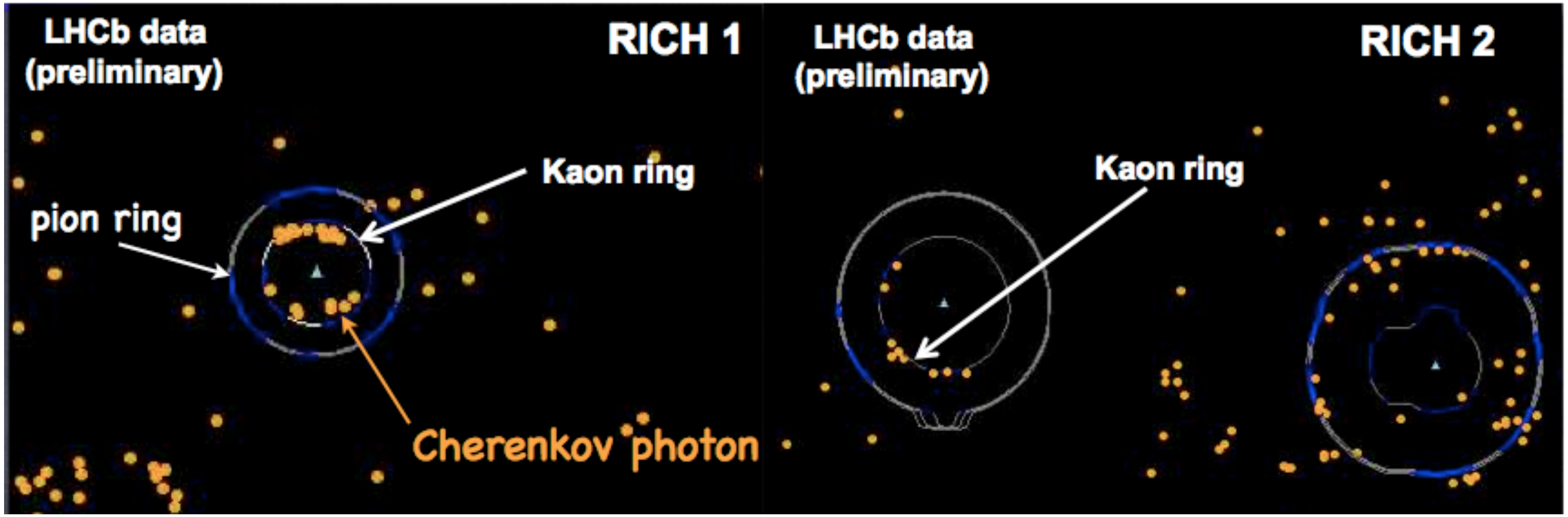
2010 : L=1.6x10^{32} cm^{-2} s^{-1},
n_b=344, μ_{max}=2.7 (6x expected!)

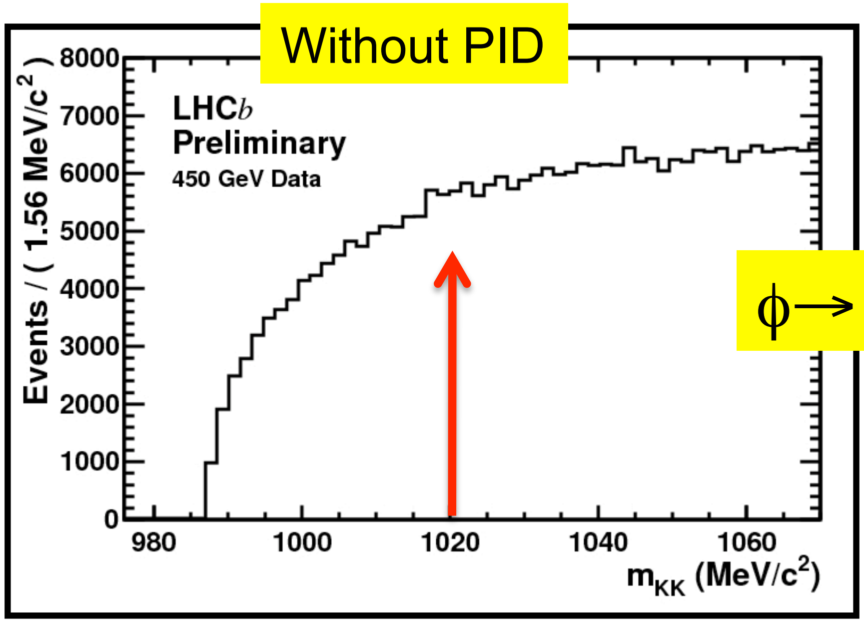




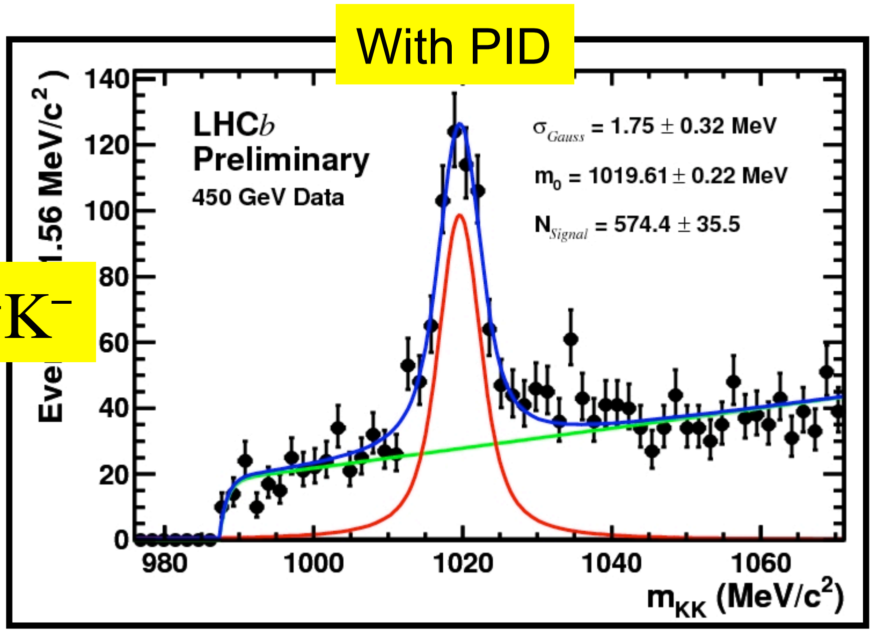
Also very useful to gauge LHCb upgrade performance

LHCb Particle Identification





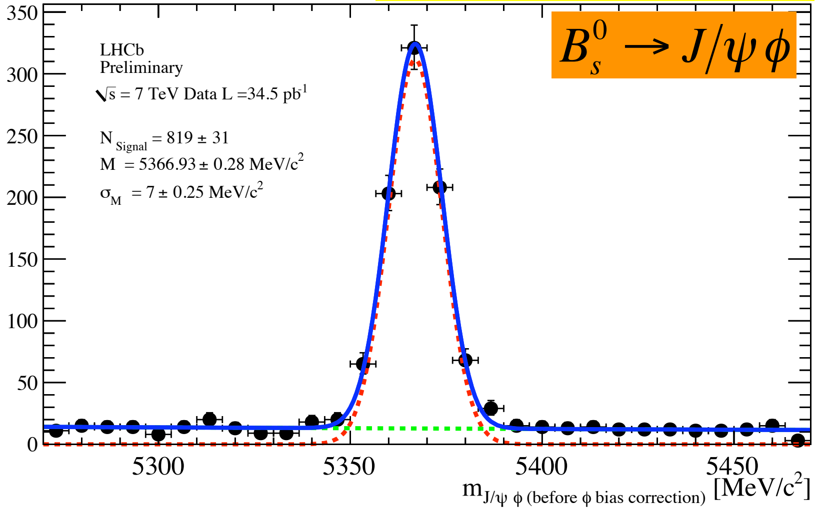
$\phi \to K^+K^-$



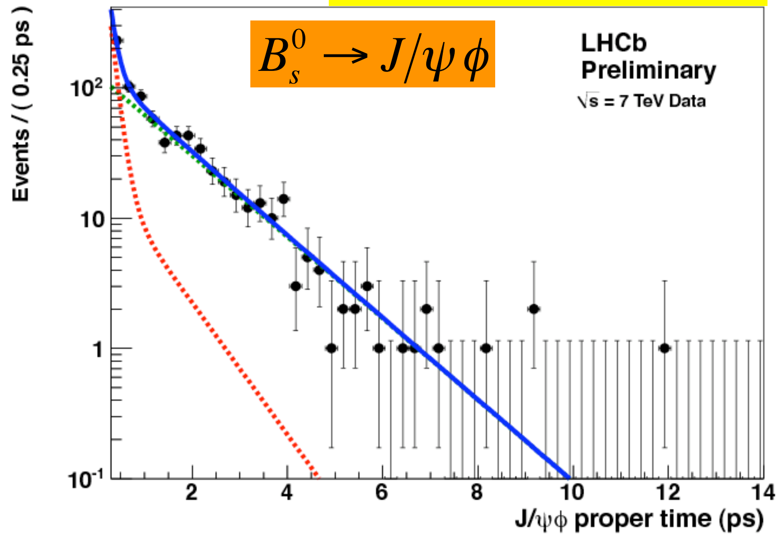
B Mass and Lifetime

LHCb has excellent mass resolution (6-10 MeV/c^2) and proper time resolution (~50 fs)

LHCb-CONF-2011-027



LHCb-CONF-2011-001

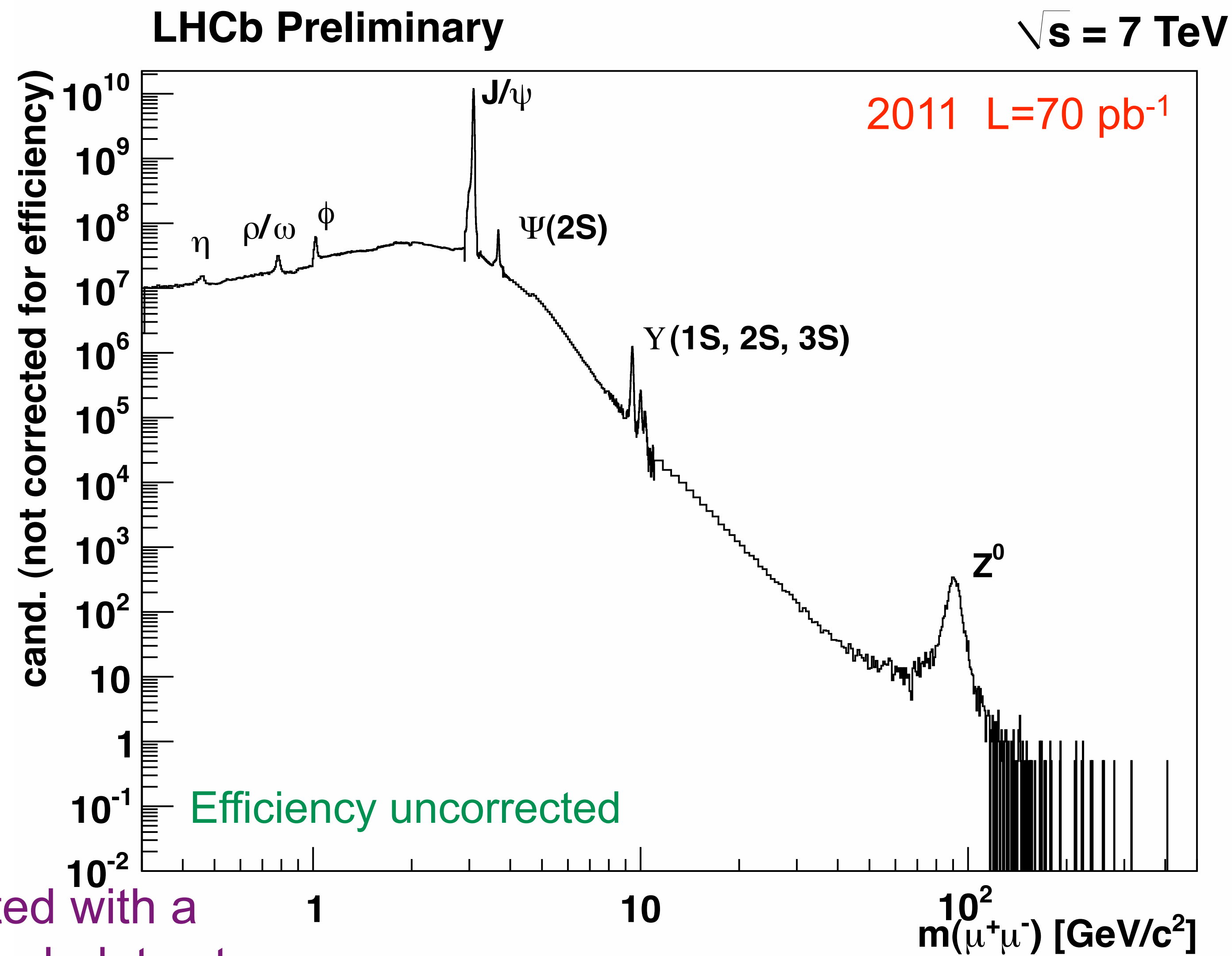


Channel	LHCb Mass, stat and sys (MeV/c^2)	PDG (MeV/c^2)
$B^+ \to J/\psi K^+$	5279.27 ± 0.11 ± 0.19	5279.17 ± 0.29
$B^0 \to J/\psi K^{*0}$ $B^0 \to J/\psi K_s$	5279.54 ± 0.15 ± 0.15 5279.61 ± 0.29 ± 0.20	5279.50 ± 0.30
$B_s \to J/\psi\phi$	5366.60 ± 0.28 ± 0.20	5366.3 ± 0.60
$\Lambda_b \to J/\psi\Lambda$	5619.48 ± 0.70 ± 0.19	5620.2 ± 1.6
$B_c \to J/\psi\pi^+$	6268.0 ± 4.0 ± 0.5	6277 ± 6

Worlds best B mass measurements! (except B_c)

Production

$\mu^+\mu^-$ mass spectrum demonstrates the excellent LHCb performance



Data collected with a neural network data stream

Exotic states

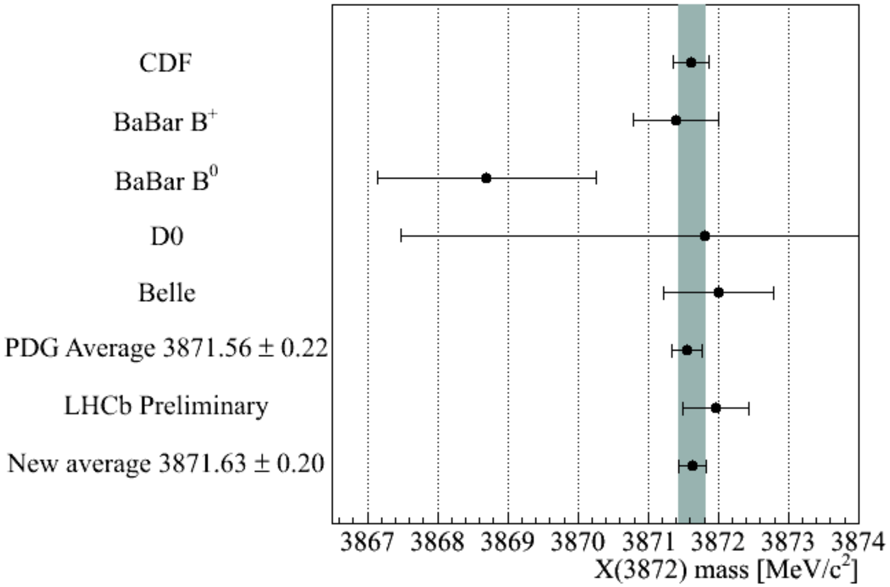
X(3872) discovered in 2003 by Belle in X(3872) $\rightarrow J/\psi\pi^+\pi^-$ decays.

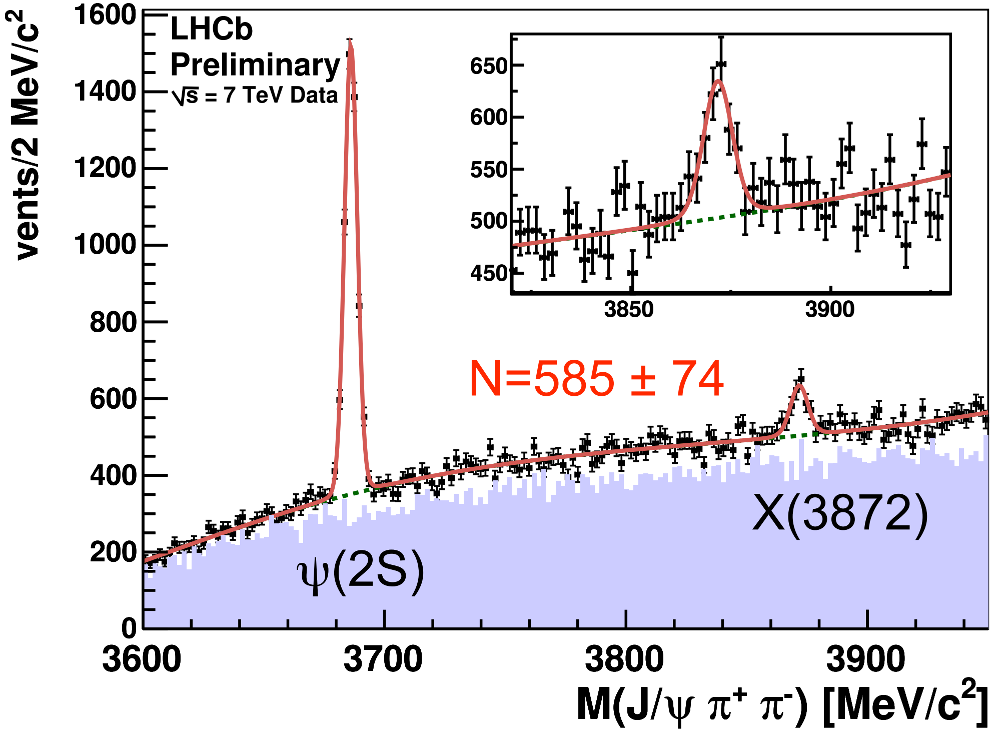
Since then observed in 4 experiments

LHCb-CONF-2011-030

Nature still unclear

- tetraquark ?
- Bound DD^* molecule?
- η_{c2}(1D) charmonium state?





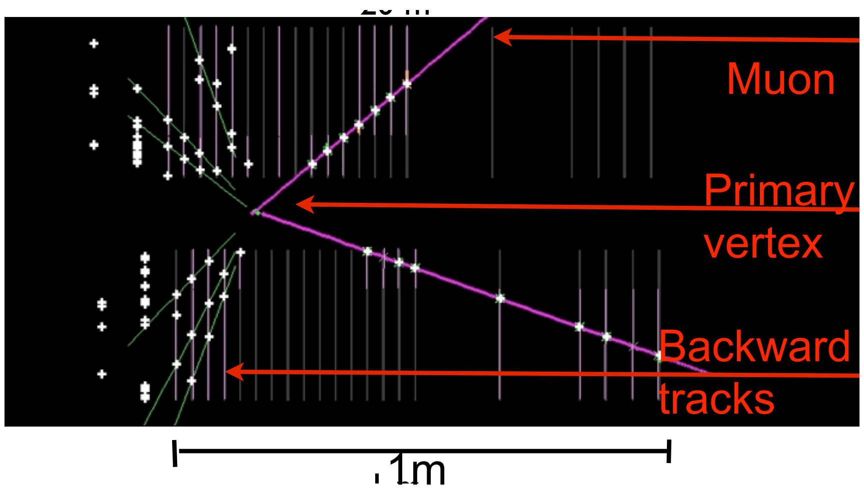
$$M_{X(3872)} = 3871.96 \pm 0.46\,(stat) \pm 0.10\,(syst)\ \mathrm{MeV}/c^2$$

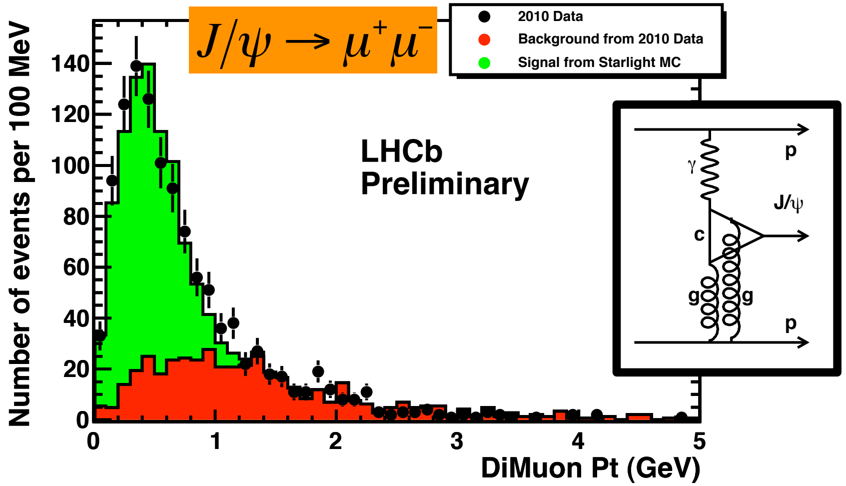
±0.14(stat) with 500 pb^{-1}

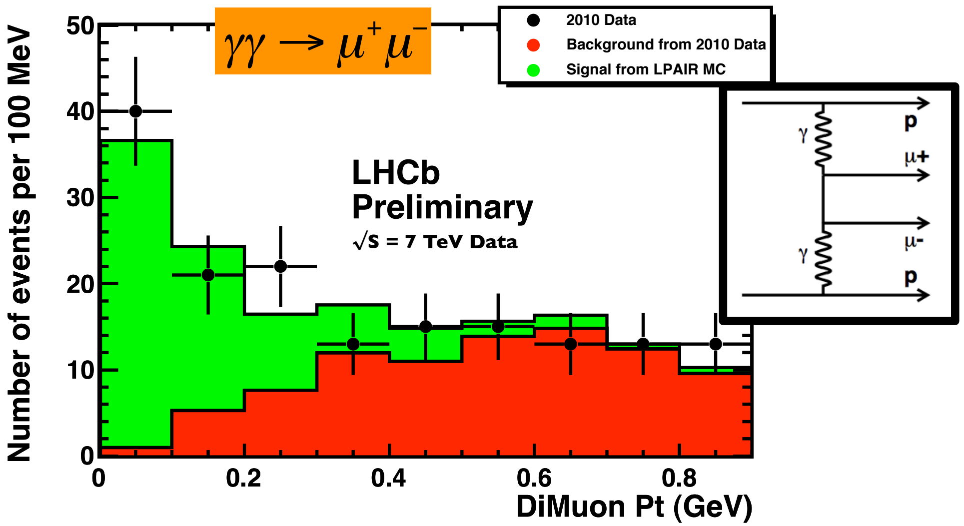
Central Exclusive Production

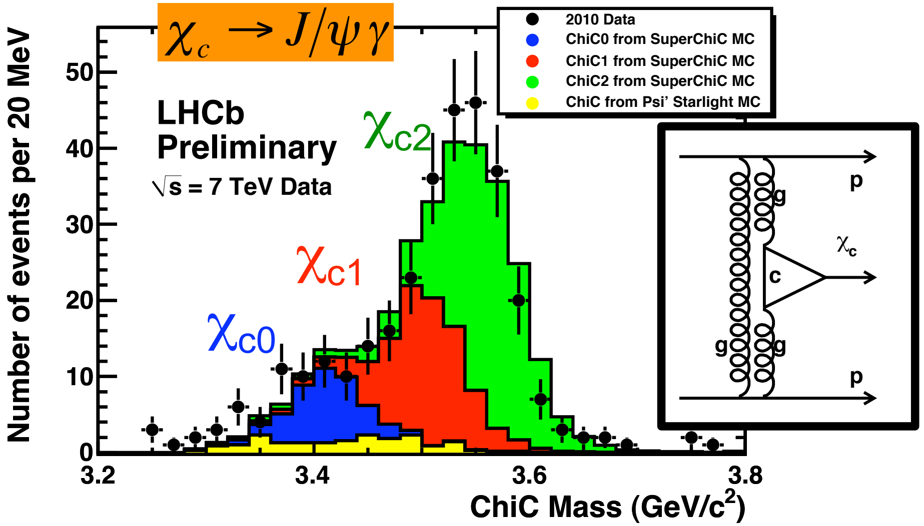
LHCb observes low-multiplicity events with large rapidity gaps.

Exclusive events have no backward tracks and only 2μ (+1γ) in forward region.









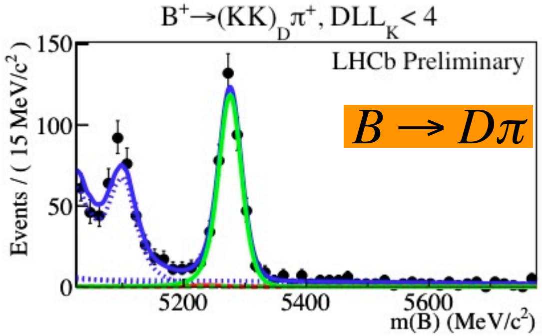
LHCb-CONF-2011-031

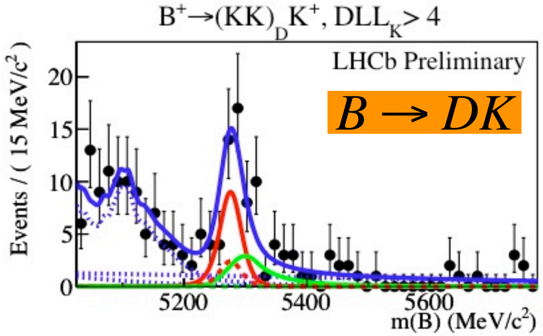
The first step to a measurement of γ

Measurement of $R^{K/\pi} = B(B^\pm \to DK^\pm) / B(B^\pm \to D\pi^\pm)$

$L = 35.6\ pb^{-1}$

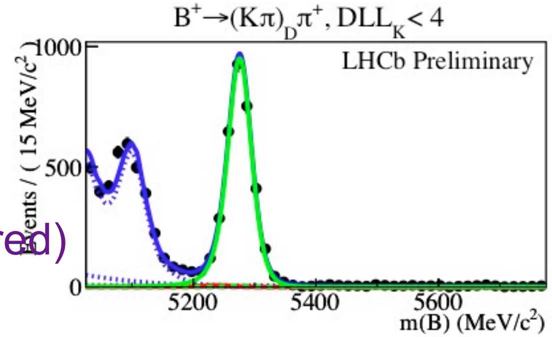
GLW

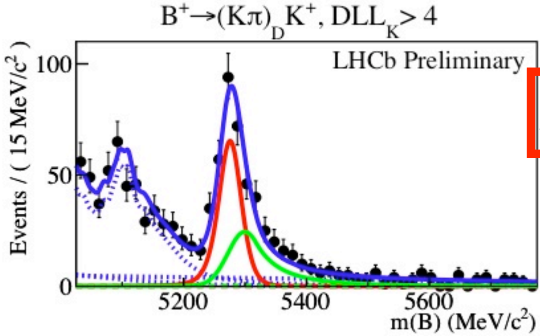




$$R_{CP+}^{K/\pi} = (9.31 \pm 1.89 \pm 0.53)\%$$

ADS (favoured)

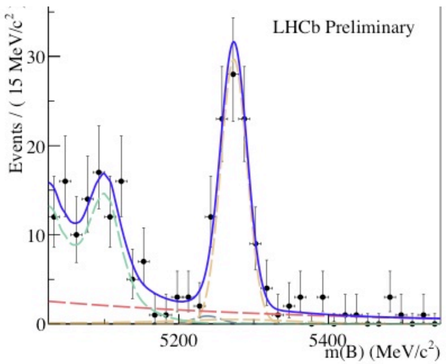


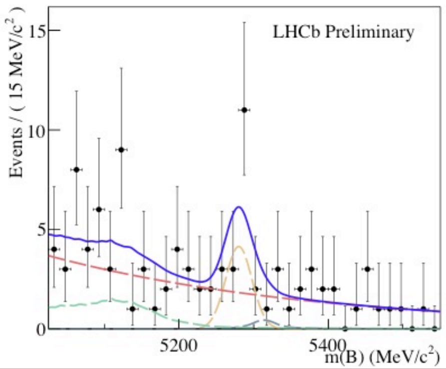


$$R_{CF}^{K/\pi} = (6.30 \pm 0.38 \pm 0.40)\%$$

includes $D^0 \to K^-\pi^+\pi^-\pi^+$

GGSZ





$$R_{K_s\pi\pi}^{K/\pi} = (12^{+6}_{-5} \pm 1)\%$$

First γ sensitive measurements

$$R_{CP+} = 1.48 \pm 0.31 \pm 0.12$$

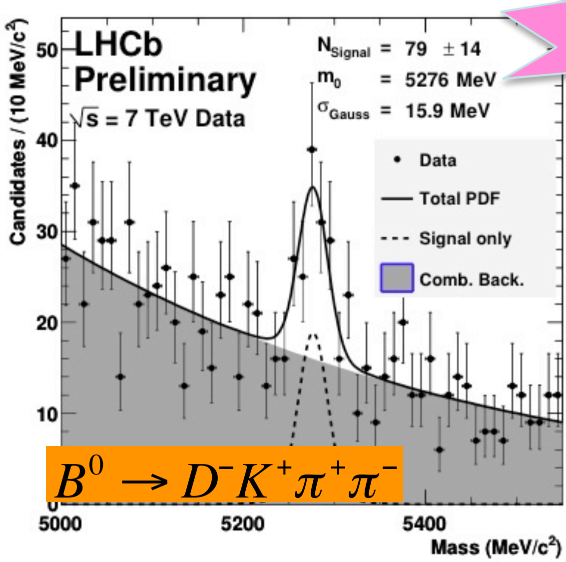
$$A_{CP+} = 0.07 \pm 0.18 \pm 0.07$$

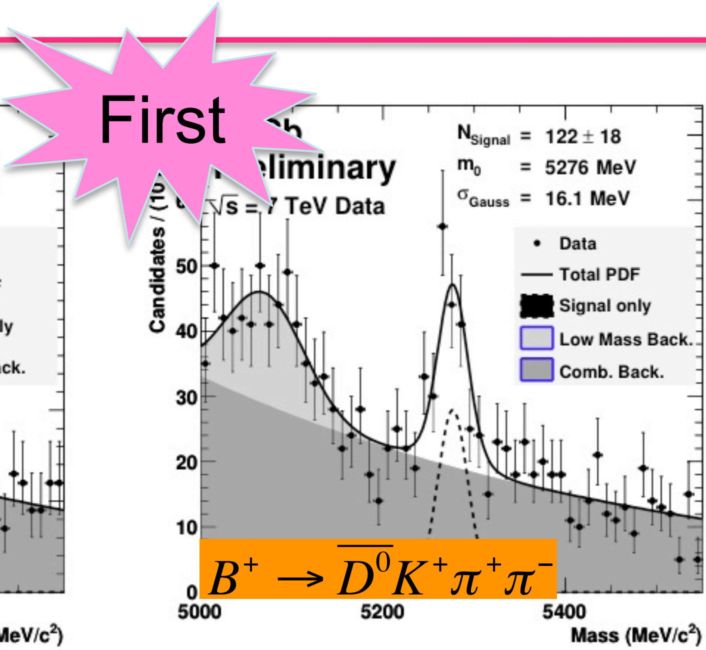
CP angle γ

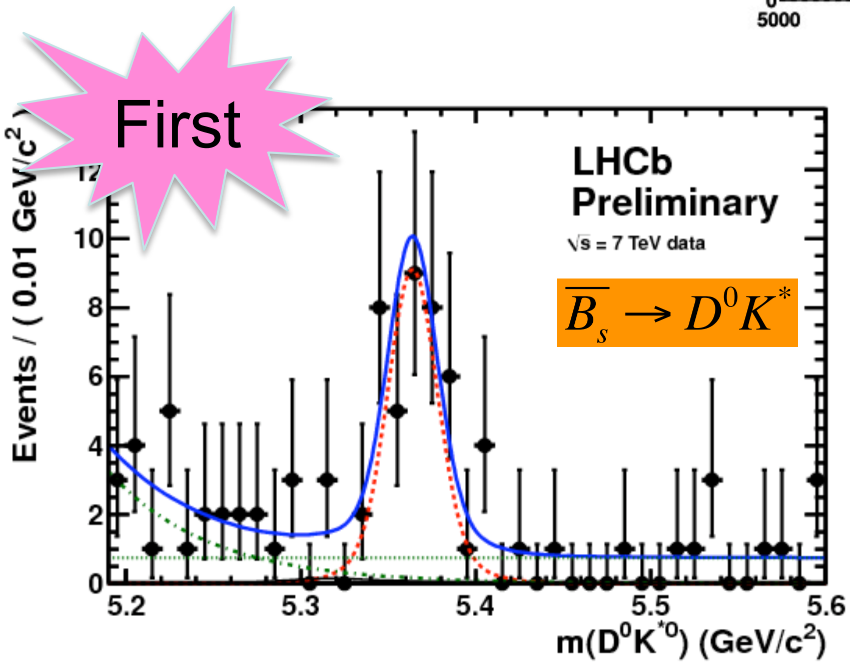
The CS decay $B^{\pm} \to D^0 K^{\pm} \pi^+ \pi^-$ can also be used to determine γ.

First observation

LHCb-CONF-2011-024







$\overline{B}_s \to D^0 K^*$ decays may be a potentially dangerous background for the measurement of γ.

First observation

LHCb-CONF-2011-008

B_s CP Phase

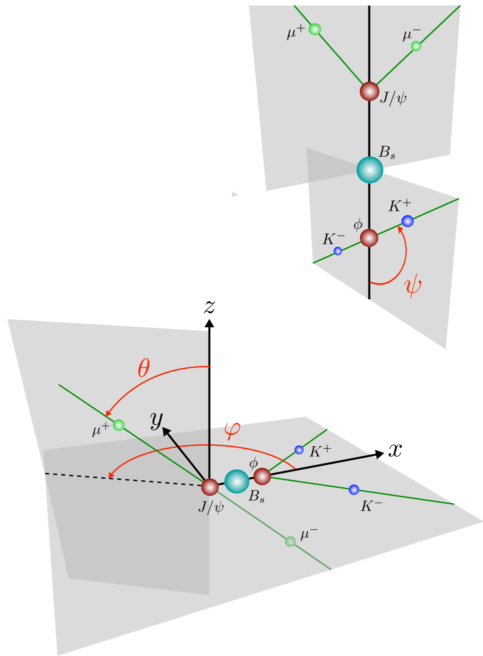
The measurement of ϕ_s is non-trivial.

- $B_s \rightarrow J/\Psi\phi$ admixture of CP even/odd eigenstates

  3 polarization amplitudes $A_\perp$ $CP\ odd\ \ell = 1$

  $A_0, A_\parallel$ $CP\ even\ \ell = 0, 2$

  3 transversity angles $\Omega = \{\vartheta, \varphi, \psi\}$



- Signal event distribution

Acceptance   Flavour tagging   Proper time resolution

$$S(\lambda, t, \Omega) = \varepsilon(t, \Omega) \times \left[\frac{1 + qD}{2} \cdot s(\lambda, t, \Omega) + \frac{1 - qD}{2} \cdot \bar{s}(\lambda, t, \Omega) \right] \otimes R_t$$

Physics parameters $\lambda = \left(\Gamma_s, \Delta\Gamma_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp, \phi_s, \Delta m_s \right)$

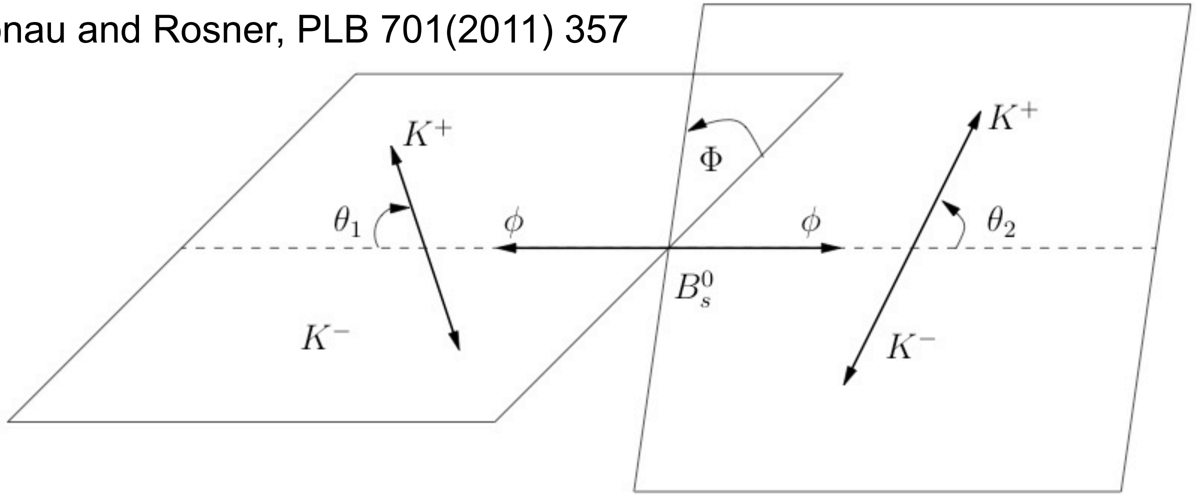
Constraint $\Delta m_s = 17.77 \pm 0.12\ \text{ps}^{-1}$

CPV in B_s Penguins: $B_s \to \phi\phi$

A powerful tool for demonstrating CP violation

→ triple product asymmetries (T violation)

Gronau and Rosner, PLB 701(2011) 357



$$\frac{d^4\Gamma}{dt d\Omega} \propto |A_0(t)|^2 \cdot f_1(\Omega) + |A_\parallel(t)|^2 \cdot f_2(\Omega) + |A_\perp(t)|^2 \cdot f_3(\Omega) + \Im(A_\parallel^*(t)A_\perp(t)) \cdot f_4(\Omega) + \Re(A_0^*(t)A_\parallel(t)) \cdot f_5(\Omega) + \Im(A_0^*(t)A_\perp(t)) \cdot f_6(\Omega),$$

$$\Omega = (\theta_1, \theta_2, \Phi)$$

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→ triple product asymmetries (T violation)

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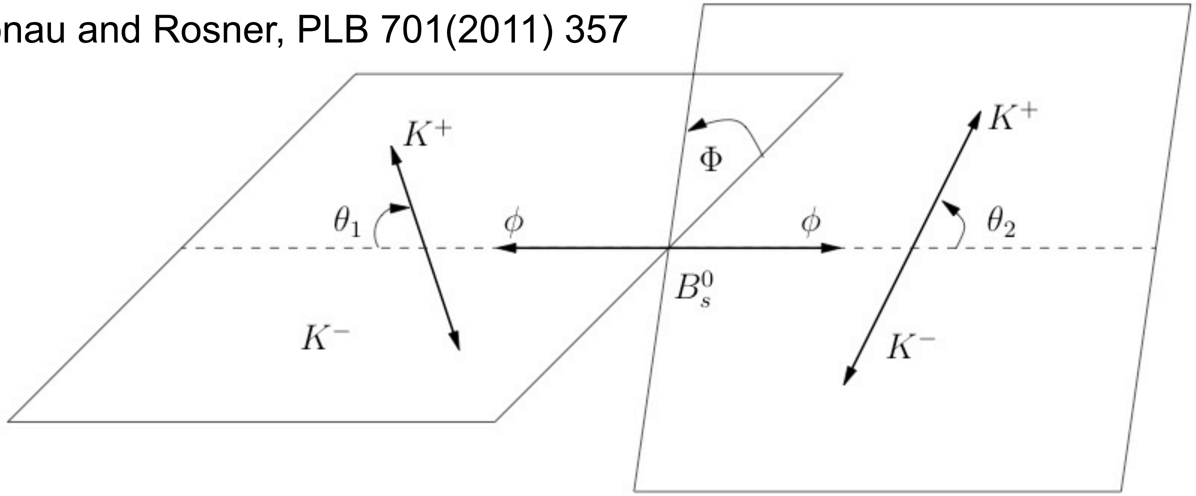

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$$\Omega = (\theta_1, \theta_2, \Phi)$$

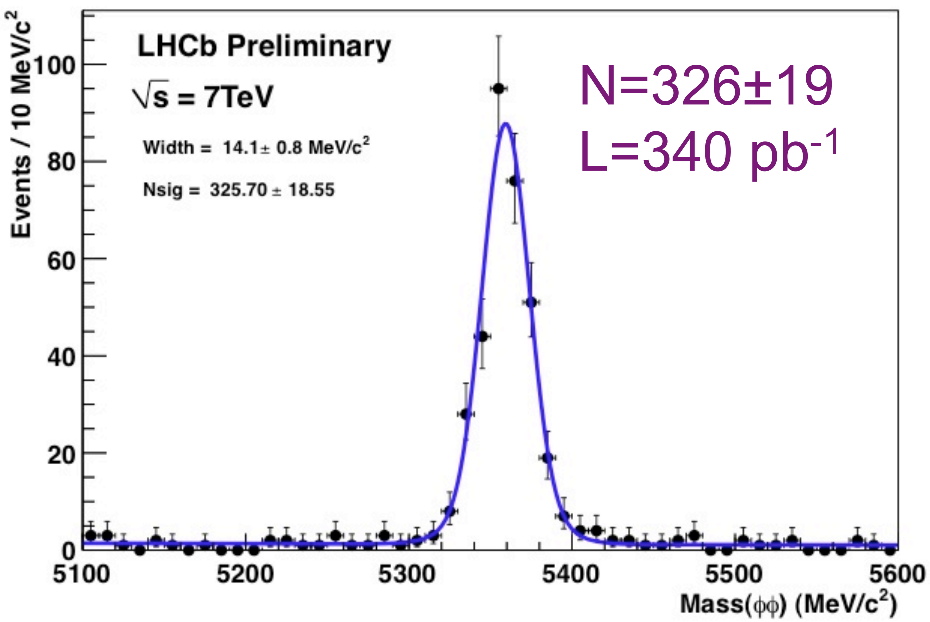
Two observable triple products:

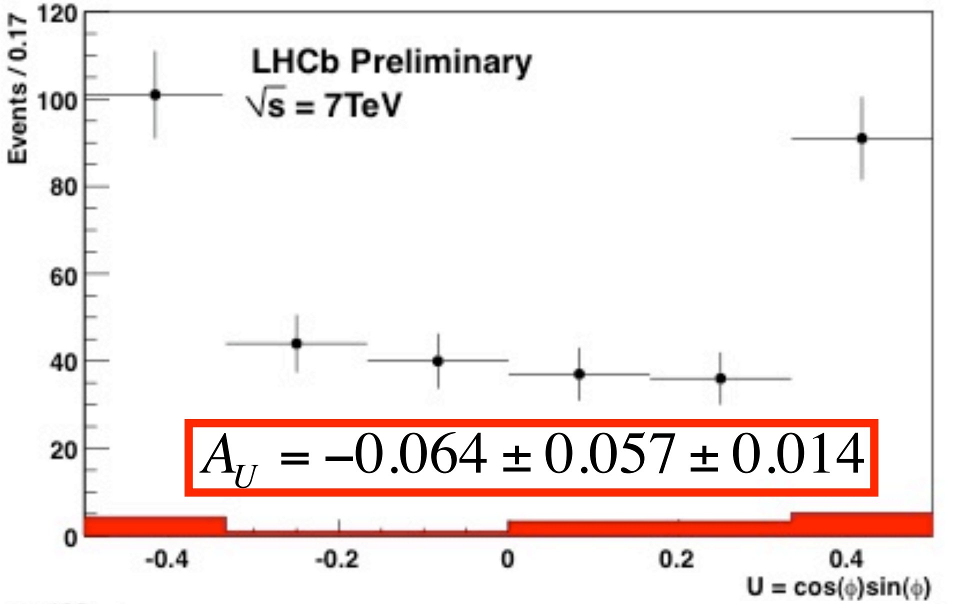
$$U = \sin 2\Phi$$

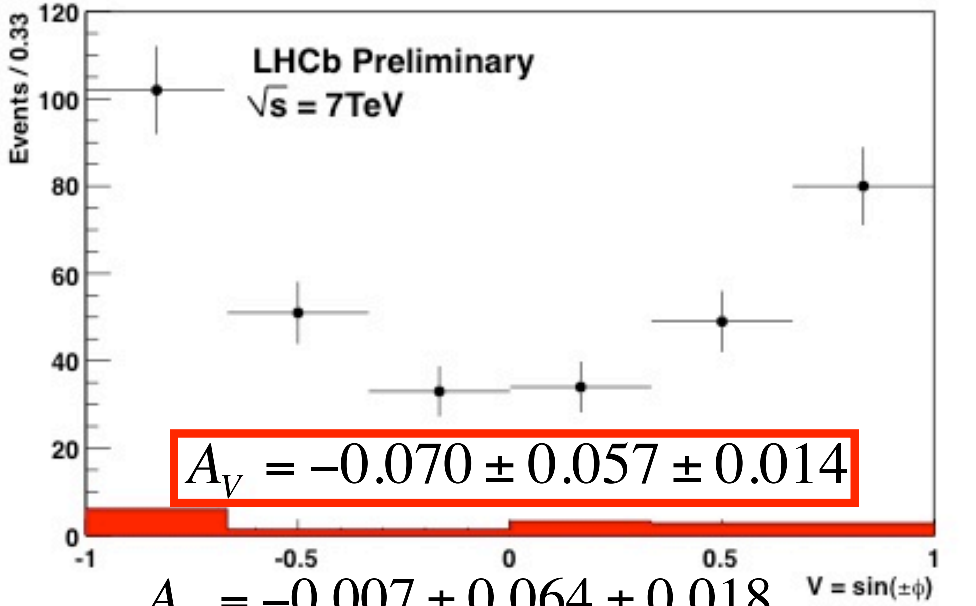
$$V = \sin(\pm\Phi)$$

Asymmetries $A_U, A_V \neq 0$: CP Violation, due to difference in weak phase for CP even/odd amplitudes → clear sign of NP

CPV in B_s Penguins: $B_s \to \phi\phi$







Measure A_U, A_V near ϕ mass

Result consistent with 0 and CDF (both fluctuating to negative values)

Next: perform full angular analysis and add $B_d \to \phi K^*$

CDF: arXiv:1107.4999

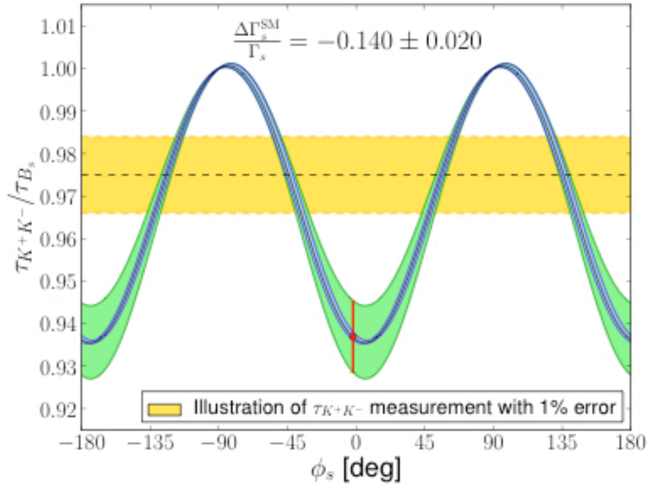
$$A_U = -0.007 \pm 0.064 \pm 0.018$$
$$A_V = -0.120 \pm 0.064 \pm 0.016$$

$B_s \to K^+K^-$ Lifetime

Decay width difference between the heavy and light B_s states is sensitive to New Physics

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = \Delta\Gamma_s^{SM} \cos\phi_s$$

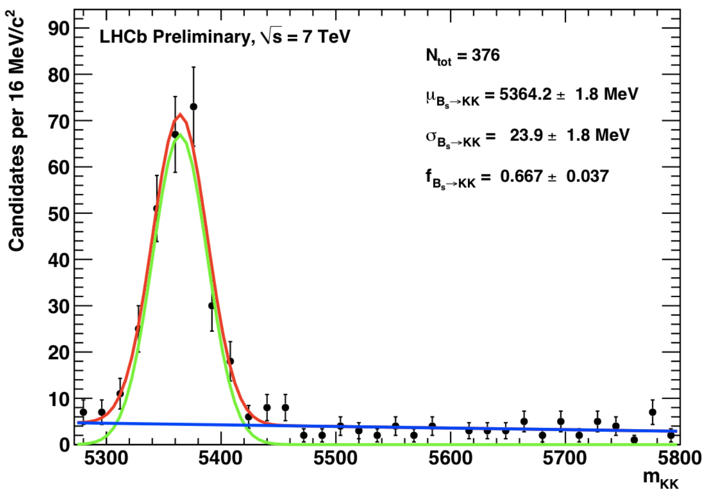
A single exponential fit to the B_s proper time distribution gives an effective lifetime measurement; B_s is almost a pure light state.

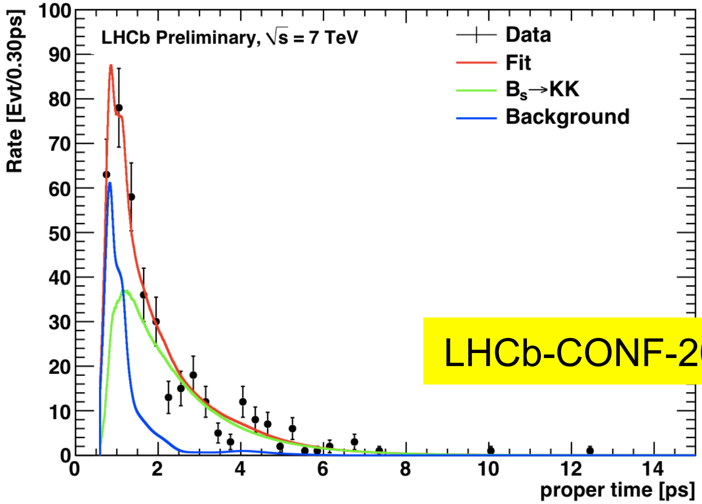


R.Fleischer, R.Knegjens, arXiv:1011.1096

With ~250 signal events, world's best measurement

$$\tau\left(B_s \to K^+K^-\right) = 1.440 \pm 0.096 \pm 0.010 \quad \text{ps}$$

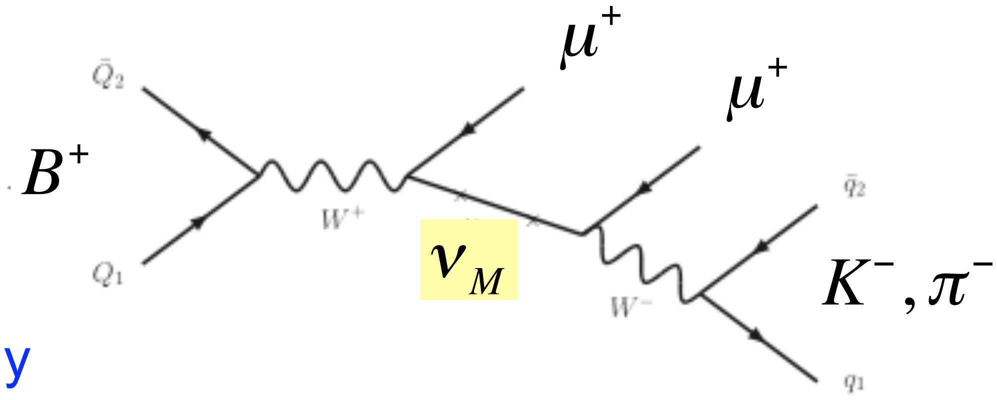




LHCb-CONF-2011-018

Lepton Flavour Violation

Search for $B^+ \to K^- \mu^+ \mu^+$ and $B^+ \to \pi^- \mu^+ \mu^+$



- $\Delta L=2$ tranistion, strictly forbidden in the Standard Model
- Sterile Majorana neutrinos of mass $O(1\ \mathrm{GeV}/c^2)$ enhance Br significantly

Observation

- < 0.3 (0.1) background events expected in $\pi^- \mu^+ \mu^+$ ($K^- \mu^+ \mu^+$) mode
- Zero events observed in both signal regions and sidebands

$$B(B^+ \to K^- \mu^+ \mu^+) < 4.3 \times 10^{-8}$$
$$B(B^+ \to \pi^- \mu^+ \mu^+) < 4.5 \times 10^{-8}$$

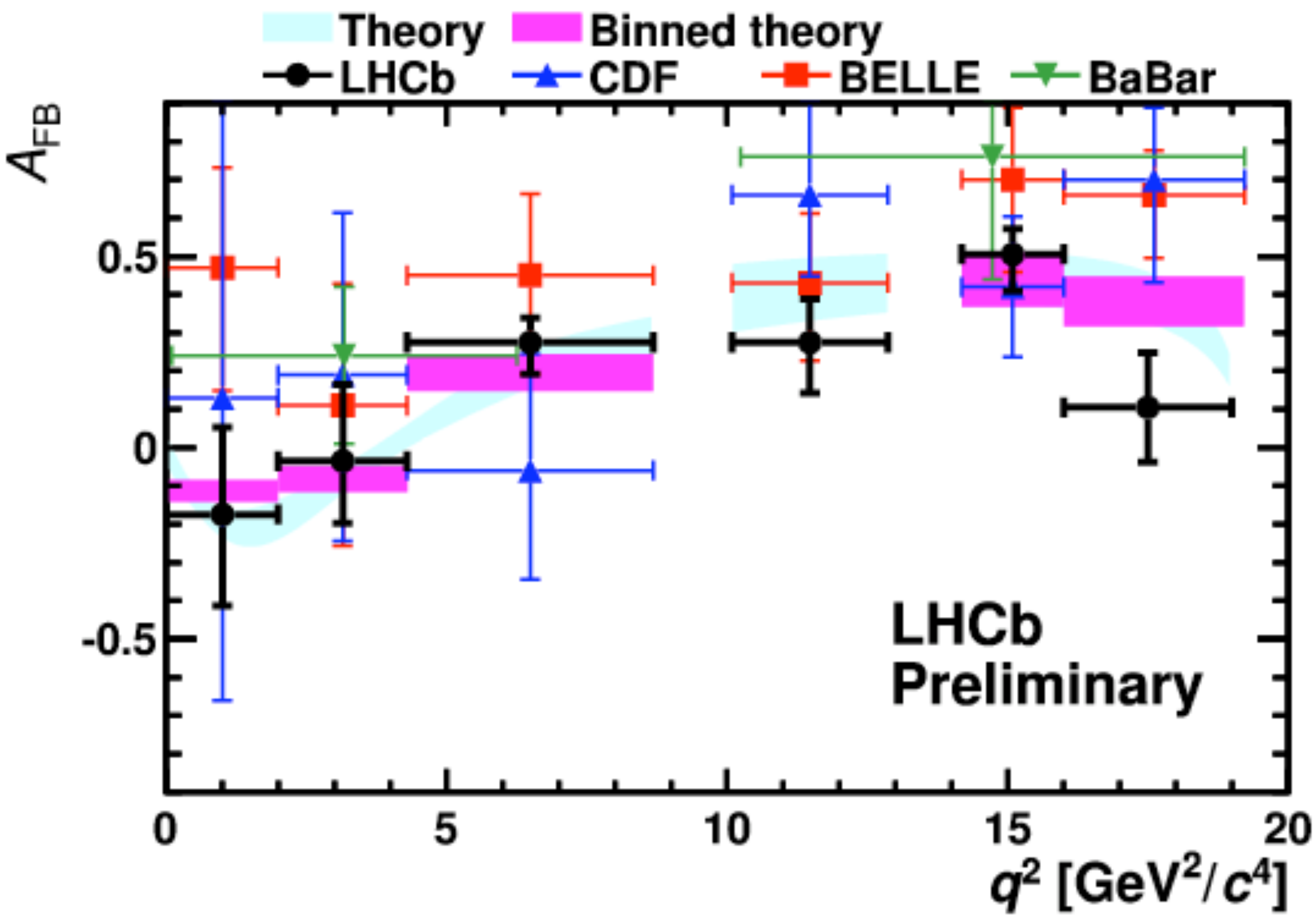
90% CL
L=36 pb^{-1}

Publication in preparation

A factor 40(30) improvement compared to previous best limits (CLEO)!

The limits are currently statistics limited, second publication later in the year.

$B_d \to K^*\mu\mu$ current status



Charge asymmetry A_{SL}

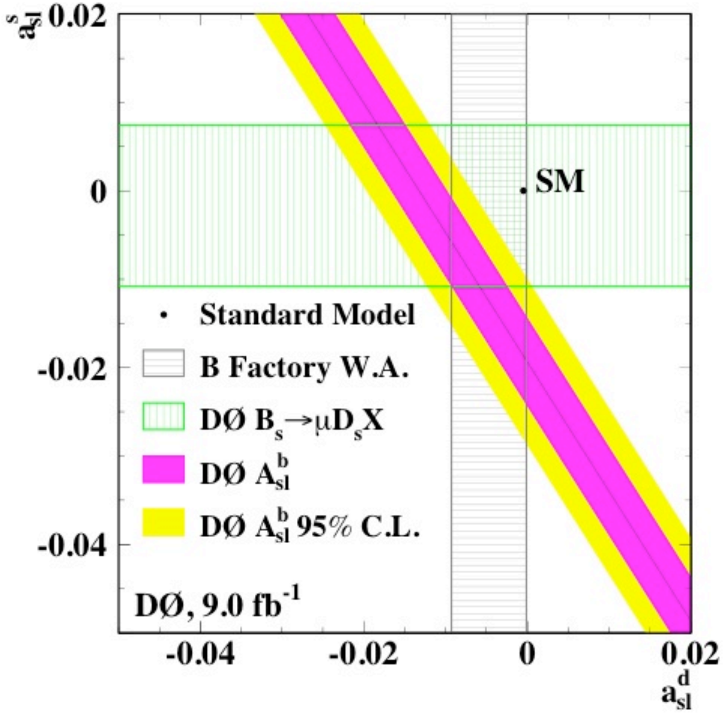
D0 : evidence for an anomalous like-sign dimuon charge asymmetry

D0 Collaboration, arXiv:1106.6308

Measurement of the anomalous like-sign dimuon charge asymmetry with 9 fb^{-1} of $p\bar{p}$ collisions

V.M. Abazov,[35] B. Abbott,[73] B.S. Acharya,[29] M. Adams,[49] T. Adams,[47] G.D. Alexeev,[35] G. Alkhazov,[39] A. Alton[a],[61] G. Alverson,[60] G.A. Alves,[2] M. Aoki,[48] M. Arov,[58] A. Askew,[47] B. Åsman,[41] O. Atramentov,[65] C. Avila,[8] J. BackusMayes,[80] F. Badaud,[13] L. Bagby,[48] B. Baldin,[48] D.V. Bandurin,[47] S. Banerjee,[29] E. Barberis,[60] P. Baringer,[56] J. Barreto,[3] J.F. Bartlett,[48] U. Bassler,[18] V. Bazterra,[49] S. Beale,[6] A. Bean,[56] M. Begalli,[3] M. Begel,[71] C. Belanger-Champagne,[41] L. Bellantoni,[48] S.B. Beri,[27] G. Bernardi,[17] R. Bernhard,[22]

We present an updated measurement of the anomalous like-sign dimuon charge asymmetry $A^b_{\rm sl}$ for semi-leptonic b-hadron decays in 9.0 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy of $\sqrt{s}$ = 1.96 TeV at the Fermilab Tevatron collider. We obtain $A^b_{\rm sl} = (-0.787 \pm 0.172\ ({\rm stat}) \pm 0.093\ ({\rm syst}))\%$. This result differs by 3.9 standard deviations from the prediction of the standard model and provides evidence for anomalously large CP violation in semi-leptonic neutral B decay. The dependence of the asymmetry on the muon impact parameter is consistent with the hypothesis that it originates from semi-leptonic b-hadron decays.



$$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$$

$$A^b_{sl}(SM) = \left(-0.028^{+0.005}_{-0.006}\right)\%$$

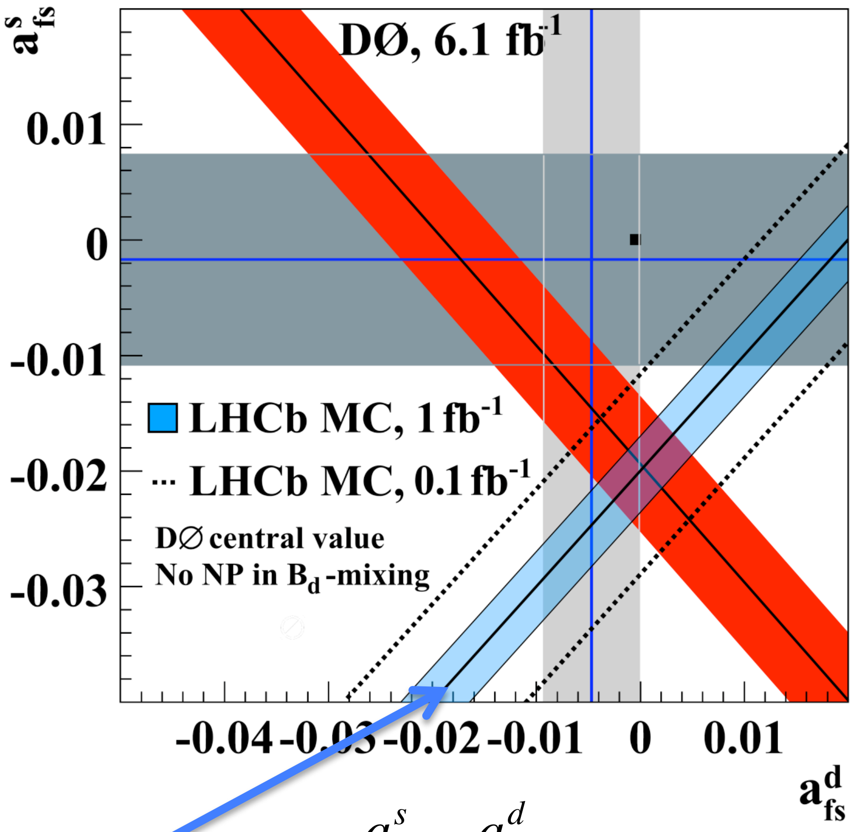
3.9σ

D0 measure $A^{SM}_{sl} \approx \dfrac{a^s_{fs} + a^d_{fs}}{2}$ where $a^q_{fs} = \mathrm{Im}\dfrac{\Gamma^q_{12}}{M^q_{12}}$

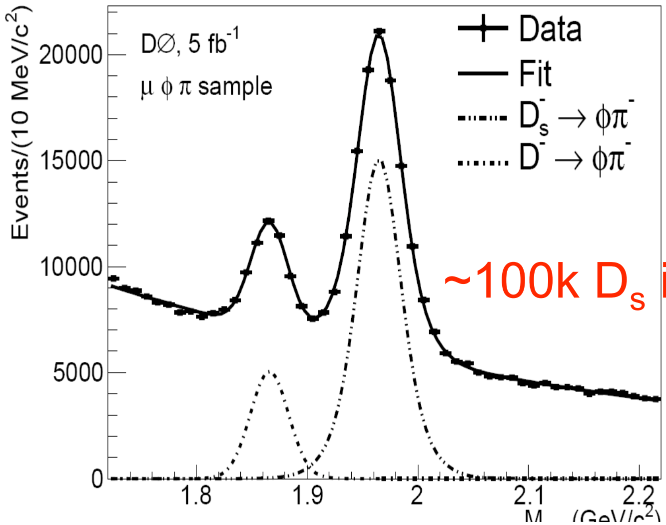
Charge asymmetry A_{SL}

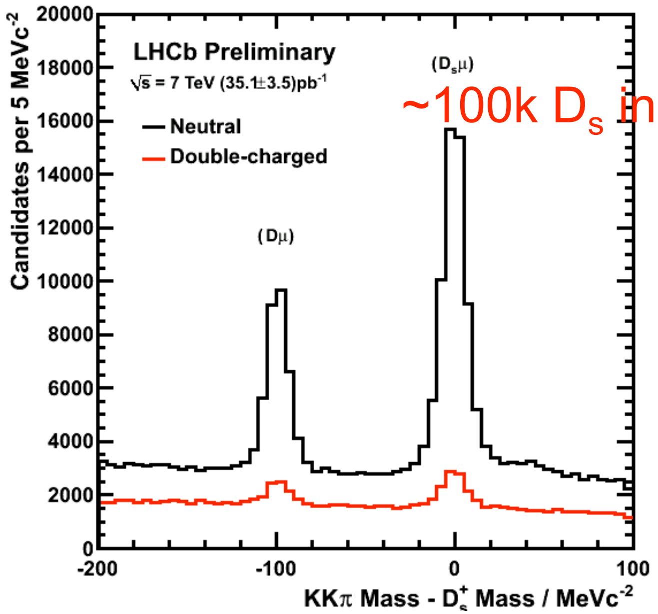
LHCb is catching up with D0 very quickly.

Reconstruct $B_d \to D^{\pm}\mu^{\mp}\nu$ and $B_s \to D_s^{\pm}\mu^{\mp}\nu$



$$\Delta A_{sl}^{b}(SM) \approx \frac{a_{fs}^{s} - a_{fs}^{d}}{2} = (0.021 \pm 0.003)\%$$





LHCb sensitivities

Type	Observable	Current precision	LHCb (5 fb^{-1})	Upgrade (50 fb^{-1})	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7^\circ$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-