# CPV and Flavour

20th September 2010

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# Why Study Flavour Physics?

- BR($B \to X_s \gamma$)

  SM prediction: $E_\gamma > 1.6$ GeV    M. Misiak et al., hep-ph/0609232

  $\mathcal{B}(\bar{B} \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$

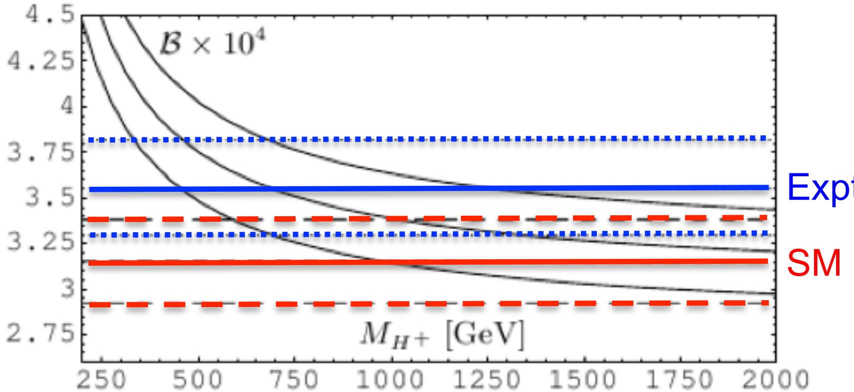
  World average:

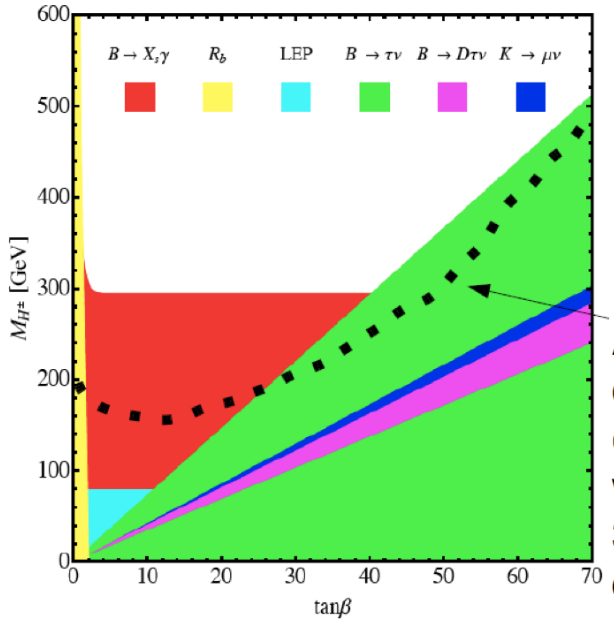
  $B(\bar{B} \to X_s\gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$

  Already gives the best lower limit on the charged Higgs mass:

  $M_{H^+} > 295$ GeV@95%CL

Ciuchini, CKM 2010




ATLAS, 30fb$^{-1}$

- BR($B^+ \to \tau^+\nu$)

- Not channels well suited to the LHC environment

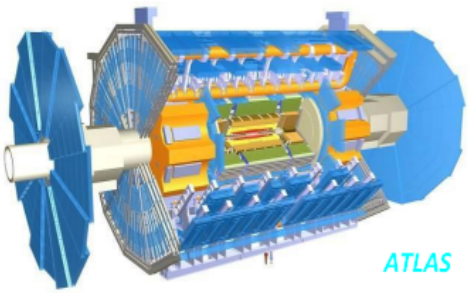
# Outline

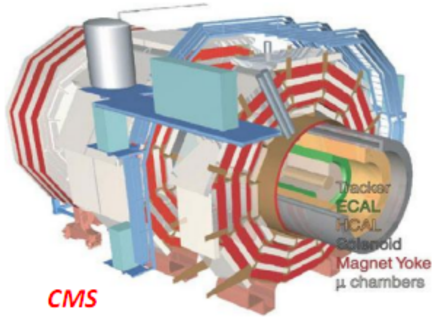
- B physics at the LHC experiments

- Try and focus on a few representative areas where there have been first validation studies:
  - $B_s \rightarrow \mu\mu$
  - $B_d \rightarrow K^* \mu\mu$
  - $B_s \rightarrow J/\psi\phi$

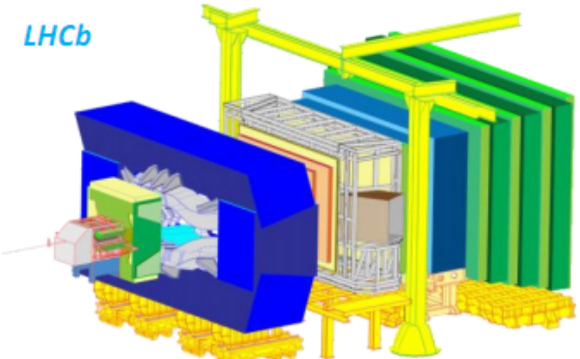
- Will also mention other CPV observables we will see in 2011 and beyond

# B physics at the LHC Experiments

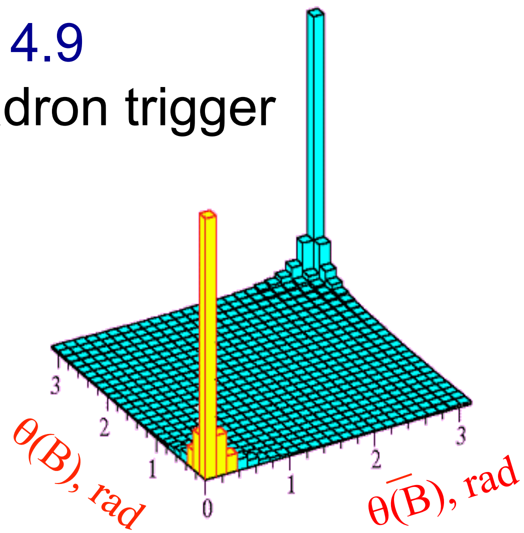



- Central detectors $|\eta|<2.5$
- High $p_T$ muon triggers




- B-physics dedicated experiment
- Forward detector $1.9<\eta< 4.9$
- Low $p_T$ muon triggers, hadron trigger
- Defocus LHC beams




- $b\bar{b}$ pairs are produced correlated and predominately in the forward- or backward-direction

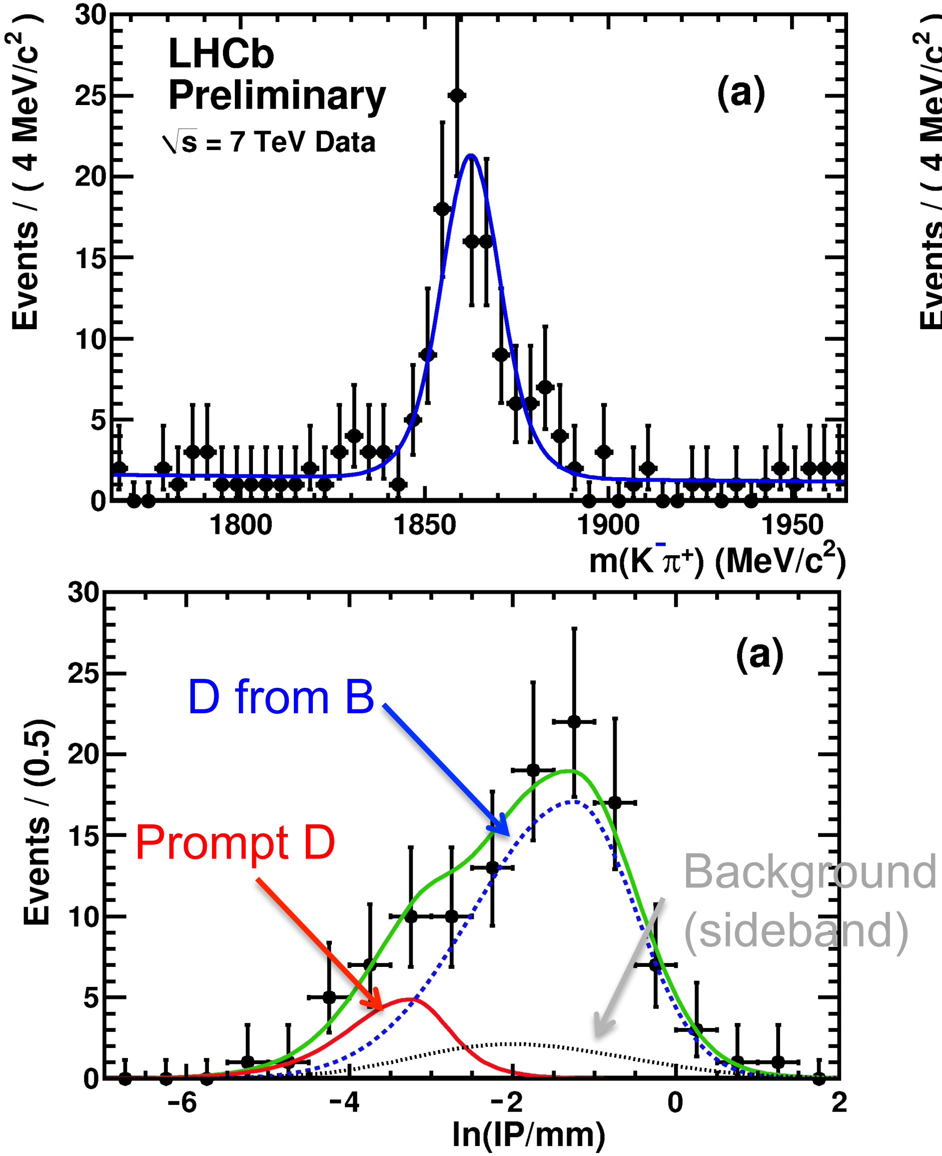
- LHC goal for 2010 to reach $\mathcal{L}$~$10^{32}$ $cm^{-2}s^{-1}$
    - Steady running in 2011 → $1fb^{-1}$
    - ~50% of nominal for LHCb, ~10% for ATLAS/CMS

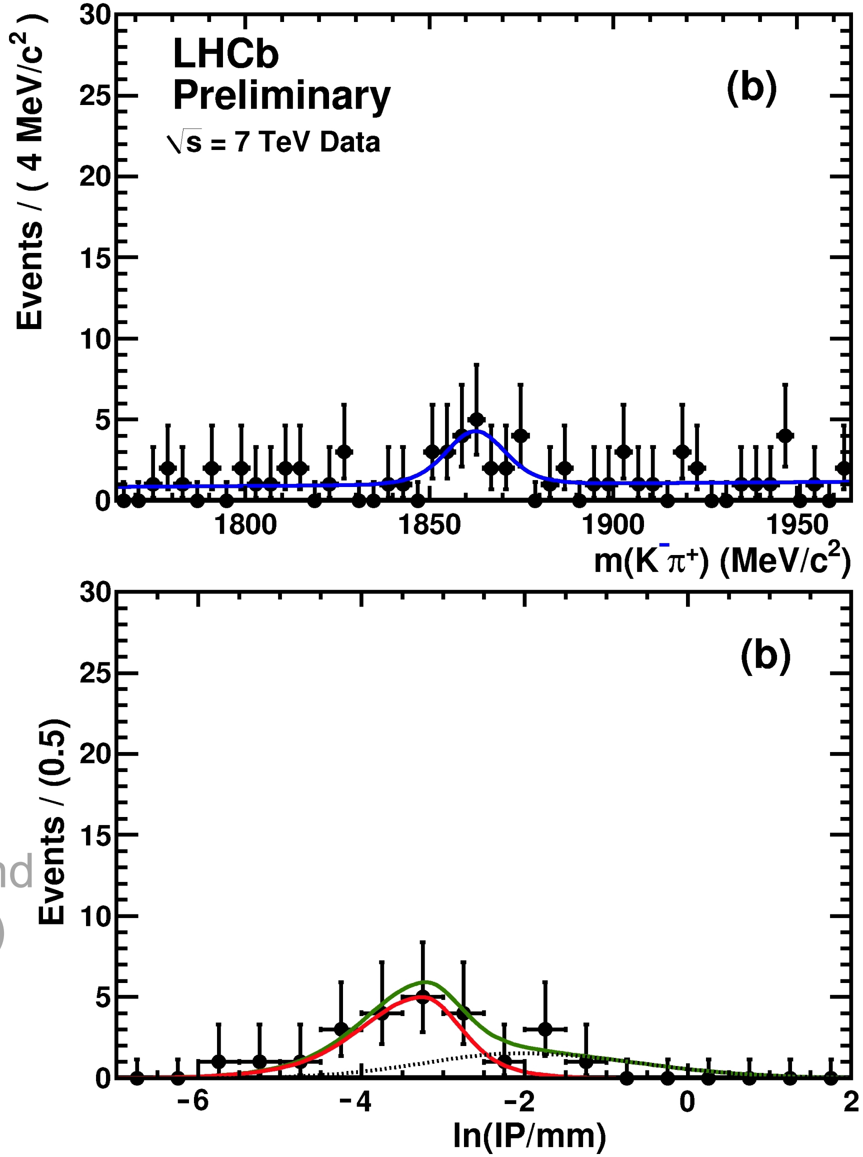
# The b Production Cross Section

- The production cross section is interesting from a QCD point of view
- Also important for normalising expectations for the future
- $\sigma$ ($pp \rightarrow b\bar{b}X$) from $b \rightarrow J/\psi X$ [ATLAS,CMS,LHCb]
- $\sigma$ ($pp \rightarrow b\bar{b}X$) from $b \rightarrow D(K\pi)\mu\nu X$ and $b \rightarrow D^*\mu\nu X$ [LHCb]
  - Find $D^0 \rightarrow K\pi$ decays and look for muon with right sign for semi-leptonic B decay
    - Use wrong sign decays to understand background

## Right sign

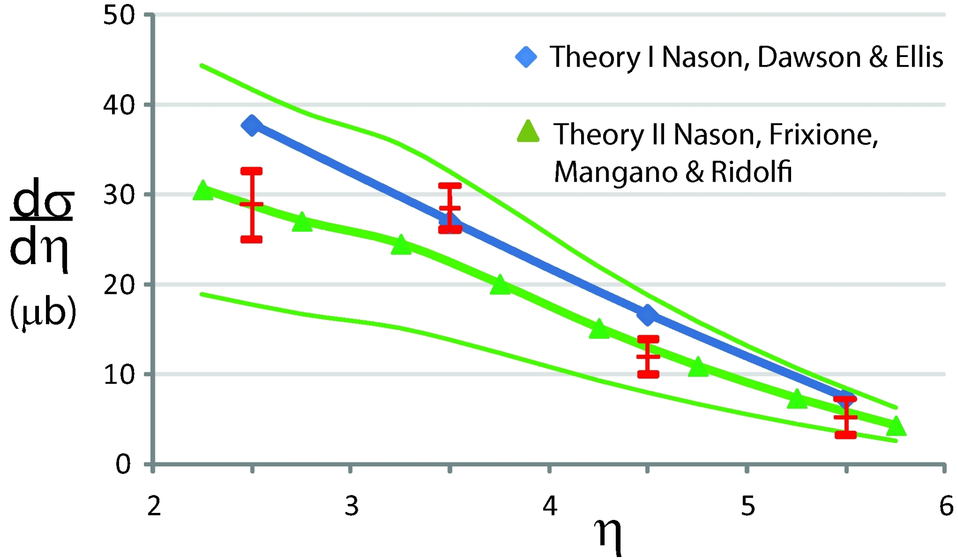
## Wrong sign



# The b Production Cross Section

- Production is measured in bins of pseudorapidity




*The LHCb collaboration, arXiv:1009.2731*

- Find,

  $\sigma(pp \rightarrow H_b\ X;\ 2<\eta<6) = 74.9 \pm 5.3 \pm 12.8\ \mu b$

- Pythia extrapolation to the full phase space gives,
  - $\sigma(pp \rightarrow b\bar{b}) = 292 \pm 15 \pm 43\ \mu b$

  (sensitivity studies previously assumed 250$\mu$b)

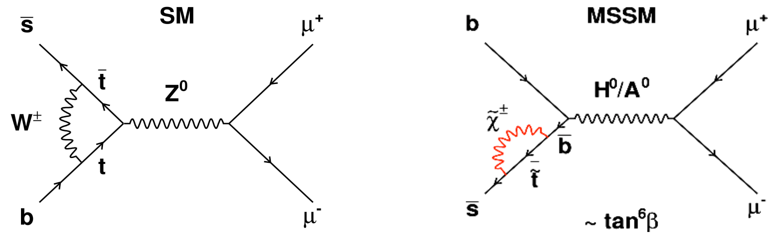
# $B_s \rightarrow \mu\mu$

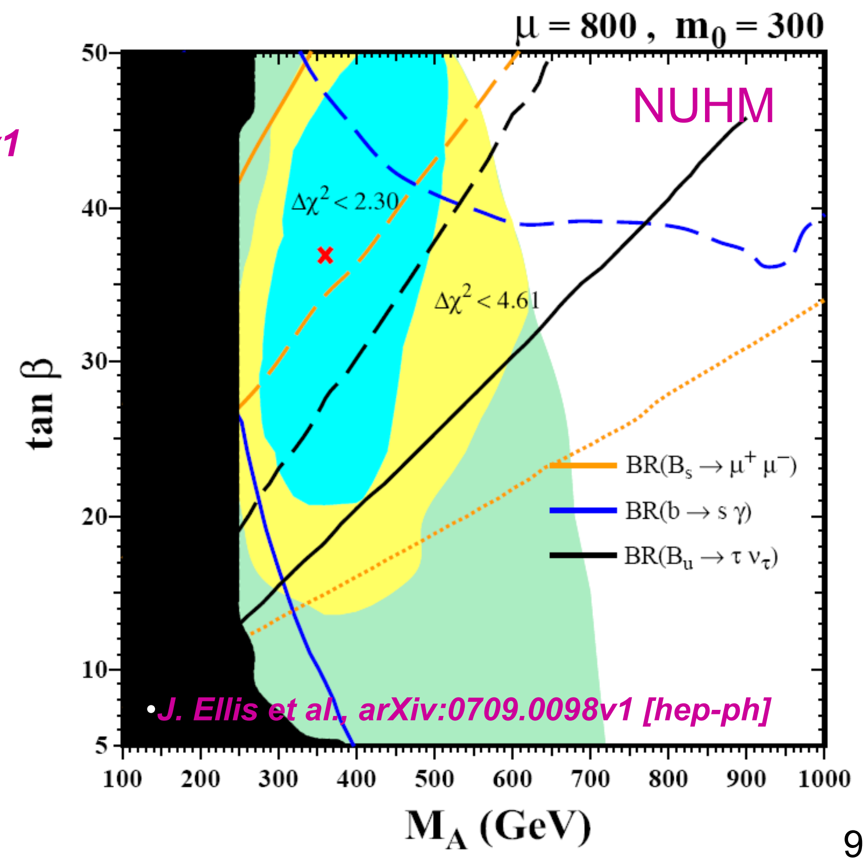
# $B_s \to \mu\mu$ – Introduction

- Sensitive probe for Higgs sector of any New Physics model
- Well predicted in SM:
  - $BR(B_s \to \mu\mu) = (3.35 \pm 0.32) \times 10^{-9}$

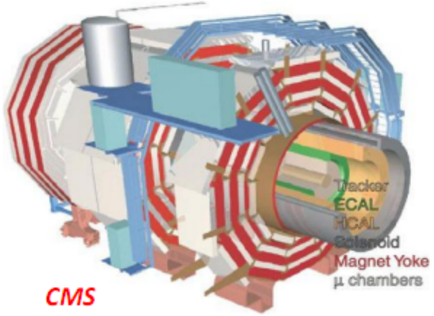
    *A. Buras arXiv:0910.1032.v1*
- Current best limit from CDF ($3.7 fb^{-1}$)
  - $BR(B_s \to \mu\mu) < 43 \times 10^{-9}$ 90% CL

  $8 fb^{-1}$ on tape → $10 fb^{-1}$ summer 2011
- LHC will quickly catch up, should know soon if this is interesting
  - If limit $< 5 \times 10^{-9}$, will be hard to identify NP



# ATLAS/CMS Selection




Muons :

$p_\perp^{\mu} > 4GeV, |\eta| < 2.4$

Bs - mesons :

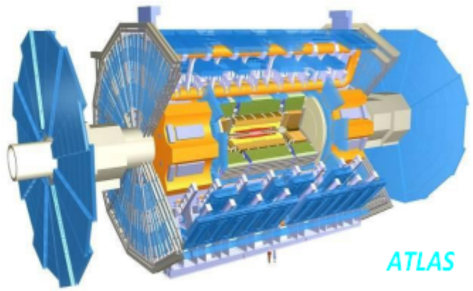
$p_\perp^{B_s} > 5GeV, \alpha_{\text{pointing}} >$ 3.1 degrees

Flight distance significance $\dfrac{L_{3D}}{\sigma_{3D}} > 17.0$

Global Event Cuts :

$$Iso = \frac{P_\perp^{B_s}}{P_\perp^{B_s} + \sum_i p_\perp^i(\Delta R < 1)} > 0.850$$

***CMS Coll. CMS PAS BPH-07-001***




Muons :

$p_\perp{}^{\mu} > 6GeV, |\eta| < 2.5$

Bs - mesons :

$p_\perp{}^{B_s} > 5GeV, \alpha_{\text{pointing}} >$ 1.9 degrees

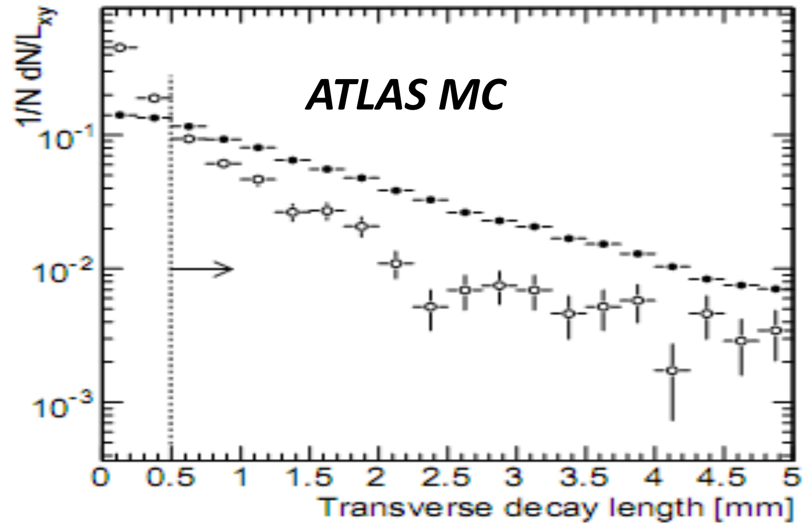
Transverse flight distance $L_{XY} > 0.5mm$

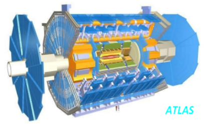
Global Event Cuts :

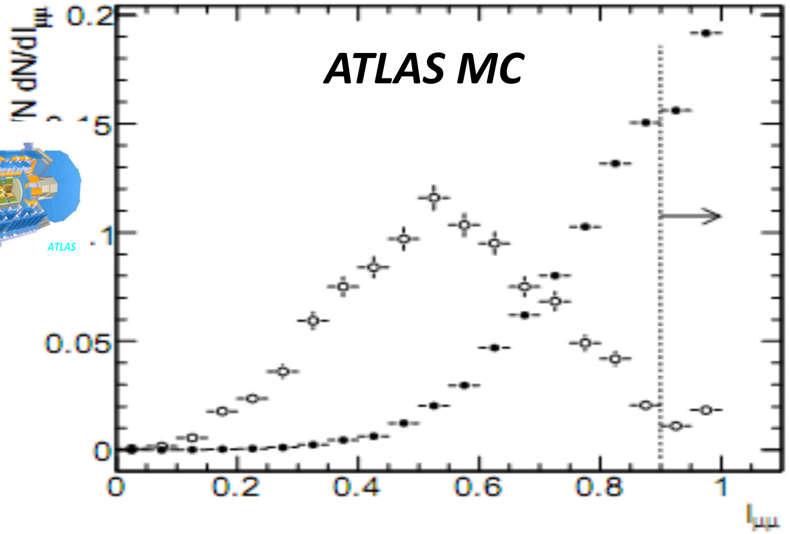
$$Iso = \frac{P_\perp{}^{B_s}}{P_\perp{}^{B_s} + \sum_i p_\perp{}^i(\Delta R < 1)} > 0.9$$

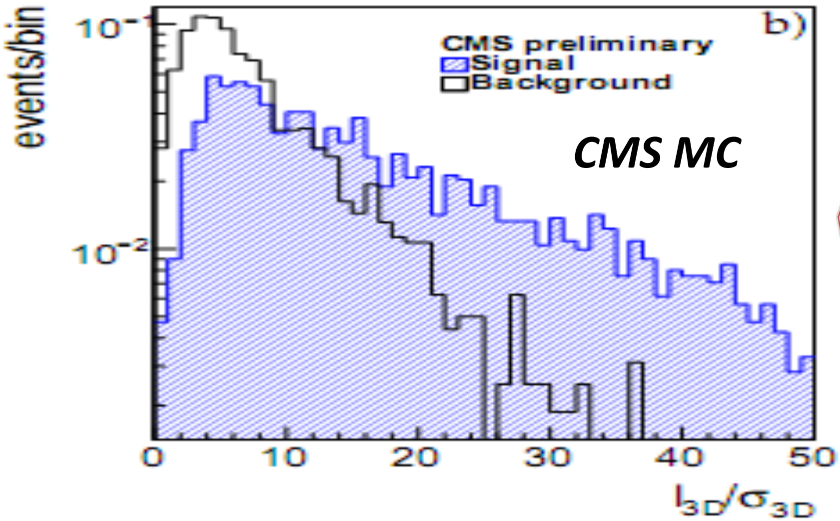
***ATLAS Coll. CERN-OPEN-2008-020***

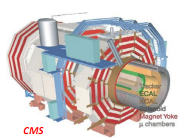
# ATLAS/CMS Selection Variables

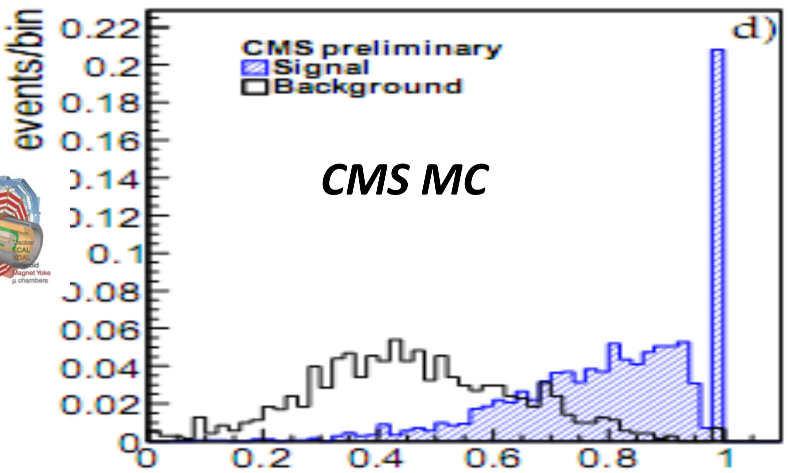


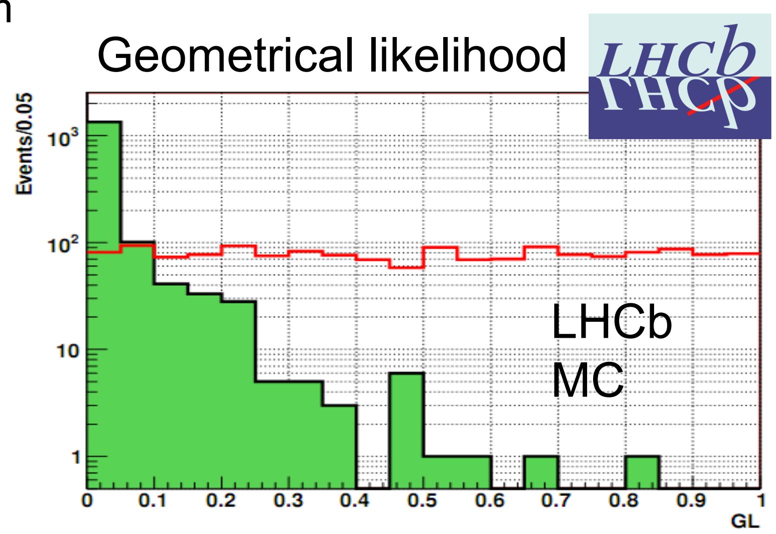



# LHCb Analysis Strategy

- Low $p_T$ di-muon trigger allows for a loose pre-selection, as common as possible with the control channels:

  $B^+ \to J/\psi K^+$, $B_d \to J/\psi K^*$, $B_{s,d} \to h^+h^-$, $B_s \to J/\psi\phi$

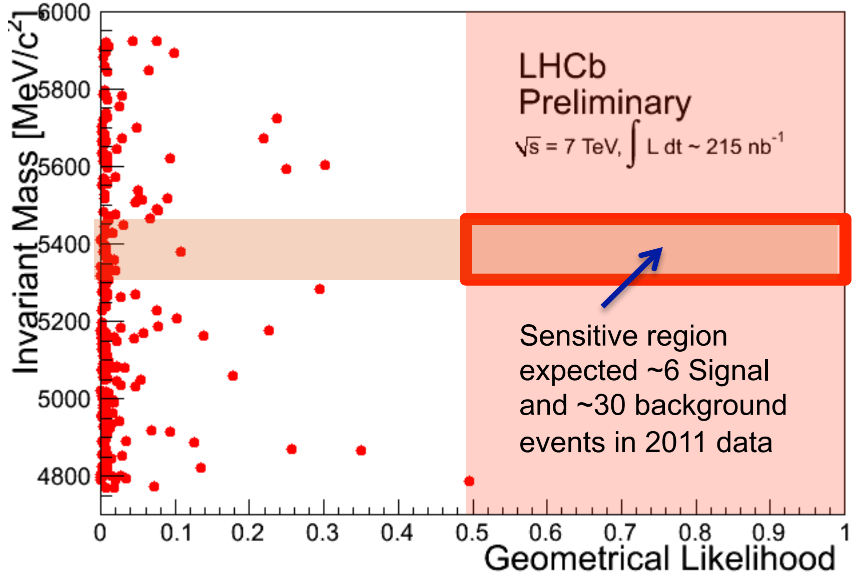
- Counting in bins based on 3 independent variables :
  - Invariant mass of the muon pair
    - Power determined by the tracking system resolution and alignment
  - Muon identification likelihood
    - Dominated by muon system but also use information from calorimeters and RICH detectors
  - Geometrical likelihood
    - Quantities where the vertex detector provides the main discrimination: impact parameters, isolation, lifetime

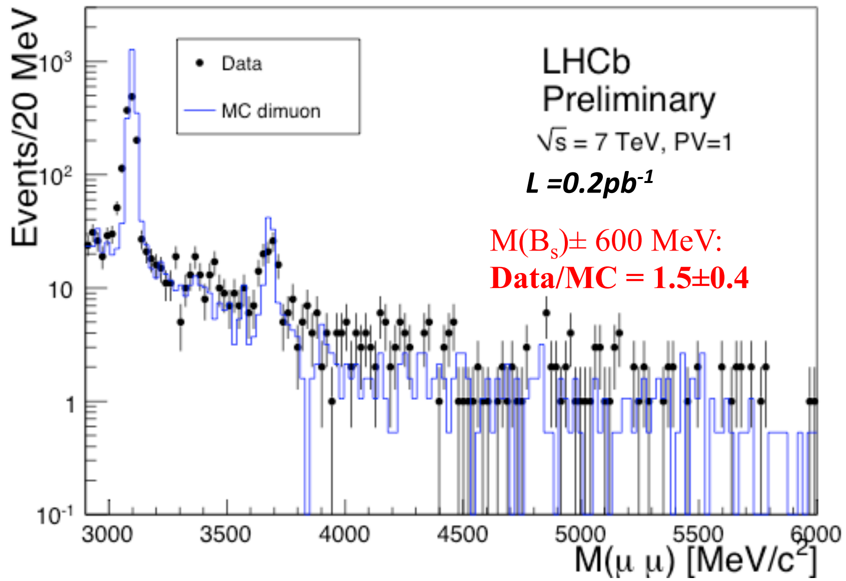


# Background Sources

- For all three experiments the main sources of backgrounds are:
  - $b\bar{b} \rightarrow \mu\mu$:
    'combinatoric' background due to muons originating from b-hadrons (BR($b \rightarrow \mu X$)≈10%)
  - $B \rightarrow hh$ with double "misid":
    e.g. $B_d \rightarrow K\pi$, $B_d \rightarrow \pi\pi$, $B_d \rightarrow KK$
  - $B \rightarrow J/\psi(\mu\mu)h$ with h misid as a $\mu$:
    e.g. $B^+ \rightarrow J/\psi K^+$

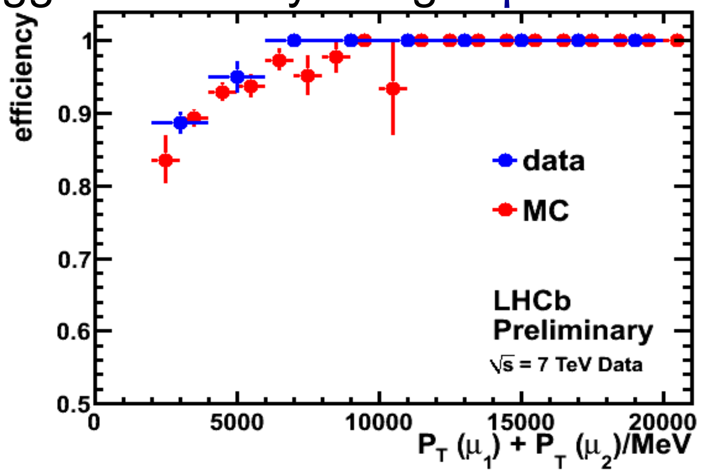
    (Latter two sources negligible in case of LHCb)



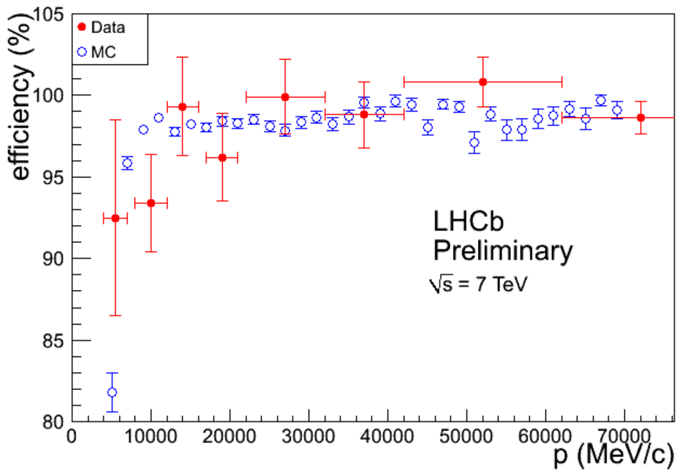
# The Road to a Measurement

Trigger efficiency using J/ψ

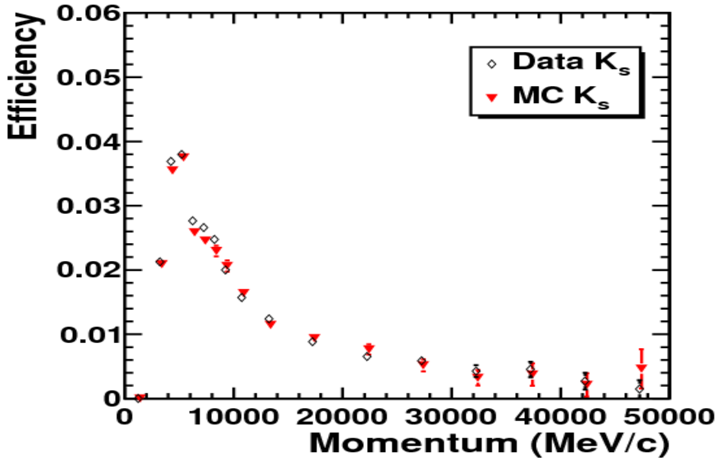



- Trigger and muon identification:
  - High efficiency
  - Good data/MC agreement
- Pion misidentification
  - Well described by MC

Muon ID Efficiency, using J/ψ tag and probe




Pion misidentification using $K_s \rightarrow \pi\pi$



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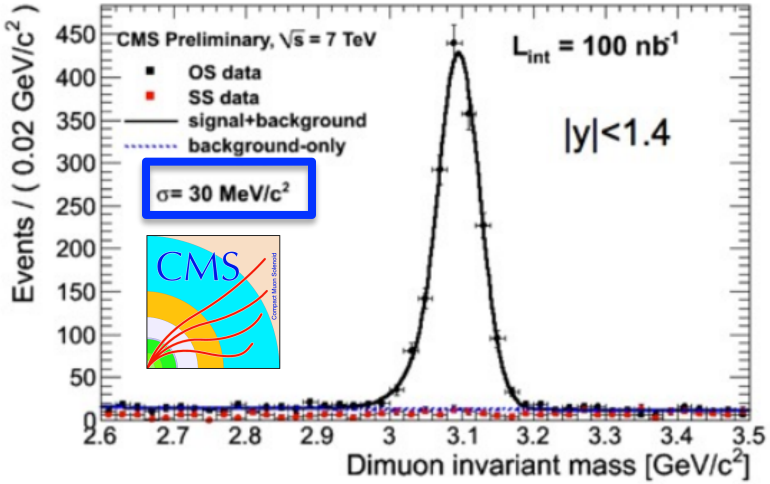
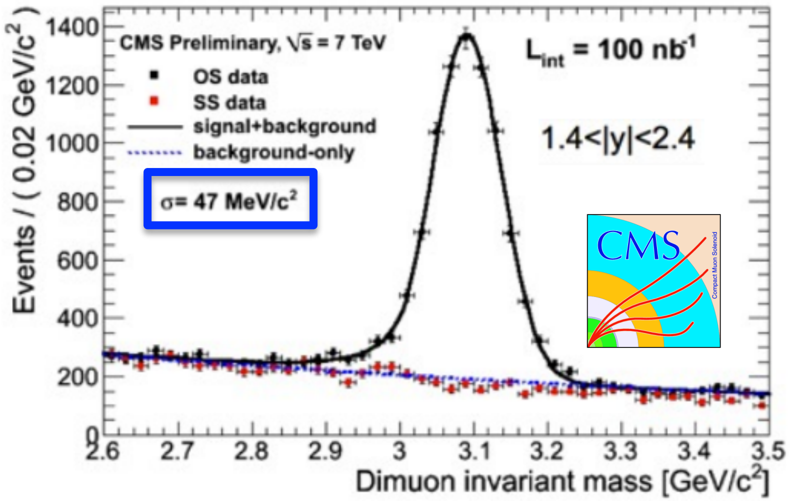
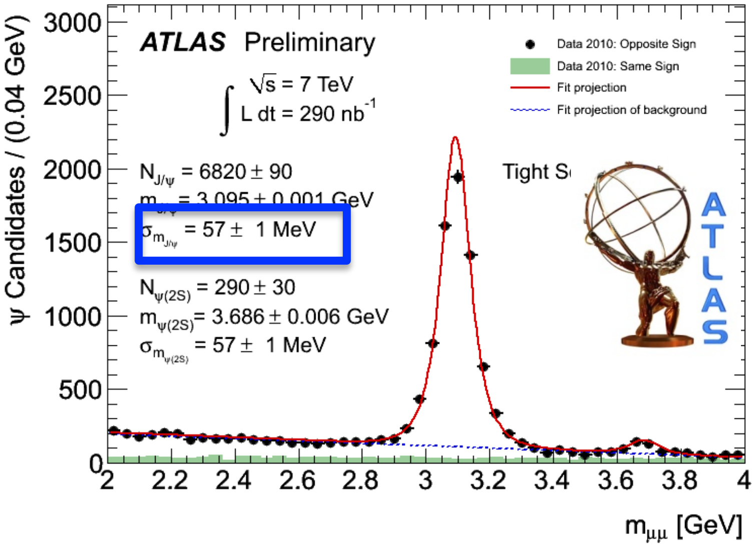
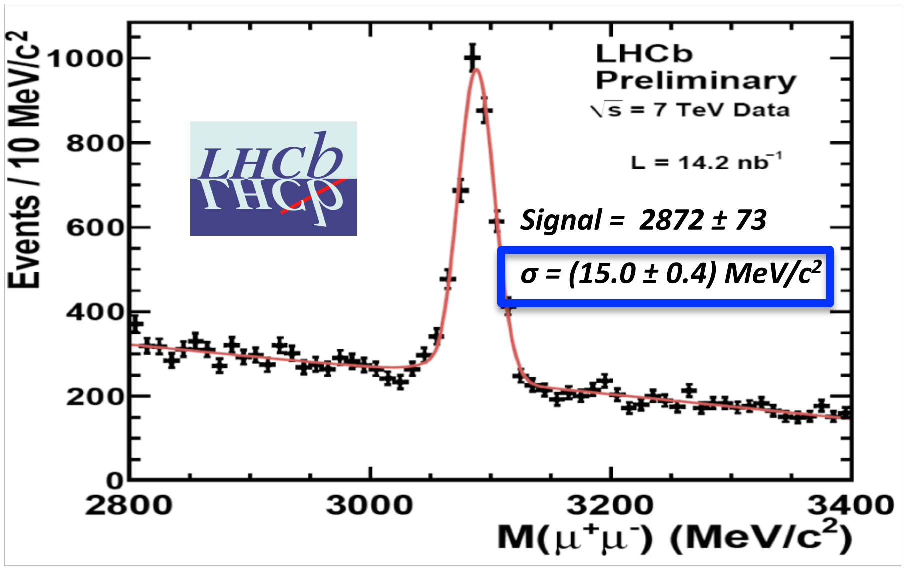


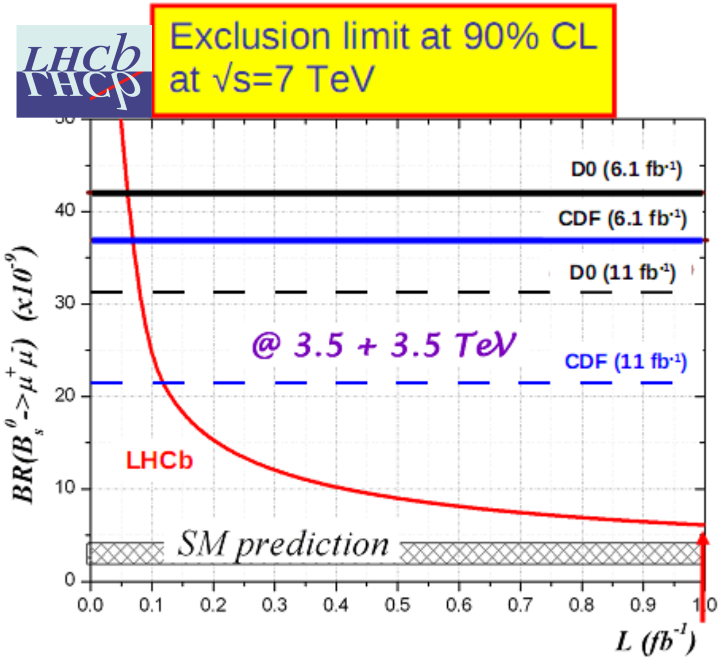



# Expected Sensitivity

| Experiment | N Signal | N Background | Upper Limit 90% CL |
|---|---|---|---|
| ATLAS (10 $fb^{-1}$ 14TeV) | 5.6 evts | $14^{+13}_{-10}$ evts (only $bb\to\mu\mu$) | ----------- |
| CMS (1$fb^{-1}$ 7TeV) | 1.4 | 4.0 (1.25 only $bb\to\mu\mu$ ) | $15.8 \cdot 10^{-9}$ **(private calcn)** |
| LHCb (1$fb^{-1}$ 7TeV) | 6.3 (most sign. region) | 32.4 (most sign. region) | $7 \cdot 10^{-9}$ |




- Limits computed using $\sigma(b\bar{b})$=292$\mu$b
- All the experiments plan to normalise to either $B^0\to J/\psi K^*$ or $B^+\to J/\psi K^+$ ($B^0\to$ dominant syst from $f_d/f_s$ - measure using $B^0\to D^-K$ and $B^+\to D_s^+\pi^-$)
- Possible to make 5$\sigma$ discovery of NP down to $B(B_s\to\mu\mu)<17\times10^{-9}$ with 1$fb^{-1}$

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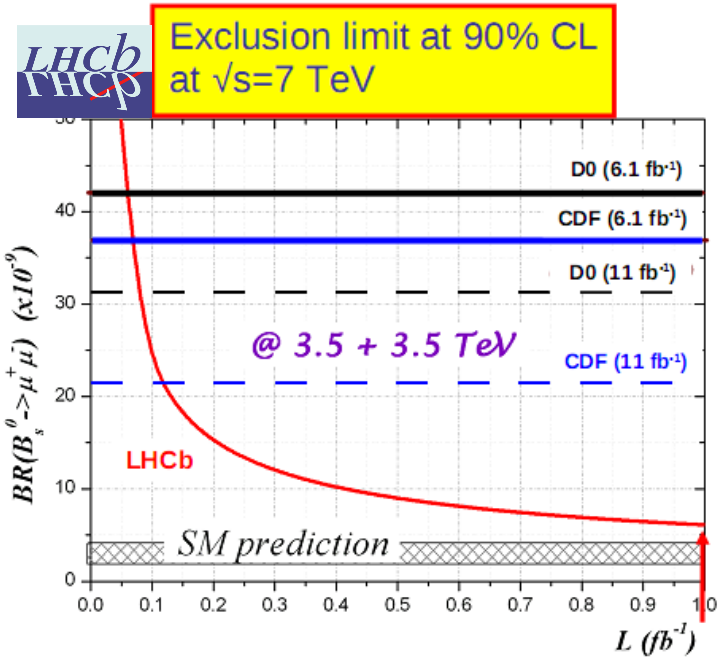
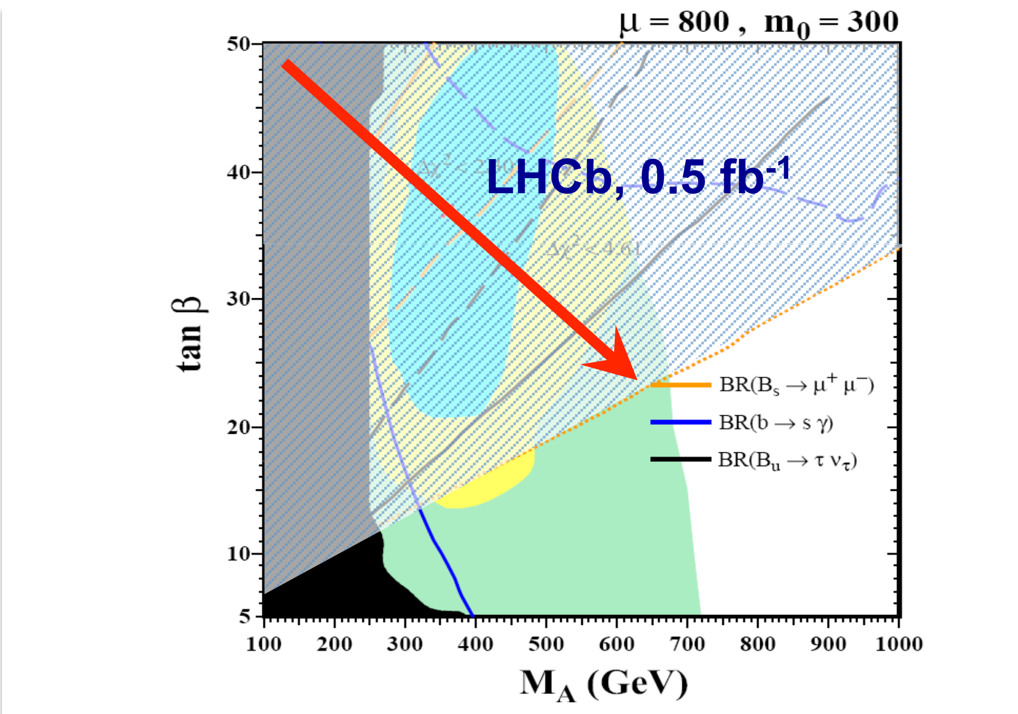
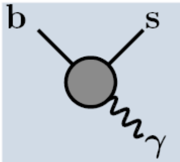


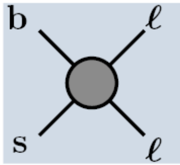



# $B_d \to K^* \mu\mu$

# $B_d \to K^*\mu\mu$ – Introduction

- Flavour changing neutral current → loop
- Sensitive to interference between

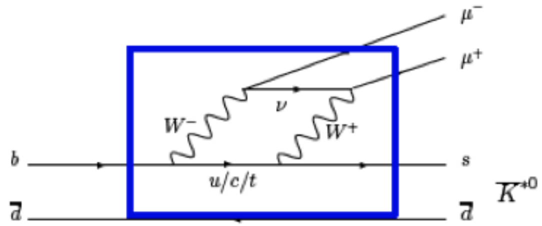


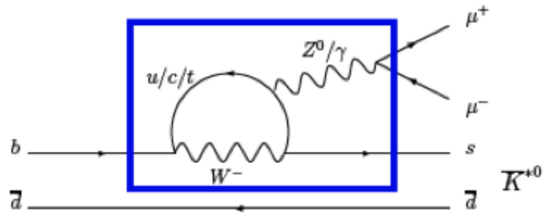



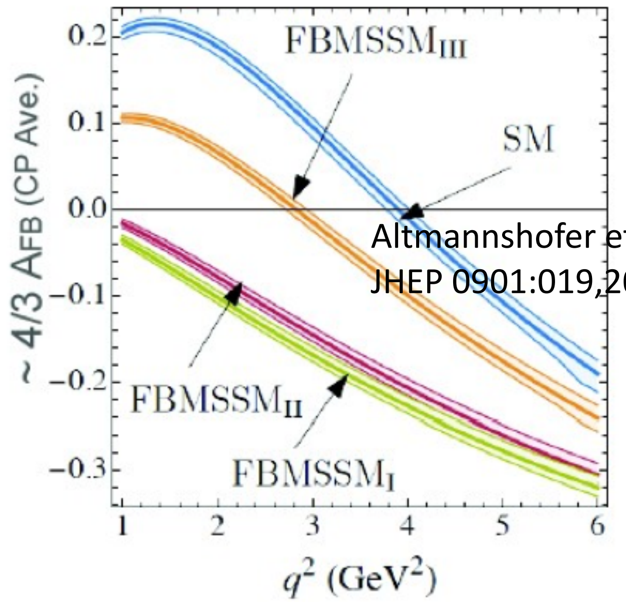

$O_{7\gamma}$ $O_{9,10}$

and their primed counterparts

- Exclusive decay → theory uncertainty from form factors
- Multitude of observables in which uncert. cancel to some extent e.g. $A_{FB}$, $A_T^{(i)}$
  - zero-crossing point of $A_{FB}$



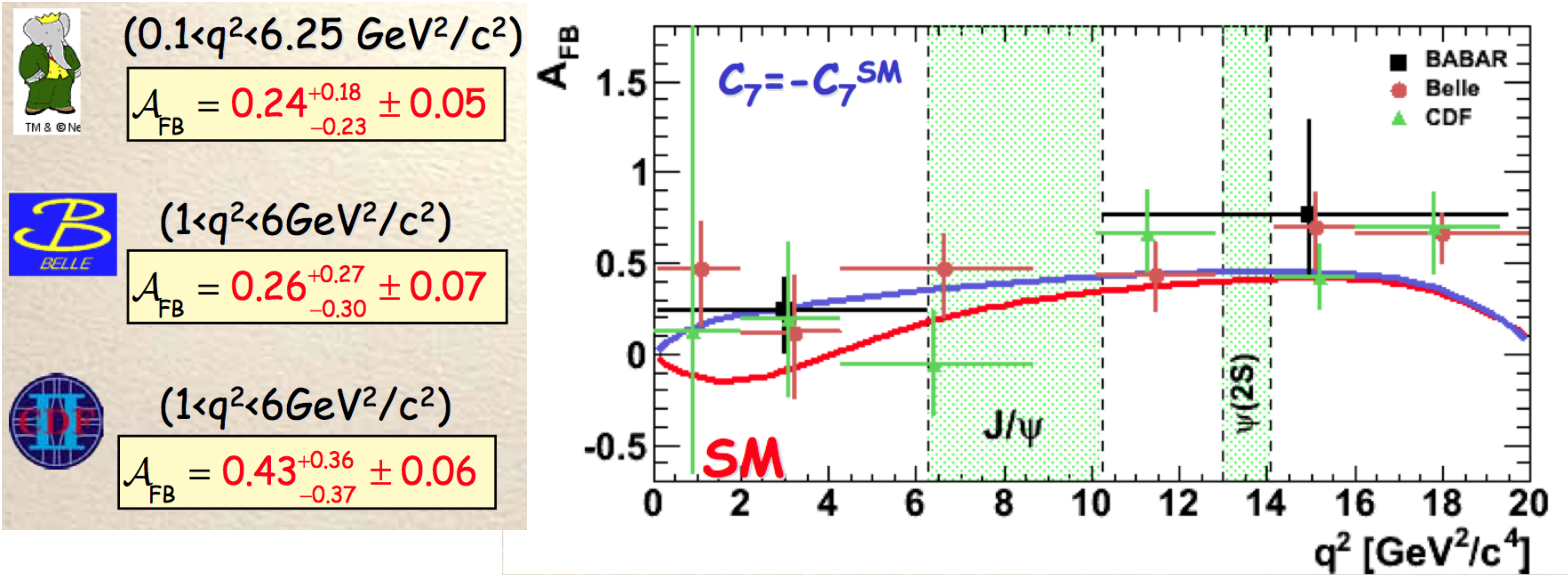




Altmannshofer et al, JHEP 0901:019,2009

# Experimental Status

- Babar, Belle and CDF have all measured angular asymmetry $A_{FB}$ :

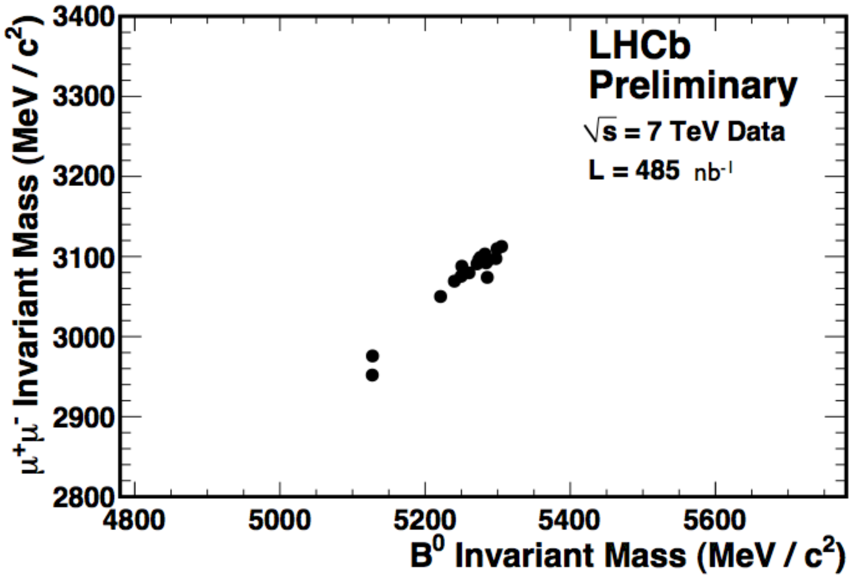


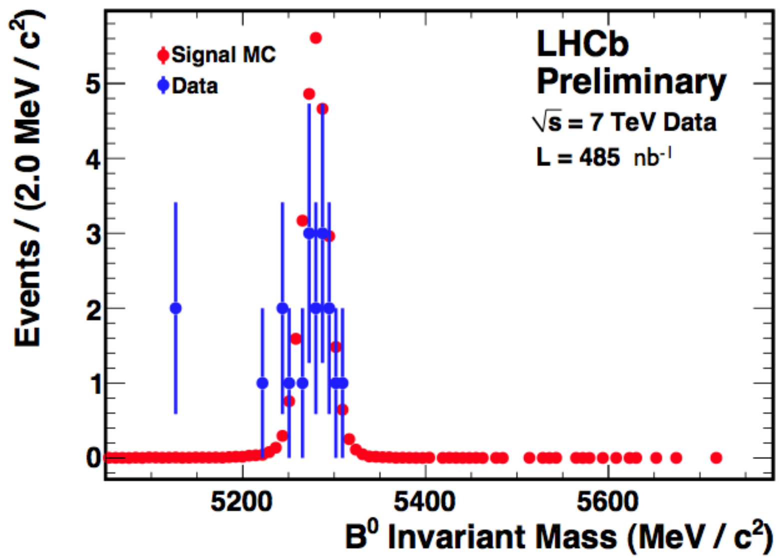

- Measurements look consistent with each other but errors too large to give real discrimination between SM and NP models

BABAR: PRL 102, 091803 (2009); CDF: Note 10047 (2010); Belle: PRL 103, 171801 (2009)

# The Road to a Measurement

- Don't yet have sufficient data to see the signal channel
- Instead look at proxies:
  - $B_d \to J/\psi K^{*0}$ for selection efficiency and background studies

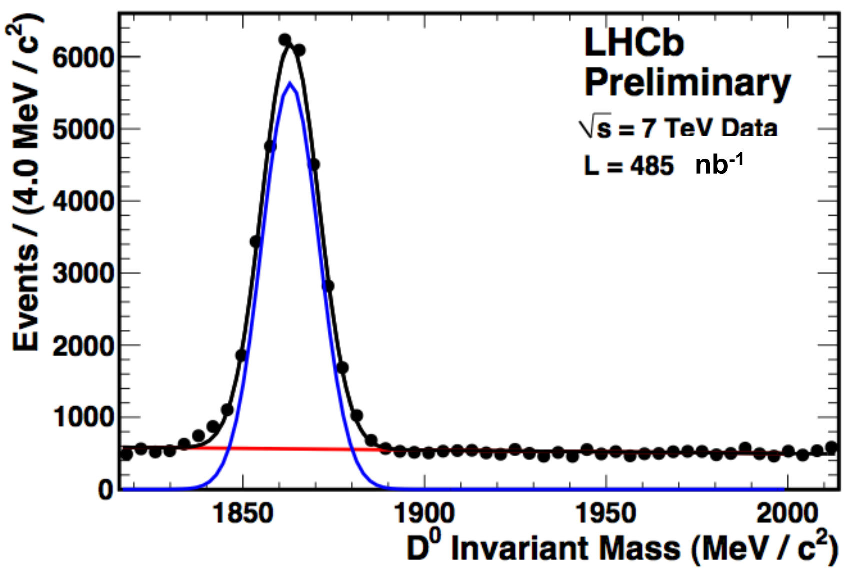


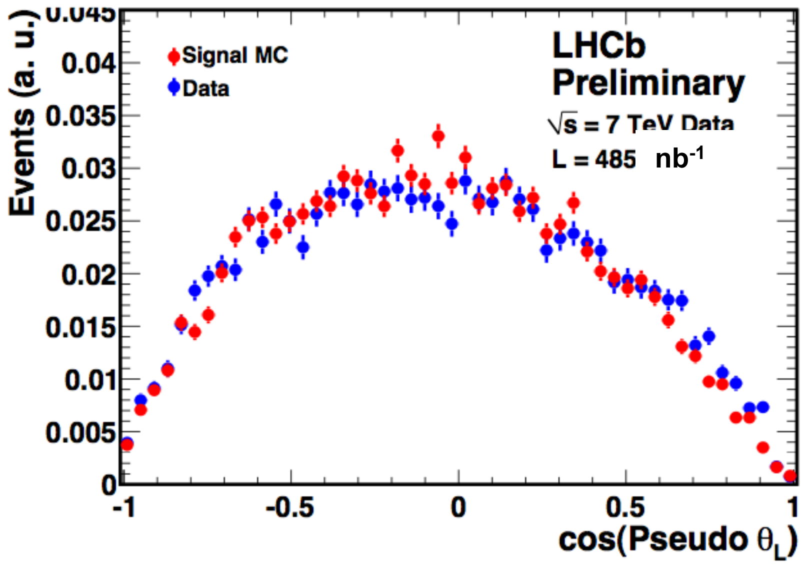




  - When applying $B_d \to K^* \mu\mu$ selection find a clear $B_d \to J/\psi K^{*0}$ peak
  - Yield as expected when measured B production cross section used for normalisation

# The Road to a Measurement

- Don't yet have sufficient data to see the signal channel
- Instead look at proxies:
  - $D^0 \to K\pi\pi\pi$ for understanding angular analysis

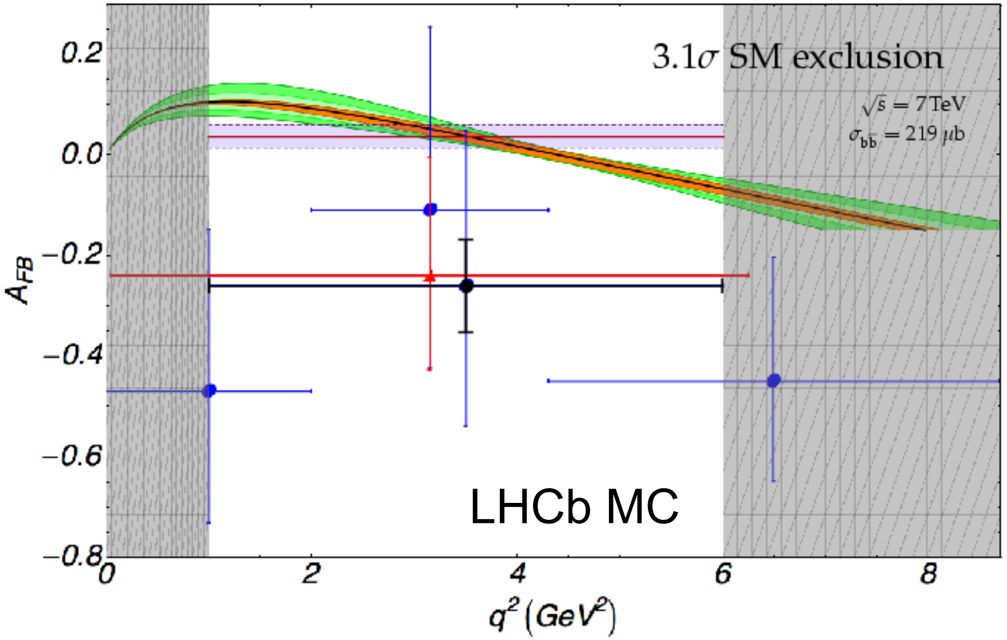



  - Use very clean $D^0$ signal to form a pseudo lepton angle $\theta_L$
  - Find a good match to expectation from MC simulation
    - No severe acceptance effect

# Expected Sensitivity

- With 0.1fb$^{-1}$, LHCb will have comparable errors to current B factory results
- 0.5fb$^{-1}$ enough to exclude SM at 3.1$\sigma$ level if Belle central value correct
  - 700 events (full $q^2$ range)
  - 200 events ($1 < q^2 < 6$ GeV)
- Central detectors will also see substantial numbers of events



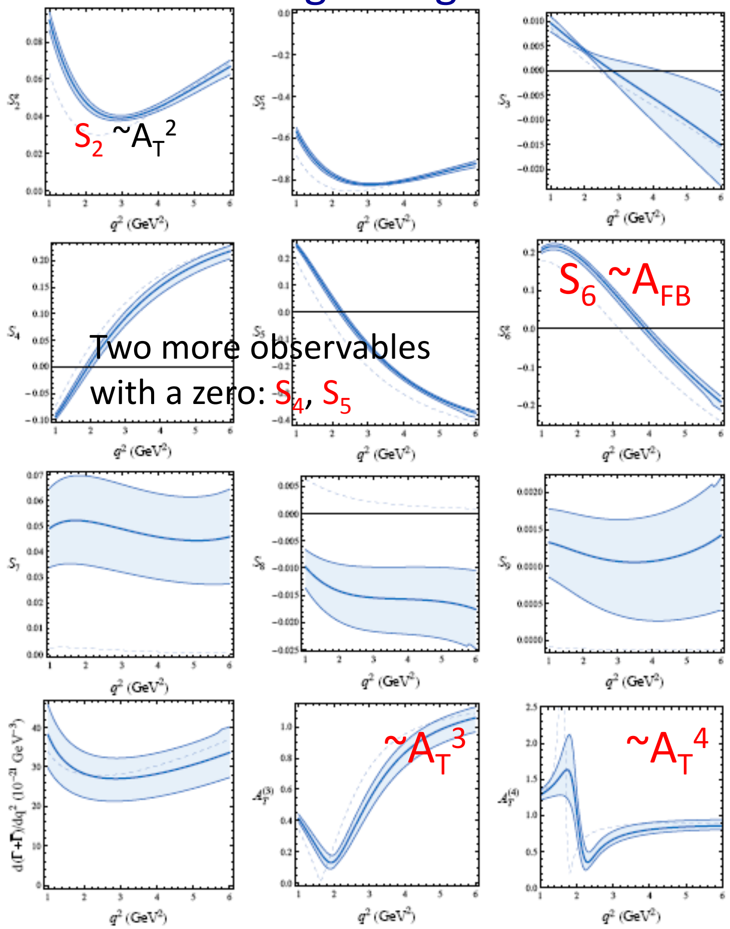

BaBar (2009) PRD 79 031102
Belle (2009) PRL 103 171801

# $B_d \rightarrow K^*\mu\mu$ – Outlook

- A competitive measurement of $A_{FB}$ with early data
- More data will enable a full angular fit to extract complete information from $B_d \rightarrow K^*\mu\mu$ decays

  → host of theoretically well calculable observables
- Correlation between measurements also of interest…

CP-averaged angular coeff.




Ball *et al.* arXiv:0811.1214v2

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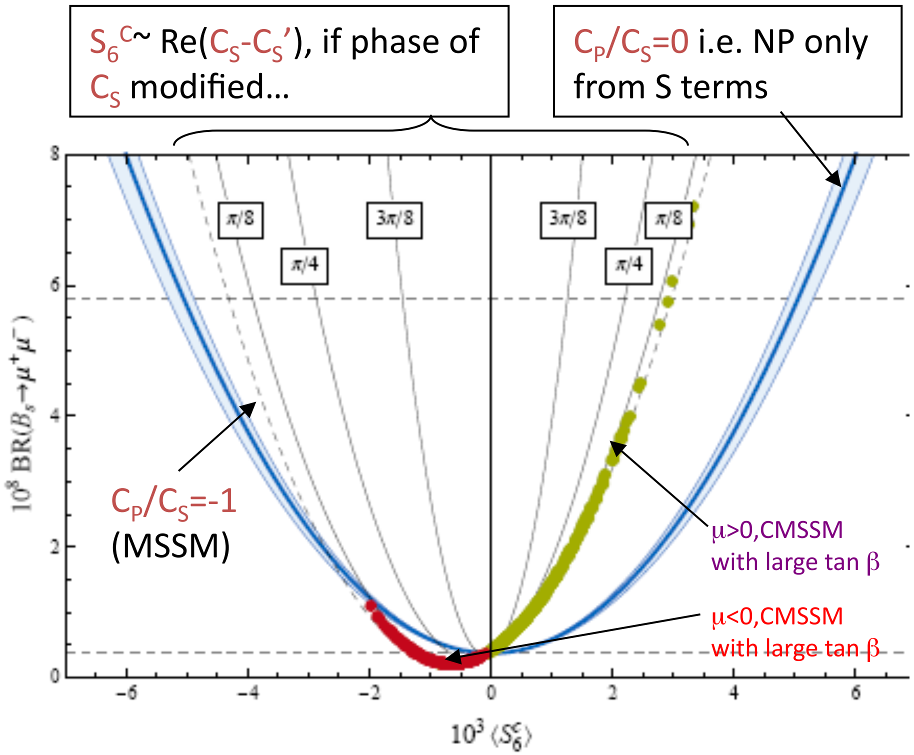
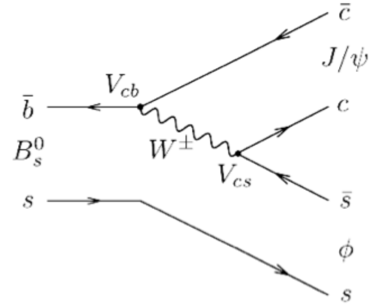


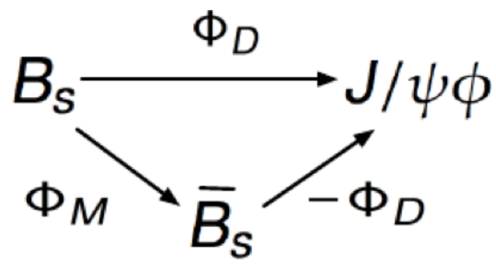
# $B_s \rightarrow J/\psi\phi$

# $B_s \to J/\psi\phi$ – Introduction

- $B_s \to J/\psi\phi$ decay dominated by $b \to c\bar{c}s$ transition
  - small penguin contribution, $\delta P$

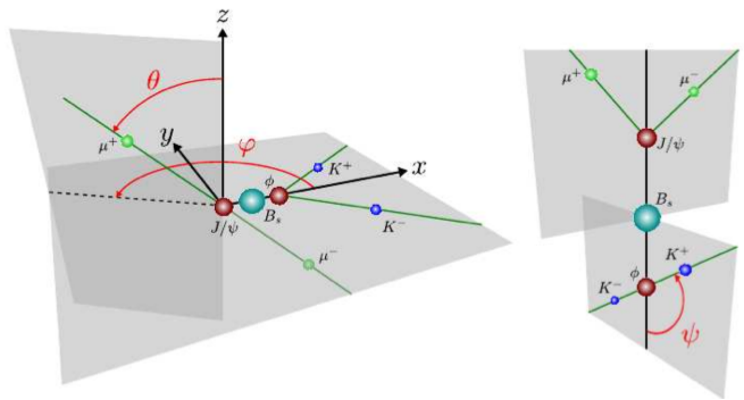



- Interference between *decay* or *mixing and then decay* results in CP violating phase:
  - $\phi_S = \phi_M - 2\phi_D$




- SM prediction:
  - $\phi_S = -2\beta_s + \delta P \sim -2\beta_s \qquad = 0.04$

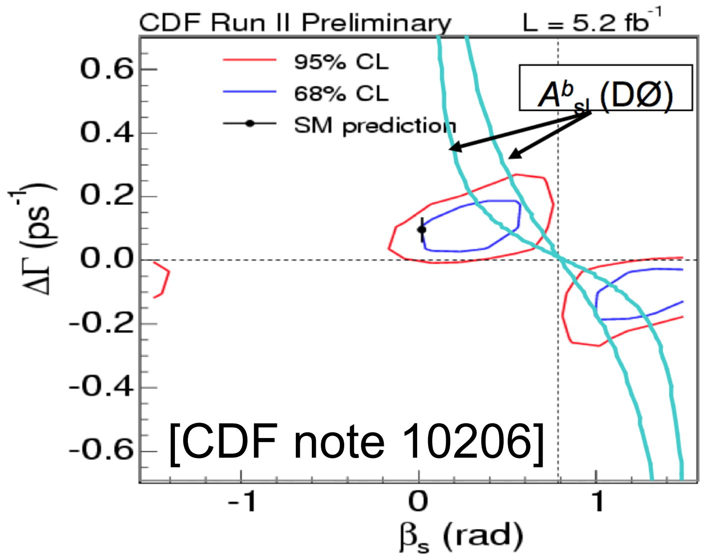
- $J/\psi\phi$ is not a CP eigenstate
  $\rightarrow$ required angular analysis (in transversity base) to statistically separate CP even/odd

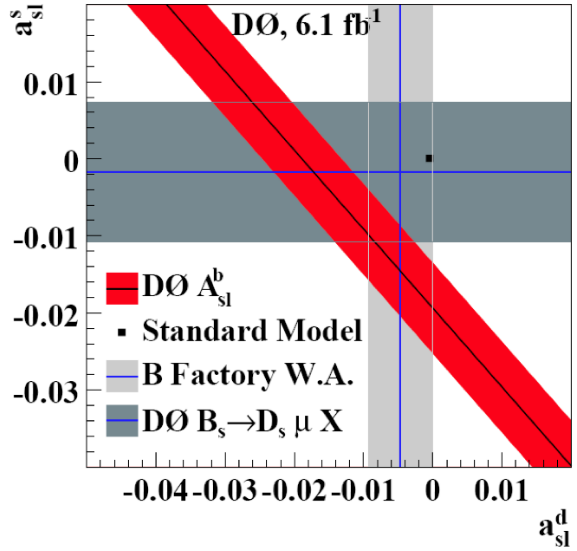


# Experimental Status

- First measurements of the $B_s$ mixing phase from CDF/D0 together with D0 measurement of semileptonic charge asymmetry $A^b_{sl}$ tantalizing :

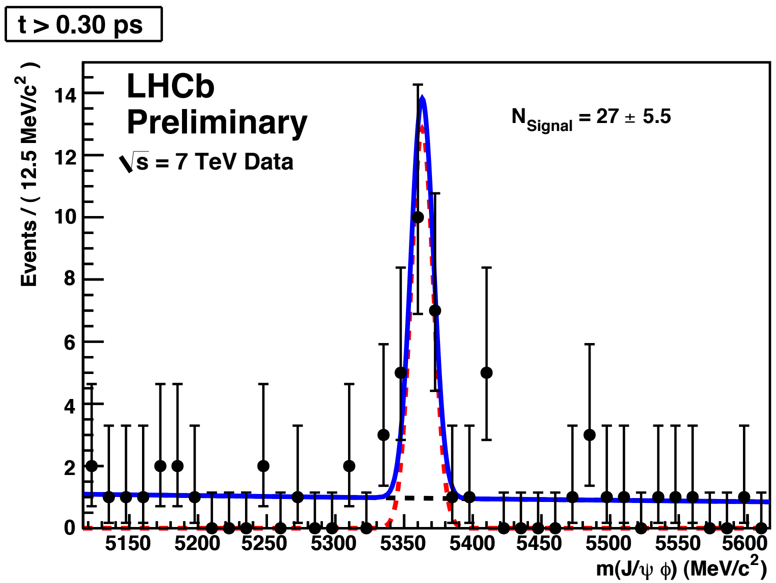
- The $A^b_{sl}$ measurement is $3.2\sigma$ from the SM expectation [PRL 105, 081801]

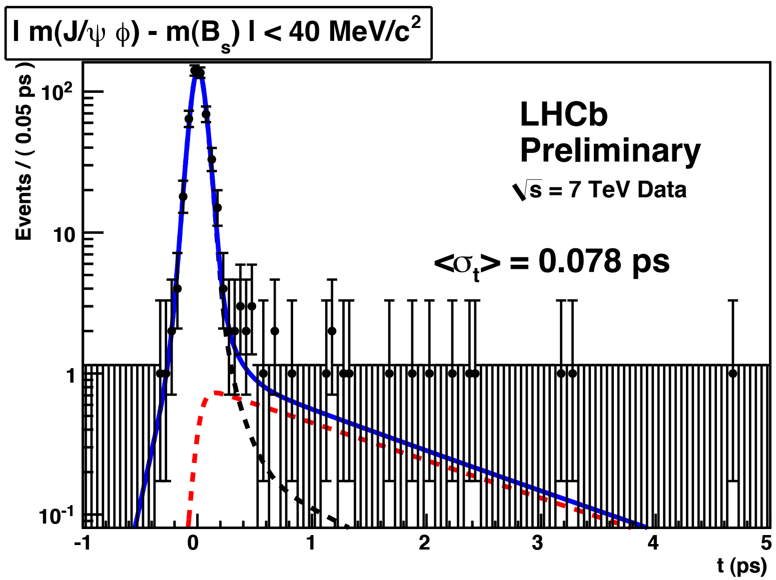


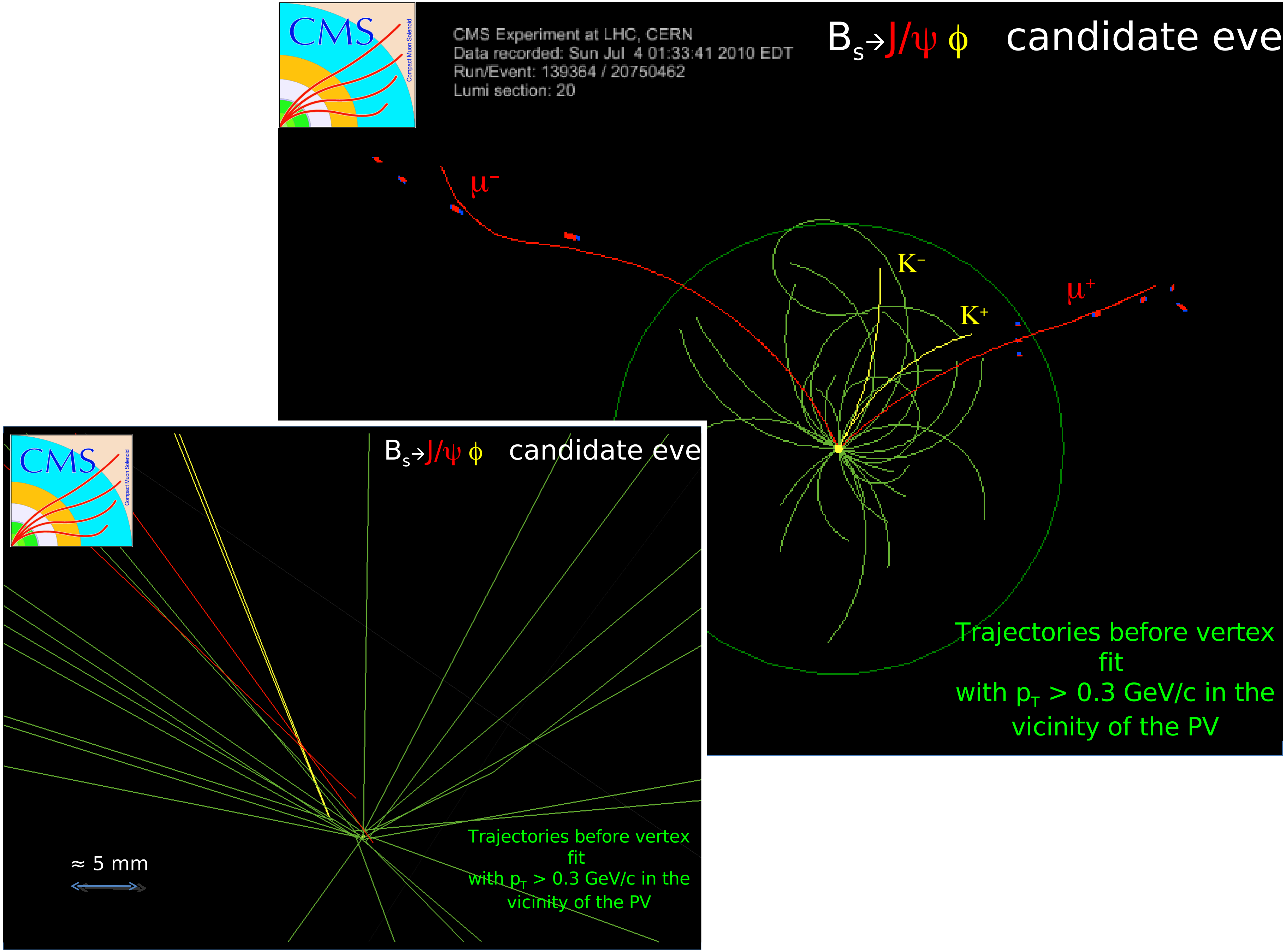
# $B_s \rightarrow J/\psi\phi$ – First Signal Events

- LHCb has the potential to quickly improve on the measurement from the Tevatron experiments
- Already see a signal sample in ~600nb$^{-1}$ ($\rightarrow$ ~50k / fb$^{-1}$ )



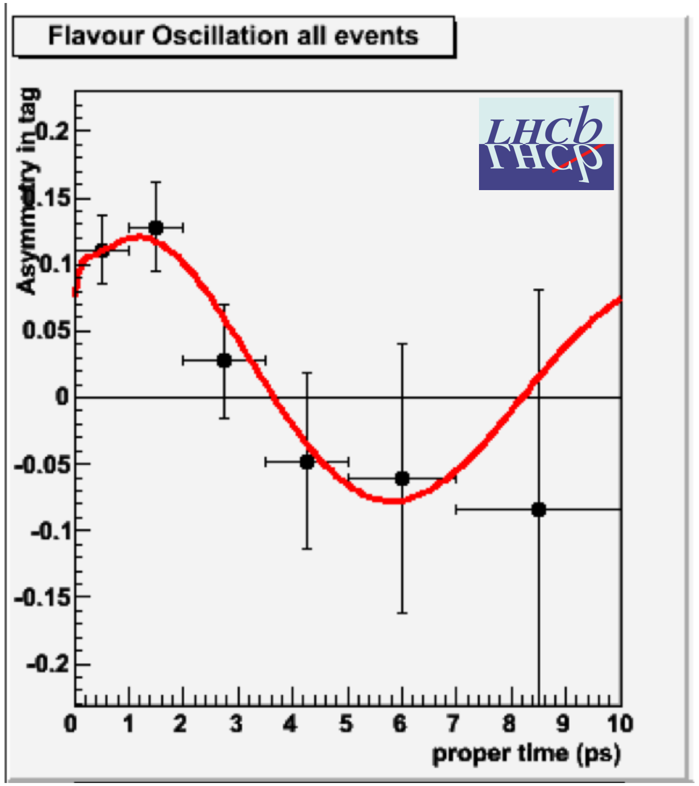

- Time resolution is 78fs
  - About factor 2 above expectation
  - Significant improvement seen with latest alignment


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 4 01:33:41 2010 EDT
Run/Event: 139364 / 20750462
Lumi section: 20
$B_s \to J/\psi\ \phi$ candidate eve
$\mu^-$
$K^-$
$K^+$
$\mu^+$
Trajectories before vertex fit
with $p_T$ > 0.3 GeV/c in the vicinity of the PV
CMS
$B_s \to J/\psi\ \phi$ candidate eve
≈ 5 mm
Trajectories before vertex fit
with $p_T$ > 0.3 GeV/c in the vicinity of the PV

# Flavour Tagging

- $B_s \rightarrow J/\psi\phi$ measurement requires flavour of the $B_s$ to be tagged
- Calibration:
  - $B^+ \rightarrow J/\psi K^+$ (flavour of B self-evident)
  - $B^0 \rightarrow D^{*+}\mu^-\nu$ (fit known osc. pattern)
- Fit the asymmetry as a function of proper time to extract:
  - Tagging efficiency, $\varepsilon$
  - Mis-tag rate, $w$

  The stat. uncertainty on the measured CP asymmetries ~ $\varepsilon(1-2w)^2$



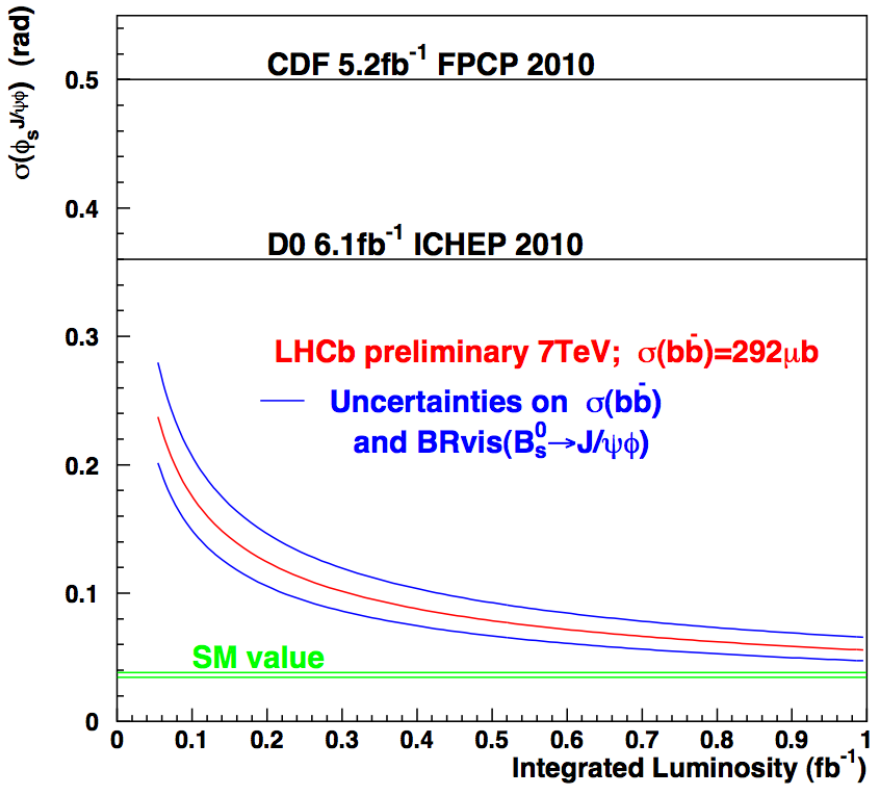

$A(t) = (N^{unmixed} - N^{mixed}) / (N^{unmixed} + N^{mixed})$

- With uncalibrated combn procedure, $\varepsilon(1-2w)^2$ ~ few %, as expected

# Expected Sensitivity

- Assuming from MC simulations
  - Background level
  - Time resolution
  - Flavour tagging efficiency
- and from data
  - B production cross section

$\rightarrow$ sensitivity down to close to SM value with $1fb^{-1}$

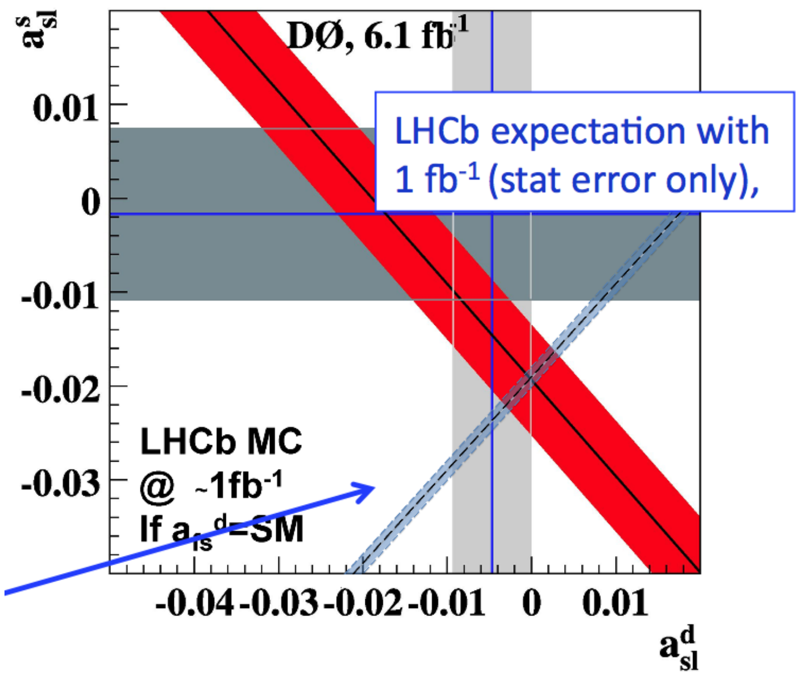


# New physics in $a^s_{sl}$ ?

- If New Physics enhances CP-violation in $B_s \rightarrow J/\psi\phi$, it will likely also dominate over the (negligible) SM CP-violation predicted in the semi-leptonic asymmetry

- Inclusive method with semileptonic decays difficult at LHC:
  - ~$10^{-2}$ production asymmetry in pp collisions
  - detector asymmetry

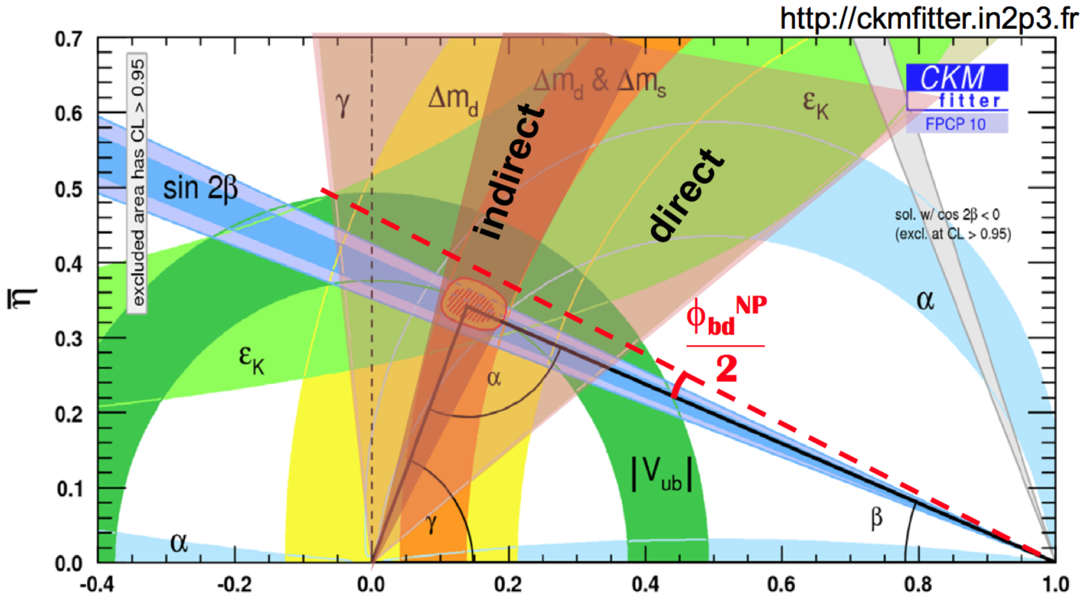
- LHCb proposes to measure $a^s_{sl} - a^d_{sl}$, by determining the difference in the asymmetry measured in $B_s \rightarrow D_s(KK\pi)\mu\nu$ and $B^0 \rightarrow D^+(KK\pi)\mu\nu$:
  - difference suppresses production asymmetry
  - same final state suppresses detector biases




This method provides an orthogonal constraint to that from D0

# CKM Measurements

# CKM Measurements




- $B_s \to J/\psi\phi$ measurement about looking for NP in $B_s$ mixing
- Still scope for NP in $B_d$ mixing?
  - CKM angle $\gamma$ determined indirectly $(68 \pm 4)^o$
  - Loop processes → $\sin(2\beta + \varphi_{bd}^{NP})$
  - cf. direct measurement of $\gamma$ from tree processes ( currently $(70\ ^{+14}\ _{-21})^o$ )

# CKM Measurements

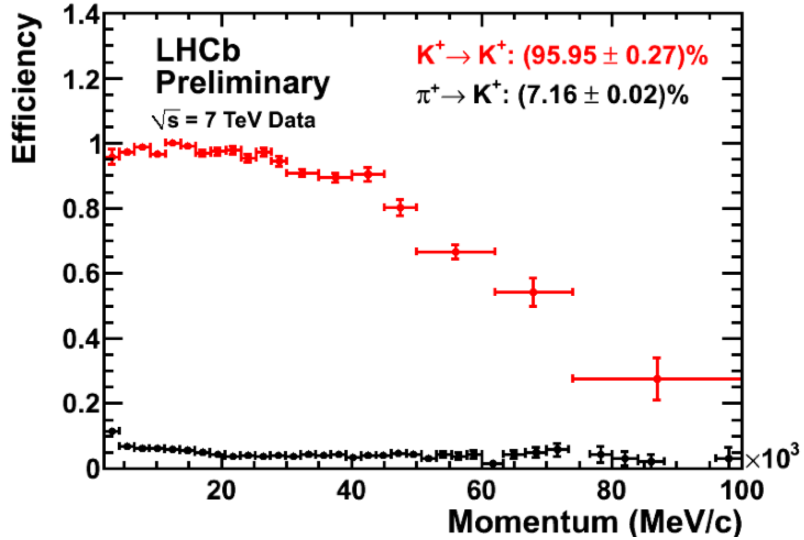
- Time independent strategies:
  - $B^+ \to D(hh)K^+$
  - $B^0 \to D(hh)K\pi^+$
  - $B^+ \to D(K_S\pi\pi)K^+$
  - $B^+ \to D(K\pi\pi\pi)K^+$
  - $B_s \to D_s\phi$

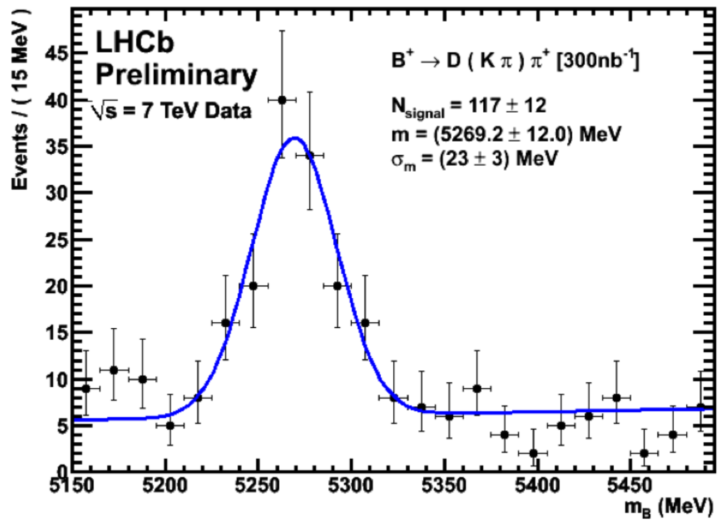
  $\sigma_\gamma$~10$^o$ with 1fb$^{-1}$

– Time dependent strategies:
  - $B_s \to D_s^- K^+$
  - $B \to hh$ [loops]

- Particle identification crucial to these measurements – increasingly well established

- Signal being seen in many channels



# Conclusions

- Even with the 2011 data, B decays can extend the search for NP:
  - $B_s \to \mu\mu$ ⟺ New scalar particles
  - $B_d \to K^*\mu\mu$ ⟺ New Lorentz structure
  - $B_s \to J/\psi\phi$ ⟺ New phases in $B_s$ mixing
- Beyond this, refining these measurements, looking at correlations between measurements, will help characterise the NP model
- Host of other measurements will probe the CKM picture in unprecedented detail, look at charm decays, exotics …