Imperial College
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Heavy Flavour Physics at the LHC

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Why ?

- Interactions of the different flavours of the quark and lepton sector
  - Any physics model (SM or NP) has to deal with this
- In SM this is through the Yukawa couplings to the Higgs field and the weak force
  - Misalignment of these gives structure of CKM matrix
    - Wide range: $m_u = O(10^{-5})\ m_t$, $|V_{ub}|=O(10^{-3})\ |V_{tb}|$ Why???
- Any NP model with new flavoured particles or flavour breaking interactions must “hide” behind SM interactions
  - NP mass scale very large (>~100 TeV)
    - or
  - NP mimics Yukawa couplings (minimal flavour violation)
- In all cases flavour physics will enlighten or constrain us

What ?

- Poke holes in the Standard Model
  - Find inconsistencies that are not (yet) explainable within the SM
- Understand the origin of mass
  - Provide evidence for an extended Higgs sector
- Provide a dark matter candidate
  - A SUSY neutralino discovered through loop diagrams of *B* decays
  - A massive Majorana neutrino
- Enlighten us on *CP* violation in Universe
  - Reveal that the *CP* violation from the Yukawa coupling cannot explain observations

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top decays

$B^0_s \to \mu^+\mu^-$

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

CPV in B^0_s decays

How ?

Think of properties of quarks that we are interested in

- Lifetime
  - Both b- and c-hadrons have lifetime in ps region. With momentum in 100 GeV region this gives decay distance around 10 mm.
- Mass of bottom and top
  - Mass of decaying quark sets transverse momentum scale
    - p_T/p sets geometry of detector
    - Forward detector for c- and b-hadrons
    - 4π for t decay

How ?

QCD background

- To see the effects of New Physics in heavy flavour decays we need to be able to calculate how the SM looks like
  - Uncertainties coming from QCD is the main problem here
- Two ways out of this
  - Look for decays with leptons in
  - Look for CP violation

Trigger

- Decays of interest range from
  - Precision CP violation in Charm → kHz signal
  - B decays with 10^{-10} branching fraction → 10 nHz signal

Where ?

LHCb, ATLAS and CMS all have a heavy flavour programme

LHCb designed for bottom and charm physics

	LHCb	ATLAS	CMS
$B\to\mu\mu$ mass resolution	✔✔✔	✔	✔✔
B vertex resolution	✔✔✔	✔✔	✔✔
Heavy flavour trigger rate	✔✔✔	✔	✔
Muon ID	✔✔✔	✔✔✔	✔✔✔
Hadron ID	✔✔✔	✔	✔
Coverage (top)	✔	✔✔✔	✔✔✔
Coverage (bottom)	✔✔✔	✔	✔

Production

Production of t and $\bar{t}$ can have different kinematic distributions

- $gg \to t\bar{t}$ symmetric but $q\bar{q} \to t\bar{t}(g)$, $qg \to t\bar{t}$ asymmetric from interference and underlying different structure functions of q and $\bar{q}$
- In SM t produced slightly closer to beam-axis than $\bar{t}$

Highly interesting to study due to unexpected results from $t\bar{t}$ forward-backward asymmetry at Tevatron

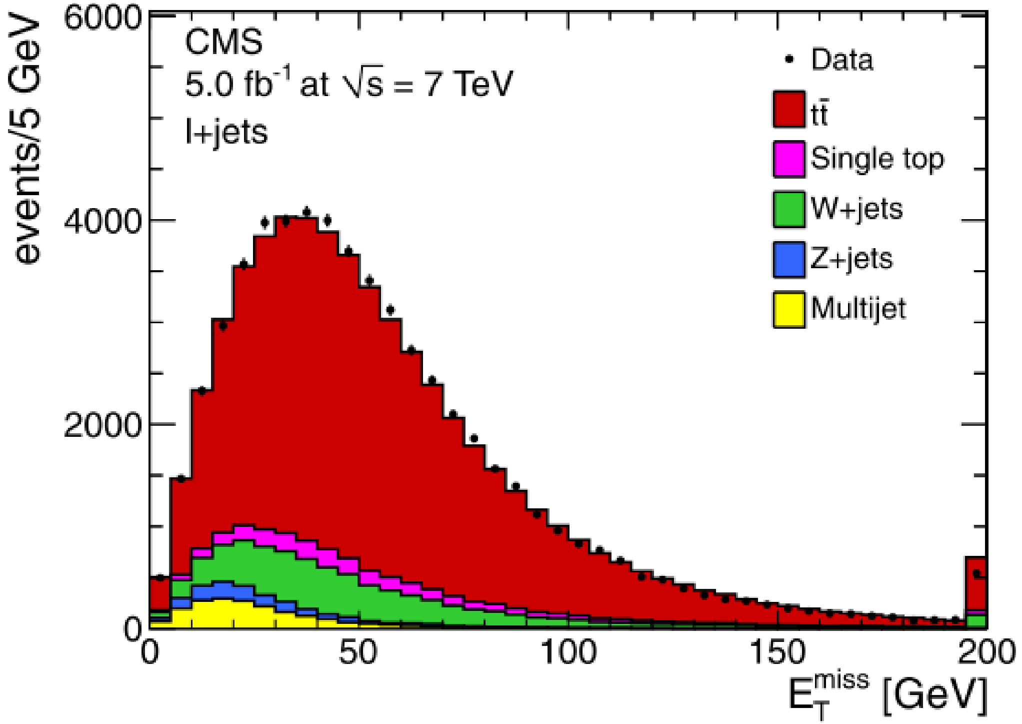
$$\Delta|y| = |y(t)| - |y(\bar{t})|$$

$$A_C = \frac{\#(\Delta|y|>0) - \#(\Delta|y|<0)}{\#(\Delta|y|>0) + \#(\Delta|y|<0)} \stackrel{SM}{=} (11.5 \pm 6) \times 10^{-3}$$

Production

CMS look in 5 fb^{-1} for $t\bar{t} \rightarrow W^{+} b W^{-} \bar{b}$ with b→hadrons, $W \rightarrow l \nu$

Selection very clean, total of 45k $t\bar{t}$ pairs



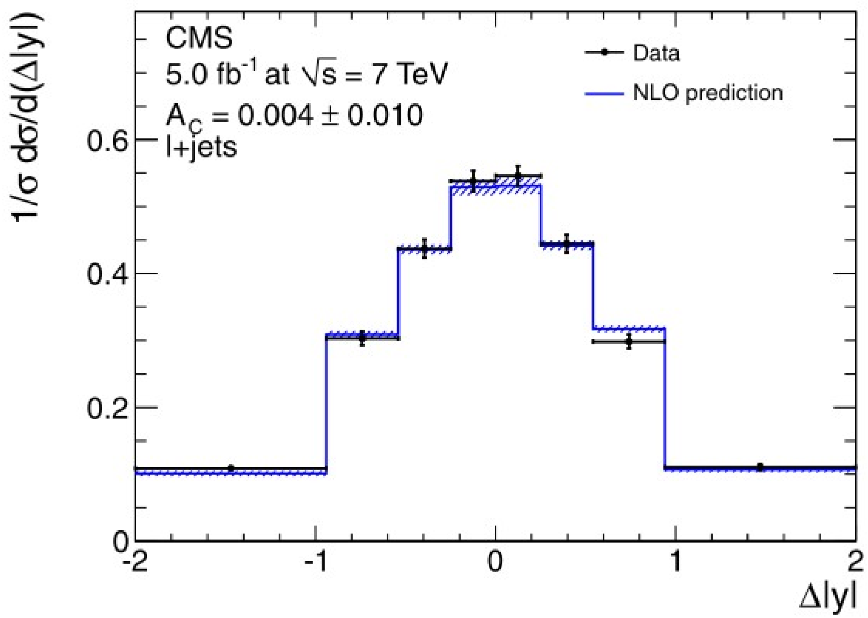
Production

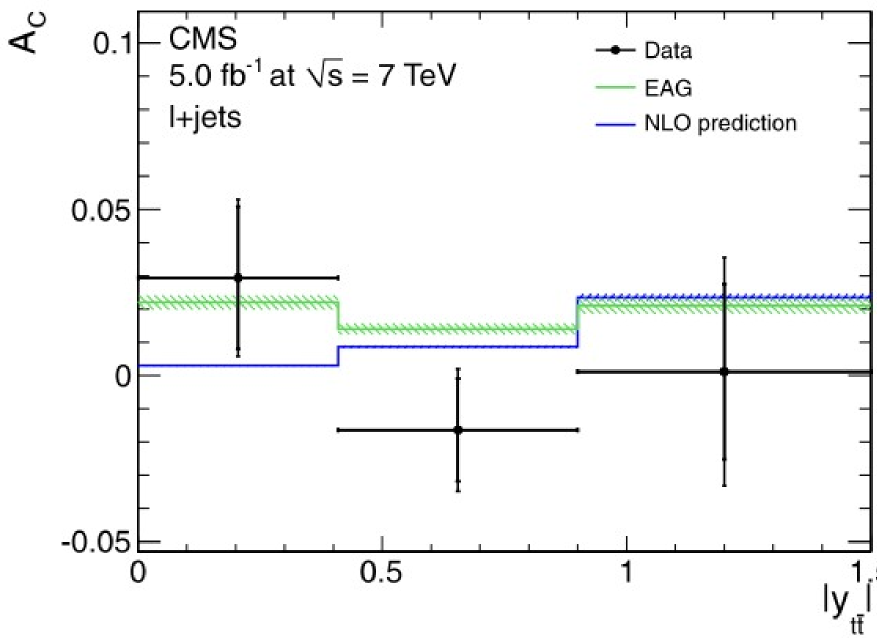
Resulting asymmetry

$$A_C = (4 \pm 10 \pm 11) \times 10^{-3} \text{ (CMS) 5 fb}^{-1}$$

$$A_C = (18 \pm 28 \pm 23) \times 10^{-3} \text{ (ATLAS) 1 fb}^{-1}$$

Tests against NP models shows that models satisfying Tevatron result are not excluded by LHC results





Production

LHCb is not sensitive to the top asymmetry but can measure the same quantity for b hadrons

Double triggered b-hadron events used for 2 b-jets

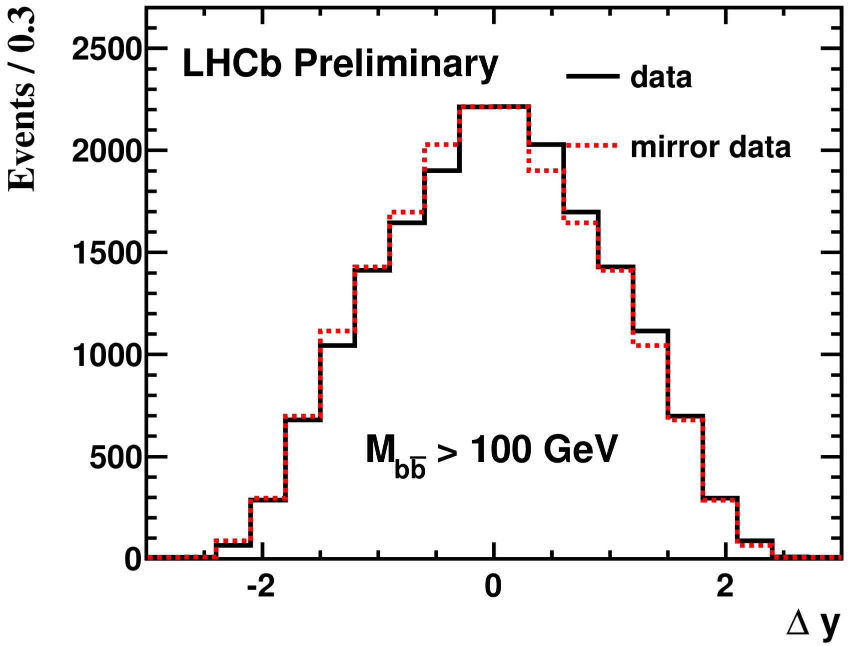
- Flavour tagged from semi-leptonic decays

$$A_C = (5 \pm 5 \pm 5) \times 10^{-3}$$

$$A_C = (43 \pm 17 \pm 24) \times 10^{-3}$$

$$m_{b\bar{b} > 100\,\mathrm{GeV}}$$

Potential to much improve this measurement

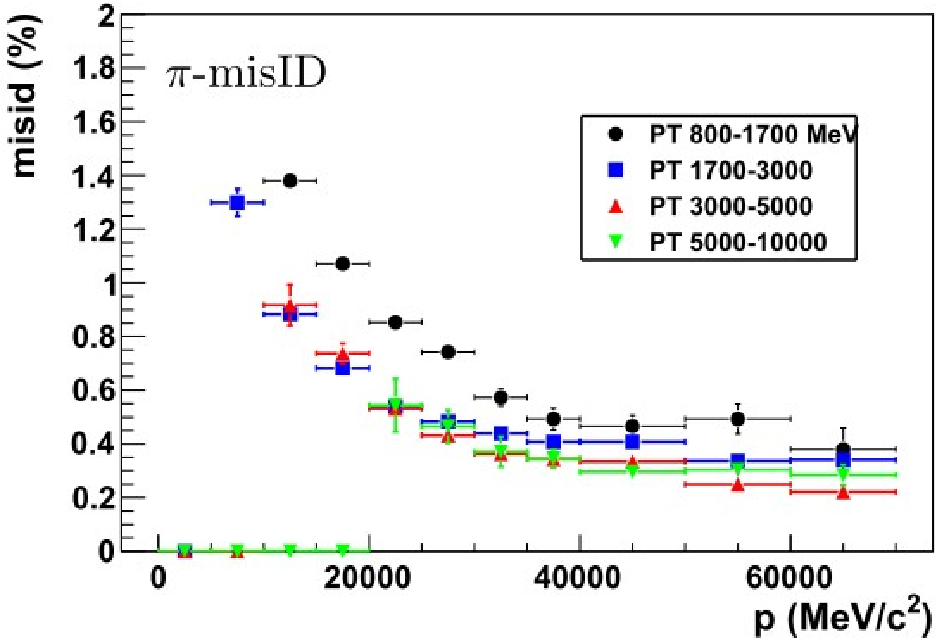


Rare decays

Look at decays which in the SM model can't happen at tree level

- Flavour changing neutral current decays the largest group
- Decays with dimuons are good candidates for rare searches
  - Rely on excellent muon identification

LHCb 2011



Rare decays

For B mesons the rare decay search started in 1984 at CLEO

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Two-body decays of *B* mesons

Various exclusive and inclusive decays of B mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a B meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

Rare decays

For B mesons the rare decay search started in 1984 at CLEO

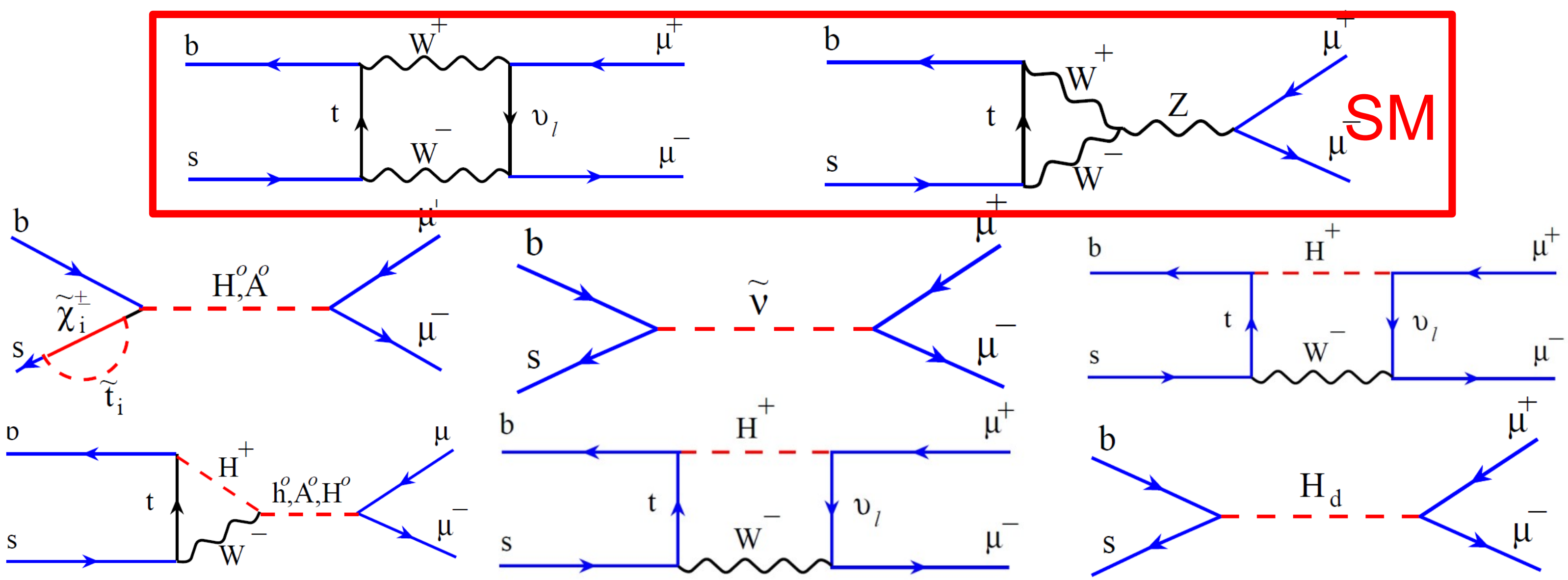
B. Search for exclusive $\overline{B}^0$ decays into two charged leptons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\overline{B}^0 \rightarrow \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

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

The two very rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ have attracted much interest

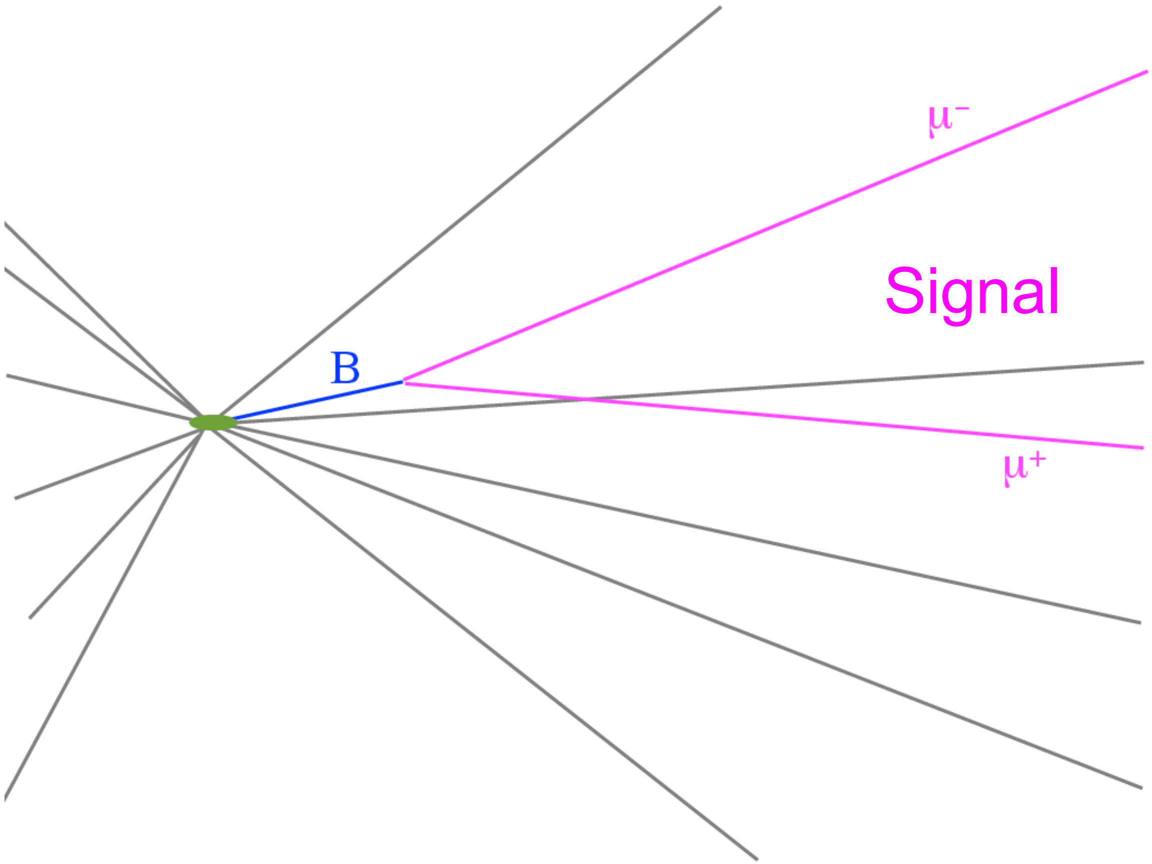
- Easy to predict SM branching fraction with great precision
  - $BF(B^0_s \to \mu^+\mu^-)_{SM} = 3.56 \pm 0.18 \times 10^{-9}$ (time averaged)
  - $BF(B^0 \to \mu^+\mu^-)_{SM} = 0.10 \pm 0.01 \times 10^{-9}$
- Sensitive to the scalar sector of flavour couplings



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

Topology of decay simple

- Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background



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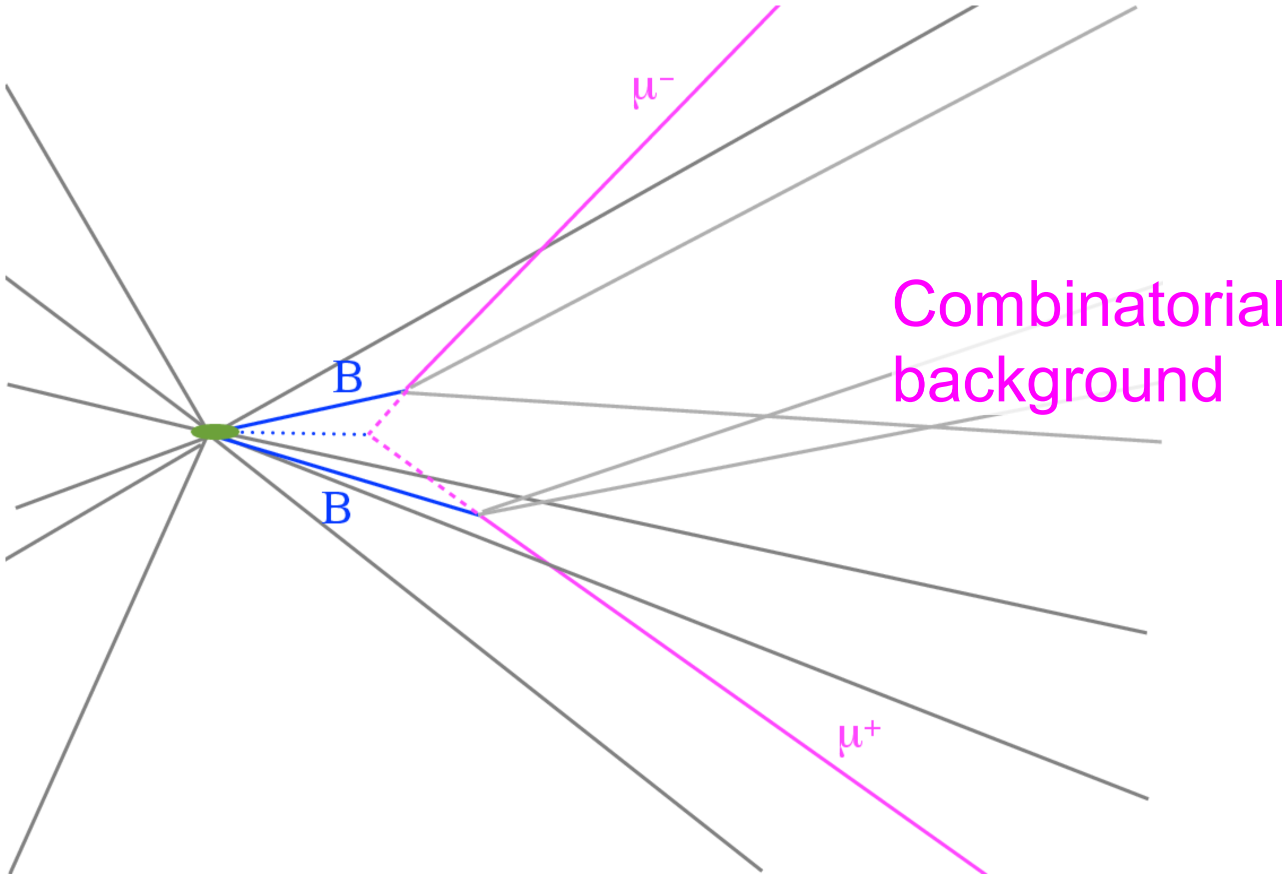


$B \to \mu^+\mu^-$

Topology of decay simple

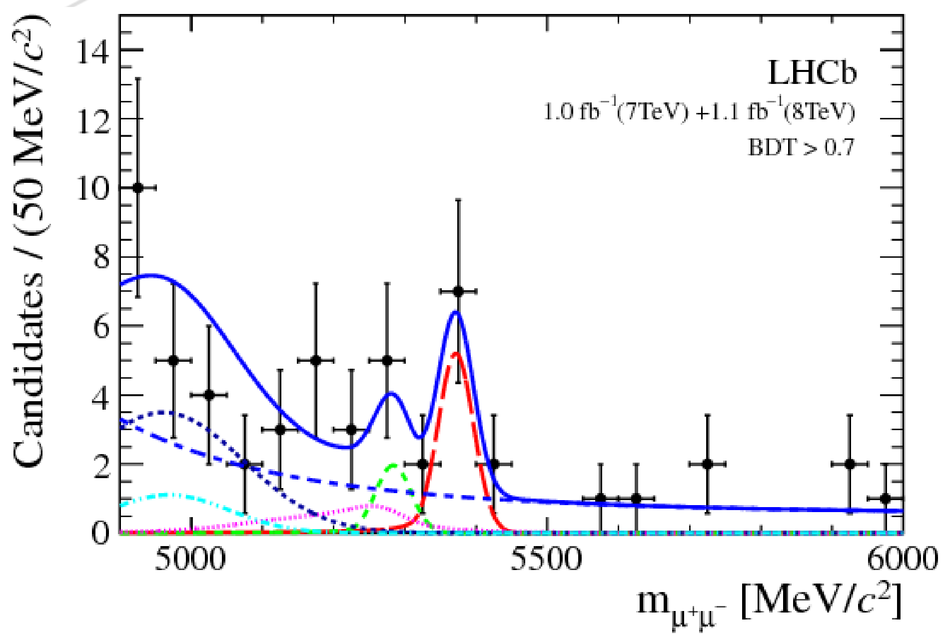
- Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background

Isolation of the dimuon vertex is very important

- For ATLAS and CMS the higher integrated luminosity compensates for lower trigger efficiency

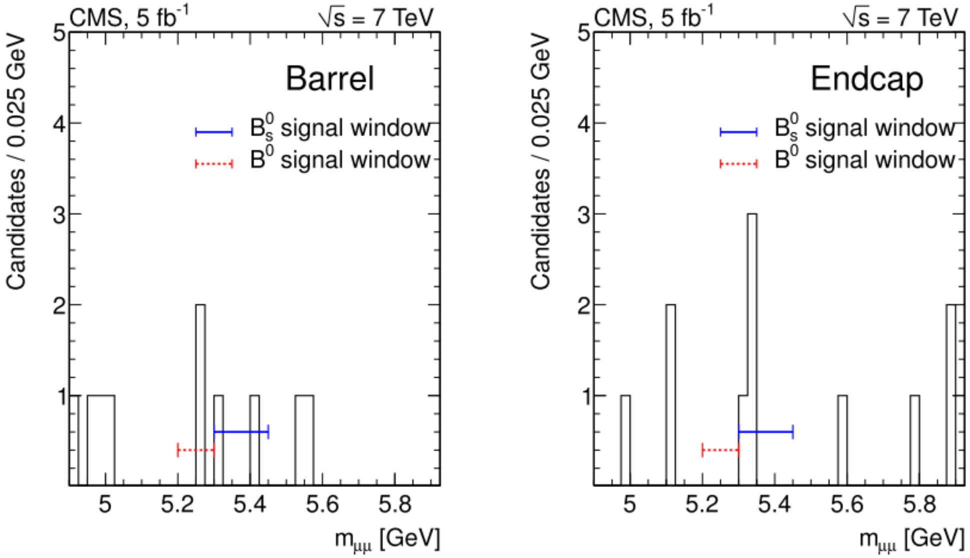
LHCb has seen first evidence of $B^0_s \to \mu^+\mu^-$

- $BF = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$
- 3.5σ significant



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

- Challenge now is to look for $B^0 \to \mu^+\mu$-
  - In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
  - New physics not following this pattern may manifest itself as a higher $B^0 \to \mu^+\mu$- rate
- However lower rate and peaking backgrounds now a real issue
  - CMS have peaking background and signal at the same level
  - CMS : <1.8 10^{-9} @95% CL
  - LHCb: <0.9 10^{-9} @ 95%CL



CMS B^0 search window in red

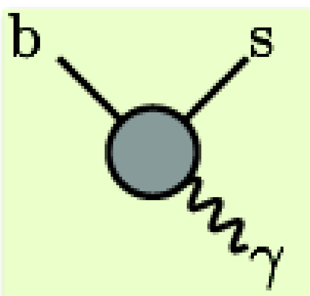
The penguin laboratory

The decay $B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^-\pi^+$ is in the SM only possible at loop level

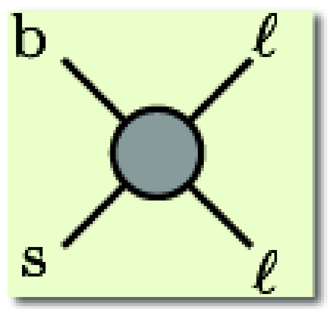
- This means that SM and NP processes are put on equal footing.

Angular analysis of 4-body $K^-\pi^+\mu^+\mu^-$ final state brings large number of observables

Interference between these

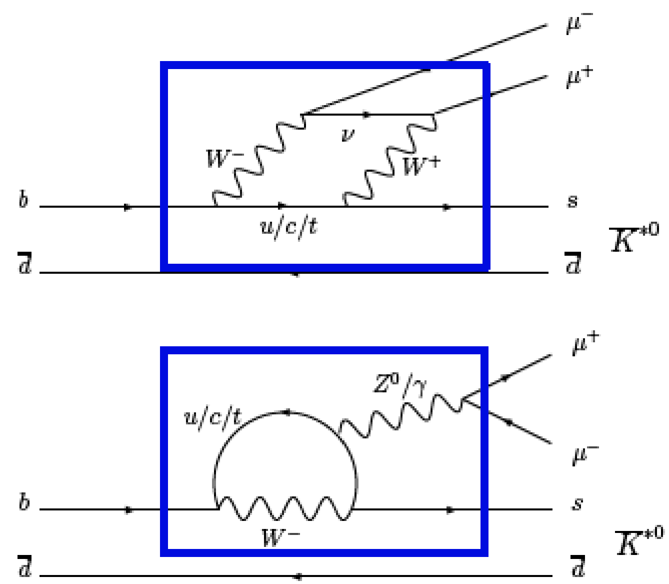


$O_{7\gamma}$



$O_{9,10}$

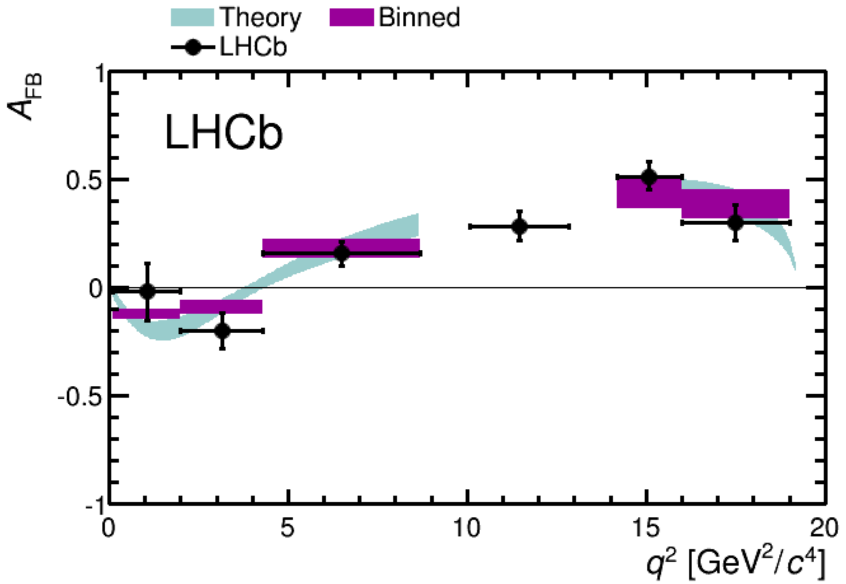
... and their right-handed counterpart

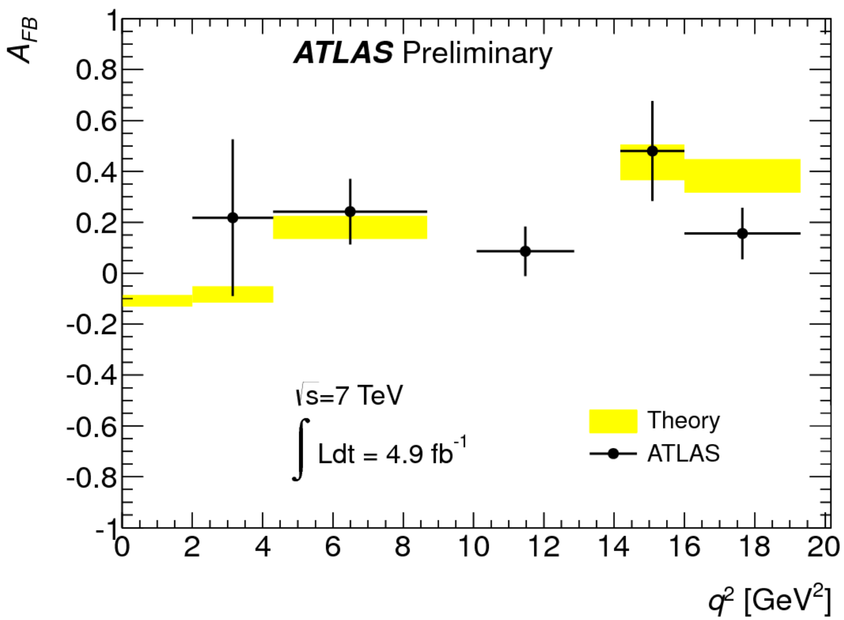


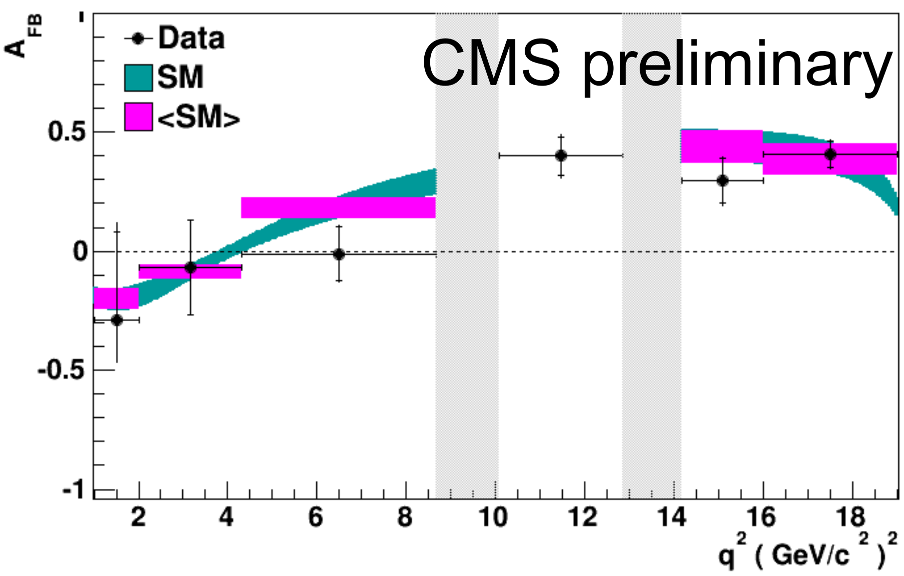
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

LHCb, ATLAS and CMS all have access to the final state.

Only LHCb cover full dimuon mass range







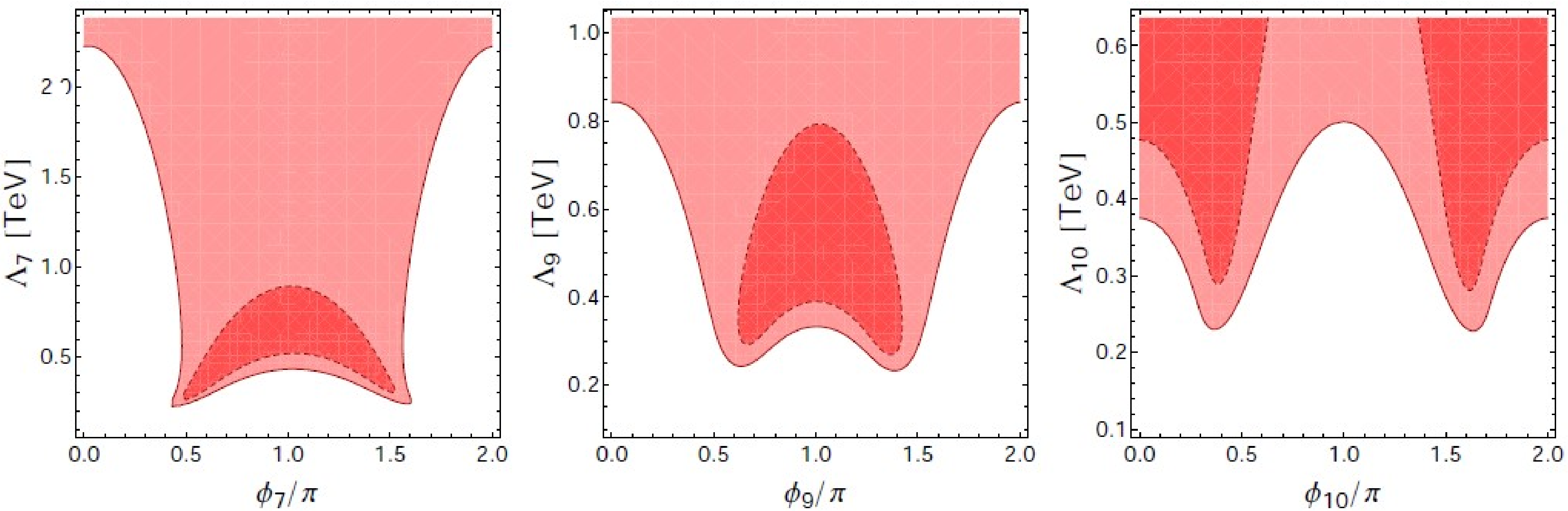
Constraints on new physics

Measurements of B→μμ, B→K*μμ, $B\to X_s\ell\ell$, b →sγ sets limits on the mass scale of non-SM contributions

Altmannshofer, Paradisi , Straub: JHEP 04 (2012) 008 + updates

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^{*}}{16\pi^2}\frac{e^{i\phi_j}}{\Lambda_j^2}\mathscr{O}_j$$

~loop level CKM-like flavour violation



Nothing with SM type flavour couplings below O(400 GeV)

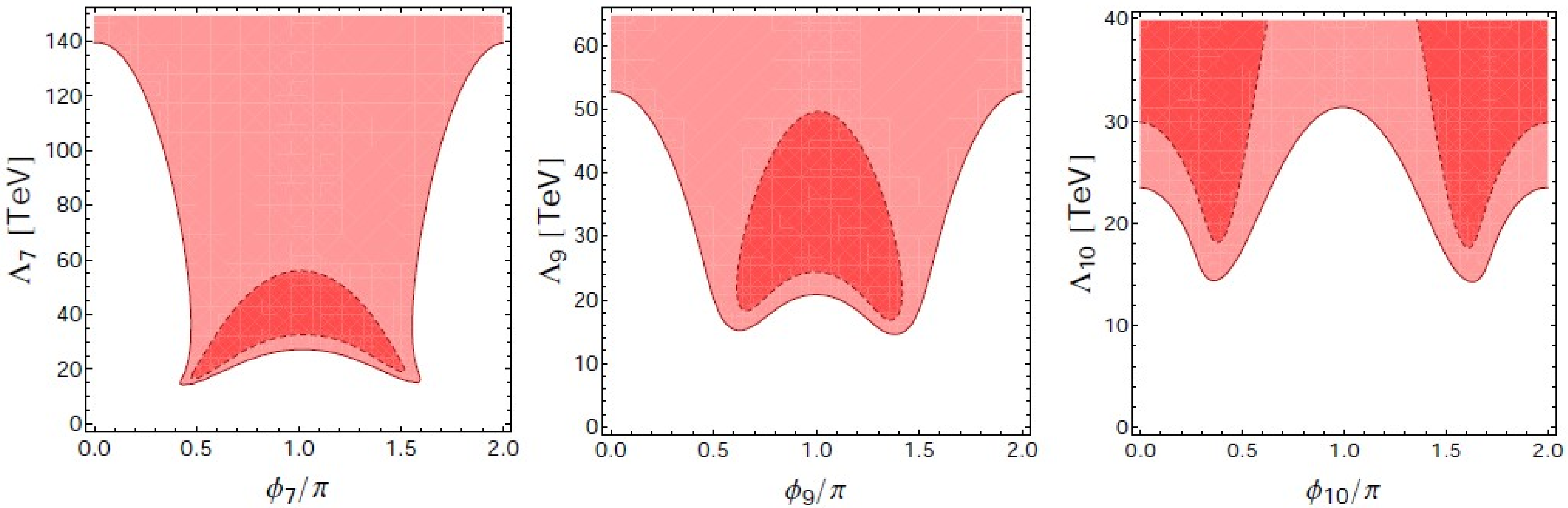
Constraints on new physics

If on the other hand considering tree level processes with O(1) couplings

- Limits on this are in excess of 15 TeV

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathscr{O}_j$$

~tree level generic flavour violation

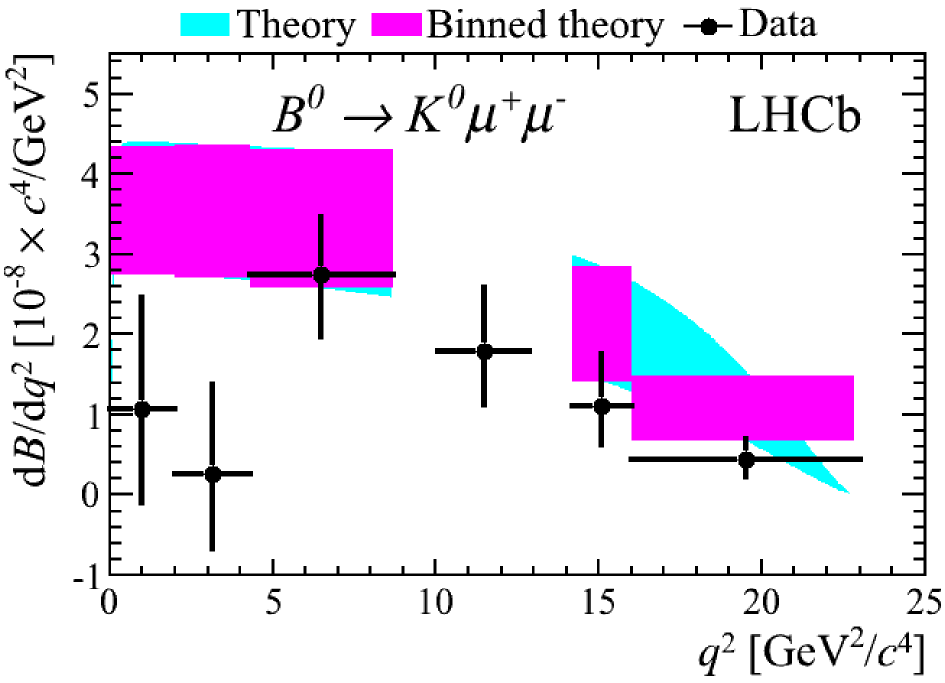


$B \to K^{(*)}\mu^+\mu^-$ isospin analysis

Can look at the isospin asymmetry in rare decays

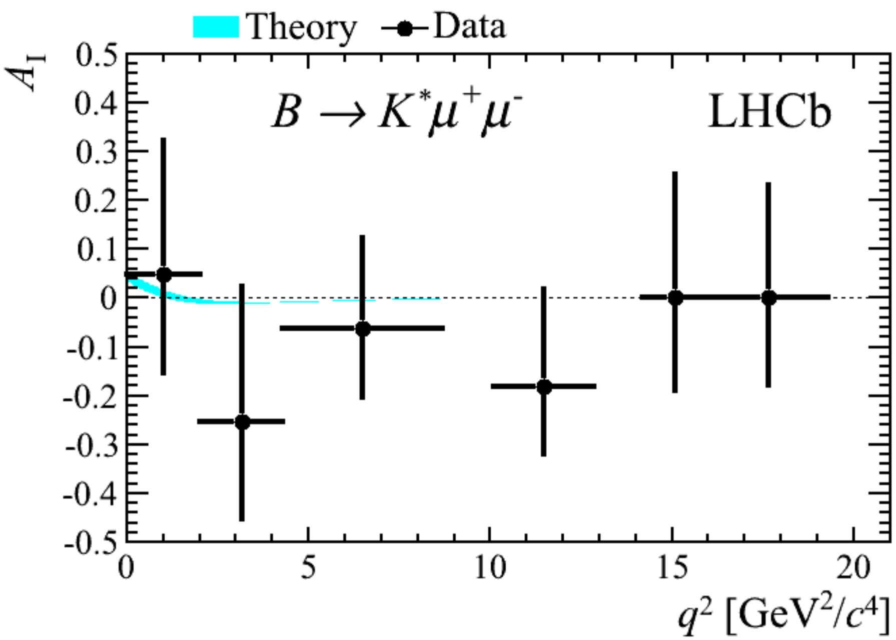
$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

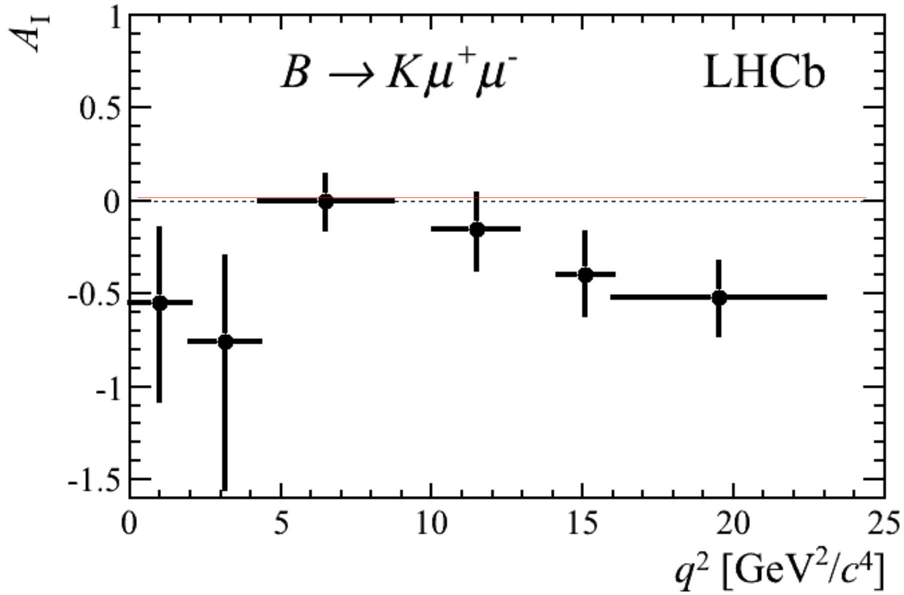
In full 2011 data, measure individual differential branching fractions



$B \rightarrow K^{(*)}\mu^+\mu^-$ isospin analysis

Then form ratios





Result for $B \rightarrow K^*\mu^+\mu^-$ in agreement with SM theory

But $B \rightarrow K\mu^+\mu^-$ differs from zero expectation of above 4σ

No theory explanation of this yet, neither in or outside SM

CP violation

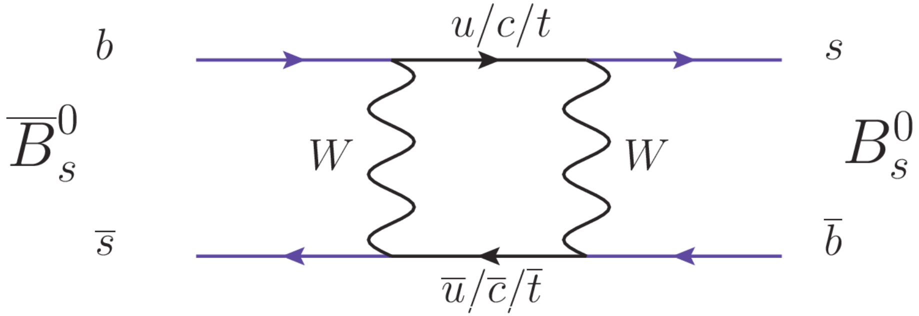
Challenges

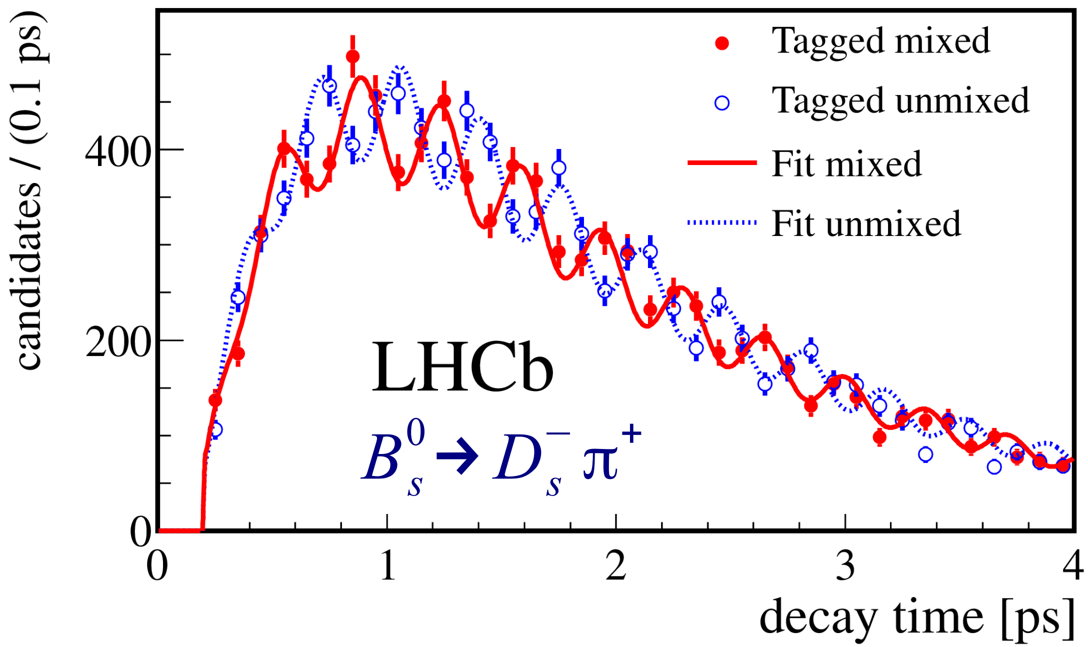
- Production asymmetries
  - Asymmetric pp system
- Detector asymmetries
  - LHCb can flip magnetic field but not matter to antimatter!
- Sub-dominant penguin diagrams
  - Need interference to measure CP violation but not of too many diagrams ...
- Trigger
  - Many hadronic final states that very hard to trigger on
- Calibration of particle identification
  - Required to understand peaking backgrounds and performance of flavour tagging

The B^0_s system

The B^0_s can oscillate into its antiparticle

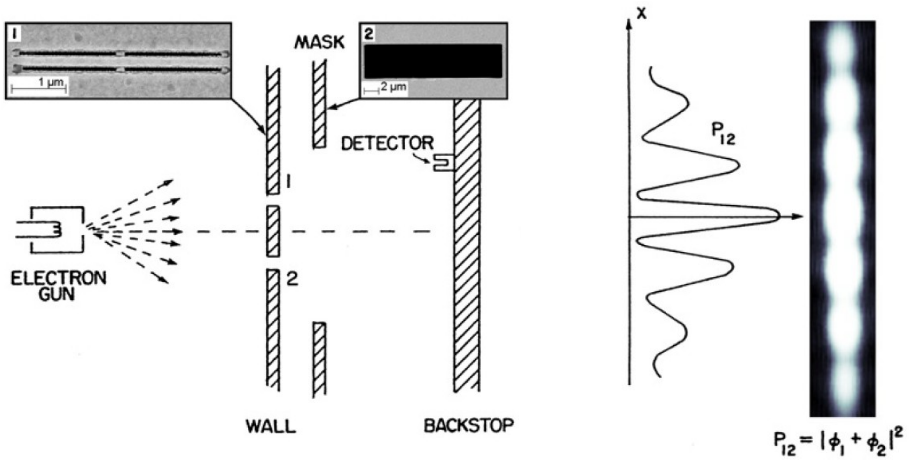
- The weak eigenstates are no longer B^0_s and $\overline{B}^0_s$
  - Two eigenstates with different mass and width

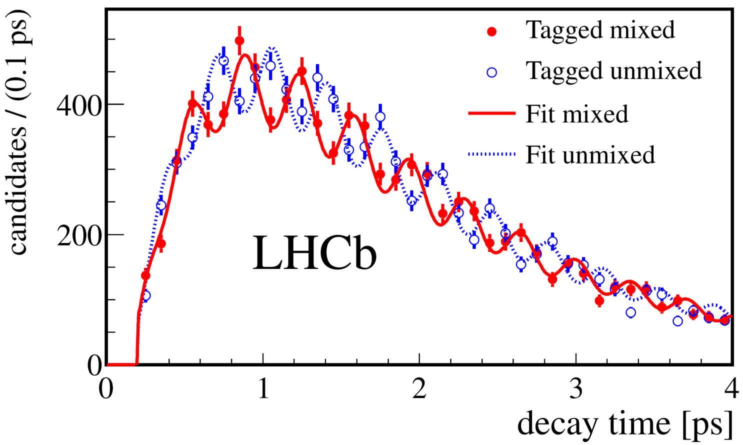




The B^0_s system

A demonstration of QM amplitude interference





Double slit experiment

- Different path length
- Same energy

Gives direct measurement of electron wavelength

B^0_s oscillation

- Different energies (mass)
- Same path length

Gives measurement of mass difference

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \text{ps}^{-1}$

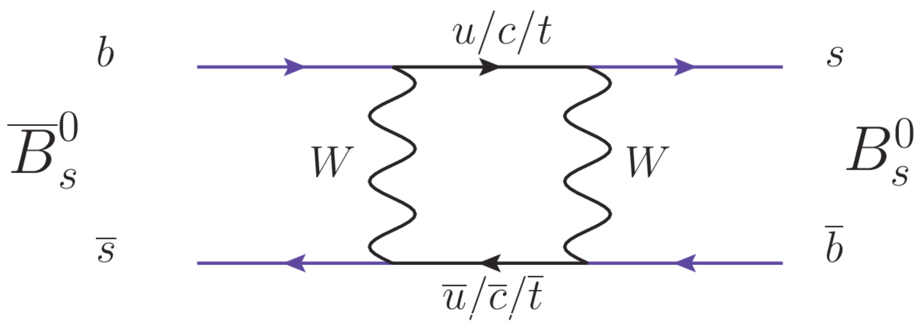
The B^0_s system

The φ_s fit

Look for shared final state between B^0_s and $\overline{B}^0_s$

$B^0_s \rightarrow J/\psi\varphi$, $B^0_s \rightarrow J/\psi\pi^+\pi^-$

Weak phase in box diagram will show up as CP violation



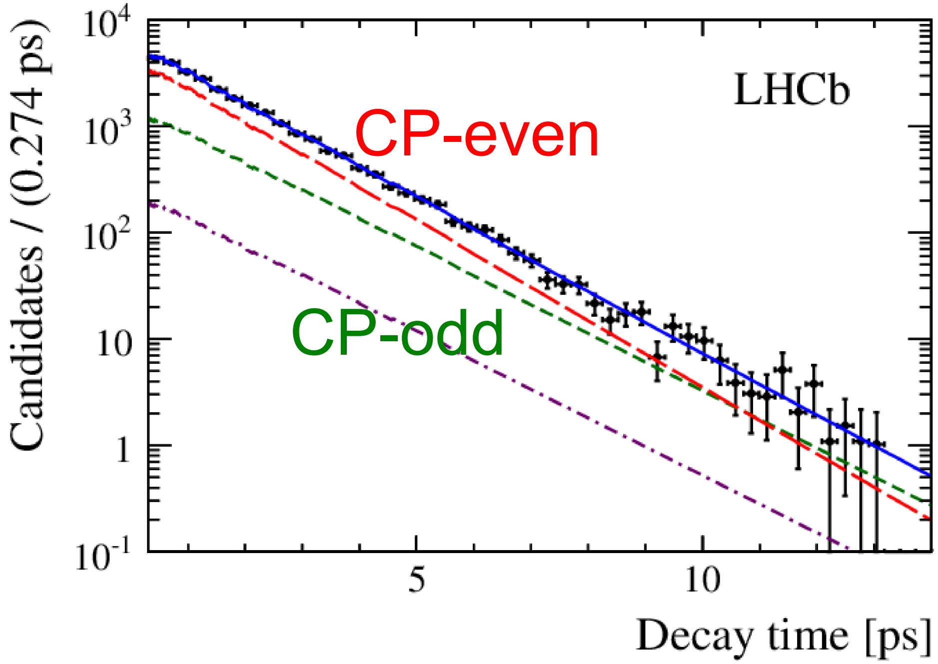
In SM the expected CP violation asymmetry has magnitude

$$\varphi_s \overset{SM}{=} 2\arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb}) = 0.036 \pm 0.02$$

Plenty of space for NP to manifest itself

The B^0_s system

Perform a simultaneous fit to lifetime, production flavour and three decay angles



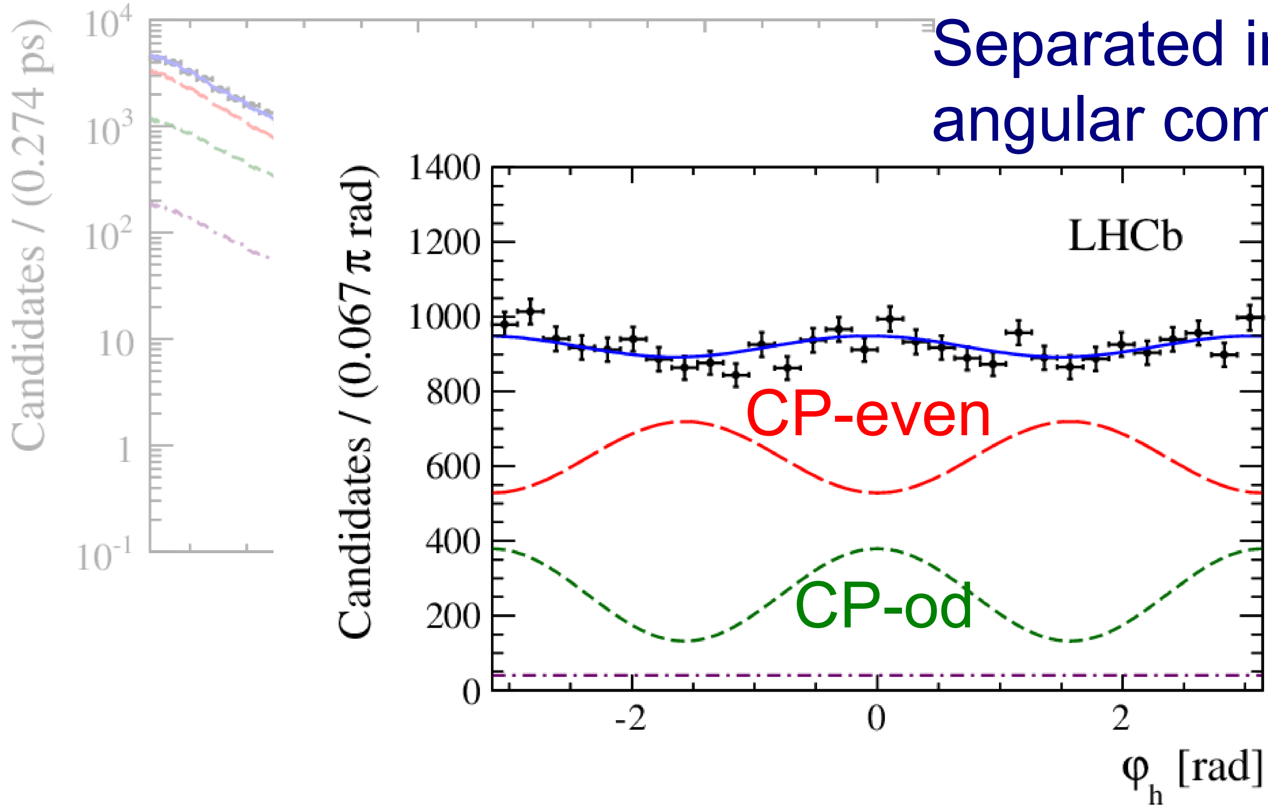
Lifetime projection

- CP-even and CP-odd components visible

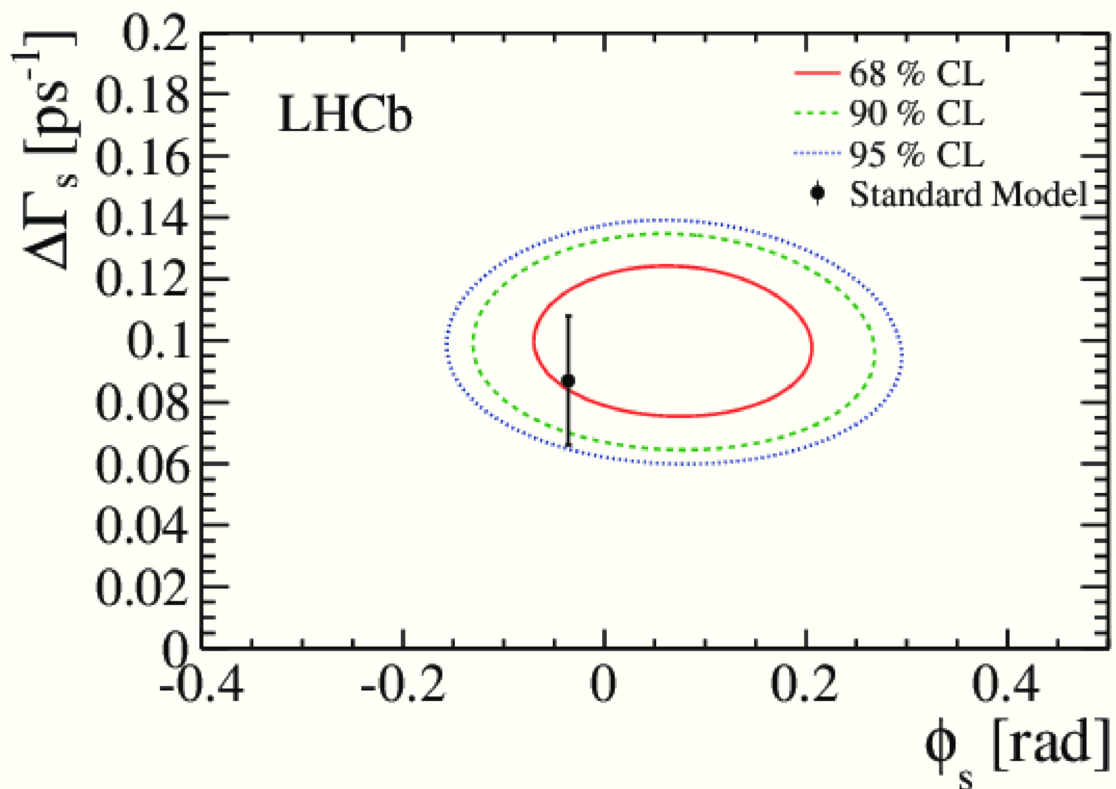
The B^0_s system

Perform a simultaneous fit to lifetime, production flavour and three decay angles

Separated in one of the angular components



The B^0_s system

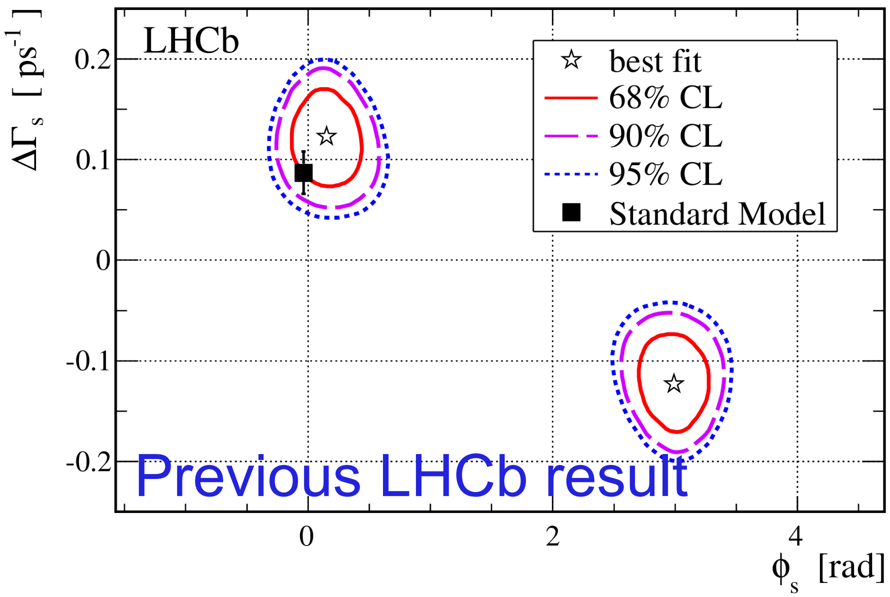


Combined result with $B^0_s \to J/\psi\varphi$, $B^0_s \to J/\psi\pi^+\pi^-$

$$\begin{aligned}\phi_s &= 0.01 \pm 0.07\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad},\\ \Gamma_s &= 0.661 \pm 0.004\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1},\\ \Delta\Gamma_s &= 0.106 \pm 0.011\ (\text{stat}) \pm 0.007\ (\text{syst})\ \text{ps}^{-1}.\end{aligned}$$

The B^0_s system

Until recently there was a two-fold ambiguity in the measurement of the CP-violating phase

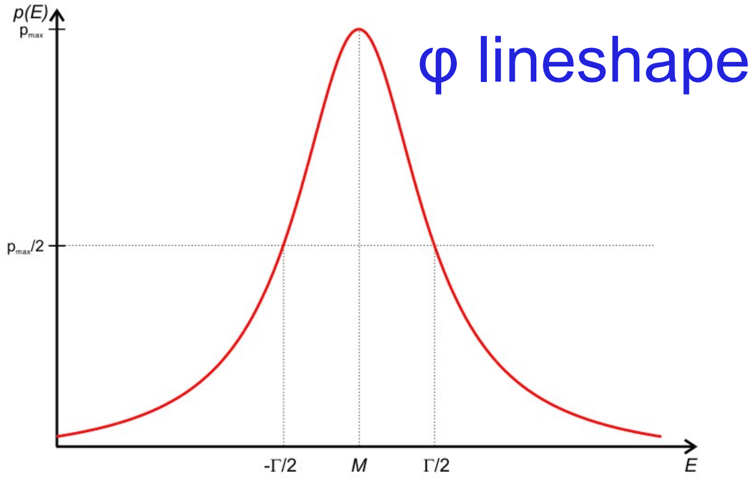


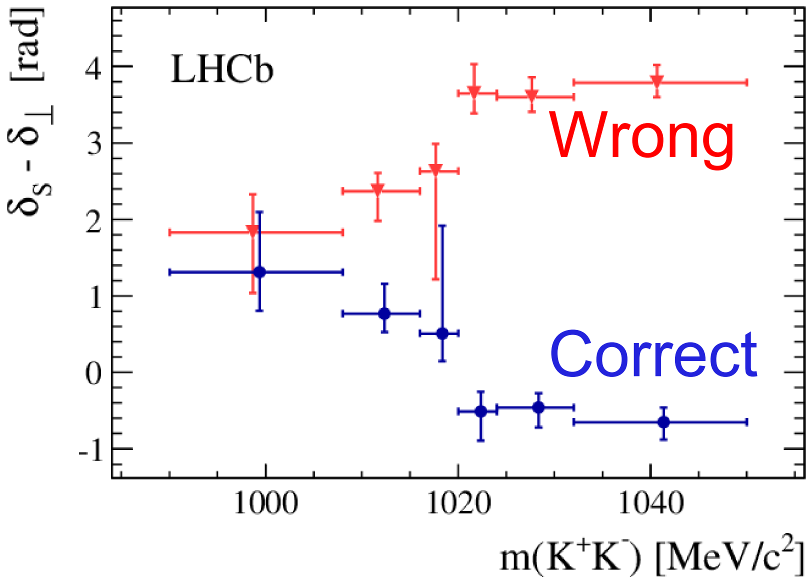
How did the other (non-SM) option go away?

Actually what was a pain turns into a blessing

The B^0_s system

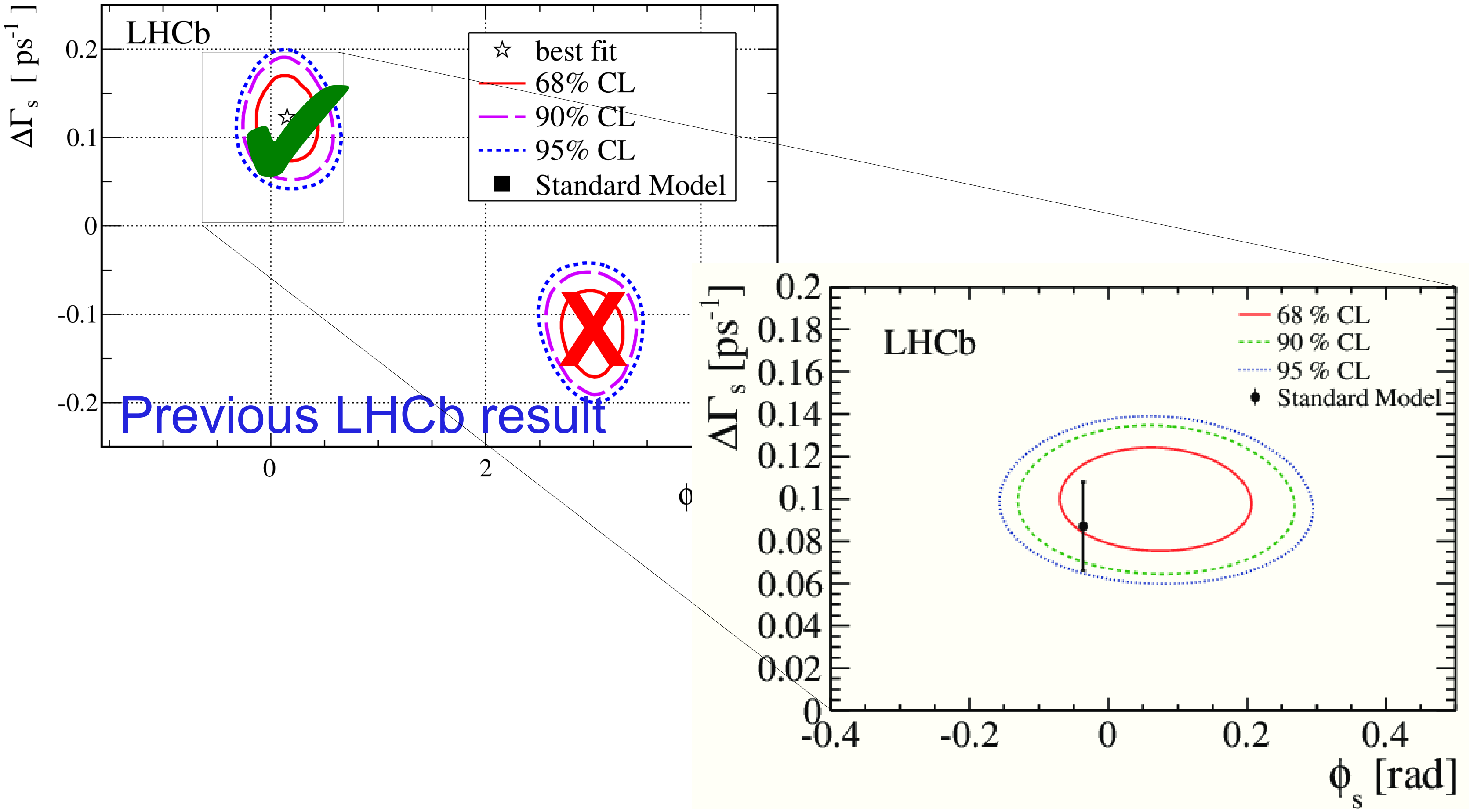
- The final state $B^0_s \to J/\psi K^+K^-$ is not all through the narrow $\varphi \to K^+K^-$ P-wave
  - Some broad S-wave at the 5% level
  - As moving across φ mass we see phase shift of Breit-Wigner
- Get the sign of phase shift wrong if picking wrong (φ,ΔΓ) solution





The B^0_s system

The unique solution can now be identified

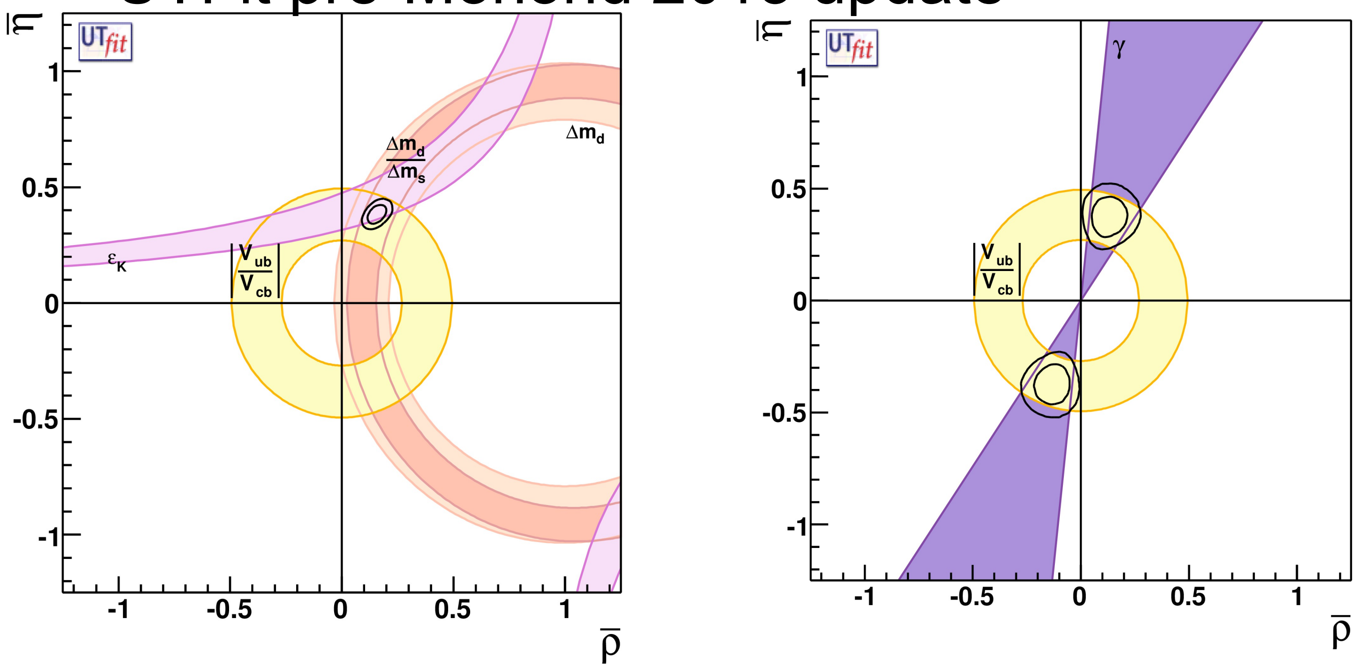


CP angle γ

The global fits to CKM parameters give a very precise prediction of CP angle γ within SM

- Precision in making the matching direct measurements only now emerging

UTFit pre-Moriond 2013 update

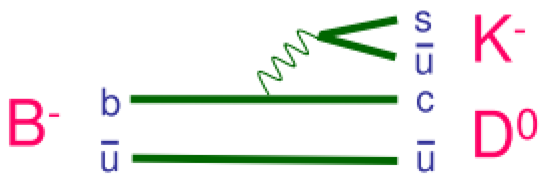


CP angle γ

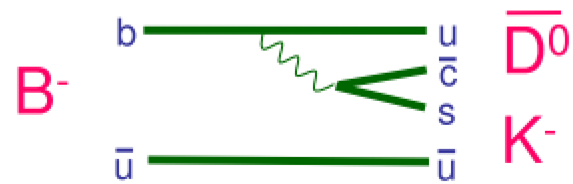
The global fits to CKM parameters give a very precise prediction of CP angle γ within SM

Only now are precise direct measurement possible

- B^- can decay into both D^0 and $\overline{D^0}$, diagrams very different amplitudes

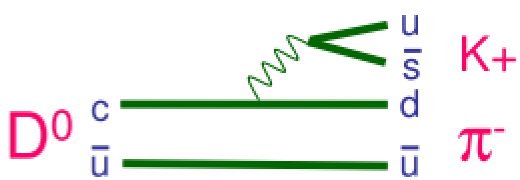


colour favoured

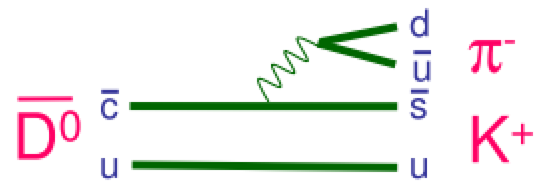


colour suppressed

- Decays of D^0, $\overline{D^0}$ to same final state gives access to interference



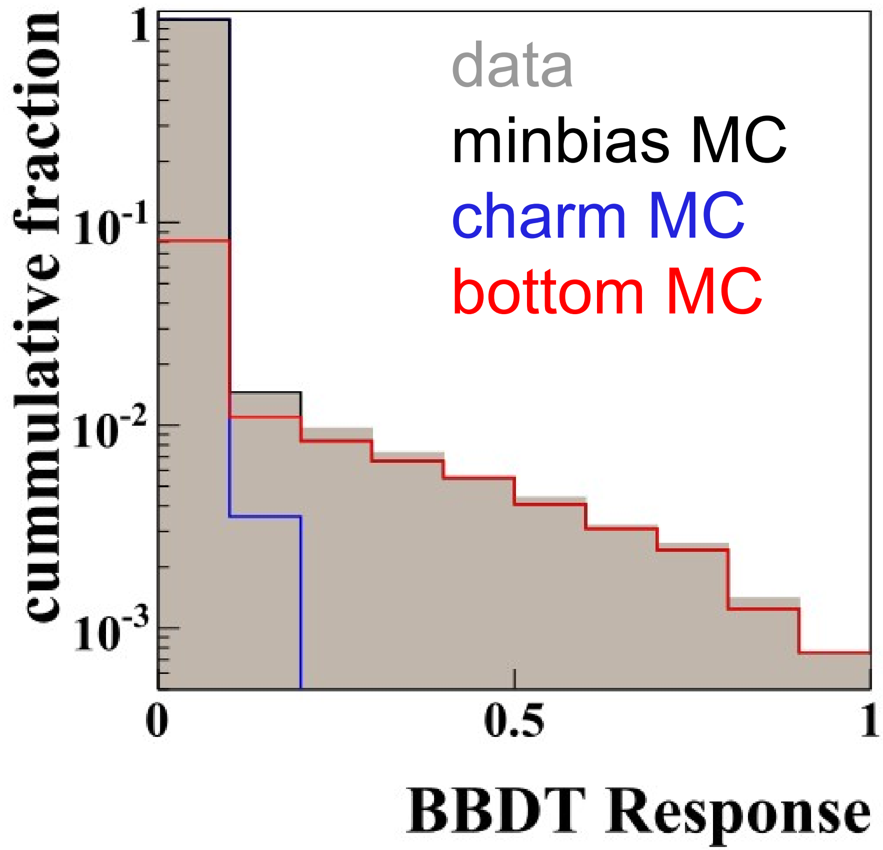
(doubly) cabibbo suppressed



cabibbo favoured

CP angle γ

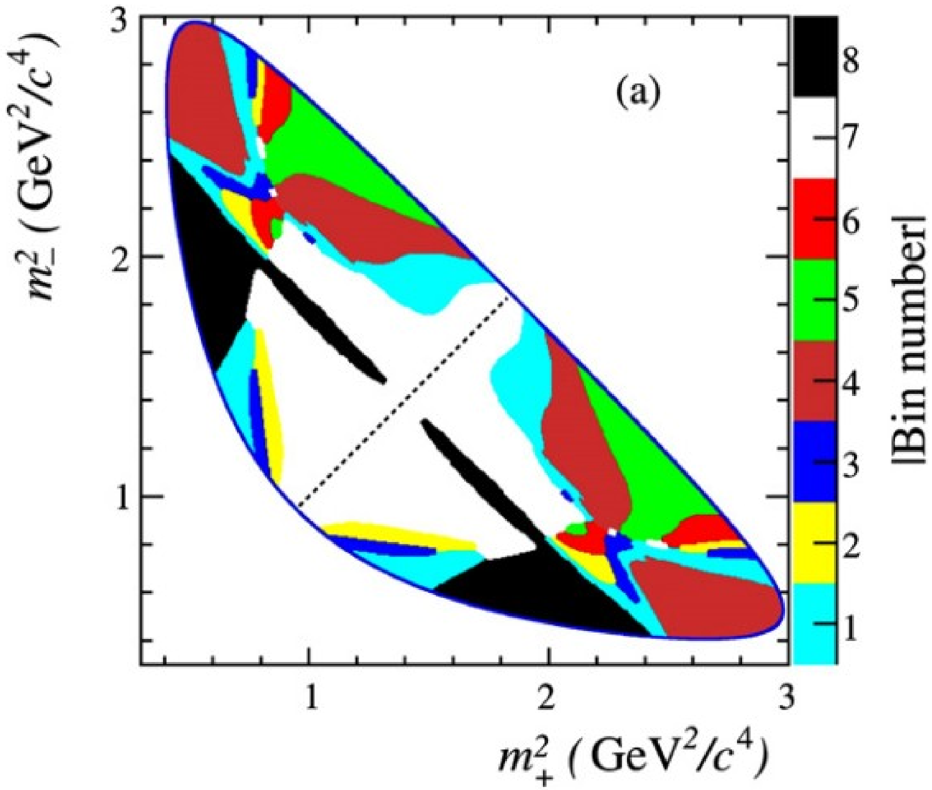
- The trigger of these decays is a challenge
  - Partial reconstruction of secondary B vertex is the only thing that works
  - A multivariate selection based on a BDT developed
  - Resolution pruned to avoid threshold effects
- Selects the events that can subsequently be used offline



CP angle γ

Illustrate method with $B^{\pm} \rightarrow D K^{\pm}$, $D \rightarrow K_s^0 \pi^+ \pi^-$ decays

- Dividing Dalitz plot in symmetric regions and comparing 4 rates for those gives strong phase and γ



CP angle γ

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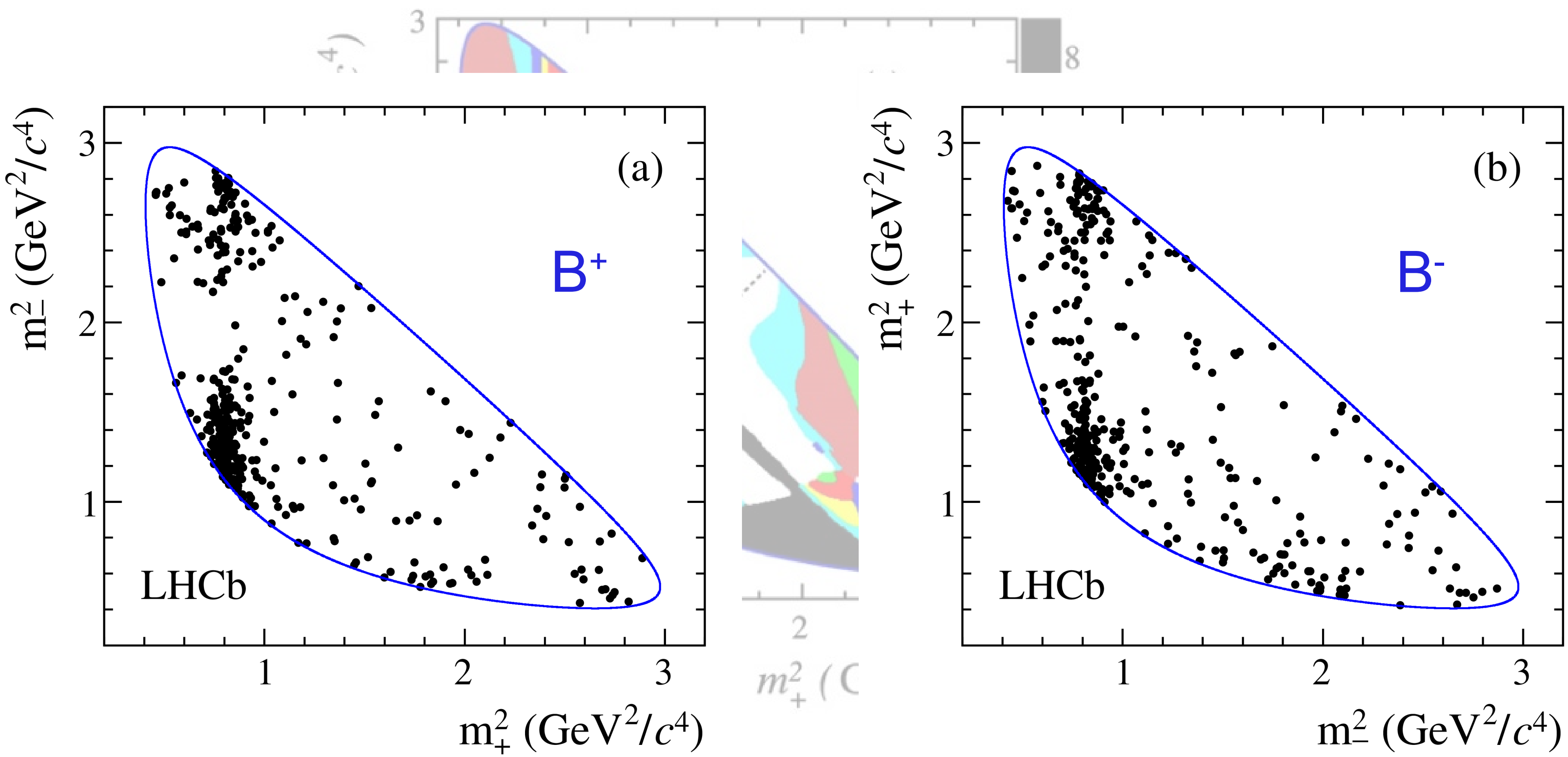
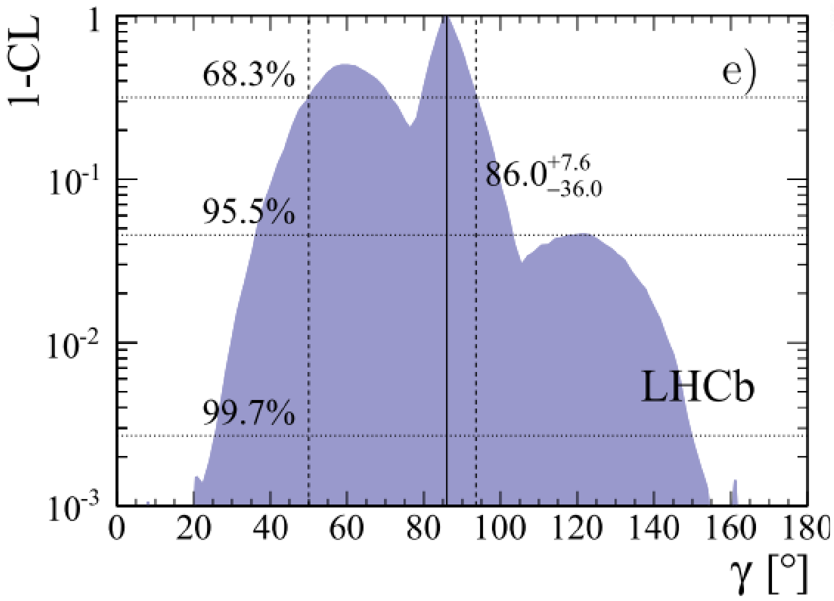
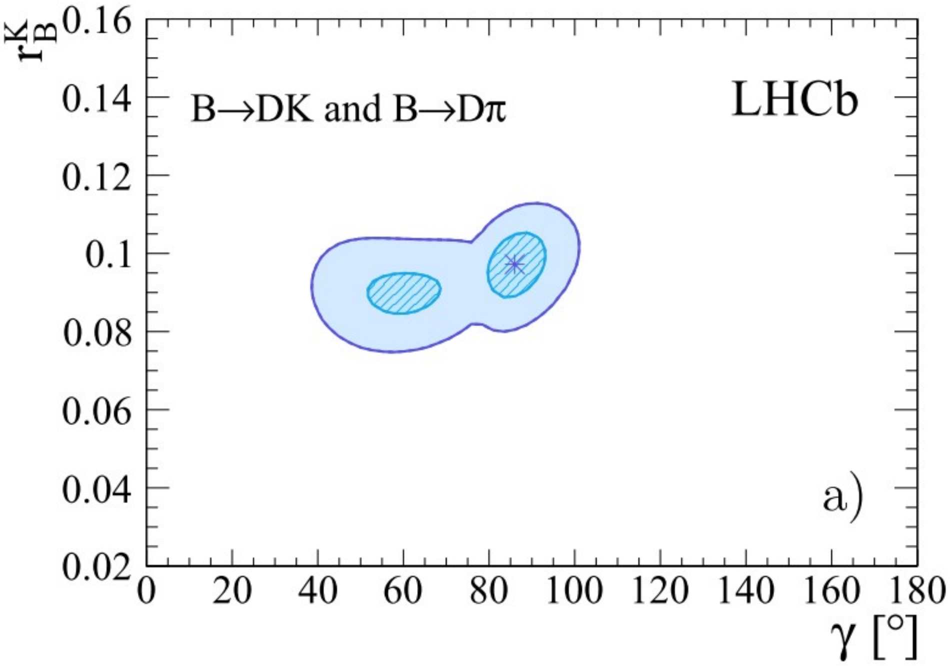


CP angle γ

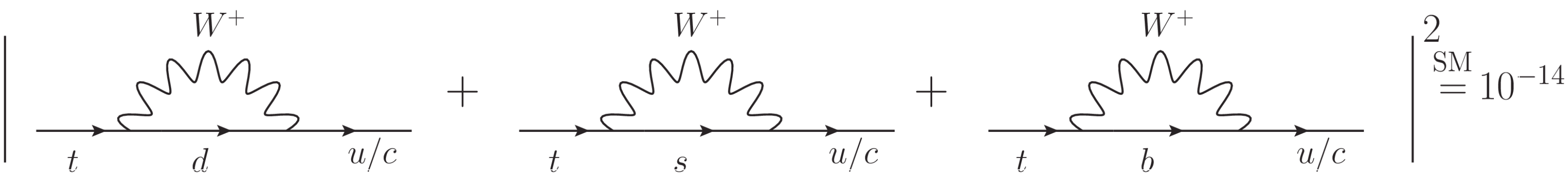
Combined result from all different B→DK and B→Dπ modes





Search for FCNC in top quark decays

With massless quarks, FCNC decays are forbidden in the SM (GIM mechanism)



- Comparing to the top mass, all other quarks **are** massless
- Hence FCNC for top ($t \rightarrow c\,X$, $t \rightarrow u\,X$) are suppressed by factor 10^{-14} in SM
- Search for $t\bar{t} \rightarrow (Z^0 u/c)(W^- b), Z^0 \rightarrow l^+ l^-, W^- \rightarrow l^- \nu$

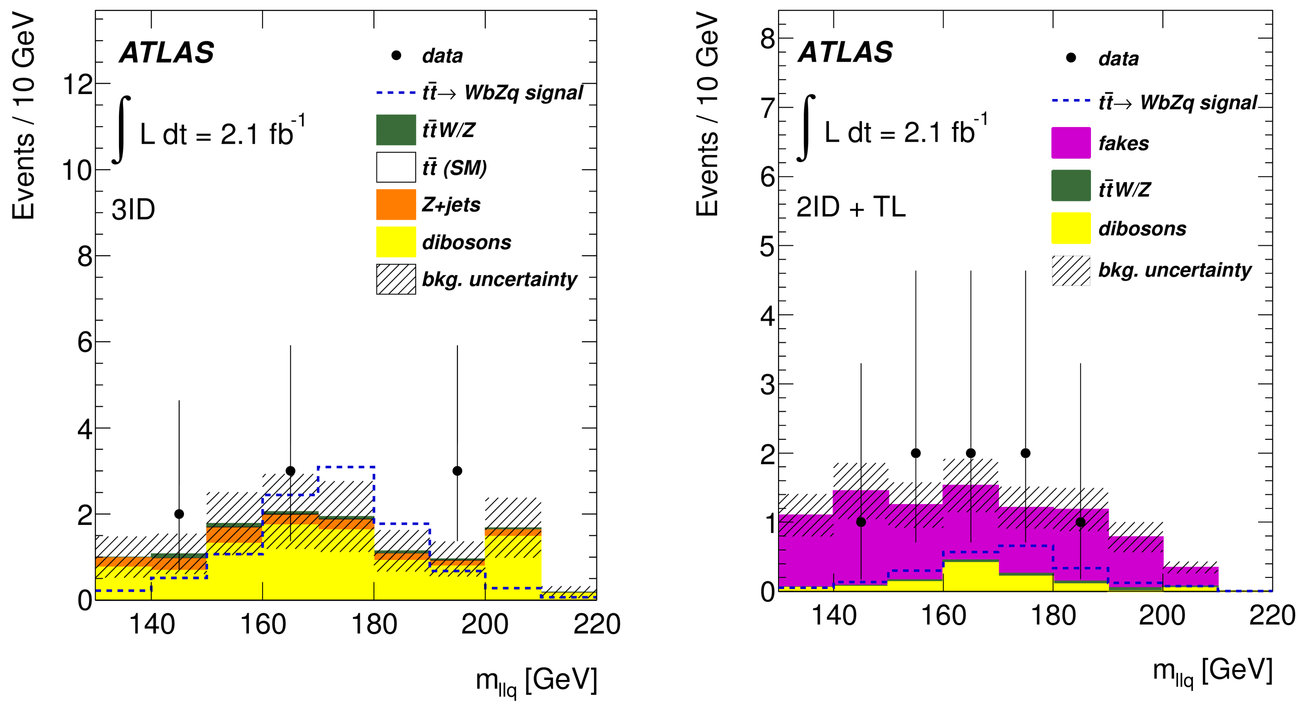
Three leptons in final state results in almost 100% trigger efficiency

Search for FCNC in top quark decays

Result is

BF($t \rightarrow Z^0 u/c$) < 0.73% @ 95% CL [ATLAS 2.1 fb^{-1}]

BF($t \rightarrow Z^0 u/c$) < 0.07% @ 95% CL [CMS 19.5 fb^{-1}] (prelim)



Where to go now for LHCb?

- Aim of upgrade during LS2 of LHC
  - Improve annual yields by factor 10 (leptonic) to 20 (hadronic)
- As elsewhere at LHC, the real limitation for progress is in the trigger
  - The hardware trigger of LHCb at 1.1 MHz starves hadronic final states at luminosities above ~3 10^{32} $cm^{-2}s^{-1}$
  - Solution is to get rid of it and run a High Level Trigger at 40 MHz
- Hardware upgrades
  - Move pixel detector closer to beam to improve light quark rejection
  - Keep occupancy low in RICH system and tracking

Conclusion

- Flavour physics has sensitivity to mass scales that are well above the direct production scale accessible
  - Many areas where measurements are far away from systematics limits imposed by experiments or theory
  - Challenge is in many cases to obtain even larger event samples
- Overall the SM comes out as matching the data very well
  - Isospin result in $B \to K\mu\mu$ the most challenging thing to explain at the moment (in or outside SM)
- Very fruitful relationship between phenomenologists and experimentalists to improve measurements and develop new channels