Imperial College
London

Future of Heavy Flavour Physics

Ulrik Egede

Physics at LHC and beyond
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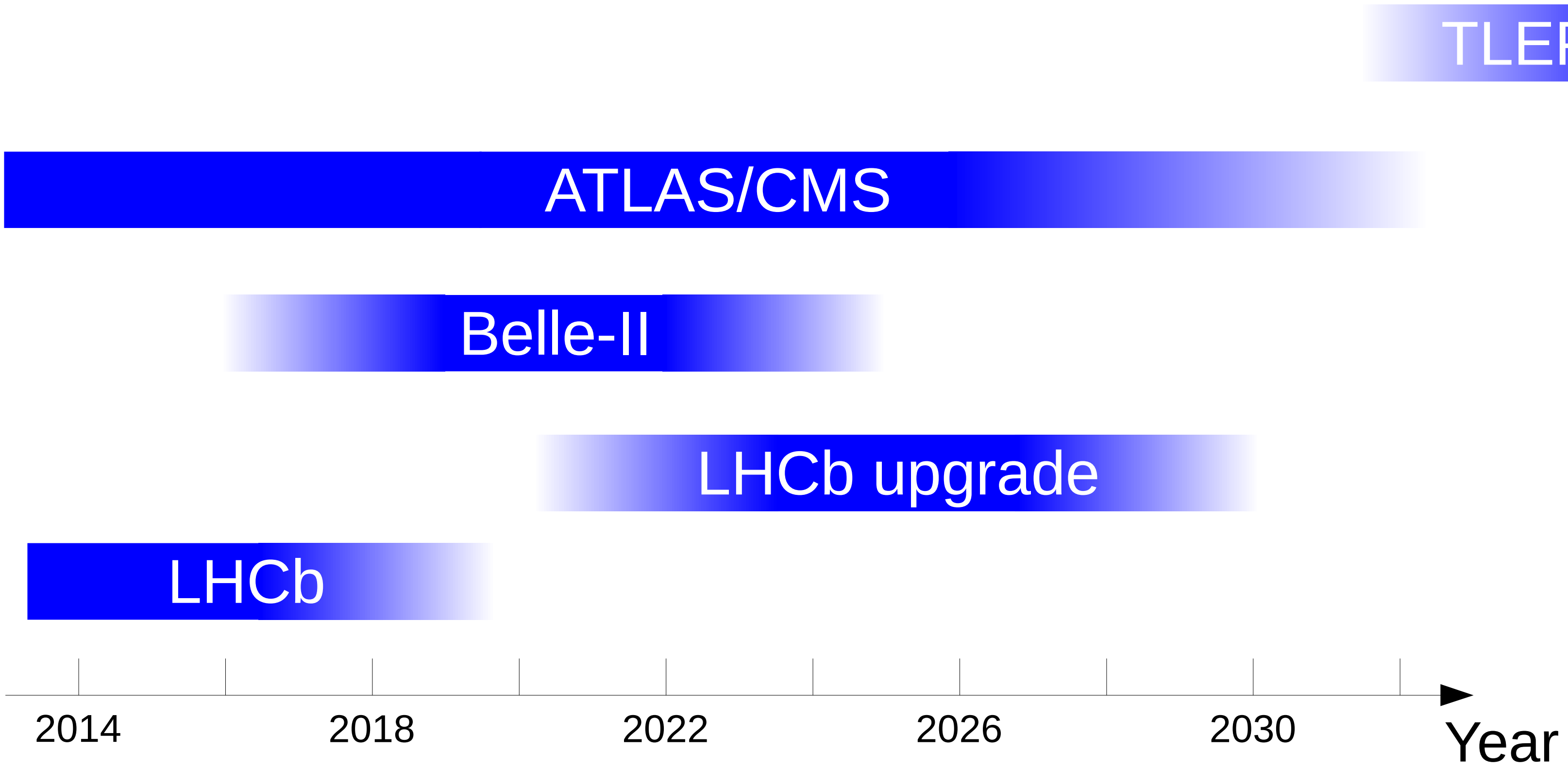
Why ?

- Interactions of the different flavours of the quark and lepton sector
  - Both Standard Model and New Physics models has to deal with this
- In SM this is through the Yukawa couplings to the Higgs field and the weak force
  - 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)
- No natural cut-off for mass scale with discovery of Higgs

What can be predicted

- Predictions with no SM theory uncertainty
  - Null tests relying on no New Physics
  - Unitarity of CKM matrix
    - Only one CP violating phase
    - Ratios of CKM matrix elements independent of processes
  - Forbidden, or nearly forbidden decays
  - Lepton universality
- Type of decays
  - Fully leptonic decays
  - Ratios in semi-leptonic decays
  - CP violation in hadronic decays

The proposed facilities available



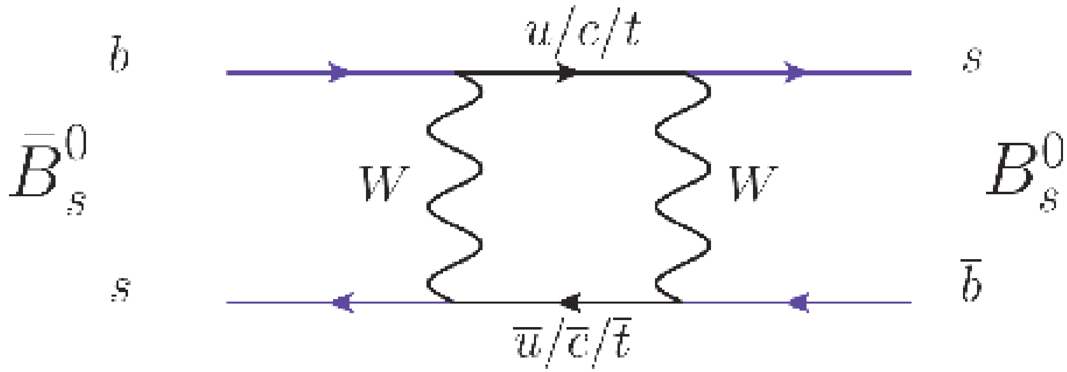
Questions to ask

- For a given prospective measurement, we need to ask the questions
  - What level of statistical accuracy could be expected?
  - How will experimental systematics be controlled?
  - What are the theoretical uncertainties with measurement and can they be reduced?
- From answers conclude if measurement is actually interesting
- Will aim to show here that there are still plenty of interesting measurements

CP violation in $B^0_s \to \varphi\varphi$

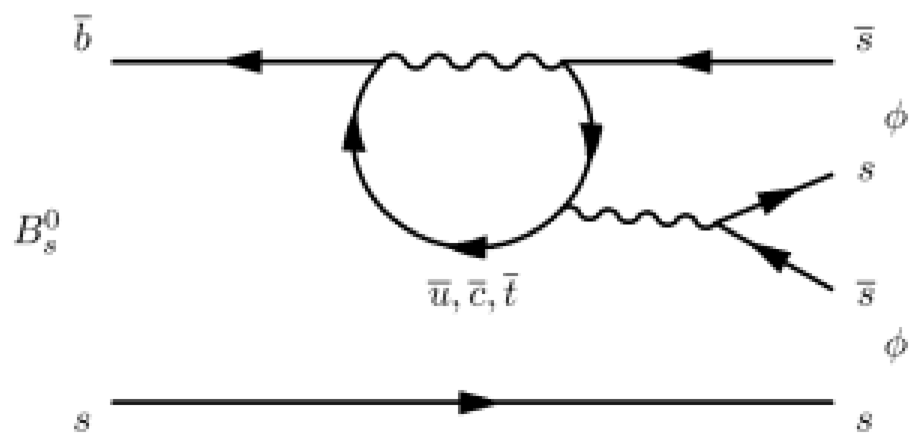
The $B^0_s \to \varphi\varphi$ decay is a unique place to look for NP in loop decays

In SM the CP violation the decay and the loop exactly cancel



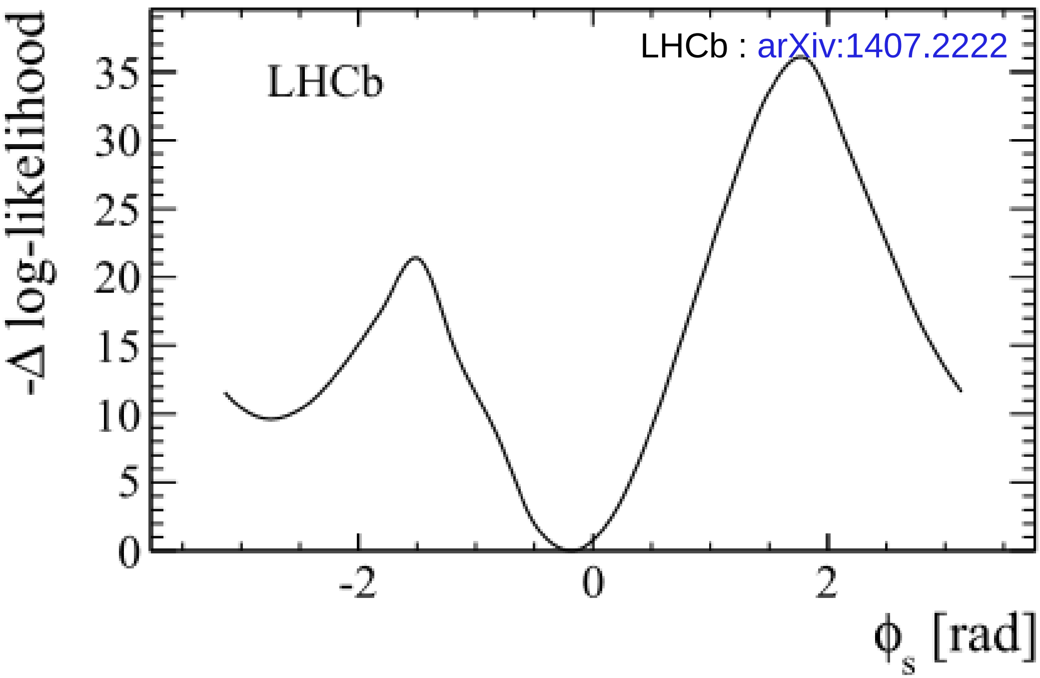
A null-test of the SM that does not depend on external input

- Uncertainties much smaller than in similar $B^0 \to \varphi K^0_s$



CP violation in $B^0_s \to \phi\phi$

Current status of LHCb $B^0_s \to \phi\phi$ measurement



No significant CP violation observed

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \ \mathrm{rad}$$

CP violation in $B^0_s \rightarrow \varphi\varphi$

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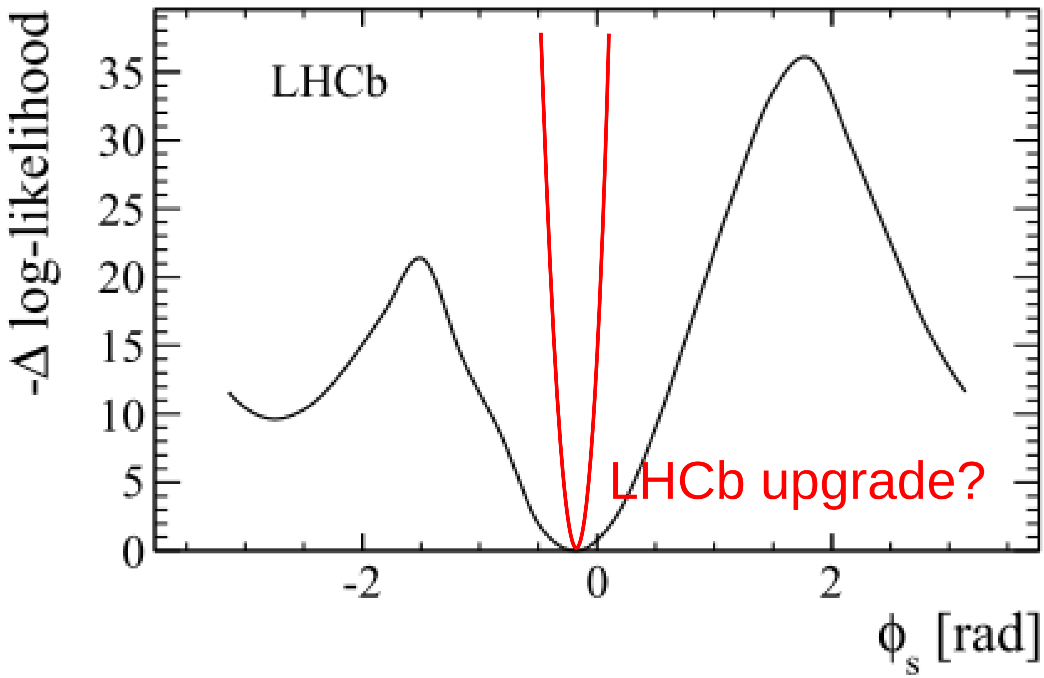


LHCb upgrade will bring precision on this down to 0.02

Same level as the current theoretical uncertainty

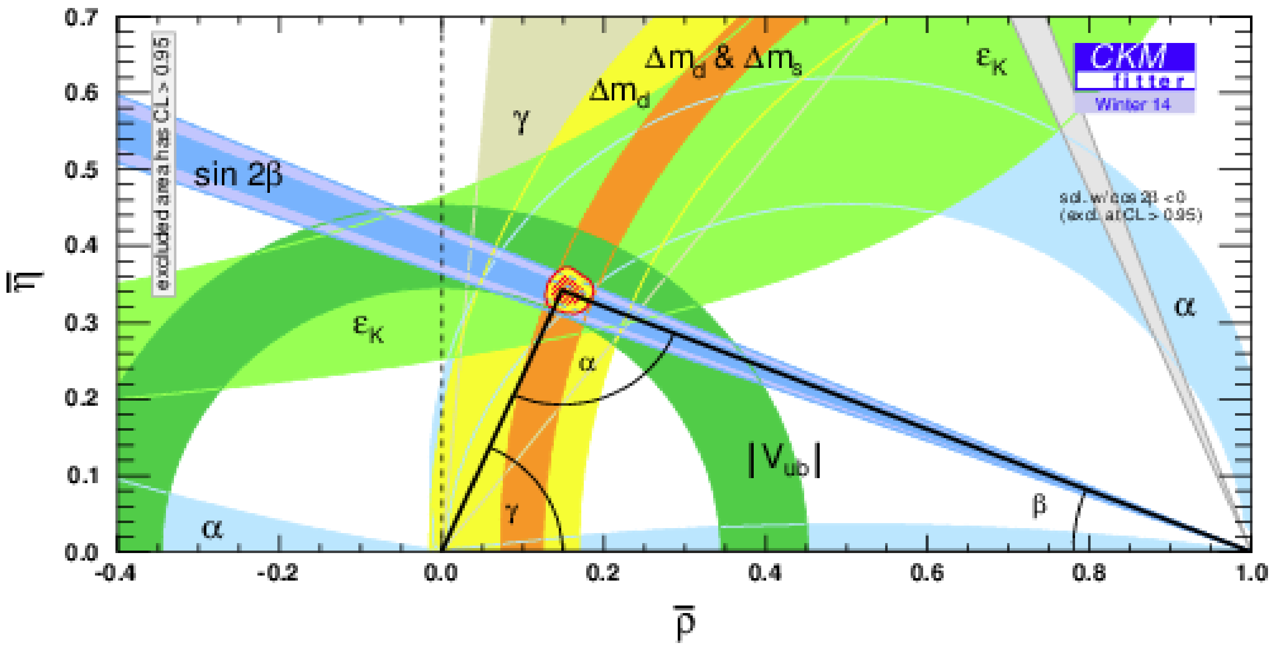
Unitarity of CKM matrix

The SM requires that many different fits to the unitary triangle all result in the same apex

- If not, there are additional amplitudes coming from NP

Largest uncertainties are coming from left side ($|V_{ub}|/|V_{cb}|$) and the angle γ

http://ckmfitter.in2p3.fr/



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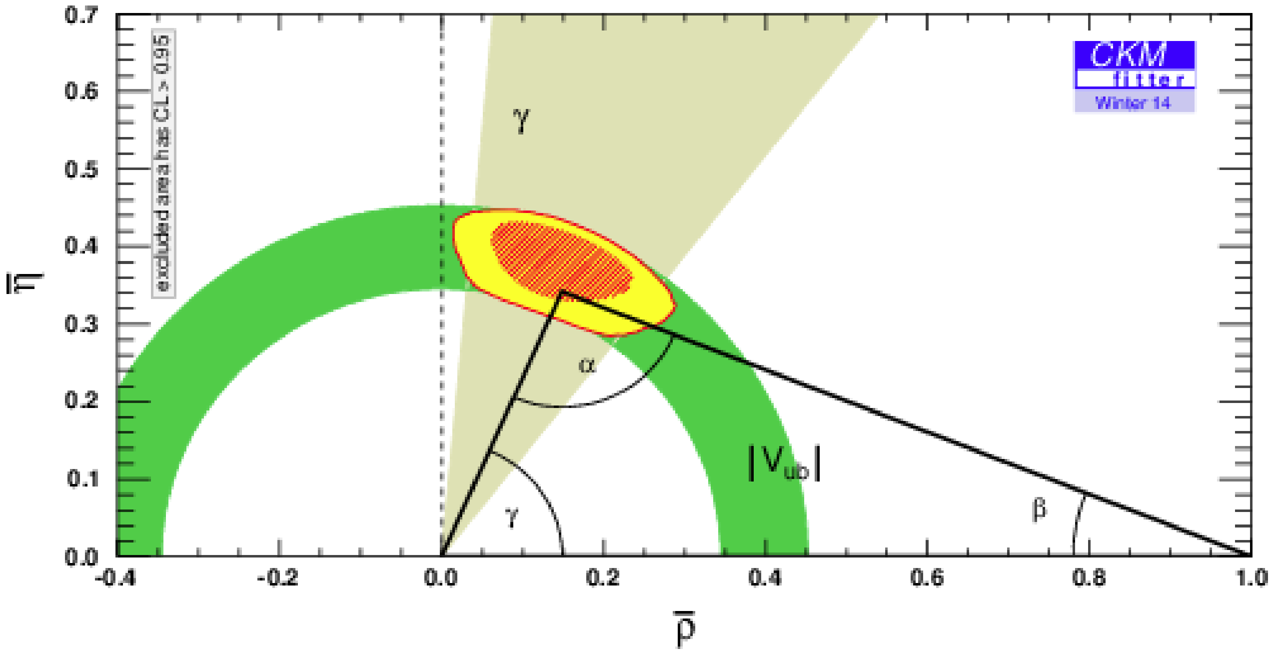
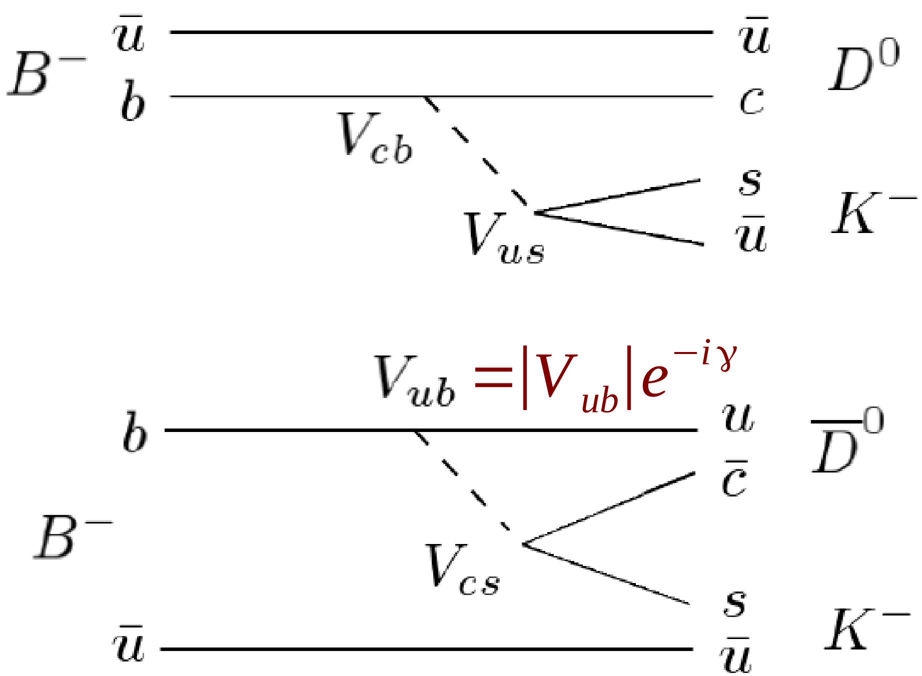


Determination of CP angle γ

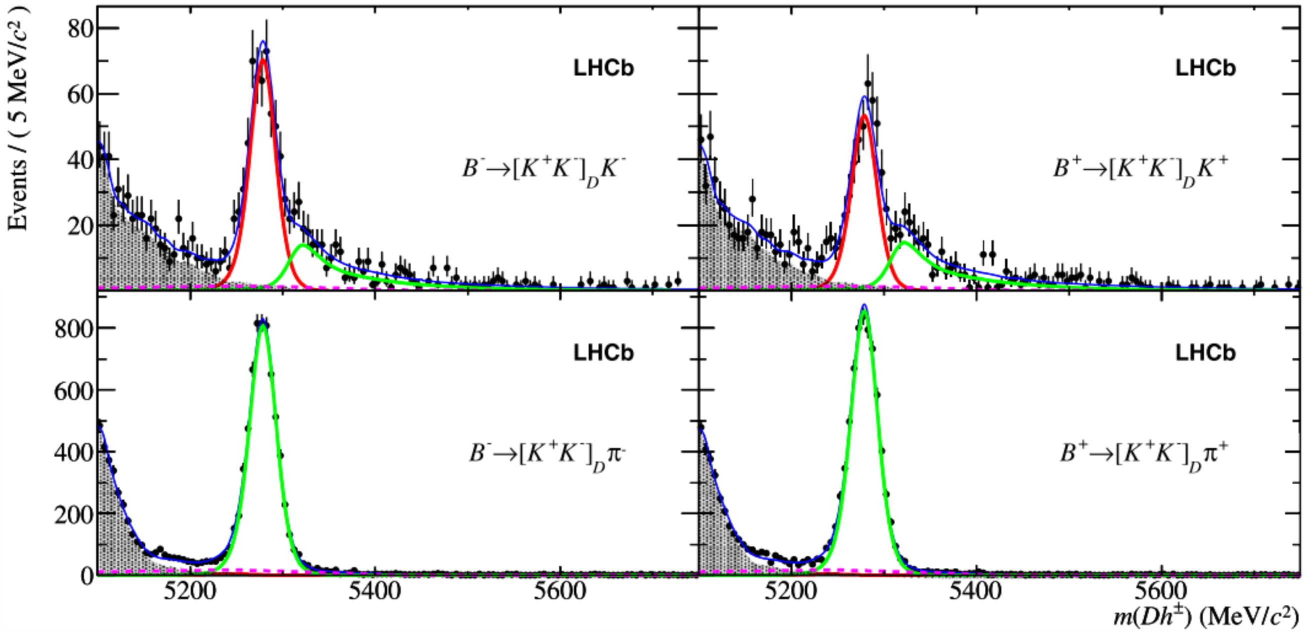
Best determined through interference between tree amplitudes



Followed by D^0 and $\overline{D}^0$ decaying to a common final state like $K^+\pi^-$, $K^+\pi^-\pi^0$, K^+K^-, ...

Theoretical uncertainty on method is at 10^{-7} level (JHEP 01 (2014) 05)

Determination of CP angle γ



PLB 712 (2012) 203

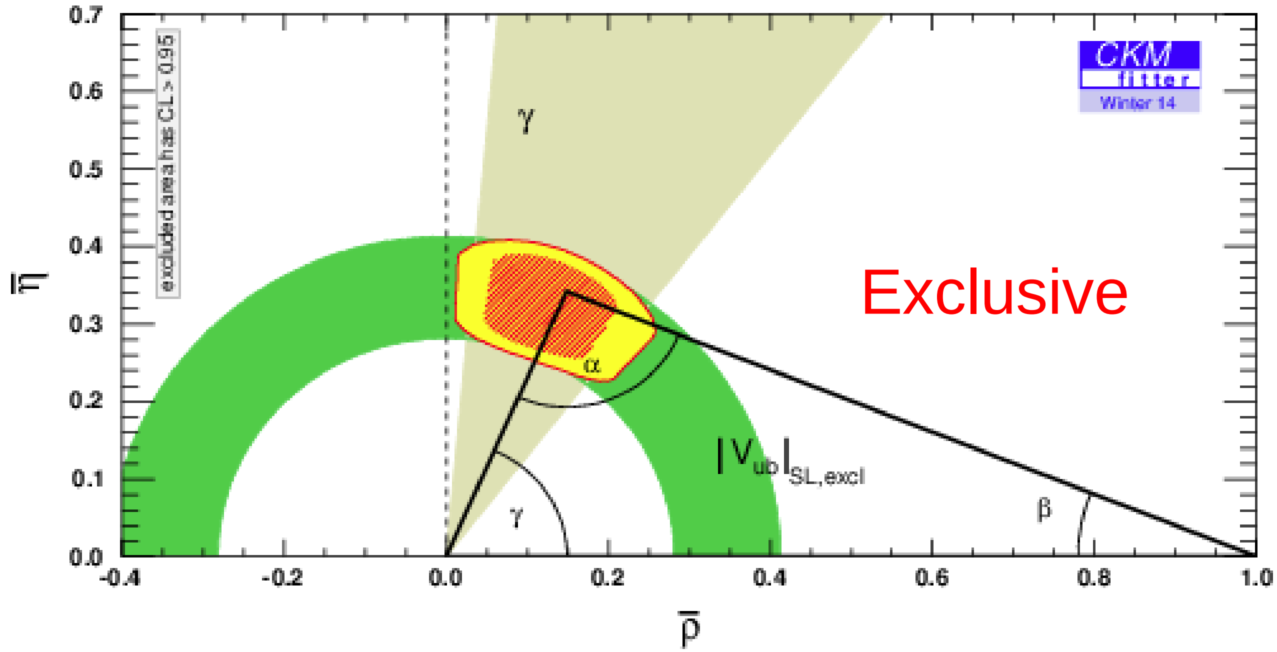
Need to understand relative signal yield in the different final states

- Statistical reach for Belle-II is 2°, for LHCb upgrade 1°
- To keep systematic uncertainty below this requires to understand tracking for positive/negative particles exceptionally well

The need to resolve the problem with $|V_{ub}|$

The measurement of $|V_{ub}|$ hides and internal inconsistency between

- Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \upsilon$
- Inclusive measurement : $B^0/B^+ \rightarrow X_u \mu^+ \upsilon$



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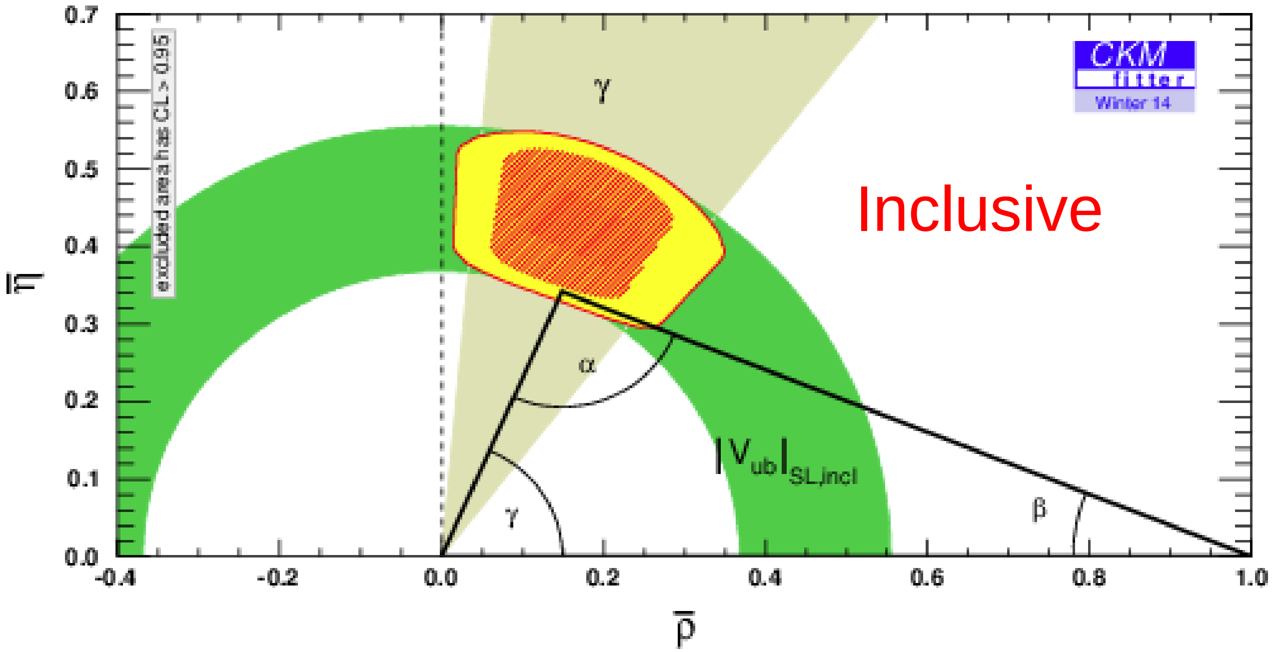

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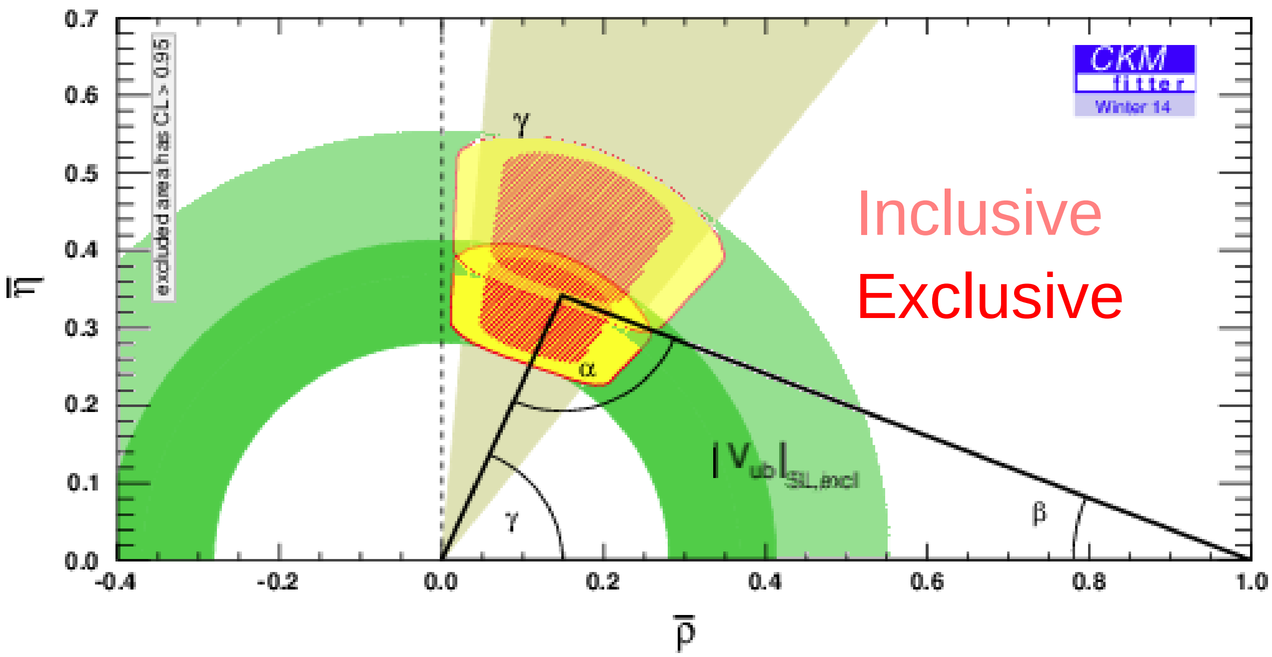


The need to resolve the problem with $|V_{ub}|$

Is internal inconsistency a sign of NP ...

- or just indicating that we do not fully understand QCD?

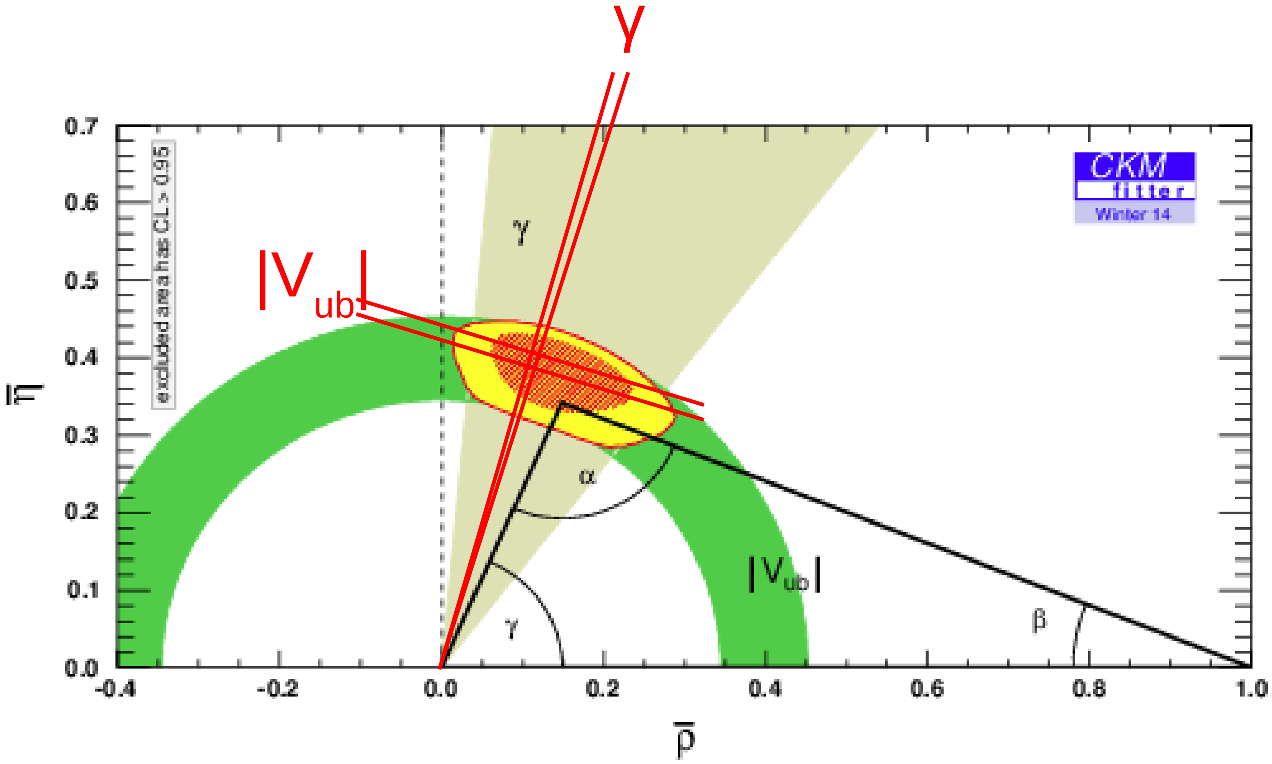
More independent measurements required

- $\Lambda_b \to p\, \mu^- \nu$
  - In progress with LHCb – rely on new $\Lambda_b \to p$ form factors from lattice
- $B^+ \to \tau^+ \nu$
  - At the moment statistics limited, Belle-II will much improve
- Inclusive measurement
  - Large gain in hadron tagged sample with Belle-II
- $B_c^+ \to D^0 \mu^+ \nu$
  - Possible at LHCb or LHCb upgrade. Interesting?

$|V_{ub}|$ at a few percent level will be possible

Unitarity of CKM matrix

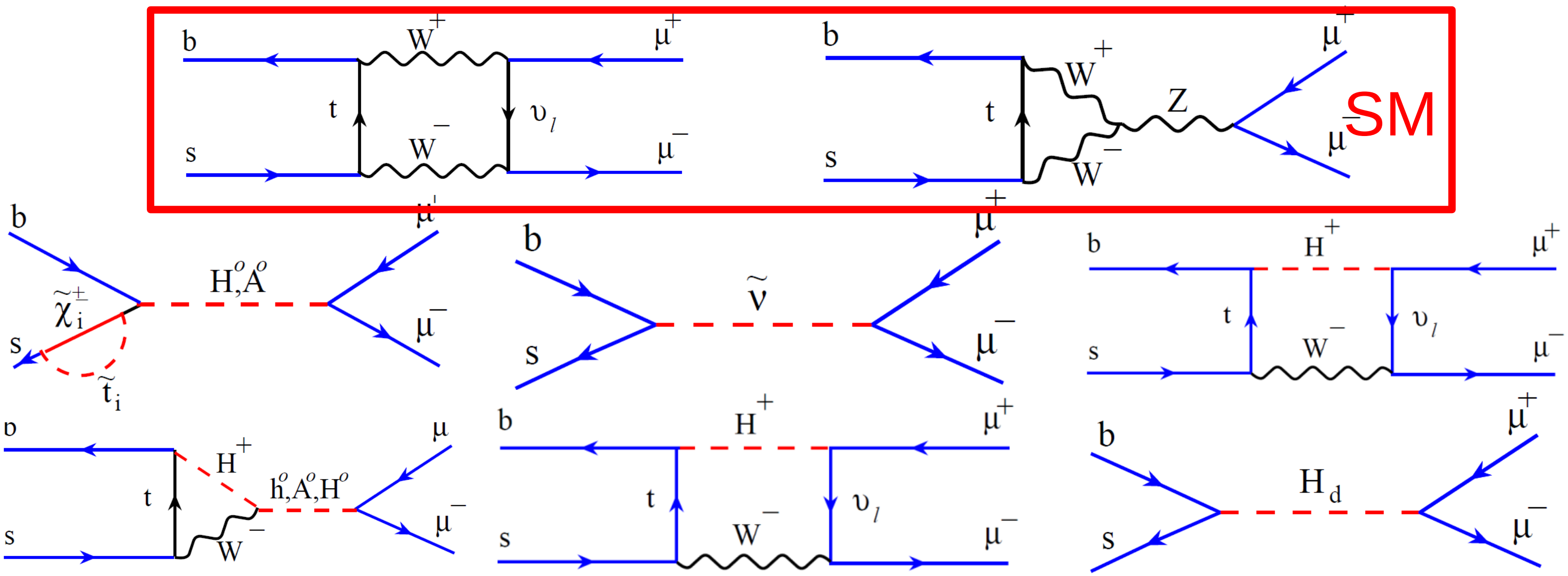
Left side ($|V_{ub}|/|V_{cb}|$) and the angle γ will be precision measurements in the future



The$B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ decays

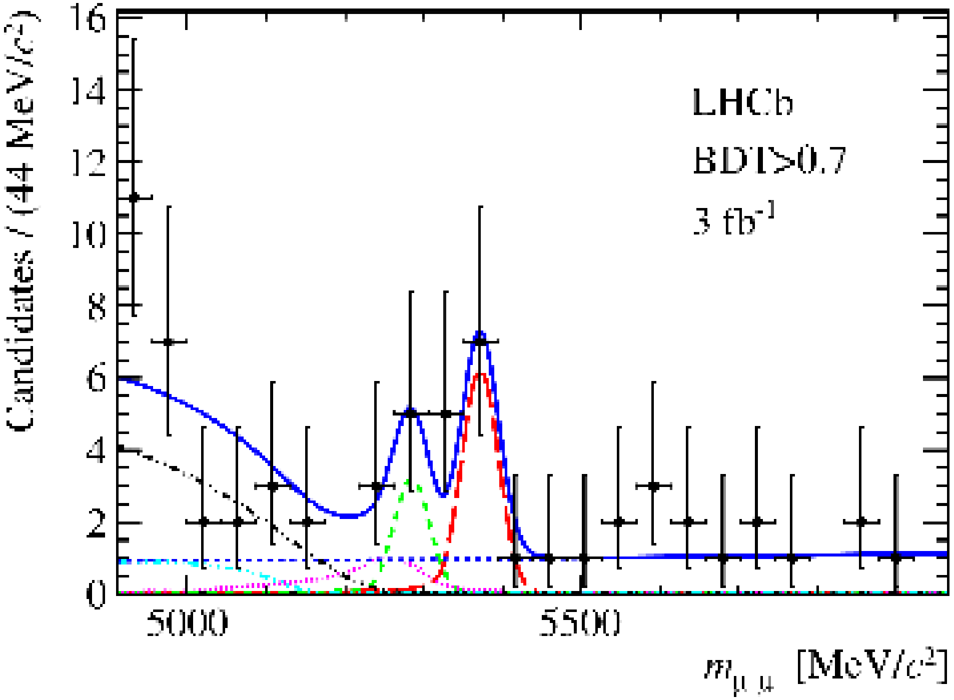
The two very rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ have attracted much interest

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



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

- Following $B^0_s \to \mu^+\mu^-$ observation, challenge now is to observe 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
- Lower rate and peaking backgrounds now a real issue
  - CMS
    - BF <1.1 10^{-9}
  - LHCb
    - BF <0.7 10^{-9}

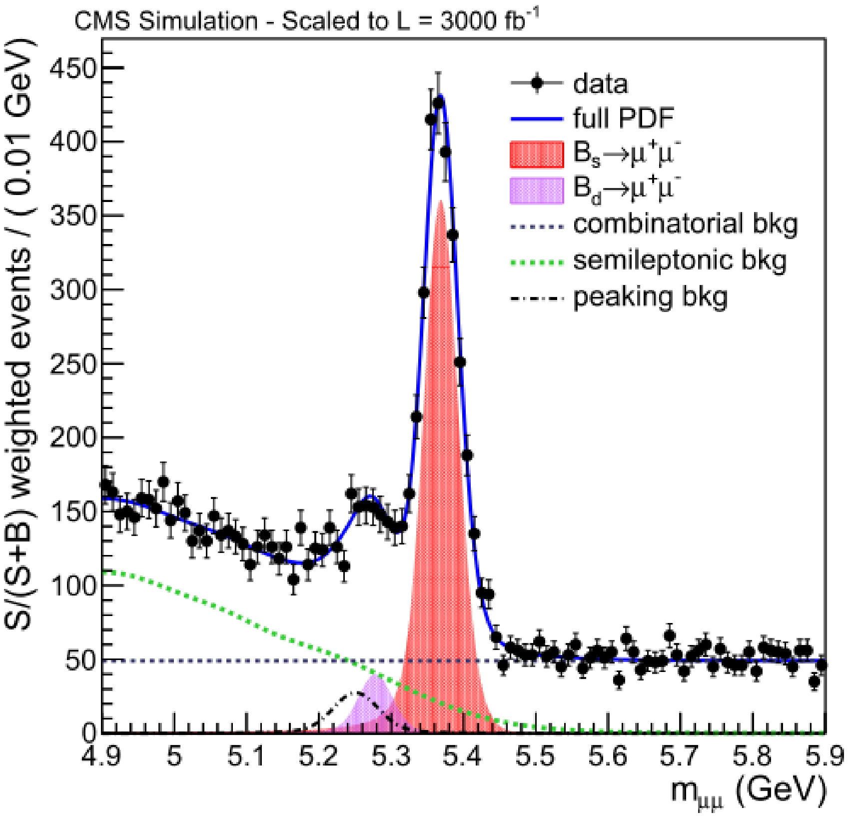


Observing $B^0 \rightarrow \mu^+\mu^-$

Prospects for the $B^0 \rightarrow \mu^+\mu^-$ decays

- LHCb upgrade expect to measure the ratio to a 35% accuracy
- CMS upgrade at full 3 ab^{-1} expected to reduce this to 21%
  - Depends critically on ability to keep peaking backgrounds under control

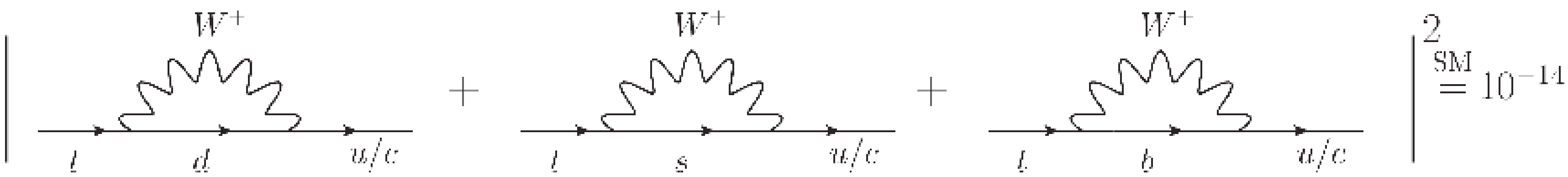
CMS PAS FTR-13-016



$B^0_s \rightarrow \tau^+\tau^-$ an interesting opportunity for TLEP

Flavour changing neutral currents in top

With massless quarks, flavour changing neutral current decays are forbidden in the SM (GIM mechanism)



Comparing to the top mass, all other quarks **are** nearly massless

FCNC for top ($t \rightarrow c X$, $t \rightarrow u X$) are suppressed by huge factor in SM

Not the case for many NP models

arXiv: 1311.2028

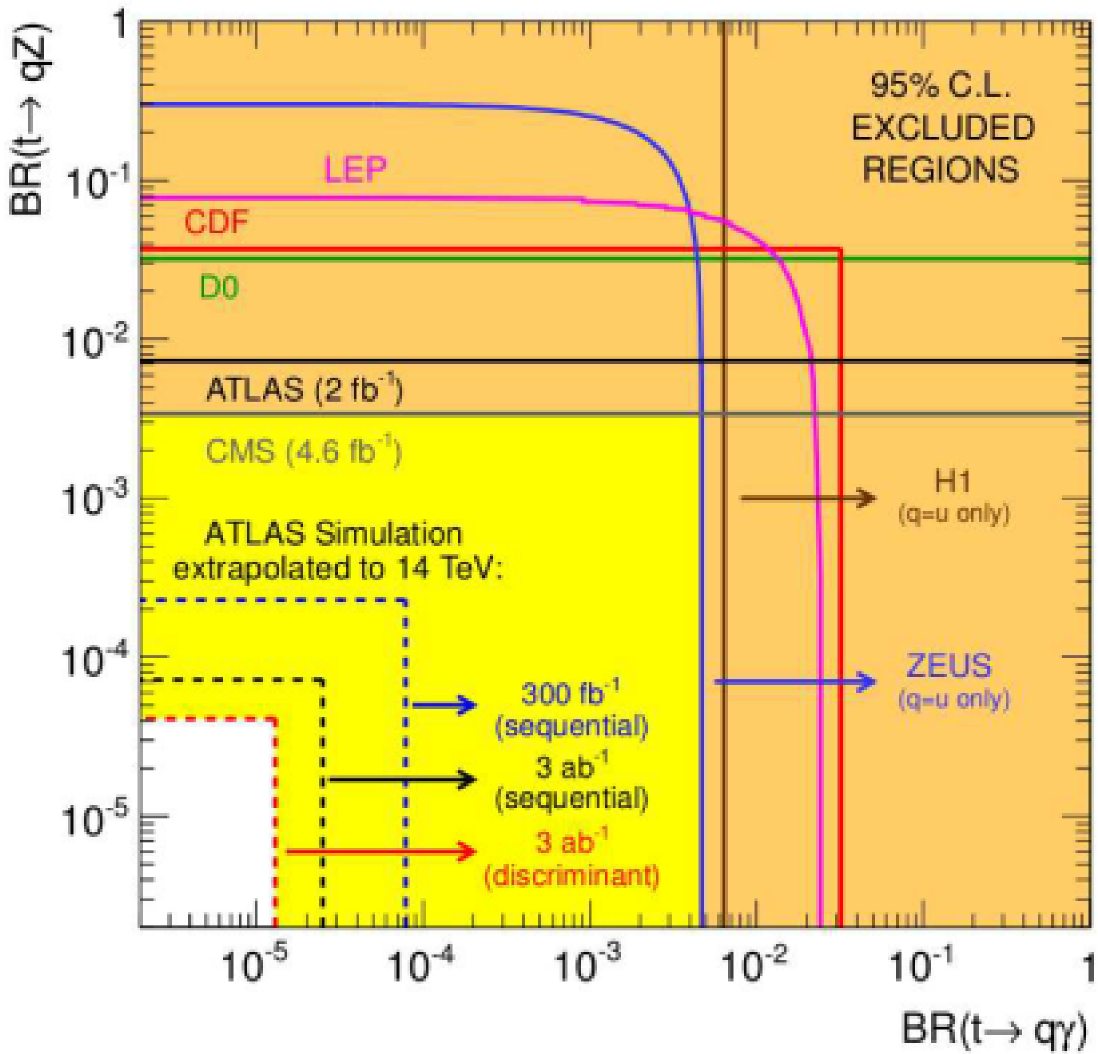
	2HDM	MSSM	RS
$t \rightarrow cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \rightarrow c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \rightarrow cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \rightarrow ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Flavour changing neutral currents in top

ATLAS/CMS searches in

- single top
- $t \rightarrow Zq$ decays

ATL-PHYS-PUB-2013-007



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But at the moment effects on B penguin decays sets a better limit (LHCb)

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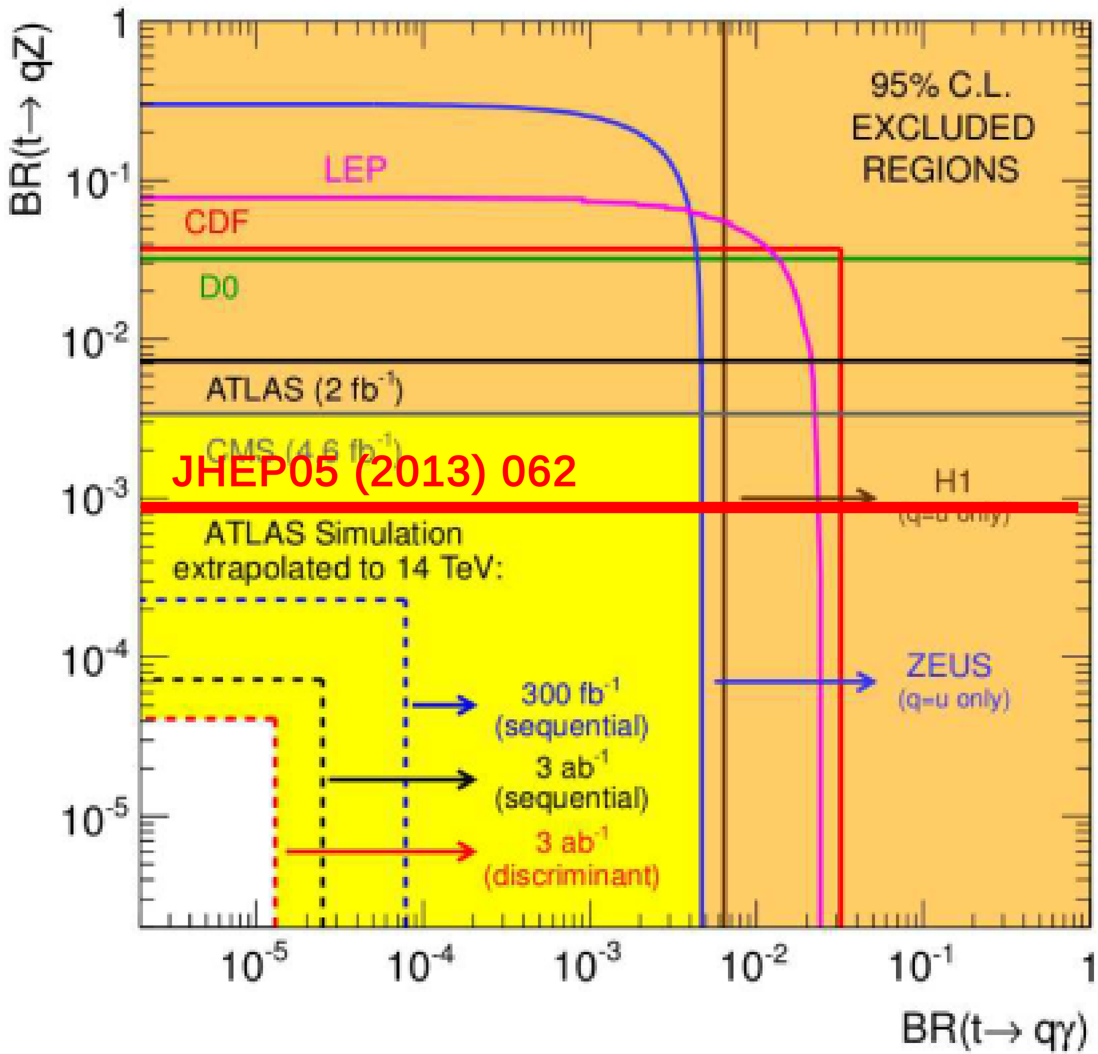
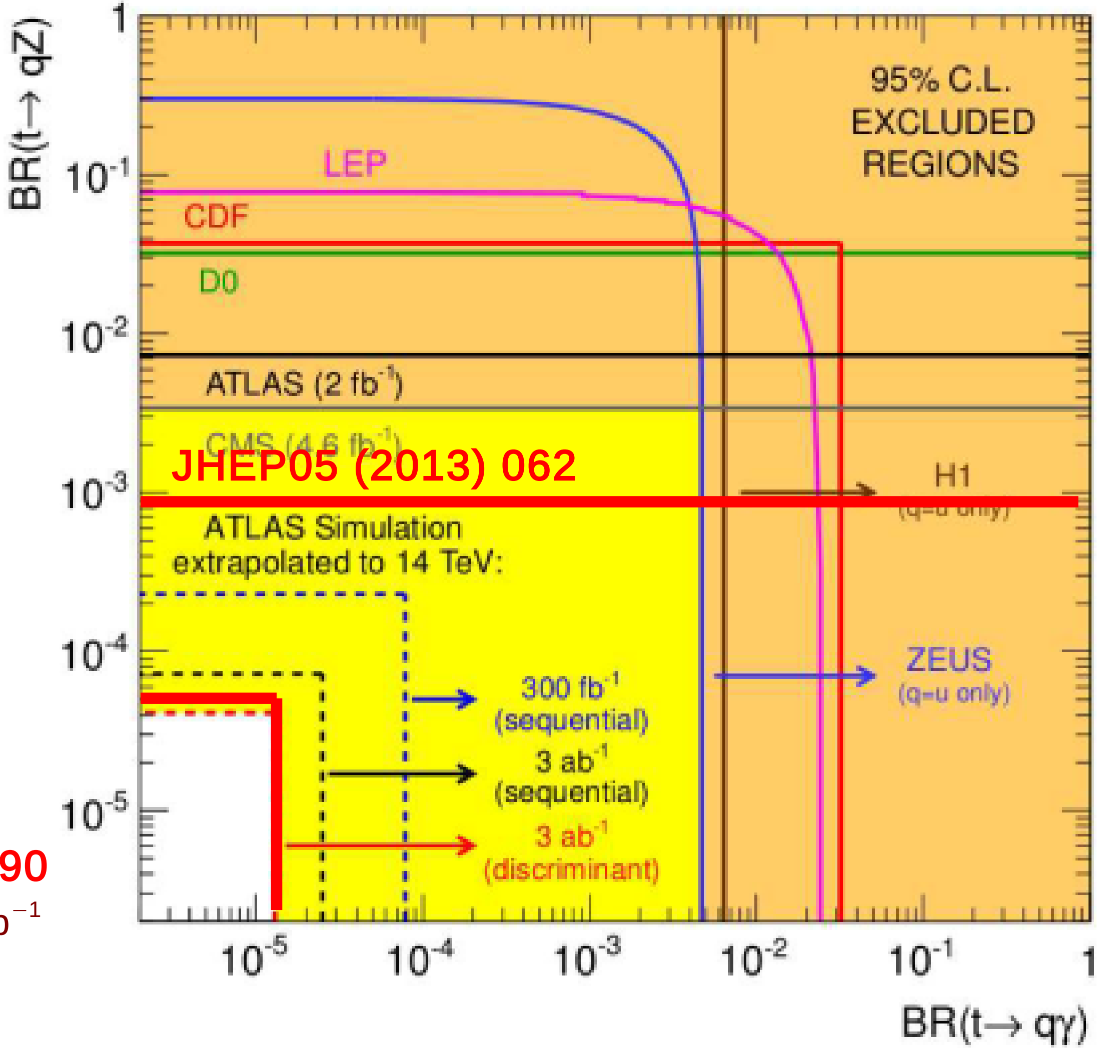


Flavour changing neutral currents in top

- ATLAS/CMS searches in
  - single top
  - $t \rightarrow Zq$ decays
- But at the moment effects on B penguin decays sets a better limit (LHCb)
- But TLEP is also very competitive

ATL-PHYS-PUB-2013-007



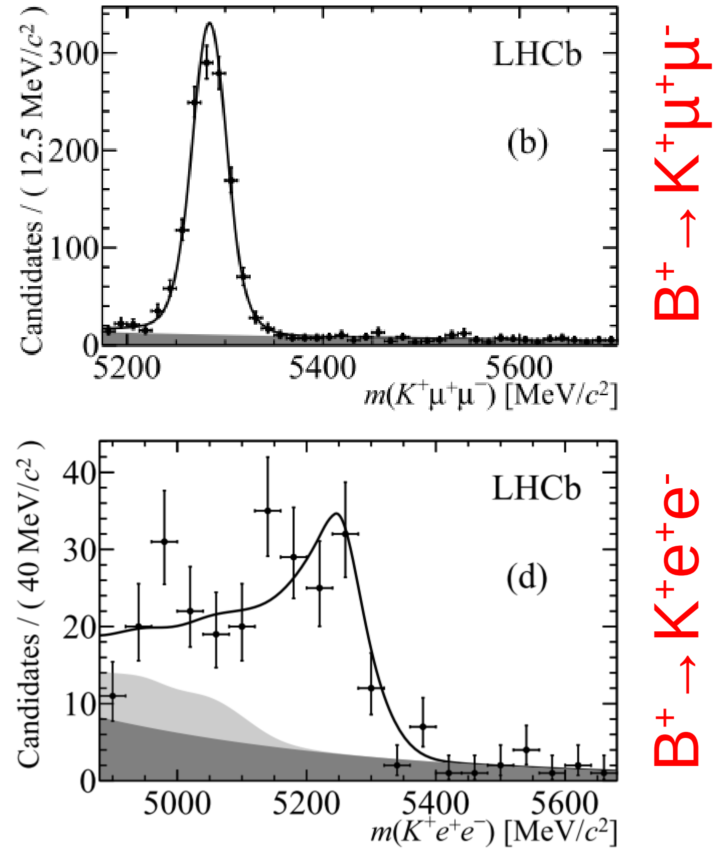
arXiv:1408.2090

$\sqrt{s}=350\,\text{GeV},\ \int L = 100\,\text{fb}^{-1}$

Lepton universality test in $B^+ \to K^+ l^+ l^-$

Due to lepton universality, the $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ decays should have same BF to within a factor 10^{-3}

LHCb : arXiv:1406.6482



The ratio

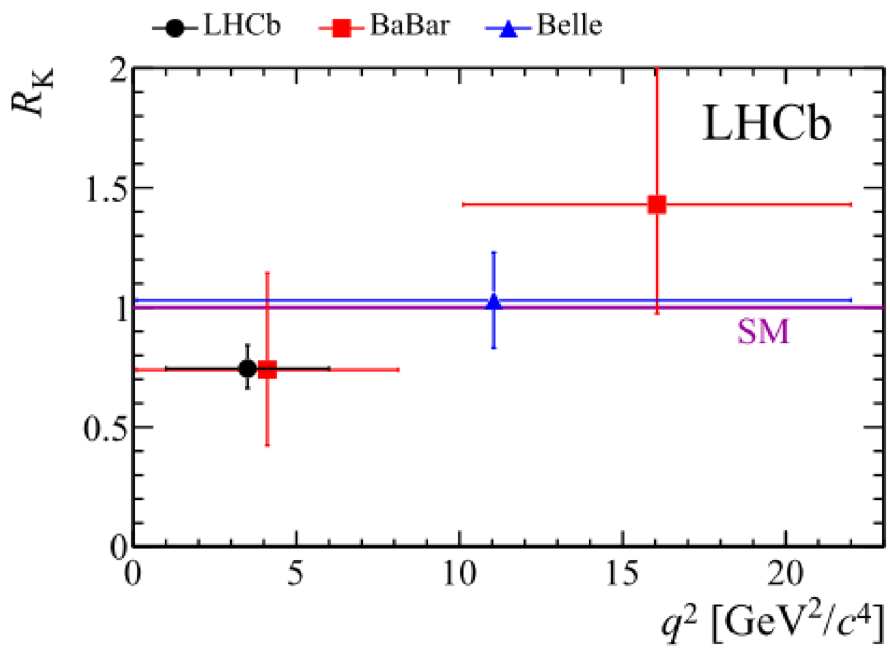
$$R_K = \frac{BF\left(B^+ \to K^+\mu^+\mu^-\right)}{BF\left(B^+ \to K^+e^+e^-\right)}$$

Sensitive to lepton flavour violating NP

- The electron mode is the challenge for LHCb

Lepton universality test in $B^+ \to K^+ l^+ l^-$

Current status of measurements as a function of dilepton mass



Expected precision from both LHCb upgrade and Belle-II at the few % level

- Limited by statistics in electron mode
- Very sensitive to the 2.6σ tension currently seen

Conclusion

Heavy flavour physics has a rich future ahead

Key is to ensure that both theoretical and systematic uncertainties are under control

All future facilities

LHCb upgrade, Belle-II, CMS/ATLAS, TLEP

have their respective strengths

As always the combined information is what will be able to reveal New Physics