Imperial College London

Cracks in the wall?

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Islay, July 2016

The Standard Model

The Standard Model is by now an old theory

- In particular in the area of flavour physics, a large number of anomalies have shown up in the past few years

Cracks are at a level where they can't be ignored

The Standard Model

Is this the rise of New Physics to prominence?

A new consistent theory arises from the ruins

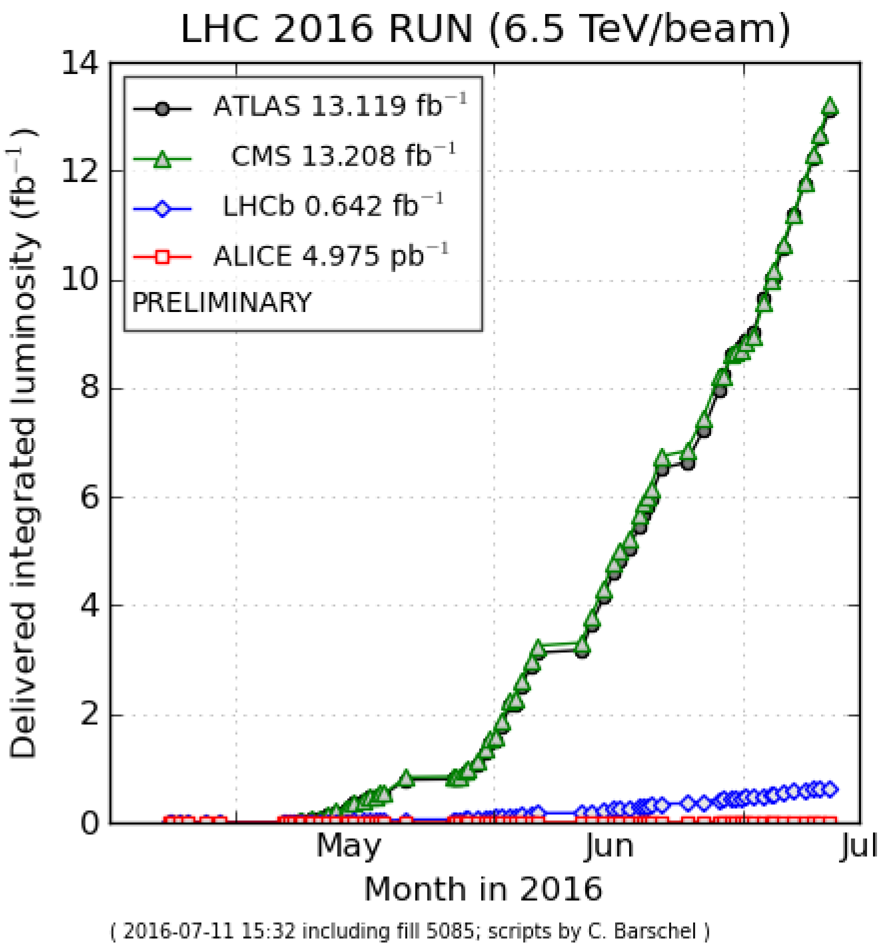
Or will the Standard Model be restored to former glory?

Reappraisal of theoretical uncertainties make anomalies go away

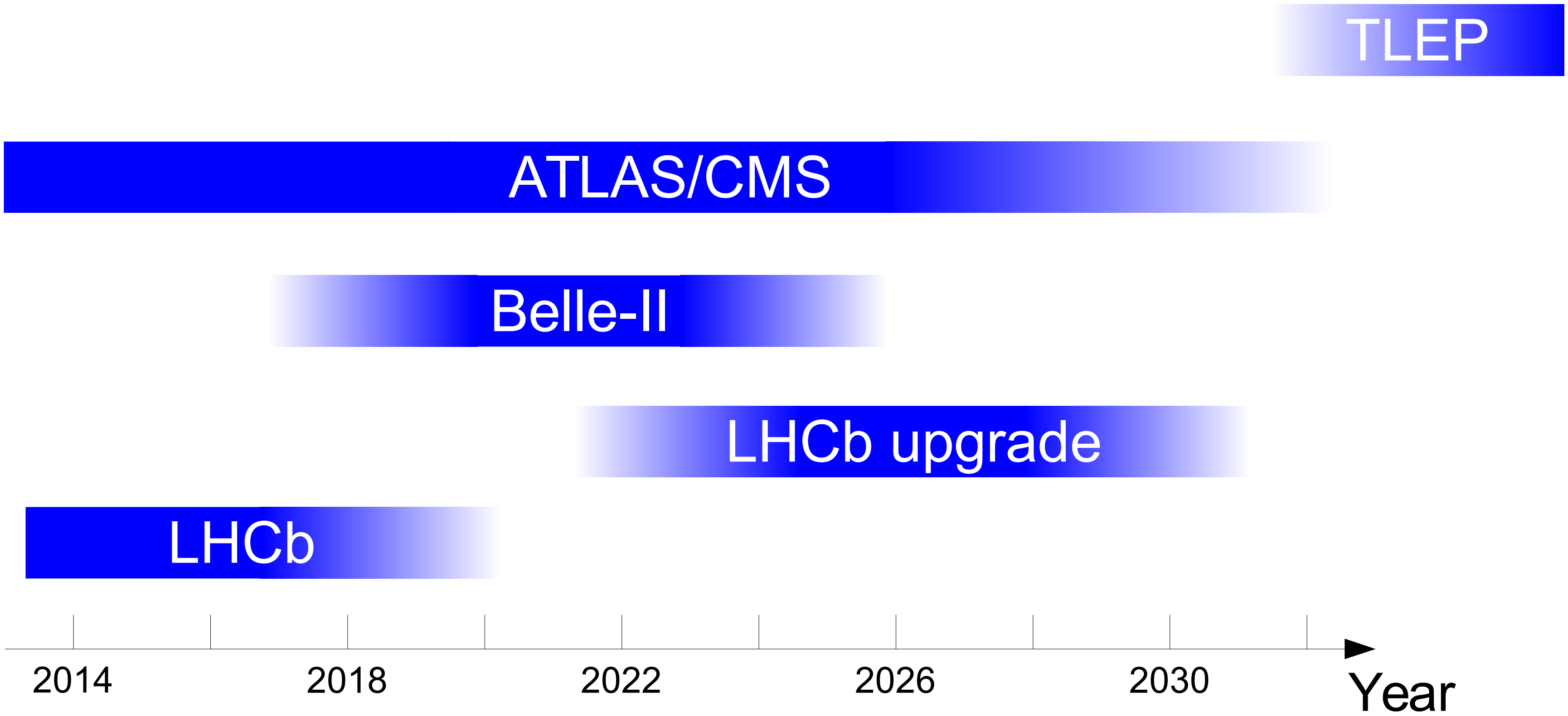
LHC status

Fantastic progress for LHC this year is fantastic

For many LHCb analyses the effective dataset might almost double with respect to Run-I at the end of 2016



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?
- How can everything be cross checked?

From answers conclude if measurement is actually interesting

Will aim to show here that there are still plenty of interesting measurements

Discussion topics

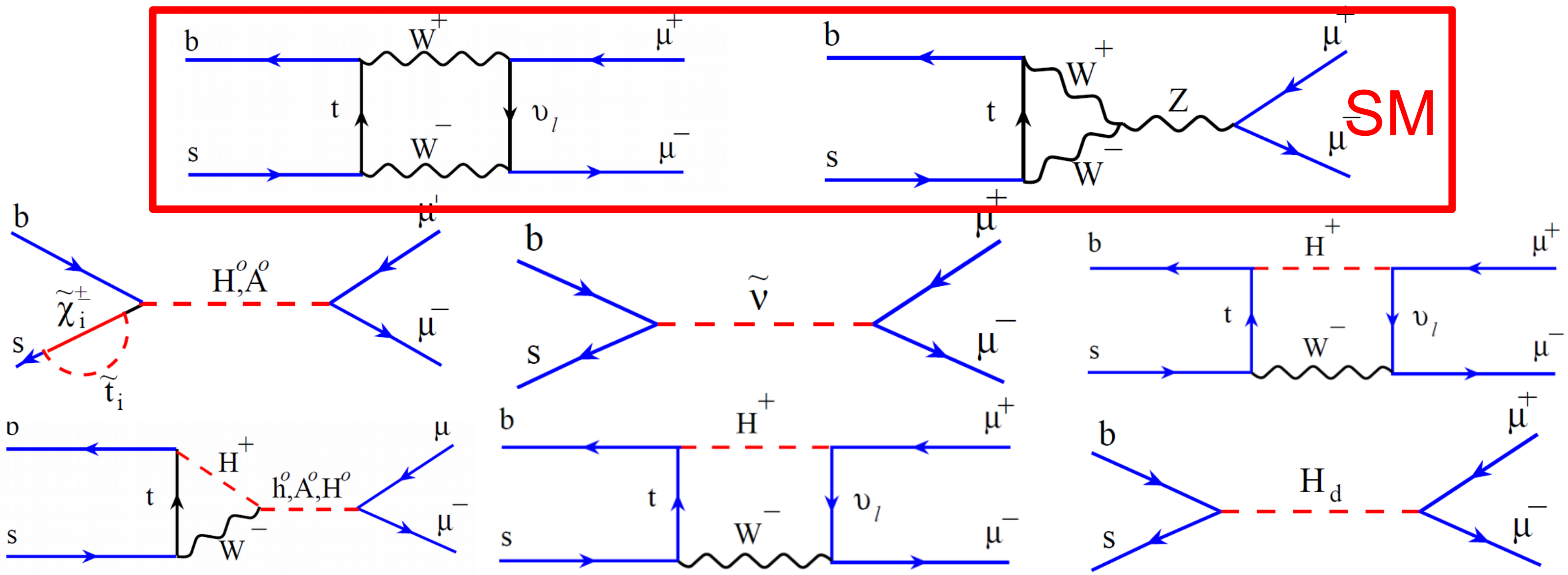
Is Flexit on the horizon?

- Theoretical uncertainties hitting a wall
- Experimental systematics levelling out
- Statistics takes too long to collect and field abandoned

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

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



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

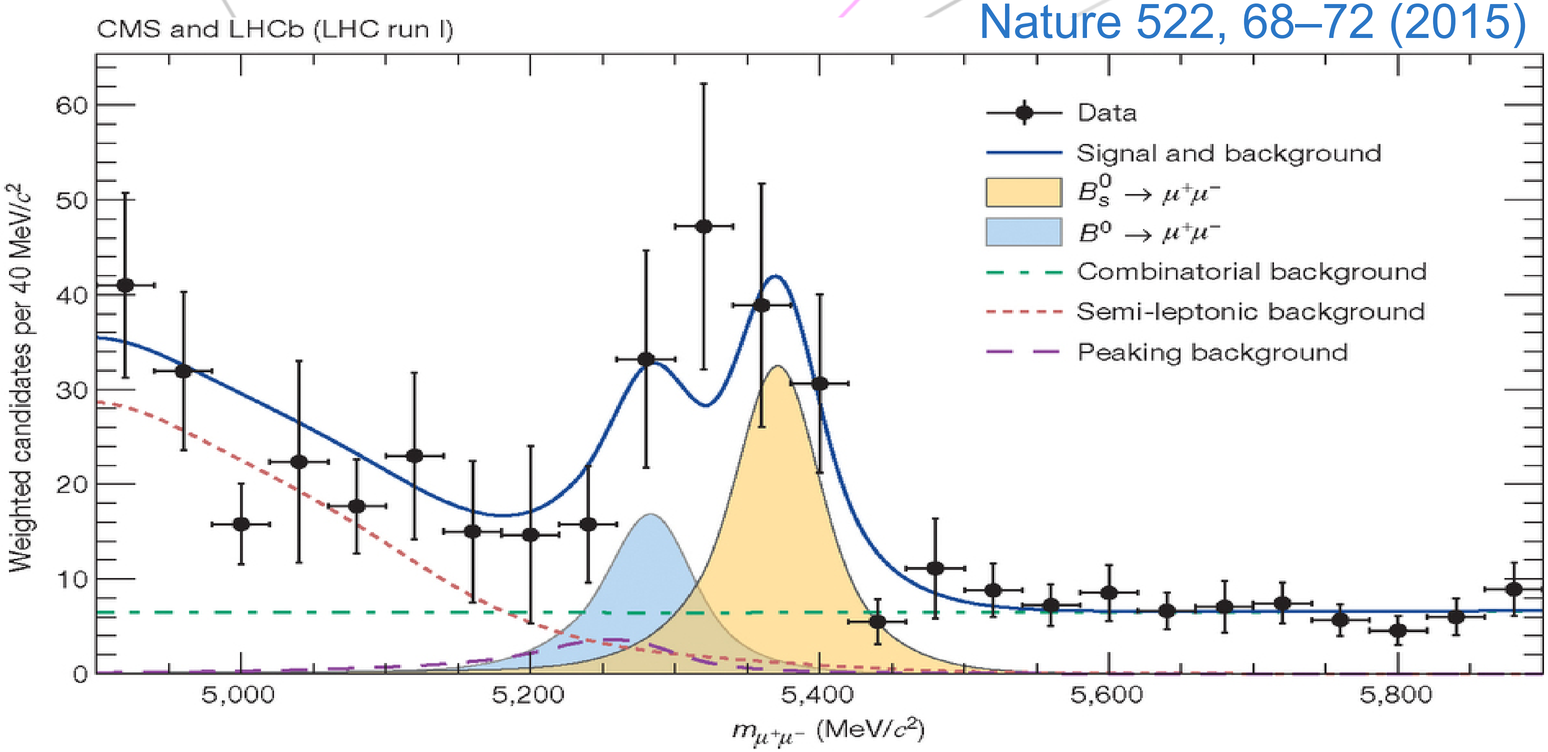
LHCb+CMS combined for observation of $B^0_s\to\mu^+\mu^-$

$$BF = \left(2.8^{+0.7}_{-0.6}\right)\times 10^{-9}$$ 6.2σ significant

Evidence for $B^0\to\mu^+\mu^-$

$$BF = \left(3.9^{+1.6}_{-1.4}\right)\times 10^{-10}$$ 3.2σ significant

Nature 522, 68–72 (2015)

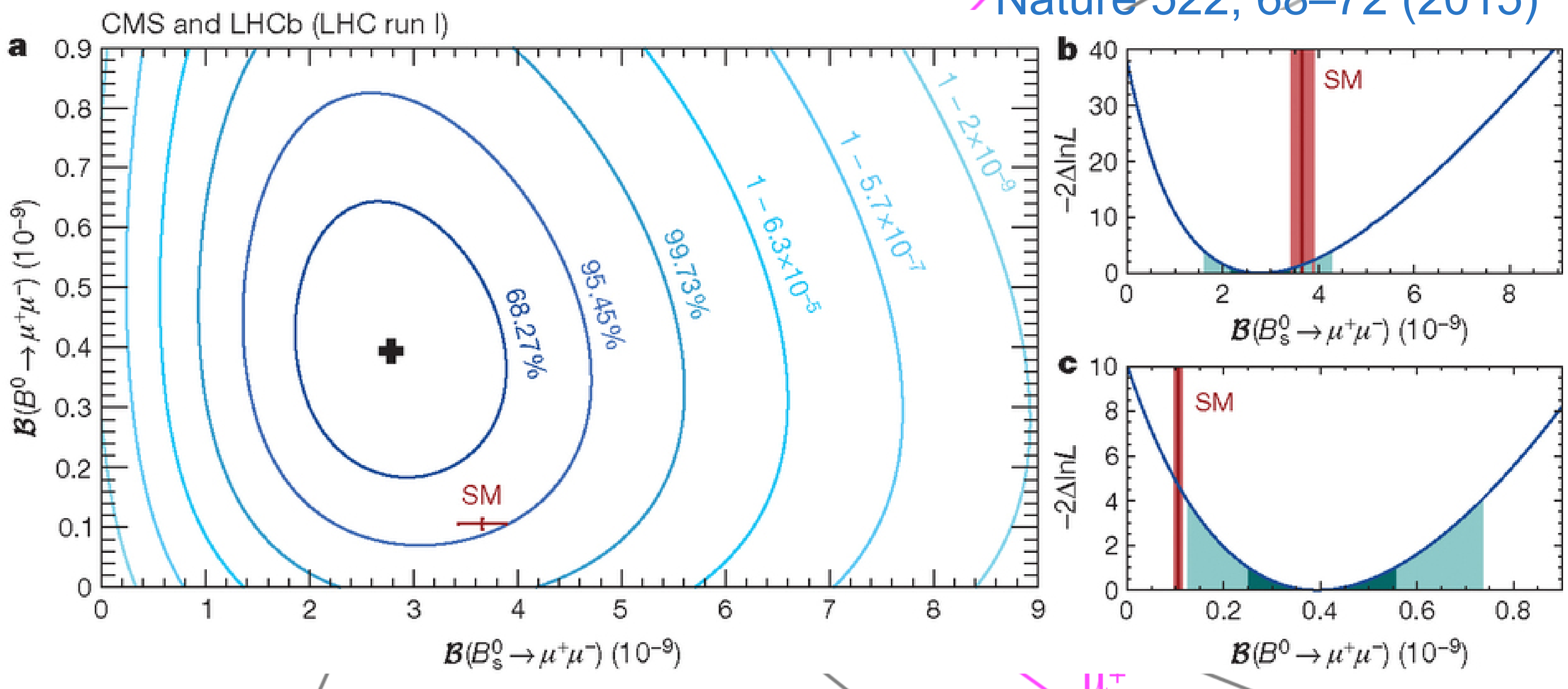


B→μ⁺μ⁻

Topology of decay simple

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

Nature 522, 68–72 (2015)



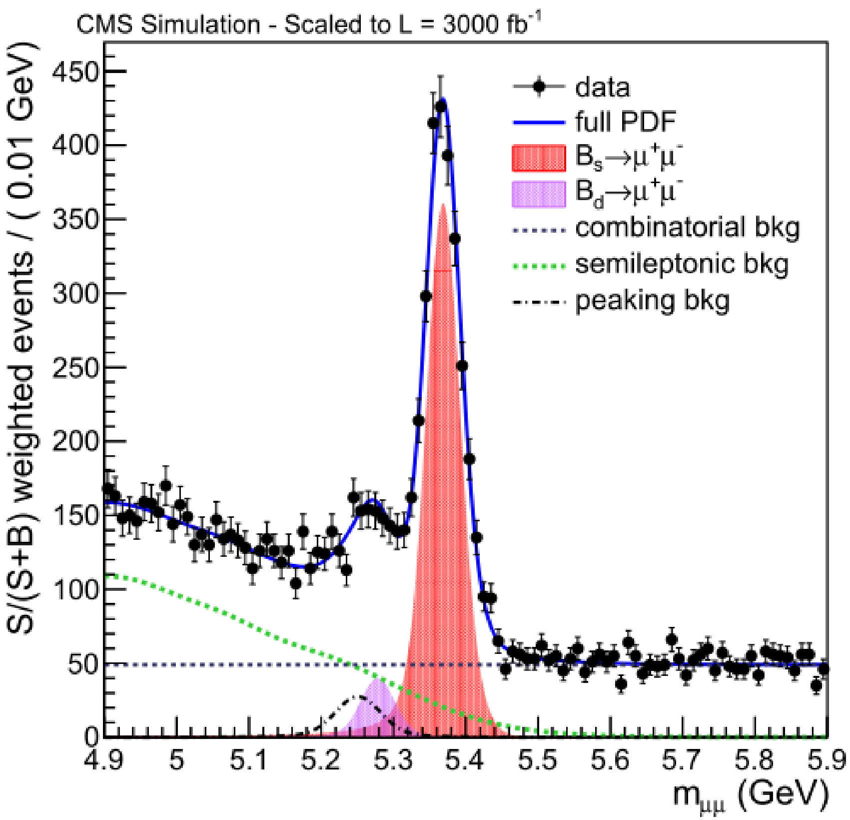
There is an ATLAS result as well, but precision is poor ...

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

For Run II, the clear goal is observation of $B^0 \to \mu^+\mu^-$

- In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
- 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



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

- Would need **huge** enhancemer to be visible in LHCb

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

Is the decay $B^0_s \to \mu^+\mu^-$ *CP*-even or *CP*-odd?

- The two weak eigenstates of the B^0_s differ by about 12% in effective lifetime ($\Delta\Gamma/\Gamma \sim 0.12$)
- The two states are almost purely CP-even and CP-odd
- Thus measurement of effective lifetime in $B^0_s \to \mu^+\mu^-$ is a measure of the CP of the decay.

A measurement like this was made for $B^0 \to K^+K^-$

- [PLB 736 (2014) 446]
- 10k candidates gives resolution of 16 fs
- Current LHCb $B^0_s \to \mu^+\mu^-$ is about 10 events equivalent
- Need a factor 200 higher yield, 300 fb^{-1}

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

Direct *CP* violation in $B^0_s \to \mu^+\mu^-$ is another challenging measurement

- Requires that the flavour of the B^0_s is known (B^0_s or $\overline{B}^0_s$)
- Efficiencies for this are approaching 6% in LHCb
- To measure a 25% direct CPV with 5σ will require 25 times current dataset times flavour tagging efficiency, 400 fb^{-1}

For a **long** time the measurement of $|V_{ts}|/|V_{td}|$ from $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ will be the only new result.

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

The Wilson coefficients describe the effective couplings from a higher energy scale

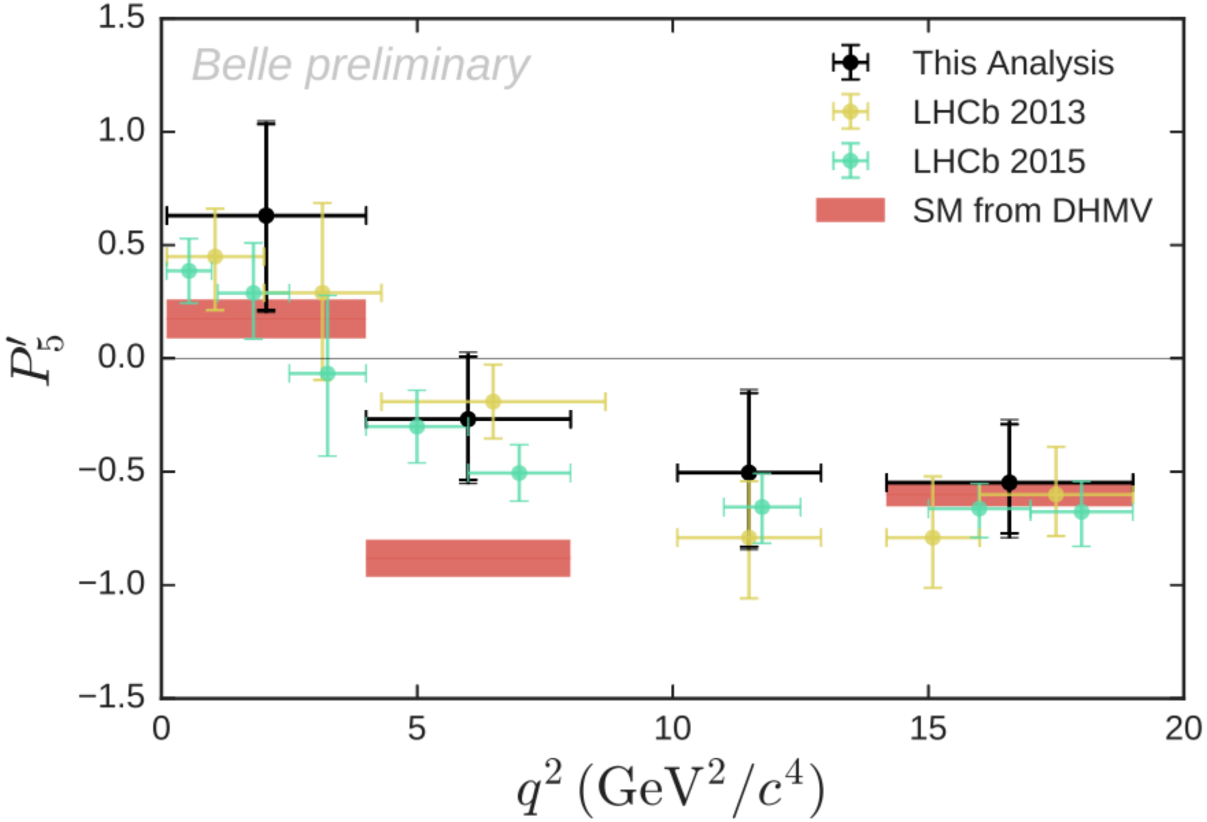
The matrix element of the decay is controlled by the K^{*0} polarisation amplitudes

- These are functions of the Wilson coefficients as well as the form factors arising from hadronic effects
  - The form factors can be calculated using light cone sum rules (mainly at low q^2) or lattice QCD (mainly large q^2)

$$A_\perp^{L,R} = N\sqrt{2}\lambda^{1/2}\left[\left\{(\mathcal{C}_9^{(\text{eff})} + \mathcal{C}_9^{\prime(\text{eff})}) \mp (\mathcal{C}_{10}^{(\text{eff})} + \mathcal{C}_{10}^{\prime(\text{eff})})\right\}\frac{V(q^2)}{m_B + m_{K^*}} + \right.$$
$$\left. + \frac{2m_b}{q^2}(\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_7^{\prime(\text{eff})})T_1(q^2)\right],$$

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

Results Run-I LHCb and full Belle dataset



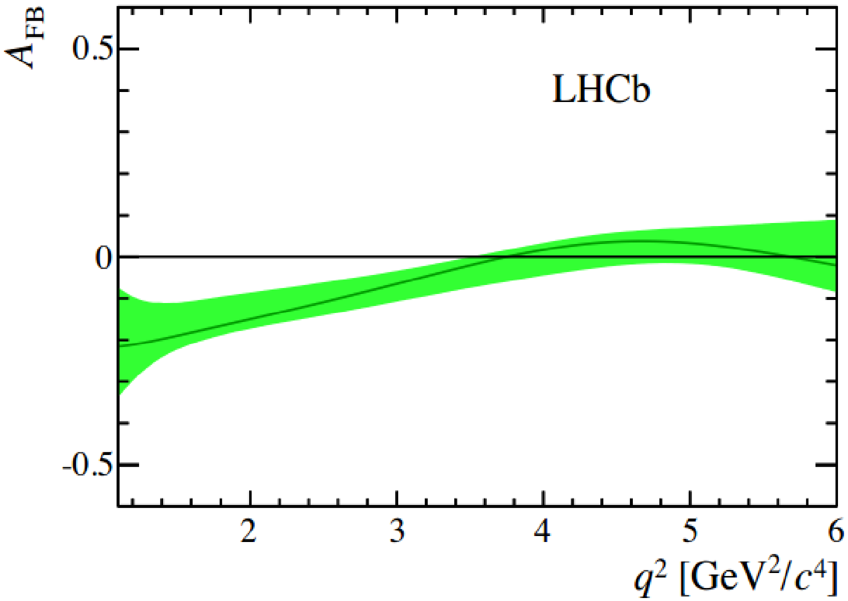
How do we progress from here?

LHCb : ArXiv: 1512.04442

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

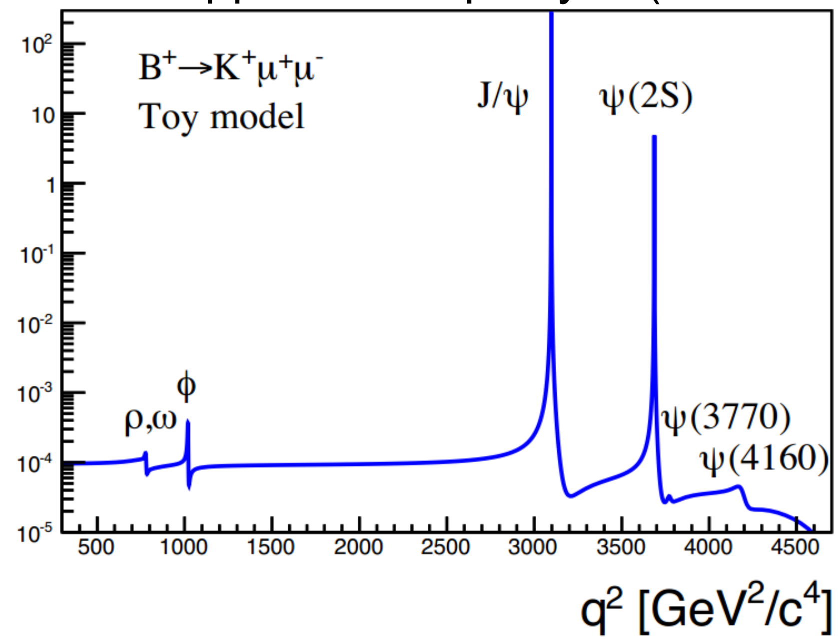
Unbinned fit result in region $1<q^2< 6$ GeV^2

[JHEP 06 (2015) 084 for method]



$$q_0^2(S_5) \in [2.49, 3.95]\ \mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$
$$q_0^2(A_{FB}) \in [3.40, 4.87]\ \mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

B→Kμμ fit in full q^2 toy fit (P. Owen)



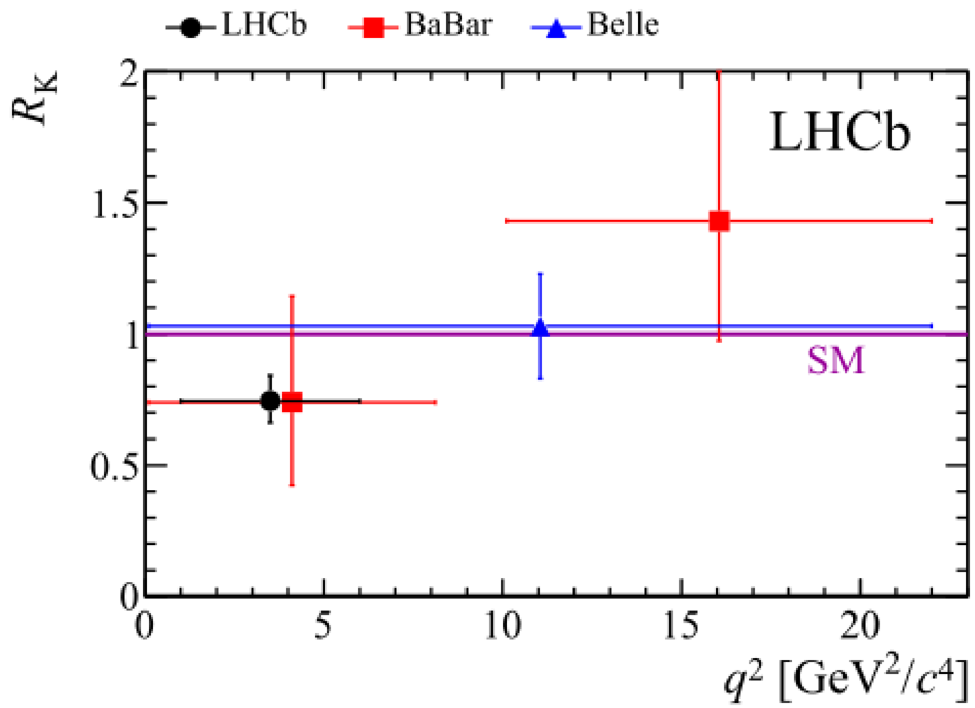
Full angular fit, unbinned in q^2, might give us a better understanding of charm contributions.

LHCb : PRL113, 151601 (2014)

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

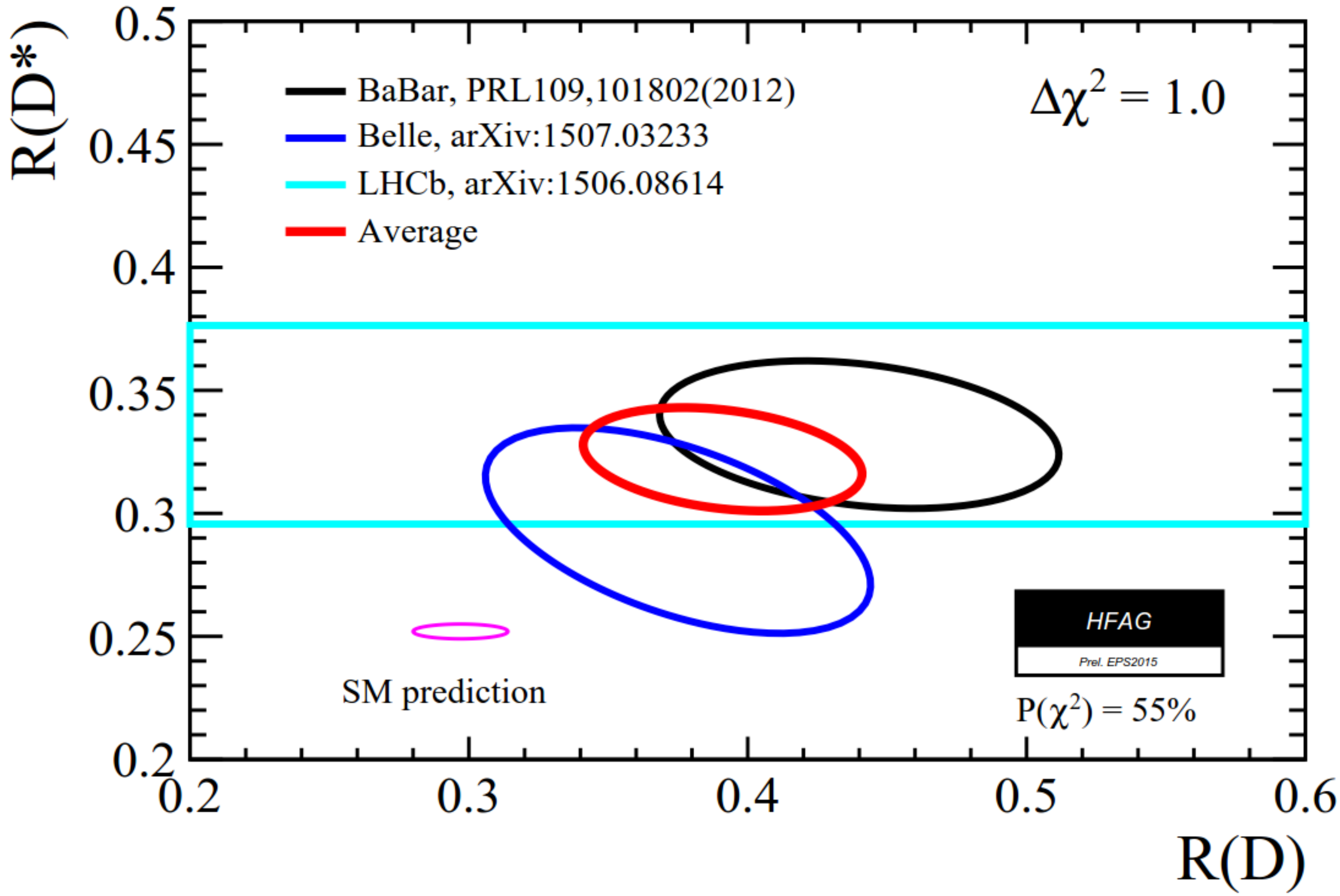
Measurement is compatible with earlier, but less precise measurements

- Belle could provide a significant update from existing data
- Will be very competitive in this measurement at Belle-II



$B^+ \to D^{(*)+} \tau \nu$ global fit

The measurements are internally consistent and have a 4σ tension with SM prediction



Lepton non-universality

- Lepton universality is one of the corner stones of the Standard Model
  - Z decays tested lepton universality at the 0.1% level
  - Heavy flavour decays test e-μ universality in $B \to Kl\nu$ at the 5% level
  - For μ-τ universality the constraints are poorer
    - In charm, a single constraint by $BF(D_s^+ \to \tau^+\nu)/BF(D_s^+ \to \mu^+\nu)$ at 10% level
- New "R" measurements with K^*, D, Λ_c^+, D^{**} on the way
  - Will provide confidence on experimental results

Lepton non-universality

- Can also consider to test $b \to u$ transitions
  - Experimentally tricky as $X_b \to X_u \mu^+ \nu$ are already hard
  - Looking at $X_b \to X_u \tau^+ \nu$ will just be even harder
  - Best prospects might be in decays that are more kinematically constrained (high mass of X_u)
    - $B^+ \to p\bar{p}\mu^+\nu$ vs. $B^+ \to p\bar{p}\tau^+\nu$
    - Form factors obviously unknown but can restriction of phase space (to let μ look like τ) help us.
    - Does $B+ \to \tau^+\nu$ already put severe restrictions on finding LNU?
  - Can careful selection of fiducial region reduce the theoretical uncertainties from form factors?

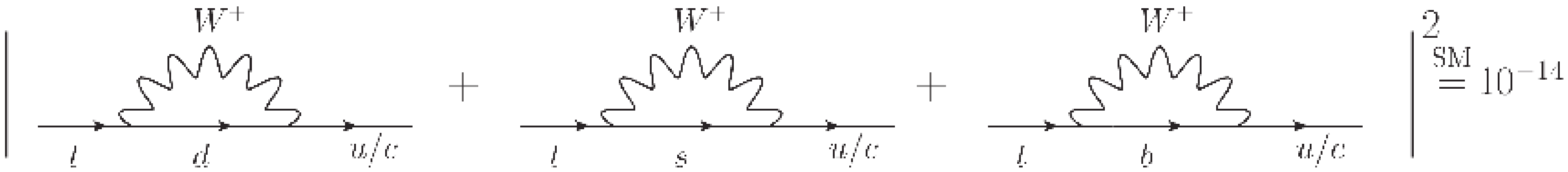
Lepton Flavour Violation

- Naural to look for Lepton Flavour Violation as well
  - Progress in LHCb to look for decays like $B \to K^{(*)}\mu\tau$, $\Lambda_b \to pK\mu e$ etc.
- Interesting idea to look for LFV in charmonium and bottomonium decays as well
  - arXiv:1607.00815 Hazard and Petrov
  - Limits are quite poor and both BES-III (for 1^{--} resonances) and LHCb could improve on many of these

$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\mathcal{B}(\Upsilon(1S) \to \ell_1\ell_2)$	6.0×10^{-6}	–	–
$\mathcal{B}(\Upsilon(2S) \to \ell_1\ell_2)$	3.3×10^{-6}	3.2×10^{-6}	–
$\mathcal{B}(\Upsilon(3S) \to \ell_1\ell_2)$	3.1×10^{-6}	4.2×10^{-6}	–
$\mathcal{B}(J/\psi \to \ell_1\ell_2)$	2.0×10^{-6}	8.3×10^{-6}	1.6×10^{-7}
$\mathcal{B}(\phi \to \ell_1\ell_2)$	n/a	n/a	4.1×10^{-6}
$\mathcal{B}(\ell_2 \to \ell_1\gamma)$	4.4×10^{-8}	3.3×10^{-8}	5.7×10^{-13}

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 ($t \to c X$, $t \to u X$) are suppressed by huge factor in SM

Not the case for many NP models

arXiv: 1311.2028

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

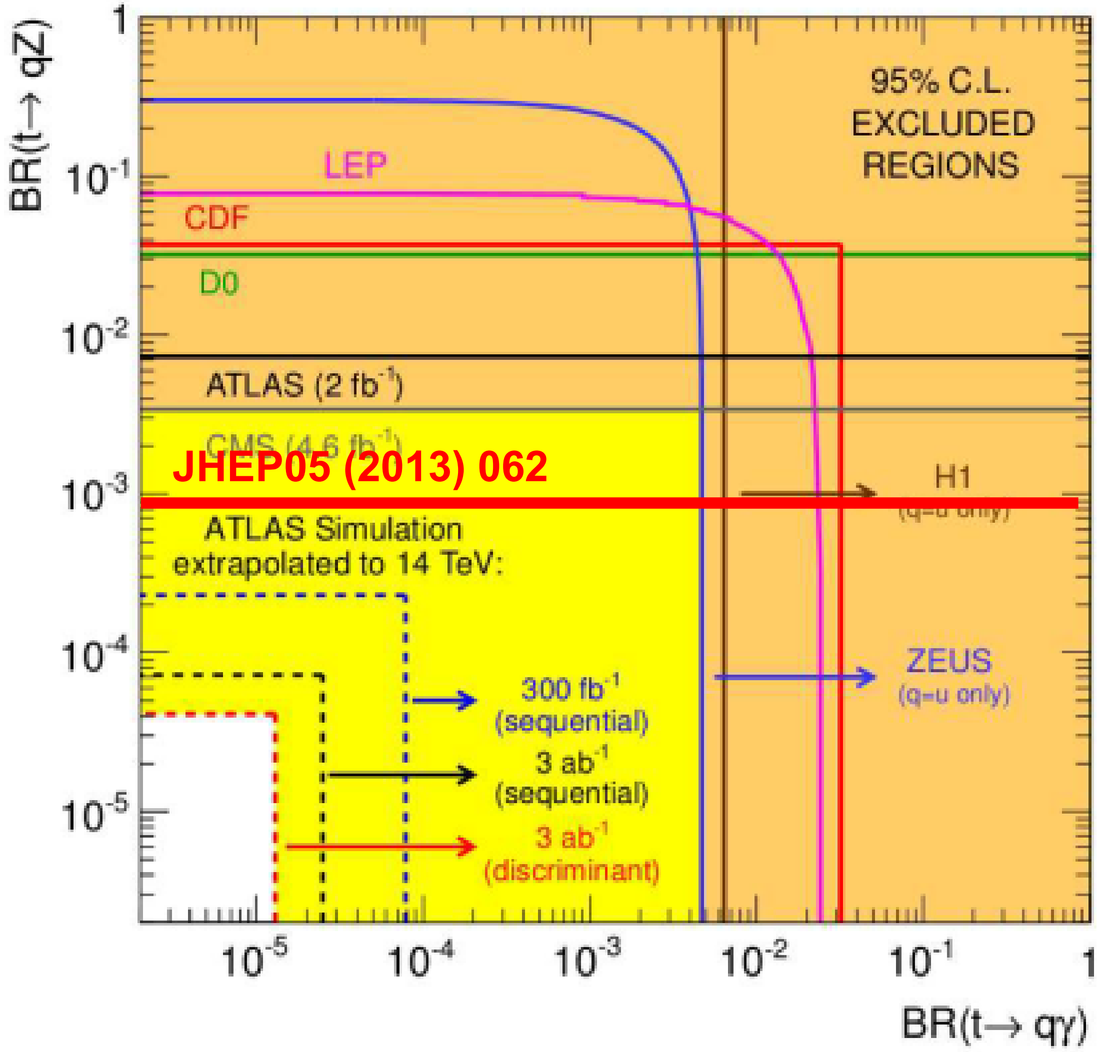
Flavour changing neutral currents in top

ATLAS/CMS searches in

- single top
- t→Zq decays

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

ATL-PHYS-PUB-2013-007



Flavour changing neutral currents in top

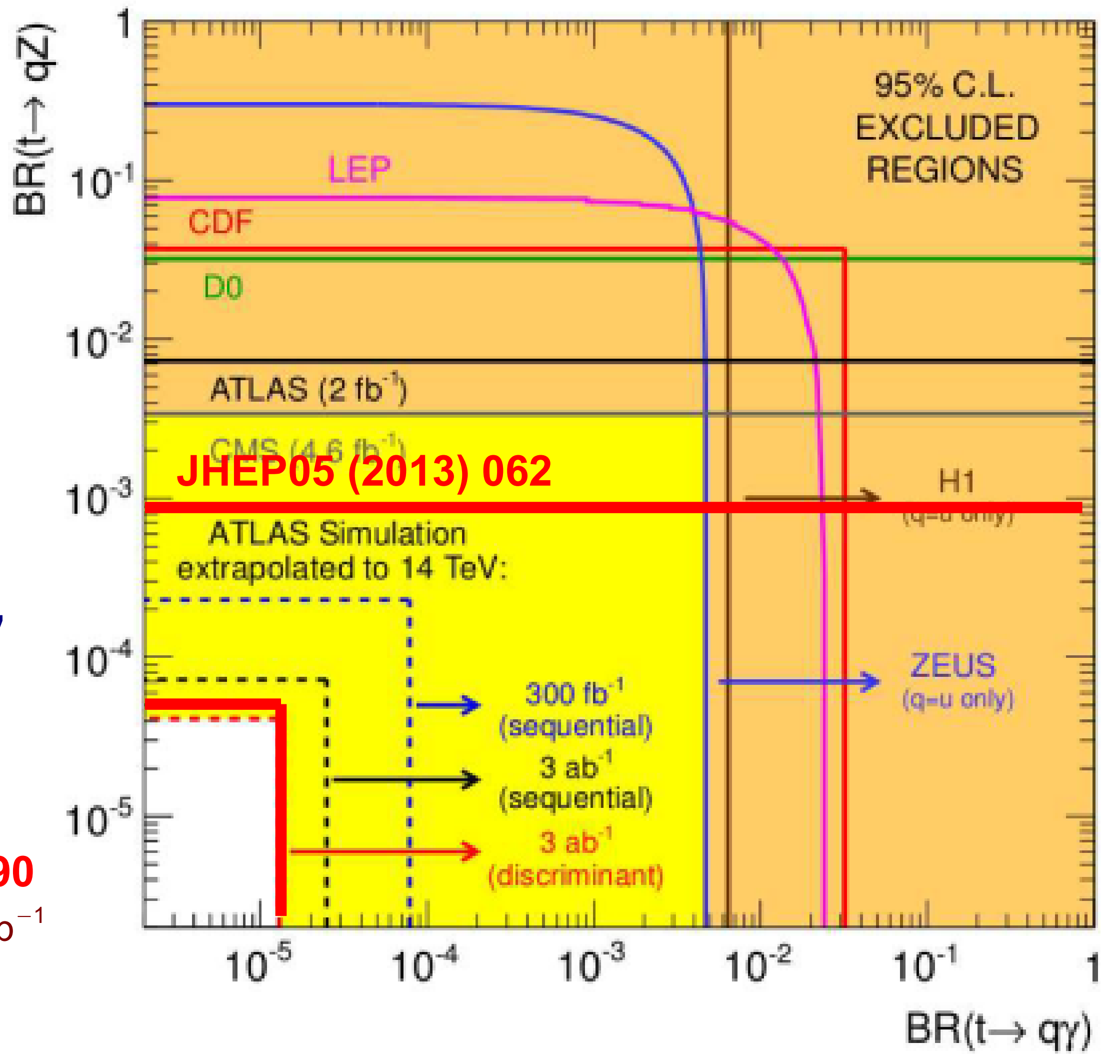
ATLAS/CMS searches in

- single top
- $t \to Zq$ 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

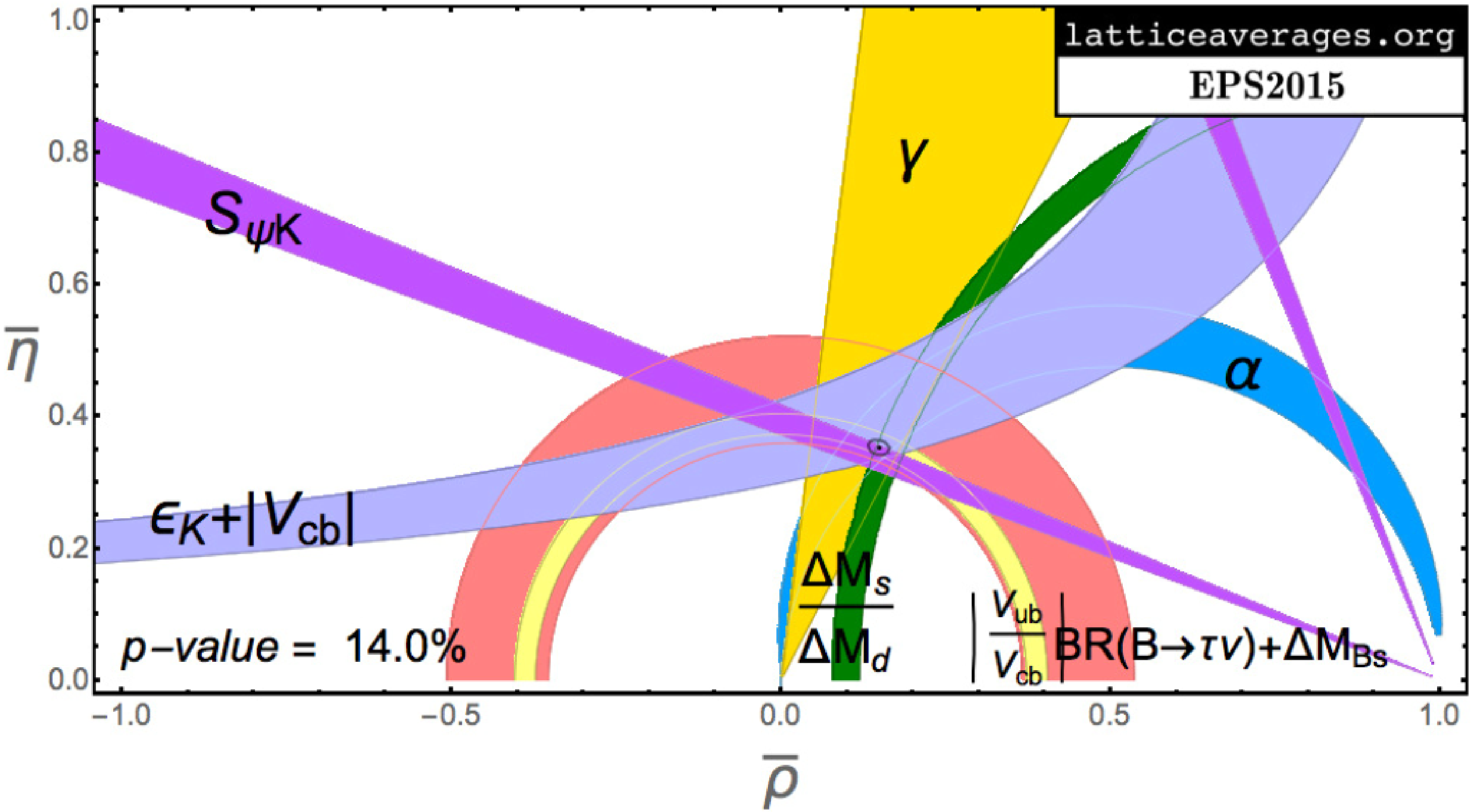


arXiv:1408.2090

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

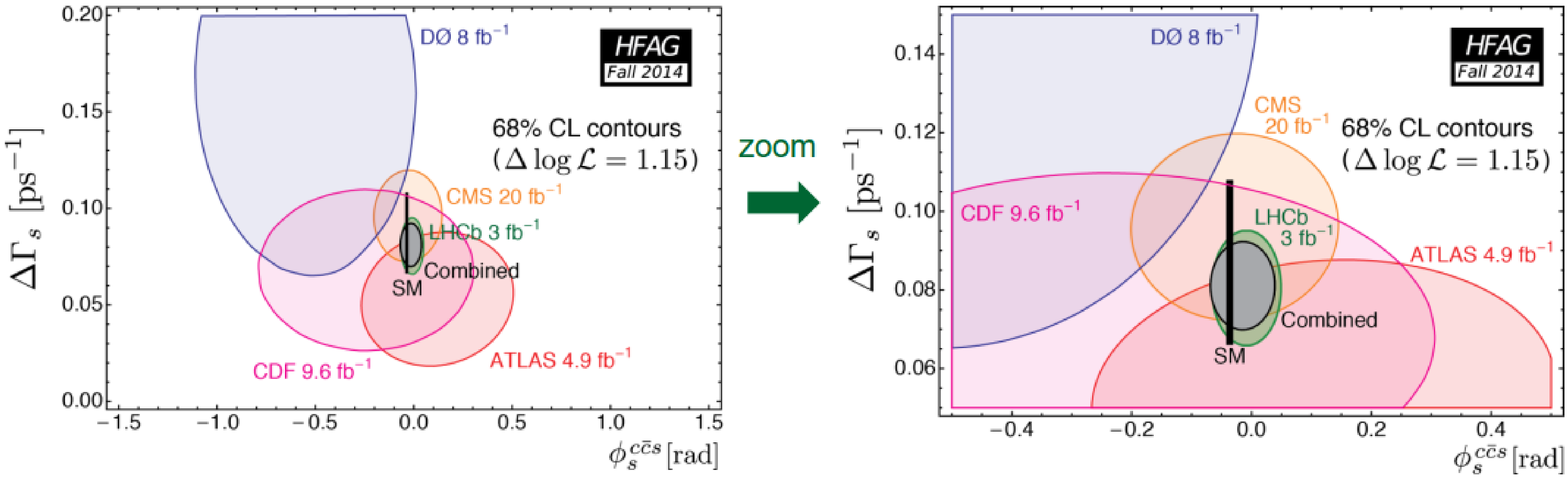
No heavy flavour *CP* violation anomalies?

The global CKM fits do not show any anomalies



No heavy flavour *CP* violation anomalies?

But there is still plenty of scope for NP to show up in B^0_s oscillations



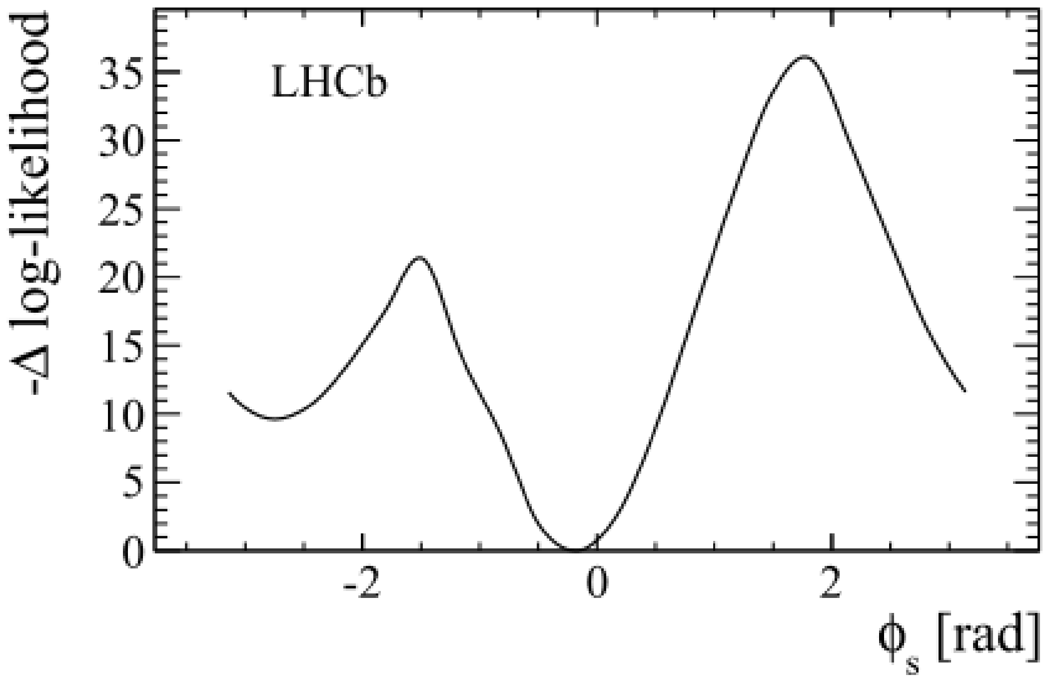
The theoretical uncertainty is still small compared to experimental uncertainty

However, are we so close that NP could never be concluded from this?

LHCb : PRD 90 (2014) 5, 052011

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

Current status of LHCb $B^0_s \rightarrow \varphi\varphi$ measurement



No significant CP violation observed

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

LHCb : PRD 90 (2014) 5, 052011

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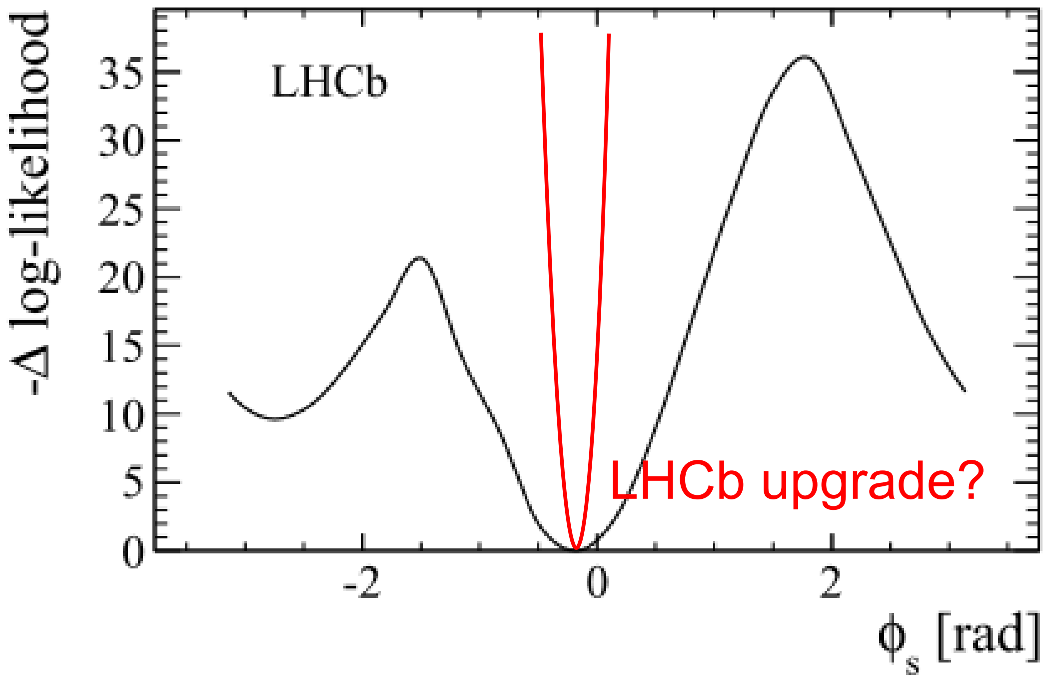


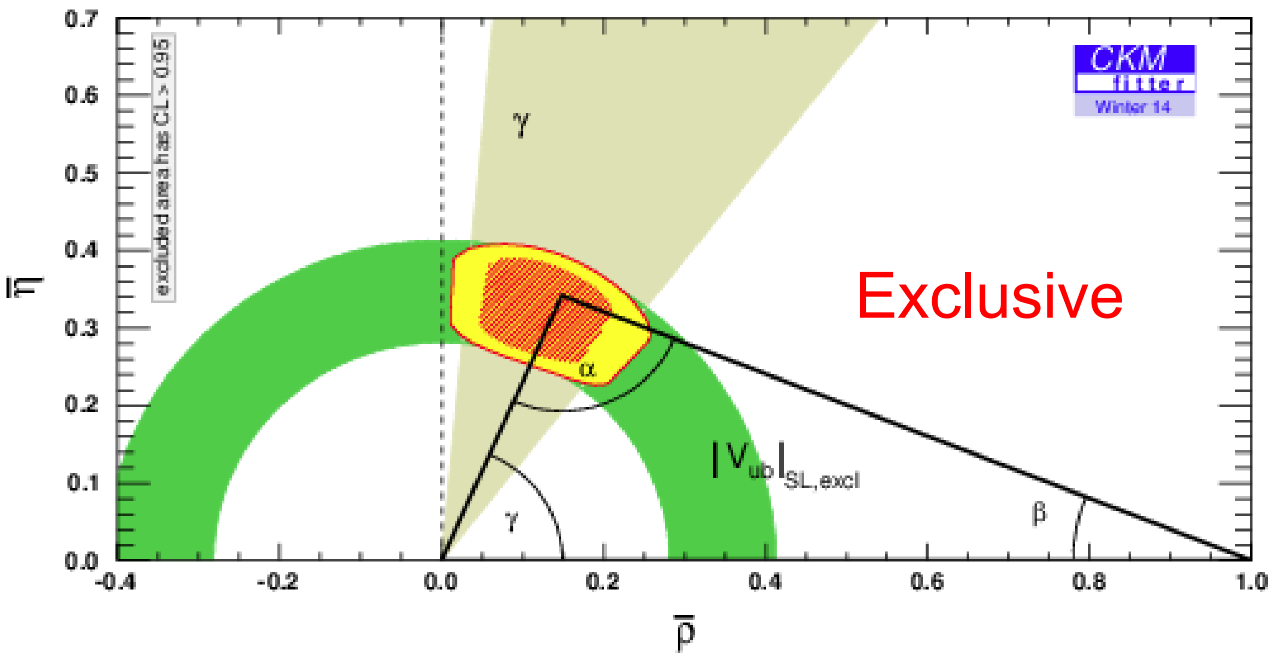
LHCb upgrade will bring precision on this down to 0.02

- Same level as the current theoretical uncertainty

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

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

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



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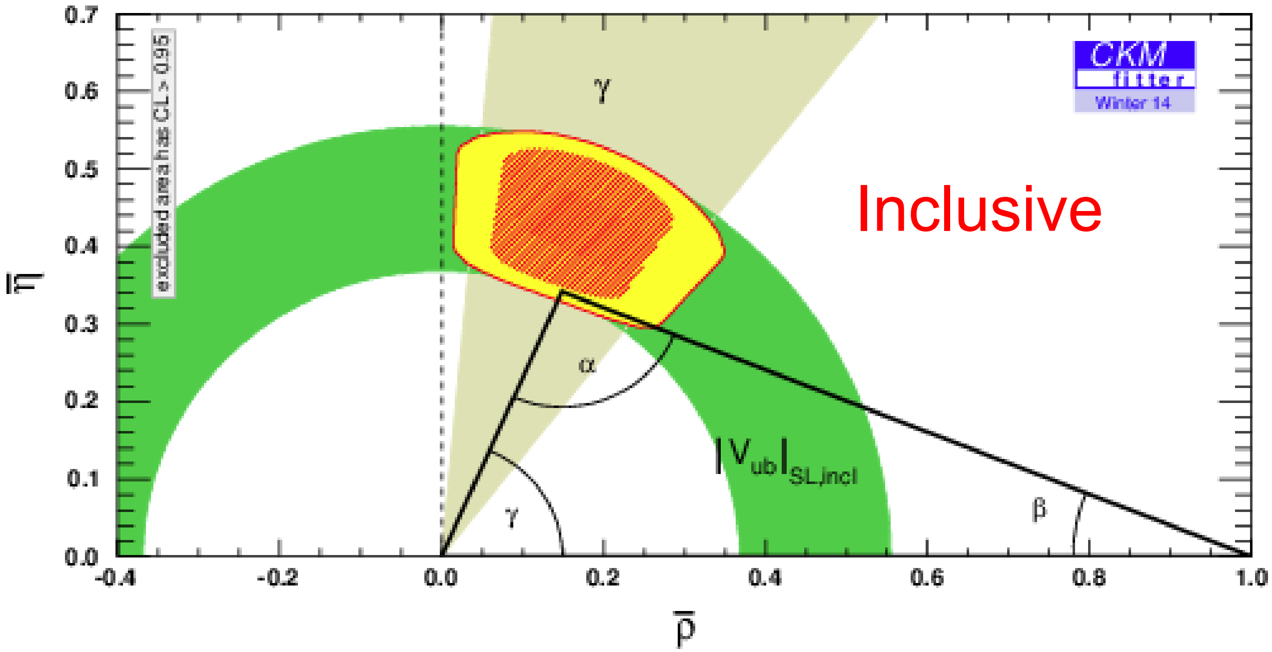

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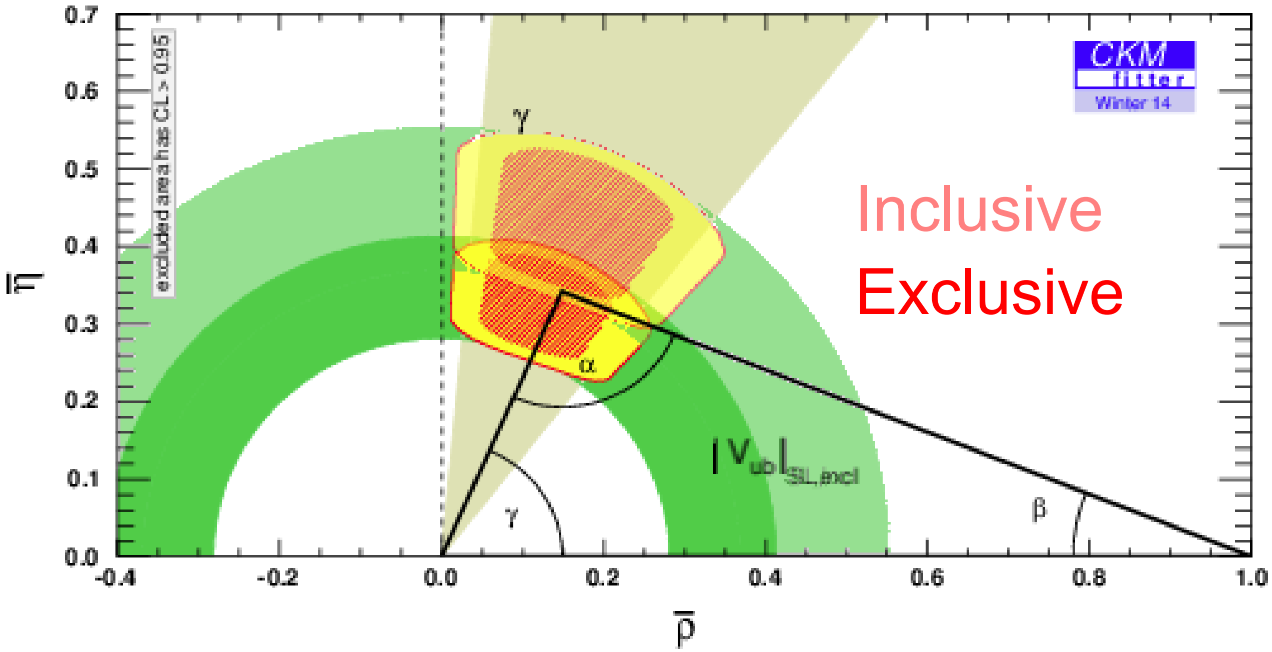


The need to resolve the problem with $|V_{ub}|$

Indicating that we do not fully understand QCD?

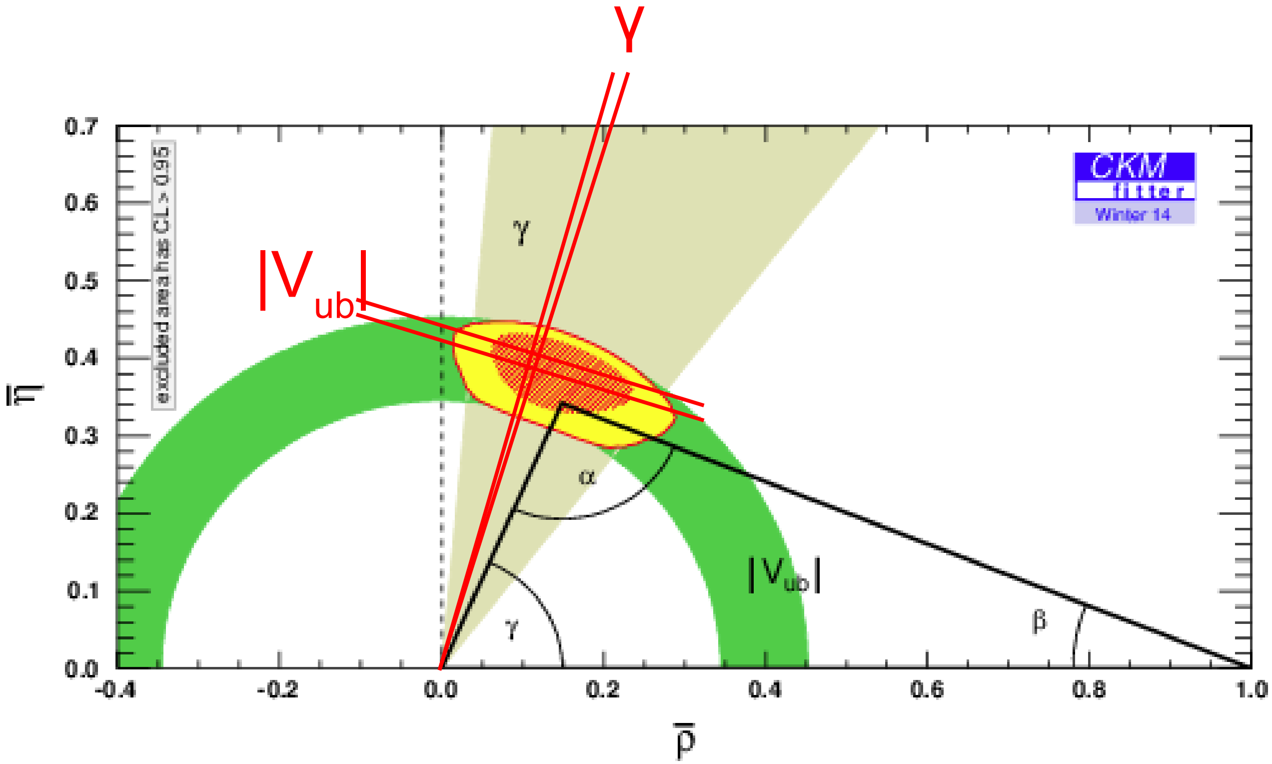
More independent measurements required

- $\Lambda_b \rightarrow p\,\mu^- \nu$
  - Sets constraints on $|V_{ub}|/|V_{cb}|$
- $B^+ \rightarrow \tau^+ \nu$
  - At the moment statistics limited, Belle-II will much improve
  - But maybe dangerous as it drags in LNU as well
- Inclusive measurement
  - Large gain in hadron tagged sample with Belle-II
- $B_c^+ \rightarrow X_c\,\mu^+ \nu$
  - 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



Bread and butter work

There are SM measurements that we need to prove

Many of the experimental measurements depends on normalisation with respect to other modes

- Often these normalisation modes are now imposing serious limits

$B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^{*0}$

Understanding of S-wave components

LHCb : arXiv:1606.04731

$$\mathcal{B}(B^0 \to K^*(892)^0 \mu^+\mu^-) = (1.036\,^{+0.018}_{-0.017} \pm 0.012 \pm 0.007 \pm 0.070) \times 10^{-6},$$

where the uncertainties, from left to right, are statistical, systematic, from the extrapolation to the full q^2 region and due to the uncertainty of the branching fraction of the normalisation mode.

$\Lambda_c^+ \to pK^+\pi^-$

- Discrepancy between Belle and BES measurement a serious limitation on all Λ_c measurements

Conclusion

Heavy flavour physics has a rich future ahead

- Will the current anomalies turn into discoveries?

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