Rare B decays in the HL-LHC era

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on behalf of the LHCb, ATLAS and CMS collaborations

Heavy flavour in the HL-LHC era

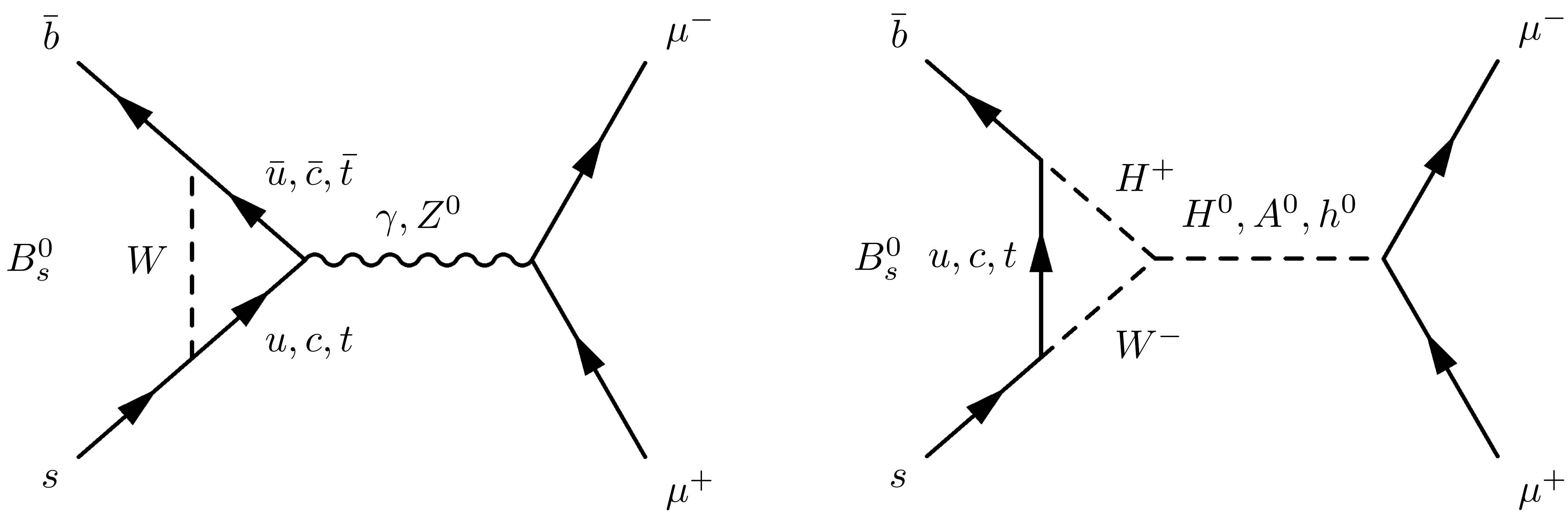
31/08/16

Assumptions

- The beauty cross-section doubles at 14TeV c.f. run I.
- Trigger/selection performance identical unless detailed studies say otherwise (e.g. CMS $B_S \longrightarrow \mu\mu$ note).
- CMS/ATLAS collect $3ab^{-1}$.
- LHCb either
  - collects $50fb^{-1}$ up until run 4
  - collects $300fb^{-1}$ until run 5 (under consideration).

Rare B decays

Sensitive to NP heavier than machine energy.



- As they are rare, less likely to hit systematic and/or theoretical uncertainties. Excellent opportunities with the HL-LHC.

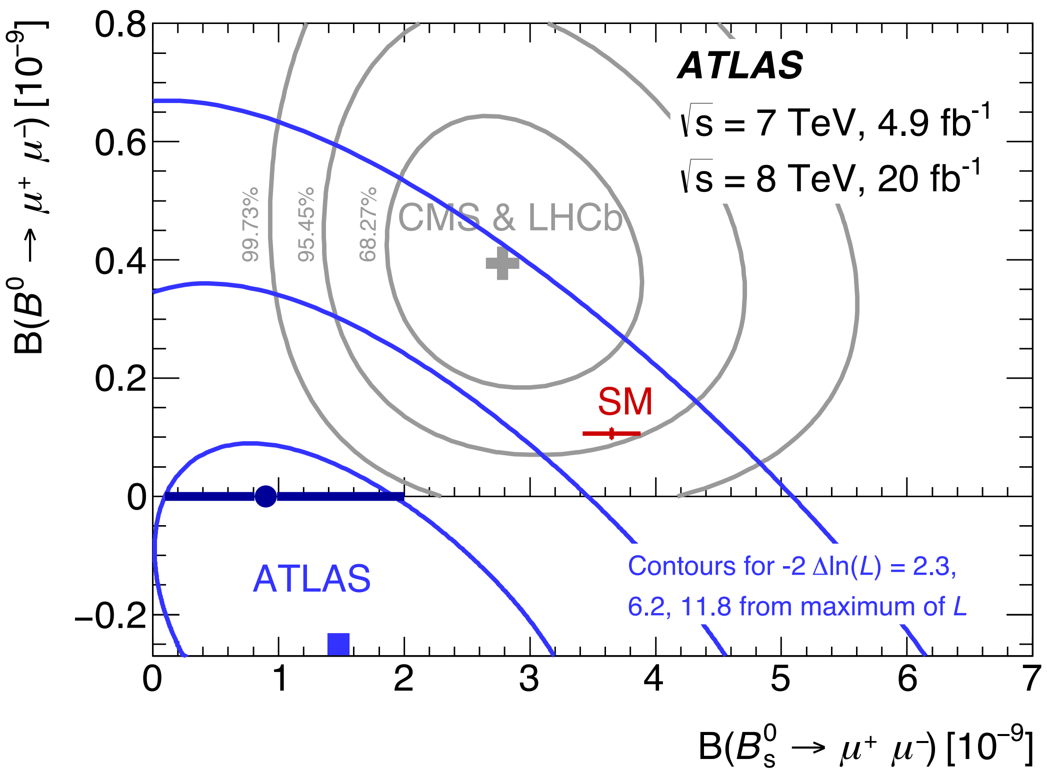
- Many observables have very precise SM predictions.

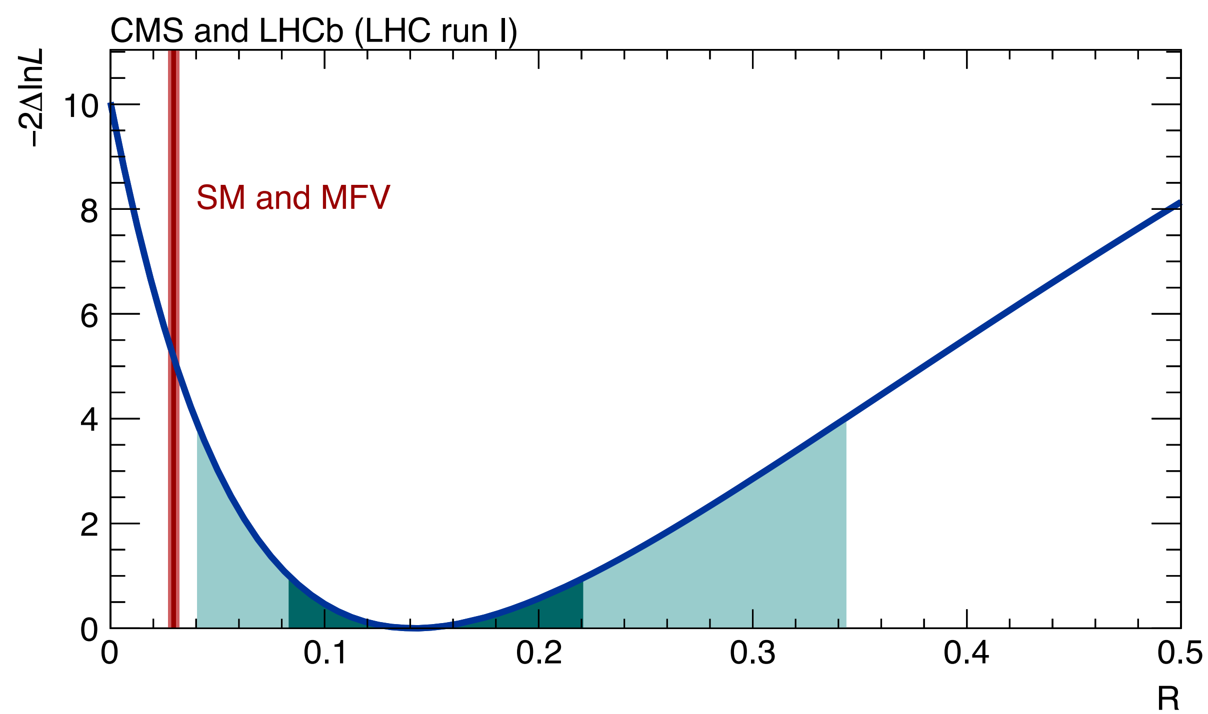
$B_{(s)} \longrightarrow \mu\mu$

- Very rare decay:

$$\mathcal{B}_{\mathrm{SM}}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}_{\mathrm{SM}}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[PRL 112 (2014) 101801]





ATLAS: JHEP 06 (2016) 081, CMS+LHCb: Nature 522 (2015) 68

$B_{(s)}$—>μμ - projections

- Detailed study in CMS PAS FTR-14-015 for CMS
  - Assuming fs/fd uncertainty 5%, B(B+->J/psi K) 3%.

With 3ab-1: $\sigma(B_s)$ = 11%

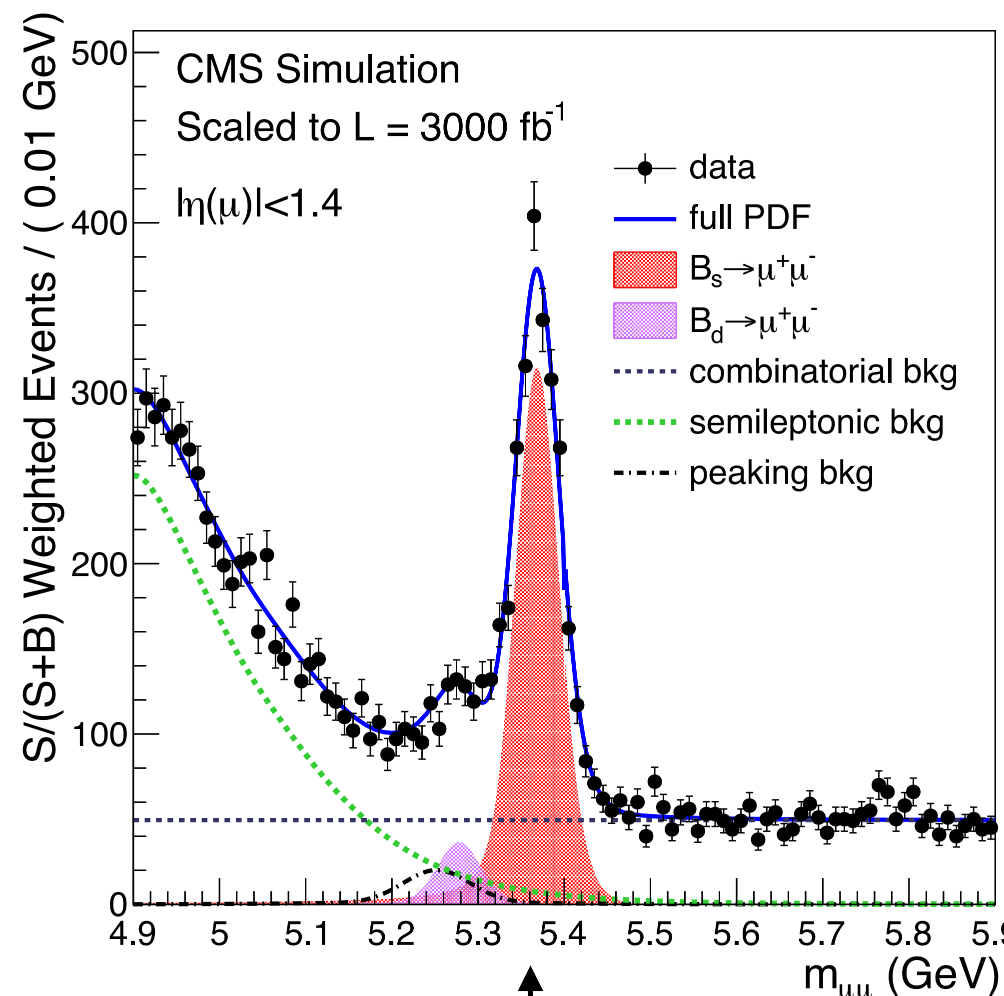
$\sigma(B_d)$ = 18%

$R_{s/d}$ = 21%

Yield comparison

	CMS	LHCb (50fb-1)	LHCb (300fb-1)
$N(B_d)$	271	40	240
$N(B_s)$	2250	400	2400

Crude extrapolations based on single event sensitivities in Phys. Rev. Lett. 111, 101805 (2013).

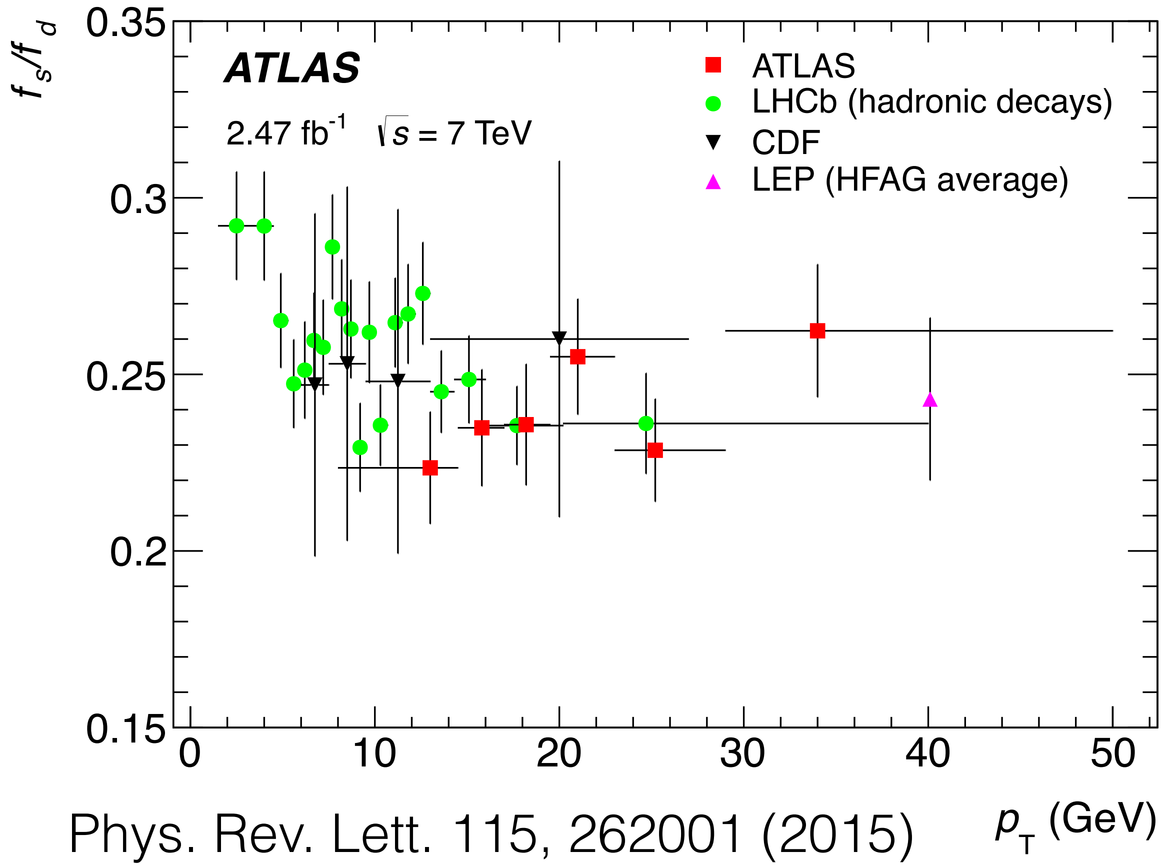


Mass resolution 28 MeV

Limiting systematics

- For the B_s mode, expect to be limited by systematic uncertainties.

- Most likely limiting one is fs/fd.



Phys. Rev. Lett. 115, 262001 (2015)

Correlated uncertainties between two LHCb methods (LHCb-CONF-2013-011)

Source	Uncertainty (%)
$\mathcal{B}(D^- \to K^+\pi^-\pi^-)$	2.2
$\mathcal{B}(D_s^- \to K^+K^-\pi^-)$	2.5
Lifetime ratio	0.9
Total	3.4

Other uncertainties include SU(3) breaking (had) and SL branching fractions.

- BES III can help push these charm branching fractions down.

Other limiting systematics

- $B(B^+ \to J/\psi K^+)$ uncertainty currently 4%.
    - Ambiguities related to isospin asymmetry at Υ(4S) need to be resolved (see M. Jung, arXiv:1510.03423), and should be by Belle 2.
- Other systematics related to semileptonic backgrounds (e.g. $B \to \pi\mu\nu$) should reduce with updated lattice calculations.
- Mis-ID background should be always controlled with data, but need to keep good $h \to \mu$ rejection in HL-LHC era.

Theoretical uncertainty

- Theo uncertainty dominated by CKM matrix elements and B decay constants.

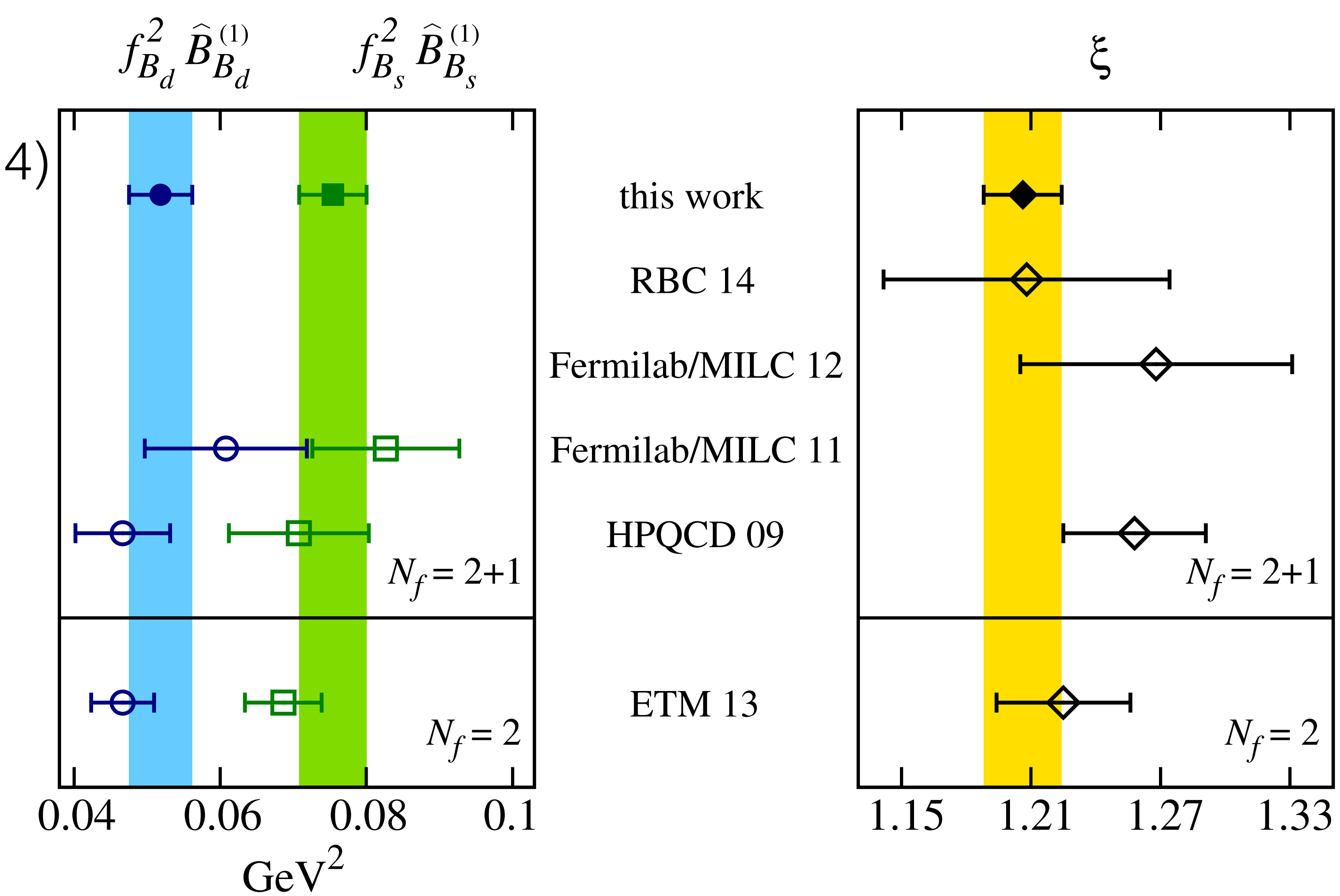
  - Both expected to decrease with lattice improvements.

C. Bobeth et al, Phys. Rev. Lett. 112, 101801 (2014)

	f_{B_q}	CKM	τ_H^q	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$\overline{\mathcal{B}}_{d\ell}$	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

TABLE II: Relative uncertainties from various sources in $\overline{\mathcal{B}}_{s\ell}$ and $\overline{\mathcal{B}}_{d\ell}$. In the last column they are added in quadrature.

Don't expect expt uncertainty to ever reach theoretical.



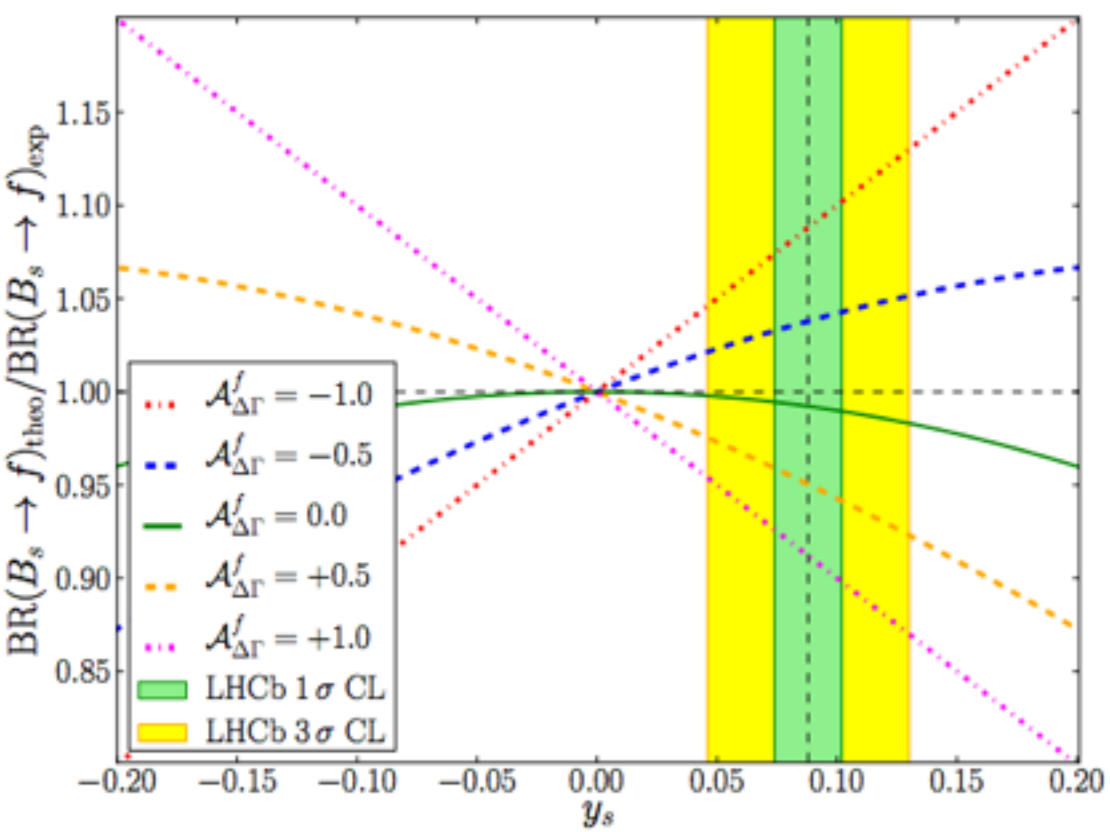
FNAL/MILC - Phys. Rev. D 93, 113016 (2016)

$B_s \longrightarrow \mu\mu$ effective lifetime

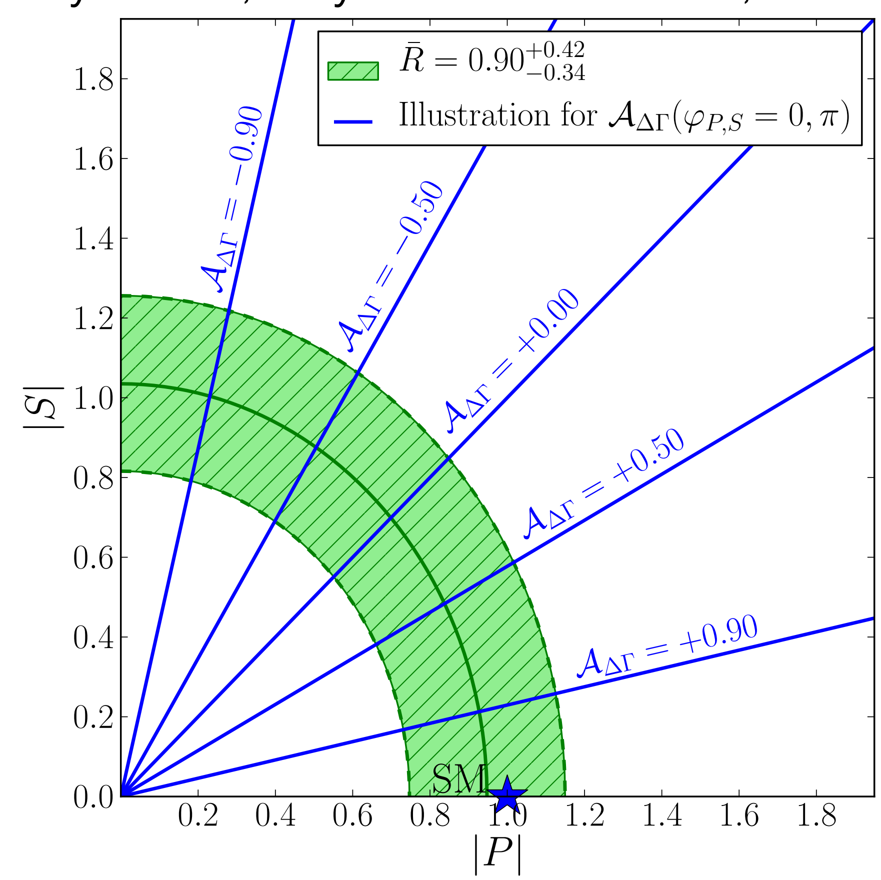
- The branching fraction cannot differentiate between scalar (S) and pseudo-scalar (vector) (P) contributions

- Fortunately, can probe these as the P amplitude results in a 20% longer lifetime than the S amplitude.

K. De Bruyn et al, Phys. Rev. D 86, 014027 (2012)



K. De Bruyn et al, Phys. Rev. Lett. 109, 041801 (2012)



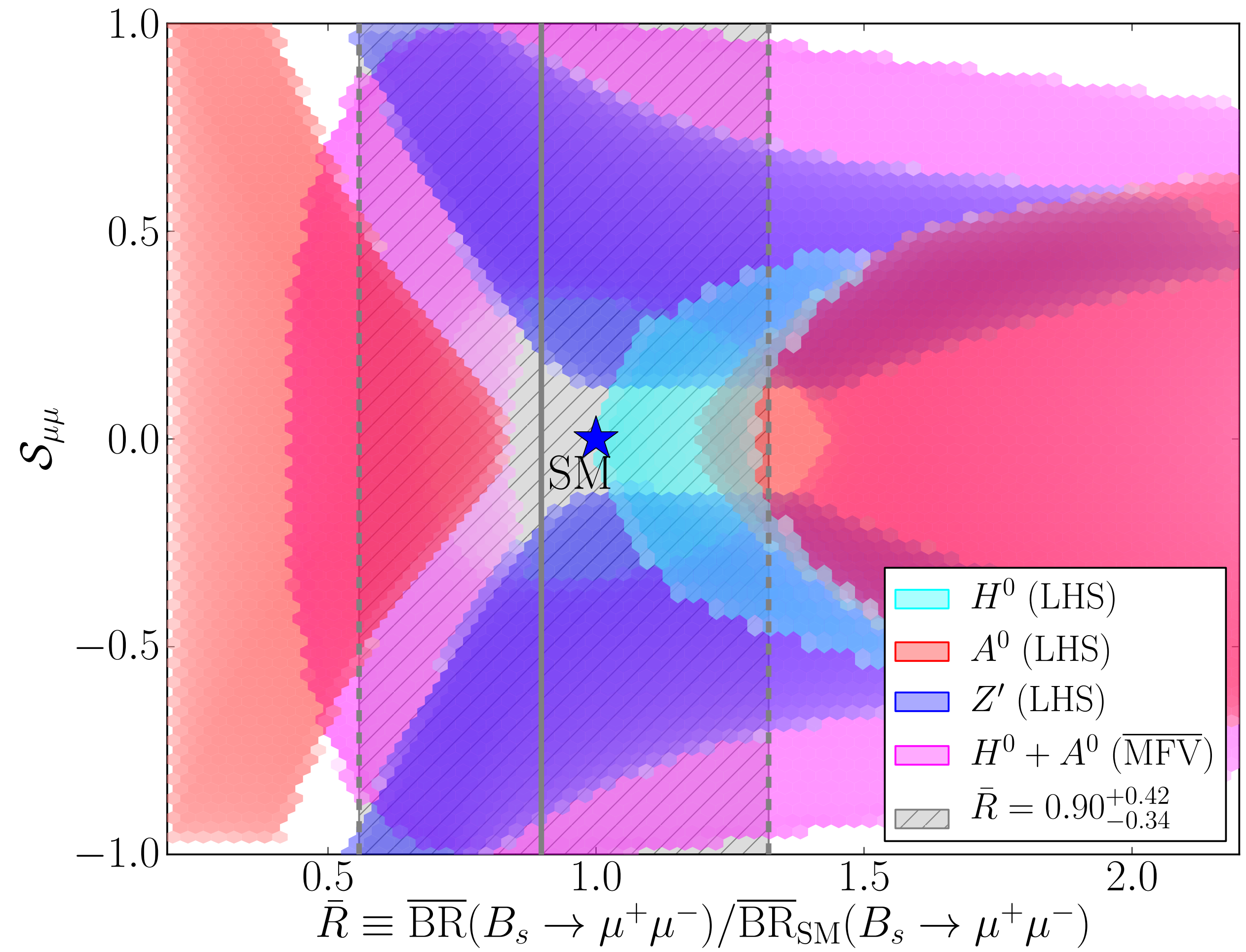
A lifetime 5% uncertainty is estimated with $50\mathrm{fb}^{-1}$ for LHCb, essential to have $300\mathrm{fb}^{-1}$ to get down to 2%.

B_s—>μμ time dependent CP asymmetry

- Reminder: In 300fb-1 scenario, get 2.4K B_s—>μμ candidates

- With 4% tagging power, corresponds to 100 perfectly tagged candidates for measuring the time dependent CP asymmetry, $S_{\mu\mu}$.

- Estimate of possible sensitivity found by comparing with measurement of A_{KK} (JHEP 10 (2013) 183)
  - With 14K candidates, get A_{KK} uncertainty of 0.12
  - Could expect uncertainty on $S_{\mu\mu}$ 0.3 with 300fb-1.



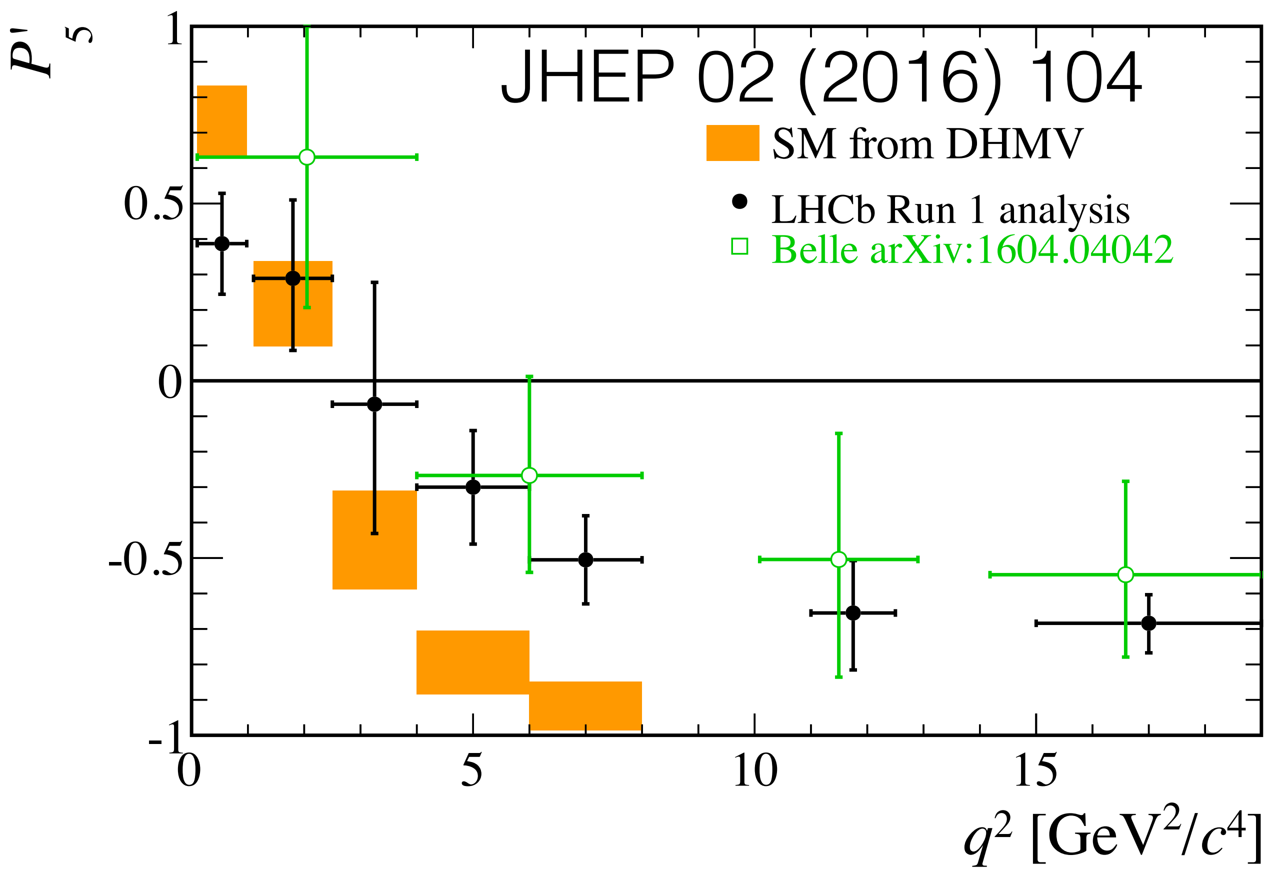
A Buras et al, JHEP 1307 (2013) 77

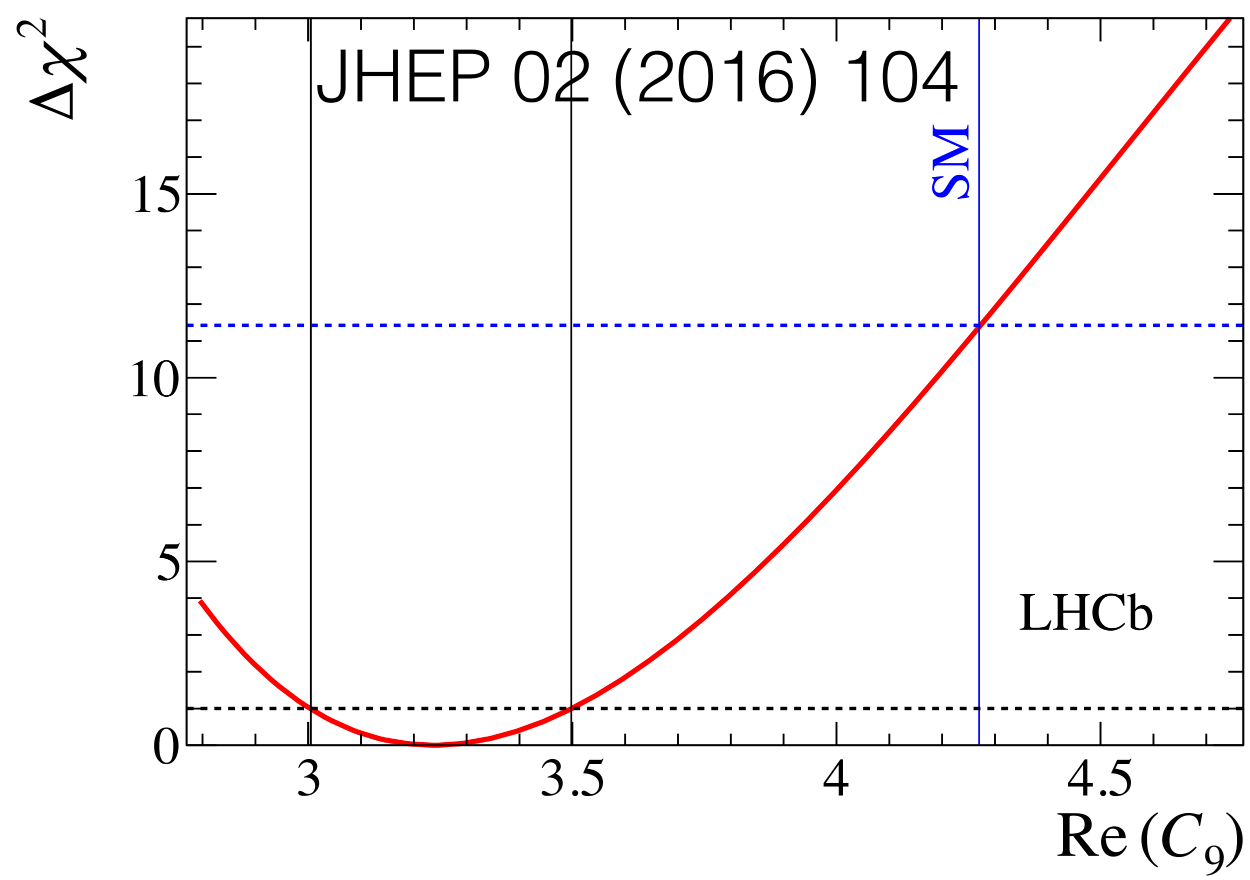
Many assumptions made here!

B—>K*μμ

- Moving to a semi-leptonic decay, more freedom - now sensitive to vector and electromagnetic operators.

- Well-documented discrepancy in the vector coupling, C9.





- Experimental uncertainties expected to be dominated by statistics for many years - most limiting systematics come from theory side.

B->K*μμ projections

- Assuming trigger/selection efficiency the same as run 1.
- Project number of B->K*μμ in $1<q^2<6$ GeV region.

	Run 1	Run 1-3(4)	Run 1-5
LHCb JHEP 02 (2016) 104	600	20,000	120,000*
CMS Phys. Lett. B 753 (2016) 424	300	10,000	100,000

- Looking forward to run 1 results from ATLAS

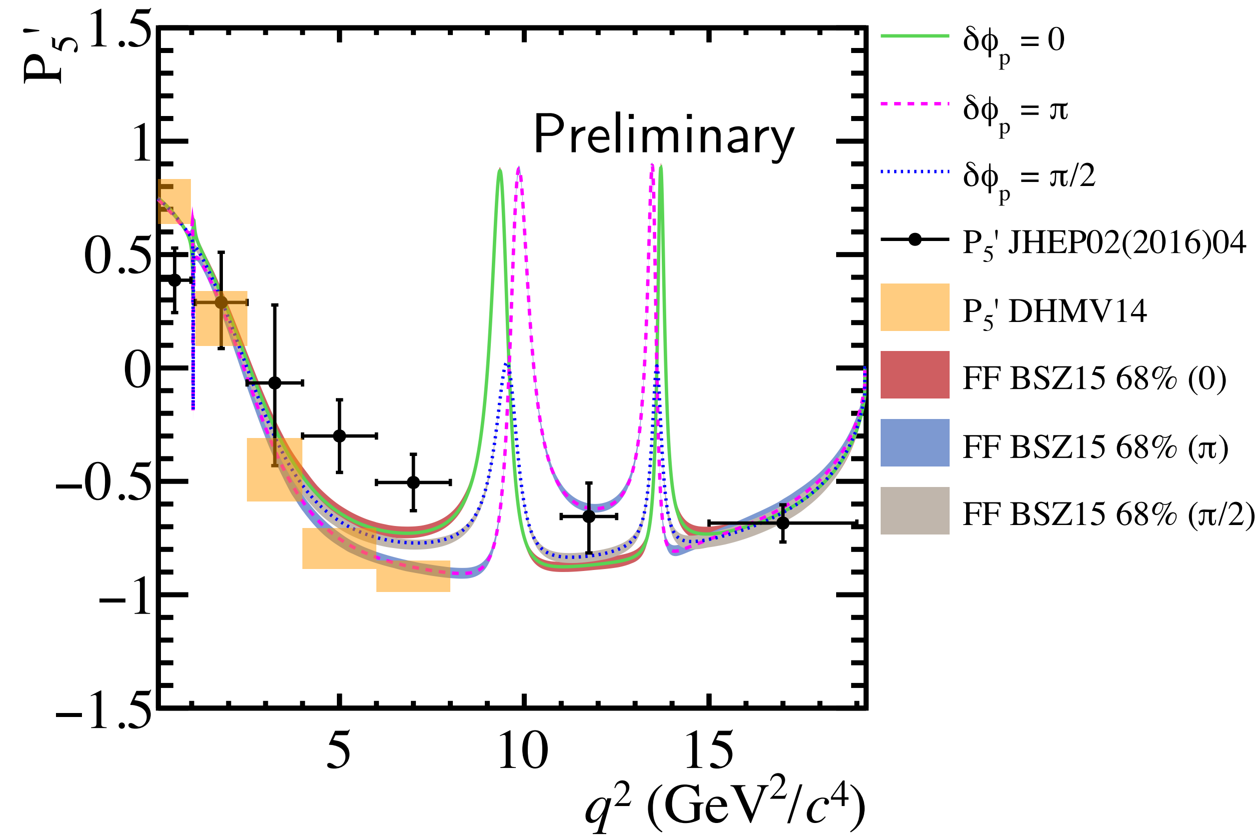
* Assuming LHCb gets $300 fb^{-1}$.

B—>K*μμ and charmonium

- Interference with charmonium resonances (dominated by B->J/psiK*) has impact on SM predictions.

- With more q^2 bins (more data), can differentiate between charm and NP.
- Can also measure phase of charmonium contribution directly.
- Constraints on C_{10} not affected by this.
  - We need K*mm to break degeneracy in B_s—>μμ

    $B(B_s \text{—>} \mu\mu) \ \alpha \ (C_{10}\text{-}C_{10}')^2$



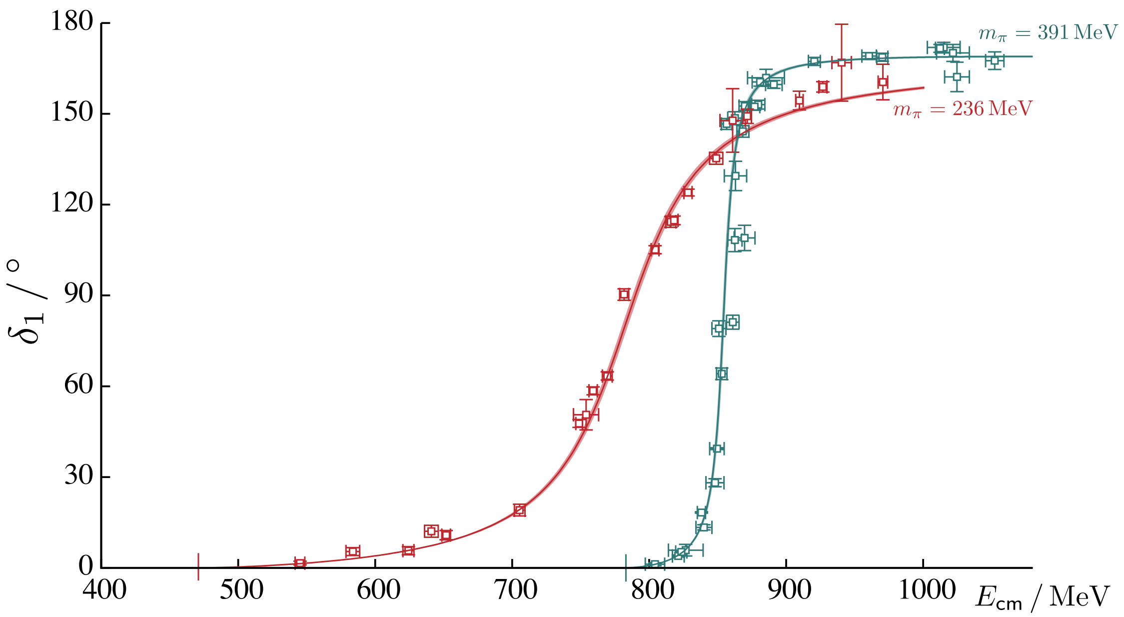
plot from K. Petridis' talk [here].

Form factors

- Improvements to form factors are essential for reducing theoretical uncertainties to experimental ones in HL-LHC era.

- Here we can profit from advances in the lattice community.

- Here ππ scattering shows potential for B—>Kπ form factors - could be available by HL-LHC timescale.

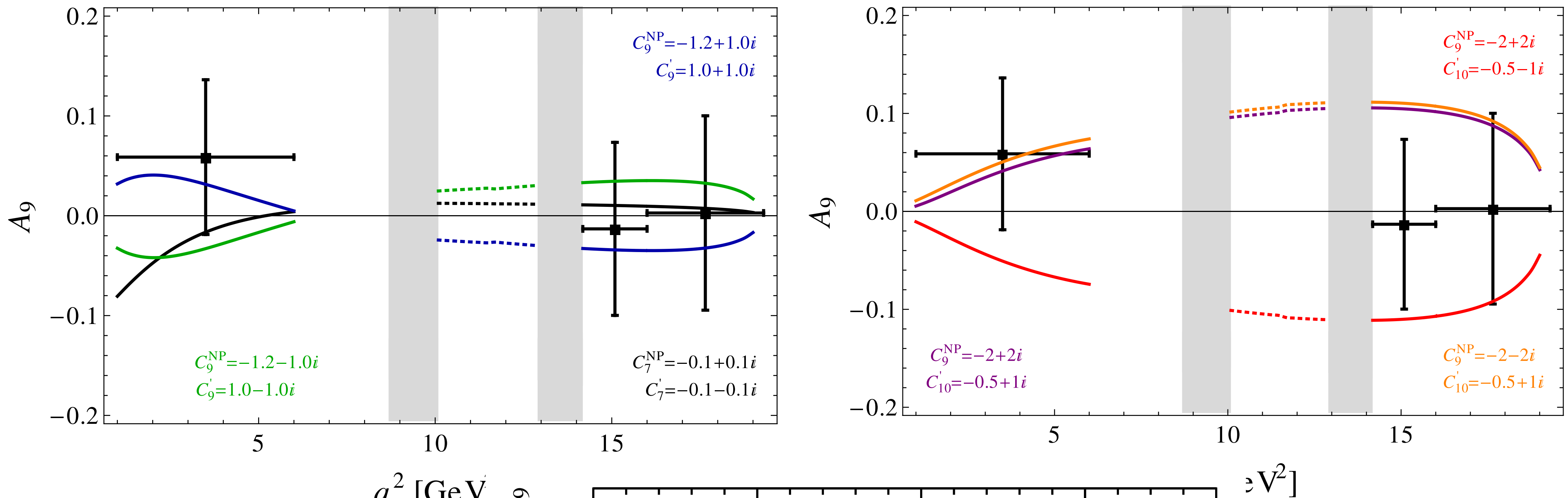


Phys. Rev. D 92, 094502 (2015)

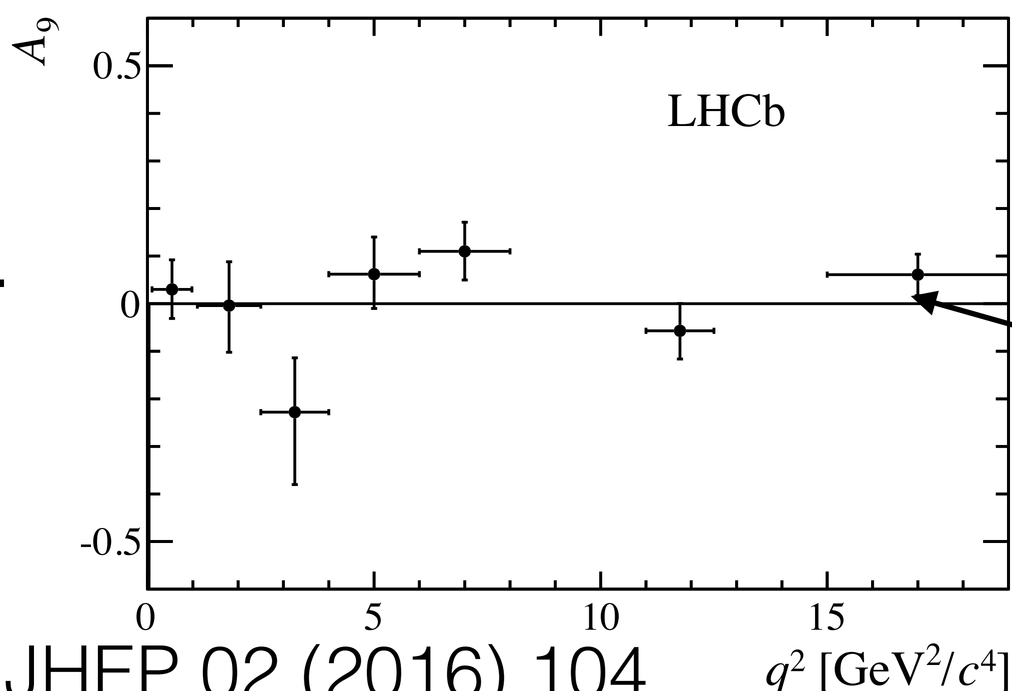
Other observables

- Easy to forget that there many B->K*μμ observables which are very theoretically clean.

W. Altmannshofer et al, Eur. Phys. J. C (2013) 73: 2646



e.g. A9, which is negligibly small in SM.

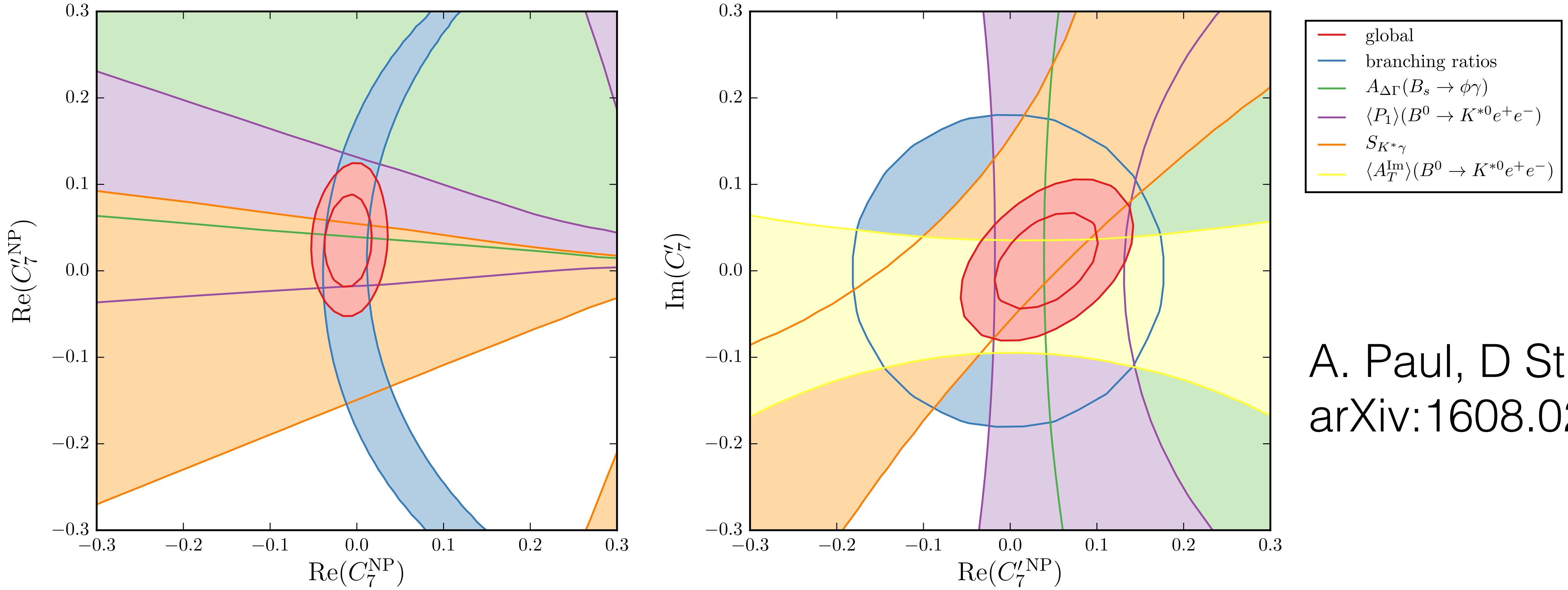


Reduce uncertainties by factor 15 with 300fb-1 and you would start to see effects seen in top plots.

JHEP 02 (2016) 104

B—>K*ee

- The decay B—>K*ee gives the most constraints on the imaginary (RH) part of the Wilson Coefficient, C_7

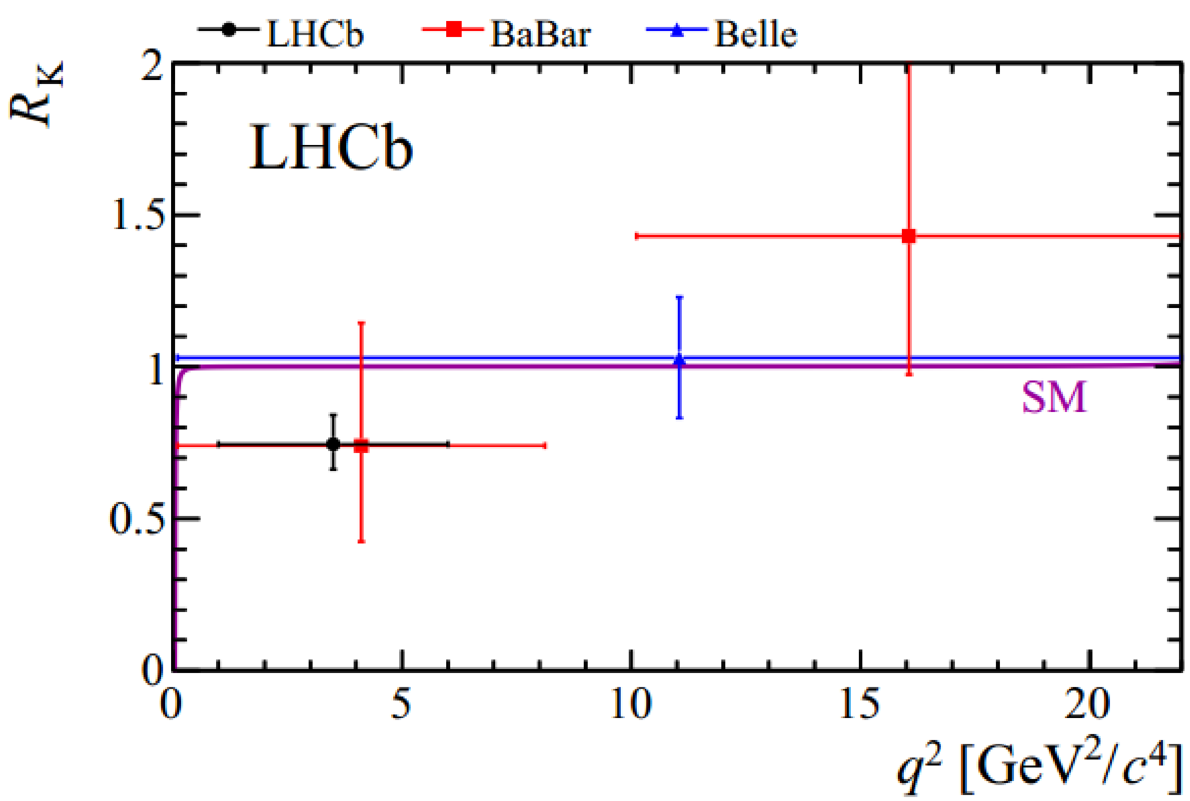


A. Paul, D Straub, arXiv:1608.02556

- With 3fb-1, LHCb's K*ee is already most constraining on RH plot.
- Belle 2 will have 50 times more data - with 300fb-1, LHCb would have 200 times more.
  - Going to 300fb-1 would significantly improve constraints if can keep electron reconstruction/trigger efficiency.

LFU tests

LFU tests also very sensitive to NP.



R(X) stat uncertainties (my own projections based on muon BF uncertainties)

Decay	Run 1	Run 2	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+\mu^+\mu^-$	11%	5%	2%	1%
$B^0 \to K^{*0}\mu^+\mu^-$	18%	8%	3%	1%
$B^0_s \to \phi\mu^+\mu^-$	36%	15%	8%	3%

- Will be mostly systematics limited by 50fb-1.
- If R_K discrepancy holds up, will want to test with b—>d transitions.
  - Will need lots of data for this.

LFV searches

Signals for B->Kll' implied if we see non-LFU.

	$B^+ \to K^+ \mu^\pm \tau^\mp$	$B^+ \to K^+ e^\pm \tau^\mp$	$B^+ \to K^+ e^\pm \mu^\mp$
	1.14×10^{-8}	3.84×10^{-10}	0.52×10^{-9}
Exp:	$< 4.8 \times 10^{-5}$	$< 3.0 \times 10^{-5}$	$< 9.1 \times 10^{-8}$

	$B_s \to \mu^\pm \tau^\mp$	$B_s \to e^\pm \tau^\mp$	$B_s \to e^\pm \mu^\mp$
	1.37×10^{-8}	4.57×10^{-10}	1.73×10^{-12}
Exp:	—	—	$< 1.1 \times 10^{-8}$

Taken from D. Guadagnoli's [talk], based on Phys. Rev. Lett. 114, 091801 (2015)

- No public expt numbers available yet, but with 50 (300) fb-1 could expect to reach interesting regions.

Summary

- Many rare B decay observables will be interesting even with a factor 10 smaller uncertainties.

- HL-LHC period will significantly improve key observables such as.

  - Bs->μμ BF, lifetime and CP observable, Bd/Bs ratio.

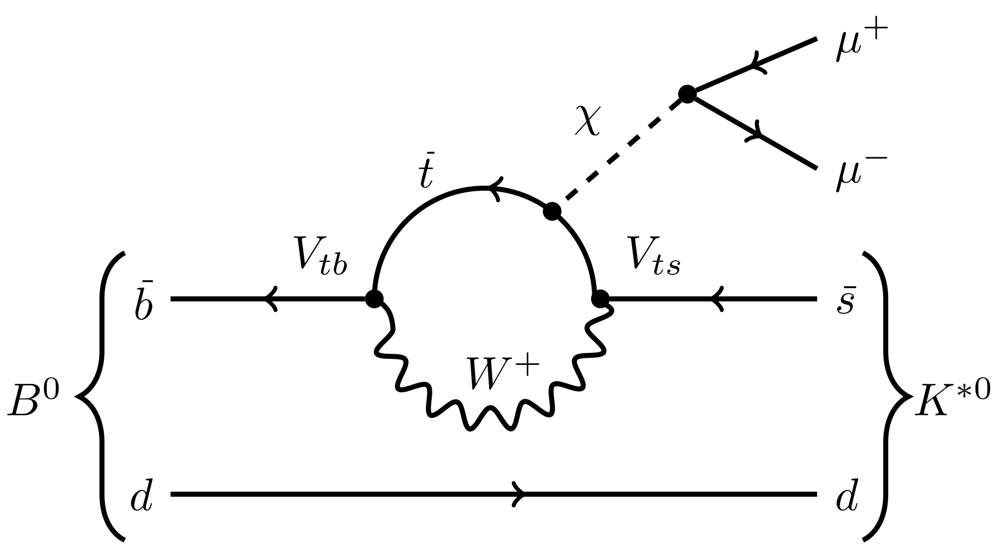
  - Observables in K*μμ/ee.

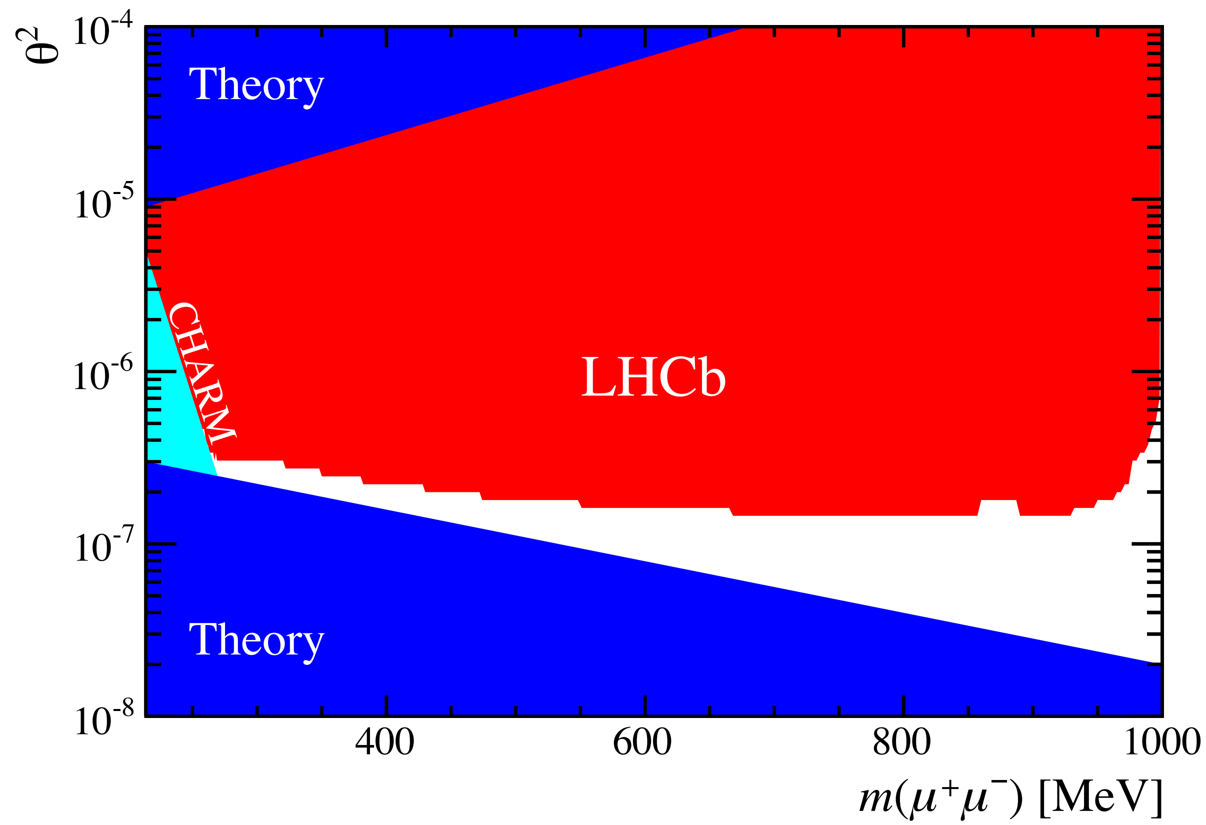
  - Deeper probes in LFV decays.

  - Extend reach in phase-space for exotics.

Direct searches

- B decays excellent places to probe dark sector.
    - Large top mass enhances coupling to models which mix with the Higgs boson.





Phys. Rev. Lett. 115 (2015) 161802

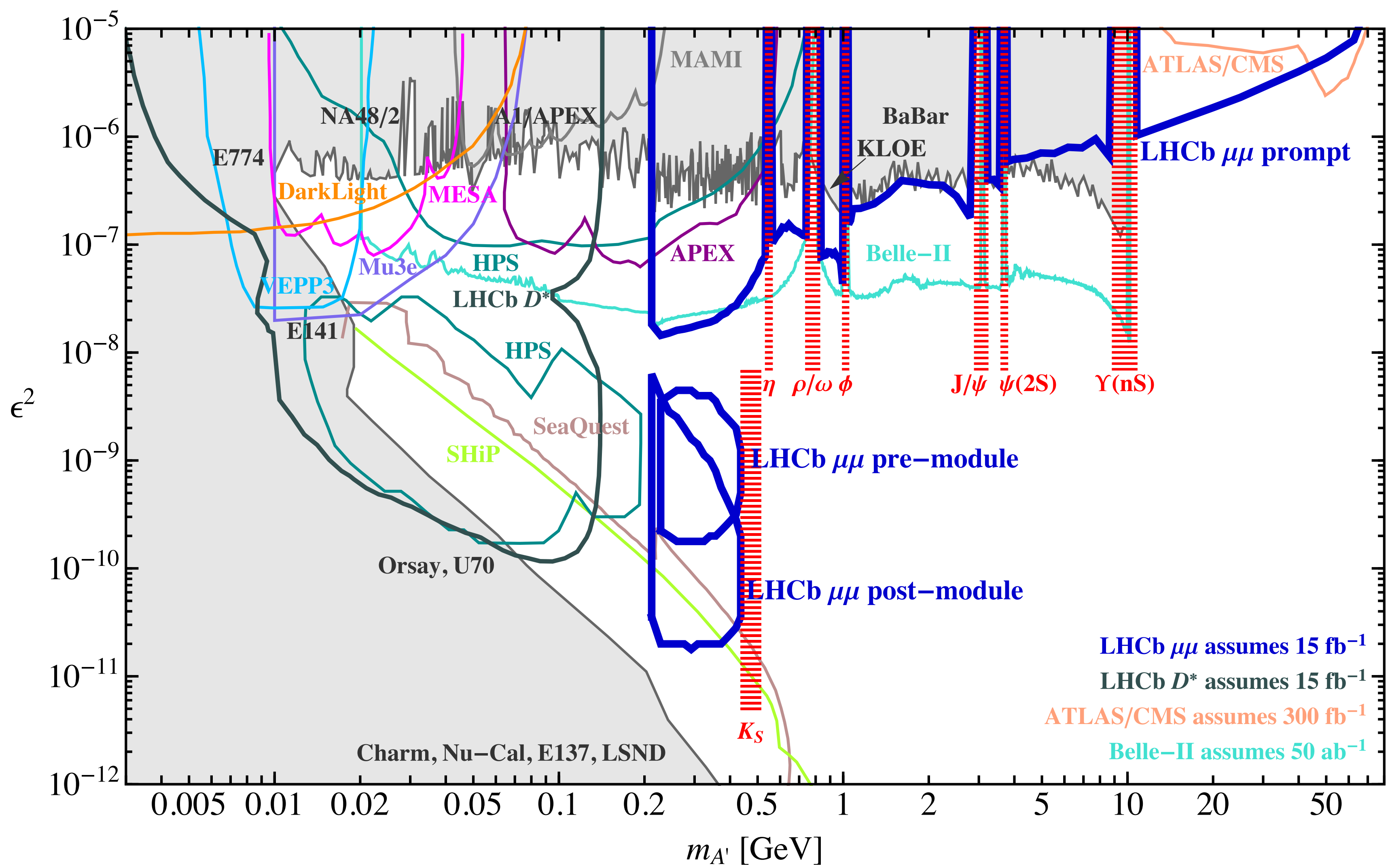
- Search in the dimuon mass distribution of B—>K*μμ decays with 3fb-1 ruled out large parameter space for several hidden sector models.

Dark photon searches.

P. Ilten et al from Phys. Rev. Lett. 116, 251803 (2016) propose an inclusive bump hunt in the dimuon spectrum in LHCb.

Important feature is ability to trigger on soft dimuons.

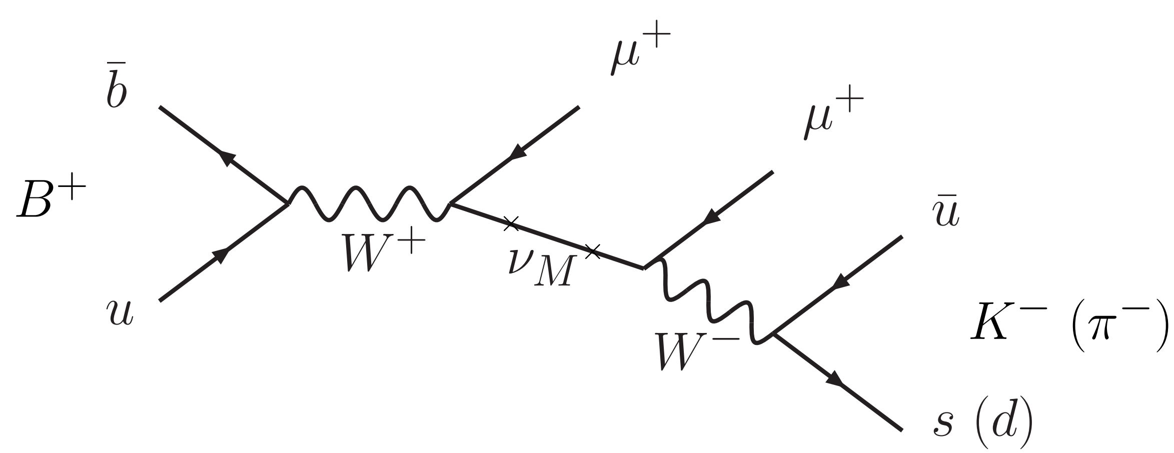
Mis-ID a key background.

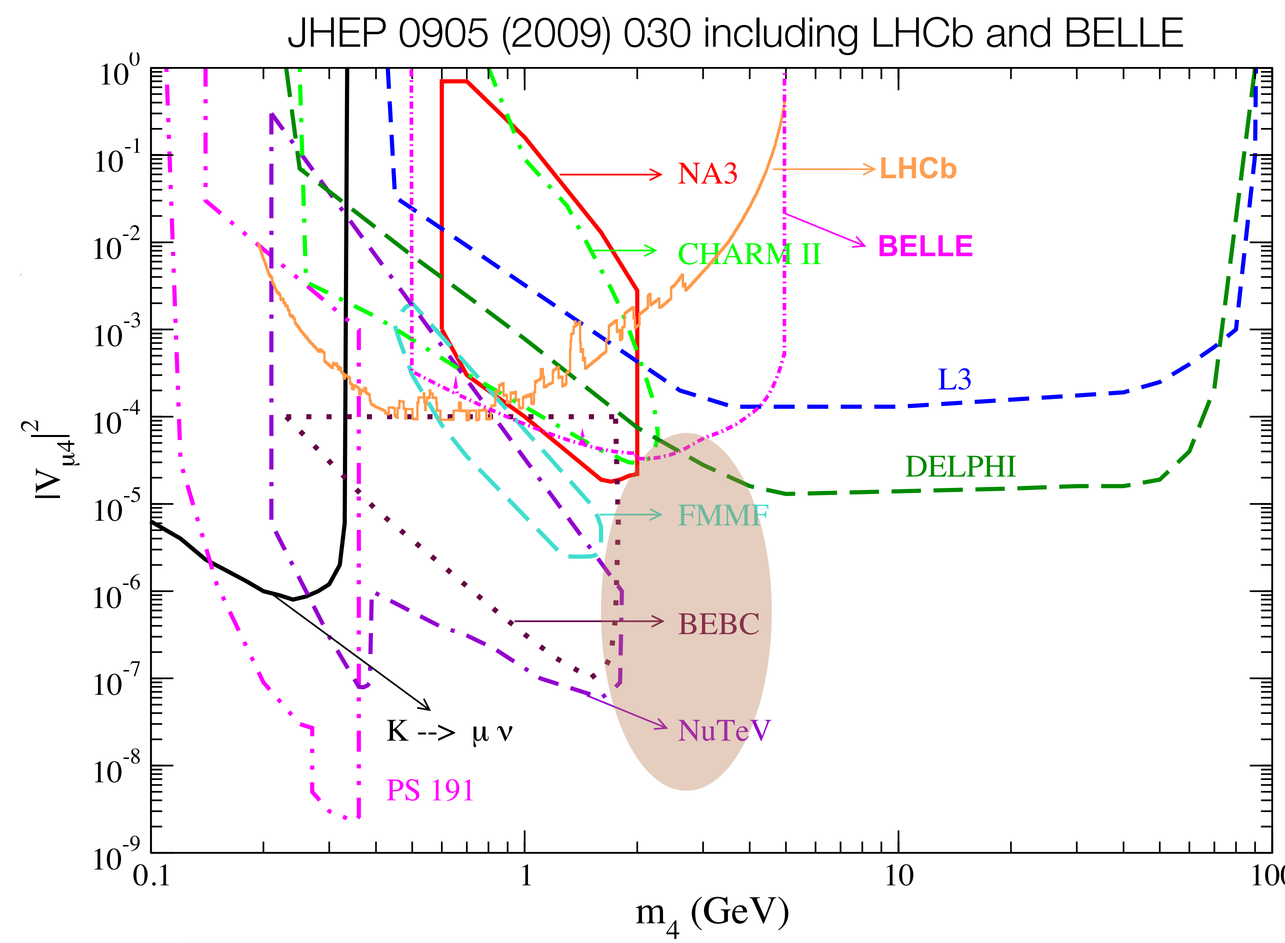


Expect limits to get better by factor 5 with 300fb-1 for LHCb and a factor 3 for ATLAS/CMS with 3ab-1.

Majorana neutrinos

- Majorana neutrinos can be produced in rare B decays, such as $B^+ \to \pi^- \mu^+ \mu^+$





LHCb result (see Phys. Rev. Lett. 112, 131802) based on 3fb-1.

Limit dependent on model assumptions (see arXiv:1607.04258).

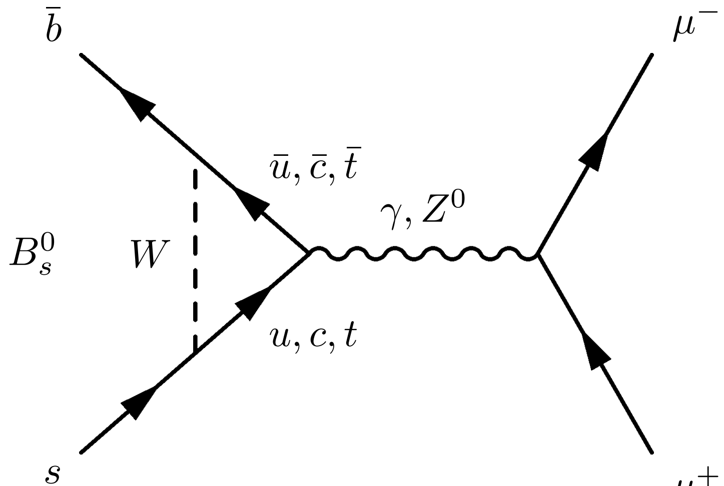
Could drastically improve limit with 300fb-1, and a more inclusive approach similar to what is proposed for the dark photon.

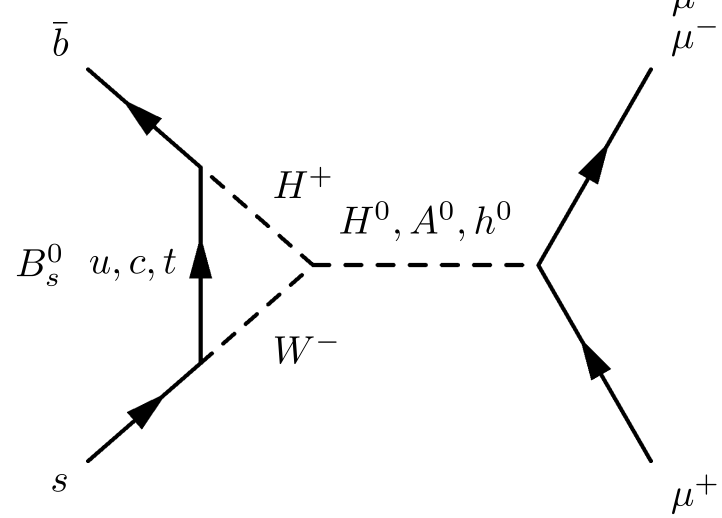
$B_{(s)}$—>μμ - LHCb projections

- Using the single event sensitivities in Phys. Rev. Lett. 111, 101805 (2013).
    - Expected 40 B_s signal and 4 B^0 with 3fb-1.
- Assuming 30% of signal has good B/S (similar to CMS projections).
    - Get 400 B_s signal and 40 B^0 with 50fb-1 in this B/S region.
- If LHCb collects 300fb-1, expect 2.4K B_s and 240 B^0.
    - Will vastly improve MFV ratio uncertainty in 300fb-1 scenario.

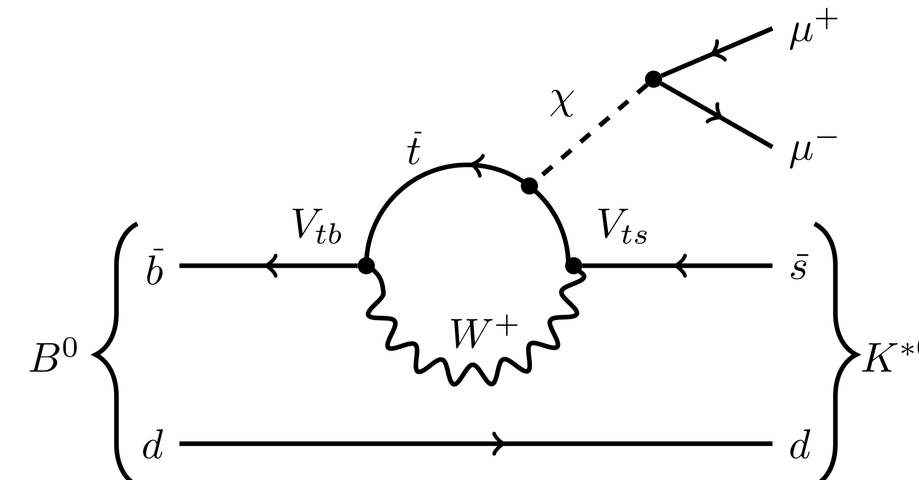
Rare B decays

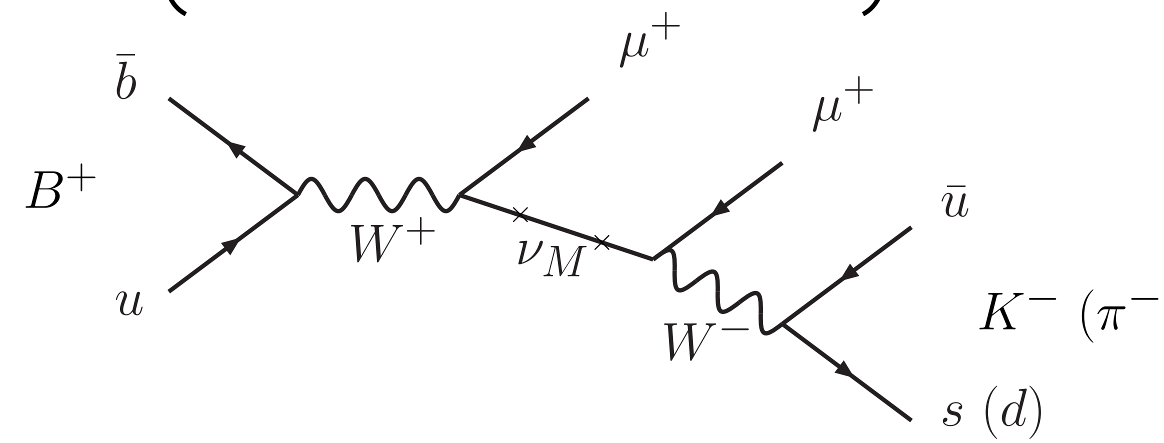
Indirect - sensitive to NP heavier than machine energy.





Direct - sensitive to very weak couplings.





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