Very rare decays and lepton flavour violation searches at LHCb

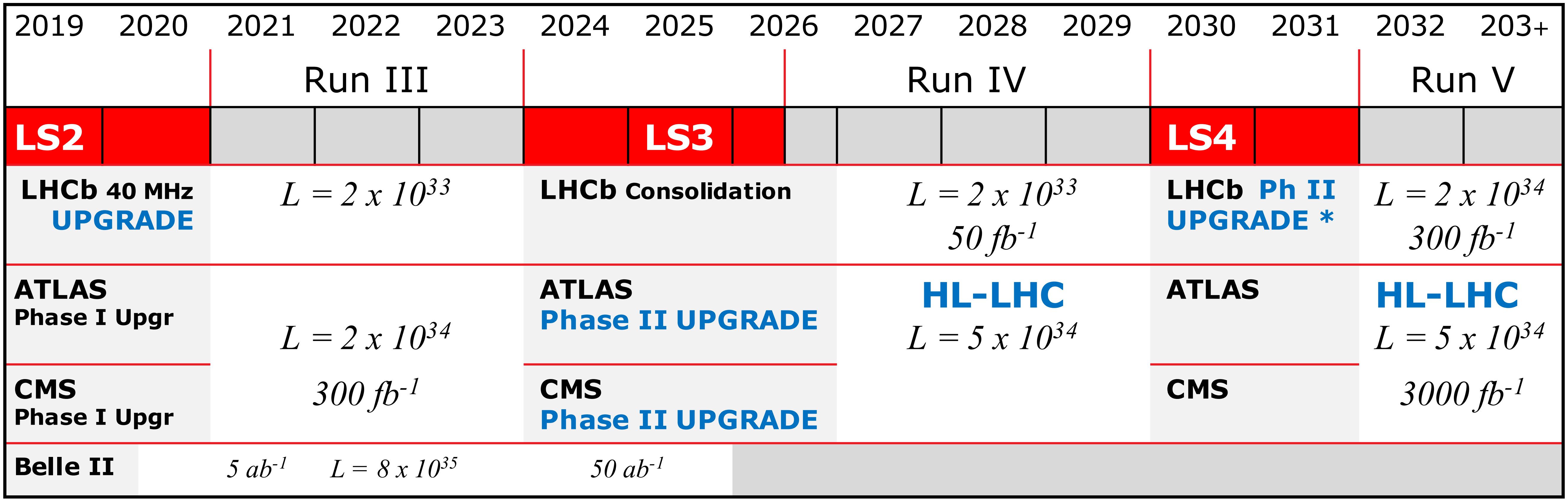
Jessica Prisciandaro
(on behalf of the LHCb collaboration)

Beyond the LHCb Phase-1 Upgrade workshop
28-31 May 2017

European Research Council
Established by the European Commission

UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

LHC schedule

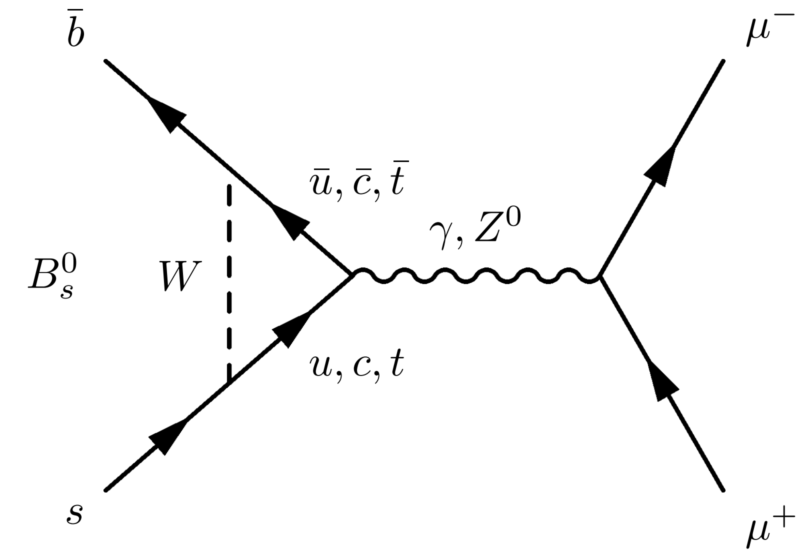


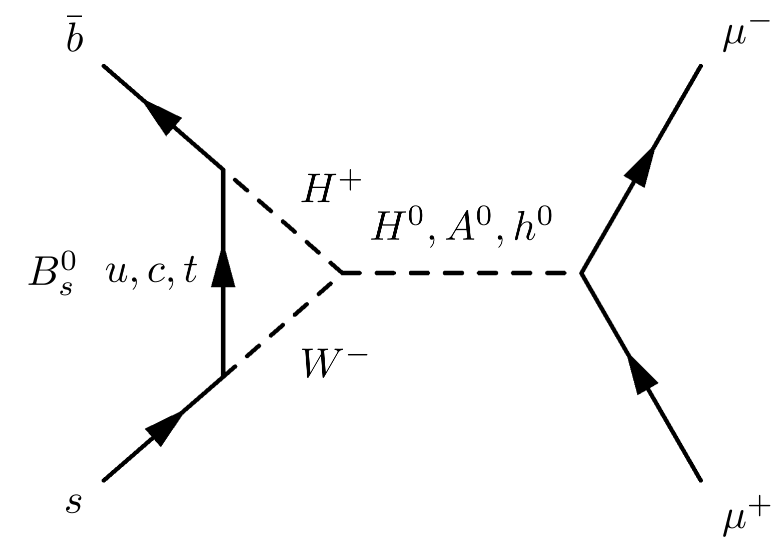
(plot from Niels Tuning)

- LHCb expects to collect 300 fb^{-1} with Phase-II upgrade (3000 fb^{-1} foreseen for ATLAS and CMS)
- Most of the predictions hereafter will assume only the foreseen accumulated statistics

  \- some studies will take in account the expected gain from a full software trigger

What do we need for Very Rare Decays?





- as much statistics as possible
  - many RD are **not** systematically limited (and won't be with HL-LHC)
  - many observables have very precise SM predictions
- Possible to reach SM predictions or NP region for many decays with 300 fb^{-1}
- More opportunities in Run5 with an upgraded detector:
  - Improved electron reconstruction/selection
  - More precise downstream track reconstruction
- Keep a full software trigger that cover the all $p_{(T)}$ spectrum, is fundamental for many analyses

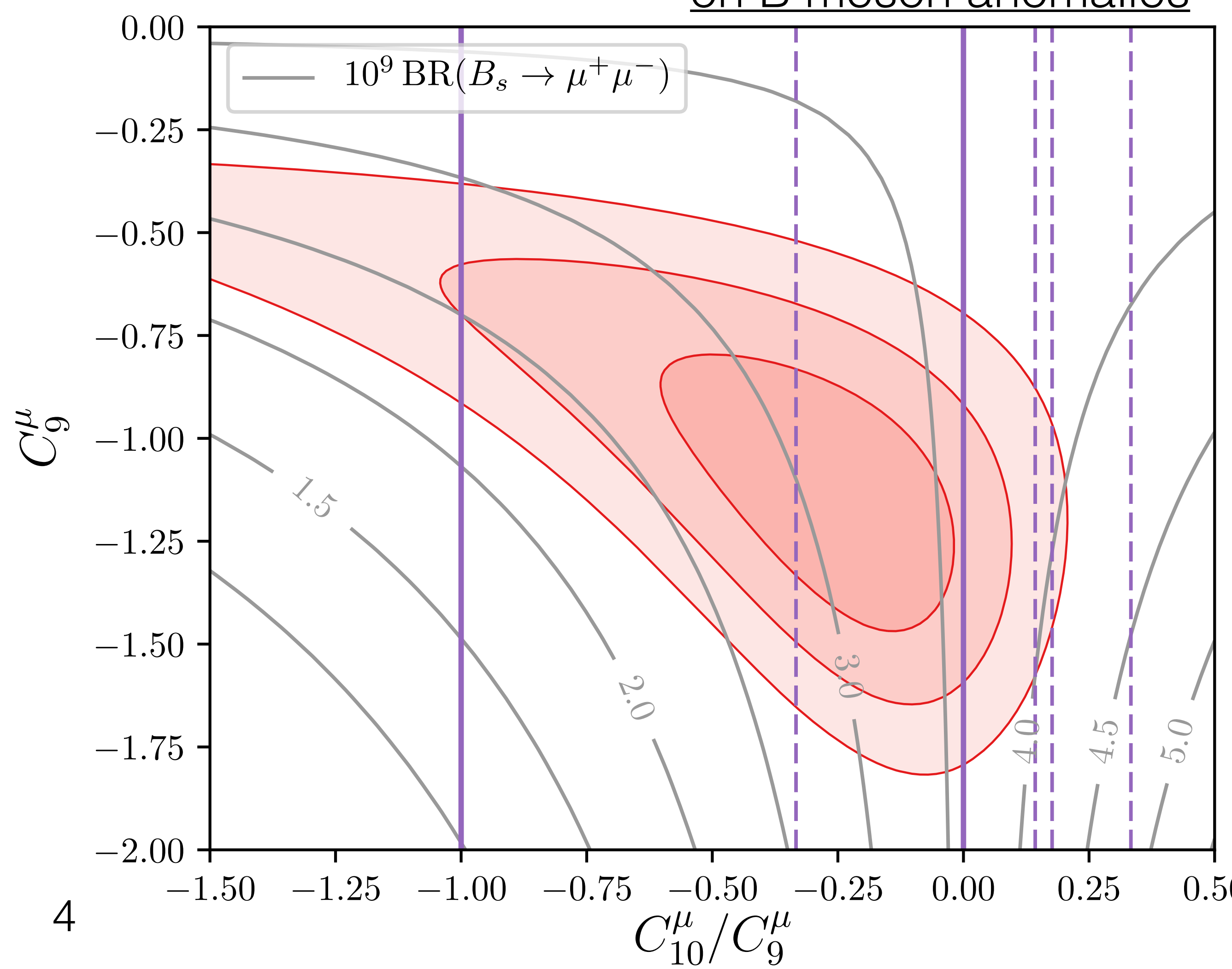
$B_{(s)} \to \mu\mu$: branching fraction

- Very rare decay, FCNC and helicity suppressed
- Very sensitive to possible (pseudo)scalar new physics contributions
- Precisely predicted in the SM

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

- Very clean probe of C^{μ}_{10}

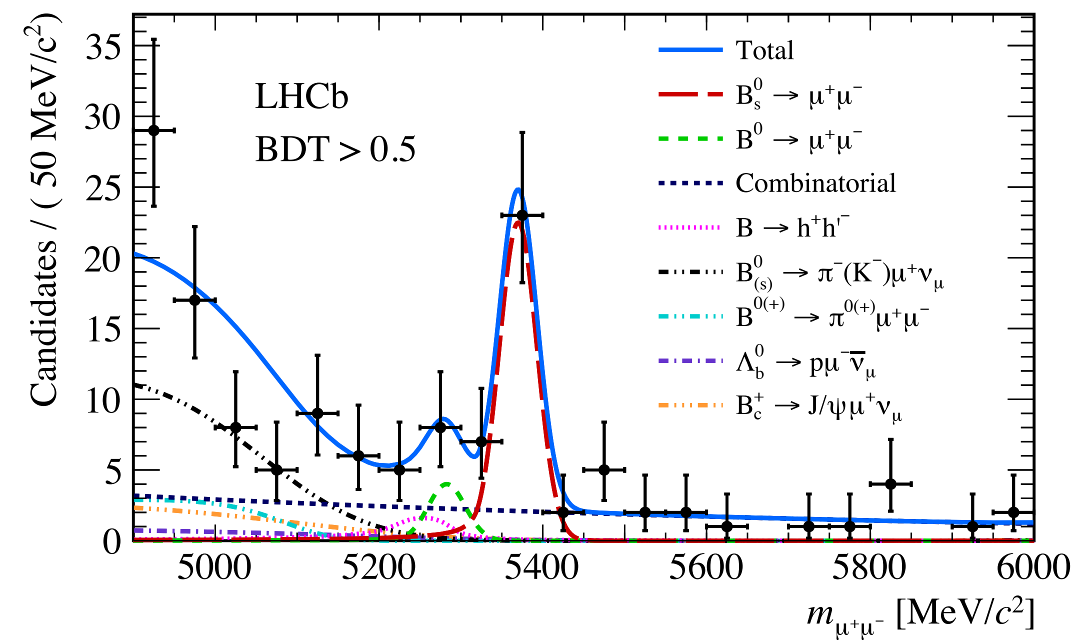
Straub - Instant workshop on B meson anomalies



$B_{(s)} \to \mu\mu$: branching fraction

- Very rare decay, FCNC and helicity suppressed
- Very sensitive to possible (pseudo)scalar new physics contributions
- Precisely predicted in the SM

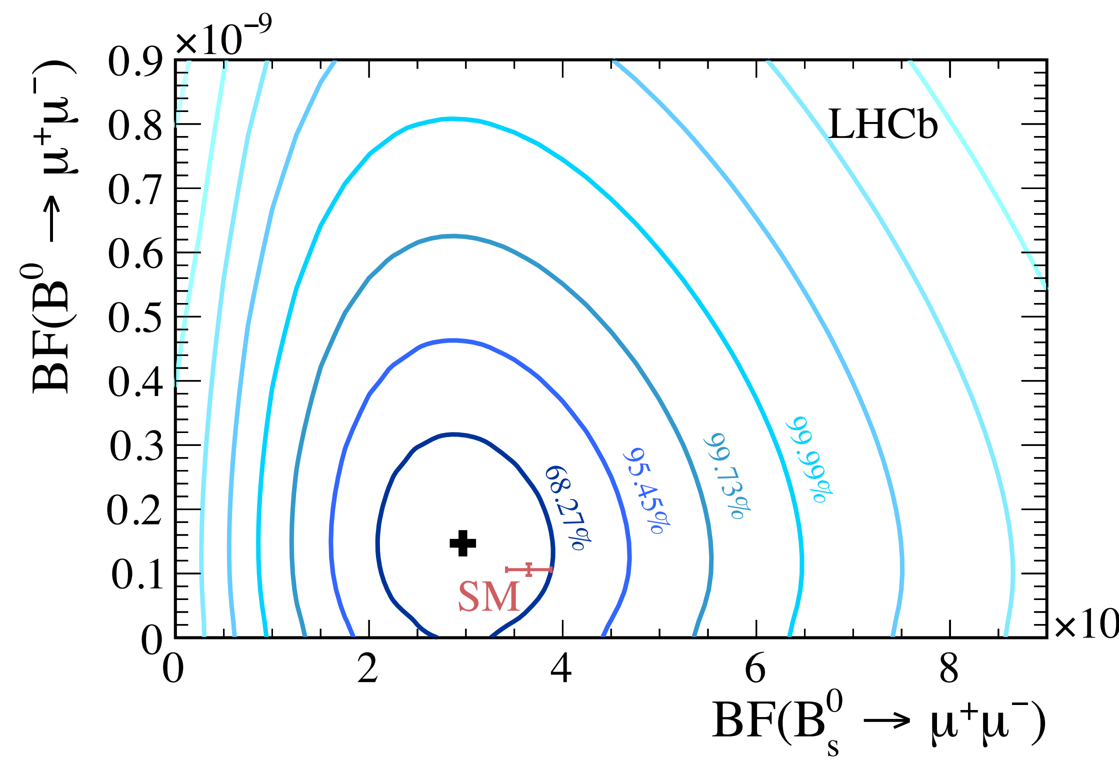
$$\mathcal{B}_{\rm SM}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}_{\rm SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$



New results:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ @ 95\% CL}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

first observation by a single experiment
7.8 σ



(Phys. Rev. Lett. 118, 191801 (2017))

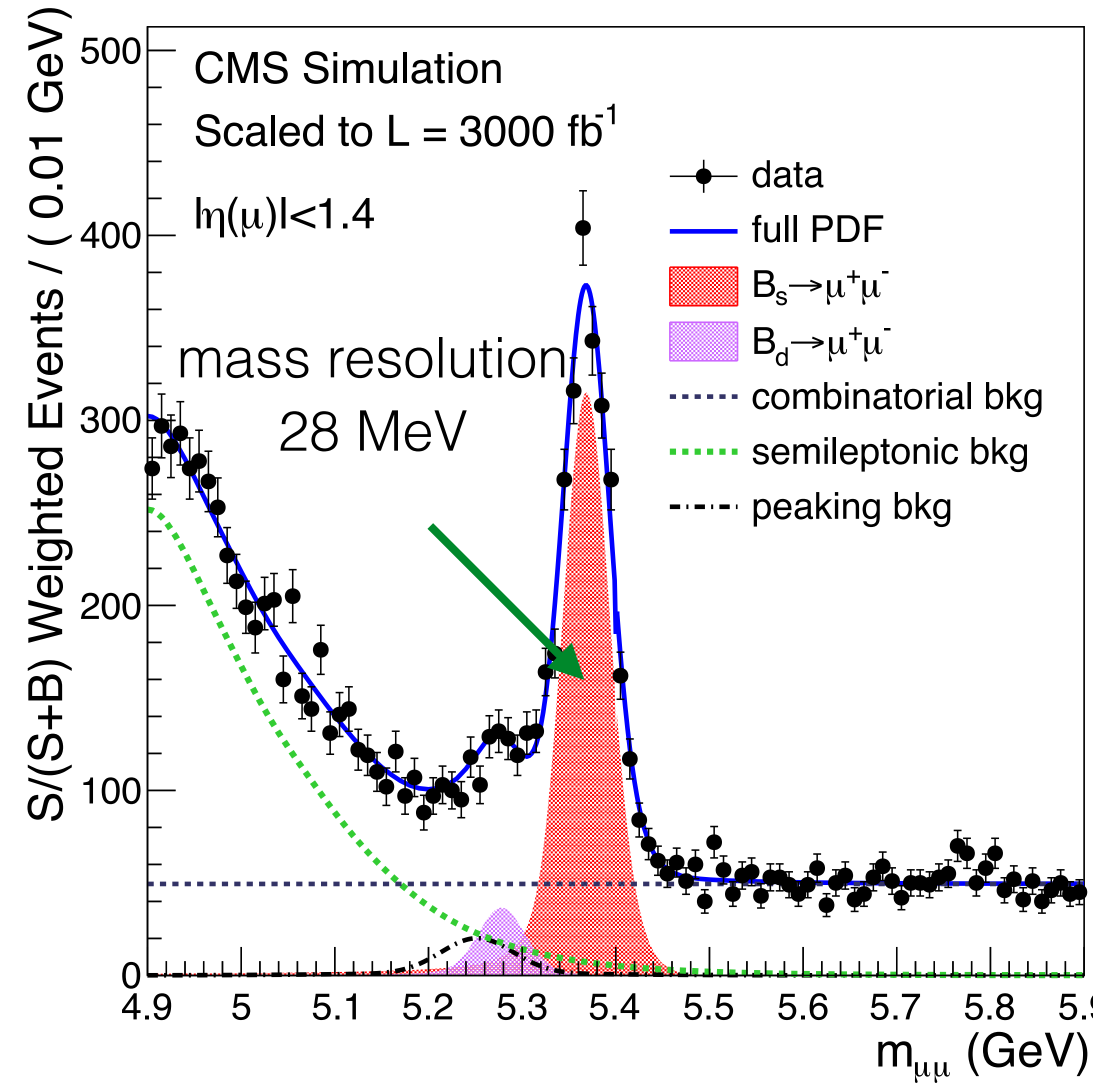
$B_{(s)} \rightarrow \mu\mu$ - projections

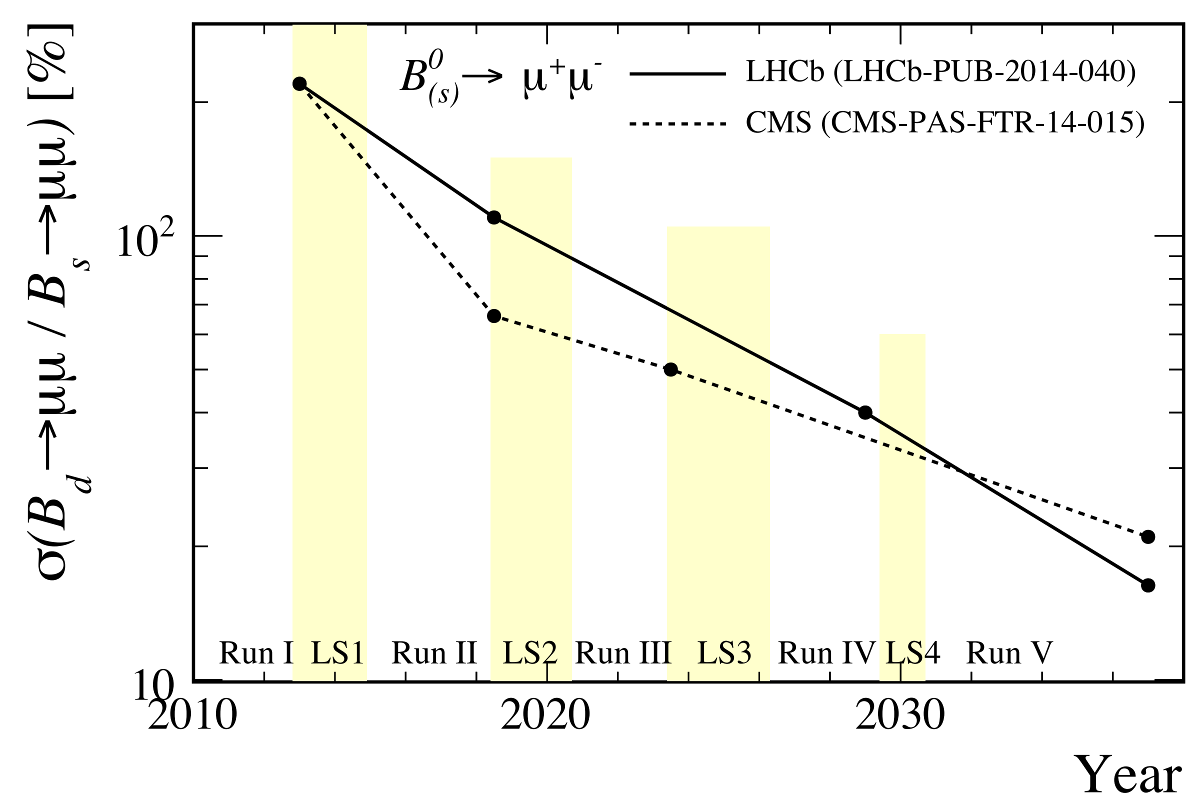
	CMS (3 ab^{-1})	LHCb (50 fb^{-1})	LHCb (300 fb^{-1})
$N(B_d)$	271	40	240
$N(B_s)$	2250	400	2400

(CMS-PAS-FTR-14-015)

- Uncertainty on $BF(B_s \rightarrow \mu\mu) \sim 0.27 \times 10^{-9}$ @ 300 fb^{-1}
- Ratio of BF is also a powerful test of MFV
- Predictions:
  - $\Delta r/r \sim [23, 27]\%$ (50 fb^{-1})
  - $\Delta r/r \sim [11, 13]\%$ (300 fb^{-1})

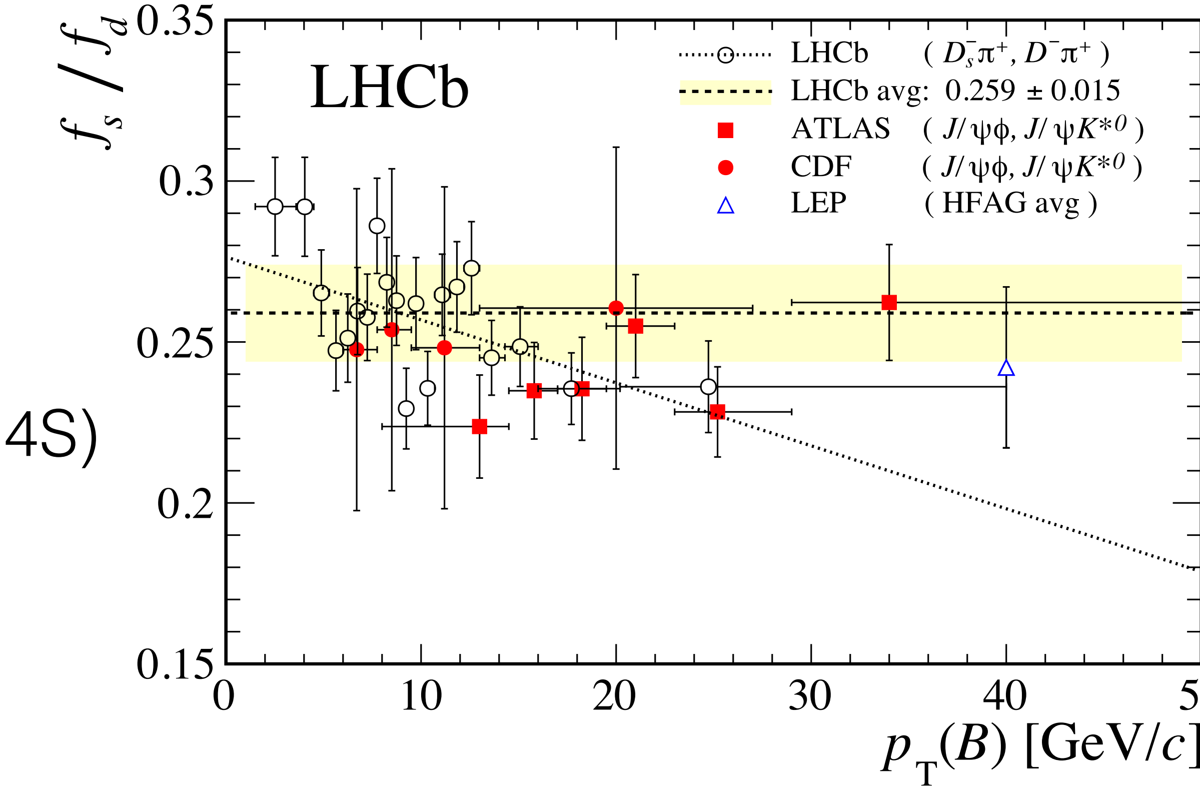
(CMS-TDR-14-015)





- Dominant source of systematic, f_s/f_d
  - current uncertainty ~5.8% (LHCb-CONF-2013-011)

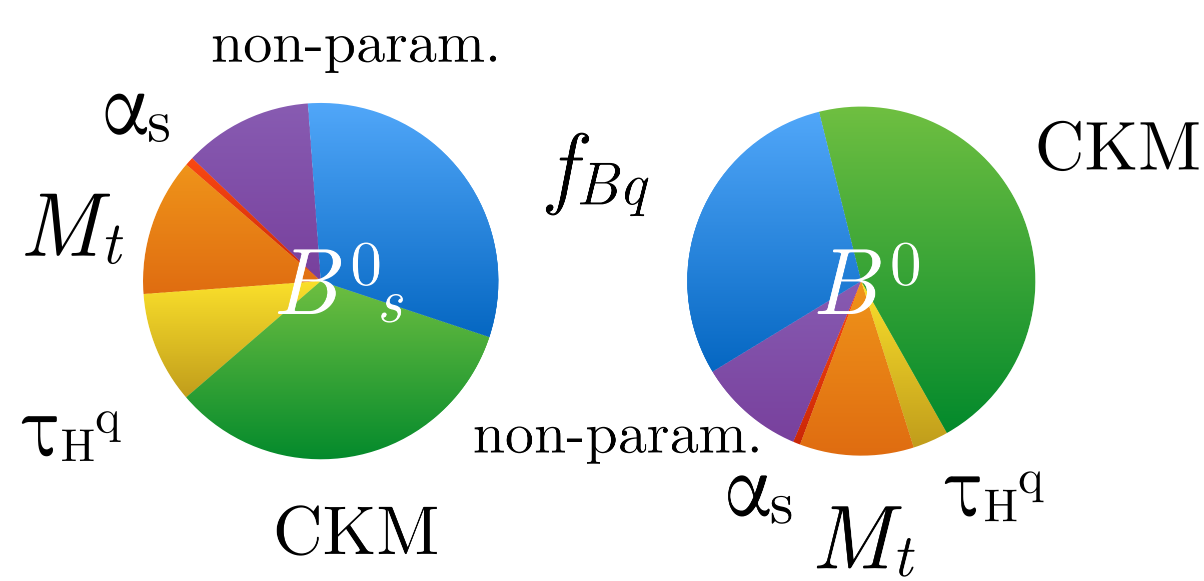
Phys. Rev. Lett. 115, 262001 (2015)



- BR($B^+ \to J/\psi K^+$): ~3%
  - ambiguities related to isospin asymmetry at Y(4S)
  - will improve with Belle 2 measurement

- Semileptonic background
  - updated lattice calculations needed
  - inputs from LHCb measurements are fundamental

- Theoretical uncertainty dominated by:
  - CKM matrix element (experimental inputs needed)
  - B decays constant (improvement expected from lattice calculations)



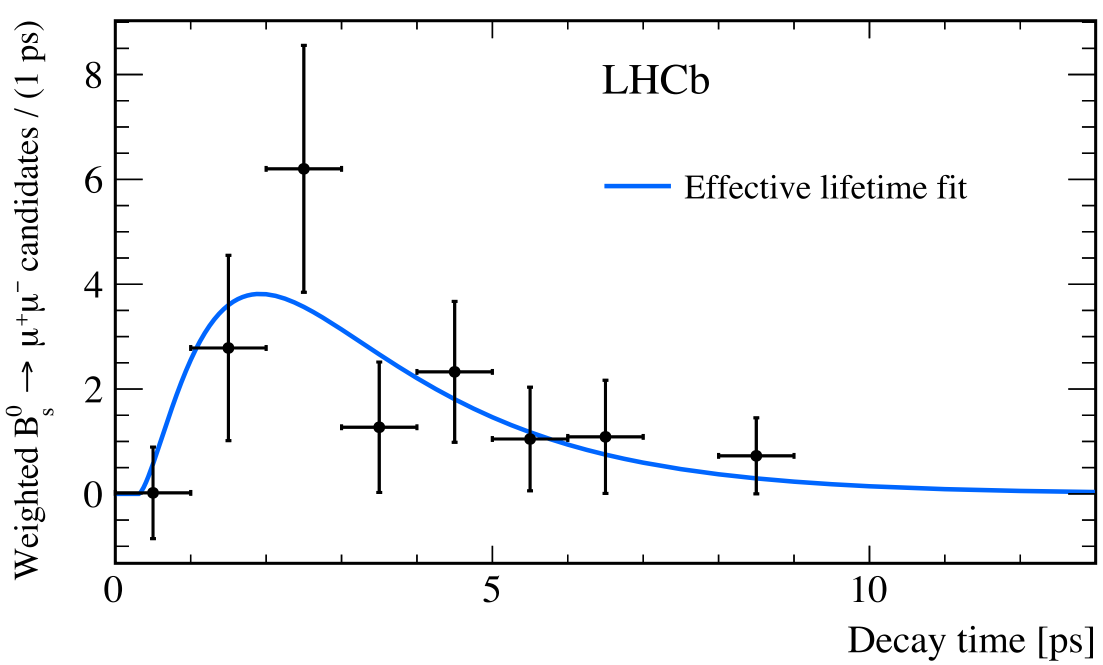
C. Bobeth et al
Phys. Rev. Lett. 112, 101801

- Exp. uncertainty will reach theoretical uncertainty

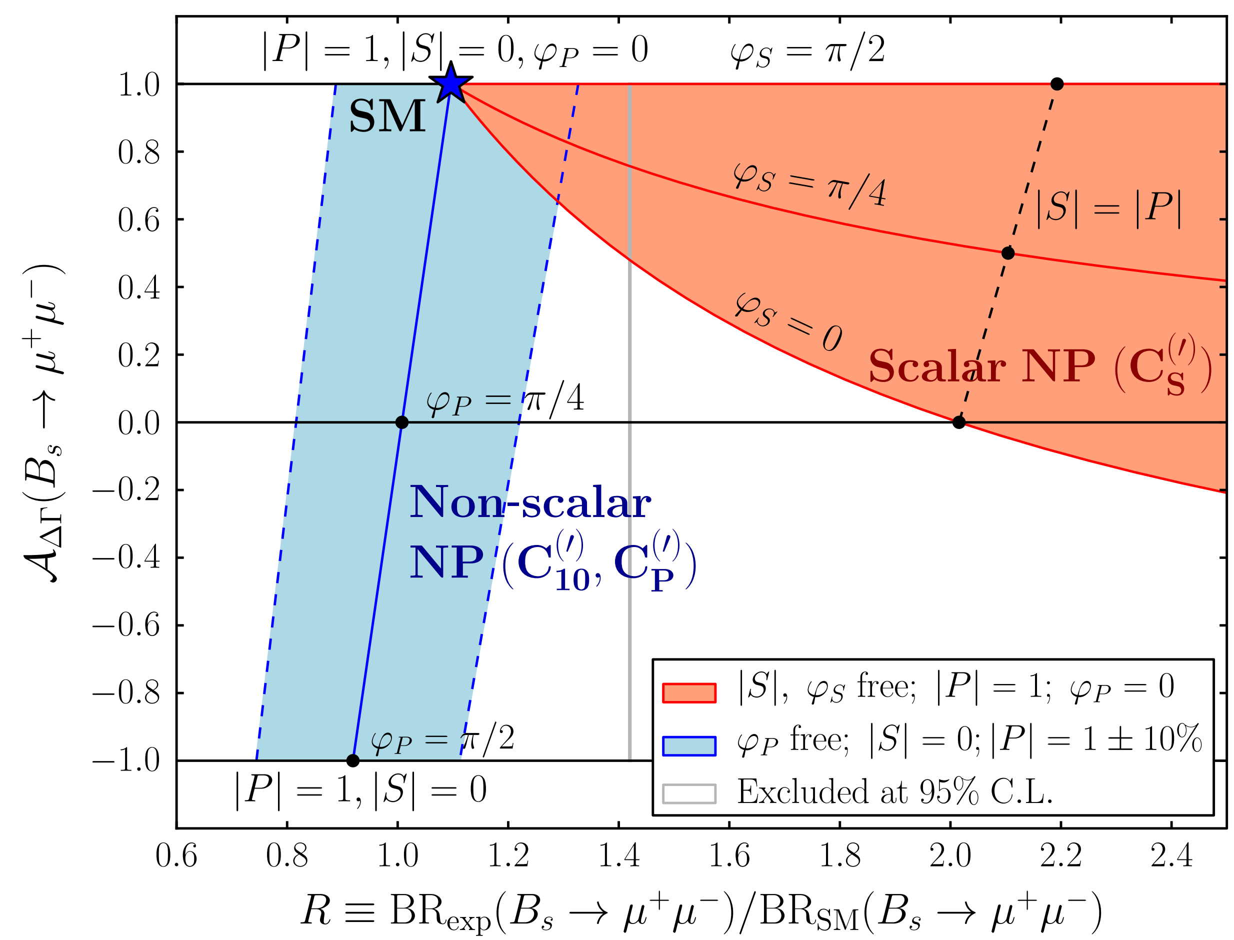
$B_s \to \mu\mu$ - lifetime

- Effective lifetime: complementary probe of new physics
- In the SM, only the heavy mass eigenstate decays to $\mu^+\mu^-$
  - $A_{\Delta\Gamma} = +1$
  - $\tau_{\mu\mu} = 1.610 \pm 0.012$ ps
- Assuming extreme NP scenario of $\tau_{\mu\mu} = \tau_L$,for a 5 σ observation the precision needed is 0.038 ps
- LHCb measurement:

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05\,\mathrm{ps}$$



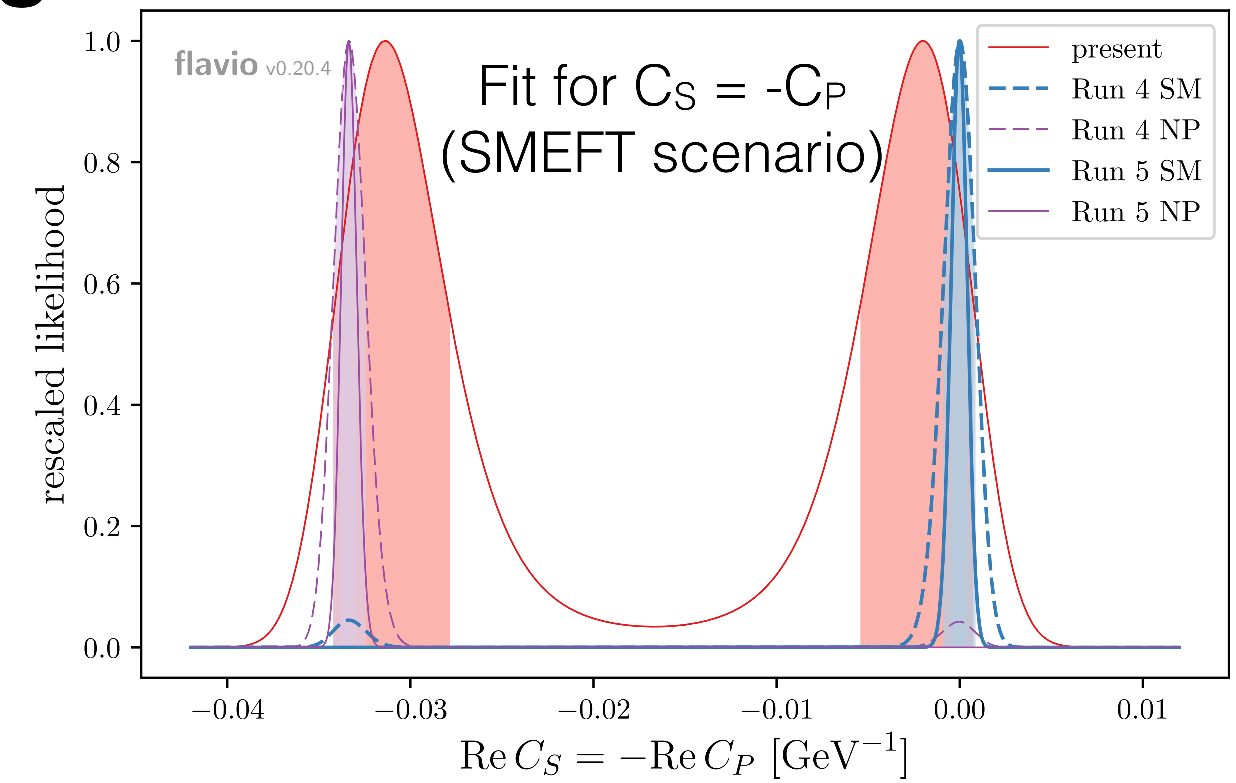
(Phys. Rev. Lett. 118, 191801 (2017))



(PRL 109, 041801 (2012))

$B_s \to \mu\mu$ - lifetime predictions

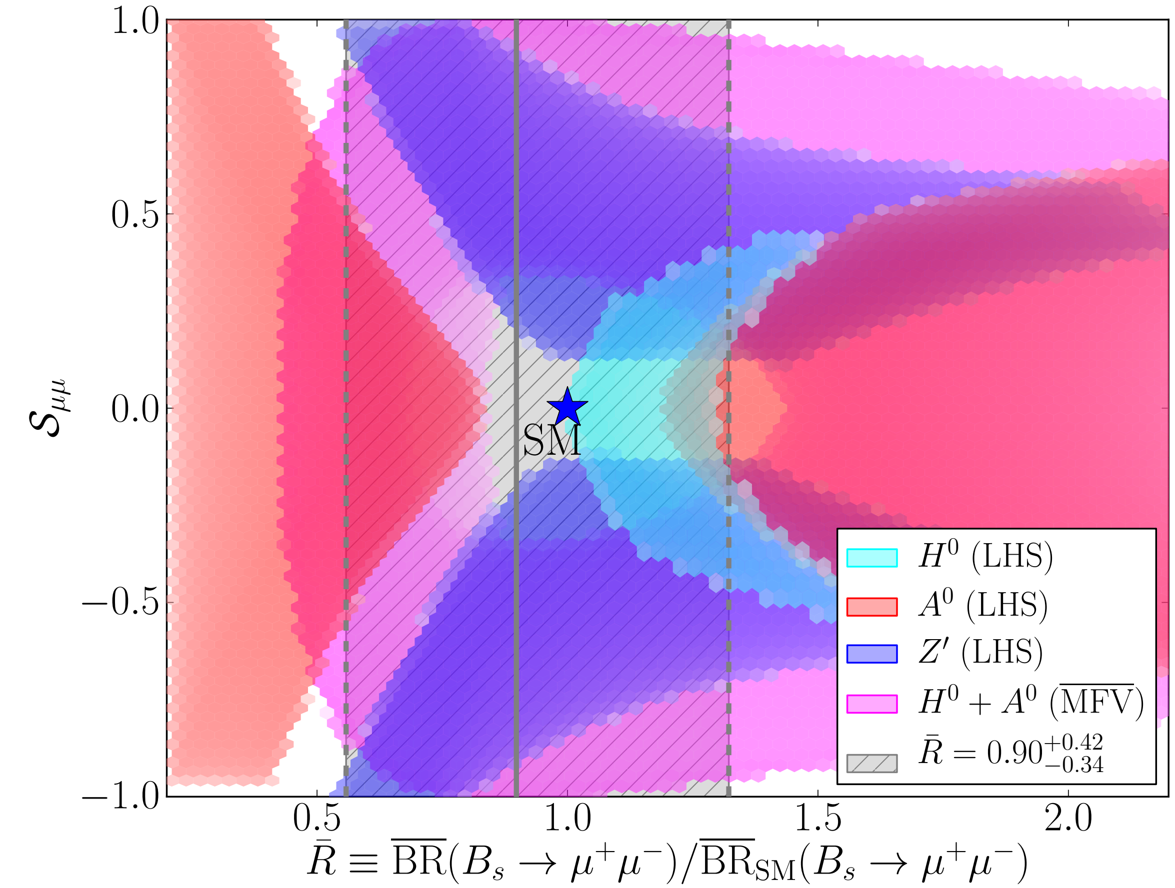
(arXiv:1702.05498)



- ~ 5% uncertainty estimated with 50fb^{-1}
- can get down to 2% with 300 fb^{-1}

$B_s \to \mu\mu$ - what else?

- Time dependent CP violation
- Expected $\sigma(S_{\mu\mu}) = 0.3$ (assuming 4% tagging eff)



(A Buras et al, JHEP 1307 (2013) 77)

Lepton flavour violation

- Measurements involving b->sll decays showed deviations from the SM and hints of LU violation
- Several models explains LNU involving multi-TeV new physics particle
- LNU implies LFV if leptons are not mass eigenstate
- Experimentally reachable BF are predicted

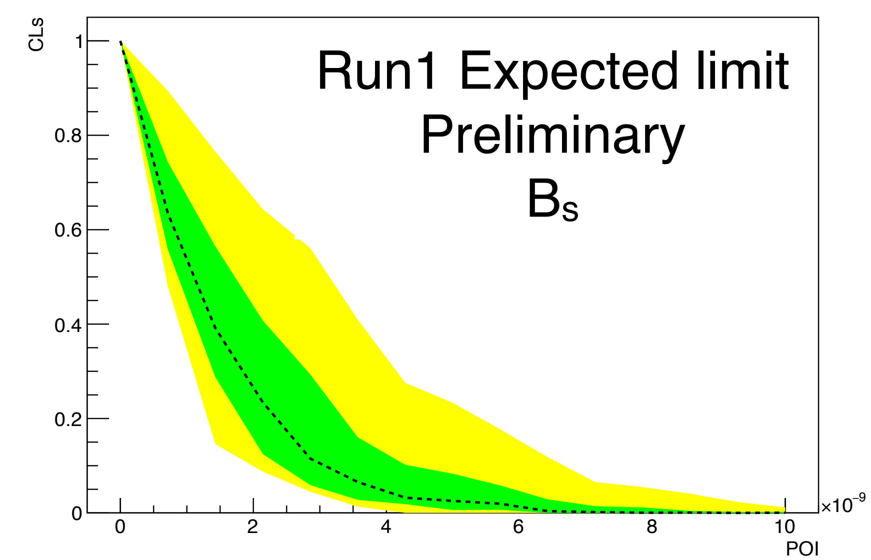
	Theo	Exp
$B^+ \to K^+\mu^\pm\tau^\mp$	$0.89\times\mathbf{10^{-6}}$	$<4.8\times10^{-5}$
$B^+ \to K^+e^\pm\tau^\mp$	3.84×10^{-10}	$<3.0\times10^{-5}$
$B^+ \to K^+e^\pm\mu^\mp$	0.52×10^{-9}	$<9.1\times10^{-8}$
$B_s \to \mu^\pm\tau^\mp$	$1.06\times\mathbf{10^{-6}}$	-
$B_s \to e^\pm\tau^\mp$	4.57×10^{-10}	-
$B_s \to e^\pm\mu^\mp$	1.73×10^{-12}	$<1.1\times10^{-8}$

Guadagnoli and Lane
Physics Letters B 751 (2015) 54–58

Lepton flavour violation: ongoing analyses

- $B_{(s)}$->τμ

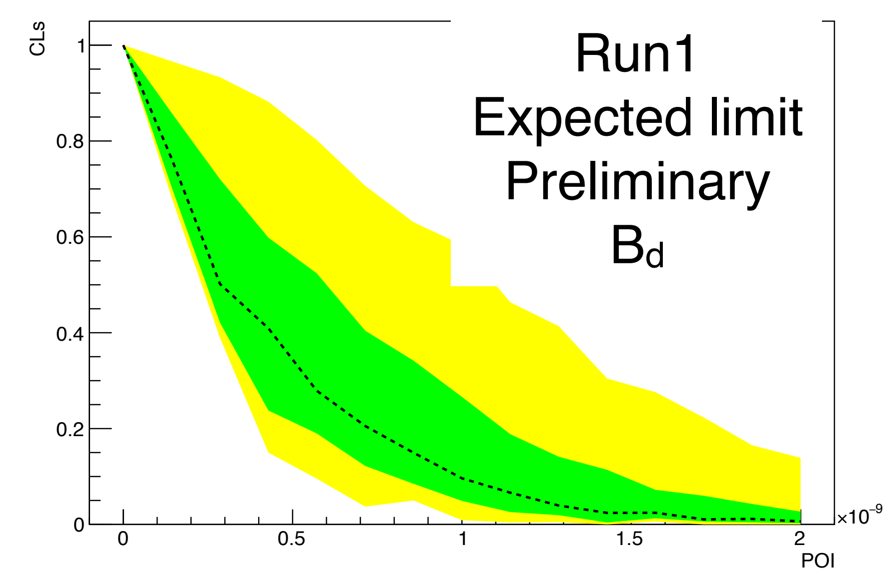
- B^+->K^+eμ:
  - limit ~O(10^{-8}) expected with Run1 data
  - one order of magnitude (at least) improvement expected for Run5: sensitive to the NP region!
  - no expected systematic limitations



- $B_{(s)}$->eμ:

  - same constraint to theoretical models as B^+->K^+eμ
  - less background contamination

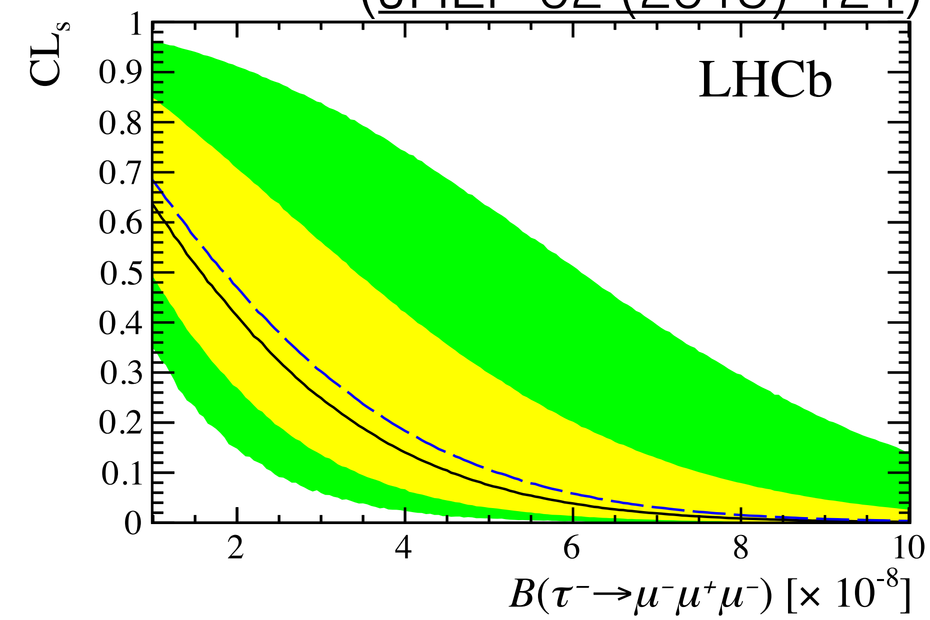
	1fb^{-1} (Phys. Rev. Lett. 111 (2013) 141801)	3fb^{-1} (exp)	300fb^{-1} (exp)
B_s->$e^{\pm}\mu^{\mp}$	< 1.4x10^{-8} @ 90% CL	~3.8x10^{-9}	~3x10^{-10}
B->$e^{\pm}\mu^{\mp}$	< 3.7x10^{-9} @ 90% CL	~1.2x10^{-9}	~1x10^{-10}



Lepton flavour violation: more prospects

- $\tau^- \rightarrow \mu^+\mu^-\mu^-$:

(JHEP 02 (2015) 121)



- Several BSM theories predict an BF enhancement (seesaw models..)

- EFT based on a $U(2)^n$ flavor symmetry:

  - explains anomalies in b->sll decays

  - BR ($\tau \rightarrow 3\mu$)~ 10^{-9}

Current limit :

$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 4.6 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

Extrapolation @ 300 fb^{-1}:

$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 3 \times 10^{-9}$$

- not systematically limited
- similar to prospects for Belle2 @ 50 ab^{-1}
  - confirmation from LHCb fundamental if any sign of NP

Many other LFV searches foreseen:

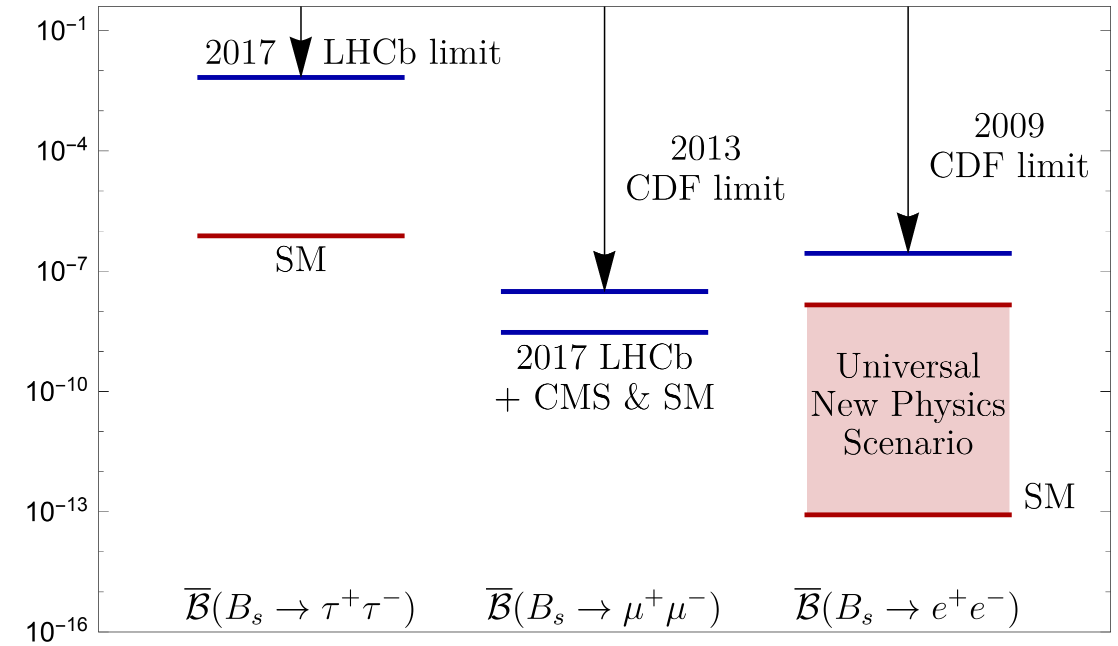
- $B \rightarrow K^* e\mu/\tau$, - $B \rightarrow \Phi e\mu$
- $B^+ \rightarrow K^+ e\tau$ - …

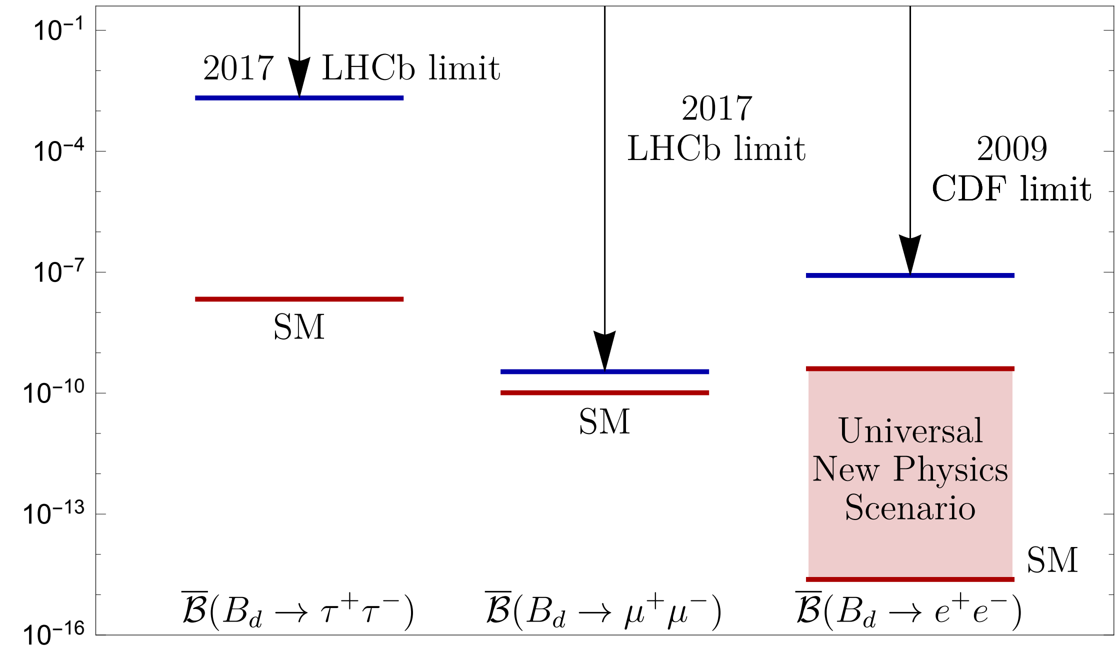
$B_{(s)} \to ee$

- Same considerations as for the Bs->μμ, in terms of SM predictions and NP
- $B_{(s)}$->ee is an excellent probe. NP can lift the helicity suppression
- BR($B_{(s)}$->ee) may be enhanced
- Search for B_s->ee ongoing in LHCb:
  - Expected limit Run1: [4-11]*10^{-9}
  - Expected limit Run5: [3-9]*10^{-10}

Moreover, let's keep in mind that:

- $\varepsilon_{ee}/\varepsilon_{\mu\mu}$ ~ 1/5 (from B->K*J/ψ)
- better calorimeter performance can increase further the sensitivity
- No L0 bottleneck will be certainly beneficial





(arXiv:1703.10160 - Fleischer et al.)

$B_{(s)} \to \tau\tau$

- MFV models which accomodate LFU anomalies predict enhancement of BR($B_{(s)} \to \tau\tau$)

- SM predictions: $\mathcal{B}(B^0 \to \tau^+\tau^-)_{\rm SM} = (2.22 \pm 0.19) \times 10^{-8}$

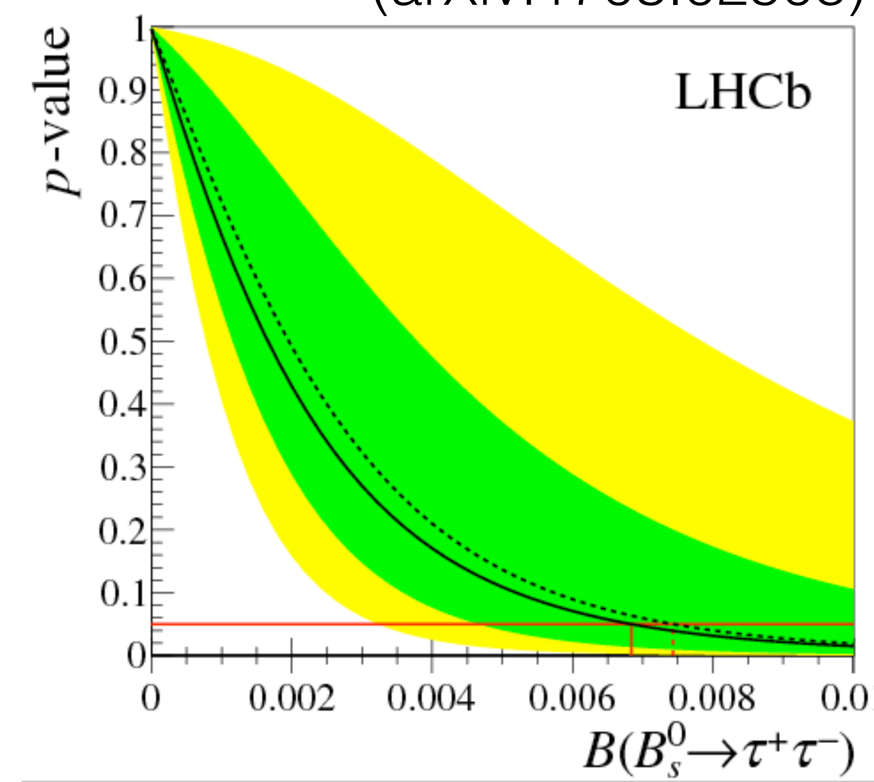
  $\mathcal{B}(B^0_s \to \tau^+\tau^-)_{\rm SM} = (7.73 \pm 0.49) \times 10^{-7}$

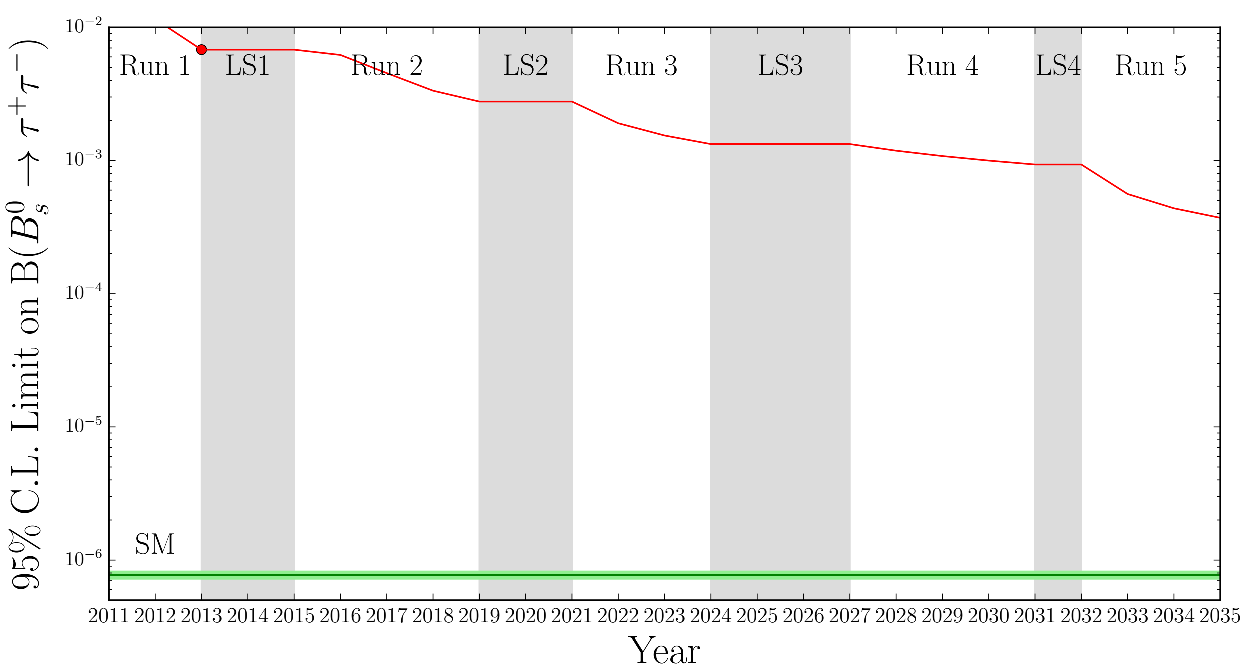
- Run1 analysis:

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ CL}$$

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ CL}$$

(arXiv:1703.02508)

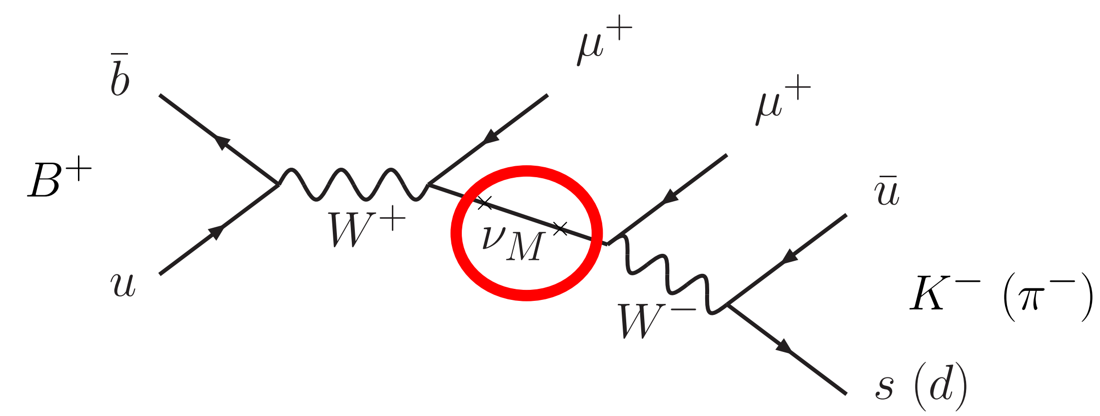


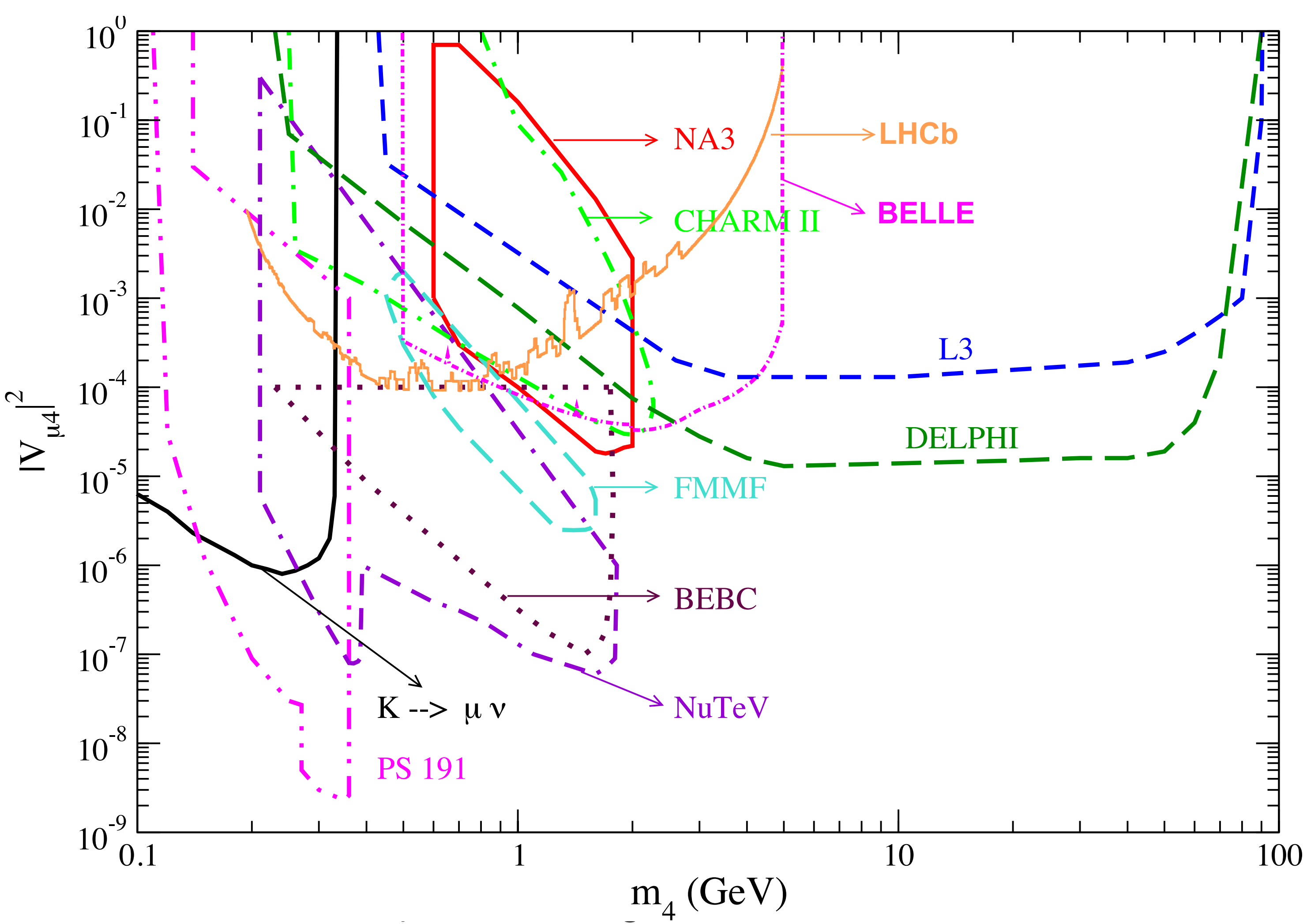


- First (B_s) and world best (B^0) limits
- Still very far from SM
- Tracking stations inside the magnet could improve the sensitivity

Majorana neutrinos

- Massive sterile neutrinos can potentially exist at any mass scale
- Would explain the tiny neutrino mass

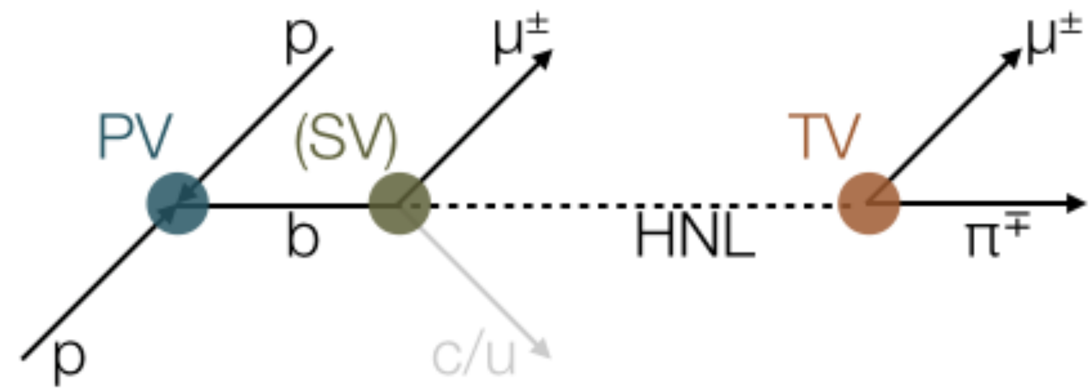




- Exclusive search@ LHCb: $B^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ channel ($3 fb^{-1}$)
  - Measurement competitive in the region above the charm mass

Majorana neutrinos: what next?

- Inclusive search, ongoing with Run1 data: O(10) improvement expected over Belle limit



- Dedicated trigger in Run2 + mN > 1.5 GeV + lifetime > 10ps: background free analysis

- We can get an O(1000) improvement with 300 fb^{-1}

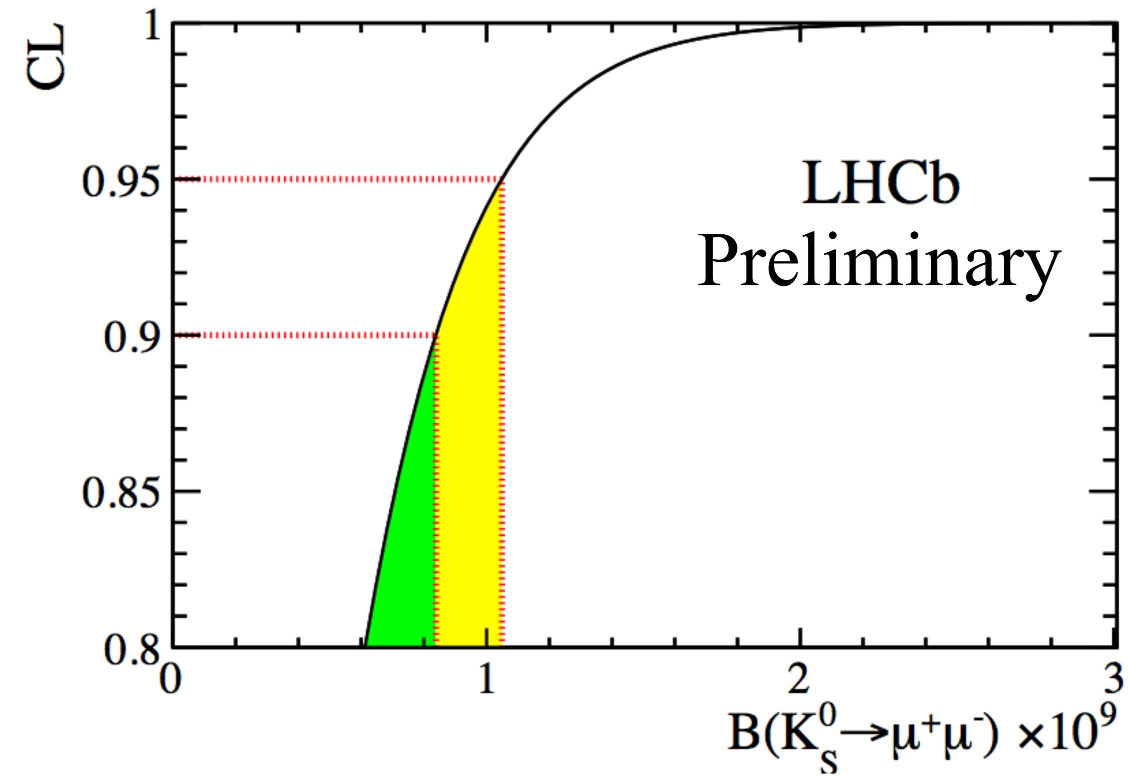
…but we might do even better:

- Improve (**downstream**) reconstruction will certainly be beneficial
- Some ideas already proposed (chambers inside magnet?)

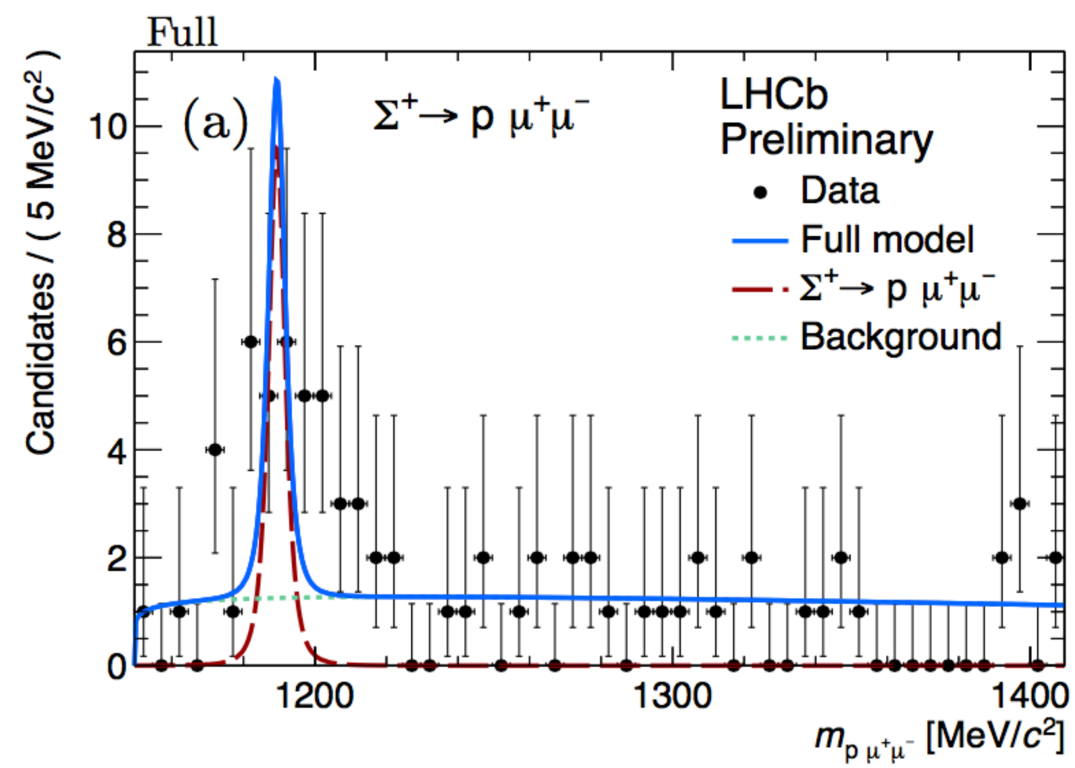
Strange decays

- LHCb is a strange factory: cross-section ~ 10^5 μb @ 13 TeV
- Growing interest in strange decays @ LHCb
- Analyses/studies with Run1 data:

- **Search for $K_s \to \mu\mu$:**
  BF($K_s \to \mu\mu$) < 0.8×10^{-9} @ 90% CL
  (preliminary) Best upper limit!



- **Search for $\Sigma \to p\mu\mu$:**
  No excess observed in the μμ mass spectrum
  (CONF-2016-013 - paper coming soon)



- **Prospects for $K_s \to \pi\pi ee$** (LHCb-PUB-2016-016)
- **Prospects for $K_s \to \pi^0\mu\mu$** (LHCb-PUB-2016-017)

- **K+ mass measurement** : paper expected soon!

Strange decays - limitations

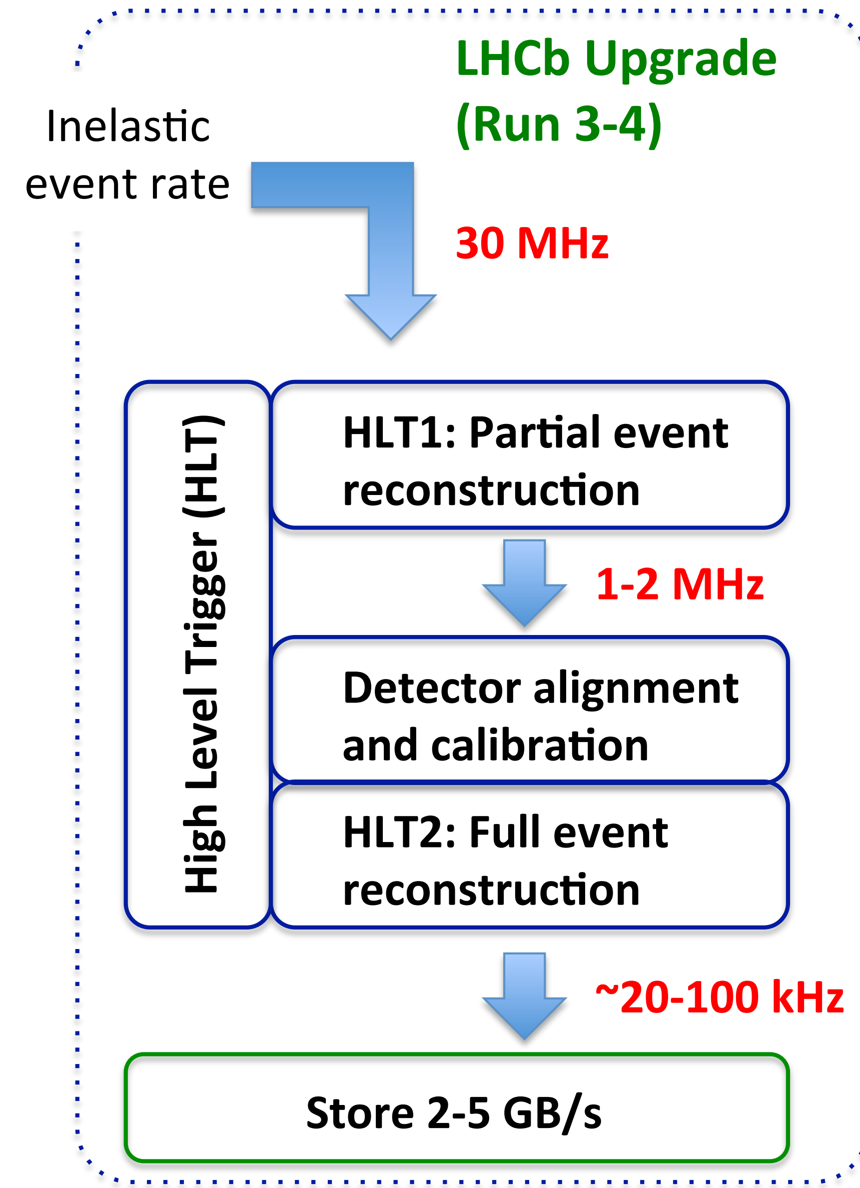
- Very different signature compared to b-physics:
  - Lower (transverse) momentum
  - Larger lifetime

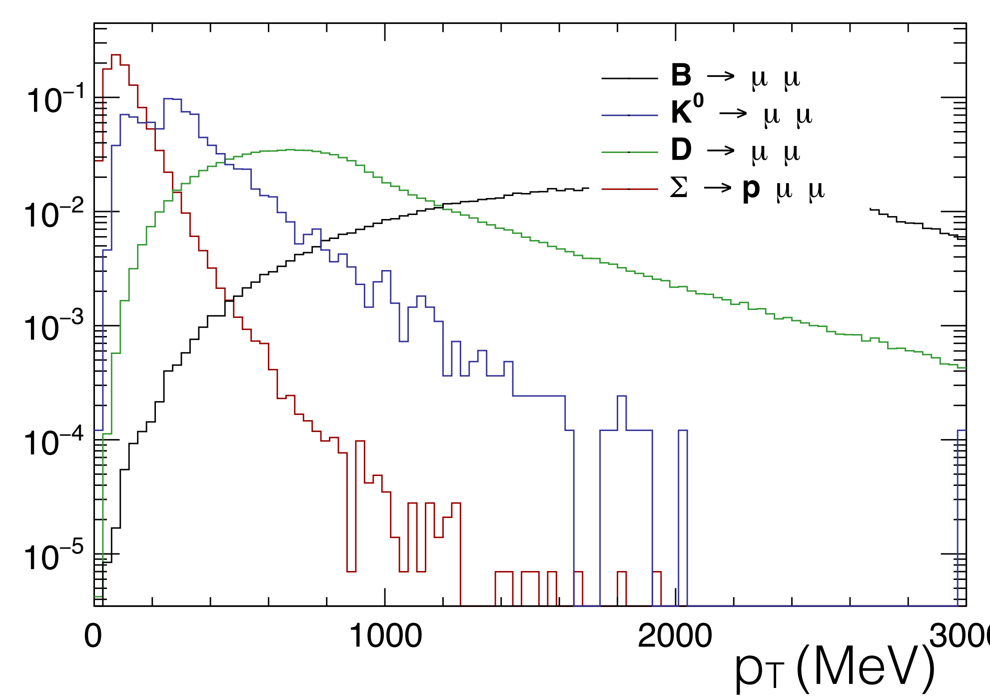
  → behave as background!

- L0, main bottleneck (Run2 efficiency cannot be larger than 20%)

- Fully-software trigger in Upgrade will strongly benefit the strange physics program:
  - trigger efficiency O(100%) is possible for Kaon decays (limited by bandwidth and CPU)

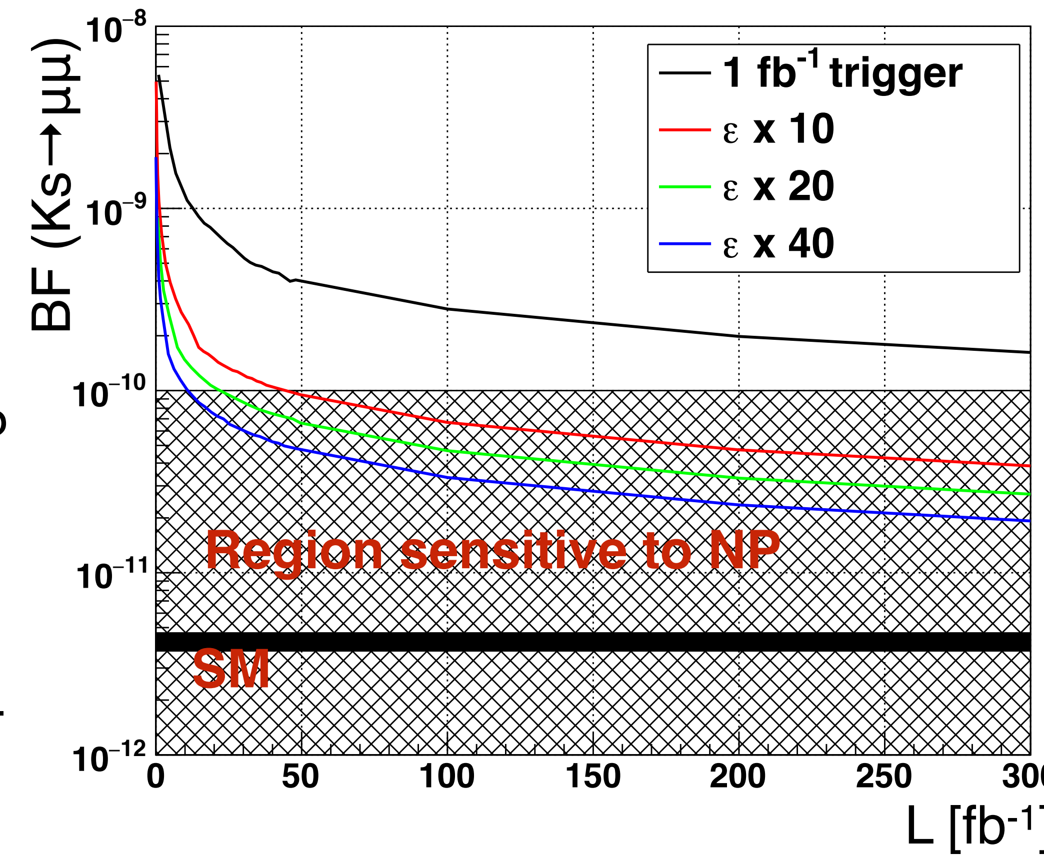
- Low p_T particles reconstructions is essential





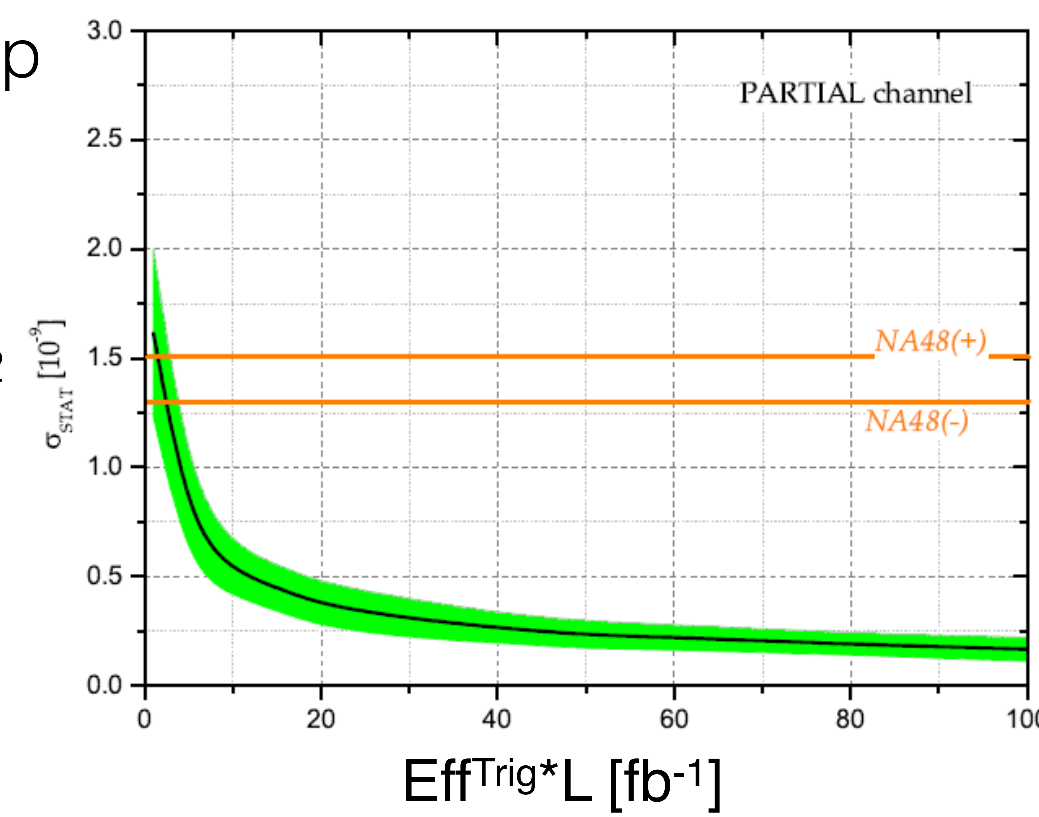
Strange decays - some prospects

- Run5, assuming a total trigger efficiency of 50%:
  - Sensitive to BF ($K_S \to \mu\mu$)~1×10^{-11}
  - Close to the SM prediction, region sensitive to NP

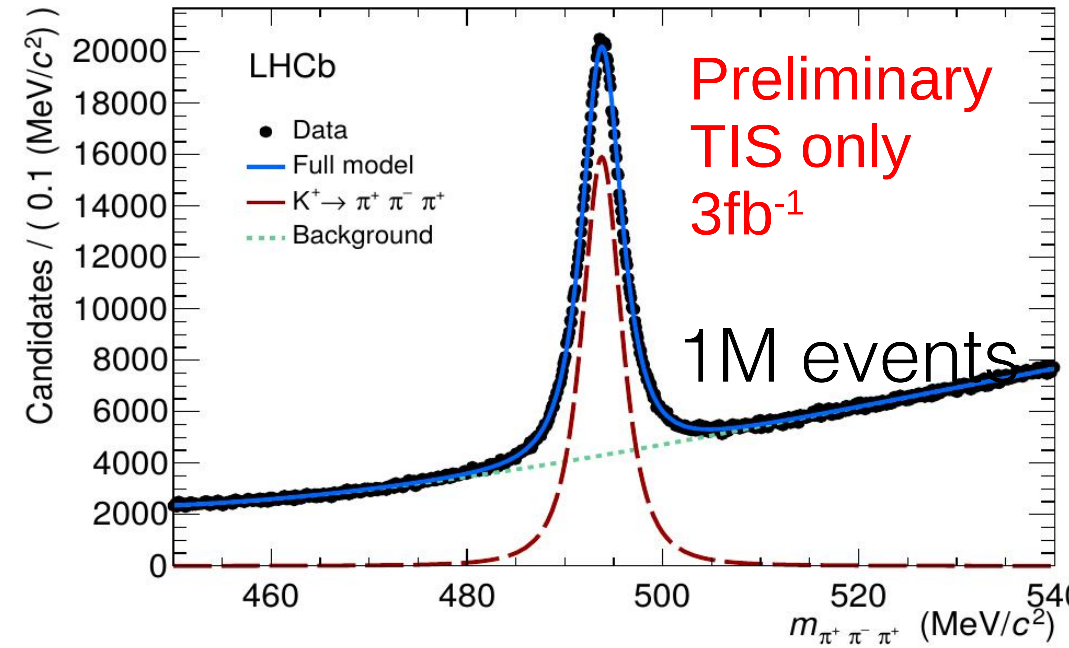


- $K_L \to \pi^0\mu\mu$ can be very sensitive to NP (ED models - JHEP 09(2010) 017):
  - large theoretical uncertainty in the SM BF
  - precision measurement of the $K_S \to \pi^0\mu\mu$ BF will help to reduce K_L BF theoretical uncertainty

- $K_S \to \pi^0\mu\mu$: also sensitivity to C9, measurement of q^2 dependence



Strange decays - more possibilities



- Given the enormous production of Kaon at LHCb not only short-lived Kaons can be studied

- $2x10^{10}$ reconstructed K^+ decay per fb^{-1} in the upgrade are expected (with full software trigger)

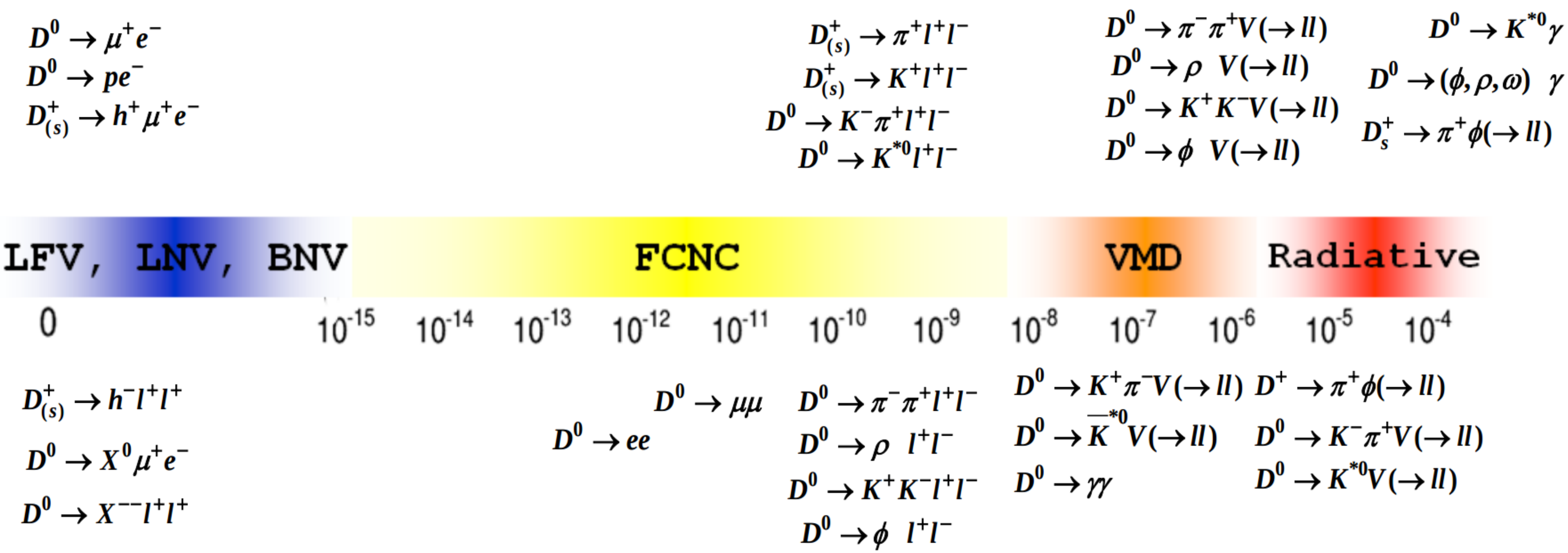
- $K^+ \to \pi^+ ll$ decays with BF $O(10^{-7})$ are accessible.

…but we can do much more

With the upgrade detector, why not using kaons from ϕ?

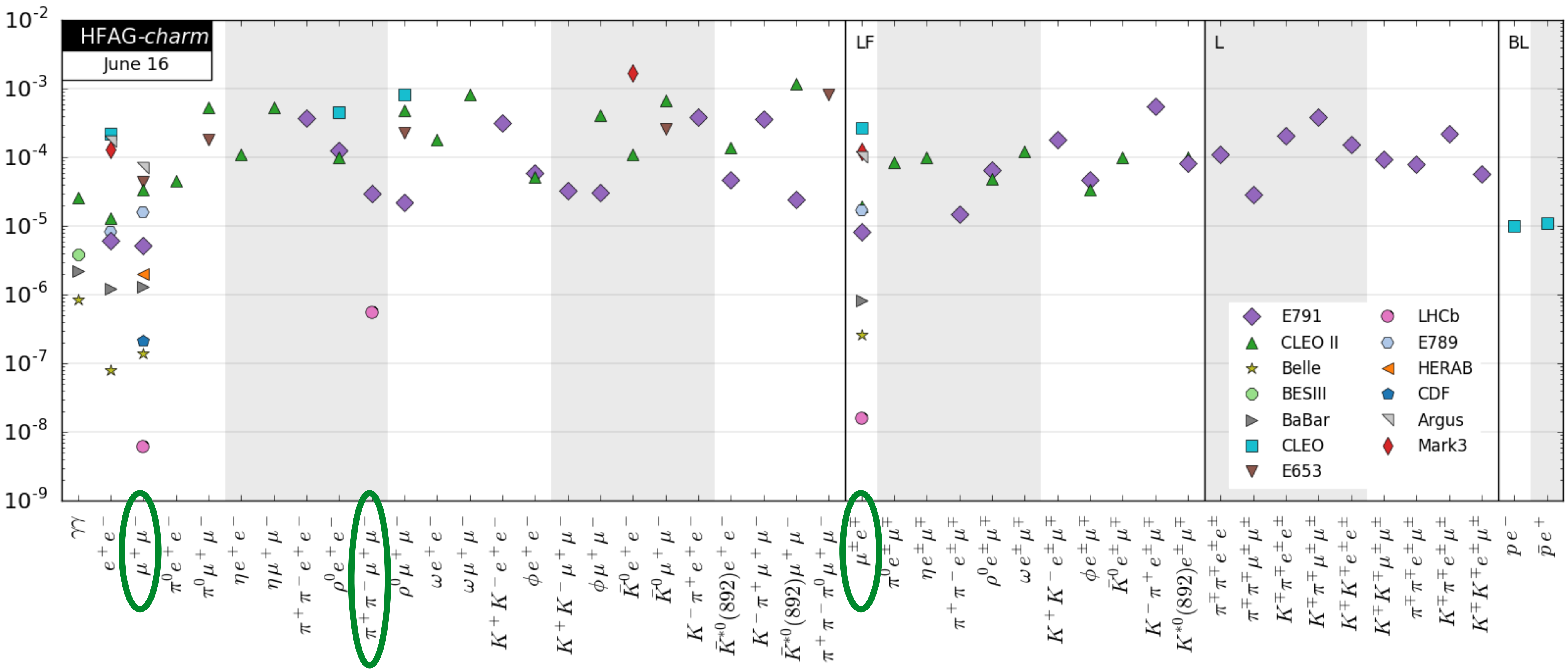
- $2x10^{13}$ $\phi \to K^+K^-$ per year expected
- Kinetic constraints and access to decays with neutrinos possible

Rare charm



- Dominated by long distance contributions
- Possible to access short distance contribution away from resonances in some channels ($D \to X_u \, l^+ \, l^-$)
- SM predictions typically $< 10^{-9}$ for non resonant decays
- NP could enhance BF up to $O(10^{-6})$

(Burdman et al. PHYSICAL REVIEW D 66, 014009 2002)



- Most precise results from LHCb analyses (No competitors for fully charged final states)
- Several analysis ongoing:
  - $D^0 \rightarrow \mu\mu$ (update Run1)
  - $D^+_{(s)} \rightarrow hll$, $D^0 \rightarrow hhll$ (Run1+Run2)
  - $\Lambda_c \rightarrow pll$ (Run1+Run2)

Rare charm - what can we expect?

Predictions @ 300fb^{-1}:

	BF(Short Distance)
$D^0 \to hh'\mu^+\mu^-$	10^{-9} - 10^{-8}
$D^0 \to \mu^+\mu^-$	10^{-11} - 10^{-10}
$D^+ \to h'\mu^+\mu^-$	10^{-10} - 10^{-9}
$D_s^+ \to h'\mu^+\mu^-$	10^{-9} - 10^{-8}
$L \to p\mu^+\mu^-$	10^{-9} - 10^{-8}
$D^0 \to e^+\mu^-$	10^{-10} - 10^{-9}

	Asymmetry uncertainty	Yields (LD+SD)
$D^0 \to K^+K^-\mu^+\mu^-$	1.6%	9K
$D^0 \to K^+ \pi^-\mu^+\mu^-$	5%	1.8K
$D^0 \to K^- \pi^+\mu^+\mu^-$	0.12%	600K
$D^0 \to \pi^-\pi^+\mu^+\mu^-$	0.4%	90K
$D^+ \to \pi^+\mu^+\mu^-$	0.08%	1800K

- We can reach sensitivities comparable with the SM prediction for the SD contributions
- More observable accessible A_{FB}, A_{CP}
- Combine constraints for all charm rare decays

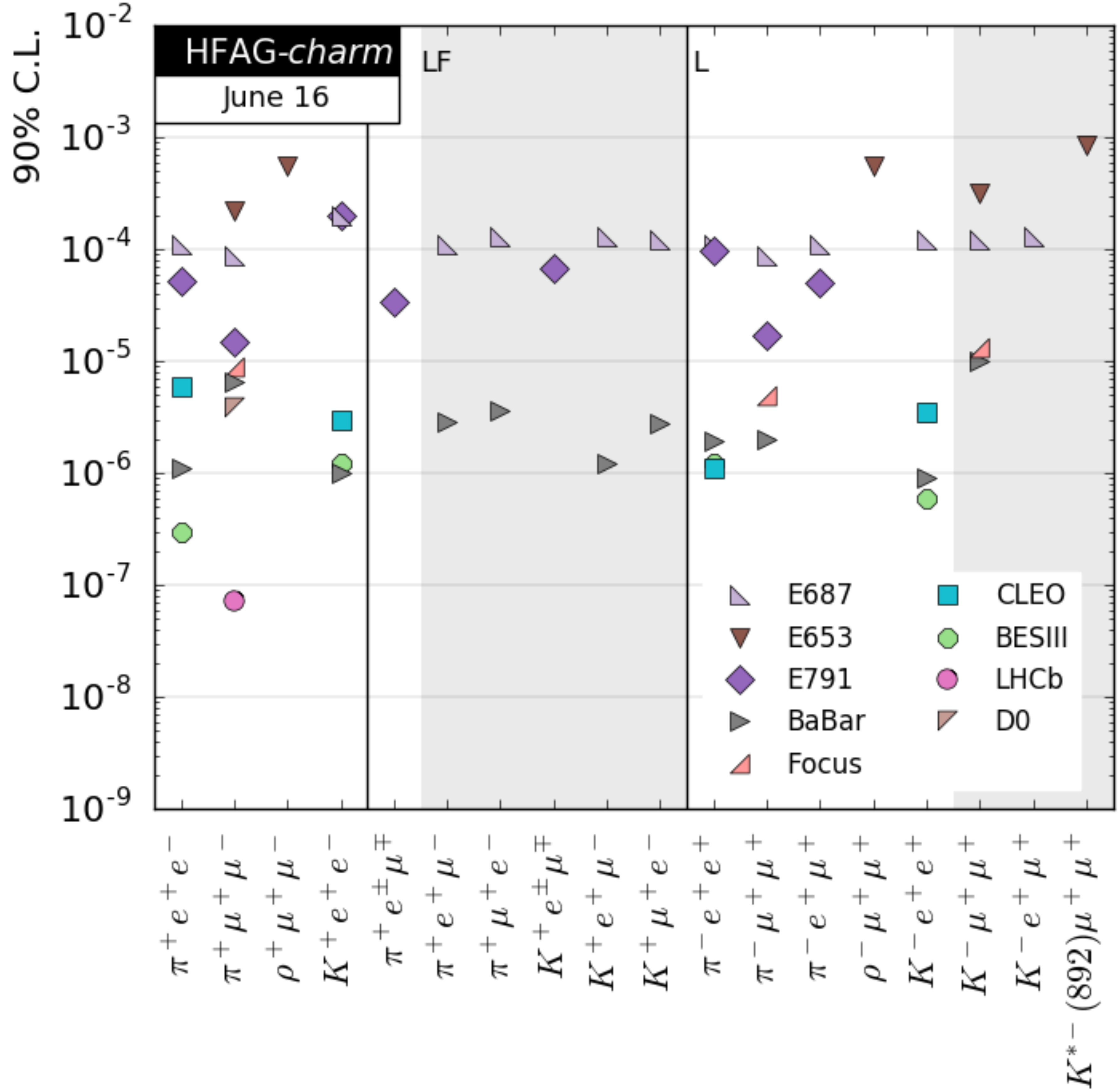
Summary

- Phase-II upgrade will open the door to many new possibilities in VRD:
  - we will accumulate enough statistics to reach the SM predictions
  - we will be sensitive to possible NP effects in several channels

- Many analyses won't be systematically limited

- Better results can be achieved with an upgraded detector:
  - software trigger can be extremely beneficial for electrons and for strange physics program
  - upgraded ECAL can give better performance in electron reconstruction

BACKUP



HFAG-charm
June 16
90% C.L.
LF
L
E687
E653
E791
BaBar
Focus
CLEO
BESIII
LHCb
D0
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\pi^+e^+e^-$
$\pi^+\mu^+\mu^-$
$\rho^+\mu^+\mu^-$
$K^+e^+e^-$
$\pi^+e^\pm\mu^\mp$
$\pi^+e^+\mu^-$
$\pi^+\mu^+e^-$
$K^+e^\pm\mu^\mp$
$K^+e^+\mu^-$
$K^+\mu^+e^-$
$\pi^-e^+e^+$
$\pi^-\mu^+\mu^+$
$\pi^-e^+\mu^+$
$\rho^-\mu^+\mu^+$
$K^-e^+e^+$
$K^-\mu^+\mu^+$
$K^-e^+\mu^+$
$K^{*-}(892)\mu^+\mu^+$

	Run1	Run2	Upgrade (300fb-1)
$D^0 \to hh'\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-9} - 10^{-8}
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	10^{-11} - 10^{-10}
$D^+ \to h'\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	10^{-10} - 10^{-9}
$D_s^+ \to h'\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-9} - 10^{-8}
$L \to p\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-9} - 10^{-8}
$D^0 \to e^+\mu^-$	few 10^{-8}	fewer 10^{-8}	10^{-10} - 10^{-9}