$B_s^0 \to K^- \mu^+ \nu_\mu$ @ LHCb

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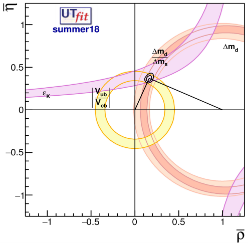
Challenges in Semileptonic B Decays, Barolo, April 21, 2022

Disclaimer

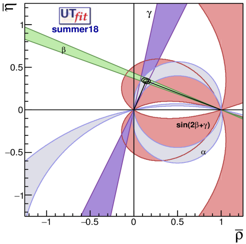
- The purpose of these slides is to provoke discussions and spark ideas not to present formal LHCb statements
- My (messy) slides are the discussion which follows a formal talk ... not the actual talk!
  - Formal LHCb results are shown at CKM 2021
  - Slides assume you are aware of $B_s^0 \to K^- \mu^+ \nu_\mu$ results @ LHCb and familiar/aware with LHCb Upgrades plans
- Slides contain combination of theory work(not all of them), formal results and *personal* projections [Please do not qoute them outside the workshop]

$B_s^0 \to K^- \mu^+ \nu_\mu$: Constrain CKM picture

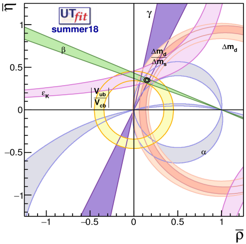
- β and V_{ub}/V_{cb} over-constrain the same side of B^0 unitary angle
- Tensions are a clear sign for New Physics



CP conserving

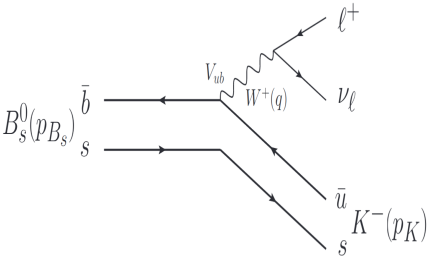


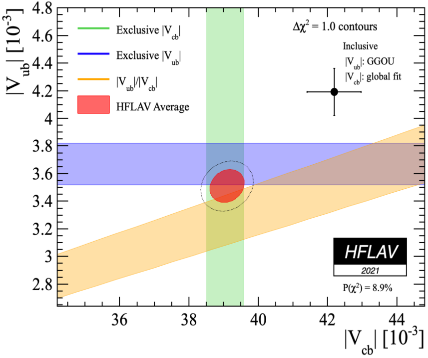
CP violating



All

- $b \to u$ transition: measure V_{ub}
- Inclusive & exclusive measurements are in disagreement ($\sim 3\sigma$)

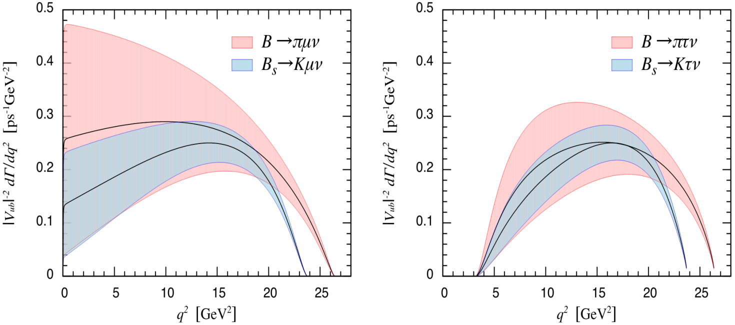




HFLAV 2021

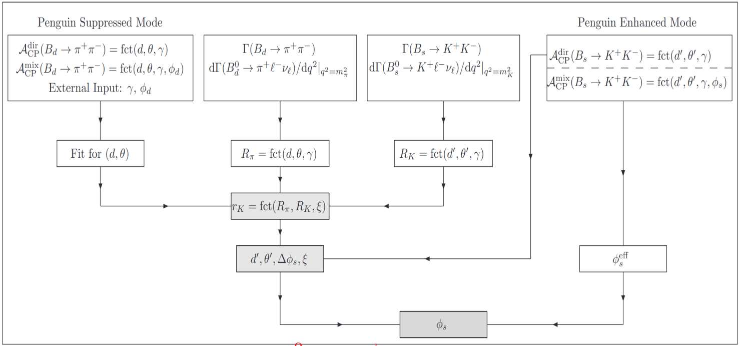
$B_s^0 \to K^- \mu^+ \nu_\mu$: V_{ub} Golden mode

- Better Lattice precision for $|V_{ub}|$ due to favorable Kaon mass for the Lattice
- Comparison from Phys. Rev. D 91, 074510 (2015)



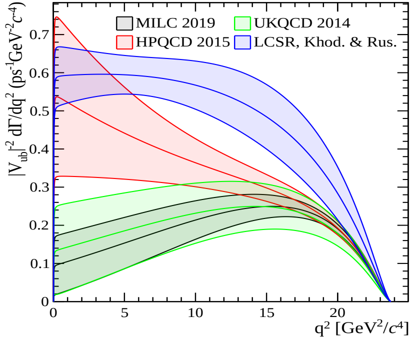
$B_s^0 \to K^-\mu^+\nu_\mu$: Control penguins

- Upgrade era: need to control penguin contributions for CPV phases very precisely
- Semileptonic deferential decay rates can be used to control penguins!
  1. Cross check penguin pollution for $B^0 \to J/\psi K_S^0$ ($\sin(2\beta)$) using new strategy[arxiv.2010.14423]
  2. Provide better strategy [arxiv.1608.00901] to precisely control penguins for $B_s^0 \to K^+K^-$ (ϕ_s)
- These strategies requires measurement of the decay rate shape at $q^2 = m_{J/\psi}(m_{K^+})$



$B_s^0 \to K^- \mu^+ \nu_\mu$: Form Factor disagreement

- Solve long-standing disagreement between LCSR and some LQCD calculations



$|V_{ub}|/|V_{cb}|$ in $B_s^0 \to K^- \mu^+ \nu_\mu$ [Phys. Rev. Lett. 126 (2021) 081804]

- Measure of BRs ratio of $B_s^0 \to K^- \mu^+ \nu_\mu$ & $B_s^0 \to D_s^- \mu^+ \nu_\mu$

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\textbf{experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{d\Gamma(B_s^0 \to K^- \mu^+ \nu_\mu)/dq^2}{d\Gamma(B_s^0 \to D_s^- \mu^+ \nu_\mu)/dq^2}}_{\textbf{theory input}}$$

- Convert to $|V_{ub}|/|V_{cb}|$: requires calculations of Form Factors
- Theory input: Complementary approaches, decay rates predicted as a function of q^2 ($\mu\nu$ invariant mass)
  - $B_s^0 \to K^- \mu^+ \nu_\mu$: LCSR(precise at low q^2) & LQCD(precise at high q^2)
  - $B_s^0 \to D_s^- \mu^+ \nu_\mu$: LQCD(precise over full q^2 spectrum)

$|V_{ub}|/|V_{cb}|$ in $B_s^0 \to K^- \mu^+ \nu_\mu$ [Phys. Rev. Lett. 126 (2021) 081804]

1. Ratio of Branching fractions of $B_s^0 \to K^- \mu^+ \nu_\mu$ & $B_s^0 \to D_s^- \mu^+ \nu_\mu$

$$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$$

2. Two partial BRs ratios:
   - Split in two q^2 regions for $B_s^0 \to K^- \mu^+ \nu_\mu$ ($q^2{}_{B_s^0 \to K^- \mu^+ \nu_\mu} < (>) 7\,\mathrm{GeV}^2$)
   - Use the full q^2 spectrum of $B_s^0 \to D_s^- \mu^+ \nu_\mu$

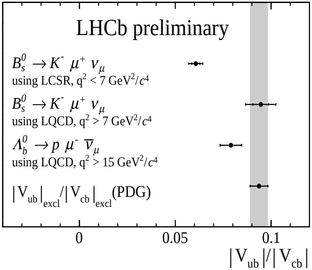
$$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)_{q^2<7}}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)_{\mathrm{Full}\ q^2}} \quad , \quad \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)_{q^2>7}}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)_{\mathrm{Full}\ q^2}}$$

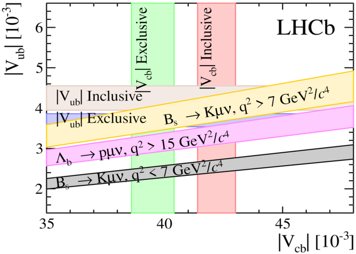
- q^2 Bin choice: balance visible yields with theory uncertainty → worse FF uncertainty
- Will be optimized in future (full Run1+Run2 data) to exploit the precise FF prediction at very high q^2

Results: $\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)$ [Phys. Rev. Lett. 126 (2021) 081804]

$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF})$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(\text{FF})$$

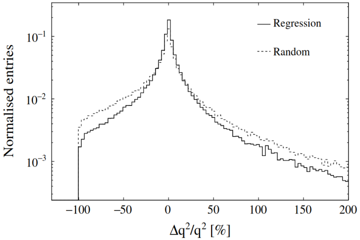


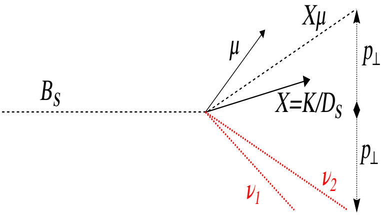


- $|V_{ub}|/|V_{cb}|(\text{high})$: compatible with $\Lambda_b \to p\mu^-\nu_\mu$, similar experimental uncertainties
- Discrepancy $|V_{ub}|/|V_{cb}|(\text{low})$: clash in theory predictions → solved when measuring full q^2 shape of $B_s^0 \to K^- \mu^+ \nu_\mu$

$|V_{ub}|/|V_{cb}|$ @ LHCb: Strategy [Phys. Rev. Lett. 126 (2021) 081804]

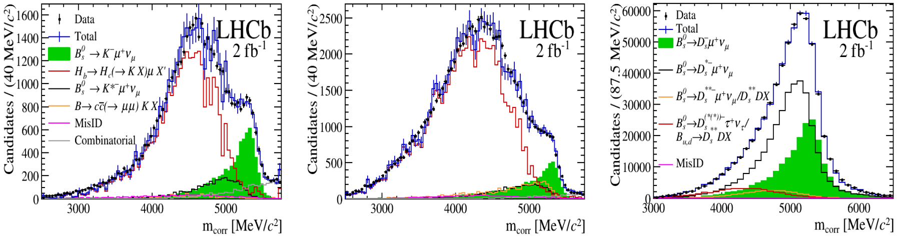
- Analysis requires q^2 reconstruction:
    1. Infer P_ν from B_s^0 topology $\rightarrow$ two-fold ambiguity
    2. Use linear regression (JHEP 02 (2017) 021) to choose correct P_ν solution
- $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$ & $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$
    - Fit data using "corrected mass"
    - $M_{corr} = \sqrt{M_{X\mu}^2 + p_\perp^2} + p_\perp$
- Similar vetoes to select/reconstruct $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$& $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$
    - Use inclusive $D_s^- \rightarrow K^+ K^- \pi^-$ decays





Yields: $B_s^0 \to K^- \mu^+ \nu_\mu$& $B_s^0 \to D_s^- \mu^+ \nu_\mu$ [Phys. Rev. Lett. 126 (2021) 081804]

- Statistical uncertainty is dominated by $B_s^0 \to K^- \mu^+ \nu_\mu$
- Analysis uses only 2 $\mathrm{fb}^{-1}$of LHCb data, $\sim$ 20% of available data
  - Potential for $\times 2$ improvement on statistical uncertainty
- Large backgrounds contributions reduce fit sensitivity
  - New method is currently underway to reduce it



$N_{K(\mathrm{low})} = 6922 \pm 285$, $N_{K(\mathrm{high})} = 6399 \pm 370$, $N_{\mathrm{D_s}} = 201450 \pm 5200$

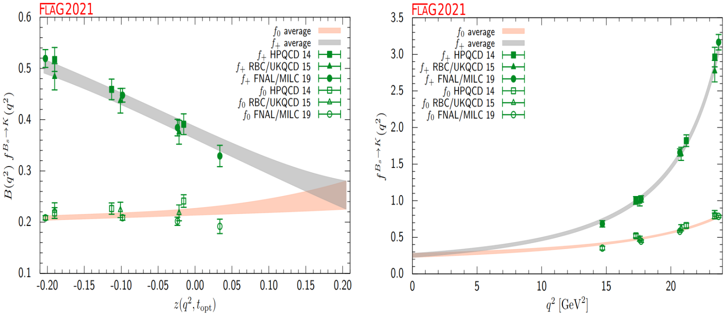
Systematics breakdown [Phys. Rev. Lett. 126 (2021) 081804]

Uncertainty	$\frac{\mathcal{B}(B_s \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)}$ [%]		
	No q^2 sel.	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle ID	1.0	1.0	1.0
$m_{\rm corr}$ error	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration		2.0	2.0
ε gen& reco	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
$\mathcal{B}(D_s^- \to K^-K^+\pi^-)$	2.8	2.8	2.8

- Better strategy is developed to reduce the number of systematic sources
- Multiple Systematic sources for ϵ relies on $B^+ \to J/\psi K^+$ as control channel $\to$ reducible with larger data sets
- Fit systematics dominated by simulation size $\to$ we produced $\sim 10\times$ larger sample to reduce this effect
- BESIII: Plans to better measure $\mathcal{B}(D_s^- \to K^-K^+\pi^-) \to \sim 1.5\%$ on $|V_{ub}|/|V_{cb}|$

Form Factor systematic

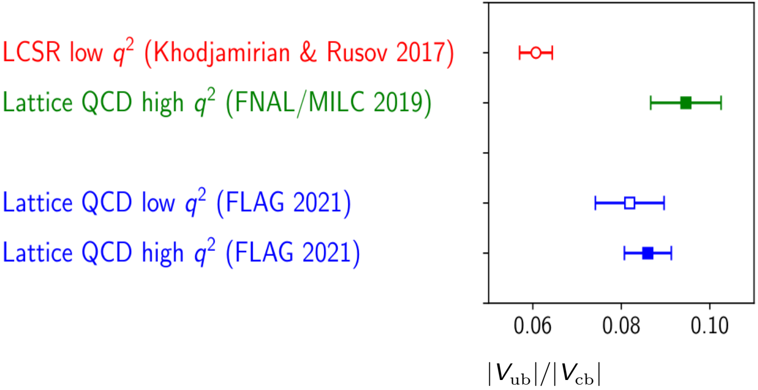
- Recent average from FLAG in 2021:
  http://cds.cern.ch/record/2791030/files/2111.09849.pdf



- Our choice of bins for high q^2 caused higher FF uncertainty
- Next measurement will have finer bins any way

Form Factor systematic

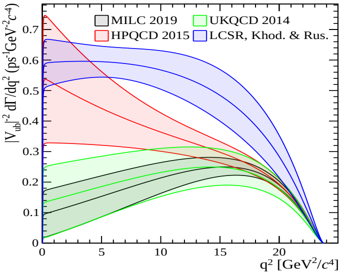
- At CKM 2021: reduction of FF uncertainty by 40%@ high q^2

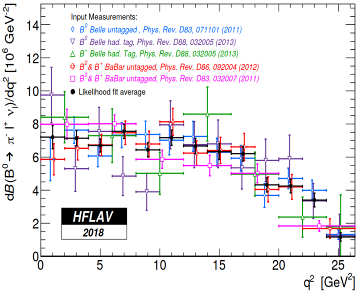


- We plan to use FLAG average instead of individual results in future measurements

Form Factor measurement

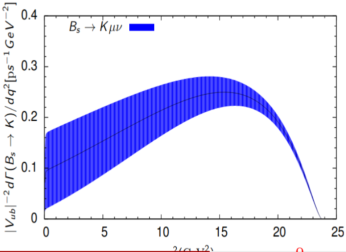
- Measuring the partial Decay rate for $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ in more bins of q^2
- This will enable determining the shape similarly to BaBar and Belle approach
  - At LHCb we have to nrmalize to a known channel, $\mathrm{B}^+ \to \mathrm{J}/\psi \mathrm{K}^+$?
  - B^+ Lifetime as input (possibly f_s/f_d)
- Run 2 has enough stats. to devide the q^2 into 6-8 bins
- Important feed-back to theory community and our simulation and for ...

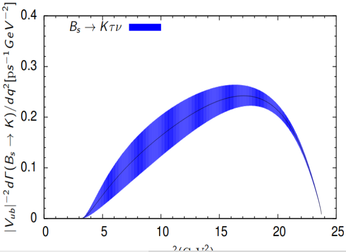




Extreme precision on $|V_{\rm ub}|/|V_{\rm cb}|$

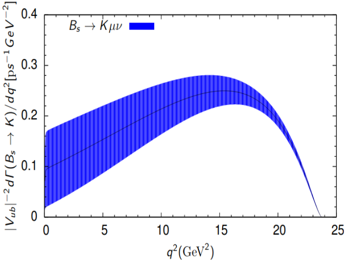
- $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$ is dubbed "Golden-mode" for lattice QCD due to precise FF calculations
- Those are quite precise in the "last" bin of the q^2 spectrum
- Plots below inform us (Phys. Rev. D 100, 034501 (2019)):
  - Current estimation: 3.5% in the bin 17-23 GeV/c^2 using $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$
  - Current estimation: 1.5% in the bin 17-23 GeV/c^2 using $\mathrm{B_s^0} \to \mathrm{K}^- \tau^+ \nu_\tau$
- That bin has little stat.(O(100)) with Run1 + Run2 data
- for $\mathrm{B_s^0} \to \mathrm{K}^- \mu^+ \nu_\mu$: Run 3 provides the needed statistics ($\sim 10\times$ current) to be at theory level

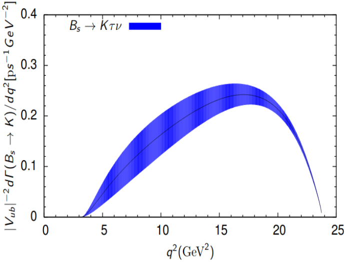




Extreme precision on $|V_{ub}|/|V_{cb}|$

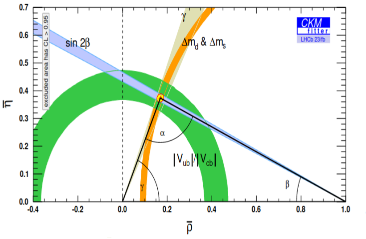
- Future Lattice QCD plans(numbers extracted from Belle II Physics book):
  - $\sim 1\%$ in the bin 17-23 GeV/c^2 using $B_s^0 \to K^- \mu^+ \nu_\mu$
  - $< .5\%$ in the bin 17-23 GeV/c^2 using $B_s^0 \to K^- \tau^+ \nu_\tau$
- For the $B_s^0 \to K^- \tau^+ \nu_\tau$ mode: we need to wait till the end of HL-LHC to be as good as the future theory projections
- Experimentally $B_s^0 \to K^- \tau^+ \nu_\tau$ is quite challenging but still feasible as demonstrated by measurements of $\mathcal{R}(D^{*-})$-and-friends at LHCb

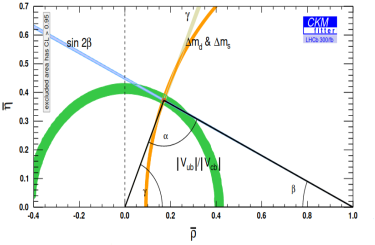




About LHCb upgrade ...

- LHCb Upgrades document [arXiv:1808.08865] provide projections for $V_{\rm ub}$



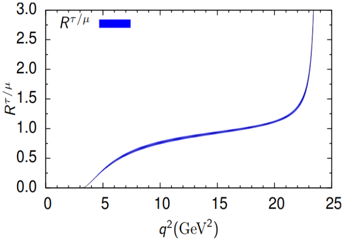


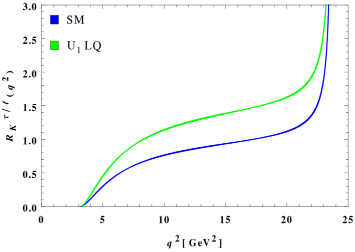
Upgrade I ($23\ \rm fb^{-1}$) , Upgrade II ($300\,\rm fb^{-1}$)

- $|V_{\rm ub}|/|V_{\rm cb}|$: for UpgradeI $\sigma \sim 3\%$, while Upgrade II $\sigma \sim 1\%$ (total experimental uncertainty)
- Improvement of PID(TORCH) and enhancement of VELO design will improve Mcorr variable greatly

Lepton Flavour Universality in $\mathrm{b} \to \mathrm{u}\ell\nu_\ell$ transitions

- LFU anomalies in $\mathrm{b} \to \mathrm{c}\ell\nu_\ell$ transitions ($R(\mathrm{D}^{*-}), R(\mathrm{D}^-)$)
- SM versus NP [1], [2], [3] , [4] + other I probably forgot!
  - $R(\mathrm{K}^-)^{\mathrm{SM}}_{\mathrm{SL}} = \frac{\mathrm{B}^0_\mathrm{s} \to \mathrm{K}^- \tau^+ \nu_\tau}{\mathrm{B}^0_\mathrm{s} \to \mathrm{K}^- \mu^+ \nu_\mu} = 0.836 \pm 0.034$
  - $R(\mathrm{K}^-)^{\mathrm{NP}}_{\mathrm{SL}} = \frac{\mathrm{B}^0_\mathrm{s} \to \mathrm{K}^- \tau^+ \nu_\tau}{\mathrm{B}^0_\mathrm{s} \to \mathrm{K}^- \mu^+ \nu_\mu} = 1.133 \pm 0.104$
- Stat. are needed to prob the $R(\mathrm{K}^-)_{\mathrm{SL}}$ in full and (per-bin of) q^2 spectrum
- Need Upgradae II to be at the level of theory





Phys. Rev. D 100, 034501 (2019) , Nucl. Part. Phys. 48 (2021) 075006

Conclusion

- It has been two years since we published $|V_{\rm ub}|/|V_{\rm cb}|$ using $\mathrm{B}_s^0 \to \mathrm{K}^- \mu^+ \nu_\mu$ and $\mathrm{B}_s^0 \to \mathrm{D}_s^- \mu^+ \nu_\mu$ in two q^2 regions
  - The Form Factor measurement of $\mathrm{B}_s^0 \to \mathrm{K}^- \mu^+ \nu_\mu$ is starting
  - But slowly ...
- $\mathrm{B}_s^0 \to \mathrm{K}^- \mu^+ \nu_\mu$ program and LHCb upgrades need each other:
  - Form Factors, extreme precision on $|V_{\rm ub}|/|V_{\rm cb}|$ and LFU ideal place to look for NP
  - $\mathrm{B}_s^0 \to \mathrm{K}^- \mu^+ \nu_\mu$ is also crucial to control penguins for mixing phases ϕ_s, sin(2β) at Upgrade era
  - $+\ \mathrm{B}_s^0 \to \mathrm{K}^{*-} \mu^+ \nu_\mu$ and $\mathrm{B}^+ \to \phi \mu^+ \nu_\mu$
  - HI-LHC era is the ideal place to perfrom such measurements
- However start is complicated by:
  - Demanding activities around Run 3 (hardware, software)
  - Availability of resources