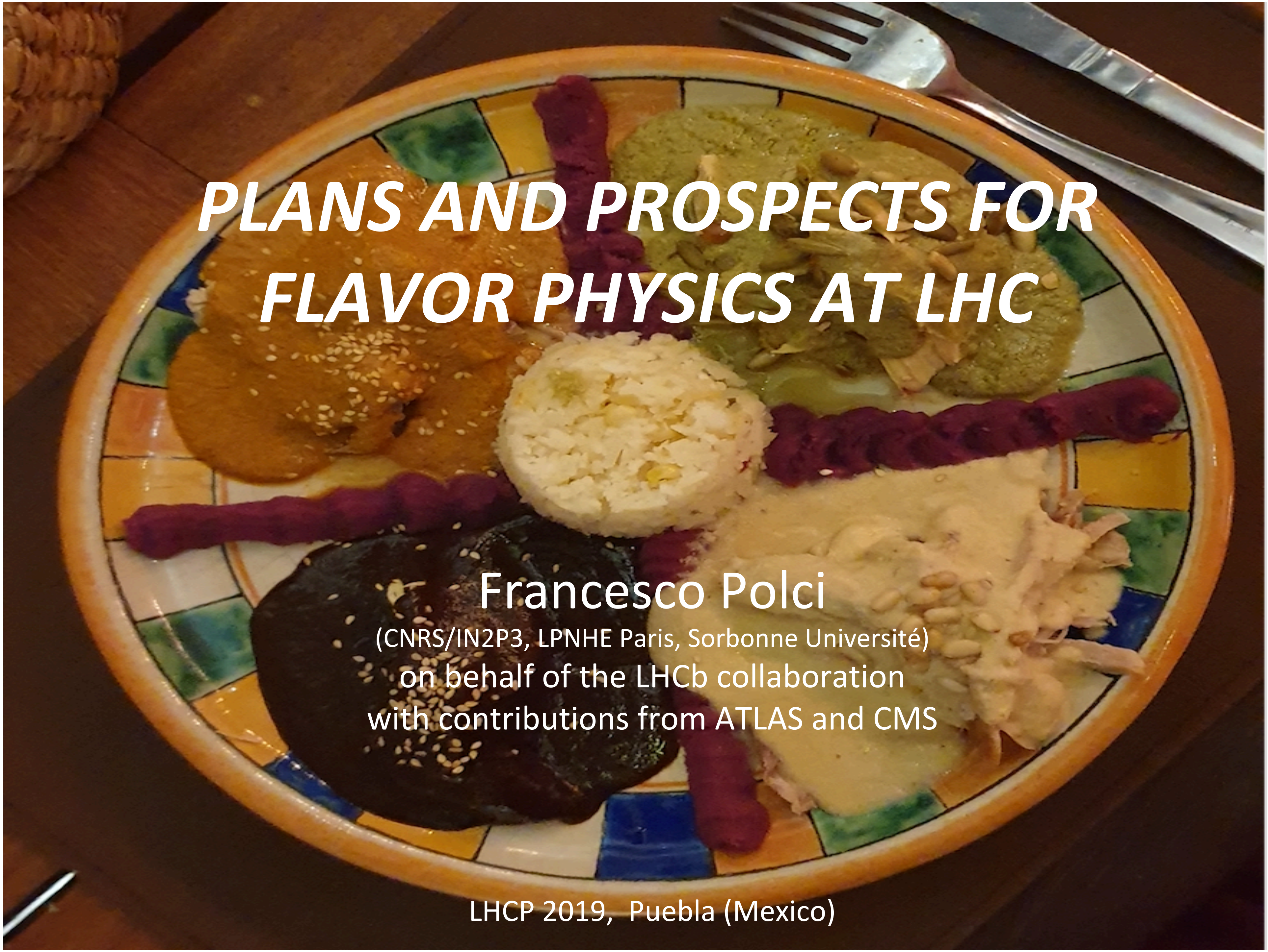


PLANS AND PROSPECTS FOR FLAVOR PHYSICS AT LHC

Francesco Polci

(CNRS/IN2P3, LPNHE Paris, Sorbonne Université)

on behalf of the LHCb collaboration

with contributions from ATLAS and CMS

LHCP 2019, Puebla (Mexico)

INTRODUCTION

Main outcome of LHC Run1-2:

1) Discovery of a SM Higgs-like boson
2) No direct observation of new physics particles

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{NP}}{\Lambda^2}$$

NP coupling

NP scale

$\Rightarrow$ New physics scale should be higher than expected

Flavor physics can explore higher scales than the energy of the collisions already now

- Large number of tests of SM consistency performed
- Intriguing anomalies at hands to be further investigated
- Most measurements are statistically dominated

➔ **the case for keeping doing flavor physics at LHC is stronger than ever!**

With future upgrades, expect a factor 1.9 gain on the energy scale probed by processes with loop diagrams!

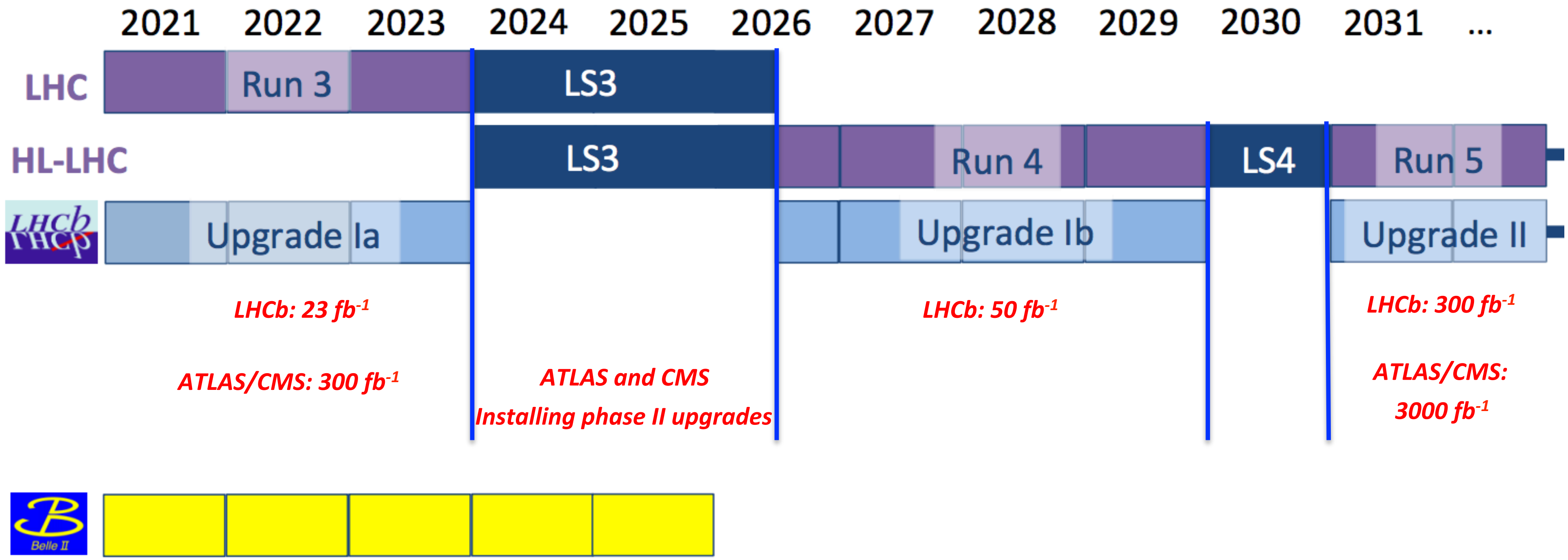
MOST RESULTS ARE CURRENTLY STATISTICALLY LIMITED

Observable	Current LHCb	σ(stat)/σ(sys)	Largest source of systematic
EW Penguins			
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	2.5	Mass shape & trigger eff
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	2.2	MC correction & residual bkgd
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	3	Δm_s, time res, tagging, det asymmetry
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	-	
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	8	Decay time: bias and efficiency
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	8	Angular efficiency
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	8	Decay time resolution
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	5	Acceptance (angular and time)
a_{sl}^s	33×10^{-4} [211]	1.3	Track reco asymmetry
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [201]	0.5	External BR(Λ_c)
$B_s^0, B^0 \to \mu^+\mu^-$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	6	f_d/f_s
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	9	Decay time acceptance
$S_{\mu\mu}$	–		
$b \to c\ell^-\bar{\nu}_l$ LUV studies			
$R(D^*)$	0.026 [215, 217]	1	MC sample size
$R(J/\psi)$	0.24 [220]	1	$F(B_c \to J/\psi)$ form factor
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	2.7	Mass model
A_Γ ($\approx x \sin\phi$)	2.8×10^{-4} [240]	2.8	Contribution from sec $b \to D^*X$ decays
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	2	Contribution from sec $b \to D^*X$ decays

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

TIMELINE

arXiv:1808.08865



NEED TO KEEP THE SAME SUCCESSFULL LHC STRATEGY FOR HL-LHC:

- AN EXPERIMENT OPTIMIZED FOR ALL FLAVOR PHYSICS MEASUREMENTS
- KEEP FLAVOR PHYSICS CAPABILITIES OF GENERAL PURPOSE DETECTORS

In the coming years, also Belle II is entering the game, but will not cover all the physics potential of LHC (no B_s, no b-baryons produced…)

WHAT WE NEED FOR FLAVOR PHYSICS AT HL-LHC?

Key ingredients:

- ***Performing triggers**, to fully profit of the high luminosity*
- *Be able to **cope with high pileup** (up to 200 p-p interactions in GPD)*
- ***Vertex reconstruction capabilities** to identify the B decay, especially in time-dependent measurements*
- ***Good mass resolution** to identify signal over backgrounds*
- ***Flavor tagging of initial states** for CPV measurements*
- ***Particle identification**, in particular for hadrons*

The experiments work to keep these ingredients at hands!

ATLAS and CMS (GPD):

- New inner tracker, improvements in muon system, topological triggers, tracks in trigger at early stages, dedicated low pT triggers, timing detector.

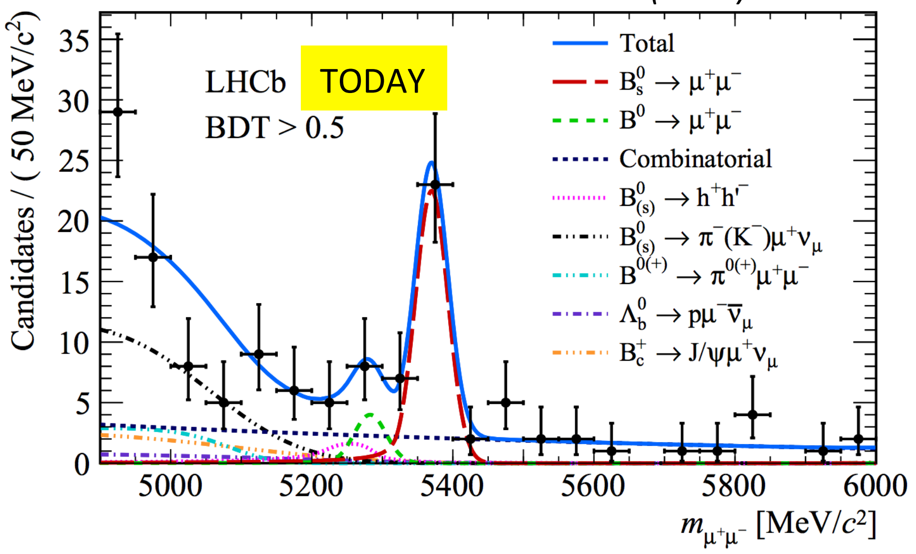
LHCb:

- Full software trigger at 30 MHz in Upgrade I and real-time analysis.
- Ongoing exploration of many detector technology options for Upgrade II

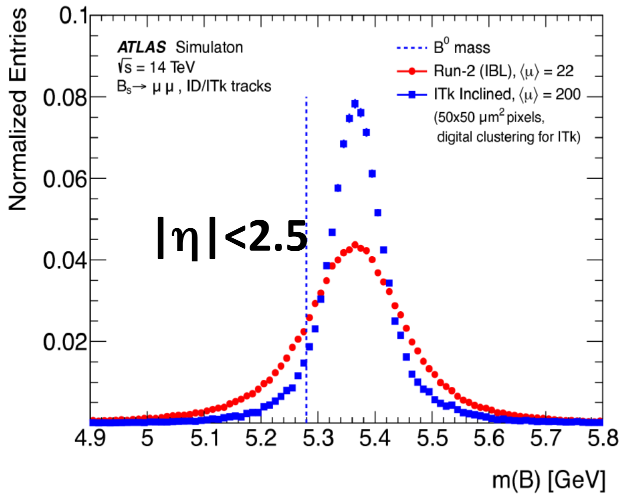
IMPROVED MASS RESOLUTION AT UPGRADED DETECTORS

$B_s \to \mu\mu$

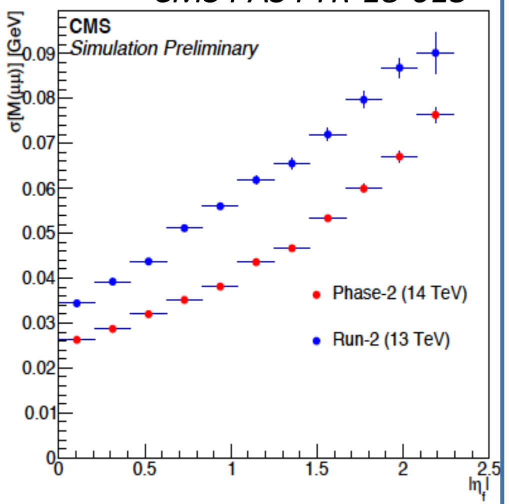
PHYS. REV. LETT. 118 (2017) 191801



ATL-PHYS-PUB-2018-005

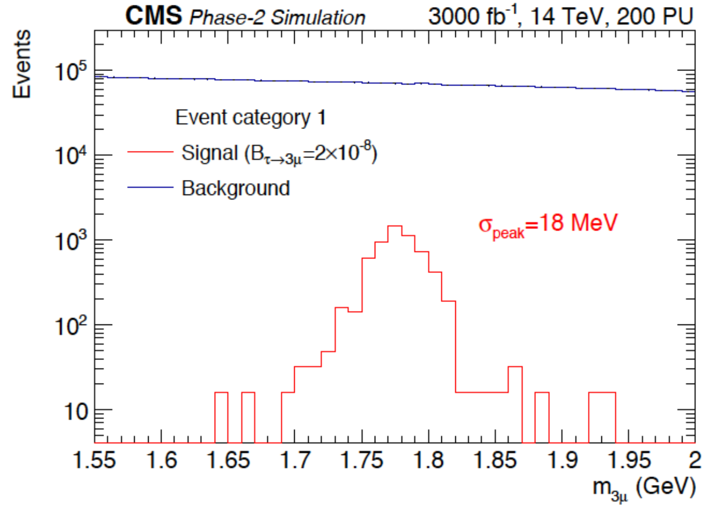


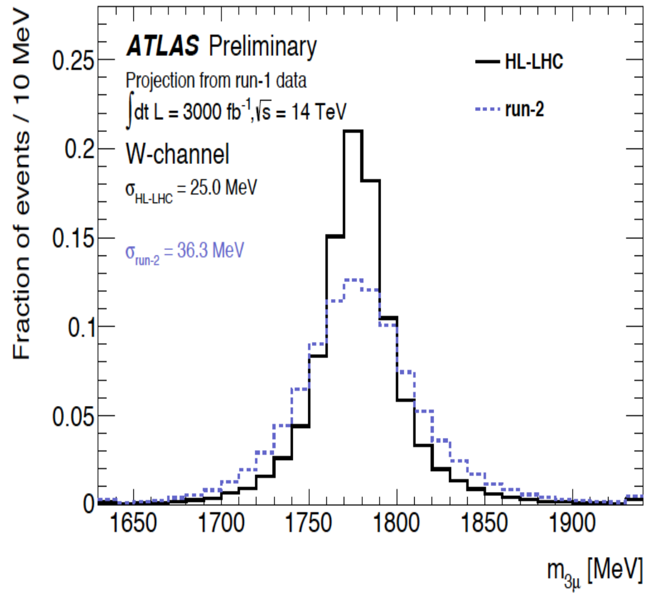
CMS PAS FTR-18-013



$\tau \to \mu\mu\mu$

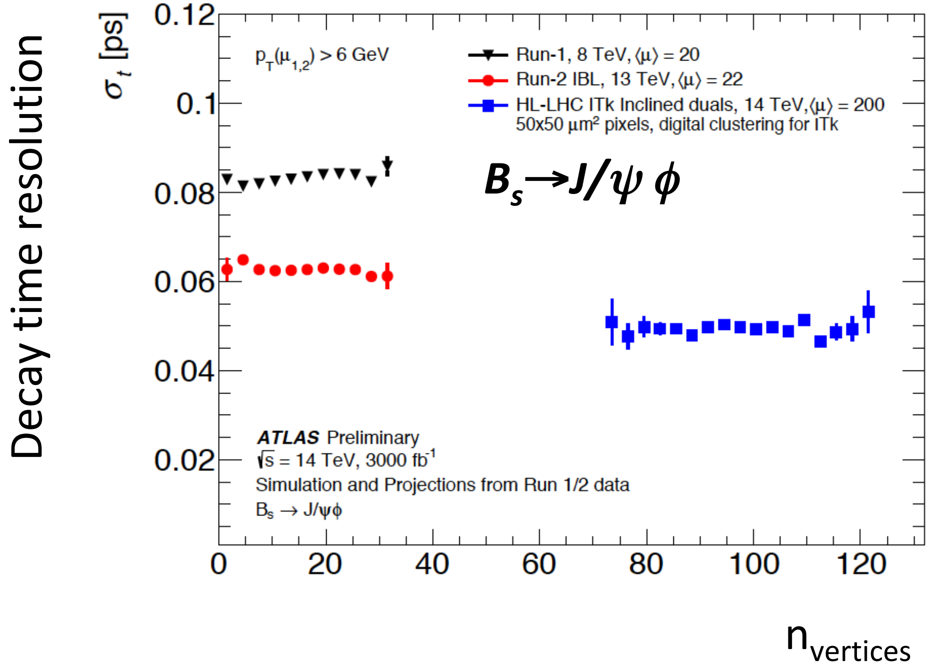
arXiv:1812.07638



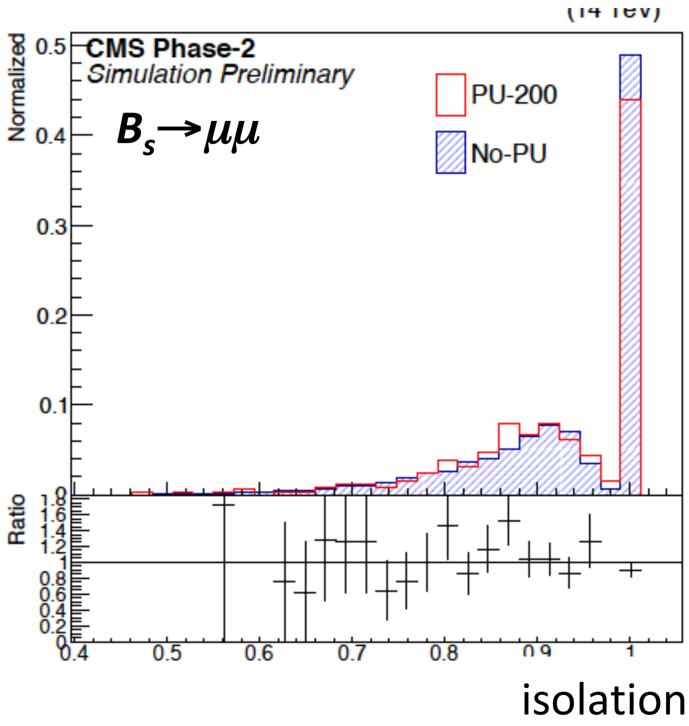


STABLE PERFORMANCES EVEN WITH HIGH PILEUP

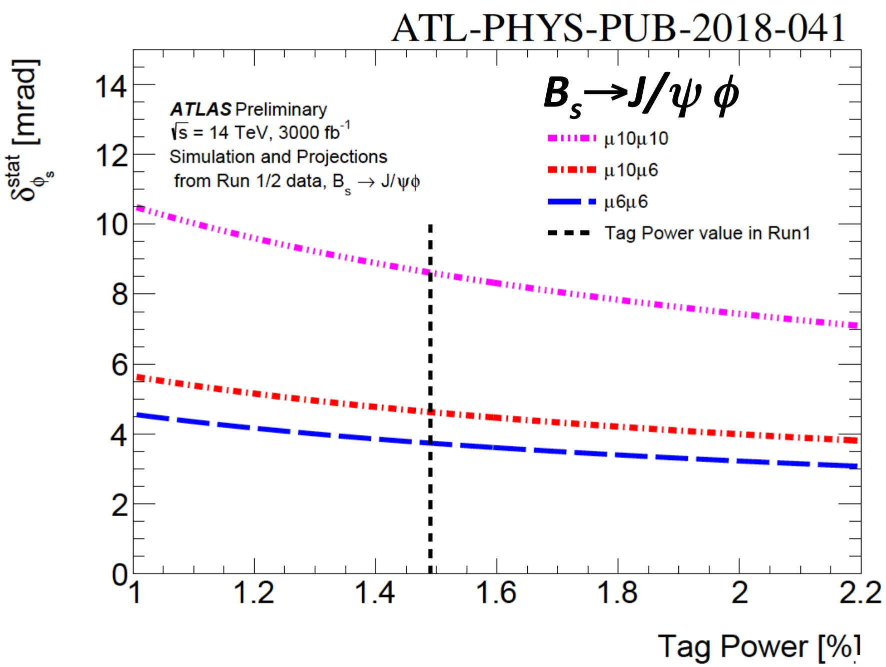
ATL-PHYS-PUB-2018-041

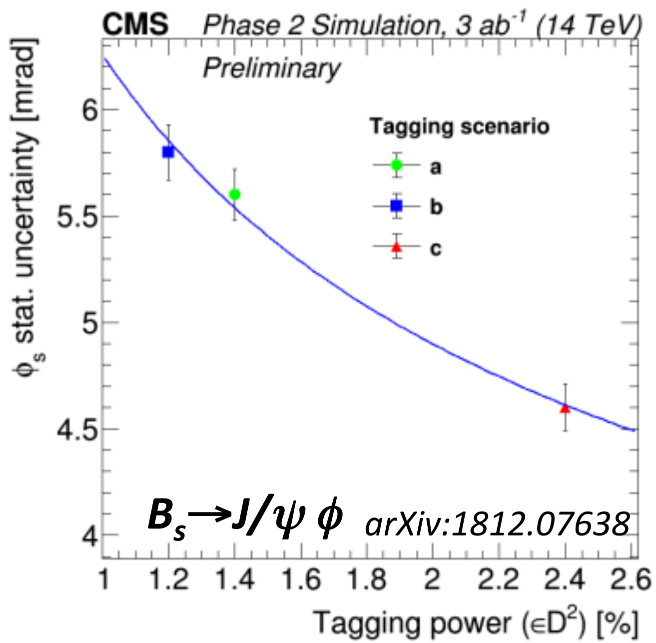


CMS PAS FTR-18-013

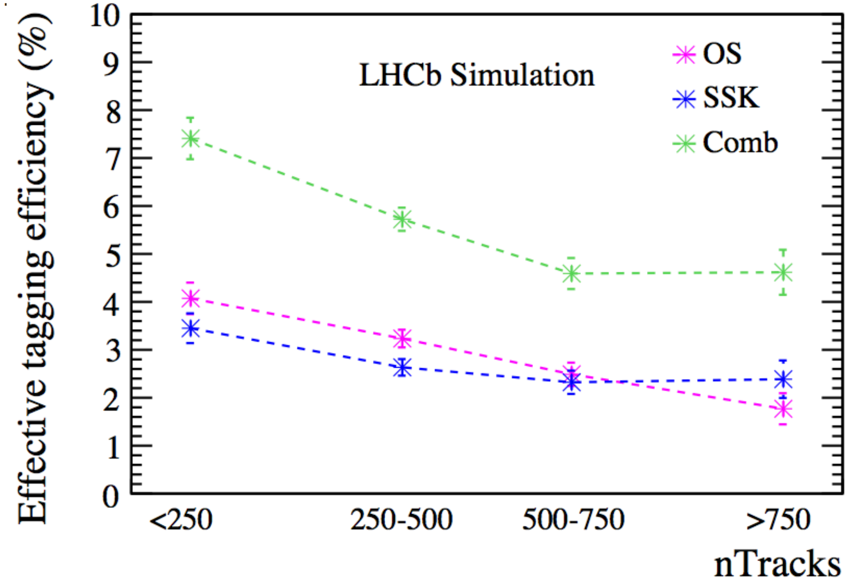


GOOD TAGGING PERFORMANCES





- Crucial for CPV measurements.
- At least keep current capabilities in LHCb, despite an increase of number of tracks (and keep room for improvements)

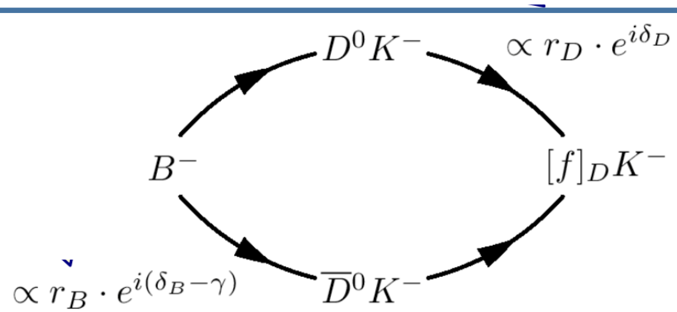


PROJECTIONS ON
SOME SELECTED MEASUREMENTS

(based on "*Opportunities in Flavour Physics at the HL-LHC and HE-LHC*", arXiv:1812.07638)

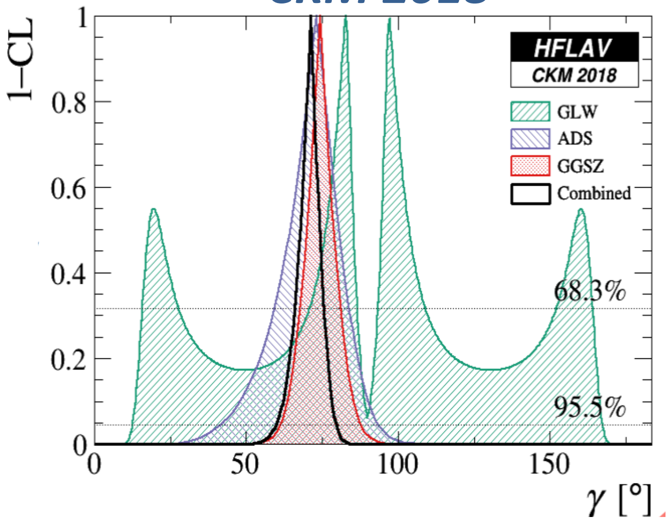
CPV MEASUREMENTS: GAMMA

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

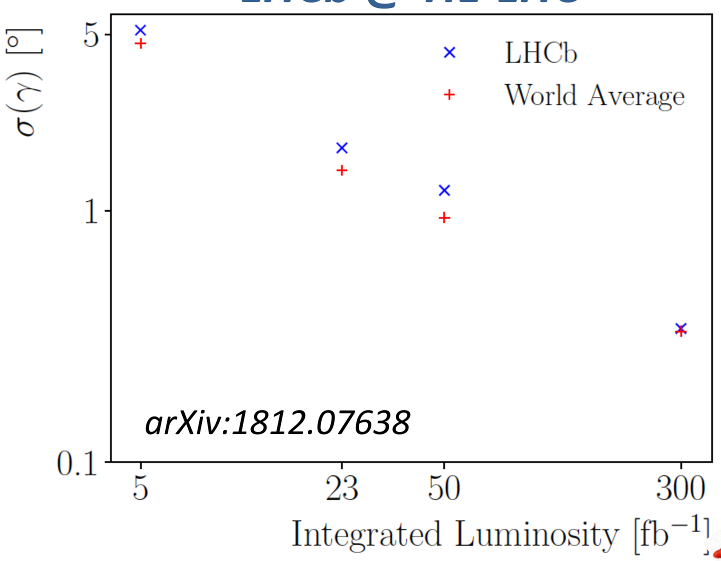


- Interference between *b*→*c* and *b*→*u* transitions at tree level *B*→*DK decays* provides a SM candle => *strong constraint in unitarity triangle*
- Comparison with measurements with potential new physics contribution:
  - γ from modes involving loops (charmless *b* decays)
  - $\gamma + \phi_s$ from time dependent analysis of $B_s \to D_s K$
- Currently γ **= (71.1 + 4.6 - 5.3)°** (fully dominated by LHCb)

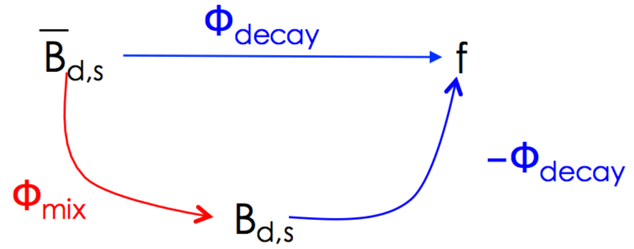
CKM 2018



LHCb @ HL-LHC



CPV MEASUREMENTS : 2β and ϕ_s

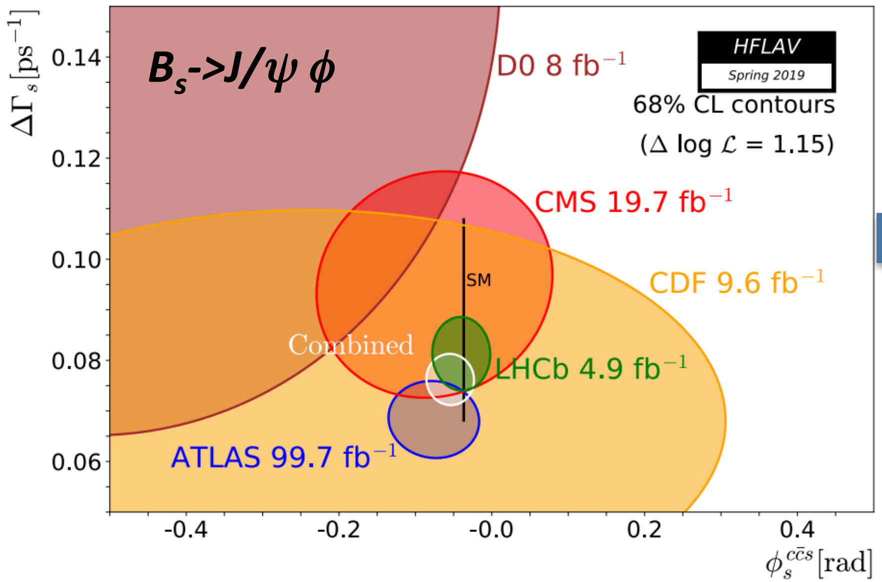


- Measure CPV in the interference between mixing and decay: $\Phi = \Phi_{mix} - 2\,\Phi_{decay}$

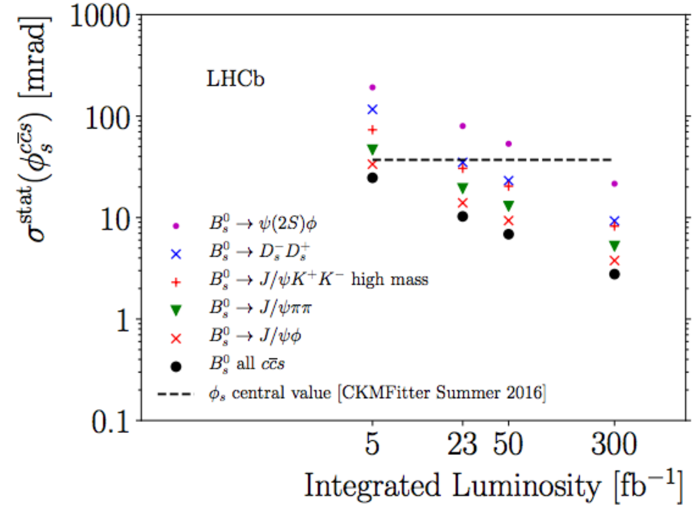
  $\Phi = \Phi^{SM} + \Delta\Phi_{peng} + \Delta\Phi_{NP}$

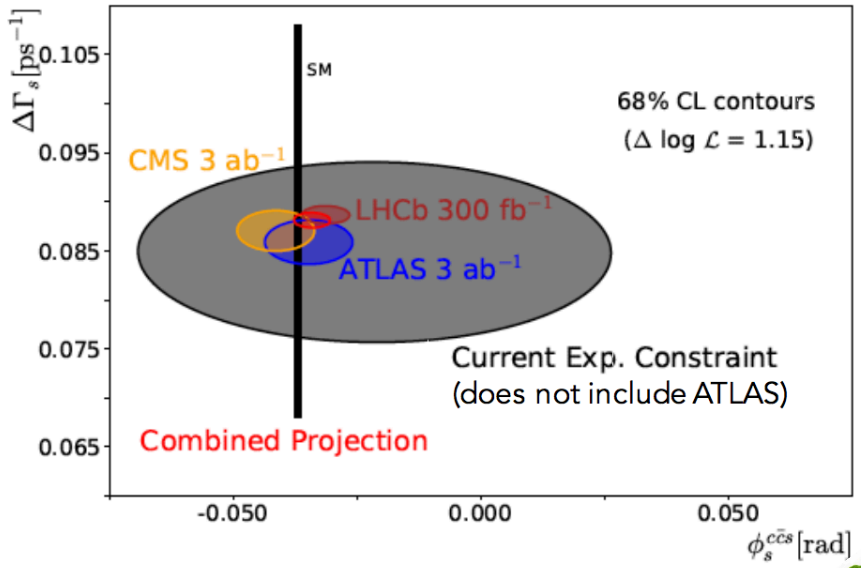
- Keep constraining penguin pollution from data
- Requires: tagging, decay time measurement

Preliminary 2019



B_s->J/ψ φ ***HL-LHC*** *arXiv:1812.07638*





CPV MEASUREMENTS : CHARM

Challenges:

- Handling the large amount of data
- Improve the theoretical predictions

Direct CPV

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}$$

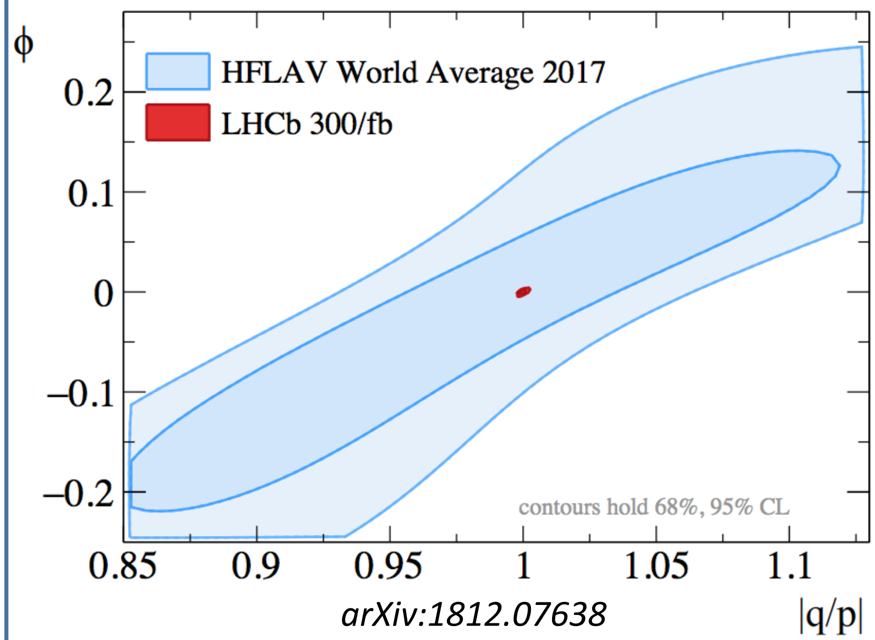
- Wide range of expectations: 10^{-3} - 10^{-4}
- Measured as:
  $\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
- Observed at 5.3 σ!
  (March 2019, *arXiv: 1903. 08726*)

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- Expect increasing precision in HL-LHC of one order of magnitude (3×10^{-5})

Indirect CPV

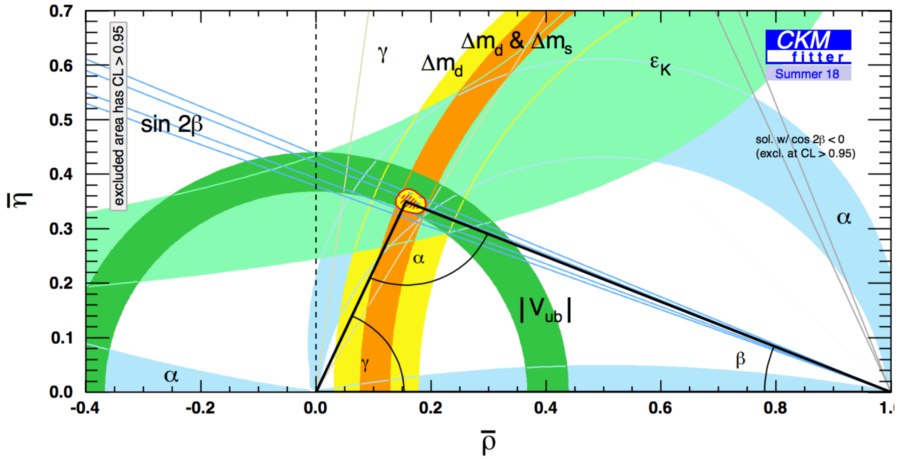
- Expected order 10^{-5} in SM;
- Anything larger would be new physics!



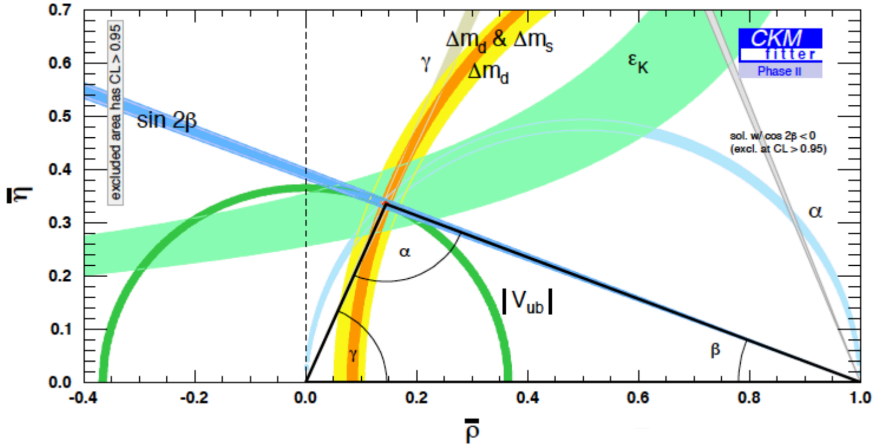
arXiv:1812.07638

OVERVIEW OF UNITARITY TRIANGLE

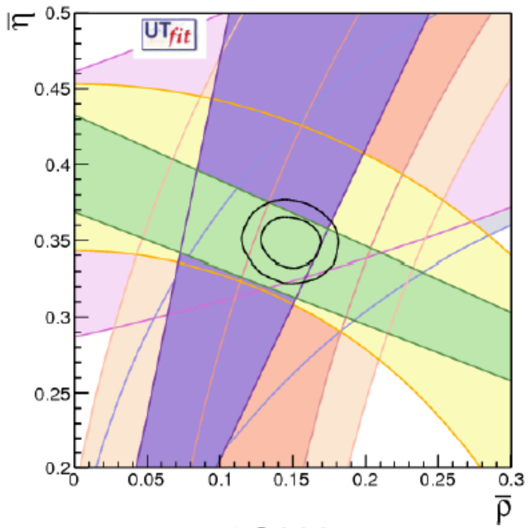
2018



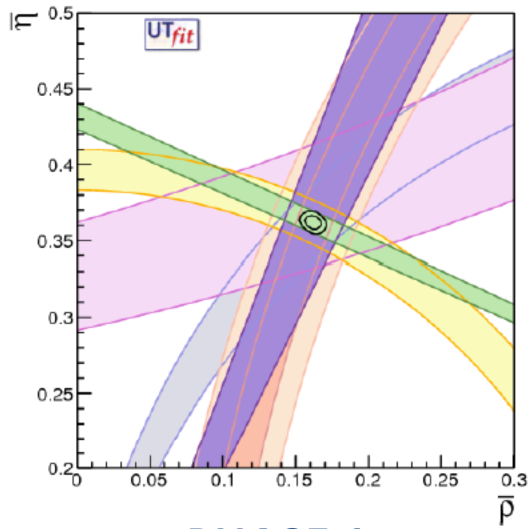
HL-LHC



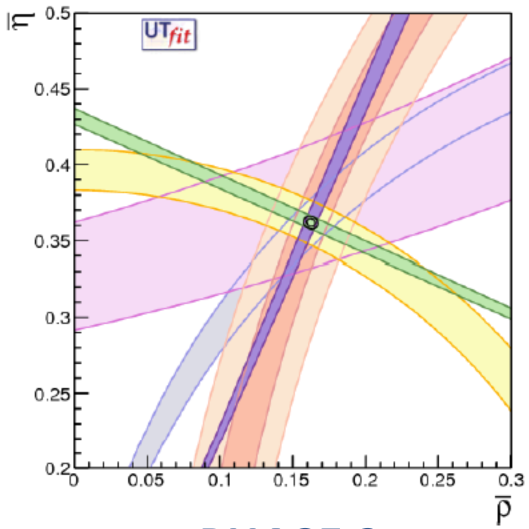
Zooming on the vertex region:



NOW



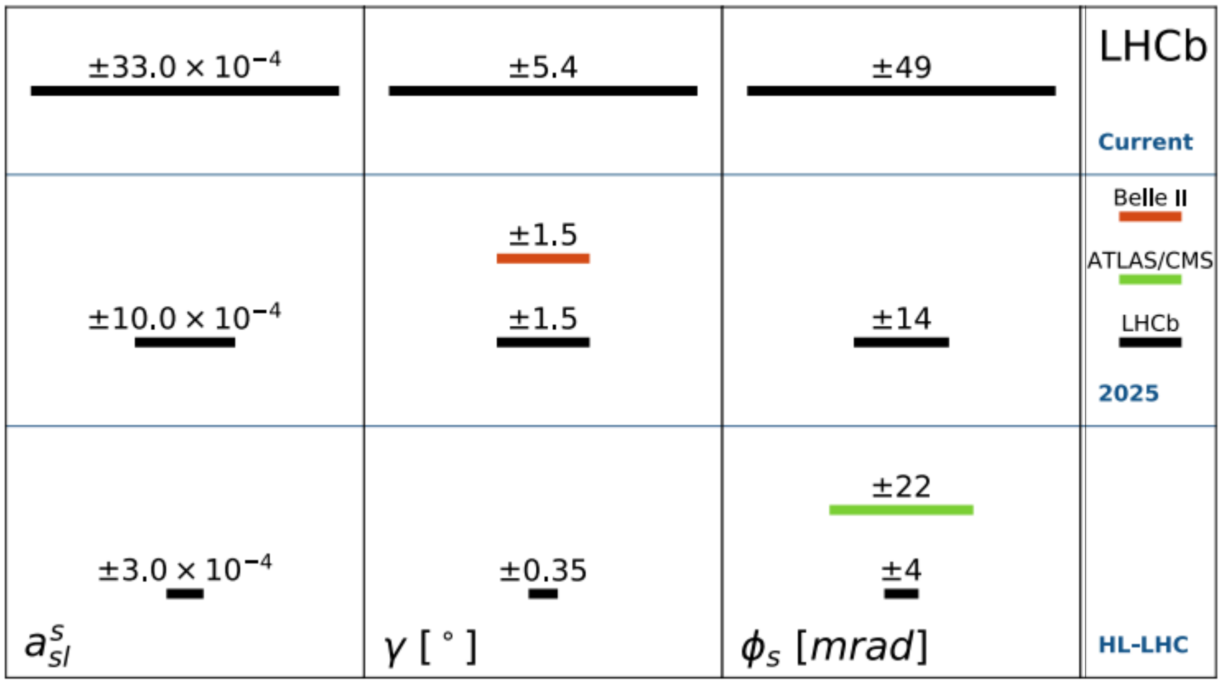
PHASE 1



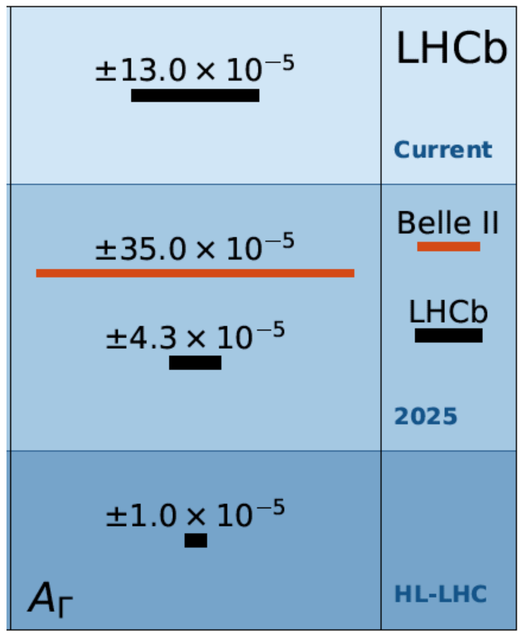
PHASE 2

OVERVIEW OF CPV MEASUREMENTS

Warning: as of mid-2018 *arXiv:1808.08865*

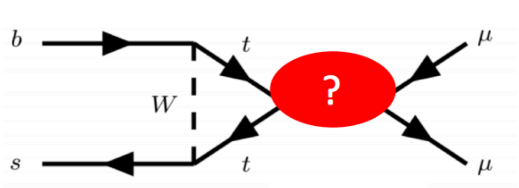


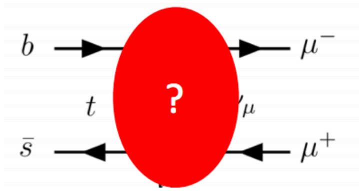
arXiv:1812.07638



RARE DECAYS: $B_s \to \mu\mu$

- Rare in SM: FCNC, CKM and helicity suppressions
- Sensitive to extended Higgs sector





- Requires good mass resolution

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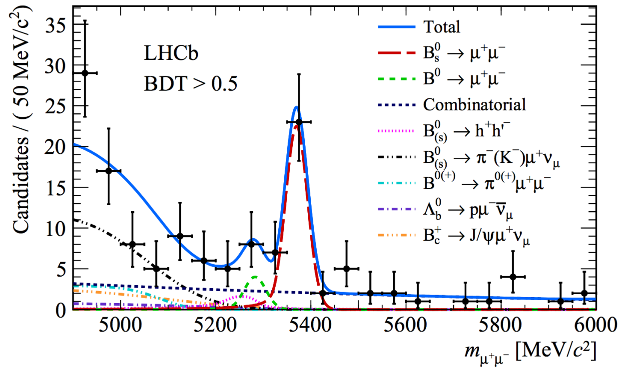

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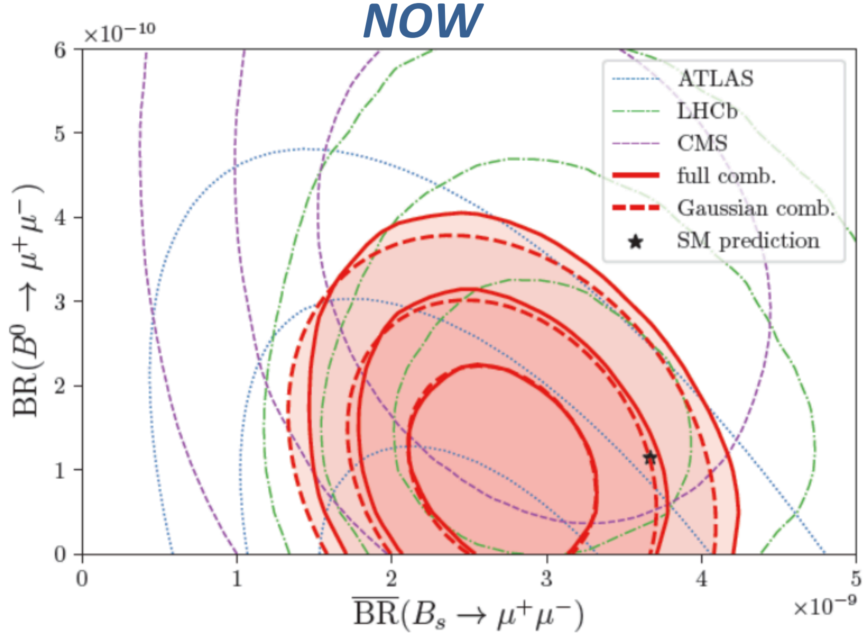
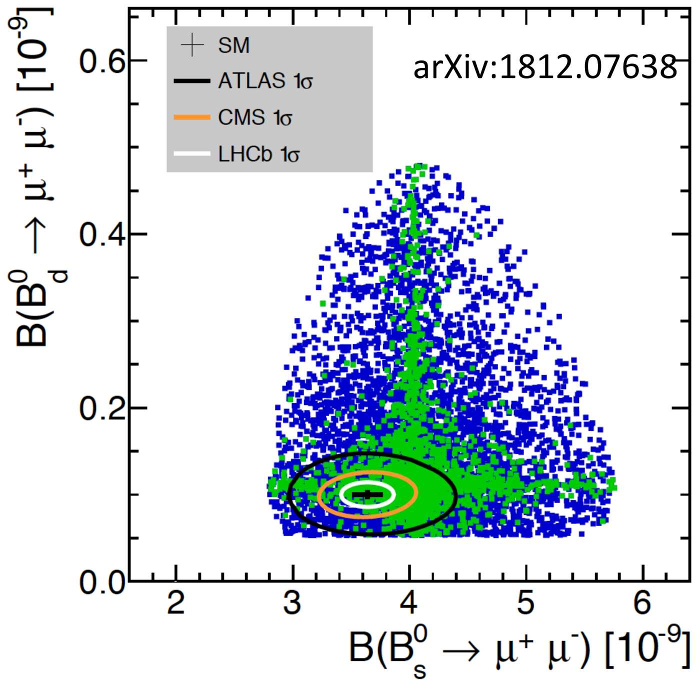


D. Straub Moriond 2019

HL-LHC



RARE DECAYS: $B_s \to \mu\mu$

Additional observables will be precisely measured:

- Effective lifetime
- Time dependent CP asymmetry

NOW

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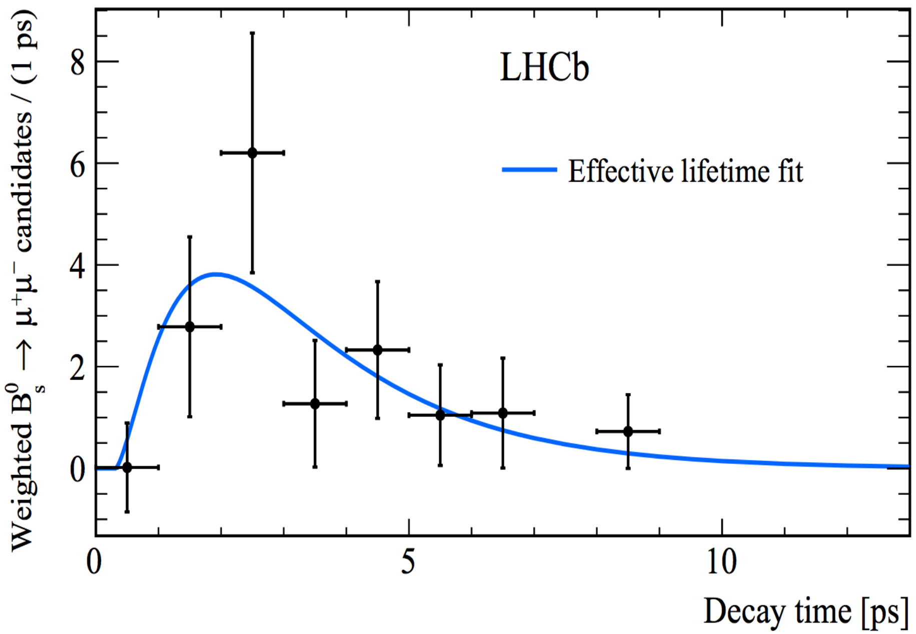
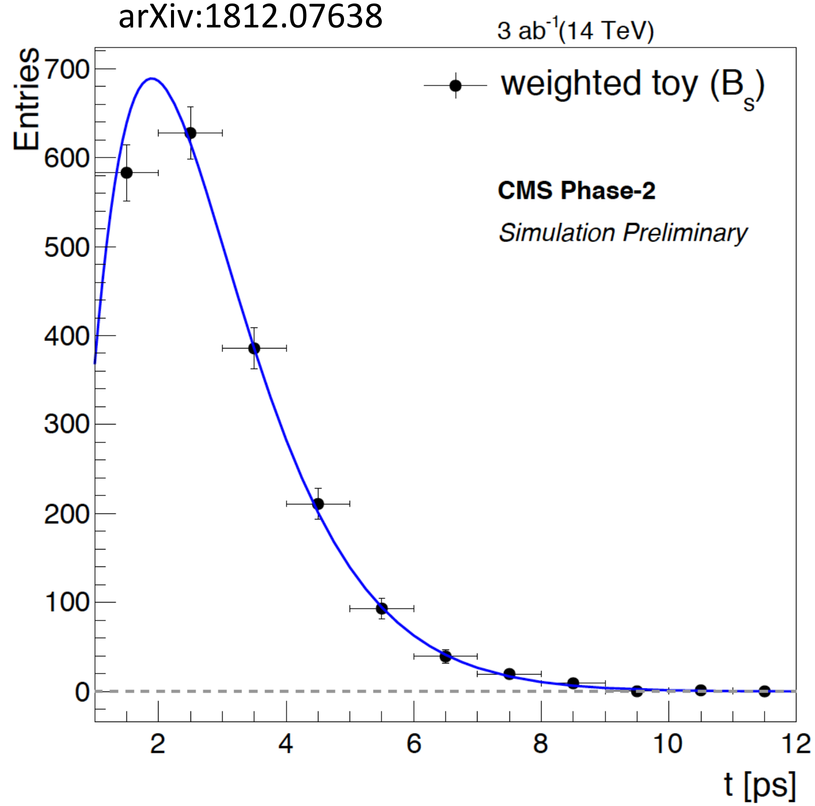
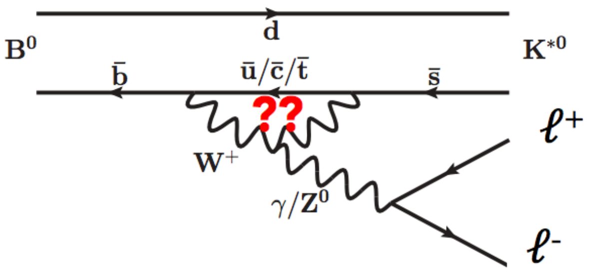


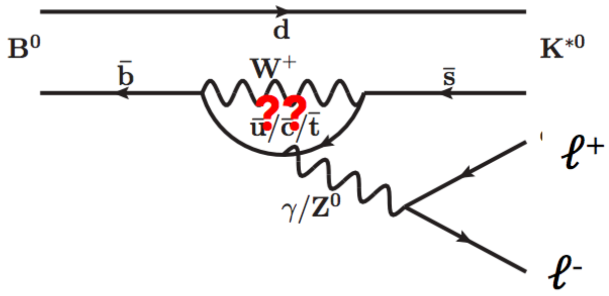
HL-LHC

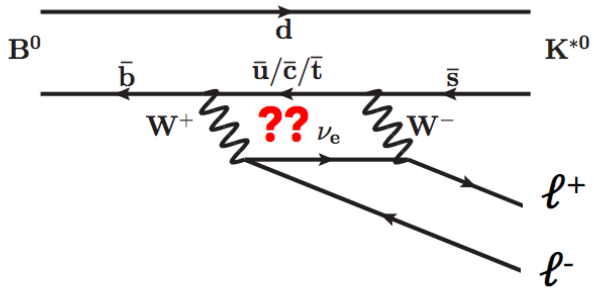
arXiv:1812.07638



RARE DECAYS: $B \rightarrow K^*\mu\mu$



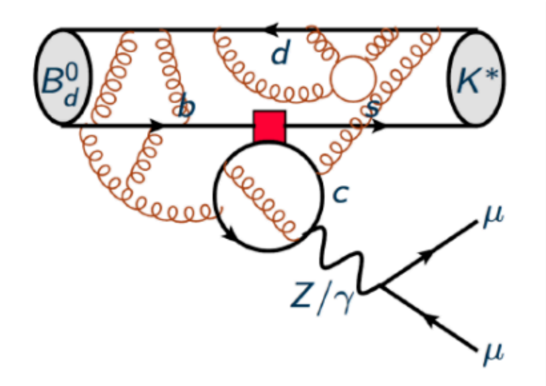


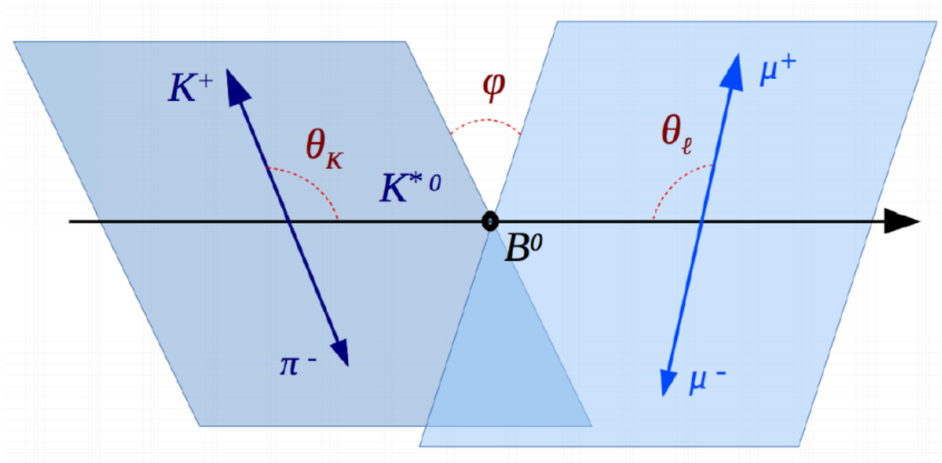


Powerful probe for new physics

Angular analysis showing tension with SM.

But beware of charm loops!



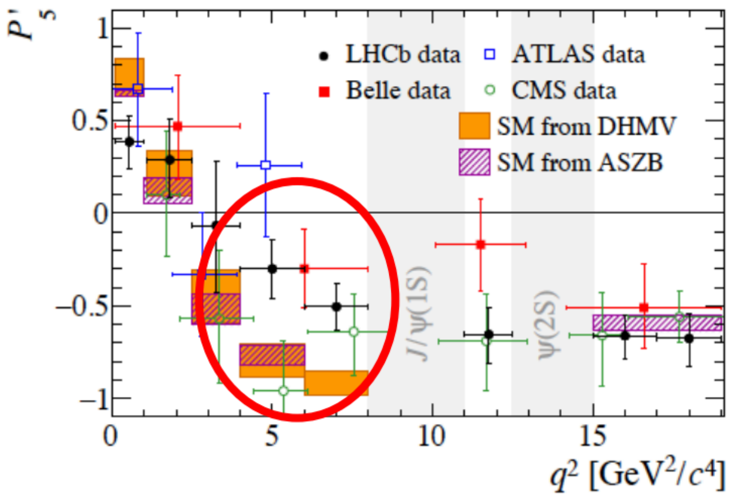


RARE DECAYS: $B \to K^*\mu\mu$

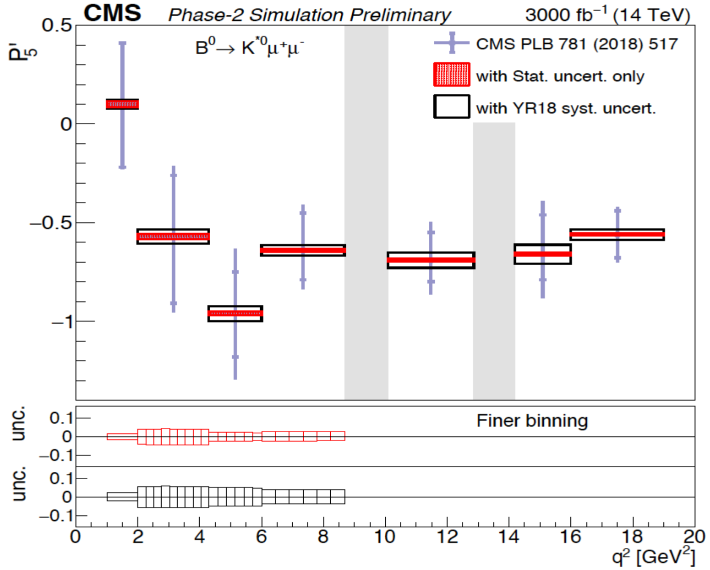
arXiv:1812.07638

TODAY

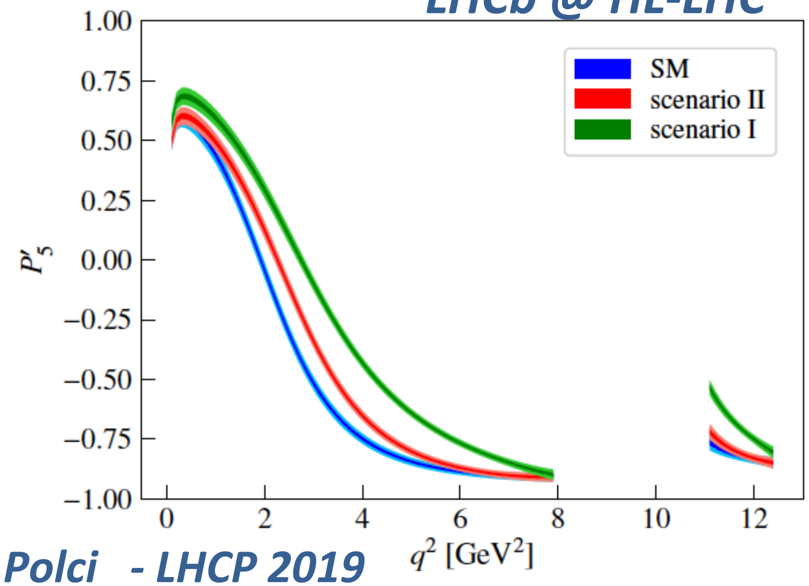
LHCb JHEP 02(2016) 104
ATLAS JHEP 10 (2018) 047
CMS PLB 753 (2016) 424
Belle (PRL 118 (2017) no.11, 111801)



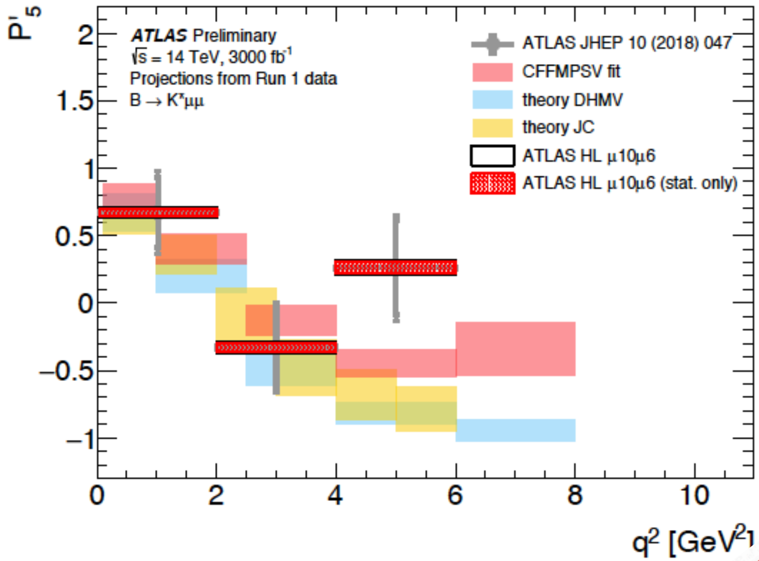
CMS @ HL-LHC



LHCb @ HL-LHC



ATLAS @ HL-LHC



RARE DECAYS: LFU tests in *b→sll*

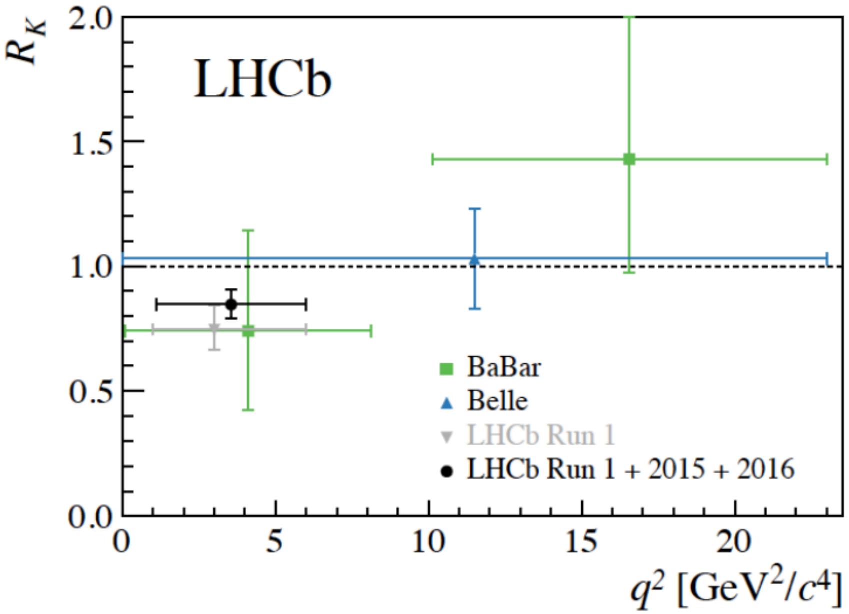
$$R_{H_s} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(H_b \to H_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(H_b \to H_s e^+e^-)}{dq^2} dq^2}$$

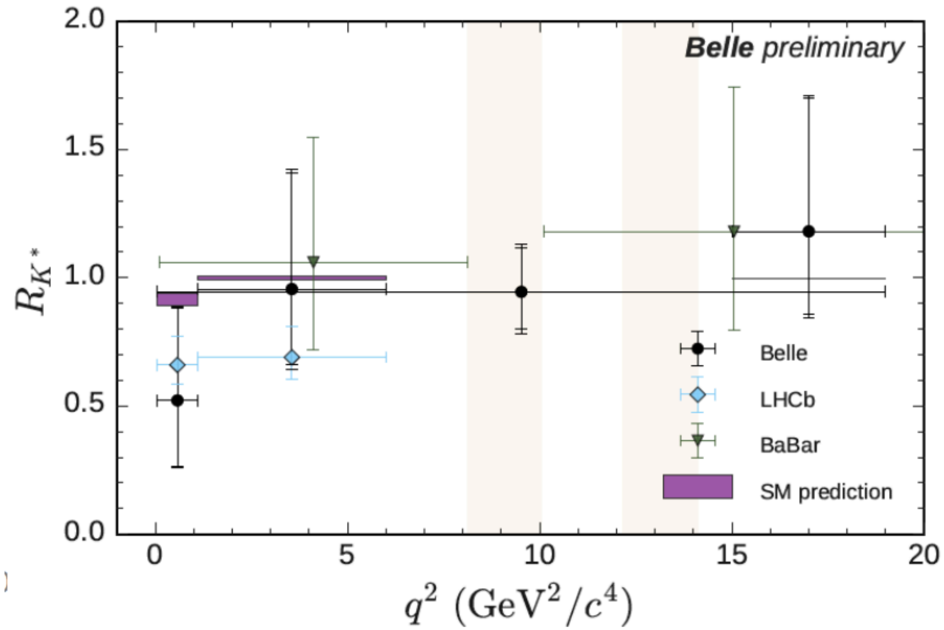
$H_s = K, K^*, \phi$

R_{Hs} =1 (at 10^{-3}) in the SM

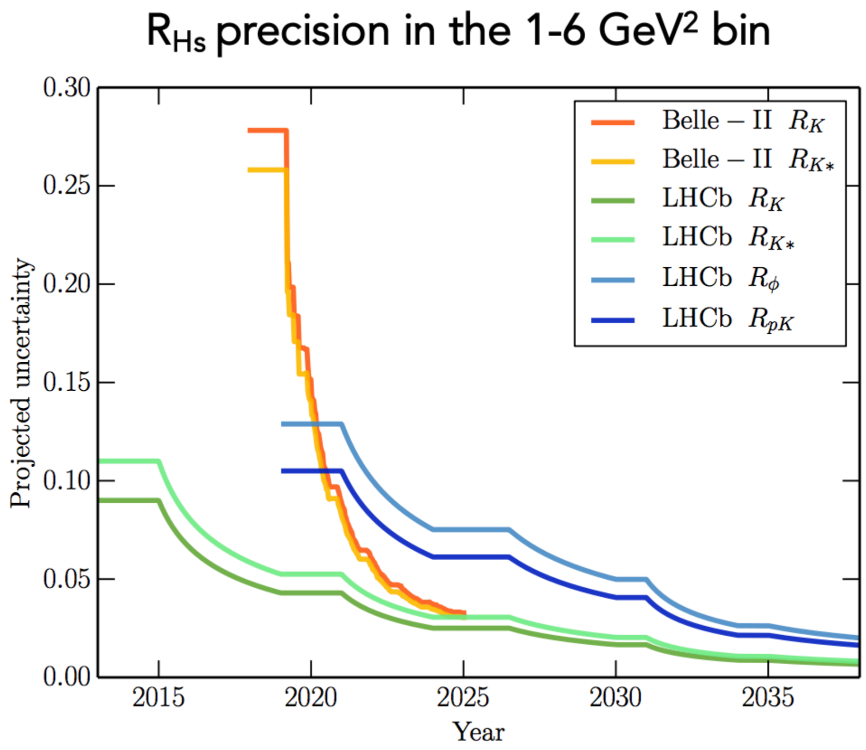
QED effects ~ % arXiv:1605.07633

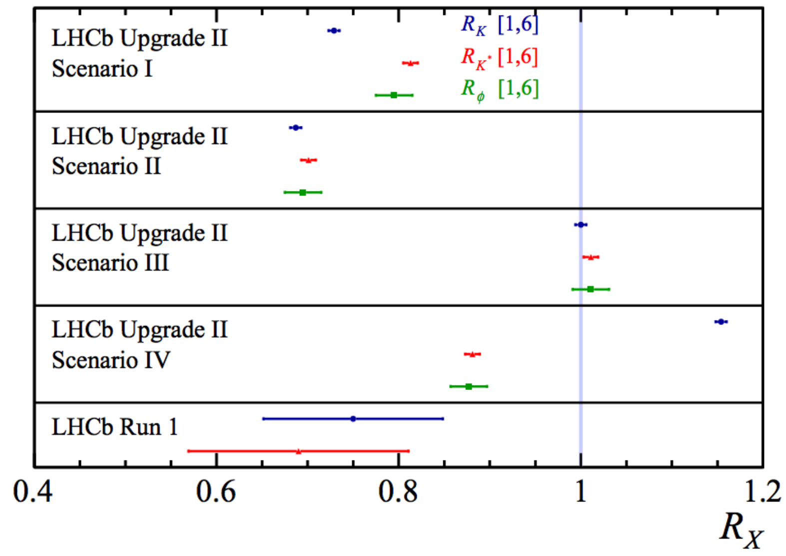
LU : an accidental symmetry of the SM





RARE DECAYS: LFU tests in *b→sll*





Also:

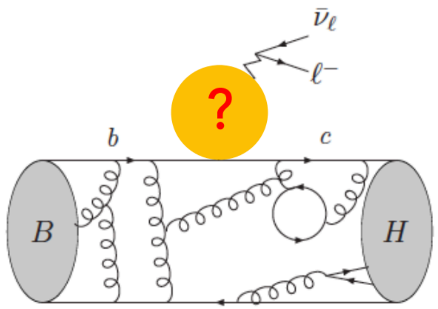
- LFU tests with angular distributions
- b→dll transitions accessible

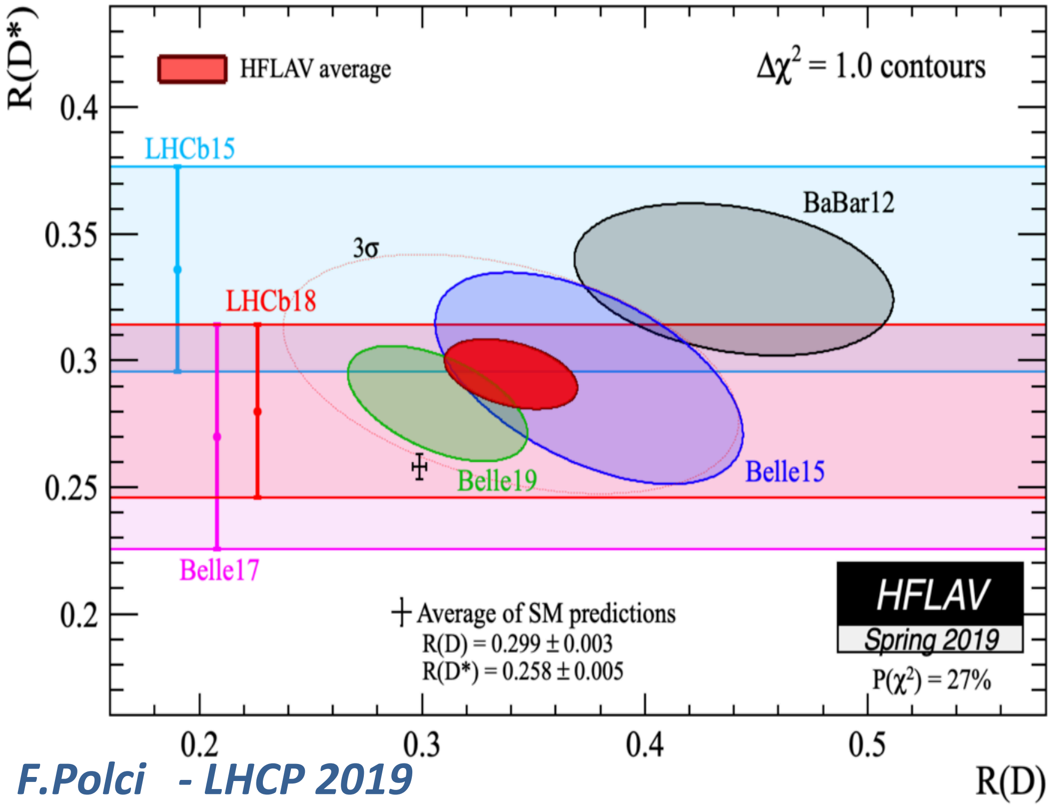
RARE DECAYS: LFU tests in $b \rightarrow cl\nu$

$$R_{H_c} = \frac{\mathcal{B}(H_b \rightarrow H_c \tau^- \overline{\nu}_\tau)}{\mathcal{B}(H_b \rightarrow H_c \ell'^- \overline{\nu}_{\ell'})}$$

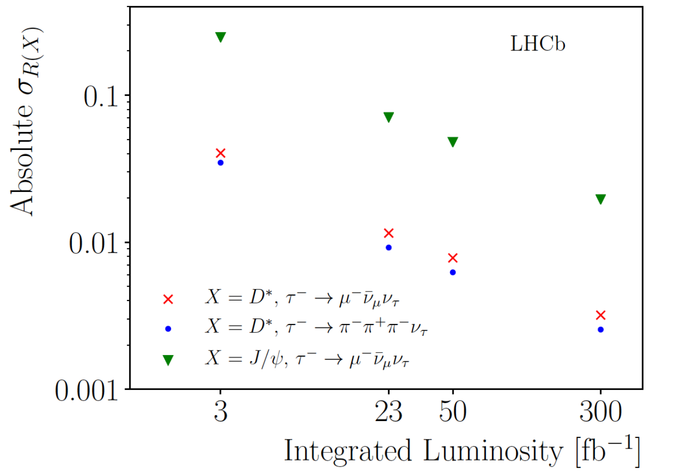
$H_c = D, D^*, D_s, \Lambda_c \ldots$

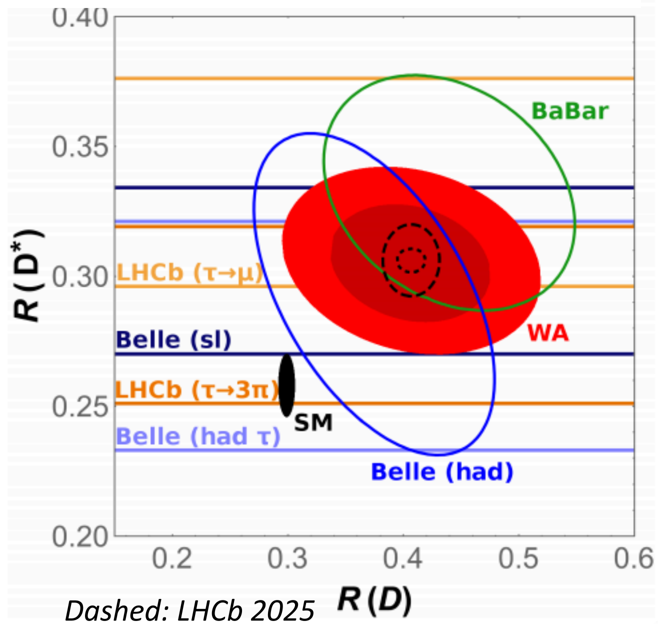
e or μ





LHCb @ HL-LHC
arXiv:1812.07638



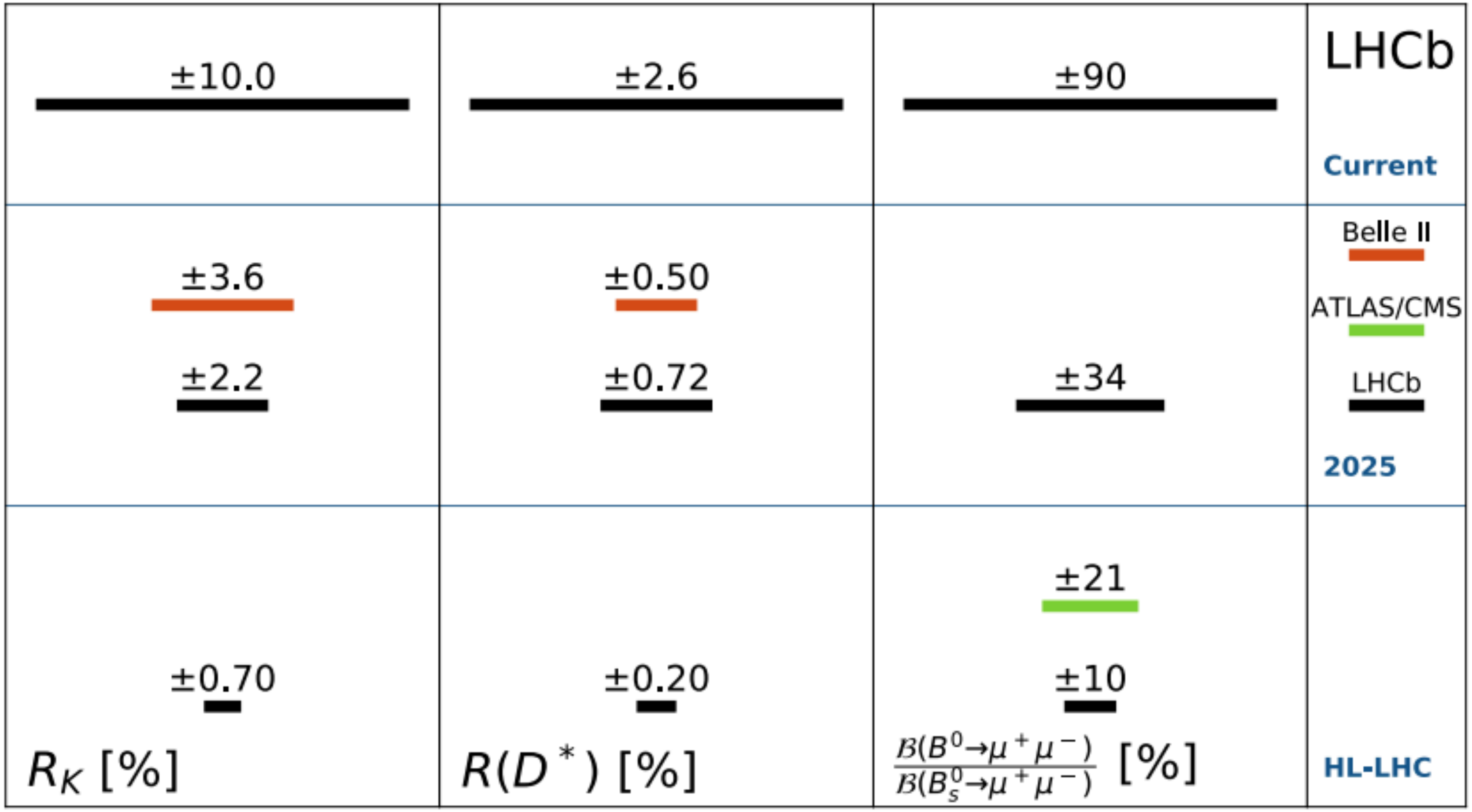


Dashed: LHCb 2025
Dotted: LHCb upgrade II…

OVERVIEW OF RARE AND LFU MEASUREMENTS

Warning: as of mid-2018

arXiv:1808.08865



MANY OTHER MEASUREMENTS!!!

Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [5]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [6]	0.031	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	0.02, 0.02, 0.05
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [7]	4°	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [8]	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [9]	0.011	0.003
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [10]	14 mrad	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [11]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [12]	39 mrad	11 mrad
a_{sl}^s	33×10^{-4} [13]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [14]	3%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [15]	34%	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [15]	8%	2%
$S_{\mu\mu}$	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**			
$R(D^*)$	0.026 [16, 17]	0.0072	0.002
$R(J/\psi)$	0.24 [18]	0.071	0.02
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [19]	1.7×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [20]	4.3×10^{-5}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [21]	3.2×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K3\pi)$ 8.0×10^{-6}

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

Disclaimer: some of the "current" are already outdated

CONCLUSION

Physics case for flavor physics at LHC is stronger than ever.

Crucial element in the particle physics strategy

Capability of working at high luminosity is demonstrated

Healthy competition and complementarity in some measurements among experiments

(and not only within LHC)

Dedicated flavor experiment needed to cover the whole flavor program

Potential for NP discovery and/or indications for future choices of experiments