



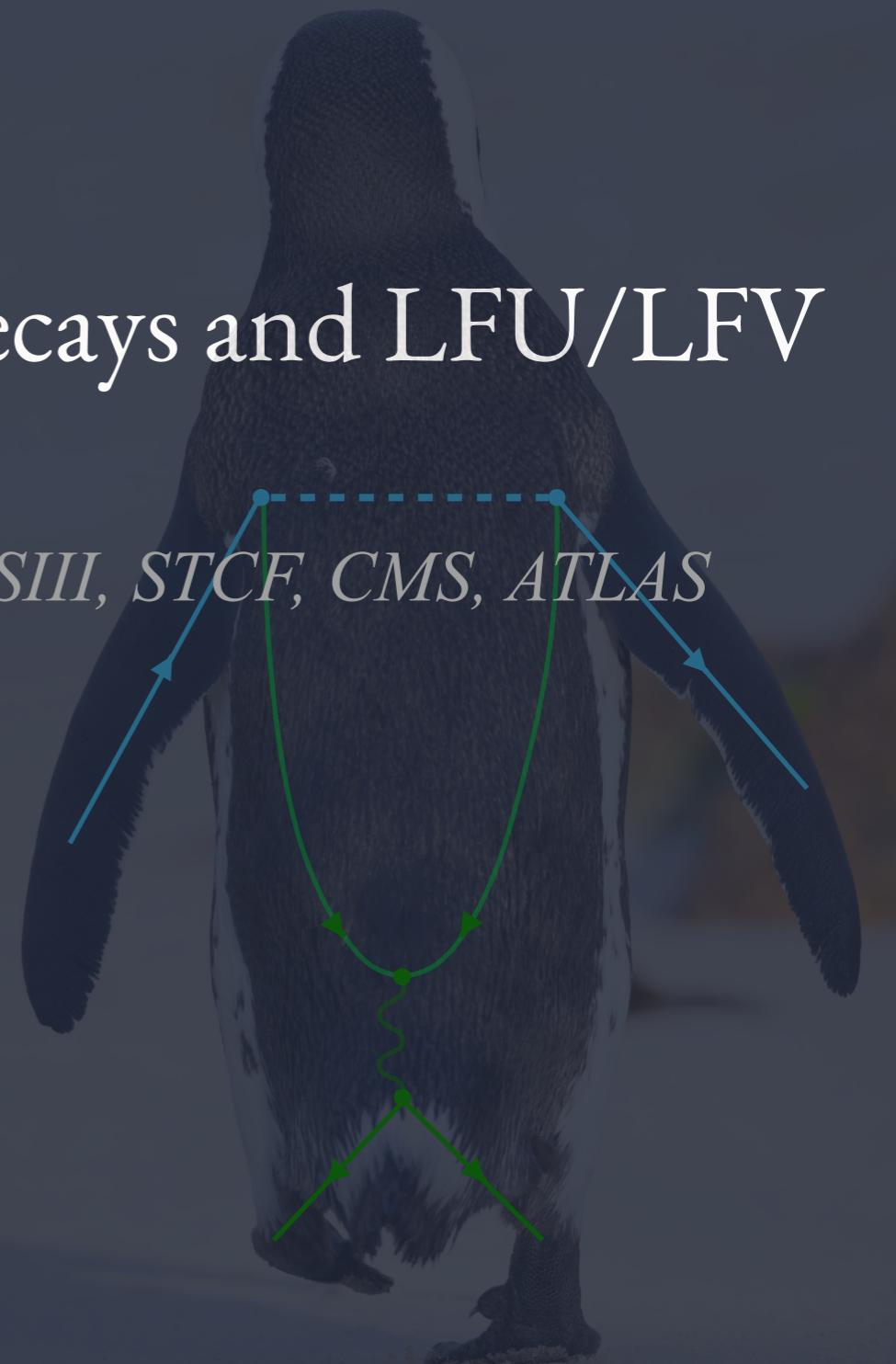
Experimental prospects on rare decays and LFU/LFV

On the complementary of LHCb, Belle 2, BESIII, STCF, CMS, ATLAS

Rafael Silva Coutinho

Syracuse University

Snowmass Rare and Precision Measurements Frontier meeting
May 17th, 2022



RARE DECAYS?

[EXTRAORDINARY, LIMITED, OCCASIONAL, SCARCE, SINGULAR,
STRANGE, SUBTLE, UNCOMMON, UNIQUE, UNLIKELY]*



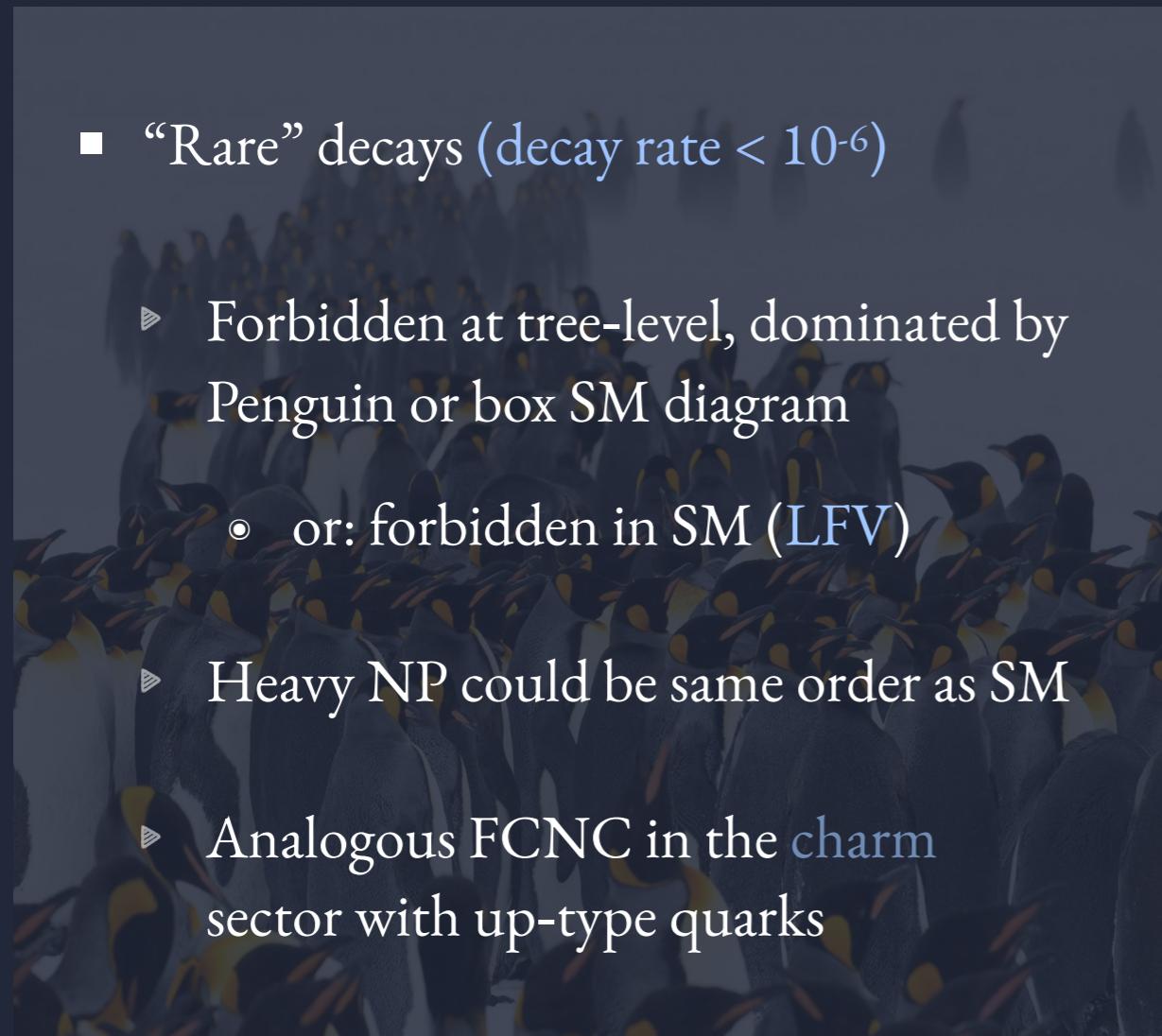
[COMMON, FREQUENT, REGULAR, USUAL, NORMAL,
ORDINARY, TYPICAL, FAMILIAR]



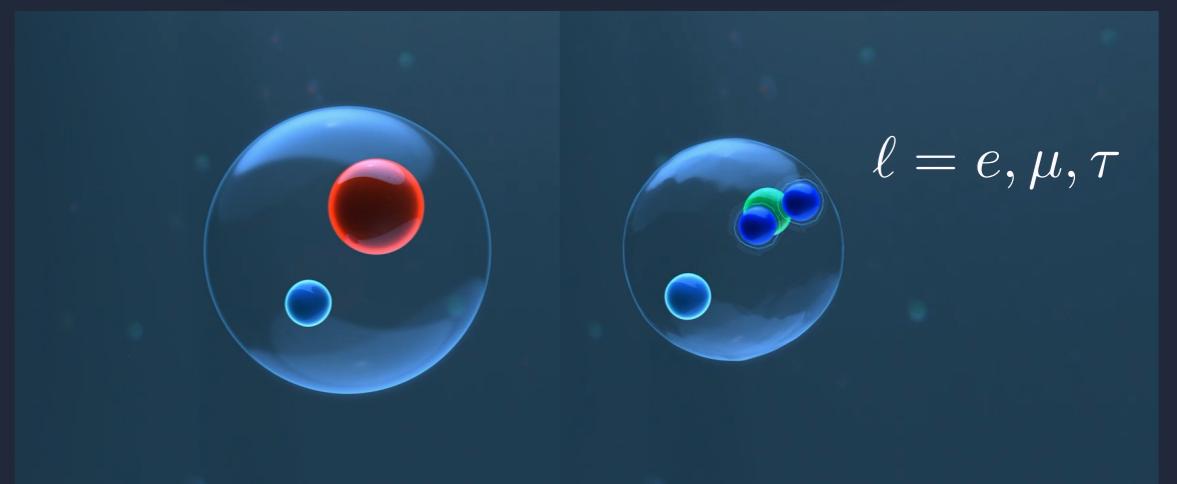
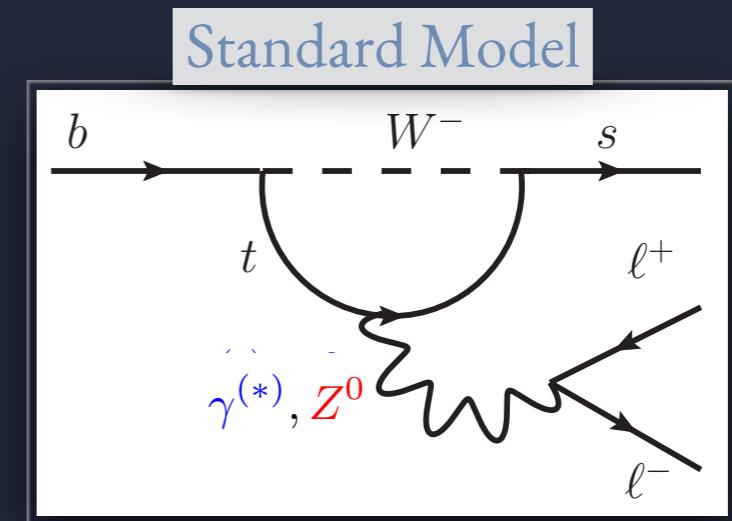
*THESAURUS.COM

RARE DECAYS?

[EXTRAORDINARY, LIMITED, OCCASIONAL, SCARCE, SINGULAR,
STRANGE, SUBTLE, UNCOMMON, UNIQUE, UNLIKELY]



- “Rare” decays (decay rate $< 10^{-6}$)
 - ▶ Forbidden at tree-level, dominated by Penguin or box SM diagram
 - or: forbidden in SM (LFV)
 - ▶ Heavy NP could be same order as SM
 - ▶ Analogous FCNC in the charm sector with up-type quarks



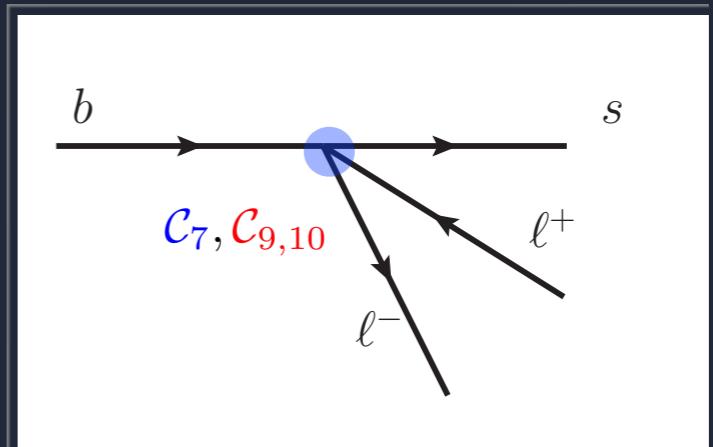
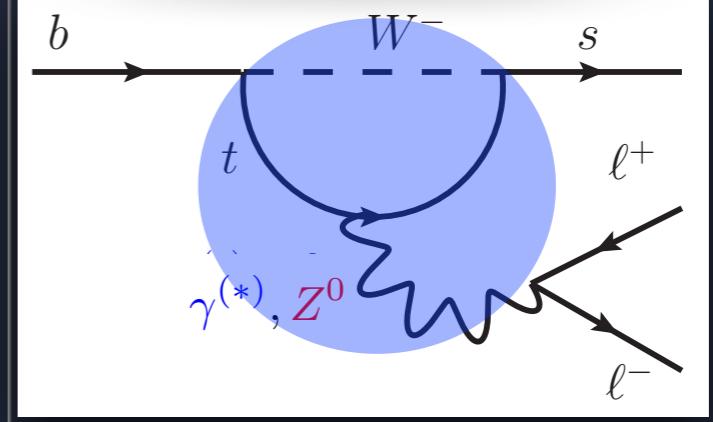
$B^+, B^0, B_s^0, \dots \quad K^+, K^{*0}, \phi, \dots$

RARE DECAYS?

[EXTRAORDINARY, LIMITED, OCCASIONAL, SCARCE, SINGULAR,
STRANGE, SUBTLE, UNCOMMON, UNIQUE, UNLIKELY]

- “Rare” decays (decay rate $< 10^{-6}$)
 - ▶ Forbidden at tree-level, dominated by Penguin or box SM diagram
 - or: forbidden in SM (LFV)
 - ▶ Heavy NP could be same order as SM
 - ▶ Analogous FCNC in the charm sector with up-type quarks

Standard Model

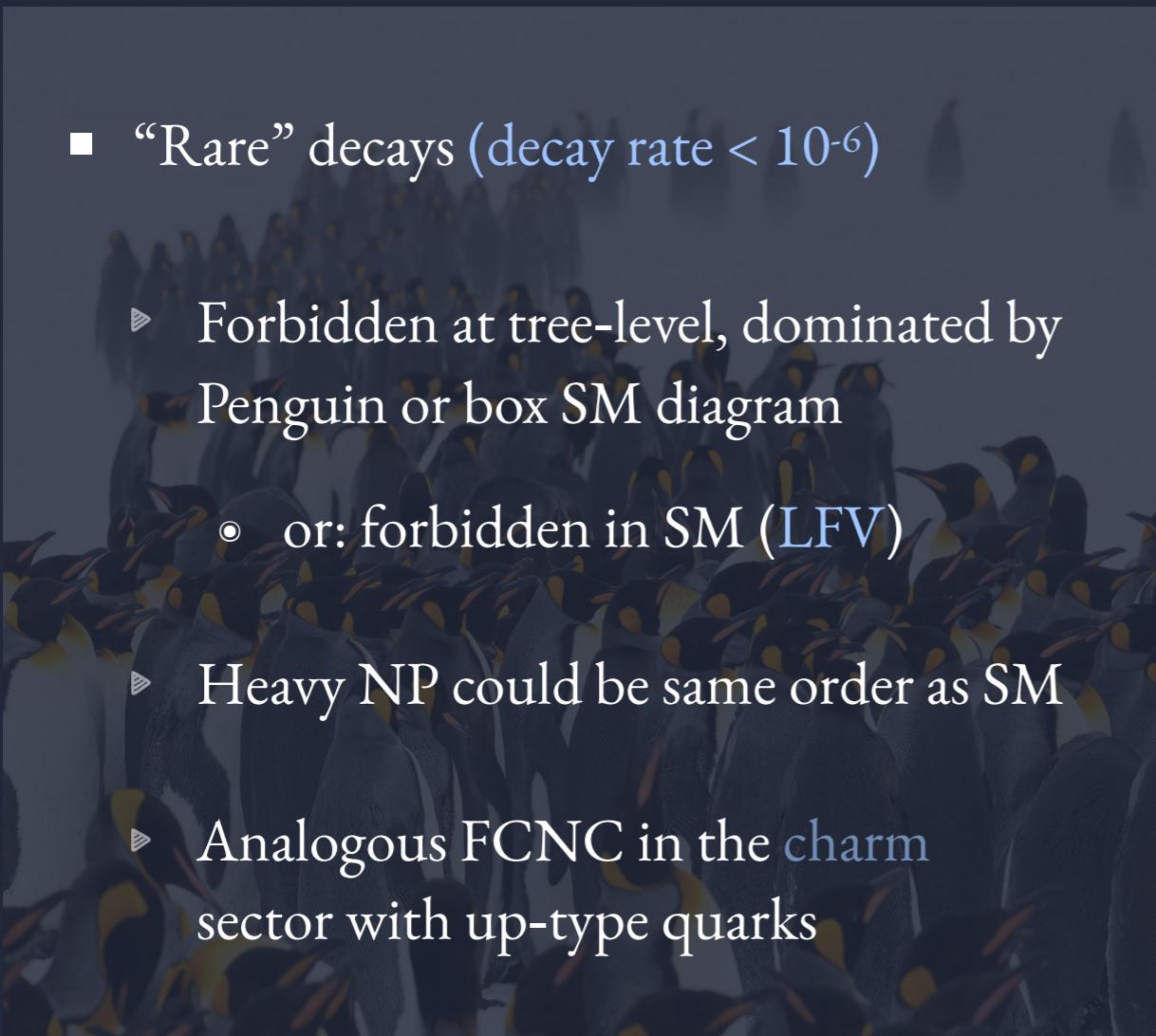


$$B_s^0 \rightarrow \ell^+ \ell^-$$

$$[\mathcal{C}_{10}, \mathcal{C}_{S,P}]$$

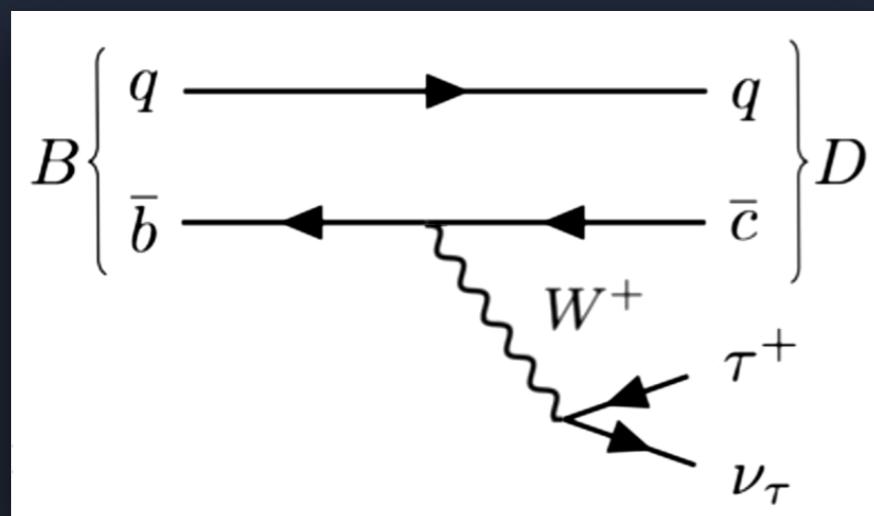
$$b \rightarrow s \ell^+ \ell^-$$

$$[\mathcal{C}_7, \mathcal{C}_{9,10}]$$



RARE DECAYS? no ... but LFU tests!

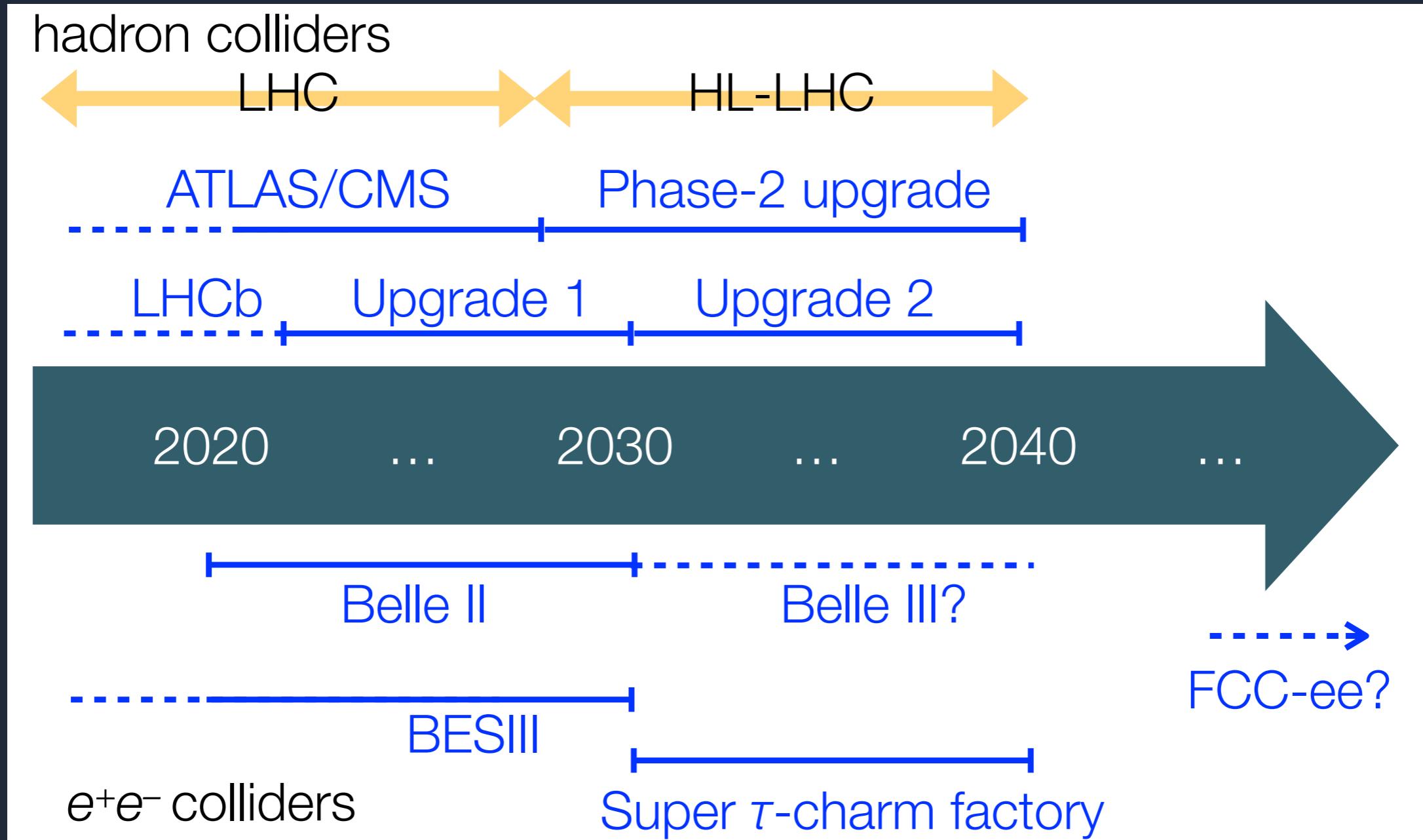
[COMMON, FREQUENT, REGULAR, USUAL, NORMAL,
ORDINARY, TYPICAL, FAMILIAR]



- “Semileptonic” decays (decay rate $\sim 10\%$)
 - ▶ Tree-level transitions
 - ▶ Integrated and differential BFs
 - Sensitive to CKM matrix elements
 - ▶ Precision measurement of neutral meson mixing and CP-violation
 - ▶ Lepton Universality tests



PROSPECTS?



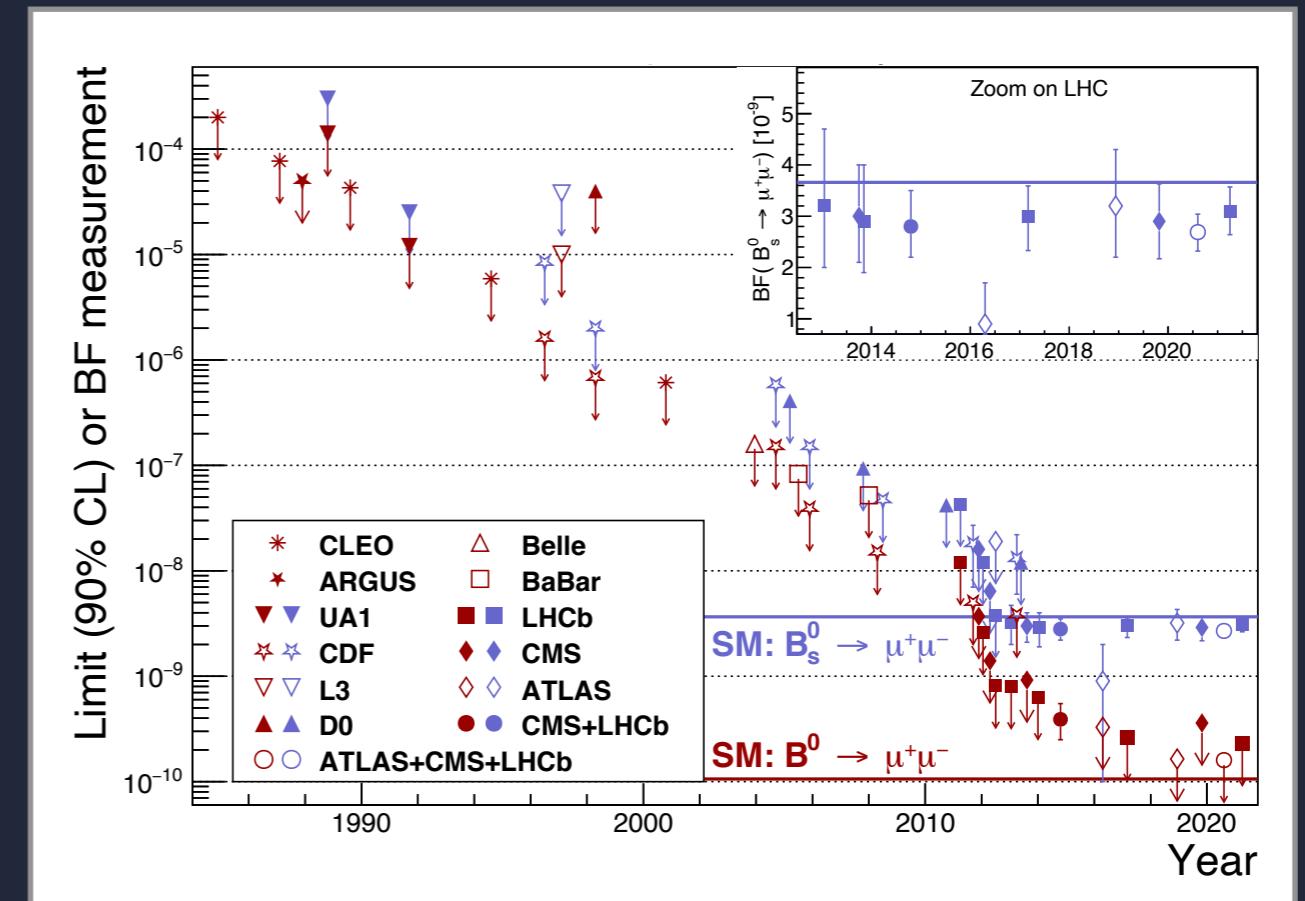
[Stolen from Angelo di Canto and Stefan Meinel talk's]

$$B_{(s)}^0 \rightarrow \ell^+ \ell^-$$



“The” very rare decay, FCNC and helicity suppressed in SM

A 30 years endeavour



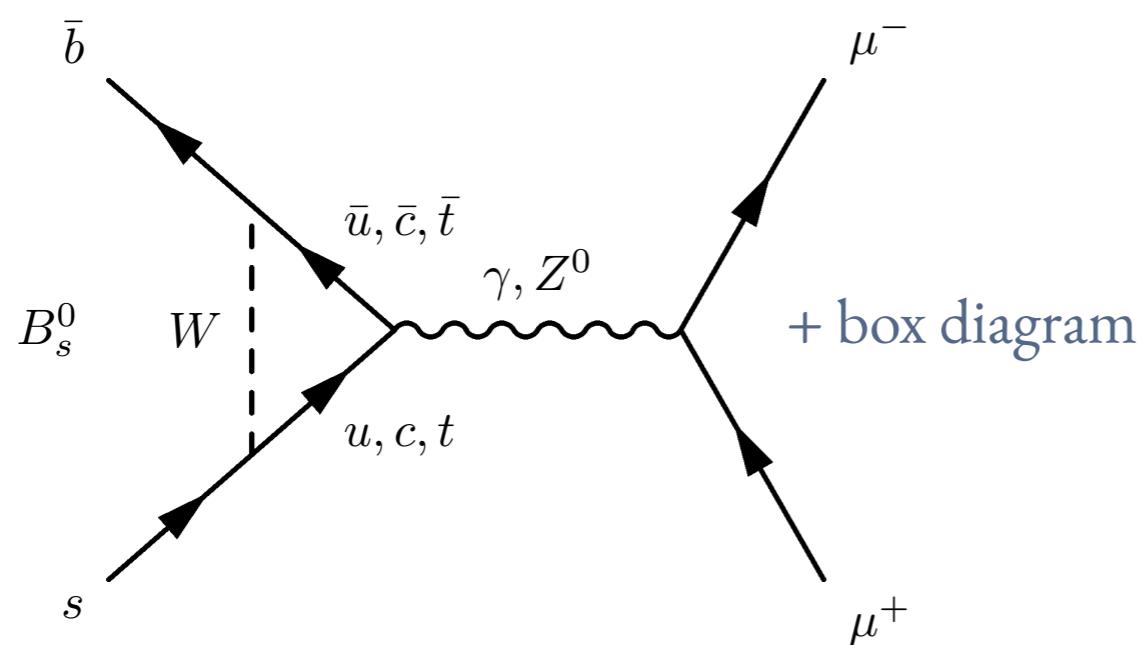
The “golden” channel $B^0_{(s)} \rightarrow \mu^+ \mu^-$

Clean theoretical predictions

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]



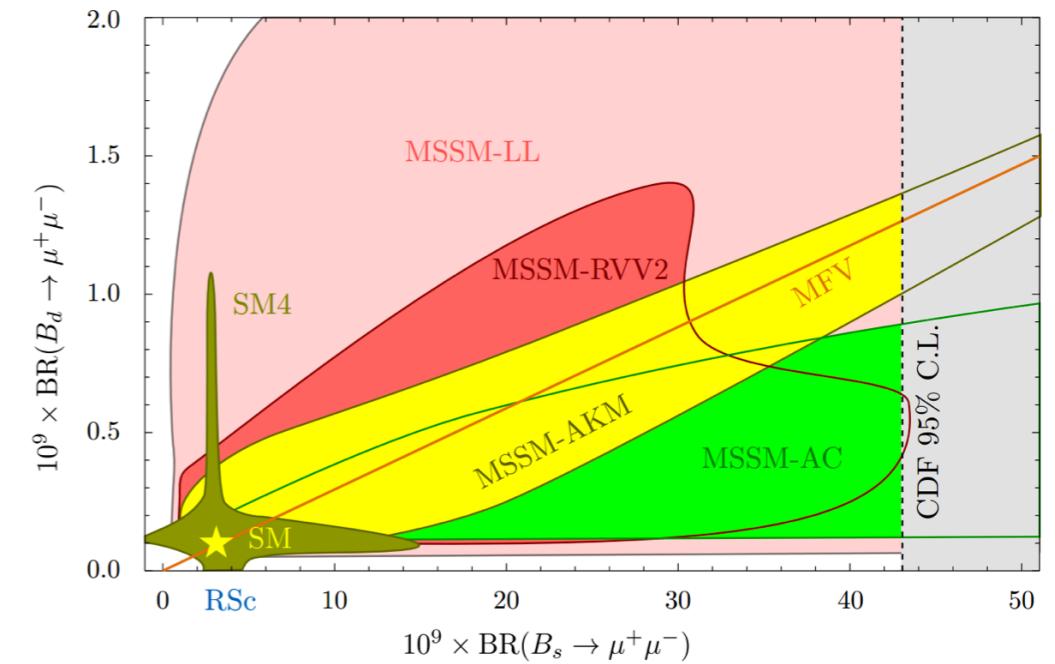
1. BRANCHING FRACTION

$$B \propto |V_{tb} V_{tq}|^2 \left[\left(1 - \frac{4m_\mu^2}{M_B^2}\right) |C_S - C'_S|^2 + |C_P - C'_P|^2 + \frac{2m_\mu}{M_B} (C_{10} - C'_{10})|^2 \right]$$

2. RATIO OF BRANCHING FRACTIONS

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}} \left(\frac{f_{B_d}}{f_{B_s}} \right)^2 \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{m_{B_d} \sqrt{1 - \frac{4m_\mu^2}{m_{B_d}^2}}}{m_{B_s} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}}$$

[Nuovo Cim.C 035N1 (2012) 249]



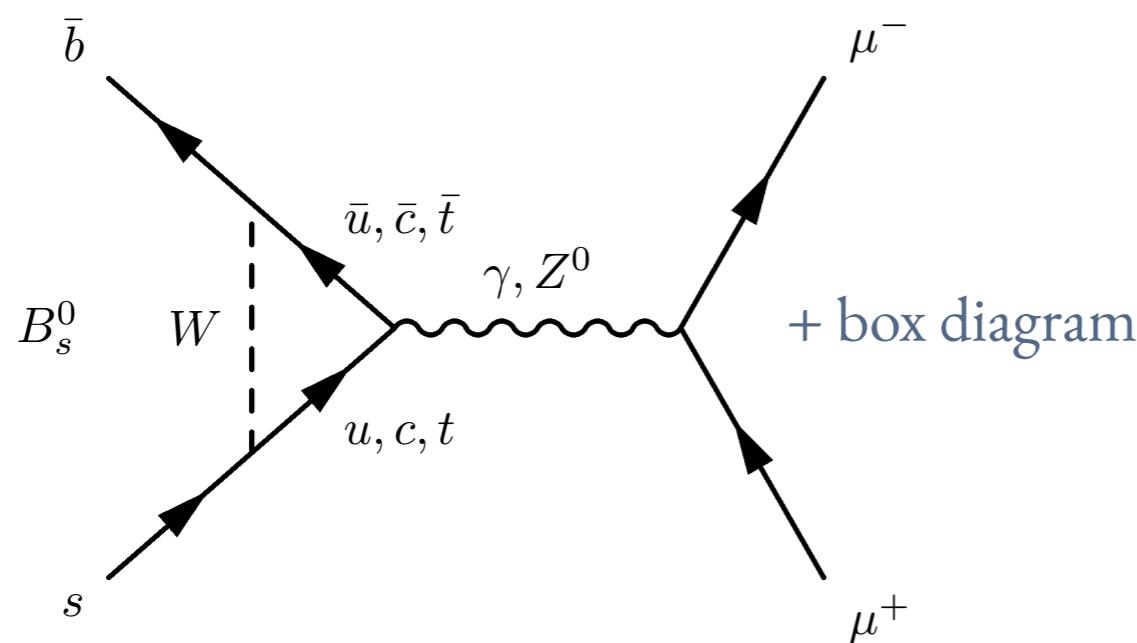
The “golden” channel $B^0_{(s)} \rightarrow \mu^+ \mu^-$

Clean theoretical predictions

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]



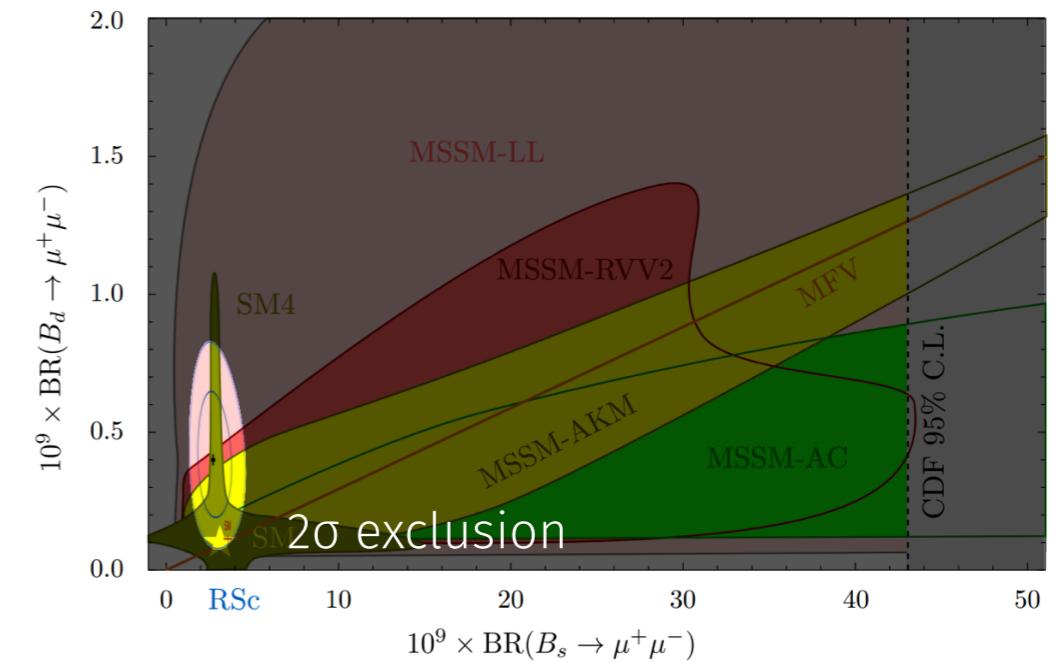
1. BRANCHING FRACTION

$$B \propto |V_{tb} V_{tq}|^2 \left[\left(1 - \frac{4m_\mu^2}{M_B^2}\right) |\mathcal{C}_S - \mathcal{C}'_S|^2 + |\mathcal{C}_P - \mathcal{C}'_P|^2 + \frac{2m_\mu}{M_B} (\mathcal{C}_{10} - \mathcal{C}'_{10})|^2 \right]$$

2. RATIO OF BRANCHING FRACTIONS

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}} \left(\frac{\mathcal{f}_{B_d}}{\mathcal{f}_{B_s}} \right)^2 \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{m_{B_d} \sqrt{1 - \frac{4m_\mu^2}{m_{B_d}^2}}}{m_{B_s} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}}$$

[Nuovo Cim.C 035N1 (2012) 249]



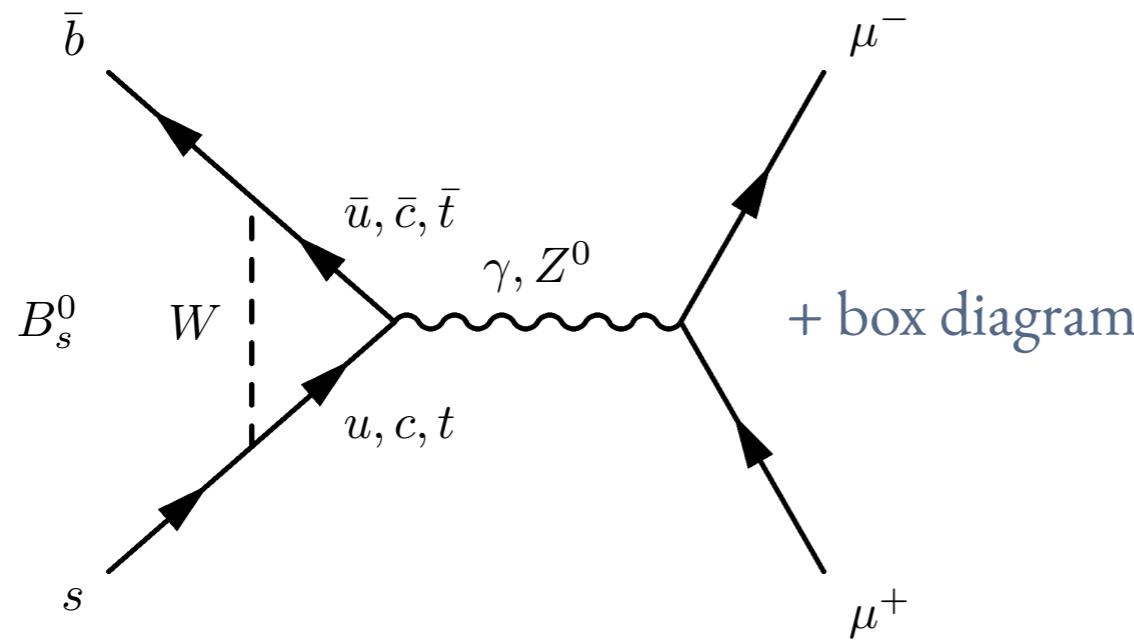
The “golden” channel $B^0_{(s)} \rightarrow \mu^+ \mu^-$

Clean theoretical predictions

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

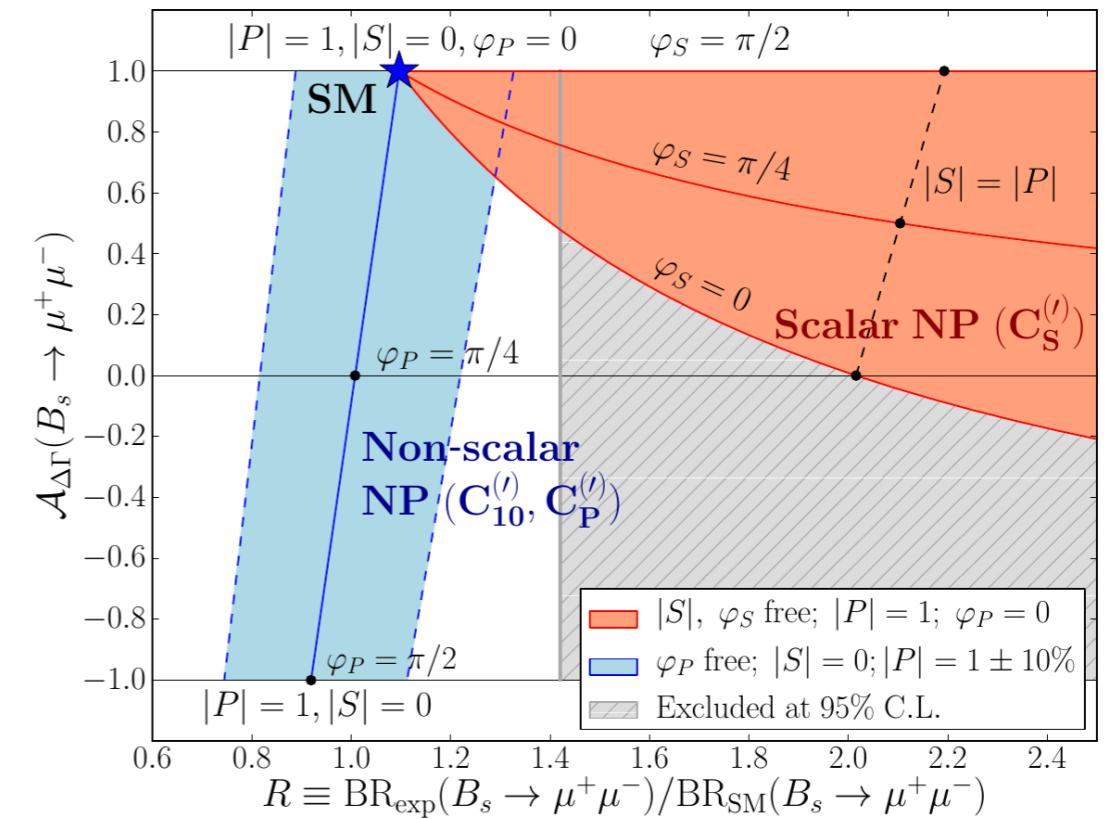
[JHEP 10 (2019) 232]



3. EFFECTIVE LIFETIME

$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{(1 - y_s^2)} \frac{1 + 2y_s \mathcal{A}_{\Delta\Gamma} + y_s^2}{1 + y_s \mathcal{A}_{\Delta\Gamma}}$$

[PRL 109 (2012) 041801]



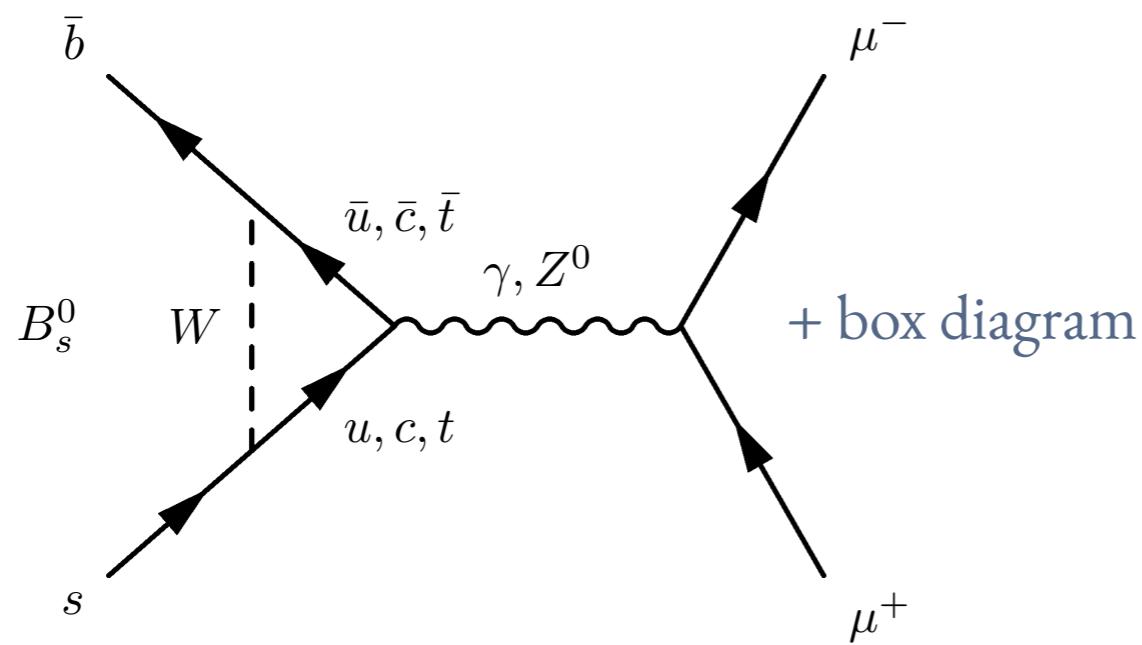
The “golden” channel $B^0_{(s)} \rightarrow \mu^+ \mu^-$

Clean theoretical predictions

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

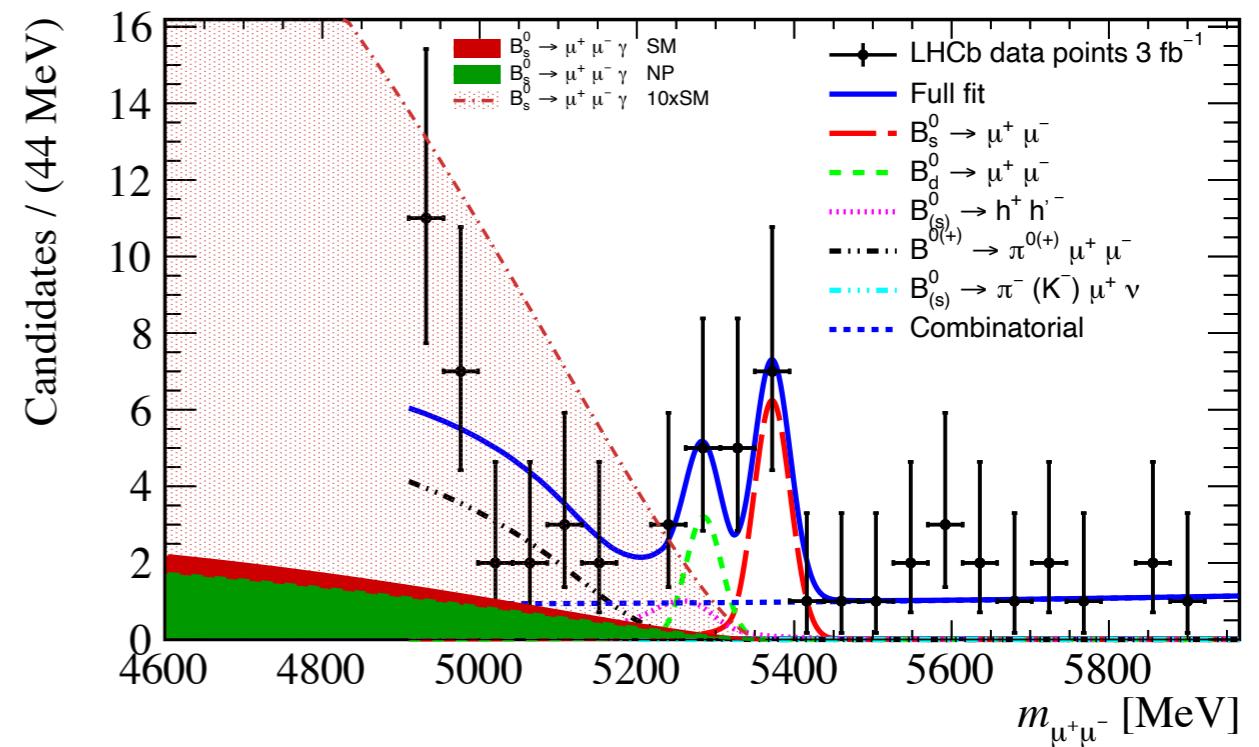
[JHEP 10 (2019) 232]



4. RADIATIVE DECAY $B^0_s \rightarrow \mu^+ \mu^- \gamma$

Not helicity suppressed and also sensitive to C_9

[Phys.Lett.B 768 (2017) 163-167]



The “golden” channel $B^0_{(s)} \rightarrow \mu^+ \mu^-$

[LHCb-CONF-2020-002, CMS PAS BPH-20-003, ATLAS-CONF-2020-049]

Combined LHC results [today]



$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.5^{+1.2}_{-1.0} {}^{+0.2}_{-0.1}) \times 10^{-10}$$

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+0.7}_{-0.6} \pm 0.2) \times 10^{-9}$$

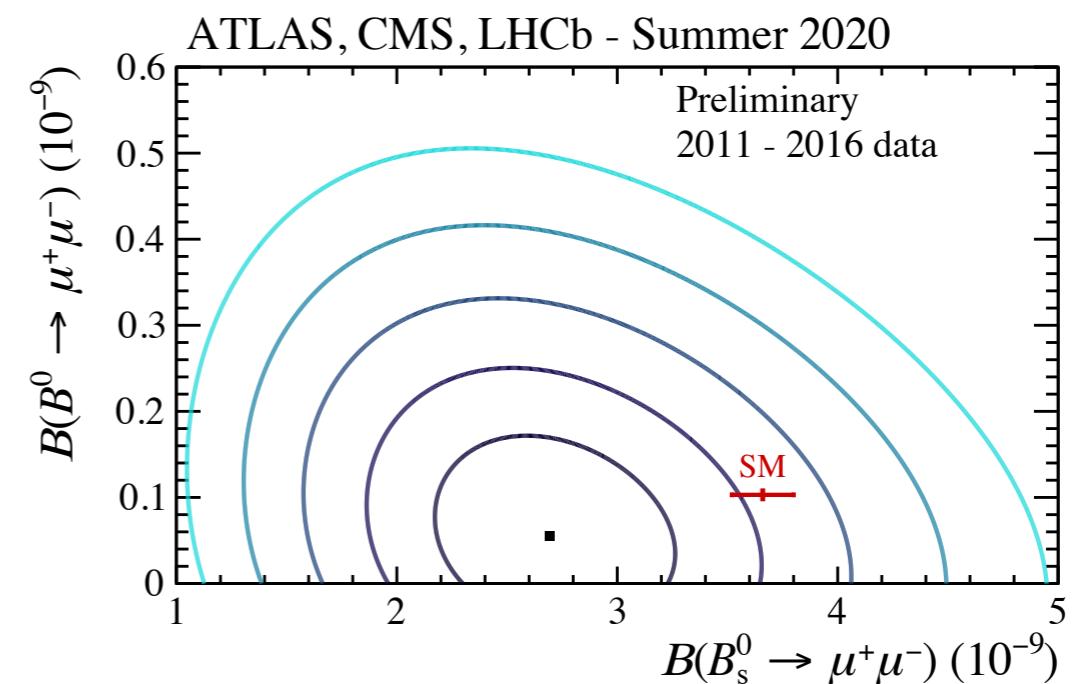
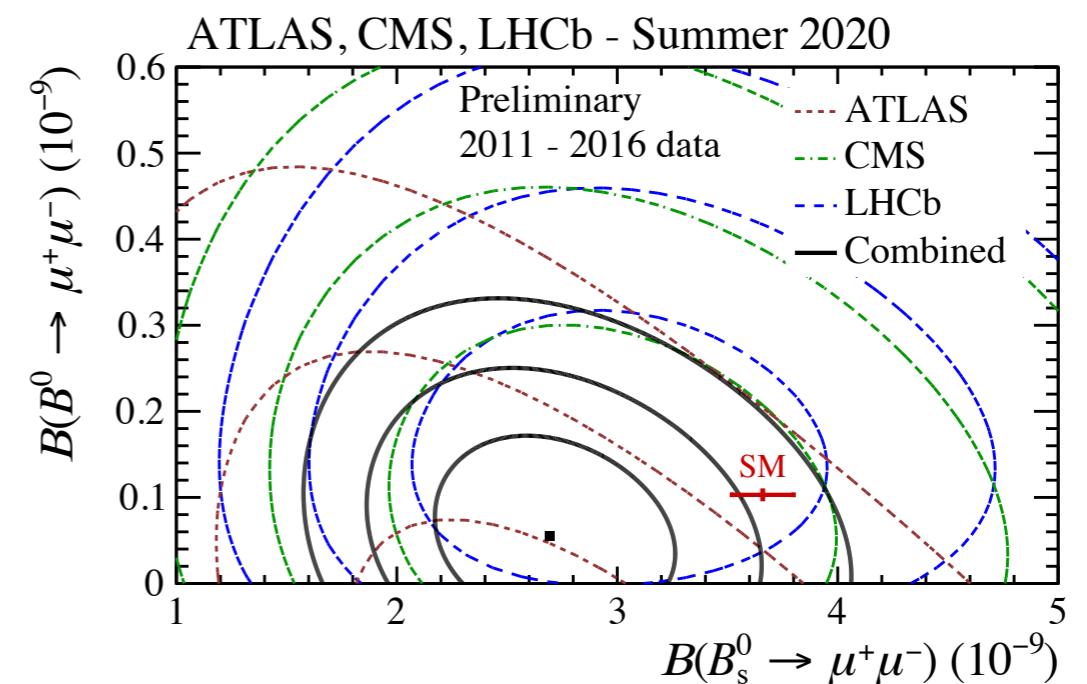
$$B(B^0 \rightarrow \mu^+ \mu^-) = (0.8^{+1.4}_{-1.3}) \times 10^{-10}$$

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$

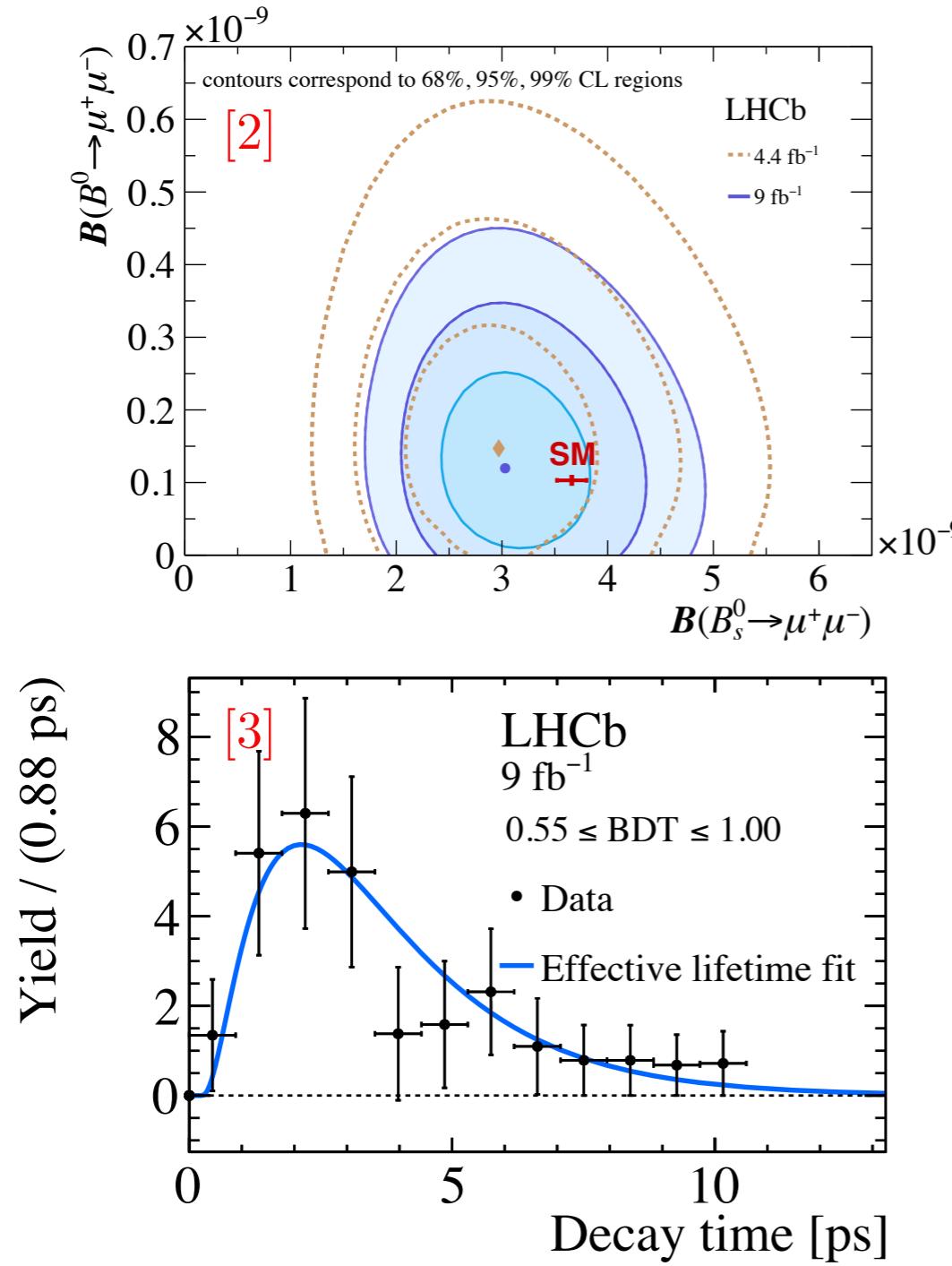
$$B(B^0 \rightarrow \mu^+ \mu^-) = (-1.9 \pm 1.6) \times 10^{-10}$$



LHCb+ATLAS+CMS results on BR
at 2.1σ below SM in the 2D plane

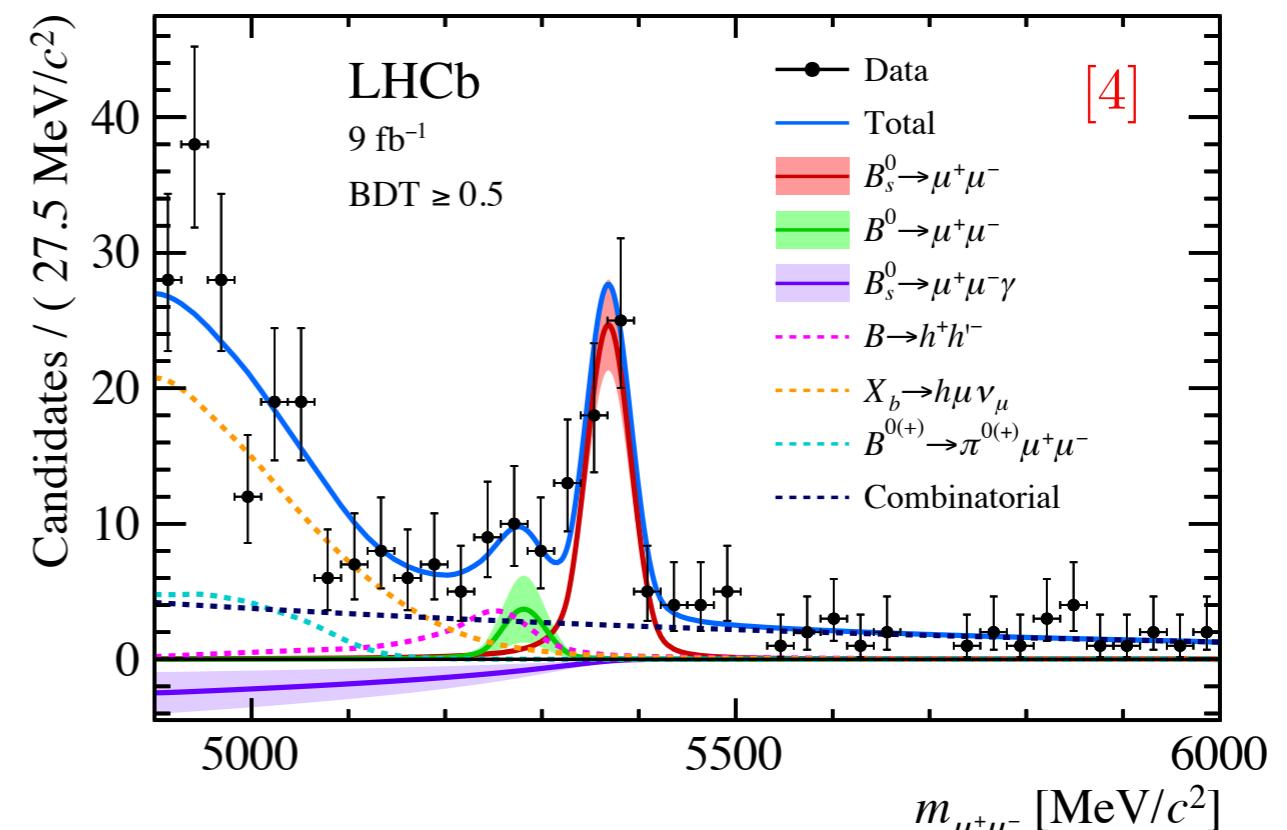


The “golden” channel $B^0_{(s)} \rightarrow \mu^+ \mu^-$



[LHCb, PRL 128 (2022) 4, 041801]

Exploring the full information on data



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)_{m_{\mu\mu} > 4.9 \text{ GeV}} < 2.0 \times 10^{-9}$$

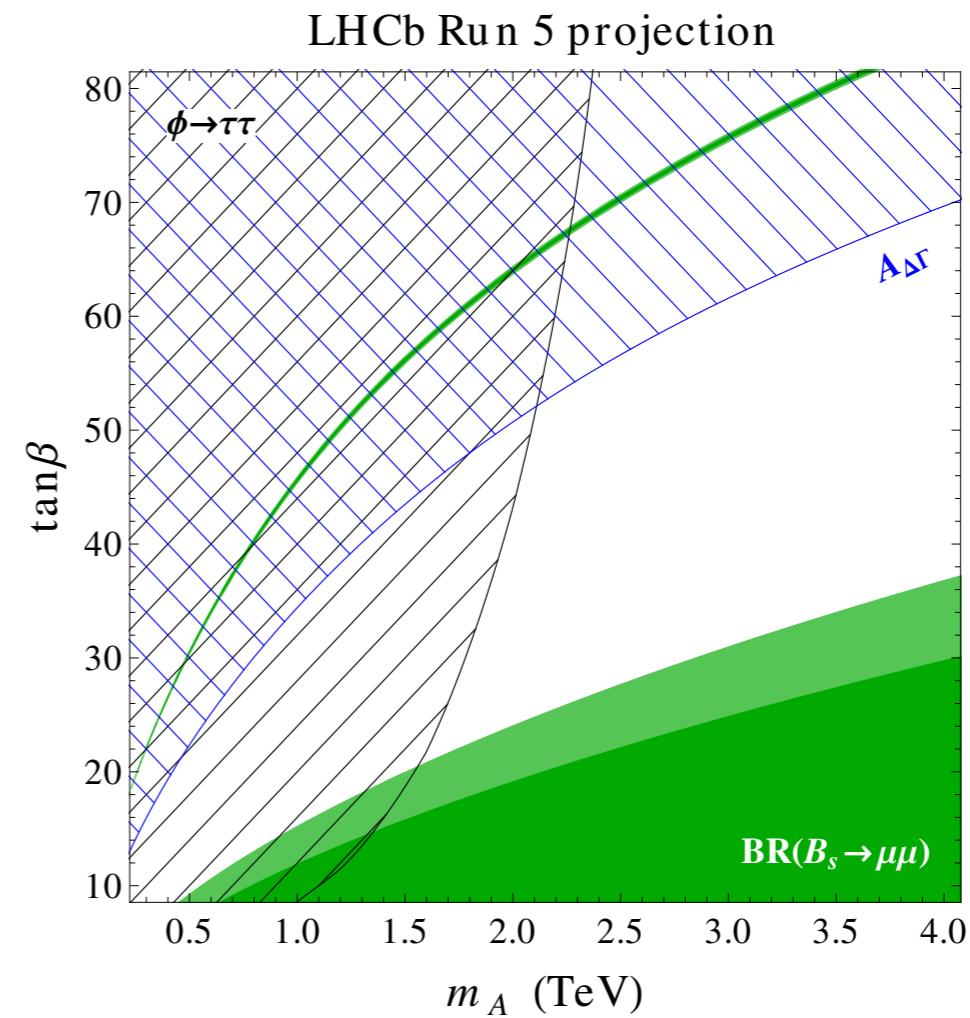
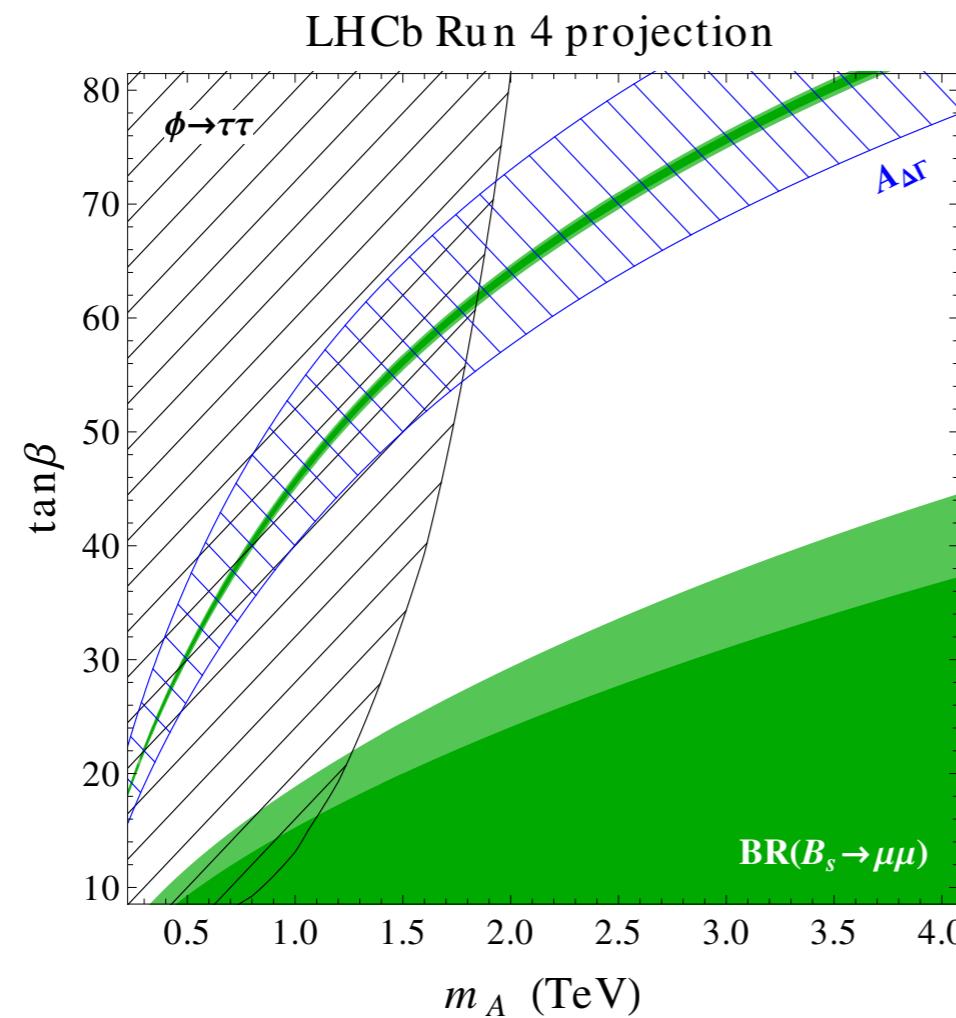
Prospects for $B^0_{(s)} \rightarrow \mu^+ \mu^-$

[LHCb-PUB-2018-009, ATL-PHYS-PUB-2018-005, CMS PAS FTR-14-013/-015]

Large Hadron Collider (LHC)															HL-LHC					
Run 1		LS1			Run 2				LS2		Run 3			LS3		Run 4 - 5...				
7 TeV		8 TeV			13 TeV						13/14 TeV									
2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	...2038				
LHCb	current								9fb ⁻¹				23fb ⁻¹				300fb ⁻¹			
	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$\pm 0.6^{+0.3}_{-0.2} \times 10^{-9}$					$+0.46^{+0.15}_{-0.43} \times 10^{-9}$				$\pm 0.30 \times 10^{-9}$				$\pm 0.16 \times 10^{-9}$					
	$\frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)}$	90 %					70 %				34 %				10 %					
CMS	$\tau_{\mu^+ \mu^-}$ (ps)	$\pm 0.44 \pm 0.05$					$\pm 0.29 \pm 0.03$				± 0.16				± 0.04					
	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$^{+0.7}_{-0.6} \pm 0.2 \times 10^{-9}$					150fb ⁻¹				300fb ⁻¹				3000fb ⁻¹					
	$\frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)}$										$\pm(0.43 - 0.46) \times 10^{-9}$				$\pm(0.39) \times 10^{-9}$					
ATLAS	$\tau_{\mu^+ \mu^-}$ (ps)	$^{+0.61}_{-0.44}$									50 %				21 %					
	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$^{+0.8}_{-0.7} \times 10^{-9}$					$\pm 0.83 \times 10^{-9}$								$\pm(0.46 - 0.55) \times 10^{-9}$					
	$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	$< 2.1 \times 10^{-10}$					$\pm 1.43 \times 10^{-10}$								$\pm(0.28 - 0.54) \times 10^{-10}$					

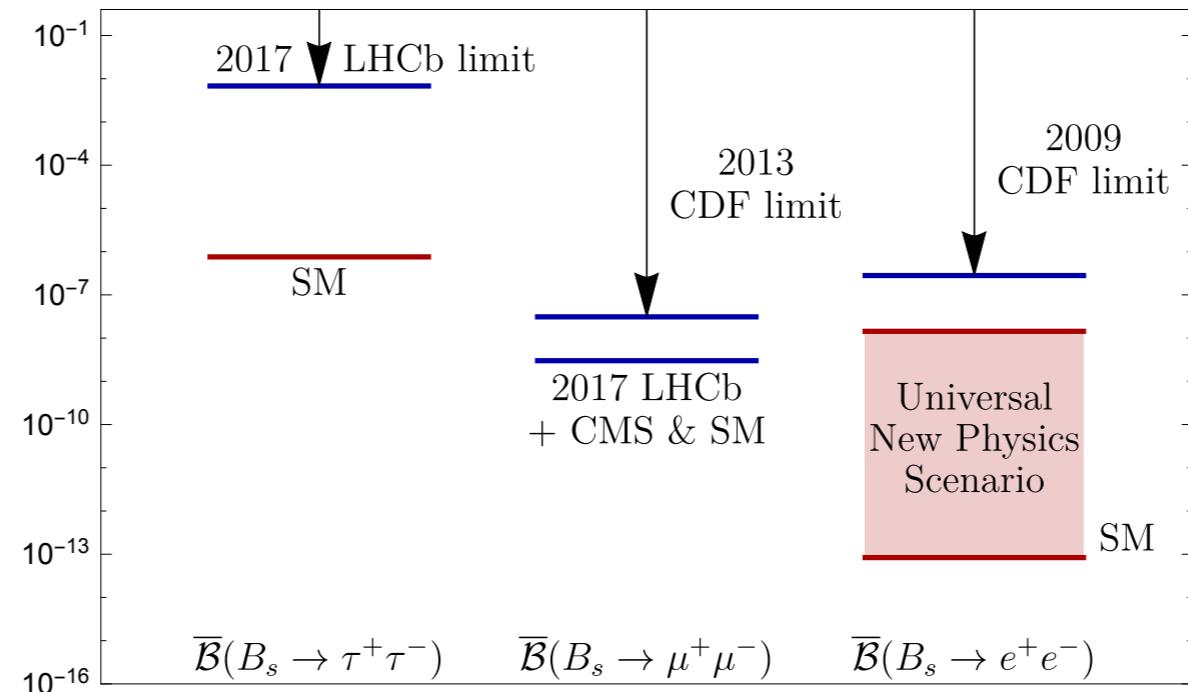
Prospects for $B^0_{(s)} \rightarrow \mu^+ \mu^-$

[JHEP 05 (2017) 076]

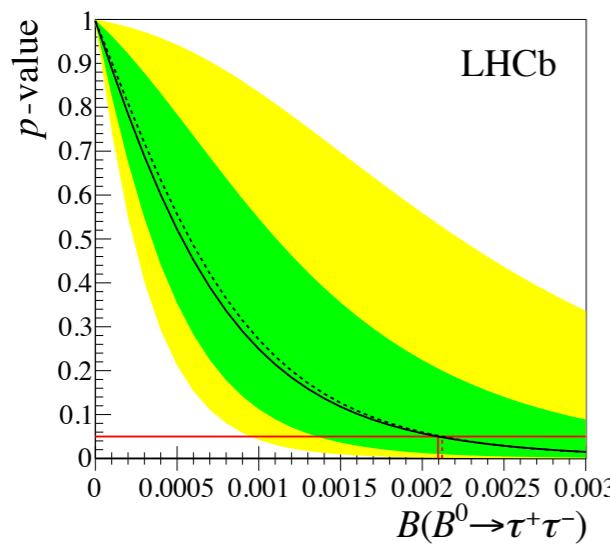


Prospects for $B^0_{(s)} \rightarrow l^+l^-$

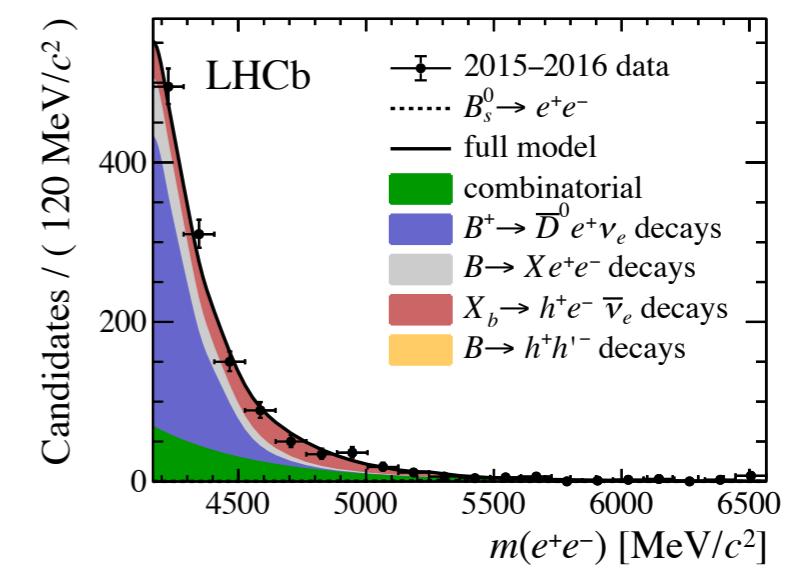
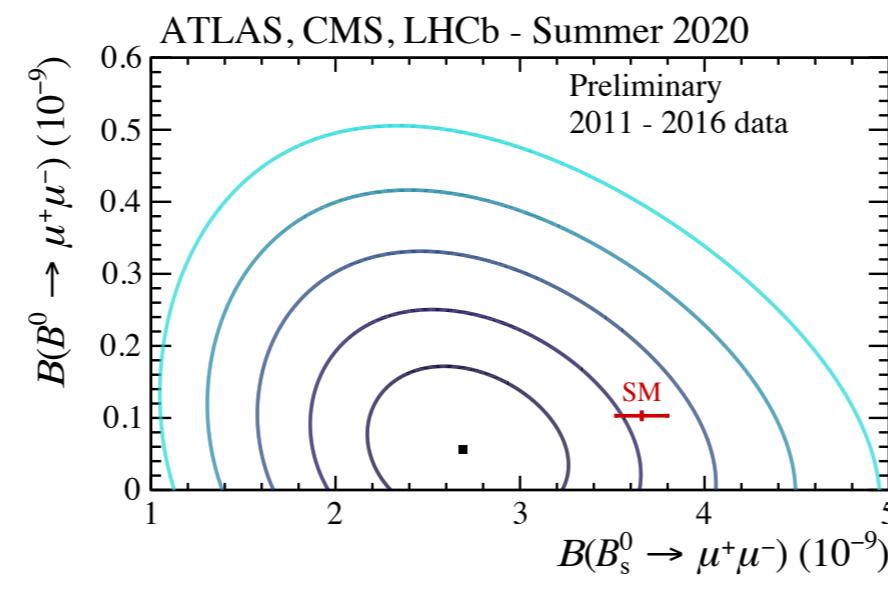
[JHEP 05 (2017) 156]



[PRL 118 (2017) 251802]



[PRL 124 (2020) 211802]

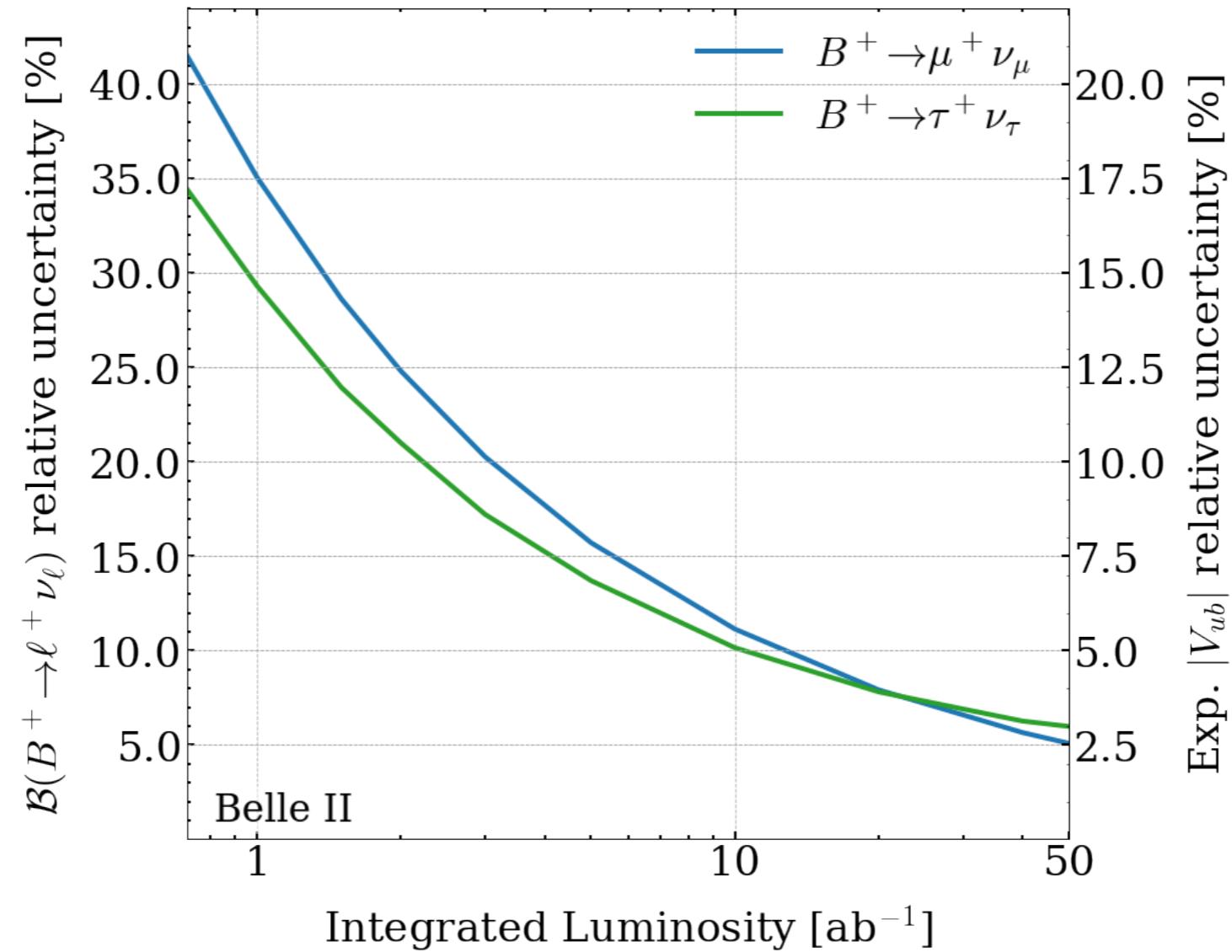


Prospects for $B^+ \rightarrow l\nu$



[JHEP 05 (2017) 156]

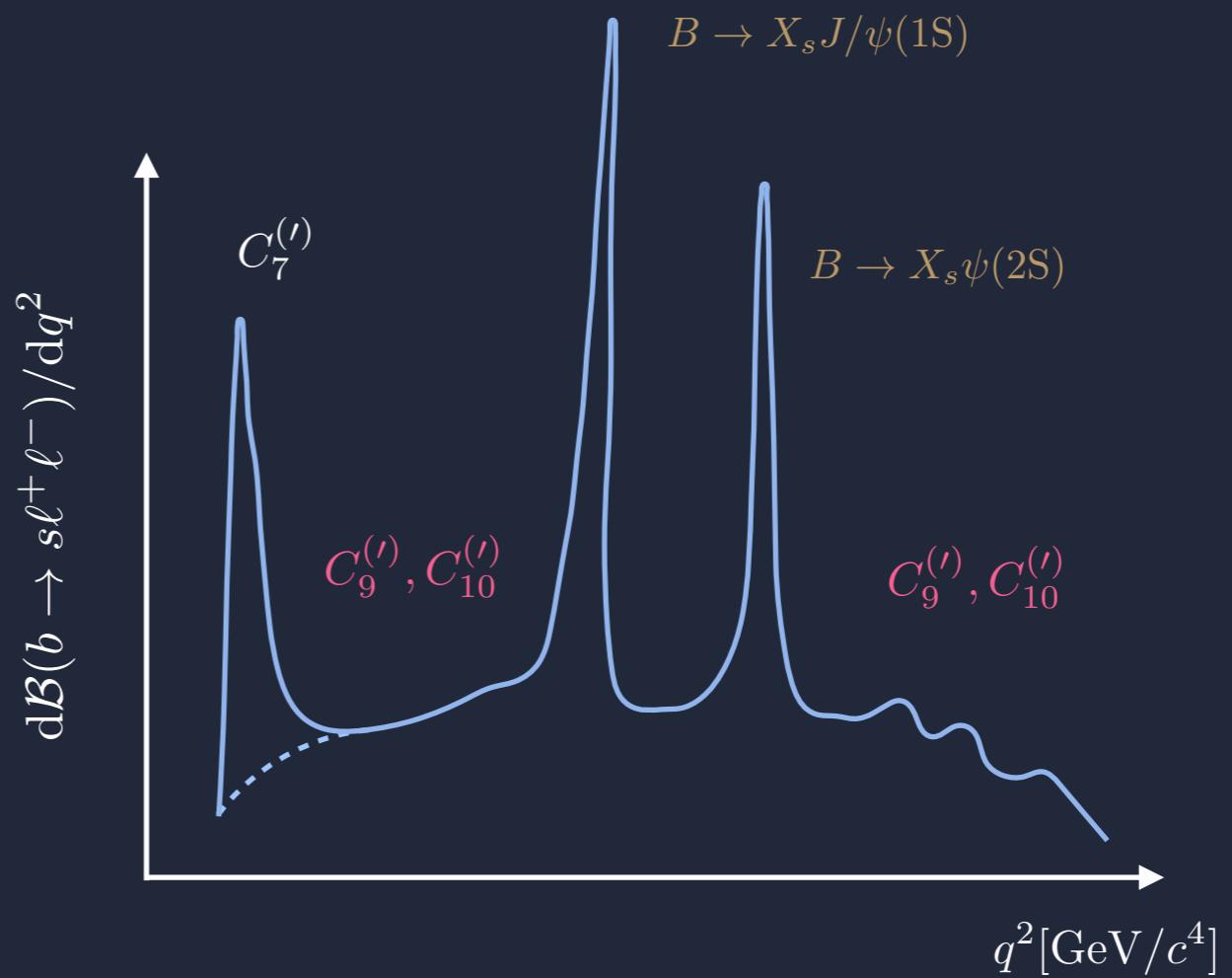
Unique opportunity for the Belle II experiment (with missing energy)



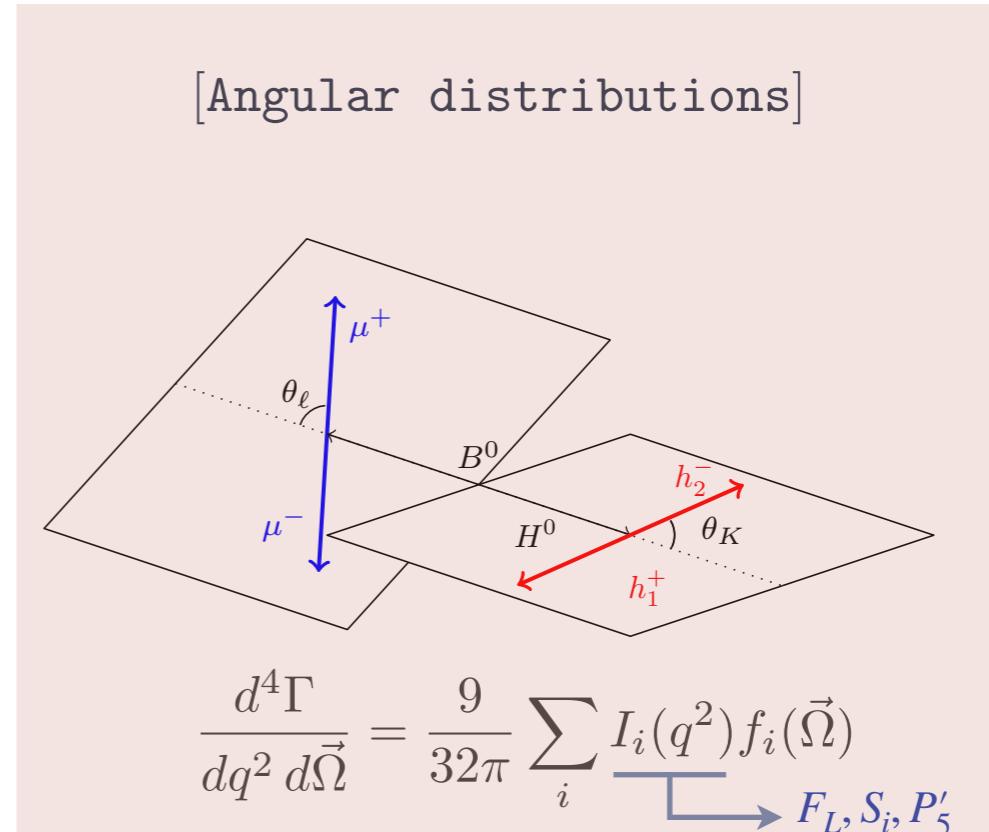
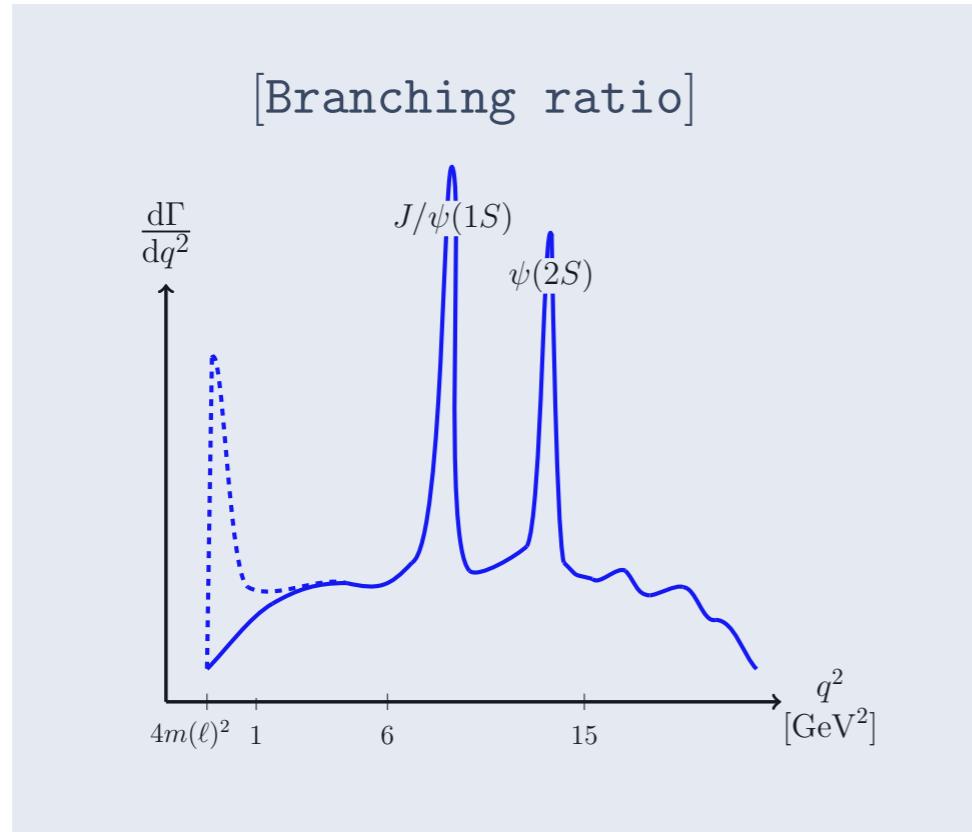
$b \rightarrow s\ell^+\ell^-$



The branching ratio/angular “anomalies”



The *flavour anomalies* in $b \rightarrow s l^+l^-$



Higher theory uncertainties

$$B^0 \rightarrow K^{*0}[K\pi]\mu^+\mu^-$$

spin-1

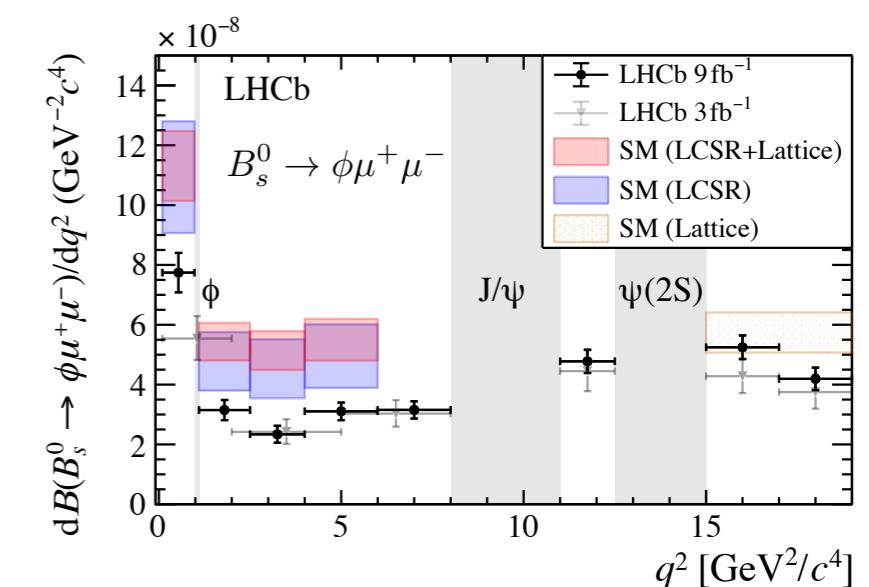
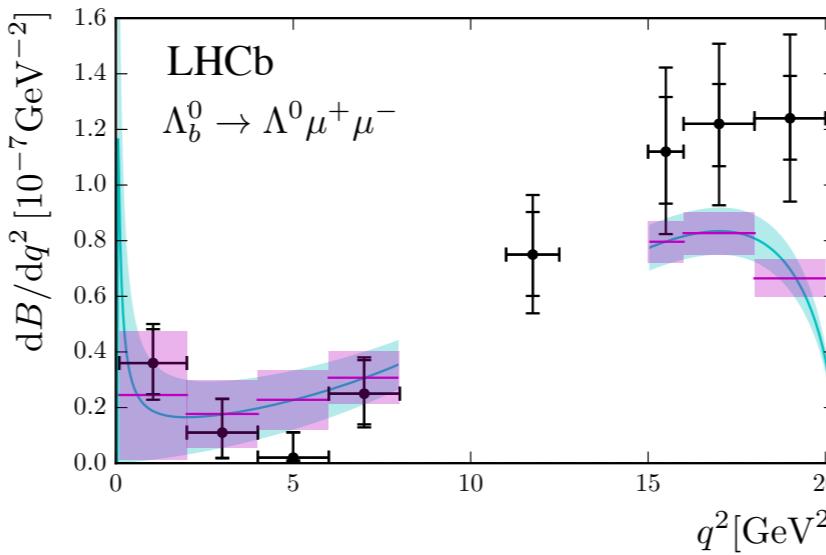
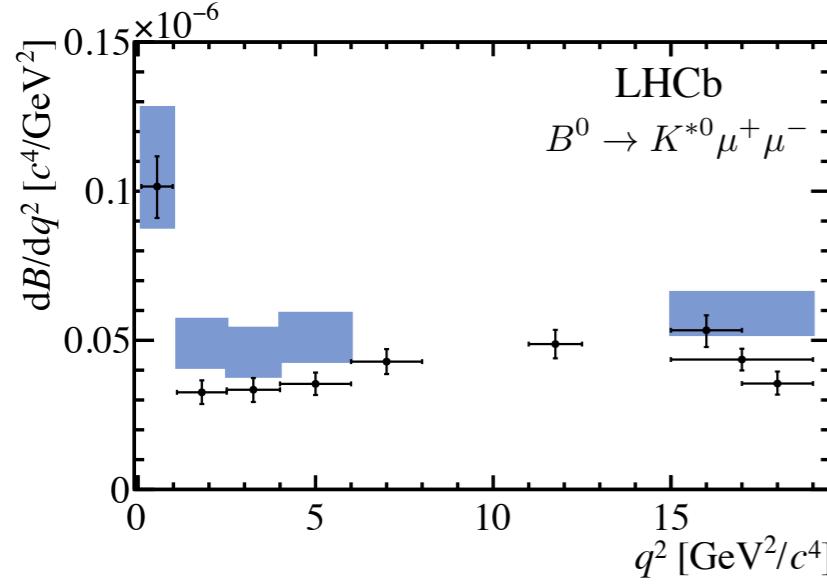
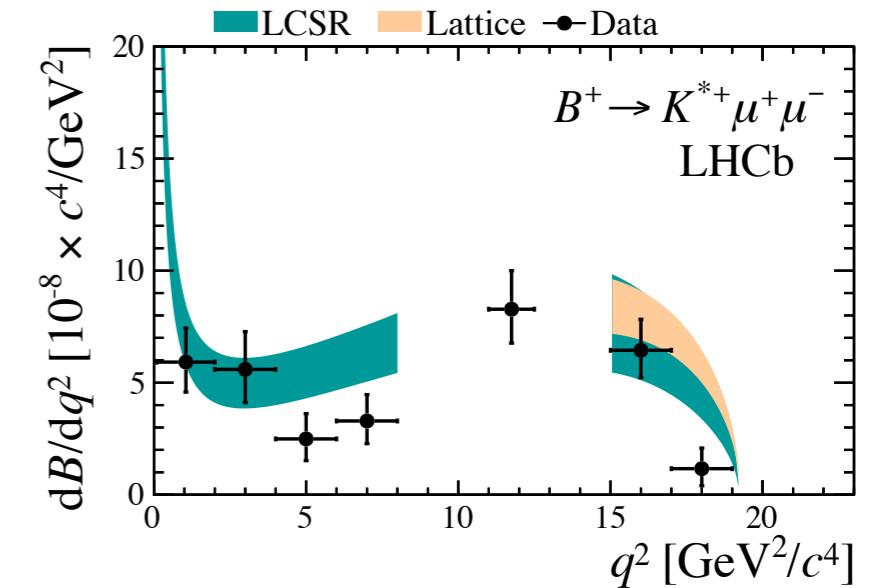
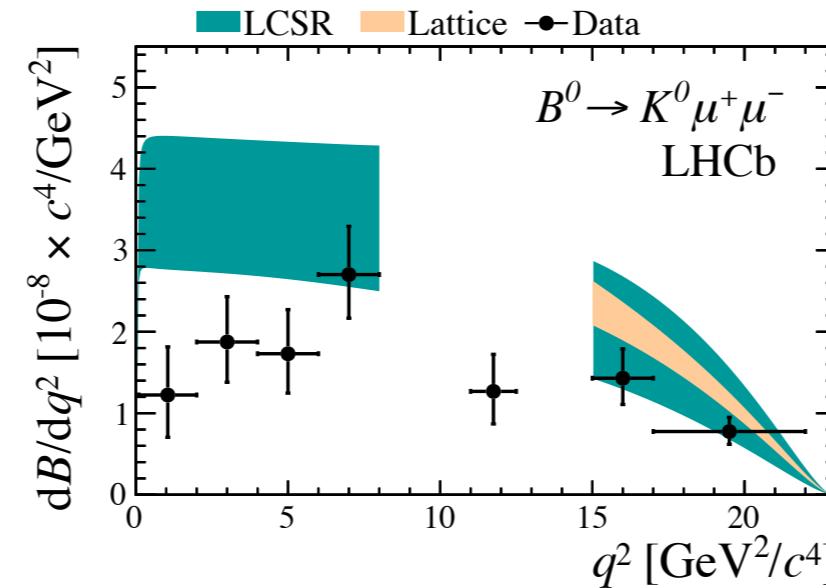
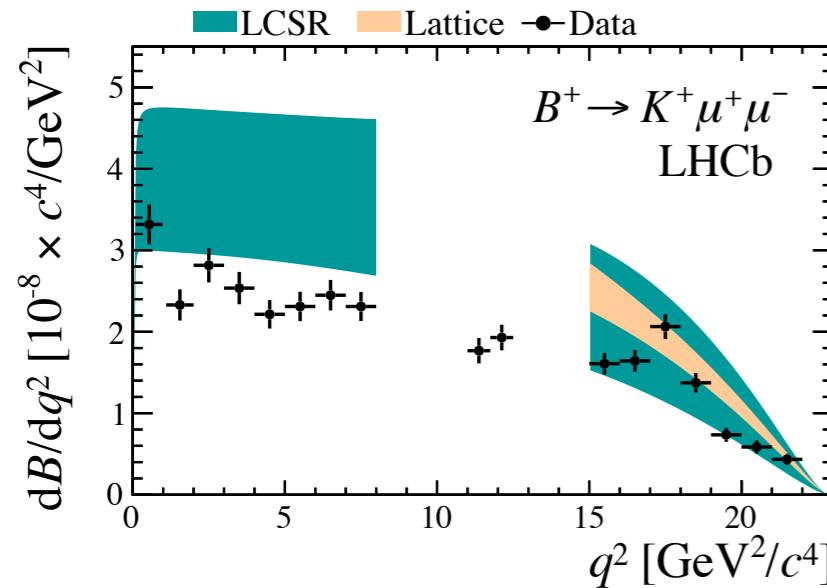
Lower theory uncertainties

$$\mathcal{A}_\lambda^{(\ell) L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$b \rightarrow s\mu^+\mu^-$ decay rates



[LHCb, JHEP 06 (2014) 133, 11 (2016) 047, 06 (2015) 115, PRL 127 (2021) 151801]



$b \rightarrow s\mu\mu$ decay rates systematically below the SM predictions

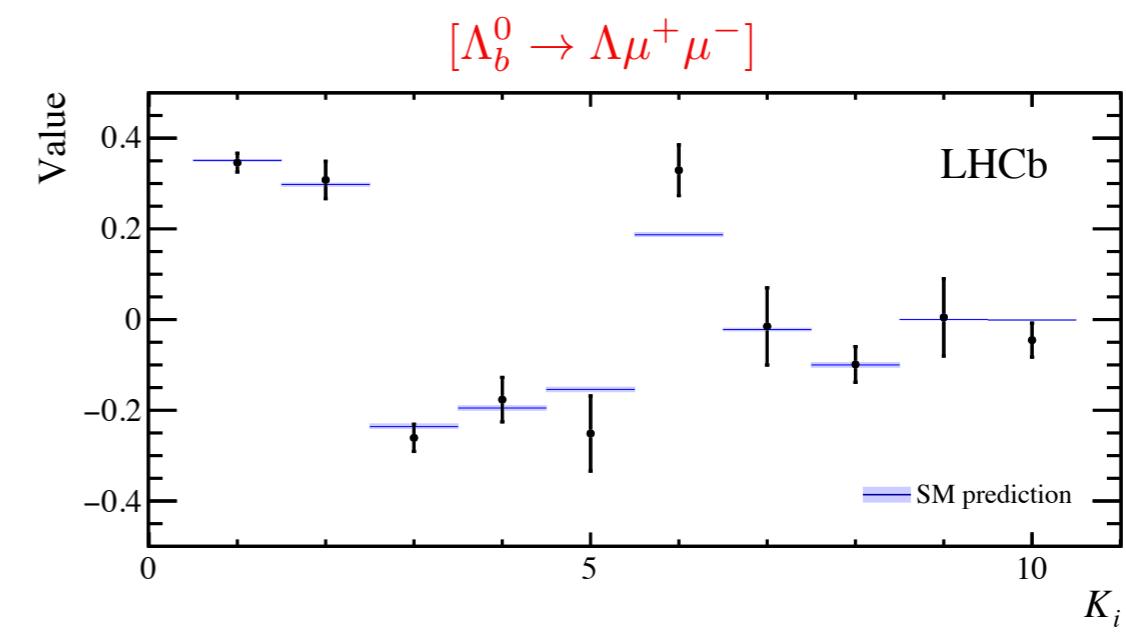
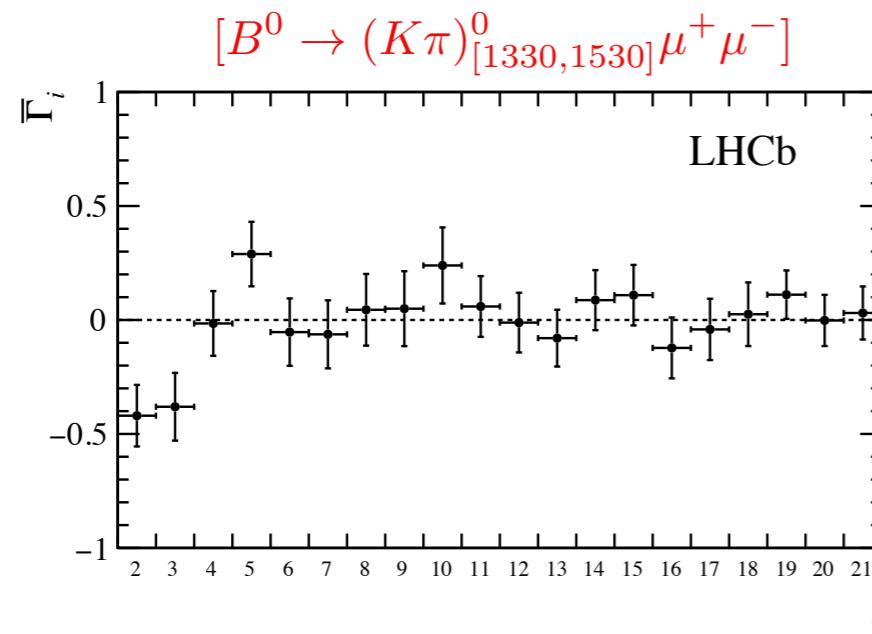
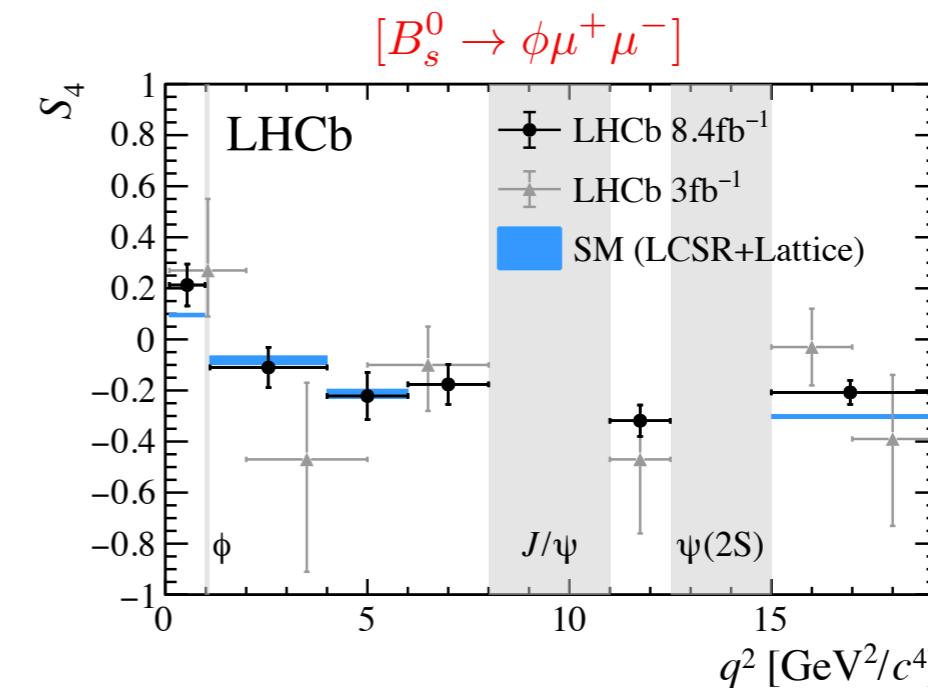
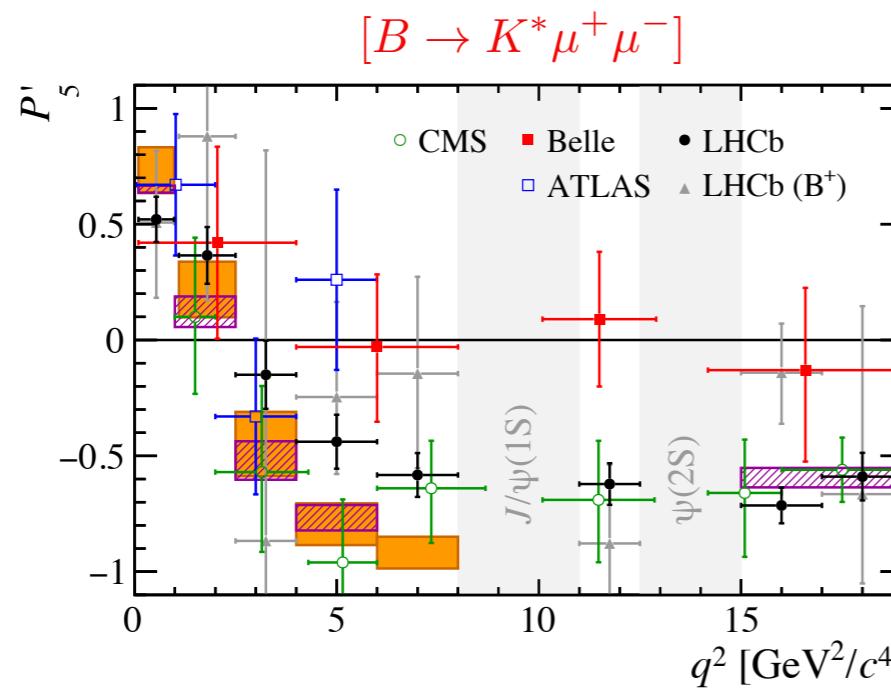


$b \rightarrow s\mu^+\mu^-$ angular measurements



[LHCb, PRL 125 (2020) 011802, 126 (2021) 161802, JHEP 11 (2021) 043, 12 (2016) 065, 09 (2018) 146]

[Belle, PRL 118 (2017) 11, 111801, ATLAS, JHEP 10 (2018) 047, CMS, PLB 781 (2018) 517]

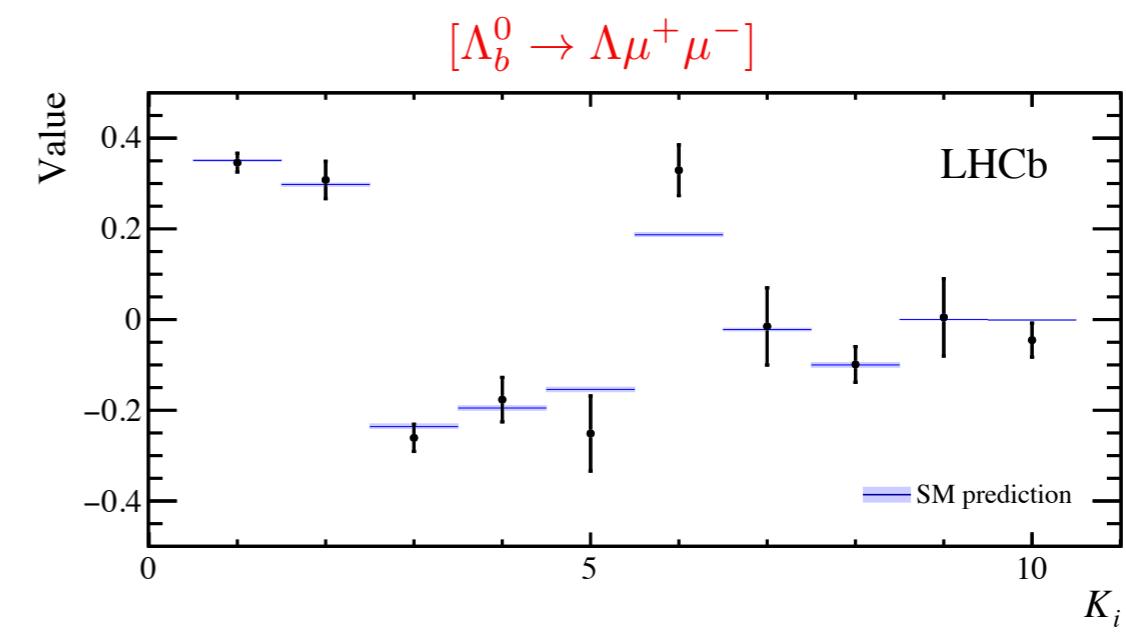
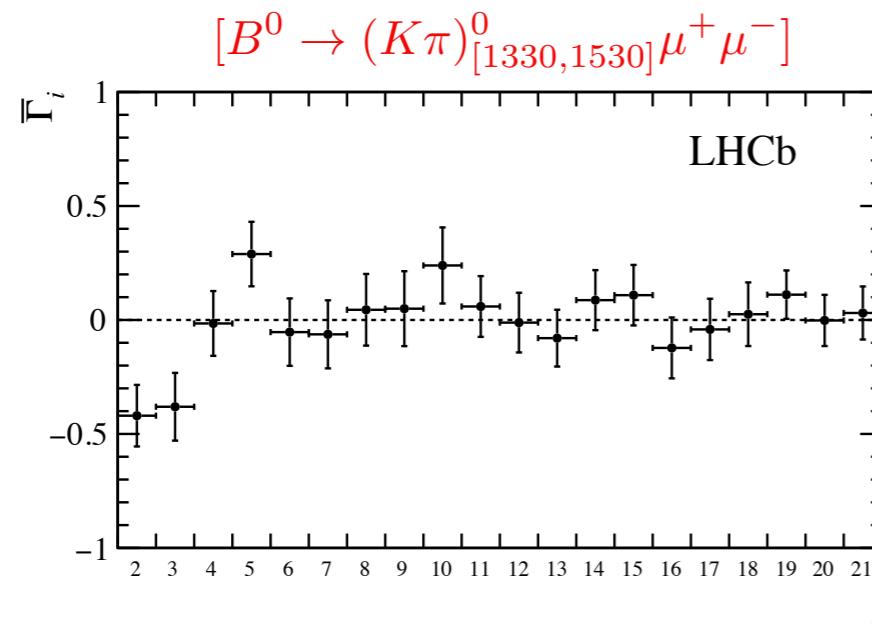
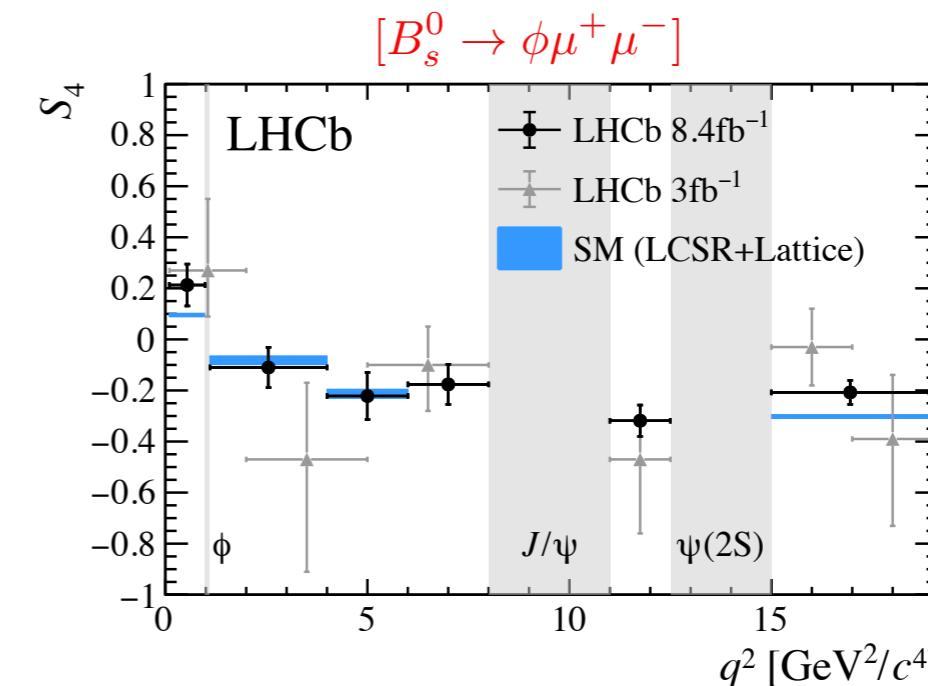
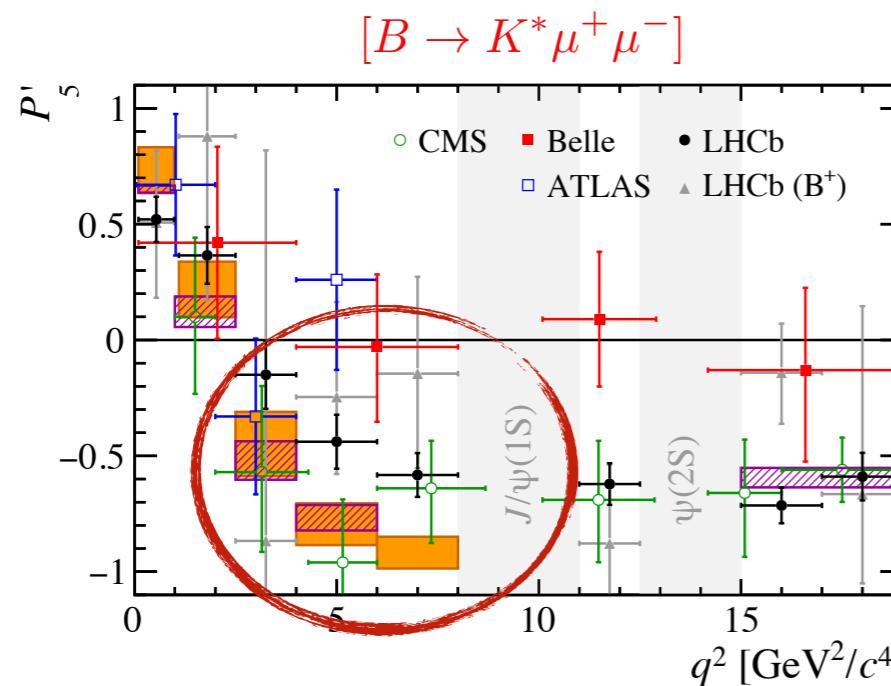


$b \rightarrow s\mu^+\mu^-$ angular measurements



[LHCb, PRL 125 (2020) 011802, 126 (2021) 161802, JHEP 11 (2021) 043, 12 (2016) 065, 09 (2018) 146]

[Belle, PRL 118 (2017) 11, 111801, ATLAS, JHEP 10 (2018) 047, CMS, PLB 781 (2018) 517]



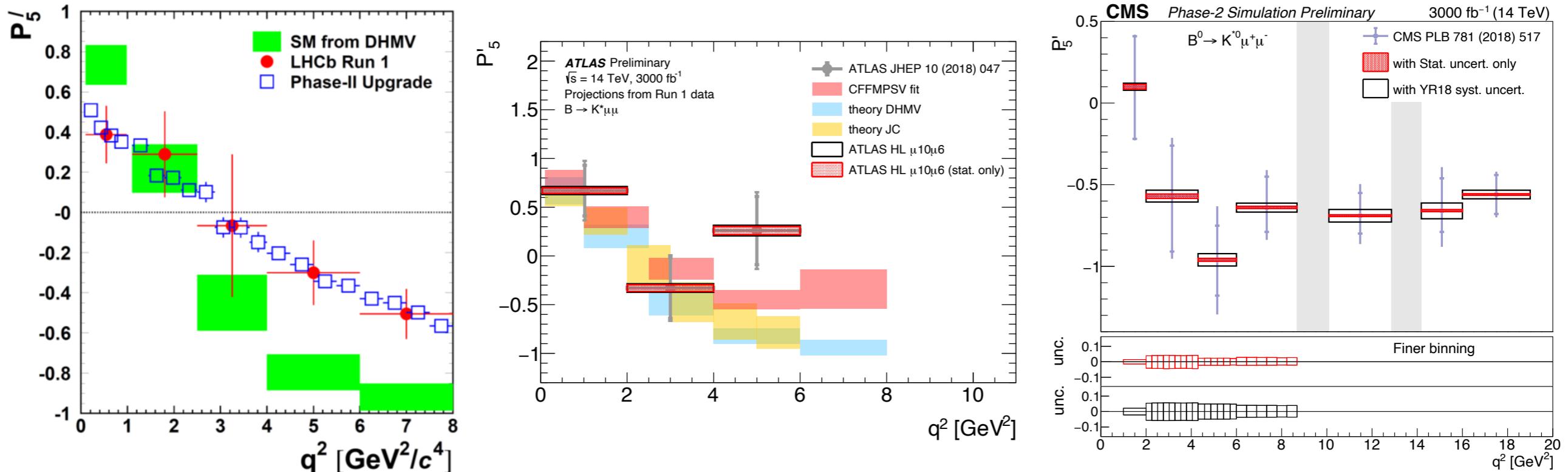
What comes “next”?



[CERN-LHCC-2017-003, ATL-PHYS-PUB-2022-018 CMS PAS FTR-22-001]

More data, more channels, more observables (*e.g.* CP violation), novel ideas ...

“PRECISION ERA”



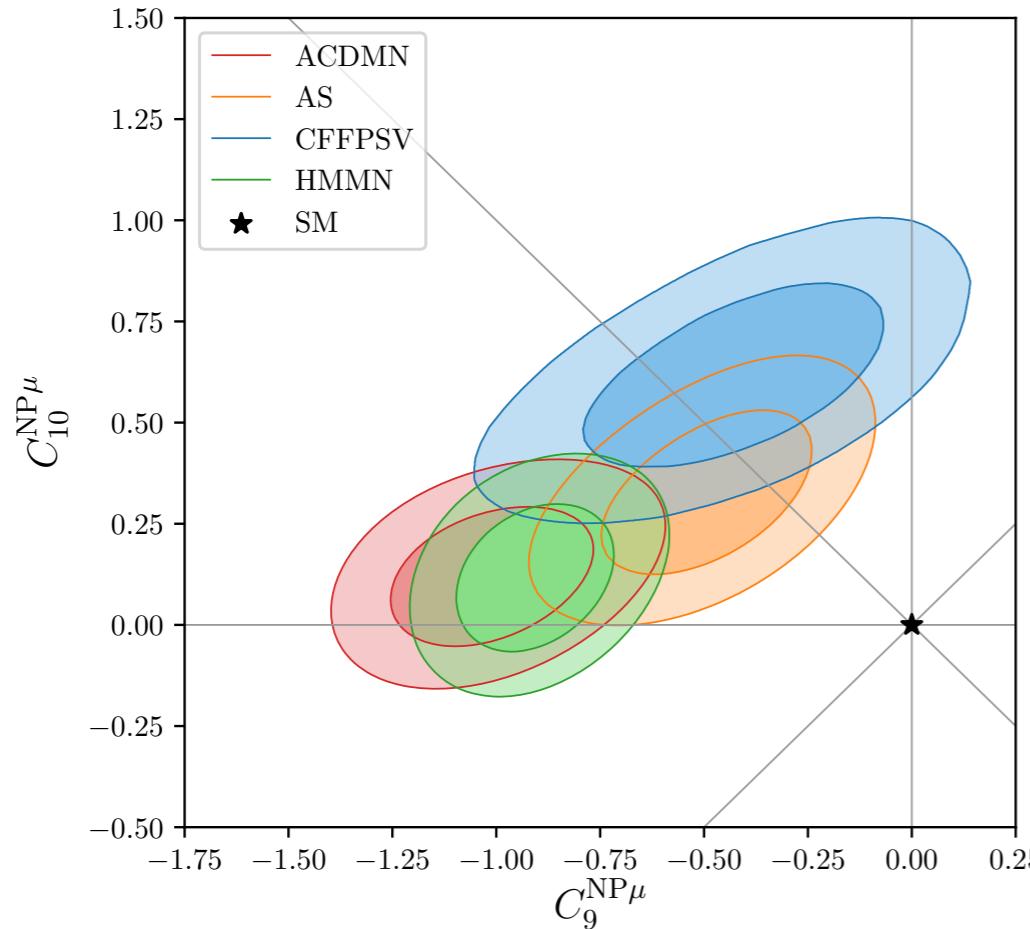
Fundamental information on the understanding on the current SM deviations

What comes “next”?

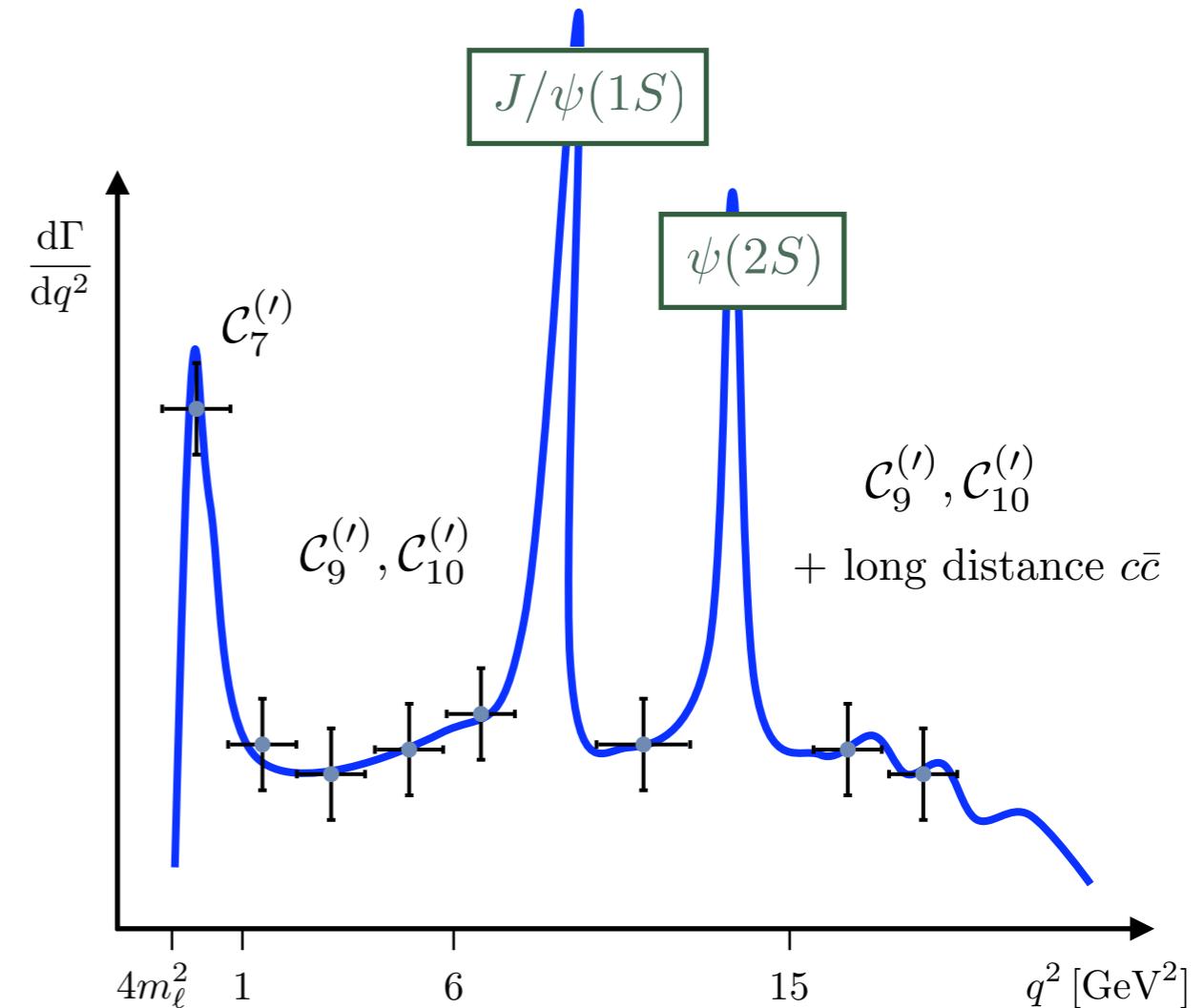
1

“TODAY”

[Flavour anomalies workshop 2021 - summary]



To “bin” or not to “bin”?



[Angular]: A_{FB} , F_L , P'_5 , ...

[Amplitude]: C_9 , C_{10} , hadronic terms ...

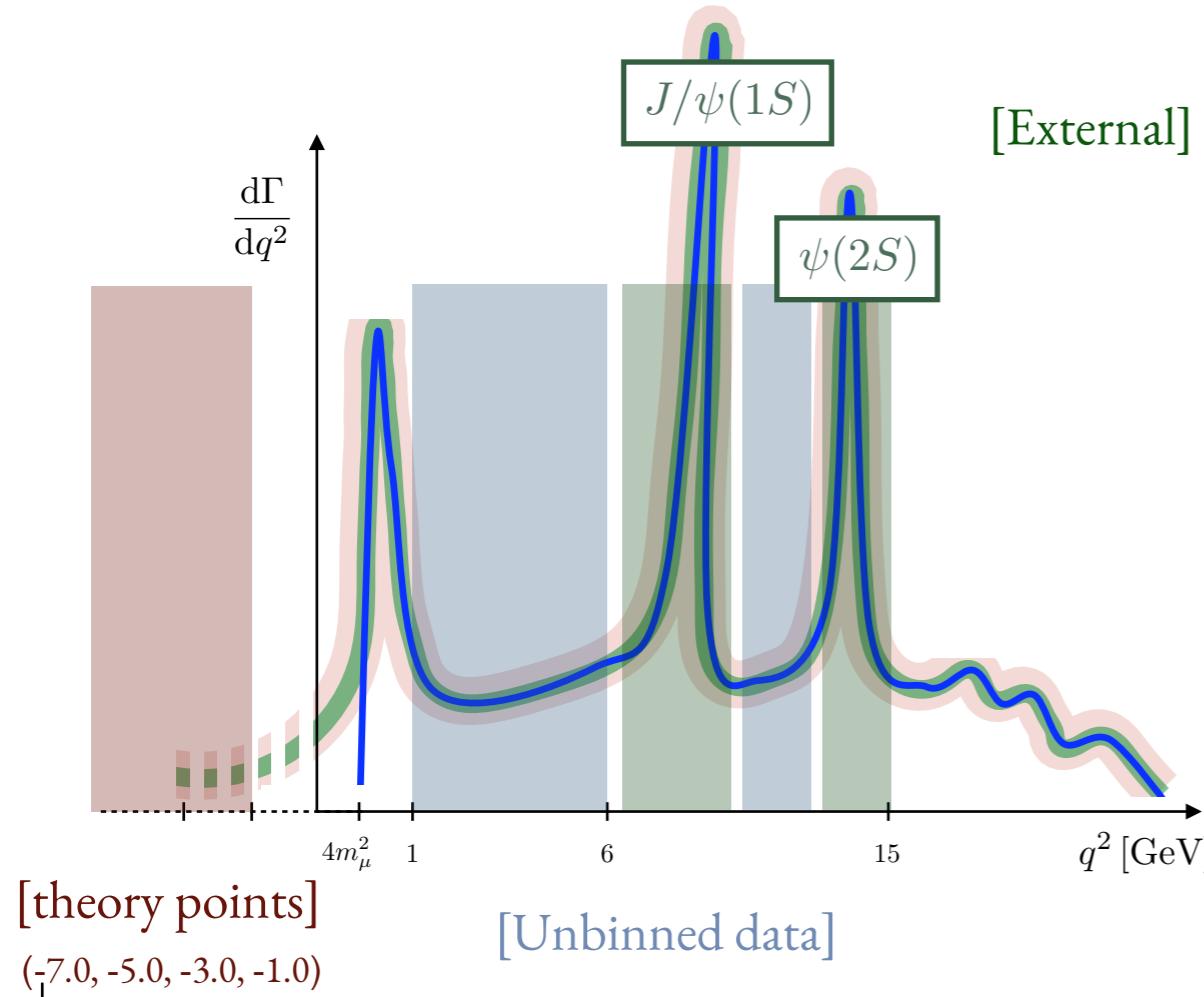
What comes “next”?



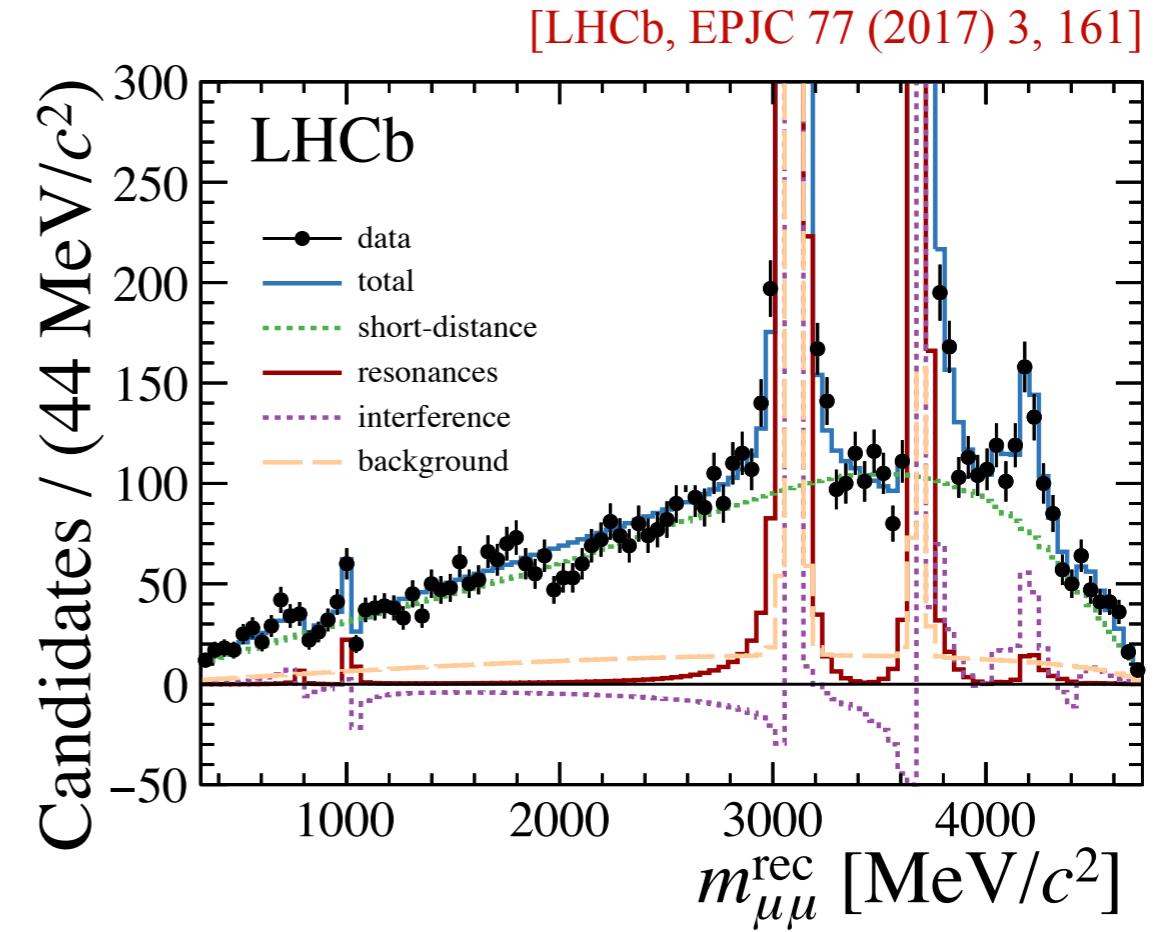
[EPJC 78 6 (2018) 451, JHEP 10 (2019) 236, EPJC 78 (2018) 453, EPJC 80 (2020) 12]

“Unbinned” analyses can significantly improve the understanding of the fields

WCs fits with hybrid theory-experimental info



“Isobar-like” WCs fits

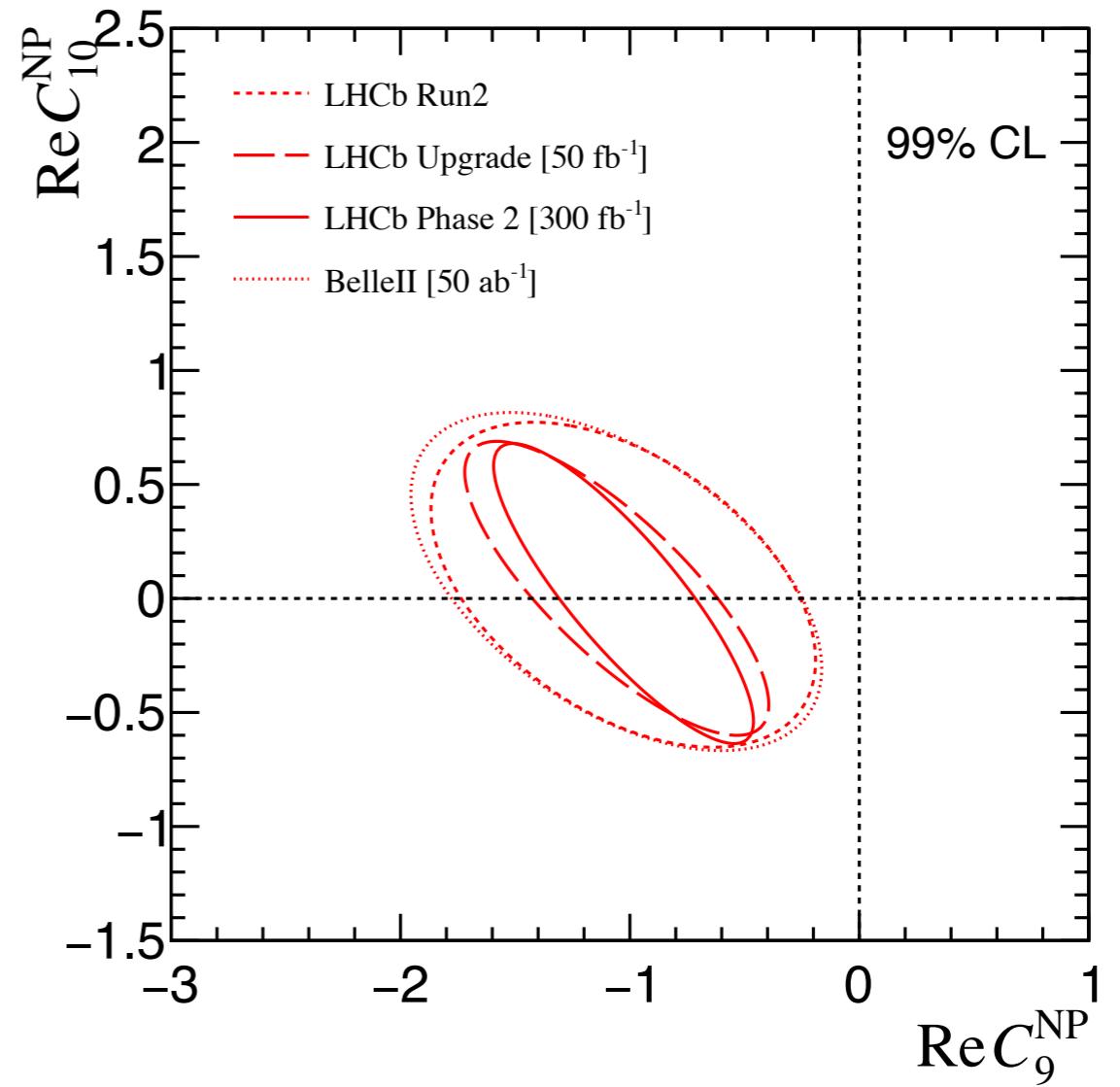
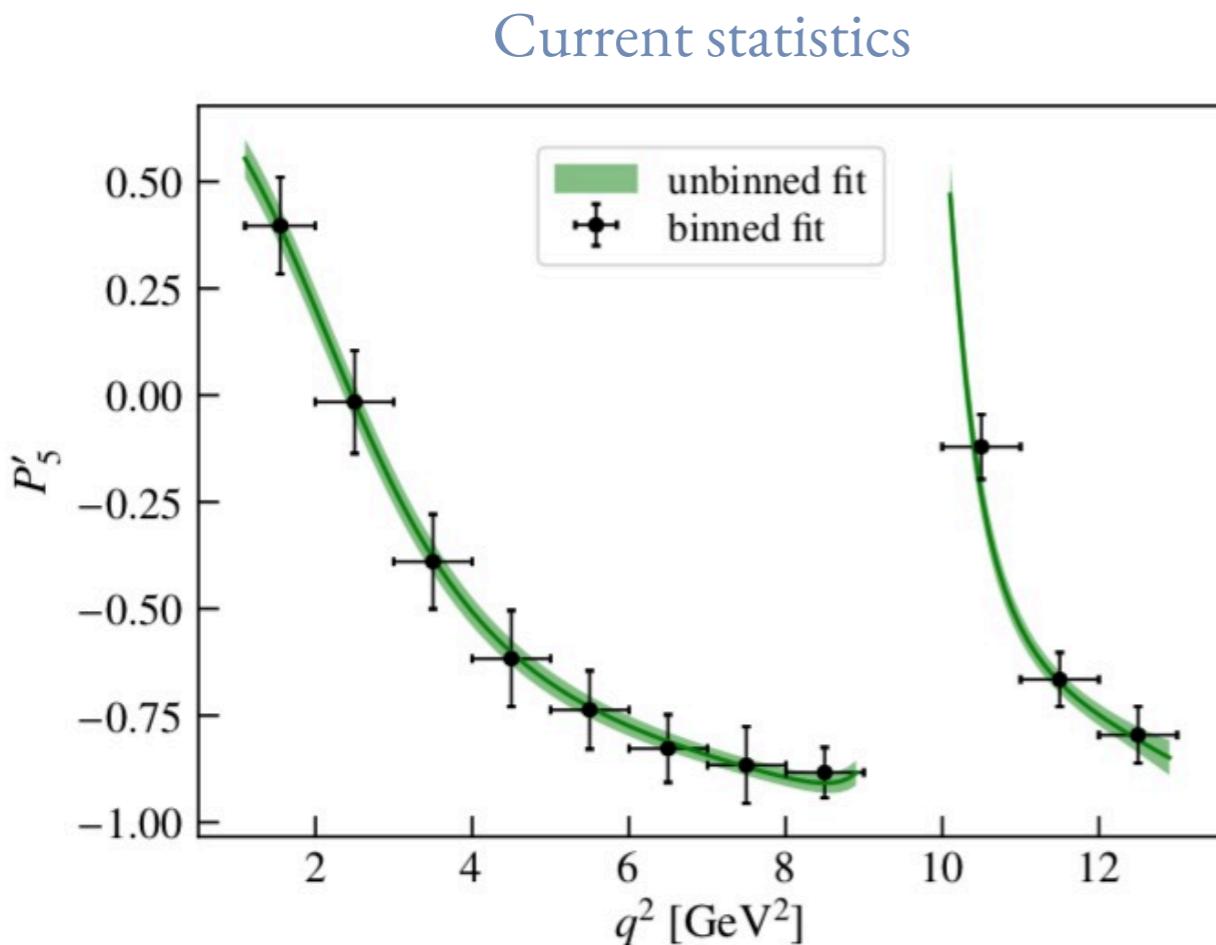


What comes “next”?



[JHEP 10 (2019) 236]

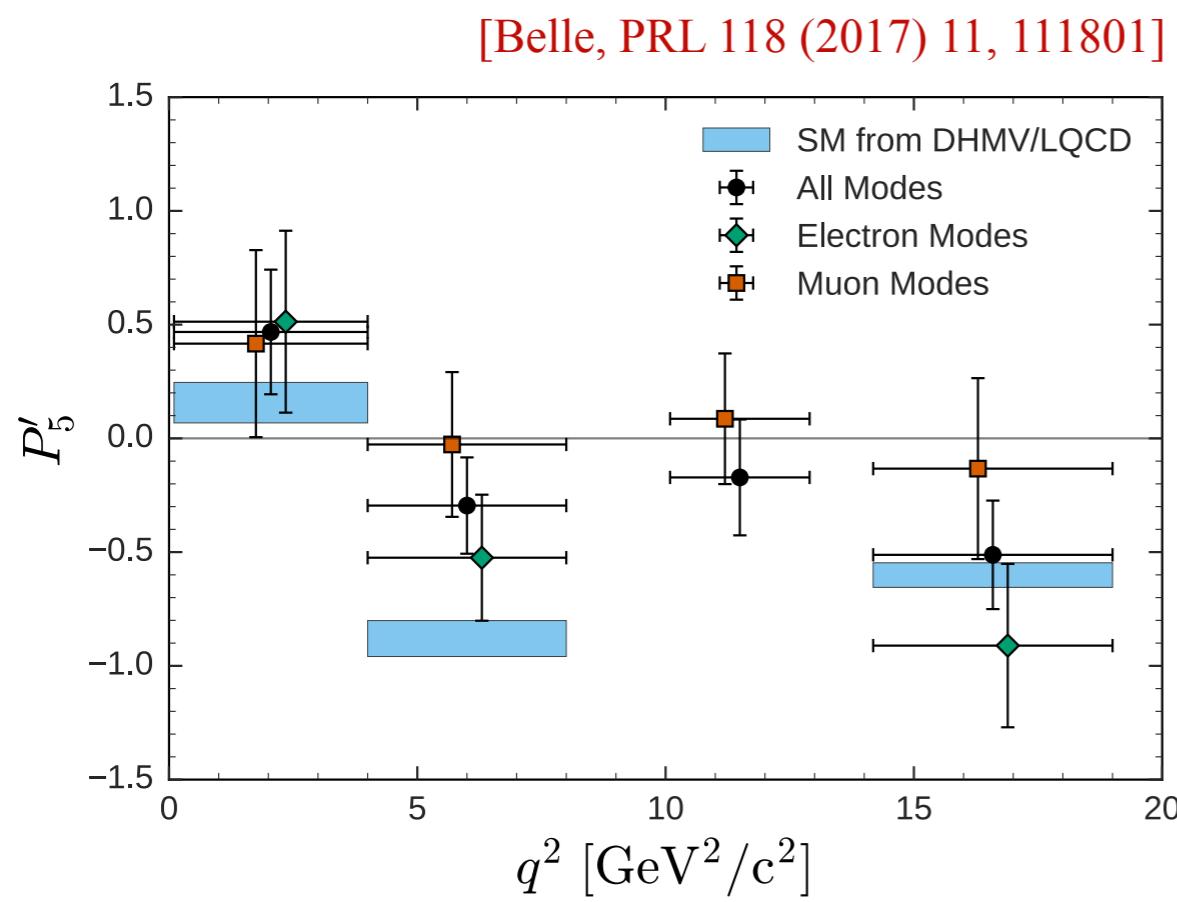
“Unbinned” analyses can significantly improve the understanding of the fields



What about other leptons? $[B^0 \rightarrow K^{*0} e^+ e^-]$

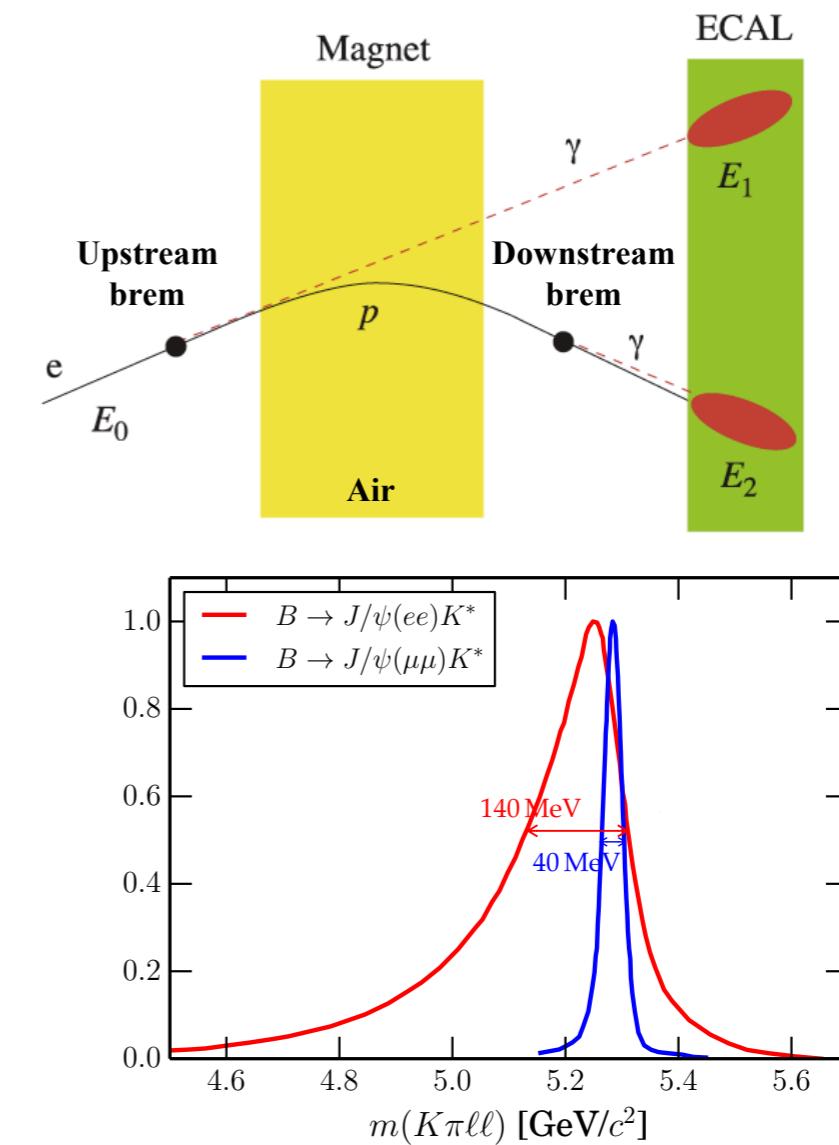


Similar rate for muons and electrons in Belle II



Interesting complementary to LHC results

Challenging analysis for LHCb



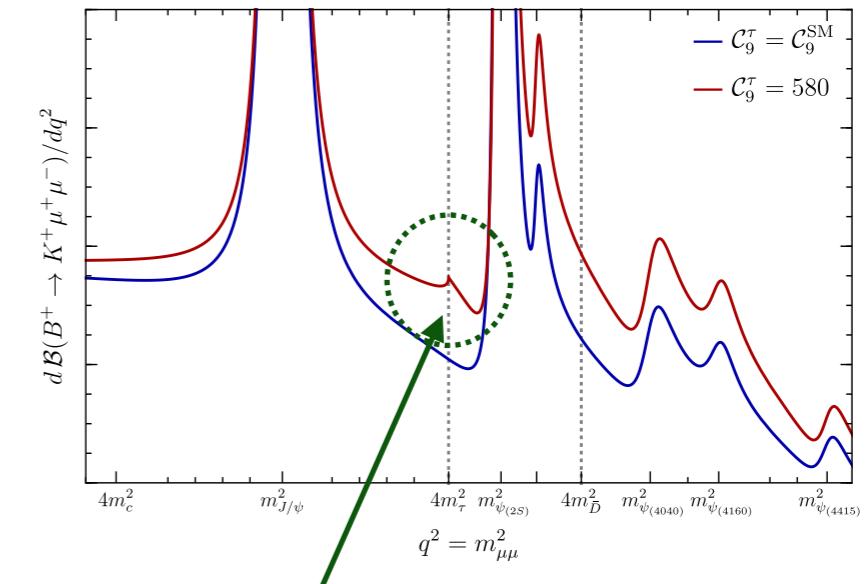
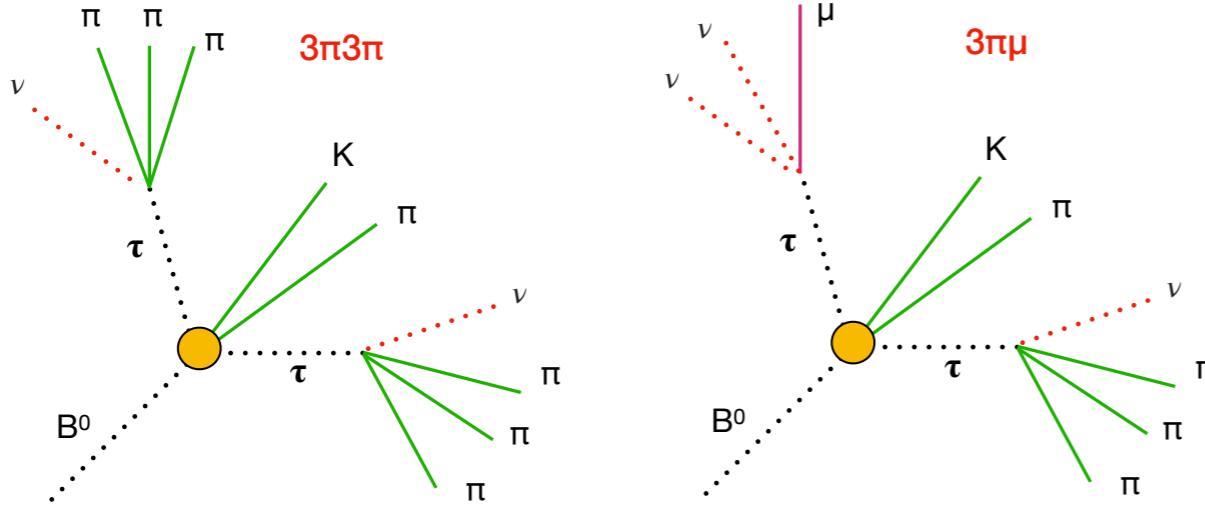
Current sensitivity for P'_5 at ~ 0.12 in 1.1-7.0 GeV q^2

What about other leptons? $[B^0 \rightarrow K^{*0}\tau^+\tau^-]$



[JHEP 05 (2017) 156, EPJC 80 (2020) 12]

Experimentally extremely challenging, in particular for LHCb



Belle II will offer unprecedented sensitivity to this mode

$\mathcal{B}(B^0 \rightarrow K^{*0}\tau\tau)$ (had tag)		
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

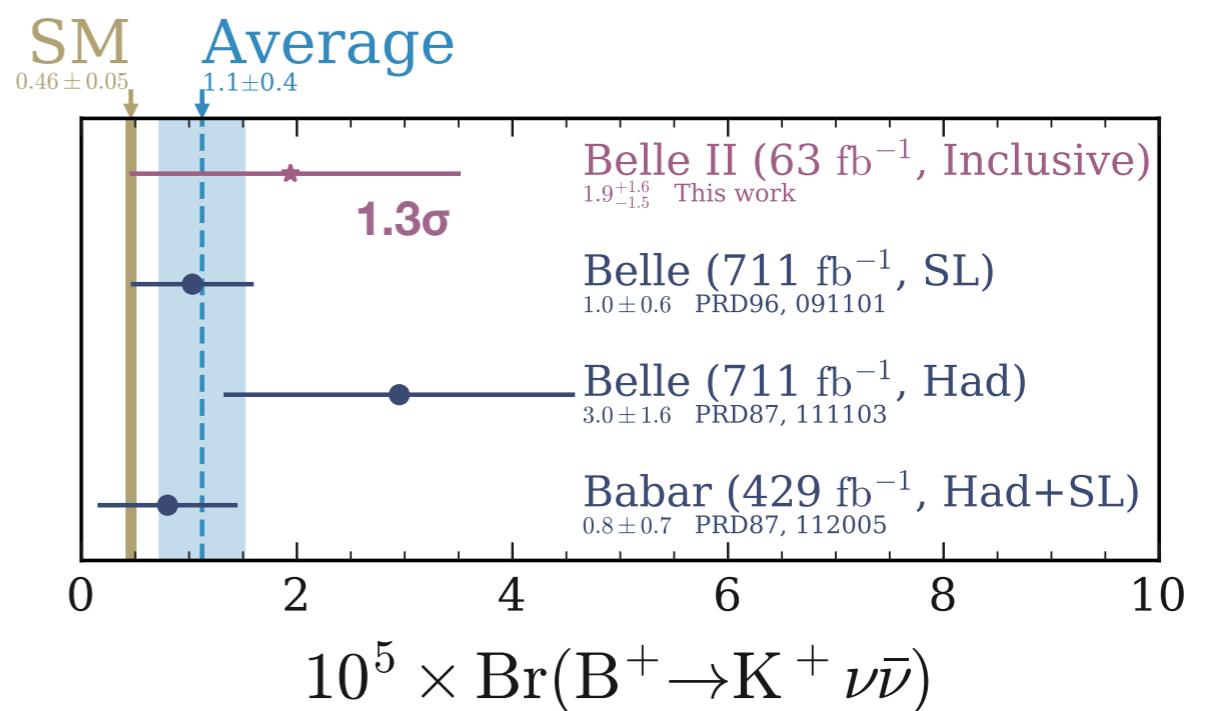
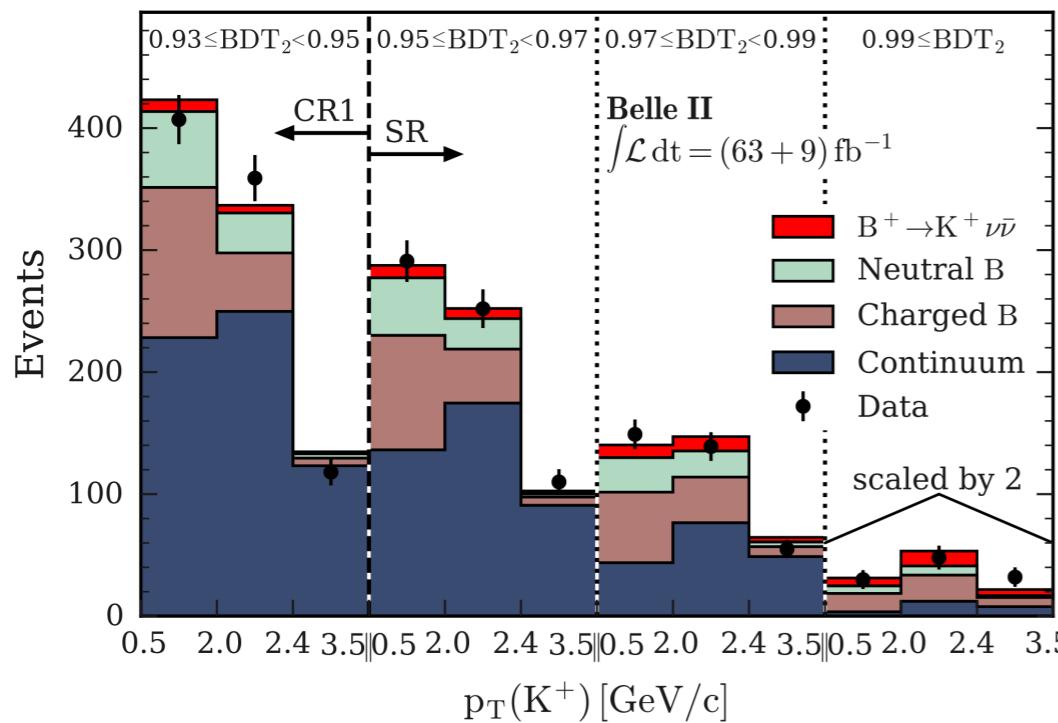
What about other leptons? $[B \rightarrow K^{(*)}\nu\bar{\nu}]$



[Belle II, PRL 127 (2021) 18, 181802]

Belle II has a unique physics reach to study final states with missing energy

Set a competitive limit with only 63 fb^{-1} !



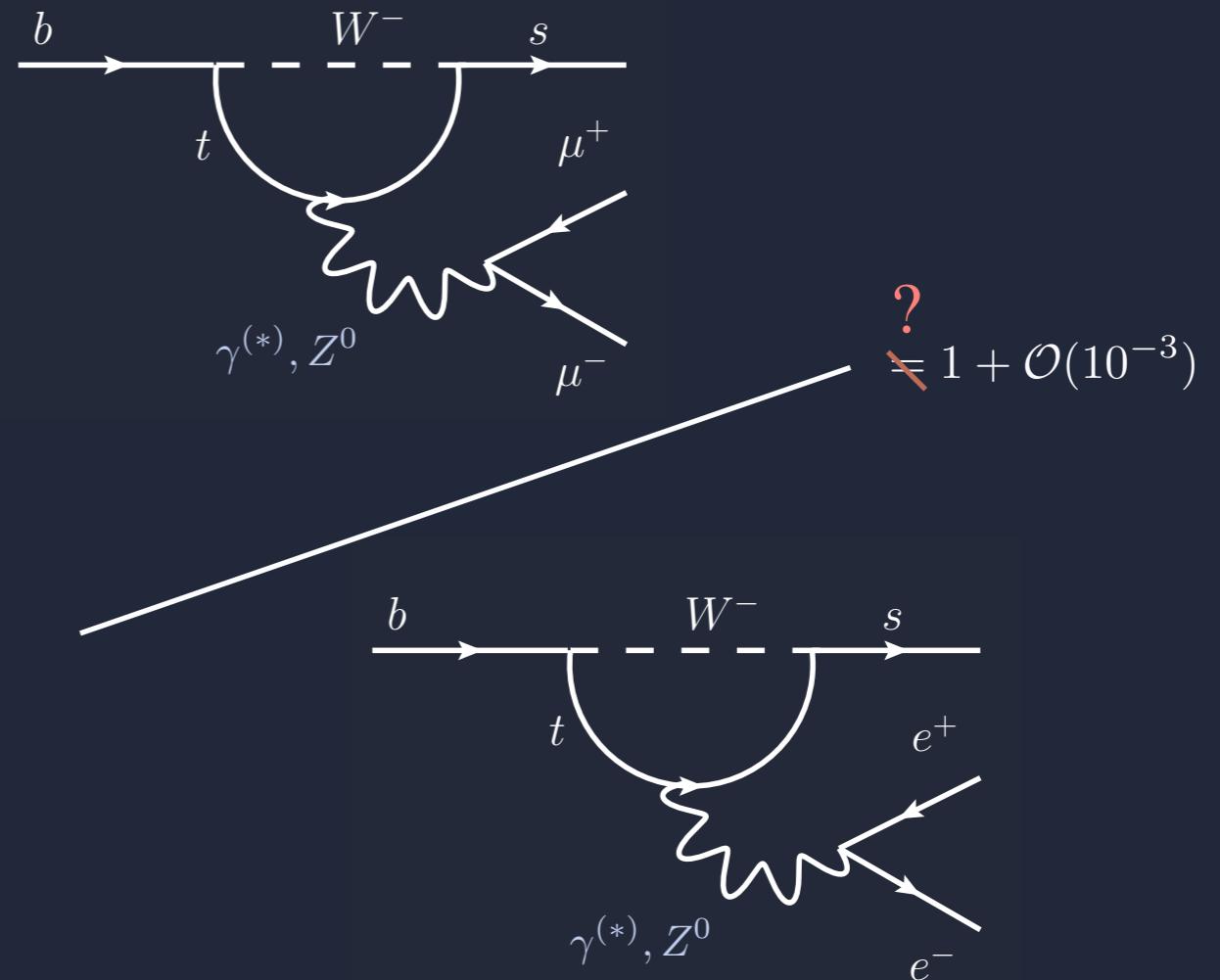
Exciting physics range to be explored!

Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \rightarrow K^+ \nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \rightarrow K_S^0 \nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \rightarrow K^{*+} \nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \rightarrow K^{*0} \nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

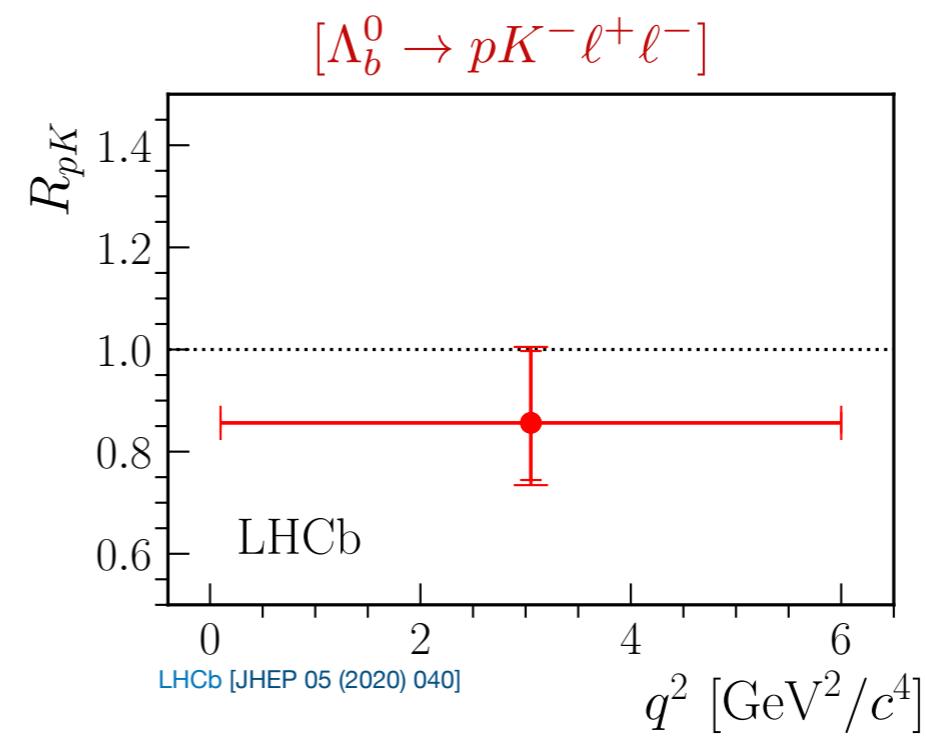
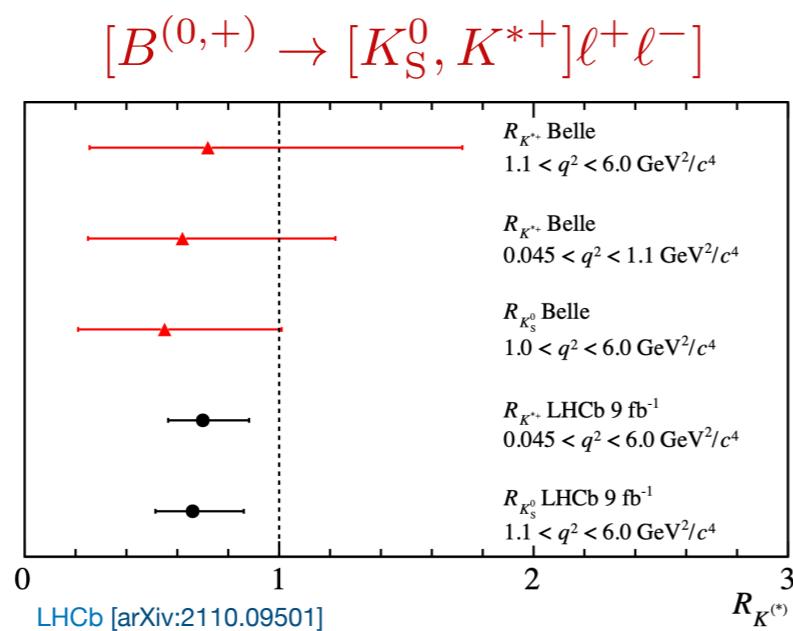
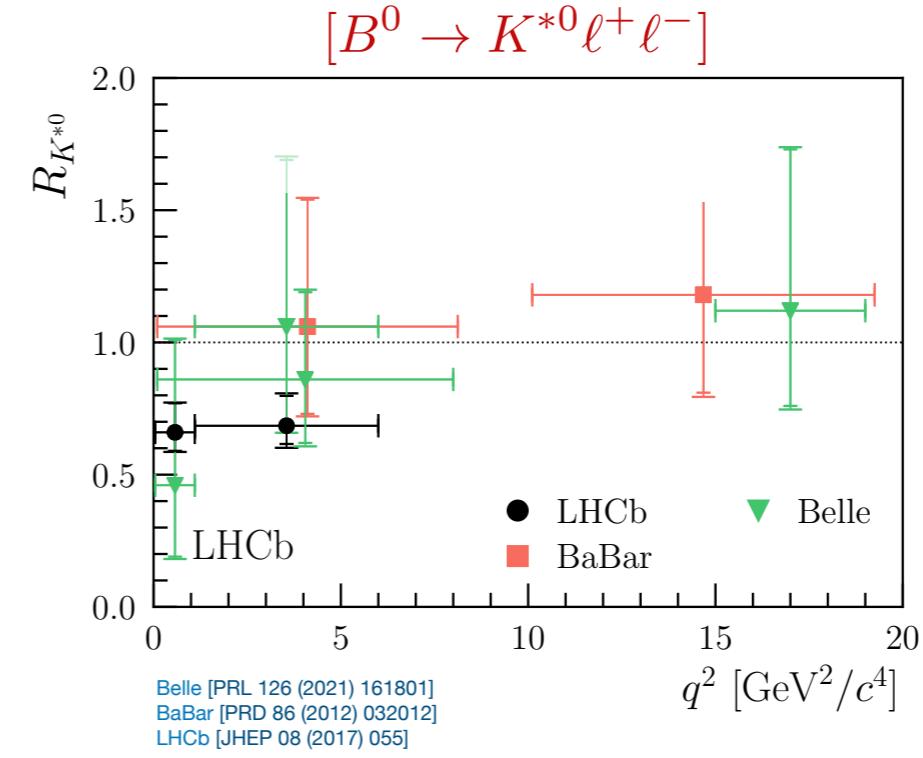
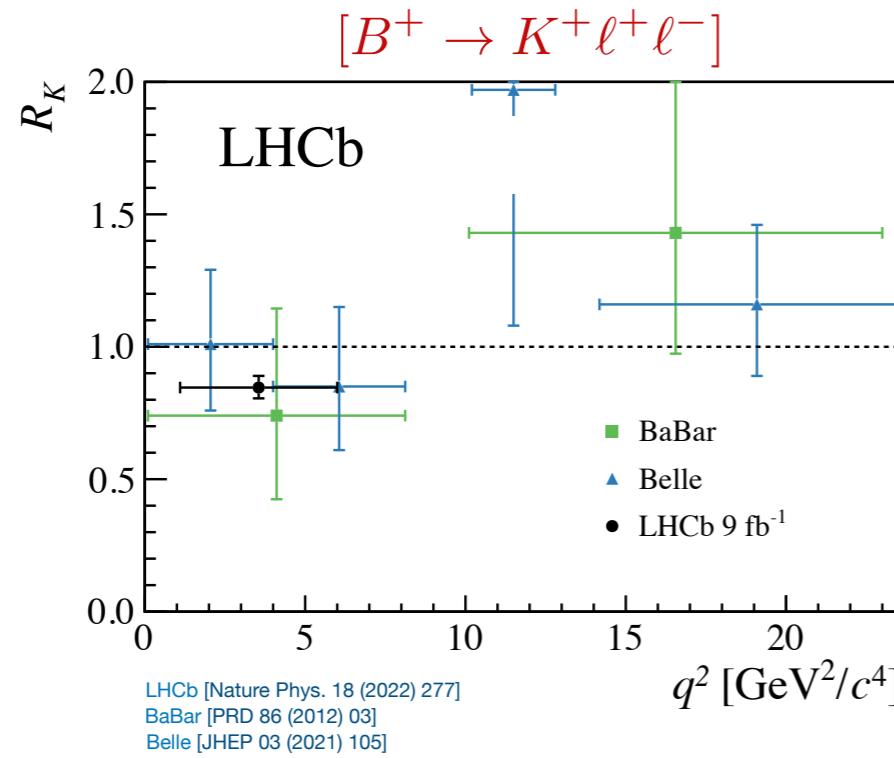
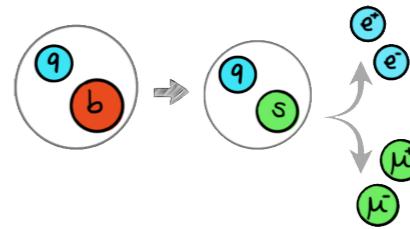
Lepton Flavour Universality



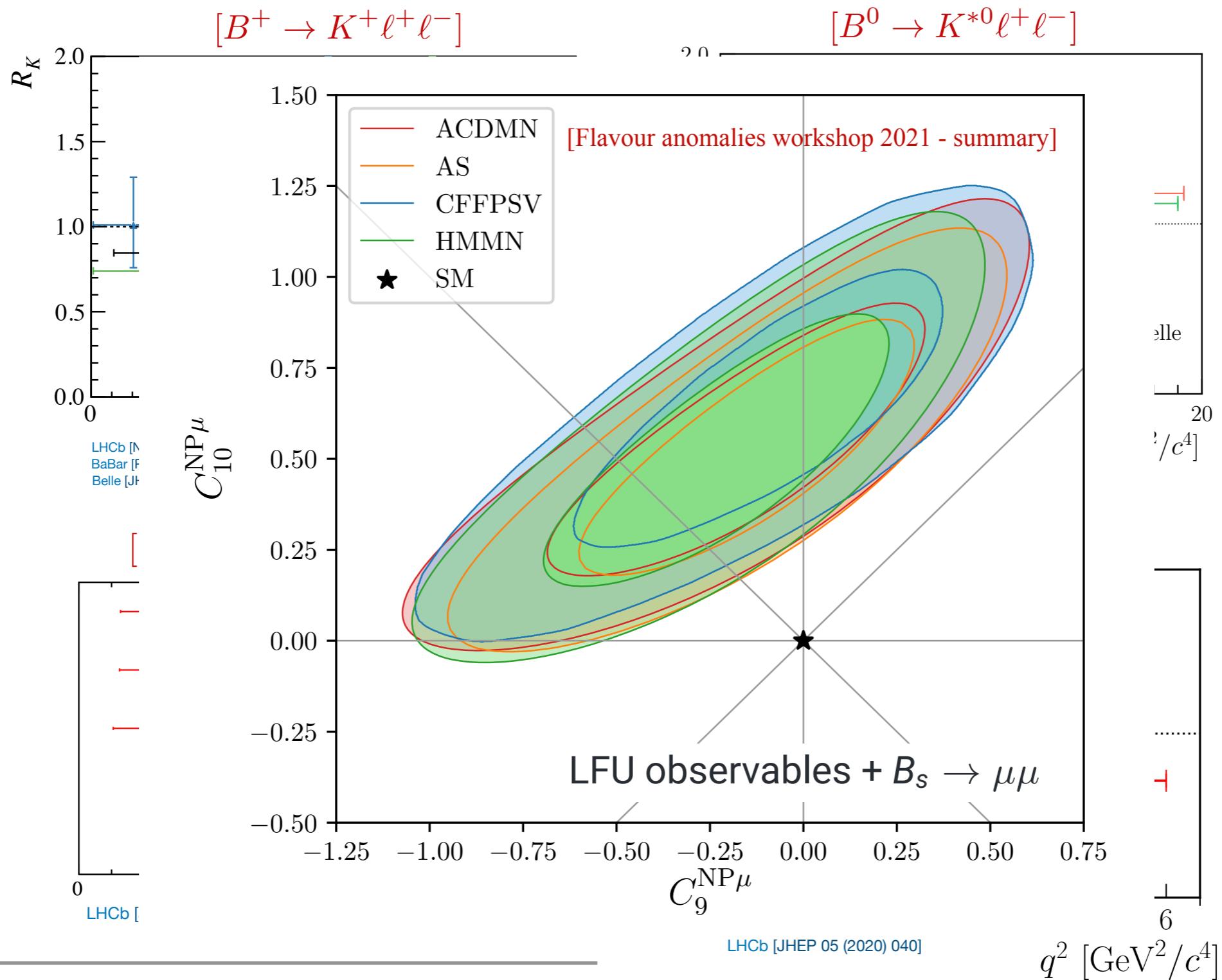
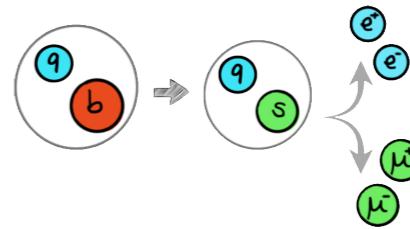
The “third” anomalies: from $b \rightarrow s ll$ to $b \rightarrow cl\nu$



LFU in $b \rightarrow s l^+l^-$ [today]



LFU in $b \rightarrow s l^+l^-$ [today]



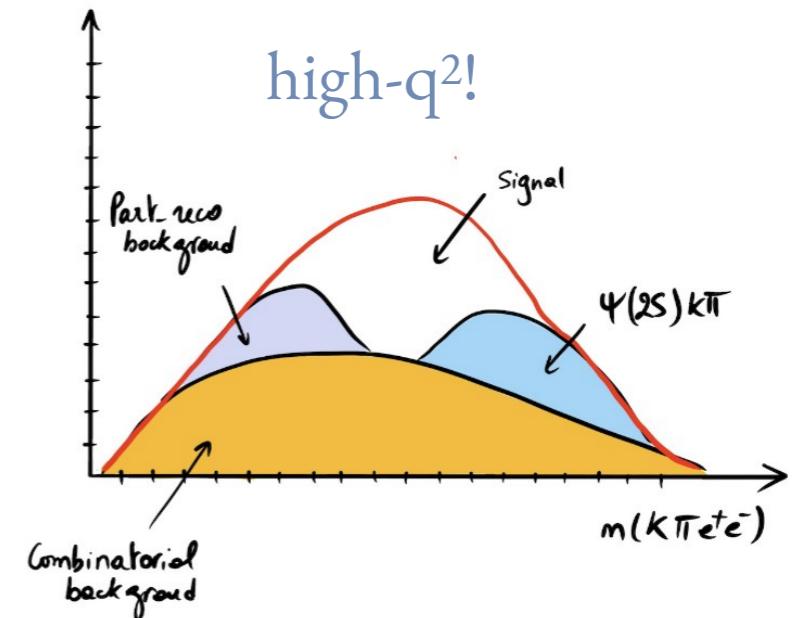
LFU in $b \rightarrow s l^+l^-$ [next]



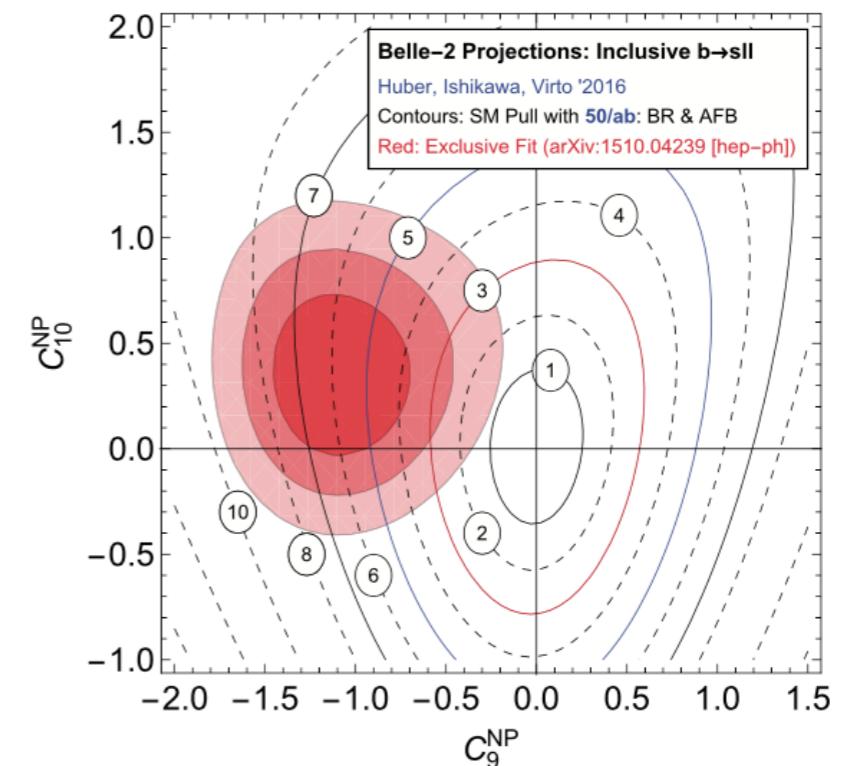
[LHCb, arXiv:1808.08865, Belle II physics book]

More data, more channels, more observables, novel ideas ...

R_X precision	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}
R_K	0.043	0.025	0.017
$R_{K^{*0}}$	0.052	0.031	0.020
R_ϕ	0.130	0.076	0.050
R_{pK}	0.105	0.061	0.041
R_π	0.302	0.176	0.117



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$R_K ([1.0, 6.0] \text{ GeV}^2)$	28%	11%	3.6%
$R_K (> 14.4 \text{ GeV}^2)$	30%	12%	3.6%
$R_{K^*} ([1.0, 6.0] \text{ GeV}^2)$	26%	10%	3.2%
$R_{K^*} (> 14.4 \text{ GeV}^2)$	24%	9.2%	2.8%
$R_{X_s} ([1.0, 6.0] \text{ GeV}^2)$	32%	12%	4.0%
$R_{X_s} (> 14.4 \text{ GeV}^2)$	28%	11%	3.4%

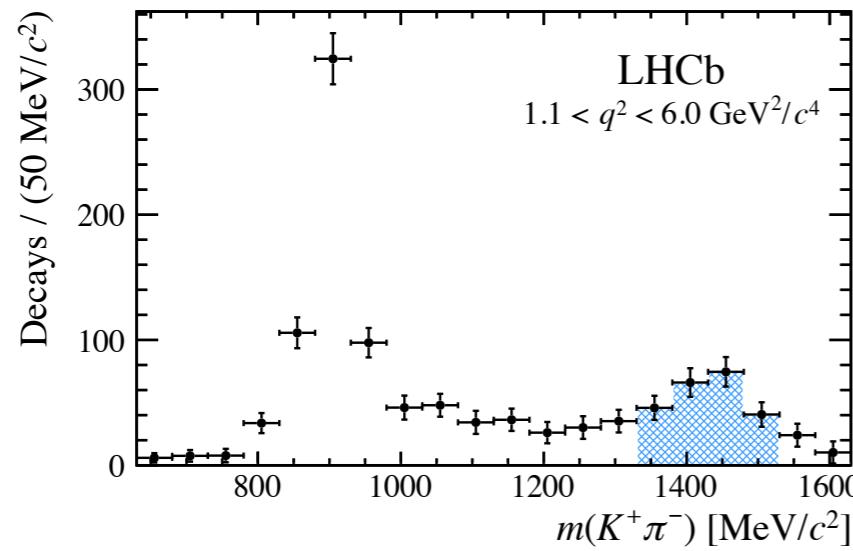


LFU in $b \rightarrow s l^+l^-$ [next]

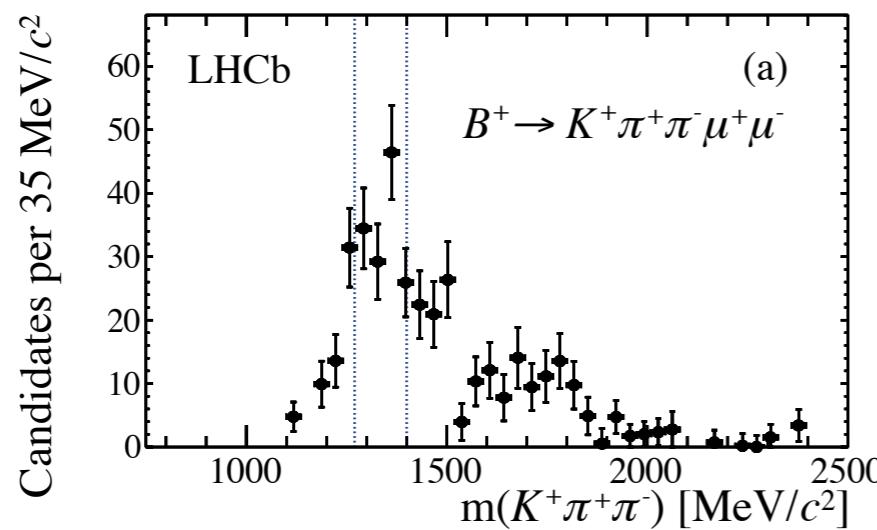


More data, more channels, more observables, novel ideas ...

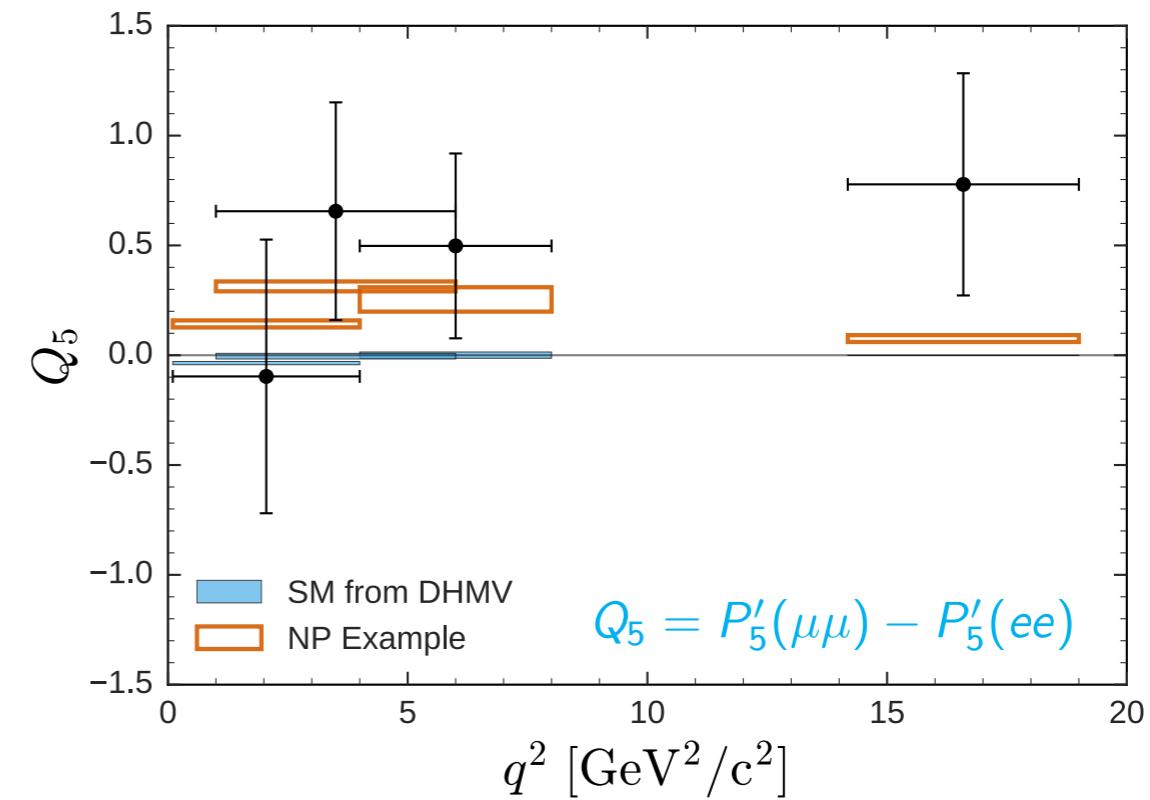
[LHCb, JHEP 12 (2016) 065]



[LHCb, JHEP 1410 (2014) 064]



[Belle, PRL 118 (2017) no.11, 111801]



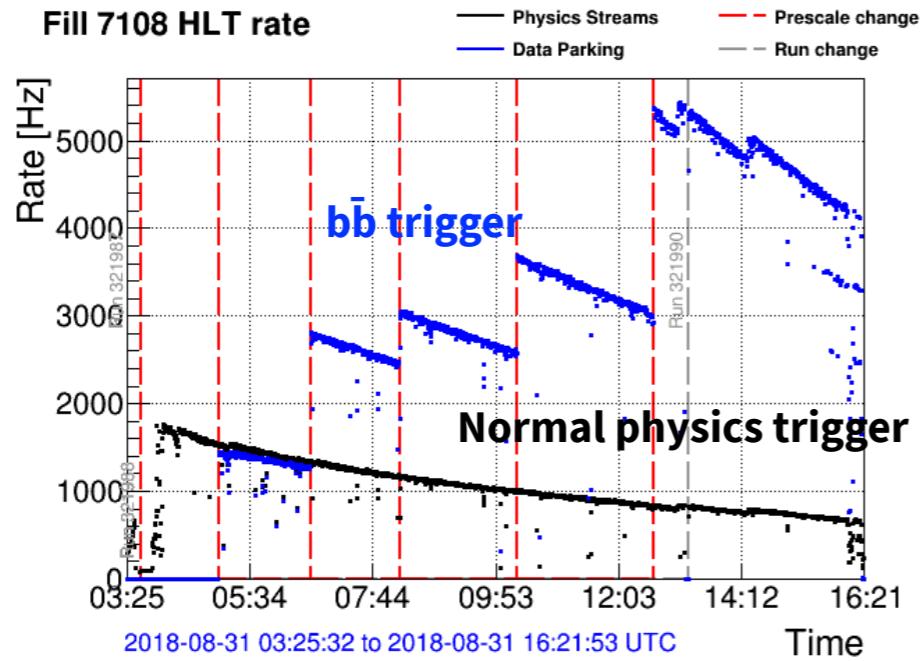
First steps towards an experimental direct connection, *i.e.* probes of LFU in observables

LFU in $b \rightarrow s l^+l^-$ [LHC]

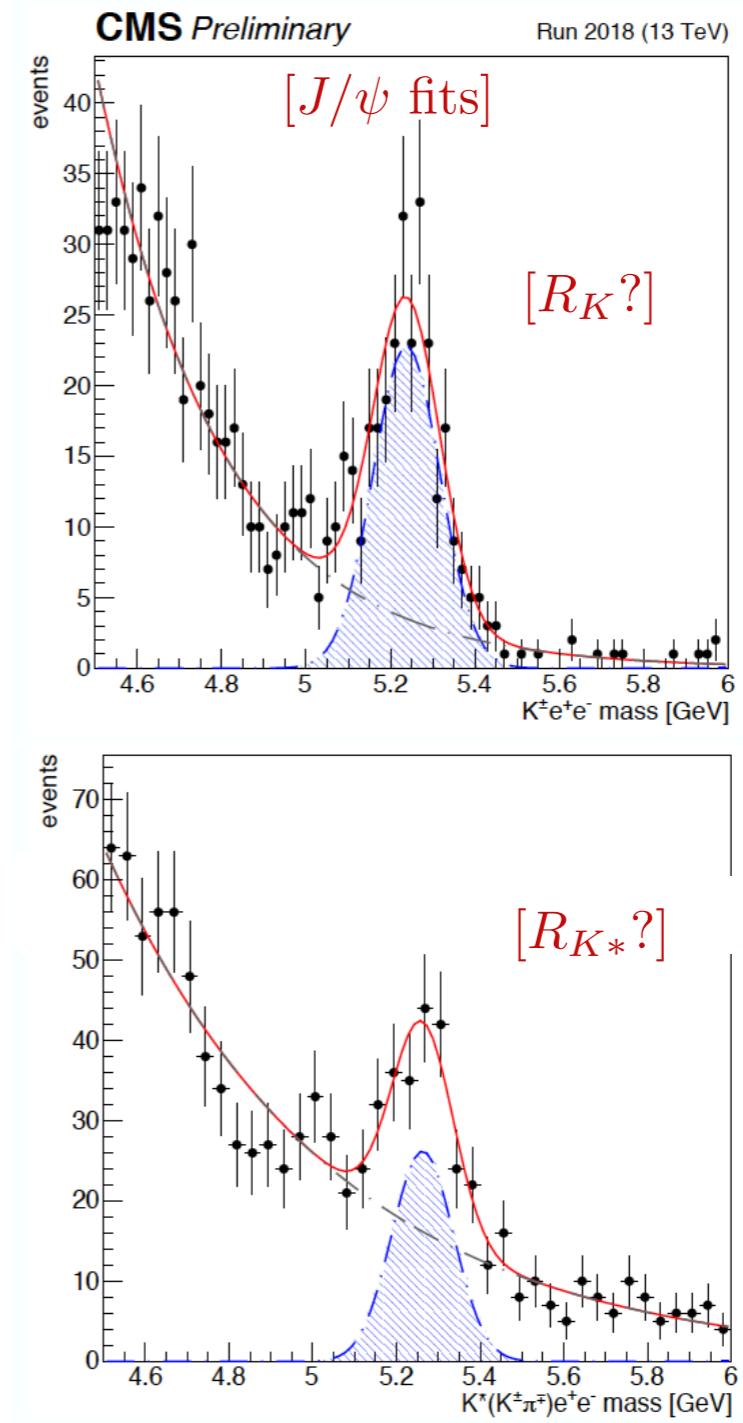
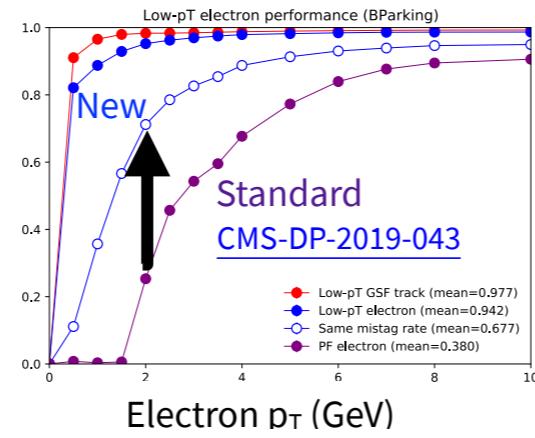


Several activities towards B-physics programme

“B-parking”



Mode	N_{2018}
B_d^0	4.0×10^9
B^\pm	4.0×10^9
B_s	1.2×10^9
b baryons	1.2×10^9
B_c	1.0×10^7
Total	1.0×10^{10}



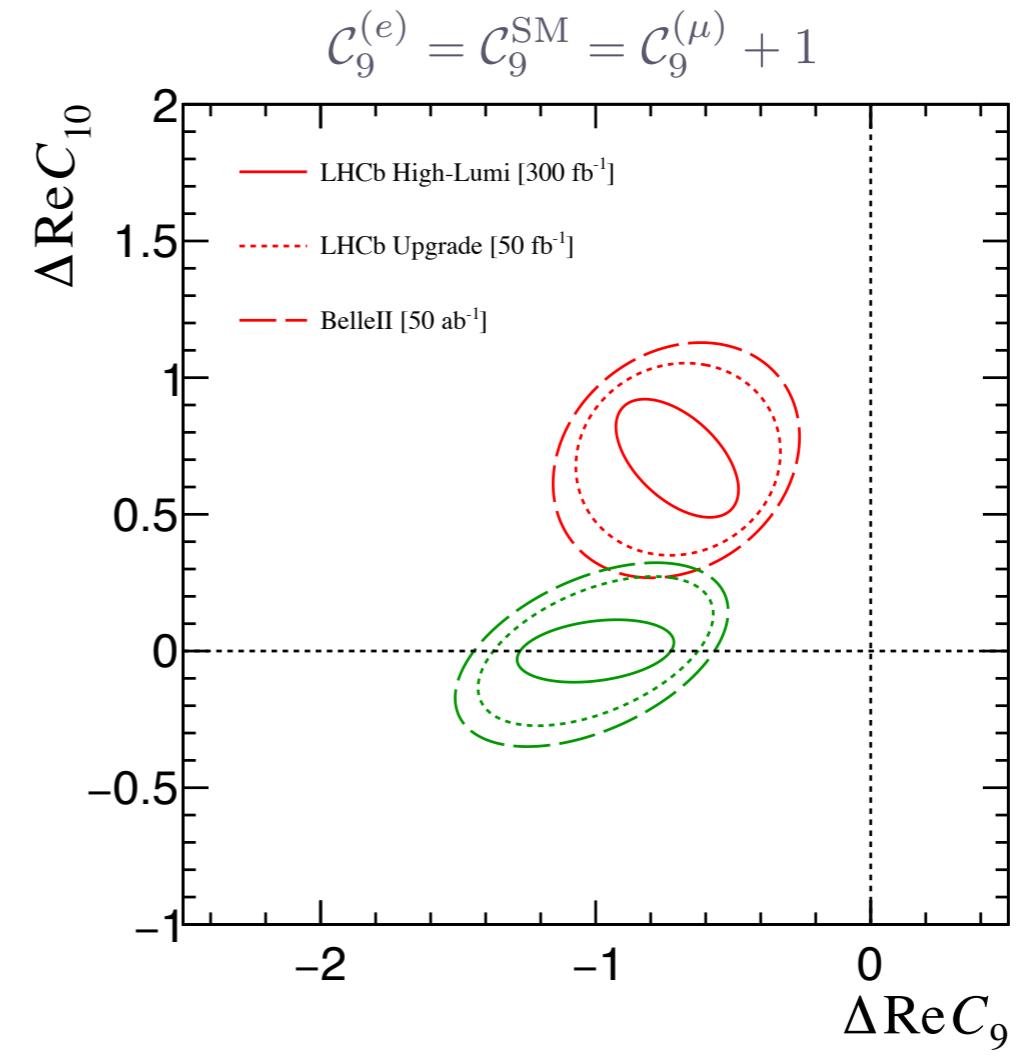
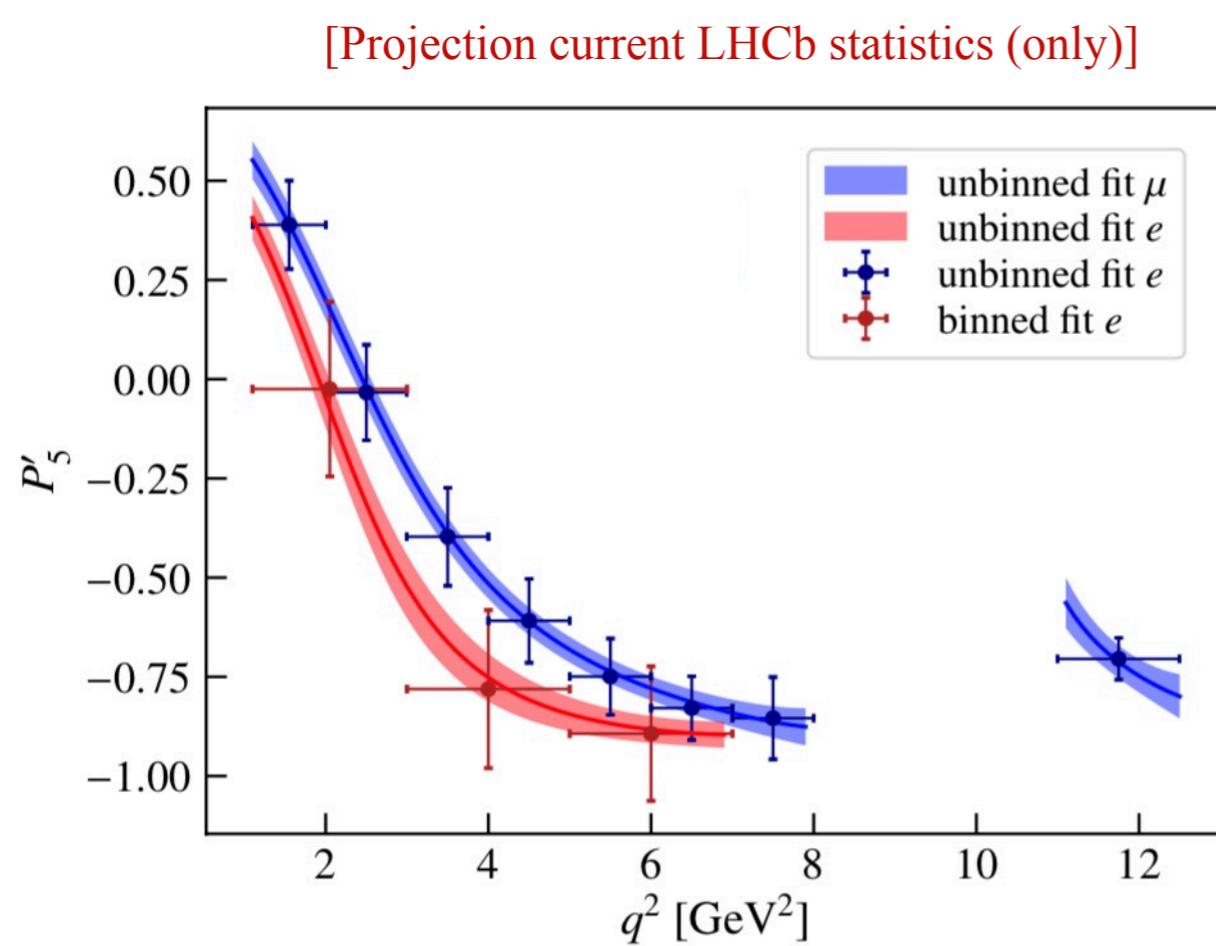
LFU in $b \rightarrow s l^+l^-$ [next]



To “bin” or not to “bin” (LFU)?

[PRD 99 (2019) 013007, arXiv:2203.06827]

Simultaneous unbinned analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0 \rightarrow K^{*0}e^+e^-$

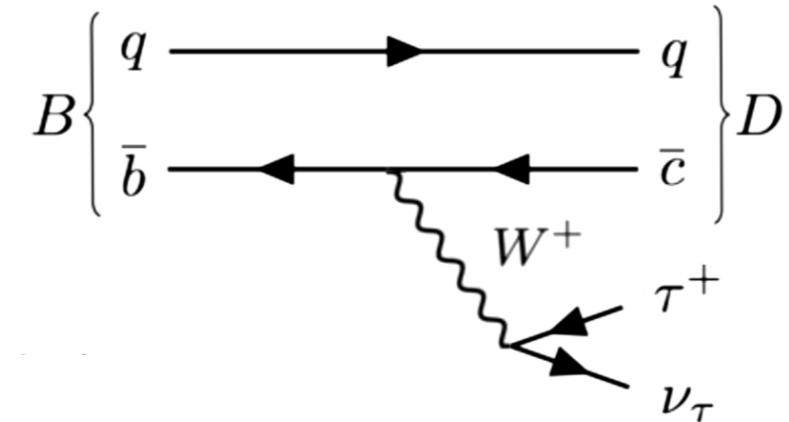


LFU in $b \rightarrow c l \nu$ [today]

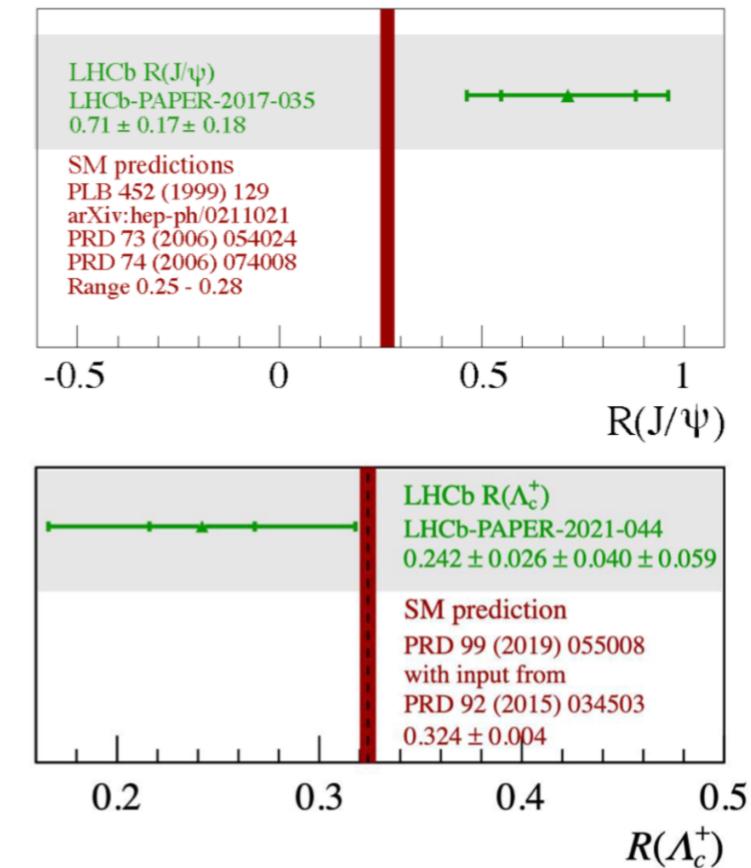
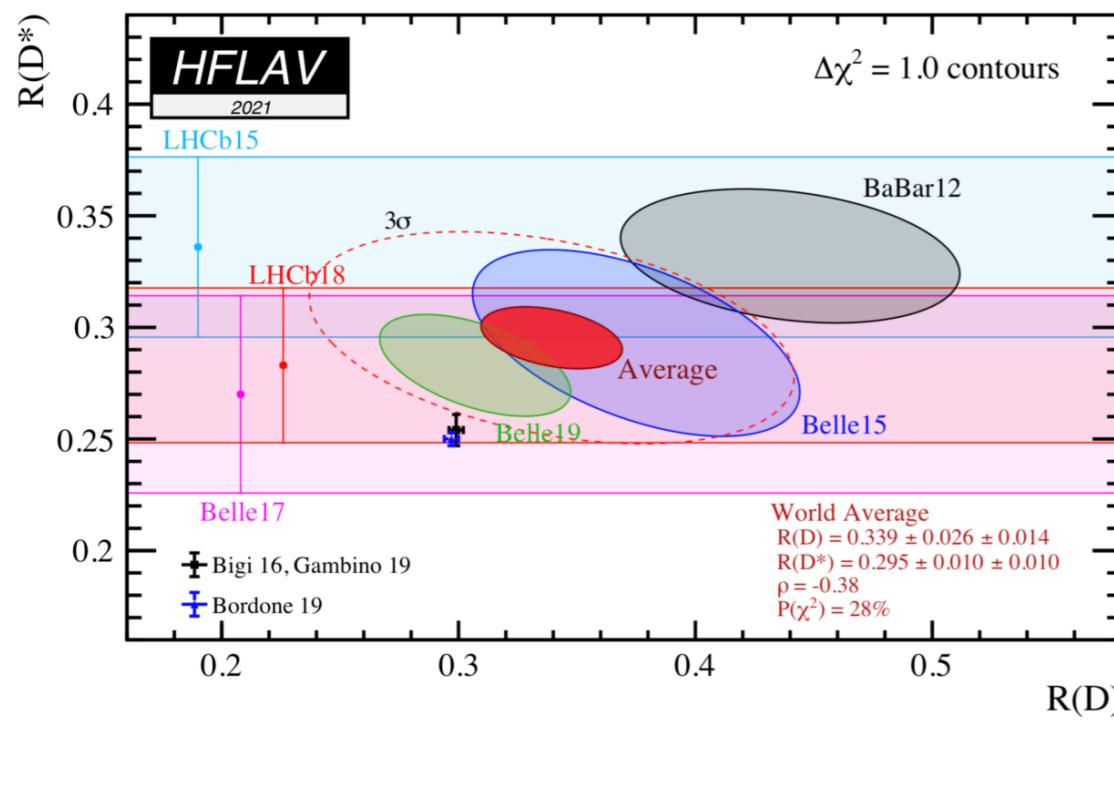
$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \rightarrow \mathcal{H}_c \tau \bar{\nu}_\tau)}{\mathcal{B}(\mathcal{H}_b \rightarrow \mathcal{H}_c \mu \bar{\nu}_\mu)}$$

$\mathcal{H}_b = B^0, B_{(c)}^+, \Lambda_b^0, B_s^0 \dots$
 $\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \dots$

$\ell' = e/\mu$ (B -factories)
 $\ell' = \mu$ (LHCb)



Measurements from the B-factories and LHCb in tension at the $> 3\sigma$ level wrt the SM

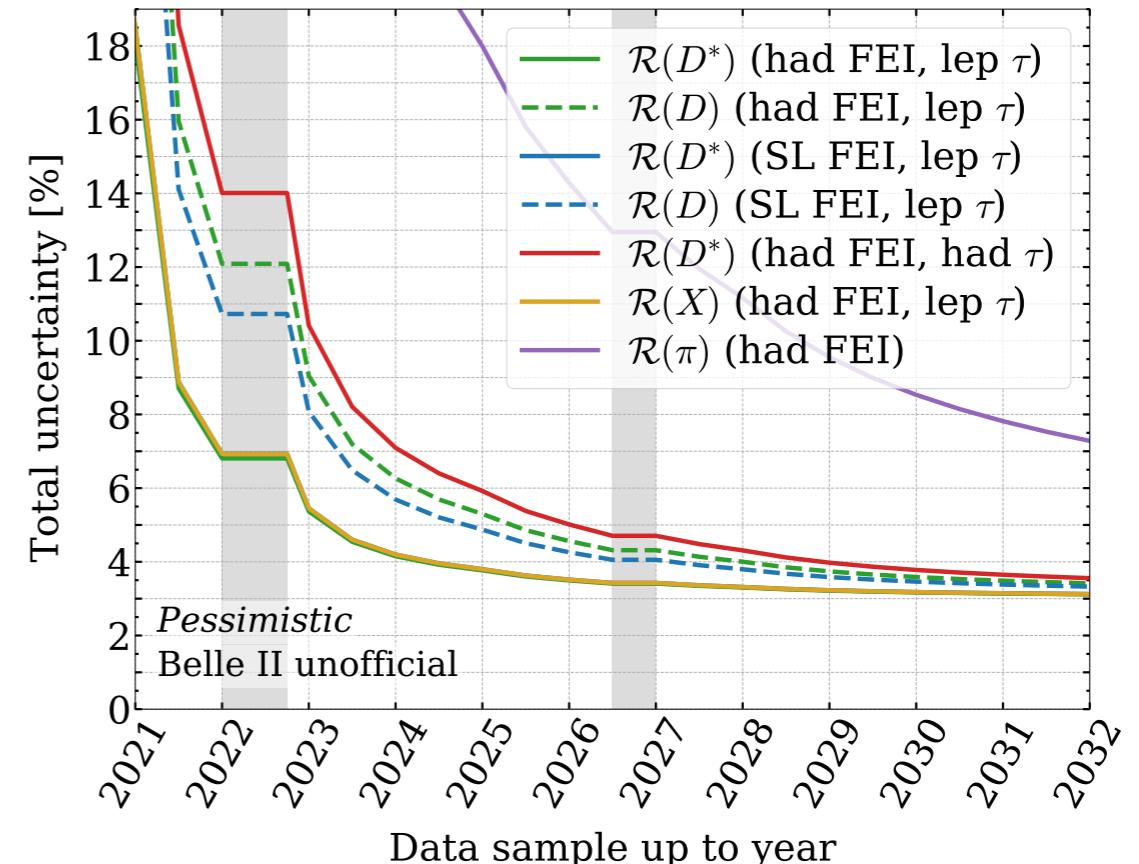
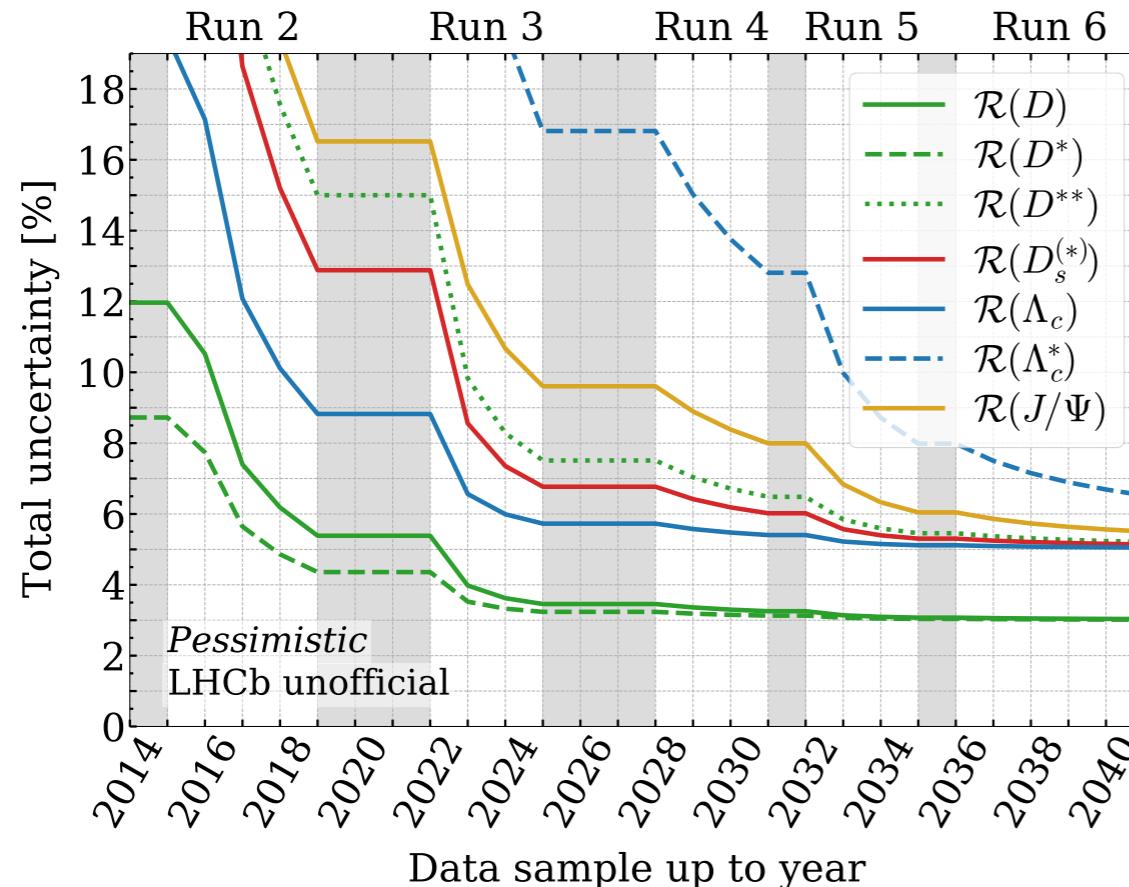


LFU in $b \rightarrow c l \nu$ [next]



[*Rev.Mod.Phys.* 94 (2022) 1, 015003]

Exciting prospects in the LFU for both experiments!



Can other LHC experiments also contribute to this picture?

LFU in $b \rightarrow cl\nu$ [next]

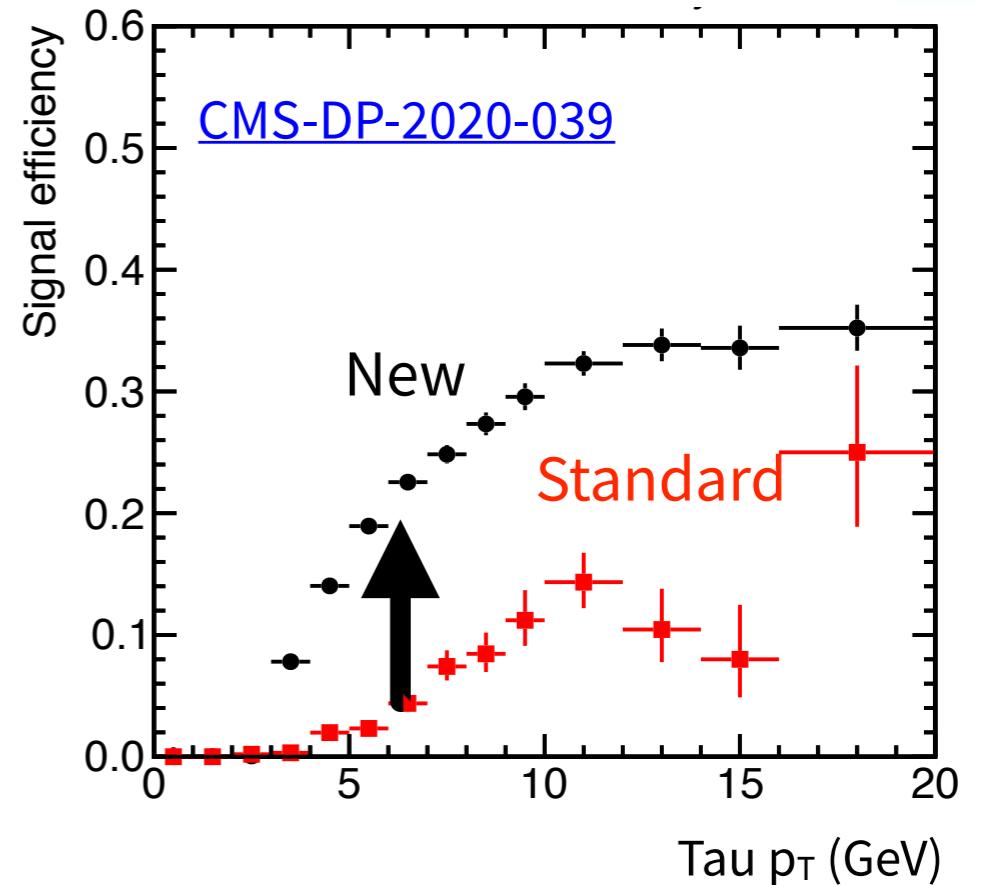


Historically B -physics in CMS is possible using dimuon trigger (low rate)

- Ongoing analysis of $R(J/\psi)$ analysis (both muonic and hadronic tau decays)
- “B-parked” data also allowed single muon trigger, e.g. $R(D^*)$

ATLAS is also working on semileptonic B decays with Run 2 data and preparing devoted trigger lines for Run 3.

New low- p_T tau reconstruction algorithm dedicated to hadronic $\tau \rightarrow \pi\pi\pi\nu$ decay



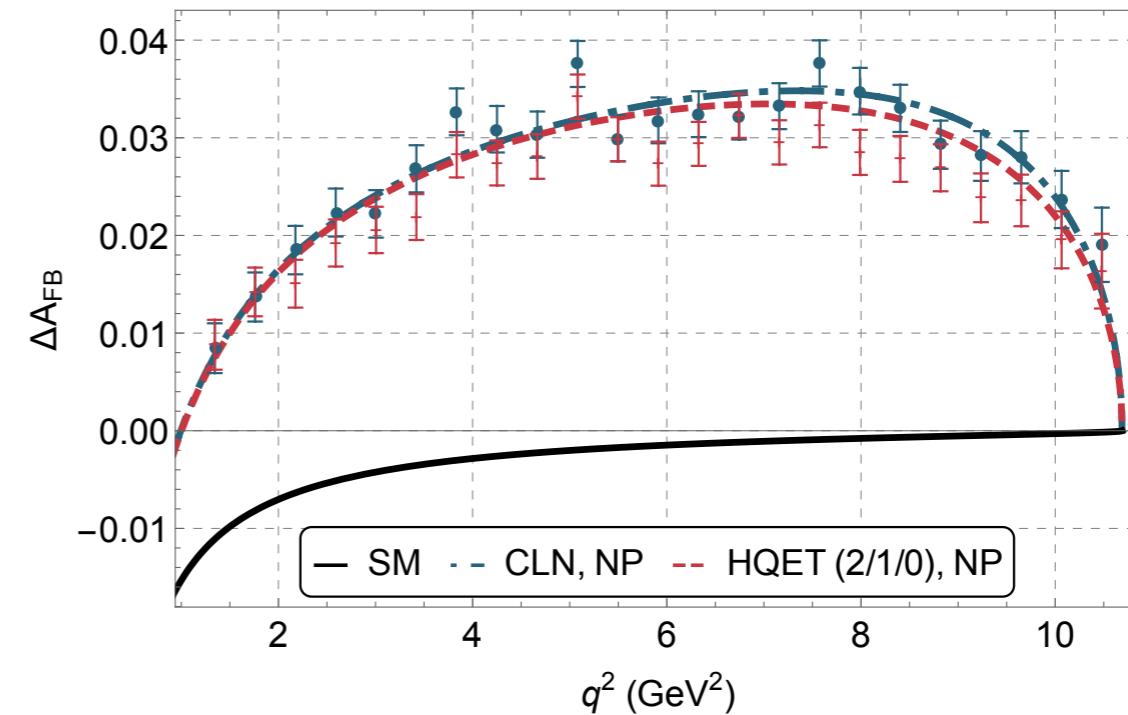
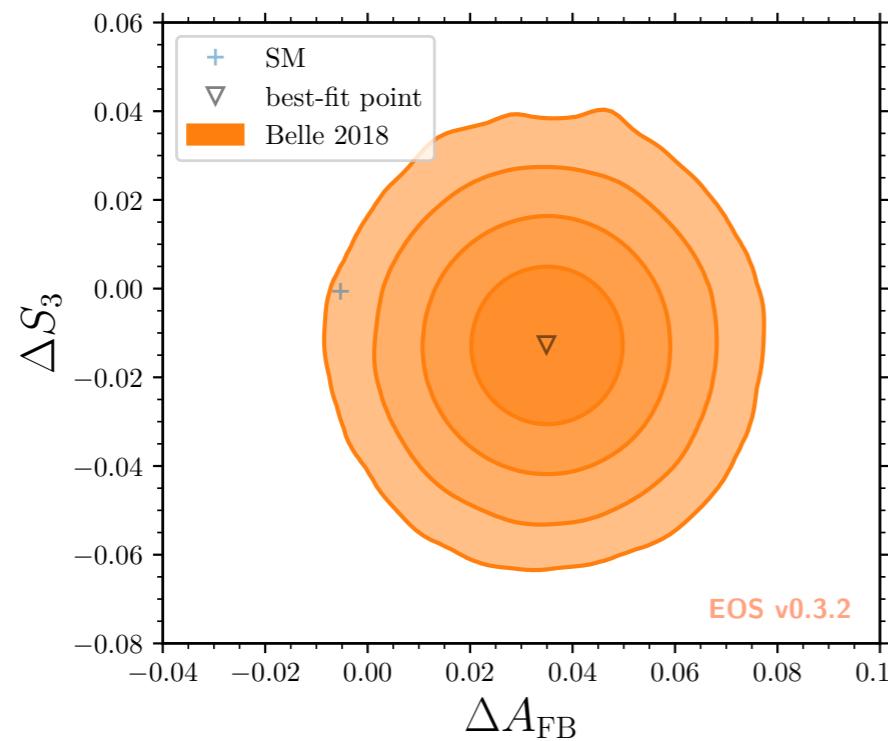
LFU in $b \rightarrow cl\nu$ [next]



[PRD 103 (2021) 7, 079901, EPJC 81 (2021) 11, 984, arXiv:2203.07189]

The forward-backward asymmetry it is an interesting observable to investigate

$$\langle A_{FB}^\tau \rangle = \int A_{FB}^\tau(q^2) = \frac{\int_0^1 \frac{d\Gamma^\tau}{dq^2 d \cos(\theta_\ell)} d \cos(\theta_\ell) - \int_{-1}^0 \frac{d\Gamma^\tau}{dq^2 d \cos(\theta_\ell)} d \cos(\theta_\ell)}{\frac{d\Gamma^\tau}{dq^2}}$$



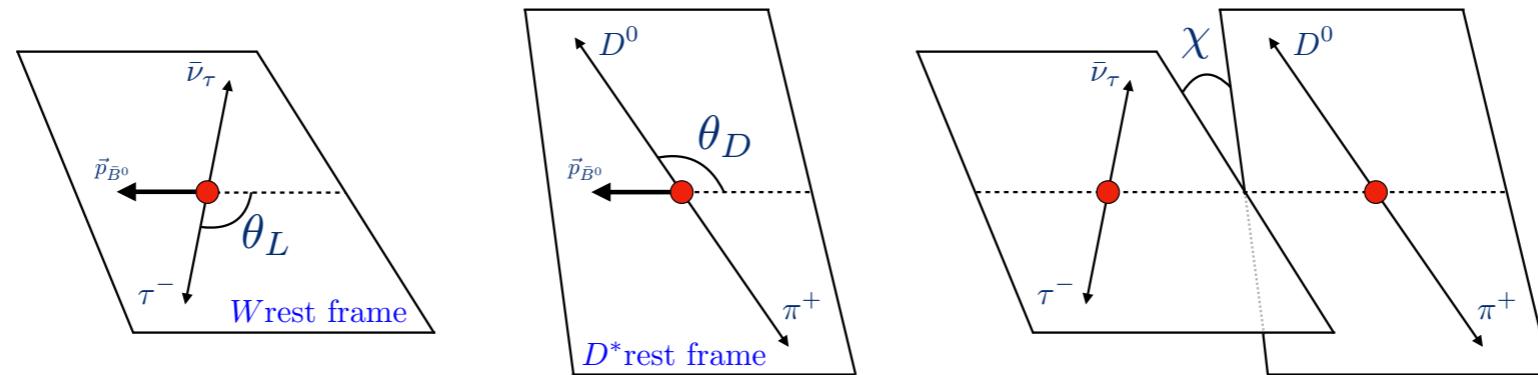
Differential measurements involving different lepton species will improve the experimental precision on this observables significantly

LFU in $b \rightarrow cl\nu$ [next]



[JHEP 11 (2019) 133]

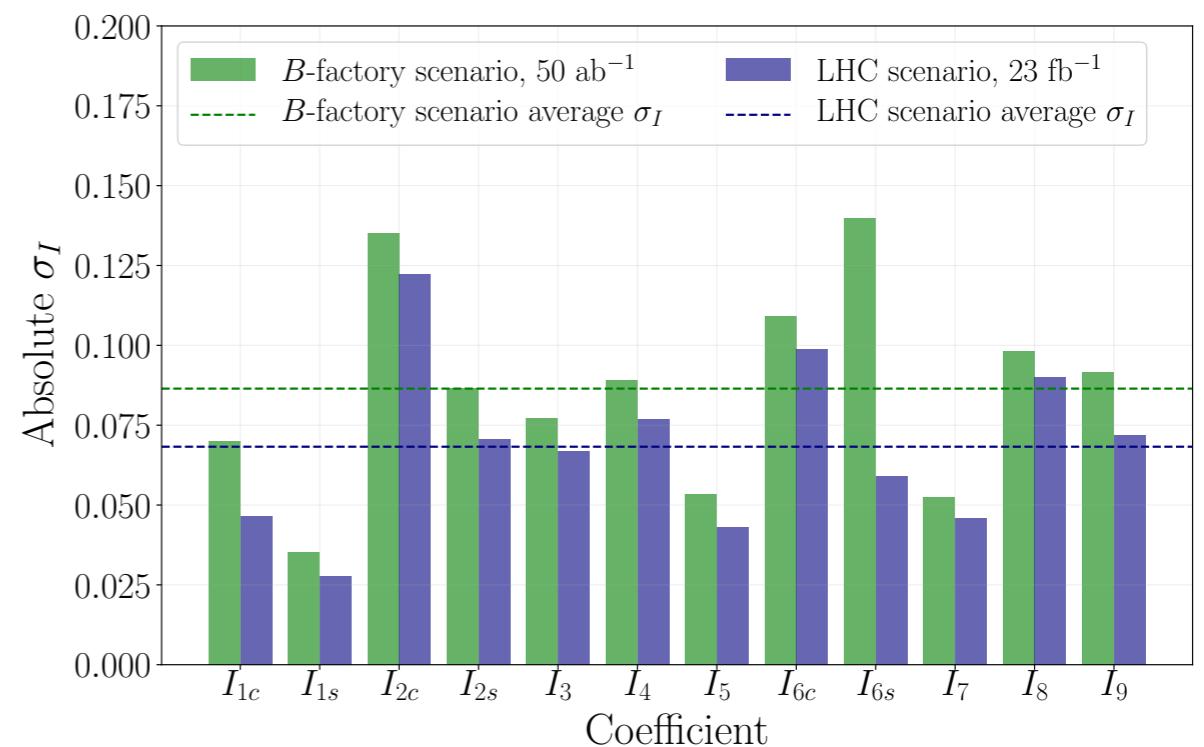
With enough data one can measure all the angular coefficients



Similar “methodology” as in $b \rightarrow s l^+l^-$

$$\frac{d^4\Gamma}{dq^2 d(\cos\theta_D) d(\cos\theta_L) d\chi} \propto I_{1c} \cos^2\theta_D + I_{1s} \sin^2\theta_D + \dots$$

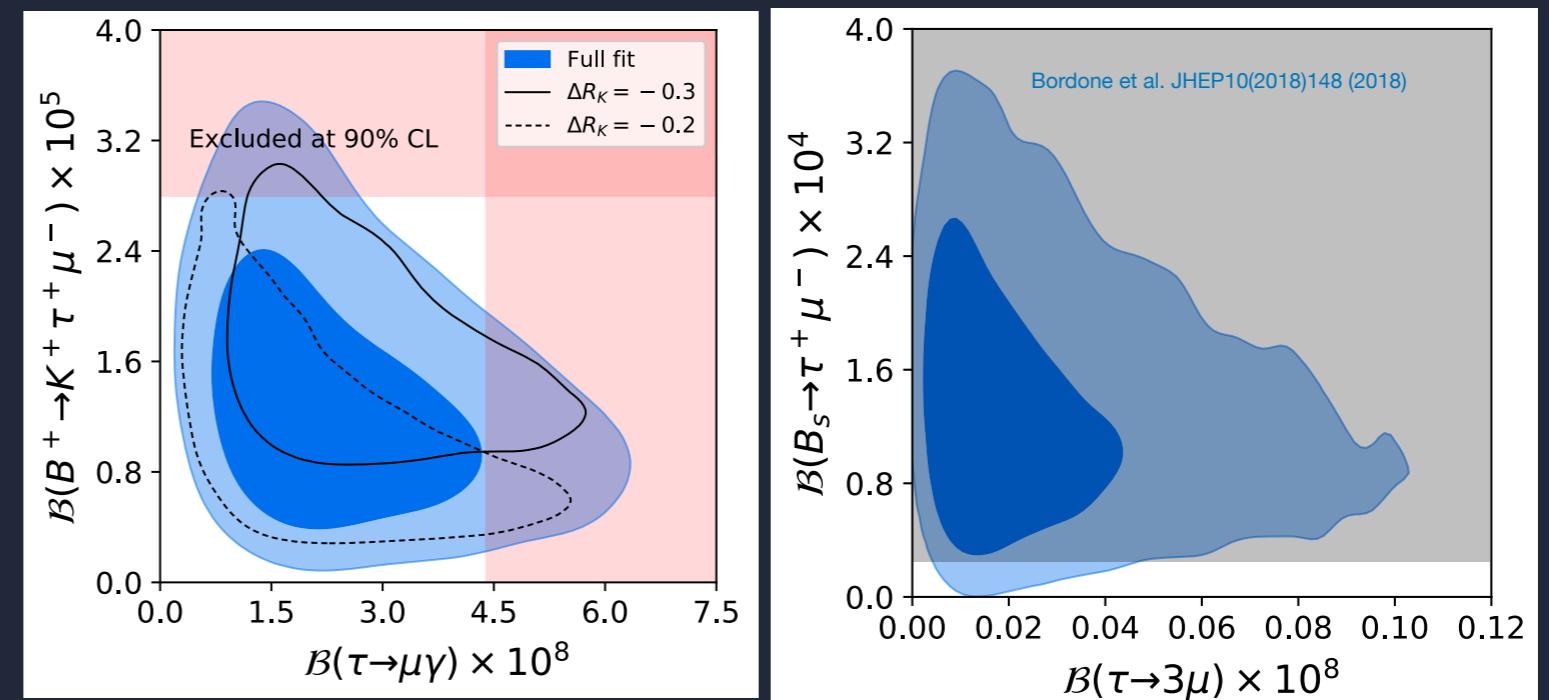
Naturally the WC fits is the next step!



LFV measurements



On the searches for LFV signatures

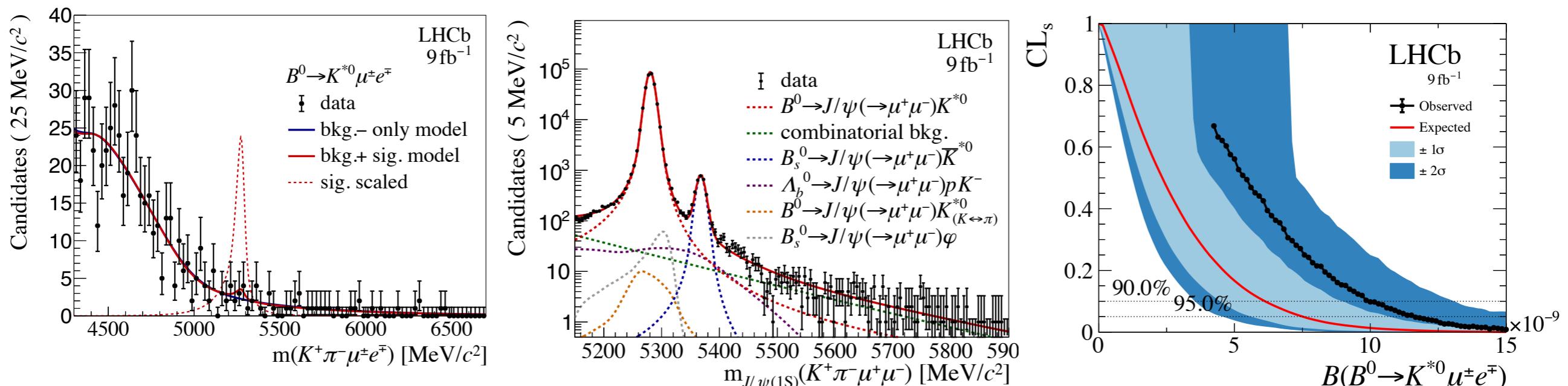


LFV analyses [today]

[Preliminary - LHCb-PAPER-2022-008]

Lepton flavour is not protected by any fundamental symmetry in the SM
 Many models explaining LFU breaking naturally predict the LFV

Recent search performed at LHCb

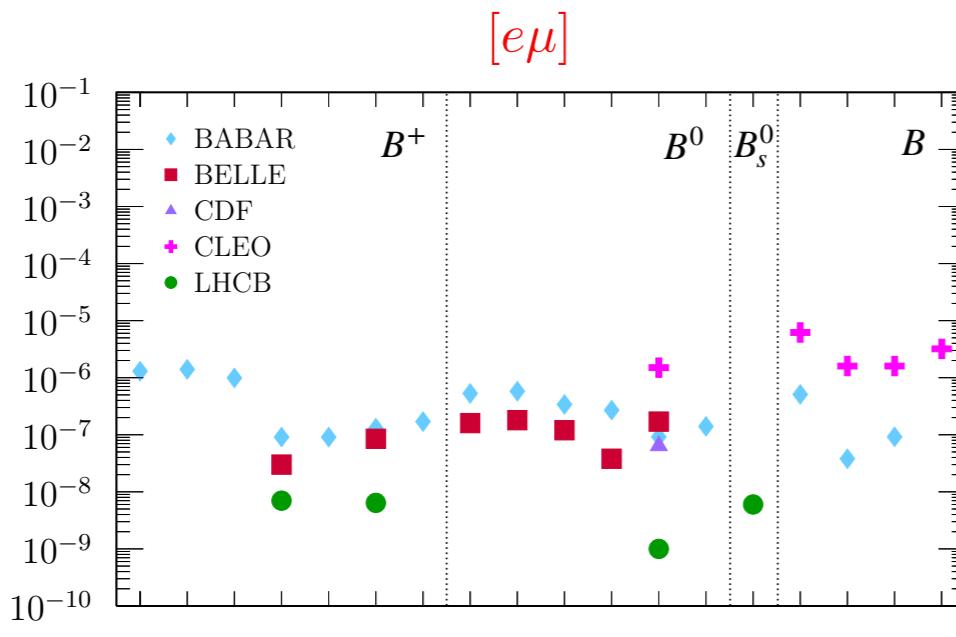


$$\mathcal{B}(B^0 \rightarrow K^{*0} \mu^\pm e^\mp) < 9.9 (11.6) \times 10^{-9}$$

Two orders of magnitude than previous searches

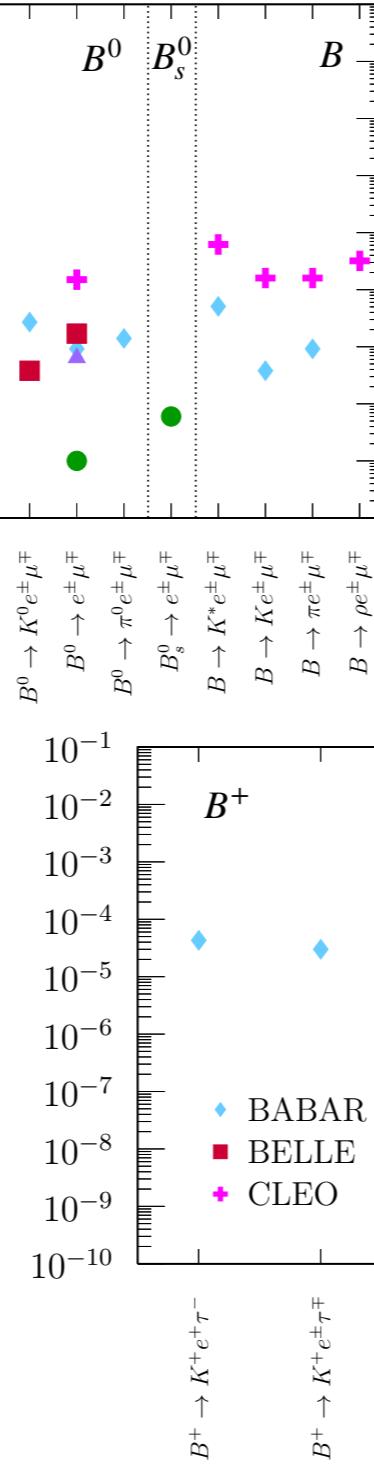
LFV analyses [today]

Upper limit at 90% C.L.



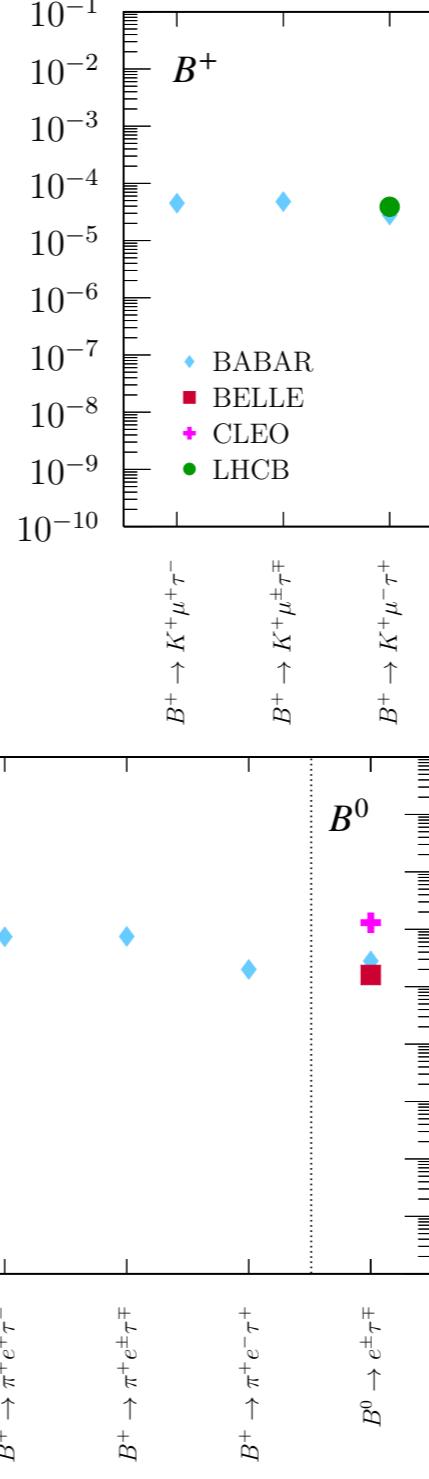
[$e\mu$]

Upper limit at 90% C.L.

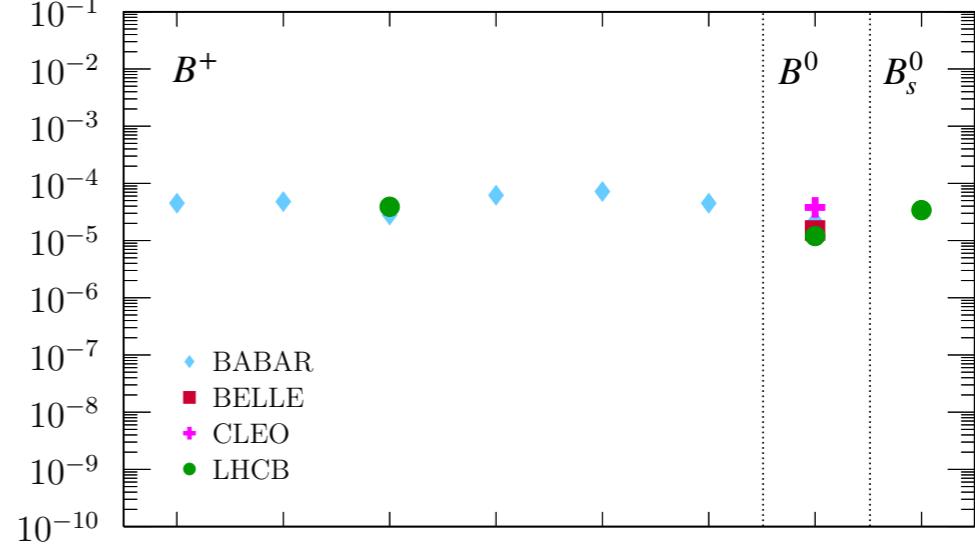


[$e\tau$]

Upper limit at 90% C.L.



[$\mu\tau$]



LFV analyses [next]



Significant improvements foreseen for the next decade

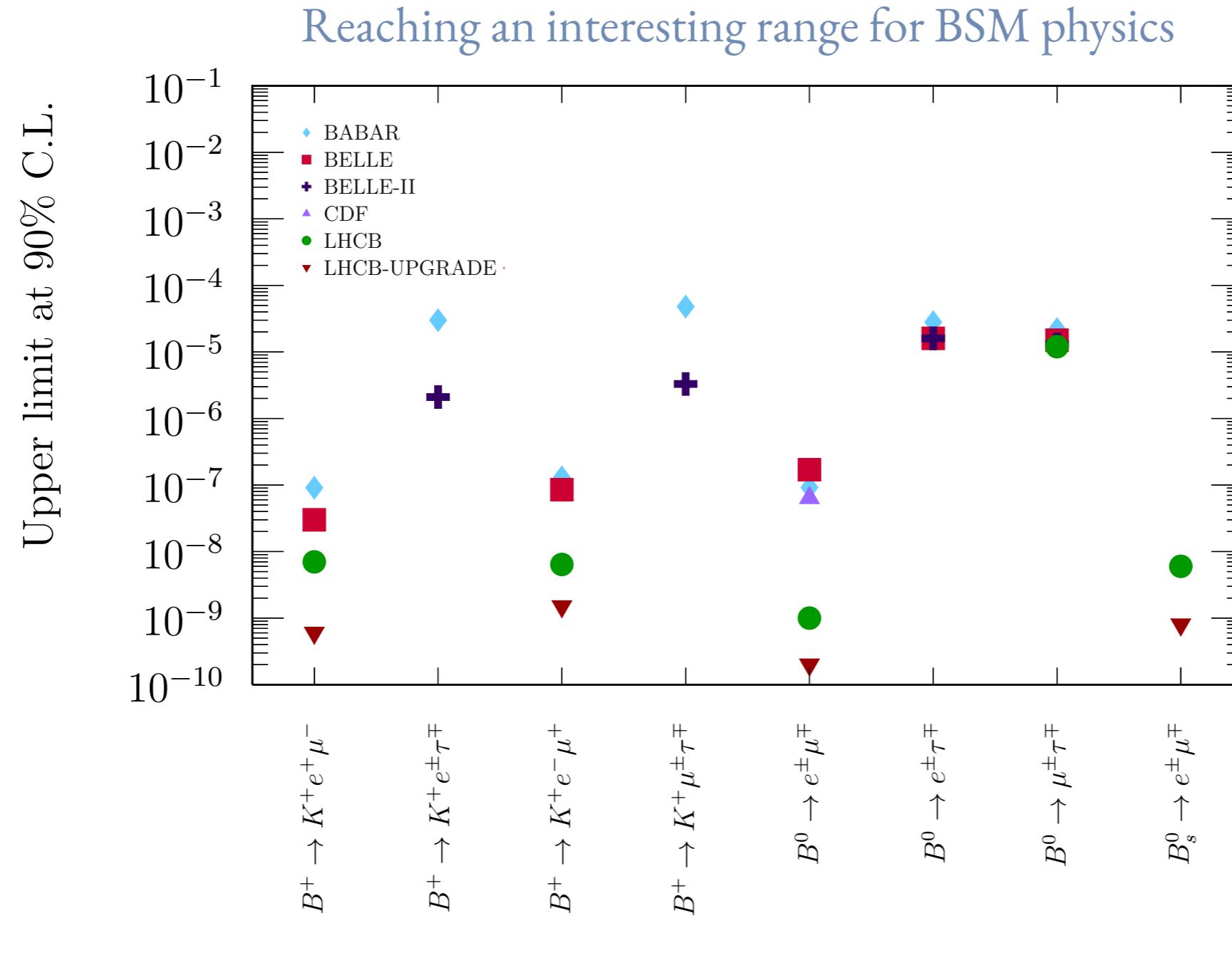
Decay	Limit @ 90% C.L.	Luminosity	Reference	Upgrade I	Upgrade II
$B^0 \rightarrow e \mu$	1.0×10^{-9}	3 fb^{-1} (Run1)	<i>JHEP 03 (2018) 078</i>	$\sim 2 \times 10^{-10}$	$\sim 9 \times 10^{-11}$
$B_s \rightarrow e \mu$	5.4×10^{-9}			$\sim 8 \times 10^{-10}$	$\sim 3 \times 10^{-10}$
$B^+ \rightarrow K^+ e^+ \mu^-$	7.0×10^{-9}	3 fb^{-1} (Run1)	<i>Phys. Rev. Lett. 123 (2019) 241802</i>	$\sim 4 \times 10^{-10}$	$\sim 7 \times 10^{-11}$
$B^+ \rightarrow K^+ e^- \mu^+$	6.4×10^{-9}			$\sim 4 \times 10^{-10}$	$\sim 6 \times 10^{-11}$
$B^0 \rightarrow K^{*0} \mu^\pm e$	9.9×10^{-9}	9 fb^{-1} (Run1+2)	<i>LHCb-PAPER-2022-008 (preliminary)</i>	$\sim 4 \times 10^{-9}$	$\sim 2 \times 10^{-9}$
$B^0 \rightarrow K^{*0} \mu^- e^+$	6.7×10^{-9}			$\sim 3 \times 10^{-9}$	$\sim 1 \times 10^{-9}$
$B^0 \rightarrow K^{*0} \mu^+ e^-$	5.7×10^{-9}			$\sim 4 \times 10^{-9}$	$\sim 1 \times 10^{-9}$
$B_s \rightarrow \phi \mu^\pm e$	1.6×10^{-8}			$\sim 4 \times 10^{-9}$	$\sim 4 \times 10^{-9}$
$B^0 \rightarrow \tau \mu$	1.2×10^{-5}	3 fb^{-1} (Run1)	<i>Phys. Rev. Lett. 123 (2019) 211801</i>	$\sim 3 \times 10^{-6}$	$\sim 1 \times 10^{-6}$
$B_s \rightarrow \tau \mu$	3.4×10^{-5}			$\sim 8 \times 10^{-6}$	$\sim 3 \times 10^{-6}$
$B^+ \rightarrow K^+ \tau \mu$	3.9×10^{-5}	9 fb^{-1} (Run1+2)	<i>JHEP 06 (2020) 129</i>	$\sim 1 \times 10^{-5}$	$\sim 5 \times 10^{-6}$
				$\sim 3 \times 10^{-9}$	$\sim 1 \times 10^{-9}$

Also: $BR(\tau \rightarrow \mu \mu \mu^-) < 4.6 \times 10^{-8}$ at 90% C.L. with 3 fb^{-1} (Run1) [*JHEP 02 (2015) 121*]

LFV analyses [next]



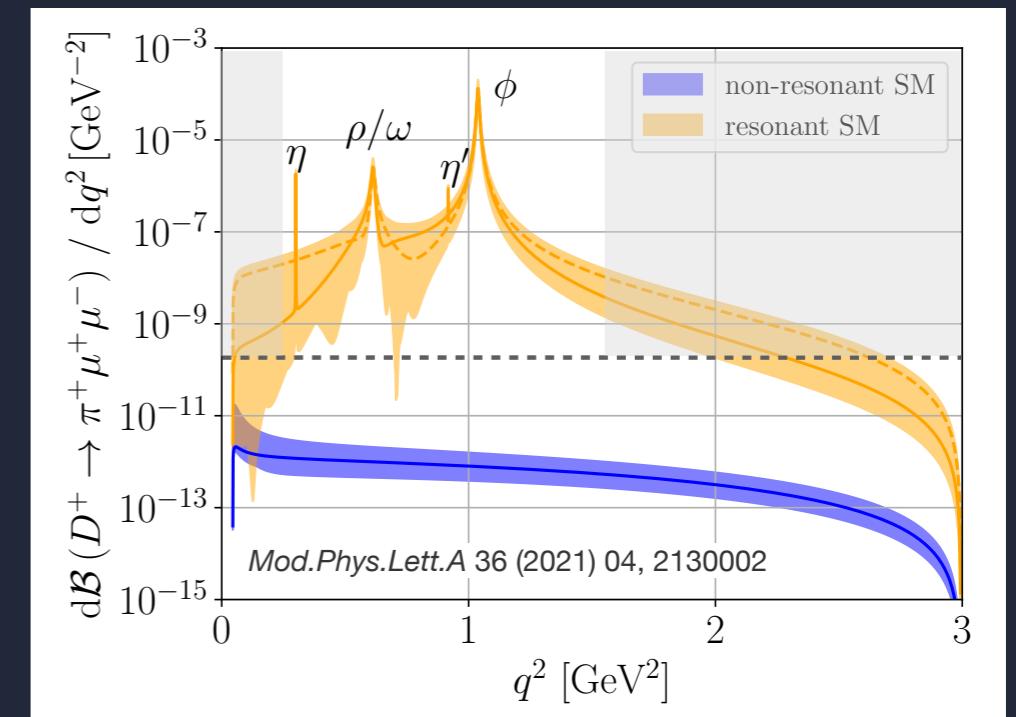
[LHCb, arXiv:1808.08865, The Belle II Physics Book]



Charm rare decays



An extensive and complementary physics programme



Charm rare decays

Unique probe of up-type quark FCNC and complementary to B and K physics

- $c \rightarrow u l^+ l^-$ FCNC more rare than the ones involving b quark
- SM can be tested with clean null-tests
- Different type of physics channels, from forbidden to not-so-rare

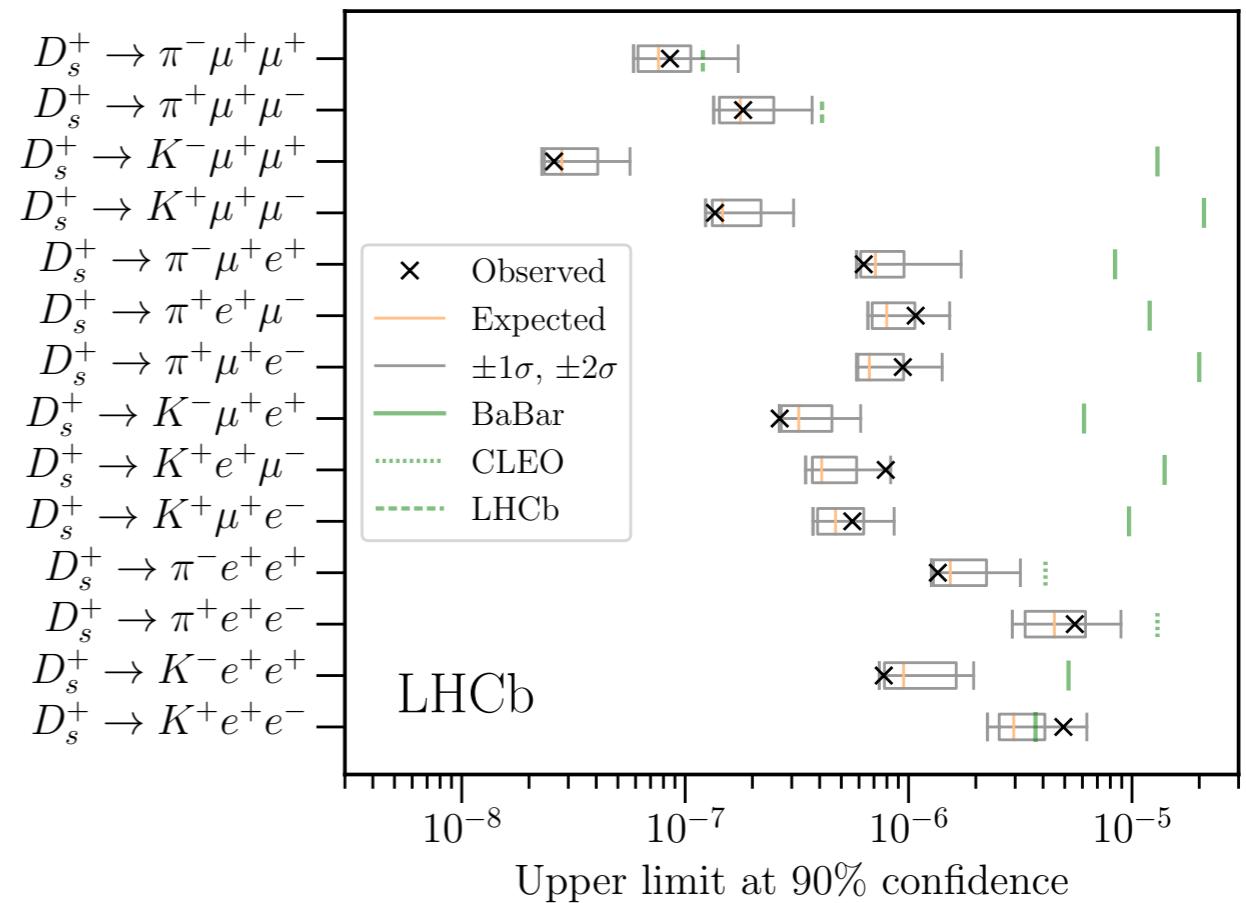
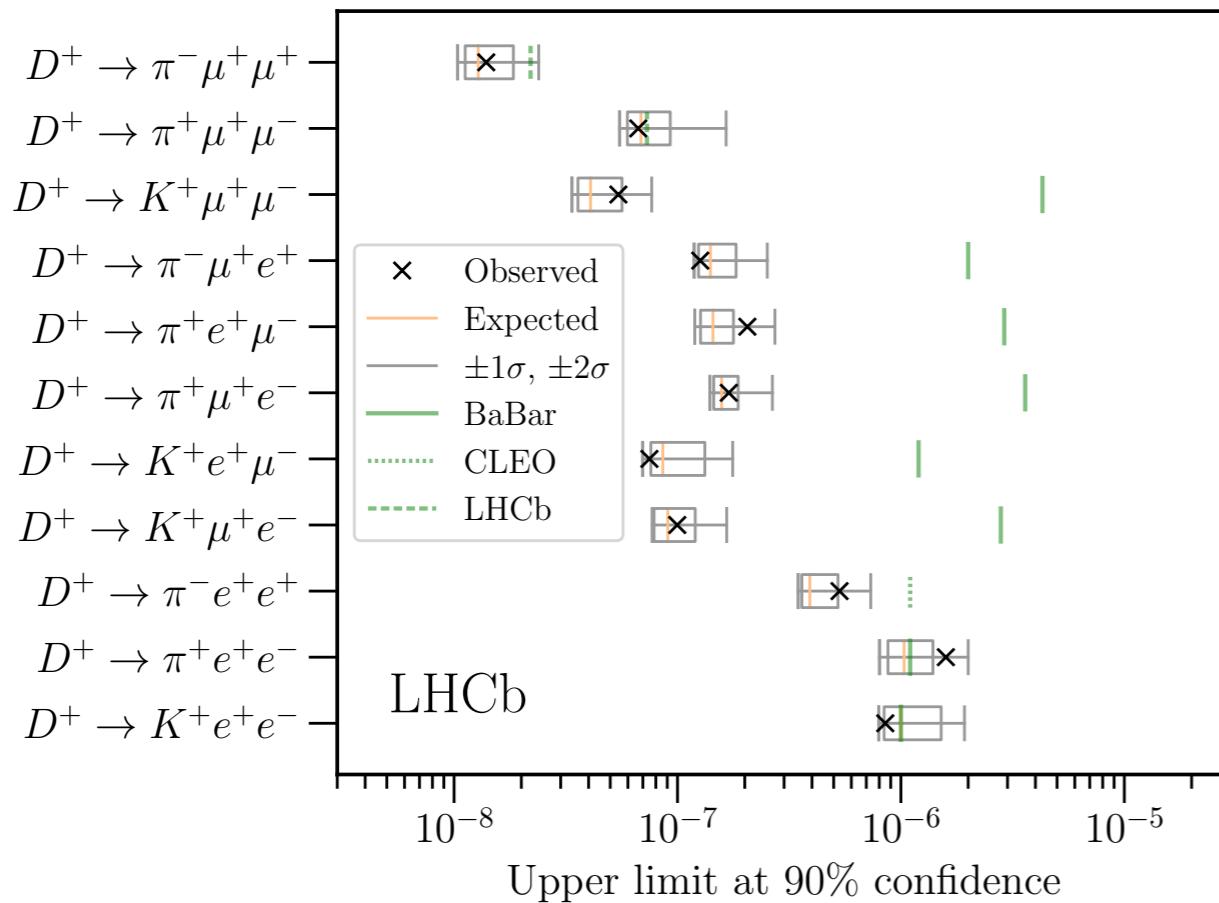
$D^0 \rightarrow \mu^+ e^-$	$D_{(s)}^+ \rightarrow \pi^+ l^+ l^-$	$D^0 \rightarrow \pi^- \pi^+ V(\rightarrow ll)$	$D^0 \rightarrow K^{*0} \gamma$
$D^0 \rightarrow p e^-$	$D_{(s)}^+ \rightarrow K^+ l^+ l^-$	$D^0 \rightarrow \rho^- V(\rightarrow ll)$	$D^0 \rightarrow (\phi, \rho, \omega) \gamma$
$D_{(s)}^+ \rightarrow h^+ \mu^+ e^-$	$D^0 \rightarrow K^- \pi^+ l^+ l^-$	$D^0 \rightarrow K^+ K^- V(\rightarrow ll)$	$D_s^+ \rightarrow \pi^+ \phi(\rightarrow ll)$
	$D^0 \rightarrow K^{*0} l^+ l^-$	$D^0 \rightarrow \phi^- V(\rightarrow ll)$	
LFV, LNV, BNV	FCNC	VMD	Radiative
10^{-15}	10^{-14}	10^{-8}	10^{-4}
$D_{(s)}^+ \rightarrow h^- l^+ l^+$	$D^0 \rightarrow \mu\mu$	$D^0 \rightarrow K^+ \pi^- V(\rightarrow ll)$	$D^+ \rightarrow \pi^+ \phi(\rightarrow ll)$
$D^0 \rightarrow X^0 \mu^+ e^-$	$D^0 \rightarrow ee$	$D^0 \rightarrow \bar{K}^{*0} V(\rightarrow ll)$	$D^0 \rightarrow K^- \pi^+ V(\rightarrow ll)$
$D^0 \rightarrow X^{--} l^+ l^+$	$D^0 \rightarrow K^+ K^- l^+ l^-$	$D^0 \rightarrow \gamma\gamma$	$D^0 \rightarrow K^{*0} V(\rightarrow ll)$
	$D^0 \rightarrow \phi^- l^+ l^-$		

Charm rare decays [today]



[LHCb, JHEP 06 (2021) 044]

Searches for 25 new charm rare/LFV/LNV



Results improve upon the prior world's best constraints by up to a factor of 500

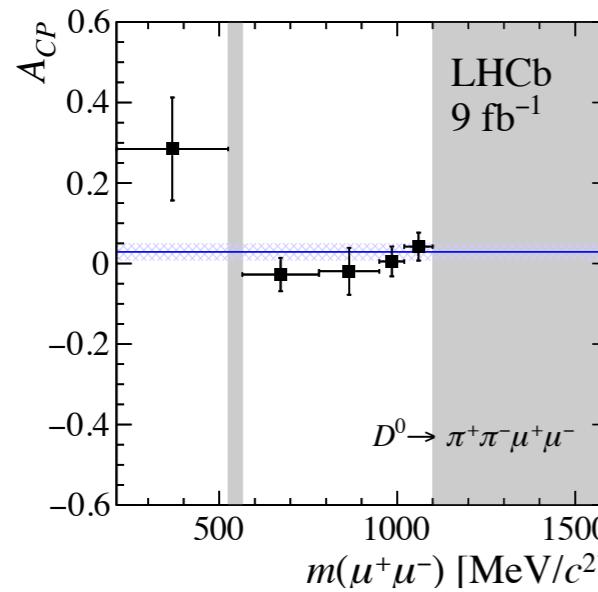
Charm rare decays [today]



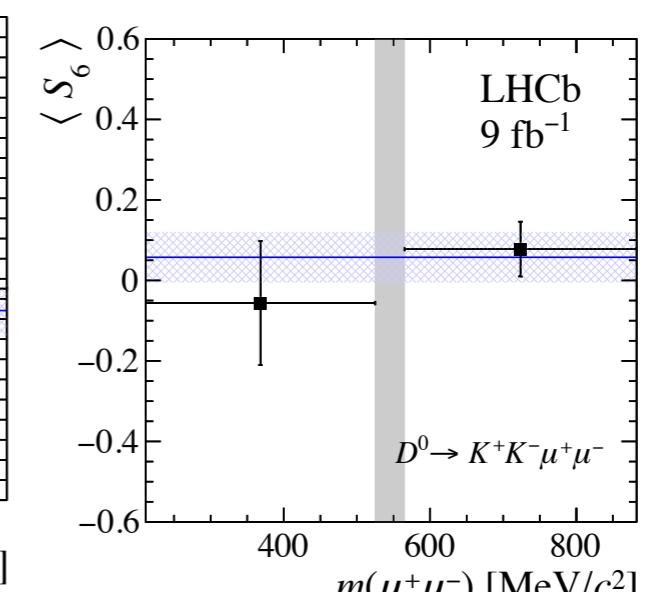
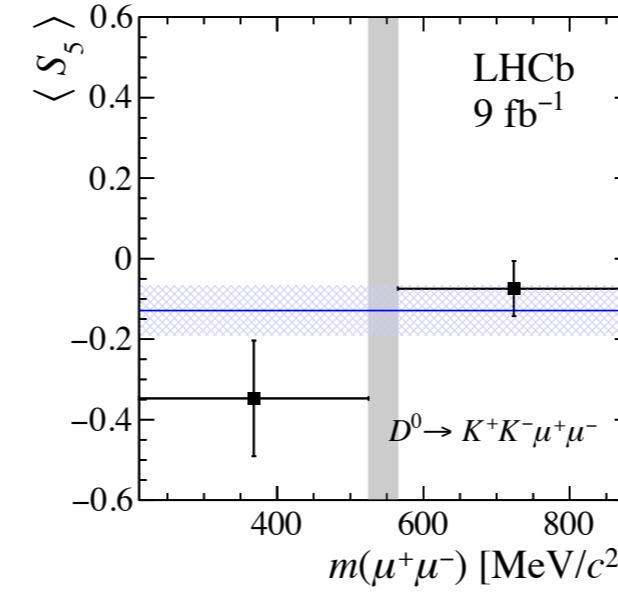
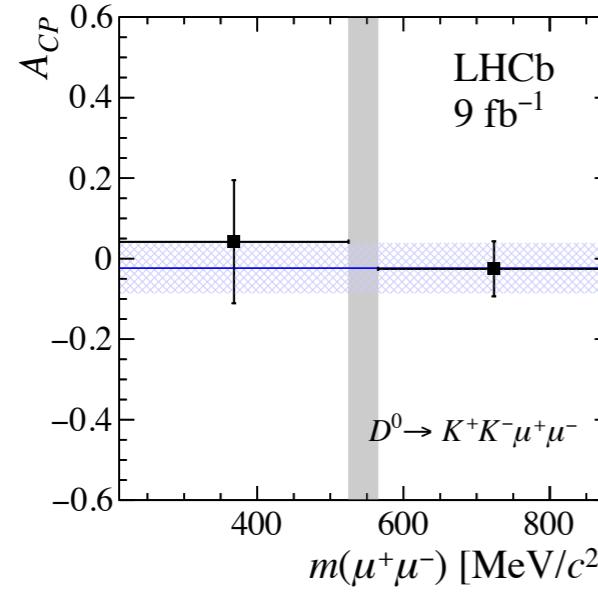
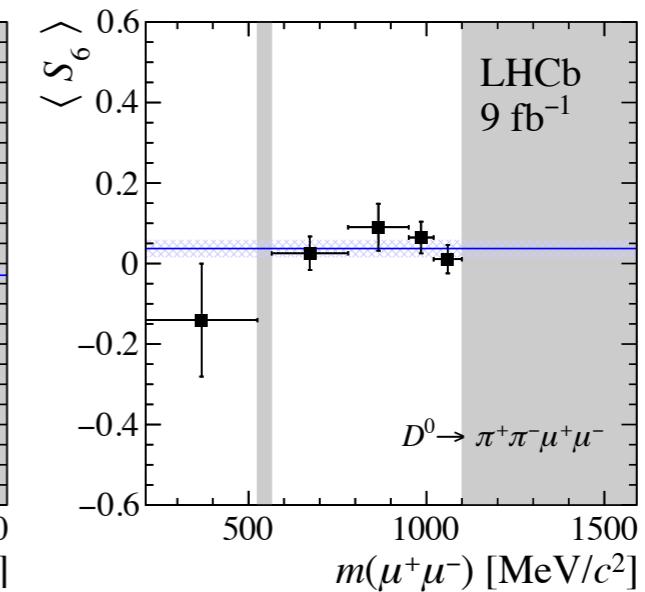
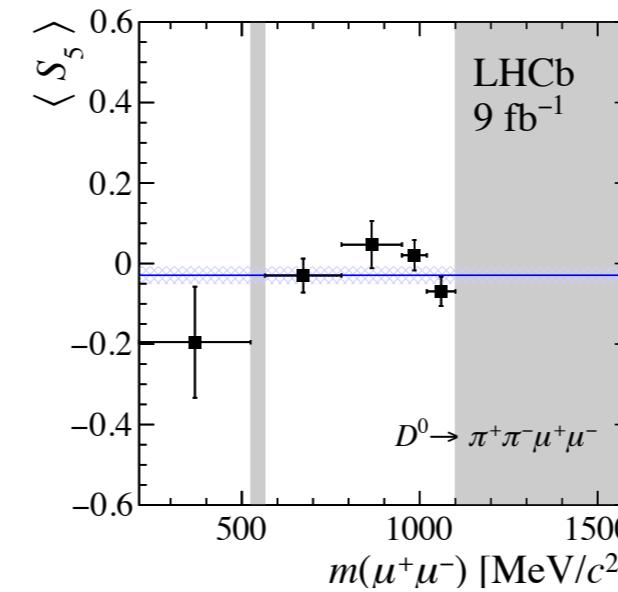
[LHCb, arXiv:2111.03327]

Similar to the B Full angular analysis of four body decays

[CP asymmetries]



[CP-averaged angular observables]





Charm rare decays [next]



[LHCb, arXiv:1808.08865]

Limits foreseen for the branching ratio

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
$D^0 \rightarrow \mu^+ \mu^-$	4.2×10^{-10}	1.3×10^{-10}
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$	10^{-8}	3×10^{-9}
$D_s^+ \rightarrow K^+ \mu^+ \mu^-$	10^{-8}	3×10^{-9}
$\Lambda_c \rightarrow p \mu^+ \mu^-$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \rightarrow e^\pm \mu^\mp$	10^{-9}	4.1×10^{-9}

Statistical precision in the asymmetry

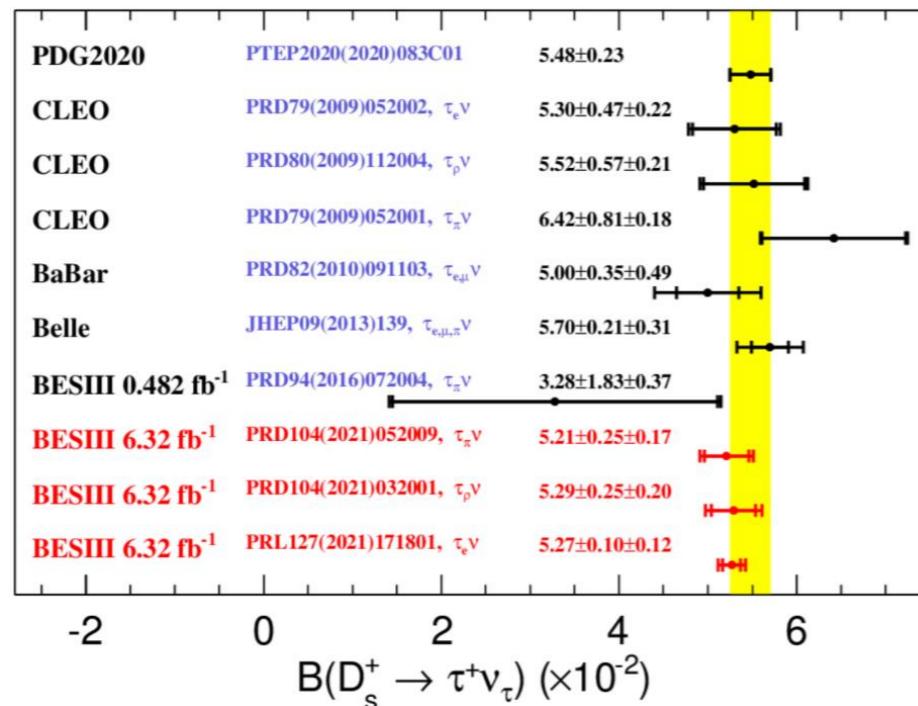
Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$	0.2%	0.08%
$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$	1%	0.4%
$D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$	0.3%	0.13%
$D^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$	12%	5%
$D^0 \rightarrow K^- K^+ \mu^+ \mu^-$	4%	1.7%

Charm rare decays [next]



[BESIII, PRD 104 (2021) 091103]

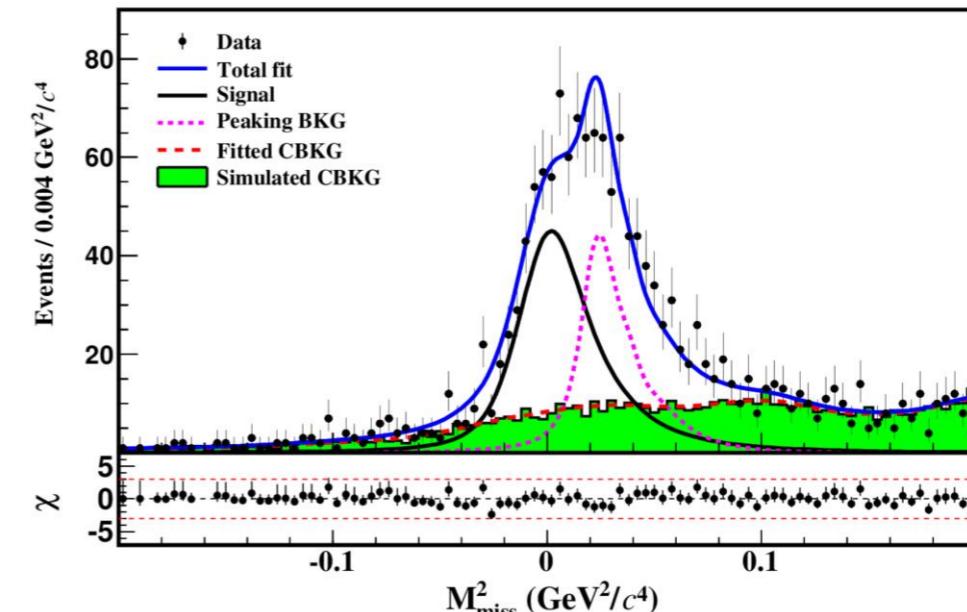
Rich environment for purely leptonic and semi-leptonic decays



$$R_{\tau/\mu} = \frac{\bar{\Gamma}(D_s^+ \rightarrow \tau^+ \nu_\tau)}{\bar{\Gamma}(D_s^+ \rightarrow \mu^+ \nu_\mu)} = \frac{m_{\tau^+}^2 \left(1 - \frac{m_{\tau^+}^2}{m_{D_s^+}^2}\right)^2}{m_{\mu^+}^2 \left(1 - \frac{m_{\mu^+}^2}{m_{D_s^+}^2}\right)^2}$$

$$= 9.67 \pm 0.34 \quad [\text{SM} : 9.75 \pm 0.01]$$

Lots of channels yet to be explored!



$$\frac{\mathcal{B}(D^0 \rightarrow \rho^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \rightarrow \rho^- e^+ \nu_e)} = 0.90 \pm 0.11 \quad \text{SM prediction } [0.93, 0.96]$$

Precision for $D^+ \rightarrow l\nu$ or D_s in purely leptonic of 10% and 3%



Charm rare decays [next]

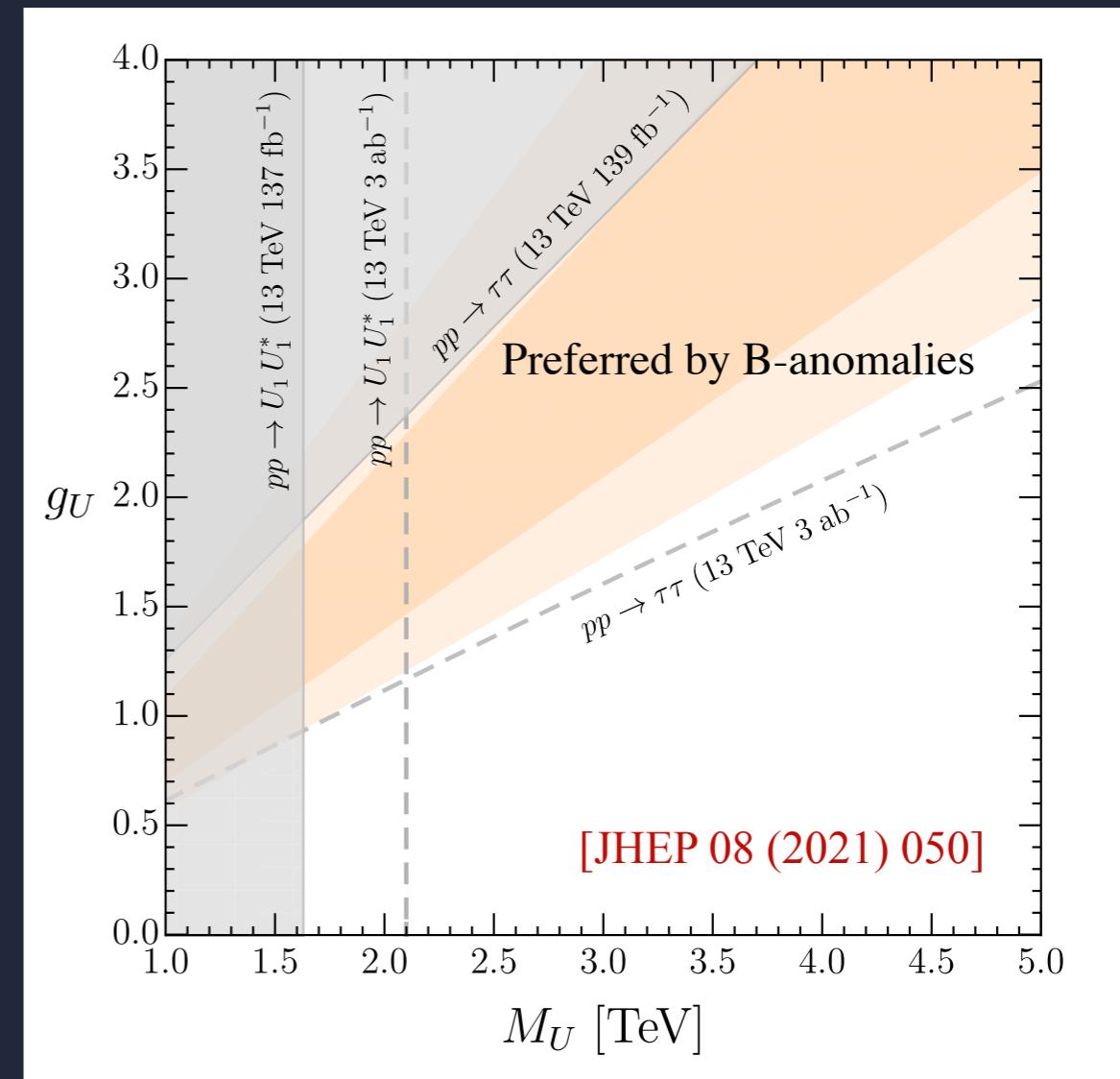
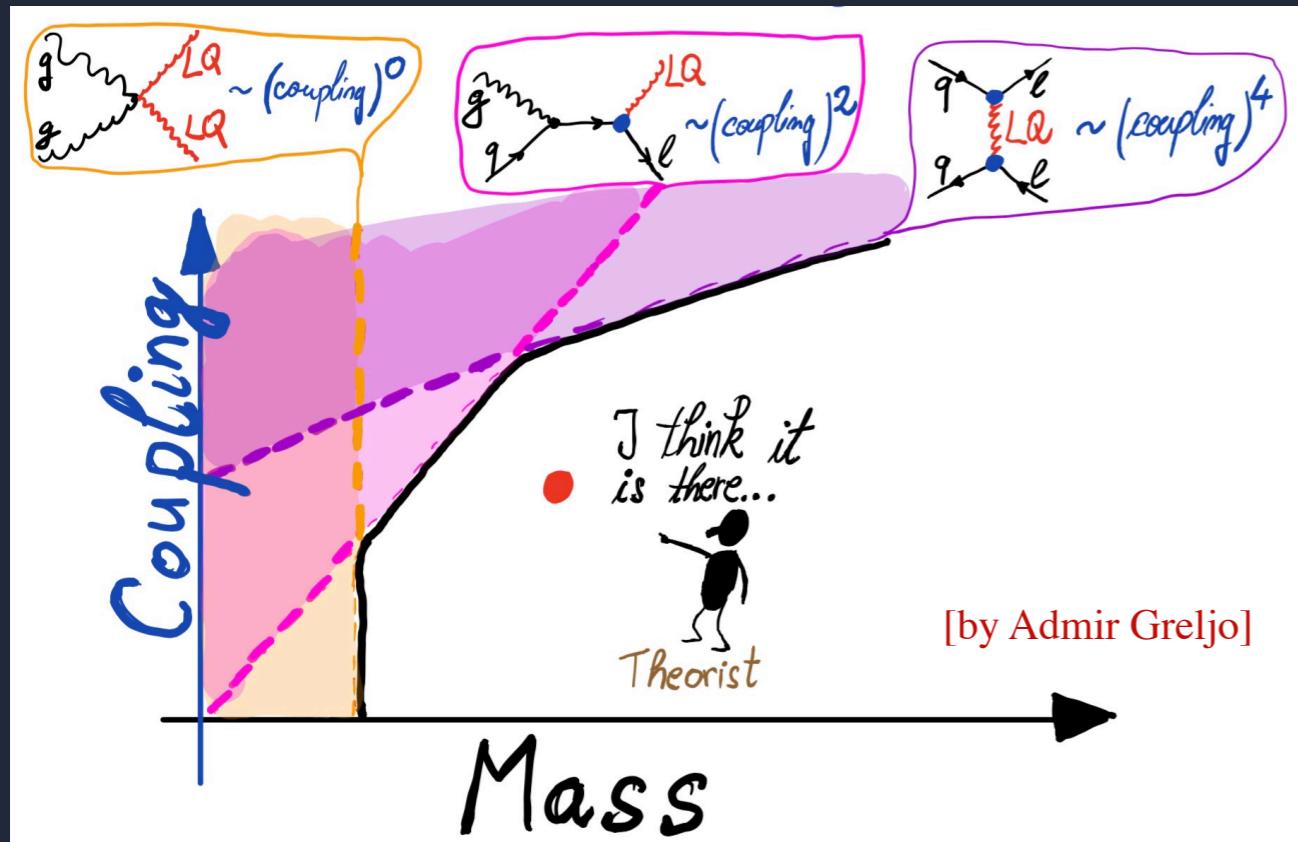


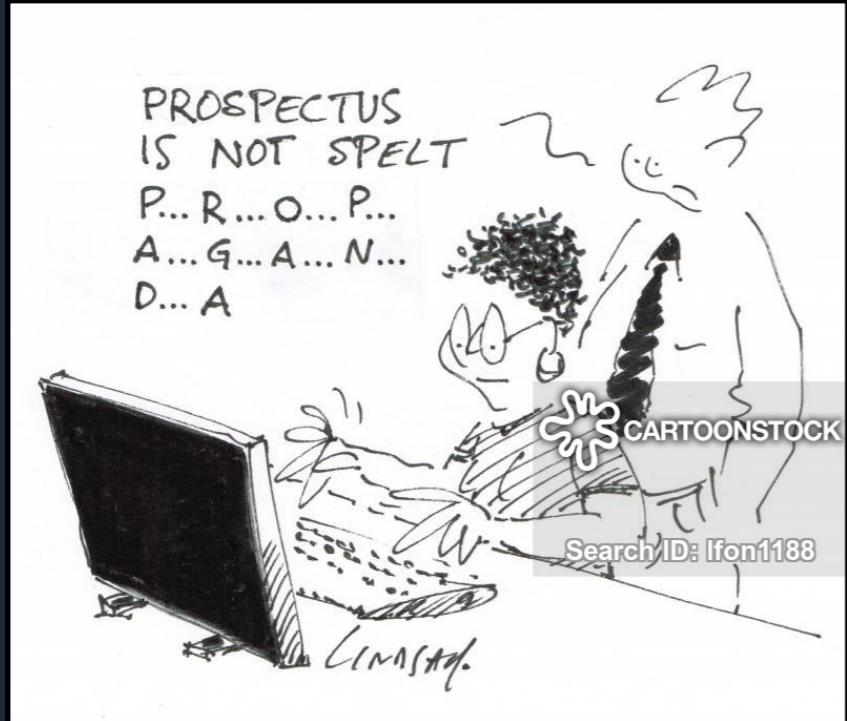
[STCF, arXiv: 2203.03211]

	BESIII	STCF	Belle II
Luminosity	2.93 fb ⁻¹ at 3.773 GeV	1 ab ⁻¹ at 3.773 GeV	50 ab ⁻¹ at $\Upsilon(nS)$
$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu)$	5.1% _{stat} 1.6% _{syst} [6]	0.28% _{stat}	—
f_{D^+} (MeV)	2.6% _{stat} 0.9% _{syst} [6]	0.15% _{stat}	—
$ V_{cd} $	2.6% _{stat} 1.0% _{syst} [*] [6]	0.15% _{stat}	—
$\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau)$	20% _{stat} 10% _{syst} [7]	0.41% _{stat}	—
$\frac{\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau)}{\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu)}$	21% _{stat} 13% _{syst} [7]	0.50% _{stat}	—
Luminosity	3.2 fb ⁻¹ at 4.178 GeV	1 ab ⁻¹ at 4.009 GeV	50 ab ⁻¹ at $\Upsilon(nS)$
$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)$	2.8% _{stat} 2.7% _{syst} [8]	0.30% _{stat}	0.8% _{stat} 1.8% _{syst}
$f_{D_s^+}$ (MeV)	1.5% _{stat} 1.6% _{syst} [8]	0.15% _{stat}	—
$ V_{cs} $	1.5% _{stat} 1.6% _{syst} [8]	0.15% _{stat}	—
$f_{D_s^+}/f_{D^+}$	3.0% _{stat} 1.5% _{syst} [8]	0.21% _{stat}	—
$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau)$	2.2% _{stat} 2.6% _{syst} [†]	0.24% _{stat}	0.6% _{stat} 2.7% _{syst}
$f_{D_s^+}$ (MeV)	1.1% _{stat} 1.5% _{syst} [†]	0.11% _{stat}	—
$ V_{cs} $	1.1% _{stat} 1.5% _{syst} [†]	0.11% _{stat}	—
$\overline{f}_{D_s^+}^{\mu\&\tau}$ (MeV)	0.9% _{stat} 1.0% _{syst} [†]	0.09% _{stat}	0.3% _{stat} 1.0% _{syst}
$ \overline{V}_{cs}^{\mu\&\tau} $	0.9% _{stat} 1.0% _{syst} [†]	0.09% _{stat}	—
$\frac{\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)}$	3.6% _{stat} 3.0% _{syst} [†]	0.38% _{stat}	0.9% _{stat} 3.2% _{syst}

A “flavourful” path to NP?

On the interplay between direct and indirect searches





SUMMARY

- Very rich physics programme with unprecedented discovery potential in the near future
- Intriguing set of anomalies in B meson decays
i.e. decay rates, angular analysis, LFU analyses

WHAT COMES NEXT?

- More data, more channels, more observables, novel ideas
- Full understanding of the field will require a combined effort of the different experiments
- A PRECISION FLAVOUR PHYSICS ERA AHEAD OF US!
[a “compass” to the LHC searches?]

'Strange pale penguin': rare yellow and white bird discovered among king

