

B-flavour constraints on BSM

Flavio Archilli

Lepton Photon 2019

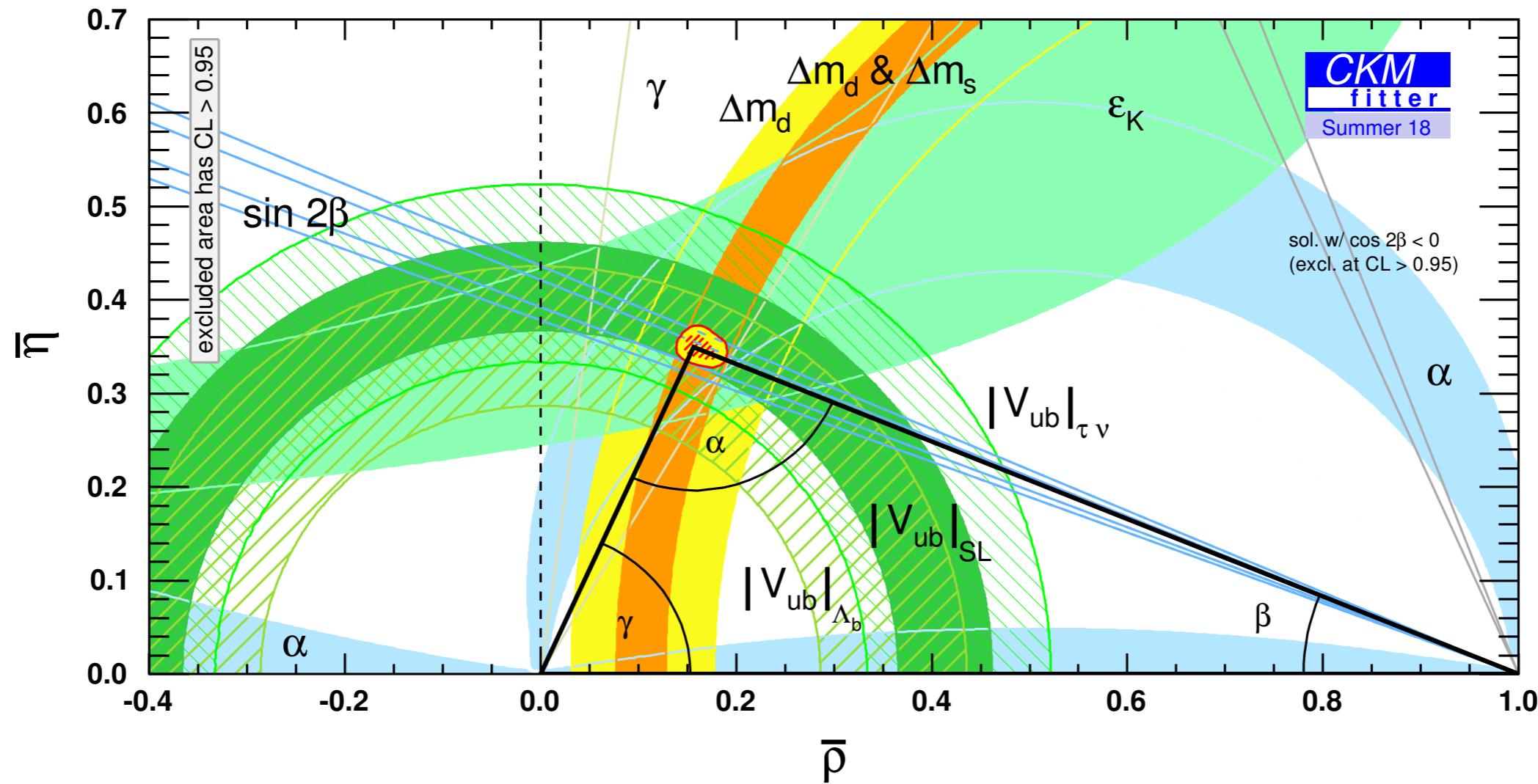
5/8/2019 - 10/8/2019



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Why flavour physics?



- SM very successful theory able to explain physics up to the EW scale
- **Still incomplete theory**
- O(20%) NP effects to loop-level process still allowed

Why flavour physics?

- SM as a effective theory at low energy
- New degrees of freedom expected above the EW scale

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}$$

- Precise measurement of precision process at low energy

$$\mathcal{A}_{i \rightarrow j} = \mathcal{A}_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

The diagram illustrates the relationship between the Standard Model (SM) and New Physics (NP). A green circle labeled "coupling" points from the NP scale term (c_{NP}/Λ^2) to the SM term (c_{SM}/M_W^2). A red circle labeled "NP scale" points from the NP scale term back to itself, indicating that it is a theoretical input.

- **SM predictions and inputs** have to be under theoretical control

Main players

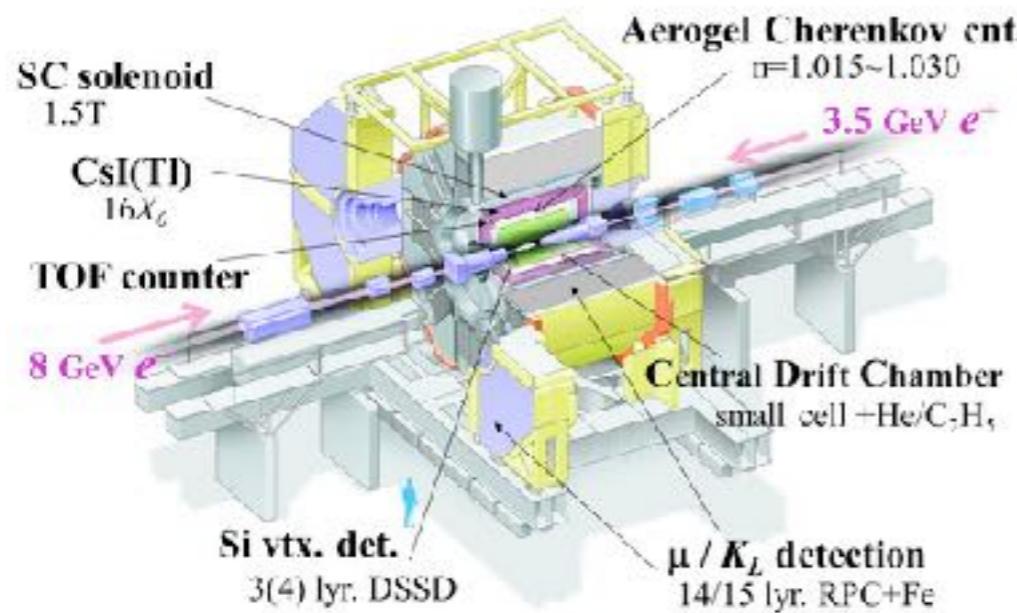
Nucl.Instrum.Meth. A479 (2002) 117-232

Nucl.Instrum.Meth.A479:1-116,2002

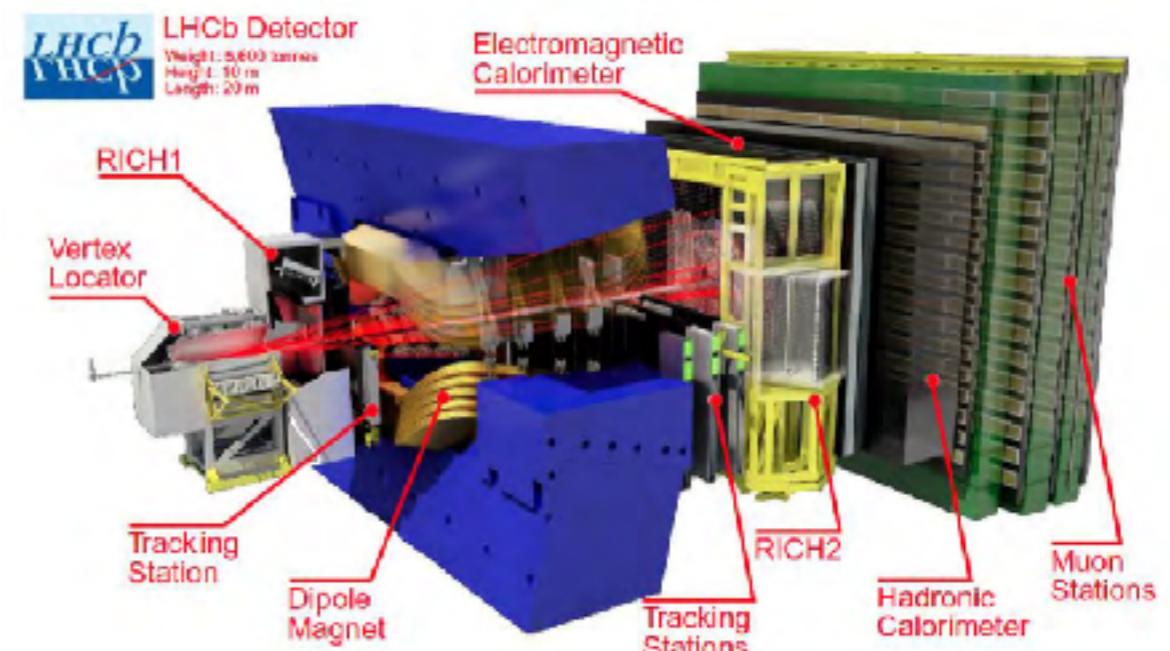
JINST 3 (2008) S08005

B-factories

The Belle detector



hadronic machines - LHCb

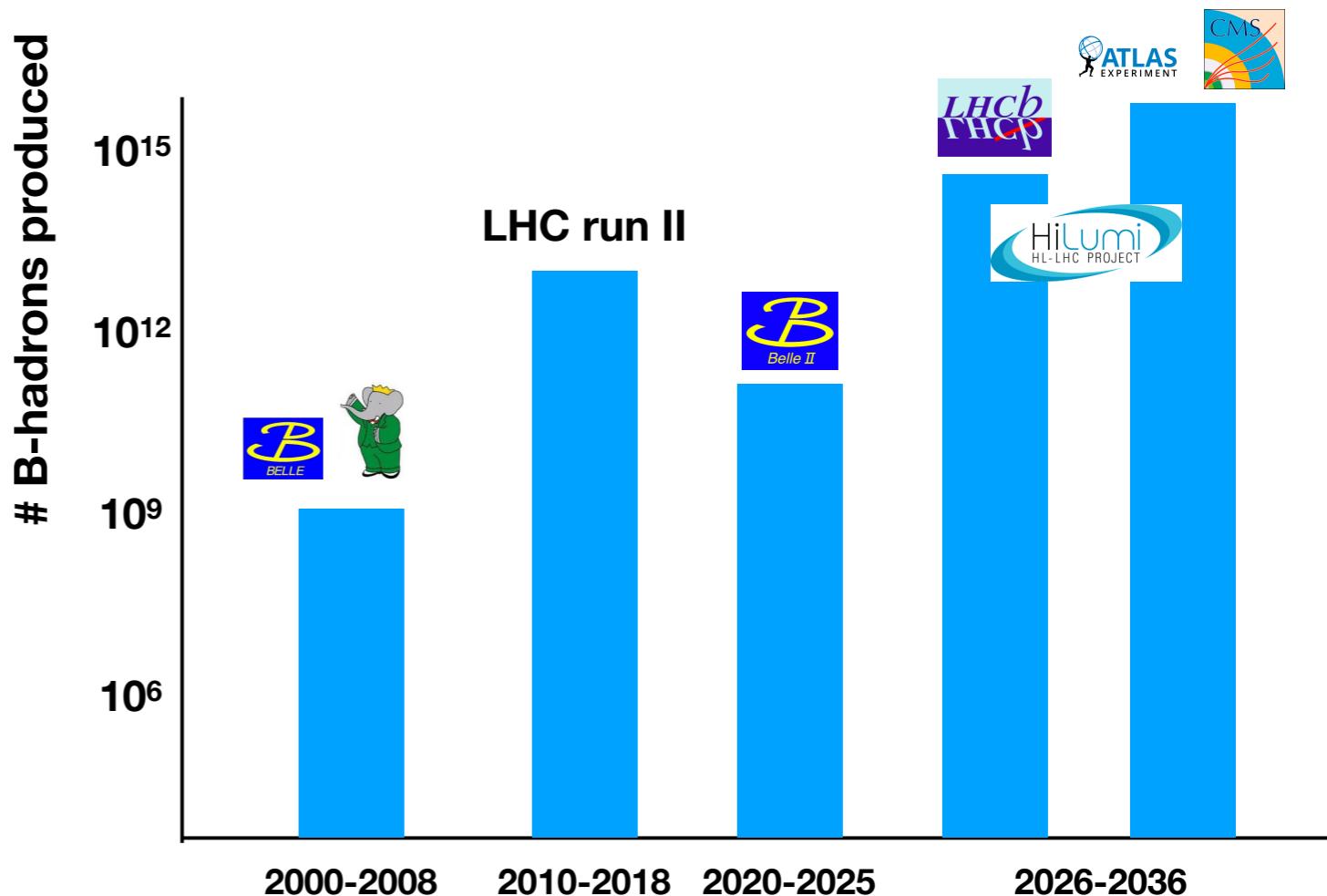


- bb x-section $\sim 0.001\mu\text{b}$
- Cleaner environment, simpler trigger
- Smaller production rate, mostly B⁰/B⁺ physics

- bb x-section $\sim 500\mu\text{b}$
- Larger production rate, all b-hadron species
- Harsher environment, difficult trigger

B-physics Precision era

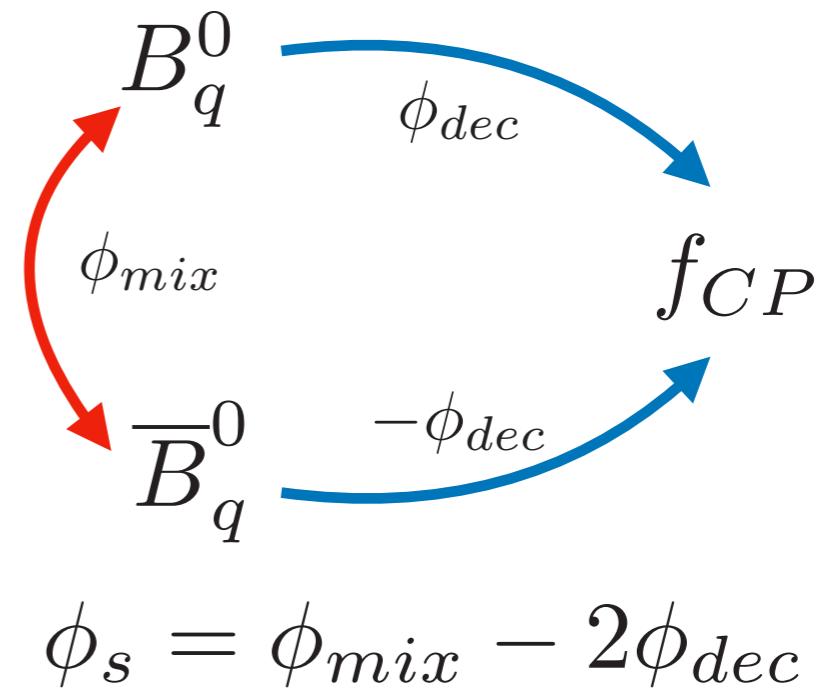
- New precision era in B physics
- In the future CMS and ATLAS will produce a B-factory (10^9 B's) dataset every 20s



CP violation in B_s -system

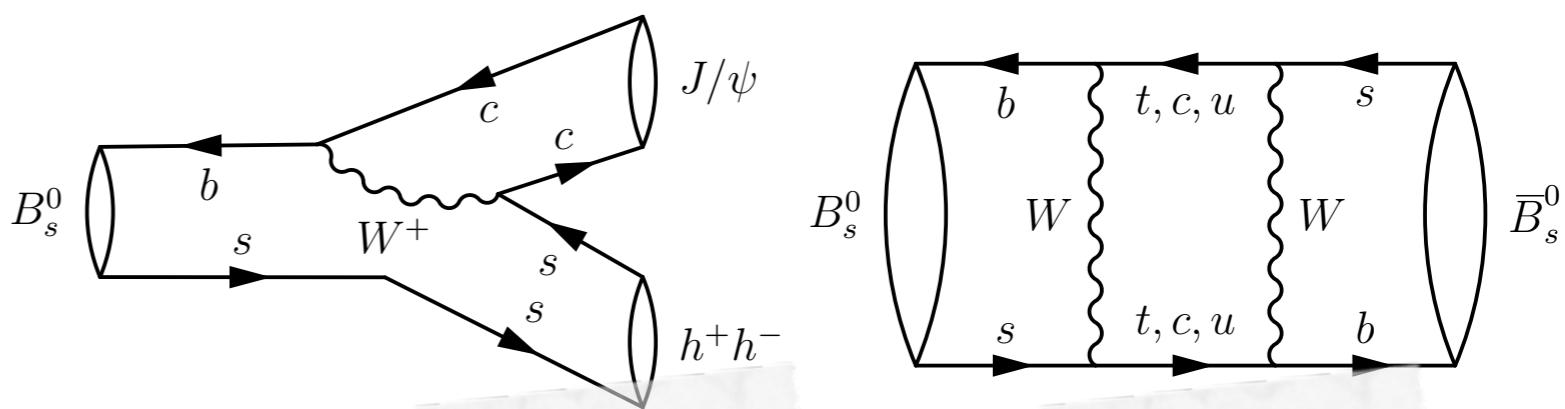
- Interference between the **decay amplitudes** and the **mixing** can give rise to a CP violating phase.
- CP-asymmetry small in SM \rightarrow particularly sensitive to new particles

$$\phi_s^{\text{SM}} = -36.86^{+0.96}_{-0.68} \text{ mrad}$$



- time dependant angular analysis:

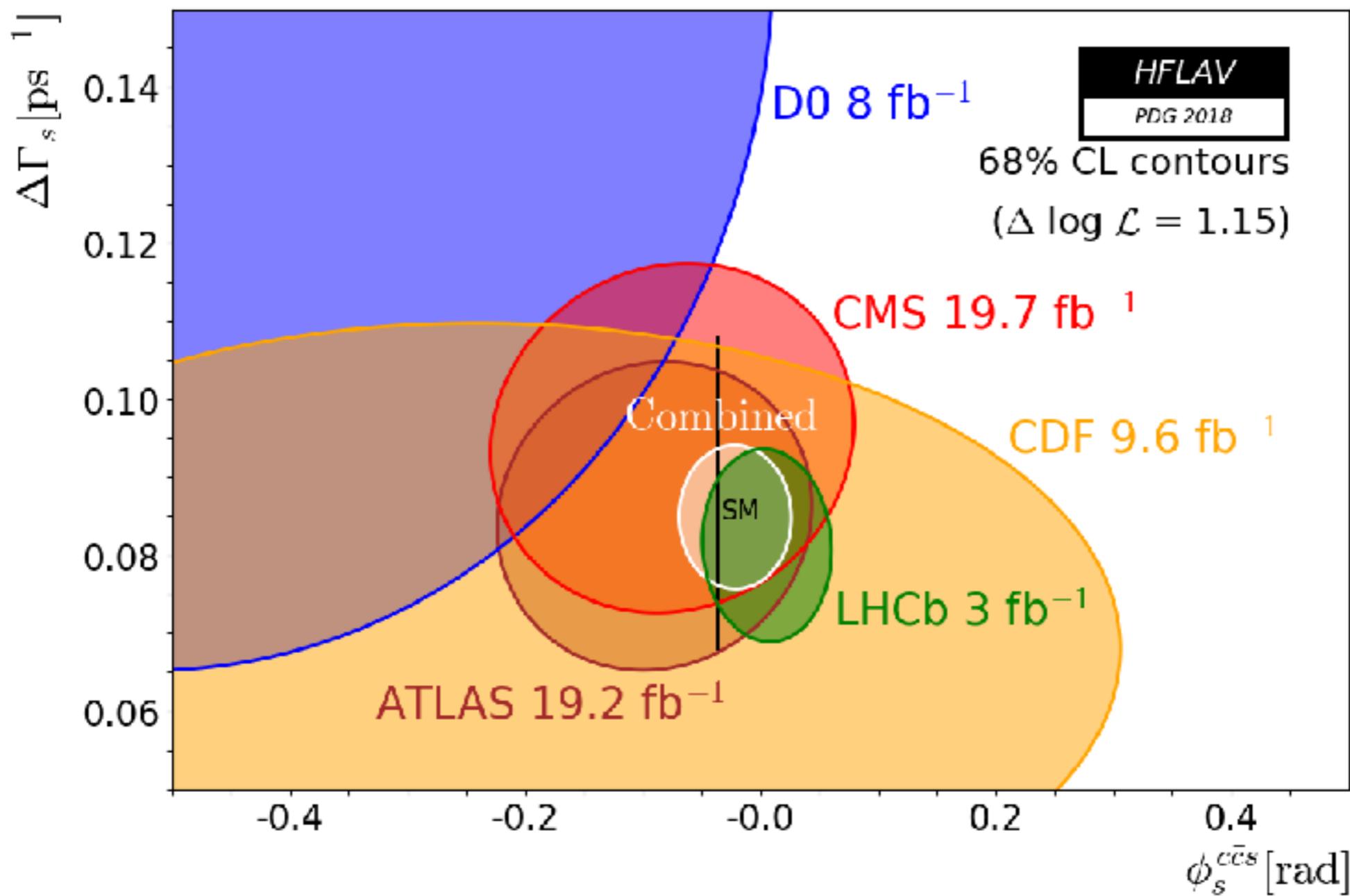
- good time resolution
- flavour tagging
- decay time acceptance
- Update with $B_s^0 \rightarrow J/\psi K K$ and $B_s^0 \rightarrow J/\psi \pi \pi$



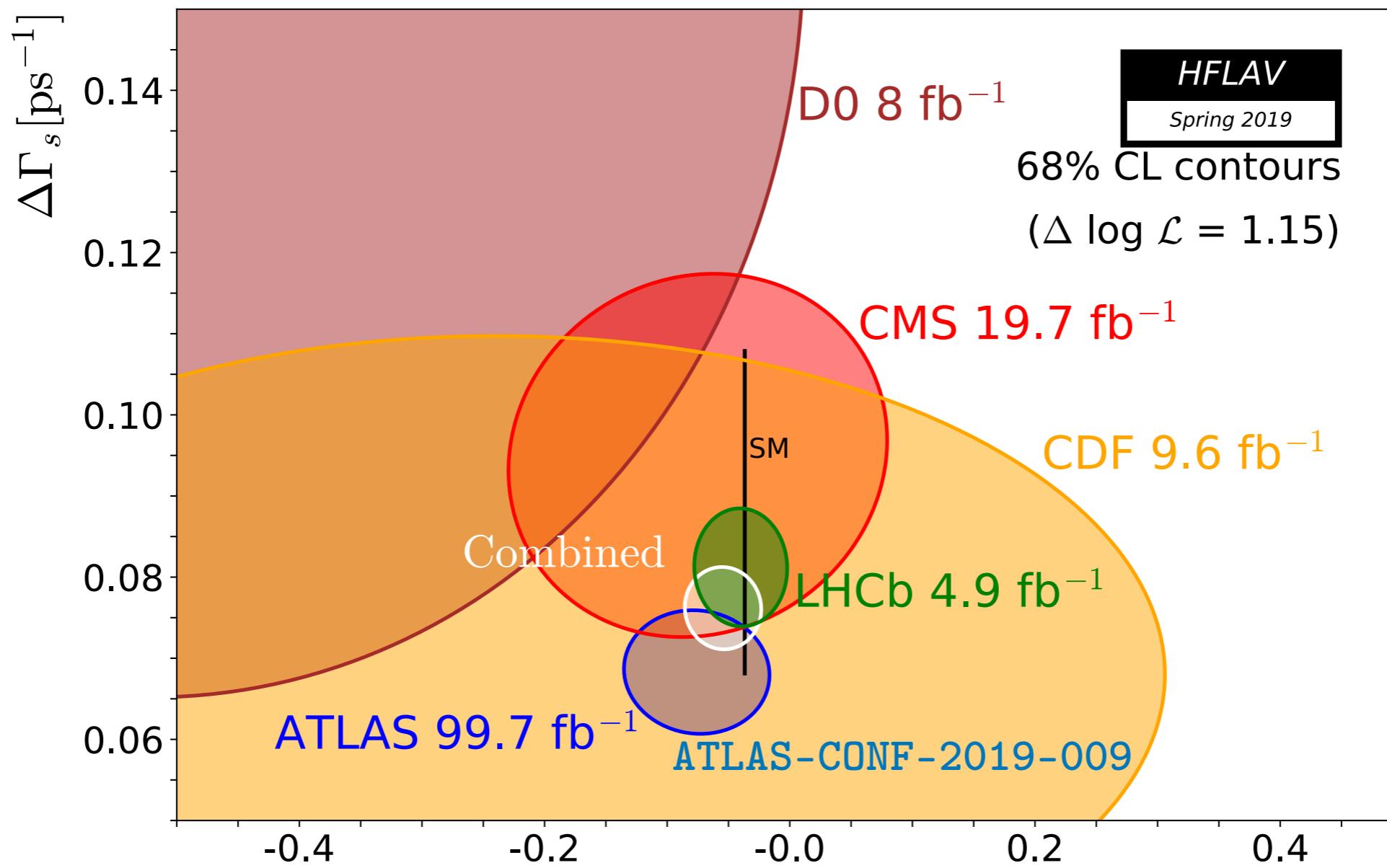
more details in
Cibran Santamarina
Rios's talk

and Shohei Nishida's
talk

CP violation in B_s -system



CP violation in B_s -system



LHCb combined

arXiv:1906.08356

$$\phi_s^{c\bar{c}s} = -0.041 \pm 0.025 \text{ rad}$$

$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$

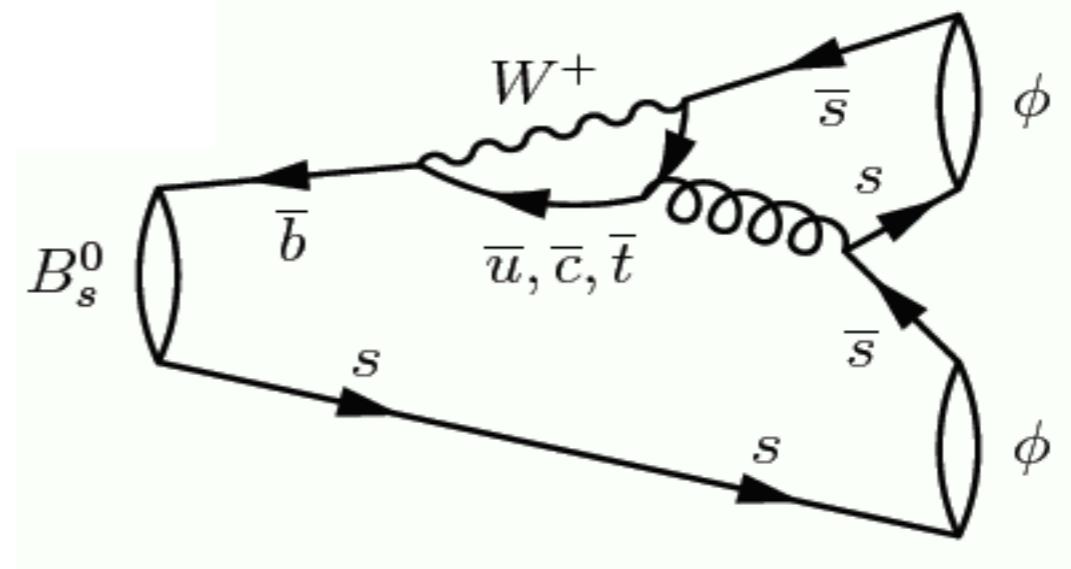
HFLAV average

$$\phi_s^{c\bar{c}s} = -0.055 \pm 0.021 \text{ rad}$$

$$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1}$$

ϕ_s from penguin

- In penguin-dominated decays $B_s^0 \rightarrow \phi\phi$, it gets very close to zero assuming SM \rightarrow Null test of the SM.
- Based on Run1+'15+'16 LHCb dataset.
- flavour-tagged, time-dependent and angular analysis



$$\phi_s^{s\bar{s}s} = -0.073 \pm 0.115 \pm 0.027 \text{ rad}$$

$$|\lambda| = 0.99 \pm 0.05 \pm 0.01$$

In agreement with the SM expectation

Flavour anomalies

$$b \rightarrow c l \bar{\nu}_\ell$$

- Tree-level charged current process
- Theoretically clean observables: $R(D)$ & $R(D^*)$, $R(J/\psi)$
- Large datasets
- $\Lambda \sim 4 \text{TeV}$

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

- FCNC process suppressed in the SM
- Several observables:
 - Smallness of $B_s^0 \rightarrow \mu^+ \mu^-$ decay rate
 - Smallness of all $B \rightarrow H_s \mu^+ \mu^-$ rates [$H_s = K, K^*, \phi$ (from B_s)]
 - P'_5 anomaly [$B \rightarrow K^* \mu^+ \mu^-$ angular distribution]
 - LFU ratios (μ vs. e) in $B \rightarrow K^* \ell^+ \ell^-$ & $B \rightarrow K \ell^+ \ell^-$
- $\Lambda \sim 40 \text{TeV}$

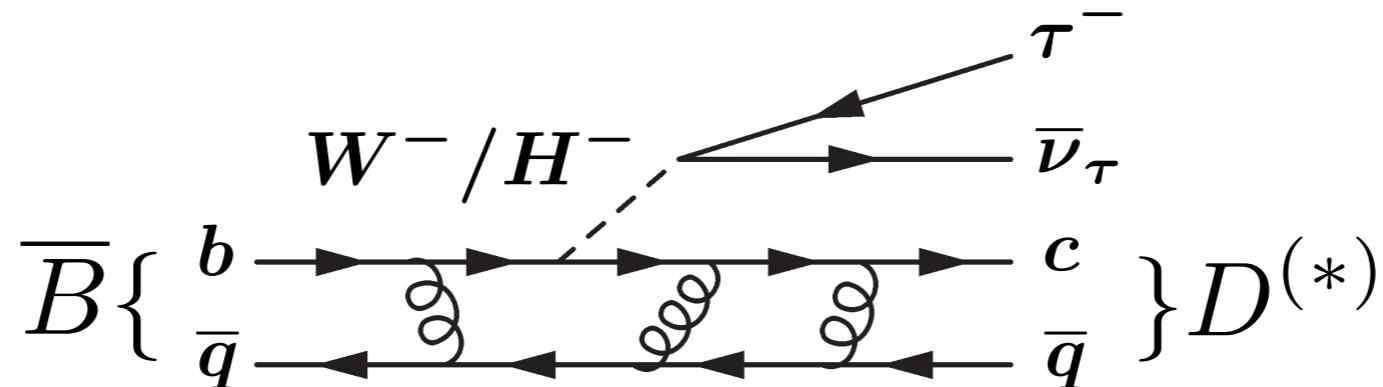
more details in
Carla Marin
Benito's talk

LFU in charged transitions

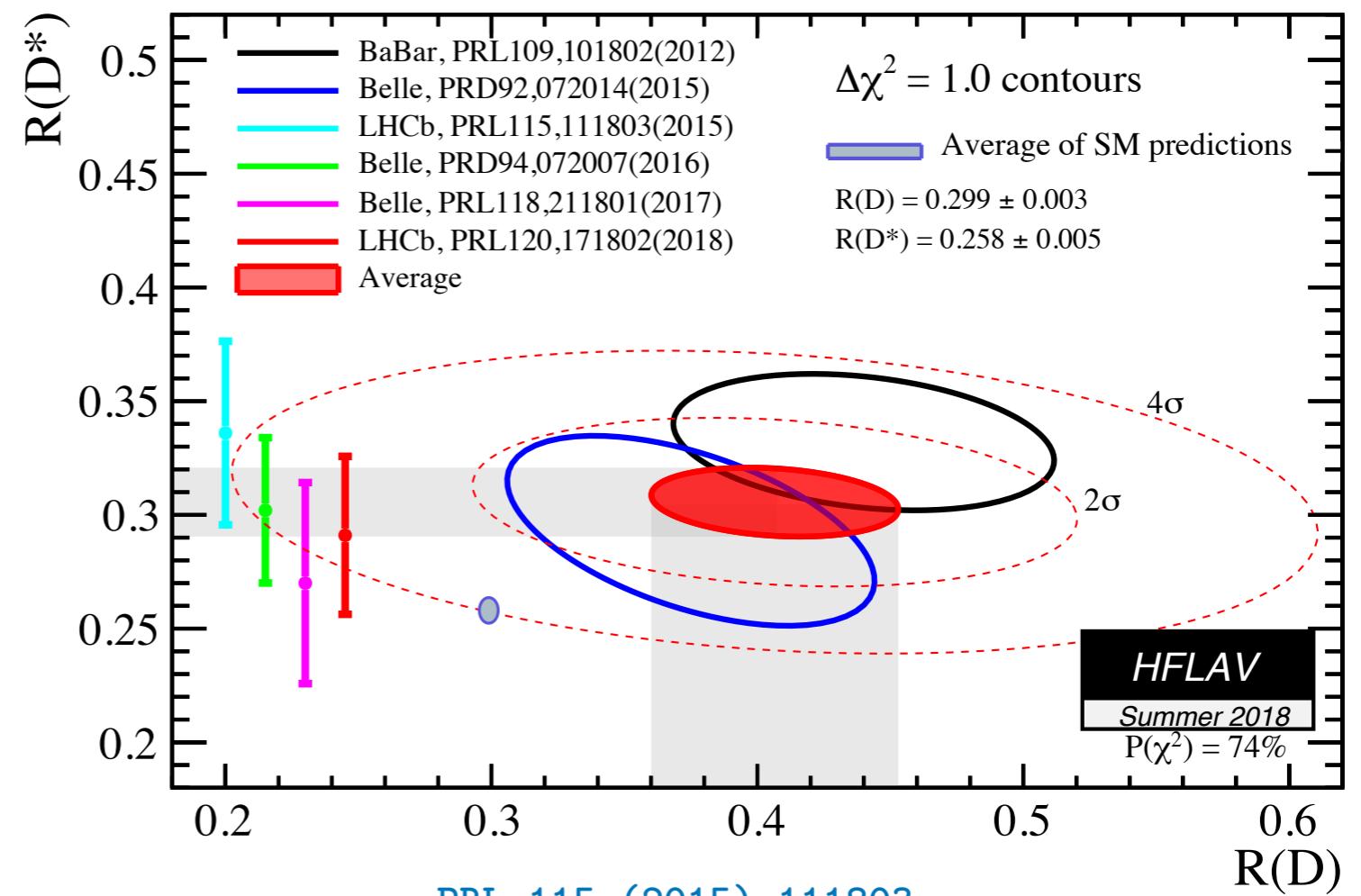
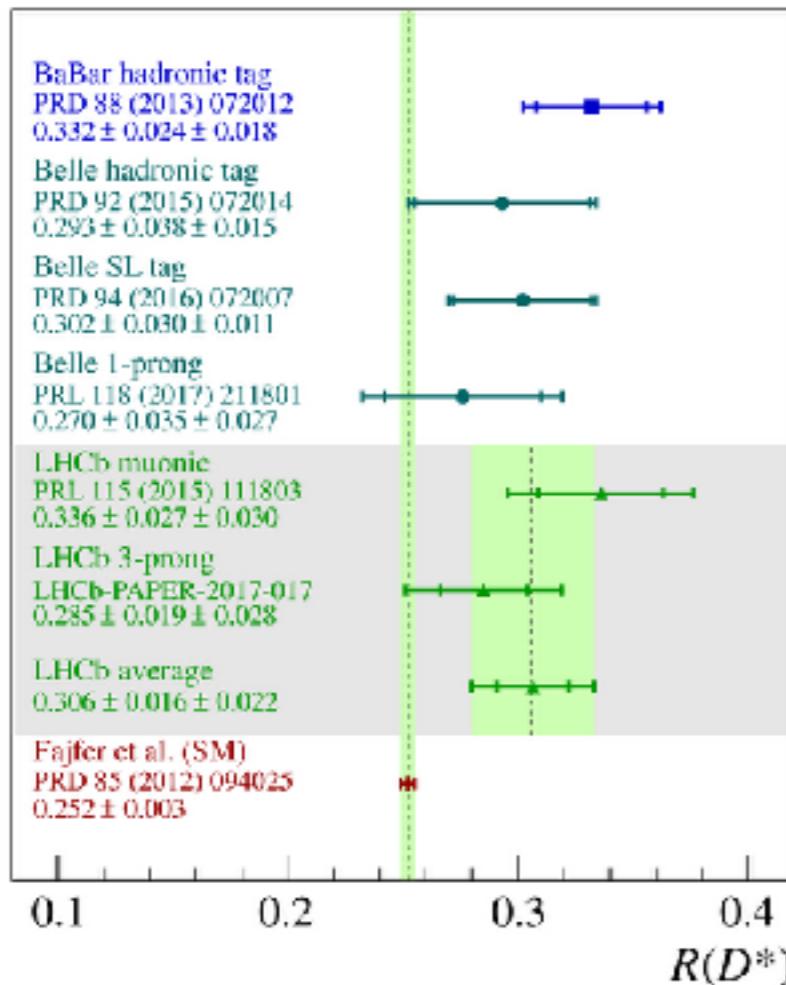
- Access to a large rate of charged current decays
- Ratio of decays with different lepton generations
 - Theoretically clean due cancellation of form factor uncertainties
 - Cancellation of experimental uncertainties

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu_\ell)}$$

- Sensitive to any physics model favouring 3rd generation leptons



$R(D)$ & $R(D^*)$



- LHCb combination 2.1σ from SM
PRL 115 (2015) 111803
PRD 97, 072013 (2018)
PRL 120, 171802 (2018)
- All the experiments see an excess of signal w.r.t. SM predictions
- HFLAV average 3.8σ from SM

R(D) & R(D*)

- At Moriond EW, new results were presented by Belle
[arXiv:1904.08794](https://arxiv.org/abs/1904.08794)

- Simultaneous R(D*)-R(D) analysis with SL-tagging

- Using the full $\gamma(4S)$ data set with $772 \times 10^6 B\bar{B}$ events

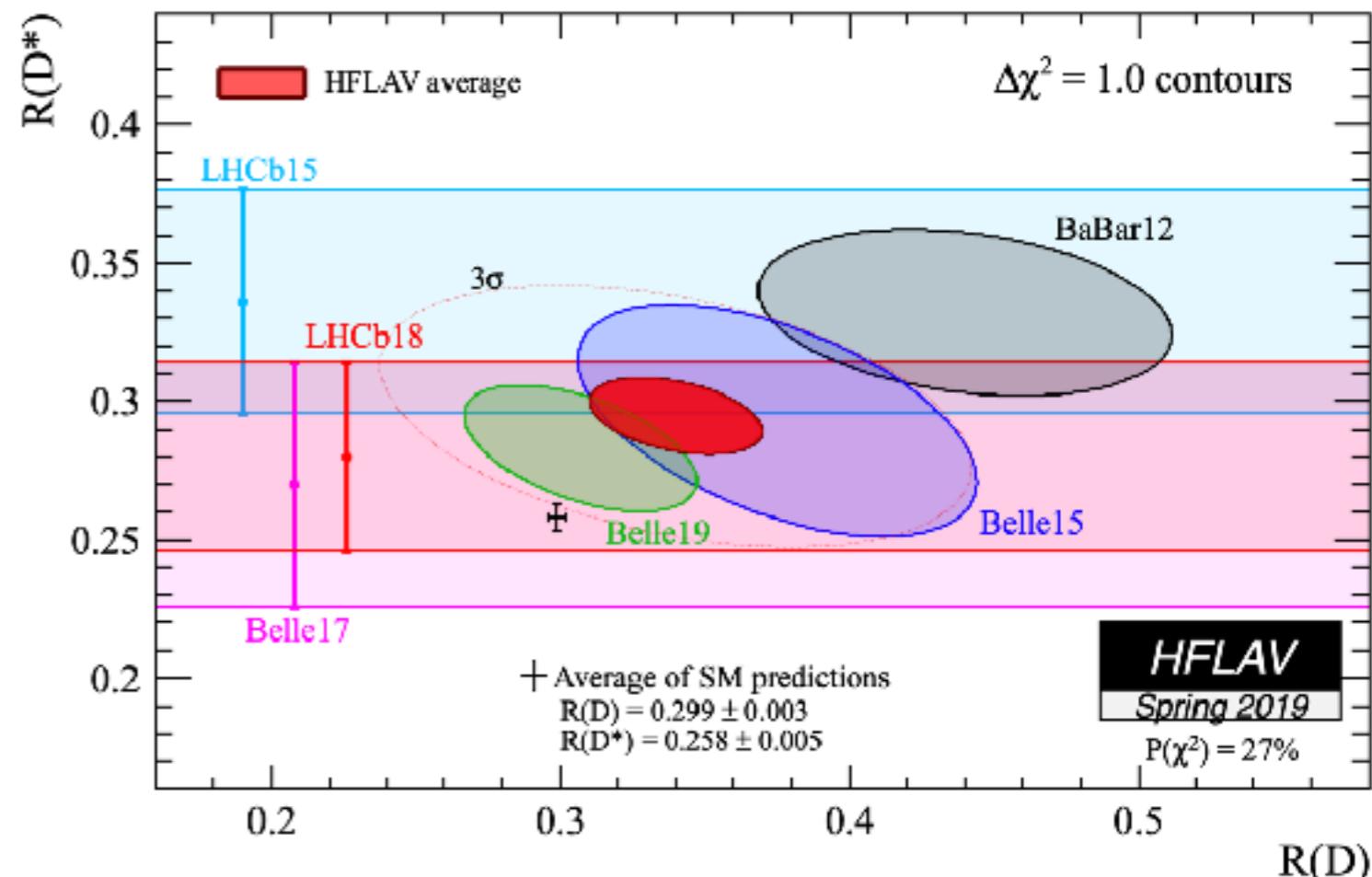
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$

$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

- New average from HFLAV 3.1 σ difference with SM

$$\mathcal{R}(D) = 0.349 \pm 0.027 \pm 0.015$$

$$\mathcal{R}(D^*) = 0.298 \pm 0.011 \pm 0.007$$



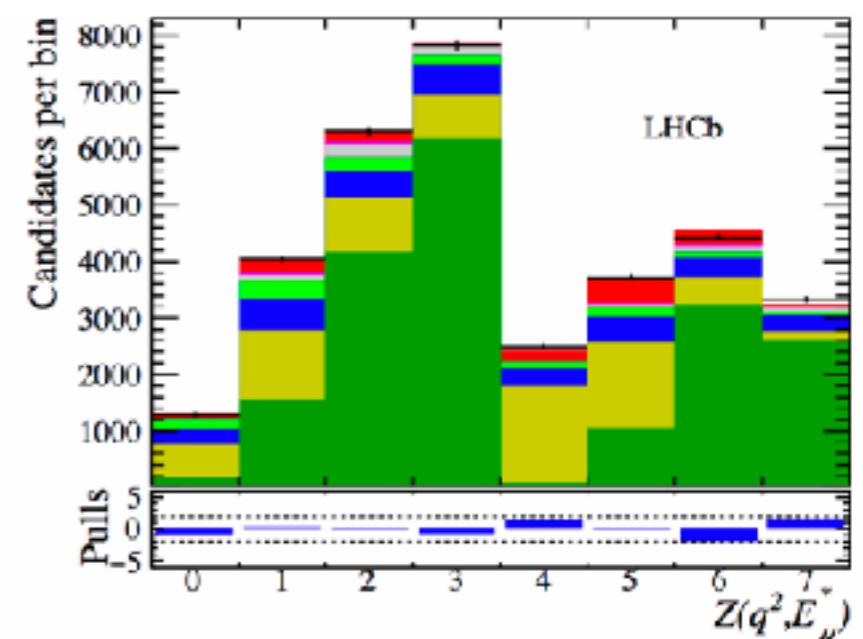
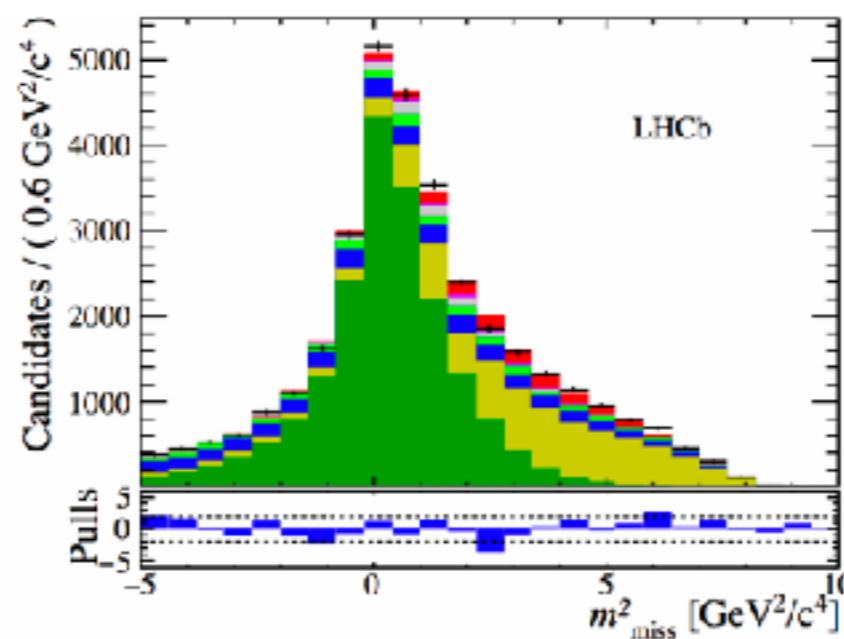
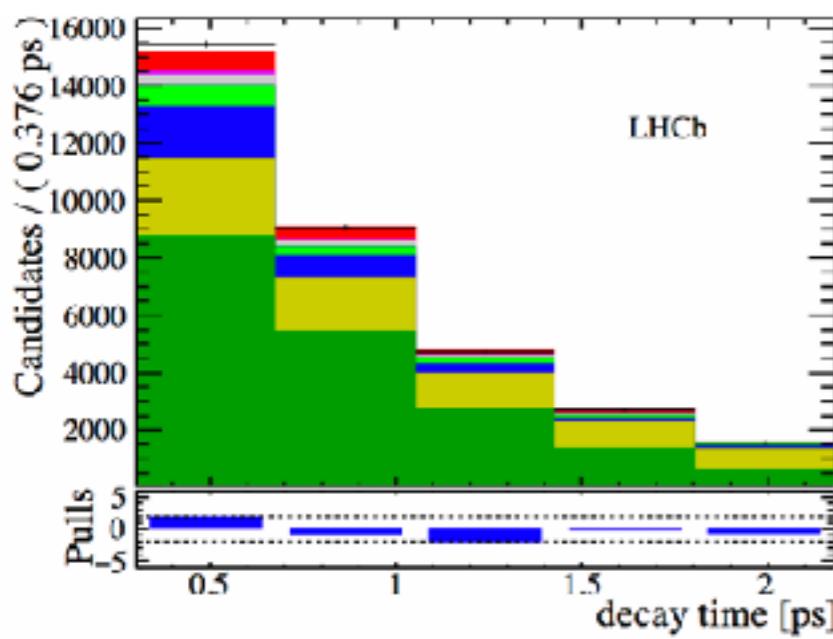
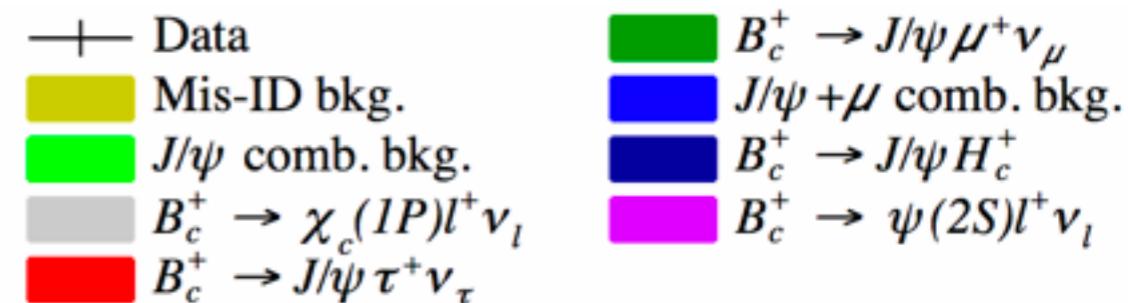
more details in Karol Adamczyk's talk

R(J/ψ)

PRL 120, 121801 (2018)

- $R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$
- Compatible with SM at 2σ level
- Systematics from limited sample simulations, but largest from uncertainty on form factors. Will improve with lattice calculations.

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c \rightarrow J/\psi \tau \nu_\tau)}{\mathcal{B}(B_c \rightarrow J/\psi \mu \nu_\mu)}$$



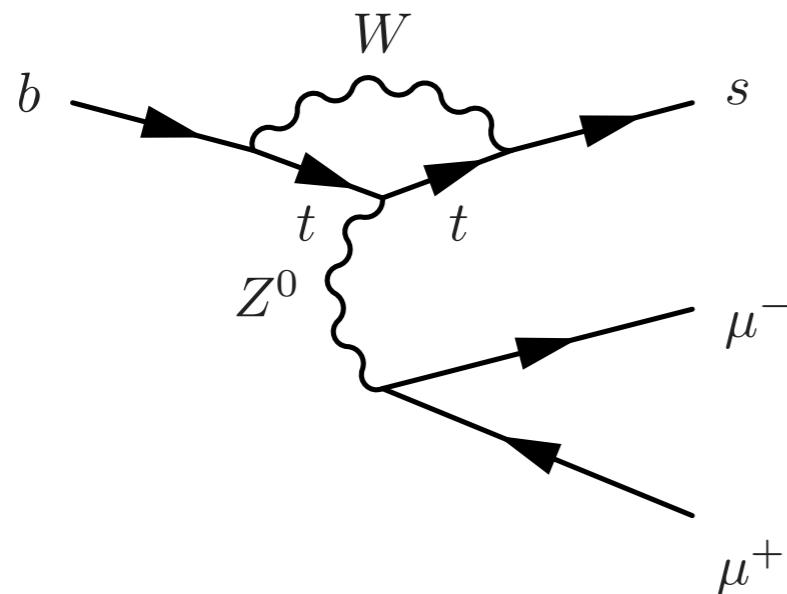
A wide-angle photograph of Niagara Falls. The falls are visible in the distance, where a massive wall of white water cascades over a rocky ledge into a dark blue pool. The sky above is filled with soft, greyish-white clouds. In the foreground, the dark, choppy surface of the river is visible, with some green foliage in the bottom right corner.

Rare decays anomalies

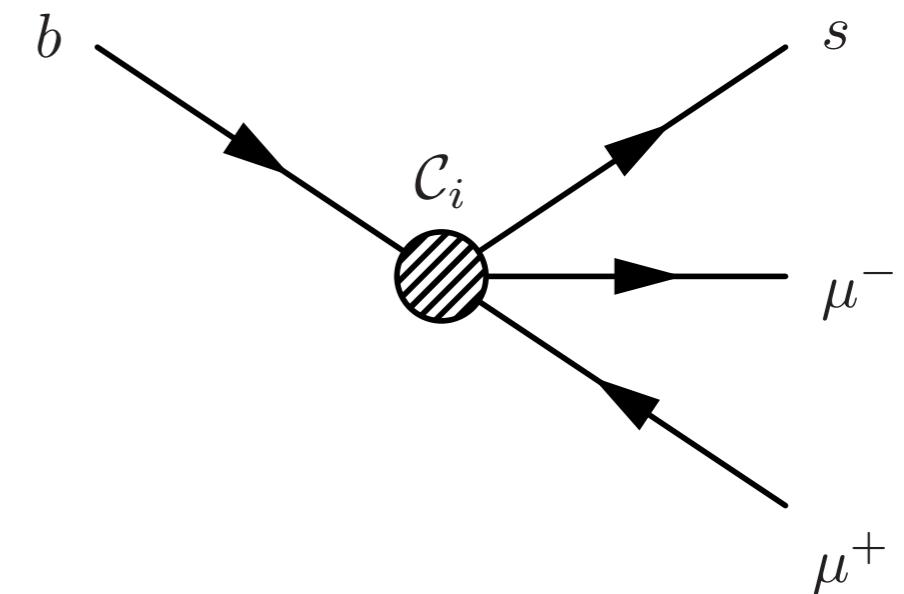
RD - Effective field theory

- Similarly to the β -decay we can integrate out the heavy field of the SM

Full theory



Effective description



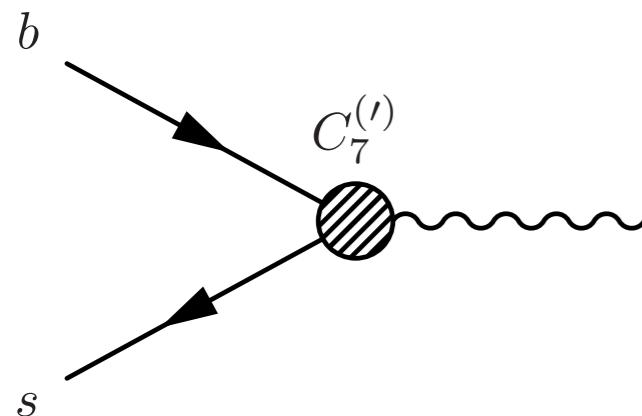
$$\mathcal{A}(i \rightarrow f) = \langle f | \mathcal{H}_{eff} | i \rangle$$

Effective Hamiltonian

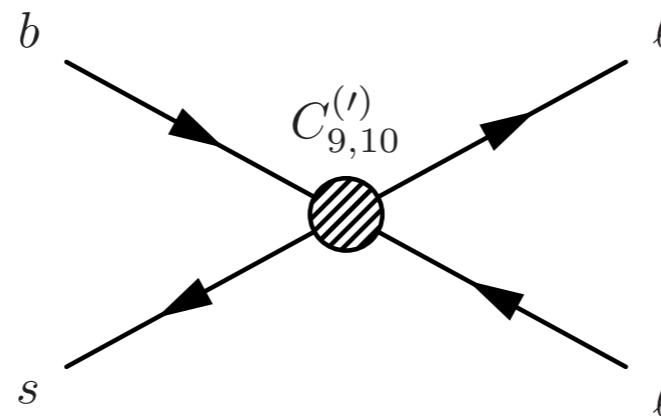
- Model independent description in effective field theory

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \sum_i [C_i \mathcal{O}_i + C'_i \mathcal{O}'_i]$$

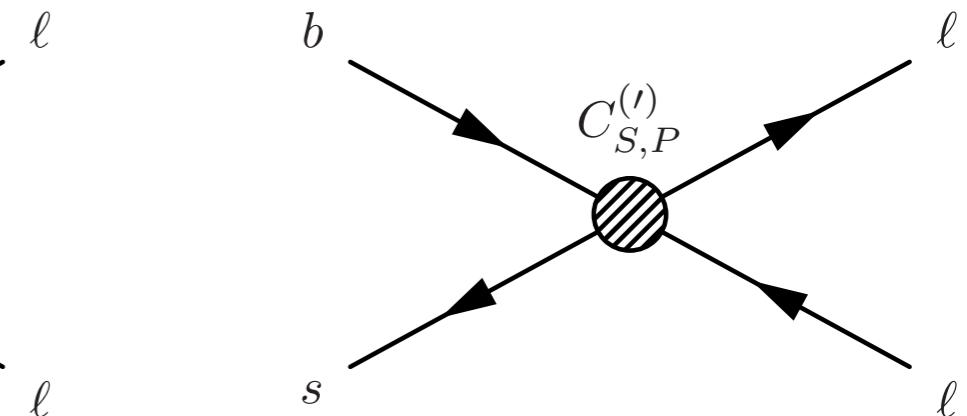
- C_i Wilson coefficients encoding info of the short distance physics
- \mathcal{O}_i four-fermion operators



$$\mathcal{O}_7^{(')} \propto (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$



$$\mathcal{O}_9^{(')} \propto (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma^\mu l)$$



$$\mathcal{O}_S^{(')} \propto (\bar{s} P_{R(L)} b) (\bar{l} l)$$

$$\mathcal{O}_{10}^{(')} \propto (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma^\mu \gamma_5 l)$$

$$\mathcal{O}_P^{(')} \propto (\bar{s} P_{R(L)} b) (\bar{l} \gamma_5 l)$$

b \rightarrow s γ

b \rightarrow sll

B_s⁰ \rightarrow ll

Effective Hamiltonian

- Model independent description in effective field theory

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \sum_i [C_i \mathcal{O}_i + C'_i \mathcal{O}'_i]$$

- C_i Wilson coefficients encoding info of the short distance physics
- \mathcal{O}_i four-fermion operators

- NP can modify SM or introduce new operators

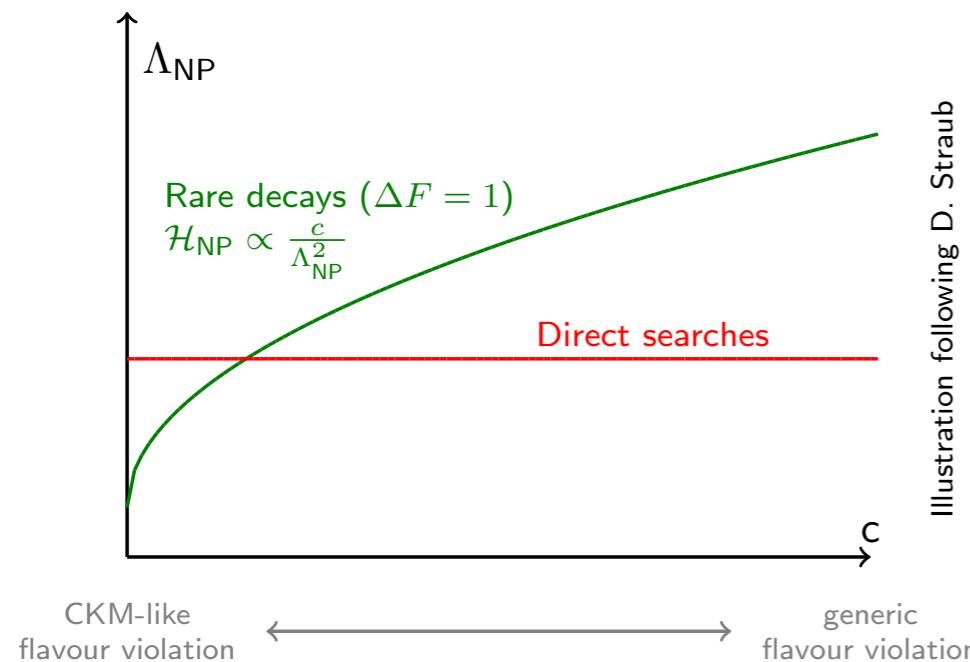
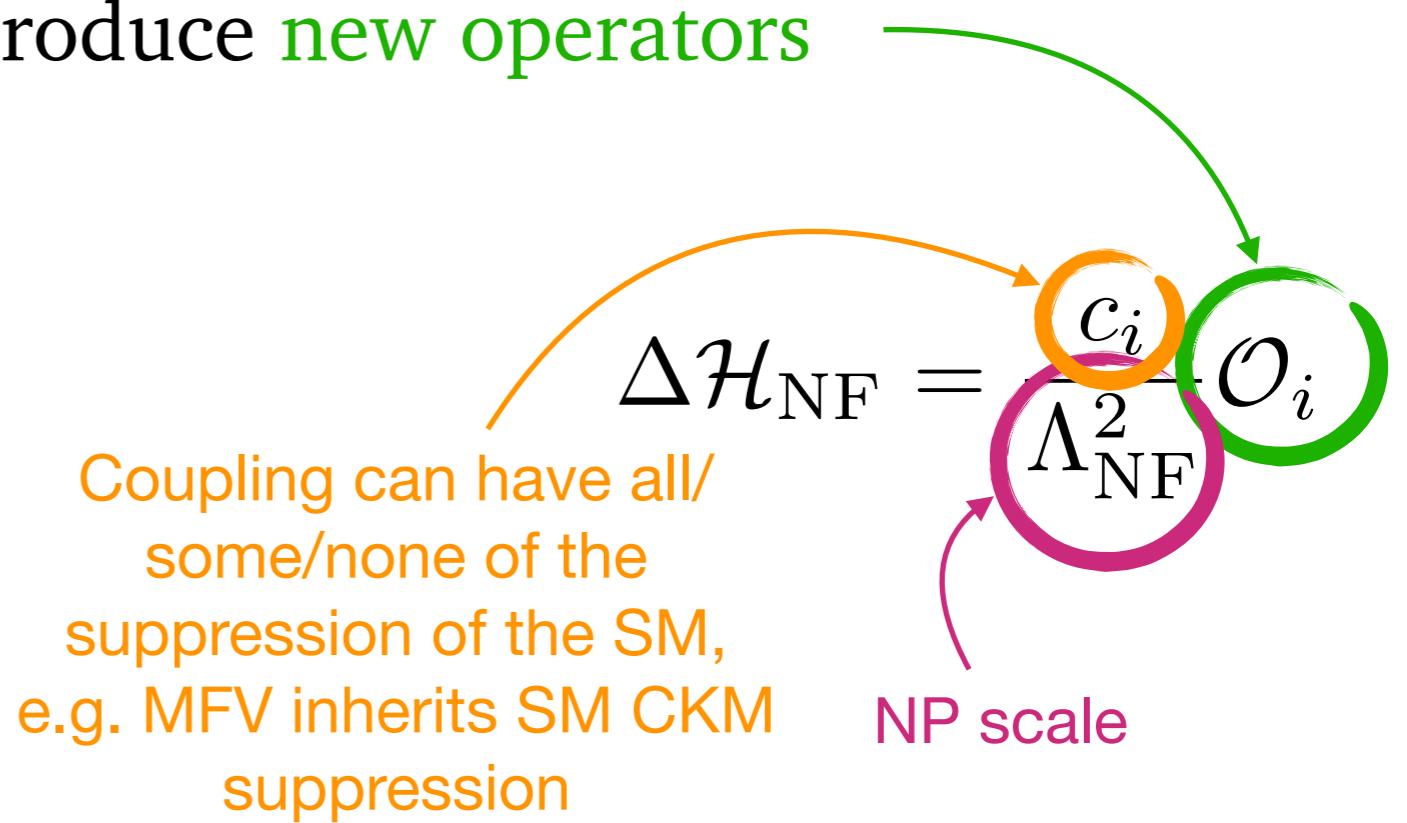


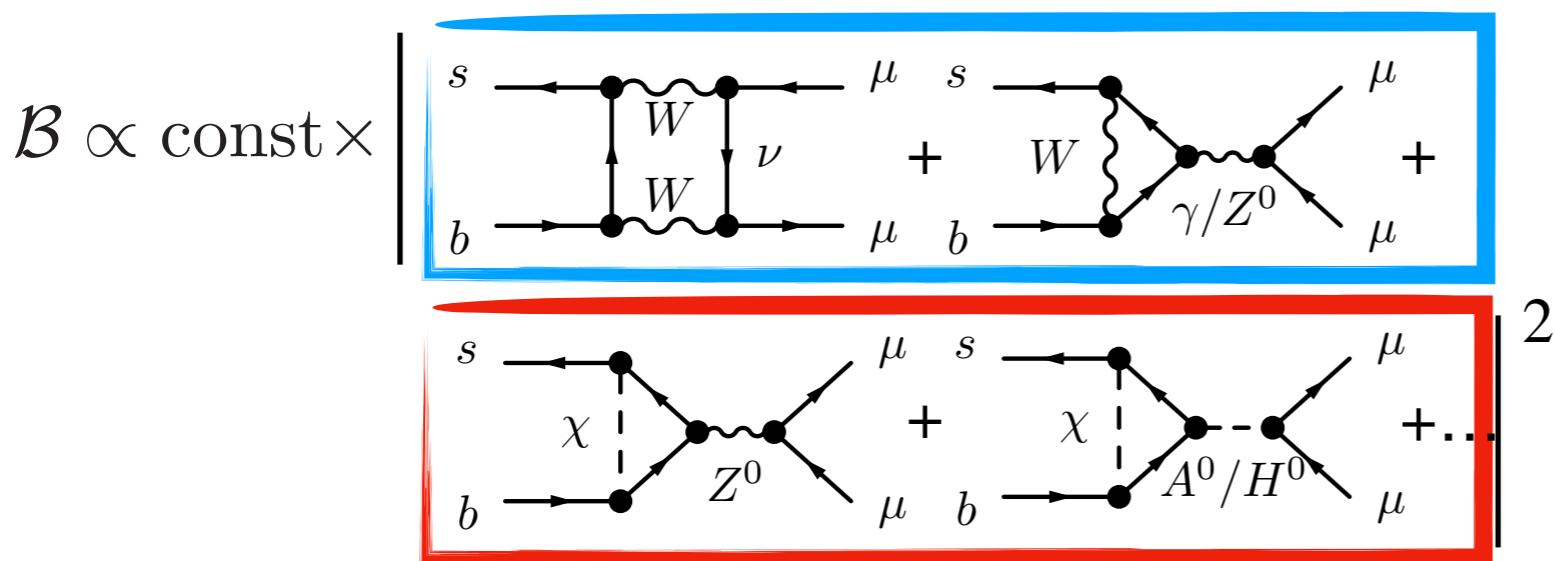
Illustration following D. Straub



$B_s \rightarrow \mu^+ \mu^-$

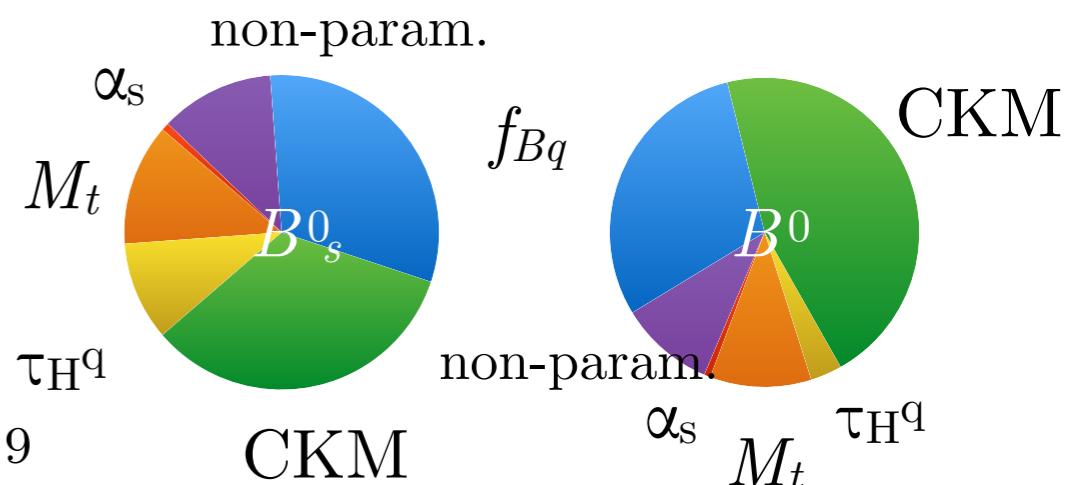
- FCNC pure leptonic decays $B^0_s \rightarrow \ell^+ \ell^-$ are even rarer in the SM due to helicity suppression

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



Bobeth et al.
[PRL 112 (2014) 101801]

error budgets



- SM prediction:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$B_s \rightarrow \mu^+ \mu^-$

LHCb PRL 118 (2017) 191801

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

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

$< 3.4 \cdot 10^{-10}$ @ 95% CL

CMS PRL 111, 101804 (2013)

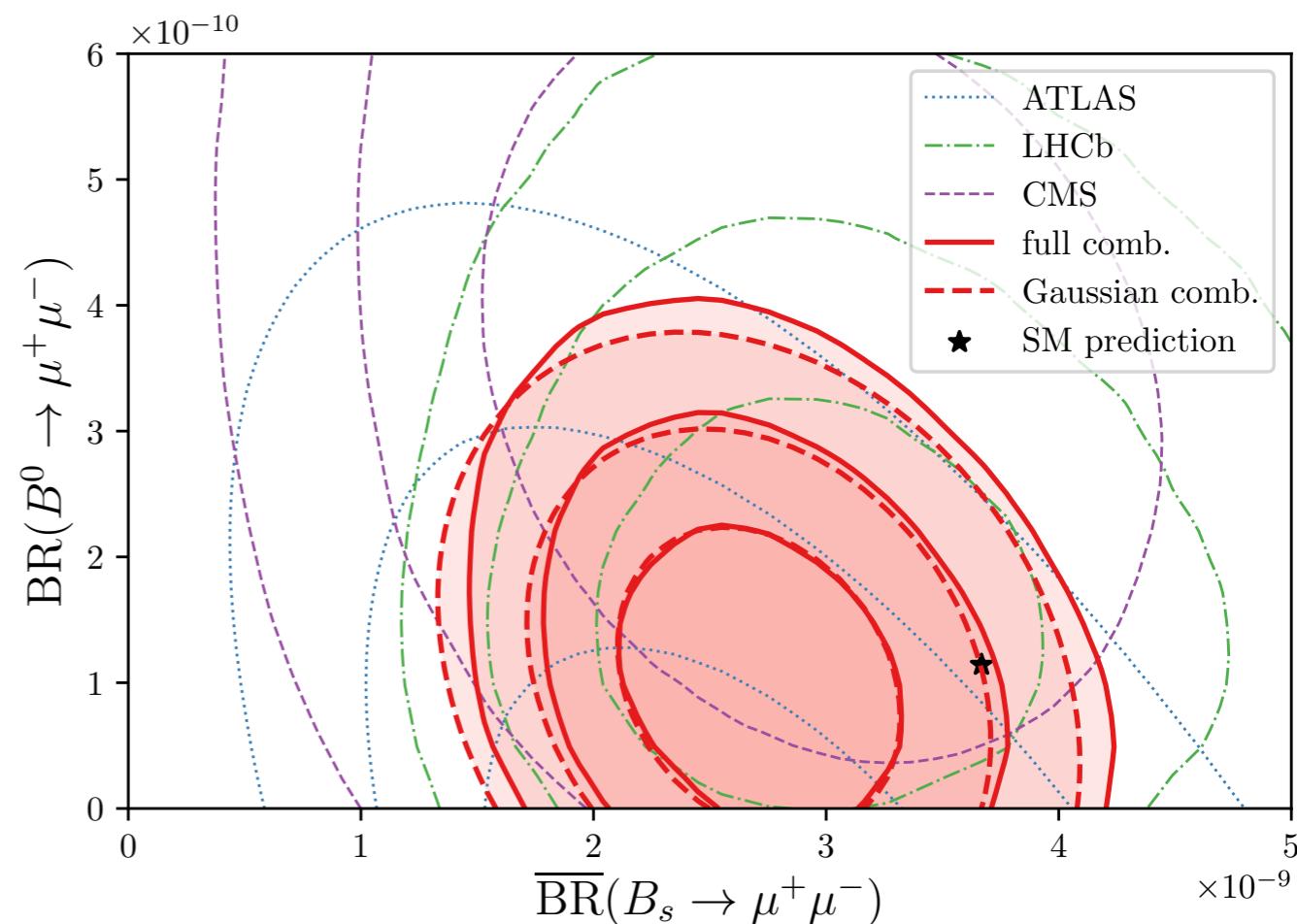
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8_{-0.9}^{+1.1}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (4.4_{-1.9}^{+2.2}) \times 10^{-10}$$

ATLAS JHEP 04 (2019) 098

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

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} \text{ @95% CL}$$



From naive combination of LHCb+ATLAS+CMS results $\text{BF}(B_s^0 \rightarrow \mu^+ \mu^-) \sim 2\sigma$ below SM

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.7_{-0.4}^{+0.5}) \times 10^{-9}$$

key measurement to understand NP contribution to C_{10}

$B_s \rightarrow \mu^+ \mu^-$

LHCb PRL 118 (2017) 191801

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

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

$< 3.4 \cdot 10^{-10}$ @ 95% CL

CMS PRL 118 (2017) 191802
new result (P. McBride's talk)

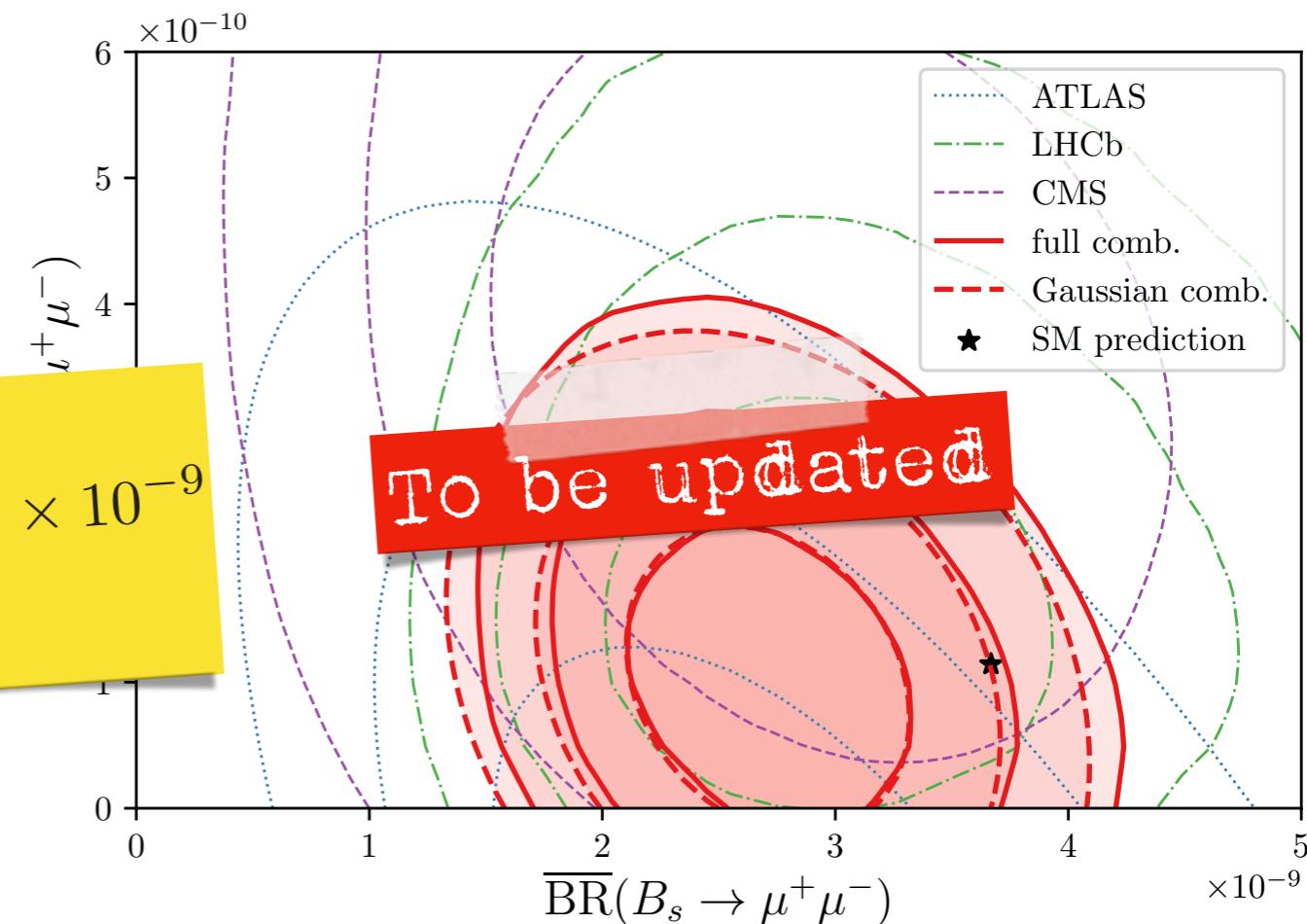
$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (2.9_{-0.6}^{+0.7}(\text{exp}) \pm 0.2(f_s/f_u)) \times 10^{-9}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 3.6 \times 10^{-10}$$
 @ 95% CL

ATLAS JHEP 04 (2019) 098

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2_{-1.0}^{+1.1}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$$
 @ 95% CL



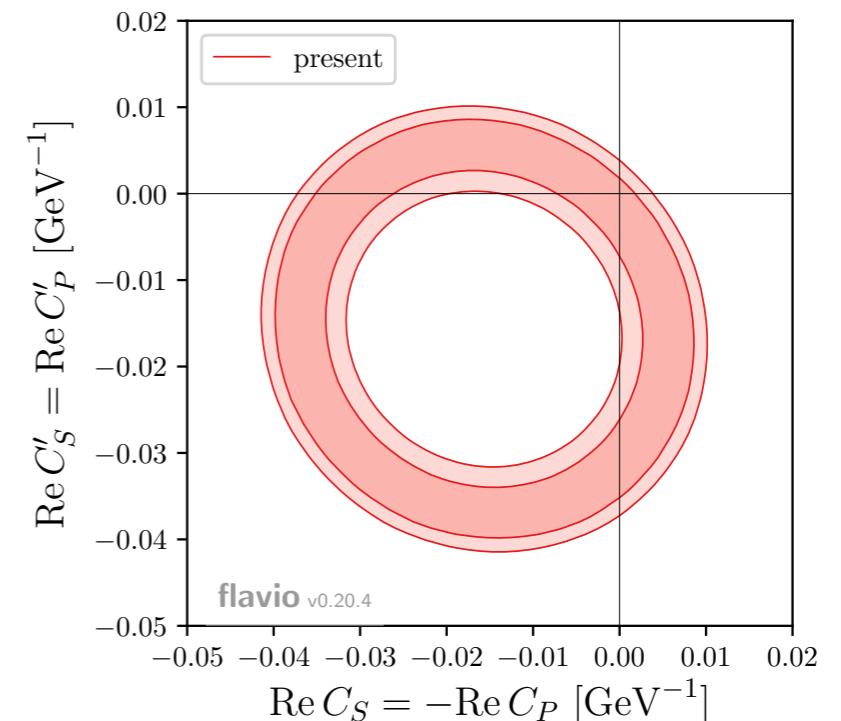
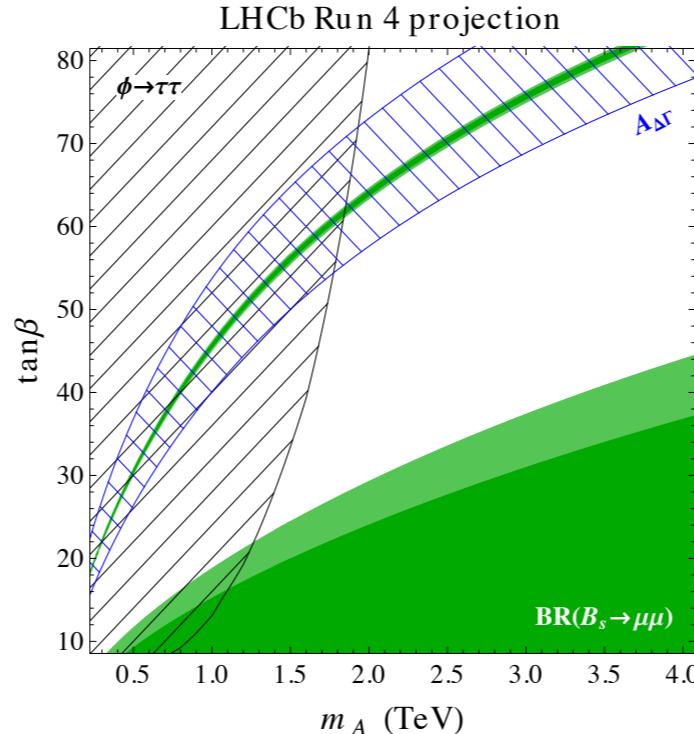
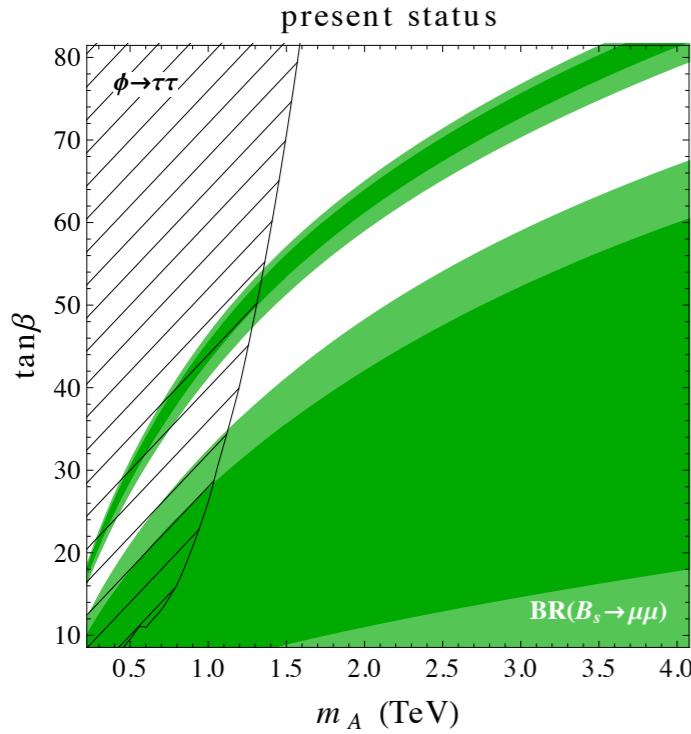
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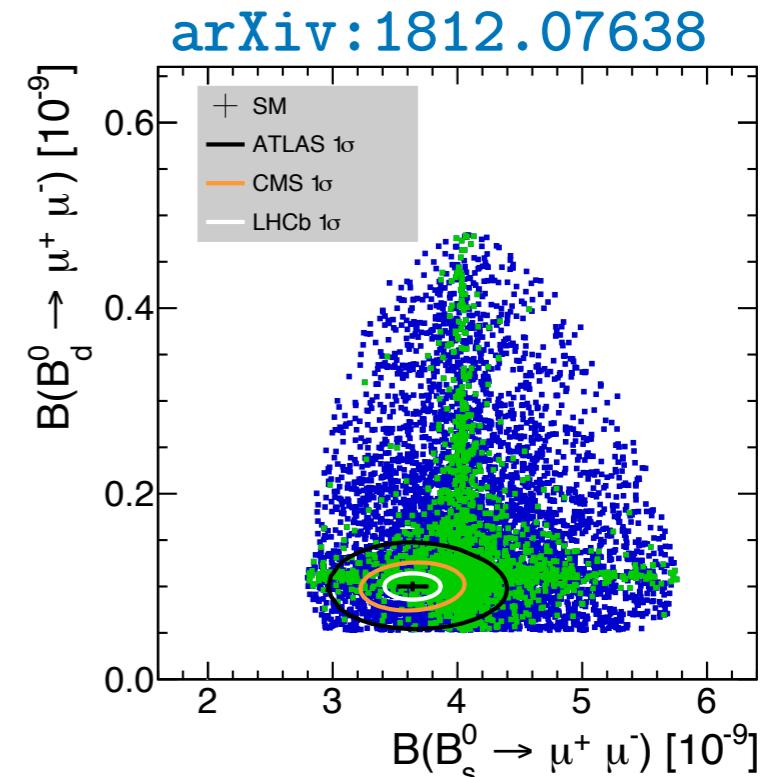
key measurement to understand NP contribution to C_{10}

$B_s \rightarrow \mu^+ \mu^-$

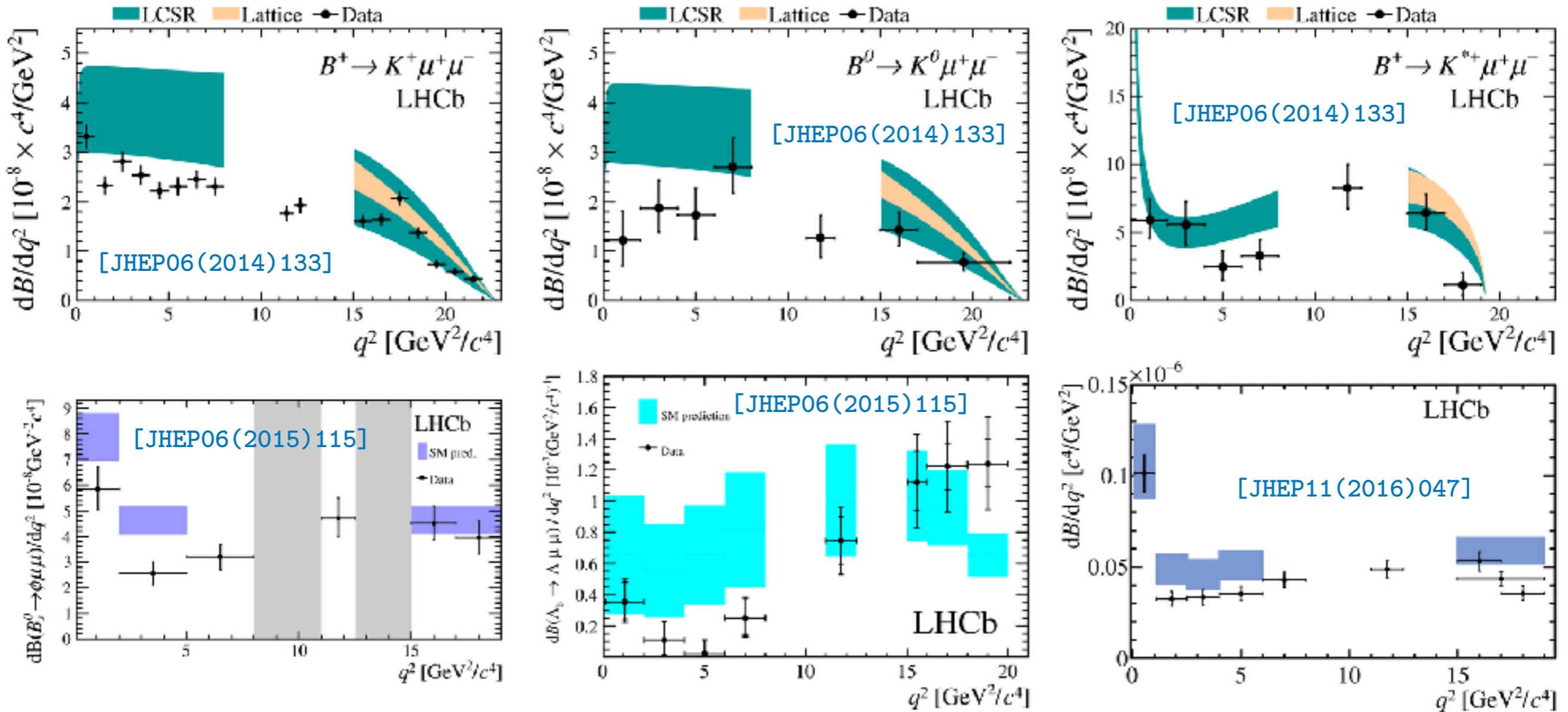
Straub 1702.05498



- In MSSM $BF(B_s^0 \rightarrow \mu\mu) \propto \tan^6 \beta / m_A^4$
- Present status assume $BF(B_s^0 \rightarrow \mu\mu) = (3.00 \pm 0.55) \times 10^{-9}$. With full Run1+Run2 $\Delta BF/BF \sim 13\%$ can be reached \rightarrow Together with ATLAS and CMS $\Delta BF/BF \sim 7\%$, which is the expected uncertainty at the end of Run4 for LHCb only
- Complementary to direct searches of $\tau\tau$ resonances
- Effective lifetime useful to break the degeneracy



Decay Rates



Measurements of $b \rightarrow s \ell \ell$ decay rates systematically below the SM predictions, 2-3 σ depending on the final state

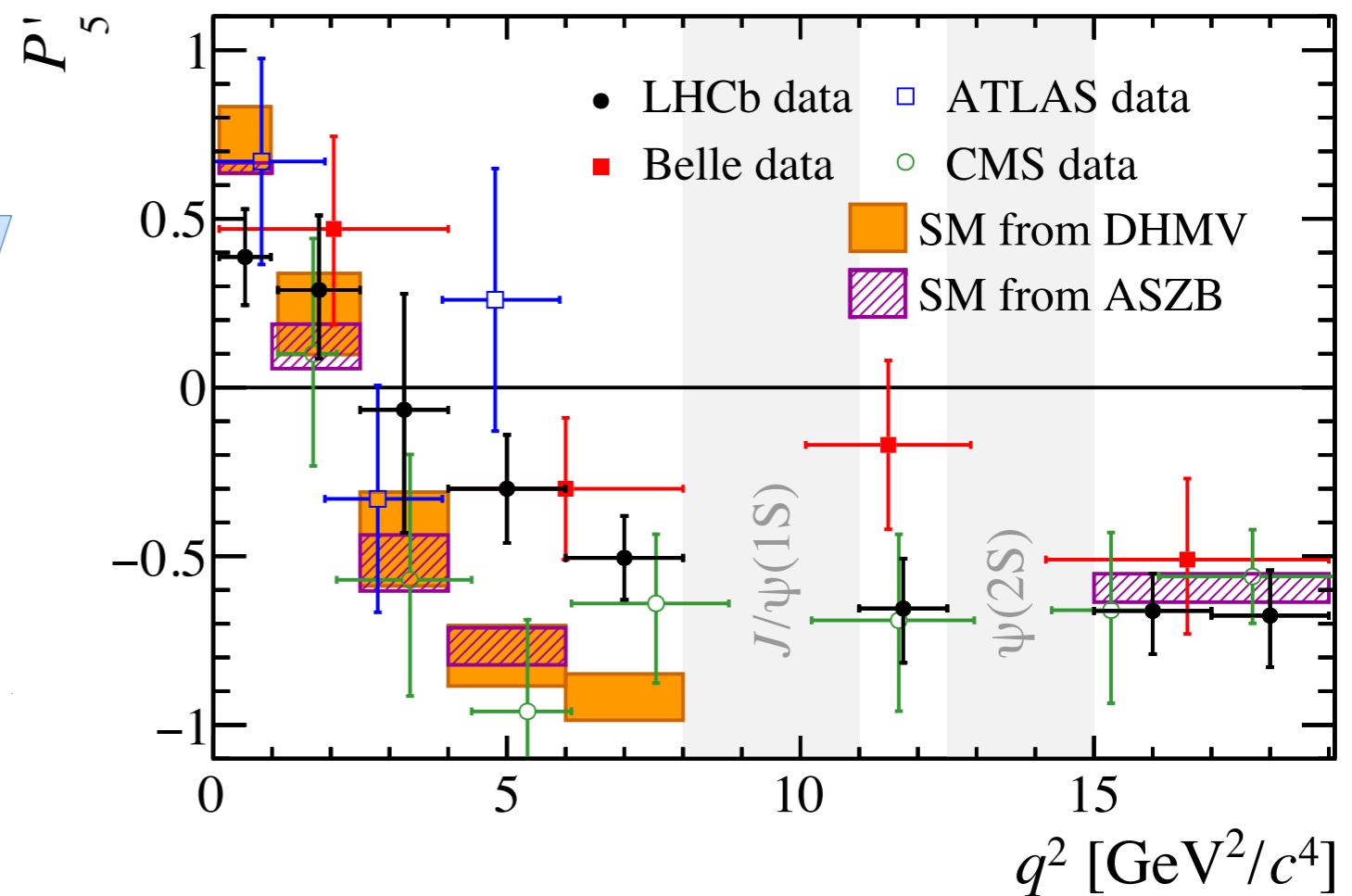
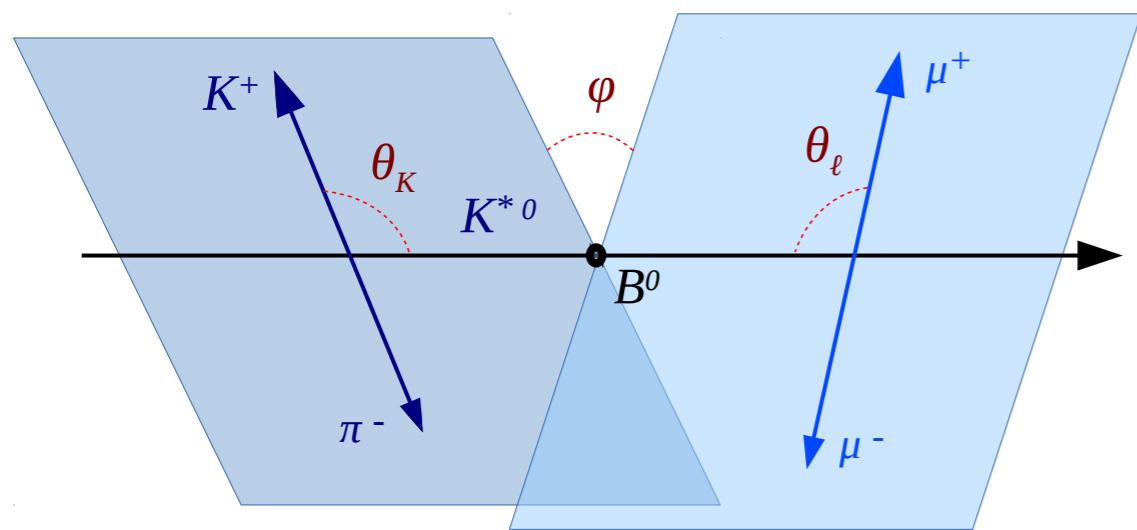
Angular distributions

[LHCb, JHEP 02 (2016) 104]

[Belle, PRL 118 (2017) 111801]

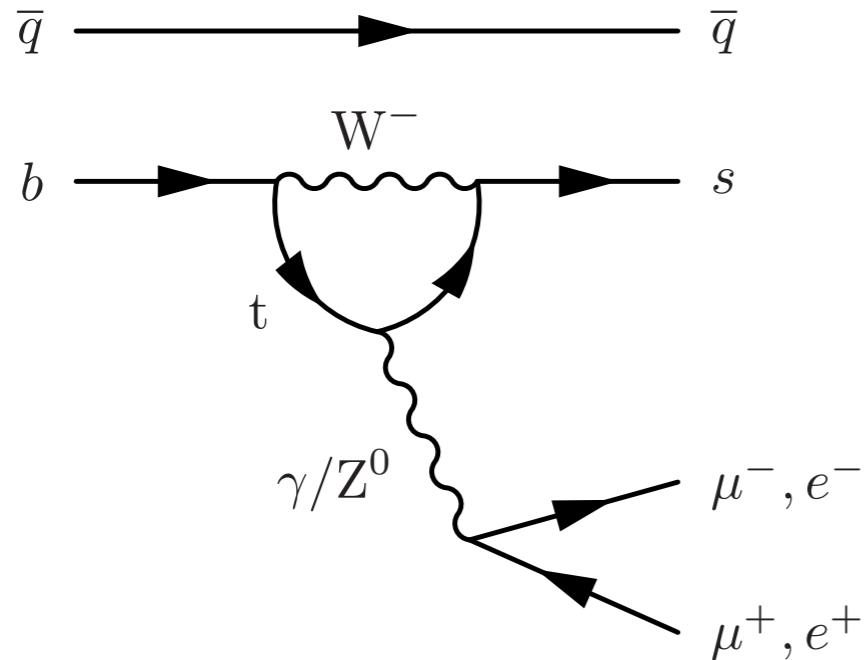
[CMS-PAS-BPH-15-008]

[JHEP 10 (2018) 047]



- Access to observables with reduced hadronic uncertainties
- LHCb found a deviation from SM at the level of 3.4σ

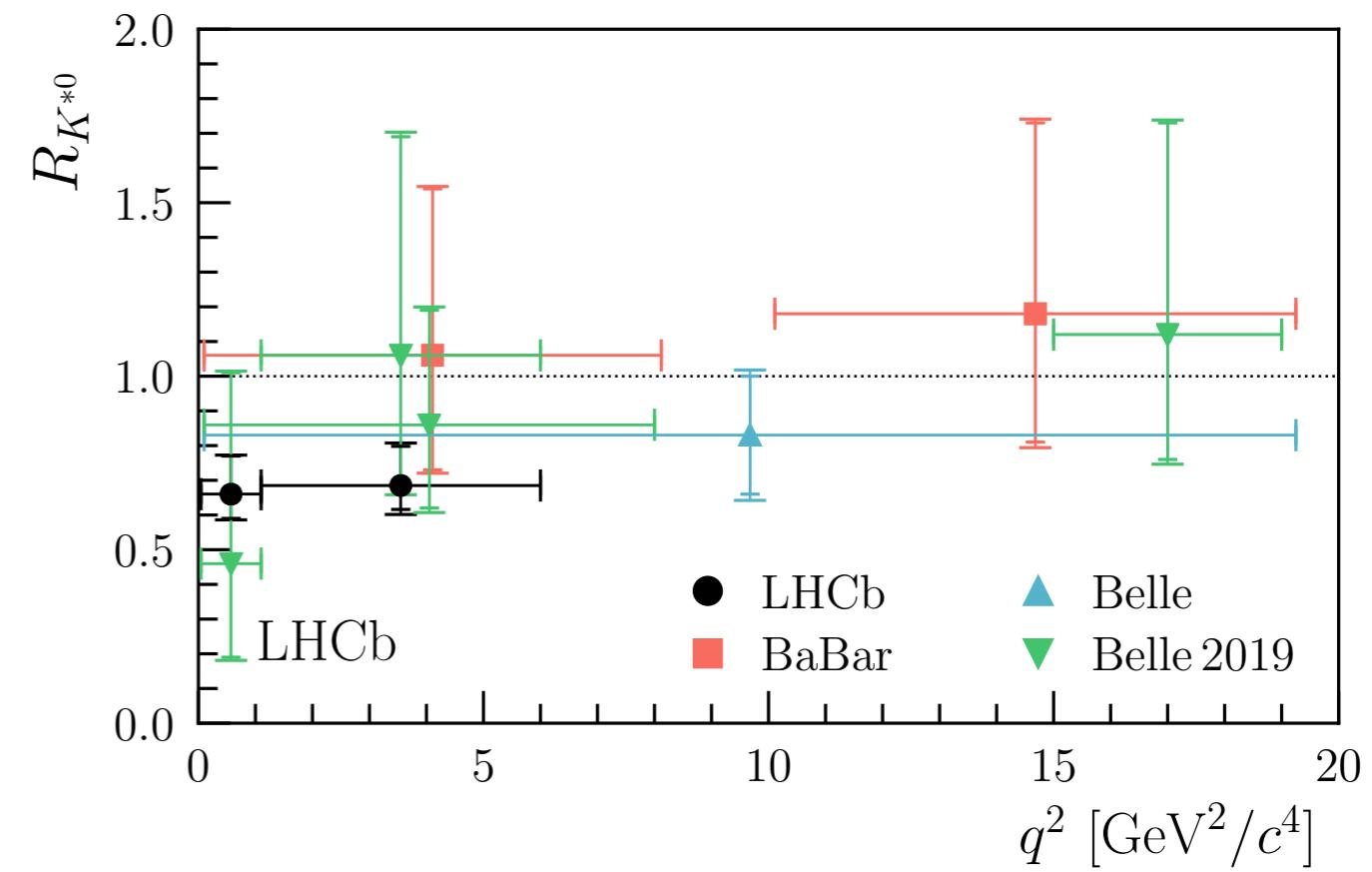
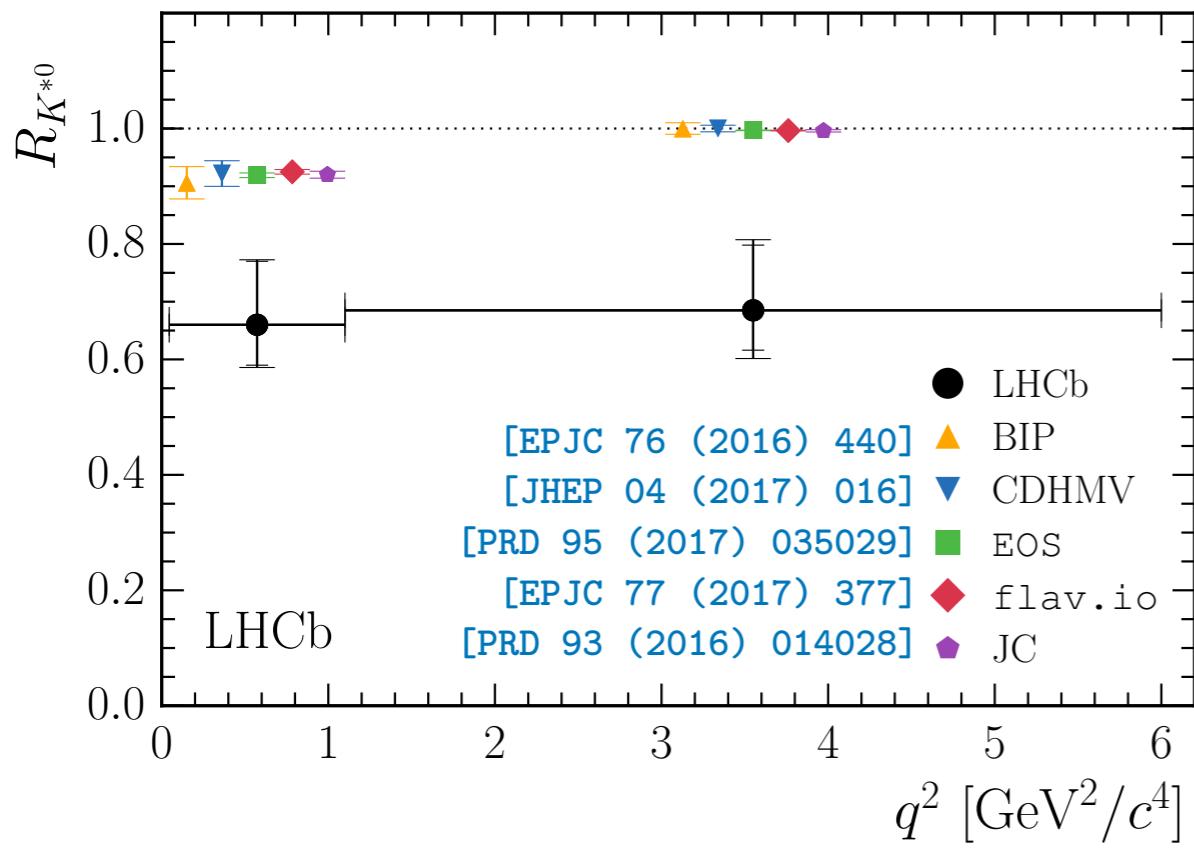
Lepton flavour universality



$$R_H = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B \rightarrow H\mu^+\mu^-]}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B \rightarrow He^+e^-]}{dq^2} dq^2}$$

- Extremely clean test: cancellation of hadronic form-factors uncertainties in predictions
- $R_{K,K^*} = 1 \pm O(10^{-3})$ ($m_\ell \ll m_b$)
 - R_{K,K^*} is close to unity in SM, with very small uncertainties
 - Possible deviation from QED corrections $\sim 1\%$ in the central q^2

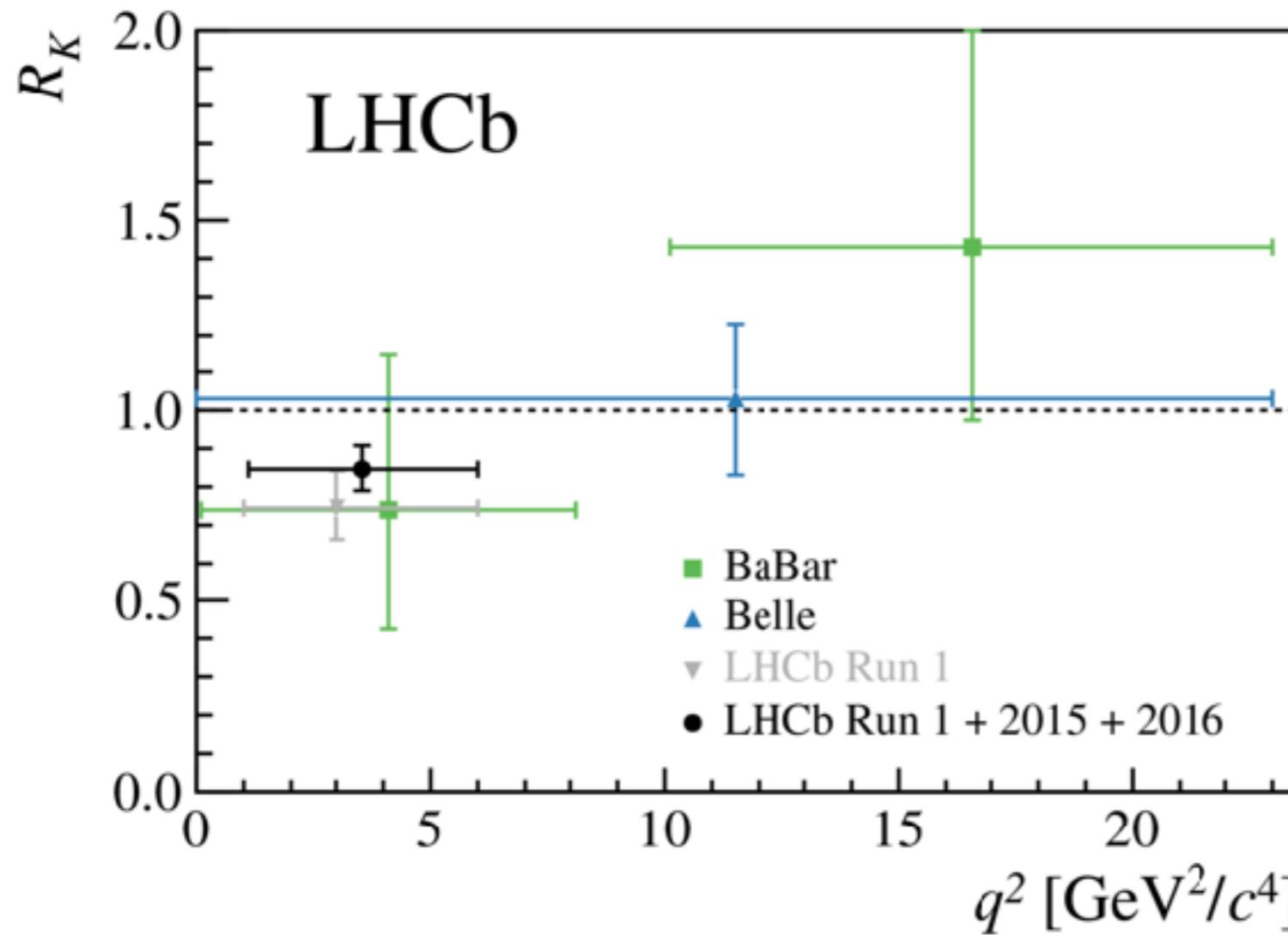
LFU with $B \rightarrow K^* \ell \ell$



- LHCb result in tension with the SM at $\sim 2\sigma$ level
- New results from Belle in agreement with SM and previous experimental results

[LHCb, JHEP 08 (2017) 055]
 [BaBar, PRD 86 (2012) 032012]
 [Belle, PRL 103 (2009) 171801]
 [Belle, arXiv:1904.02440]

LFU with $B \rightarrow K \ell \ell$



Babar [PRD 86 (2012) 032012]
 Belle [PRL 103 (2009) 171801]
 LHCb [PRL 113 (2014) 151601]
 LHCb [PRL 122 (2019) 191801]

- LHCb recently reanalysed Run1 data adding 2015-2016 dataset

$$R_K = 0.846^{+0.060}_{-0.054}(stat)^{+0.014}_{-0.016}(syst)$$

- New result still compatible with the SM expectation at 2.5σ

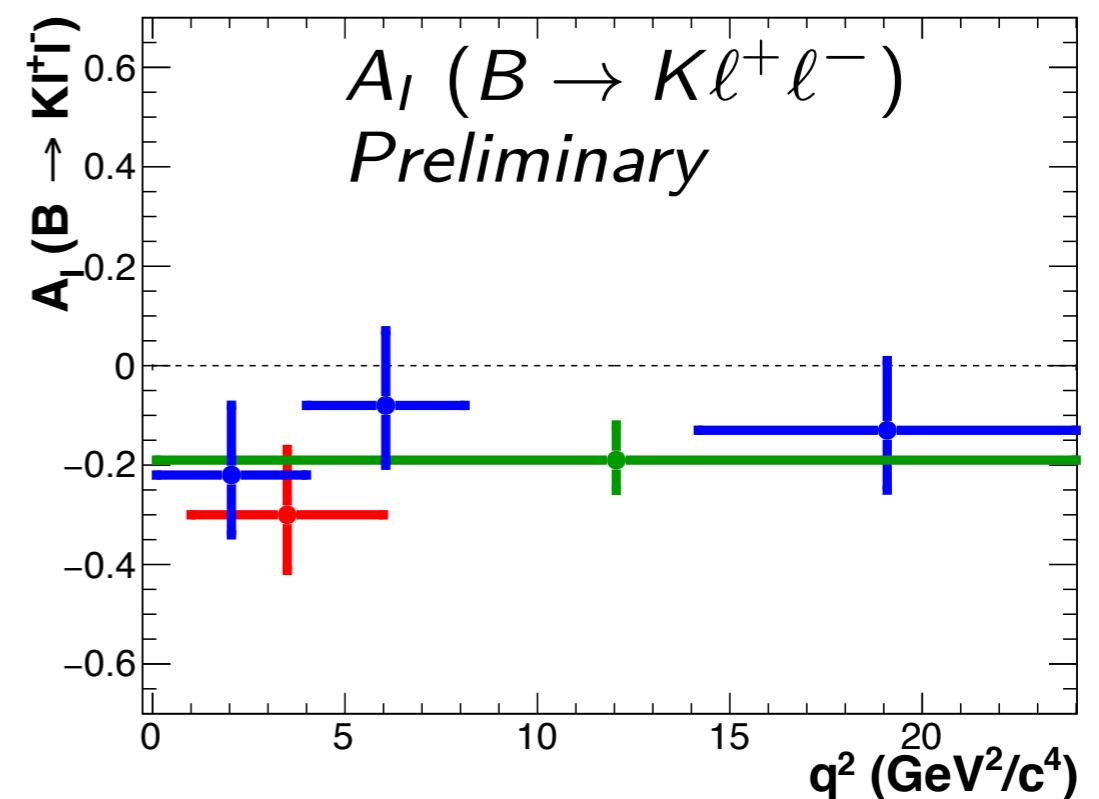
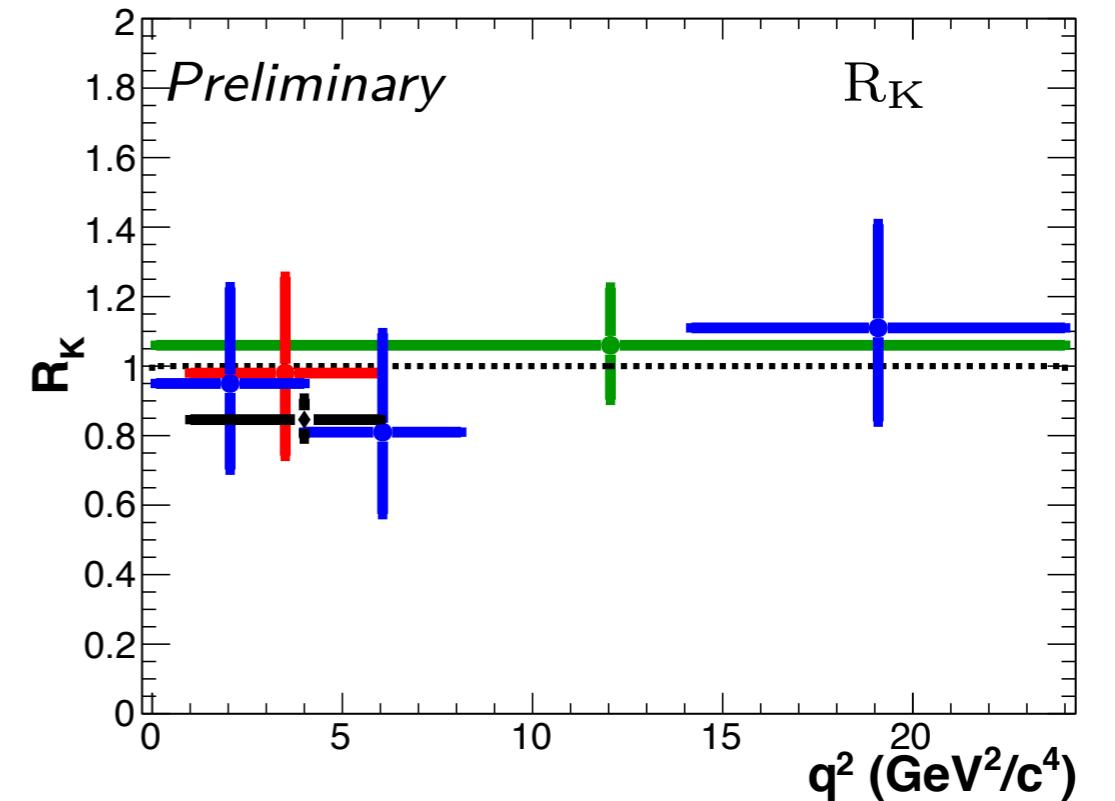
LFU with $B \rightarrow K\ell\ell$

- New results from Belle with 711 fb^{-1}
- Both charged and neutral mode and R_K measured as the weighted average
- R_K measured for $[0.1, 4.0], [4.0, 8.12], [1.0, 6.0], > 14.18$ and > 0.1 q^2 bins
- Isospin asymmetry also measured
- Deviation found at $\sim 2.5\sigma$ level in the first bin

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(B^0 \rightarrow K^0 \ell\ell) - \mathcal{B}(B^+ \rightarrow K^+ \ell\ell)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(B^0 \rightarrow K^0 \ell\ell) + \mathcal{B}(B^+ \rightarrow K^+ \ell\ell)}$$

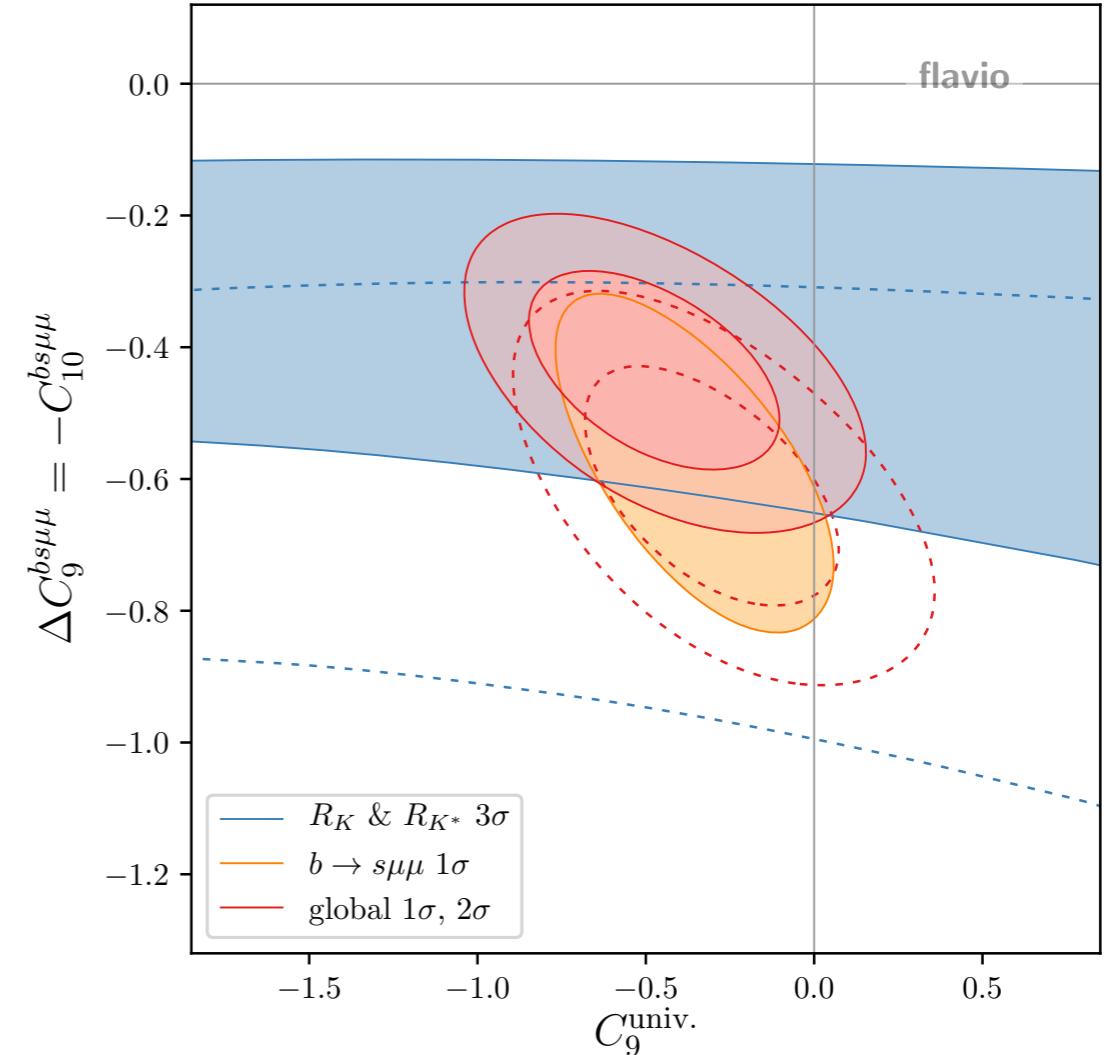
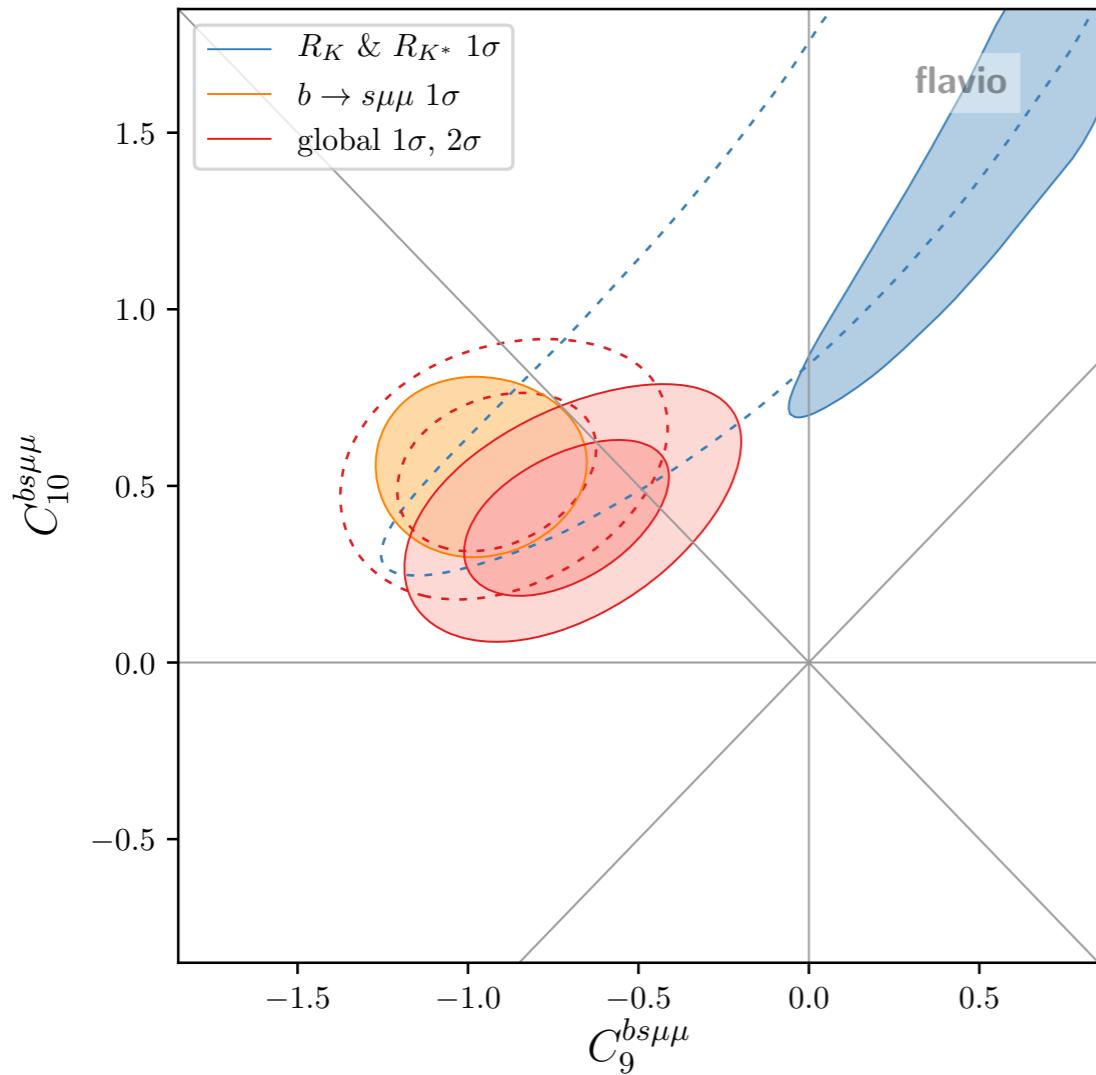
S. Choudhury for the
Belle collaboration

@EPS19



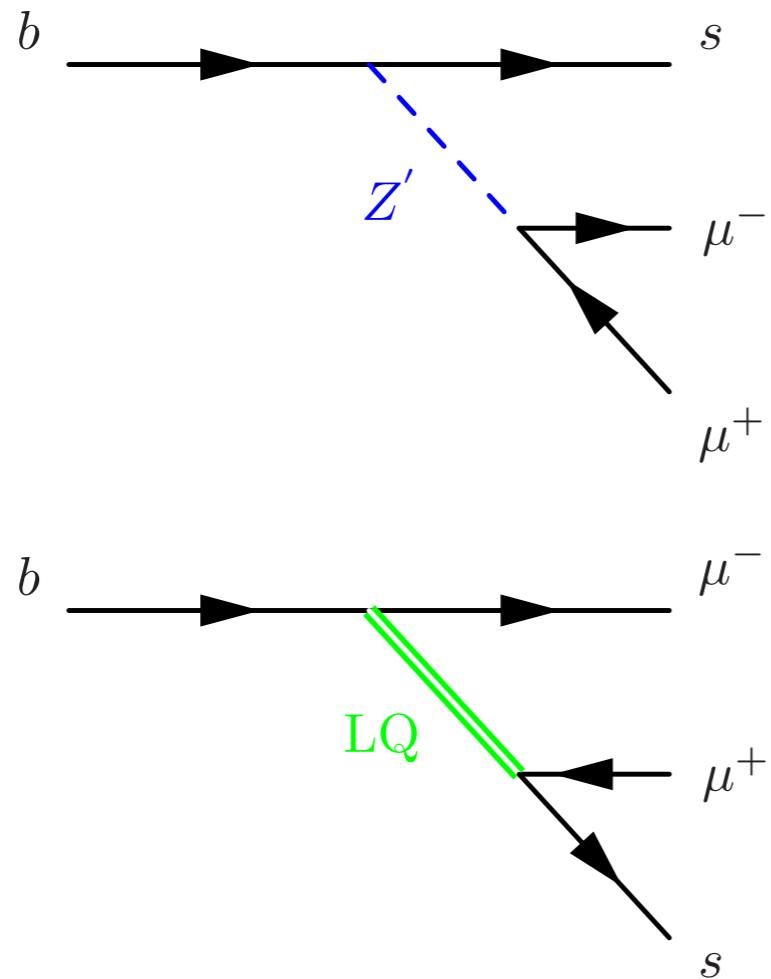
Global fits

D. Straub et al. 1903.10434



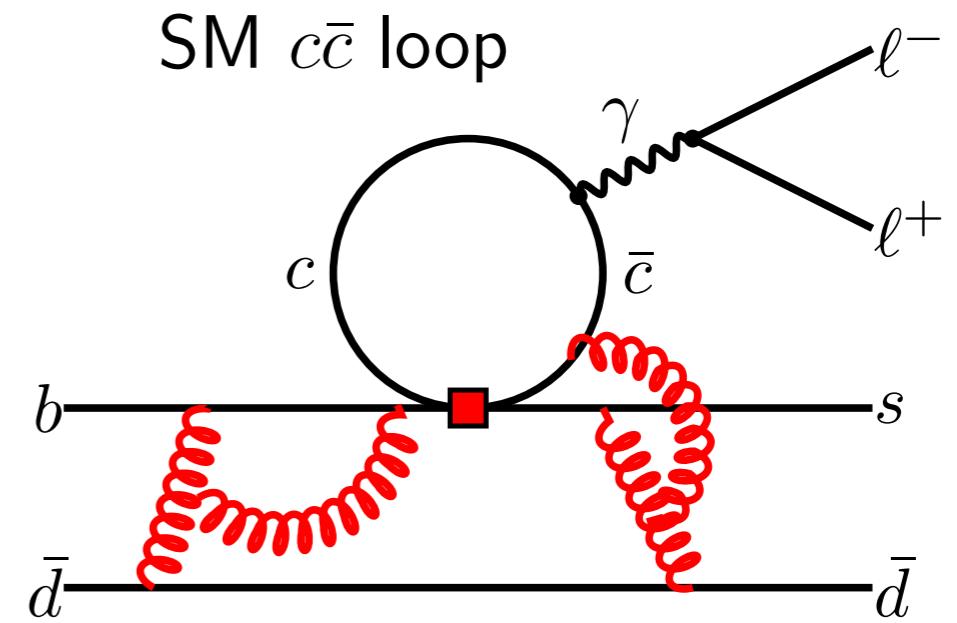
- Global fits of $b \rightarrow sll$ observables favour NP in C_{10} and C_9
- Consistency between $R_{K(*)}$ and other observables

New physics?



New vector Z' , leptoquarks ...

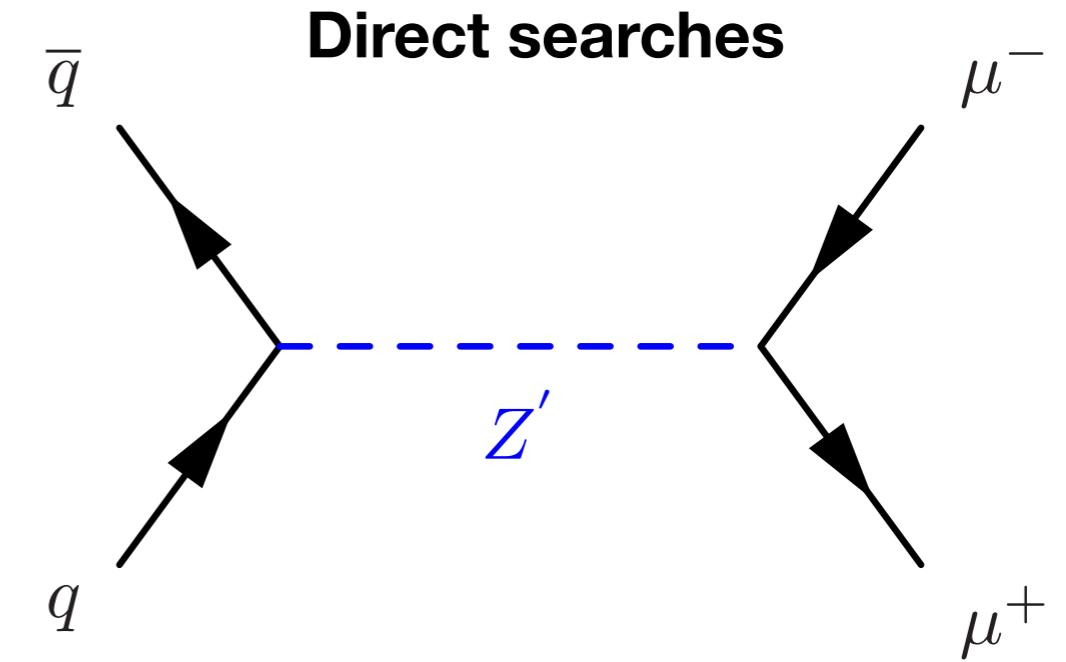
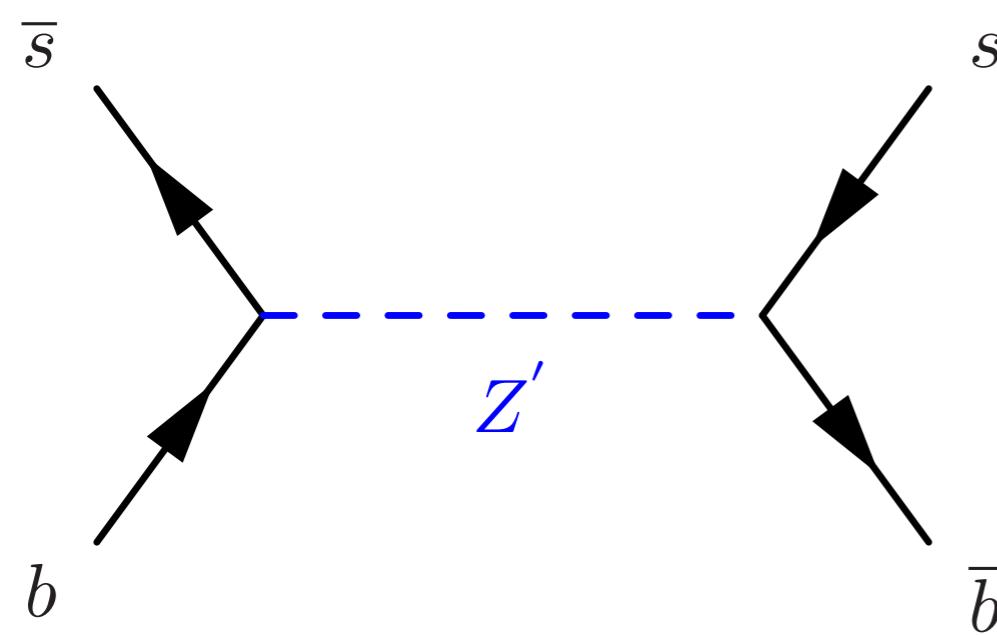
- [PRD 89 (2014) 095033] [PRL 114 (2015) 151801] [arxiv:1503.06077] [PRD 91 (2015) 075006] [PRD 92 (2015) 015007] [JHEP11 (2015) 173] [PRD 93 (2016) 074003] [PLB766 (2017) 77] [JHEP 03 (2017) 117] [arxiv:1704.06005] [arxiv:1705.03447] [arxiv:1705.00915]
- [PRL 116 (2016) 141802] [JHEP 06 (2015) 072] [arxiv:1704.05835] [EPJC 76 (2016) 67] [PLB 755 (2016) 270] [PRD 90 (2014) 054014] [JHEP 05 (2015) 006] [JHEP 10 (2015) 184] [PRL115(2015)181801] [PR641(2016)1] [JHEP 11 (2016) 035] [JHEP 12 (2016) 027] [arxiv: 1704.05849] . . .



$c\bar{c}$ contribution can mimic vector-like NP effect (corrections to C_9)

- Lyon, Zwicky [1406.0566]
- Altmannshofer Straub [1503.06199]
- Ciuchini et al [1512.07157]

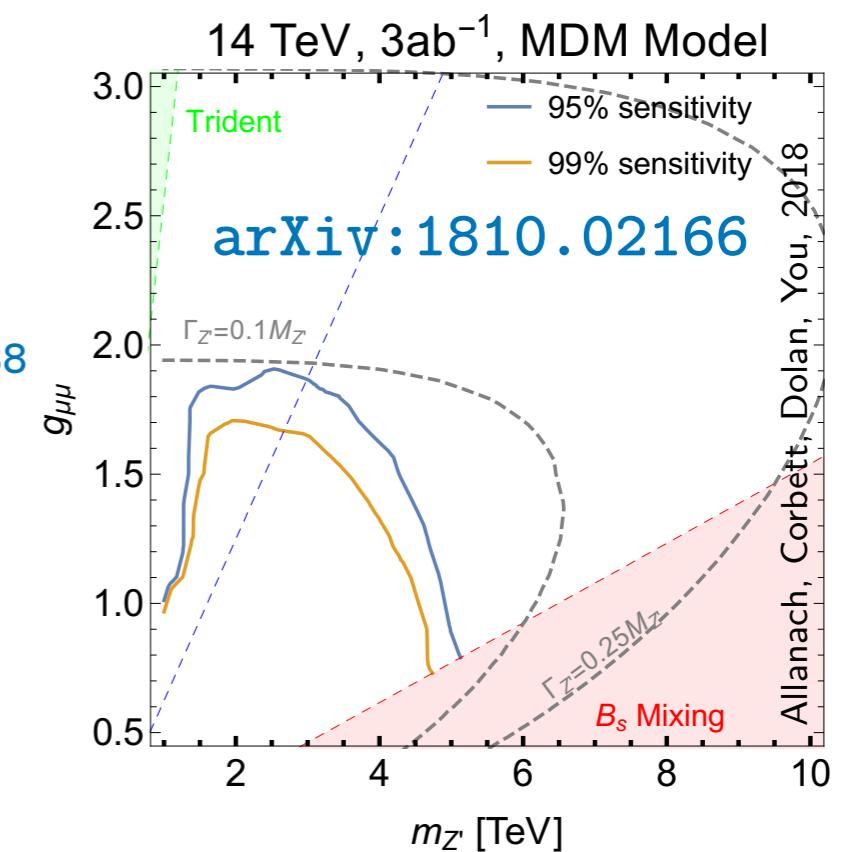
Experimental constraints



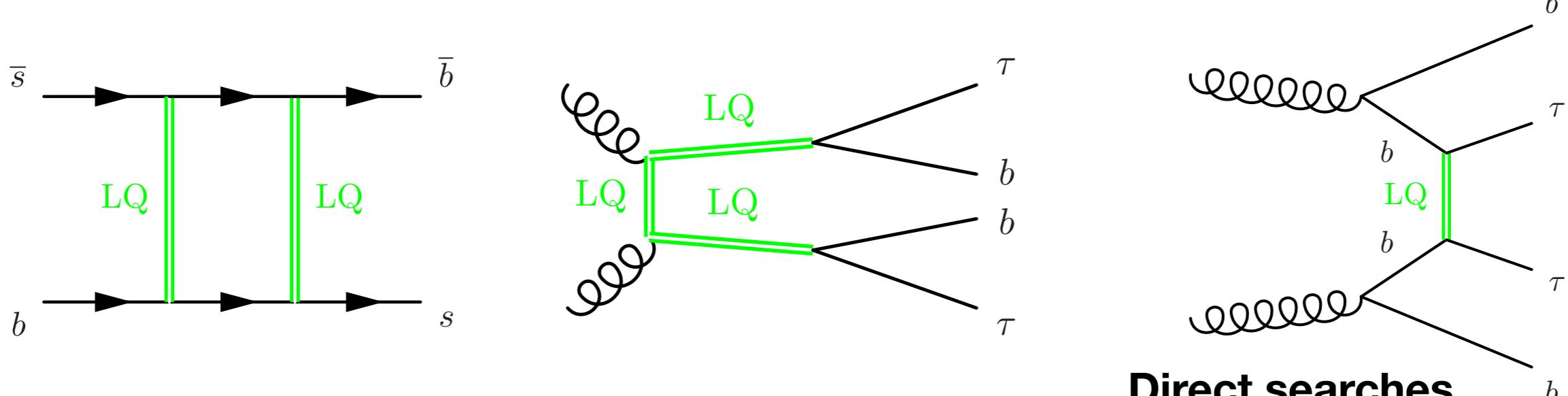
- Masses typically heavy $m_{Z'} \sim O(\text{TeV})$

[arxiv:1705.03465](https://arxiv.org/abs/1705.03465) [arxiv:1704.06188](https://arxiv.org/abs/1704.06188)

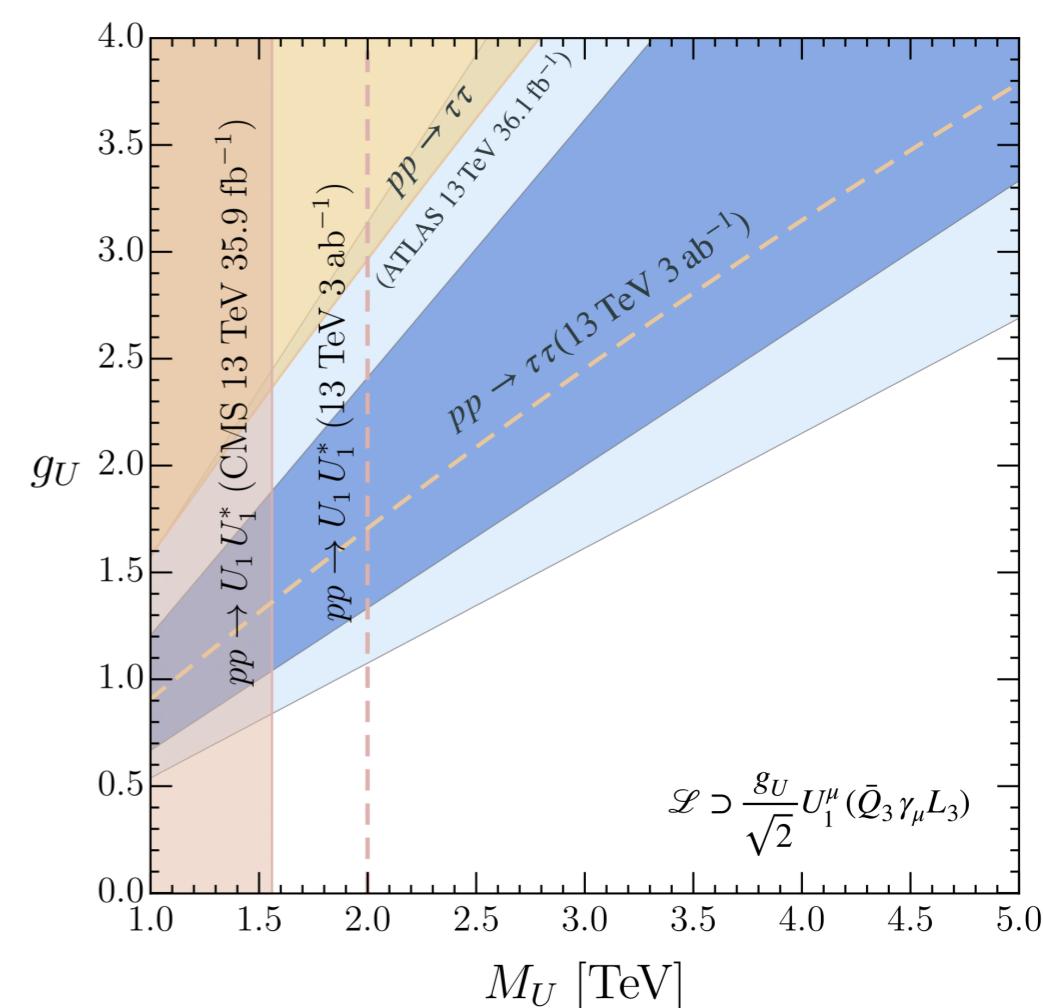
- Strong constraint from B_s mixing
 $g/m_{Z'} < 0.01/2.5\text{TeV}$



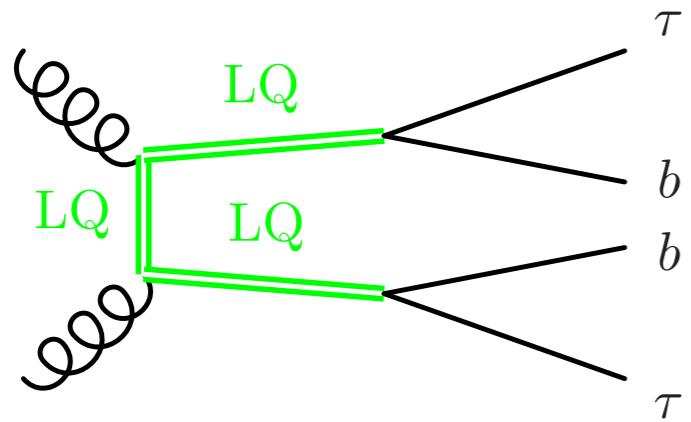
Leptoquark



- Model addresses anomaly and explain $C_{9^\mu} = - C_{10^\mu}$
- Clear advantages concerning constraints from non semi-leptonic constraints (B_s mixing)
- Limits from direct searches

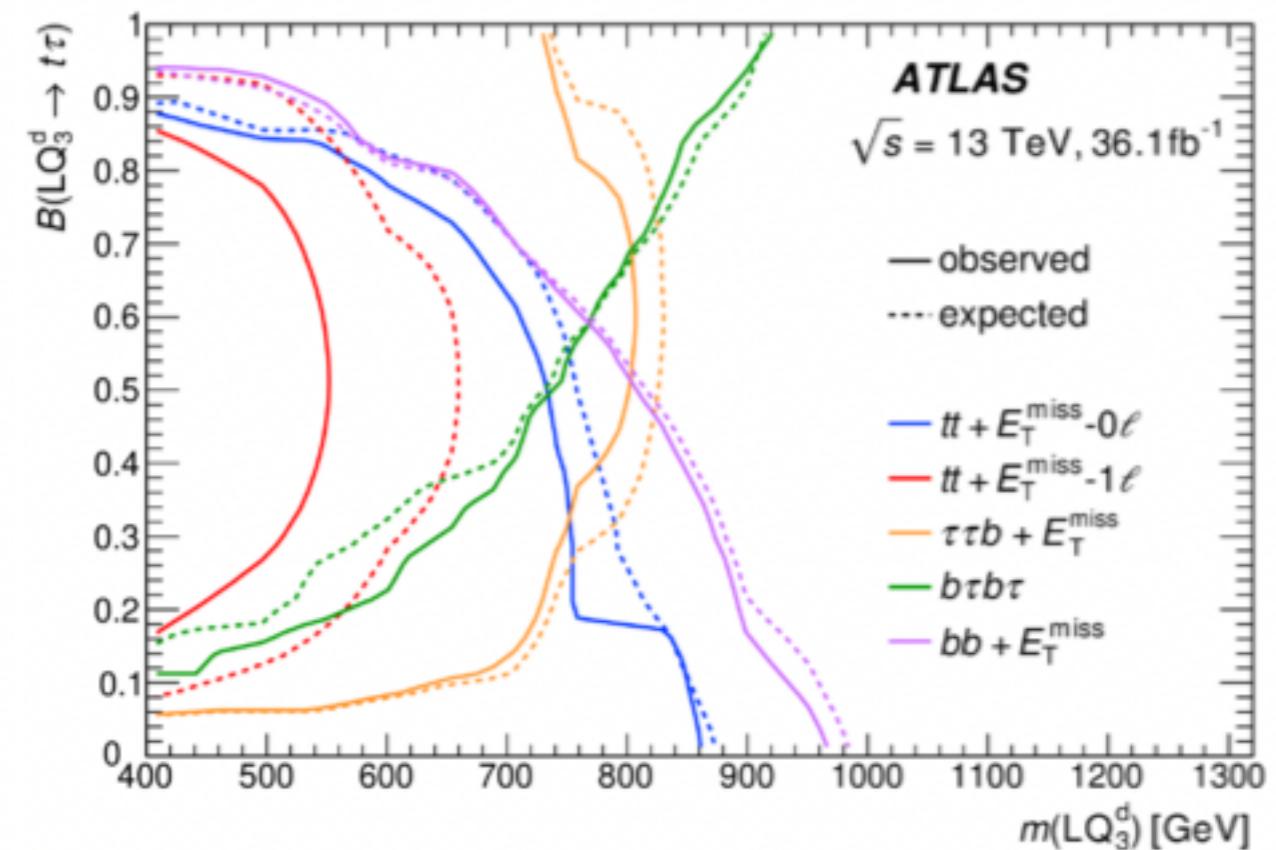
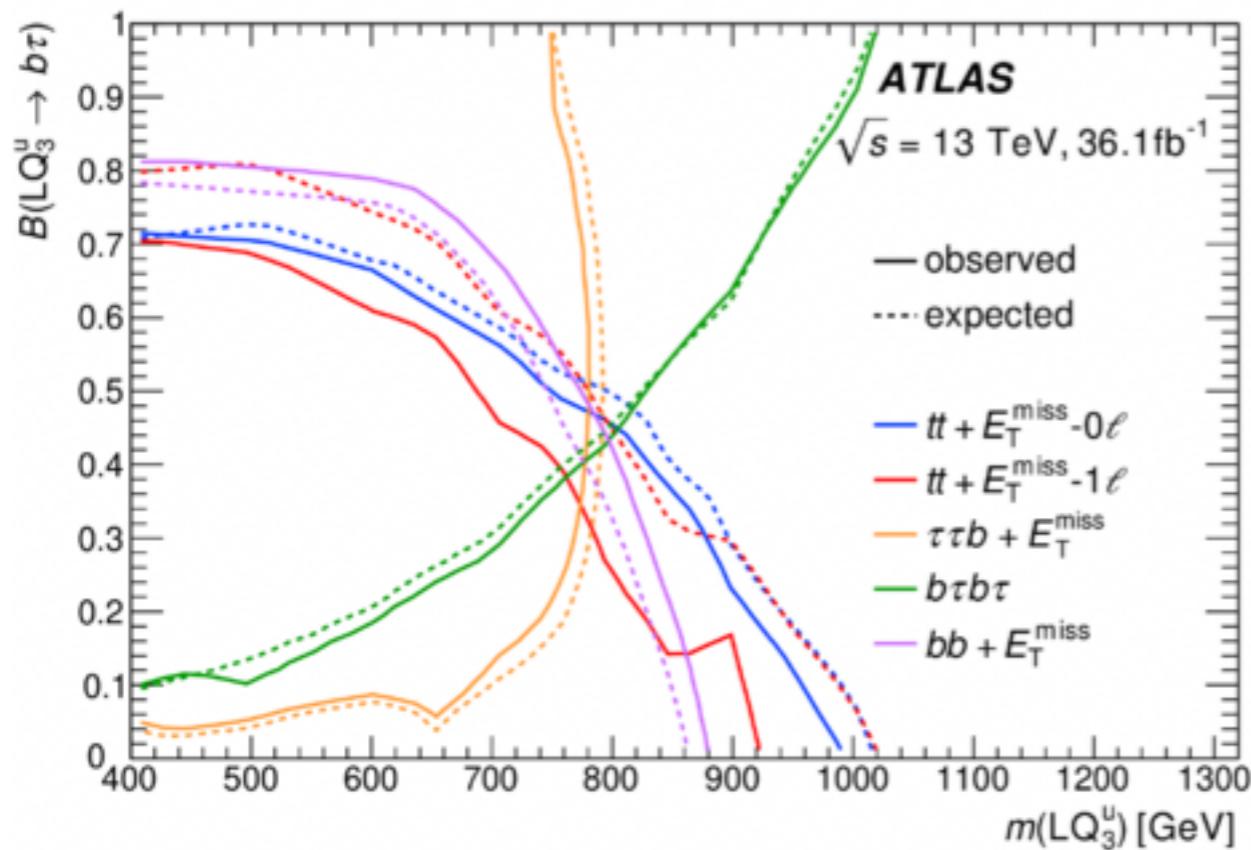


Leptoquark



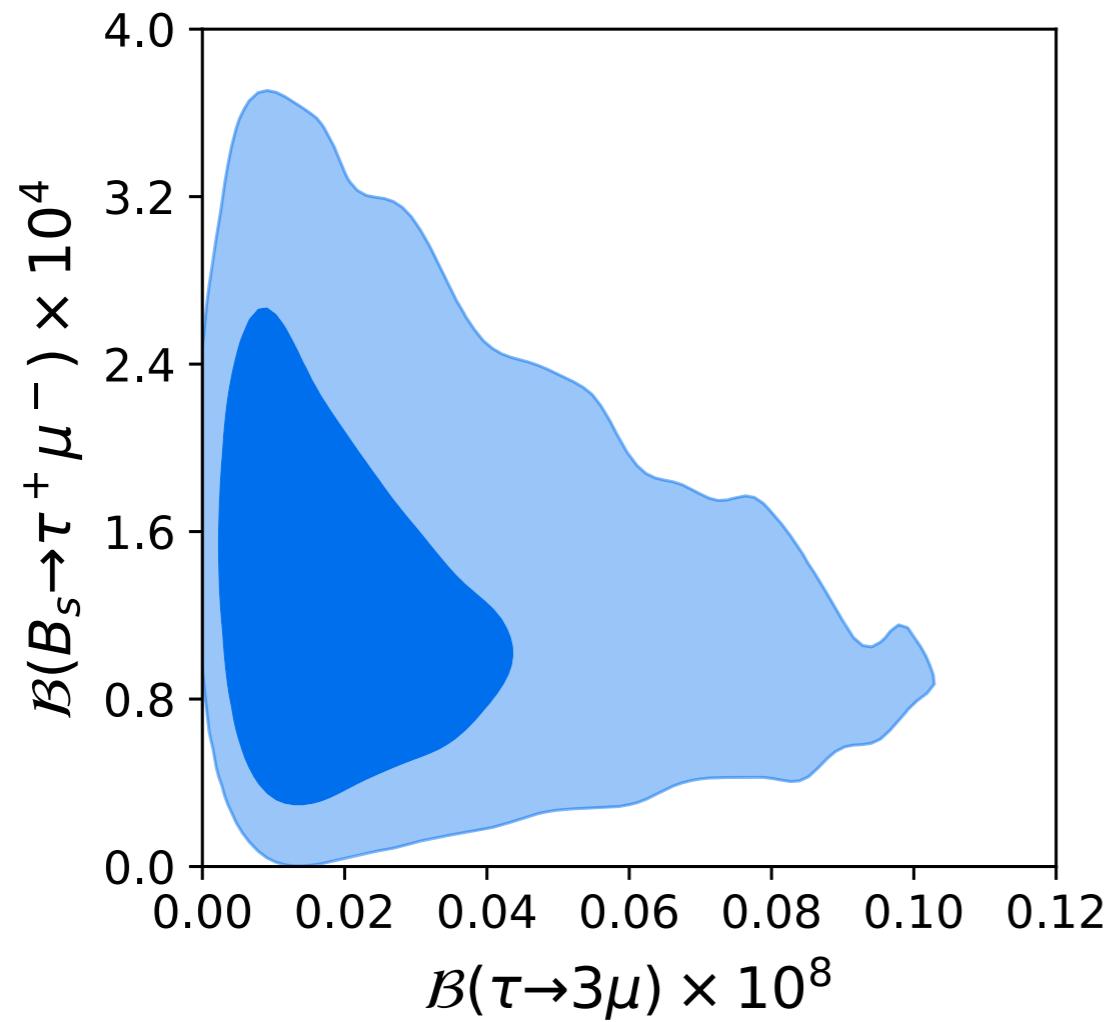
- Atlas experiment re-optimised/re-interpreted relevant HH or SUSY searches to produce LQ limits
- Exclude $m_{LQ} < 800$ GeV for LQ^u_3 and LQ^d_3 independently of the branching ratio (assuming LQ couples only to the 3rd generation)

JHEP 06 (2019) 144

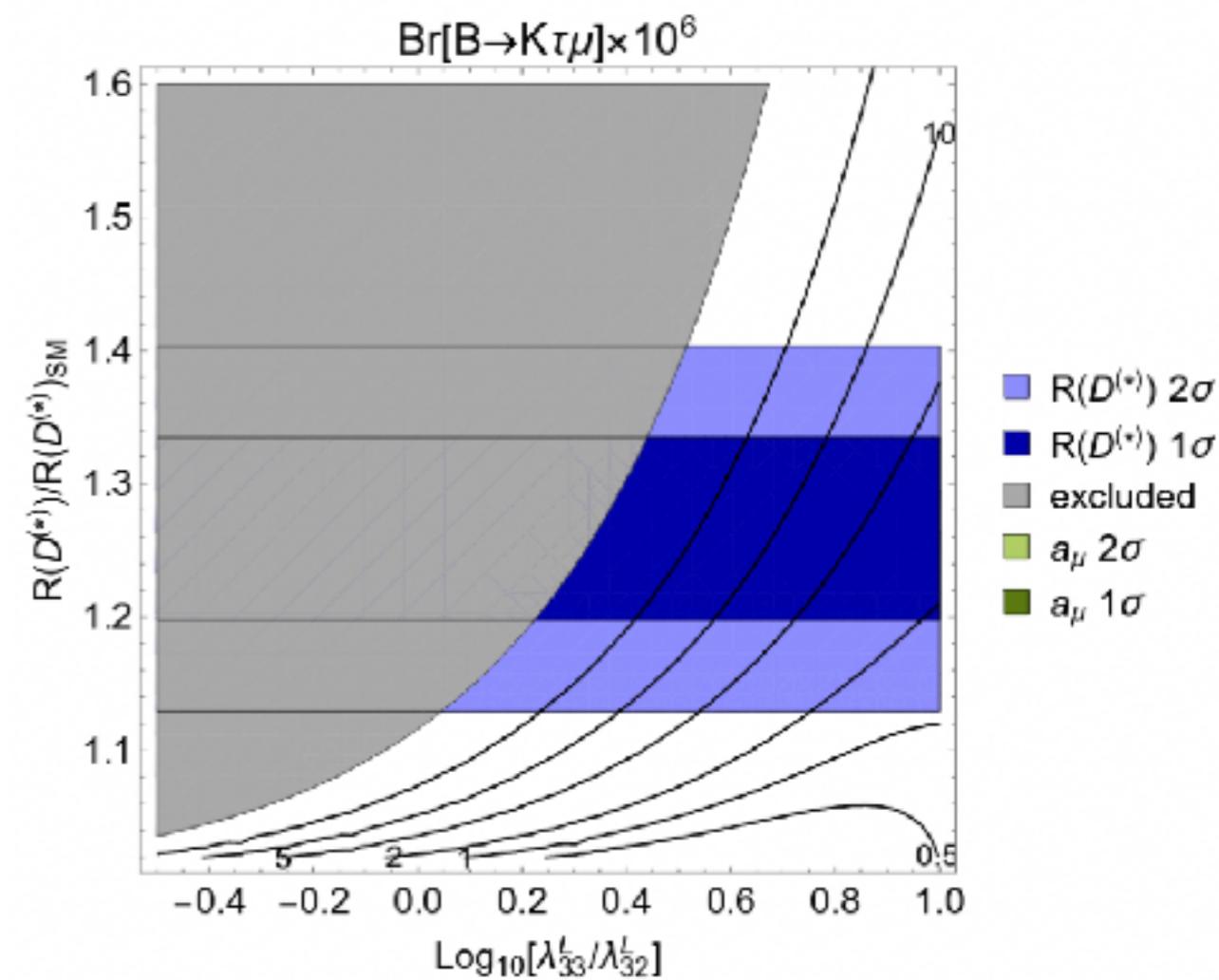


Searches for LFV

- If LFUV confirmed several LFV NP signature expected in $b \rightarrow s\tau\mu$ and $b \rightarrow s\mu e$



Bordone et al.
JHEP10(2018)148 (2018)



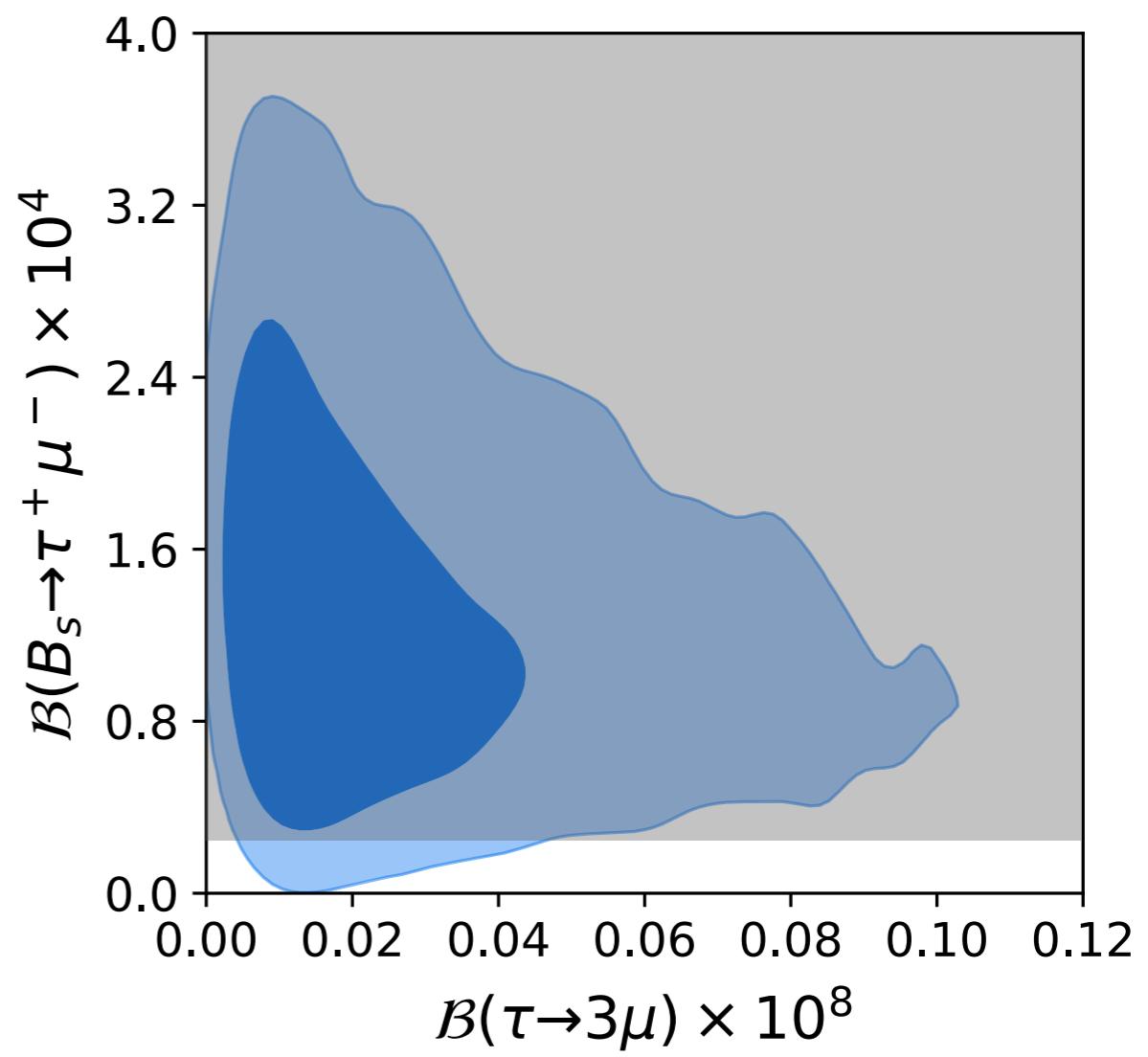
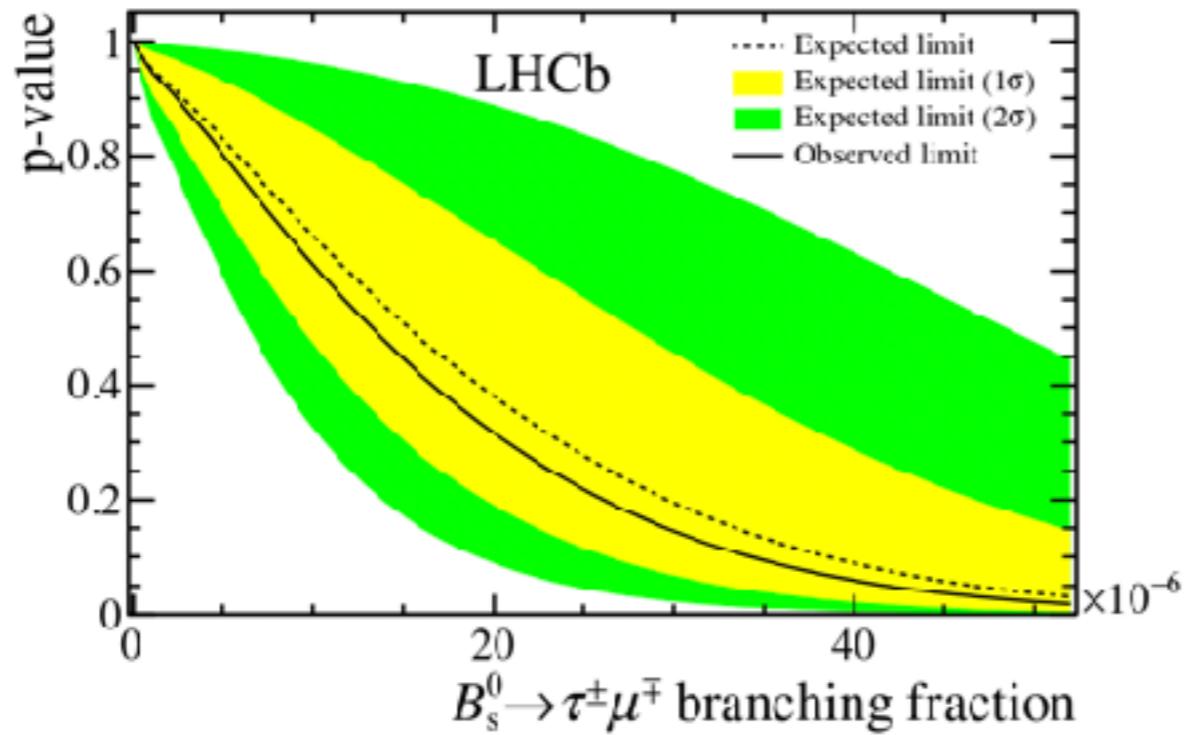
Crivellin, Mueller,
Ota JHEP09(2017)040

$B^0_s \rightarrow \tau^\pm \mu^\mp$

arXiv:1905.06614

- LHCb analysis with Run 1 data (3 fb^{-1})
- Reconstruct $B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$ candidates using the 3-prong τ decay

Bordone et al.
JHEP10(2018)148 (2018)



| Mode | Limit | 90% CL | 95% CL |
|--------------------------------------|----------|----------------------|----------------------|
| $B_s^0 \rightarrow \tau^\pm \mu^\mp$ | Observed | 3.4×10^{-5} | 4.2×10^{-5} |
| | Expected | 3.9×10^{-5} | 4.7×10^{-5} |
| $B^0 \rightarrow \tau^\pm \mu^\mp$ | Observed | 1.2×10^{-5} | 1.4×10^{-5} |
| | Expected | 1.6×10^{-5} | 1.9×10^{-5} |

Conclusions

- Intriguing pattern of anomalies in rare and semi-leptonic decays, measured, by LHCb, BaBar and Belle → still need larger statistics to disentangle BSM effects
- More results will come from LHCb Run2 analyses for both anomalies.
- Belle II and LHCb Upgrades will allow to further clarify the situation and if these anomalies are due to NP to disentangle between different scenarios
- Flavour physics is and it will remain strategically important for the HEP community:
 - If flavour anomalies **will be confirmed**, the interest towards the physics results of LHCb, BelleII (and other experiments!) cannot be underestimated.
 - If flavour anomalies **will disappear and no evidence of NP on-shell at LHC**, flavour physics will remain a unique probe to test higher energy scales in a indirect way

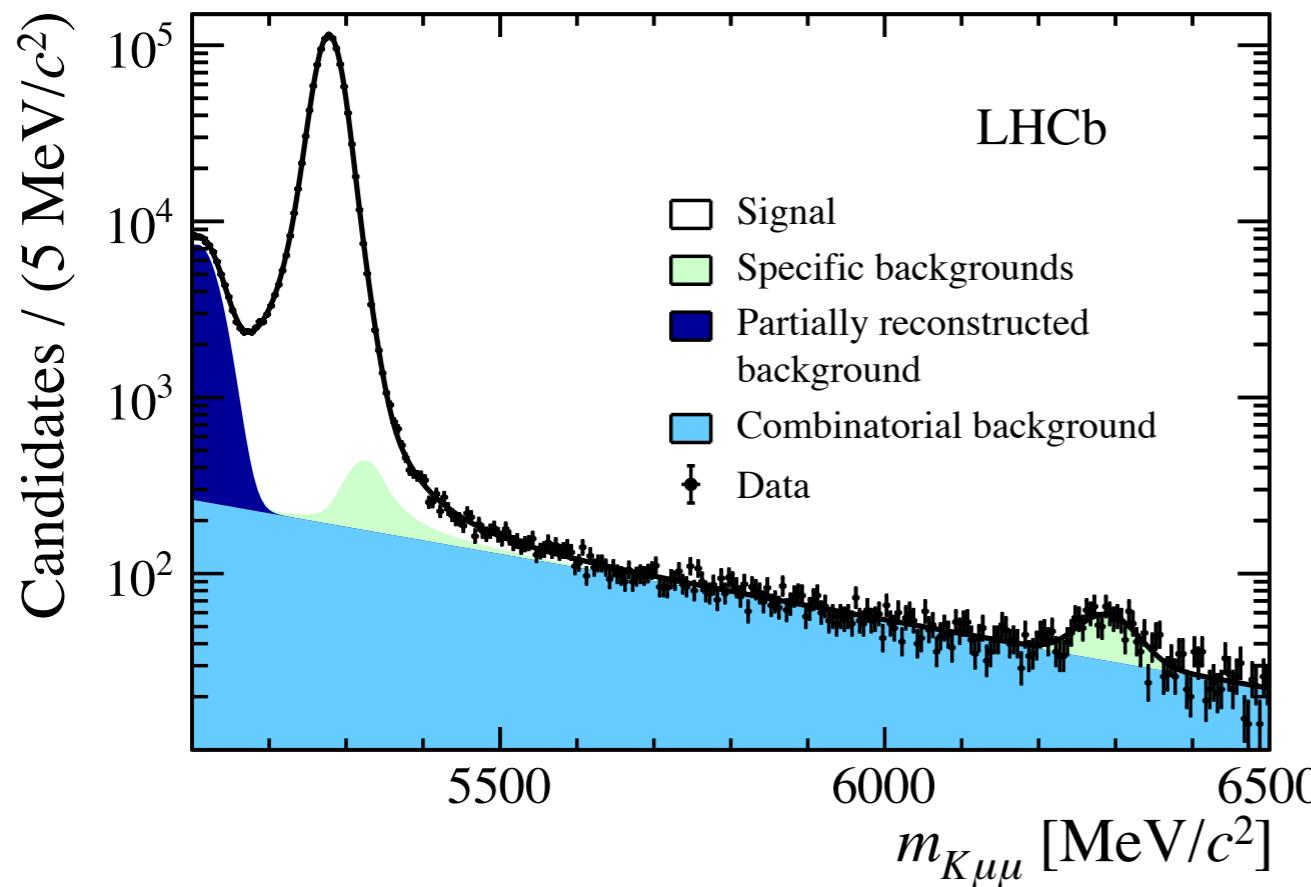
Marco Nardecchia

Backup



Impact of dilepton vector coupling

- Important to understand how much the long distance contribution from SM and interference with the short distance
- Measurement of the phase difference between the short-distance and narrow resonances in $B^+ \rightarrow K^+ \mu^+ \mu^-$



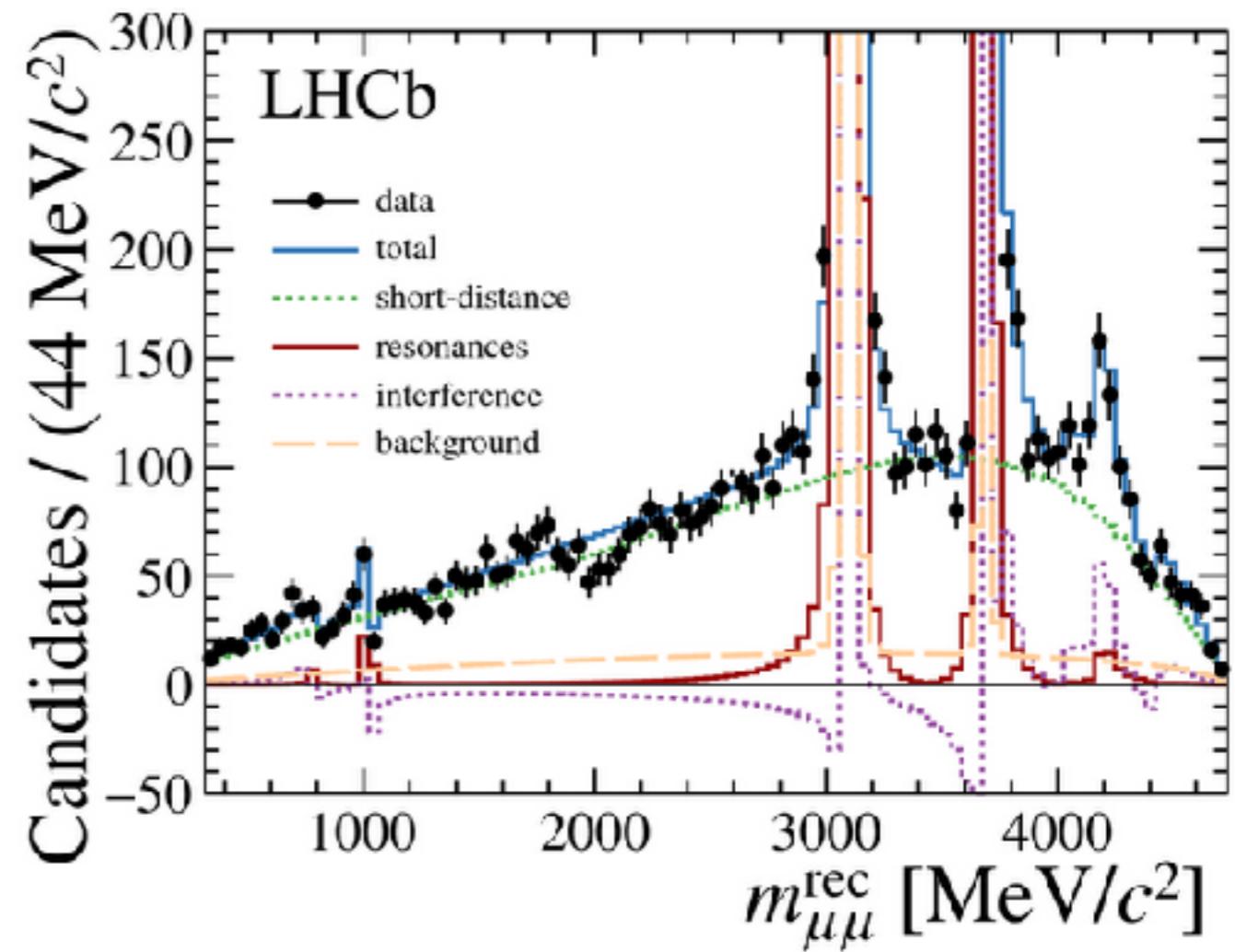
- Dependence of the observables enters through C_9
$$C_9^{\text{eff}} = C_9 + Y(q^2).$$
- $Y(q^2)$ summarises contributions from $b\bar{s}q\bar{q}$ operators
- Main culprit is the large $c\bar{c}$ component such as the J/ψ

[Eur. Phys. J. C(2017)77:161]

Measuring phase differences

- Fit to full di-muon mass distribution including:
- Resonances: ρ , ω , ϕ , J/ψ , $\psi(2S)$
- Broad charmonium states: $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$
- Four-fold ambiguity in J/ψ and $\psi(2S)$ phases signs:
- compatible with $\pi/2 \rightarrow$ minimal interference with non resonant
- Dedicated analysis needed for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

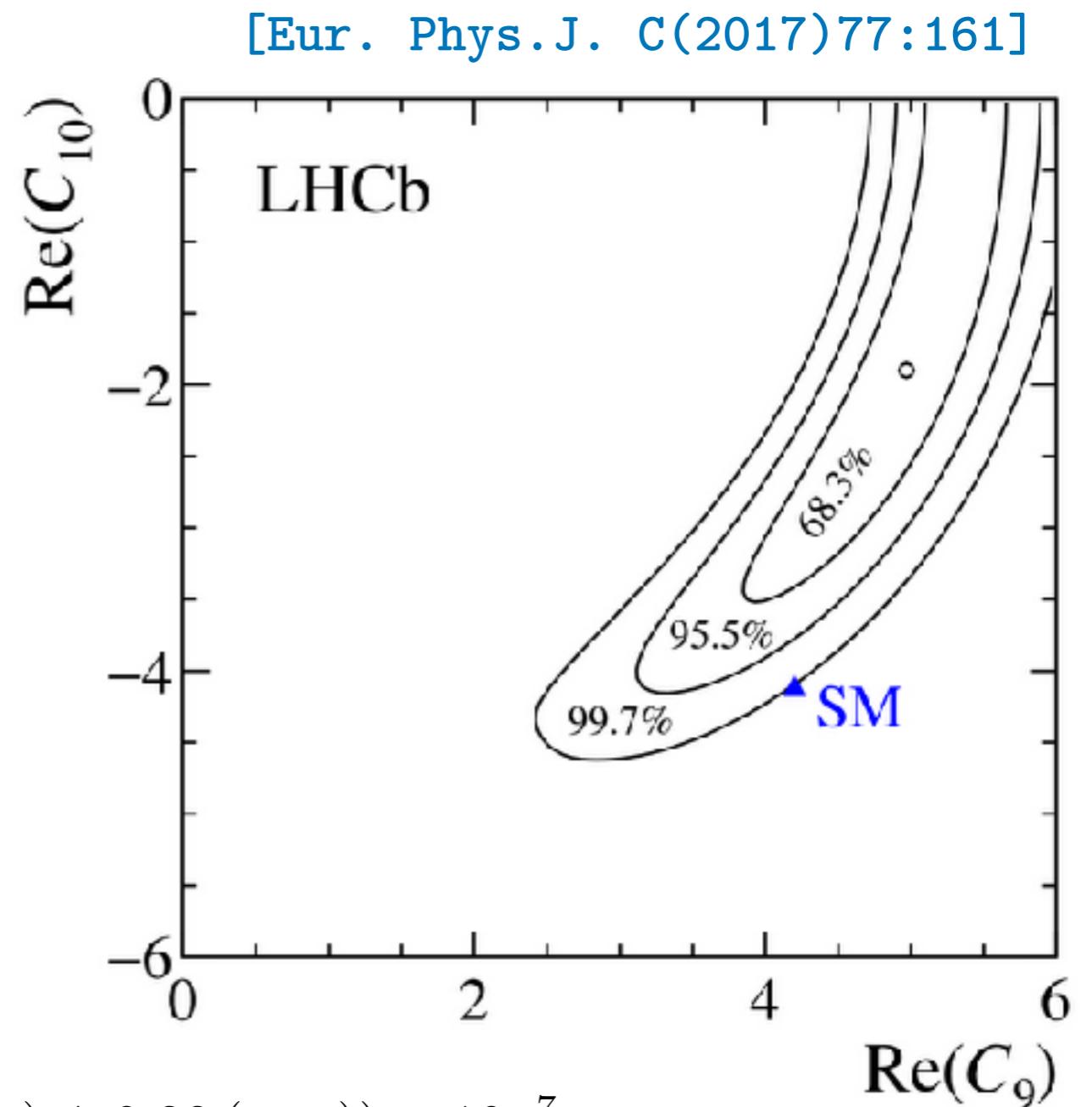
[Eur. Phys. J. C(2017)77:161]



Fit to Wilson coefficients

- Non resonant sensitive to C_9 and C_{10}
- Deviation of 3.0σ from SM
- Low $B^+ \rightarrow K^+ \mu^+ \mu^-$ BR not explain by resonance interferences
- Its measurement in agreement with previous measurement

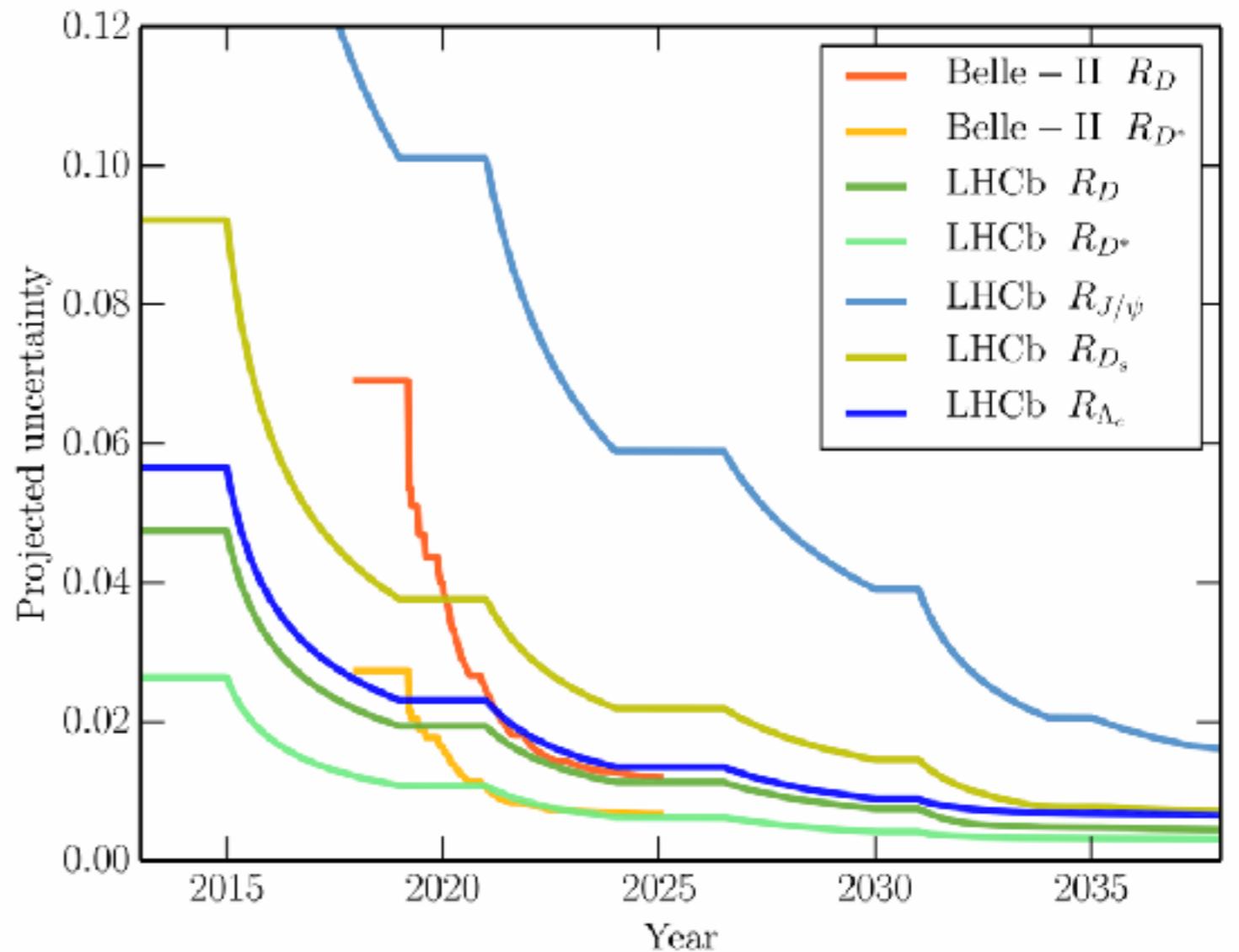
$$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \text{ (stat)} \pm 0.23 \text{ (syst)}) \times 10^{-7}$$



LFU $R(D^*)$

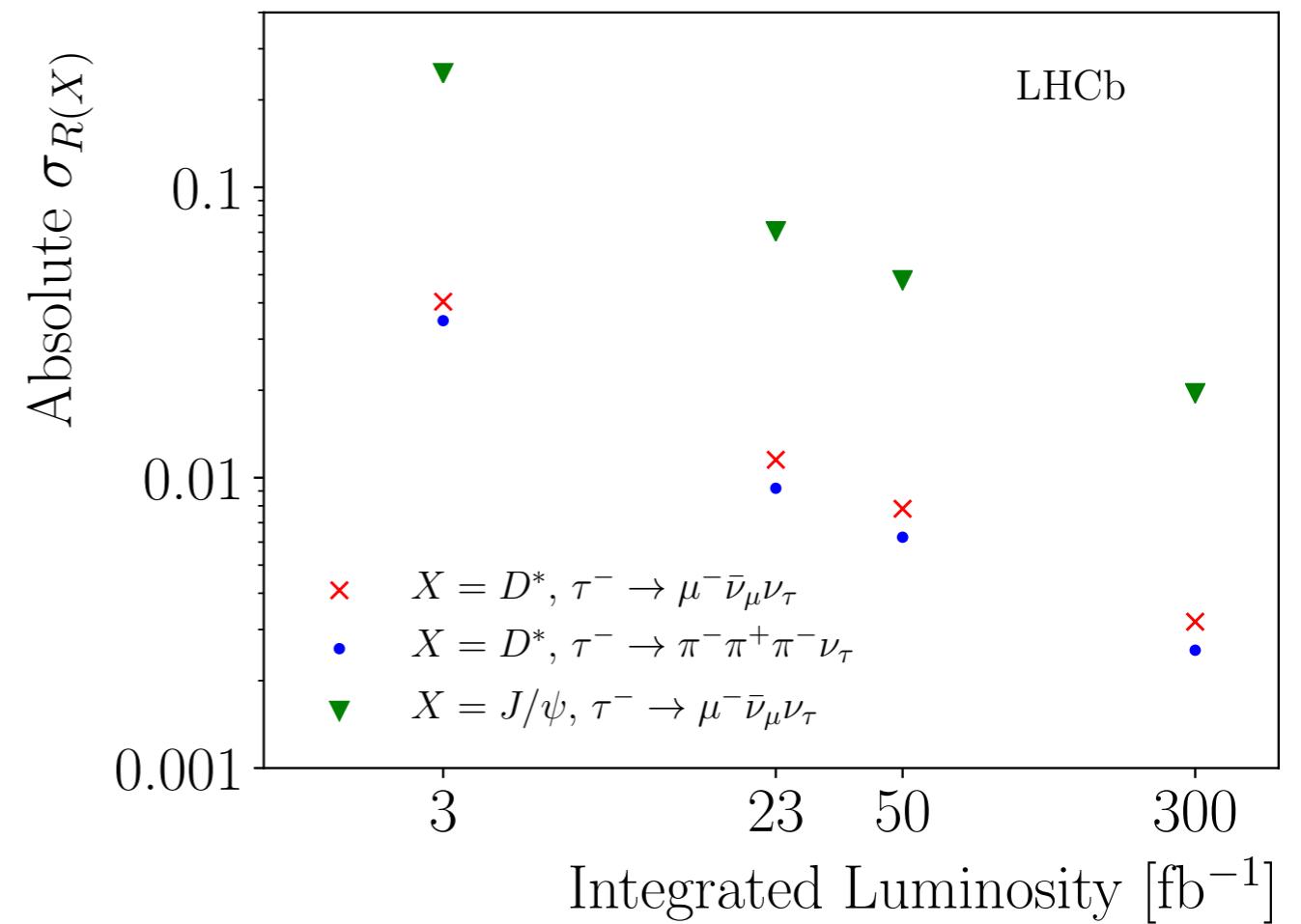
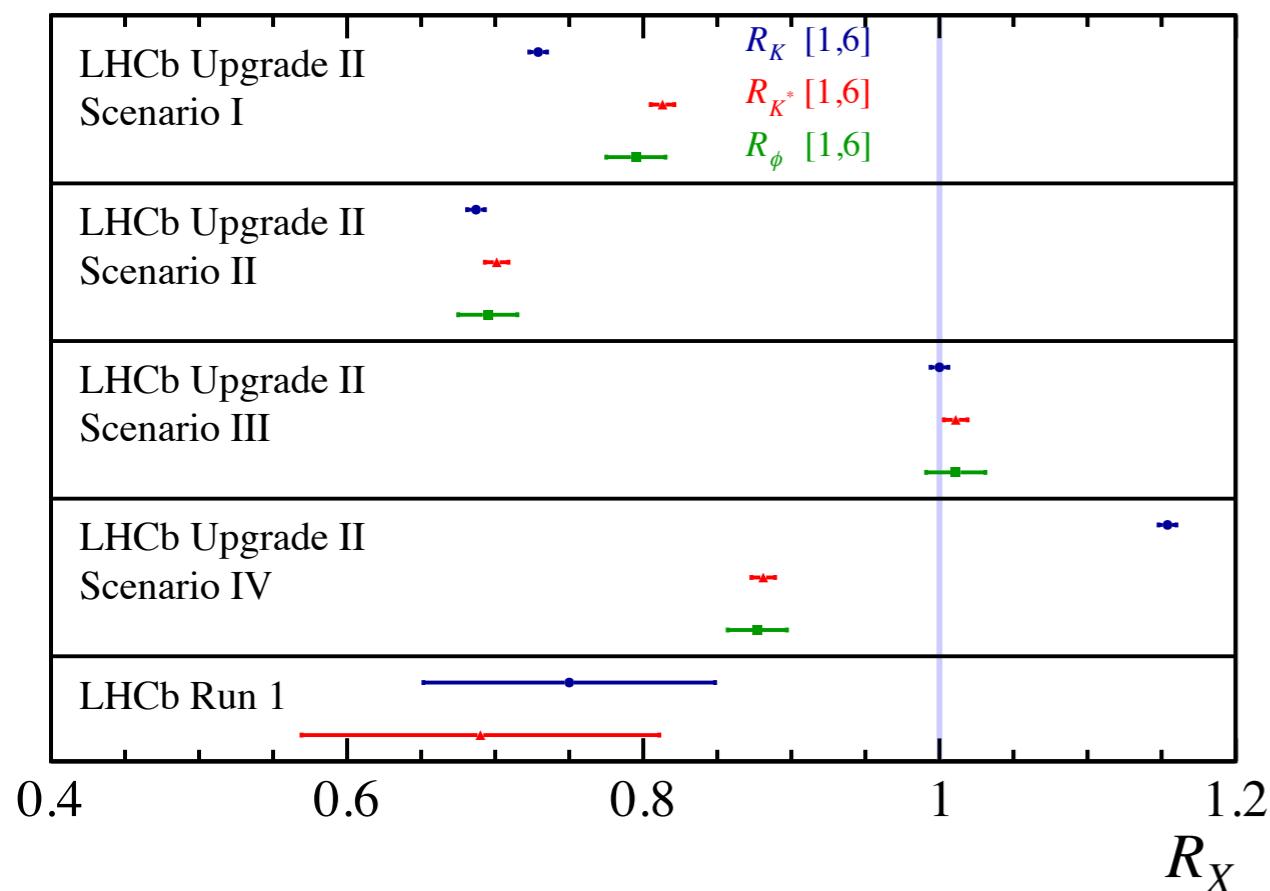
J. Phys. G: Nucl. Part. Phys. 46 (2019) 023001

- Prospects for several modes in the coming years
- systematics wall at 0.5%



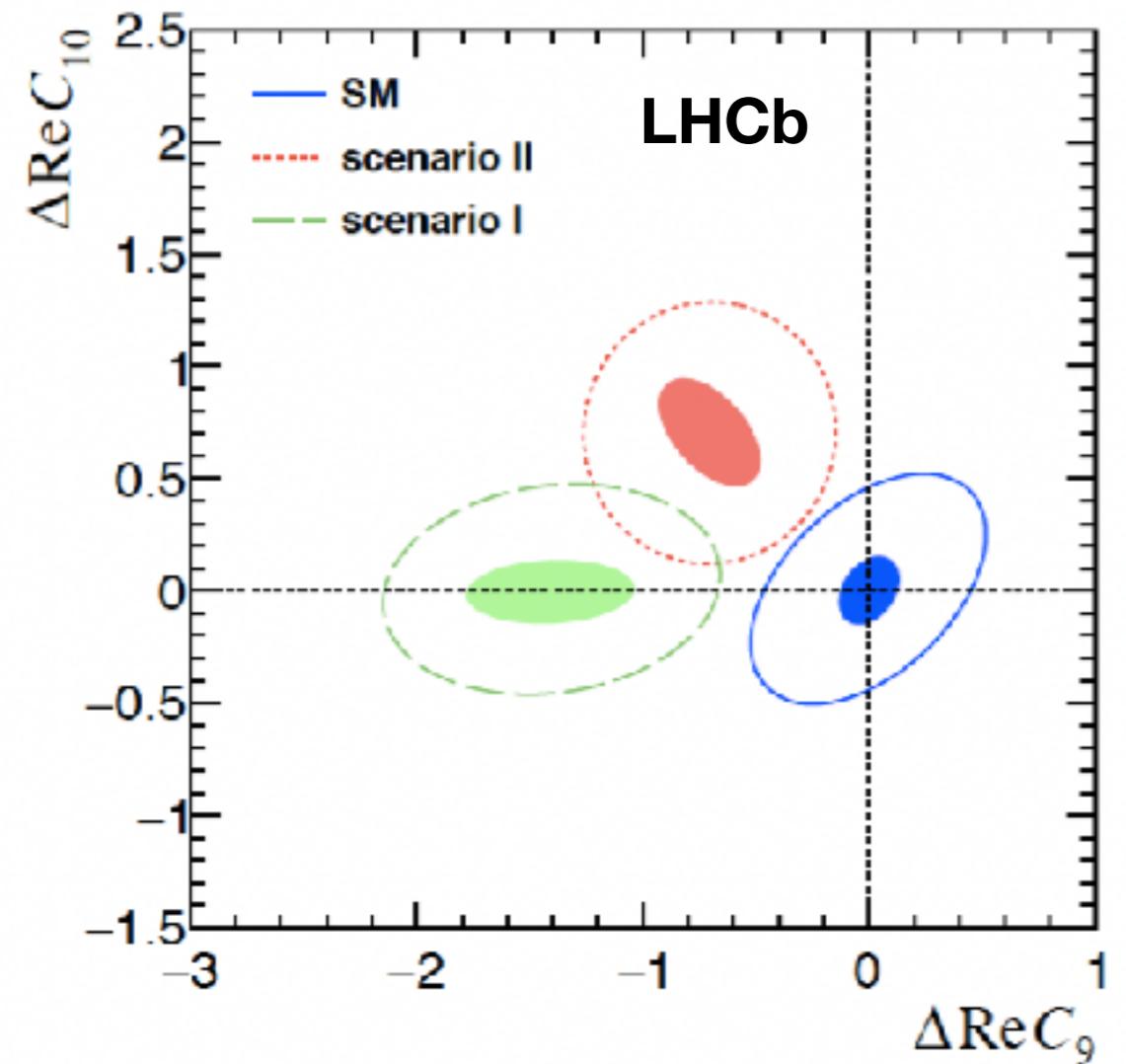
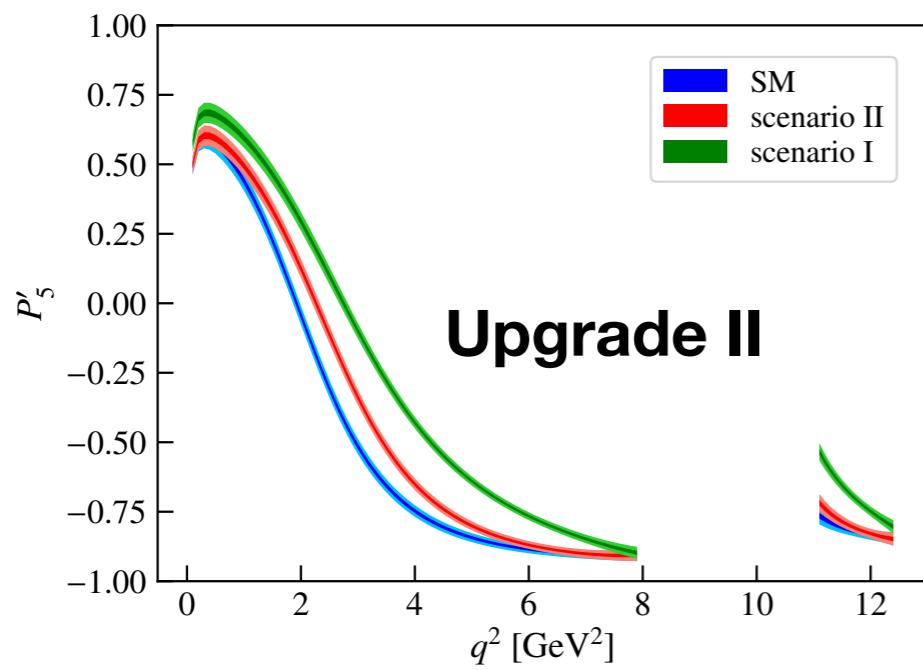
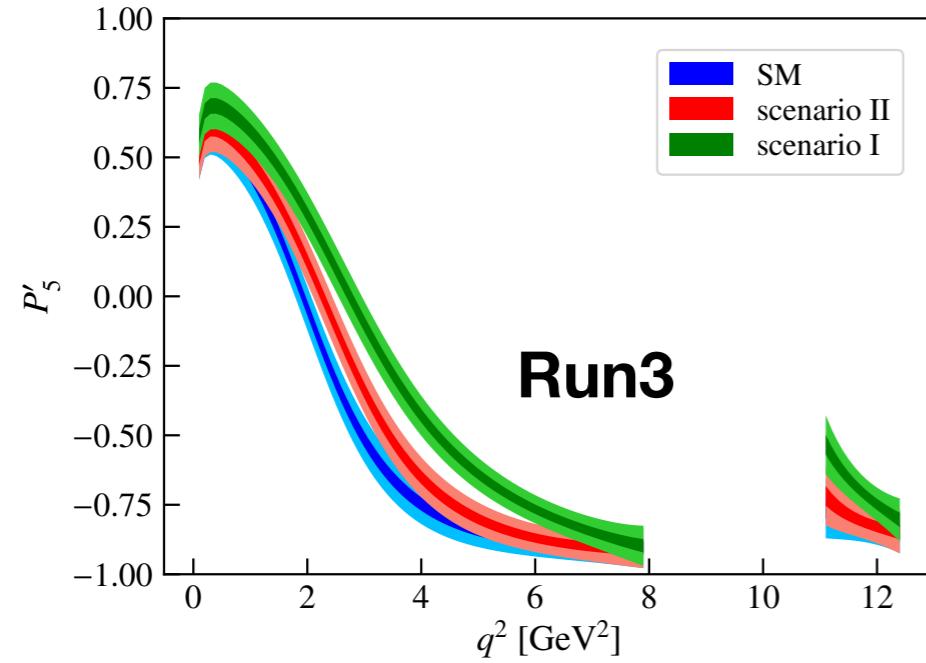
LFU R(X)

[arxiv:1808.08865](https://arxiv.org/abs/1808.08865)



| scenario | C_9^{NP} | C_{10}^{NP} | C'_9 | C'_{10} |
|----------|-------------------|----------------------|--------|-----------|
| I | -1.4 | 0 | 0 | 0 |
| II | -0.7 | 0.7 | 0 | 0 |
| III | 0 | 0 | 0.3 | 0.3 |
| IV | 0 | 0 | 0.3 | -0.3 |

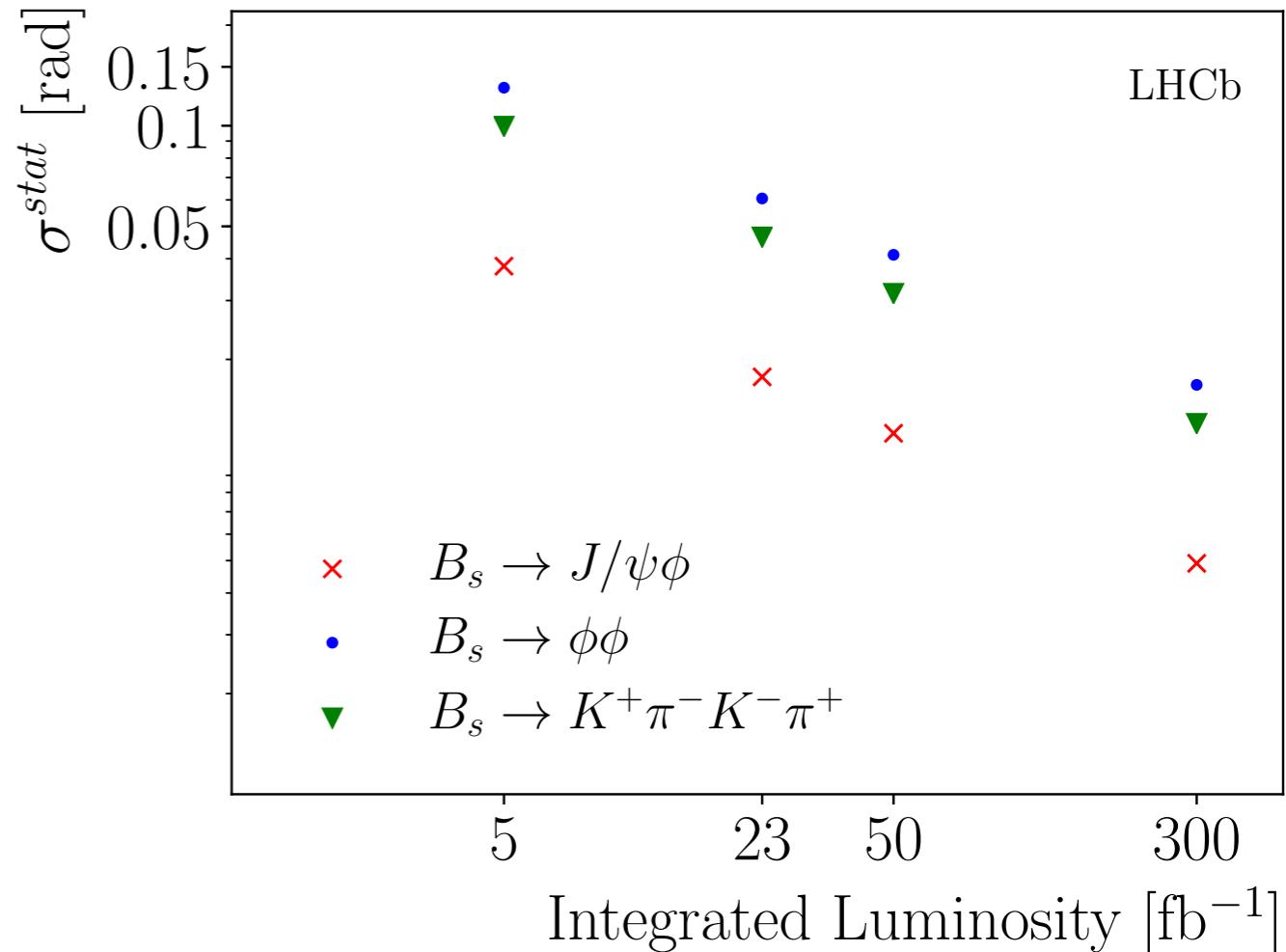
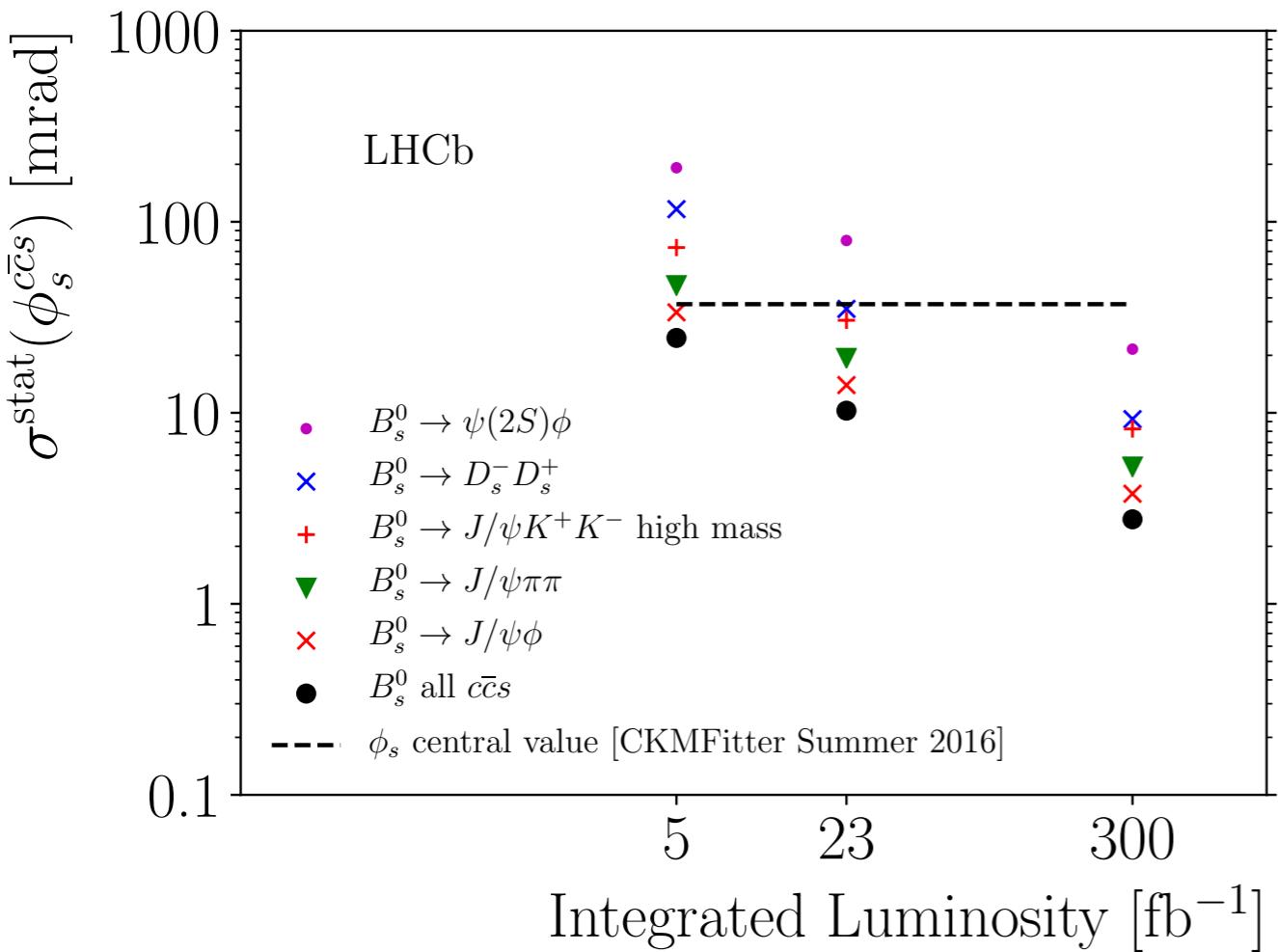
Projections



| scenario | C_9^{NP} | C_{10}^{NP} | C'_9 | C'_{10} |
|----------|-------------------|----------------------|--------|-----------|
| I | -1.4 | 0 | 0 | 0 |
| II | -0.7 | 0.7 | 0 | 0 |

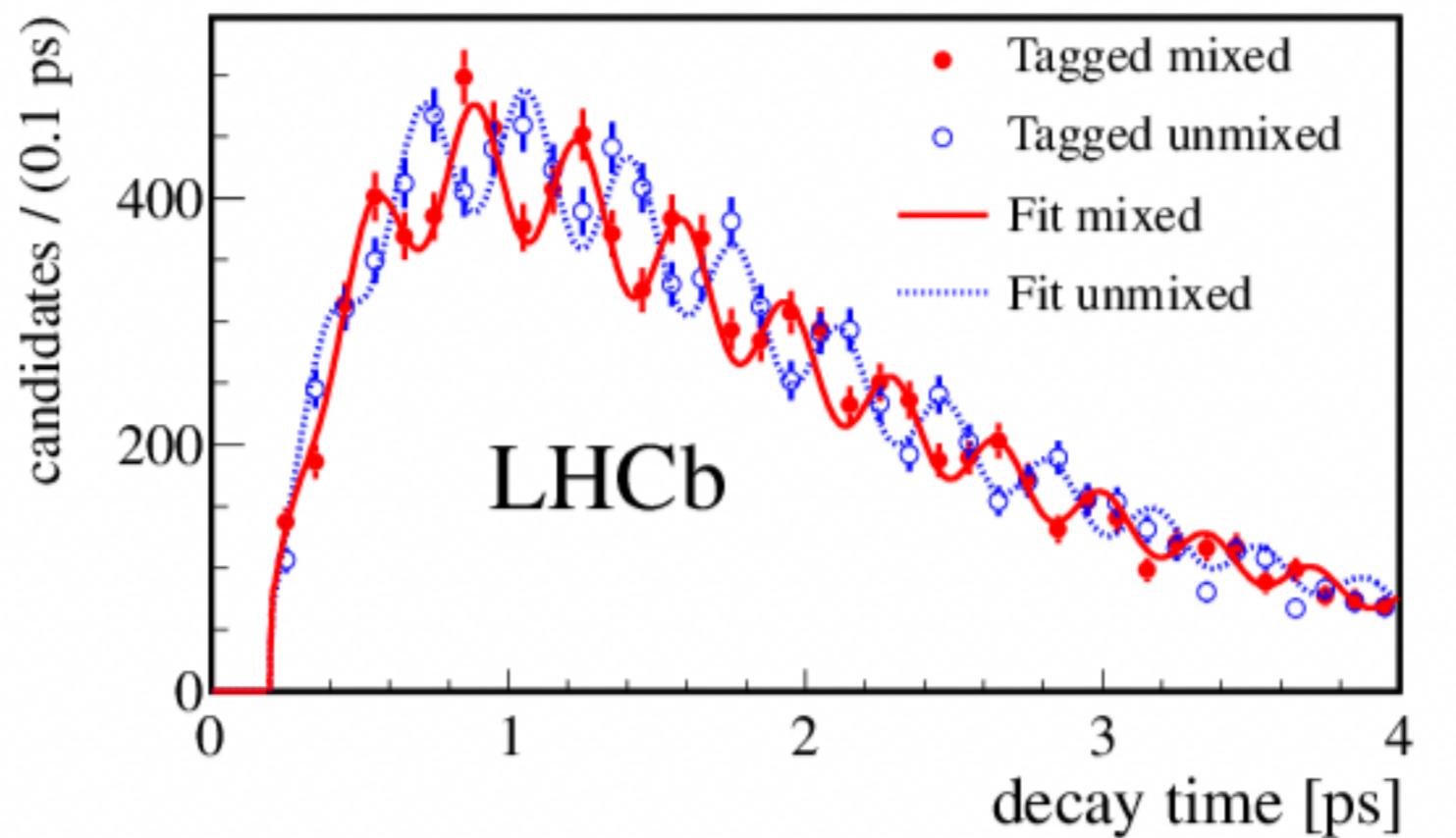
Φ_s

Comparison of ϕ_s sensitivity from different decay modes



B_s mixing

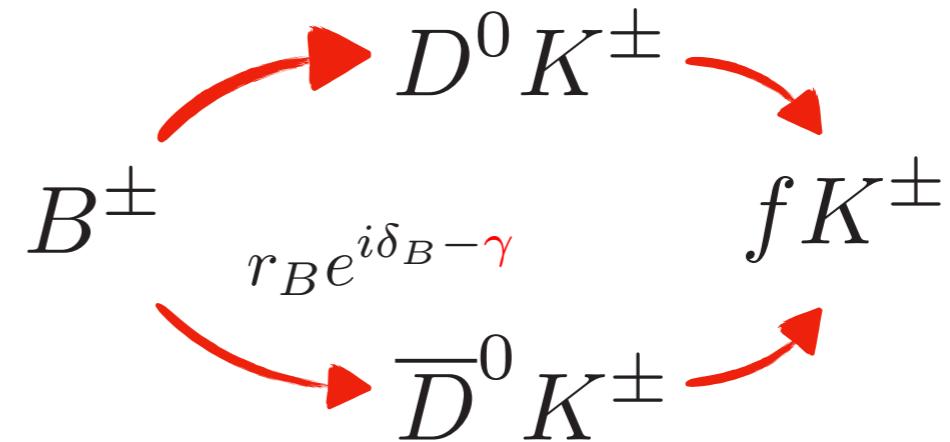
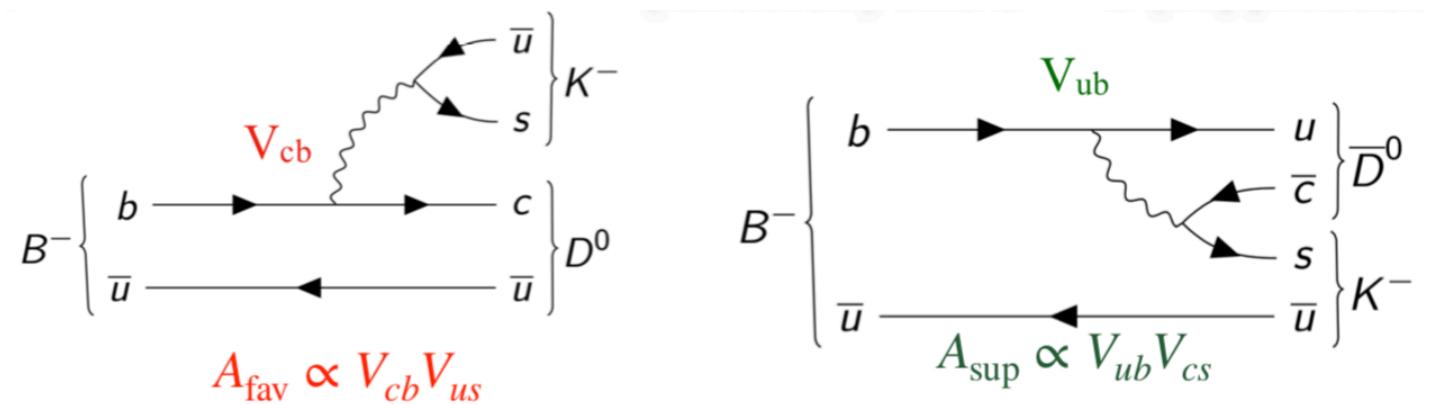
New J. Phys. 15 (2013) 053021



- Mixing frequency from $B_s \rightarrow D_s^- \pi^+$:
- $\Delta m_s = 17.768 \pm 0.023^{\text{stat}} \pm 0.006^{\text{syst}} \text{ ps}^{-1}$
- Standard Model: $\Delta m_s = 20.31 \pm 1.34 \text{ ps}^{-1}$
- (2016: A. Lenz: arXiv:1603.07770)

CKM angle γ

- The only CP violating parameter that can be measured from tree-level decays
- Measured using $B \rightarrow D h$ decays
- Exploit interference between amplitudes $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed)



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

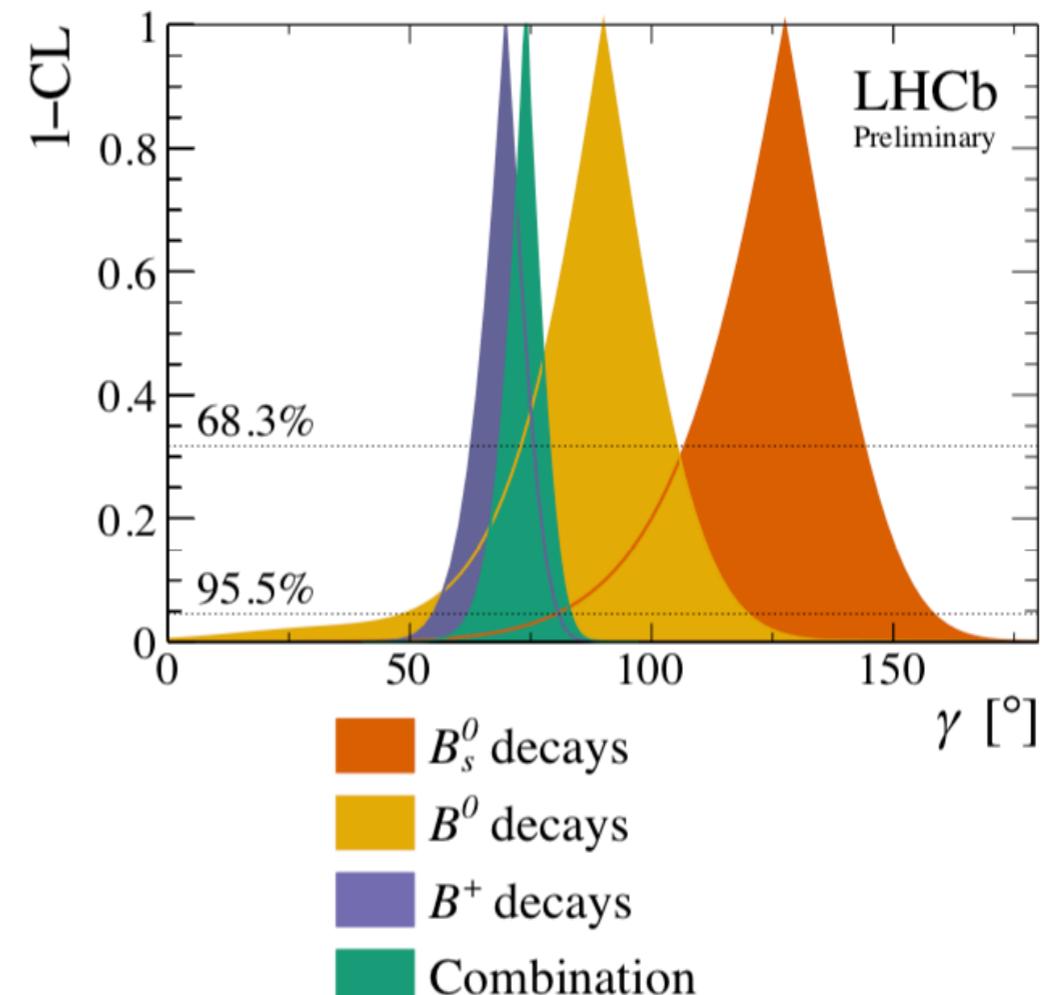
more details in
Shohei Nishida's talk

CKM angle γ

LHCb-CONF-2018-002

- Combined several measurement from tree-level decays

| B decay | D decay | Method | Ref. | Dataset [†] | Status since last combination [3] |
|-----------------------------------|------------------------------------|------------|------|----------------------|-----------------------------------|
| $B^+ \rightarrow DK^+$ | $D \rightarrow h^+h^-$ | GLW | [14] | Run 1 & 2 | Minor update |
| $B^+ \rightarrow DK^+$ | $D \rightarrow h^+h^-$ | ADS | [15] | Run 1 | As before |
| $B^+ \rightarrow DK^+$ | $D \rightarrow h^+\pi^-\pi^+\pi^-$ | GLW/ADS | [15] | Run 1 | As before |
| $B^+ \rightarrow DK^+$ | $D \rightarrow h^+h^-\pi^0$ | GLW/ADS | [16] | Run 1 | As before |
| $B^+ \rightarrow DK^+$ | $D \rightarrow K_s^0 h^+h^-$ | GGSZ | [17] | Run 1 | As before |
| $B^+ \rightarrow DK^+$ | $D \rightarrow K_s^0 h^+h^-$ | GGSZ | [18] | Run 2 | New |
| $B^+ \rightarrow DK^+$ | $D \rightarrow K_s^0 K^+\pi^-$ | GLS | [19] | Run 1 | As before |
| $B^+ \rightarrow D^*K^+$ | $D \rightarrow h^+h^-$ | GLW | [14] | Run 1 & 2 | Minor update |
| $B^+ \rightarrow DK^{*+}$ | $D \rightarrow h^+h^-$ | GLW/ADS | [20] | Run 1 & 2 | Updated results |
| $B^+ \rightarrow DK^{*+}$ | $D \rightarrow h^+\pi^-\pi^+\pi^-$ | GLW/ADS | [20] | Run 1 & 2 | New |
| $B^+ \rightarrow DK^+\pi^+\pi^-$ | $D \rightarrow h^+h^-$ | GLW/ADS | [21] | Run 1 | As before |
| $B^0 \rightarrow DK^{*0}$ | $D \rightarrow K^+\pi^-$ | ADS | [22] | Run 1 | As before |
| $B^0 \rightarrow DK^+\pi^-$ | $D \rightarrow h^+h^-$ | GLW-Dalitz | [23] | Run 1 | As before |
| $B^0 \rightarrow DK^{*0}$ | $D \rightarrow K_s^0\pi^+\pi^-$ | GGSZ | [24] | Run 1 | As before |
| $B_s^0 \rightarrow D_s^\mp K^\pm$ | $D_s^+ \rightarrow h^+h^-\pi^+$ | TD | [25] | Run 1 | Updated results |
| $B^0 \rightarrow D^\mp\pi^\pm$ | $D^+ \rightarrow K^+\pi^-\pi^+$ | TD | [26] | Run 1 | New |

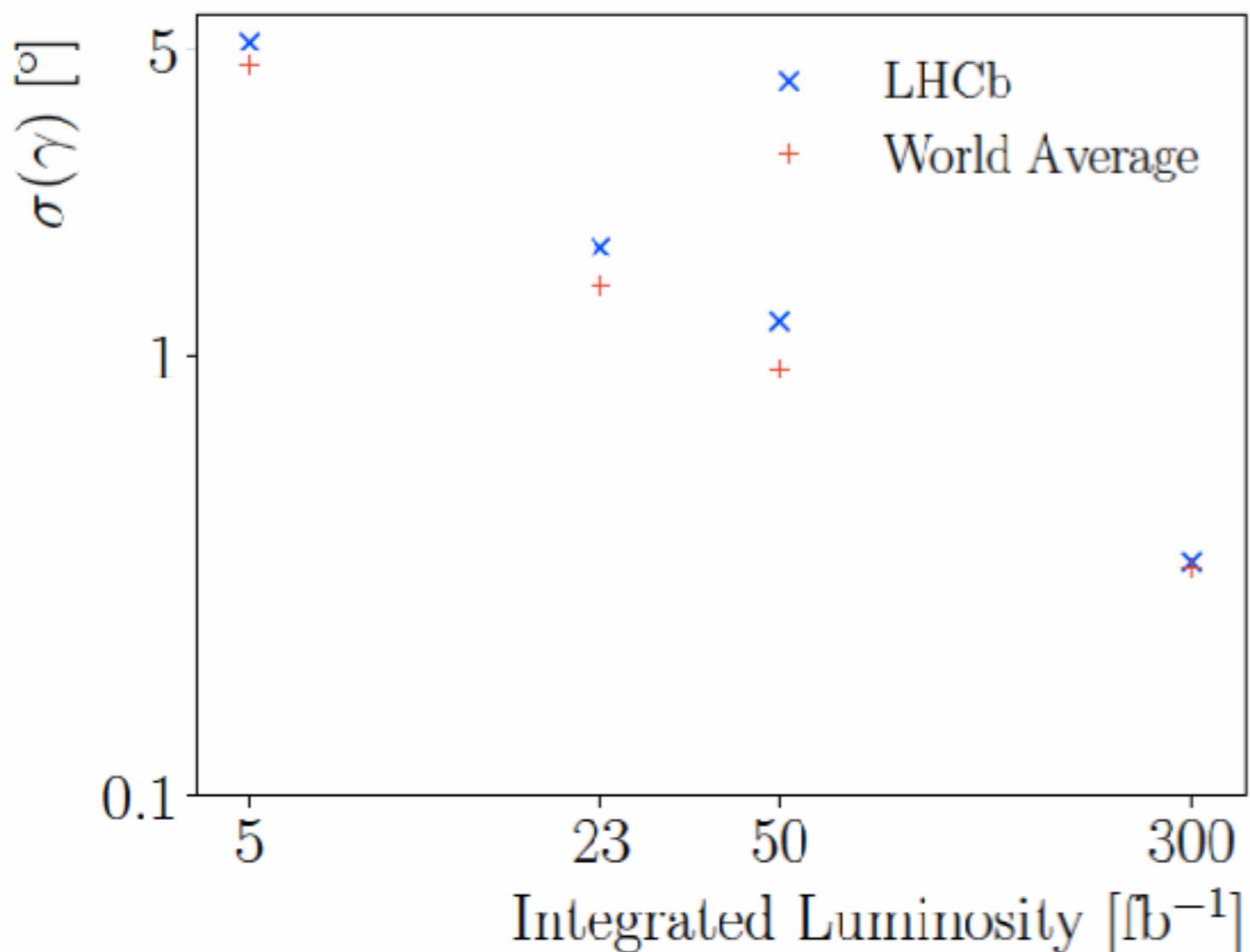


- most precise measurement from single experiment
- in agreement with world averages

LHCb combination

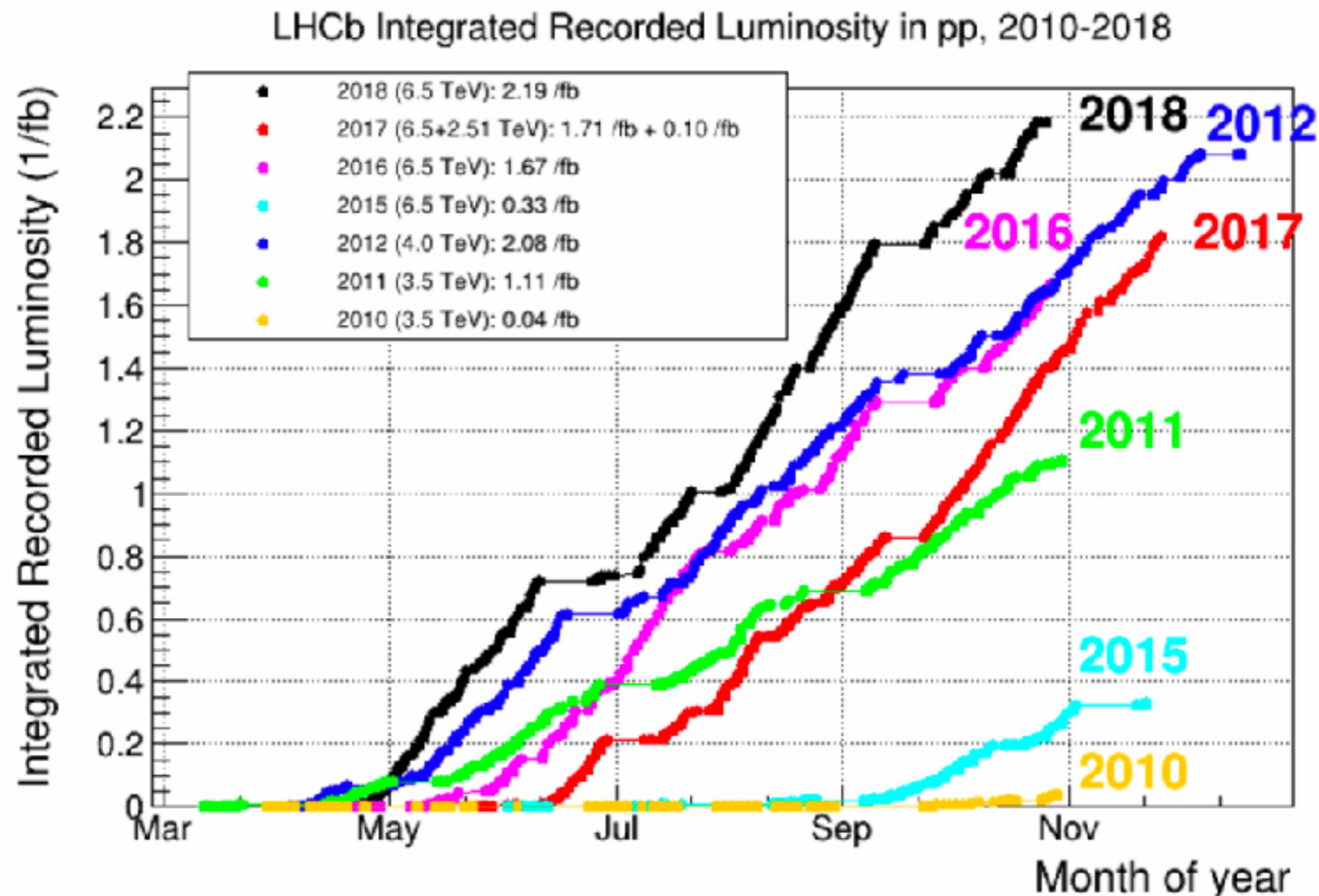
$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

γ angle projections

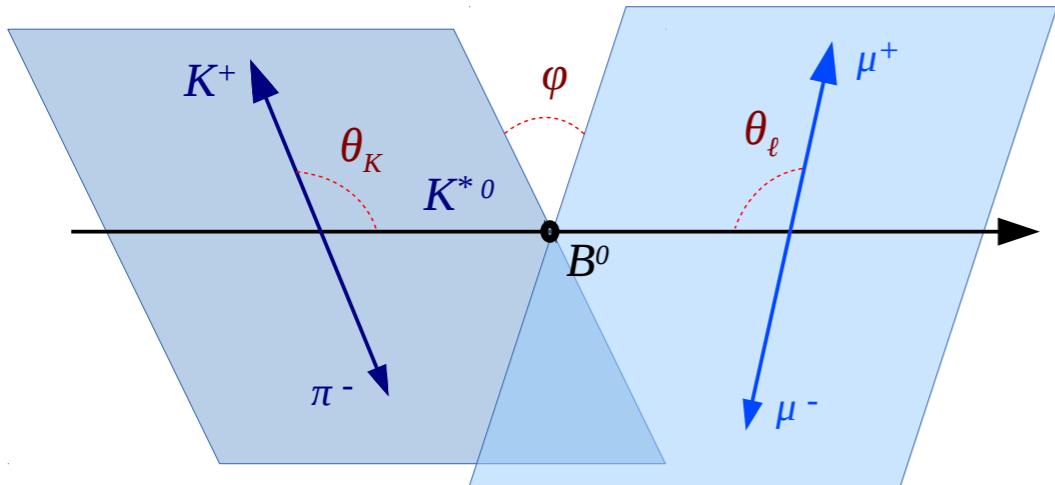


In $\sim 2030 \sigma_{\text{LHCb-U1}} \sim \sigma_{\text{Belle-II}} = 1.5^\circ$

LHCb - recorded luminosity



Angular distributions

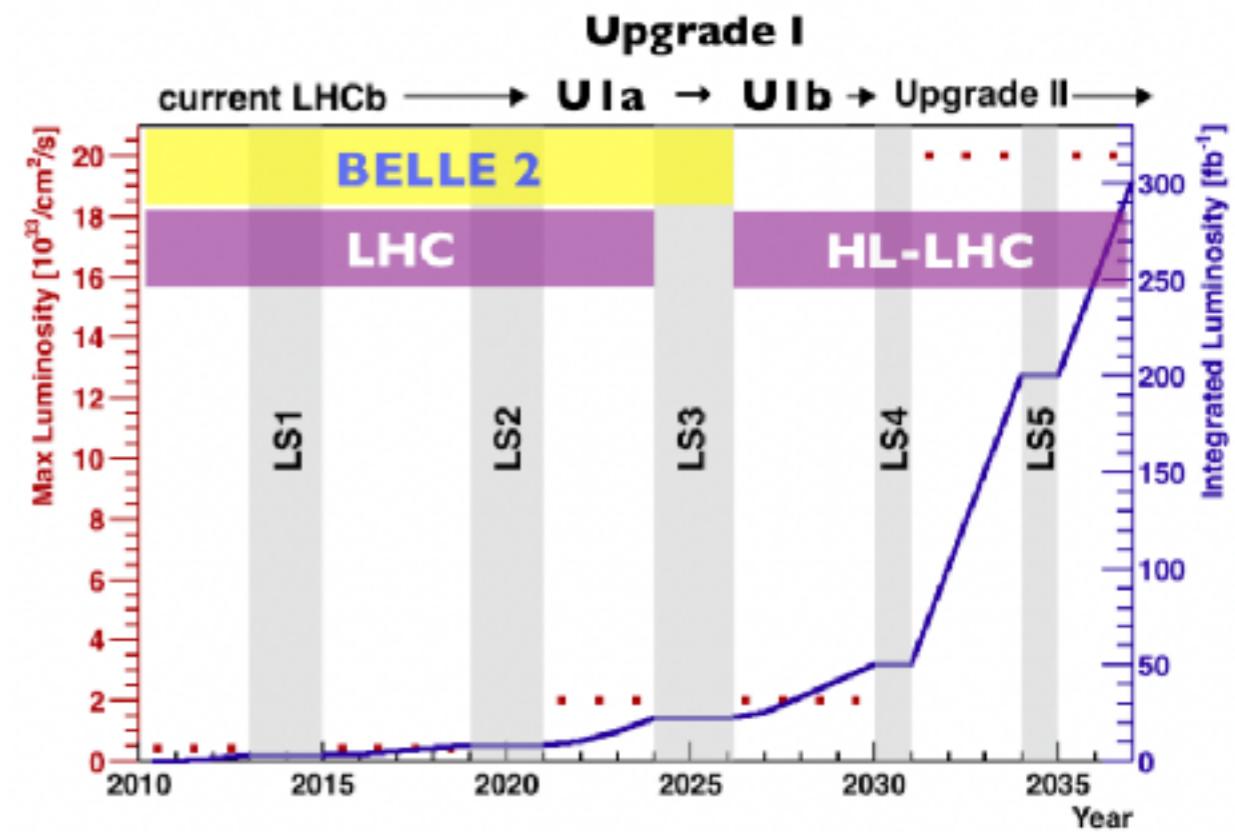


$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[\begin{aligned} & \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \\ & - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\ & + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ & + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ & + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \end{aligned} \right]$$

$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

LHCb upgrade

- LS2 (2019-20):
 - Change subdetector electronics to 40 MHz readout
 - All trigger decision software
 - Start data taking in 2021
 - Upgrade detector qualified to accumulate 50fb^{-1}
- In order to exploit the full potential of the LHC, it is natural to have a further major LHCb upgrade during LS4
- The Upgrade II will allow to increase data sample from 50fb^{-1} to 300fb^{-1}



LHCb upgrade

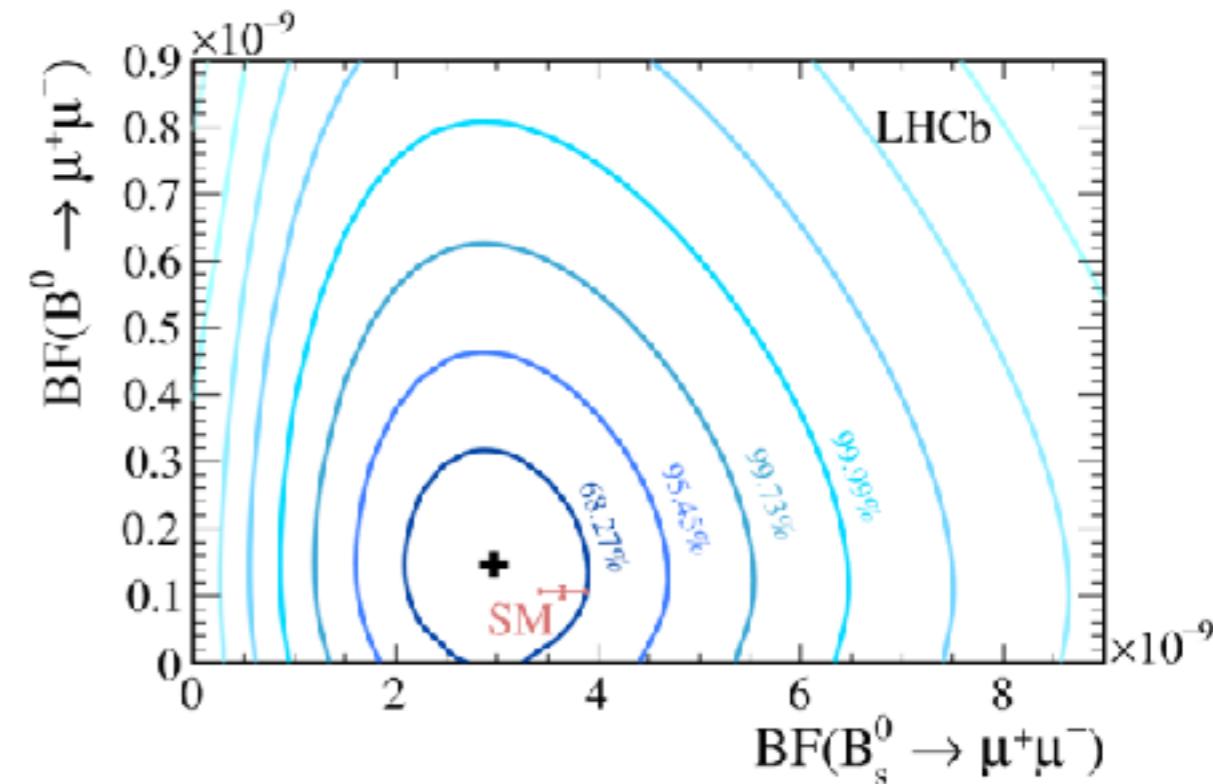
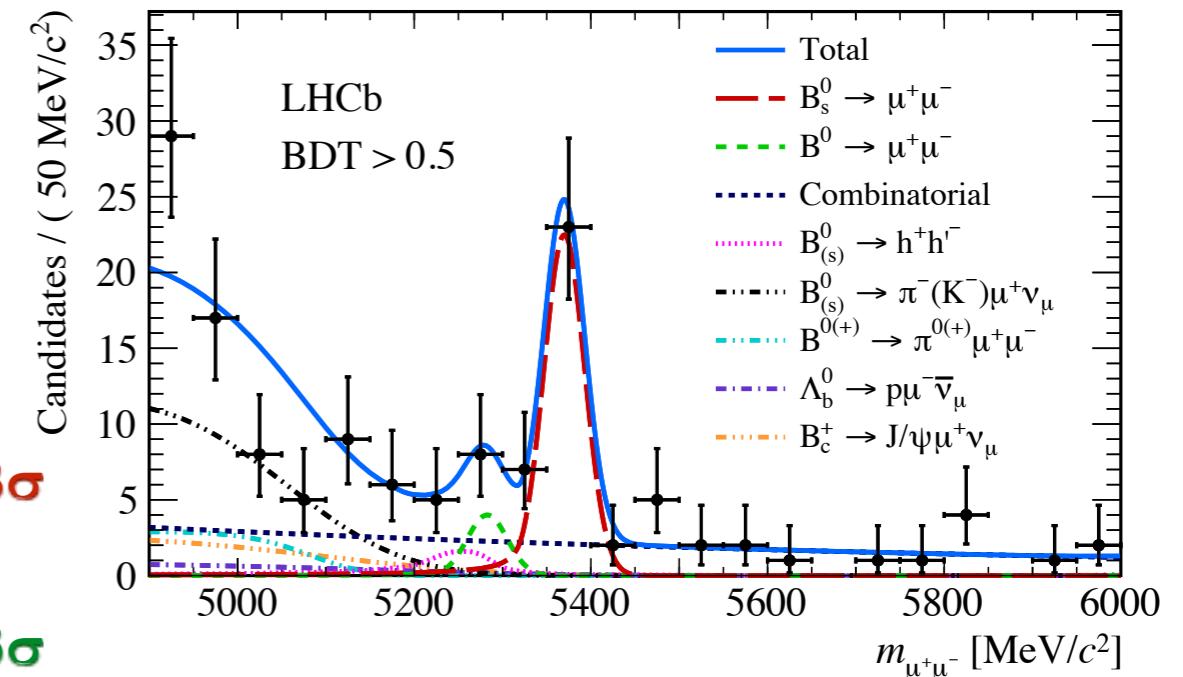
$B_s \rightarrow \mu^+ \mu^-$

- Improved analysis using 3fb^{-1} of Run1 data + 1.4fb^{-1} of Run2

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 + 0.6(\text{stat})^{+0.3}_{-0.2}(\text{syst})) \times 10^{-9} \quad 7.8\sigma$$

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &= (1.5^{+1.2}_{-1.0}(\text{stat})^{+0.2}_{-0.1}(\text{syst})) \times 10^{-10} \\ &< 3.4 \cdot 10^{-10} @ 95\% \text{ CL} \end{aligned}$$

- Main source of systematics:
 - $B_s^0 \rightarrow \mu^+ \mu^-$: knowledge of f_s/f_d
 - $B^0 \rightarrow \mu^+ \mu^-$: exclusive backgrounds



Impact on NP