Status and plans for EFT fits in LHCb

Andrea Mauri

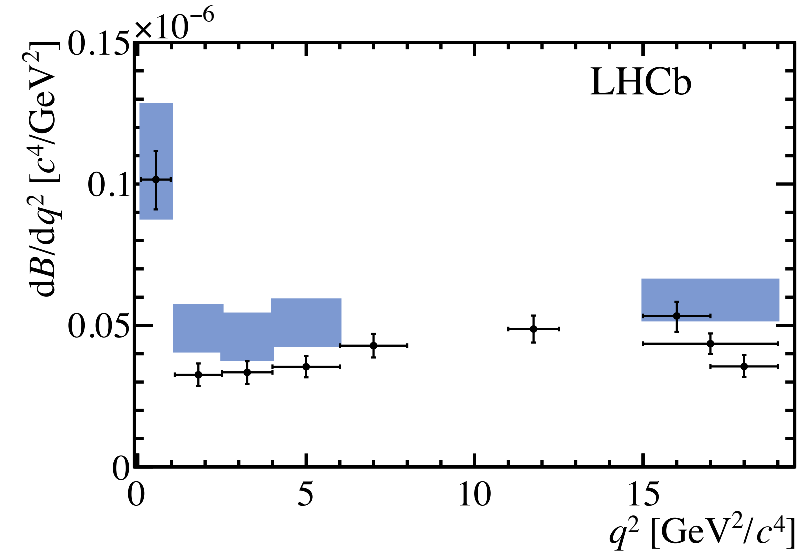
LHC EFT meeting

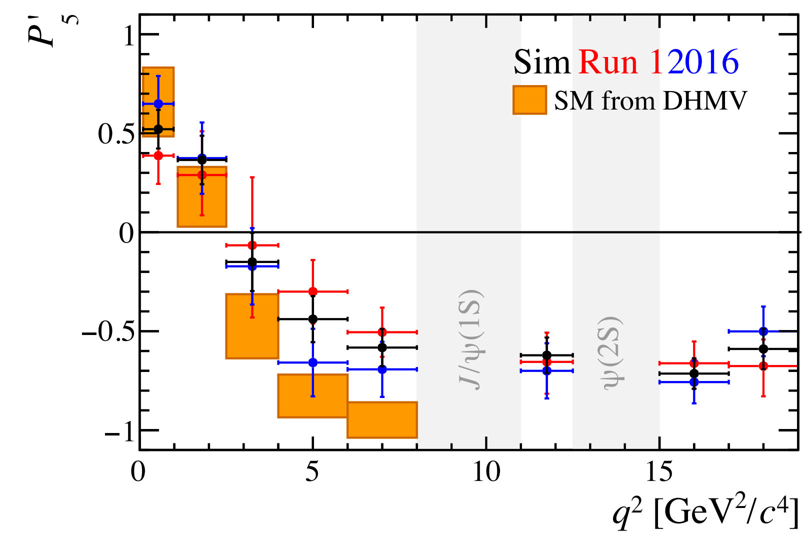
April 12th, 2021

$b \to s\ell^+\ell^-$ observables

Great variety of observables:

1. *Branching ratio*:
   - large theory uncertainties
2. *Angular observables*:
   - reduced theory uncertainties
     (be aware of charm loop)
3. *LFU test (ratio of BR, etc.)*
   - clean: theory uncertainties cancel

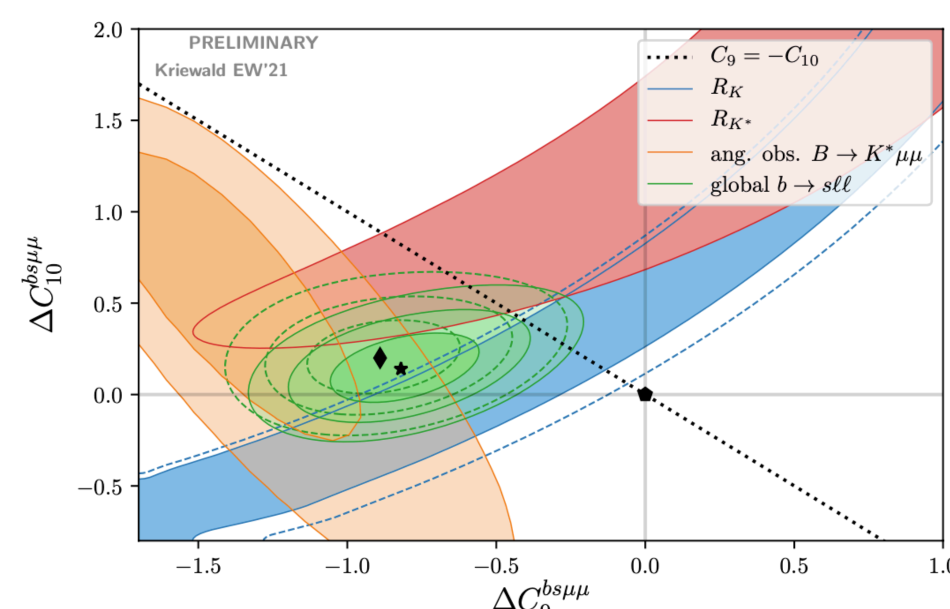




- Have always been measured in bins of q2 and interpreted via global fits

  q^2: squared di-lepton invariant mass

Can we do an q2 unbinned analysis…?



Unbinned amplitude fits

Extract Wilson coefficients directly from data

- Advantages:
  - Better sensitivity
    - Avoid loosing information when binning in q2
    - Exploit all the correlation present in data
  - Possibility to constrain theoretically unknown contribution from data

- Challenges:
  - Build theoretical assumptions into the fitted pdf
  - The choice of the parametrization makes the measurement **model-dependent**

$b \to s\ell^+\ell^-$ as an effective field theory

- Low-energy processes (B decays) can be described by an **effective theory** by integrating out the heavy fields

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Wilson coefficients (*effective couplings*) → $\mathcal{C}_i$

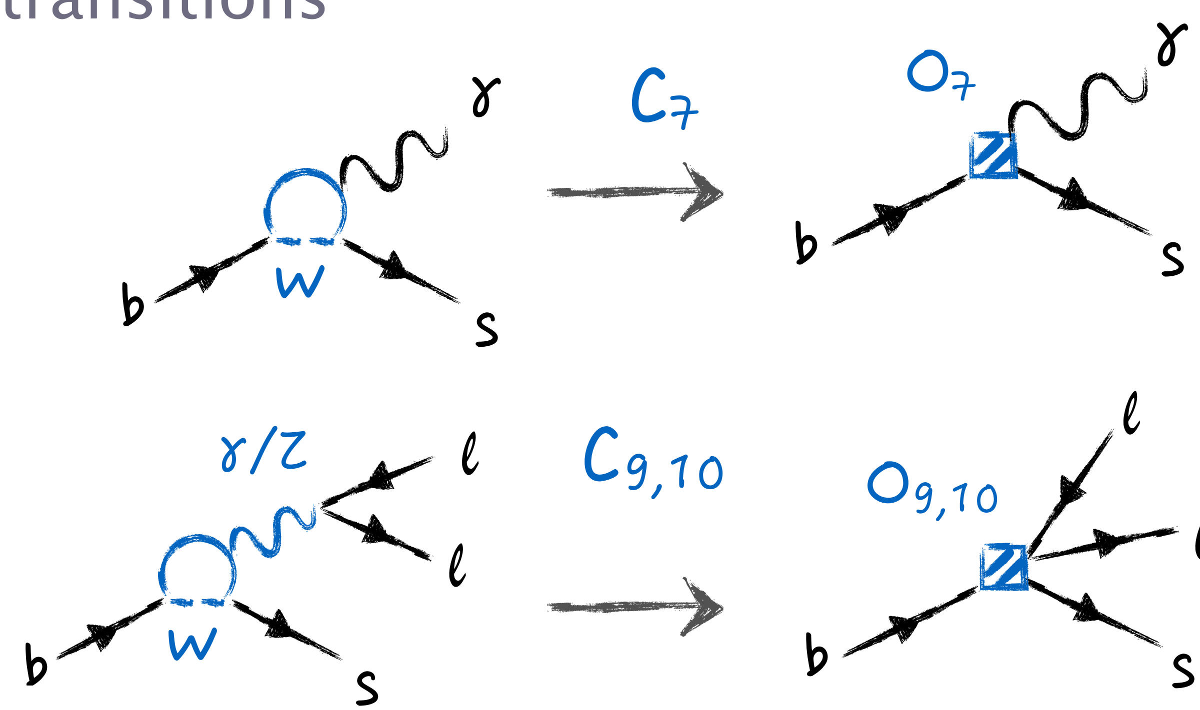
Local operators → $\mathcal{O}_i$

- SM operators contributing to $b \to s\ell^+\ell^-$ transitions

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha \,, \qquad \textit{photon}$$

$$\mathcal{O}_{9V} = \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell} \gamma_\mu \ell \,, \qquad \textit{vector}$$

$$\mathcal{O}_{10A} = \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell} \gamma_\mu \gamma_5 \ell \,, \qquad \textit{axial-vector}$$

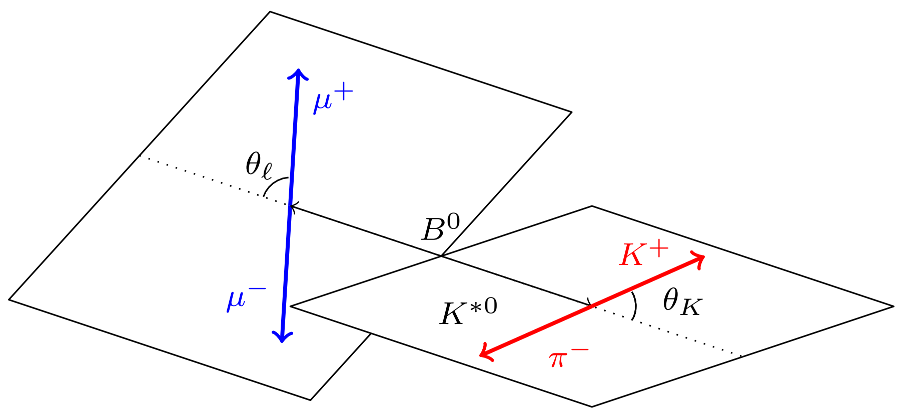


Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$

- $B^0 \to K^{*0}\mu^+\mu^-$ decays are mediated by FCNC
  - Decay fully described by

$$\frac{d^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\vec{\Omega})$$

angular coefficients angular functions



  - Decay amplitudes

$$A_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10}) F_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7 F_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} H(q^2) \right] \right\}$$

→ Needed inputs from theory

$F_\lambda(q^2)$: local (form factors)

$H_\lambda(q^2)$: non-local (charm-loop)

Theory inputs

- $B \to K^*$ Form factors
  - Lattice and Light-Cone Sum Rule JHEP08(2016)098
  - O(10%) uncertainty
  - usually make use of narrow-width approximation
  - recent work on $B \to K\pi$ form factor JHEP12(2019)083
- Non-local hadronic uncertainties (charm loop)
  - Difficult to predict reliably from theory
  - Can be extracted from data…?

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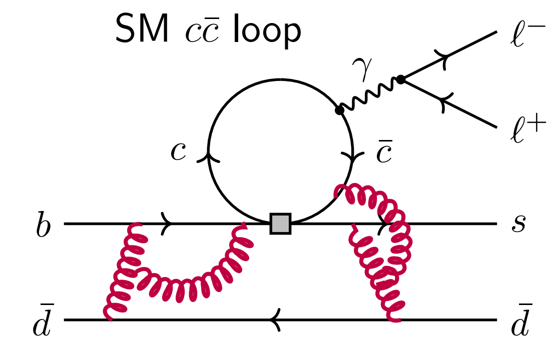
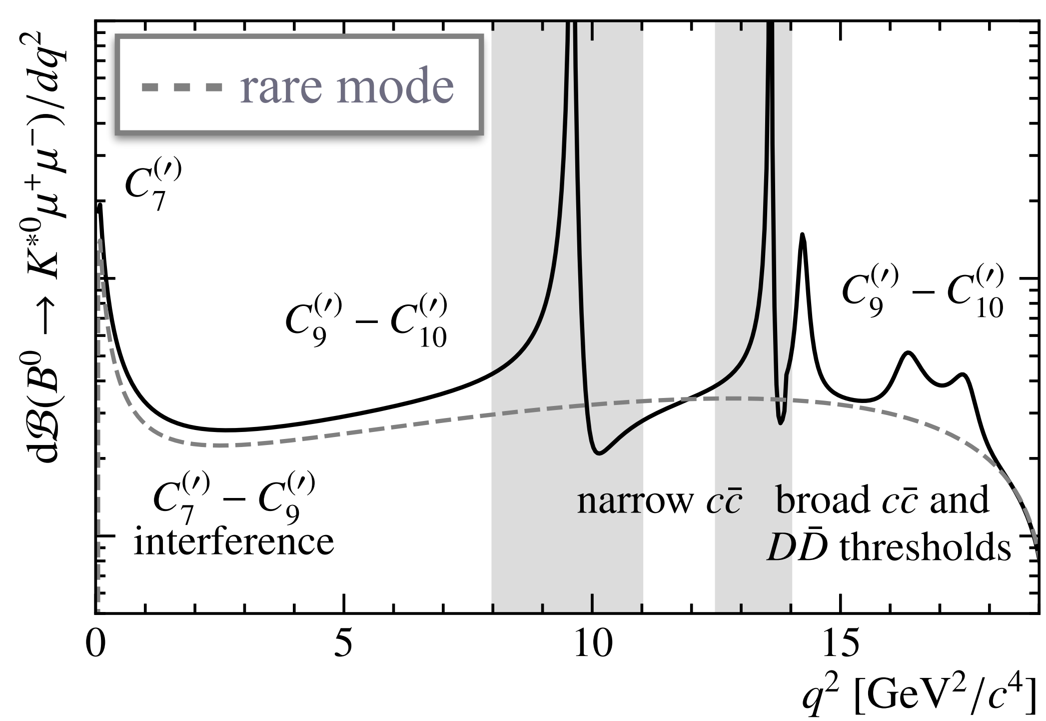
Need a functional form

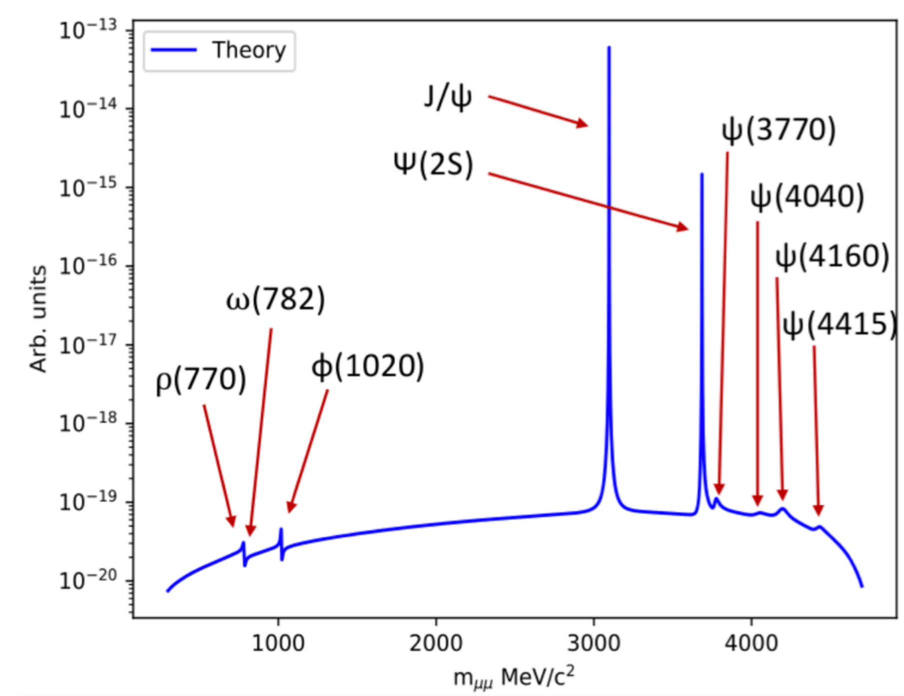




Alternative approaches

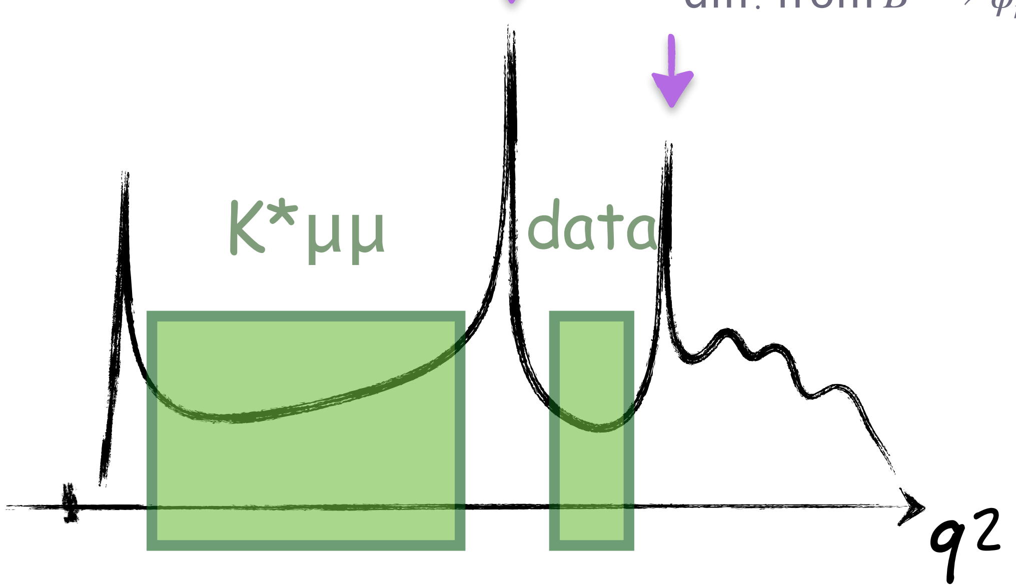
1. *Isobar model*
   - $c\bar{c}$ resonances parametrized with Breit-Wigner amplitudes
   - Dispersion relation for non-resonant contributions (e.g. $D\bar{D} \to \mu\mu$)

LHCb, **EPJ C (2017) 77, 161**
Blake et al, **EPJ C78 (2018) 6, 453**
Cornella et al, **EPJ C80 (2020) 12, 1095**



2. *z-expansion*
   - inspired by parametrization of form factors
     - $\text{Poles} \times \sum \alpha_k z^k$
   - truncated at a given order z^K
   - can be constrained using experimental data & theory inputs

BR, pol. frac. and phase diff. from $B^0 \to \psi_n K^{*0}$

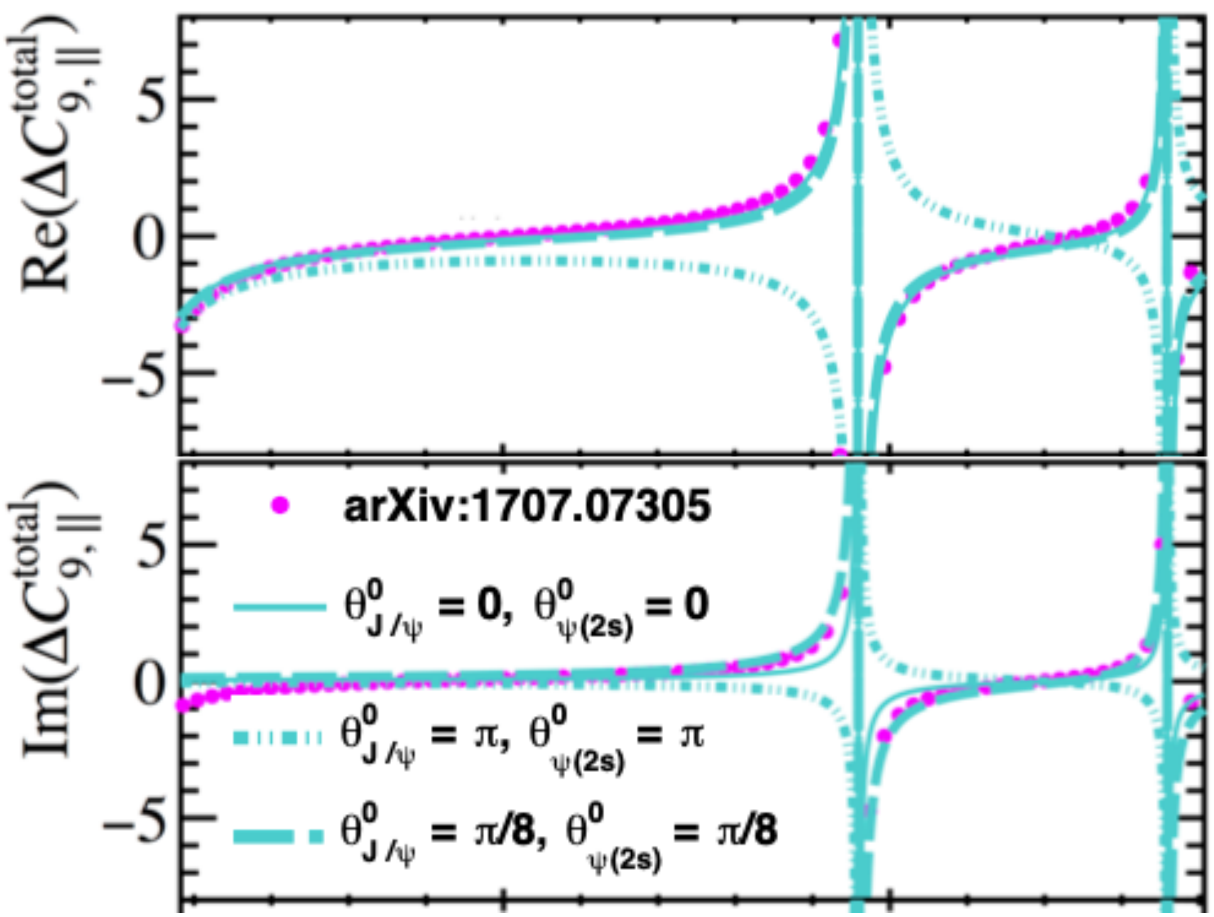


Bobeth et al, **EPJ C78 (2018) 6, 451**
Chrzaszcz et al, **JHEP 10 (2019) 236**
Gubernari et al, **JHEP 02 (2021) 088**

Alternative approaches: validation

- Useful validation: compatibility between *“Isobar”* and *“z-expansion”*
- Can provide useful indication on the behavior of non-local hadronic contribution in data

Isobar vs *z-expansion*

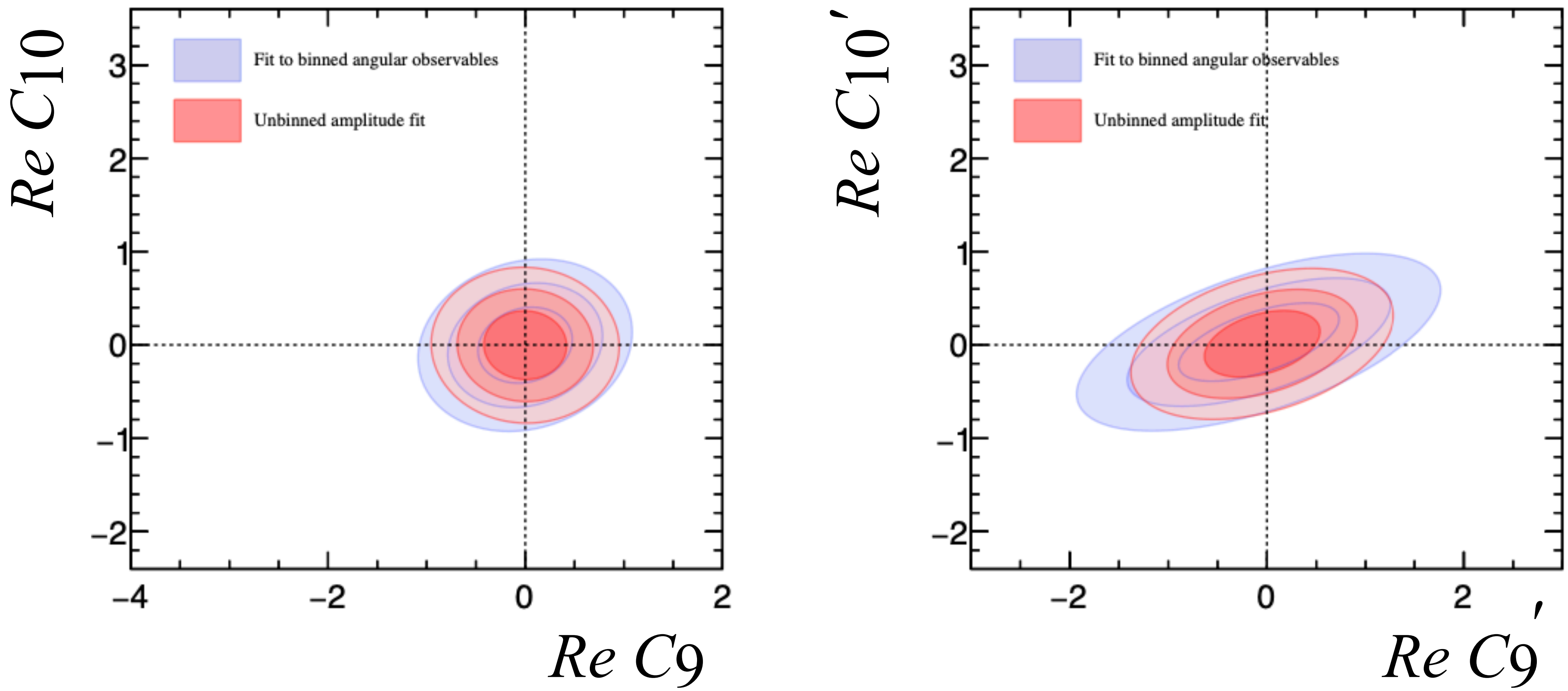


Blake et al, **EPJ C78 (2018) 6, 453**

Binned VS unbinned sensitivity

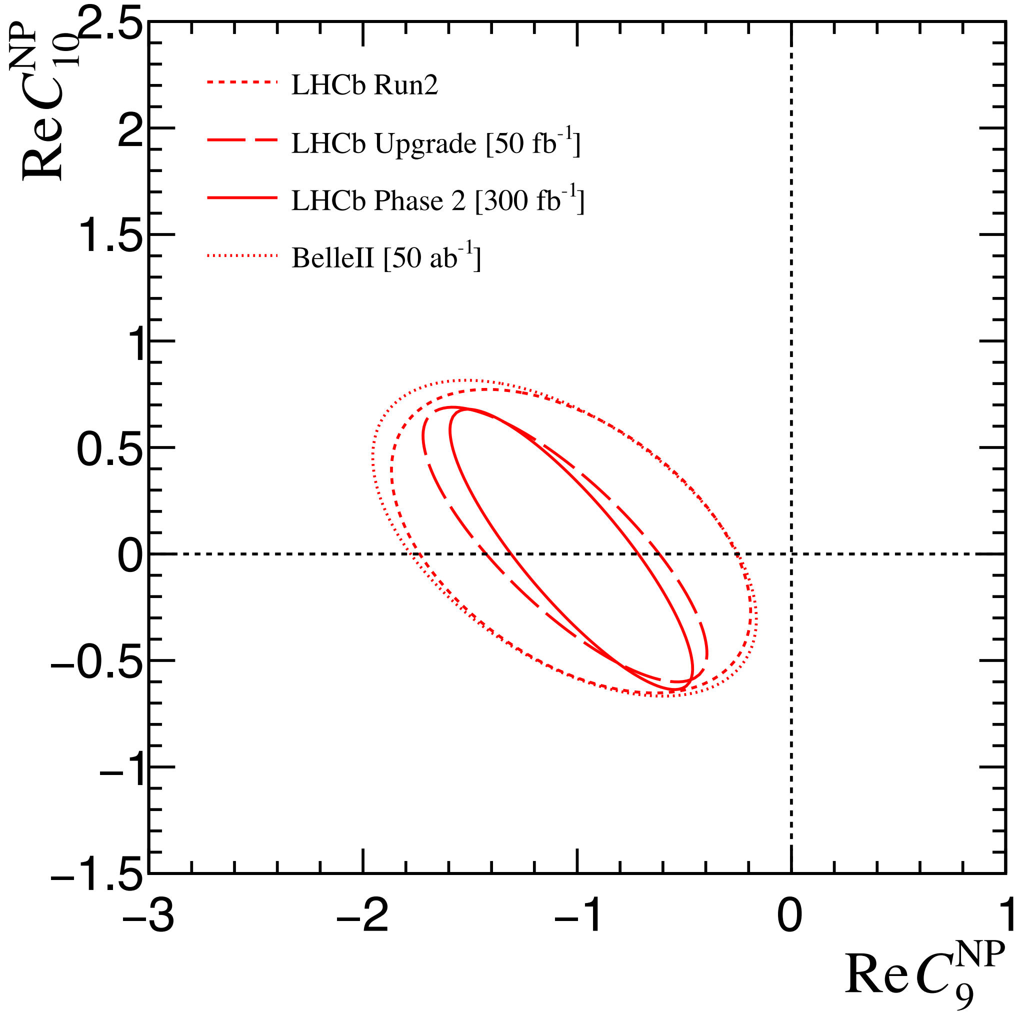
- Compare direct fits to WCs to the sensitivity obtained from global fits to binned observables
  - same amplitude parametrization (with constraints)
- Depending on the scenario, up to 50% improvement in sensitivity

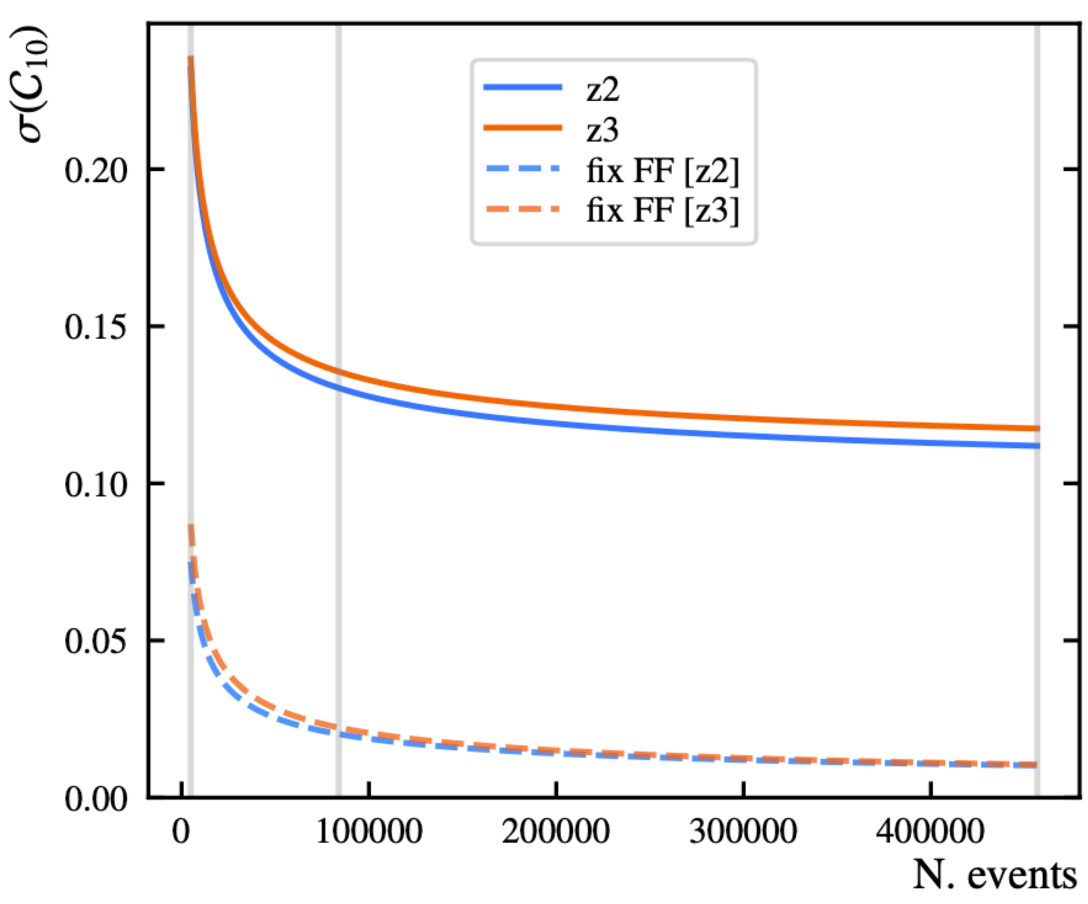
Binned vS unbinned



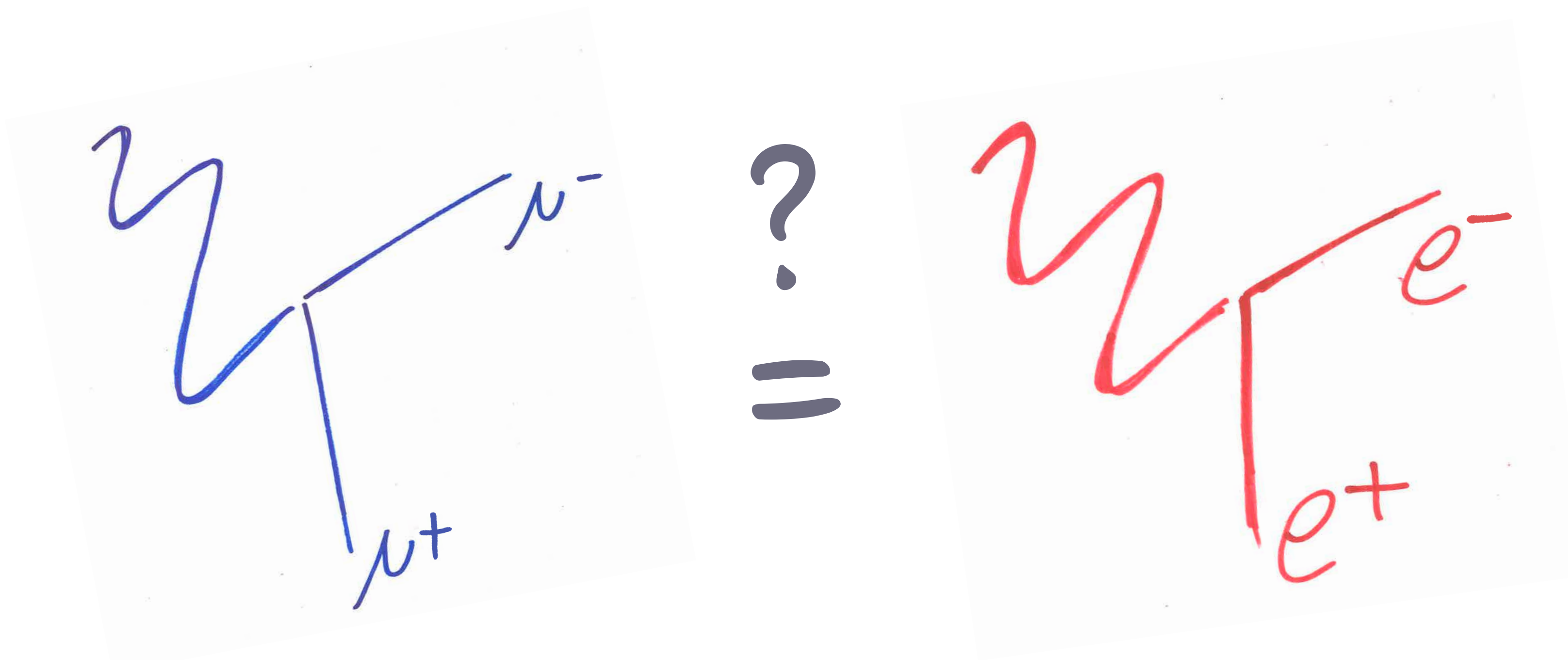
Long term sensitivity

Sensitivity saturates after
Upgrade 50 fb^{-1} due to
form factor uncertainties





Extend this approach to LFU test



can we benefit from uncertainty cancellation typical of LFU test?

Simultaneous fit to $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$

- $C_i^{(\ell)}$: strongly dependent on the model assumption (without external inputs)

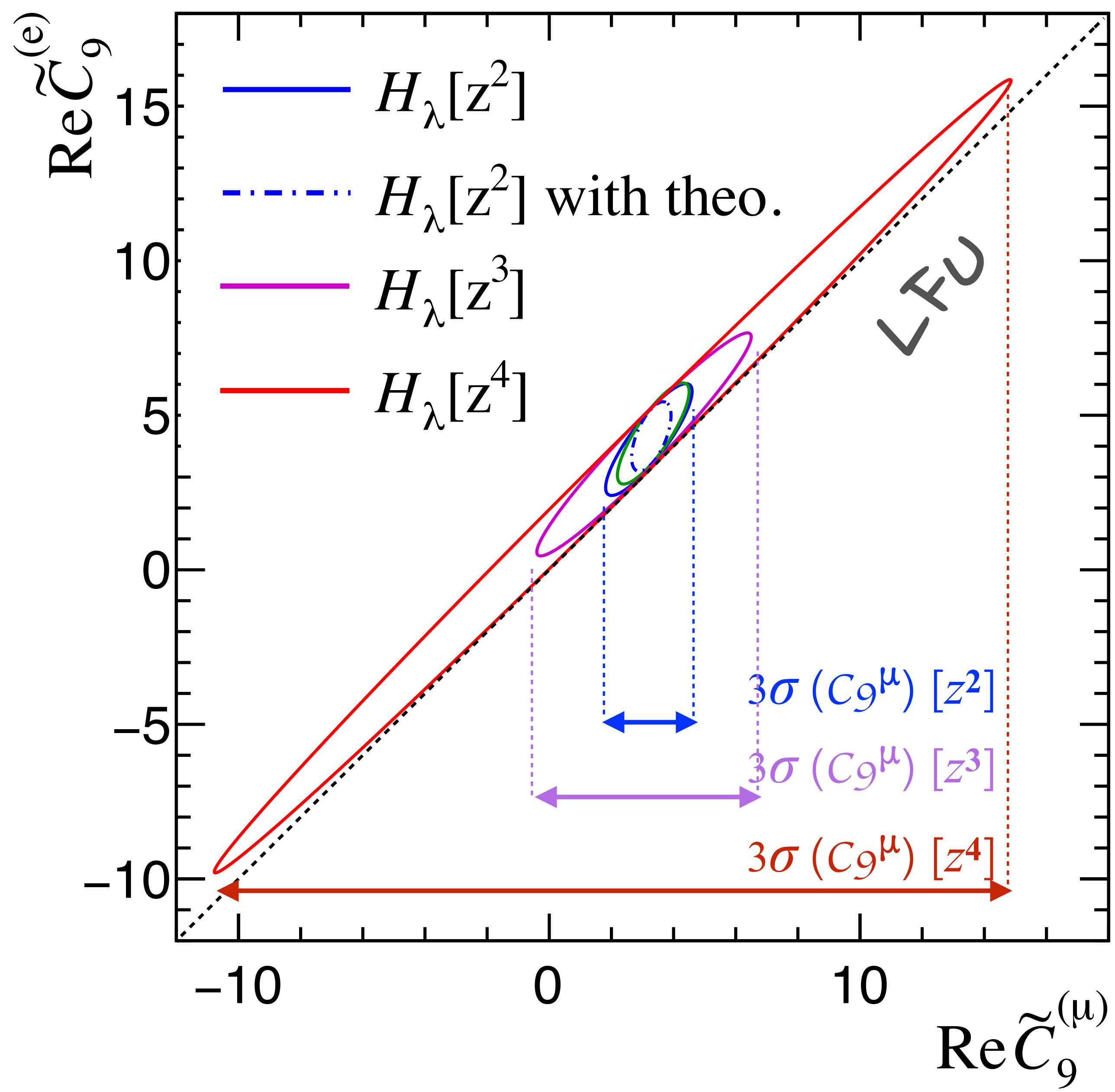
Key feature: all hadronic terms all lepton universal

↓

Nuisance parameters shared between muons and electrons

Define: $\Delta C_i = \widetilde{C}_i^{(\mu)} - \widetilde{C}_i^{(e)}$

AM, Serra, Coutinho, PRD 99 (2019) 013007

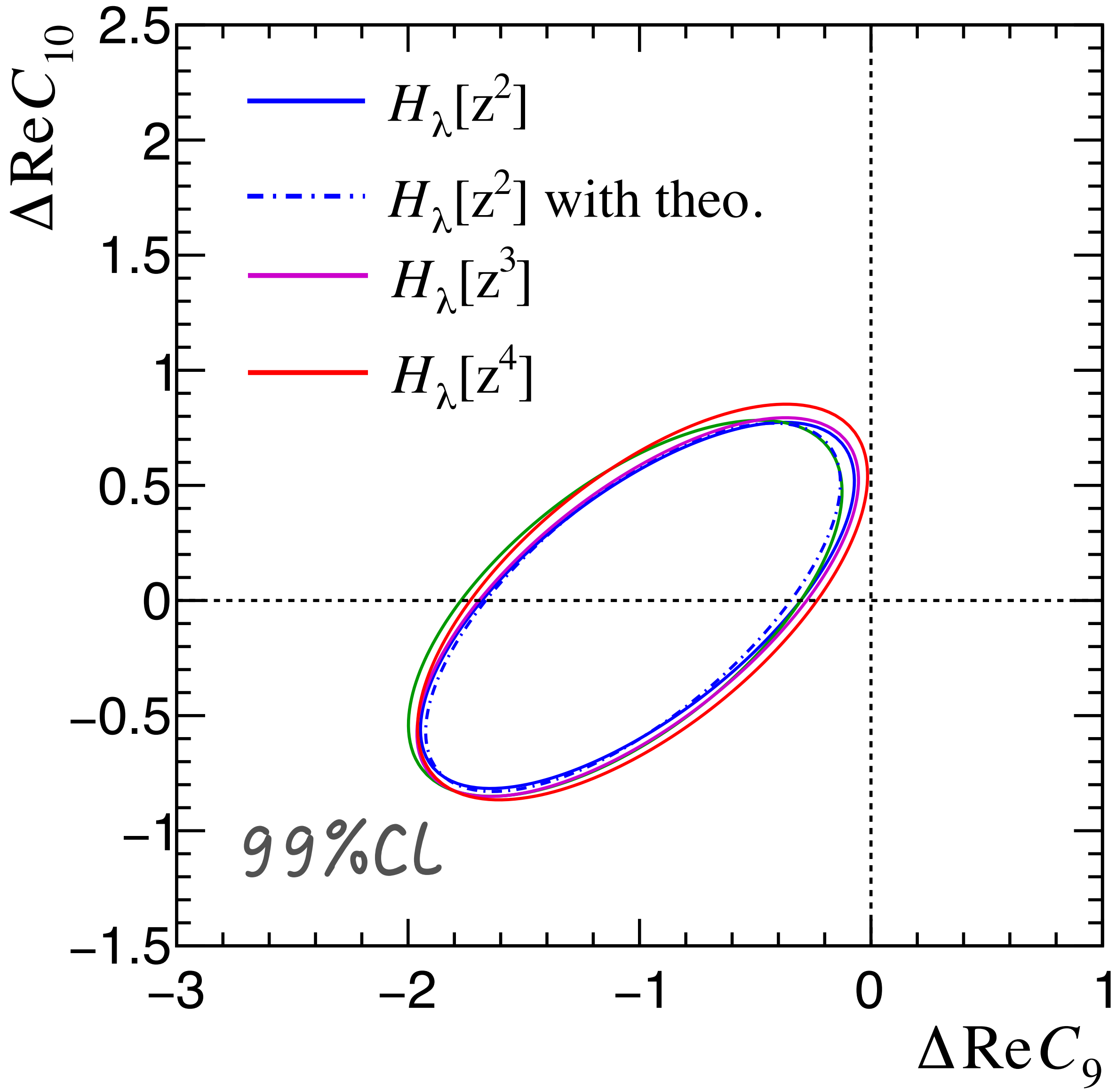


- Insensitive to the parametrization of hadronic contributions!

Sensitivity to ΔC_i

PRD 99 (2019) 013007

NP scenario: $\mathcal{C}_9^{(e)} = \mathcal{C}_9^{\rm SM} = \mathcal{C}_9^{(\mu)} + 1$

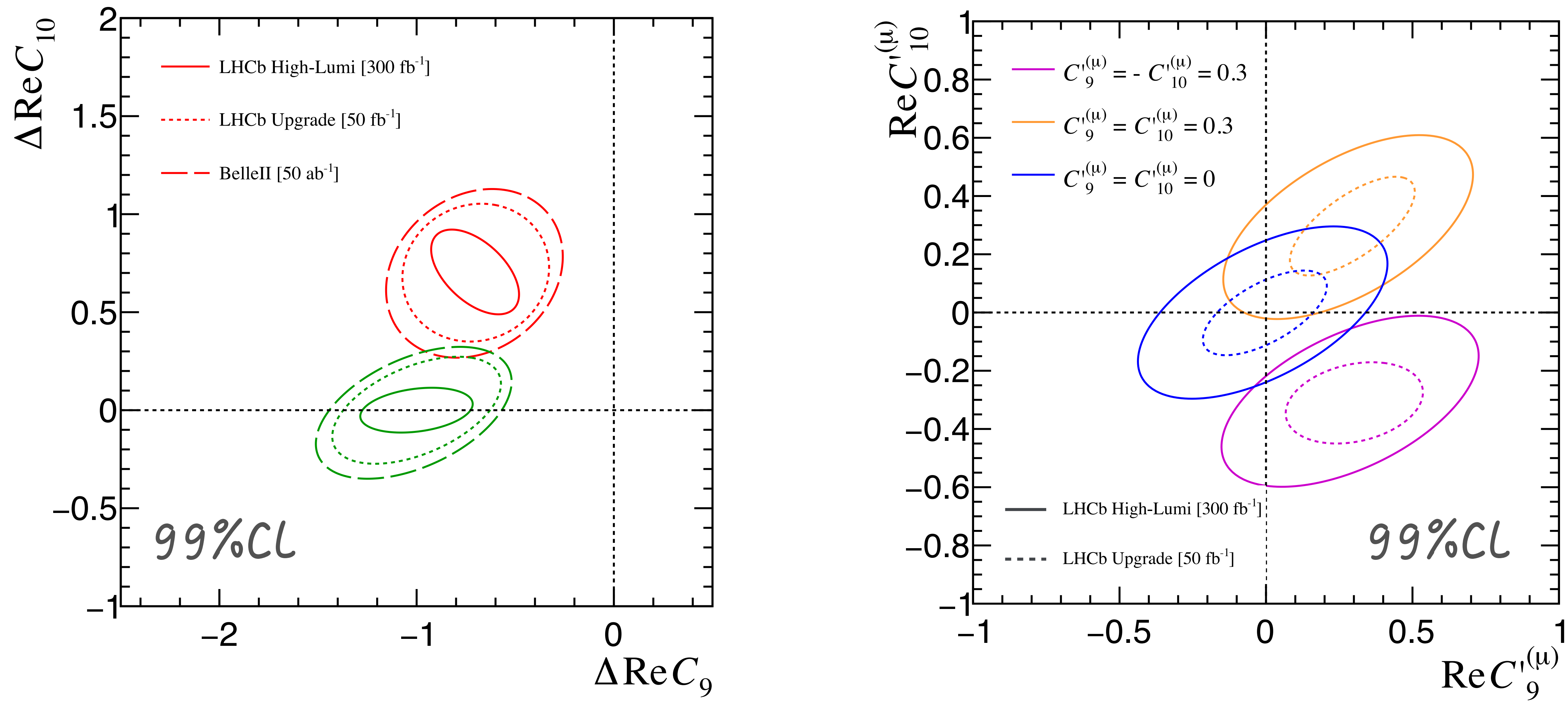


LHCb Run II statistics

- Determination of ΔC_i is stable and model-independent
- Depending on the NP scenario, sensitivity can exceed 4σ
- Extended maximum-likelihood fit
  - includes R_{K^*} information

Long term sensitivity to ΔC_i

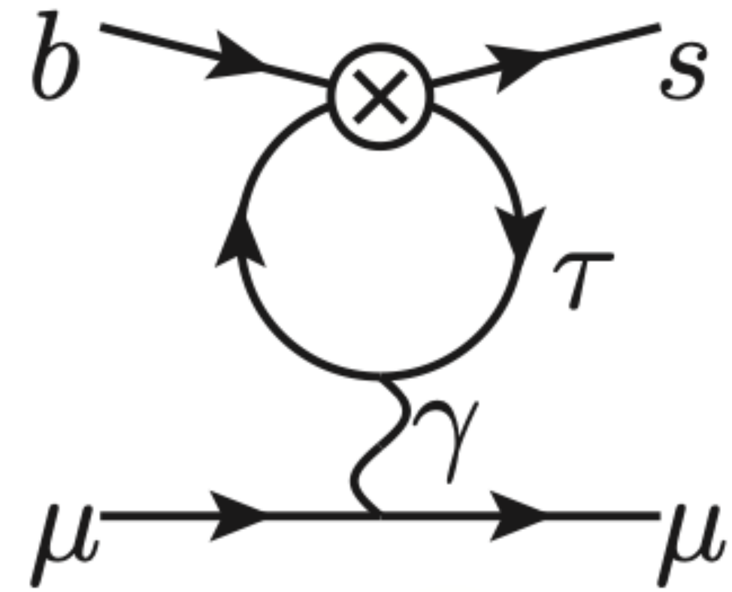
PRD 99 (2019) 013007



- Resolution on ΔC_i not bound anymore to the form factors
- Interesting opportunity to disentangle different NP hypotheses with a single measurement

Hunting for τ imprints in di-μ spectrum

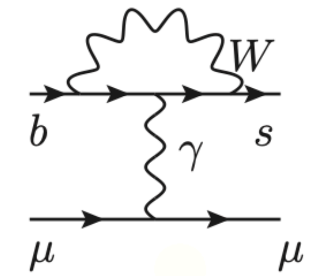
Based on Cornella et al, **EPJ C80 (2020) 12, 1095**



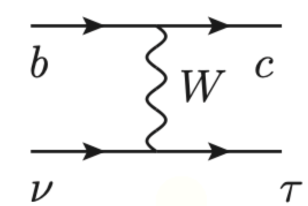
Slide by M. König

Anomalies in semileptonic B-decays:

$B \to K\mu^+\mu^-$ FCNC ($\to$ loop level) process in the Standard Model



$B \to D\tau\nu$ Charged current ($\to$ tree level) process in the Standard Model



New physics explanations favor NP mostly in the **third generation**, possible connection to the SM flavor puzzle!
$\to$ large effects in τ, smaller effects in μ

In these cases, one expects **large effects** from τ in $B \to K$ as well!

Slide by M. König

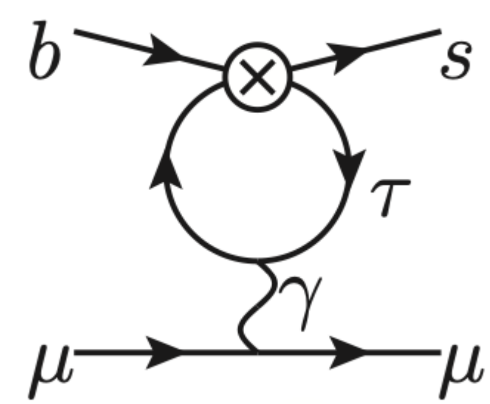
What's the sitaution on $b \to s\tau\tau$?

- $B \to K\tau^+\tau^-$ experimentally **challenging**:
  $\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) < 2.25 \cdot 10^{-3}$
  $\mathrm{Br}_{\mathrm{SM}}(B^+ \to K^+\tau^+\tau^-) = 1.2 \cdot 10^{-7}$

[BaBar (*2017*), Phys.Rev.Lett. 118 no.3, 031802]

There is **a lot** of room for **new physics**!

Idea: Can we probe $b \to s\tau\tau$ through its **loop-contribution** to the $b \to s\mu\mu$ spectrum?



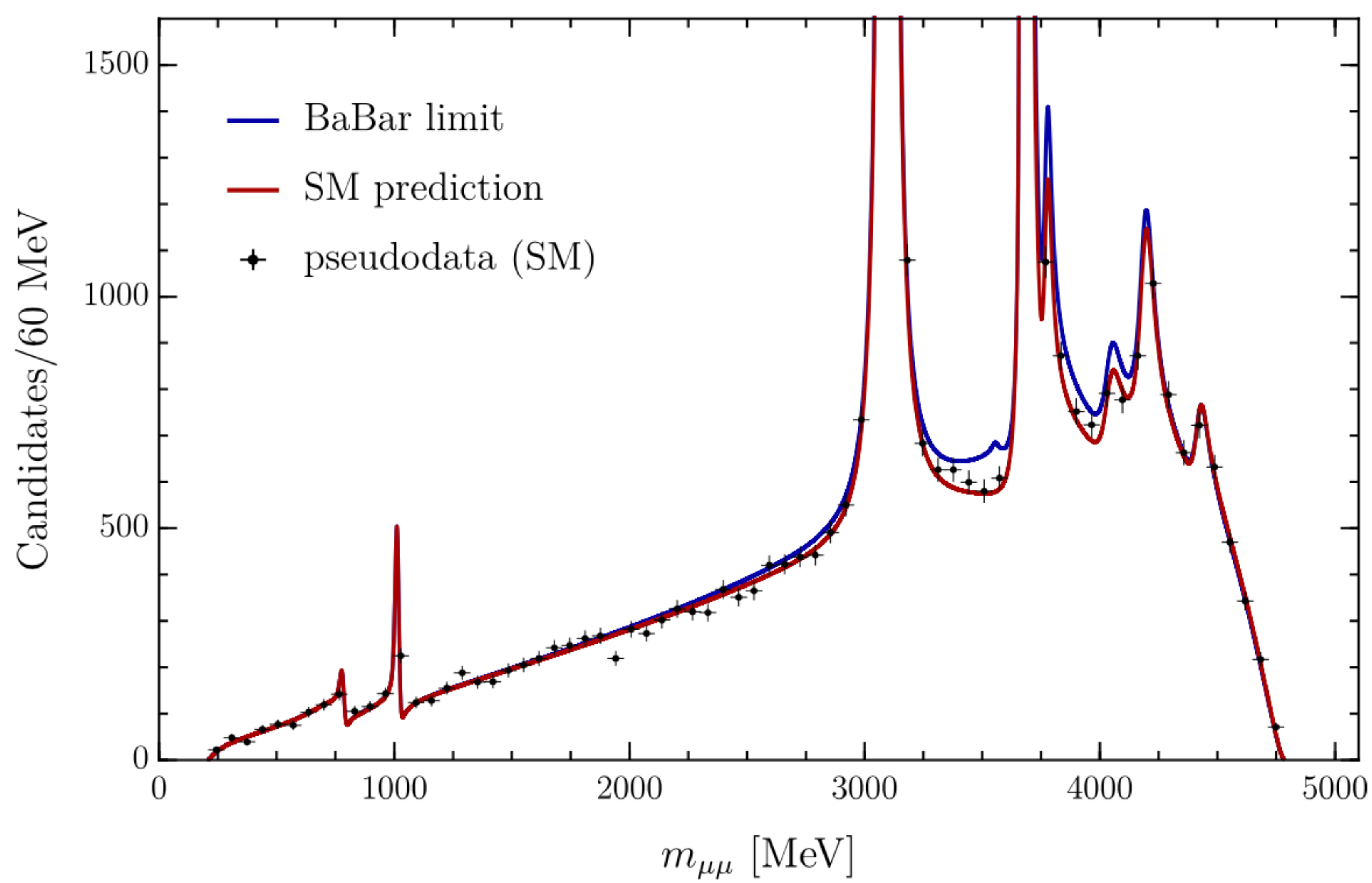
- Current bound on C_9^τ from direct limit:
  - $|C_9^\tau| \leq 5.1 \times 10^2 \quad (C_9^\tau = C_{10}^\tau)$
  - $|C_9^\tau| \leq 9.1 \times 10^2 \quad (C_{10}^\tau = 0)$

Effect on di-μ spectrum

- Consider $B^+ \to K^+\mu^+\mu^-$ decays
  - approx. 40,000 events in full LHCb Run II

EPJ C80 (2020) 12, 1095

- Plot di-μ spectrum SM vs saturated C_9^τ limit
  - very distinct shape of the spectrum
  - “cusp” at $q^2 = 4m_\tau^2$ (taus on-shell)
  - distortion of the non-resonant $B^+ \to K^+\mu^+\mu^-$ shape



Indirect limit on $Br(B^+ \to K^+\tau^+\tau^-)$

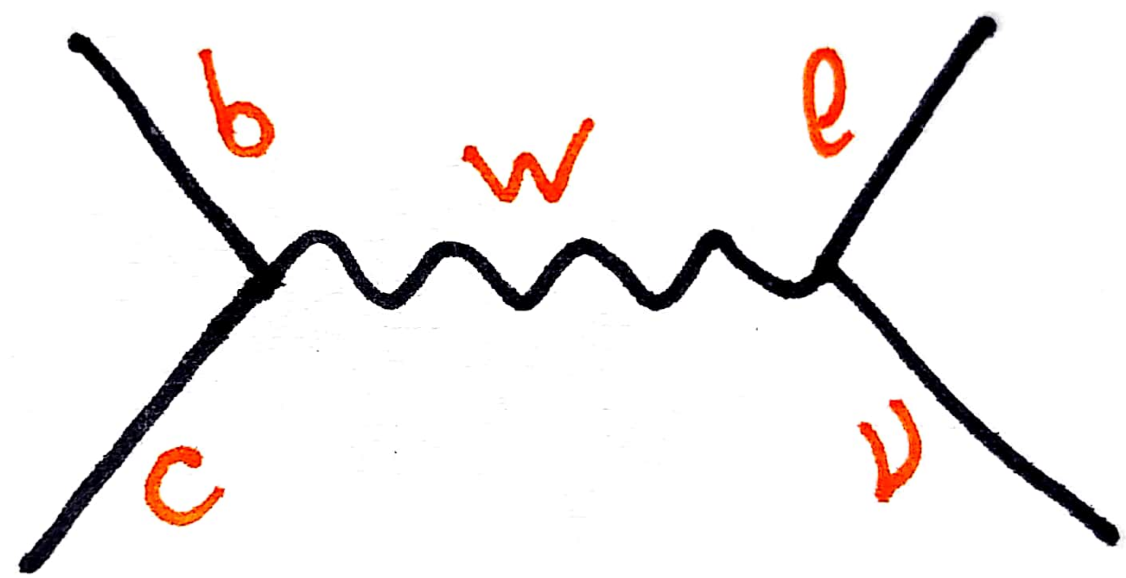
Scenario	C_9^τ (90% CL)	$\mathcal{B}$ $(C_{10\tau} = -C_{9\tau})$	$\mathcal{B}$ $(C_{10\tau} = 0)$
Run I-II dataset	533	2.7×10^{-3}	0.8×10^{-3}
Run I-V dataset	139	1.8×10^{-4}	0.5×10^{-4}

Table 1: Sensitivity to $C_{\tau\tau}$ according to various LHCb scenarios. **EPJ C80 (2020) 12, 1095**

- Indirect limit on $Br(B^+ \to K^+\tau^+\tau^-)$ already comparable with current bounds when considering LHCb Run II statistic
- LHCb Upgrade II will be competitive with projected sensitivity of Belle II experiment

EFT IN SEMILEPTONIC DECAY

(CHARGED CURRENT)



EFT in $b \to c l \nu$

- Effective Field Theory for $b \to c l \nu$

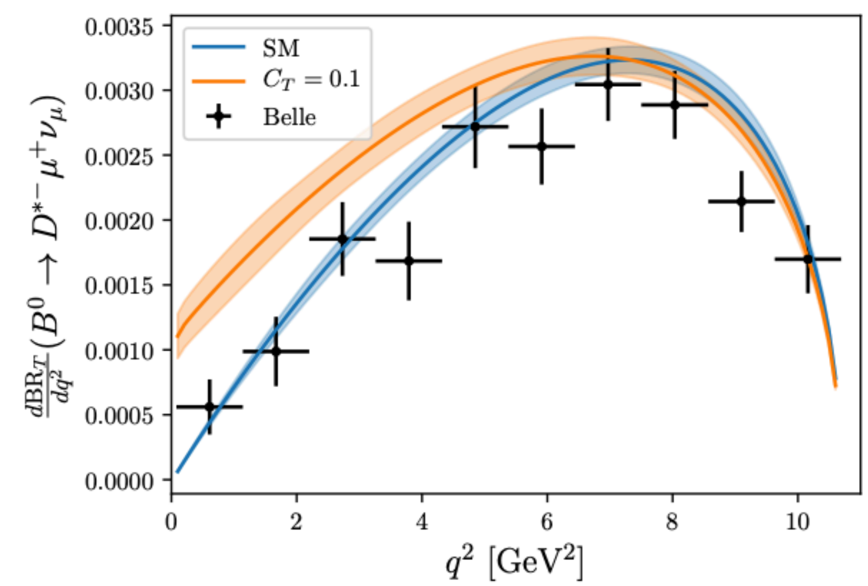
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_L}) \mathcal{O}_{C_{V_L}} + C_{V_R} \mathcal{O}_{C_{V_R}} + C_{S_L} \mathcal{O}_{C_{S_L}} + C_{S_R} \mathcal{O}_{C_{S_R}} + C_{T_L} \mathcal{O}_{C_{T_L}} \right] + h.c.$$

where $C_i = 0$ in the SM, and the relevant four-fermion operators are

$$\mathcal{O}_{C_{V_L}} = \bar{c}_L \gamma^\mu b_L \, \bar{\ell}_L \gamma_\mu \nu_L \,, \qquad \mathcal{O}_{C_{V_R}} = \bar{c}_R \gamma^\mu b_R \, \bar{\ell}_L \gamma_\mu \nu_L \,,$$

$$\mathcal{O}_{C_{S_L}} = \bar{c}_R b_L \, \bar{\ell}_R \nu_L \,, \qquad \mathcal{O}_{C_{S_R}} = \bar{c}_L b_R \, \bar{\ell}_R \nu_L \,, \qquad \mathcal{O}_{C_{T_L}} = \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\ell}_R \sigma_{\mu\nu} \nu_L \,.$$

Jung, Straub, **JHEP 01 (2019) 009**



- Different LHCb analyses ongoing involving
  - (mesons) e.g. $B \to D^* \mu \nu$
  - (barions) e.g. $\Lambda_b^0 \to \Lambda_c^+ \mu \bar{\nu}$
- Main challenge: experimental resolution (missing neutrino)
  - unfolded by using a **migration matrix**

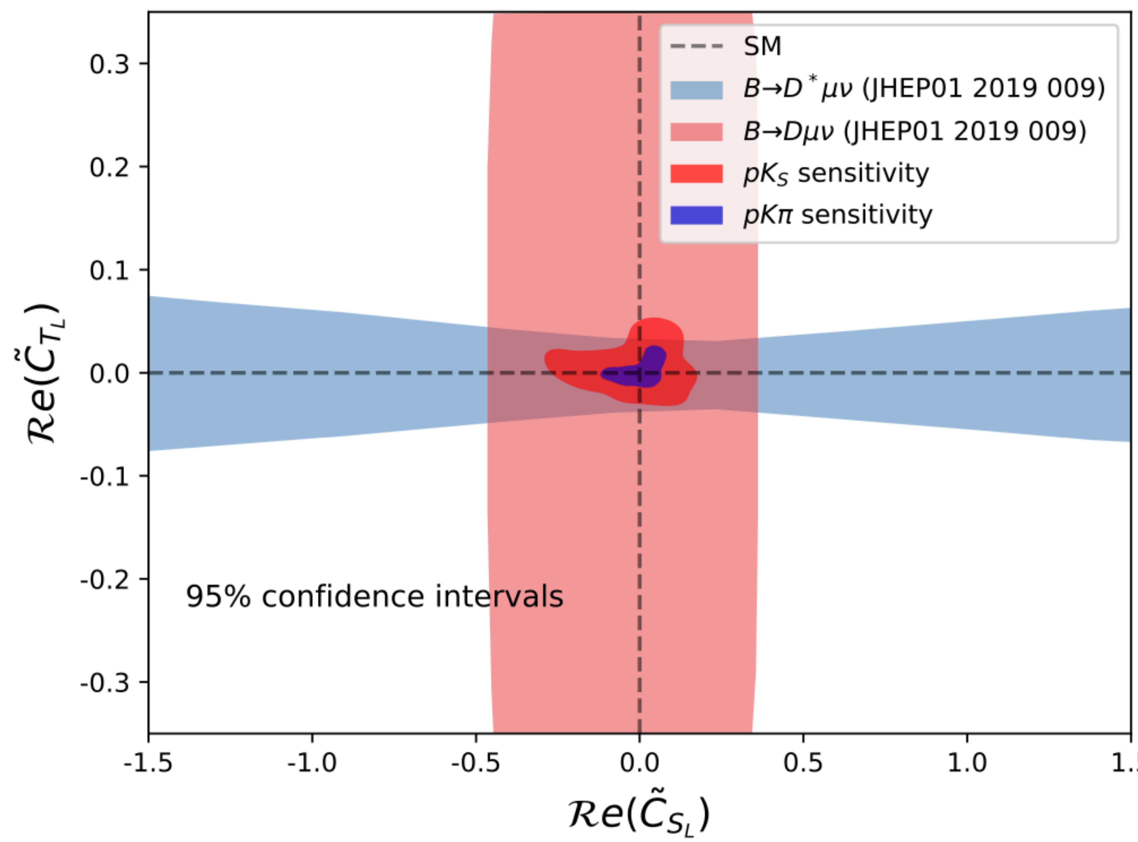
Sensitivity to semileptonic operators

$\Lambda_b^0 \to \Lambda_c^+ \mu \bar{\nu}$

- Sensitivity expected to be significantly better than current constraints
  - Mainly due to the huge signal yield expected at LHCb

Free parameters	pK^0_S case	$pK^-\pi^+$ case
C_{V_R}	0.005	0.001
C_{S_R}	0.046	0.018
C_{T_L}	0.020	0.007
C_{S_L}	0.091	0.039
$P_{\Lambda_b^0}$	0.13	–
$\alpha_{\Lambda_c^+}$	0.003	–

Ferrillo et al, **JHEP 12 (2019) 148**



$B \to D^* \mu \bar{\nu}$

- $O(10^{-3})$ sensitivity expected with full Run II

Conclusion

- Several new analysis involving EFT fits in LHCb
- Synergy between theory and experiment
- Higher sensitivity
- Help to constrain from data theory uncertainty (e.g. $B \to K^* \mu^+ \mu^-$)
- Risk of model dependence and difficult re-interpretation of data