$B_s^0 \to \mu^+\mu^-\gamma$ without photon reconstruction: status and prospects at LHCb

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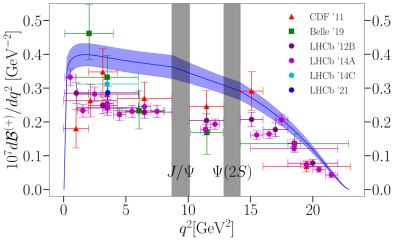
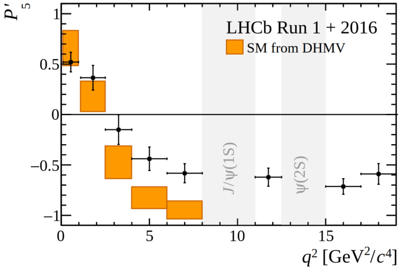
"$b \to s$ anomalies"

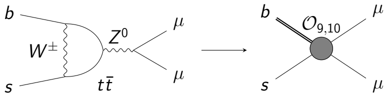
- The $b \to s$ anomalies are a series of discrepant data described by a $b \to s$ transition.
- Many observables give information on these transitions, with various ways to "dress" the quarks, and various decay properties:
  - Branching ratios (BR): $\mathcal{B}(B \to K\mu\mu)$
    [Parrott, Bouchard, Davies, Phys. Rev. D 107 (2023) 014510]
  - Angular observables: $P_5'(B \to K^*\mu\mu)$
    [LHCb collaboration, Phys. Rev. Lett. 125 (2020) 011802].

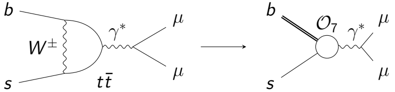




Effective Theory of $b \to s$ decays

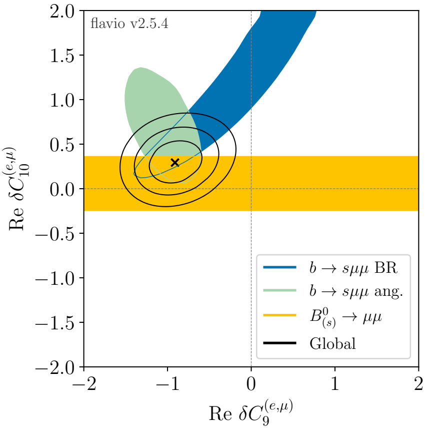
$$\mathcal{L}_{\text{eff}}^{b \to s\mu^+\mu^-} = 2\sqrt{2} G_F \lambda^{\text{CKM}} \sum_i C_i^{\mu} \times O_i$$





- Coupling strength of operator $\mathcal{O}_i$ given by the Wilson coefficient (WC) C_i.
- $C_{7,9,10}^{\mu}$ are the WCs relevant to the loop-suppressed FCNCs.

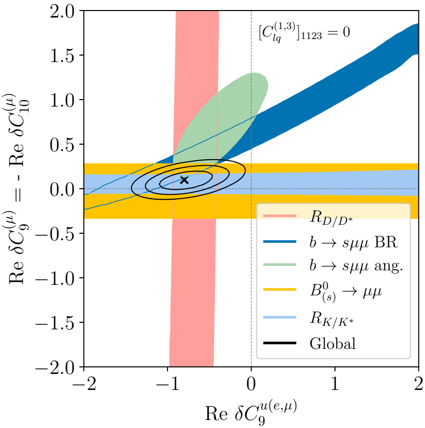
$\delta C_9^{\mu} = \delta C_9^{e}$ vs. $\delta C_{10}^{\mu} = \delta C_{10}^{e}$



- Equality between electronic and muonic Wilson coefficients removes the $R_{K^{(*)}}$ constraints
- All subsets of data in agreement at the 1σ level.
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ gives C_{10} compatible with the SM at less than 2σ.
- $C_9^{\mu} = C_9^{e}$ in tension with the SM !

[D. Guadagnoli, CN, S. Simula, L. Vittorio (2023), JHEP 10 (2023) 102]

Connection with chargent current anomalies



- Shift hinted at separately by $b \to s$- and $b \to c$-anomalies of the same order of magnitude.

[B. Bhattacharya, A. Datta, D. London, and S. Shivashankara (2014), Phys. Lett. B, 742 (2015) 370-374]

[D. Guadagnoli, CN, S. Simula, L. Vittorio (2023), JHEP 10 (2023) 102]

The question

“How do we confirm, or infirm, such a tension observed between predictions and measurements ?”

✓ *“Are we observing New Physics ?”*

or

✗ *“A lack of knowledge of QCD ? (prediction)”*

or

✗ *“A mis-understanding of the data ? (measurement)”*

The question

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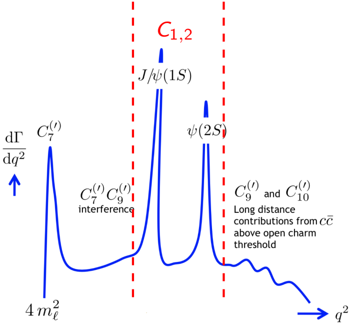
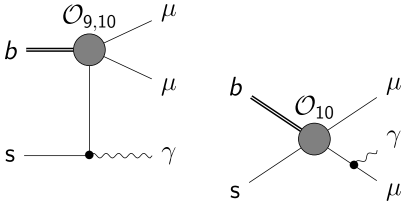
$B_s^0 \to \mu^+\mu^-\gamma$ in the high-q^2 region.

The high-q^2 region

- $B \to V\mu\mu$ transition has a typical $q^2 = m(\mu\mu)^2$ spectrum:





Initial and Final State Radiation

The high-q^2 region

High-q^2 region $\Longrightarrow$ 4.2 GeV $< \sqrt{q^2} < m(B_s^0)$, sensitive to C_9 and C_{10}.
$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)[4.2, m(B_s^0)]\,\text{GeV} = (1.63 \pm 0.80) \times 10^{-10}$ in the SM.

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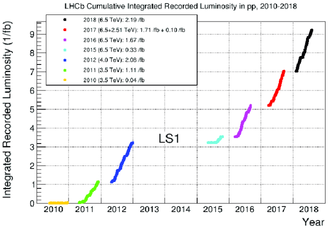
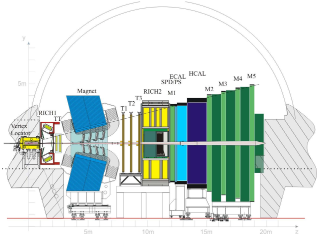
The LHCb experiment



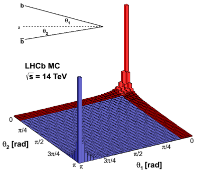
Integrated luminosity per year.

- Dedicated to b- and c-physics, here focus on proton-proton collisions.
- The amount of collected data, characterized by the integrated luminosity, totals $9\,\mathrm{fb}^{-1}$.
- The collected data are divided into separate "runs"
  Run 1 in 2011-2012 and Run 2 in 2015-2018.

- Forward spectrometer:



The LHCb detector.

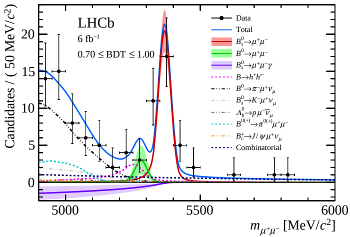


The $b\bar{b}$ cross-section.

From $B_s^0 \to \mu^+\mu^-$ to $B_s^0 \to \mu^+\mu^-\gamma$

- The latest measurement of $B_s^0 \to \mu^+\mu^-$ by LHCb shows that $B_s^0 \to \mu^+\mu^-\gamma$ can be accessed without reconstructing the (soft) photon

[LHCb collaboration, Phys. Rev. Lett. 125 (2020) 011802].



- Using only the di-muon information
  - ✓ increases the reconstruction efficiency
  - ✗ specializes the analysis to high-q^2
- Enlarging downward the mass region
  - ✓ increases the signal yield
  - ✗ increases the background yield

- The analysis is based on muon pairs with $\boldsymbol{m(\mu^-\mu^+) \in [4.2, 6.0]}$ GeV, and this requirement is understood throughout the talk.

- Current limit: $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ with $\boldsymbol{m(\mu^-\mu^+) < 4.9}$ GeV.

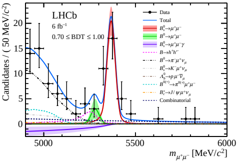
Measuring $N(B_s^0 \to \mu^+\mu^-\gamma)$

- The final expression reads

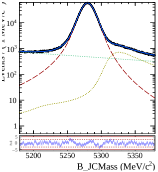
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) = \frac{\mathcal{B}_{\text{norm.}}}{N_{\text{norm.}}} \times \frac{\epsilon_{\text{norm.}}}{\epsilon_{\text{sig.}}} \times \frac{f_d}{f_s} \times N(B_s^0 \to \mu^+\mu^-\gamma)^{\text{obs.}} \ .$$

  We choose two different normalisation channels, $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi K^+$.

- $N(B_s^0 \to \mu^+\mu^-\gamma)^{\text{obs.}}$ is extracted from a fit to the invariant di-muon mass similar to the $B_s^0 \to \mu^+\mu^-$ analysis



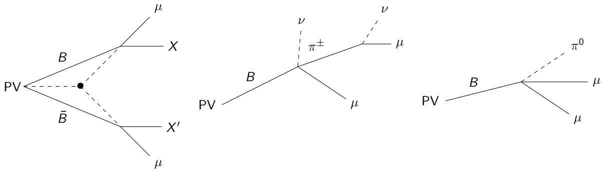
Normalization:



- Normalisation and signal efficiencies are determined on MC samples with inclusion of systematic uncertainties (ongoing).

Backgrounds

- Several background sources:



Combinatorial, mis-identified and signal-like backgrounds.

[1] apart from the combinatorial background

Backgrounds

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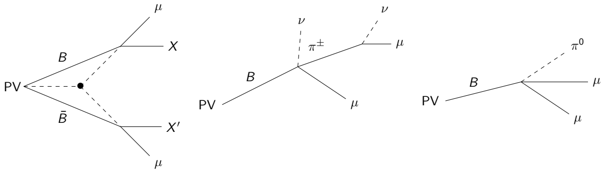

Combinatorial, mis-identified and signal-like backgrounds.

- Each background[1] comes with its efficiency, $\epsilon_{\text{back.}}$, computed individually.
  We want to minimize $\epsilon_{\text{back.}}$.

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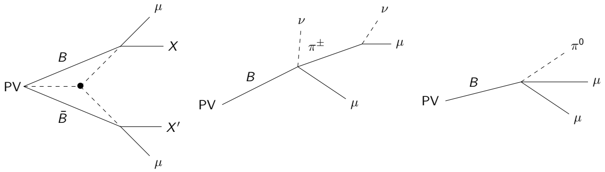


Combinatorial, mis-identified and signal-like backgrounds.

- Each background[1] comes with its efficiency, $\epsilon_{\mathrm{back.}}$, computed individually. We want to minimize $\epsilon_{\mathrm{back.}}$.
- Estimates for the number of background events:

$$\mathcal{B}(\mathrm{back.}) = \frac{\mathcal{B}_{\mathrm{norm.}}}{N_{\mathrm{norm.}}} \times \frac{\epsilon_{\mathrm{norm.}}}{\epsilon_{\mathrm{back.}}} \times \frac{f_d}{f_i} \times N(\mathrm{back.}) \; .$$

[1] apart from the combinatorial background

Backgrounds

- Determine the number of observed events and the efficiencies for

  ✓ the normalization channels (from the $B_s^0 \to \mu^+\mu^-$ analysis)

  ✗ the signal channel

- For the backgrounds, the tasks are to
  - list the dominant backgrounds i.e. identify which processes could mimic our signal,
  - determine the efficiencies,
  - model the shape from MC samples,
  - estimate the number of expected events (and the signal mass shape) from measured BRs.

Signal efficiency

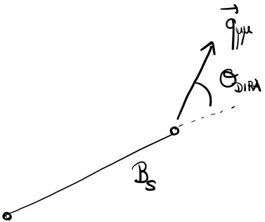
$$\epsilon_{\text{tot}} = \epsilon^{\text{Acc}} \times \epsilon^{\text{Trig}|\text{Acc}} \times \epsilon^{\text{RecSel}|\text{Trig}} \times \epsilon^{\text{PID}|\text{RecSel}} \times \epsilon^{\text{BDT}|\text{PID}} .$$

- $\epsilon^{\text{Acc}} = (48.195 \pm 0.090)\%$
  The decay products are in the acceptance of the detector.
- $\epsilon^{\text{Trig}|\text{Acc}} = (95.56 \pm 0.07)\%$
  The decay products trigger the recording of the event.
- $\epsilon^{\text{RecSel}|\text{Trig}} = (6.25 \pm 0.21)\%$
  Requirements to separate signal from backgrounds and "clean" the samples.
- $\epsilon^{\text{PID}|\text{RecSel}} = (92.76 \pm 0.09)\%$ vs $(6.5 \pm 1.0)\%$ for $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$.
  Requirements dedicated to reducing mis-ID'd backgrounds.
- $\epsilon^{\text{BDT}|\text{PID}} \approx 30\%$
  Multivariate Tool targetting combinatorial background.

N_{exp}	2.41 ± 1.21
$N_{exp}[\mathcal{B}(m(\mu^+\mu^-) > 4.9\,\text{GeV}) = 2 \times 10^{-9}]$	267 ± 113

Boosted Decision Tree (BDT)

- Isolation variables, vertex fit quality, kinematic variables.



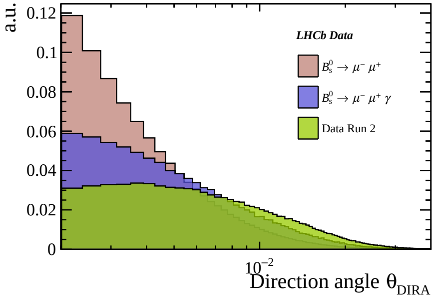


Figure: Distribution of the direction angle for $B_s^0 \to \mu^+\mu^-\gamma$ (signal), $B_s^0 \to \mu^+\mu^-$, and data (combinatorial).

q^2-dependent efficiency

- The signal spans in q^2, such that the q^2 dependency of the efficiency "shapes" the signal distribution.

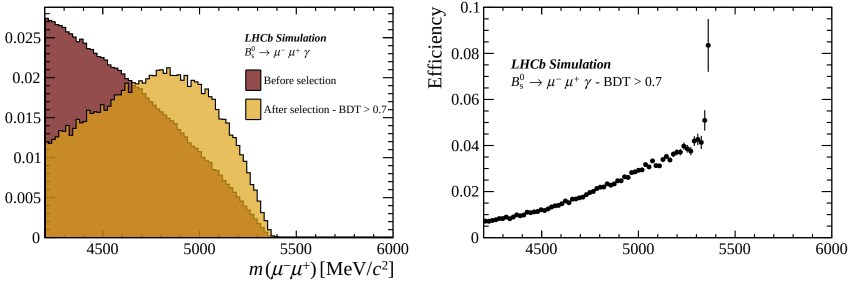
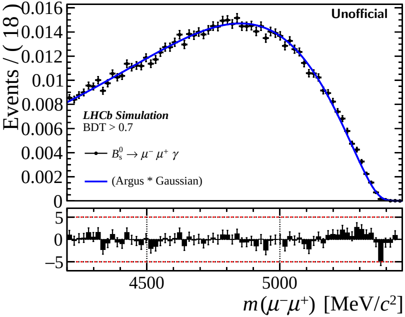


Figure: Di-muon invariant mass distribution of the signal (dark red) at the generation level and (light gold) after full selection containing a BDT requirement BDT>0.7.

Number of events and the signal mass shapes

- To fit the invariant mass distributions of the events, we need to describe the shape of this distribution for the signal.
- The signal mass distribution is determined from MonteCarlo (MC) simulations
- Represented by an Argus function convoluted with a Gaussian with a width fixed to the di-muon mass resolution from the $B_s^0 \to \mu^+\mu^-$ analysis at $\sigma_{\text{res}} = 22.0\,\text{MeV}$



Form factor parameterisation

- The choice of input form factor parameterisation influences the signal shape. (cf. Ludovico Vittorio's talk)

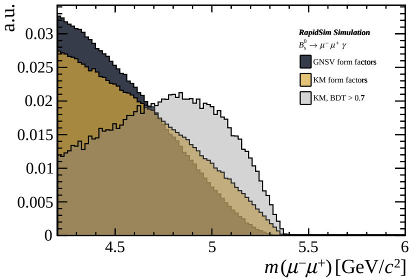


Figure: (Gold) KM parametrization and (black) the GNSV parametrization before selection.

- KM: [A. Kozachuk, D. Melikhov and N. Nikitin (2018), Phys. Rev. D97 (2018) 053007]
- GNSV: [D. Guadagnoli, CN, S. Simula, L. Vittorio (2023), JHEP 07 (2023) 112]

Form factor parameterisation

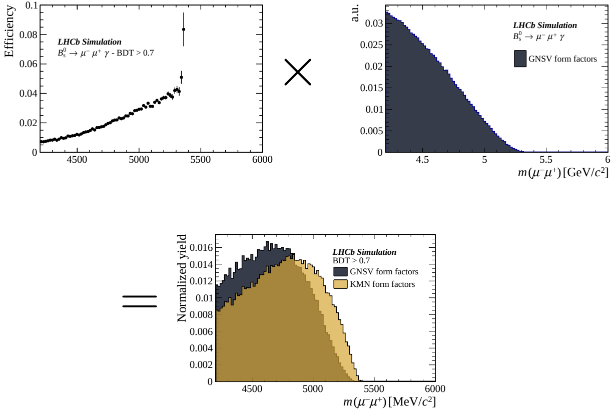


Figure: (Light) KM parametrization and (dark) the GNSV parametrization after selections.

Invariant mass fit

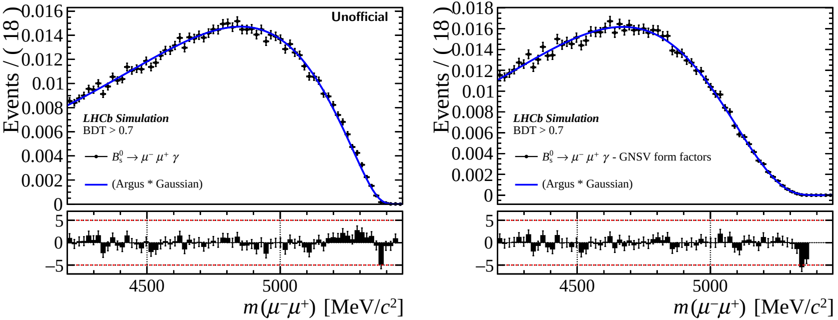


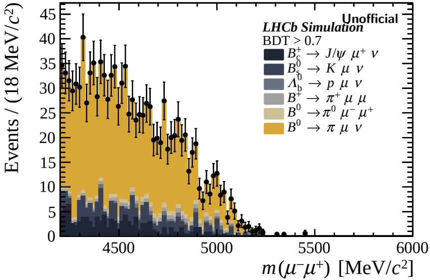
Figure: (Left) KM parameterisation and (right) GNSV parameterisation.

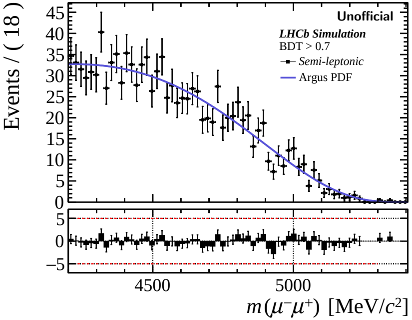
Backgrounds - Semi-leptonic decays

- Semi-leptonic decays yields

Expected yield	1136 ± 158

- Mass distribution



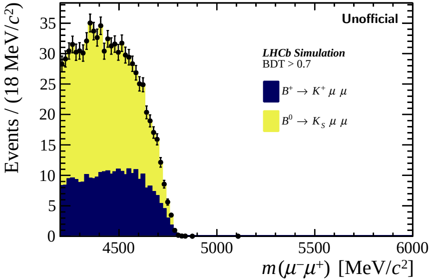


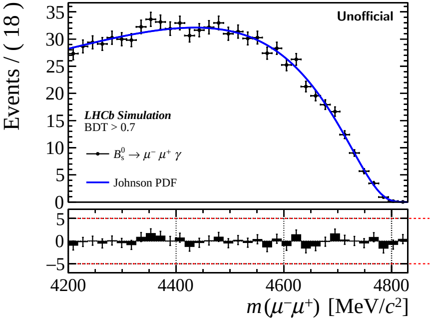
Backgrounds - $B \to K\mu\mu$ decays

- $B \to P\mu\mu$ decays yields

Expected yield	834 ± 55

- Mass distribution



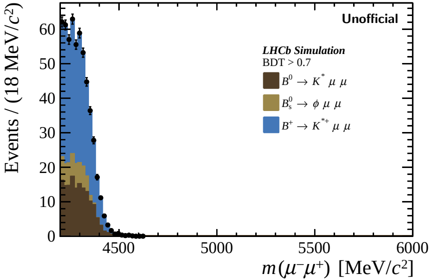


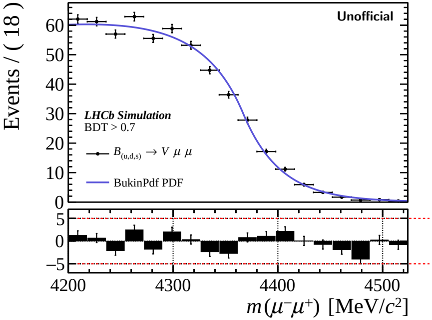
Backgrounds - $B \to V\mu\mu$ decays, $V = K^*, \phi$

- $B \to V\mu\mu$ decays yields

Expected yield	562 ± 32

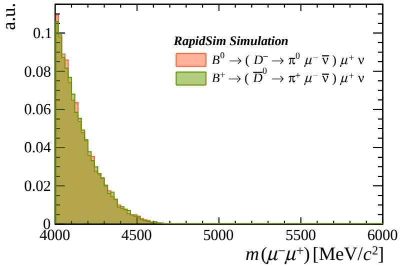
- Mass distribution



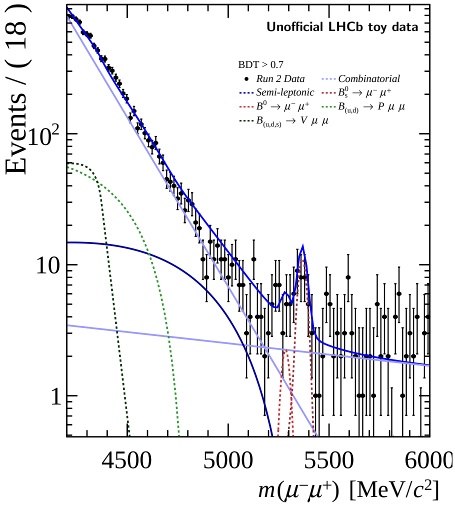


Backgrounds - Combinatorial

- Unknown yield.
- Accounted for by a double-exponential PDF:
  - One for the combinatorial above the B_s^0 mass;
  - One for partially-reconstructed "cascade decays" $B \to (D \to \pi\mu\nu)\mu\nu$.



A first look at toy data



1. Background-only fit to the data i.e. no signal component to the fit (not shown).
2. Blinding: the number of expected event ~ 3 means that the signal is not distinguishable in the data.
   $\rightarrow$ Blinding is realized by not fitting for signal.
3. From this fit, we can extract the parameters for the combinatorial background.
4. All parameters and their uncertainties can be combined to generate toy data and compute the expected sensitivity of the analysis to the branching ratio of $B_s^0 \rightarrow \mu^+\mu^-\gamma$ (not shown).

WIP and concluding remarks

- Including and constraining the cascade decays would allow for a better control of the backgrounds in the entire mass region, thus improving the upper-limit.
- Compute $\epsilon_{\mathrm{back.}}$ on higher statistics MC.
- Include systematic uncertainties: PID requirements, form factors parametrization.
- The partial reconstruction method proves to be useful to probe a challenging phase-space of the decay.

Question time !

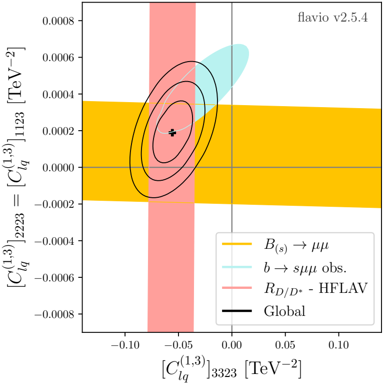
Thank you for your attention !

Back-up

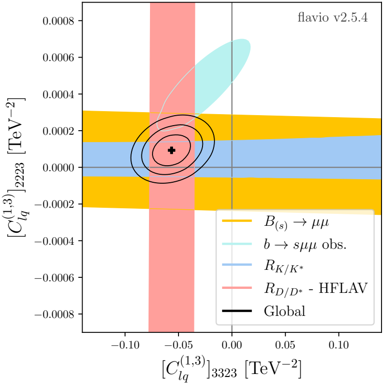
All scenarios

Scenario	Best-fit point	1σ Interval	$\sqrt{\chi^{2,\mathrm{SM}} - \chi^2}$
$(\delta C_9^{(\mu,e)}, \delta C_{10}^{(\mu,e)}) \in \mathbb{R}$	$(-0.88, +0.30)$	$([-1.08, -0.56], [0.15, 0.46])$	5.5
$\delta C_{LL}^{(\mu,e)}/2 \in \mathbb{C}$	$-0.70 - 1.36i$	$[-1.00, -0.54] + i[-1.77, -0.54]$	5.8
$\delta C_9^{(\mu,e)} \in \mathbb{C}$	$-1.08 + 0.10i$	$[-1.31, -0.85] + i[-0.70, +0.85]$	6.4
$\delta C_{10}^{(\mu,e)} \in \mathbb{C}$	$+0.68 + 1.40i$	$[+0.38, +1.00] + i[+0.69, +1.92]$	3.2
$\delta C_7 \in \mathbb{C}$	$+0.01 - 0.10i$	$[-0.015, 0.046] + i[-0.17, -0.05]$	2.6

SMEFT



flavio v2.5.4
$[C_{lq}^{(1,3)}]_{2223} = [C_{lq}^{(1,3)}]_{1123}$ [TeV^{-2}]
0.0008
0.0006
0.0004
0.0002
0.0000
−0.0002
−0.0004
−0.0006
−0.0008
−0.10
−0.05
0.00
0.05
0.10
$[C_{lq}^{(1,3)}]_{3323}$ [TeV^{-2}]
$B_{(s)} \to \mu\mu$
$b \to s\mu\mu$ obs.
R_{D/D^*} - HFLAV
Global



flavio v2.5.4
$[C_{lq}^{(1,3)}]_{2223}$ [TeV^{-2}]
0.0008
0.0006
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−0.0004
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−0.0008
−0.10
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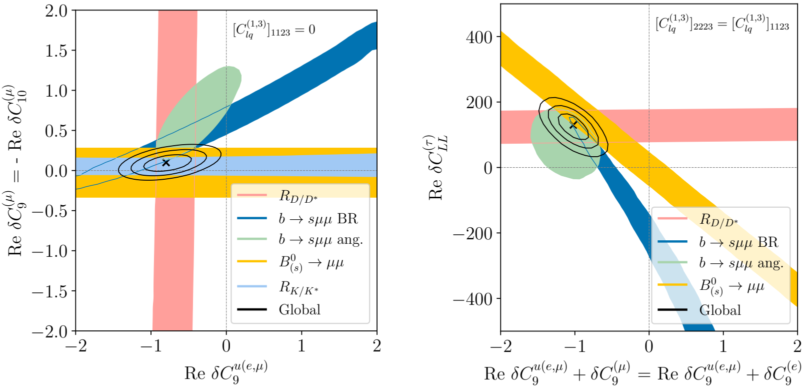
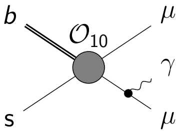
0.00
0.05
0.10
$[C_{lq}^{(1,3)}]_{3323}$ [TeV^{-2}]
$B_{(s)} \to \mu\mu$
$b \to s\mu\mu$ obs.
R_{K/K^*}
R_{D/D^*} - HFLAV
Global

SMEFT



$[C_{lq}^{(1,3)}]_{1123} = 0$
Re $\delta C_9^{(\mu)}$ = - Re $\delta C_{10}^{(\mu)}$
Re $\delta C_9^{u(e,\mu)}$
R_{D/D^*}
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
R_{K/K^*}
Global
$[C_{lq}^{(1,3)}]_{2223} = [C_{lq}^{(1,3)}]_{1123}$
Re $\delta C_{LL}^{(\tau)}$
Re $\delta C_9^{u(e,\mu)} + \delta C_9^{(\mu)}$ = Re $\delta C_9^{u(e,\mu)} + \delta C_9^{(e)}$
R_{D/D^*}
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
Global

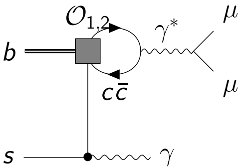
FSR



FSR component to the $B_s^0 \to \mu^+\mu^-\gamma$ amplitude

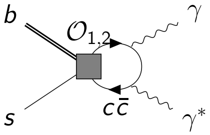
$$\bar{\mathcal{A}}_{\mathrm{FSR}} \;=\; +\,i\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_{\mathrm{em}}}{2\pi} e\; X_f\, f_{B_s}\; 2m_\mu\; C_{10} \times \left\{ \bar{u}(p_2) \left(\frac{\not{\lambda}^* \not{p}}{t - m_\mu^2} - \frac{\not{p}\not{\lambda}^*}{u - m_\mu^2} \right) v(p_1) \right\}, \qquad (1)$$

Long-distance contributions



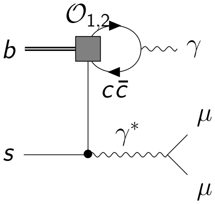
- Sum over $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ of Breit-Wigner poles:

$$
\begin{aligned}
C_9^{\text{eff}}(q^2) \quad \rightarrow \quad & C_9^{\text{eff}}(q^2) \\
+ \quad & \frac{9\pi\bar{C}}{\alpha_{\text{em}}^2} \sum_V |\eta_V| e^{i\delta_V} \frac{m_V \mathcal{B}(V \to \mu\mu)\Gamma_{\text{tot}}}{q^2 - m_V^2 + i m_V \Gamma_{\text{tot}}}
\end{aligned}
$$



- Power-suppressed at high-q^2

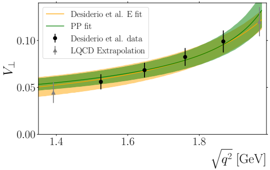
$$
\begin{aligned}
\overline{T}_\perp \quad = \quad & T_\perp \\
+ \quad & \frac{16}{3} \frac{V_{ub}V_{ud}^* + V_{cb}V_{cd}^*}{V_{tb}V_{td}^*} \frac{a_1 f_{B_s^0}}{C_7^{\text{eff}} m_{B_s^0}}
\end{aligned}
$$

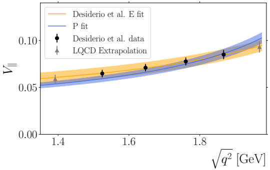


- Power-suppressed at high-q^2

$D_s \to \gamma$ form factors

- Direct Lattice computation of the form factors $V_{\perp,\parallel}$ are available





- The Lattice data are well described by the following ansatze

$$
\begin{aligned}
V_\perp^{D_s}(q^2) &= \frac{r_{\perp 1}^{D_s}}{1 - q^2/m_{D_s^*}^2} + \frac{r_{\perp 2}^{D_s}}{1 - q^2/m_{D_{s1}^*}^2}\,, \\
V_\parallel^{D_s}(q^2) &= \frac{r_\parallel^{D_s}}{1 - q^2/m_{D_{s1}}^2}\,.
\end{aligned}
$$

- The $D_{s(1)}^{(*)}$ are **physical states**:
  - D_s^* and D_{s1}^*: $J^P = 1^-$
  - D_{s1}: $J^P = 1^+$

From $D_s \to \gamma$ to $B_s^0 \to \gamma$

- We use the following ansatz

$$
\begin{aligned}
V_\perp^{B_s}(q^2) &= \frac{r_{\perp 1}^{B_s}}{1 - q^2/m_{B_s^*}^2} + \frac{r_{\perp 2}^{B_s}}{1 - q^2/m_{B_{s1}^*}^2} \,, \\
V_\parallel^{B_s}(q^2) &= \frac{r_\parallel^{B_s}}{1 - q^2/m_{B_{s1}}^2} \,.
\end{aligned}
$$

with B_s^*, B_{s1}^* and B_{s1} physical states of the B_s^0 spectrum.

From $D_s \to \gamma$ to $B_s^0 \to \gamma$

- We use the following ansatz

$$
\begin{aligned}
V_\perp^{B_s}(q^2) &= \frac{r_{\perp 1}^{B_s}}{1 - q^2/m_{B_s^*}^2} + \frac{r_{\perp 2}^{B_s}}{1 - q^2/m_{B_{s1}^*}^2} \, , \\
V_\parallel^{B_s}(q^2) &= \frac{r_\parallel^{B_s}}{1 - q^2/m_{B_{s1}}^2} \, .
\end{aligned}
$$

with B_s^*, B_{s1}^* and B_{s1} physical states of the B_s^0 spectrum.

- The **residues** $r_i^{M_i}$ can be expressed

$$
r_i^{M_i} = \frac{m_{M_i} f_{M_i}}{m_{M_i^*}} g_{M_i^* M_i \gamma} .
$$

with the **tri-couplings** $g_{M_i^* M_i \gamma}$ parameterize the coupling strength of $M_i^* \to M_i \gamma$.

From $D_s \to \gamma$ to $B_s^0 \to \gamma$

- We use the following ansatz

$$\begin{aligned} V_\perp^{B_s}(q^2) &= \frac{r_{\perp 1}^{B_s}}{1 - q^2/m^2_{B_s^*}} + \frac{r_{\perp 2}^{B_s}}{1 - q^2/m^2_{B_{s1}^*}} \,, \\ V_\parallel^{B_s}(q^2) &= \frac{r_\parallel^{B_s}}{1 - q^2/m^2_{B_{s1}}} \,. \end{aligned}$$

  with B_s^*, B_{s1}^* and B_{s1} physical states of the B_s^0 spectrum.
- The **residues** $r_i^{M_i}$ can be expressed

$$r_i^{M_i} = \frac{m_{M_i} f_{M_i}}{m_{M_i^*}} g_{M_i^* M_i \gamma}.$$

  with the **tri-couplings** $g_{M_i^* M_i \gamma}$ parameterize the coupling strength of $M_i^* \to M_i \gamma$.
- The tri-couplings are parameterized in terms of **quark magnetic moments**, which follow a $1/m_h$ scaling.
  ↳ Using the LQCD data of the charm sector, we extract the tri-coupling and **extrapolate to the bottom sector.**

Extrapolation to the bottom sector

- The form factors in the bottom sector thus require the determination of:
  - The mass m_{M_i};
  - The decay constant f_{M_i};
  - **The tri-coupling $g_{M_i^* M_i \gamma}$;**

  of the excited states of the B_s^0 with the relevant spin-parity.

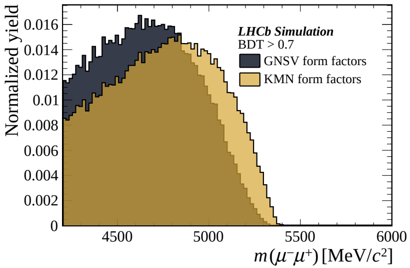
- We parameterize the tri-couplings with a **heavy-quark expansion**

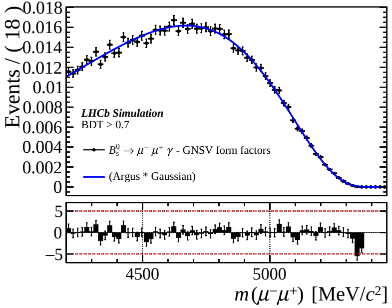
$$\begin{aligned} g_{D_{s1} D_s \gamma} &= \mu_s^{\parallel}(-Q_s + Q_c \frac{m_s}{m_c}) \ , \\ g_{B_{s1} B_s \gamma} &= \mu_s^{\parallel}(-Q_s + Q_b \frac{m_s}{m_b}) \ . \end{aligned}$$

- From the LQCD form factors fit, we extract $g_{D_{s1} D_s \gamma}$, then $\mu_s^{\parallel}$, and finally $g_{B_{s1} B_s \gamma}$.

Influence of the form factors parameterization

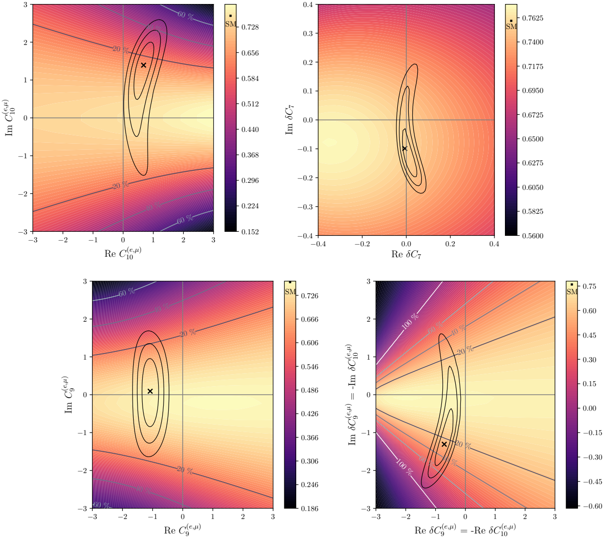
- The signal mass distribution of the MC depends on the form factors they are generated with



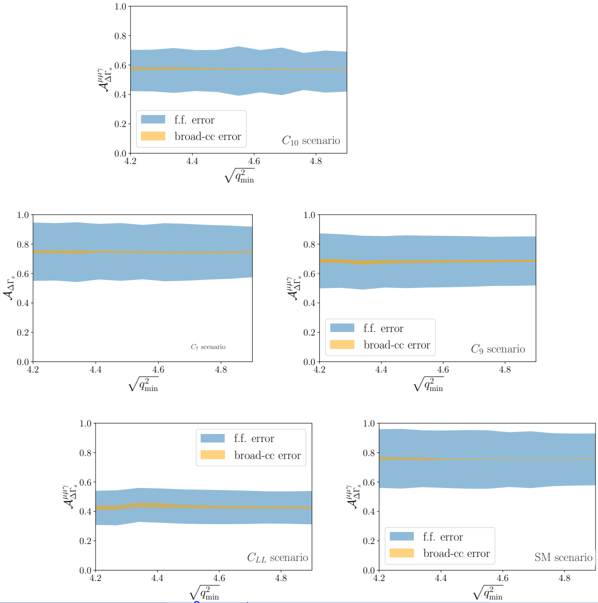


- It will be included as a systematic uncertainty.

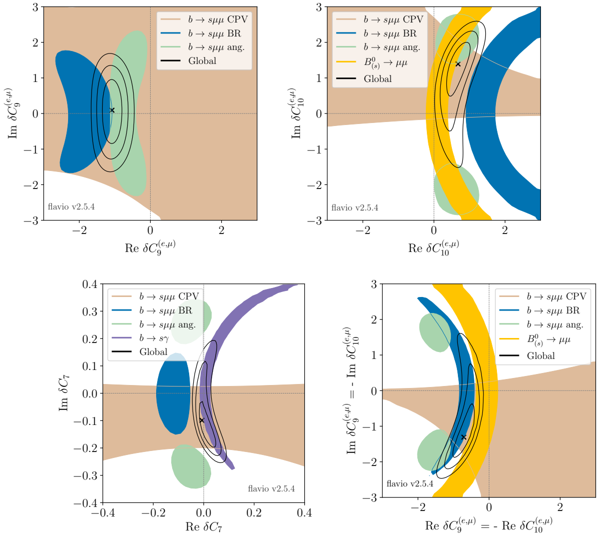
$A_{\Delta\Gamma_s}^{\mu\mu\gamma}$



$A^{\mu\mu\gamma}_{\Delta\Gamma_s}$



Complex fits



Boosted Decision Tree (BDT)

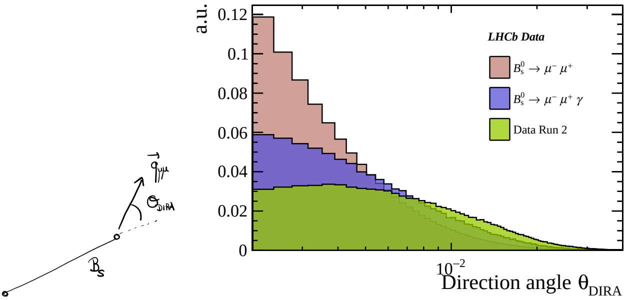


Figure: Distribution of the direction angle for $B_s^0 \to \mu^+\mu^-\gamma$ (signal), $B_s^0 \to \mu^+\mu^-$, and data (combinatorial).