Prospects for LFU and LFV at LHCb

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LHCb
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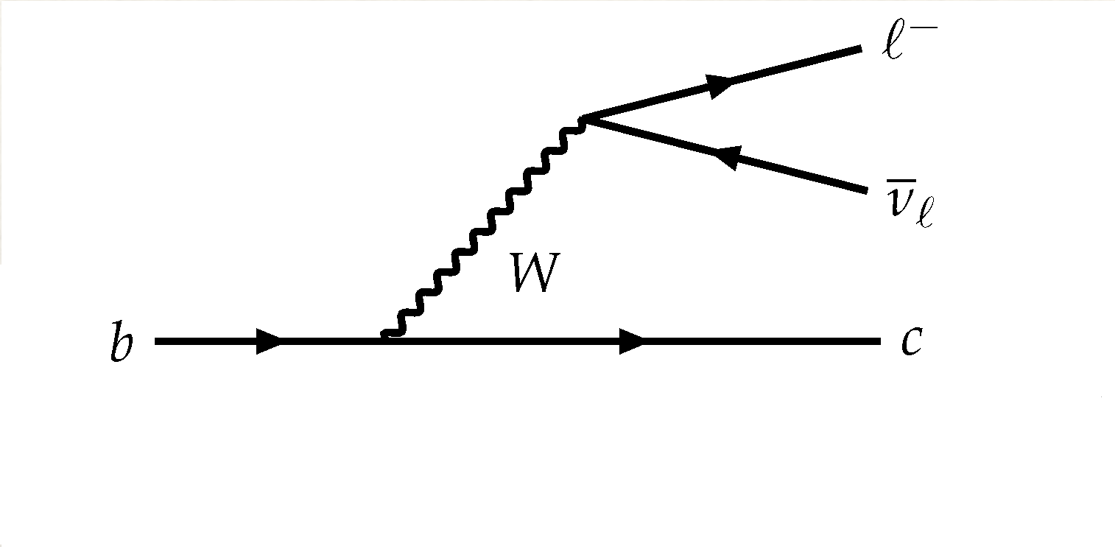
EXCELENCIA MARÍA DE MAEZTU 04/2025–03/2031

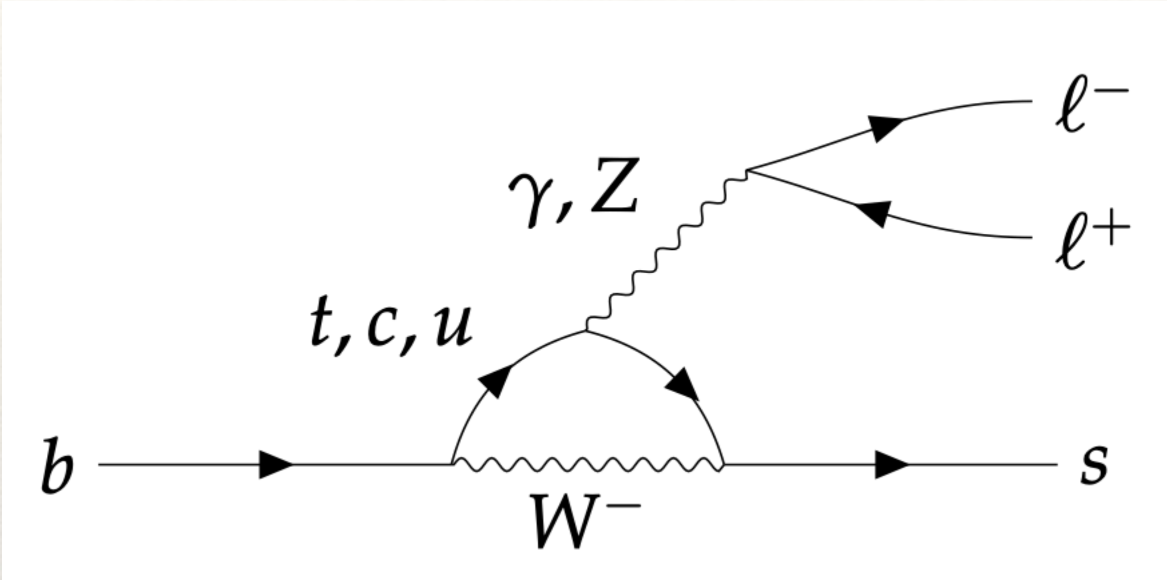
Outline

- Introduction
- Selected analyses
- Prospects at HL-LHC
- Conclusions

Semileptonic and rare decays at LHCb

- LFU measurements in tree-level $b \to c\ell\overline{\nu}_\ell$ and loop-level $b \to s\ell^+\ell^-$ transitions, provide sensitive null-tests to New Physics.





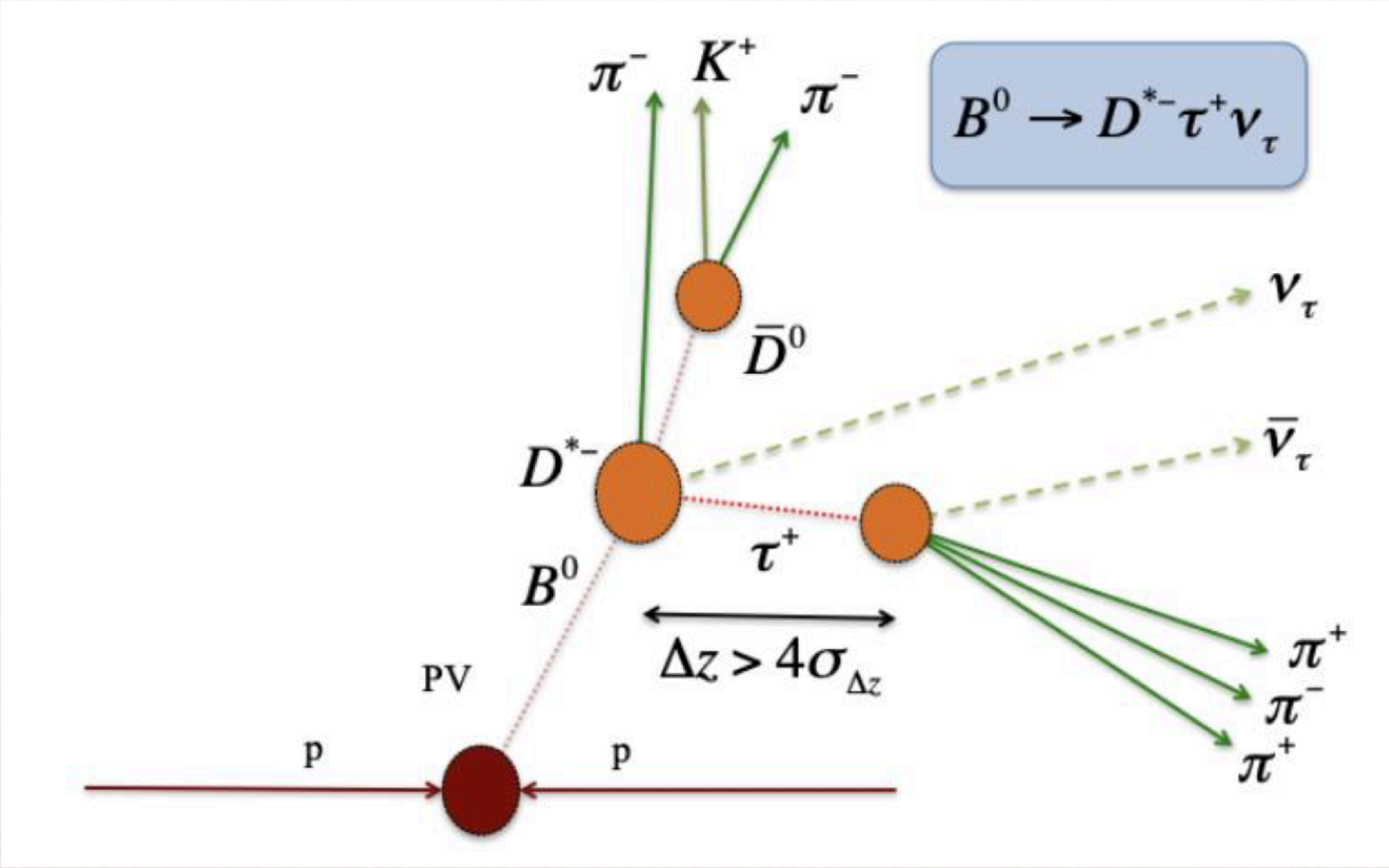
- High signal yields
- Neutrinos not reconstructed, more backgrounds
- Tau decays accessible -> probe LFU in couplings to 3rd generation

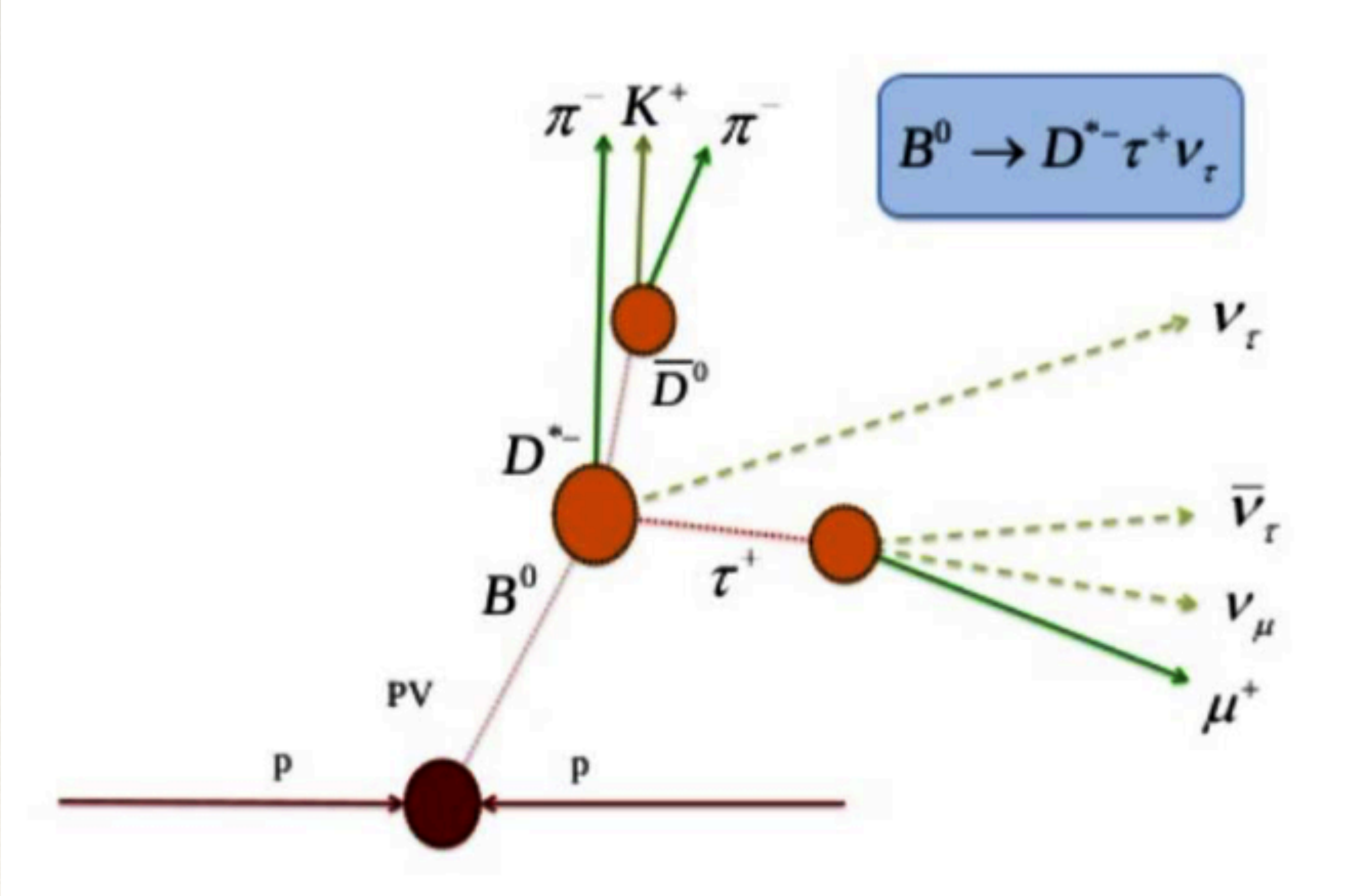
- Low signal yields
- Fully reconstructible final states
- Probe higher-loop diagrams -> sensitive to tree-level NP

- LHCb has access to all hadron species including $B_c^+, \Lambda_b^0, \Omega_b^-, \Xi_b^{0,-}$

Experimental strategy and challenges for SL

- Final states cannot be fully reconstructed due to neutrinos.
  - Many backgrounds enter, especially partially reconstructed ones.
  - Signal yields are determined from template fits.
  - Templates obtained from simulation and control samples need large statistics.
- At LHCb two decay topologies for tau decays are used:
  - hadronic: $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$
  - muonic: $\tau^+ \to \mu^+\overline{\nu}_\tau\nu_\mu$





Phys. Rev. Lett. 134 (2025) 061801

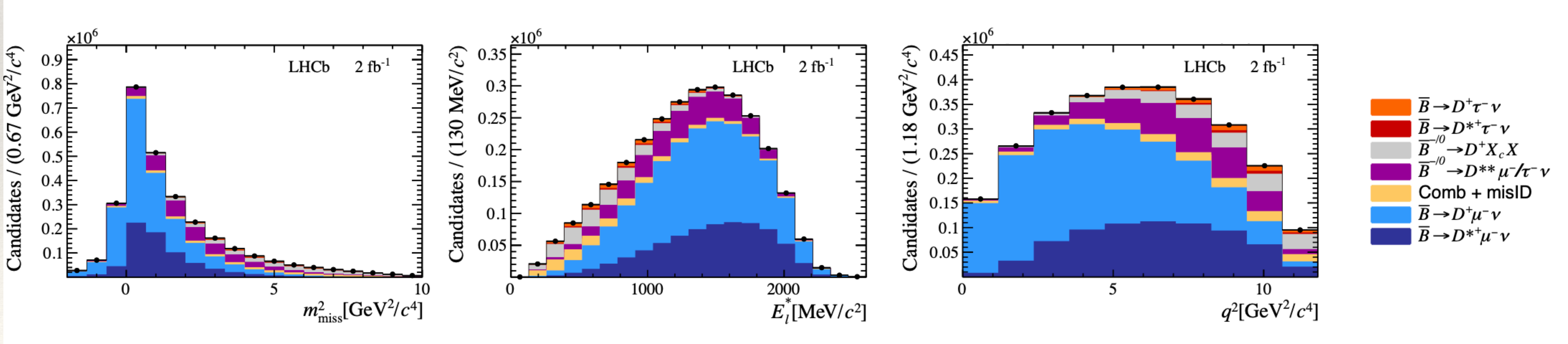
R(D⁺) and R(D*⁺) using muonic τ decays

- Measure simultaneously $R(D^+)$ and $R(D^{*+})$ using 2fb^{-1} of data from 2015-2016.
- $$R(D^{(*)+}) = \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau^-\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)+}\mu^-\nu_\mu)} = \frac{\varepsilon_\mu}{\varepsilon_\tau}\frac{N_\tau}{N_\mu}\frac{1}{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}$$

Efficiency ratio from simulation and control samples

Signal yields from 3D template fits to:

- $q^2 = (p_{B^0} - p_{D^{(*)+}})^2$
- muon energy in B^0 rest frame
- $m^2_{miss} = (p_{B^0} - p_{D^{*+}} - p_{\mu^-})^2$

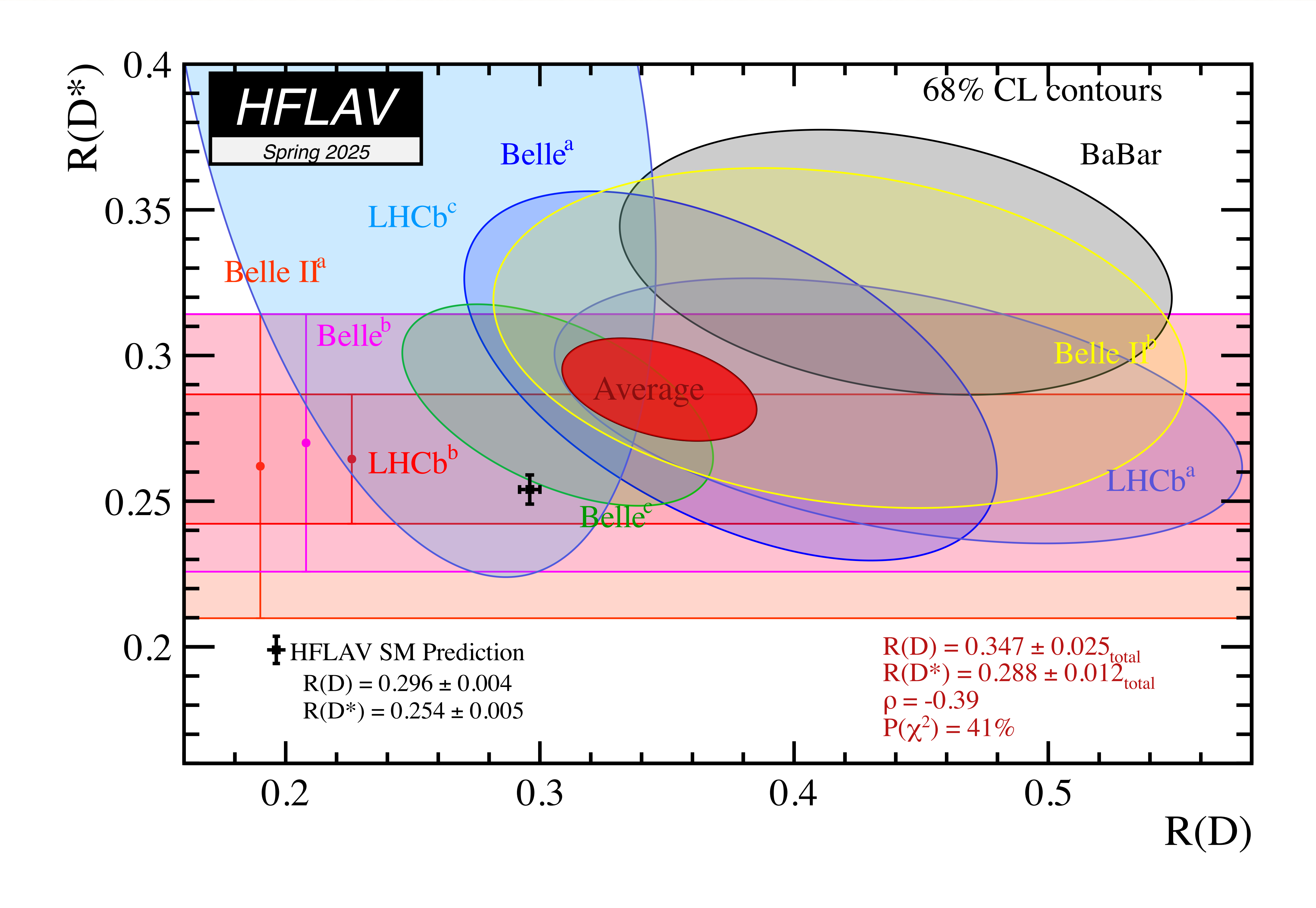


Phys. Rev. Lett. 134 (2025) 061801

$R(D^+)$ and $R(D^{*+})$ using muonic τ decays

- Largest systematic uncertainties come from form factor parametrisation and background modelling (e.g. higher excited D** states).

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$



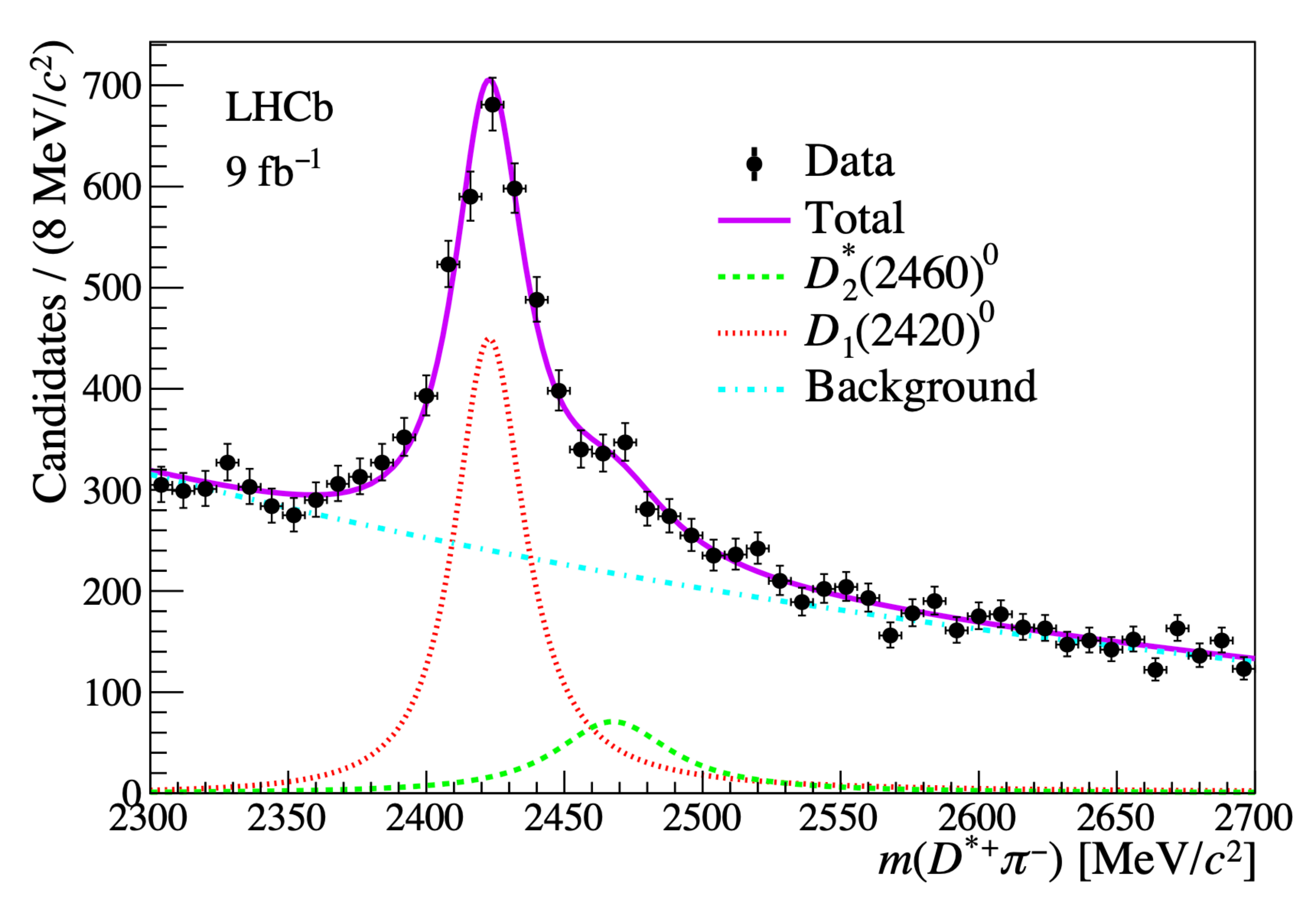
HFLAV: arXiv:2411.18639 and online updates

- Results in agreement with previous ones.
- Global discrepancies at 1.9σ for R(D) and 2.7σ for R(D*). Combined 3.8σ.

arXiv:2501.14943

Evidence for $B^- \to D^{**0}\tau^-\overline{\nu}_\tau$ decays

- Search for $B^- \to D^{**0}\tau\overline{\nu}_\tau$ using the full Run1 + Run2 dataset.
- Three BDTs to reject: fake D^{**0}, muli body D_s^+ decays, D_s^+ mimicking τ decays.
- Fit to $D^{*+}\pi^-$ spectrum to investigate D^{**0} states.
- 3.5σ significance for $B^- \to D^{**0}\tau^-\overline{\nu}_\tau$
- Estimated D^{**0} yield in $R(D^{*+})$ hadronic (8.9+/-2.1)% => 0.013 shift in $R(D^{*+})$, below uncertainty.



$$R(D^{**0}) = \frac{\mathscr{B}(B^- \to D_{1,2}^{**0}\tau\nu_\tau)}{\mathscr{B}(B^- \to D_{1,2}^{**0}\mu\nu_\mu)} = 0.13 \pm 0.04$$

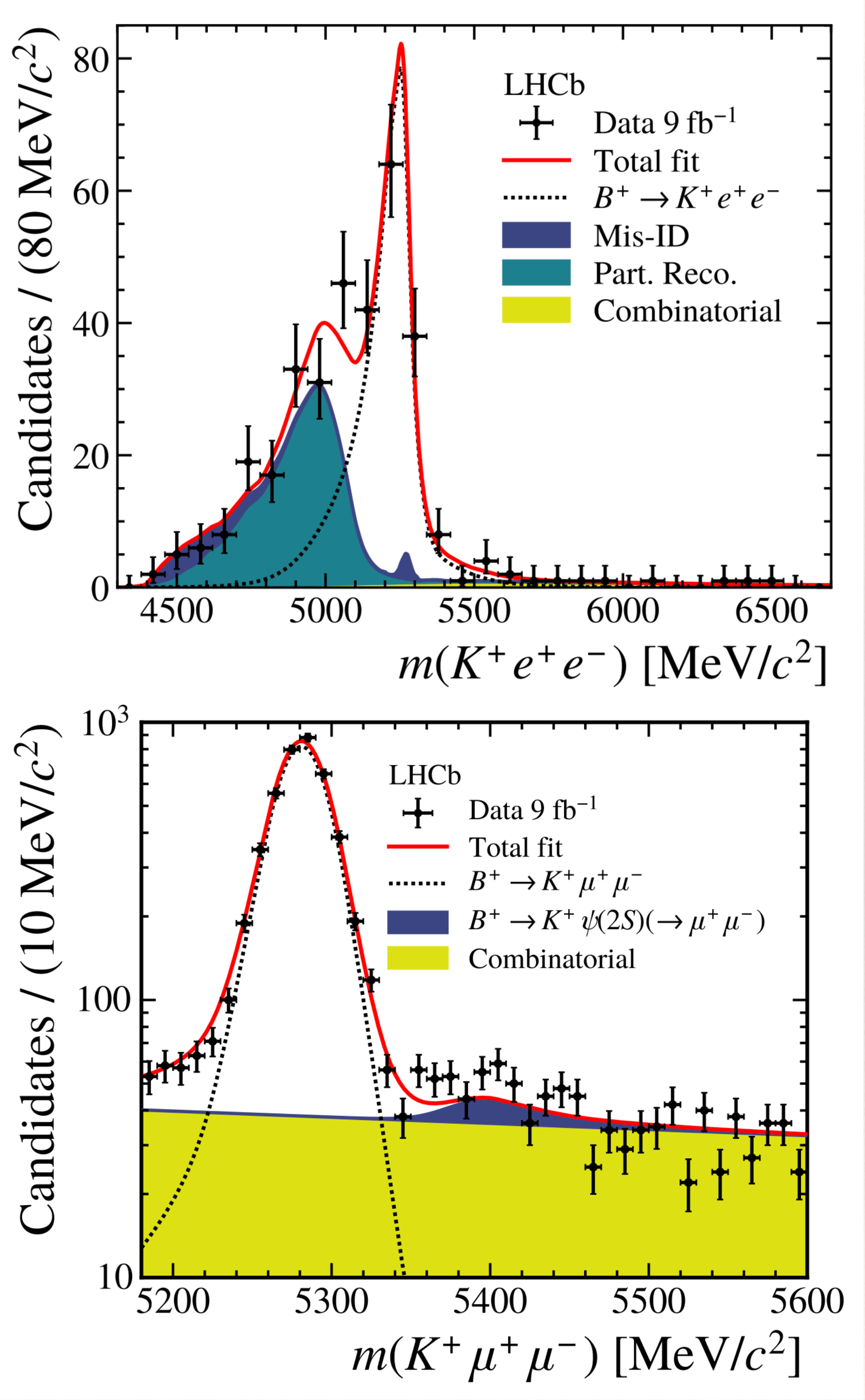
in good agreement with SM prediction.

LFU: R_K at high q^2

arXiv:2505.03483

- Test of lepton universality in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ ($\ell = e, \mu$) decays in region of dilepton mass-squared $q^2 > 14.3\,\mathrm{GeV}^2/\mathrm{c}^4$ using Run1+Run2 dataset.
- Challenges from electron bremsstrahlung corrections and distorted phase-space distribution at high q^2.
- Ratio of branching fractions R_K compatible with SM prediction.

$$R_K(q^2 > 14.3\,\mathrm{GeV}^2/\mathrm{c}^4) = 1.08^{+0.11}_{-0.09}{}^{+0.04}_{-0.04}$$

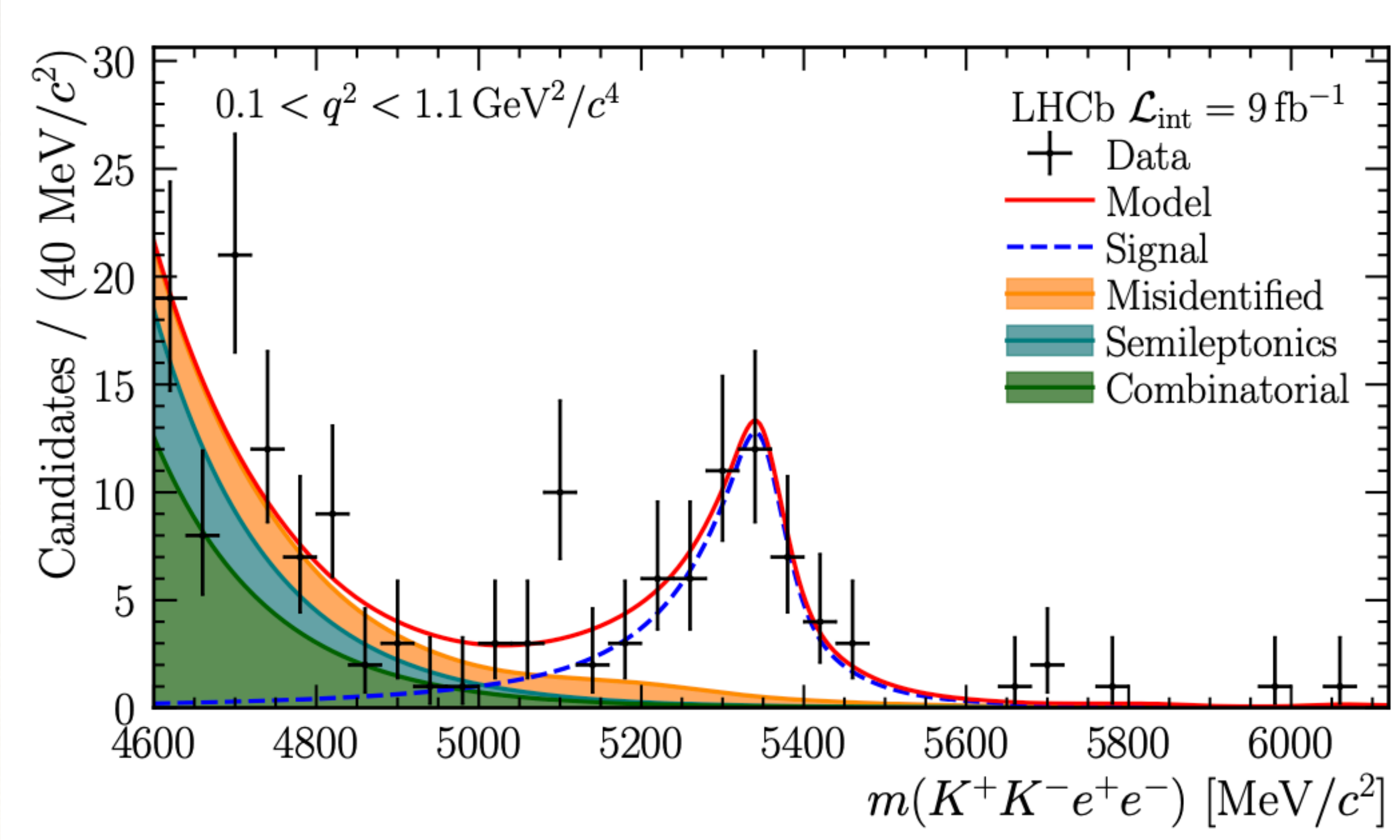


LFU on $B_s \to \phi\ell^+\ell^-$

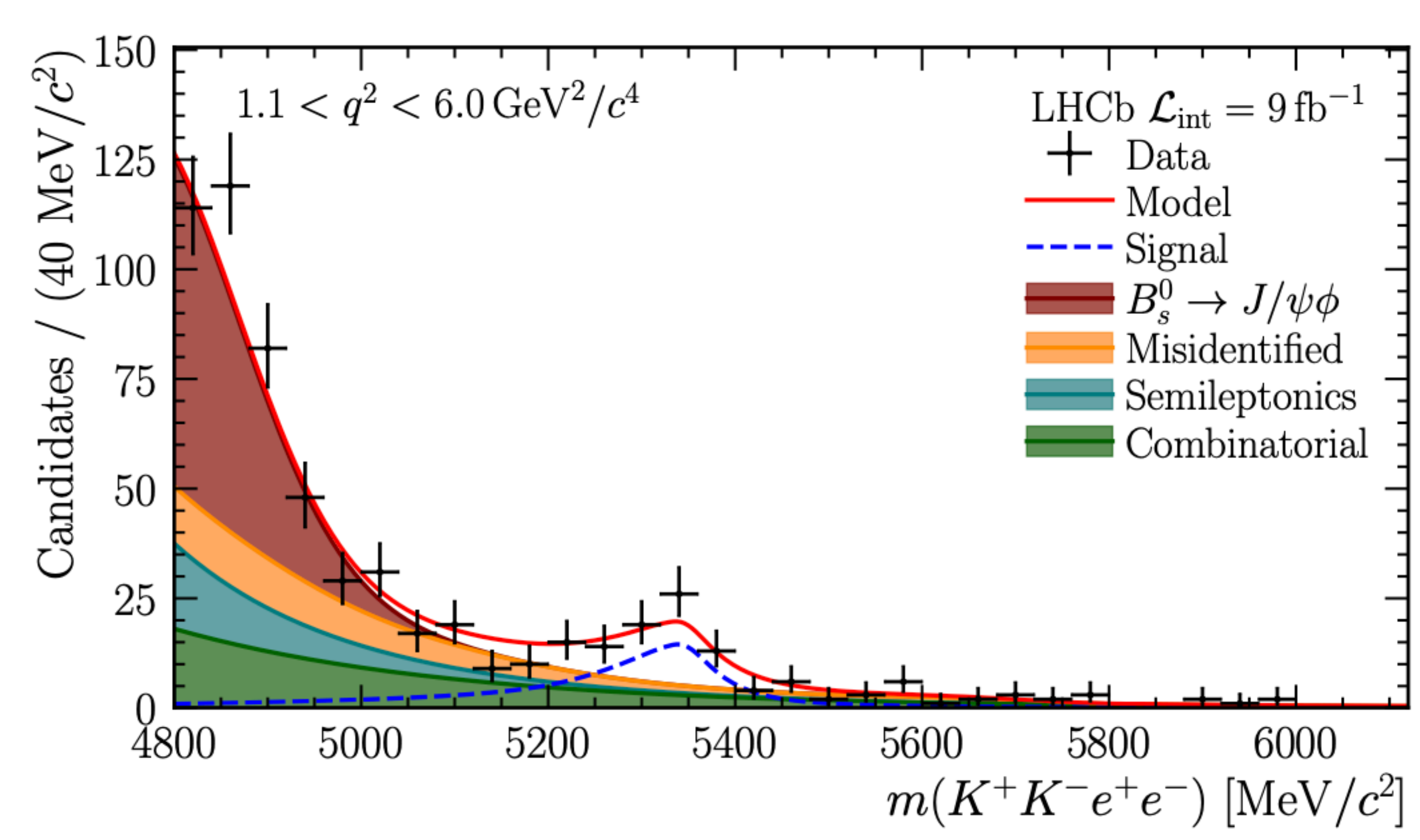
Phys. Rev. Lett. 134 (2025) 121803

- Test of lepton universality with $B_s \to \phi\ell^+\ell^-$ decays.
- First LFU with a B_s meson. Narrow ϕ meson leads to low background.
- Limited sample size, but efficient selection and clean data sample.

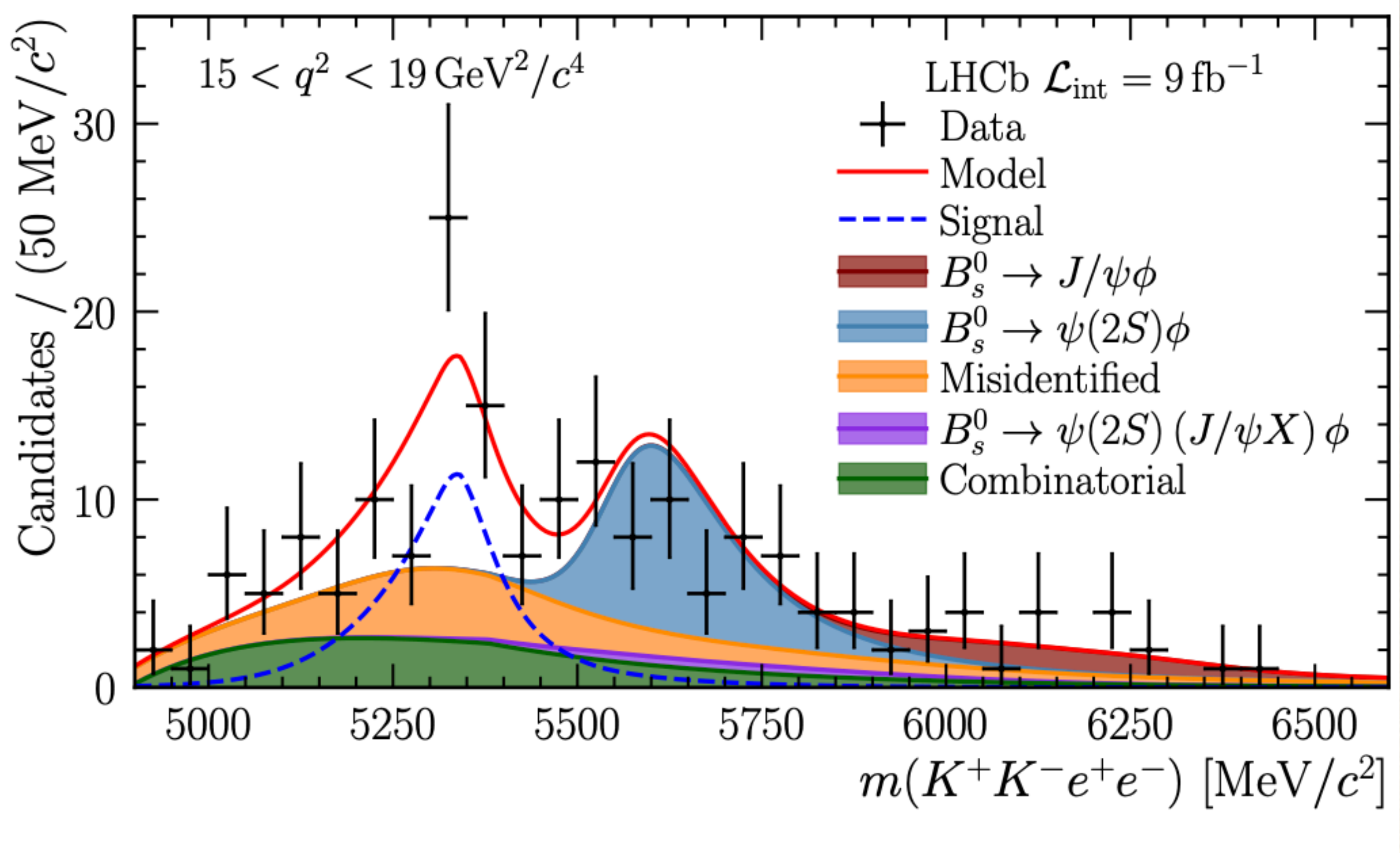
Low-q^2 bin: 6.8σ



Central-q^2 bin: 5.4σ



High-q^2 bin: 3.6σ

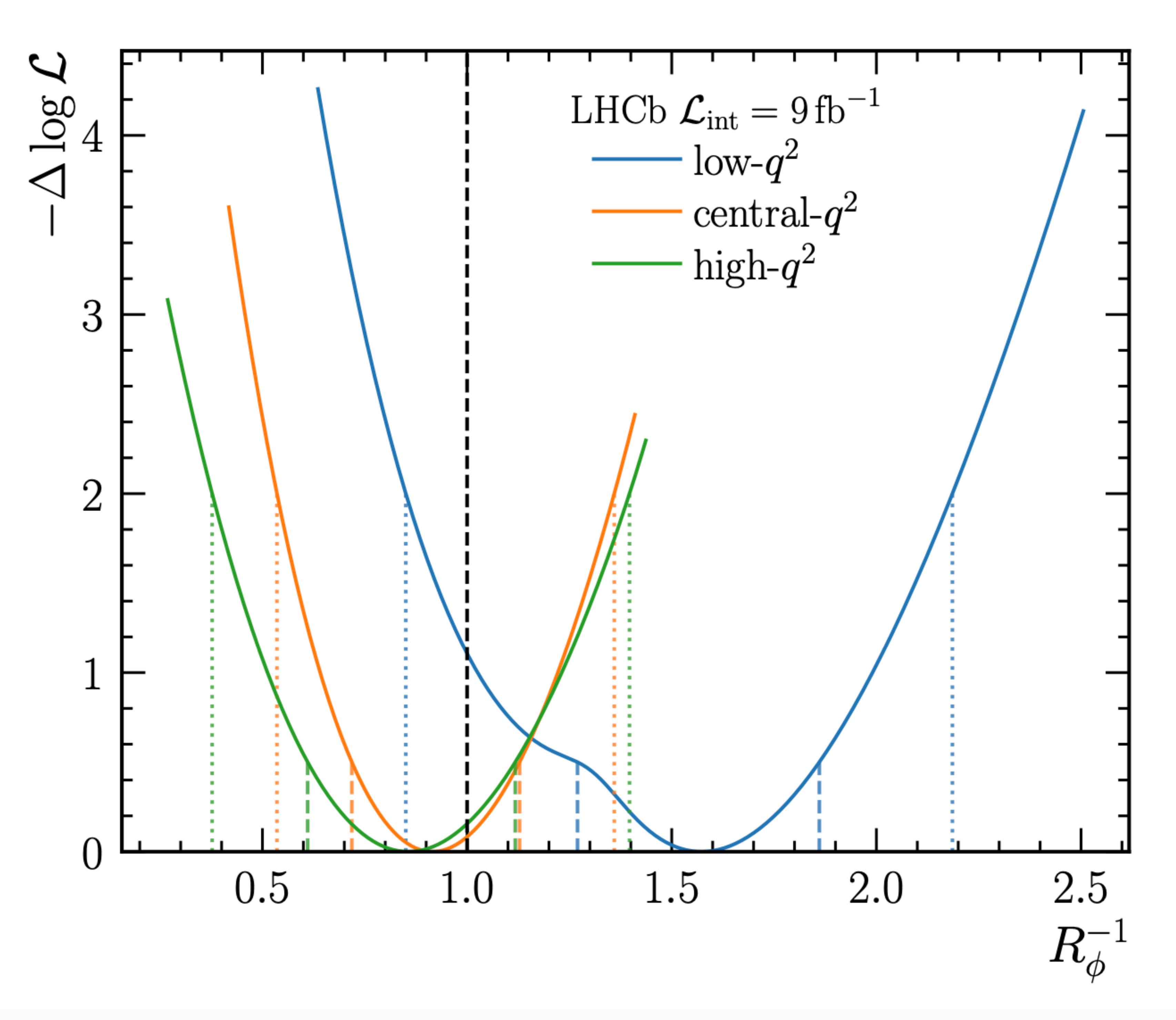


LFU on $B_s \to \phi \ell^+ \ell^-$

Phys. Rev. Lett. 134 (2025) 121803

- R_ϕ^{-1} and differential decay rate in good agreement with the SM.
  - Measurements still statistically limited. **Expect >3x data in Run3.**

q^2 [GeV$^2/c^4$]	R_ϕ^{-1}	$\mathrm{d}\mathcal{B}(B_s^0 \to \phi e^+ e^-)/\mathrm{d}q^2$ [10^{-7} GeV$^{-2} c^4$]
$0.1 < q^2 < 1.1$	$1.57^{+0.28}_{-0.25} \pm 0.05$	$1.38^{+0.25}_{-0.22} \pm 0.04 \pm 0.19 \pm 0.06$
$1.1 < q^2 < 6.0$	$0.91^{+0.20}_{-0.19} \pm 0.05$	$0.26 \pm 0.06 \pm 0.01 \pm 0.01 \pm 0.01$
$15.0 < q^2 < 19.0$	$0.85^{+0.24}_{-0.23} \pm 0.10$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02 \pm 0.02$

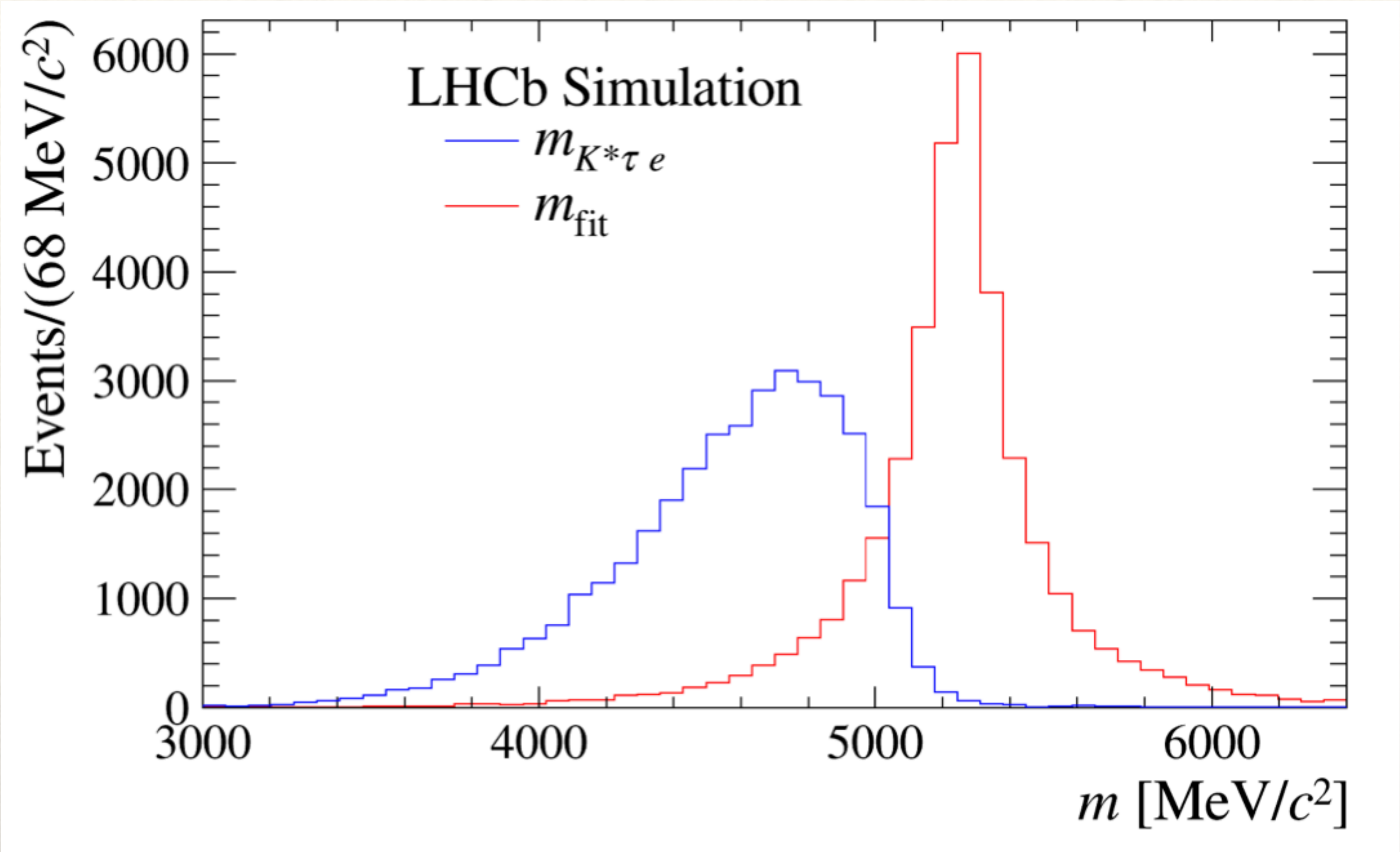


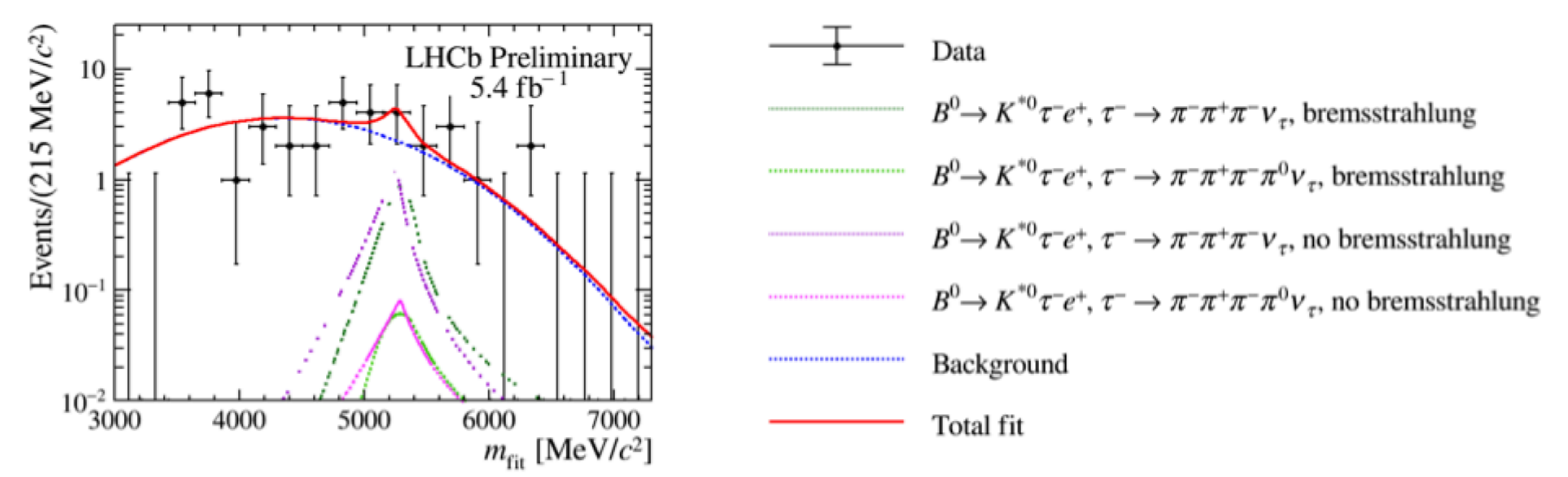
LFV: Limits on $b \to s\tau e$

LHCb-PAPER-2025-005
preliminary

- Lepton flavour violating decays would be enabled / enhanced by leptoquarks or Z' models [JHEP 01 (2020) 067].
- First LHCb search with $e\tau$ combination in $B^0 \to K^{*0}\tau^\pm e^\mp$ decays (Run 2 data).
- Some New Physics models predict BR up to 10^{-6} [arXiv:1709.00294, arXiv:1603.04993, arXiv:1504.07928]
- Use of hadronic τ decay to get decay vertex information. Improves mass resolution.

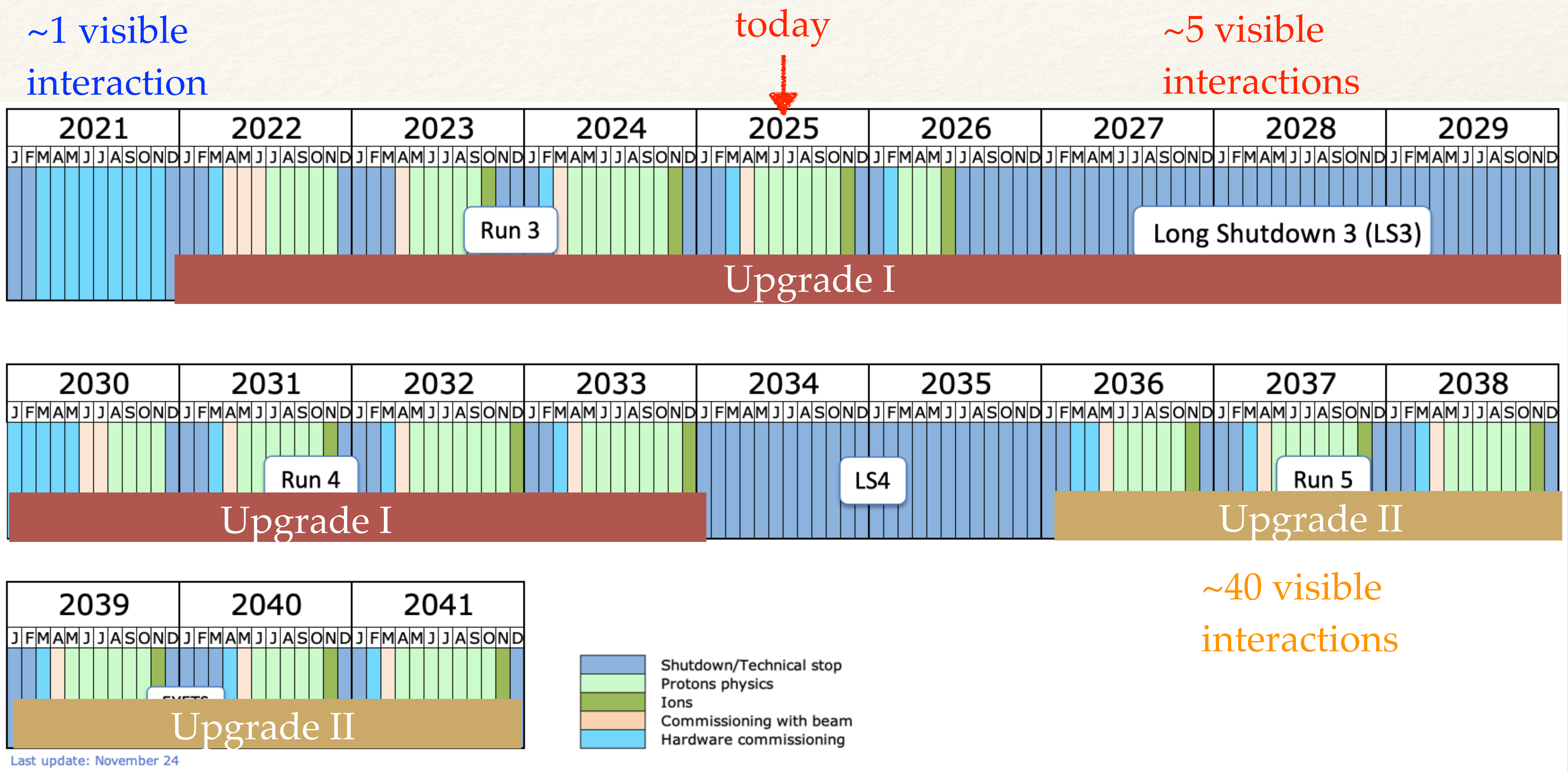
$$\mathcal{B}(B^0 \to K^{*0}\tau^- e^+) < 5.9(7.1) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+ e^-) < 4.9(5.9) \times 10^{-6}$$





Increasing and improving the data sample

- Gain in Run 2 was $\sqrt{s}$ => higher $\sigma_{b\bar{b}}$
- After Run 2, increase instantaneous luminosity.
    - Maintaining the performance.
- Beyond that:
    - improve selection efficiencies.
    - improve trigger efficiencies.
    - increase acceptance (instrument new regions of detector).



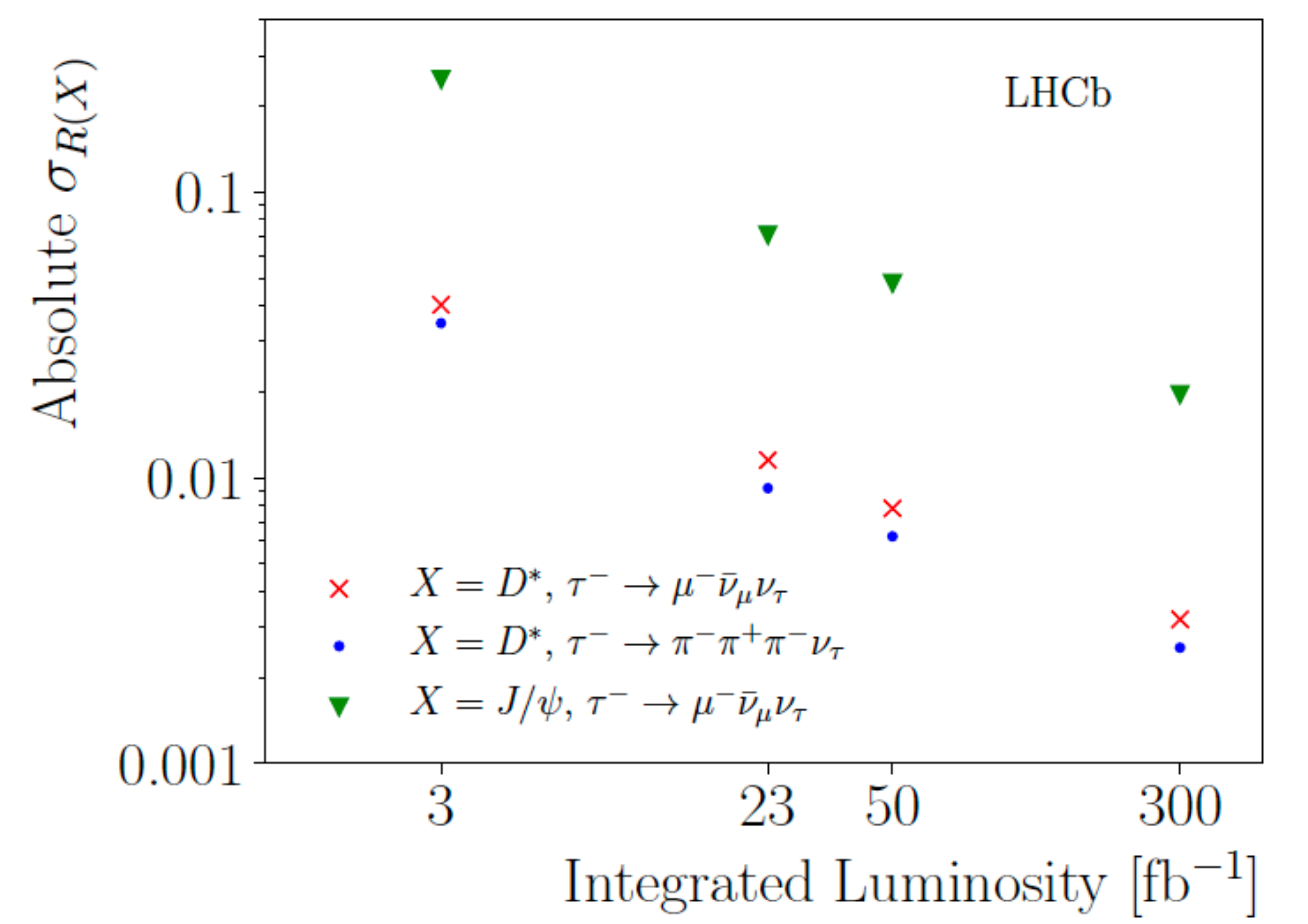
Run 1 + Run 2 *pp* data (2011-2018) = 9 fb^{-1}

Run 3 *pp* data (2023-ongoing) = 11 fb^{-1}

Prospects for SL decays

arXiv:1808.08865

- Major systematic uncertainties from background modelling and limited size of simulation samples.
  - Fast simulation tools being already used.
  - Dedicated measurements to understand backgrounds. Will improve with more statistics.
- Expected absolute uncertainties of 0.003 with 300 fb^{-1}
- More statistics opens the door to beyond BR measurements -> angular analysis already ongoing.
- Work already ongoing for other b-hadron species: i.e: B_s, B_c
- More data allow to measure $b \to u\ell\nu$ decays, i.e.: $B^+ \to p\bar{p}\ell\nu$ decays.



Prospects for rare decays and LFV

arXiv:1808.08865

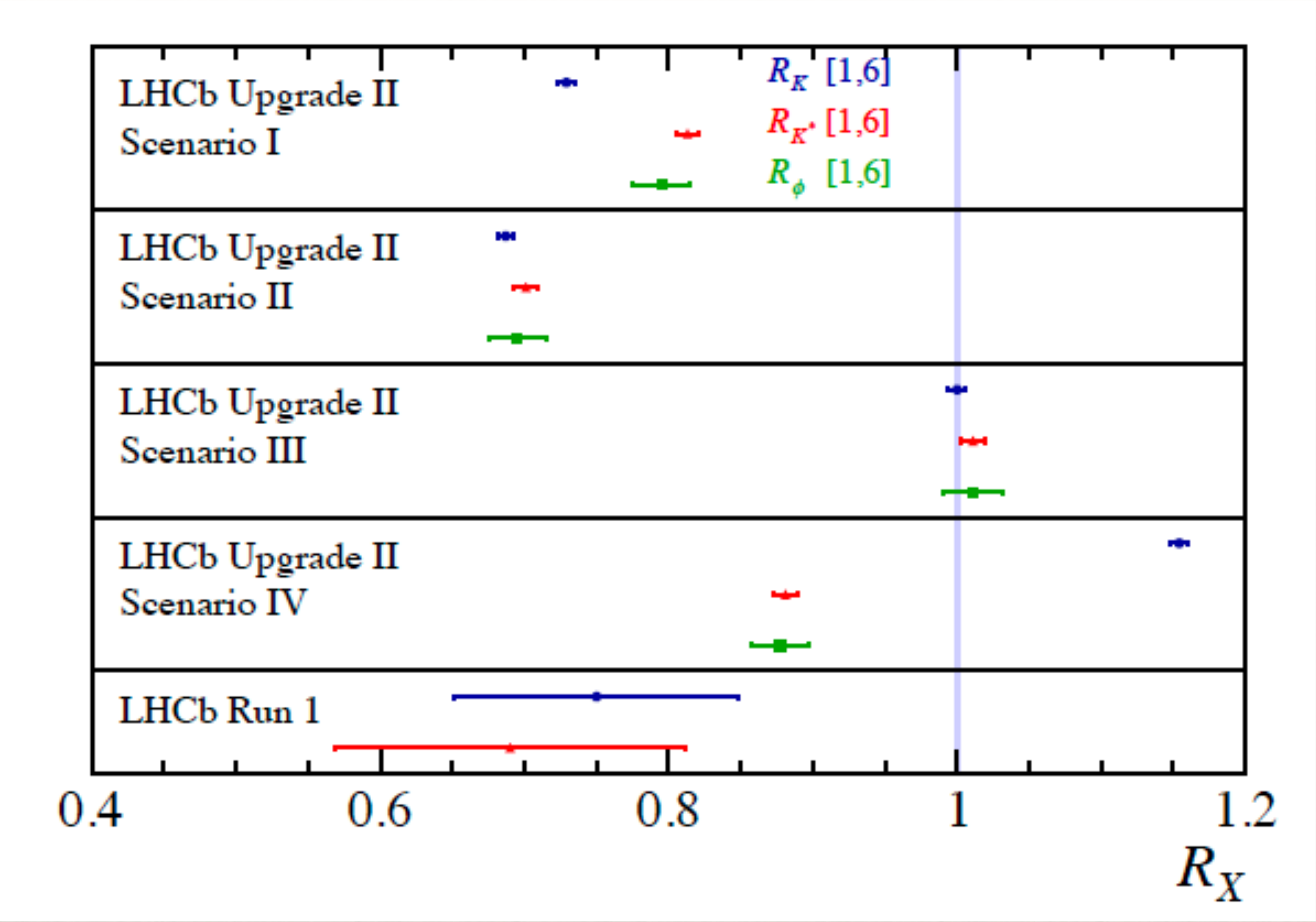
- Current limits for $B \to Ke\mu$ and $B \to K\tau\mu$ are in the 10^{-9} and 10^{-5} region.
- Complementary analysis ongoing in different channels with τμ or eμ combinations.
  - With full Run 2 expect upper limits at 10^{-10} and 10^{-6}.
  - Expected limits after Upgrade II scales with $1/\mathscr{L}$ $(1/\sqrt{\mathscr{L}})$ for decays without (with) τ in the final state.
  - Limits in the region of interest of models explaining the B anomalies.
- During Upgrade II $\tau^+ \to \mu^+\mu^-\mu^+$ decays can be probed down to 10^{-9} (current limits at 10^{-8}). Production at LHC 13.6 TeV is five orders of magnitude larger than at Belle II.
- New LHCb Calorimeter willl suppress more effectively backgrounds as $D_s^+ \to \eta(\to \mu^+\mu^-\gamma)\mu^+\nu_\mu$.

Prospects for R_X

arXiv:1808.08865

- Ultimate precision in R_X measurement will be below 1%.
- Different NP scenarios could be distinguished at more than 5σ.
- Estimated yields in $b \to se^+e^-$ and $b \to de^+e^-$ reaching thousands of events.

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900



Conclusions

- Some recent measurements and prospects for Upgrade II presented.
  - The key of LHCb's broad programme is the extremely-flexible full-software trigger.
- Many LFU tests in $b \to s\ell^+\ell^-$ statistically limited by the electron channel.
- More data brings expansion to new sectors in the (near) future.
  - LFU in B_s: $R(D_s^*)$, $R(D_s)$
  - $b \to d\ell^+\ell^-, b \to u\ell\nu$
  - heavy baryons: Ξ_b^-, Ω_b^-
  - Rare charm sector (more in backup)

Backup

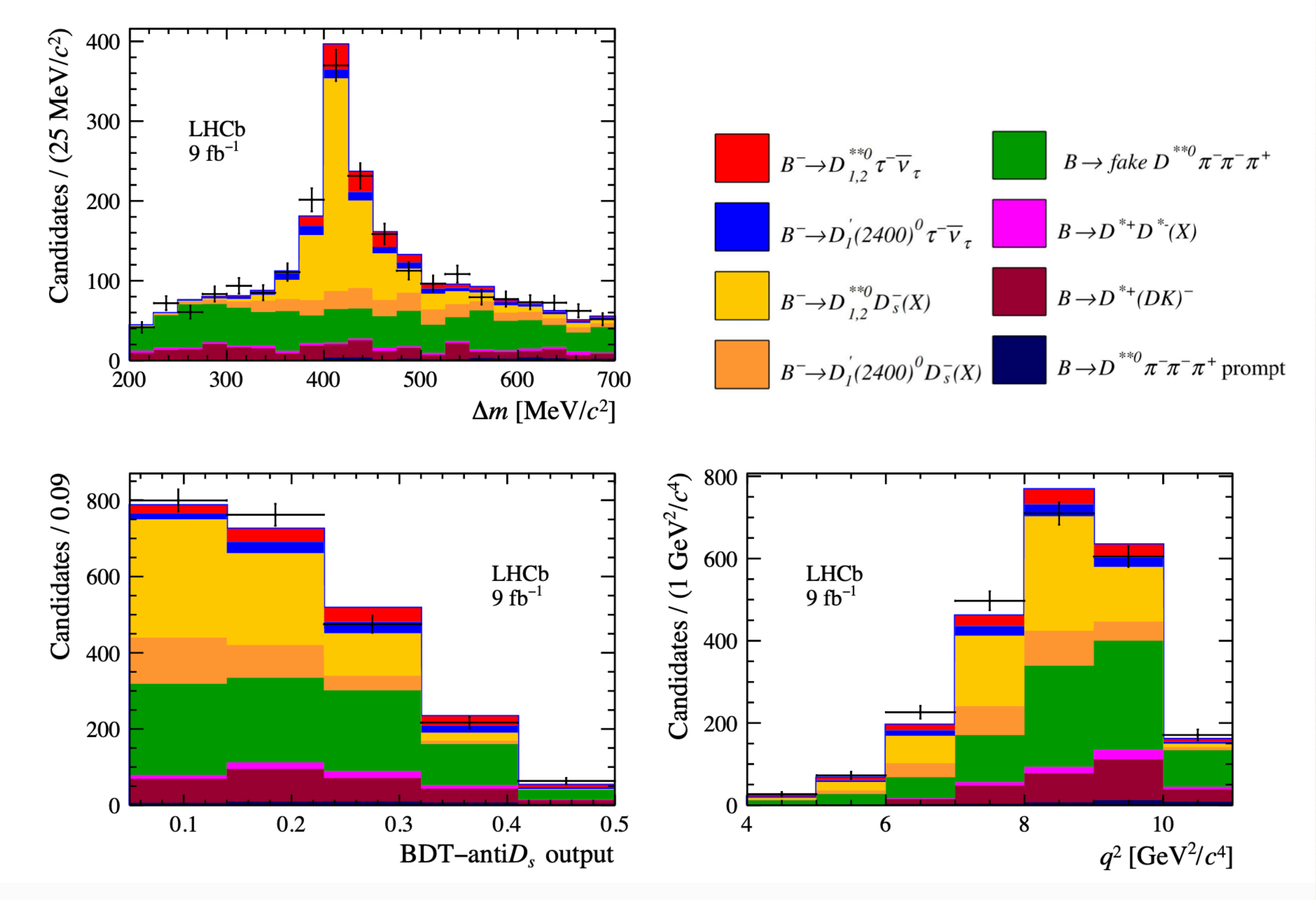
Lepton Flavour Universality (LFU)

- LFU in electroweak interactions: equal couplings of gauge bosons to the 3 lepton families.
  - Accidental symmetry in the SM.
  - Differences in decay rates can arise from phase-space of long-distance hadronic effects.
  - Yukawa coupling is flavour specific ($\mathscr{B}(H \to \mu^+\mu^-) \neq \mathscr{B}(H \to \tau^+\tau-)$)
- LFU is well established in decays of $W^\pm$, Z^0, pseudo-scalar mesons, quarkonia and purely leptonic $\tau^\pm$ decays.

$$\frac{\mathscr{B}(Z^0 \to \mu^+\mu^-)}{\mathscr{B}(Z^0 \to e^+e^-)} = 1.0009 \pm 0.0028 \qquad \frac{\mathscr{B}(Z^0 \to \tau^+\tau^-)}{\mathscr{B}(Z^0 \to e^+e^-)} = 1.0019 \pm 0.0032 \qquad \frac{\mathscr{B}(W^\pm \to \tau^\pm\nu_\tau)}{\mathscr{B}(W^\pm \to \mu^\pm\nu_\mu)} = 0.992 \pm 0.013$$

Nature Physics 17, 813 (2021); Phys. Rept. 427 (2006) 257

$B^- \to D^{**0}\tau^-\overline{\nu}_\tau$ decays



Semileptonic decays at LHCb

- At LHCb compare tau leptons with respect to muons in the final state $R(H_c) = \dfrac{\mathscr{B}(H_b \to H_c \tau^+ \overline{\nu}_\tau)}{\mathscr{B}(H_b \to H_c \mu^+ \overline{\nu}_\mu)}$
- Multiple experiments see (small) deviations from the SM in $R(D^{(*)})$ with a total significance of 3.8σ.

Yield	Run 1 result	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
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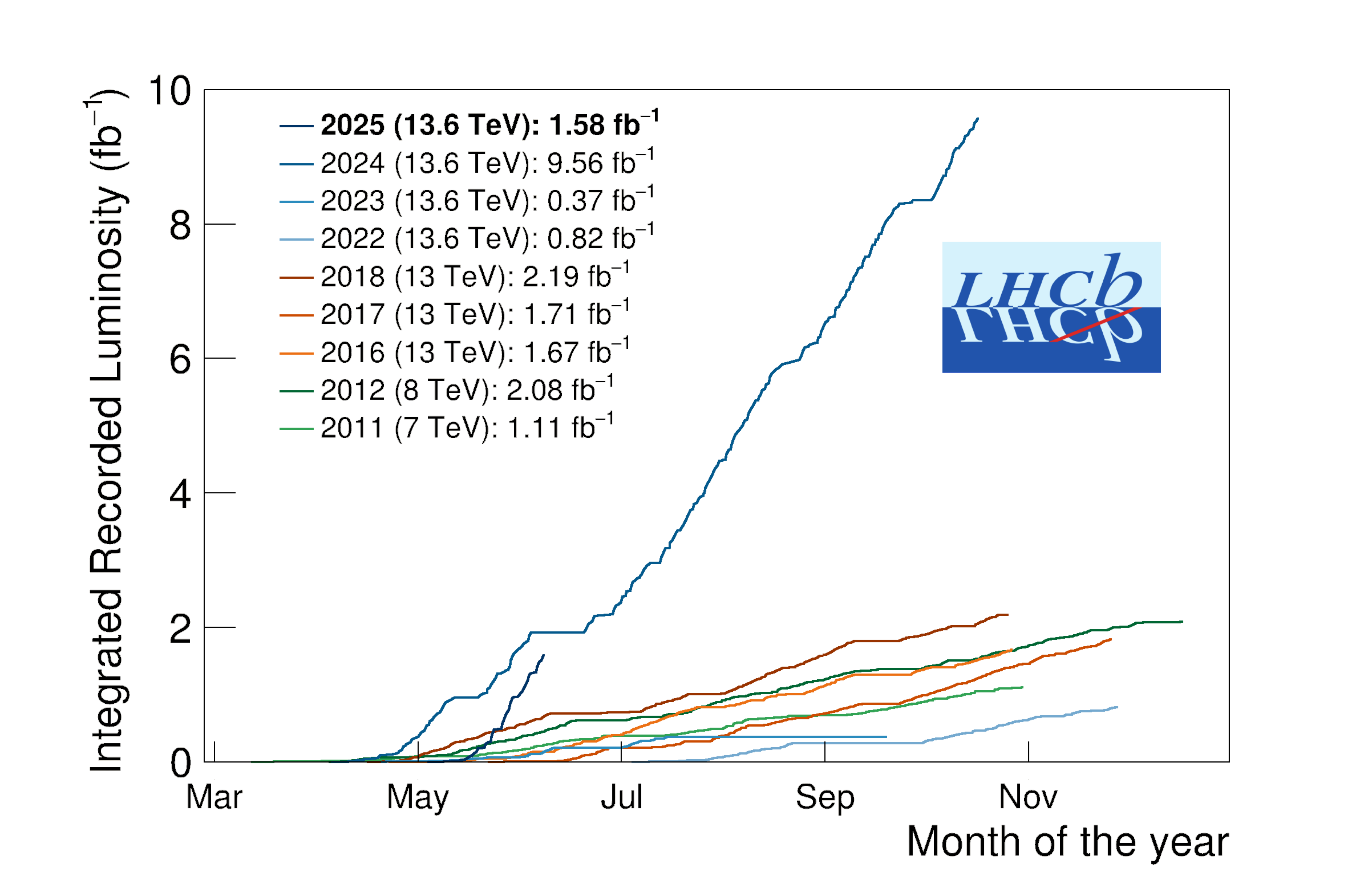
Integrated luminosity

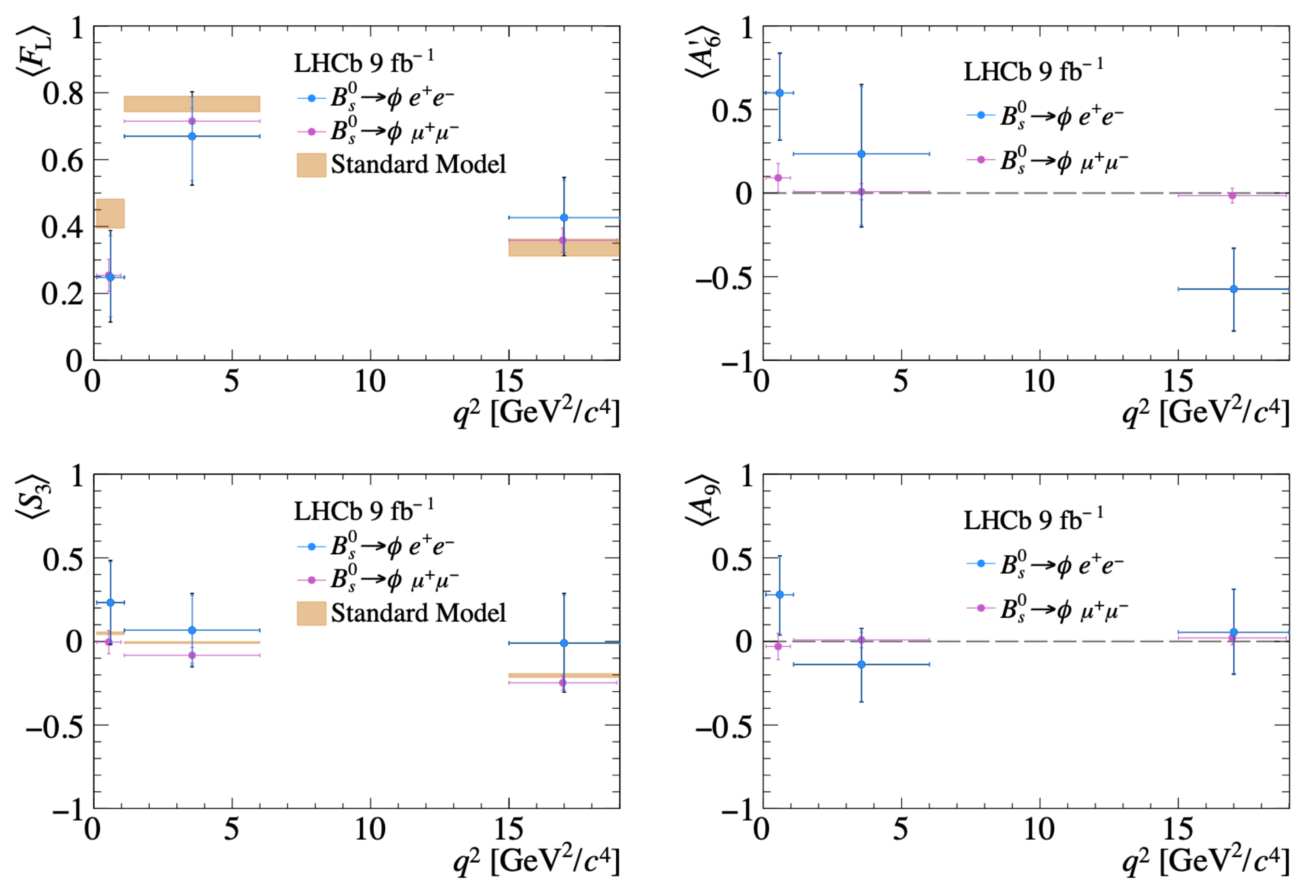


- Run 1 + Run 2 *pp* data (2011-2018) = 9 fb^{-1}
- Run 3 *pp* data (2023-ongoing) = 11 fb^{-1}

Angular analysis on $B_s \to \phi e^+e^-$

arXiv:2504.06346

- Angular analysis of the decay $B_s \to \phi e^+e^-$.
- Extend previous results to high-q².
  - Observables compatible with the muon mode and SM.



Prospects for rare charm decays

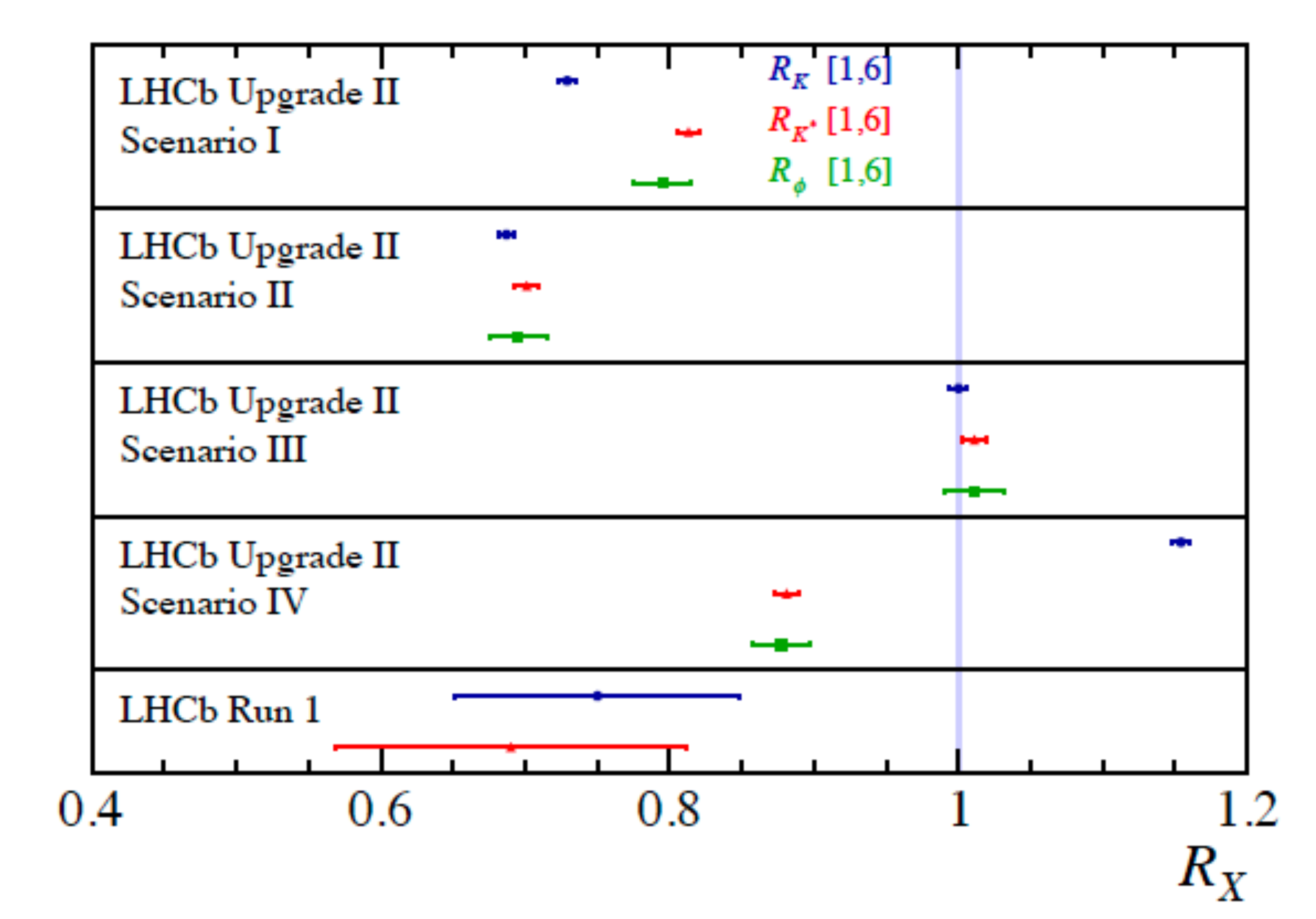
arXiv:1808.08865
JHEP 06 (2021) 044

- Current LHCb limit in $\Lambda_c^+ \to p\mu^+\mu^-$ is set to 2.9×10^{-8} away from the hadronic resonances.
- Limits for $D_{(s)}^+ \to h^\pm \ell^+ \ell'^\mp$ where $h^\pm$ is a kaon or pion and $\ell^{(\prime)\mp}$ is an electron or muon are in the $10^{-6} - 10^{-8}$ range.
  - Expect an one order of magnitude improvement after Upgrade II.
- Beyond BR, LHCb will have the ability to measure angular observables which provide additional separation between the LD and SD contributions.
- Also LFU test in charm decays can be explored via the ratios $\dfrac{\mathscr{B}(D_{(s)}^+/\Lambda_c^+ \to h^+\mu^+\mu^-)}{\mathscr{B}(D_{(s)}^+/\Lambda_c^+ \to h^+e^+e^-)}$.
- Similar improvements are expected for $D \to h^+h^-\ell^+\ell^-$ decays.

Prospects for R_X scenarios

arXiv:1808.08865

- Scenarios motivated by explanation of B anomalies, explanation of B anomalies and R(D/D*) measurements, and addition of small right-handed chirality coupling.

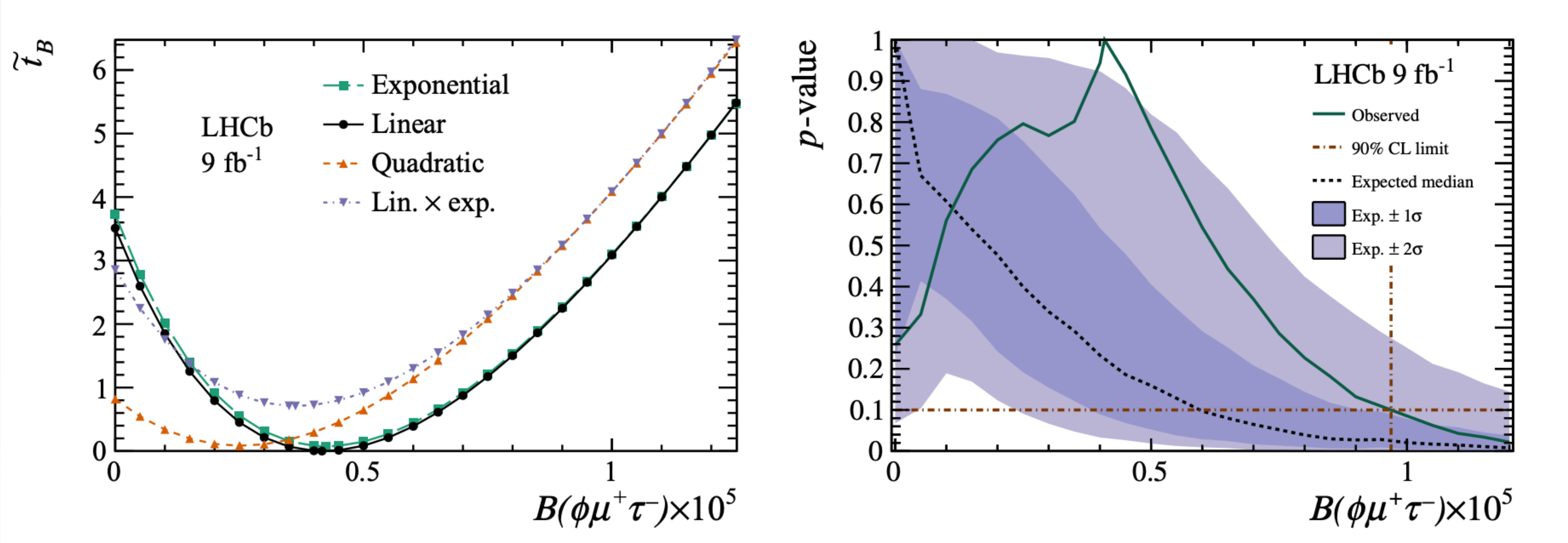


scenario	$C_9^{\rm NP}$	$C_{10}^{\rm NP}$	C'_9	C'_{10}
I	-1.4	0	0	0
II	-0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	-0.3

LFV: Limits on $B_s \to \phi\tau\mu$

Phys. Rev. D110 (2024) 7

- Leptoquark models explaining $B^+ \to K^+\nu\bar{\nu}$ results predict enhancements of LFV modes [Phys. Rev. D109 (2024) 015006, Phys. Rev. D109 (2024) 075019].
- Use of hadronic τ decay to get decay vertex information. Improves mass resolution.
- Use Run1+ Run2 data.
- Background modelled using 4 different parametrisations. Use conditional best-fit bkg descritption to get the limit.



$$\mathscr{B}(B_s \to \phi\tau^\pm\mu^\mp) < 1.0 \times 10^{-5}$$