Search for the lepton-flavour violating decay $\tau^- \to \mu^-\mu^+\mu^-$ at LHCb with Run 2 data

Moriond Electroweak Interactions & Unified Theories

60th *Rencontres de Moriond*, 16 March 2026

Domenico Riccardi

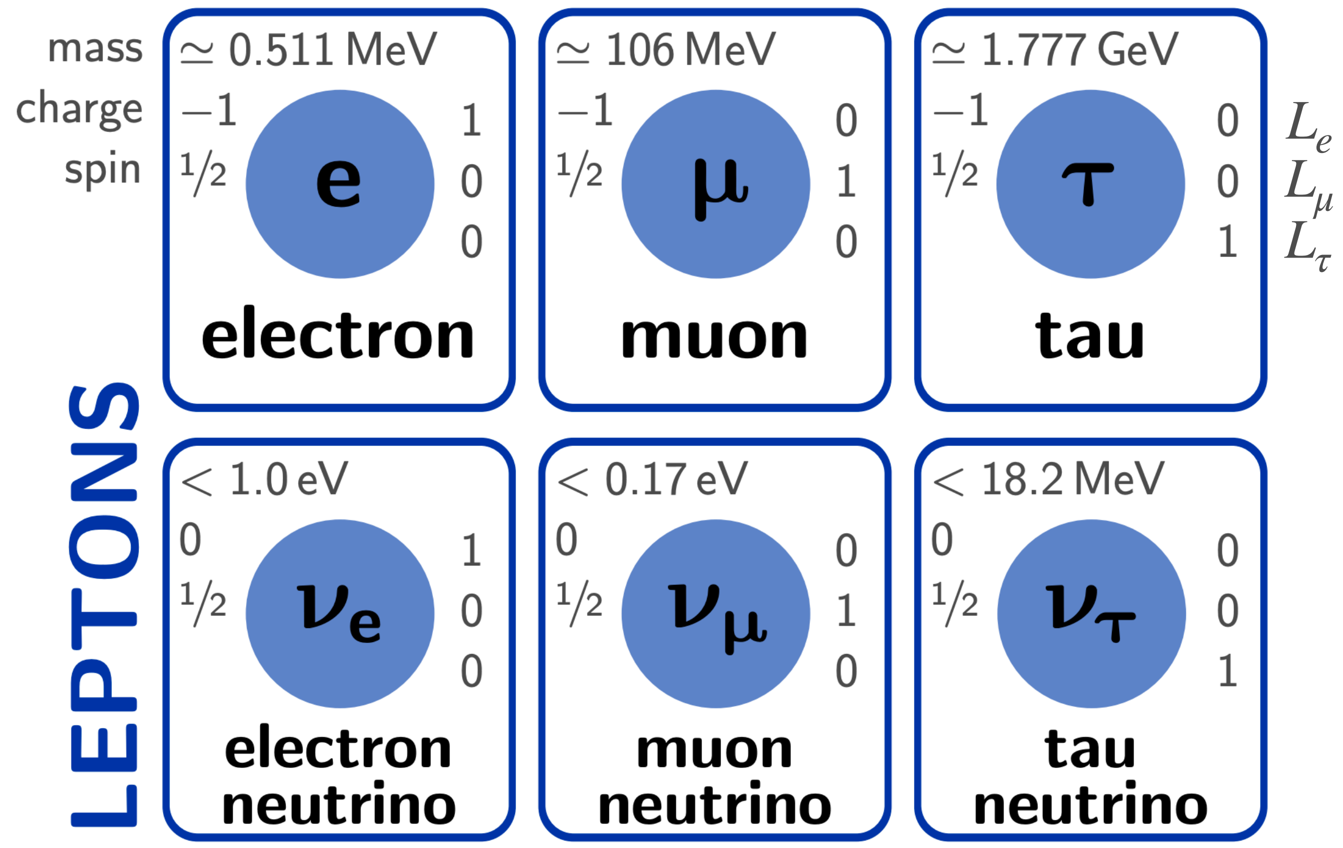
on behalf of the LHCb Collaboration

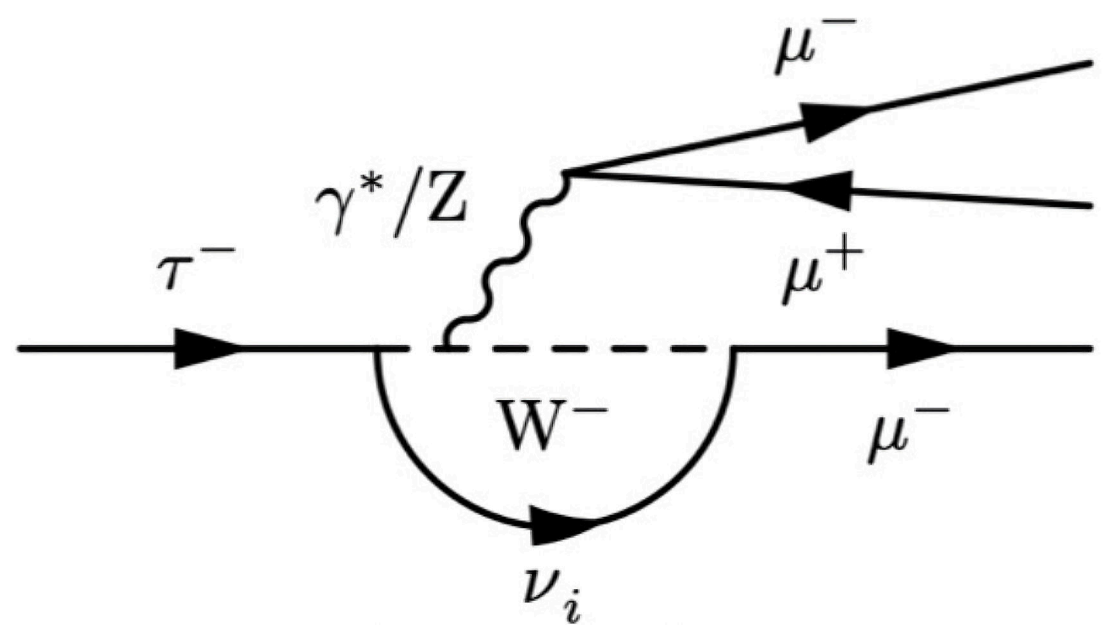
Motivations

- Three lepton flavours in the Standard Model (SM): L_e, L_μ, L_τ
- Lepton flavour violation (LFV):
  - transitions that do not conserve the lepton number
- No SM symmetry enforces LF conservation
  - Neutrino oscillations provide LFV evidence in the neutral sector [Phys. Rev. Lett. 81, 1562]
  - Charged LFV (cLFV) possible in the SM via neutrino oscillations only, with extremely small branching fractions [Eur. Phys. J. C 81, 811 (2021), Eur. Phys. J. C 80, 506 (2020)]:

$$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) \lesssim \mathcal{O}(10^{-50})$$

⇒ far beyond experimental reach





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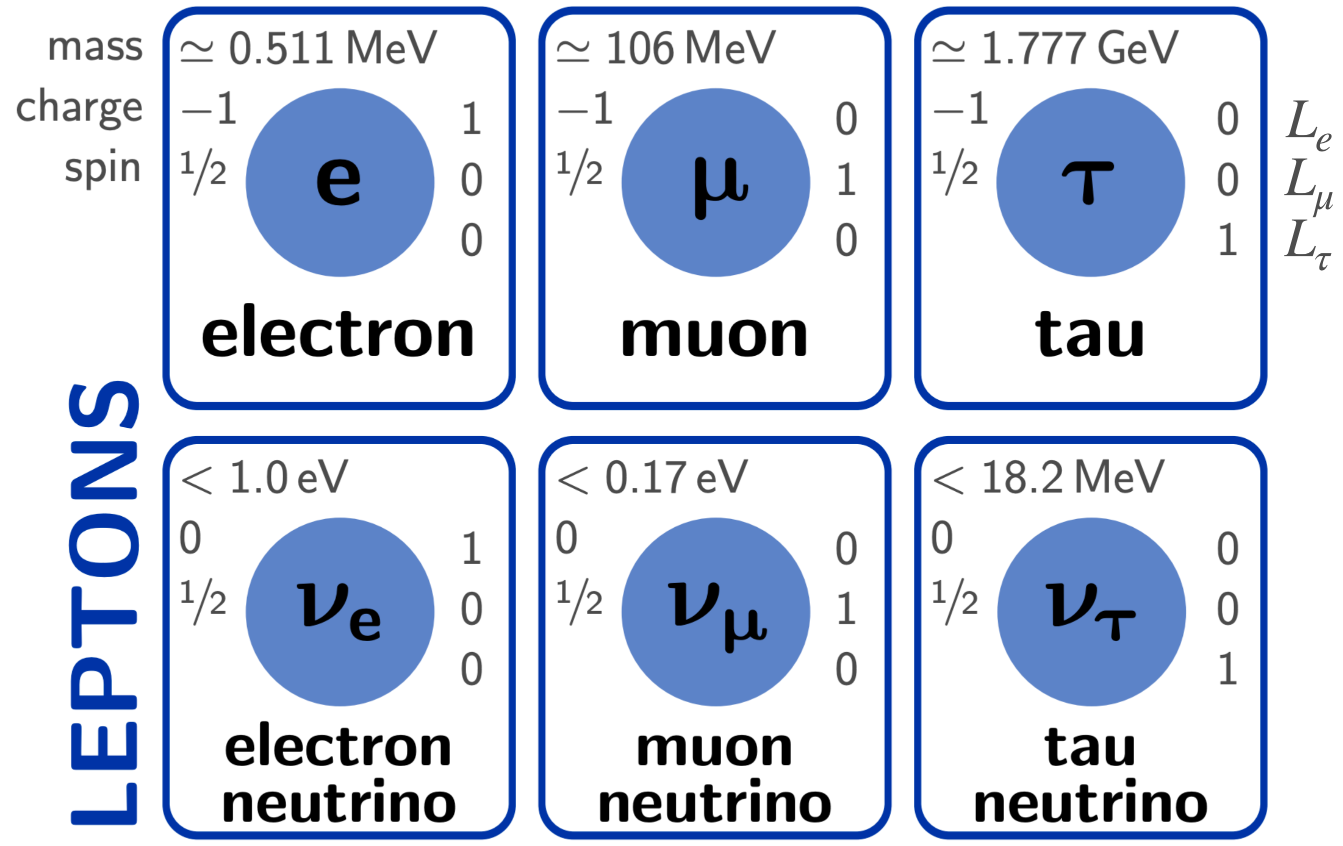

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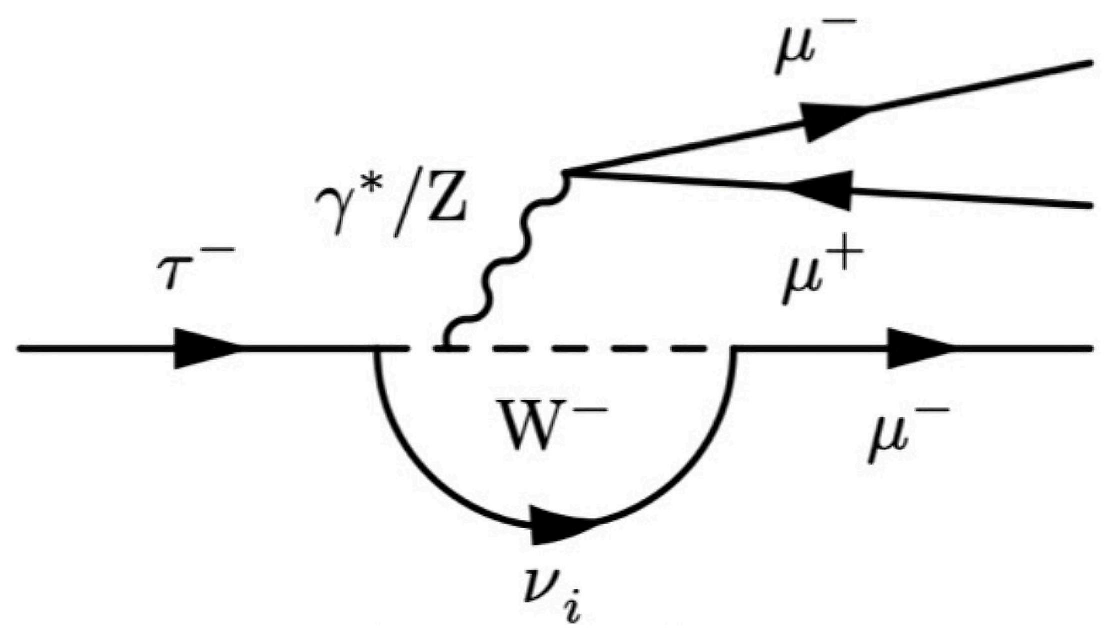

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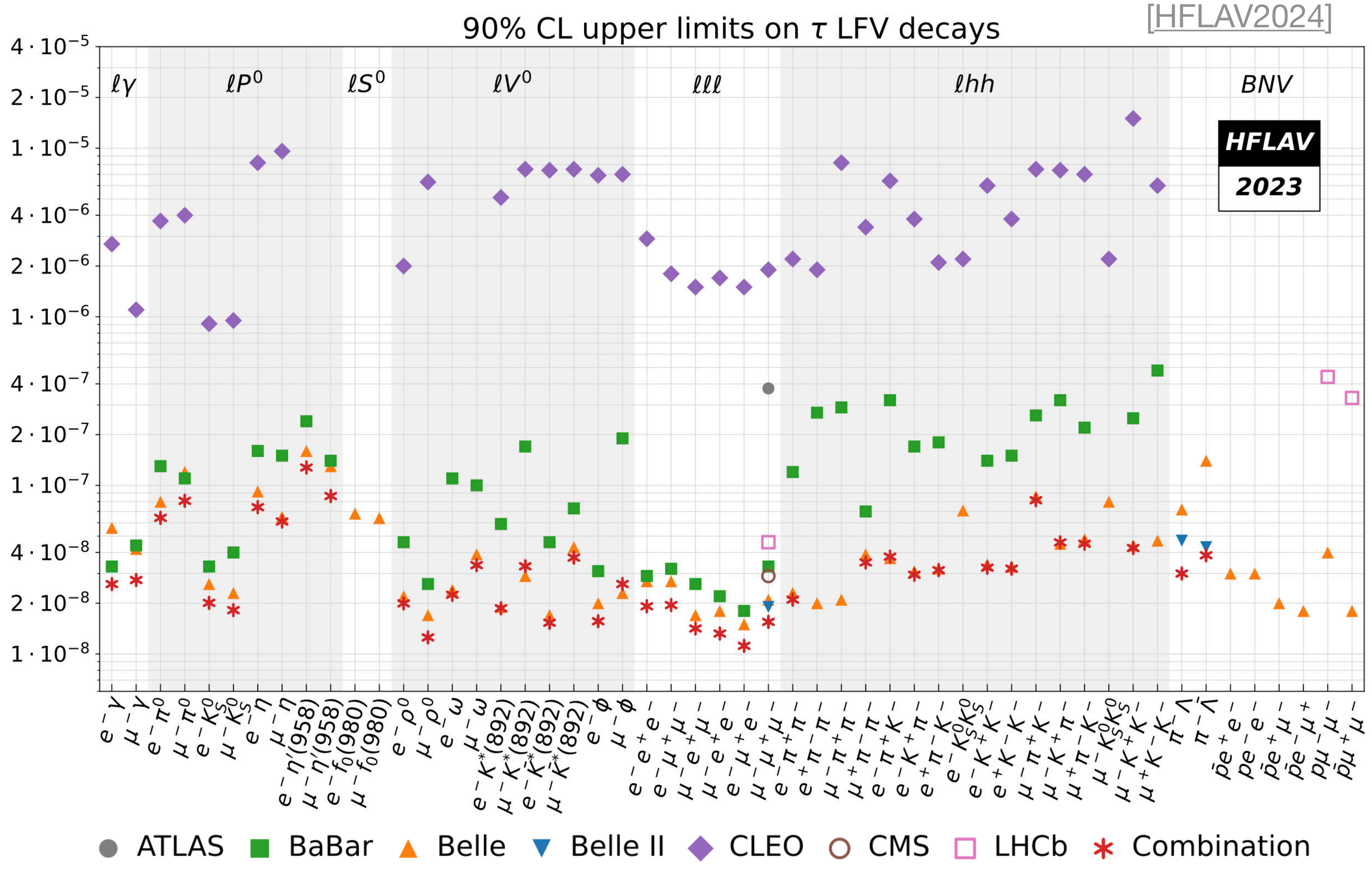
Direct observation of cLFV would be an indisputable signature of New Physics

Experimental limits on $\tau^- \to \mu^-\mu^+\mu^-$

- τ LFV searches are dominated by B-factories → clean environment

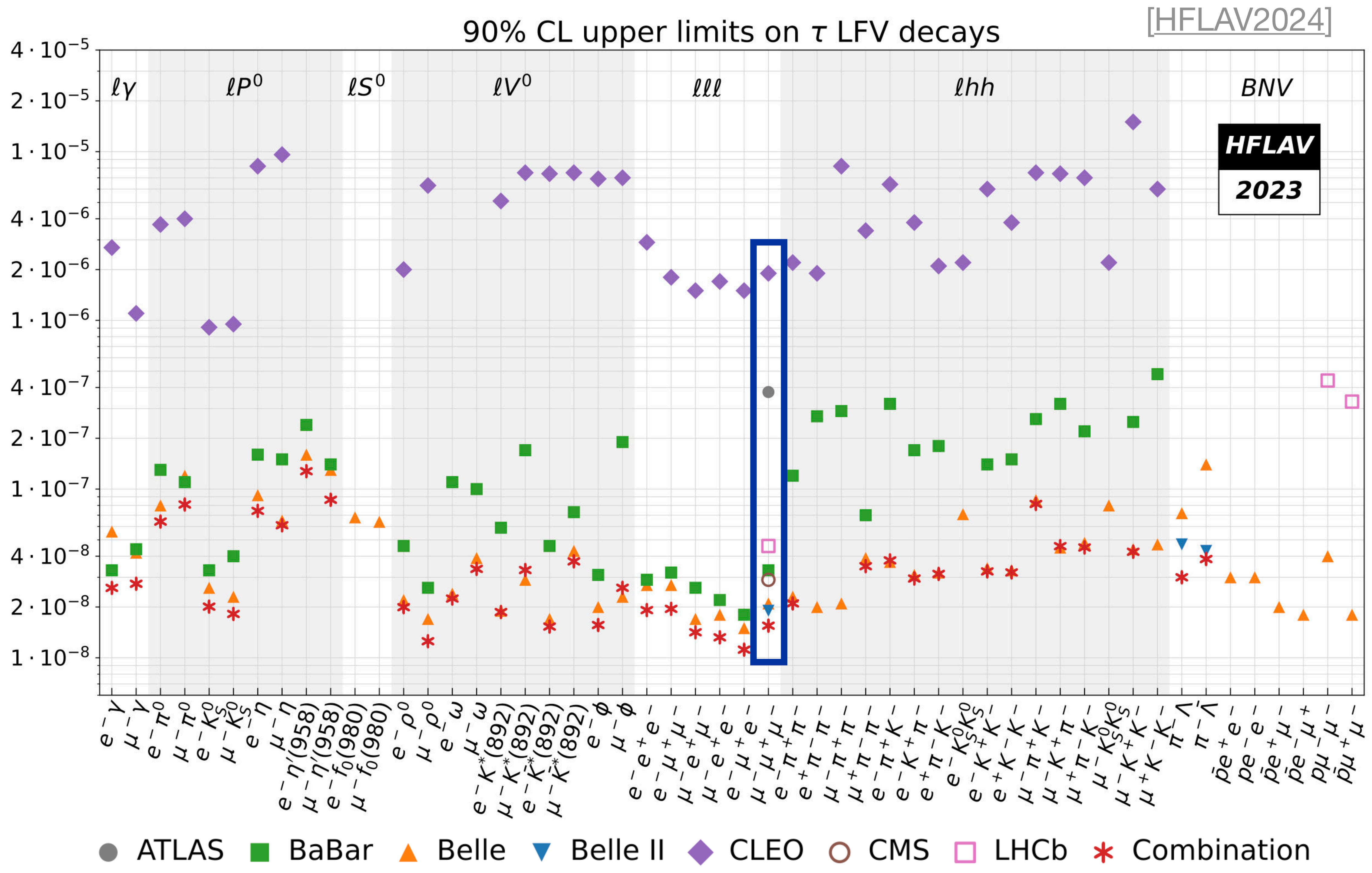
[HFLAV2024]



Experimental limits on $\tau^- \to \mu^-\mu^+\mu^-$

- τ LFV searches are dominated by B-factories → clean environment
- Current best limit from Belle II [JHEP09 (2024) 062] :

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9 \times 10^{-8} \text{ at } 90\,\%\,\text{CL}$$



- Hadron collider challenge → crowded environment

NEW RESULT

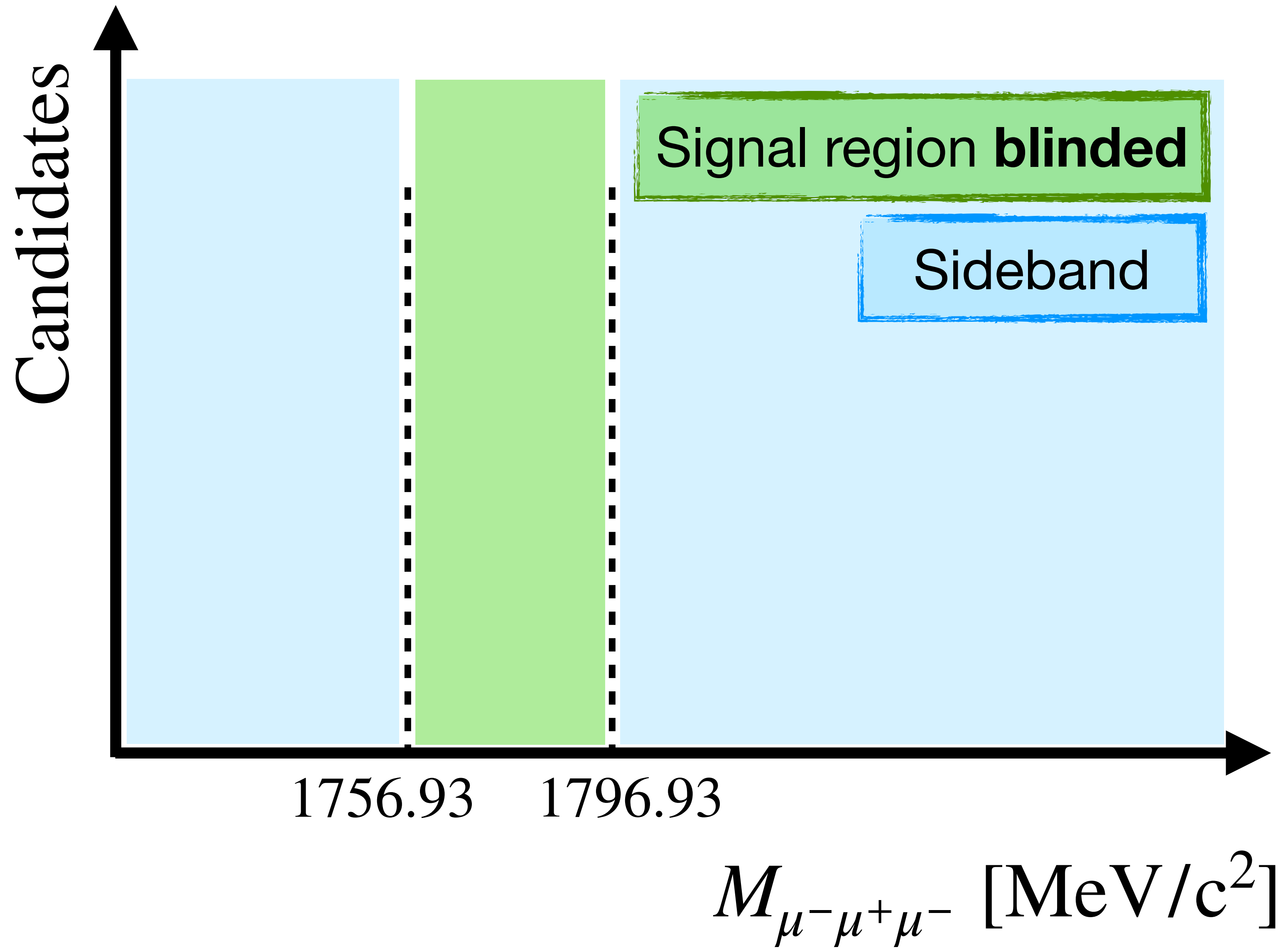
LHCb Run 2 search for $\tau^- \to \mu^-\mu^+\mu^-$ decays
(using $5.4\ \text{fb}^{-1}$ dataset at $13\ \text{TeV}$)

[arXiv:2601.20785] → Submitted to JHEP

- Previous hadron-collider searches:
  - LHCb Run 1 ($3\ \text{fb}^{-1}$ at $7-8\ \text{TeV}$) [JHEP02 (2015) 121]: 4.6×10^{-8} at $90\,\%$ CL
  - ATLAS [Eur. Phys. J. C (2016) 76:232] and CMS [Phys. Lett. B853 (2024)] also performed this search with comparable sensitivity

Analysis strategy

- Search for a narrow peak at the τ mass, $1776.93 \pm 0.09\,\mathrm{MeV/c^2}$ PDG, in the invariant mass distribution of the 3μ system
- At LHCb, τ leptons are mainly produced in charm and beauty hadron decays, dominated by $D_s^- \to \tau^- \bar{\nu}_\tau$ production



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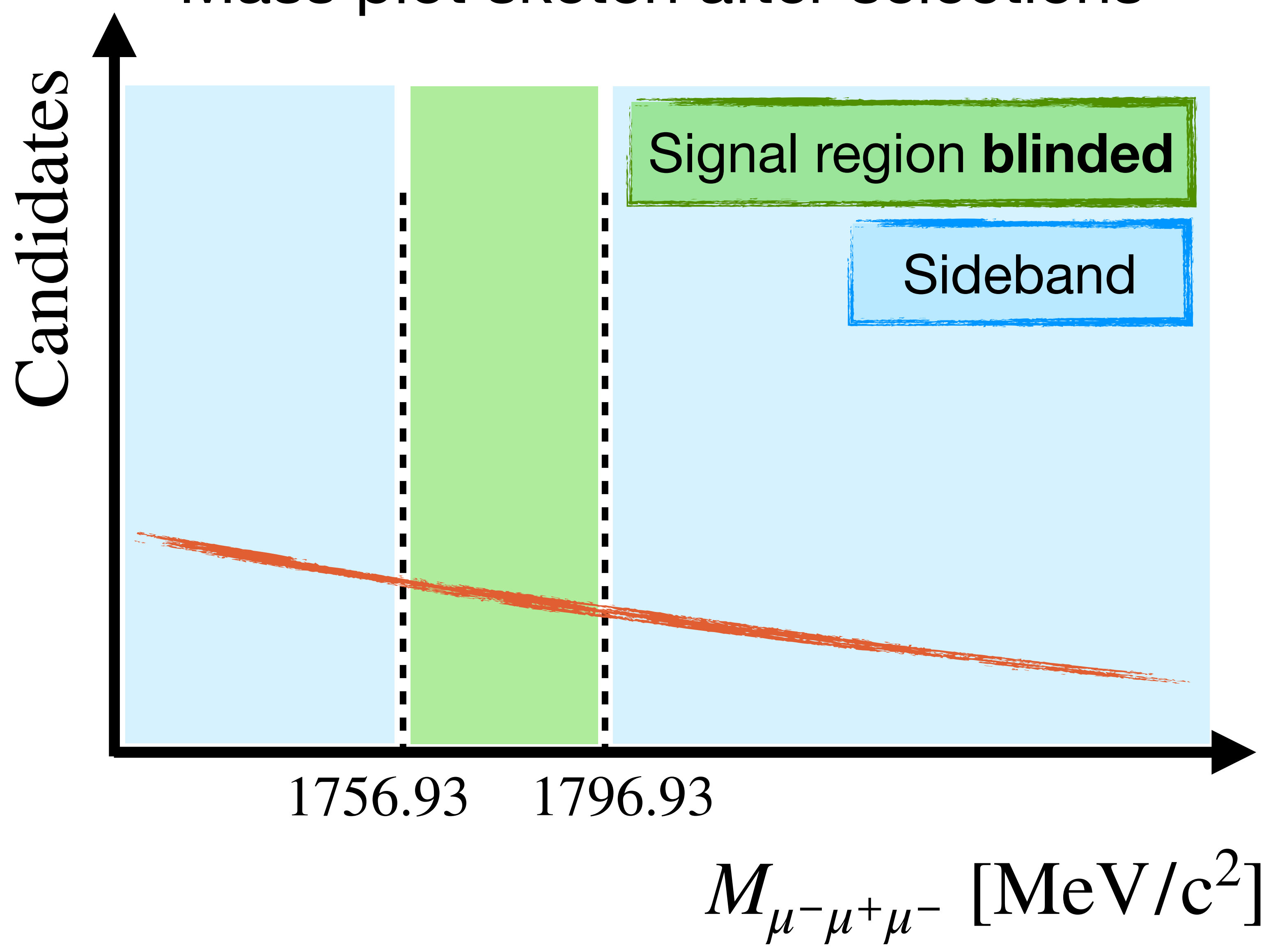

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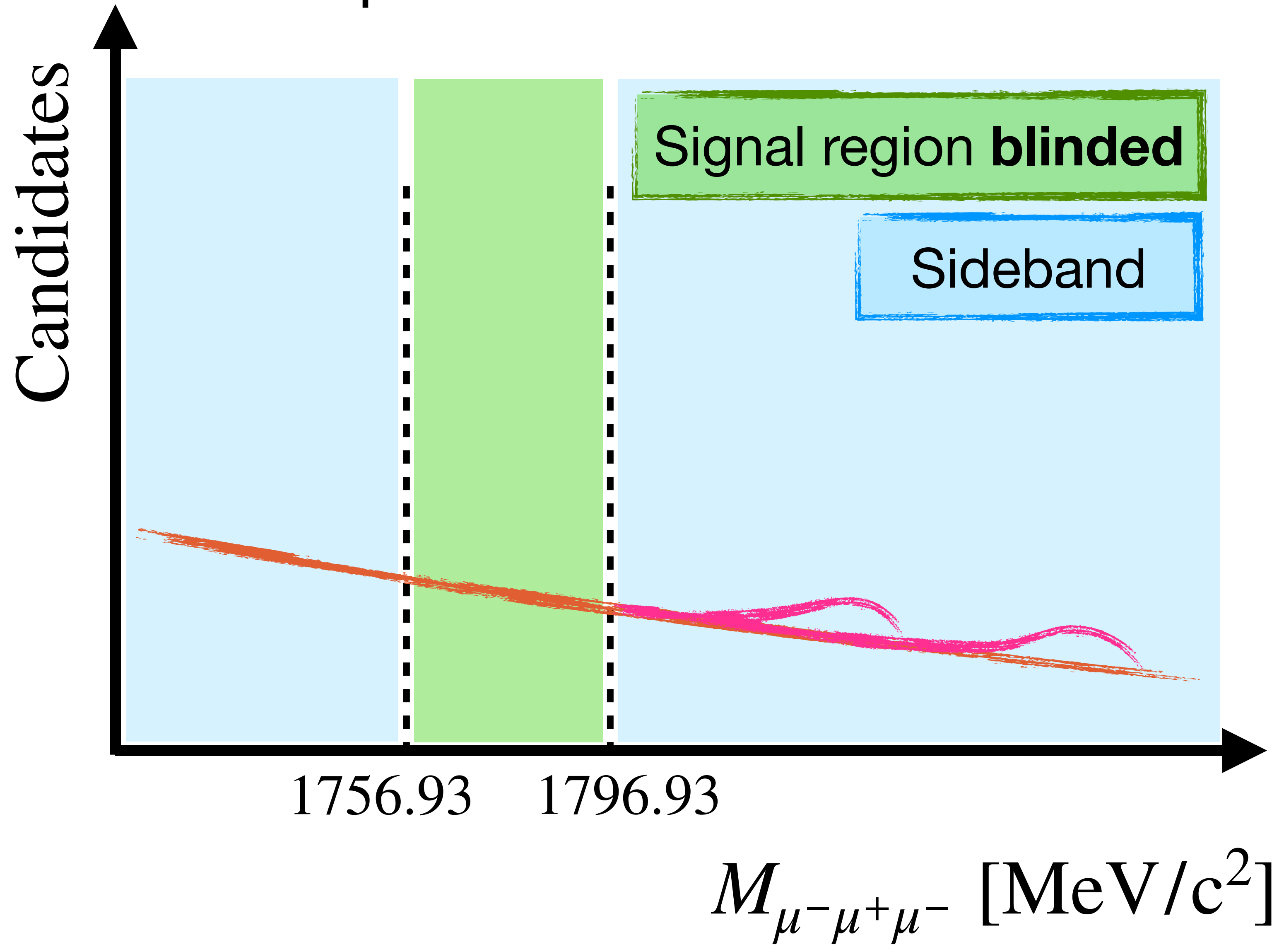

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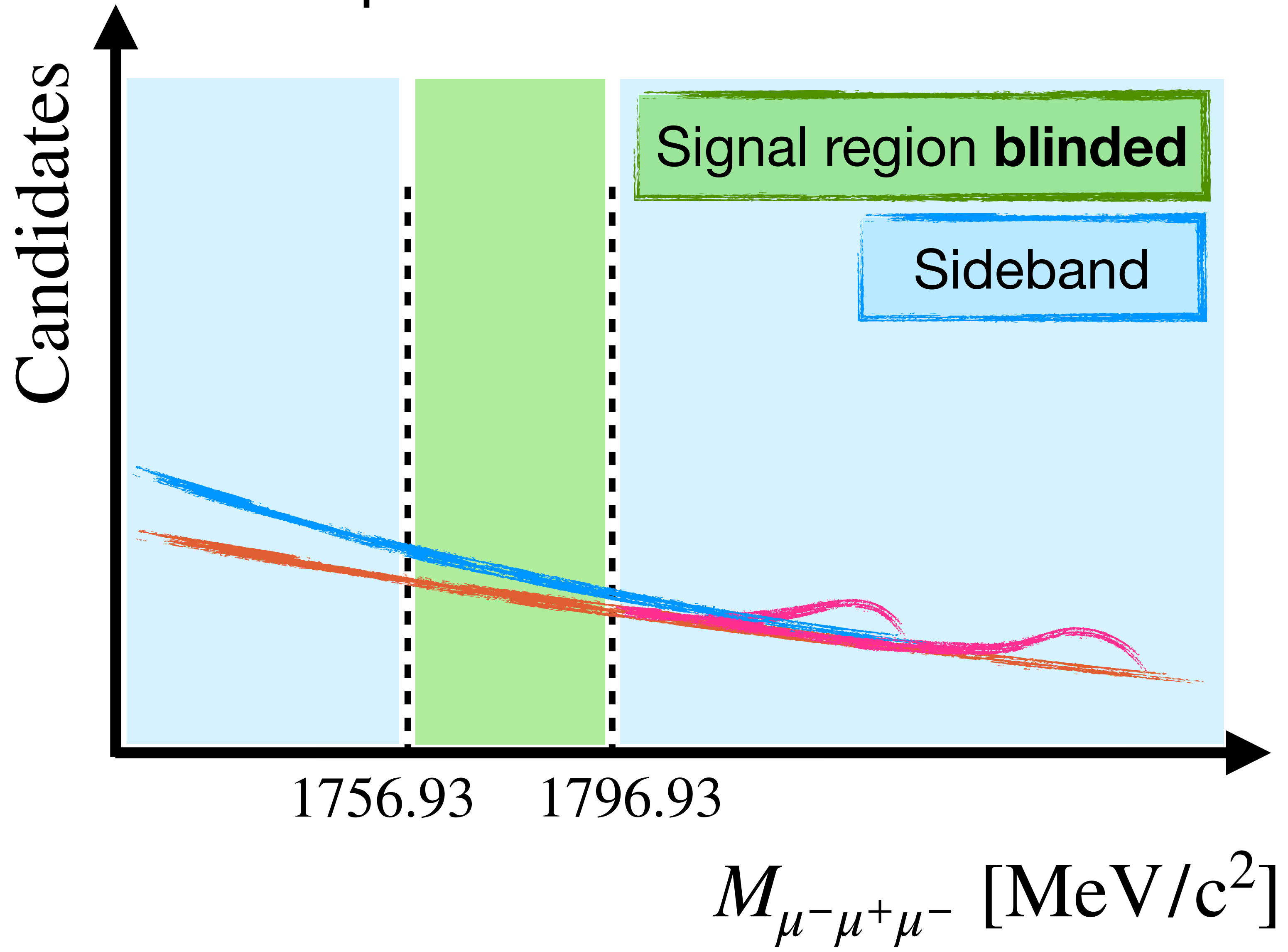

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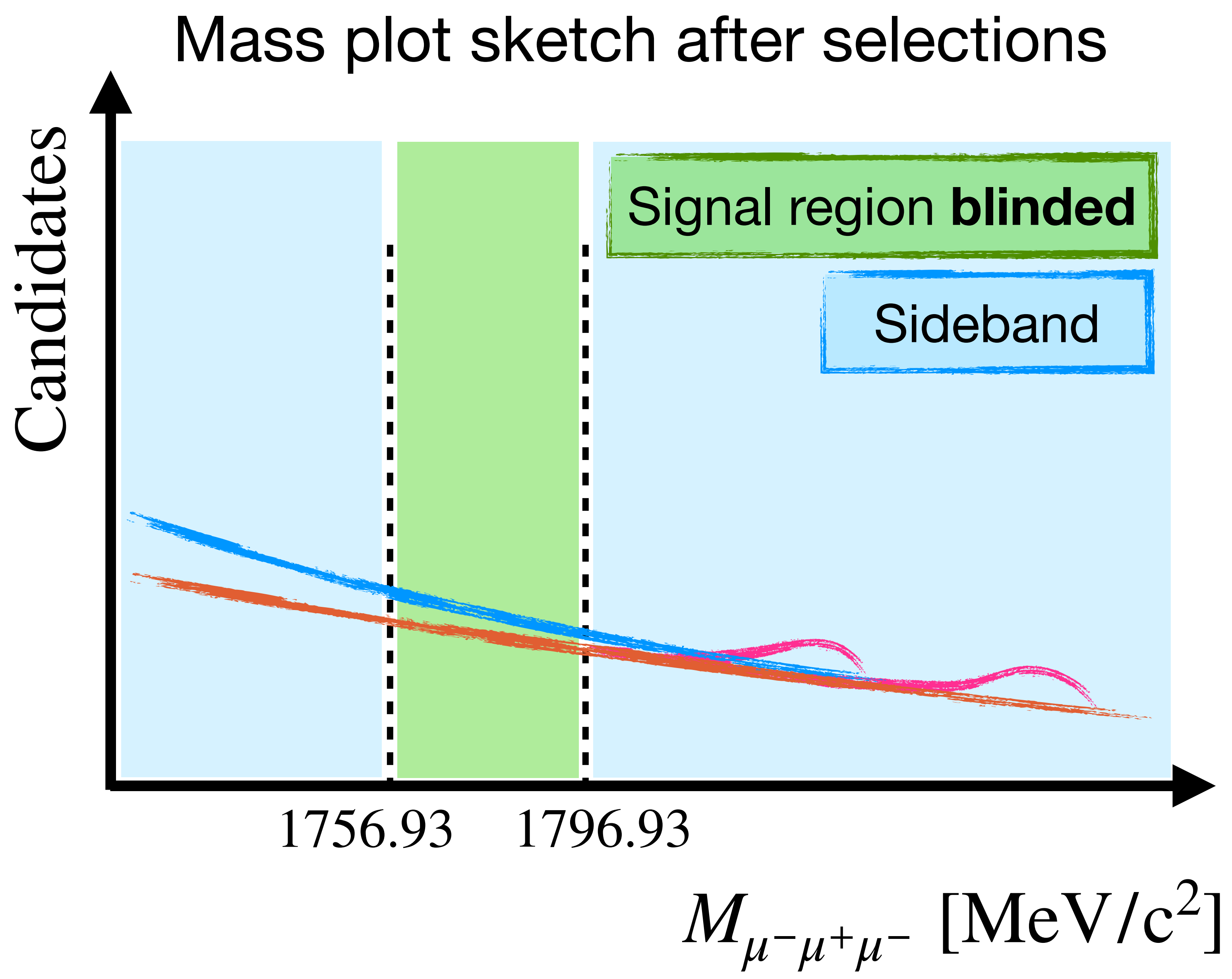

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- Branching ratio definition using $D_s^- \to \phi(\mu^-\mu^+)\pi^-$ as normalisation channel:

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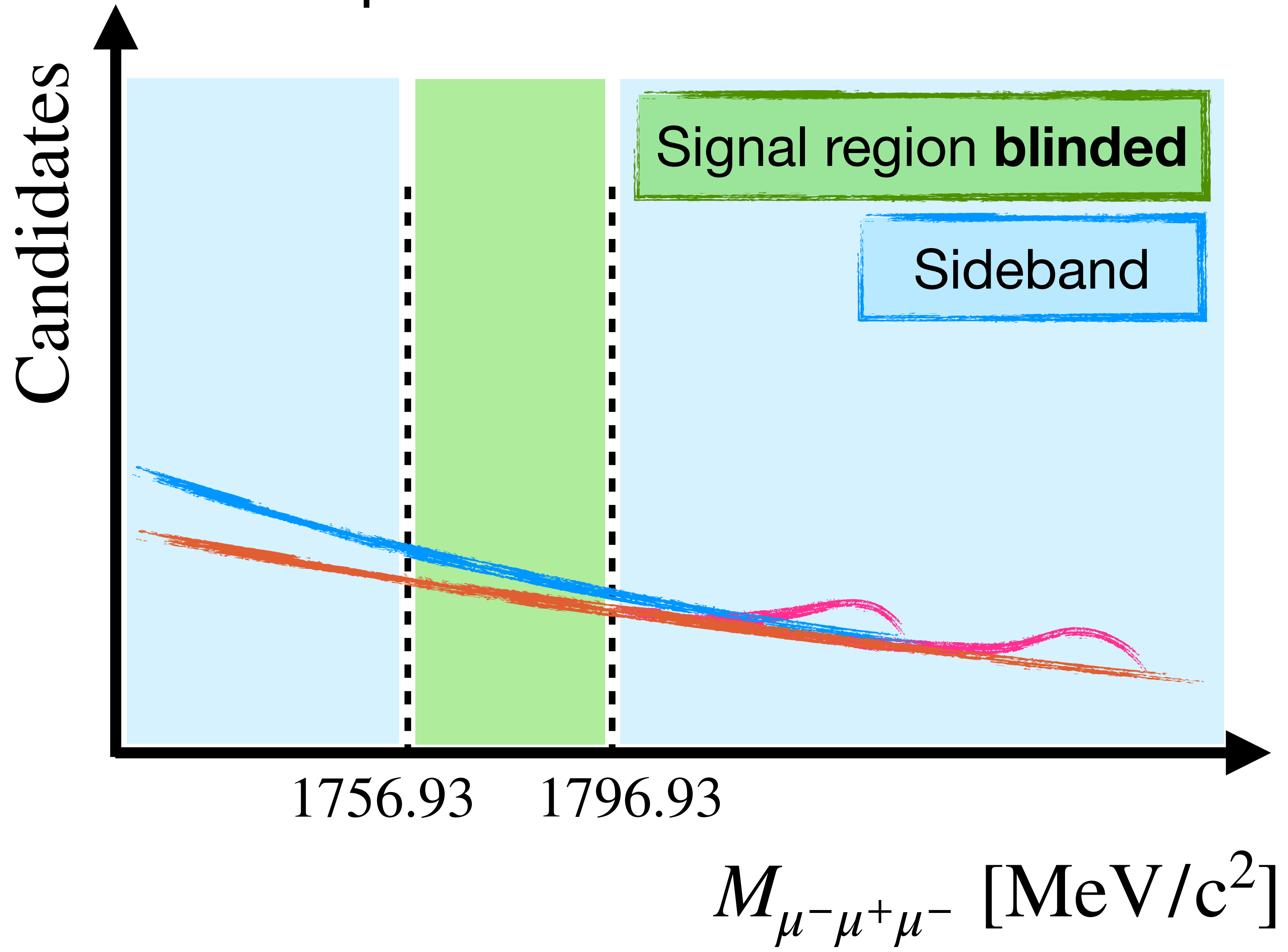
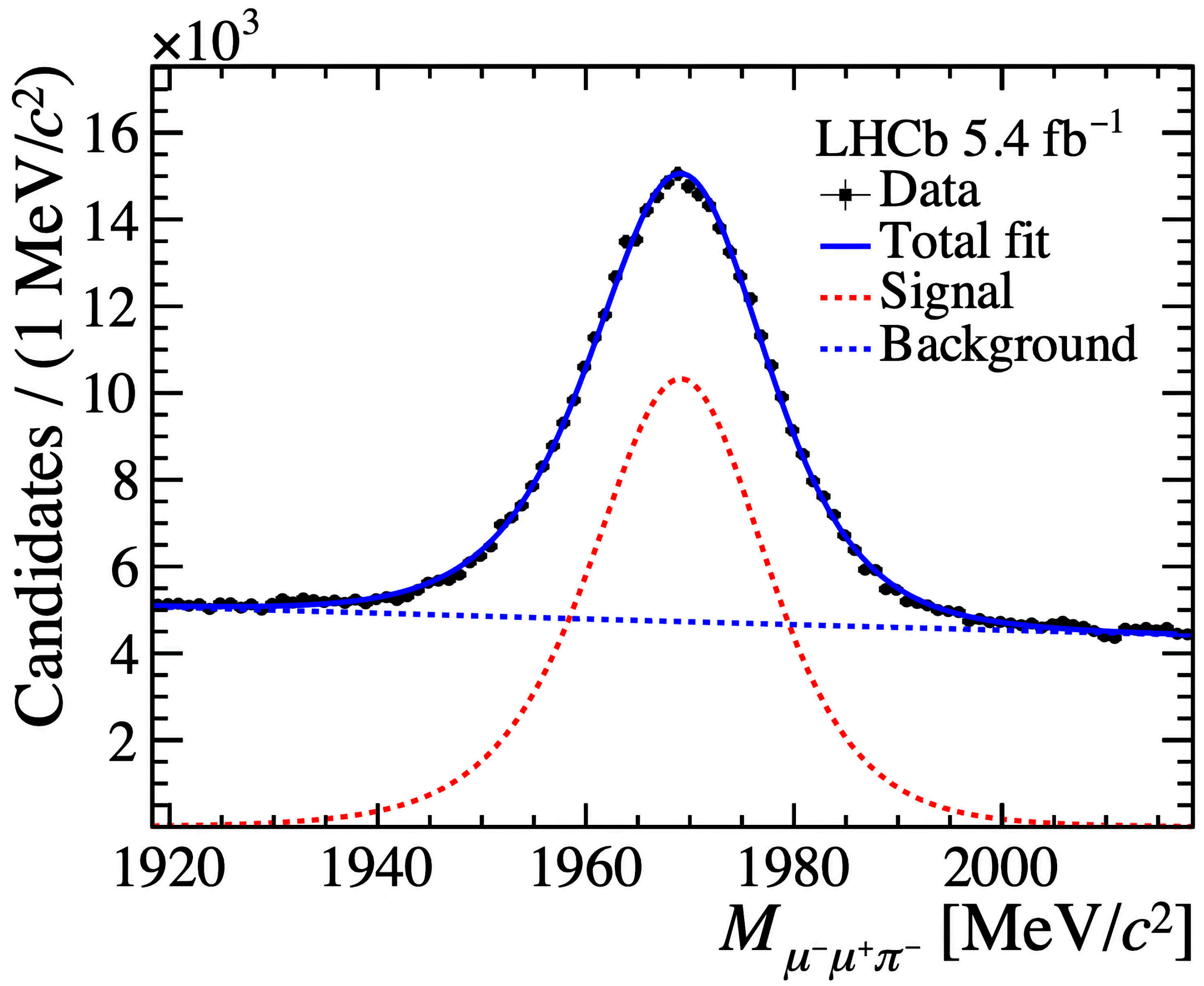


$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \mathcal{B}(D_s^- \to \phi(\mu^-\mu^+)\pi^-) \times \frac{f_{D_s}^{\tau}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon_{D_s}}{\epsilon_\tau} \times \frac{N_\tau}{N_{D_s}} = \alpha \times N_\tau$$

Single event sensitivity

Signal calibration and τ invariant-mass fit

- $D_s^- \to \phi(\mu^-\mu^+)\pi^-$ used also as calibration channel
  - $D_{(s)}^-$ production corrections
  - PID and Data/MC kinematic corrections
- MC signal mass shape calibration using
  - $D_s^- \to \phi(\mu^-\mu^+)\pi^-$ peak in data and simulation



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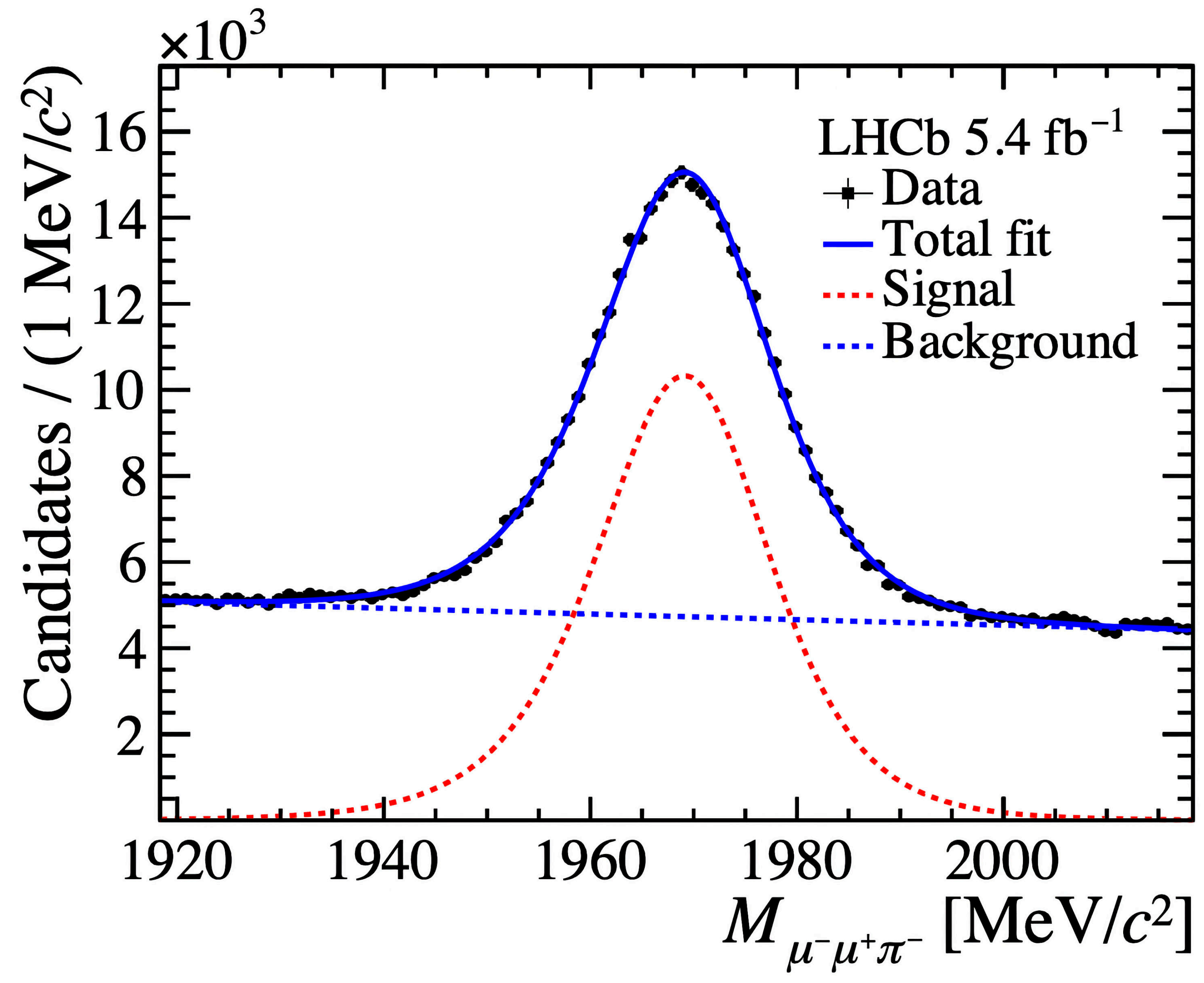
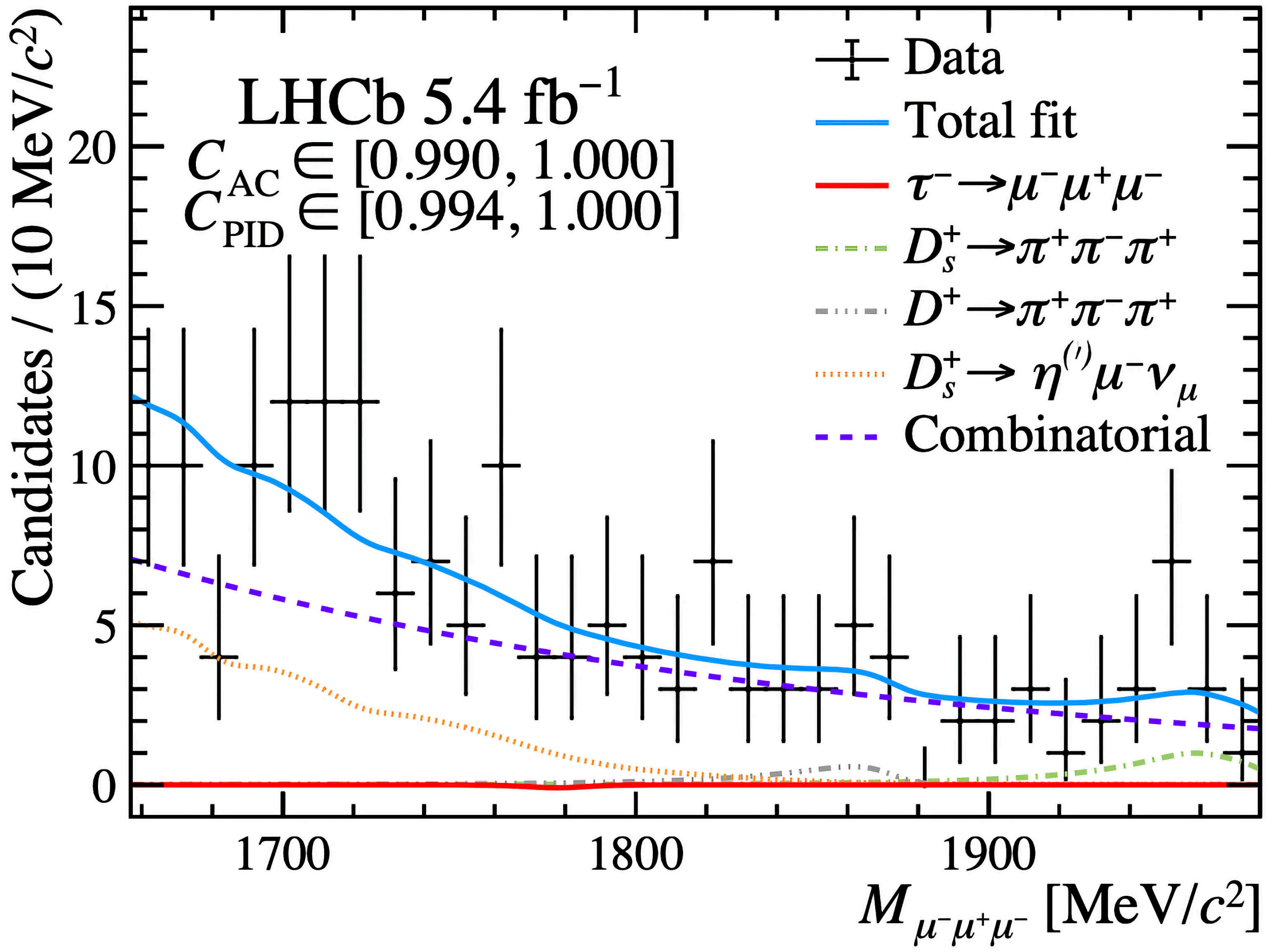


- Unbinned maximum likelihood fit to $M_{\mu^-\mu^+\mu^-}$ performed simultaneously in 15 C_{AC} and C_{PID} bins

No significant excess of signal events observed

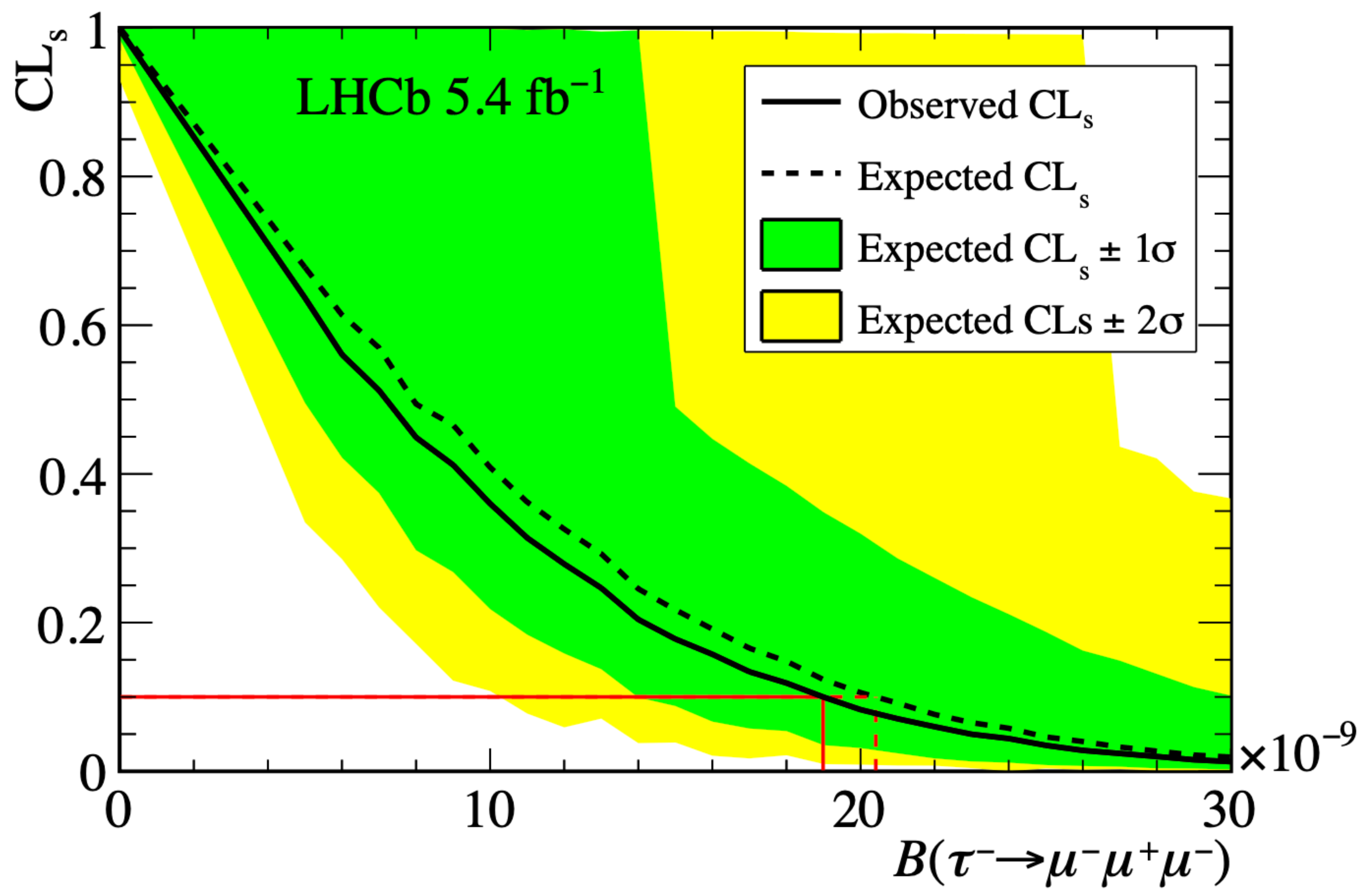


Conclusion and future prospects

- Upper limit determined using the CL_s method
- Observed 90% CL limit:

$$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9 \times 10^{-8} \text{ at } 90\,\% \text{ CL}$$

improving the previous LHCb Run 1 result by more than a factor of two and reaching Belle II sensitivity $(1.9 \times 10^{-8}$ at $90\,\%$ CL)



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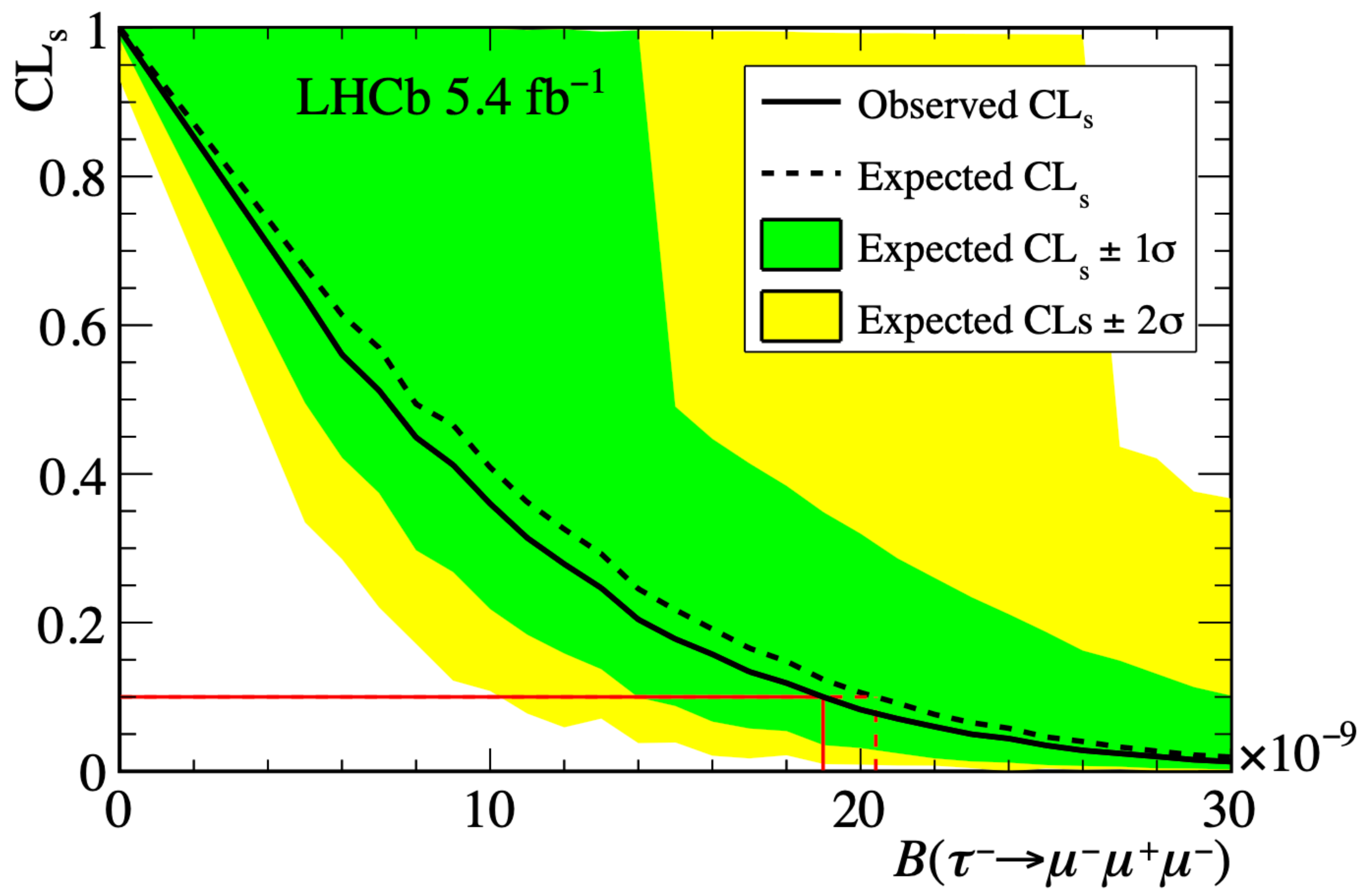


- Run 3 LHCb Upgrade 1 prospects:
  - Larger dataset and new trigger architecture
  - Extrapolated limit Run 2 + Run 3: $\sim 1.0 \times 10^{-8}$ at $90\,\%$ CL (assuming the same background level)
- Ongoing LHCb analysis to search for $\tau^- \to \phi(K^+K^-)\mu^-$ decay: first search at a hadron collider

Thanks to the LHCb Upgrade 1 and new Run 3 dataset, LHCb will continue pushing the sensitivity to τ LFV decays, demonstrating the strong potential of hadron colliders

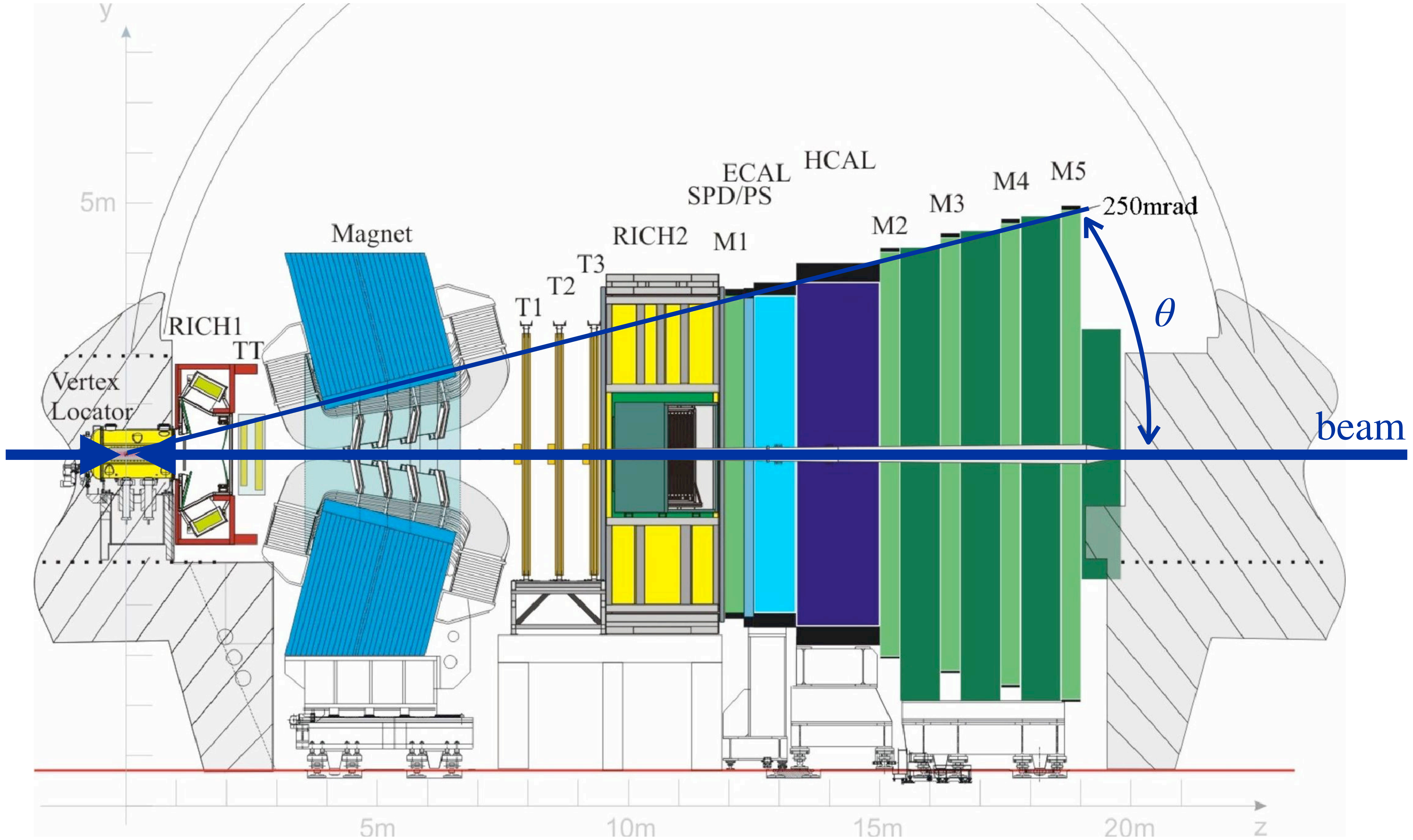
Additional material

Backup slides

LHCb detector in Run 2

Run 2 data-taking: 2015 - 2018

- Single-arm spectrometer in the forward region $(10 < \theta < 250\,\mathrm{mrad})$
- Designed for precision studies of CP violation and rare decays of beauty and charm hadrons
- Excellent momentum and vertex resolution, with ≈ 98% muon identification efficiency

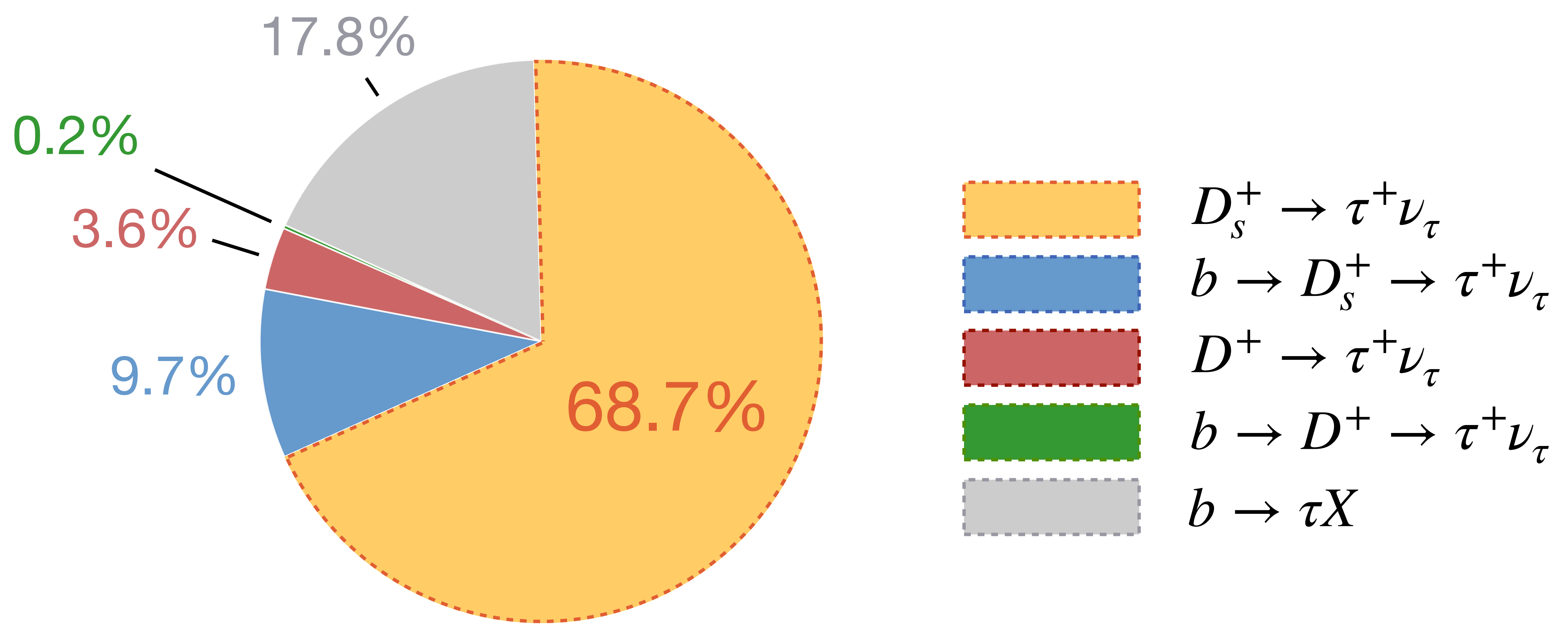


JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

τ leptons production at LHCb

- Exploit abundant τ lepton production in hadron collisions, mostly produced via c- and b-hadron decays:
  - D_s^+, D^+ and B meson decays

τ production sources (4π fractions)



Production dominated by $D_s^+ \to \tau^+\nu_\tau$ decays (~70%)

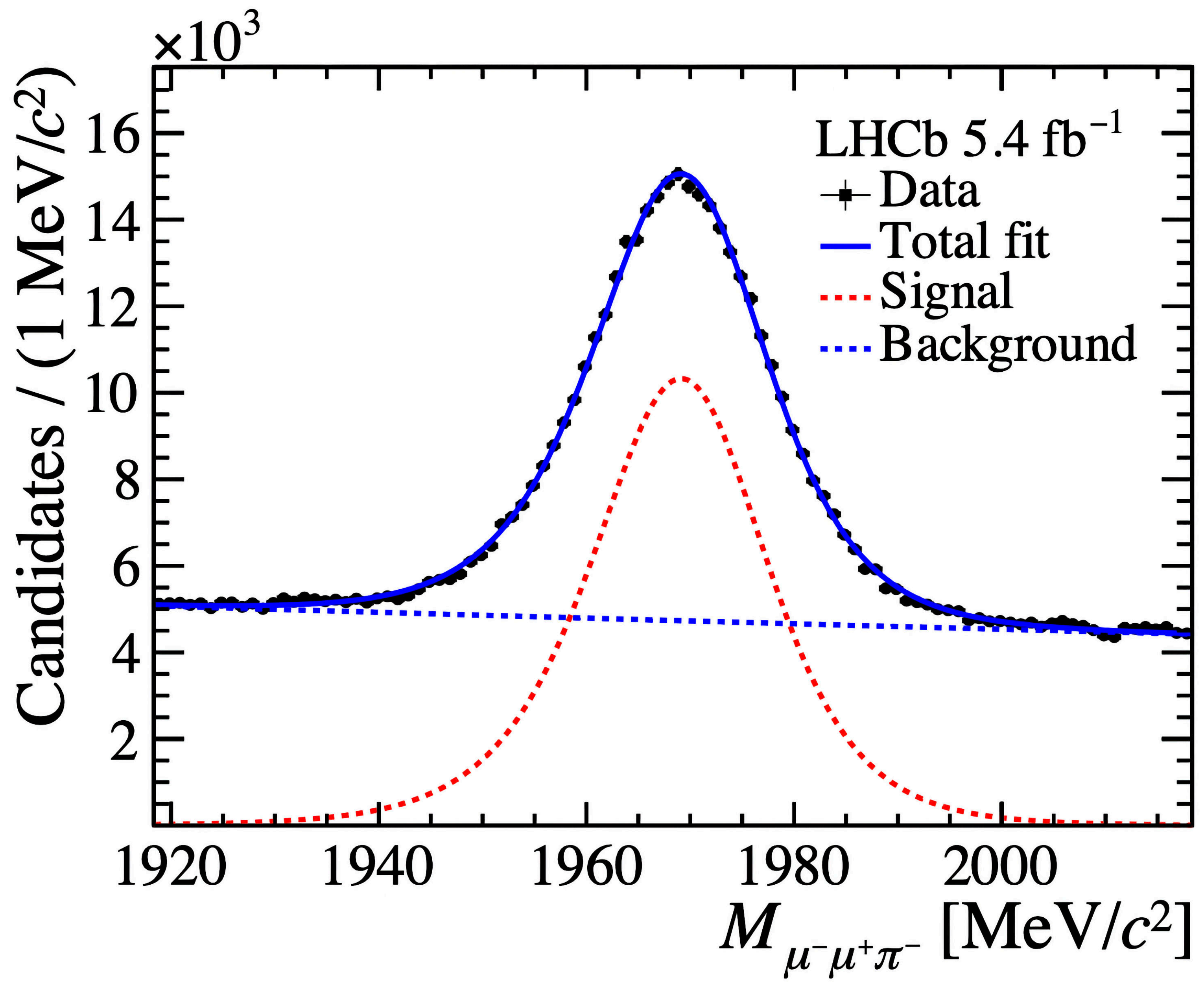
- Four additional signal production modes are considered
- Contributions from $\Upsilon(nS)$, $\psi(2S)$, Drell-Yan, $W^\pm$ and Z are negligible

Event selection

- Muon identification required for all muon candidates
- Trigger selections
  - L0: one or two high-pT muons
  - HLT1/2: selections based on kinematics, track quality and PID information
- Offline selection aligned between the signal and normalisation channel
  - Requirements based on kinematics, track quality and vertex reconstruction
- Background rejection
  - $|M_{\mu^-\mu^+} - M_\phi| > 30\,\mathrm{MeV/c^2}$ ($< 20\,\mathrm{MeV/c^2}$) to reject (select) $\phi \to \mu^-\mu^+$ in the signal (normalisation) channel
  - $M_{\mu^-\mu^+} > 450\,\mathrm{MeV/c^2}$ to remove $D_s^- \to \eta(\mu^-\mu^+\gamma)\mu^-\bar{\nu}_\mu$
  - $M_{\mu^-\mu^+} > 250\,\mathrm{MeV/c^2}$ to suppress fake tracks

Simulation calibration

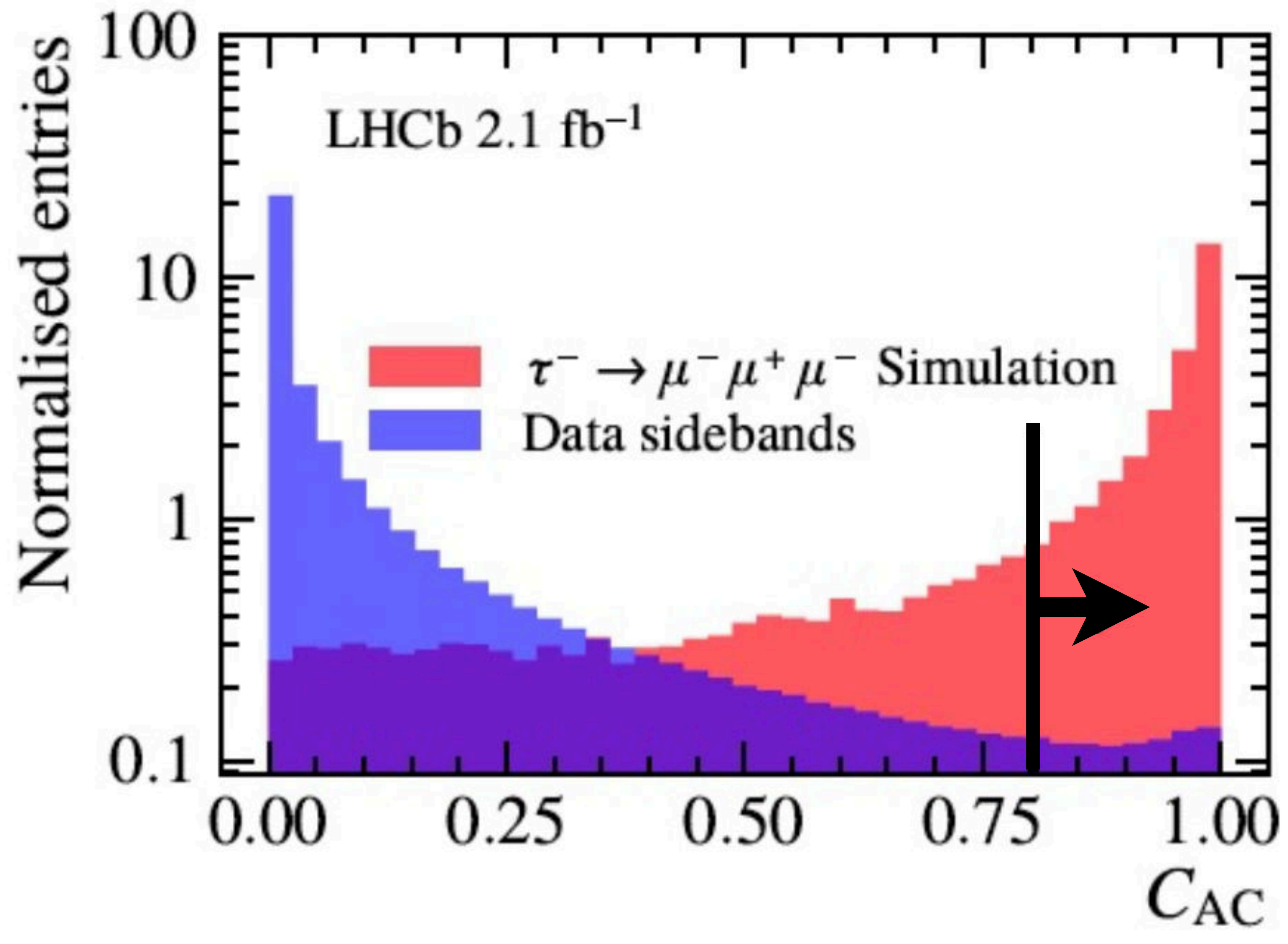
- Simulation calibrated to account for known data/MC differences in kinematics, detector response and PID
- $D_s^- \to \phi(\mu^-\mu^+)\pi^-$ used as calibration channel
  - Prompt/secondary $D_{(s)}^-$ production corrections from fits to $\log(IP_{\chi^2})^*$ in simulation and *sWeighted* data
  - Kinematic reweighting using *GBReweighter* based on topological, kinematic and nTracks variables
  - PID calibration from 4D data/MC ratios in bins of min(μ-ID probability), nTracks, $p(\mu)$ and $\eta(\mu)$
  - Corrections for residual data/MC differences in C_{AC} and C_{PID} output from 1D data/MC ratio
- Signal mass shape calibration using the $D_s^- \to \phi(\mu^-\mu^+)\pi^-$ peak in data and simulation

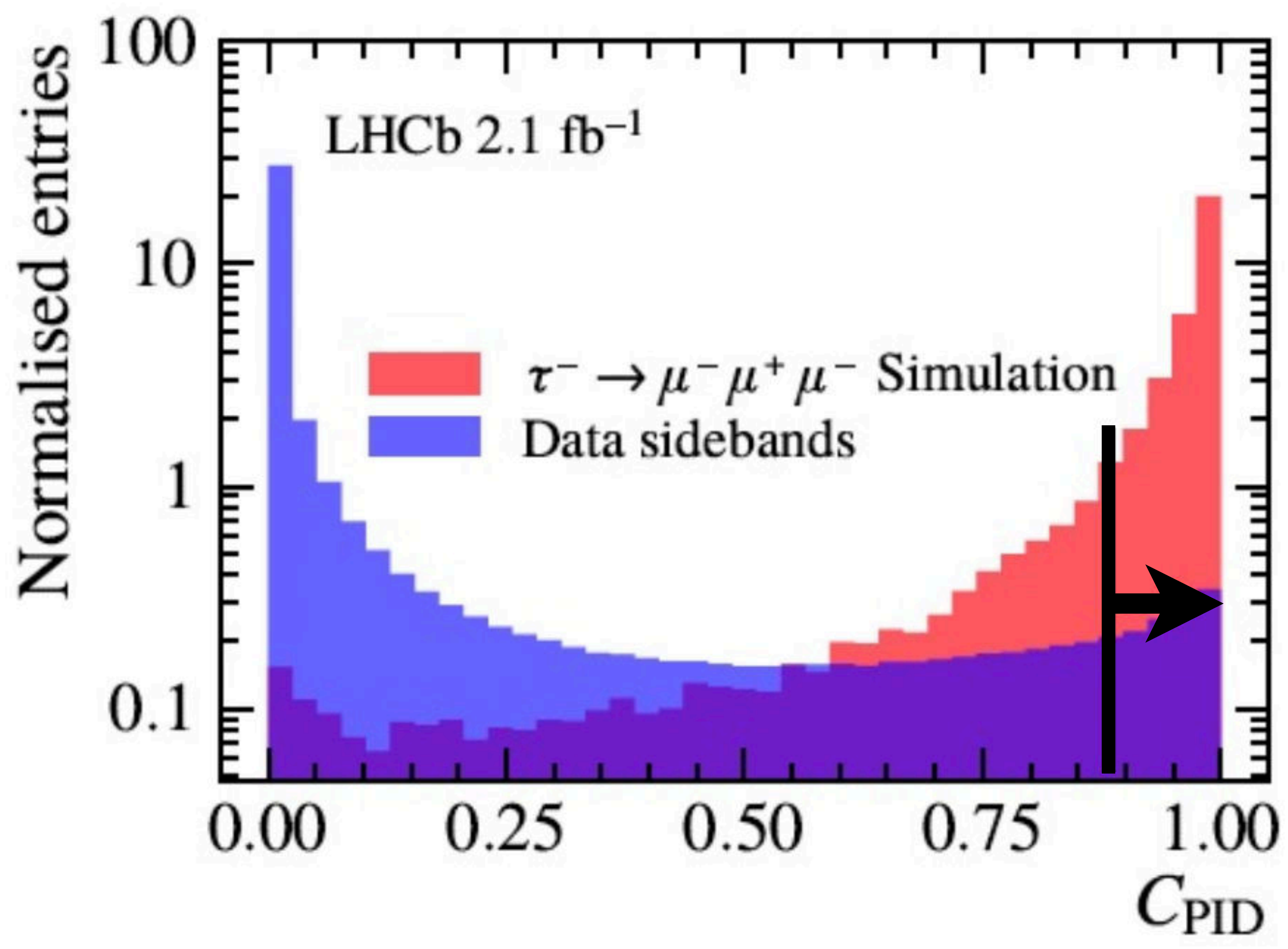


*Def. IP_{χ^2}: difference in the PV vertex-fit χ^2 with and without the track under consideration

Background suppression

- Two XGBoost classifiers trained on weighted simulated events (signal proxy) and data from SB (bkg proxy)
  - C_{AC} : anti-combinatorial classifier trained on kinematic + isolation variables
  - C_{PID} : misidentified-hadron classifier trained on PID and pseudorapidity variables
- Selection of the region $C_{\mathrm{AC}} > 0.8$ and $C_{PID} > 0.88$ with signal efficiency of $\sim 60\,\%$
- Limit evaluated in 15 C_{AC} and C_{PID} bins to increase sensitivity





Expected bkg and observed candidates

- Expected and observed background yields in the signal region across the 15 C_{AC} and C_{PID} bins

C_{AC} bin	C_{PID} bin	Expected	Observed
[0.800, 0.930]	[0.951, 0.978]	288.3 ± 7.3	284
	[0.978, 0.991]	187.3 ± 5.8	174
	[0.991, 1.000]	111.2 ± 4.6	110
[0.930, 0.974]	[0.880, 0.959]	194.5 ± 6.4	203
	[0.959, 0.982]	110.3 ± 4.7	121
	[0.982, 0.992]	79.1 ± 3.7	67
	[0.992, 1.000]	56.5 ± 3.3	41
[0.974, 0.990]	[0.880, 0.966]	129.9 ± 4.9	133
	[0.966, 0.985]	63.1 ± 3.5	62
	[0.985, 0.993]	40.8 ± 2.9	50
	[0.993, 1.000]	31.3 ± 2.5	42
[0.990, 1.000]	[0.880, 0.970]	64.6 ± 3.8	79
	[0.970, 0.987]	34.0 ± 2.9	33
	[0.987, 0.994]	33.3 ± 2.8	29
	[0.994, 1.000]	20.3 ± 2.3	23
Total		1444 ± 17	1451

Normalisation and systematics

- Single event sensitivity:

$$\alpha = \mathcal{B}(D_s^- \to \phi(\mu^-\mu^+)\pi^-) \times \frac{f_{D_s}^{\tau}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\epsilon_{D_s}}{\epsilon_\tau} \times \frac{1}{N_{D_s}}$$

	External inputs		
$\mathcal{B}(D_s^- \to \phi(\to \mu^-\mu^+)\pi^-)$	$(1.289 \pm 0.094)\ \times 10^{-5}$		
$f_{D_s}^{\tau}$	$(78.4 \pm 3.7)\ \times 10^{-2}$		
$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$	$(5.32 \pm 0.11)\ \times 10^{-2}$		
	2016	**2017**	**2018**
N_{D_s}	$(43.1 \pm 0.6)\ \times 10^3$	$(88.5 \pm 1.2)\ \times 10^3$	$(103.8 \pm 1.1)\ \times 10^3$
$\epsilon_{D_s}/\epsilon_\tau$	0.322 ± 0.022	0.562 ± 0.034	0.575 ± 0.036
α	$(1.42 \pm 0.16)\ \times 10^{-9}$	$(1.21 \pm 0.13)\ \times 10^{-9}$	$(1.05 \pm 0.11)\ \times 10^{-9}$

- Efficiency ratio $\epsilon_{D_s}/\epsilon_\tau$ evaluated using weighted simulated samples
  - Corrected to account for data/MC differences in trigger and tracking efficiency
  - Lower efficiency ratio in 2016 due to a less efficient trigger configuration
- Systematics mainly arising from external inputs and from the efficiency ratio

CERN