Search for the lepton-flavour violating decay $\tau^+ \to \phi\mu^+$ at the LHCb experiment

Italian Workshop on Physics at High Intensity - WIFAI 2025

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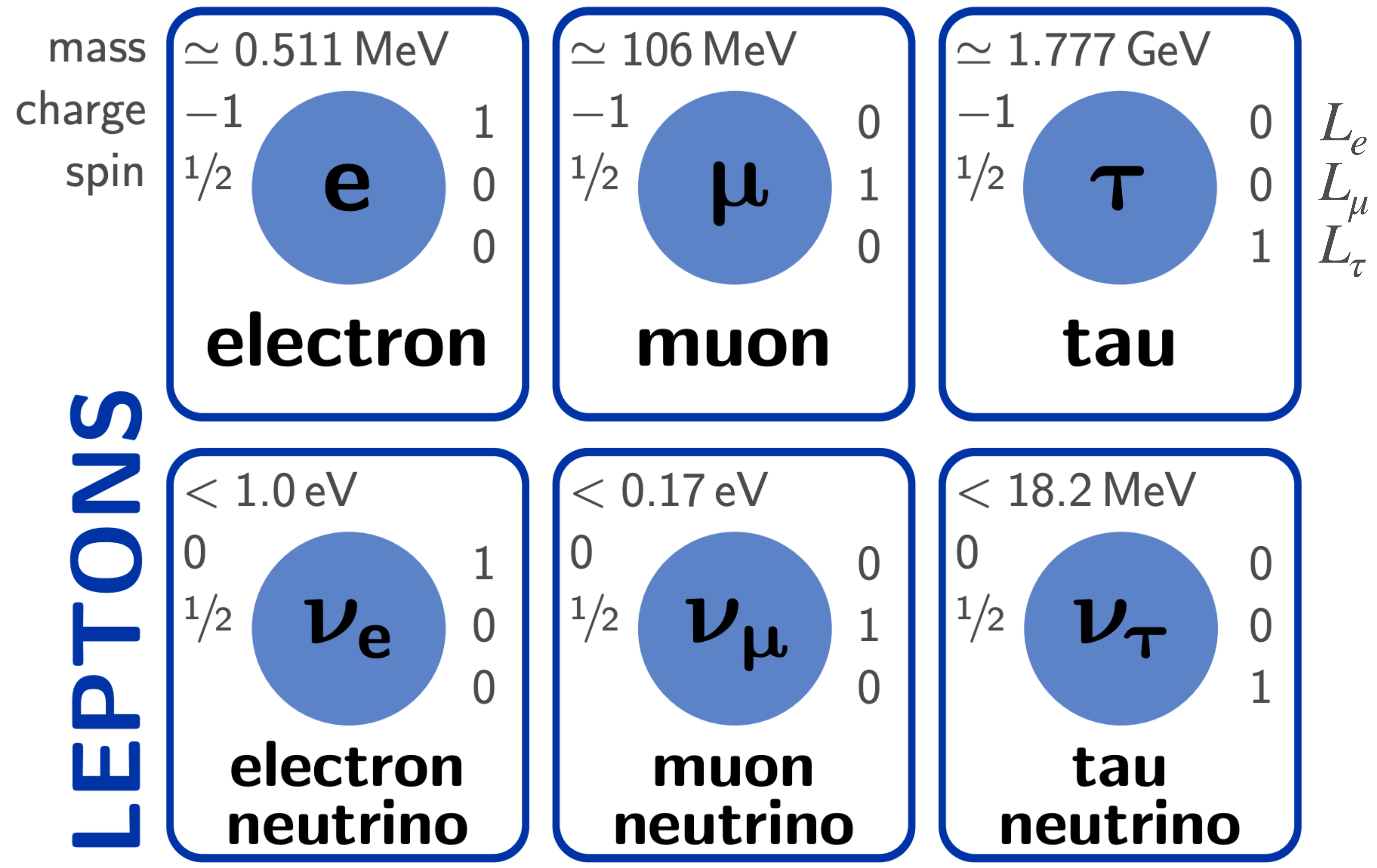
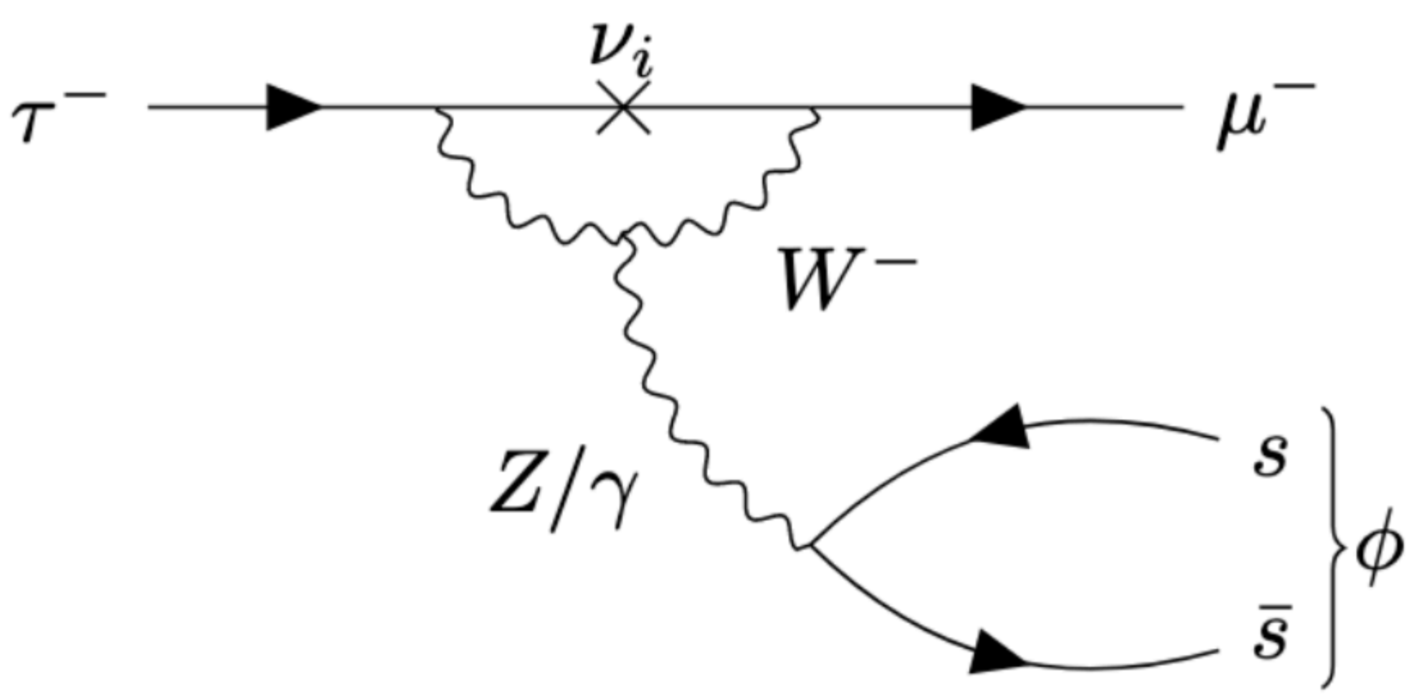
Motivations

- In the Standard Model (SM), 3 lepton flavours (L_e, L_μ, L_τ) carried by charged leptons and their associated neutrinos.
- Lepton flavour violation (LFV): transitions that do not conserve the lepton flavour number.
- No SM symmetry enforces LF conservation.
  - Neutrino oscillations provide LFV evidence in the neutral lepton sector.
  - Charged LFV (cLFV) possible in the SM via neutrino oscillations only, with extremely small branching fractions [1,2]:

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

⇒ far beyond experimental reach.





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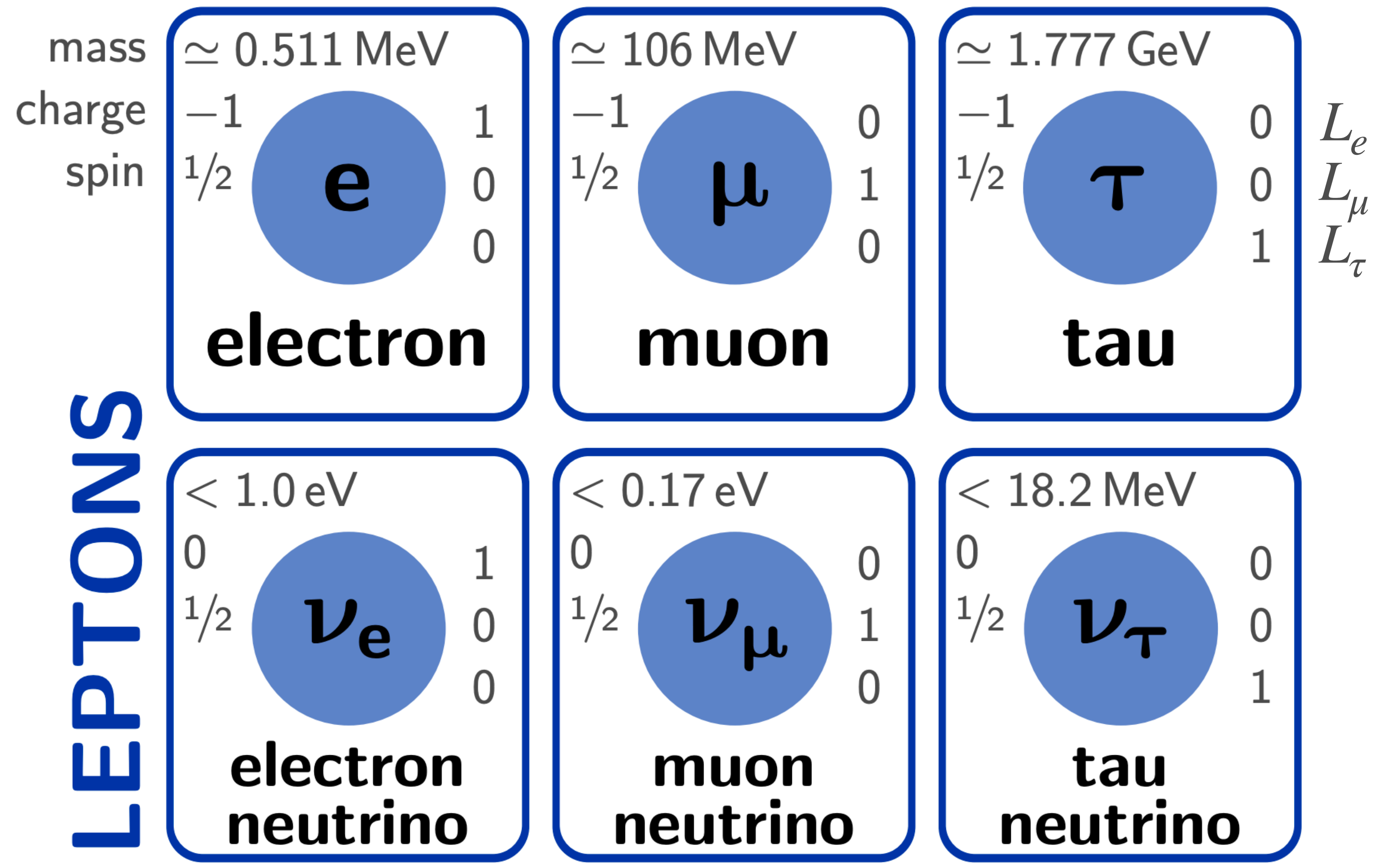

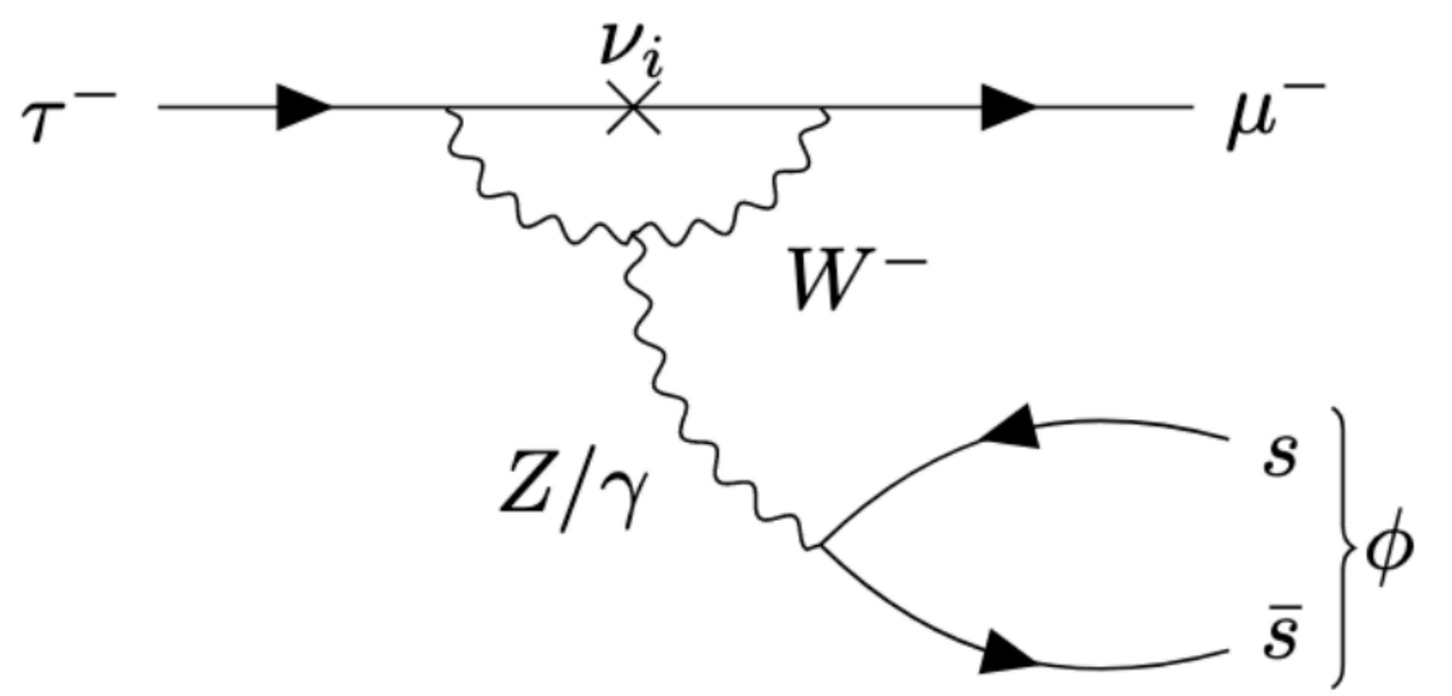

Direct observation of cLFV would be an indisputable signature of New Physics

Current status of $\tau^+ \to \phi\mu^+$ searches

- Previous searches conducted at e^+e^- machines: Belle (2.3×10^{-8} @ $90\,\%$ CL best limit), Belle II, BaBar, CLEO.

This analysis will provide the first upper limit obtained at a hadron collider

- Why e^+e^- machines are typically favorite environments where to look for LFV τ decays?
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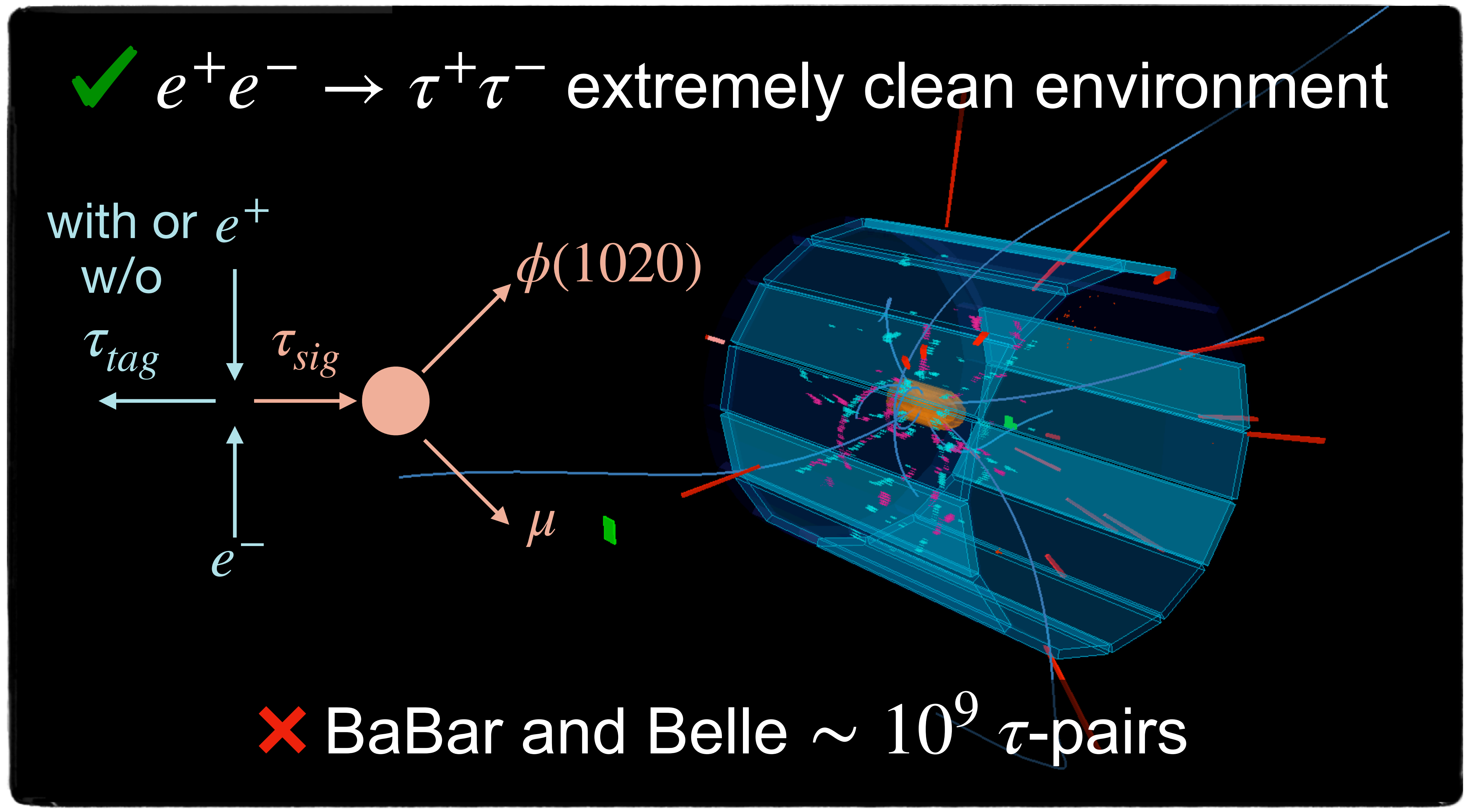
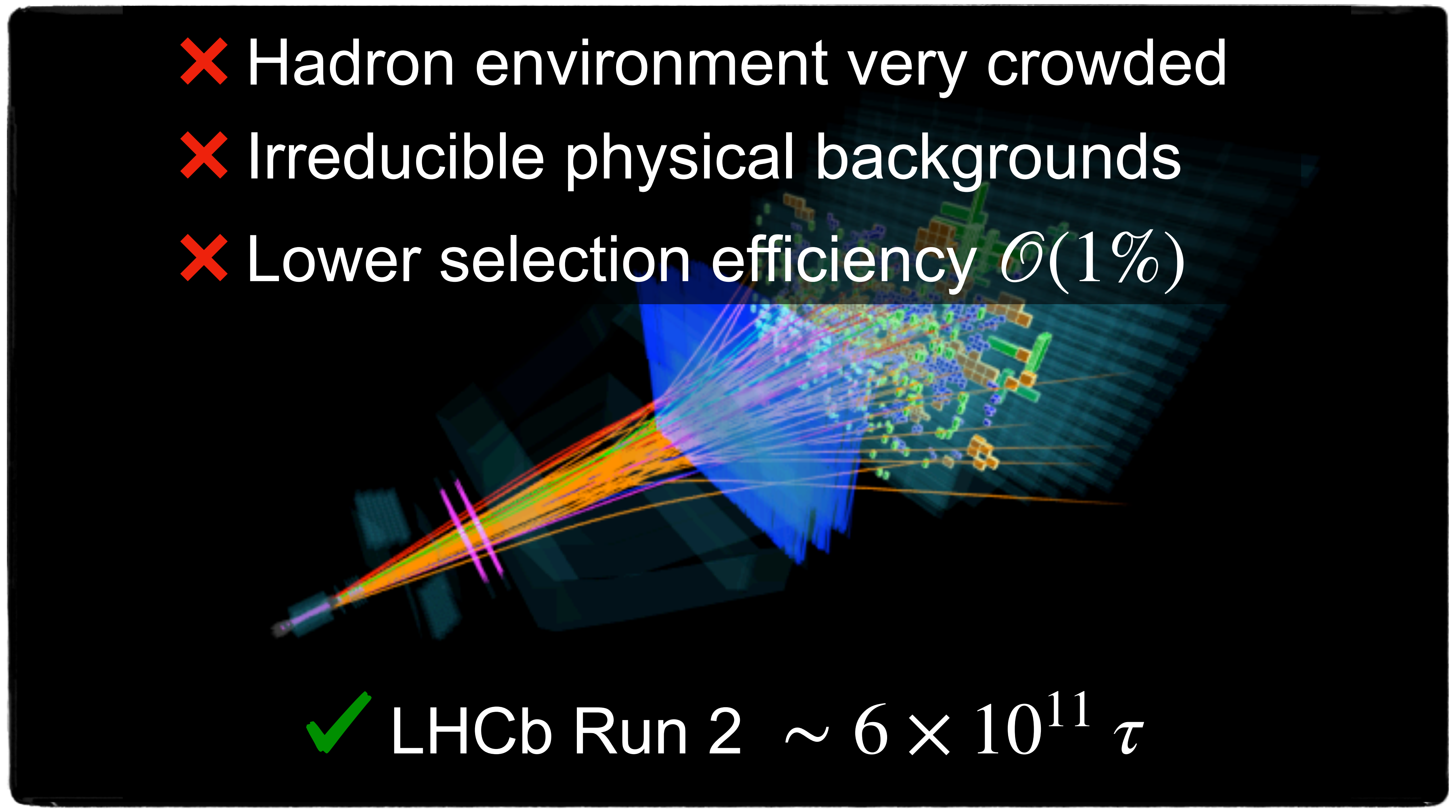
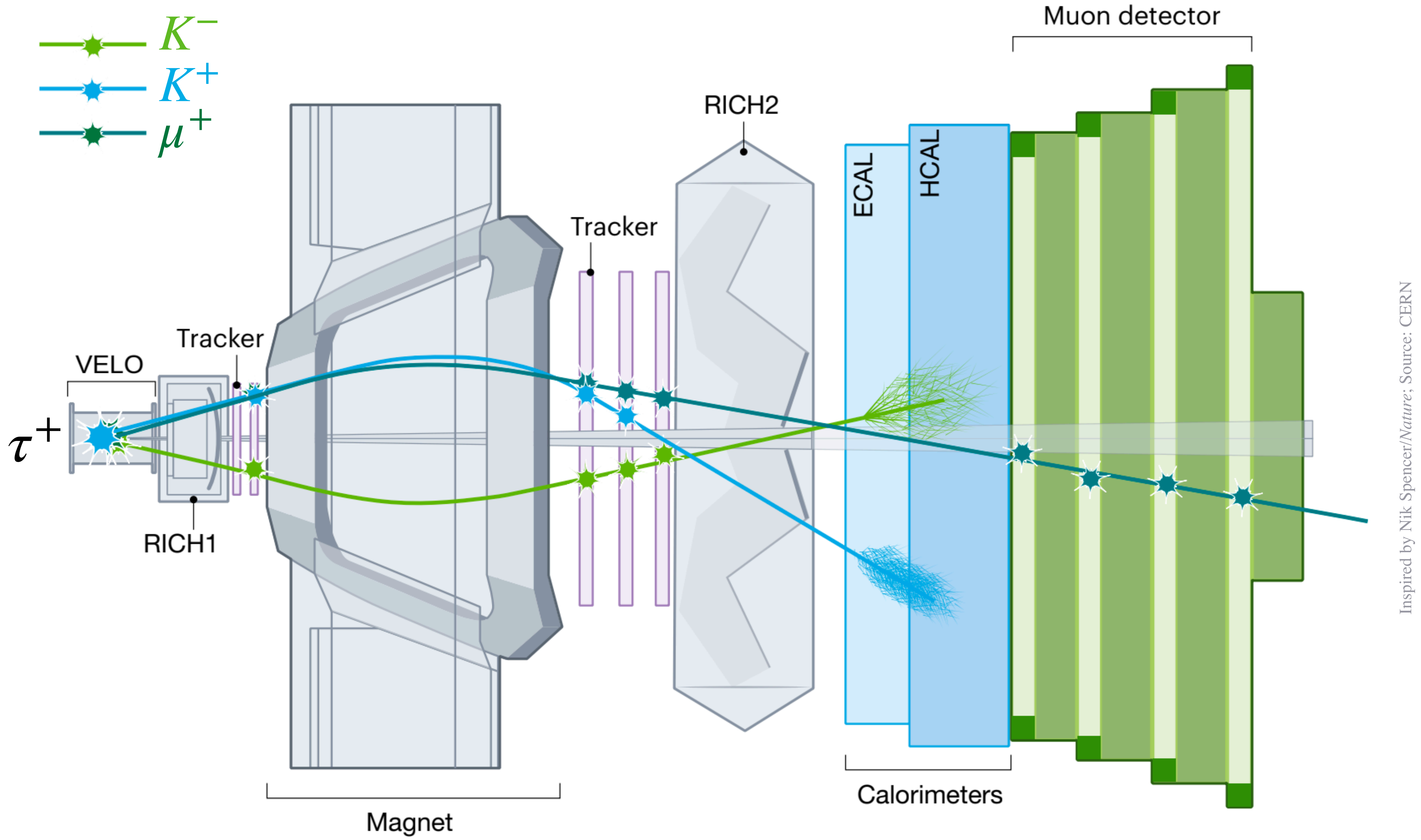




- Additional goal: demonstrate the search capabilities of high-intensity proton–proton colliders.

LHCb detector

- Single arm spectrometer in the forward region.
- Focus on CP violation and rare decays of b and c hadrons, complemented by a broader physics program.
- Excellent momentum and vertex resolution, with $\sim 98\,\%$ muon identification efficiency.

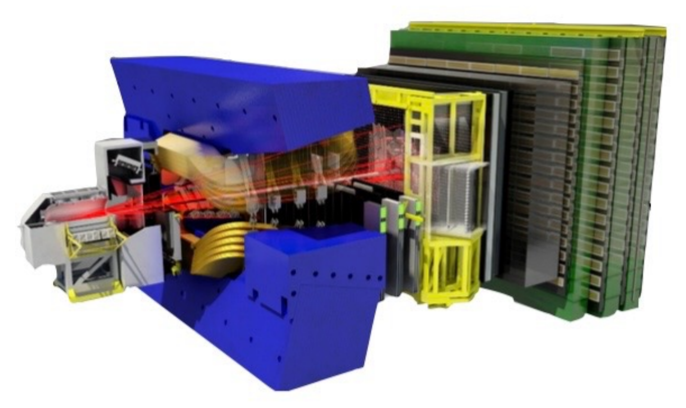


Run 2 & Run 3

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

JINST 19 (2024) P05065

Trigger selections in Run 3



$30\,\mathrm{MHz}$ → HLT1: **1st software trigger** partial reco → $1.5\,\mathrm{MHz}$ → HLT2: **2nd software trigger** full reco → $\mathcal{O}(100\,\mathrm{kHz})$ → Storage

- New trigger architecture deployed for LHCb Run 3.
- Full event reconstruction at 30 MHz *pp* bunch-crossing rate for the first High-Level Trigger stage (HLT1).

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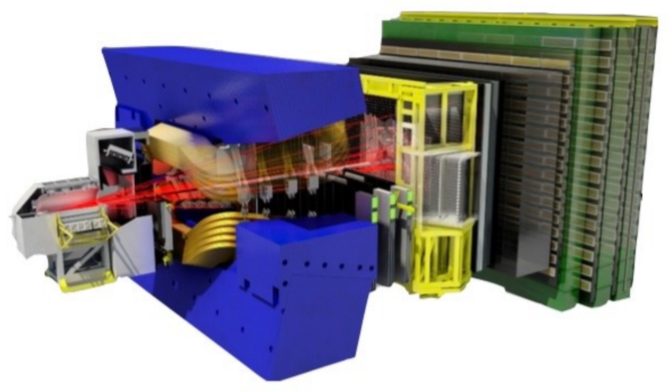

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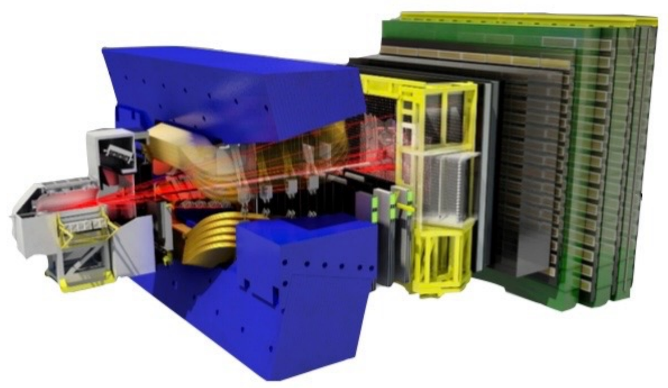

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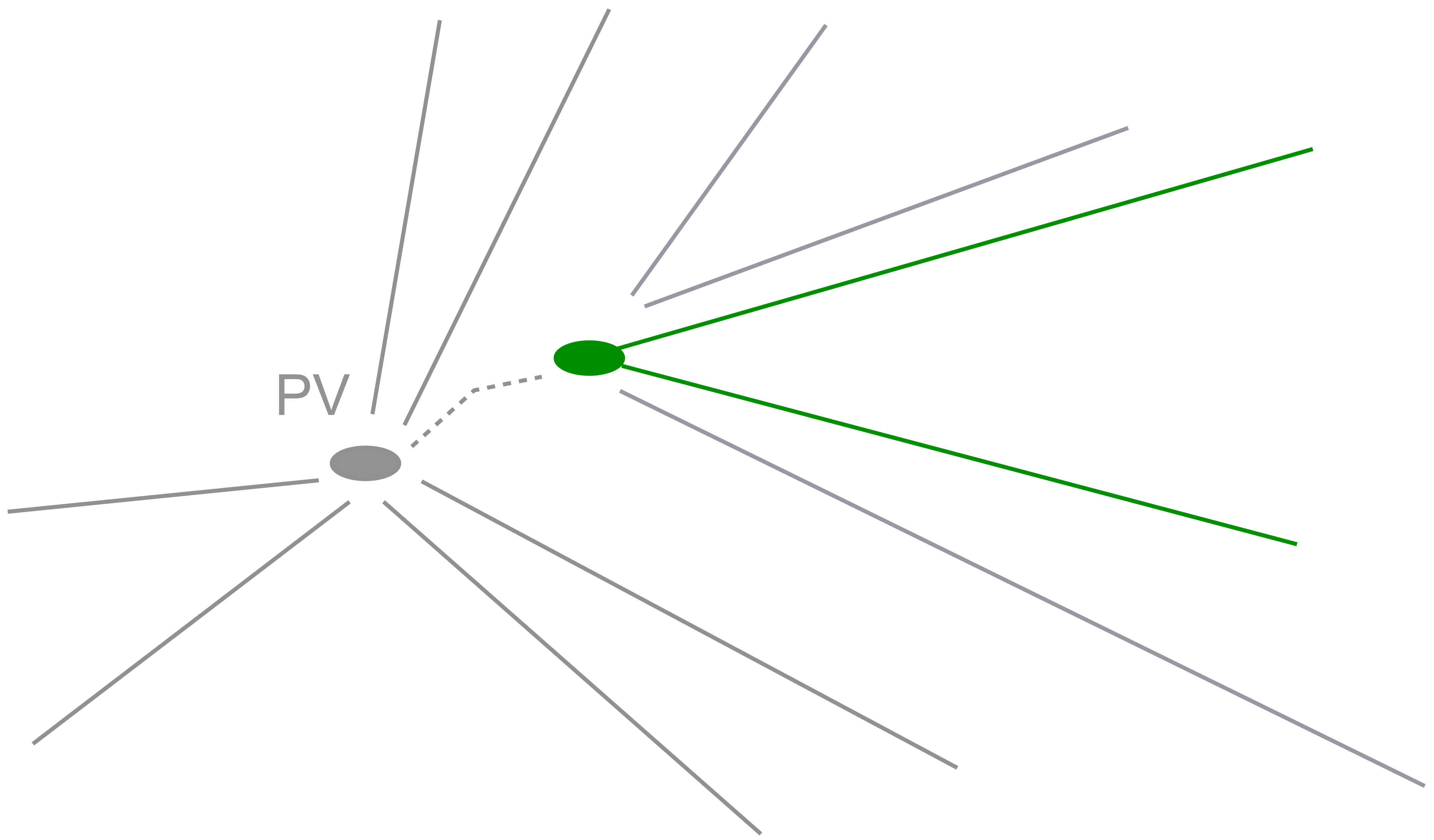
  - IDEA: develop a dedicated HLT1 trigger to enhance LHCb sensitivity on this very rare decay.
  - **First-ever exclusive trigger for a rare τ decay mode implemented at LHCb**.
  - Proof of concept of the exclusive trigger strategy for rare decay searches, paving the way for future new triggers in the high-intensity era.

Implementation of the $\tau^+ \to \phi\mu^+$ HLT1 trigger

- New trigger strategy to select candidates with:
  - Two oppositely charged tracks forming a neutral vertex with invariant mass consistent with the $\phi(1020)$.



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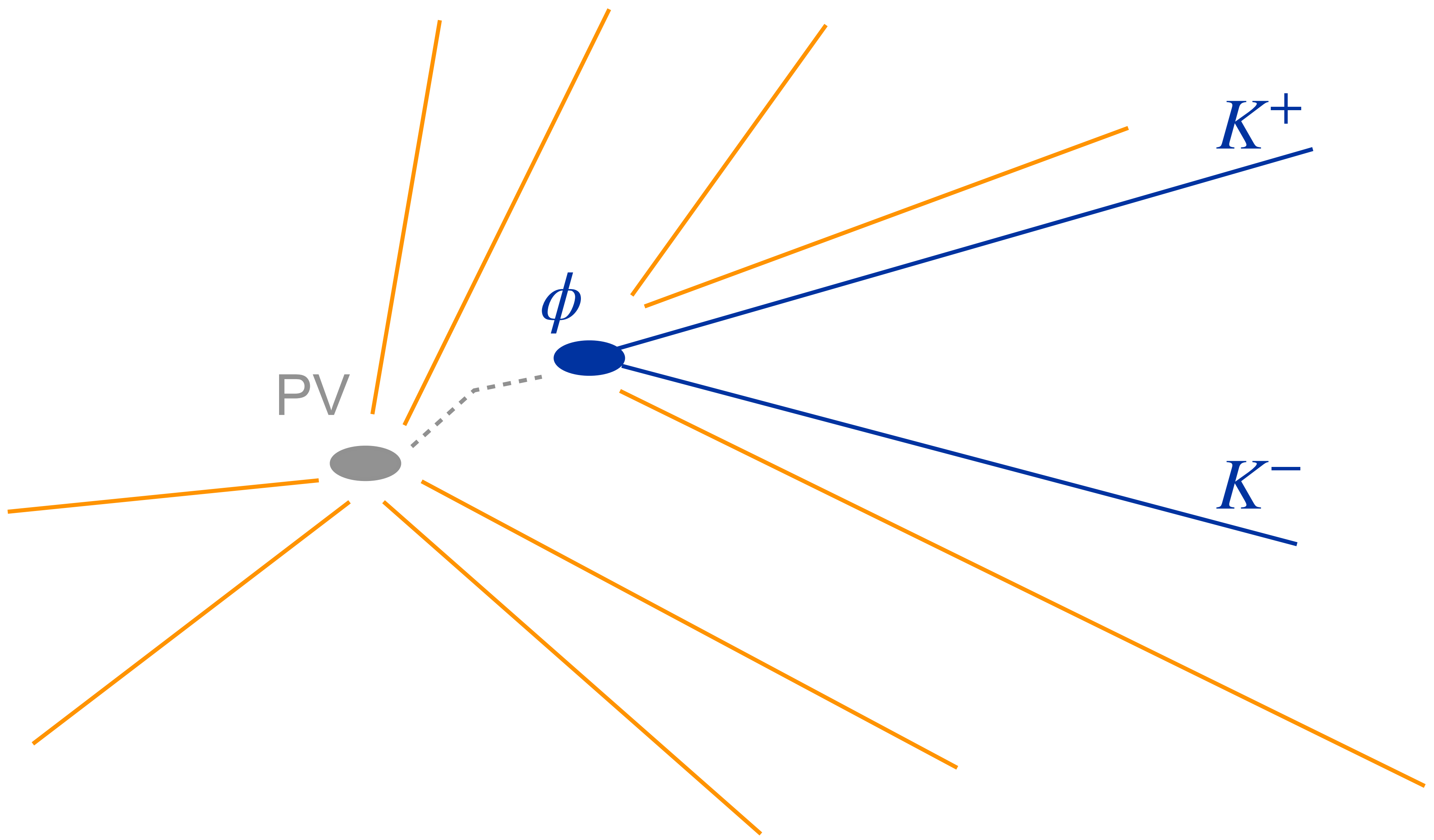

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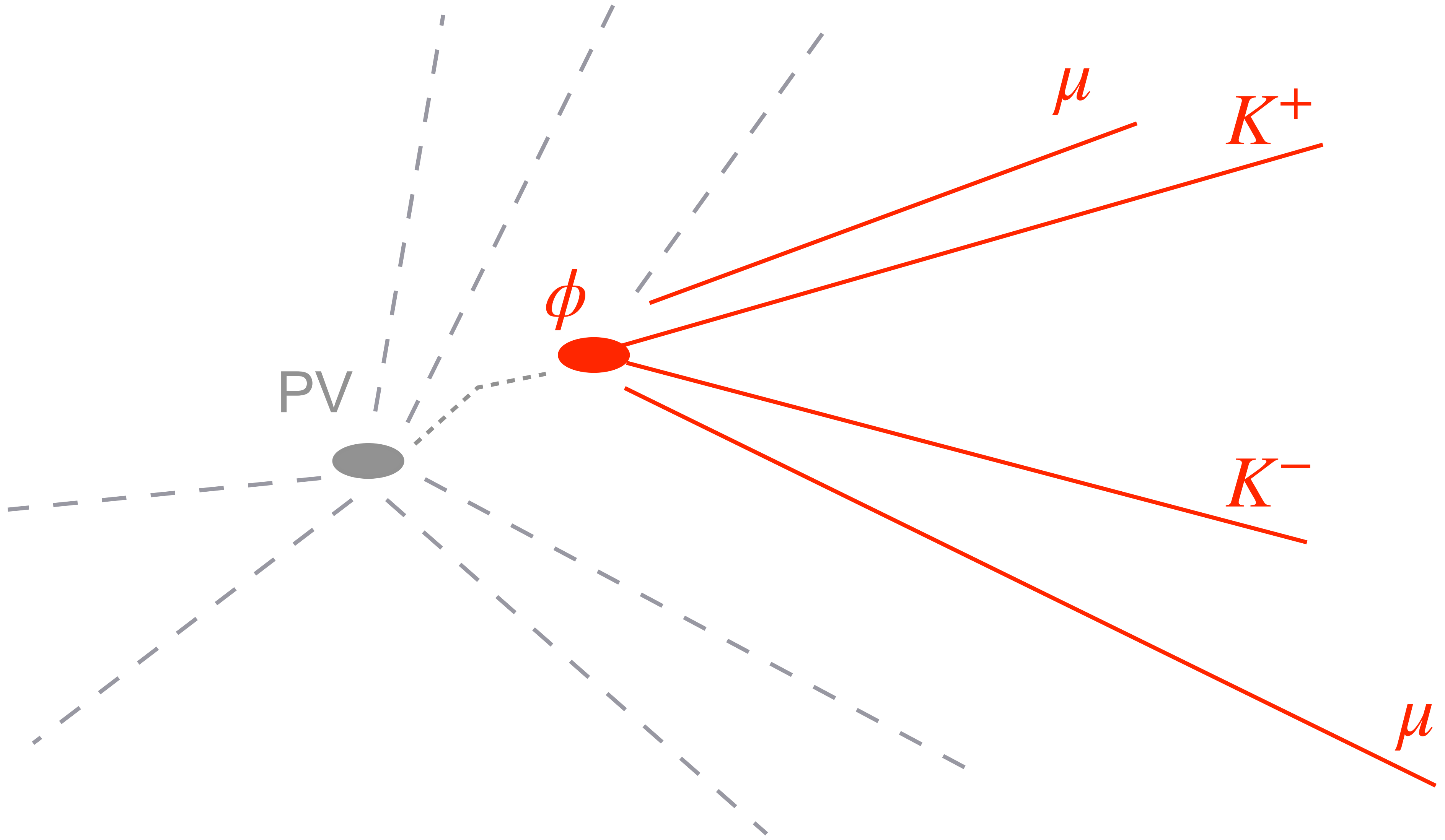

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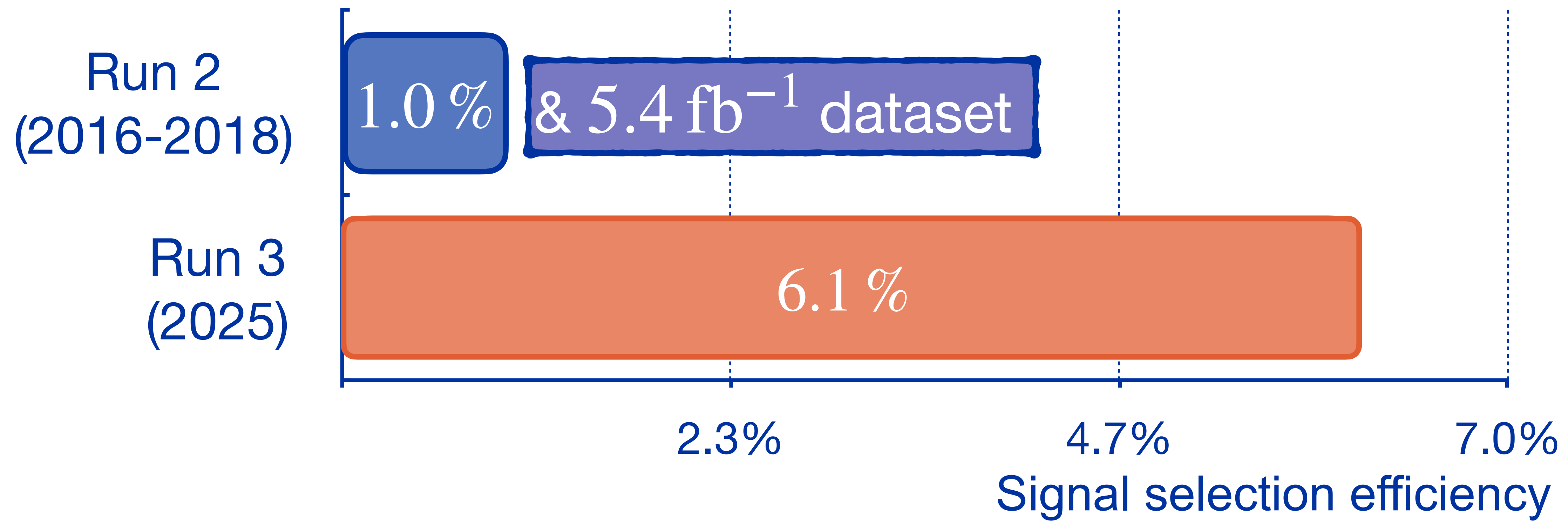
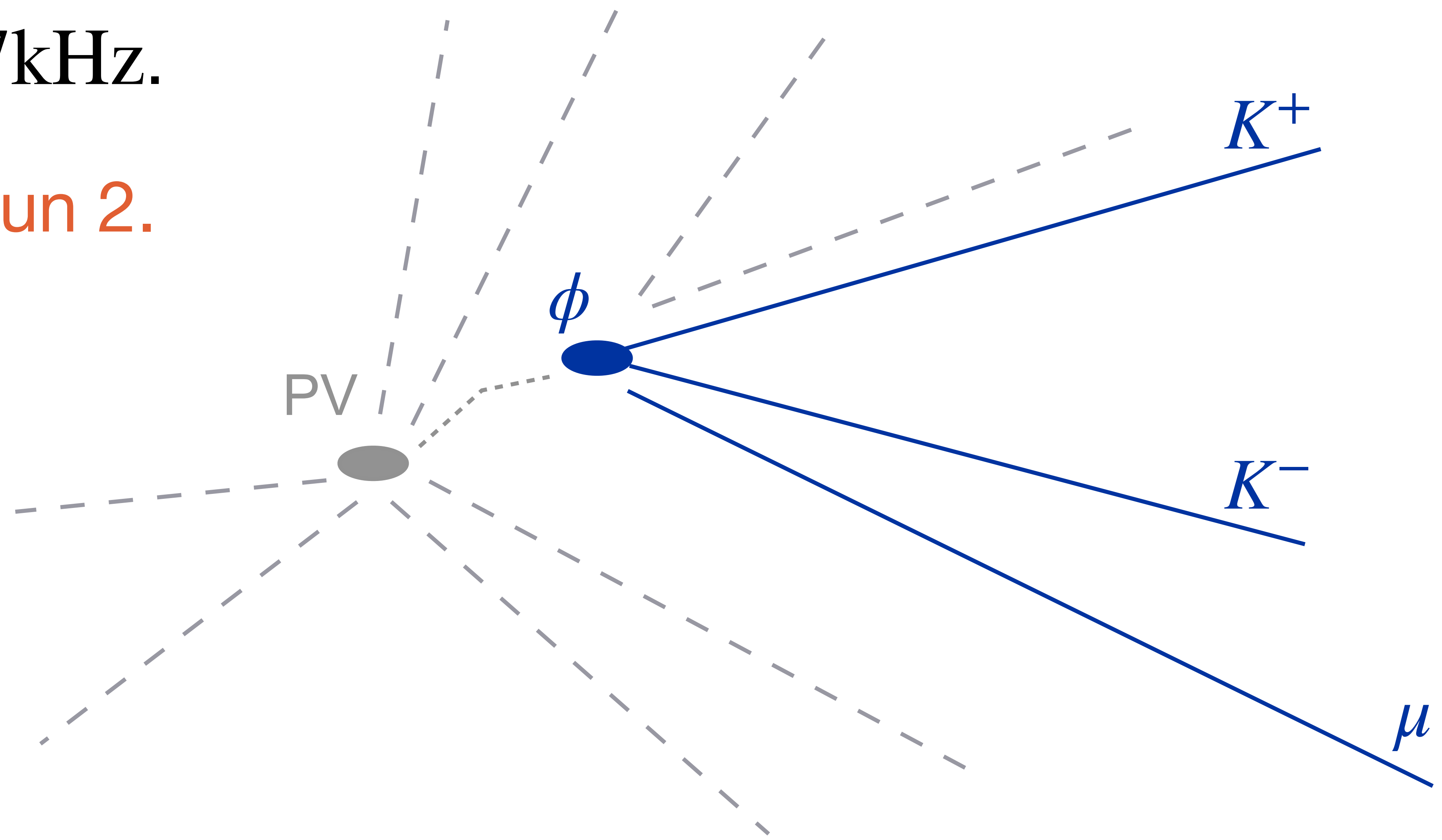
- Decay-specific features enforced an exceptionally tight selection.
  - Trigger running at only few ‰ of the total HLT1 output rate $\sim 1.7\mathrm{kHz}$.
  - Large selection efficiency gain achieved ⇒ 6 times higher than Run 2.





Analysis strategy

- Search for a peak at the τ mass ($m_\tau = 1776.93 \pm 0.09\,\mathrm{MeV}$, PDG) in the invariant mass distribution of the $\phi(KK)\mu$ system.
- Mass spectrum divided into:
    - Signal region (blinded): $[1755, 1795]\ \mathrm{MeV/c^2}$
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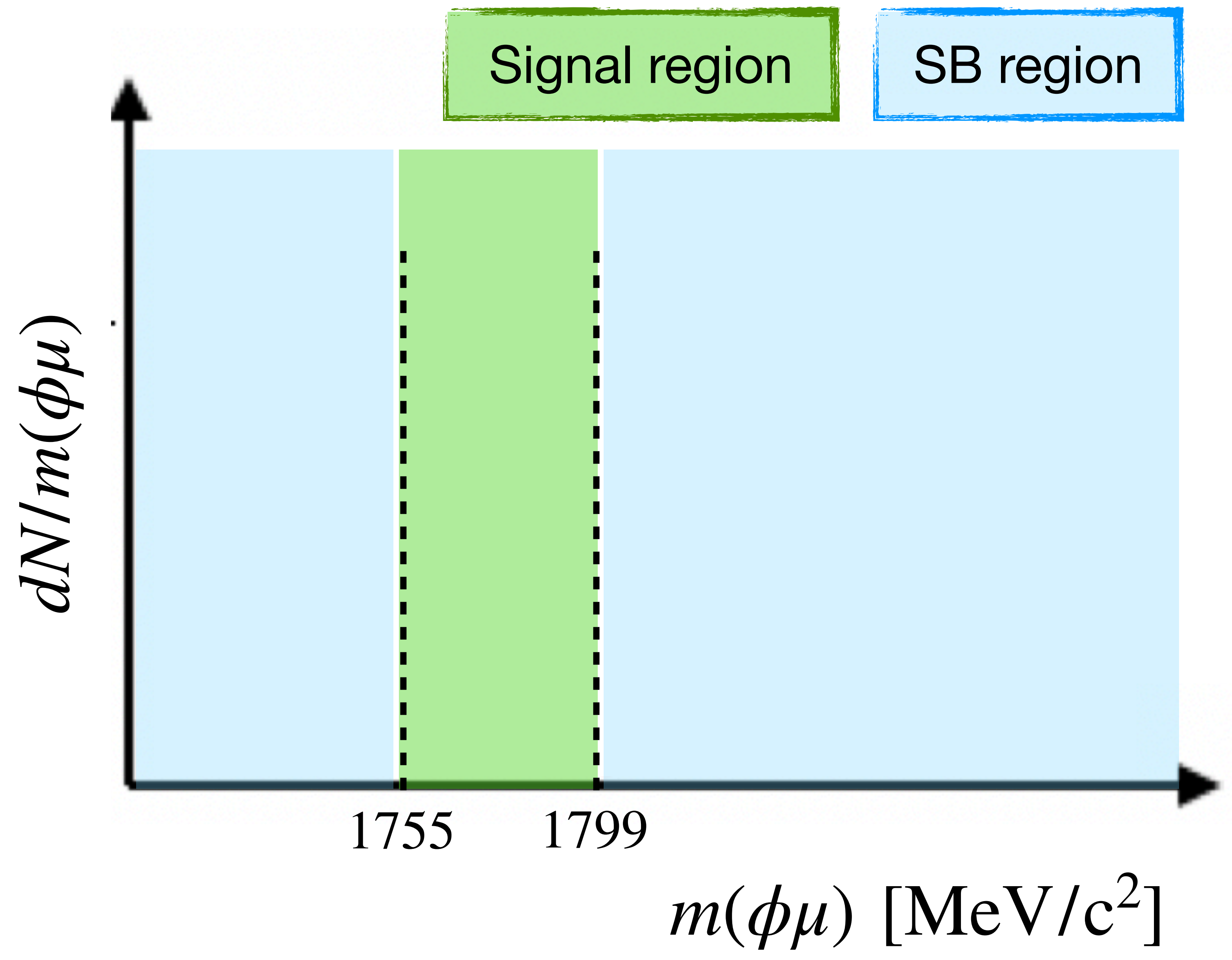

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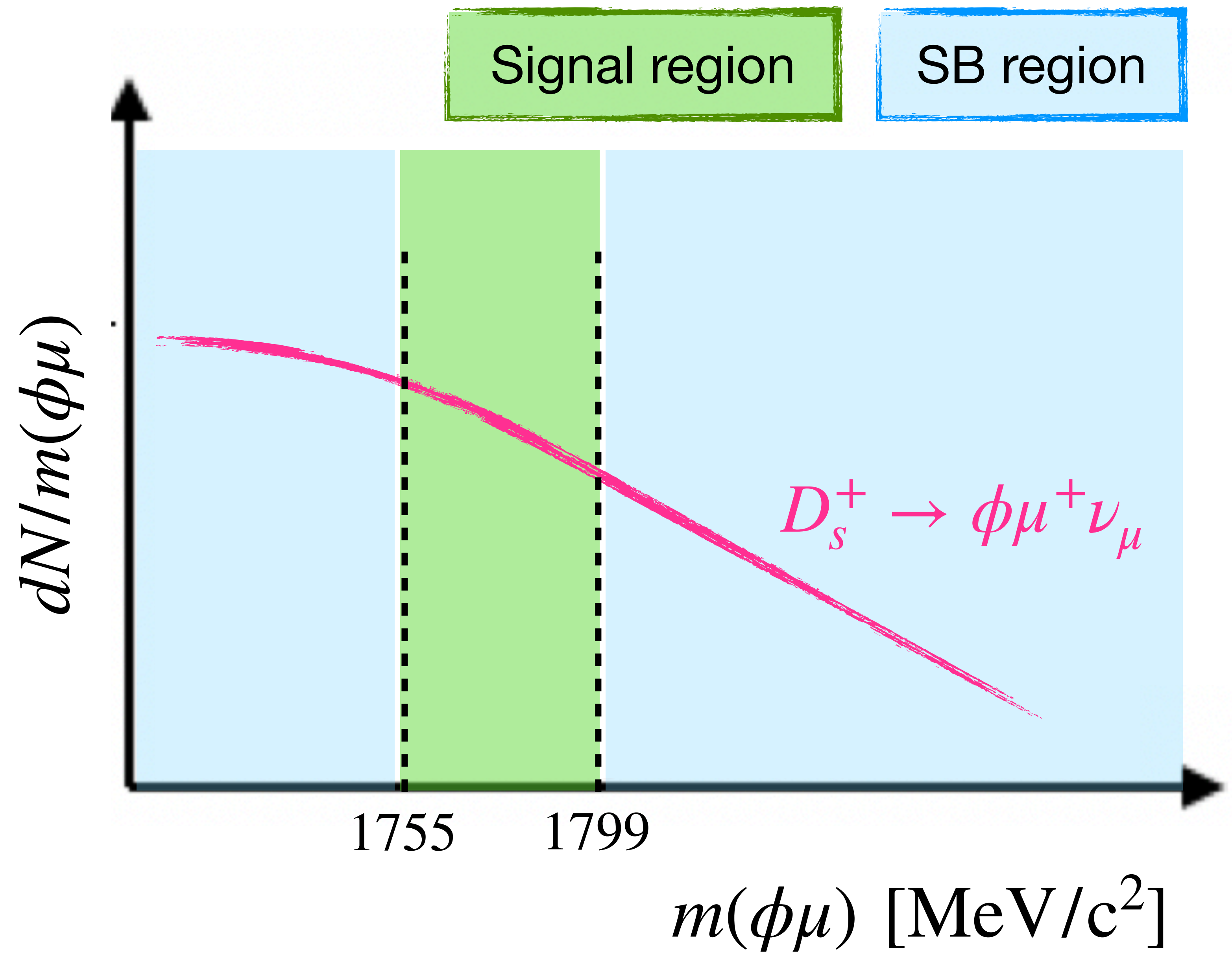

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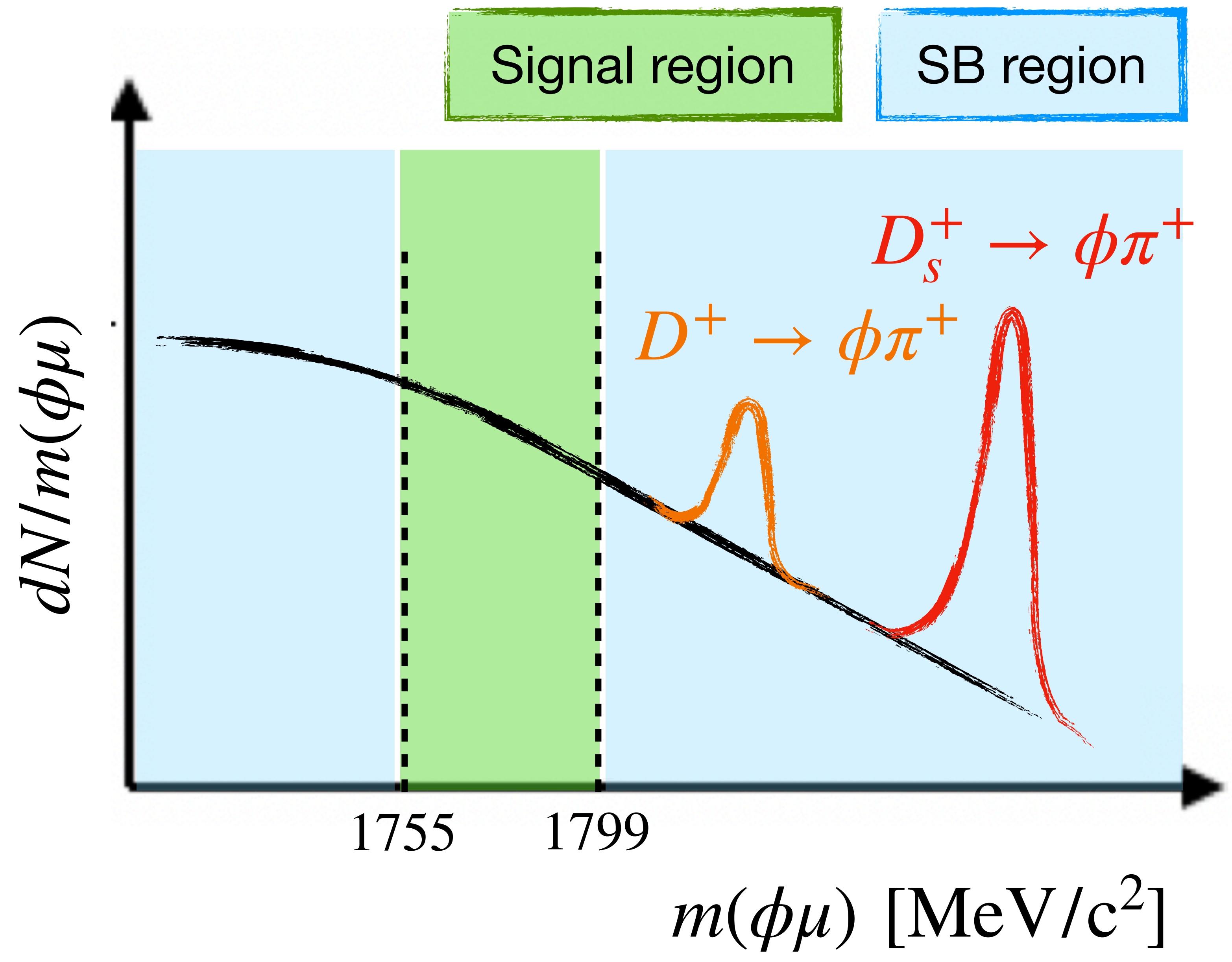

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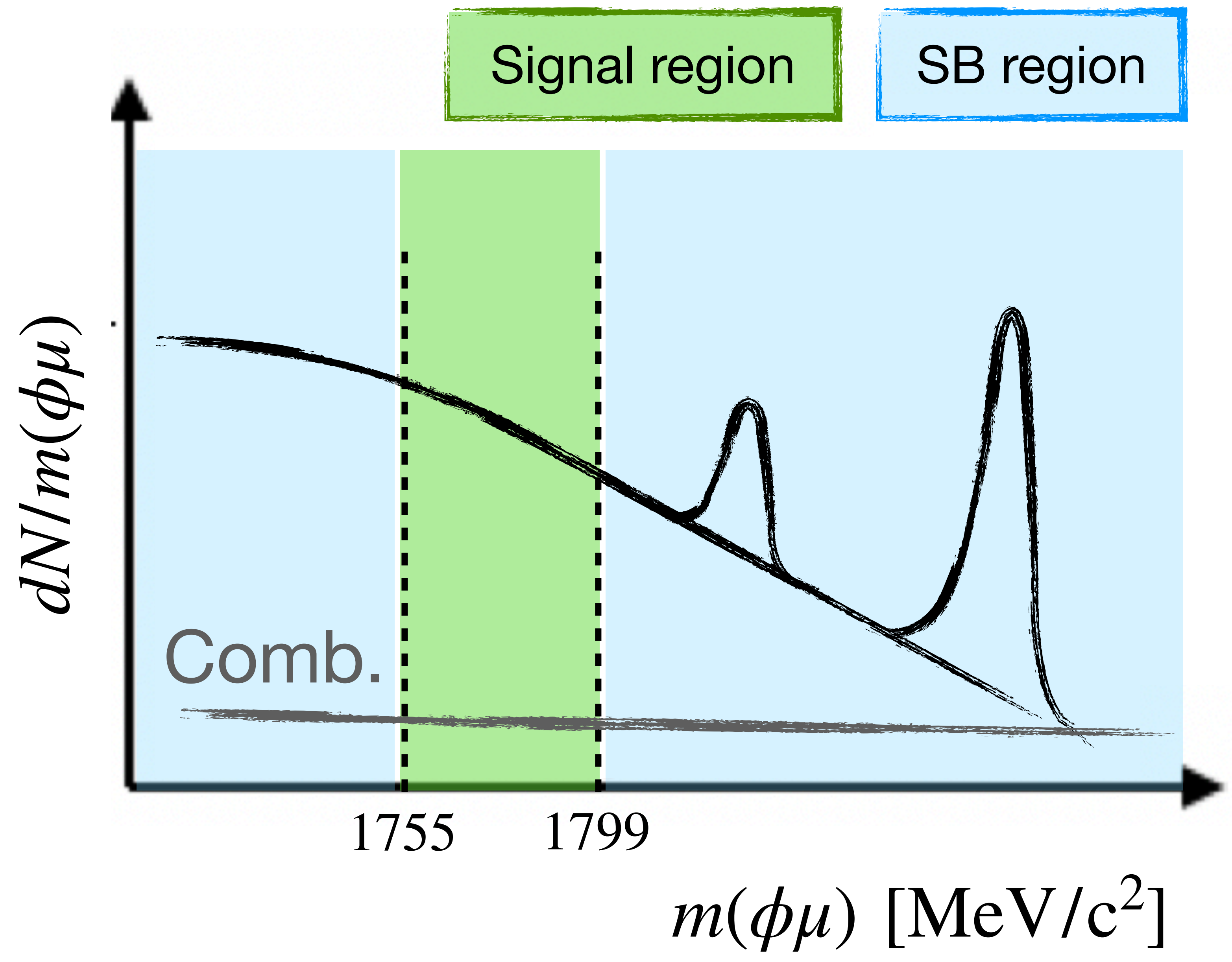

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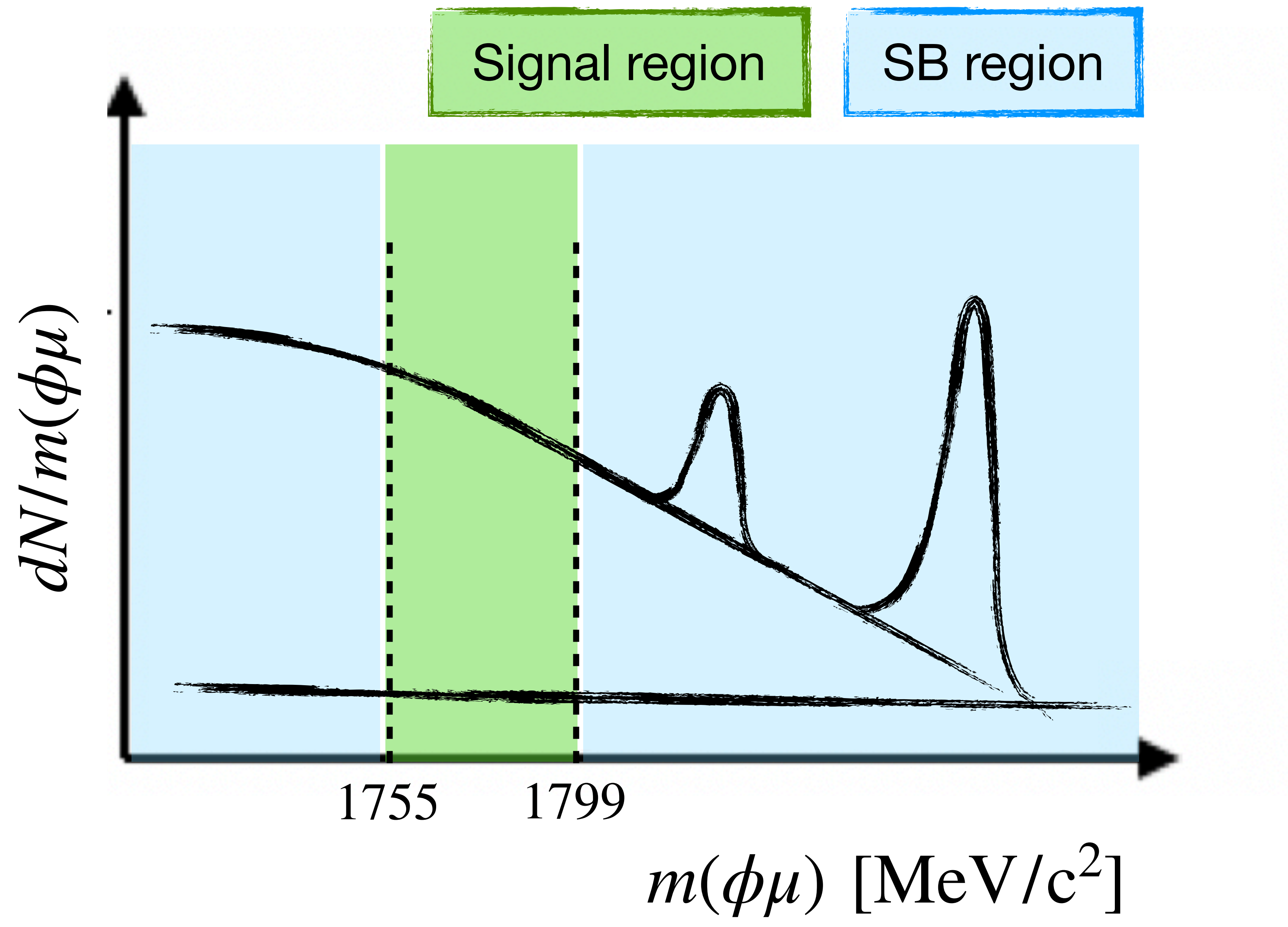
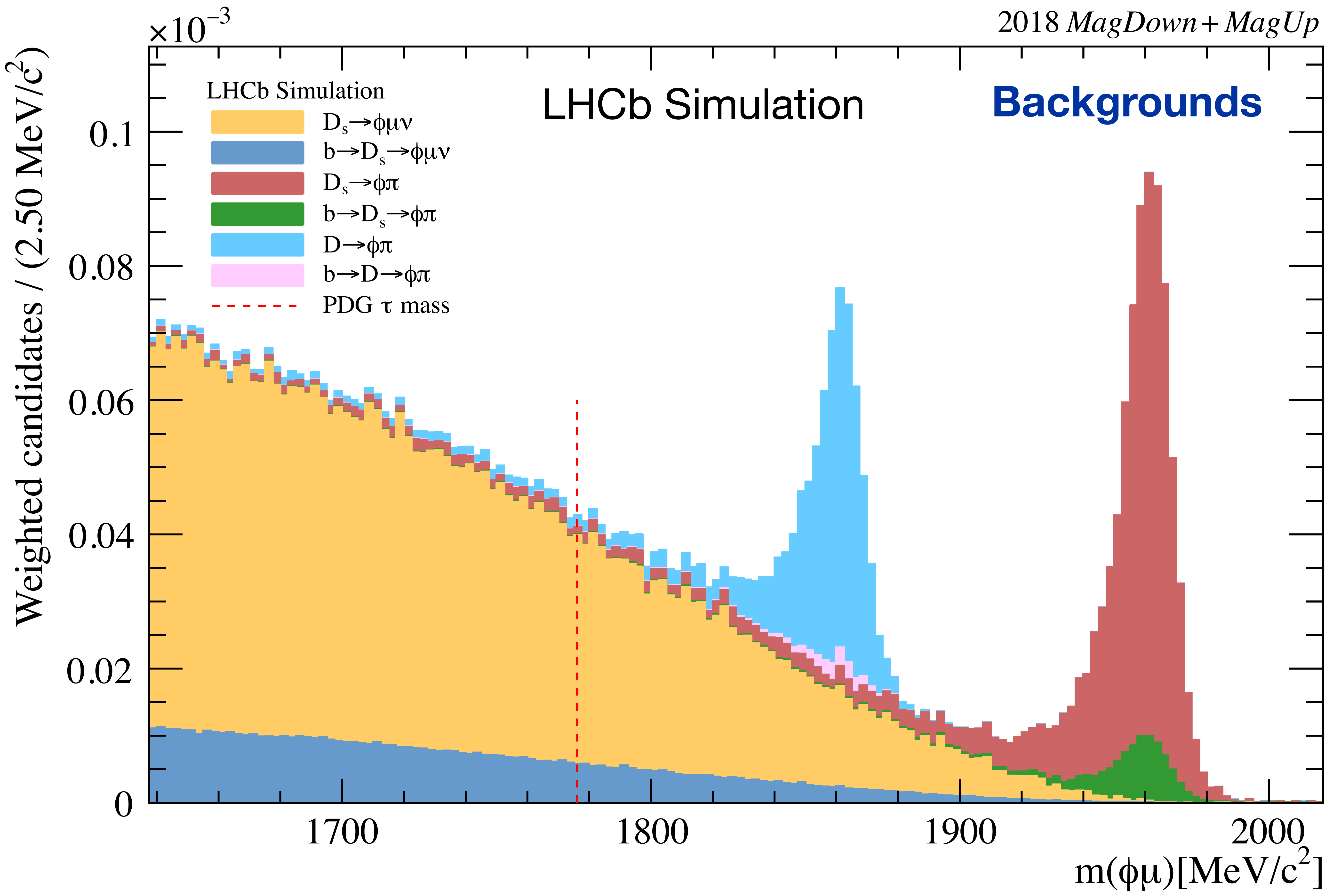
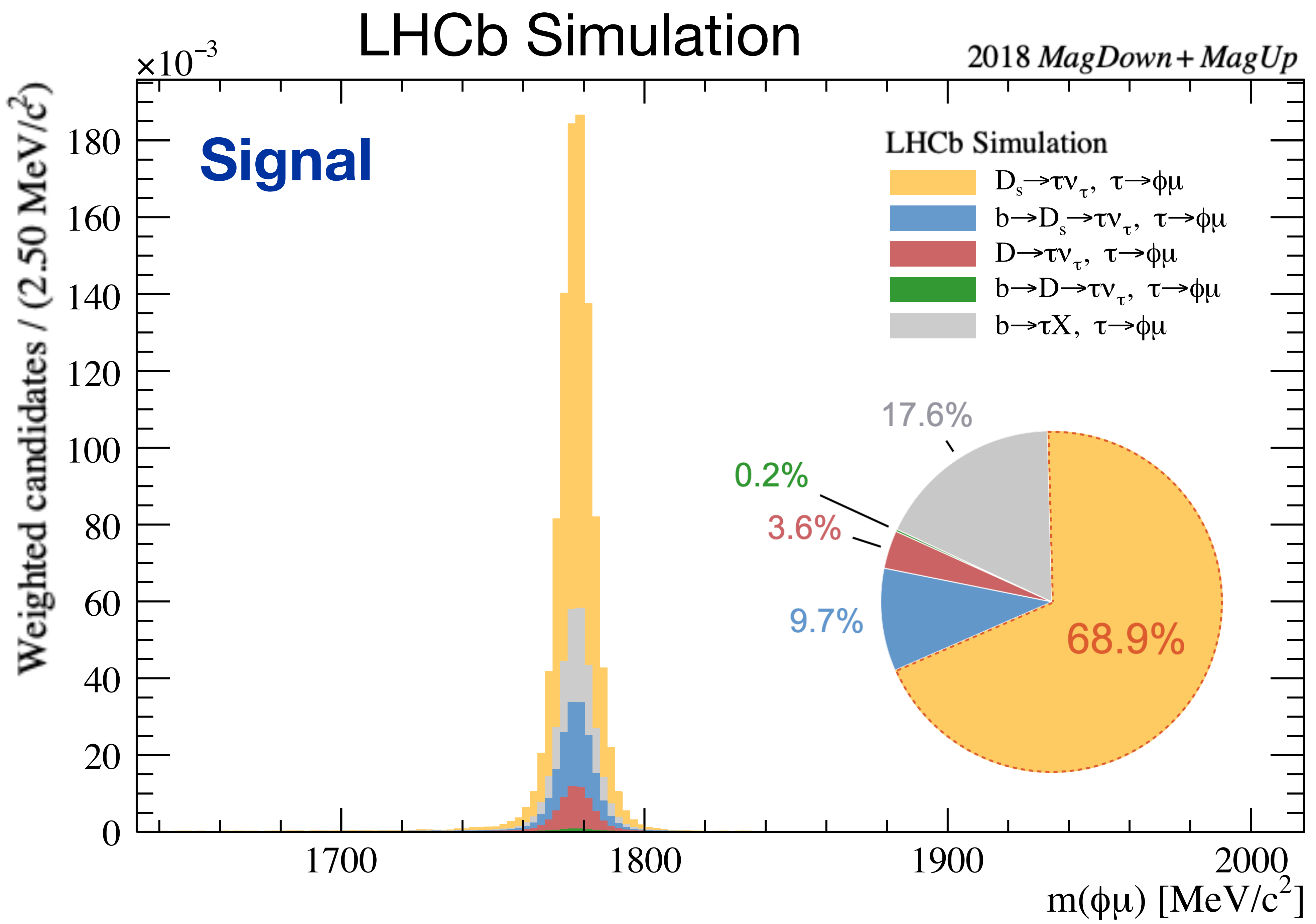


- $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$ expected in data: used to check fit procedure and selections.
- Exponential combinatorial component.
- Background suppression to improve signal sensitivity ($\propto \epsilon_{sig}/\sqrt{B}$) using multivariate classifiers.

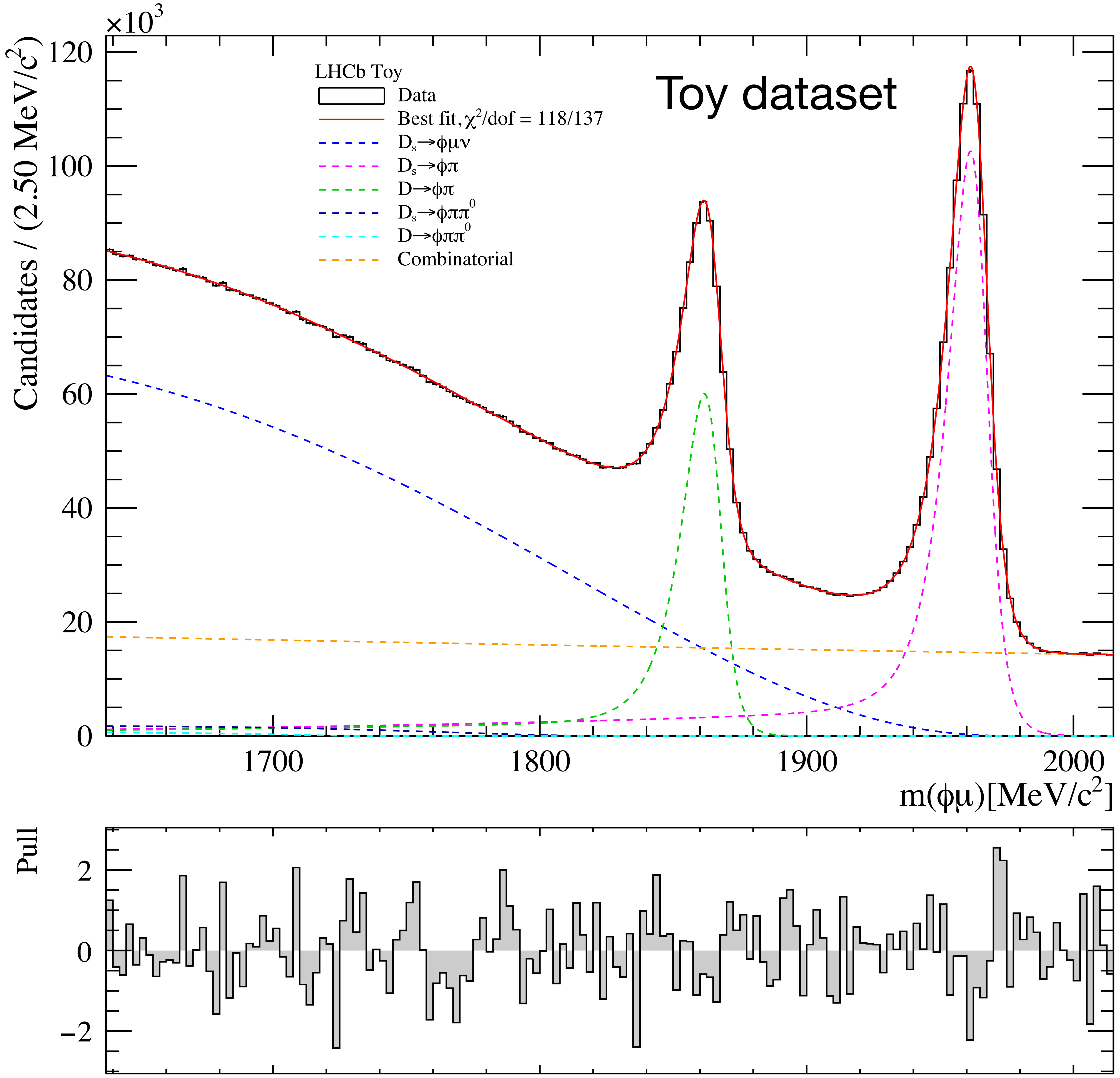
$m(\phi\mu)$ with MC simulations for Run 2 analysis

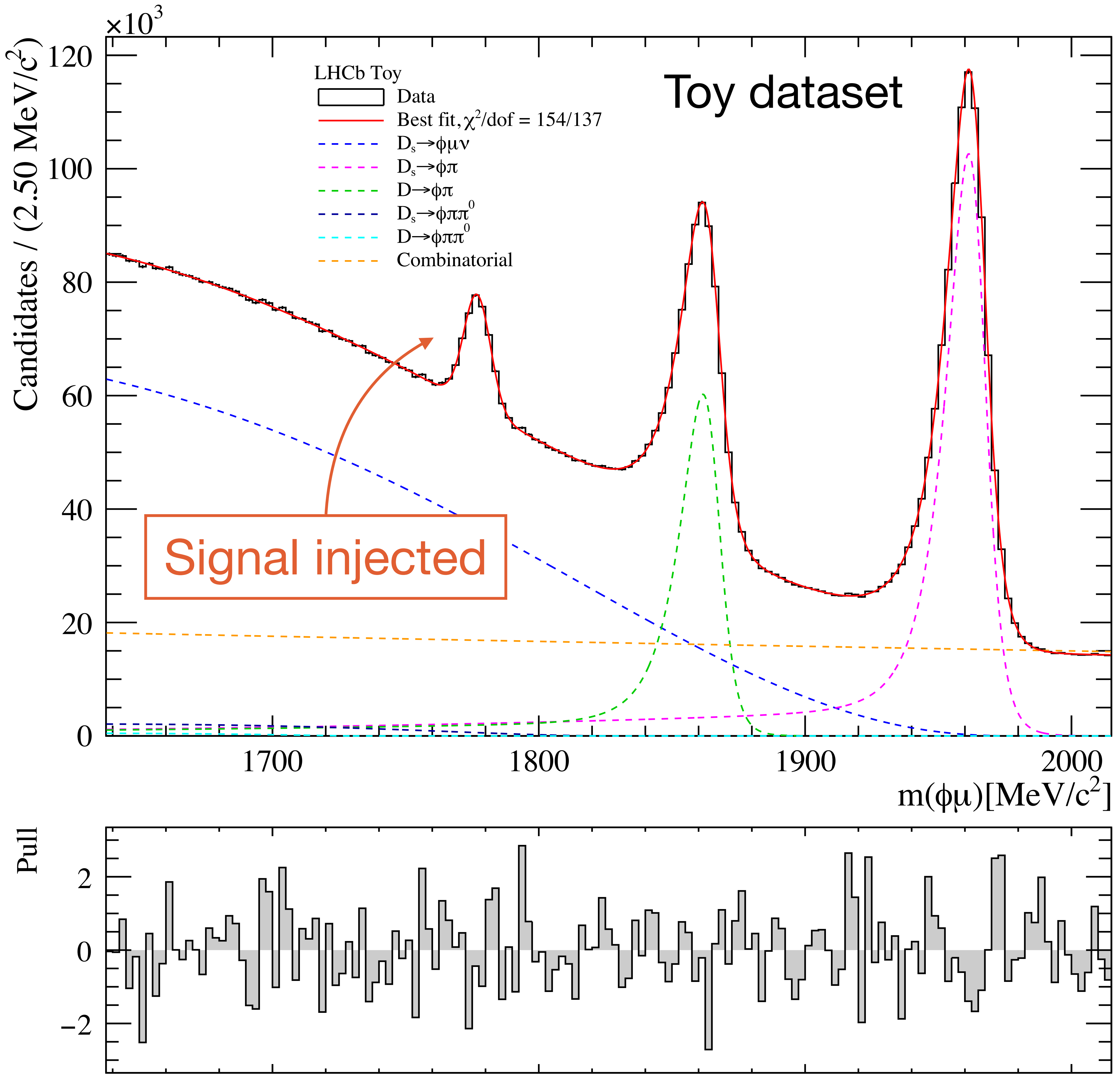




- To study signal and background channels, millions events with full detector response simulated.
- τ production dominated by $D_s^+ \to \tau^+\nu_\tau$ decays.

Complete fit to pseudo-experiments





- Toy dataset fitted with the main bkg shapes derived from MC, including the signal component.

Conclusions and future prospects

- Main takeaways:

  (i) **First search for $\tau^+ \to \phi\mu^+$ ever conducted at a hadron collider.**

  (ii) **First exclusive HLT1 trigger for $\tau^+ \to \phi\mu^+$ selection at 30 MHz in Run 3.**

- LHCb analysis ongoing $\to$ Final results expected soon.
- Preliminary blind analysis on Run 2 sets an upper limit of a $\approx 1 \times 10^{-6}$ @ $90\,\%\,\mathrm{CL}$ [CERN-THESIS-2022-221].
- Thanks to the new dedicated trigger, fully operational since the start of 2025 data-taking, expect much higher sensitivity with Run 3 (and Run 4) data.
  - Selection efficiency improved by a factor 6 compared to Run 2.
- UL projection with 2025 data (simple extrapolation with no optimization) reaches $\approx 2.5 \times 10^{-7}$ @ $90\,\%\,\mathrm{CL}$, already improving Run 2 expectation by a factor ≈ 4.

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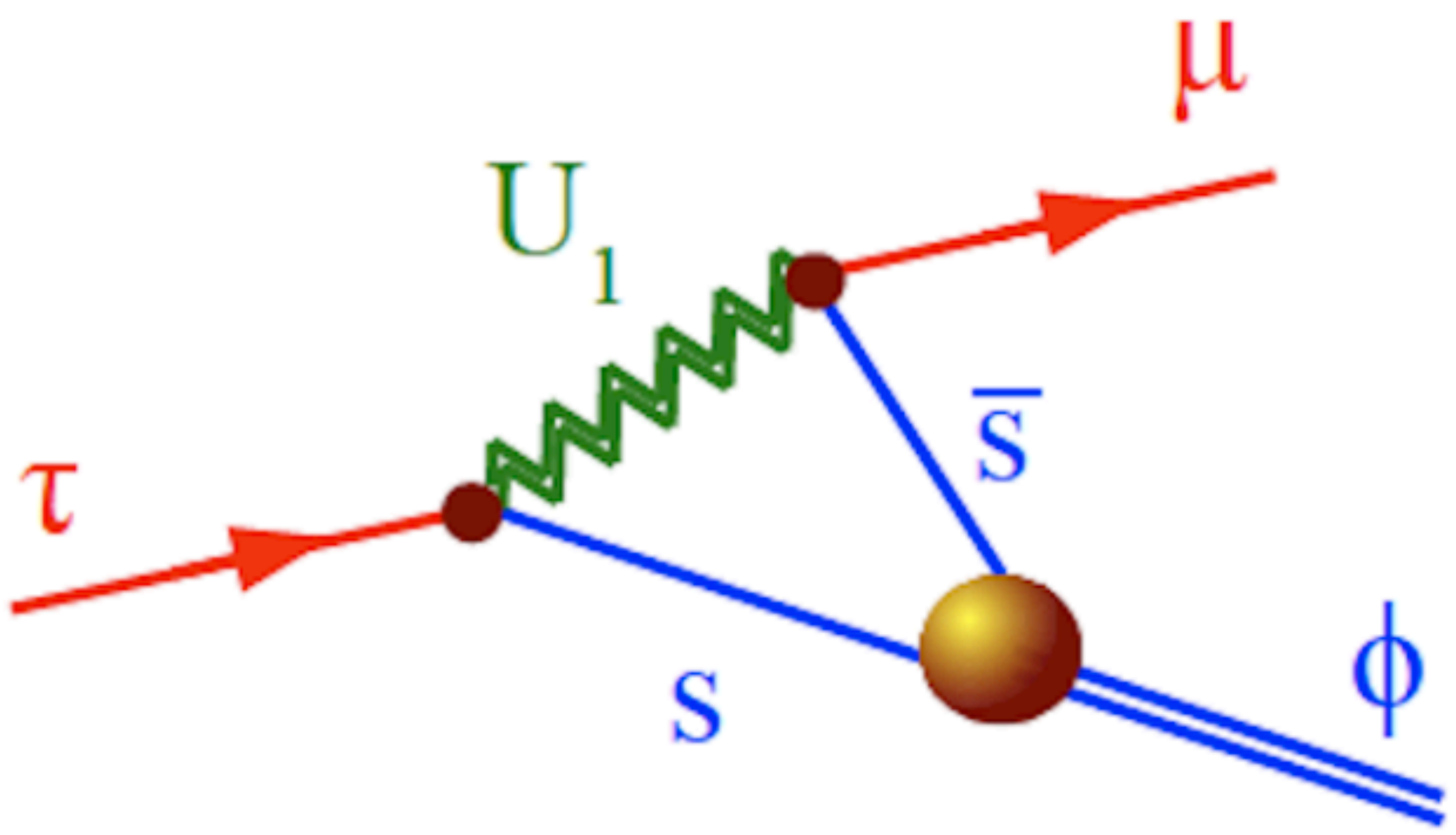
Exclusive triggers: paradigm shift unlocking new sensitivity to rare decay searches at the high-intensity frontier

Additional material

Backup slides

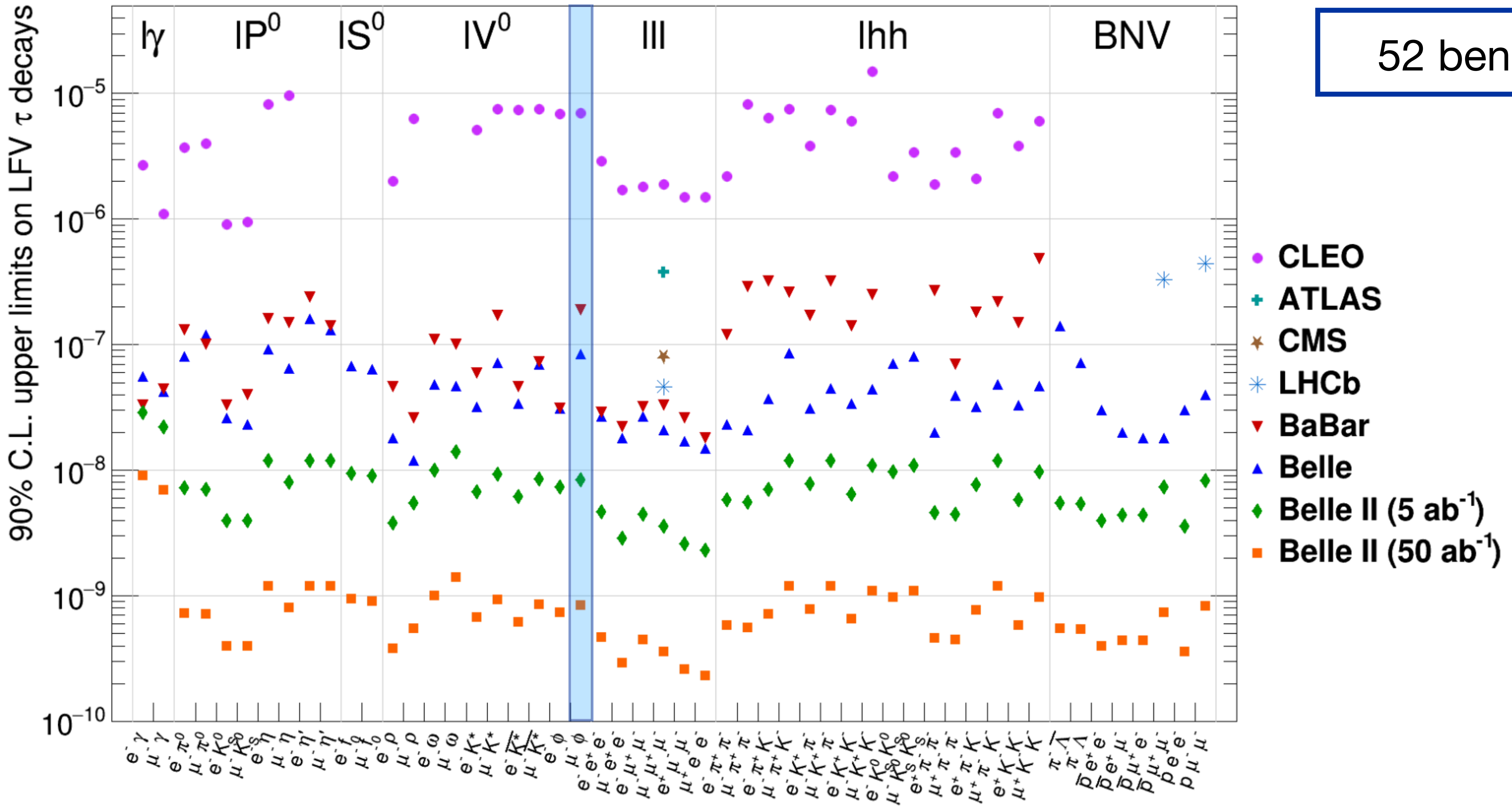
NP beyond the Standard Model for $\tau^+ \to \phi\mu^+$

- Several scenarios beyond Standard Model predict LFV at branching fraction approaching the current experimental sensitivity.
- New mediators included to make the process possible also at the tree level.
  - For instance, leptoquark model formulated by Gino Isidori *et al.* predict $\mathscr{B}(\tau^+ \to \phi\mu^+)$ in the range from 10^{-11} to few times 10^{-8} [1].



Why look for LFV in τ decays?

- The τ is the only lepton massive enough to decay both into leptons and hadrons.



52 benchmark τ decay channels

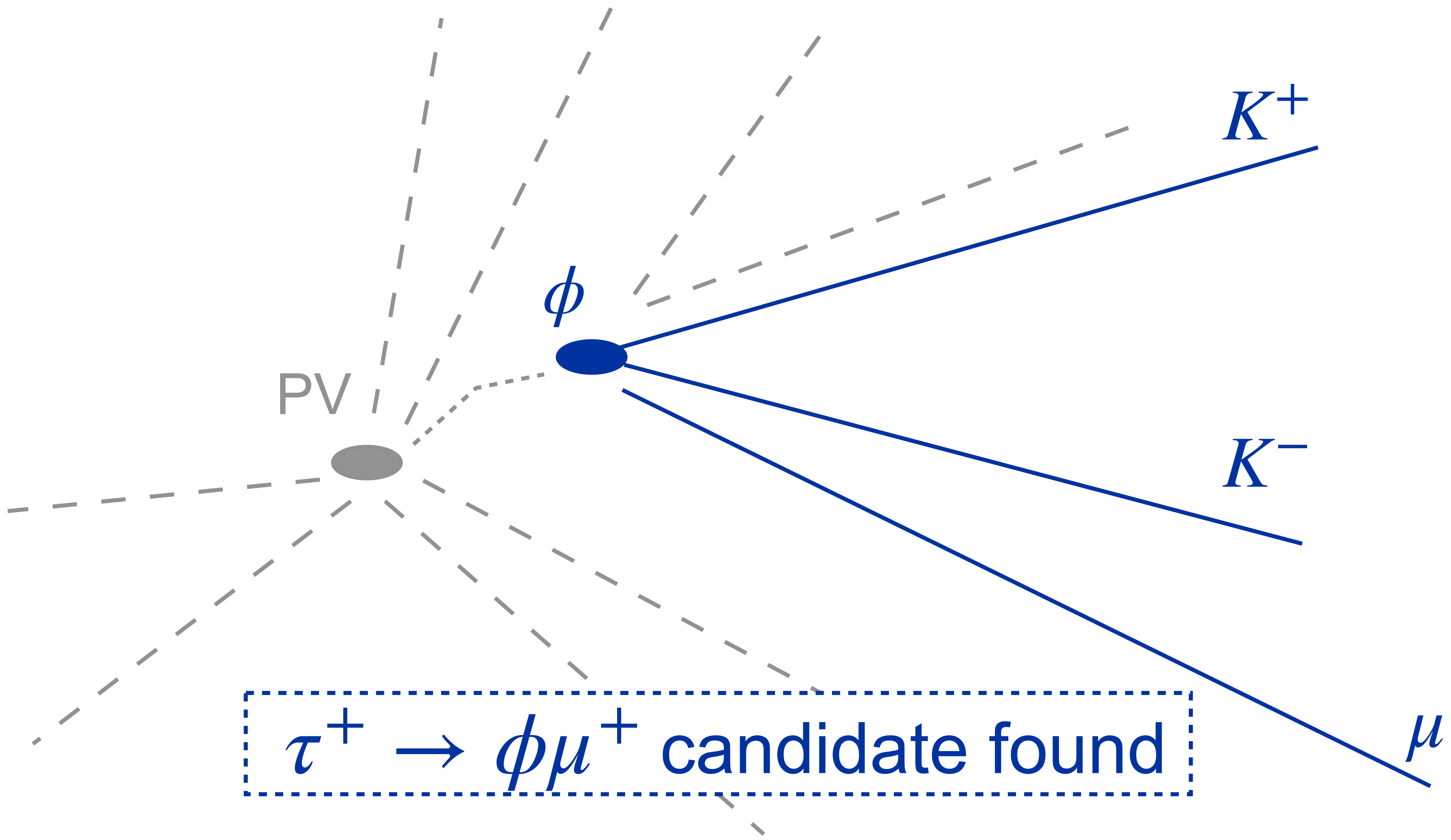
e^+e^- experiment

pp experiments

e^+e^- experiments

Candidate selection strategy @ HLT1

- Events selected combining a neutral vertex with a third track.
  - $\phi(1020)$ mass used to select V0 candidate + other selections.
  - `is_muon` requirement exploited for the third track + other selections.
  - No 3-tracks vertex fit required → τ mass requested + DOCA(ϕ, μ) to select the closest μ to ϕ + PT and $c\tau$.



Object	Variable	Requirement	Unit
Tracks to make ϕ	$\min(\chi^2_{IP})$	4	–
	$\min(IP)$	0	mm
	$\min(p_T)$	450	MeV/c
	$\min(p)$	3.0	GeV/c
	η	$[2, 5]$	–
$\phi(1020)$	$\max(DOCA)$	0.2	mm
	vertex z position	$[-200, 650]$	mm
	$\min(IP)$ w.r.t. best PV	0	mm
	$\min(dz)$ w.r.t. best PV	0	mm
	$\min(d\rho)$ w.r.t. best PV	0	–
	$\min(DIRA)$ w.r.t. best PV	0.9986	–
	$\min(p_T)$	900	MeV/c
	vertex $\max(\chi^2)$	10	–
	$\min(\chi^2_{FD})$	10	–
	$\lvert m_{K^+K^-} - m_{PDG}\rvert$	< 30	MeV/c
Third Track	$\min(\chi^2_{IP})$	9	–
	$\min(IP)$	0	mm
	$\min(p_T)$	350	MeV/c
	$\min(p)$	3.0	GeV/c
	η	$[2, 5]$	–
	is_muon()	true	–
$\phi(1020) + \mu$	$\min(p_T)$	2.5	GeV/c
	$m_{\phi\mu}$	$\in [1620, 2050]$	MeV/c^2
	$\max(DOCA)$	0.2	mm
	$c\tau$	$\in [0.07, 1]$	mm

CERN