Prospects for $b \to s\tau^+\tau^-$ and related decays at LHCb

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On behalf of the LHCb collaboration

Mini-workshop on missing particle signatures and new physics at Belle II and LHCb

6th July 2021

The charged leptons

- Three “families” of charged leptons:

The charged leptons

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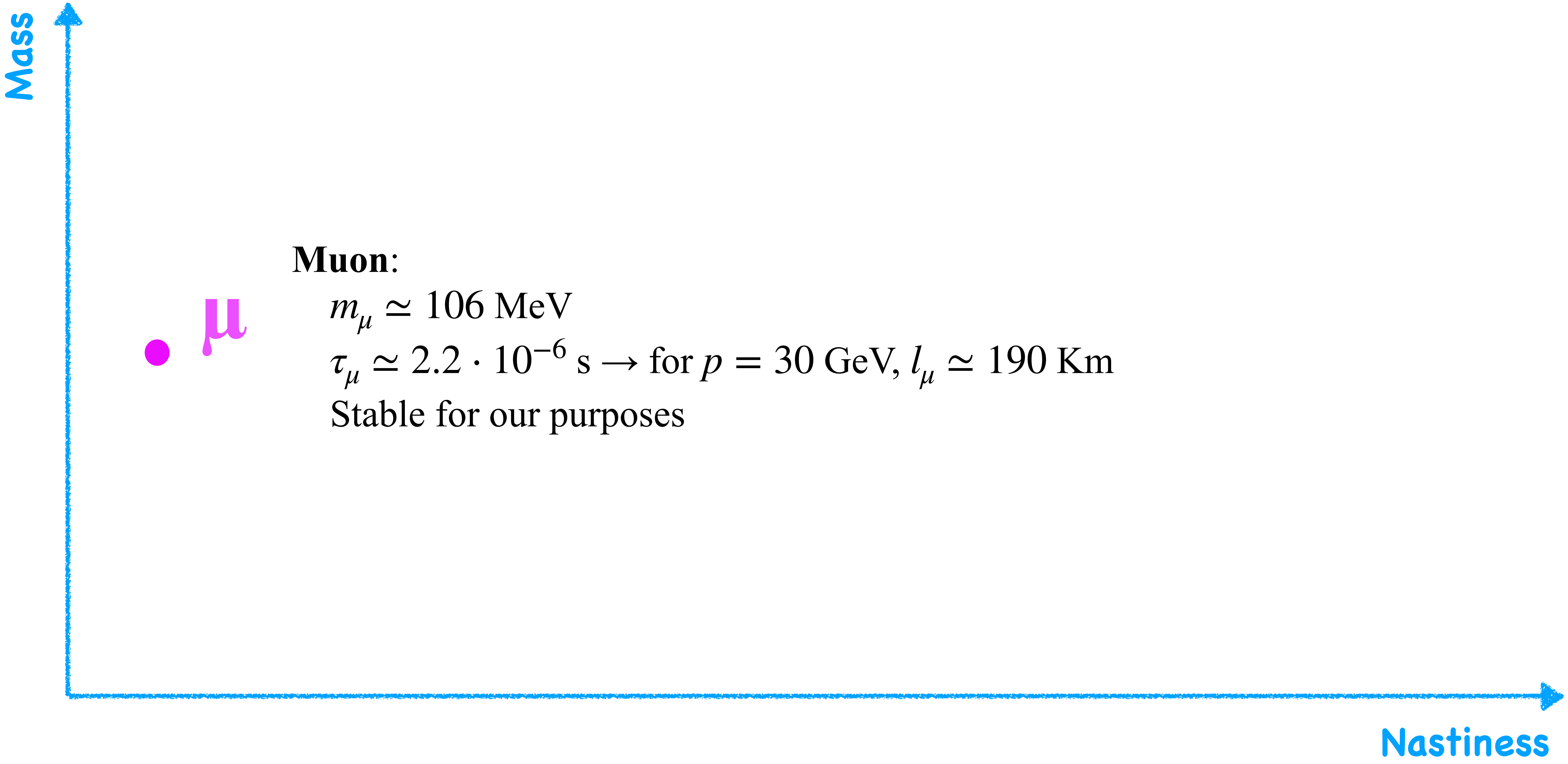

Muon:

$m_\mu \simeq 106$ MeV

$\tau_\mu \simeq 2.2 \cdot 10^{-6}$ s $\rightarrow$ for $p = 30$ GeV, $l_\mu \simeq 190$ Km

Stable for our purposes

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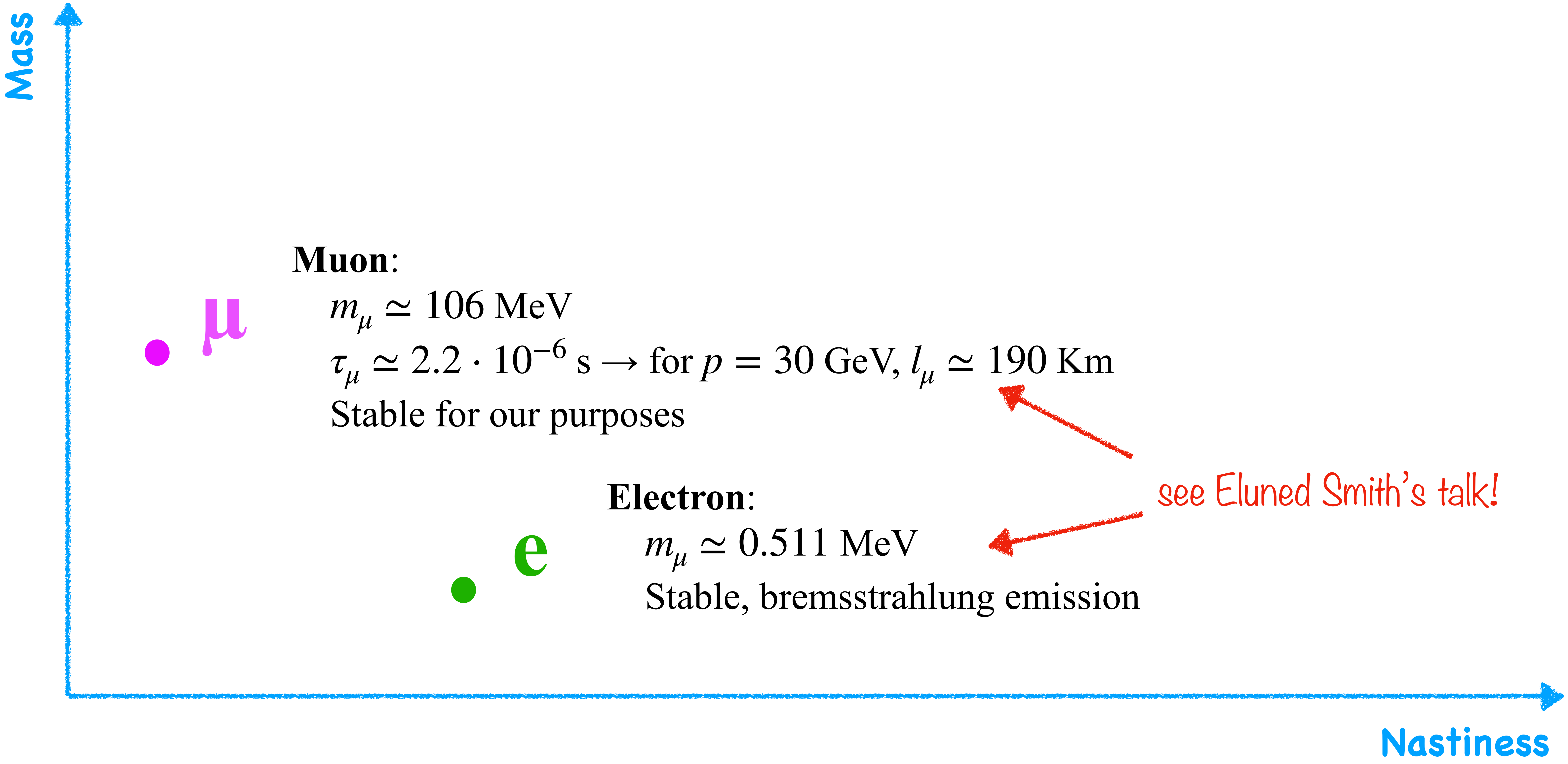

The charged leptons

- Three “families” of charged leptons:

Tau:

$m_\tau \simeq 1700$ MeV

$\tau_\tau \simeq 290 \cdot 10^{-15}$ s $\rightarrow$ for $p = 30$ GeV, $l_\tau \simeq 1.5$ mm

Decays before the detection

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Electron:

$m_\mu \simeq 0.511$ MeV

Stable, bremsstrahlung emission

see Eluned Smith’s talk!

Mass

Nastiness

τ

μ

e

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Nastiness

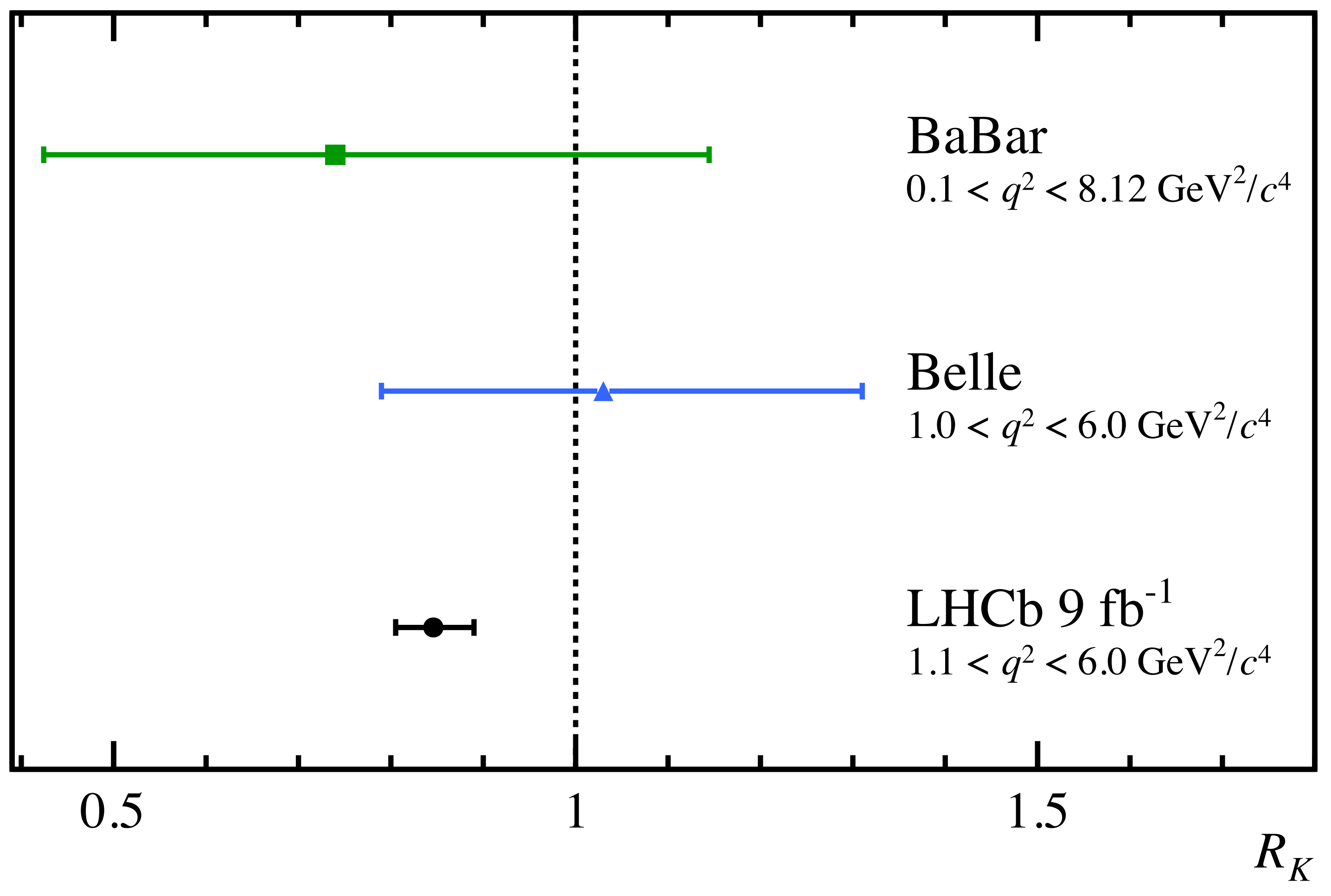
- No upper bound to number of lepton families in SM, but mass of fourth neutrino constrained experimentally: $m_{\nu_4} \gtrsim 45$ GeV [Adv. Ser. Dir. HEP 23 (2015) 89-106]

Lepton flavor (universality) violation

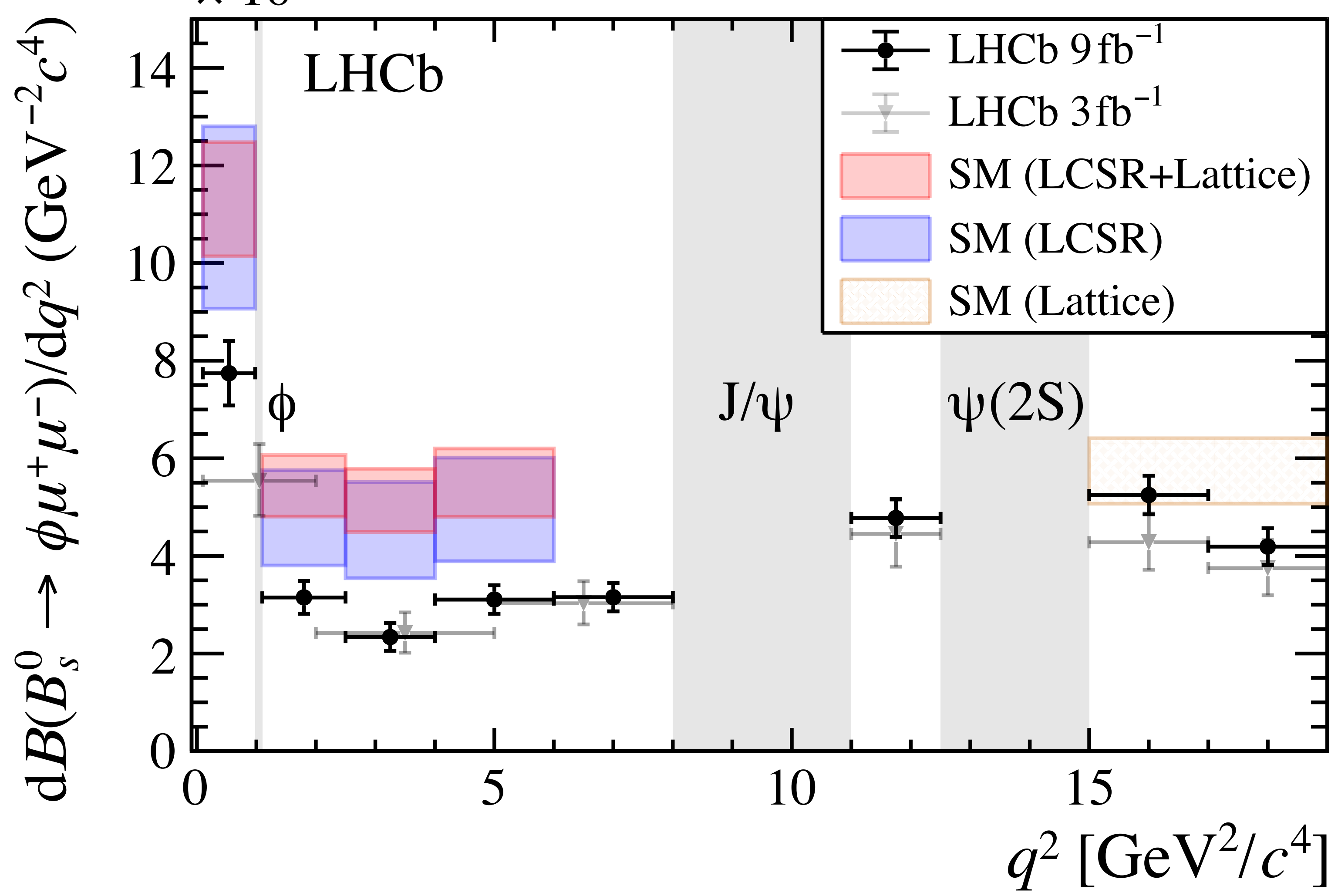
- Two properties (still) hold in the SM:
  1) **Lepton flavor number (accidentally) conserved in the SM** (by charged leptons and neutrinos)
  2) **Lepton flavor universality**: couplings to gauge bosons do not depend on lepton family
- SM could be just a "low-energy version" of a more general theory:
  - Lepton flavor conservation violated (LFV) and/or lepton families could behave very differently at high energies (LFUV)

- Recently hints of LFUV in several measurements (not an exhaustive list):

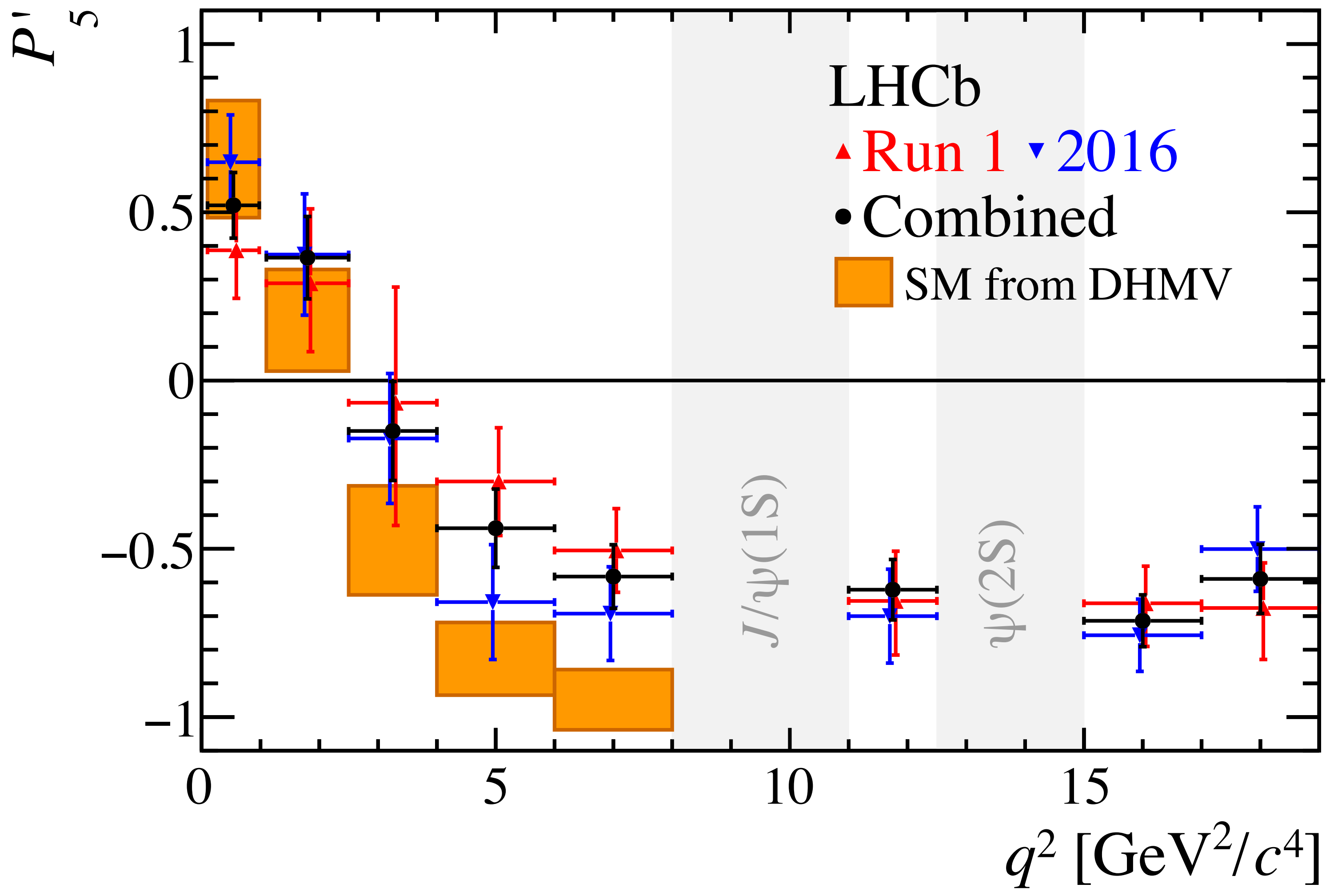
[LHCb-PAPER-2021-004]



[LHCb-PAPER-2021-014]



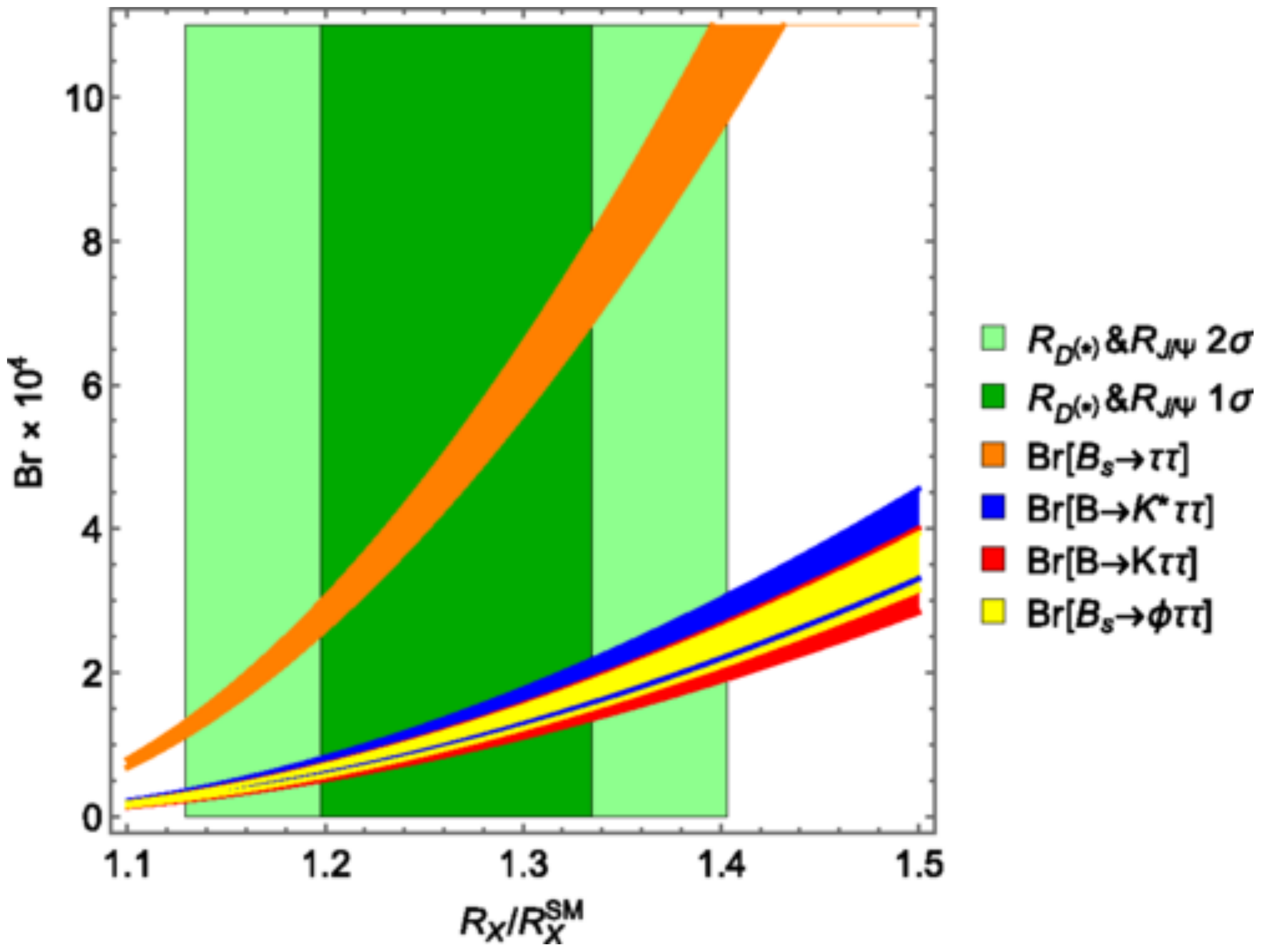
[PRL 125 (2020) 011802]



- Many BSM models (e.g. SUSY, Z', LQ, …) allow LF(U)V processes [Phys. Rev. D 59, 034019, 1999], [Phys. Rev. D 92, 054013, 2015], [arXiv:1505.05164], [arXiv:1609.08895]

Rare B decays with τ leptons in the final state

- **Rare $b \to s\, l^+ l^-$ decays** excellent probes for new physics:
  - **Branching ratios could be enhanced** by NP contributions



[Phys. Rev. Lett. 120, 181802, 2018]

- **Tau leptons in the final state**:
  - **Pros**:
    1) $m_\tau \sim 17\, m_\mu \sim 3500\, m_e$, **taus could be the most sensitive to NP** according to some models and **enhanced by up to several orders of magnitude**
    2) **τ** modes **still largely unexplored** (state of the art in the next slide)
  - **Cons**:
    1) **More complex experimentally**:
       - It decays before it can be detected, **actually measure final state particles**
       - Neutrinos in the final state, **missing energy**. LHCb has not 4π coverage!

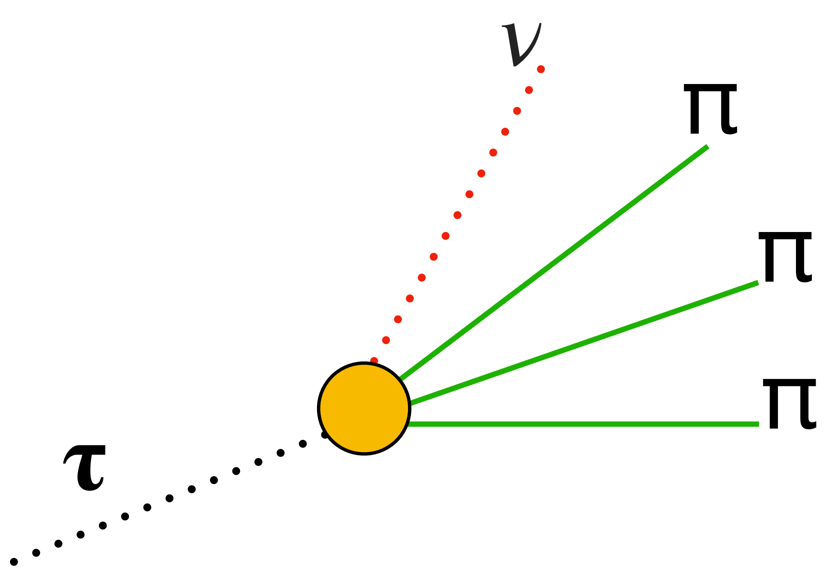
- Not only rare decays! Sophisticated reconstruction techniques used for $R(D^{(*)})$ (very short introduction in backup)

Tau modes: the state of the art

Decay	SM prediction	Measurement or limit at 90% CL		Reference
$B^0 \to \tau e$	-	$< 2.8 \cdot 10^{-5}$	(BaBar)	[Phys.Rev. D 77, 091104 (2008)]
$B_s^0 \to \tau e$	-	-		-
$B_{(s)}^0 \to \tau \mu$	-	$< 1.2\ (3.4) \cdot 10^{-5}$	(LHCb)	[Phys. Rev. Lett. 123, 211801, 2019]
$B^+ \to K^+ \tau e$	-	$< 3.0 \cdot 10^{-5}$	(BaBar)	[Phys. Rev. D 86, 012004 (2012)]
$B^+ \to K^+ \tau^+ \mu^-$	-	$< 3.9 \cdot 10^{-5}$	(LHCb)	[JHEP 2006 (2020) 129]
$B^+ \to \pi^+ \tau e$ / $B^+ \to \pi^+ \tau \mu$	-	$< 7.5 \cdot 10^{-5}$ / $7.2 \cdot 10^{-5}$	(BaBar)	[Phys. Rev. D 86, 012004 (2012)]
$B^0 \to K^{*0} \tau e$ / $B^0 \to K^{*0} \tau \mu$	-	-		-
$B^0 \to \tau \tau$	$(2.22 \pm 0.19) \cdot 10^{-8}$	$< 1.6 \cdot 10^{-3}$	(LHCb)	[Phys. Rev. Lett. 118, 251802, 2017]
$B_s^0 \to \tau \tau$	$(7.73 \pm 0.49) \cdot 10^{-7}$	$< 5.2 \cdot 10^{-3}$	(LHCb)	[Phys. Rev. Lett. 118, 251802, 2017]
$B^0 \to K^{*0} \tau \tau$	$(0.98 \pm 0.10) \cdot 10^{-7}$	-		[Phys. Rev. Lett. 120, 181802, 2018]
$B^+ \to K^+ \tau \tau$	$(1.20 \pm 0.12) \cdot 10^{-7}$	$< 2.3 \cdot 10^{-3}$	(BaBar)	[Phys. Rev. Lett. 118, 031802 (2017)]
$B^+ \to \tau^+ \nu$	$(7.7 \pm 0.6) \cdot 10^{-5}$	$(1.09 \pm 0.24) \cdot 10^{-4}$	(Belle, BaBar)	[PDG]
$B^0 \to \pi^- \tau^+ \nu$	$(9.35 \pm 0.38) \cdot 10^{-5}$	$< 2.5 \cdot 10^{-4}$	(Belle)	[Phys. Rev. D 93, 032007 (2016)]

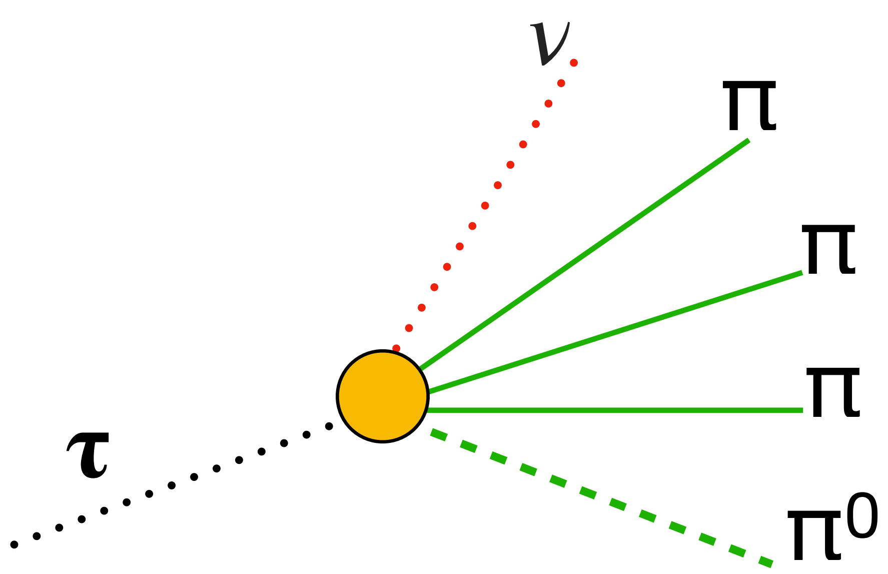
Tau decays: main channels used

- **Hadronic decay**:
  - $\tau^- \rightarrow a_1^-(1260)\ \nu_\tau \rightarrow \rho^0(770)\ \pi^-\nu_\tau \rightarrow \ \pi^-\pi^+\pi^-\nu_\tau$
  - Additional neutral pion component: $\tau^- \ \rightarrow \ \pi^-\pi^+\pi^-\pi^0\nu_\tau$
  - **Decay vertex position reconstructed** from pion tracks
  - $\rho^0(770) \rightarrow \pi^+\pi^-$: **cross-shape in pseudo-Dalitz plane**



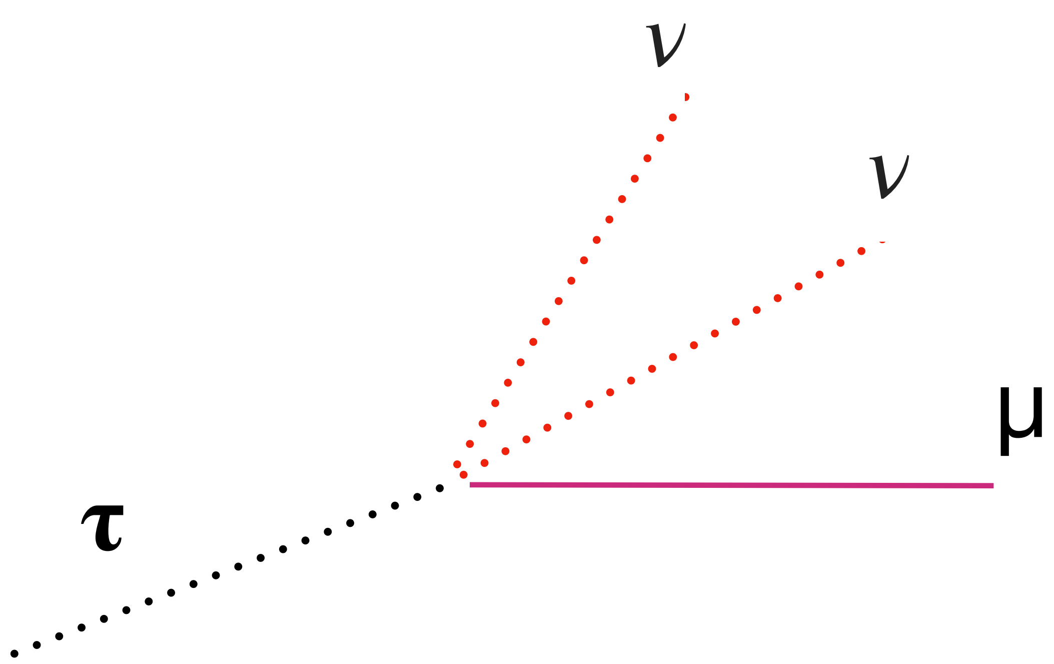
BR = (9.31 ± 0.05) %

+



BR = (4.62 ± 0.05) %

- **Muonic decay**:
  - $\tau^- \ \rightarrow \ \mu^- \ \bar{\nu}_\mu \ \nu_\tau$
  - **Decay vertex not reconstructed**, more topological constraints from the rest of the event needed

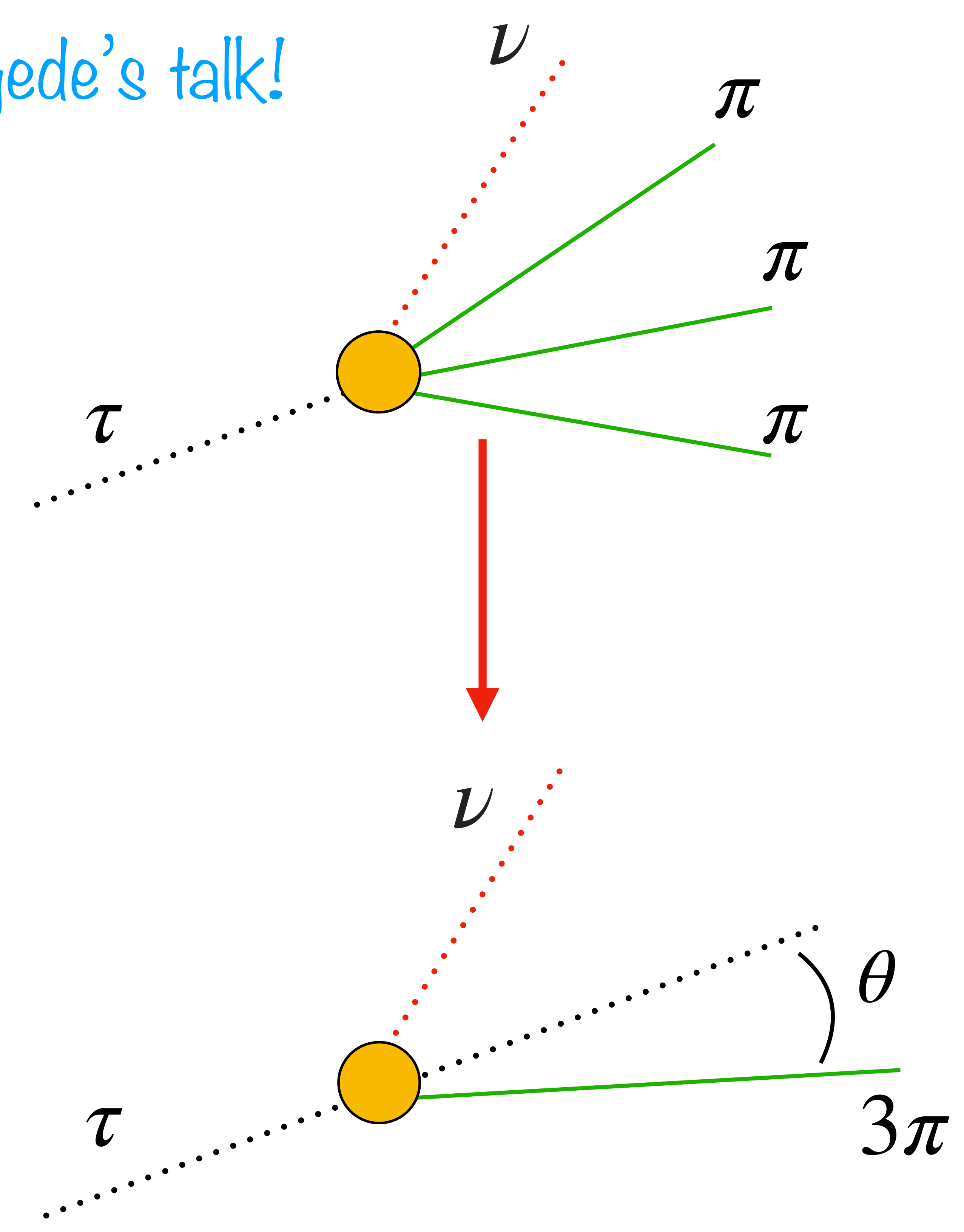


BR = (17.39 ± 0.04) %

- And many others: [PDG]

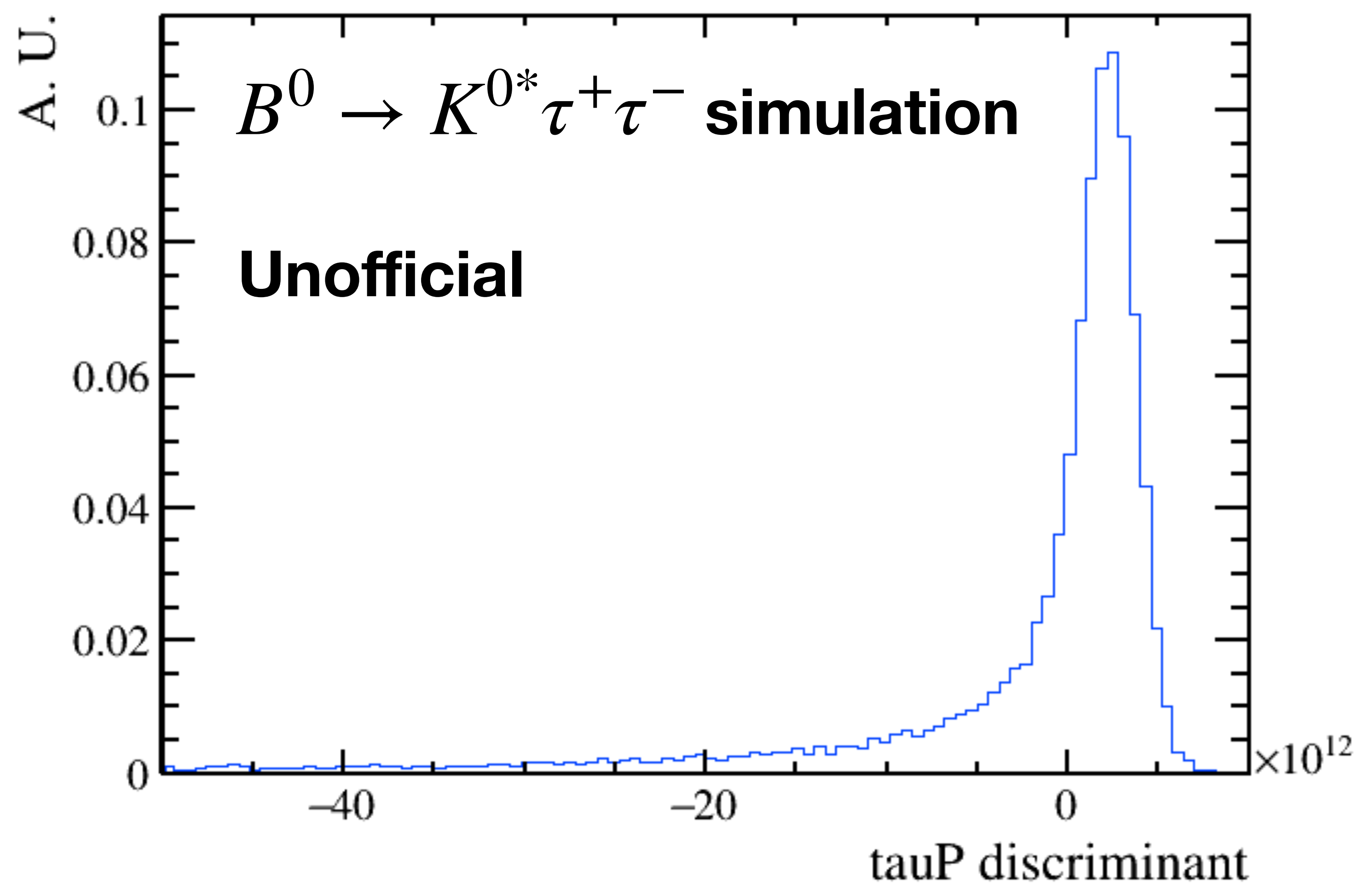
Analytic mass reconstruction

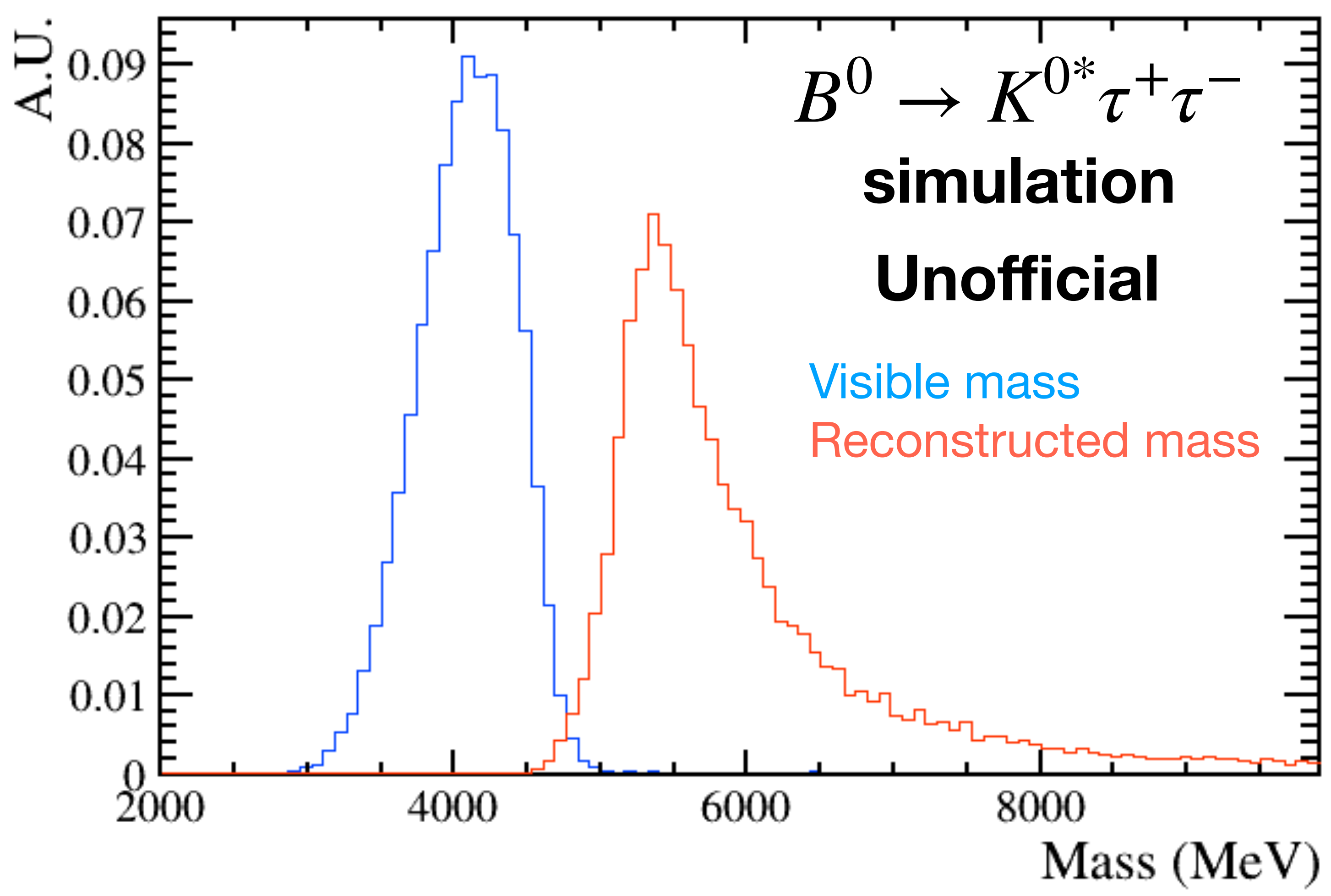
see also q^2 reconstruction in Ulrik Egede's talk!



- Hadronic tau decay reconstructable **analytically**:
  - Impose the constraint $m_\tau = 1776.86$ MeV
  - $|\vec{p_\tau}| = \dfrac{(m_\tau^2 + m_{3\pi}^2)\,|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p_{3\pi}}|^2\cos^2\theta)}$
  - Momentum direction from tau and B decay vertices (if B vertex available)
  - Square root argument can be affected by vertex resolution:
    - Apply a correction: absolute value, set to 0 if negative, vertex constraint, …

      (don't forget your systematics 🙂)

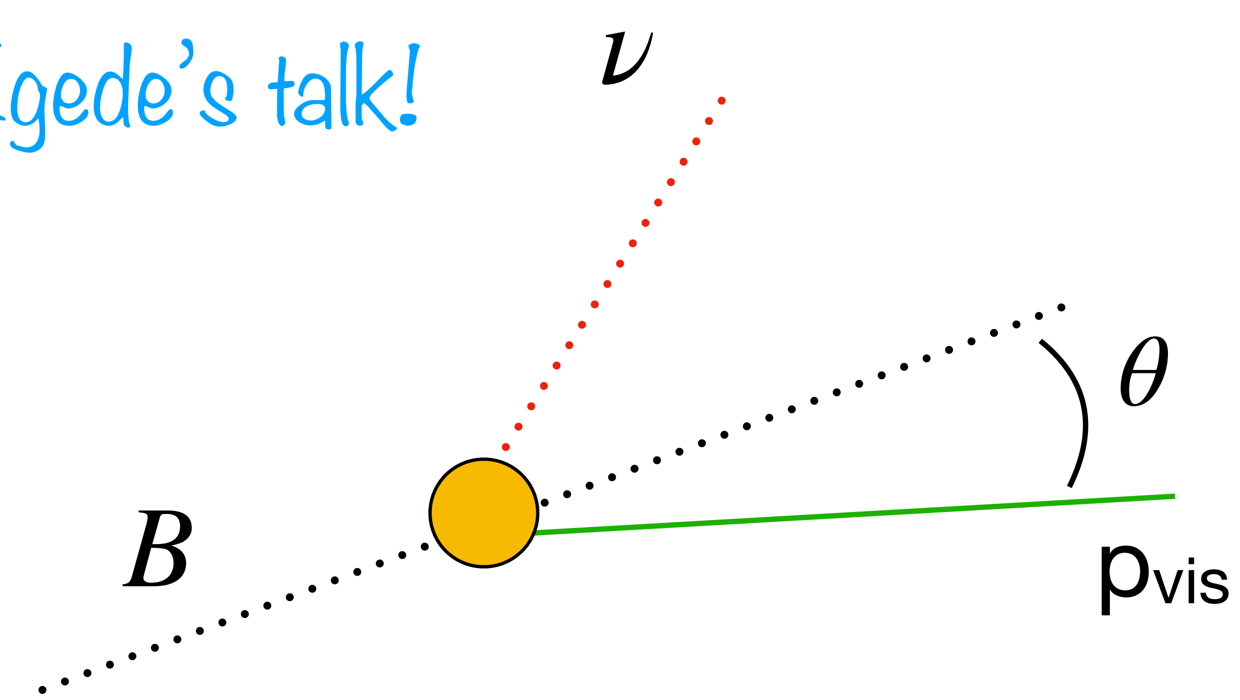




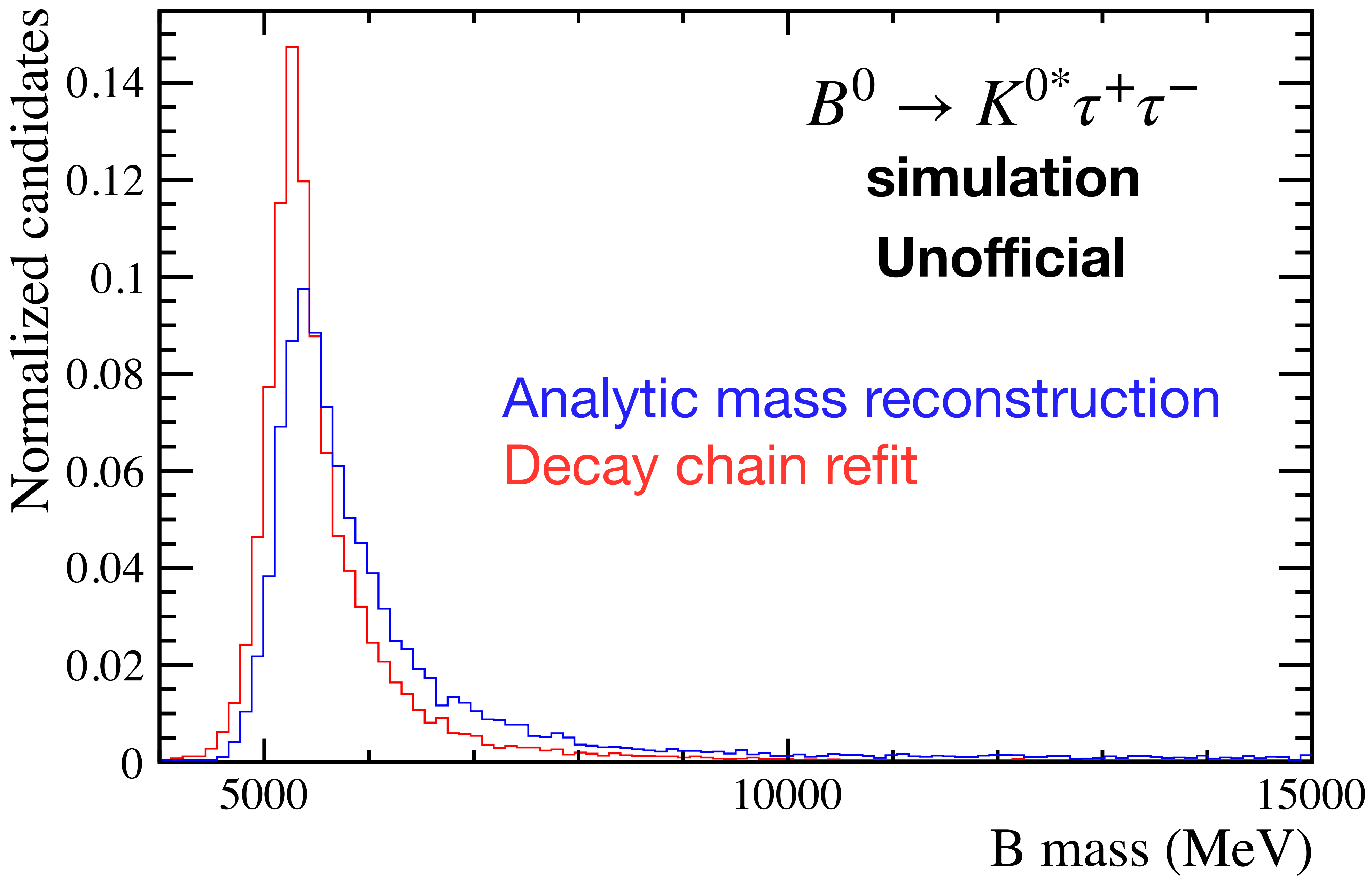
More missing energy recovering techniques

- **Minimally corrected mass**: $M_c = \sqrt{M_{vis}^2 + p_{vis}^2 \sin^2\theta} + p_{vis}\sin\theta$
  - Minimal correction to take into account neutral/undetected particles
  - $\sqrt{m^2 + p^2} + p =$ invariant mass of a two-body decay with a massless particle in the final state

see also Ulrik Egede's talk!

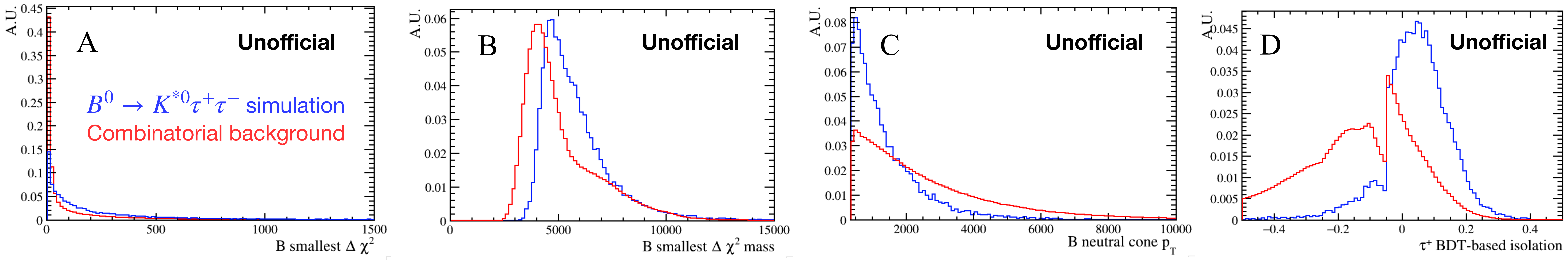


- Refit of the decay chain applying **mass constraints:**
  - Improve mass resolution
  - Need to initialize the fitter, analytic reconstruction can be used
  - Fitter can fail, reduced efficiency



Isolation variables

- Isolation variables estimate the **“activity” near signal candidate**: estimate how likely it is for a given track in proximity of the signal candidate to be actually part of it
- Examples:
  - A) **Smallest $\Delta\chi^2$**: smallest variation in vertex χ^2 when adding to the vertex an (two) additional track(s) from the event
  - B) **Smallest $\Delta\chi^2$ mass**: mass of the tracks obtained from definition A
  - C) **Cone isolation** (neutral and charged): properties of neutral or charged particles in a cone around the track (momentum, transverse momentum, track multiplicity, asymmetries, …)
  - D) **MVA-based track isolation**: obtained from MVA output using kinematic and geometrical variables of given track

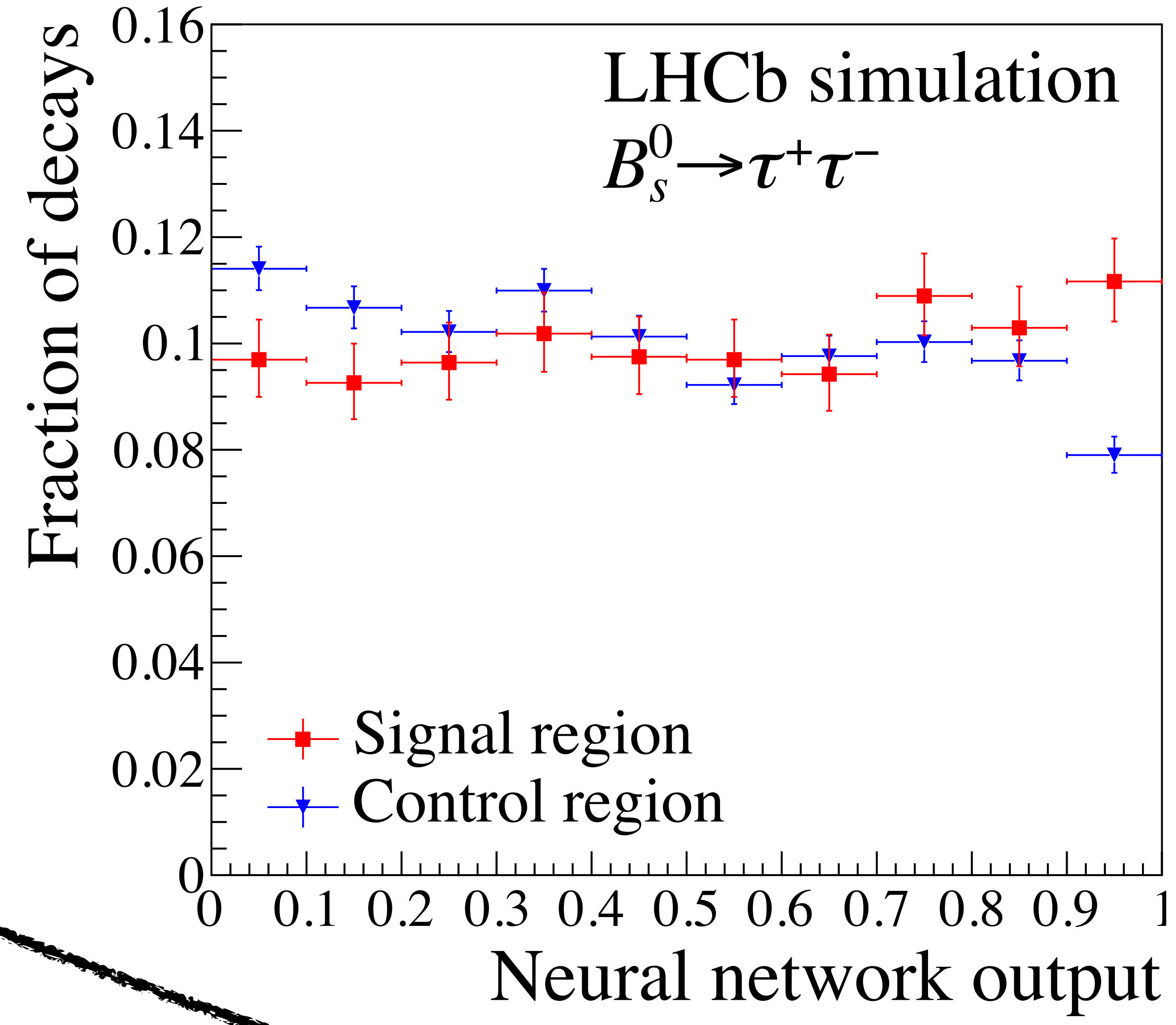


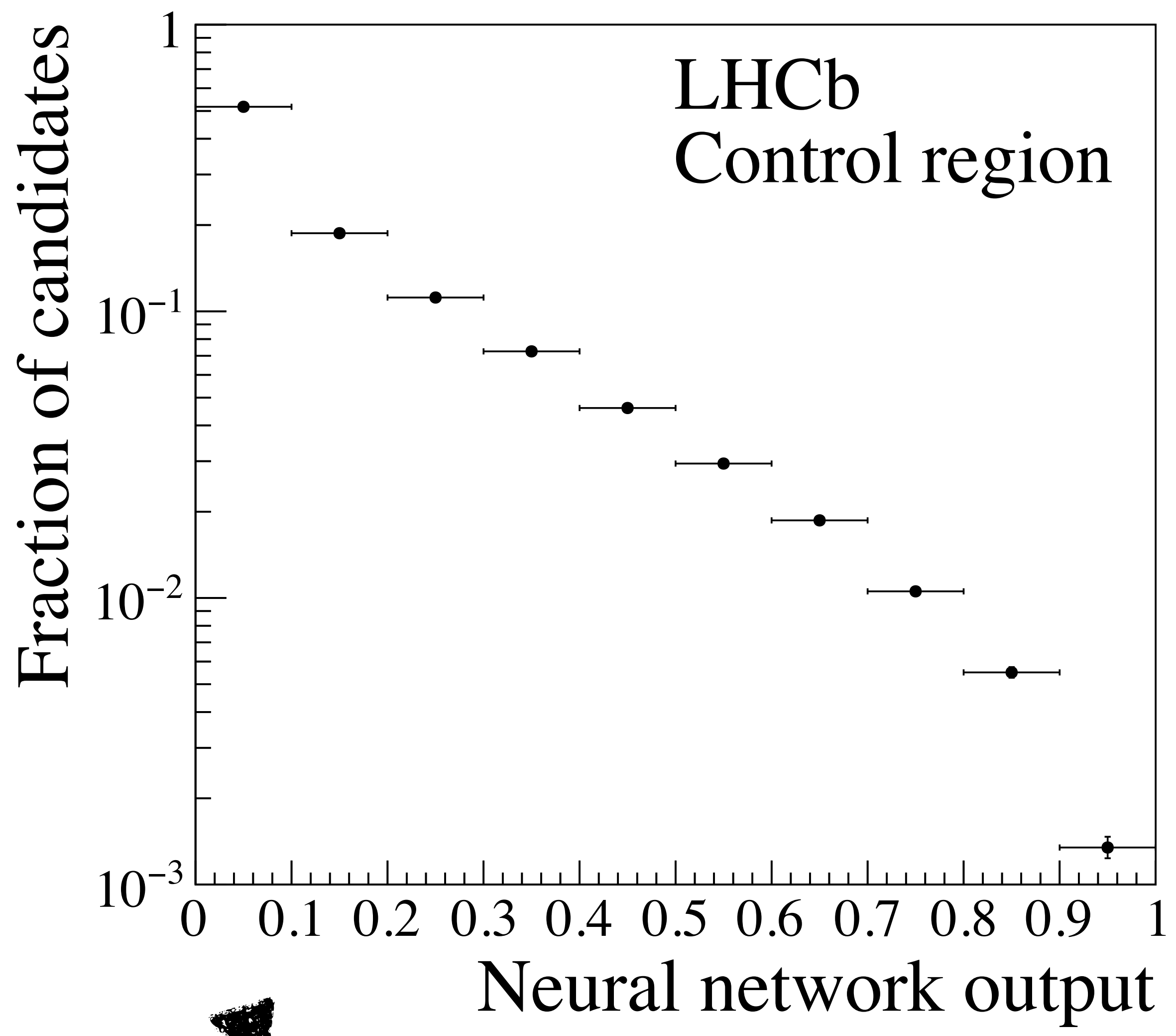
MVA techniques

- Wide variety available (BDT, NN, …), strong effort by HEP community to develop new algorithms
- Exploit correlations between input variables to enhance discriminating power
- Used at different level of the analysis:
  - **Pre-selection variables** (e.g. trigger, particle identification, BDT-based isolation, …)
  - **Selection variables** (e.g. anti-combinatorial BDT, specific background MVA, …)
  - **Fit variables**:
    - ✓ Pros: recover discriminating power by combining several less discriminating variables
    - ✗ Cons: input variables validated on other channels, background description data-driven (correlation with variable(s) used to define control region)

[Phys. Rev. Lett. 118, 251802, 2017]

- $B^0_{(s)} \to \tau^+\tau^-$: final fit performed on **neural network output**
- NN flattened on simulated signal events
- Background from control region, peaking at low values

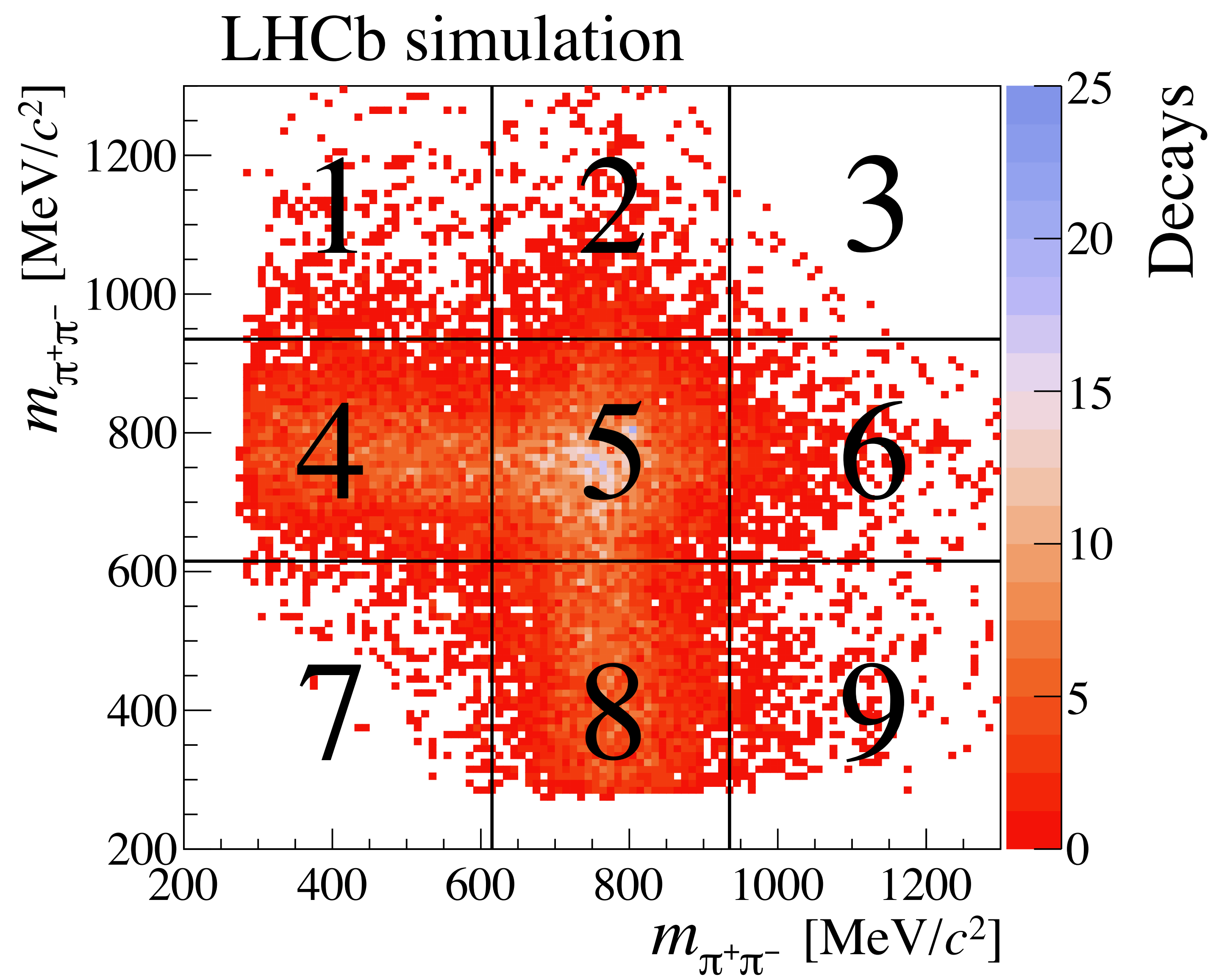




Control samples

- **Same-sign data**: require both final state leptons to have the same charge
  - Good for background modeling and cross-checks, but no exclusive events are present (always need an extra track)
  - Need to estimate peaking backgrounds

- **Pseudo-Dalitz plane**: invariant masses of oppositely charged pions from $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
  - $\rho^0(770)$ intermediate resonance forms cross-shape
  - Define signal region (e.g. box 5) and use other boxes to get background shape



[Phys. Rev. Lett. 118, 251802, 2017]

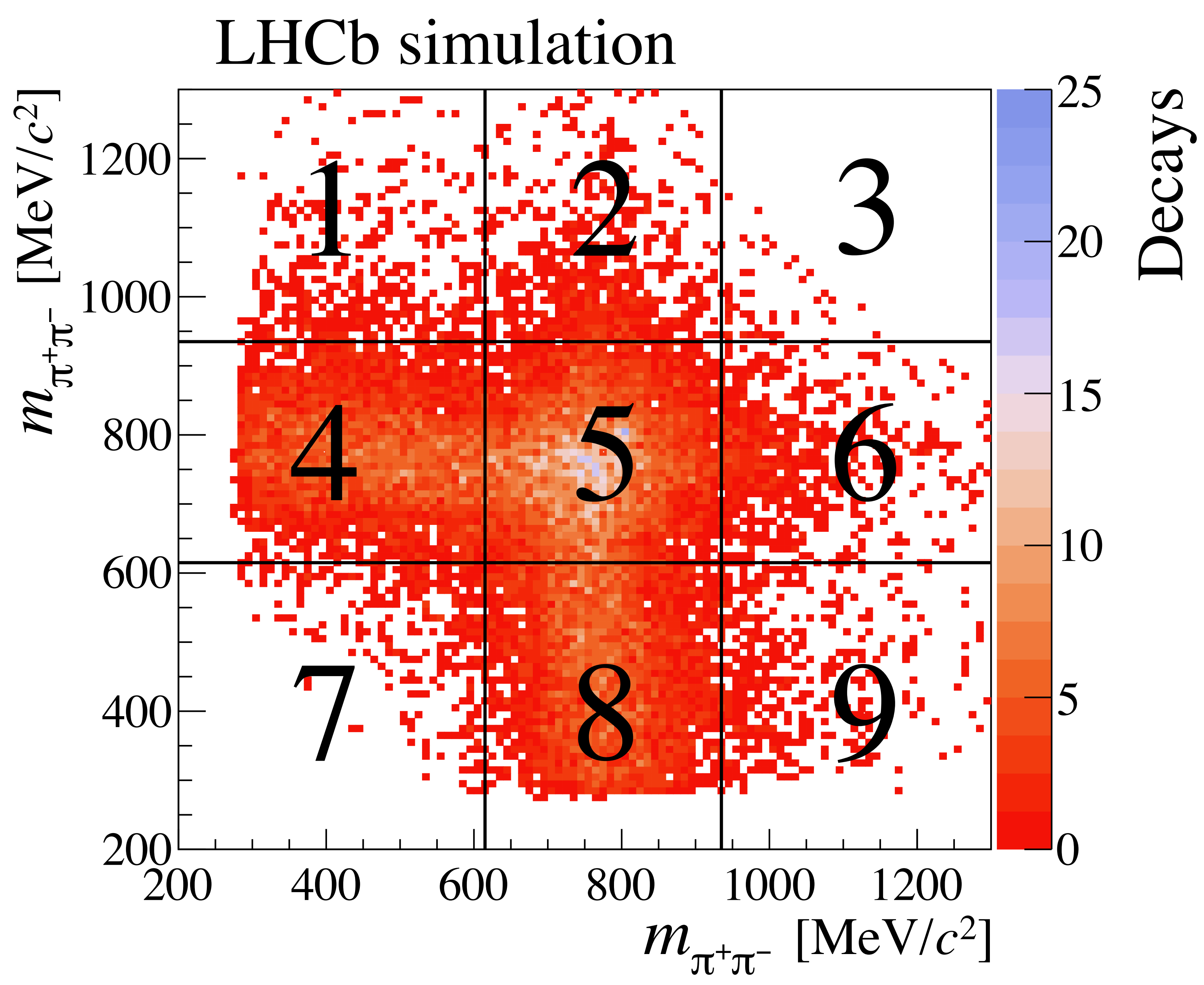
- **Mass sidebands**:
  - Fit on events close to mass peak, background shapes from sidebands

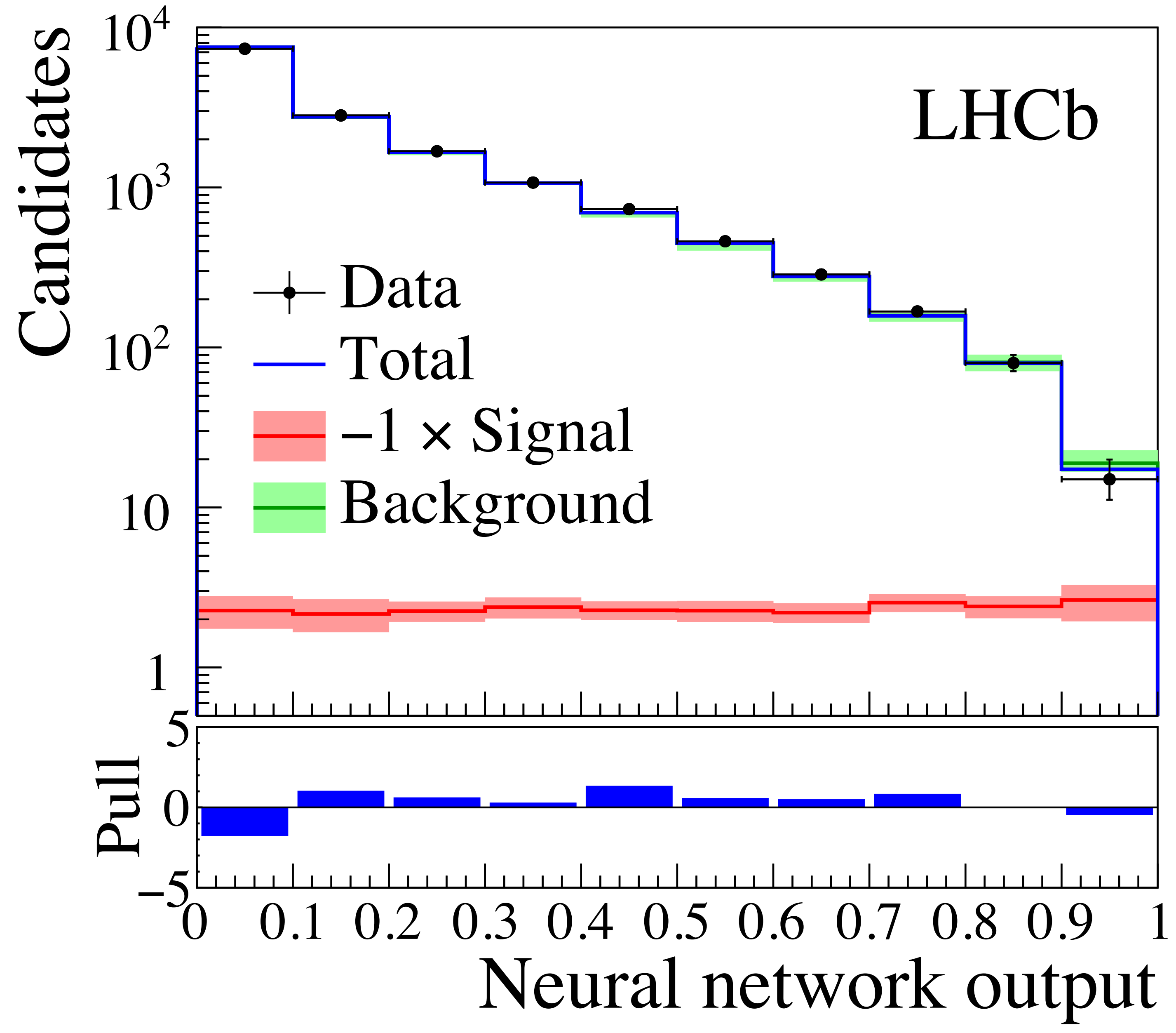
- In general if B mass is not reconstructable **hard to validate** that background MVA has same shape in signal and control region

$B^0_{(s)} \to \tau^+\tau^-$ [Phys. Rev. Lett. 118, 251802, 2017]

3 fb^{-1}

- $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- Neural network fit performed on events with **both tau's in central box** of pseudo-Dalitz
- Background from **data in control region**: one tau in boxes 4, 5 or 8 and the other in boxes 4 or 8
- Contamination from **residual signal in control region** taken into account



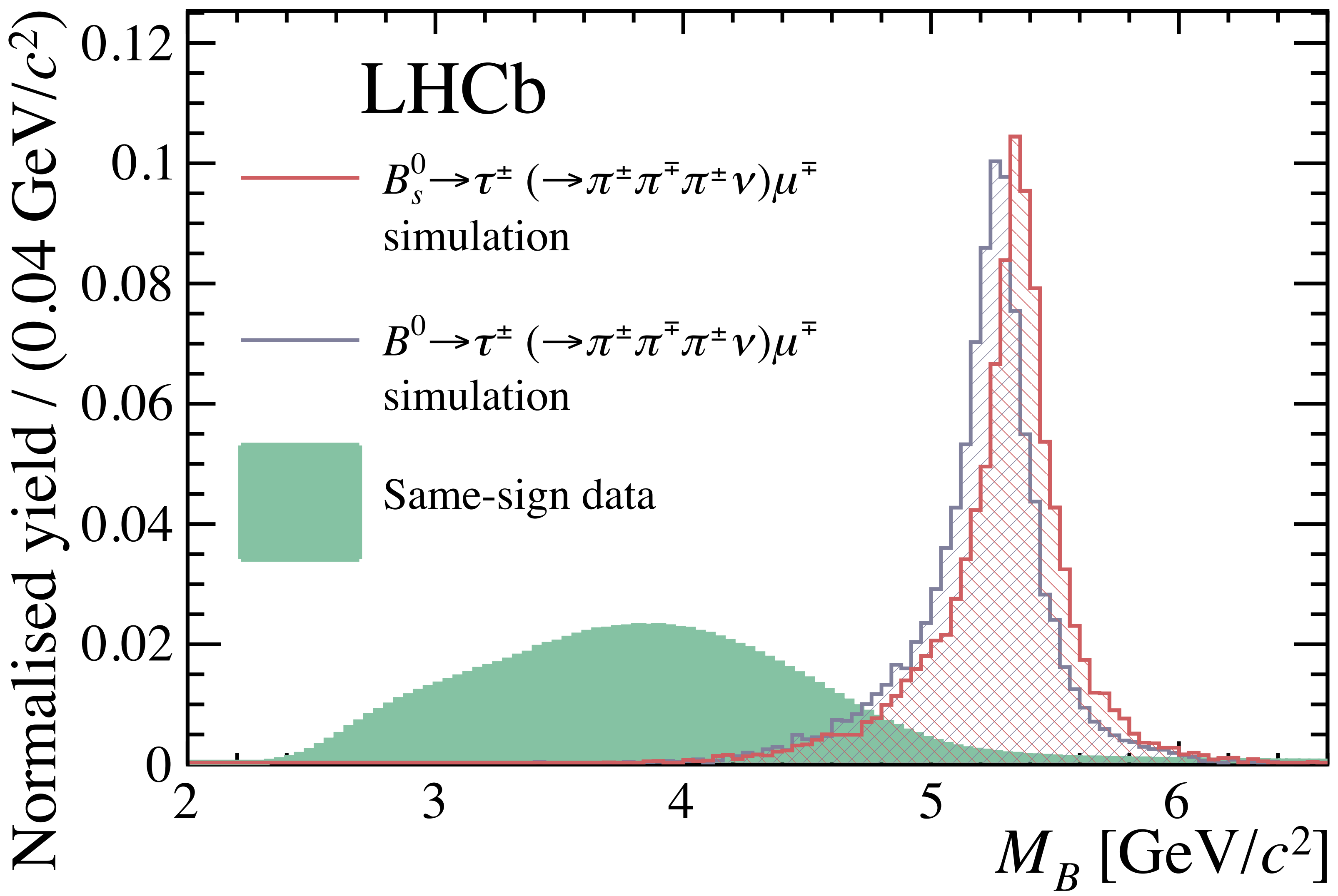


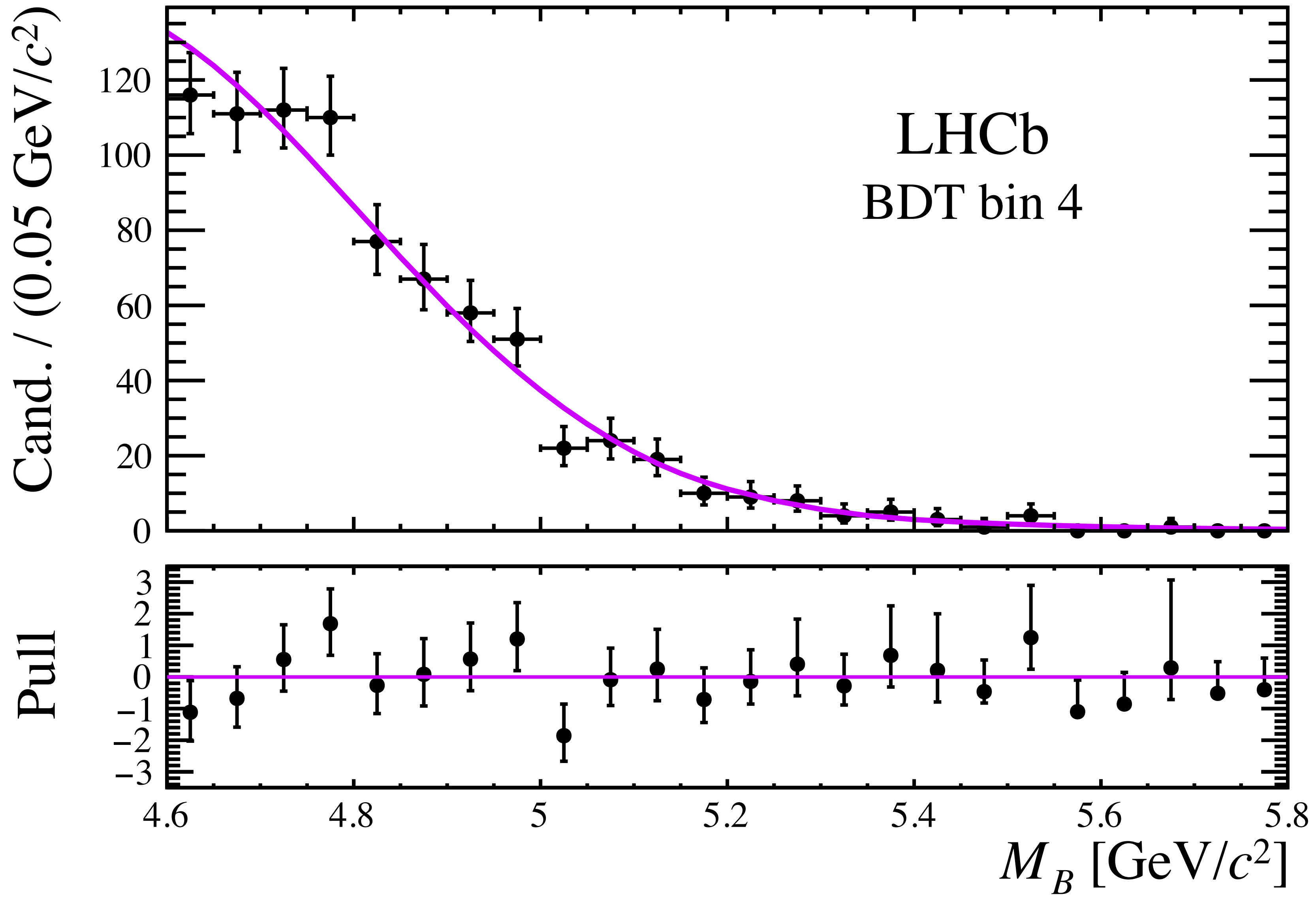
$\mathscr{B}(B^0 \to \tau^+\tau^-) < 2.1 \cdot 10^{-3}$ $\mathscr{B}(B^0_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3}$ @ 95 % CL

$B^0_{(s)} \to \tau^\pm \mu^\mp$ [Phys. Rev. Lett. 123, 211801, 2019]

3 fb^{-1}

- $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$
- **B mass reconstructed analytically, background model from same-sign data**
- Isolation-based BDT + anti-combinatorial BDT
- One more BDT used to split data in four bins, with same amount of signal in each bin
- Simultaneous fit over BDT bins, no signal excess observed



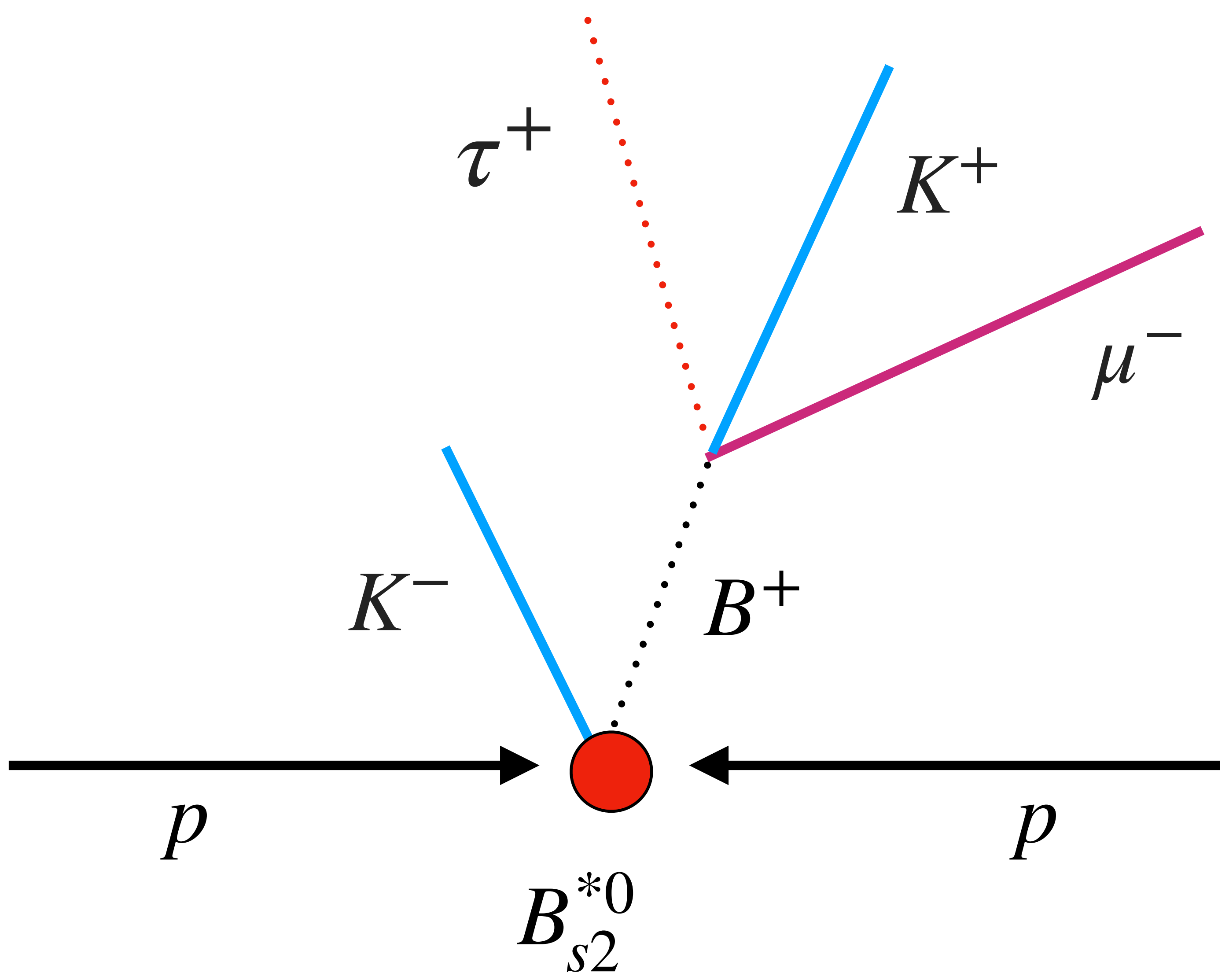


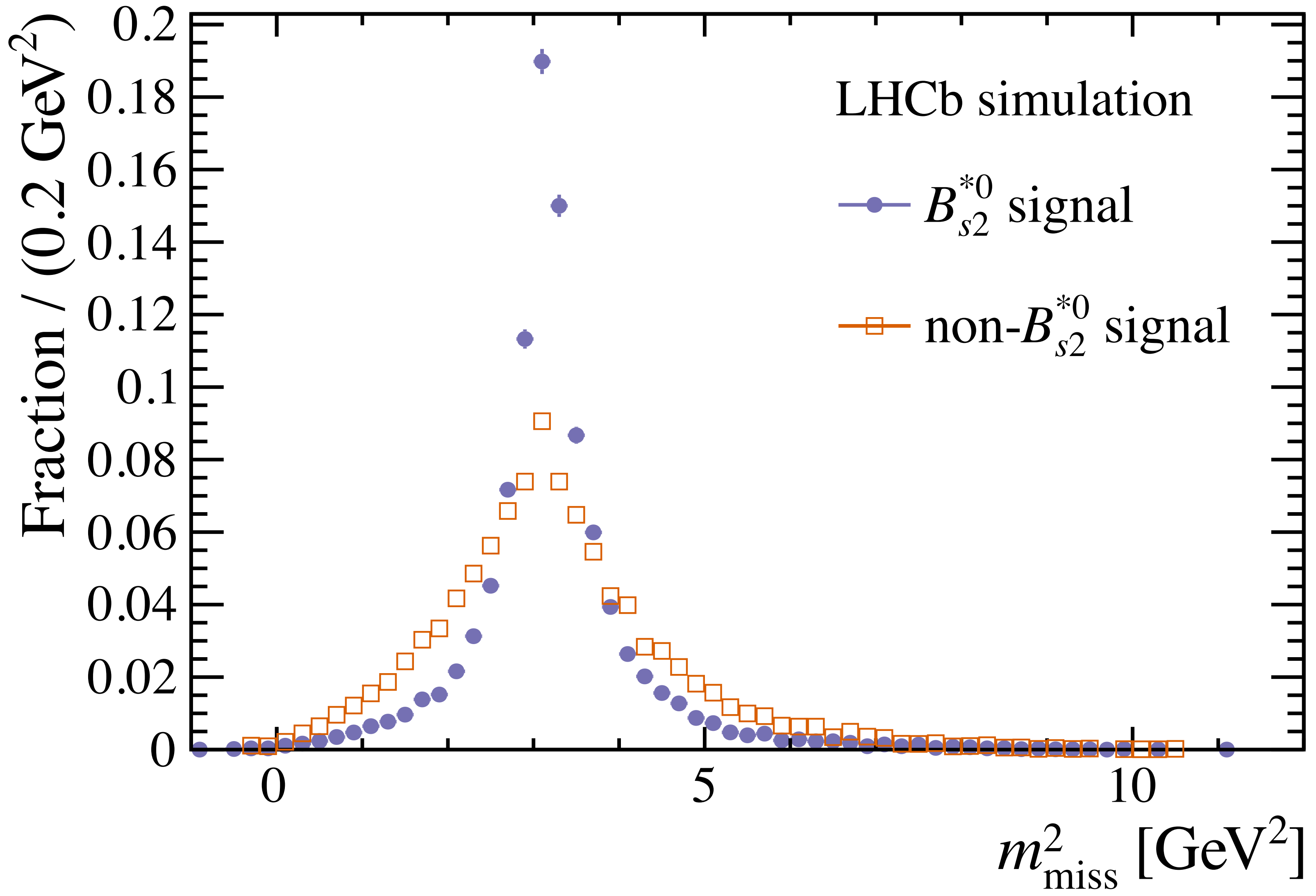
$\mathscr{B}(B^0 \to \tau^\pm \mu^\mp) < 1.4 \cdot 10^{-5}$ $\mathscr{B}(B^0_s \to \tau^\pm \mu^\mp) < 4.2 \cdot 10^{-5}$ @ 95 % CL

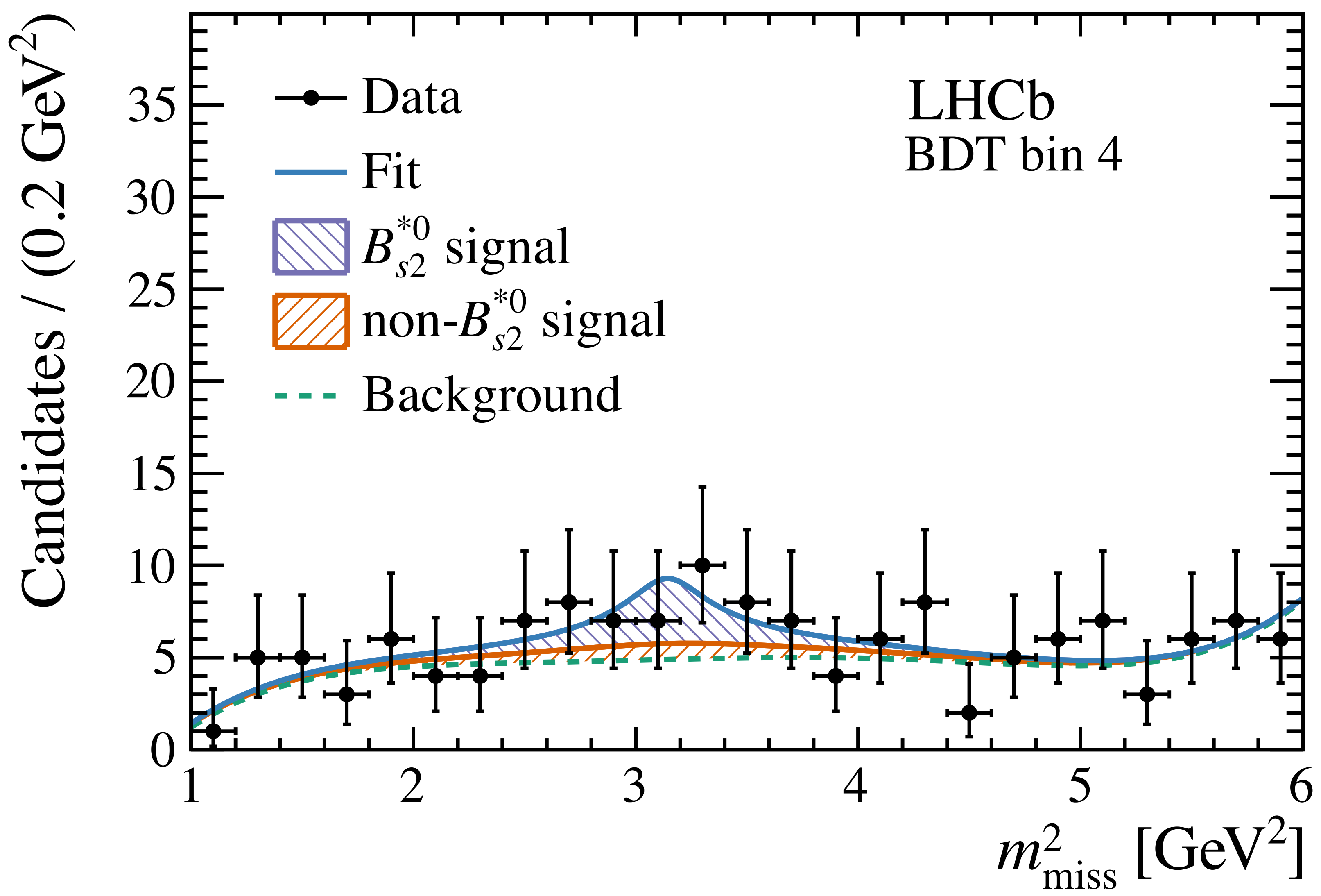
$B^+ \to K^+\tau^+\mu^-$ [JHEP 06 (2020) 129]

9 fb^{-1}

- B^+ selected from $B_{s2}^{*0} \to B^+K^-$ (B^+ coming directly from primary vertex included, worse mass resolution)
- Measure K^- and $K^+\mu^-$ momenta + mass constraints on B^+ and B_{s2}^{*0}: B^+ **four-momentum reconstructed (two-fold ambiguity)**
- **Fit the missing mass distribution** by computing $P_{miss} = P_B - P_{K\mu}$
- **Tau reconstructed inclusively**, $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ removed (suppresses background and easier to combine with other analyses)
- Background further suppressed with BDT, final fit simultaneously in 4 BDT bins, no excess found

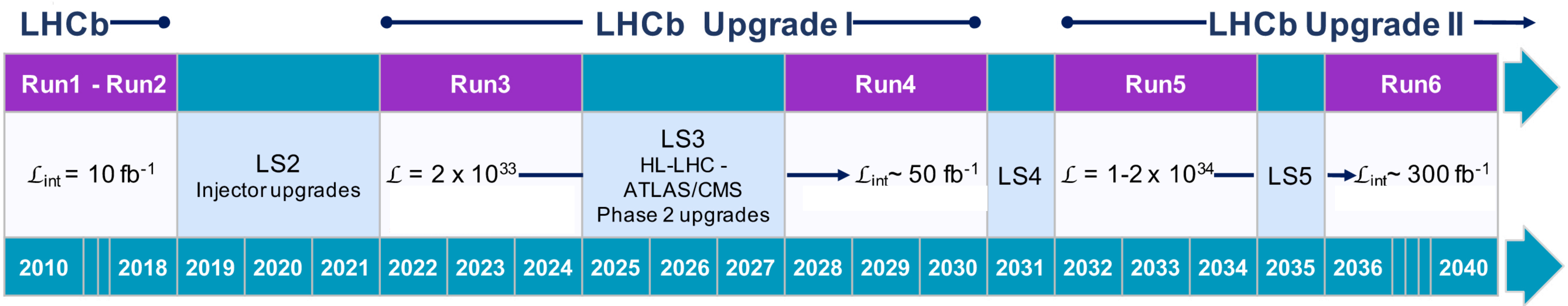






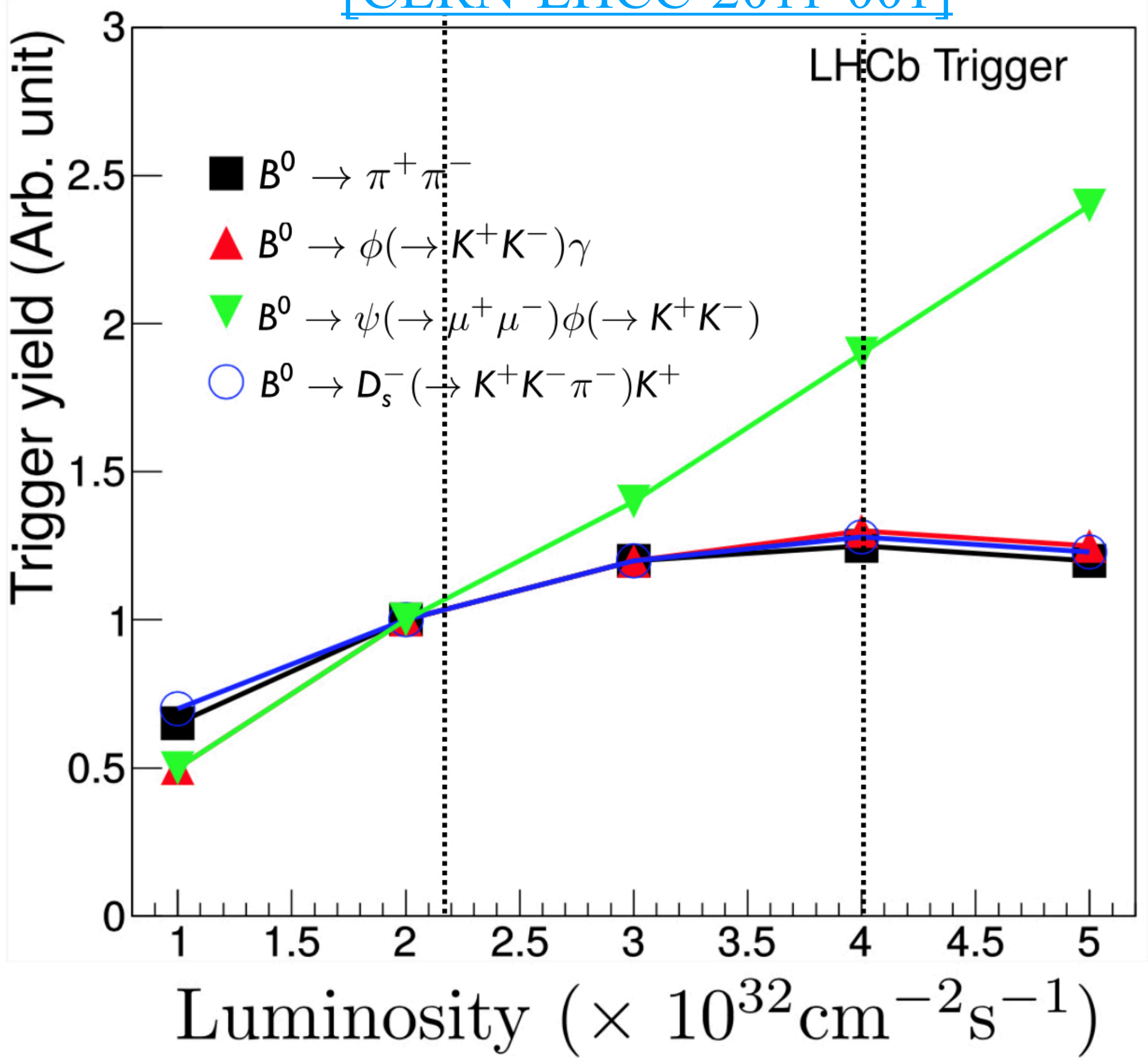
$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 4.5 \cdot 10^{-5} \quad @\ 95\ \%\ \text{CL}$$

Future prospects

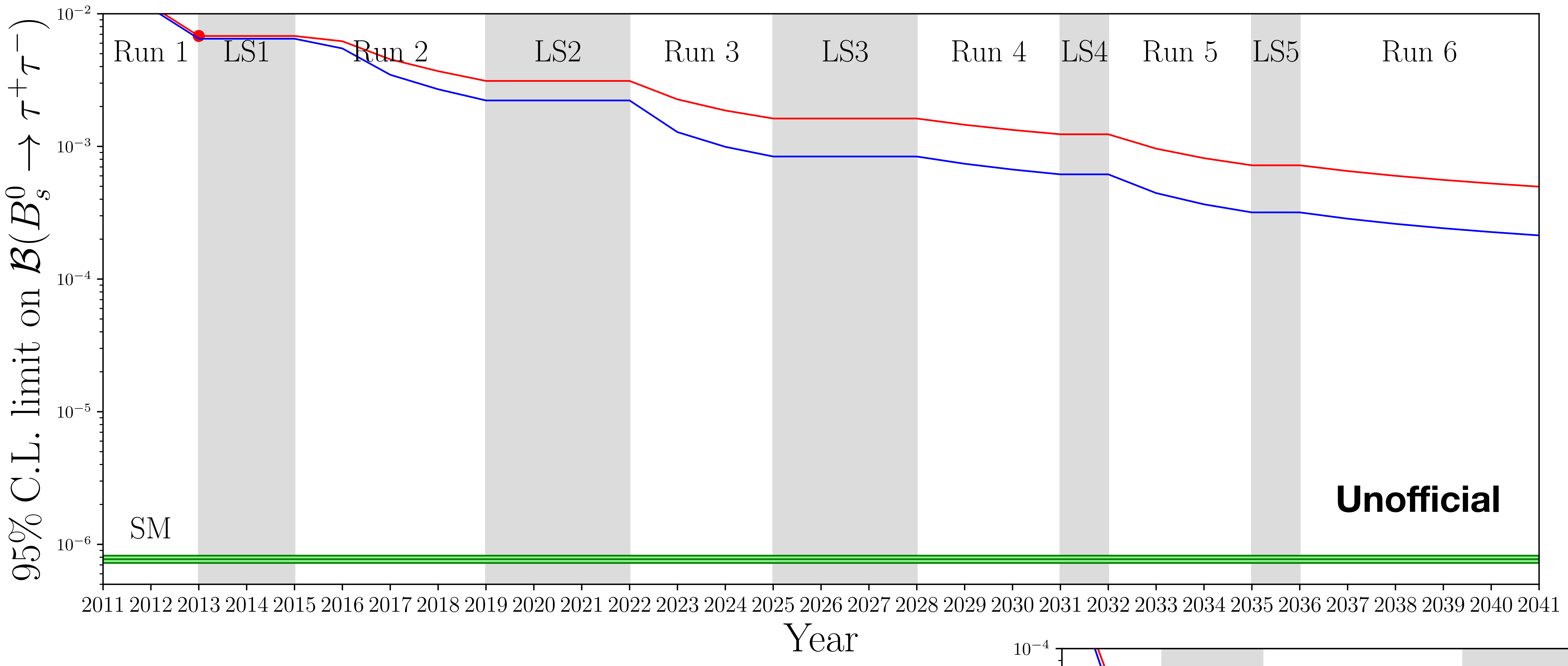


- Run 2: design luminosity $2 \cdot 10^{32}$ cm^{-2} s^{-1}, peak luminosity $4.4 \cdot 10^{32}$ cm^{-2} s^{-1}
- Run 3: 5x higher luminosity, $2 \cdot 10^{33}$ cm^{-2} s^{-1}
- Upgrade 1: new sub-detectors and hardware interventions to cope with luminosity
  - Hardware trigger bottleneck for hadronic modes, removed from Run 3
  - Full software trigger based on commercial GPUs
  - Expected ~ 2x yields for fully hadronic decays

[CERN-LHCC-2011-001]

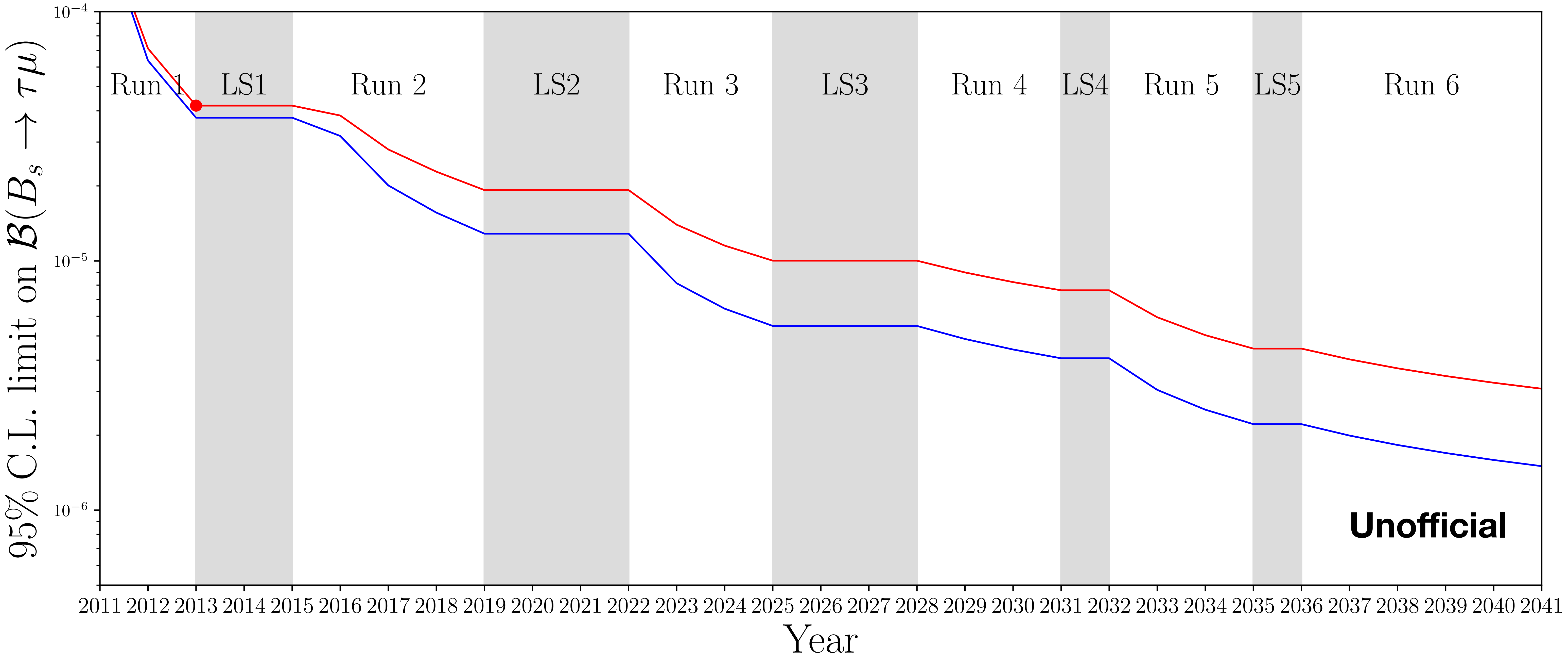


Rare B decays with tau's in Run 3 and beyond



Luminosity scaling

Luminosity scaling + reasonable performance improvements



Conclusions

- Exciting times! **Deviations from SM predictions** in observables involving LFU
- Extensive studies on rare B decays with e/μ in the final state, **tau modes still largely unexplored**
- **Tau's could be the most sensitive to NP** due to their large mass, **improved measurements are very much needed!**
- Very challenging: **missing energy** due to neutrinos in the final state
- Dedicated reconstruction techniques: analytic formulas, kinematical constraints, isolation variables, MVA fits, …
- Expected ~ 300 fb^{-1} collected by LHCb in the next 20 years + Belle 2 is entering the game

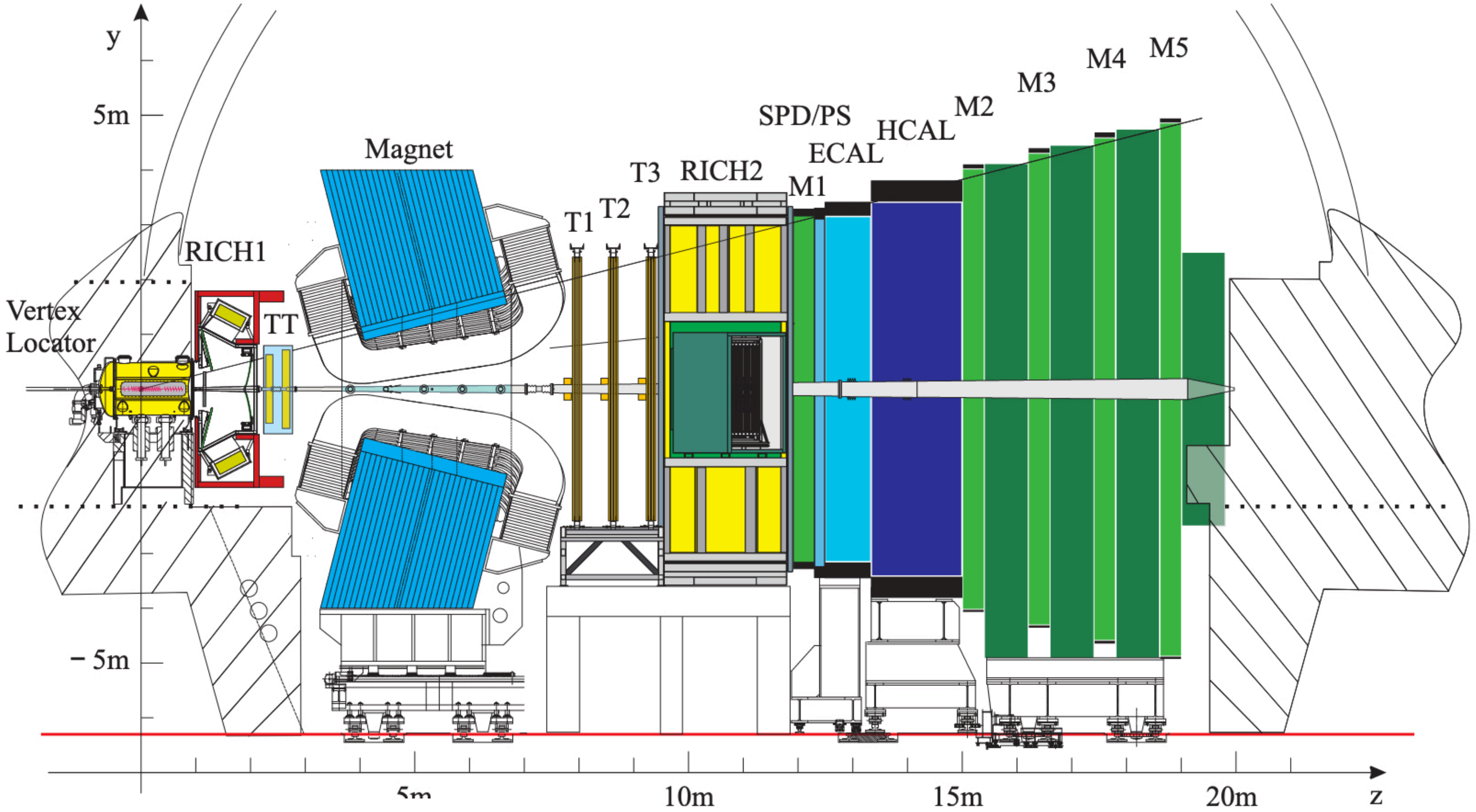
John Lund / Getty Images

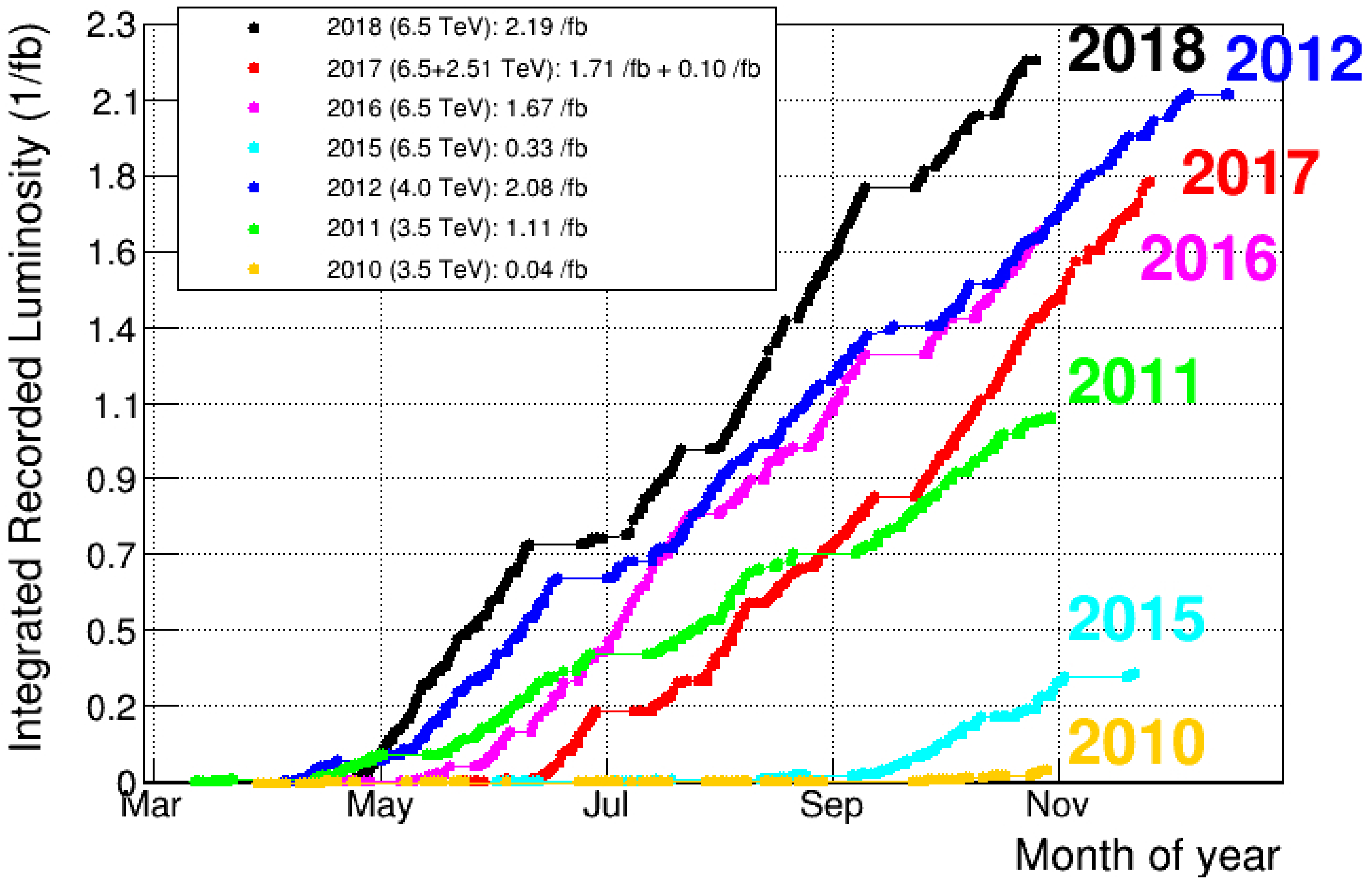
Backup

From Pinterest

The LHCb detector

[Int.J.Mod.Phys. A 30, 1530022 (2015)]
[JINST 3 (2008) S08005]





- High vertex resolution $\sigma_{IP} = 15 + 29/p_T\ \mu$m
- Low momentum muon trigger $p_T^{\mu} > 1.75$ GeV (2018)
- PID capabilities $\epsilon_{\mu} \sim 98\,\%$ with $\varepsilon_{\pi\to\mu} \sim 1\,\%$
- Good momentum resolution $\sigma_p/p = 0.5 - 1.0\,\%$, $p \in [2{,}200]$ GeV

Effective theories for $b \to s\, l^+ l^-$ decays

[Rev. Mod. Phys. 68 (1996) 1125-1144]

- Rare B decays described in a model-independent way with **effective hamiltonian**:
  - FCNC processes (high energy contributions) treated as point-like and encoded in Wilson coefficients $C_i(\lambda)$
  - Long-distance physics (low energy contributions) described by effective operators $Q_i(\lambda)$
  - $\lambda = m_b \sim 4\,\text{GeV}$ is the energy scale of the process

- Dominant SM contributions:

$$Q_7 = \frac{e^2}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} \text{ (electromagnetic operator)}$$

$$Q_9 = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) \sum_l (\bar{l}\gamma^\mu l) \text{ (semi-leptonic vector operator)}$$

$$Q_{10} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) \sum_l (\bar{l}\gamma^\mu \gamma^5 l) \text{ (semi-leptonic axial vector operator)}$$

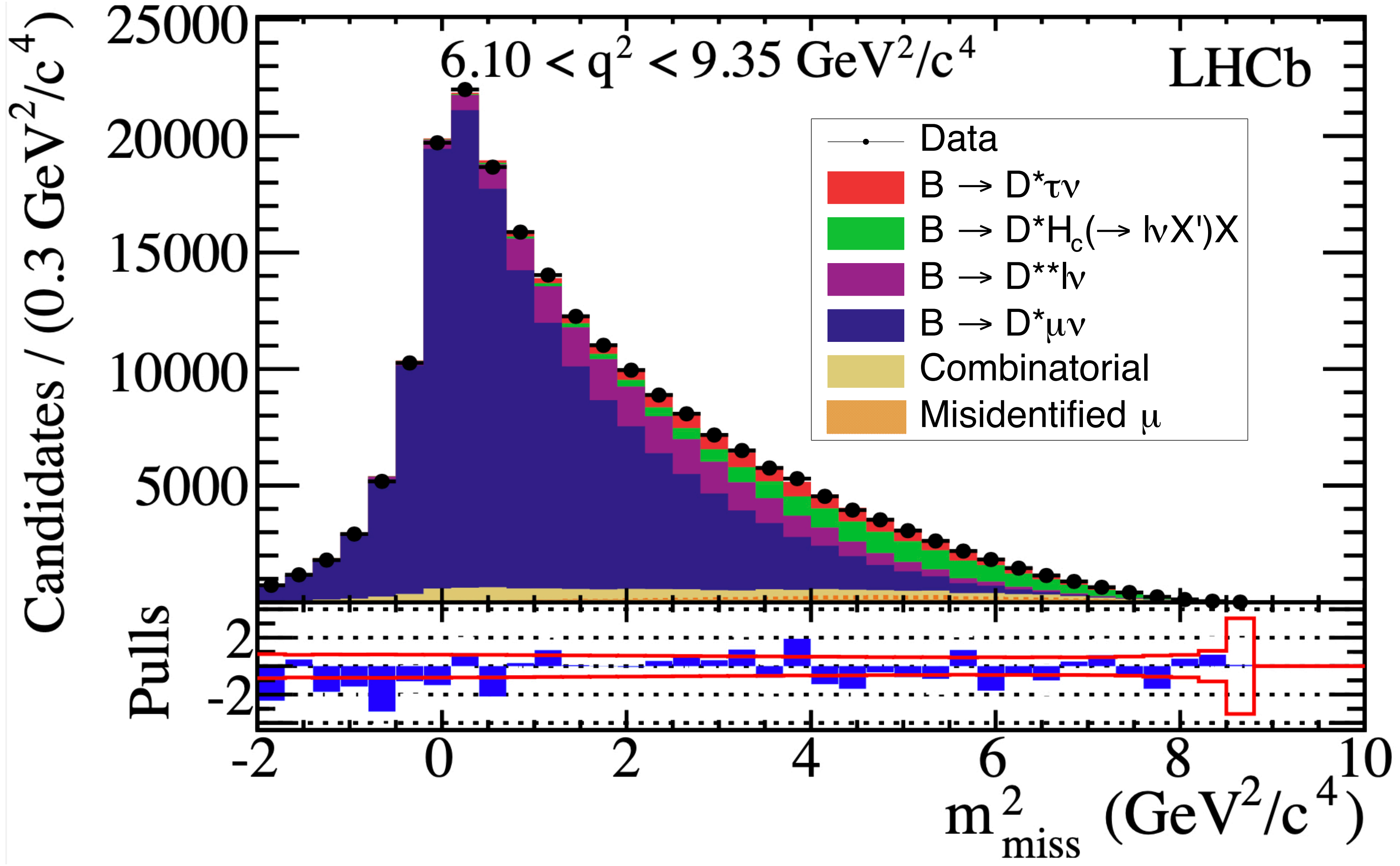
$$H_{eff}^{b\to s} = \frac{G_F}{\sqrt{2}} \sum_i V_{ib} V_{is}^* \, C_i(\lambda)\, Q_i(\lambda)$$

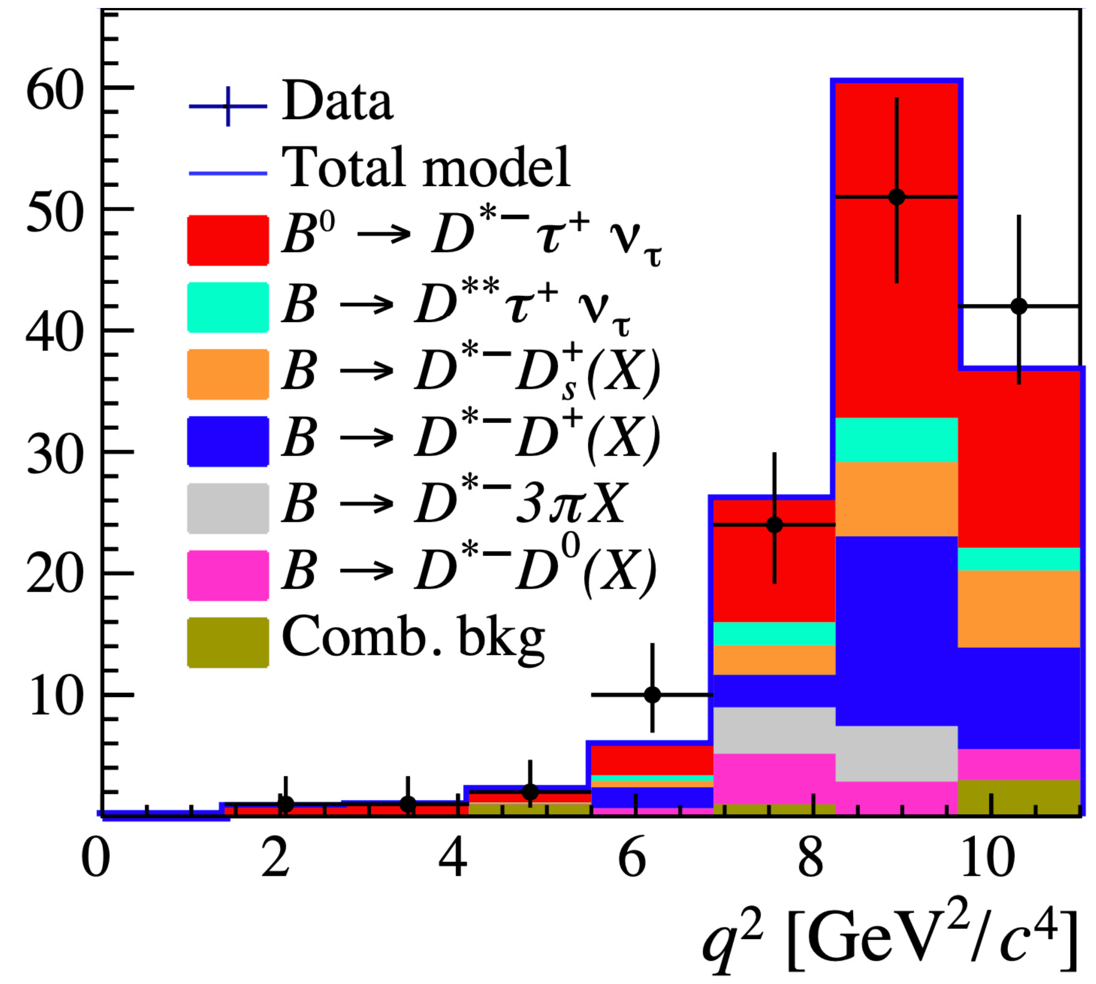
- NP can modify the values of Wilson coefficients or add new ones

Not only rare decays: $R(D^{*-})$

3 fb^{-1}

- **Tree-level** $b \to c\, l\, \nu$ processes: $R(D^{*-}) = \mathscr{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathscr{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$
- Analysis performed separately in **two tau decay modes**:
  - Hadronic $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau + \tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ [Phys. Rev. Lett. 120, 171802 (2018)]
  - Muonic $\tau^- \to \mu^-\,\bar{\nu}_\mu\,\nu_\tau$ [Phys. Rev. Lett. 115, 111803 (2015)]
- 3-dimensional binned fits to:
  - Hadronic: τ lifetime, q^2 (from analytic reconstruction!), BDT distribution $\to R(D^{*-}) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$
  - Muonic: μ energy (in B^0 rest frame), $m^2_{miss} = (p_B - p_D - p_\mu)^2$, $q^2 \to R(D^{*-}) = 0.336 \pm 0.027 \pm 0.030$





- Other results from BaBar and Belle: [Phys. Rev. D 94, 072007 (2016)] [Phys. Rev. D 97, 012004 (2018)] [Phys. Rev. D 88, 072012 (2013)]