Search for LFV with the LHCb experiment

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on behalf of the LHCb collaboration

New Frontiers in Lepton Flavour 2023

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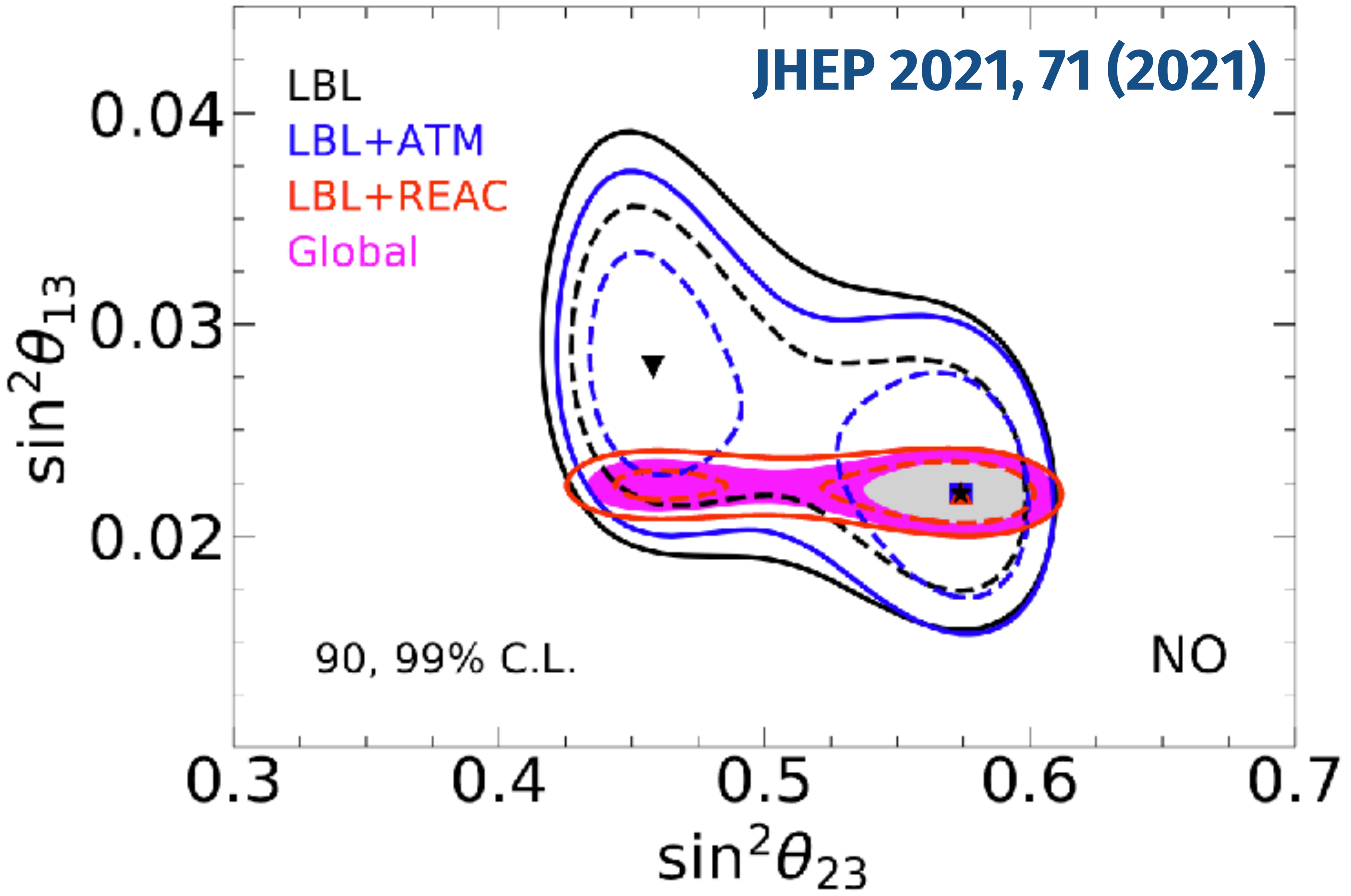
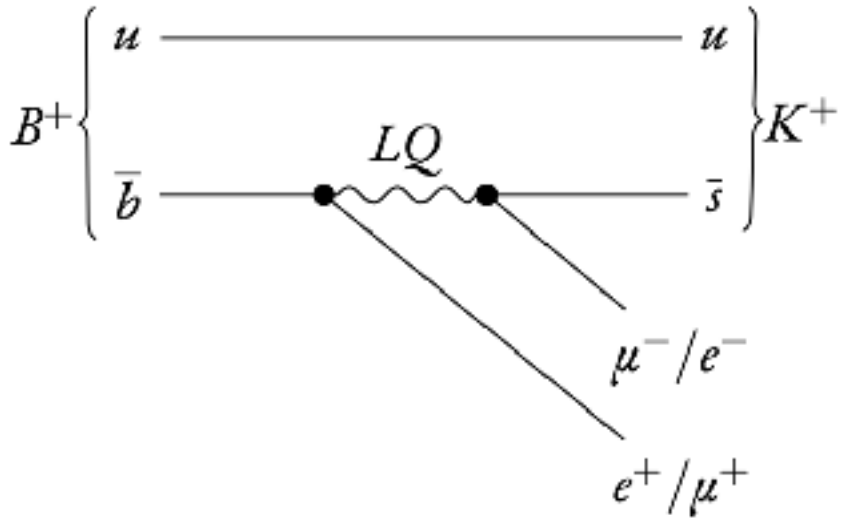
Charged Lepton Flavour Violation - why?

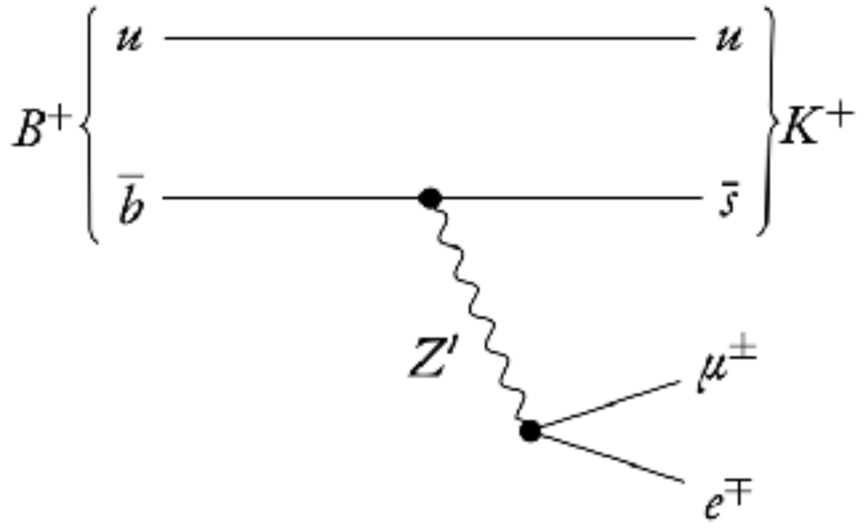
Neutrino oscillation parameters

See Lorenzo's talk

- Why not?
  - LFV in Neutrinos well established: Neutrino oscillations!
  - Where does this come from?
  - Can this happen in the charged sector as well?
- Typical New Physics extensions
  - Z' or Leptoquarks
  - R-parity violating SUSY
  - …
  - predict LFV branching fractions that are within experimental reach
- In the B sector often connected to $b \to s\ell\ell$ anomalies and $b \to c\ell\nu$ LFU tests   See talks from Renato and Rizwaan
  - Broken Lepton Flavour Universality → charged Lepton Flavour violation!

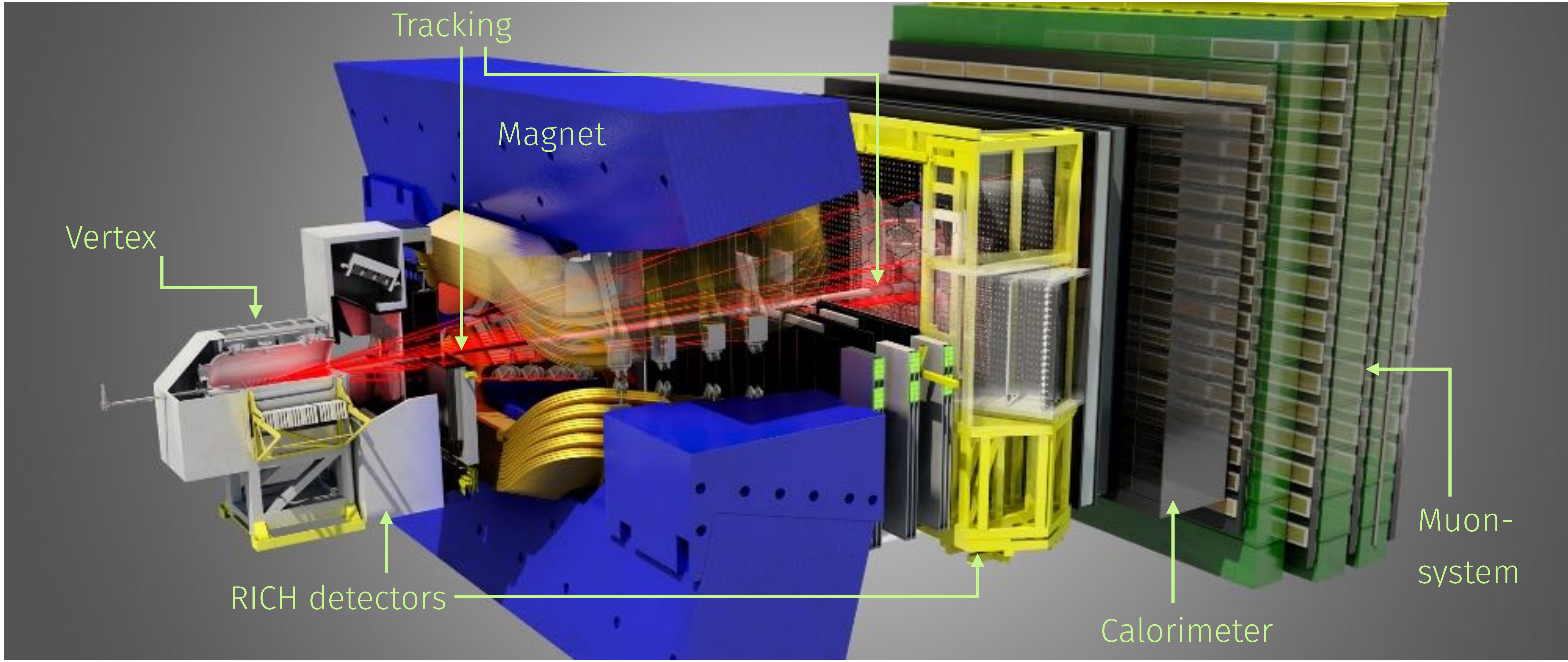






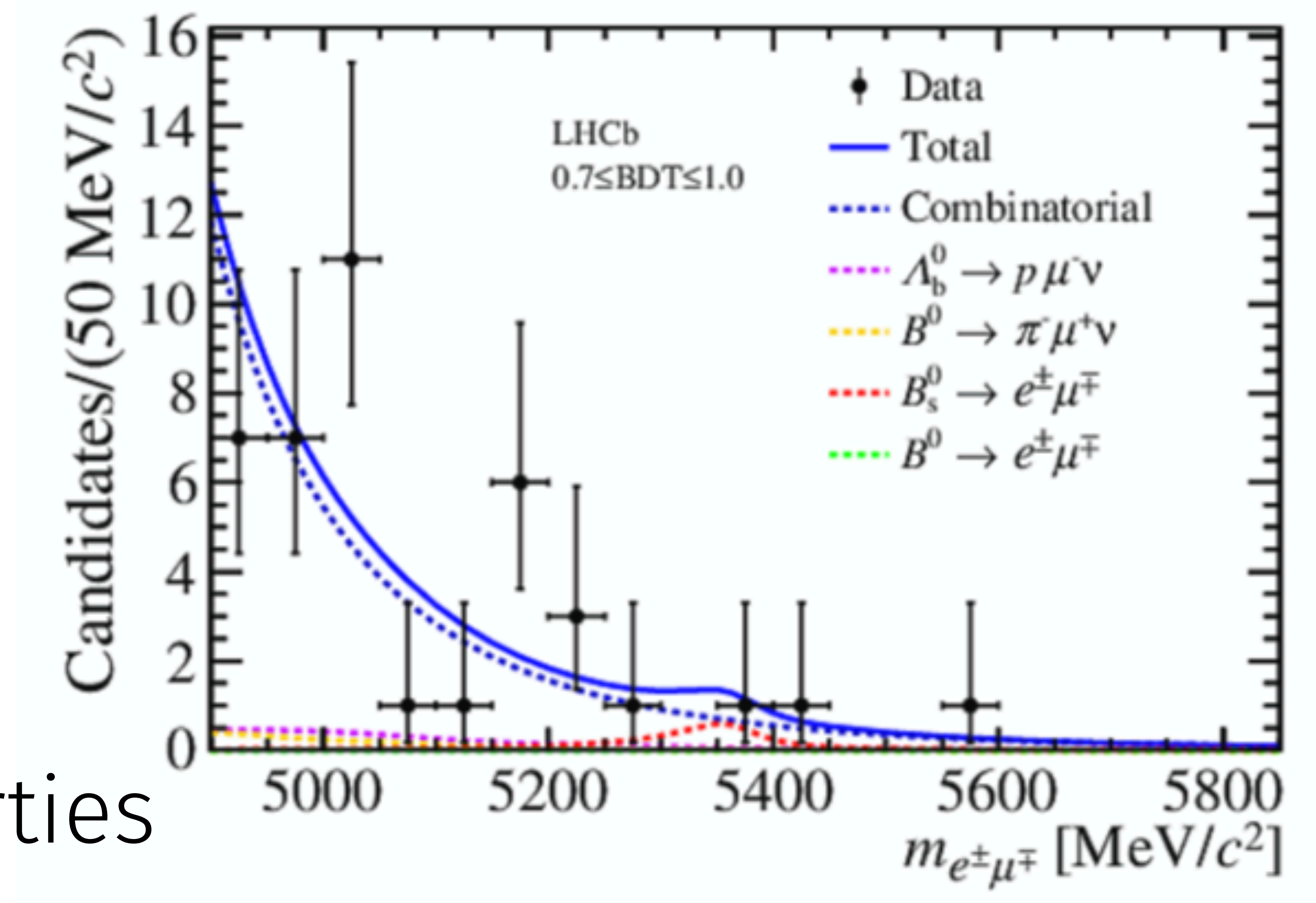
LHCb detector

- pp collisions from LHC
- Collected data
  - Run 1 (2011-2012): $3\,\text{fb}^{-1}$ at 7 & 8 TeV
  - Run 2 (2015-2018): $6\,\text{fb}^{-1}$ at 13 TeV $\rightarrow \sim 3\times$ more data
- New detector:
  - Run 3 (2023 -): 13.6 TeV



Purely leptonic B decays: $B^0_{(s)} \to e^{\pm}\mu^{\mp}$

- New Physics scenarios $\mathcal{O}(<10^{-11})$ [Crivellin et al. PRD 92 (2015) 054013] [Becirevic et al. PRD 94 (2016) 115021] [Hiller et al. JHEP 06 (2015) 072] [Ilakovac PRD 62 (2000) 036010]
- Data from Run 1
- Normalise and calibrate with $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi(\ell\ell)K^+$ decays
- Exploit particle identification, kinematic and isolation properties
- Biggest challenges:
  - Maximise sensitivity through bins of multivariate classifier output
  - Control muon and electron misID rate
- Update with full LHCb data 2011-2018 ongoing

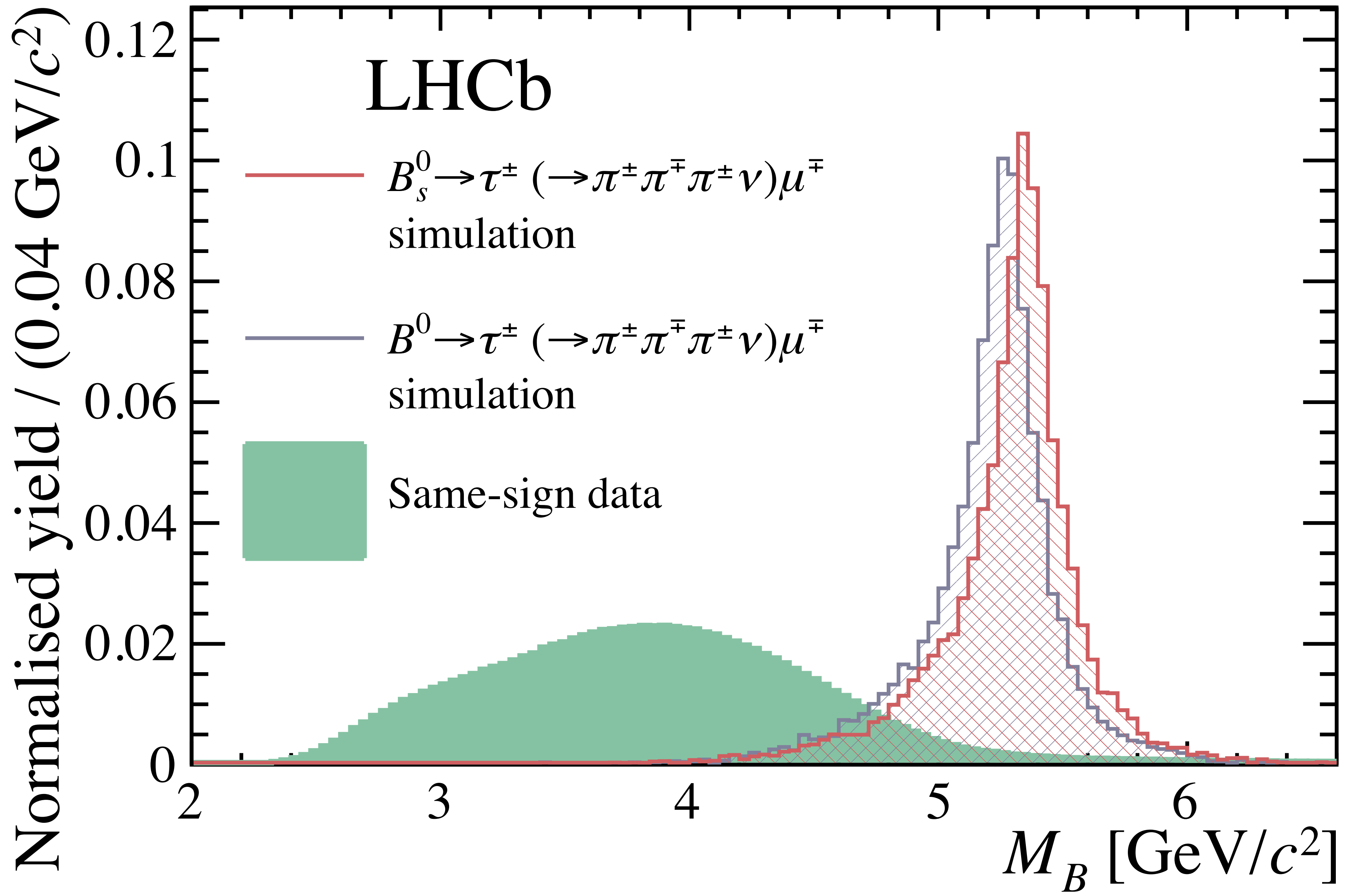


$\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp}) < 5.4 \times 10^{-9}$ @ 90% CL

$\mathcal{B}(B_d^0 \to e^{\pm}\mu^{\mp}) < 1.0 \times 10^{-9}$ @ 90% CL

Strongest limits

Purely leptonic B decays: $B^0_{(s)} \to \tau^\pm\mu^\mp$ (Run 1)

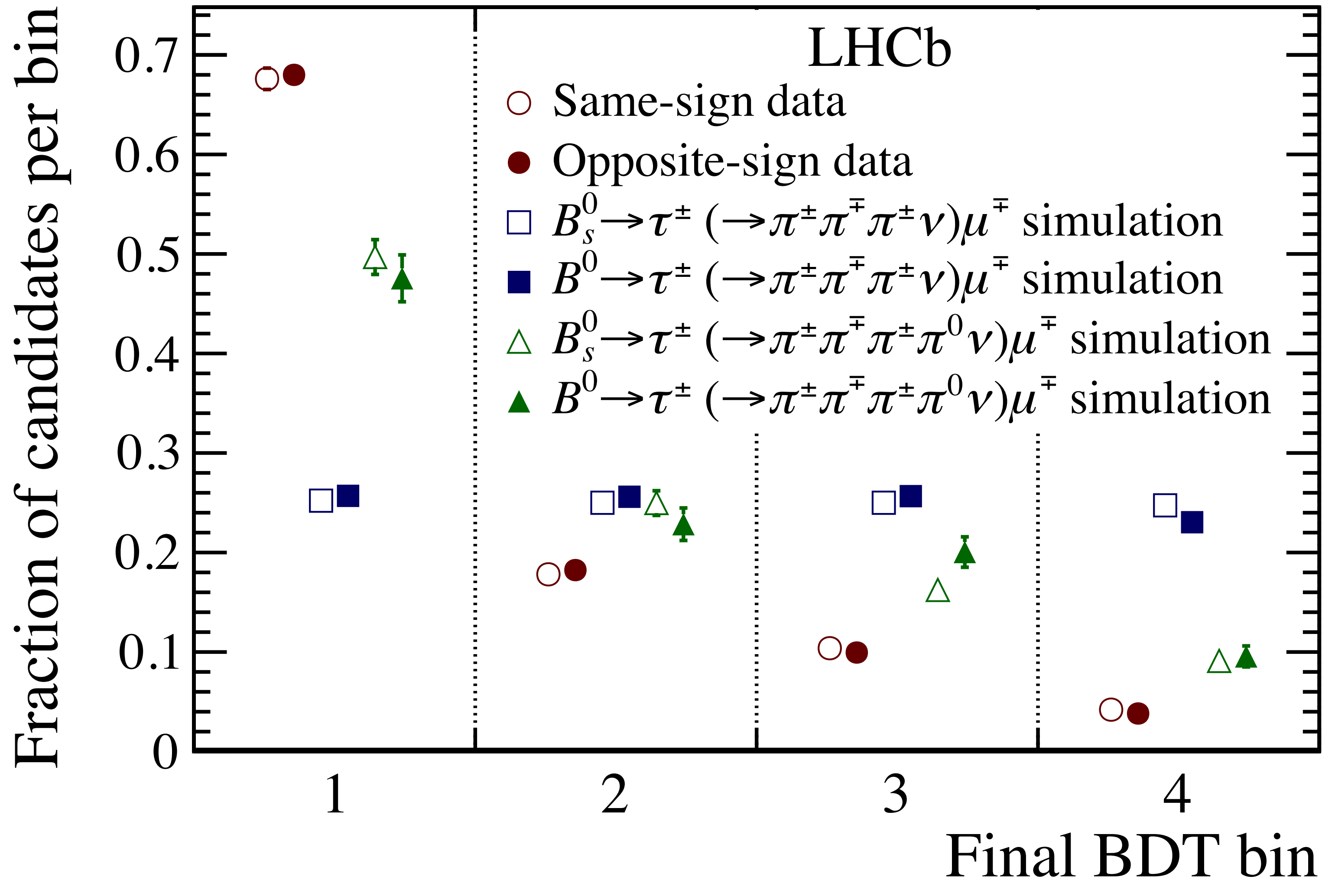


- Highly challenging
  - Reconstruction through $\tau^+ \to \pi^+\pi^-\pi^+\nu$ (9%)
    $\tau^+ \to \pi^+\pi^-\pi^+\pi^0\nu$ 5% effect after selection
  - Neutrino missing: compute B mass up to two-fold ambiguity through τ mass and vertex constraints
    $\to$ use solution with the better signal-to-background ratio (70% physical solutions, <50% background)
- Highly rewarding: New Physics range (Leptoquarks, Z' - PS3)
  $10^{-8} - 10^{-4}$!
- Normalisation through $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$,
  additional calibration with $B^+ \to J/\psi(\mu^+\mu^-)K^+$ decays

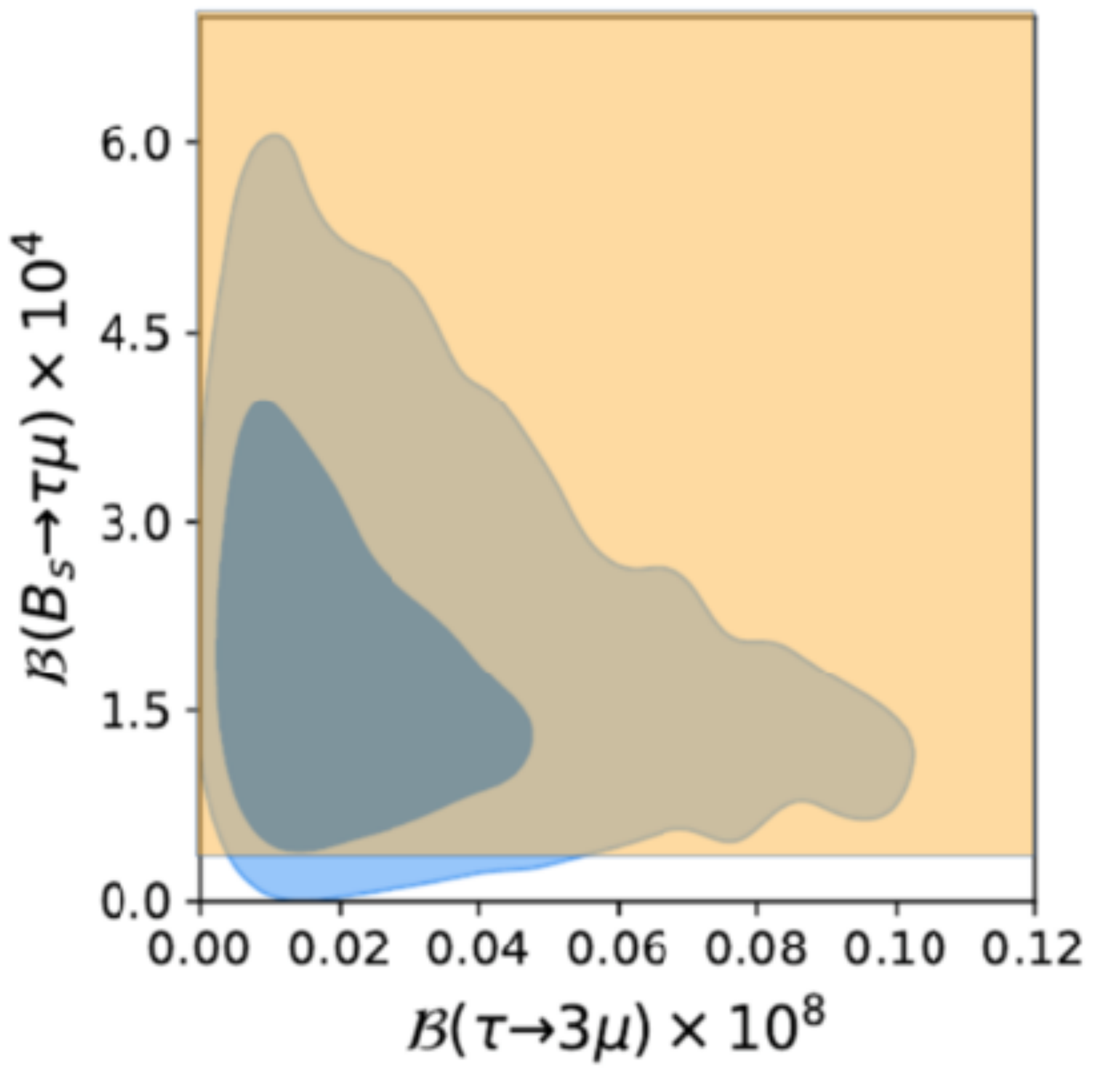
[Cornella et al. JHEP 1907 (2019) 168]
[Bordone et al. JHEP 10 (2018) 148]
[Becirevic et al. EPJ C76 (2016) 134]
[Becirevic et al. JHEP 11 (2016) 035]
[Bhattacharya et al., JHEP 01 (2017) 15]
[Smirnov, MPLA 33 (2018) 1550019]

Purely leptonic B decays: $B^0_{(s)} \to \tau^\pm\mu^\mp$

- $B^0_{(s)} \to \tau^\pm\mu^\mp$ analysis challenges:
  - Large backgrounds from $B \to D^{(+)}_{(s)}\mu X$ - modelled through empirical model from same-sign combinations
  - Low mass resolution due to missing neutrino
  - Exploit classifiers based on τ isolation, B topology and pion combinations
  - Maximise sensitivity by binning in classifier response
- First ever limit on $B^0_s \to \tau^\pm\mu^\mp$, factor 2 improvement on BaBar for $B^0 \to \tau^\pm\mu^\mp$
  - $\mathscr{B}(B^0_s \to \tau^\pm\mu^\mp) < 3.4 \times 10^{-5}$ @ 90% CL
  - $\mathscr{B}(B^0_d \to \tau^\pm\mu^\mp) < 1.2 \times 10^{-5}$ @90% CL



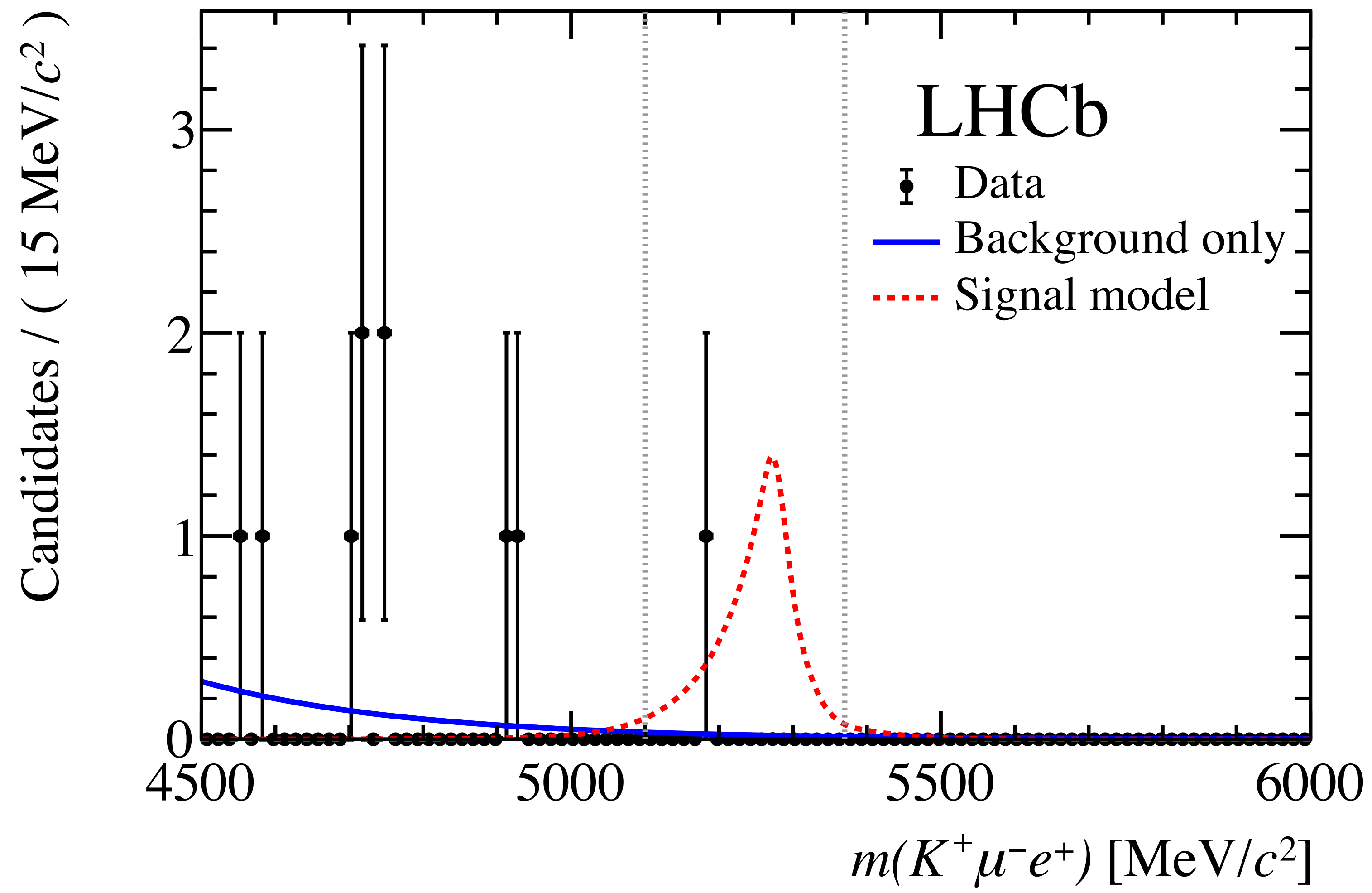
[Bordone et al. JHEP 10 (2018) 148]

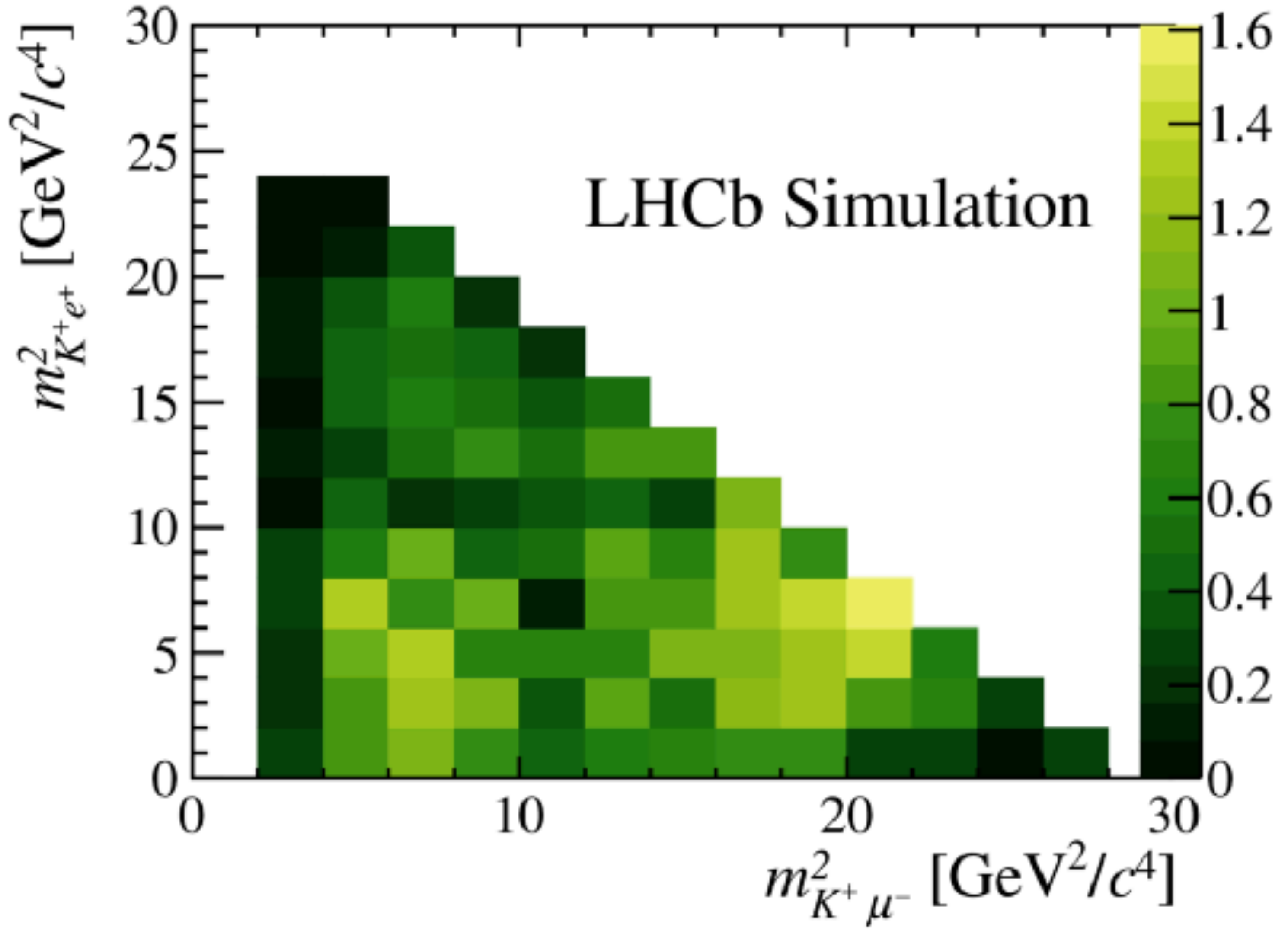


Semileptonic B decays: $B^+ \to K^+\mu^\pm e^\mp$

[Medeiros Varzeilas and Hiller JHEP06 (2015) 072]
[Hiller et al. JHEP12 (2016) 027]
[Crivellin et al. PRD 92 (2015) 054013]
[Boucenna et al PLB (2015) 09040]

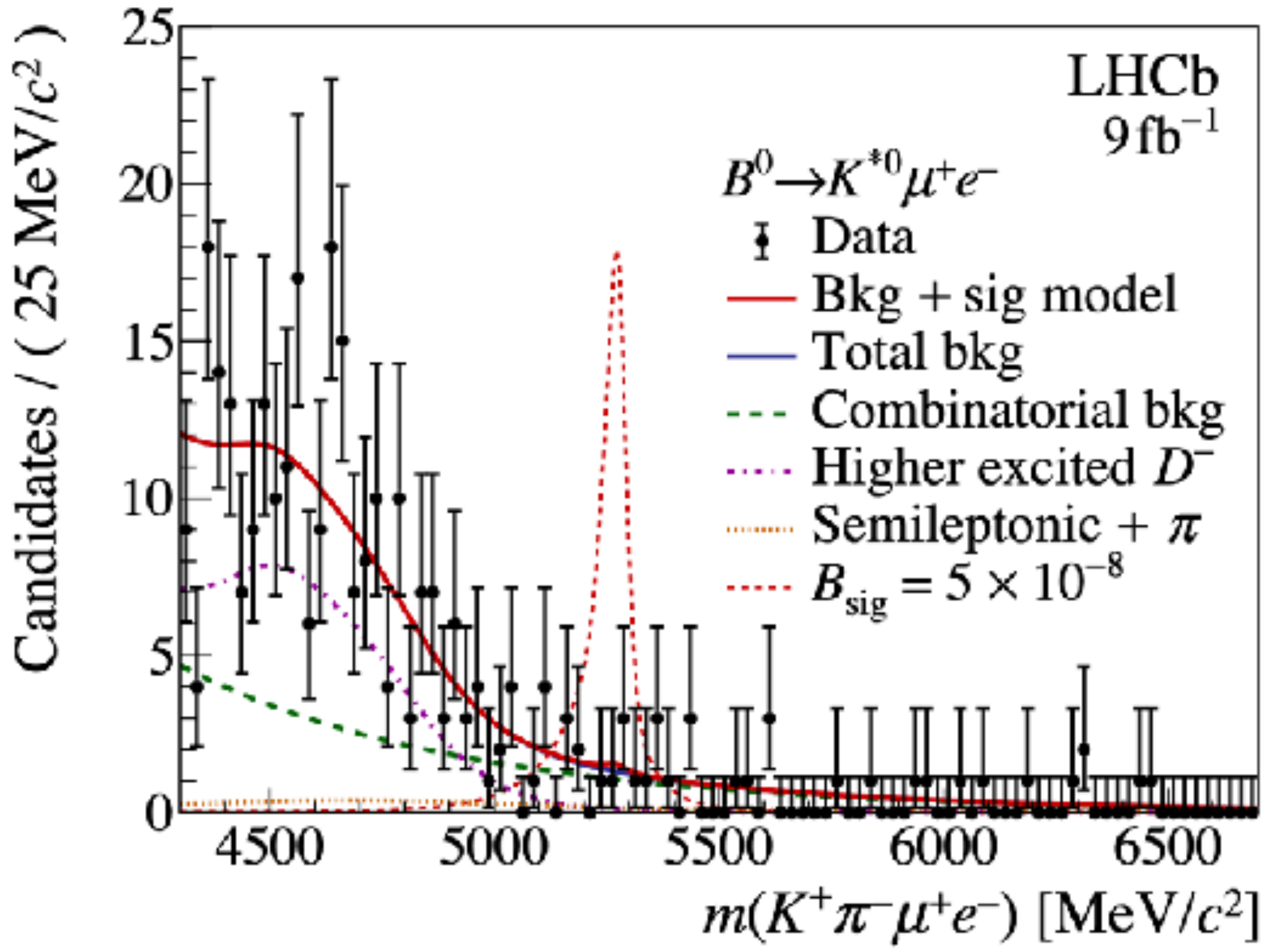
- New Physics can reach up to $10^{-10} - 10^{-8}$ (Leptoquarks, Z', models with CPV in Neutrinos)
- Search with $3\ \text{fb}^{-1}$ from Run 1
- Use high statistics modes $B^+ \to K^+J/\psi(\ell\ell)$ as control and normalisation modes
- Exploit tight particle identification and two multivariate classifiers based on B kinematics and topology:
  - Against random track combinations
  - Against partially reconstructed backgrounds ($B \to D\ell\nu$ pollute lower mass range)
- Dalitz structure unknown: efficiency distributions in the $m^2(K\mu) - m^2(Ke)$ distribution
- Observed upper limits @90% CL:
  - $\mathcal{B}(B^+ \to K^+e^-\mu^+) < 6.4 \times 10^{-9}$
  - $\mathcal{B}(B^+ \to K^+\mu^-e^+) < 7.0 \times 10^{-9}$
- Update on $B^+ \to K^+e^\pm\mu^\mp$ with full 2011-2018 data in progress

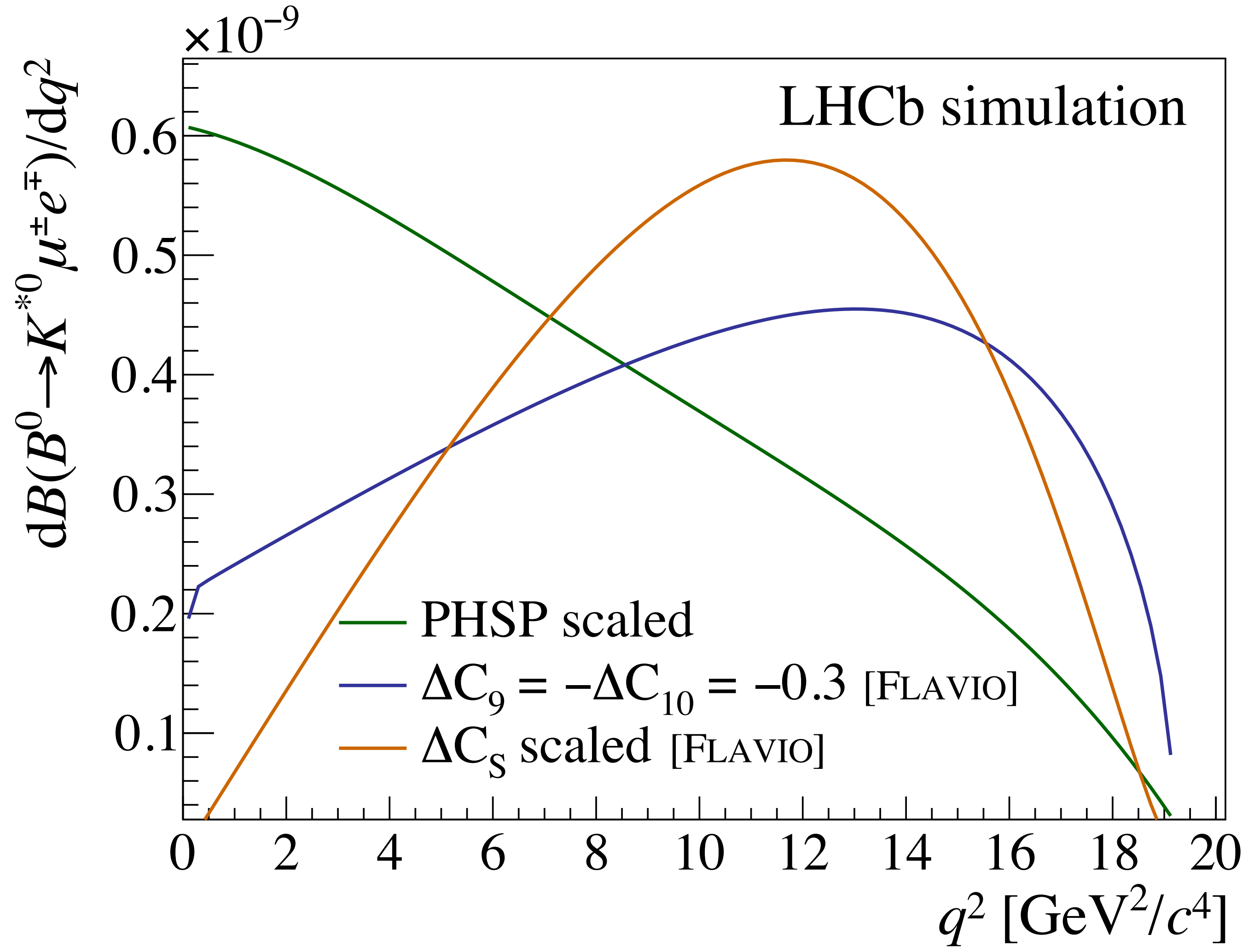




Semileptonic B decays: $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

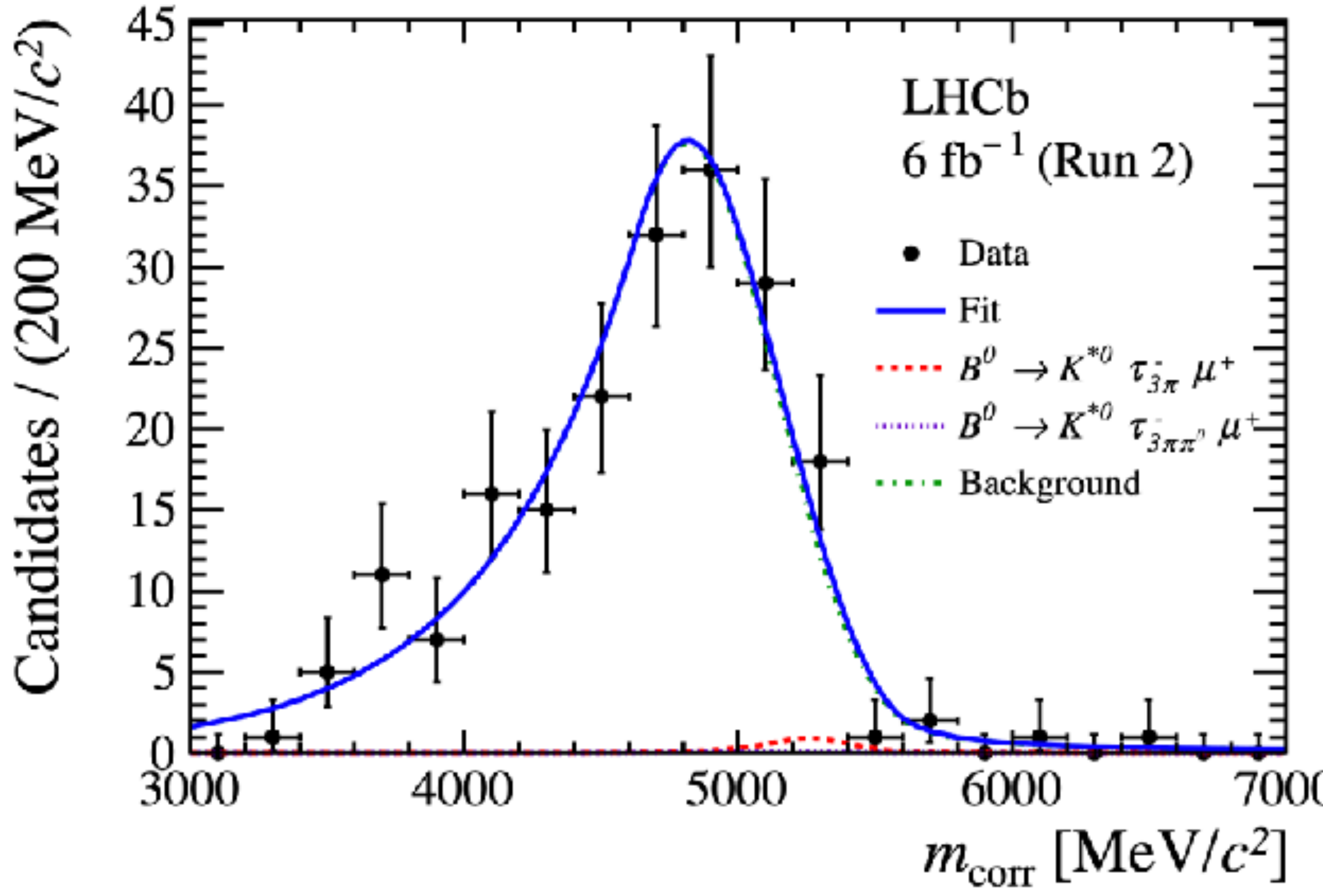
- Similar New Physics scenarios, could go up to 10^{-7}
- Using full Run 1 and Run 2 data, reconstruct $K^{*0} \to K^+\pi^-$ and $\phi \to K^+K^-$
- Use high statistics modes $B \to XJ/\psi(\ell\ell)$ as control and normalisation modes
- Exploit tight particle identification and multivariate classifiers based on B kinematics and topology
- Challenges:
  - Model the remaining background candidates
  - High branching fractions of semileptonic $B \to D\ell\nu$ decays - precise description necessary
- Upper limits @90% CL:
  - $\mathscr{B}(B^0 \to K^{*0}e^-\mu^+) < 6.8 \times 10^{-9}$
  - $\mathscr{B}(B^0 \to K^{*0}e^-\mu^+) < 5.7 \times 10^{-9}$
  - $\mathscr{B}(B_s^0 \to \phi e^\pm\mu^\mp) < 16.0 \times 10^{-9}$
- Dalitz structure unknown - recast the limit in scalar and left-handed New Physics scenarios
- Searches for $\Lambda_b^0 \to \Lambda\mu^\pm e^\mp$ in progress



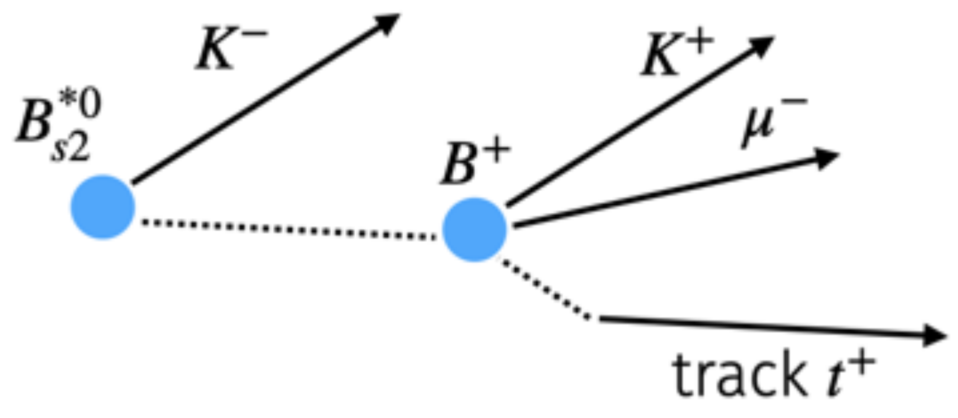


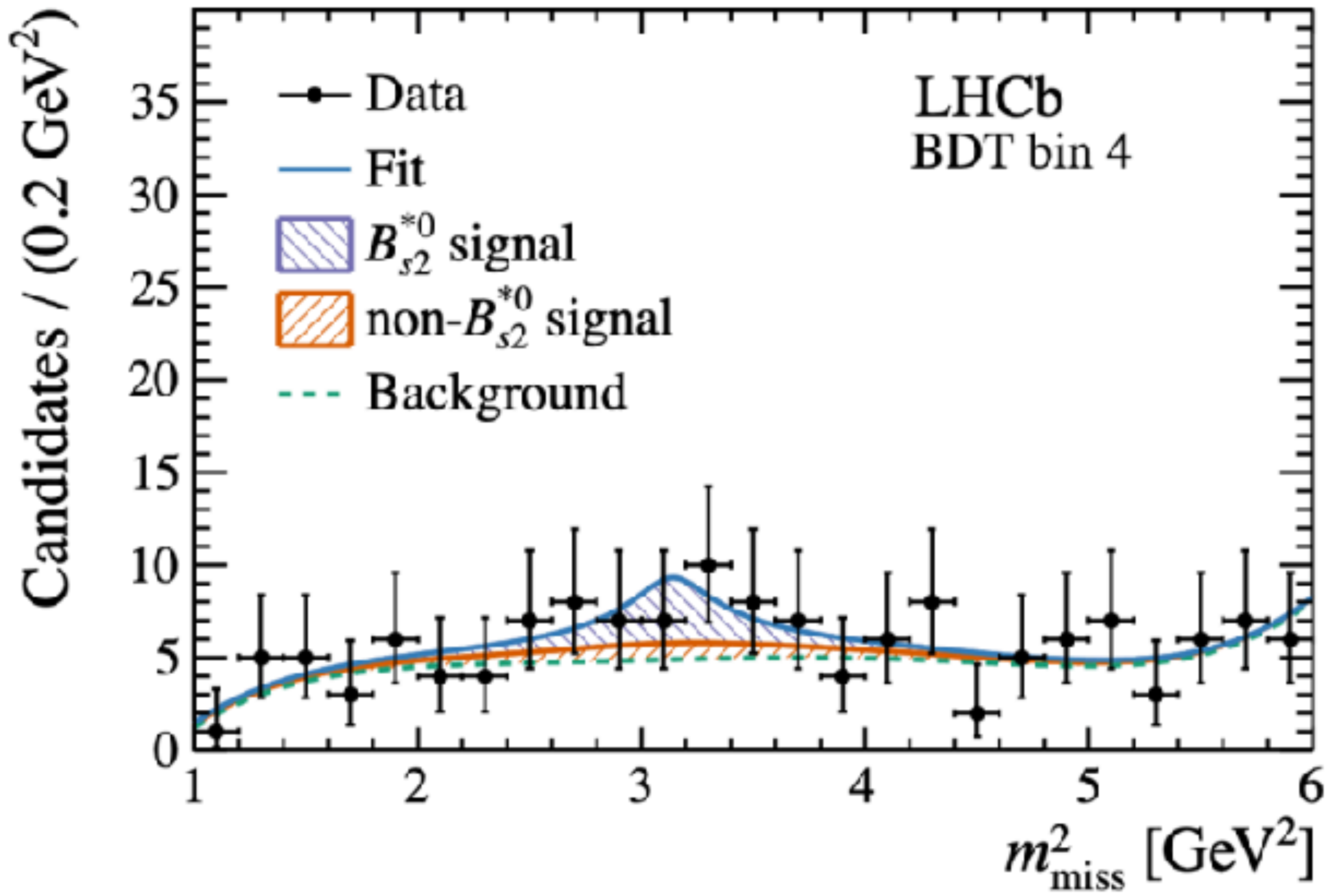
arXiv:2209.09846
JHEP 06 (2020) 129

Semileptonic decays with τ: $B \to K\tau^{\pm}\mu^{\mp}$



- Similar predictions as for $B_s^0 \to \tau^{\pm}\mu^{\mp}$
- The classical approach: $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ (9 fb^{-1})
  - Use $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\nu$ and fit in the corrected B mass
  - Normalise with $B^0 \to D^-(K\pi\pi)D_s^+(KK\pi)$
  - $\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$ at 90% CL
  - $\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6}$ at 90% CL
- New idea for $B^+ \to K^+\mu^-\tau^+$ (9 fb^{-1})
  - $B_{s2}^{*0} \to B^+K^-$ tagging: 1 % of B^+ but full τ reconstruction!
  - Inclusive τ selection (only a track needed)
  - Normalise with $B^+ \to J/\psi(\mu\mu)K^+$
  - $\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 3.9 \times 10^{-5}$ at 90% CL
- „Classical“ search for $B^+ \to K^+\mu^{\pm}\tau^{\mp}$ and $B^0 \to K^{*0}e^{\pm}\tau^{\mp}$ ongoing





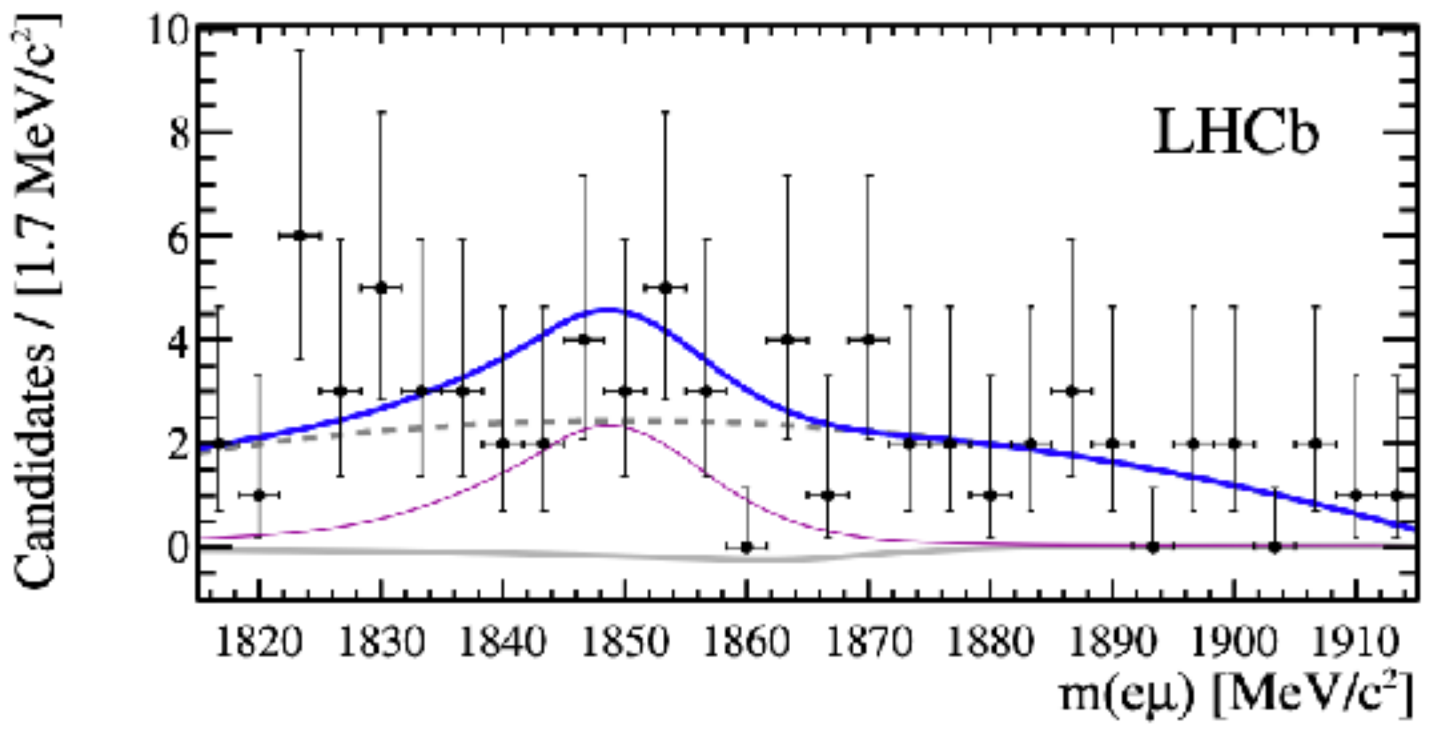
Charm decays: $D^0 \to e^{\pm}\mu^{\mp}$

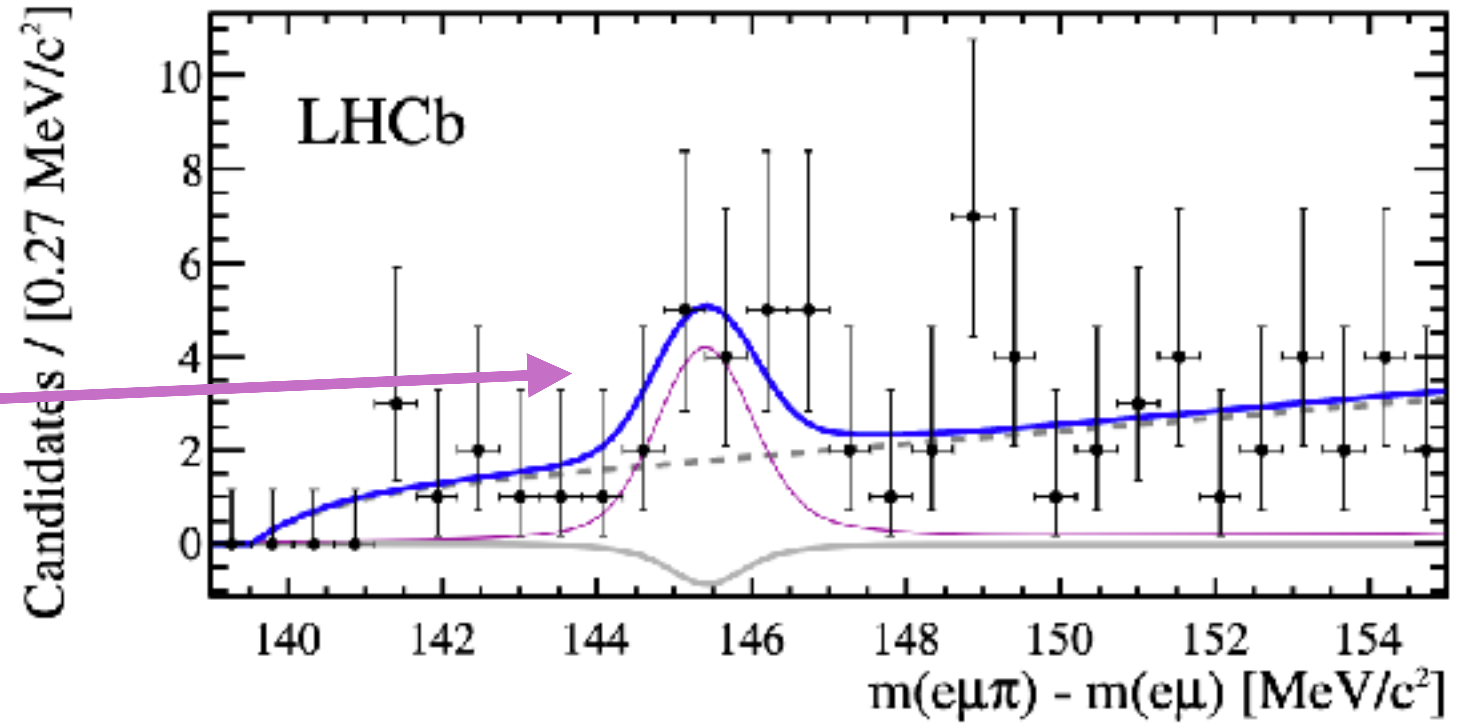
- Predictions for LFV in charm all over the place:
  - RPV SUSY: $< 10^{-8} - 10^{-6}$
  - Multiple Higgs: $< 10^{-10}$
  - Models with extra fermions: $< 10^{-14}$
  - Leptoquark models: $< 10^{-8}$

[Burdman et al PRD 66 (2002) 014009]
[Tahir et al CPC 38 (2014) 123101]
[Wang et al IJMPA 29 (2014) 1450169]
[de Boer/Hiller PRD 93 (2016) 074001]

- First search for $D^0 \to e^{\pm}\mu^{\mp}$ with $3\,\text{fb}^{-1}$ (2011/12) data
  - Using D^0 from $D^{*+} \to D^0\pi^+$ decays and normalising to $D^0 \to K^-\pi^+$
  - Exploiting particle identification criteria, multivariate classifier with vertexing and isolation criteria
  - Bin in classifier output
  - Simultaneously fit $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
  - Most dangerous background: $D^0 \to \pi^+\pi^-$
- $\mathscr{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8}$ @ 90% CL
  - Imposes interesting bounds on New Physics models

most signal-like region





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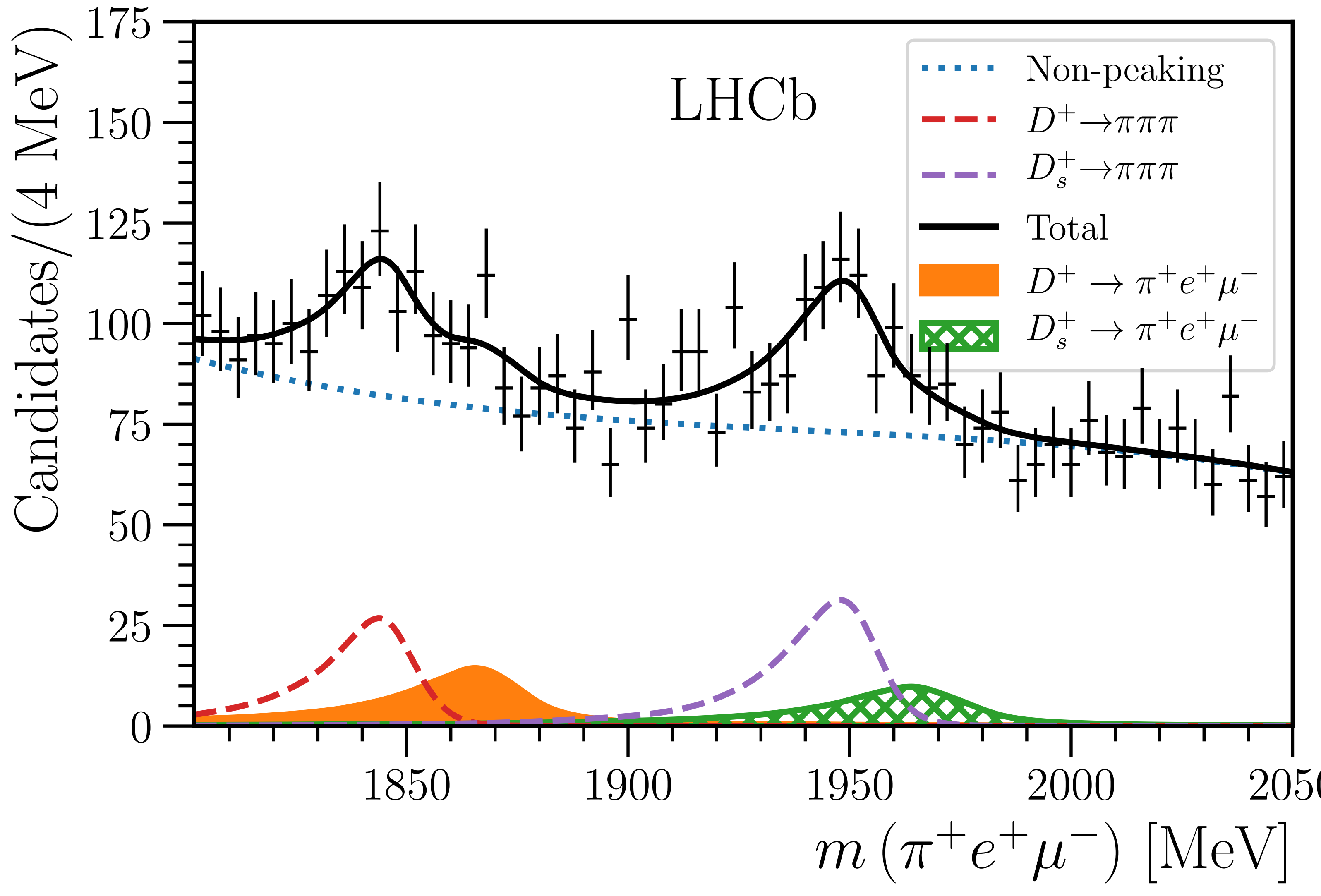
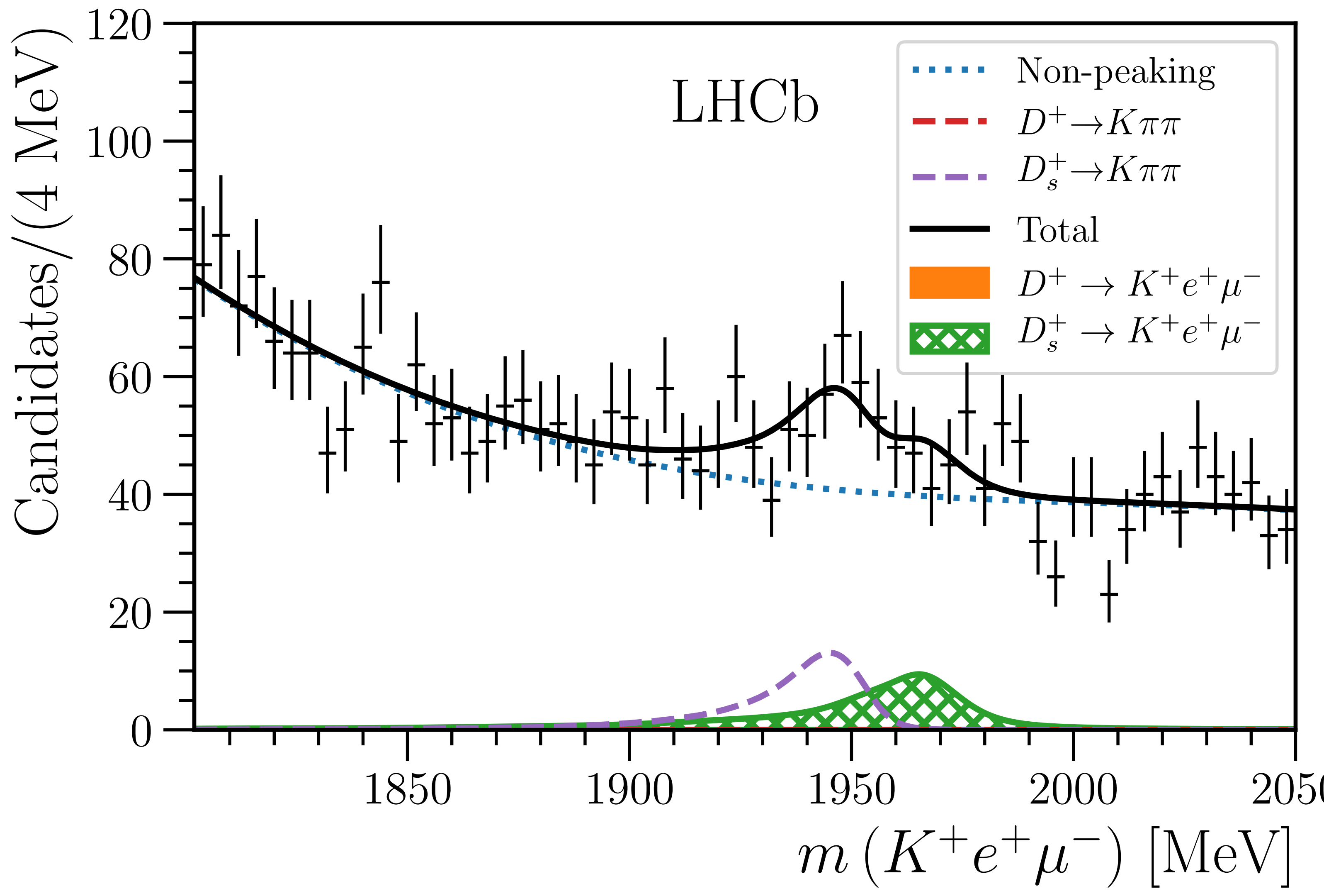
Charm decays: $D^+_{(s)} \to h\ell\ell'$

- Since 2015 new trigger model:
  - Allow to select exclusive decays, save only the signal-like particles
  - Allows much higher output rates → perfect for high charm cross sections!
- Exploit the new trigger model with $D^+_{(s)} \to K^+/\pi^+ e^\pm \mu^\mp$ and $D^+_{(s)} \to K^-/\pi^- e^+ \mu^+$ searches (and some more, 25 in total) with 2016 data ($1.6\,\text{fb}^{-1}$)
  - Normalise to $D^+_{(s)} \to \phi(\ell\ell)\pi^+$
  - Reduce background with the decay topology, final state momenta and isolation criteria, as well as particle identification
  - Combinatorial and $D \to 3h$ remain to be modelled
- Observed upper limits span $7.5 \times 10^{-8} - 1.1 \times 10^{-6}$

  → most precise result for all studied LFV modes!
- Some more Charm LFV measurements ongoing





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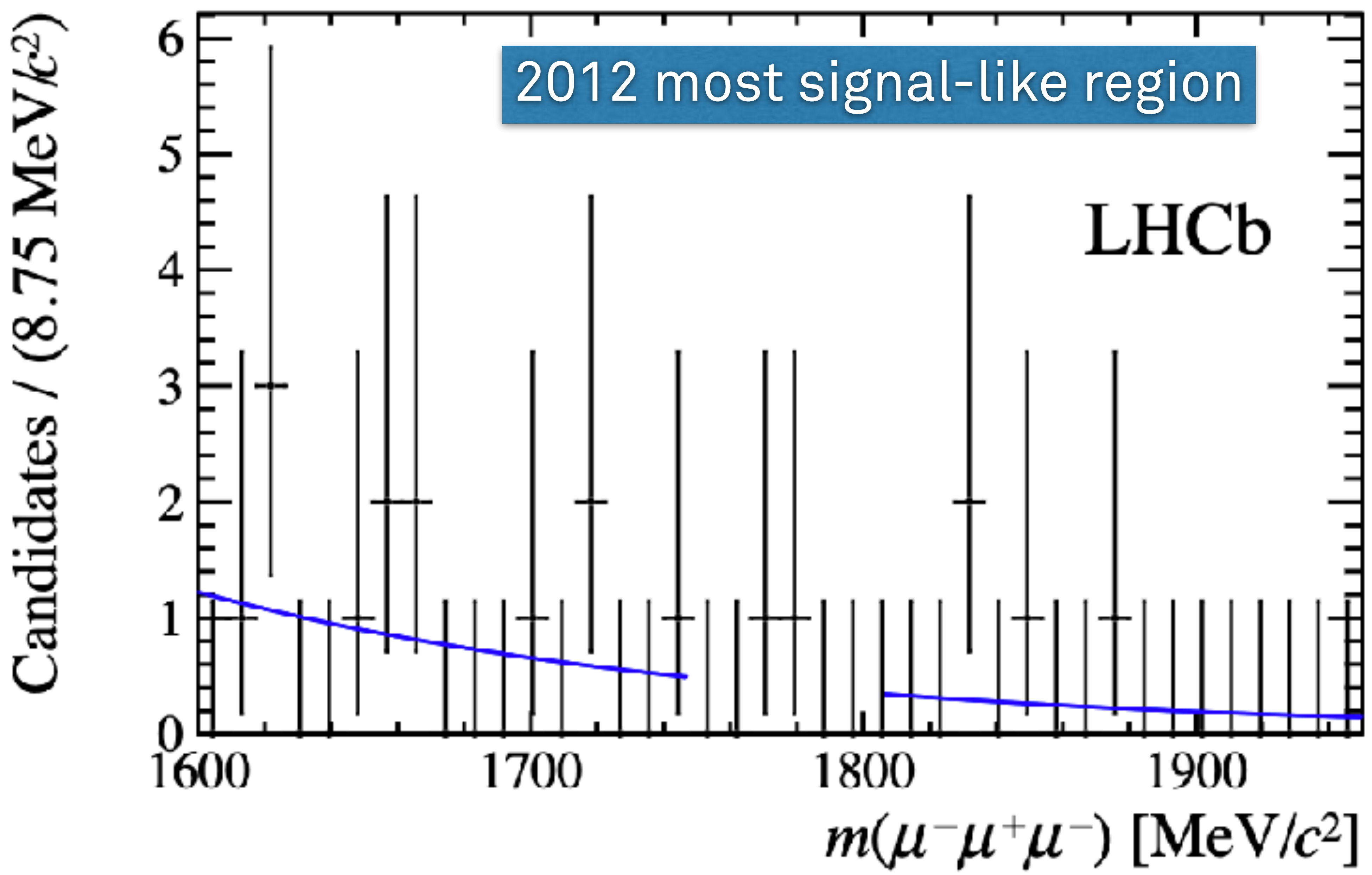
The golden mode $\tau \to 3\mu$

[Babu/Kolda PRL 89 (2002) 241802]
[Brignole/Rossi PLB 566 (2003) 217]
[Paradisi JHEP 10 (2005) 006]
[Hays et al JHEP 05 (2017) 014]

- Purely leptonic → very clean
- Muons easiest detector signature
- In New Physics models often $\mathcal{O}(10^{-9} - 10^{-8})$
- Latest search at LHCb used $3\,\mathrm{fb}^{-1}$ collected in 2011-2012
  - Normalise to $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ decays
  - Challenges:
    - Soft momenta → huge backgrounds
    - Need to describe all origins of τ: B and D decays
  - Veto $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ and $D_s^- \to \eta(\mu\mu\gamma)\mu\nu$ decays
  - 2 dedicated multivariate classifiers
    - Exploiting geometric information
    - Separating muons from other particles
    - Limit from mass fit in bins of the two classifiers
- Update with full 2011-2018 data $(9\,\mathrm{fb}^{-1})$ underway



[PLB 687 (2010) 139] Belle: $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ @90% CL

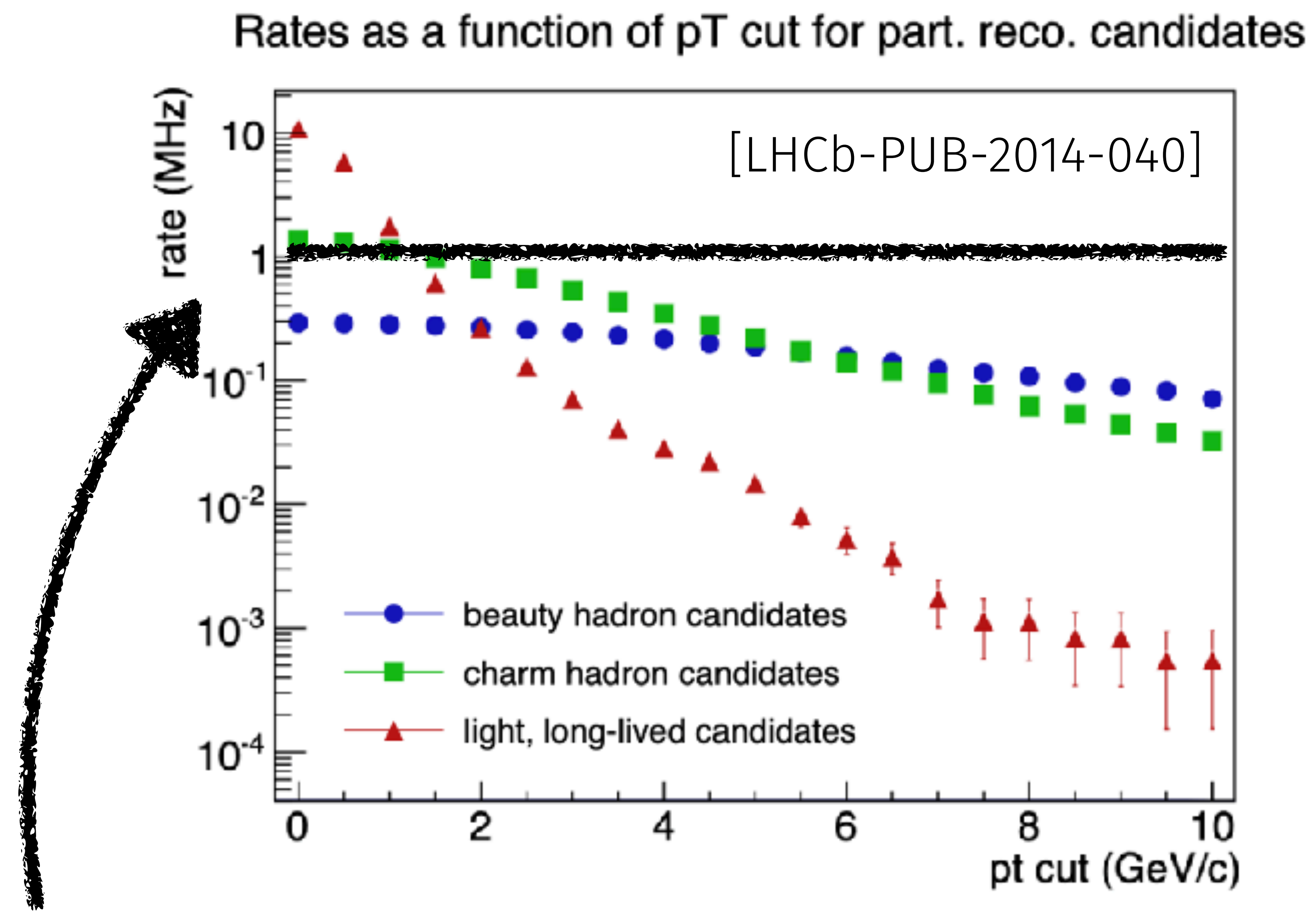
LHCb: $\mathcal{B}(\tau \to 3\mu) < 4.6 \times 10^{-8}$ @90% CL

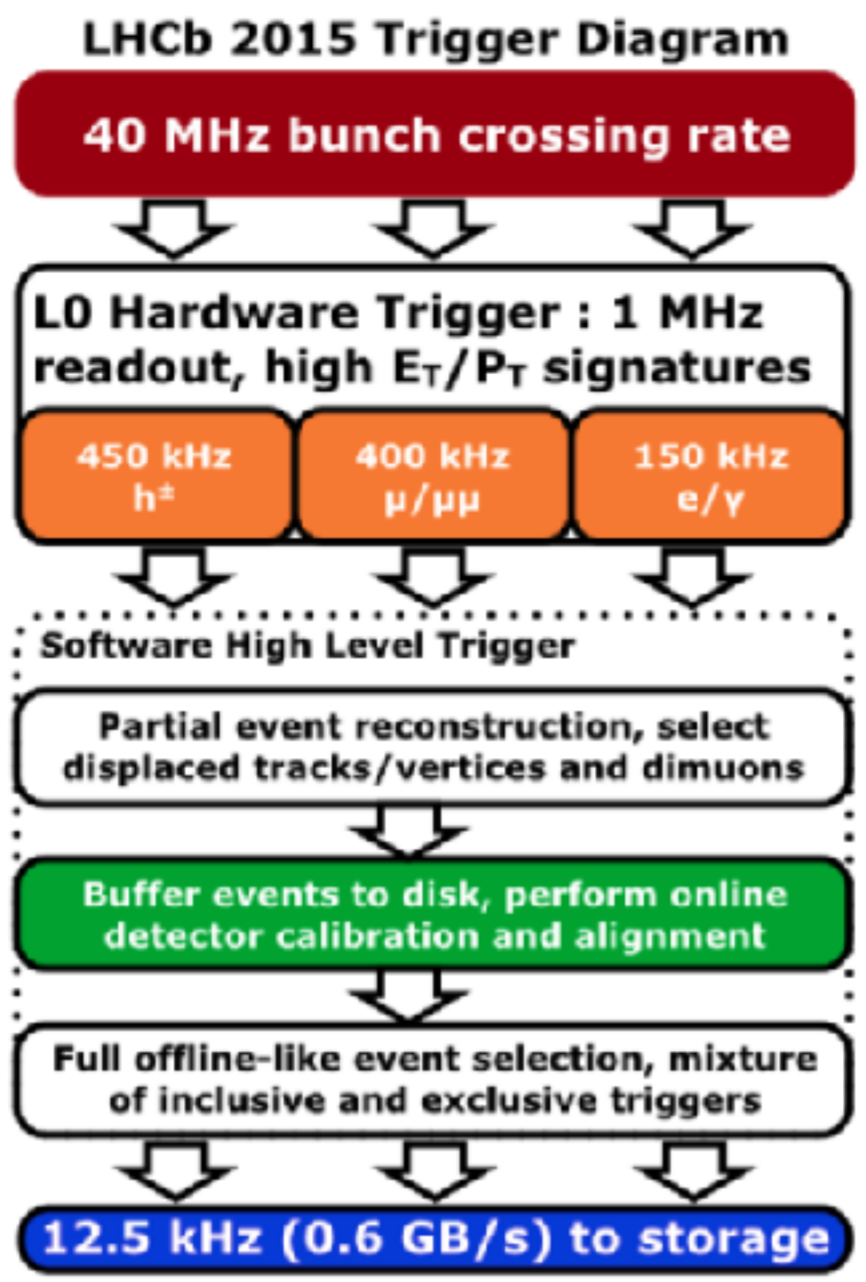
A look into the (near) future

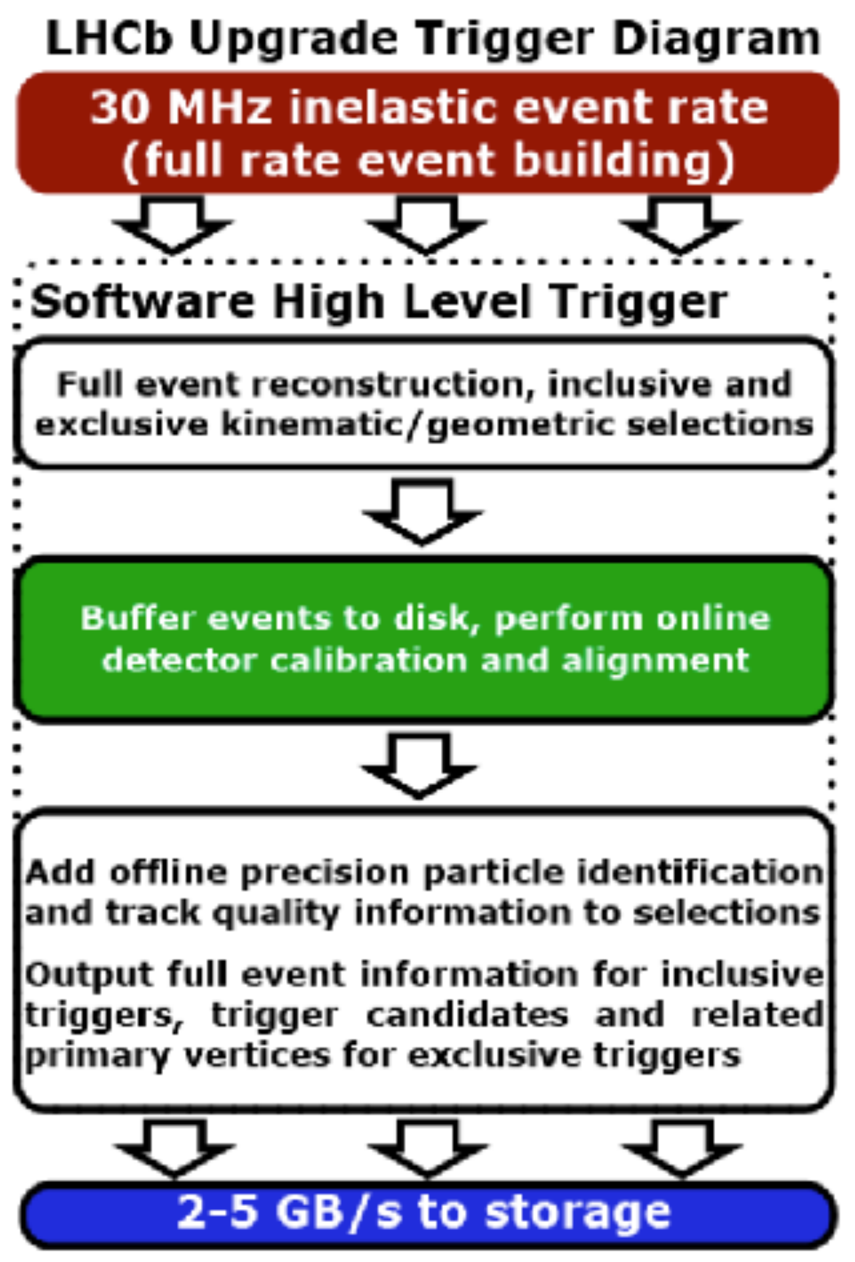
- LHCb started taking data again and commissioning is ongoing
- Completely new detector!
- Fully exploiting the new trigger model as default

  $\rightarrow$ Fully exclusive trigger lines can give large statistics boost!
  - Improve electron efficiency (was limited by hardware trigger)
  - Strongly boost soft and displaced signatures (D, τ decays), in principle can go down to $p_{\mathrm{T}} < 50$ MeV!
  - Enable new searches: LFV in strange decays!

Open to suggestions on new analyses!







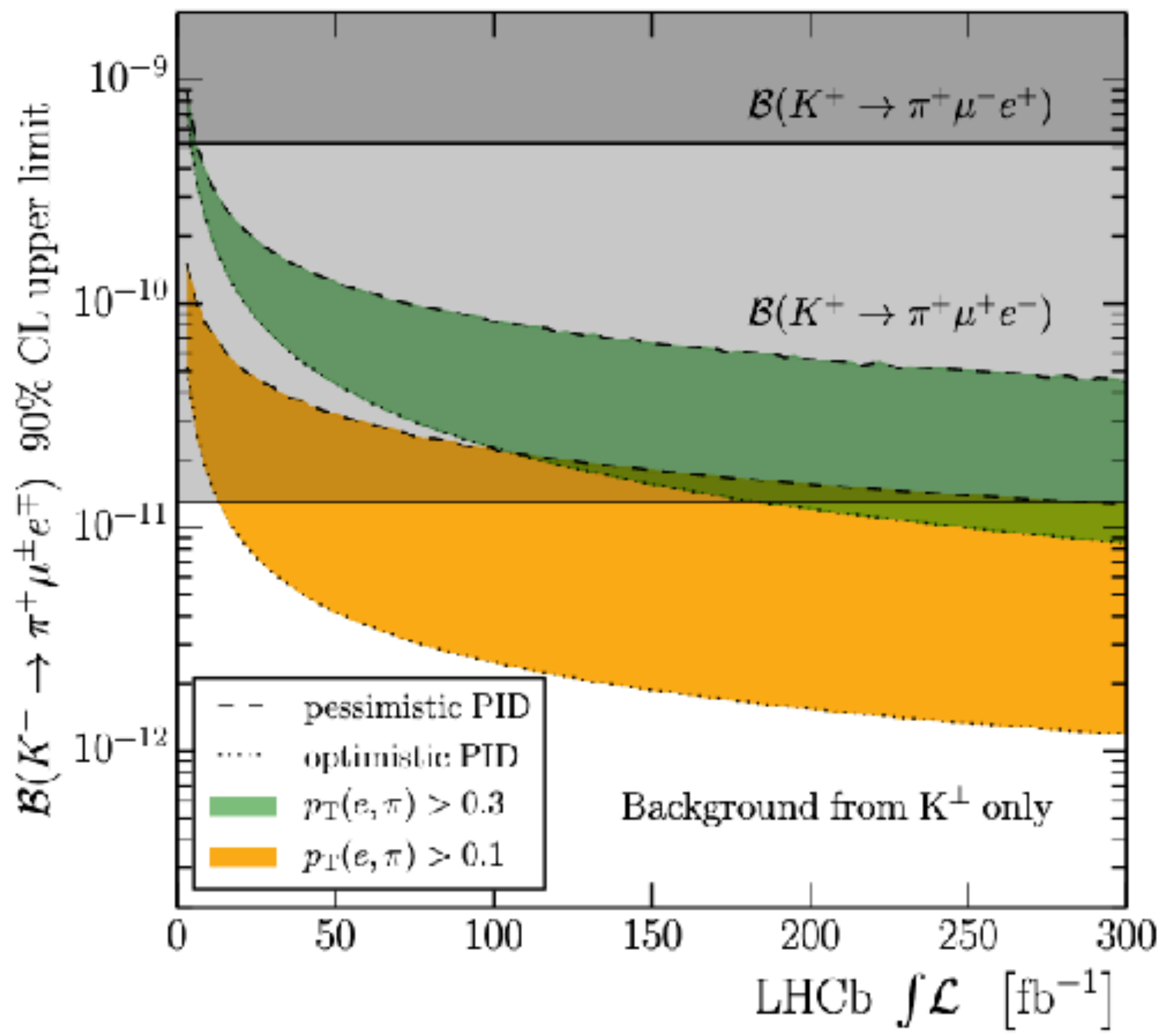
CERN-LHCC-2018-027

JHEP 05 (2019) 048

PRD 99, 055017 (2019)

A few examples already for Run 3 and 4 (~2030)

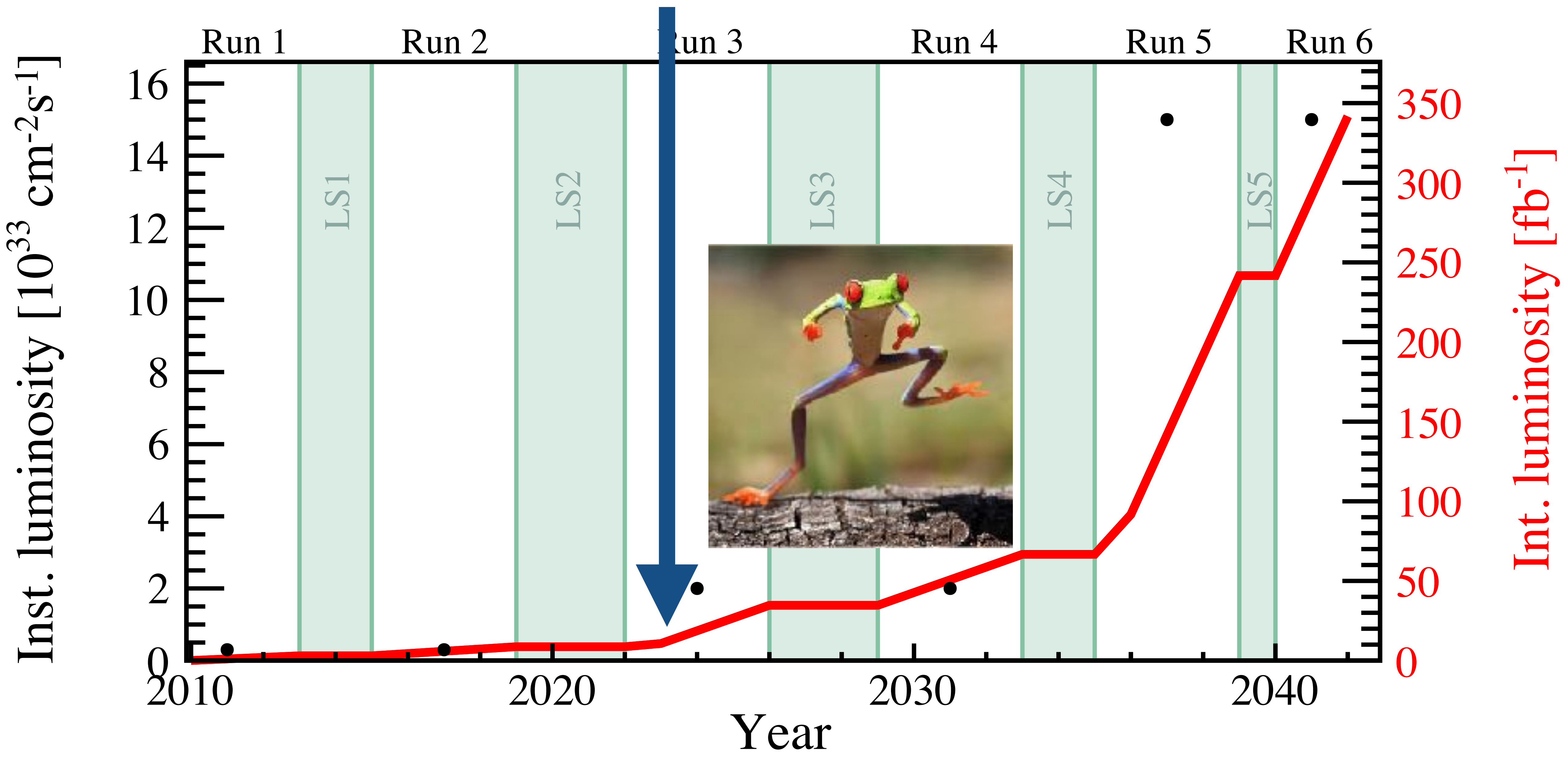
- $\mathcal{B}(B^0_{(s)} \to e^\pm\mu^\mp) \sim \mathcal{O}(10^{-10})$, not far from New Physics scenarios $\mathcal{O}(10^{-11})$
- $\mathcal{B}(B^0_{(s)} \to \tau^\pm\mu^\mp) \sim \mathcal{O}(10^{-6} - 10^{-5})$, strongly constrain New Physics scenarios $\mathcal{O}(10^{-9} - 10^{-4})$
- $\mathcal{B}(\tau \to 3\mu) \sim \mathcal{O}(< 10^{-8})$, the parameter space predicted by most scenarios
- Could do first ever search for $K^0_s \to e^\pm\mu^\mp$ and compete with NA62 on $K^+ \to \pi^+e^\pm\mu^\mp$



Summary

- LFV is an active field at LHCb
  - Stringent constraints on many models
  - Mostly significantly improving previous results or even first ever searches
  - Overcoming challenges with new analysis techniques
- Finishing analyses with full Run 1+2 data - now Run 3 has started!
  - New trigger model will give a large boost for soft modes and modes with electrons

Modulo a little COVID shift



We're living in exciting times!

Backup

Full results for the $D^+_{(s)} \to h\ell\ell$ searches