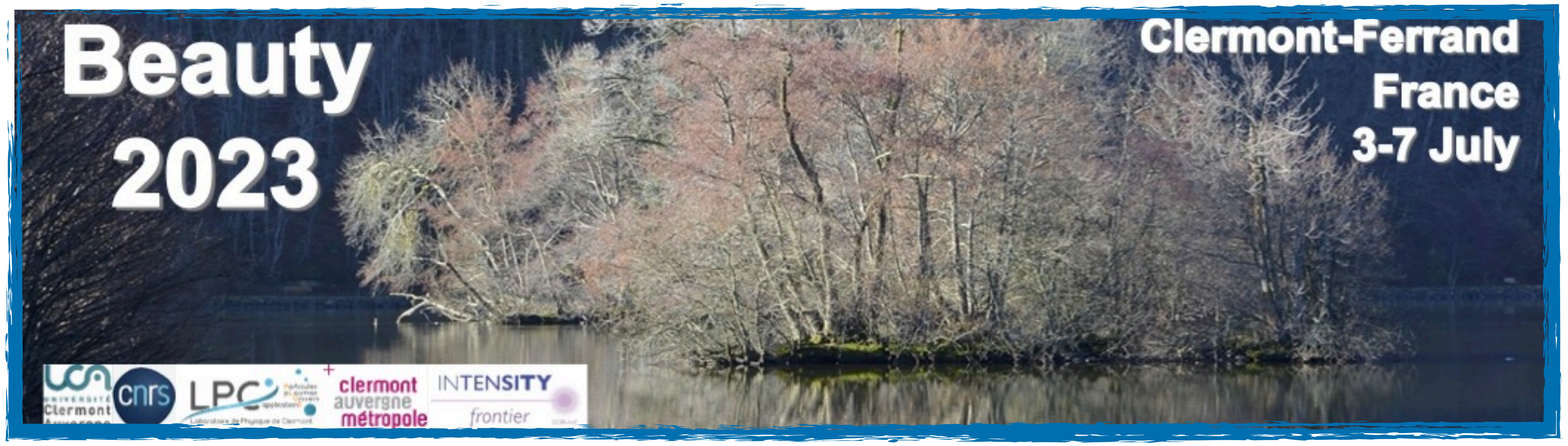
Rare B decays at LHCb

(excluding b->sll)

Irene Bachiller (LAPP, France)
on behalf of the LHCb collaboration



Rare B decays

Highly **suppressed** in SM:

- Higher orders diagrams
- FCNC box or penguin diagrams
- b → sll, dedicated presentation later

Signal different from SM?

Possible new physics!

Forbidden in SM:

- Lepton Flavour Violating
- Baryon Number Violating
- …

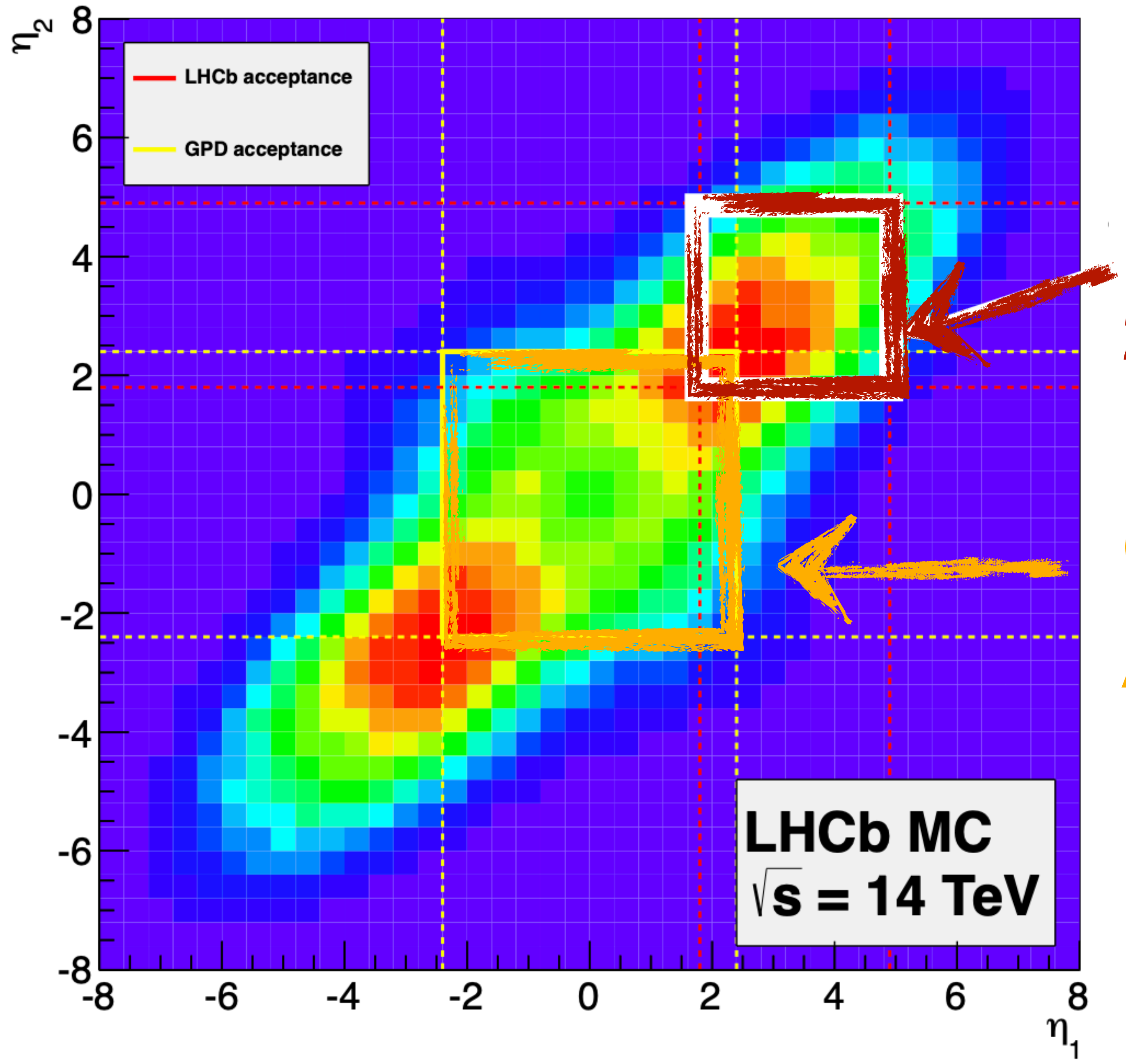
Any signal?

Possible new physics!

LHCb detector for rare B decays

- The LHC has a large cross section of b and c hadrons:
  - $\sigma(b\bar{b})_{7\ TeV} = 295\ \mu b$
  - $\sigma(b\bar{b})_{13\ TeV} = 590\ \mu b$
- LHCb designed as forward spectrometer to focus on $b\bar{b}$ production
- LHCb uses luminosity levelling:
  - Proton beams are defocused
  - Keeps run conditions more stable during fills
  - Reduces interactions per bunch crossing to 1-2

LHCb acceptance $2 < \eta < 5$



LHCb: 25% of $b\bar{b}$

CMS
ATLAS

- All results presented today make used of the full available proton-proton collisions collected by the LHCb experiment:

Run 1:
- 1 fb^{-1} at $\sqrt{s} =$ 7 TeV
- 2 fb^{-1} at $\sqrt{s} =$ 8 TeV

Run 2:
- 6 fb^{-1} at $\sqrt{s} = 13$ TeV

LHCb detector for rare B decays

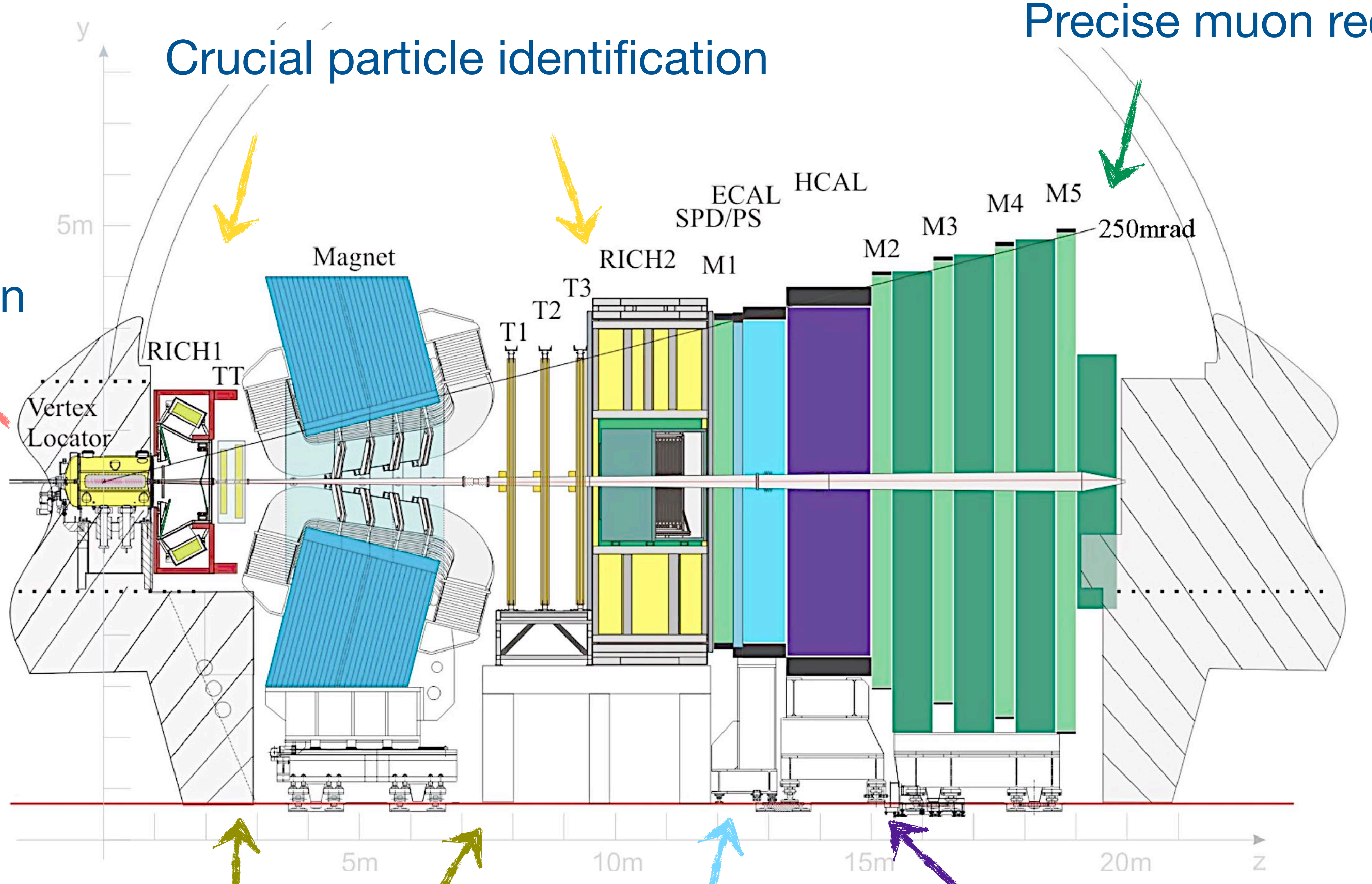
Int. J. Mod. Phys. A 30, 1530022 (2015)
CERN-LHCC-2003-030

The LHCb detector is very suitable to search for rare B decays.

Crucial particle identification

Precise muon reconstruction

High vertex resolution



Tracking: good momentum resolution

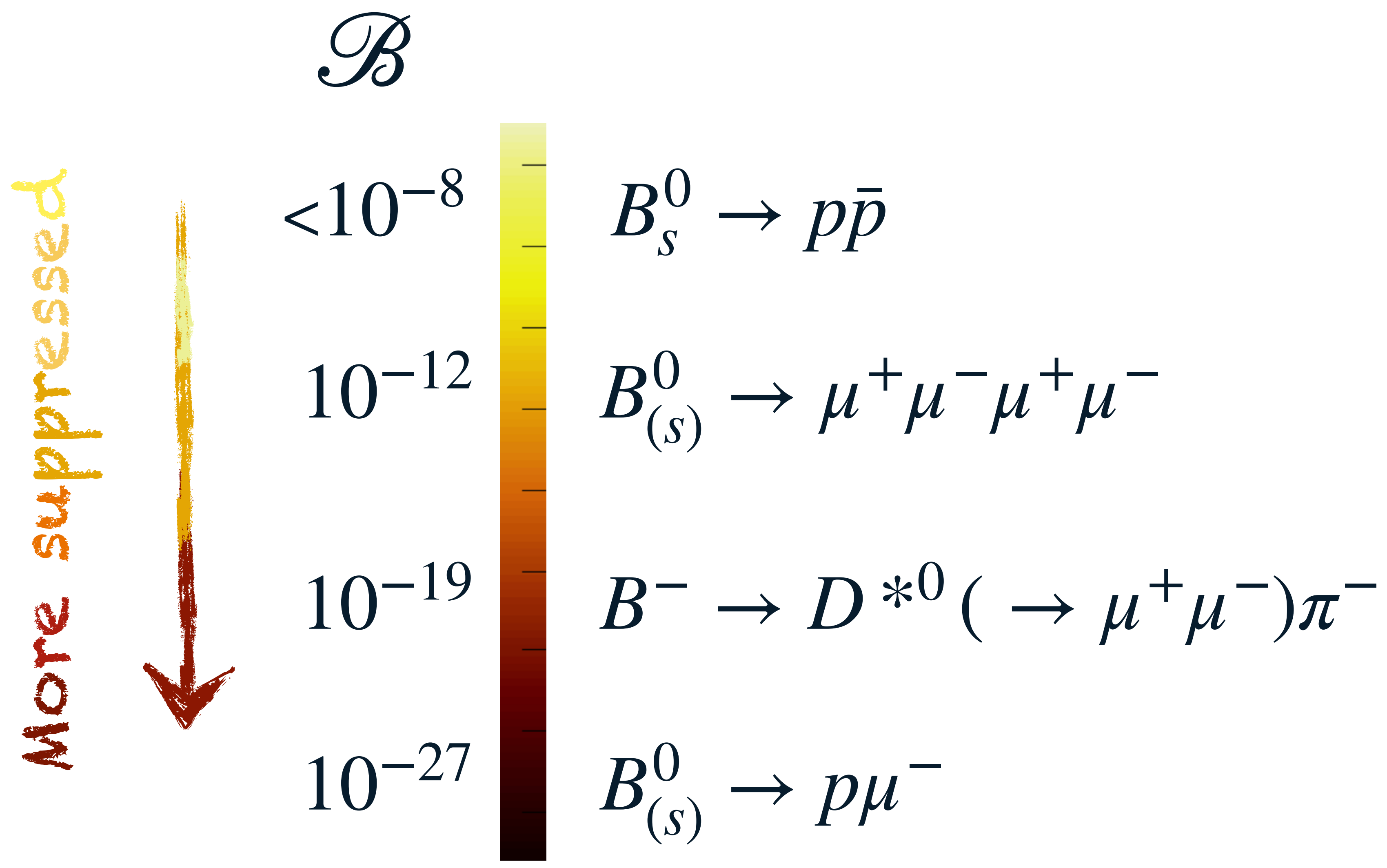
E-Calorimeter: Electromagnetic E measurement

H-Calorimeter: hadronic E measurement

Rare B decays

- In this presentation:

Theoretical predictions:



- In next presentation by Sara Celani all about b → sll.

- More B decays in presentation by Jike Wang.

$B^0_{(s)} \to p\mu^-$

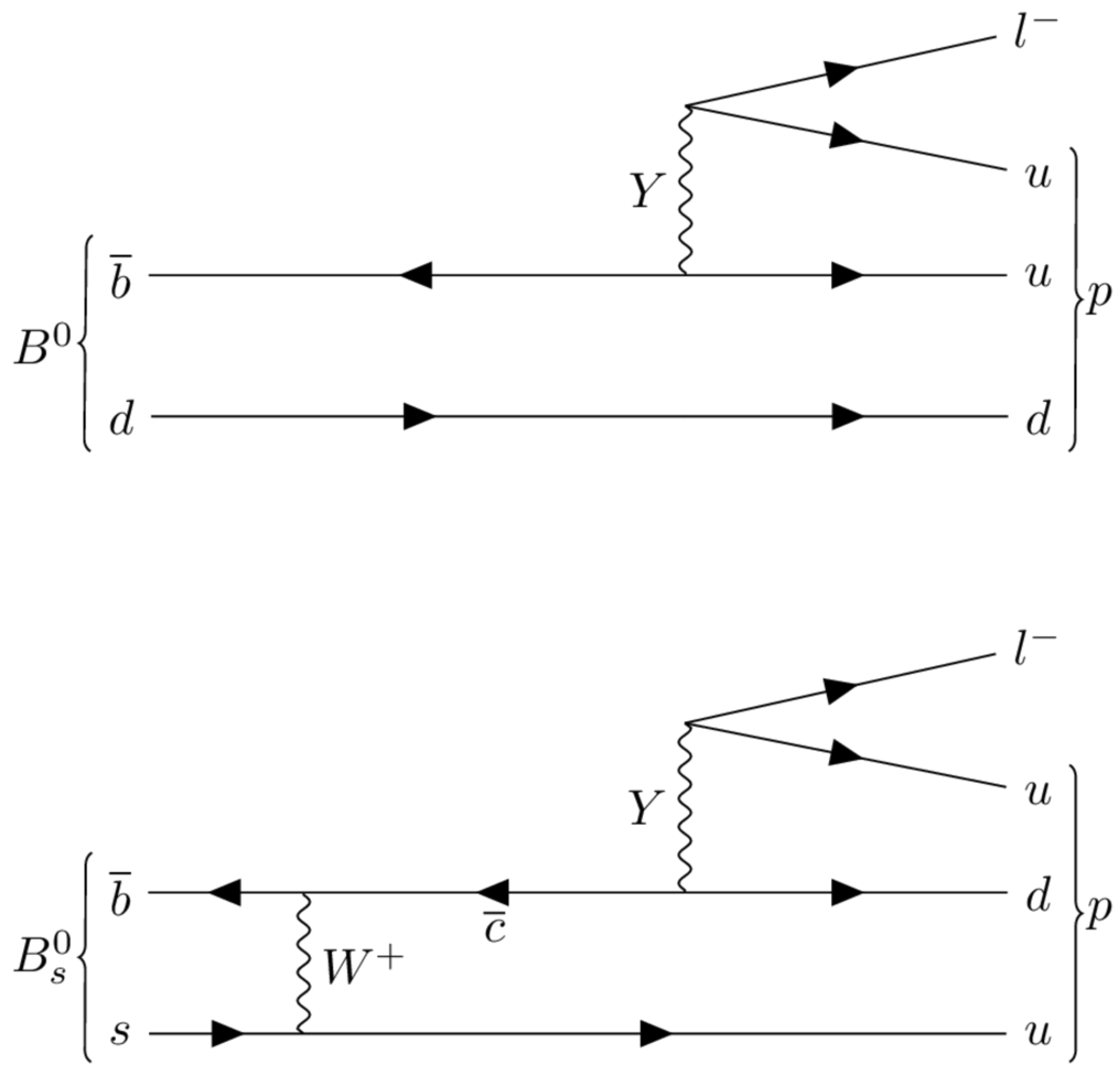
LHCb-PAPER-2022-022
arXiv:2210.10412

First time!

Hypothetical Y boson that couples quarks to leptons and leads to LNV and BNV

Motivation:

- Lepton and baryon number violation (LNV and BNV).
- Forbidden in the SM with a prediction of $\mathscr{B}(\bar{b} \to uul^-) < 2.4 \times 10^{-27}$ [1].
- Highly sensitive to new physics: GUT models. →
- Never searched before.



[1] Phys. Rev. D **72** (2005) 095001

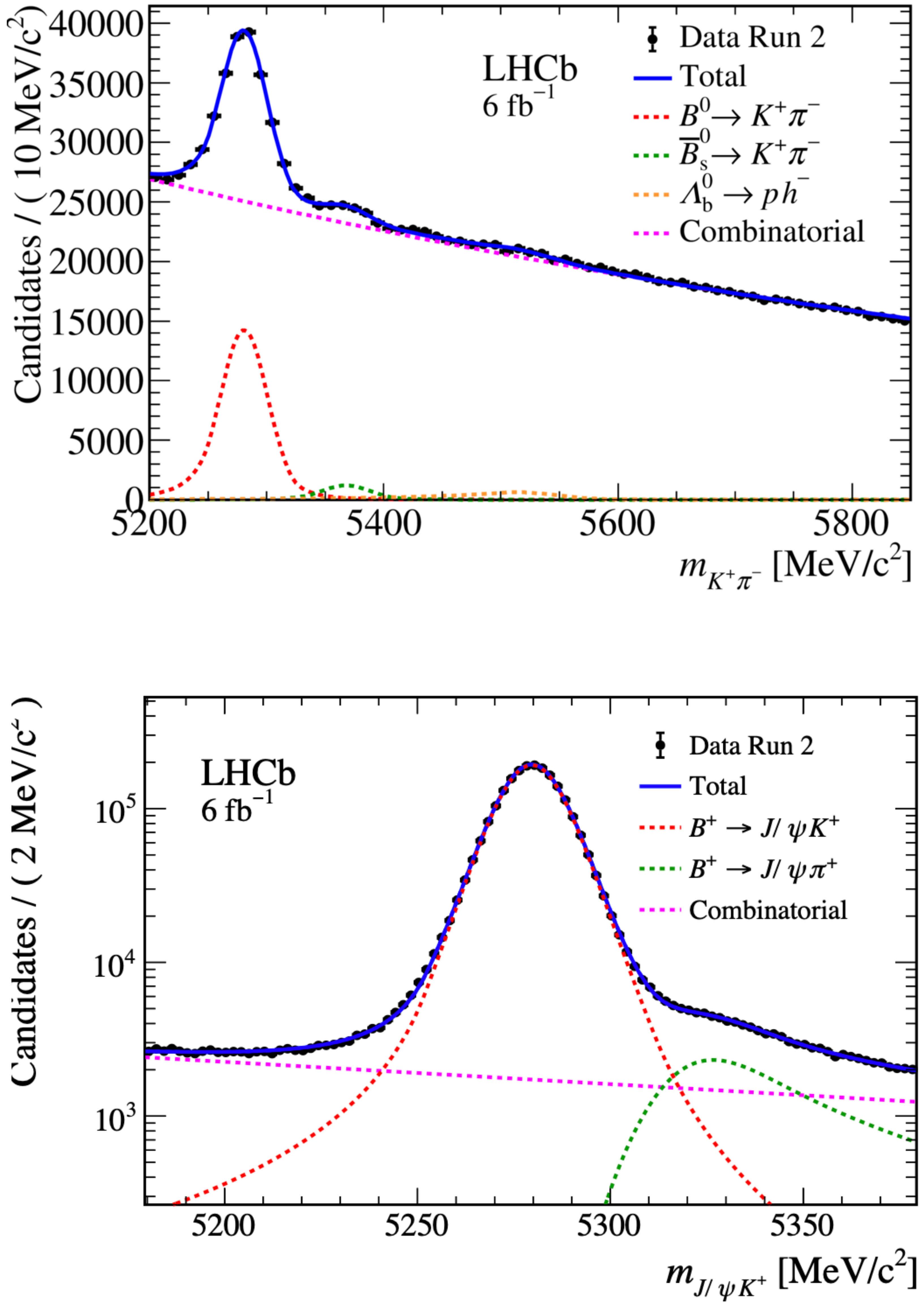
$B^0_{(s)} \to p\mu^-$

LHCb-PAPER-2022-022
arXiv:2210.10412

Strategy:

- Use PID to reject hadron misID candidates.
- A multilayer perceptron (MLP) to discriminate the combinatorial background.
- Two **normalisation** channels:
  - Similar signal topology $B^0 \to K^+\pi^-$
  - High stats. and purity $B^+ \to J/\psi(\to \mu\mu)K^+$

$$R_{\text{norm}} \equiv \frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B^+ \to J/\psi(\mu^+\mu^-)K^+)} = \frac{N_{B^0\to K^+\pi^-} \times \varepsilon_{B^+\to J/\psi(\mu^+\mu^-)K^+}}{N_{B^+\to J/\psi(\mu^+\mu^-)K^+} \times \varepsilon_{B^0\to K^+\pi^-}}$$

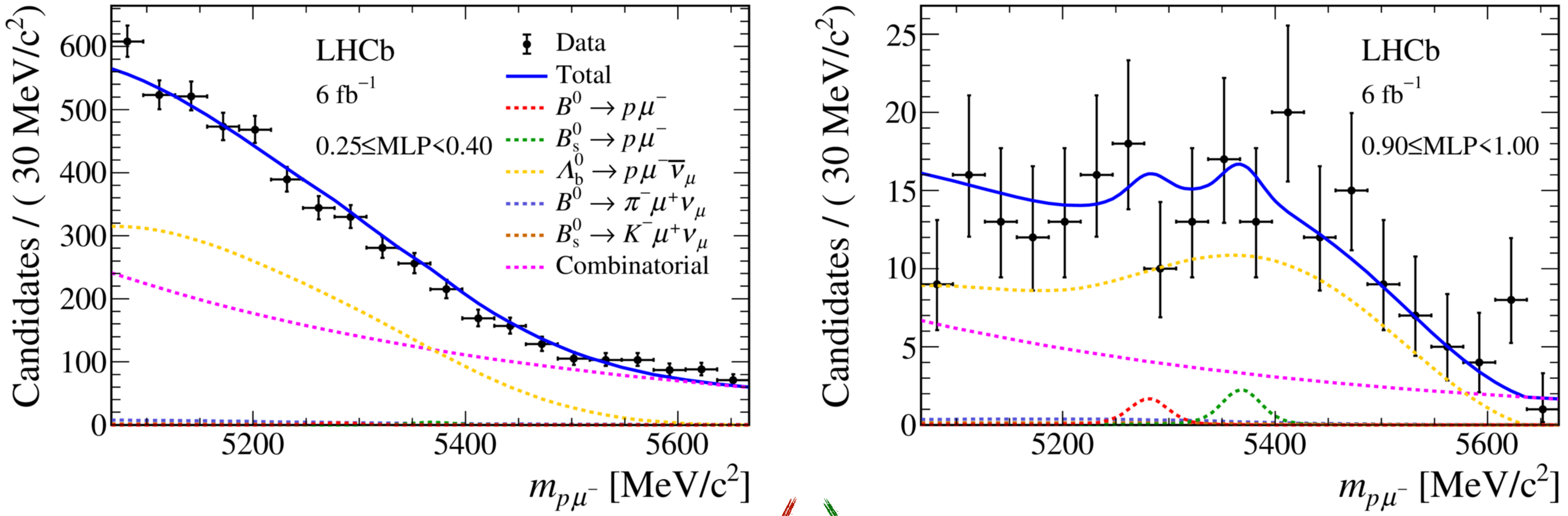


- Binned in MLP response.
- Signal mass region **blinded** until the selection and fitting procedure were finalised.

$B^0_{(s)} \to p\mu^-$

LHCb-PAPER-2022-022
arXiv:2210.10412

Mass distribution example for two MLP bins and one dataset:

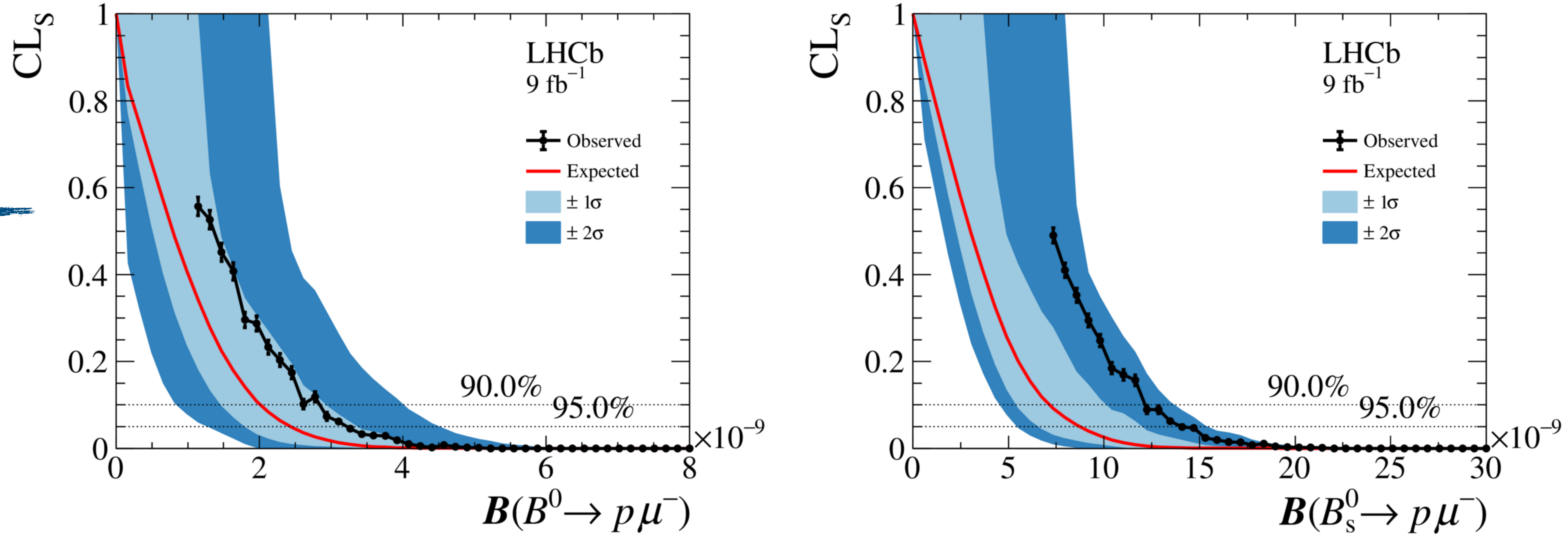


Results:

- Signal extraction using fit on $p\mu^-$ mass.
- Not evidence found, limits at 90% (95%) CL:

$$\mathcal{B}(B^0 \to p\mu^-) < 2.6\ (3.1) \times 10^{-9}$$

$$\mathcal{B}(B^0_s \to p\mu^-) < 12.1\ (14.0) \times 10^{-9}$$

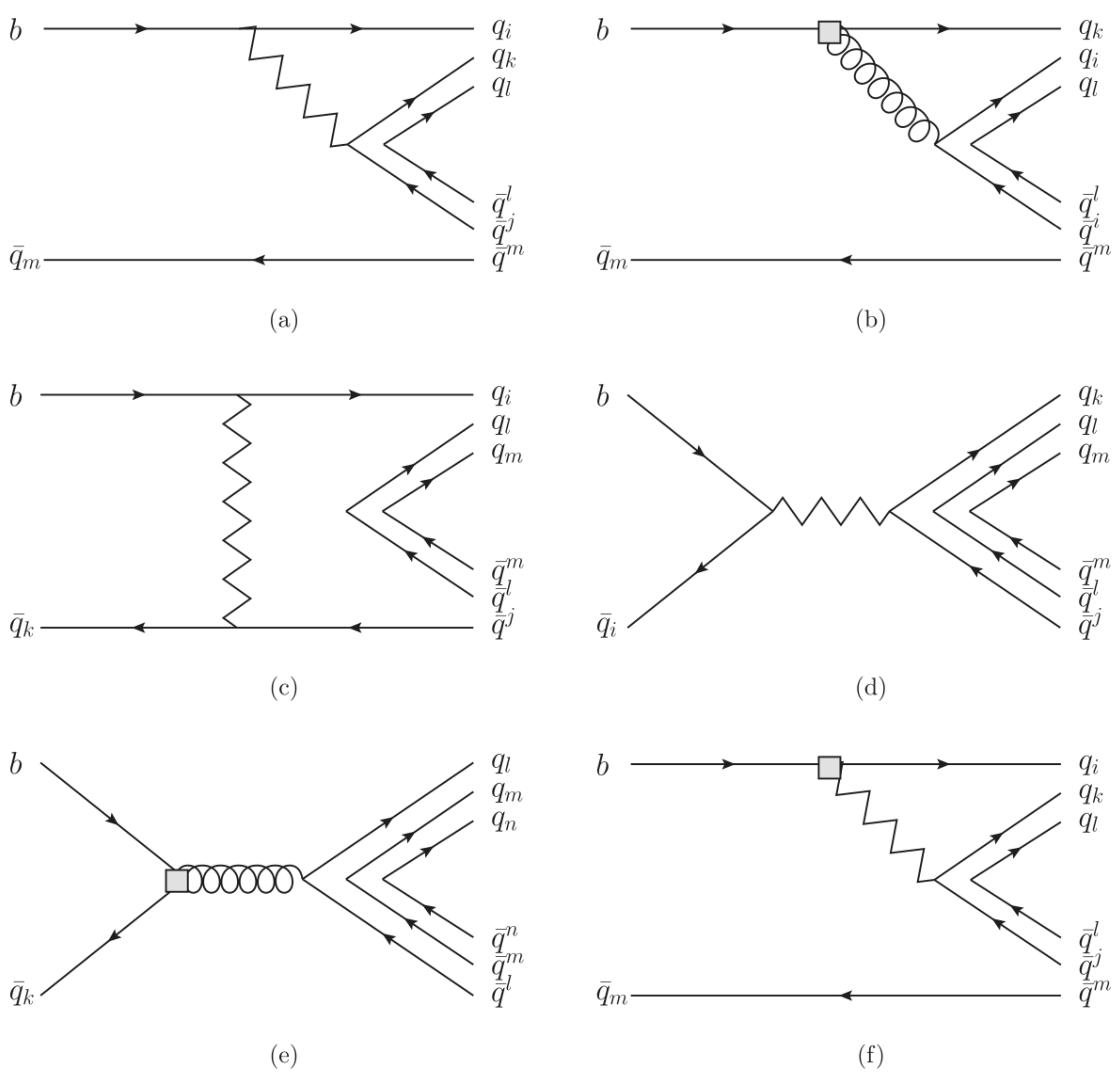


First ULs on these decays!

$B_s^0 \to p\bar{p}$

LHCb-PAPER-2022-022
arXiv:2210.10412

Tree, penguin, W-exchange, annihilation, penguin annihilation and electroweak penguin diagrams for B to baryon pair decays:



Motivation:

- The two-body baryonic decays are suppressed [1,2]
- Theoretical estimations disagree about the $\mathscr{B}$ [3,4]. Waiting for experimental results to clarify.
- Previous search of $B_s^0 \to p\bar{p}$ at LHCb with Run 1 [5]:
  $\mathscr{B}(B_s^0 \to p\bar{p}) < 1.5 \times 10^{-8}$ at 90% CL

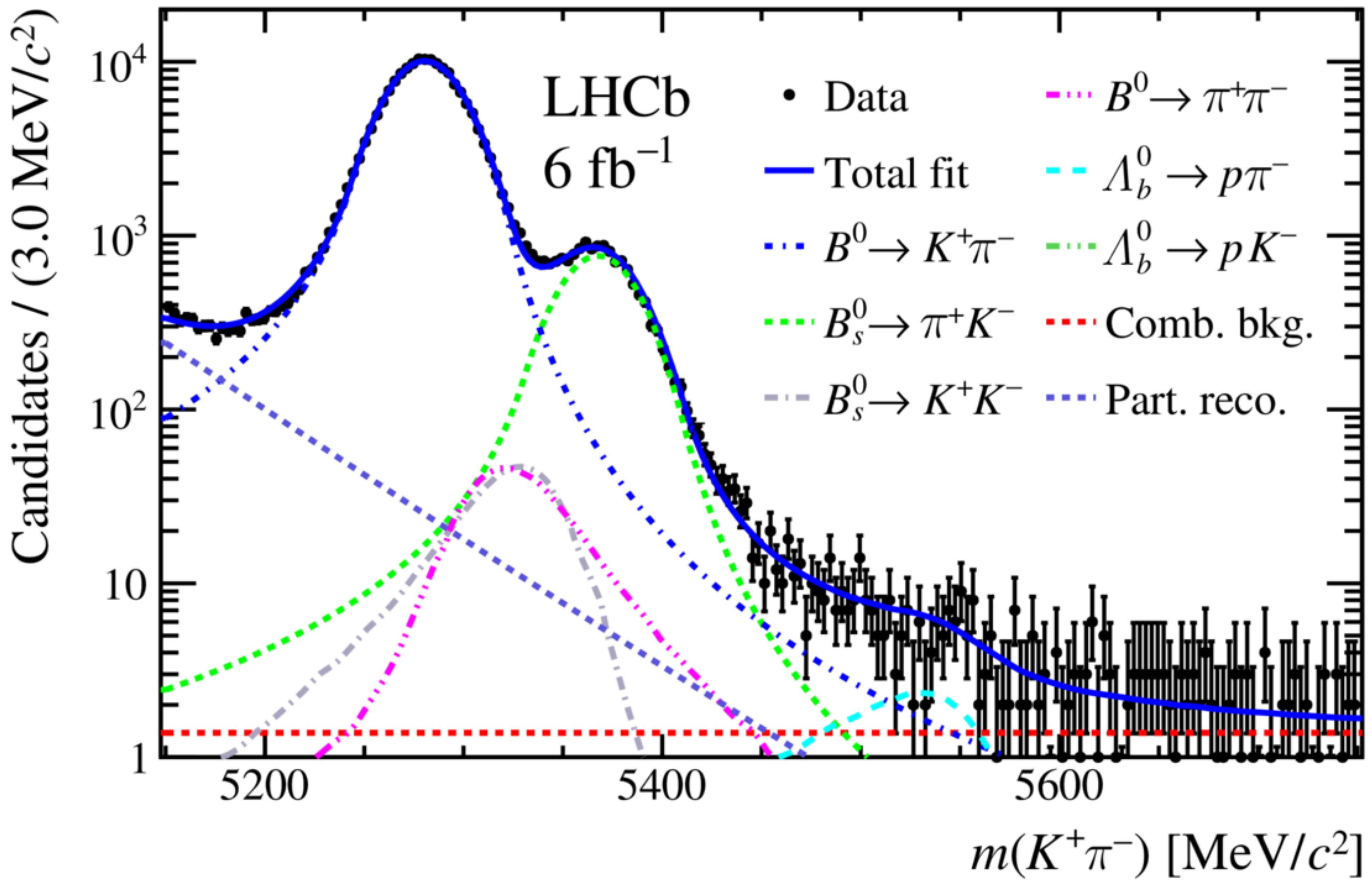
[1] High Energy Physics **2022** (2022) 4343824
[2] Phys. Rev. **D91** (2015) 036003
[3] JHEP **04** (2020) 035
[4] Pays. Rev. **D95** (2017) 096004
[5] Phys. Rev. Lett. **199** (2017) 232001

$B_s^0 \to p\bar{p}$

LHCb-PAPER-2022-004
arXiv:2206.06673

Strategy:

- Tight PID selection to reduce background from mis-identified hadrons.
- Multivariate technique: boosted decision tree (BDT), to reduce combinatorial background.
- Mass signal blinded until analysis procedure was finalised.
- Normalisation channel: $B^0 \to K^+\pi^-$



$$\mathcal{B}(B^0_{(s)} \to p\bar{p}) = \frac{N(B^0_{(s)} \to p\bar{p})}{N(B^0 \to K^+\pi^-)} \times \frac{\varepsilon_{B^0 \to K^+\pi^-}}{\varepsilon_{B^0_{(s)} \to p\bar{p}}} \times \mathcal{B}(B^0 \to K^+\pi^-) \times \frac{f_d}{f_{d(s)}}$$

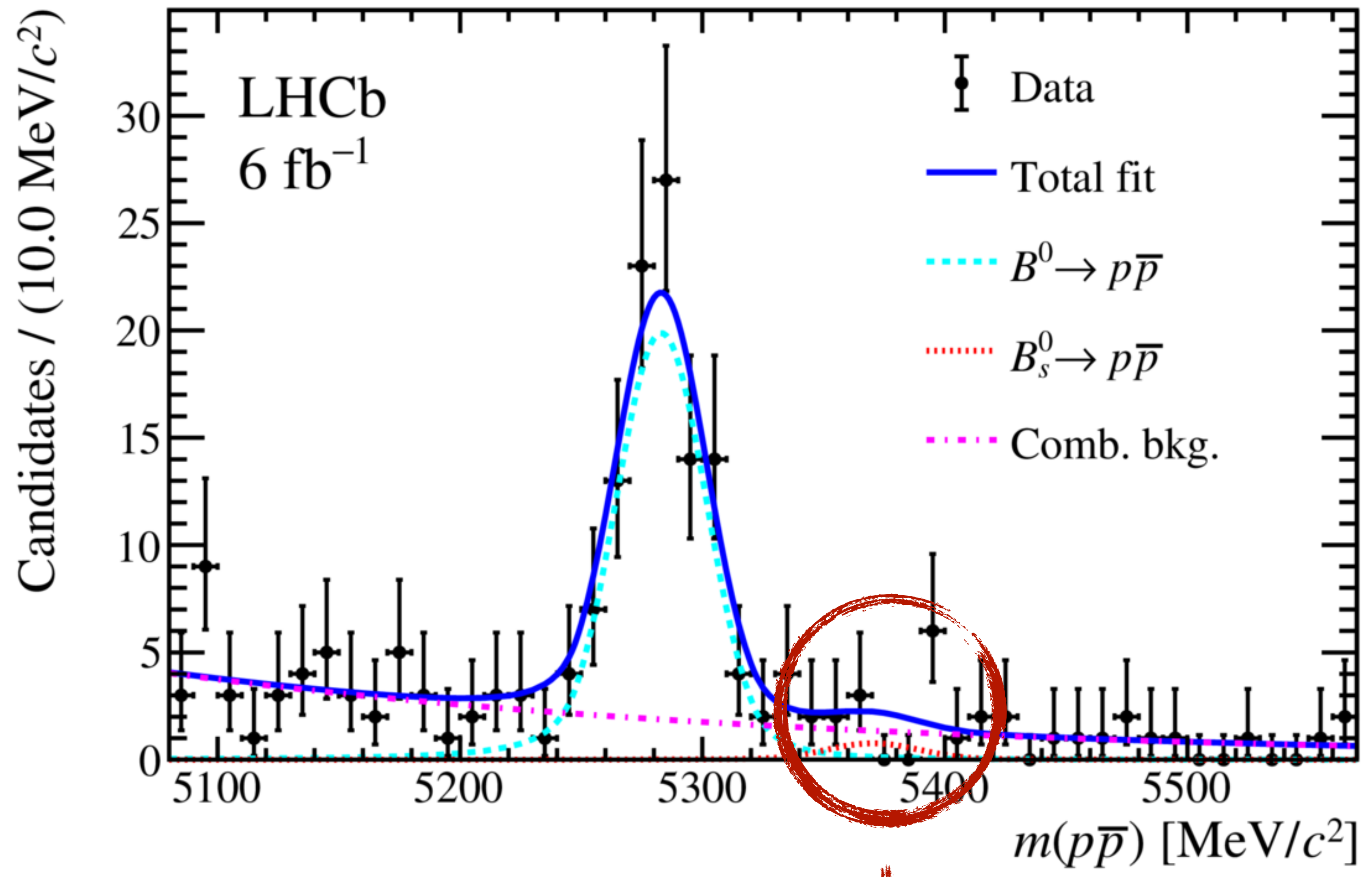
$B_s^0 \to p\bar{p}$

LHCb-PAPER-2022-004

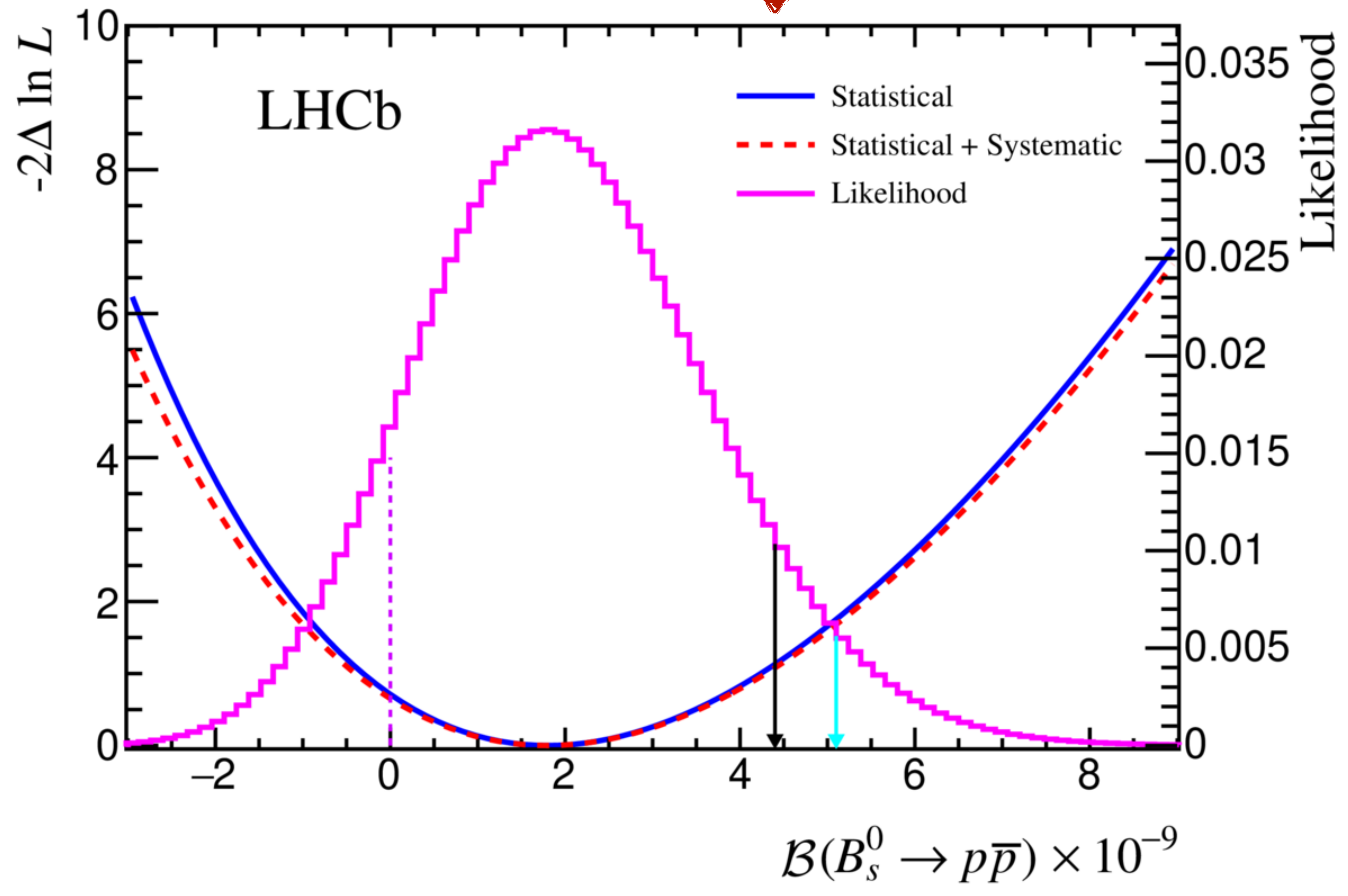
arXiv:2206.06673

Results:

- No evidence of the decay is found.
- Upper limit on the branching fraction at 90 (95)% CL:



$$\mathcal{B}(B_s^0 \to p\bar{p}) < 4.4\ (5.1) \times 10^{-9}$$



Most stringent UL of this decay to date!

LHCb-PAPER-2021-039
JHEP 03 (2022) 109

Motivation:

- FCNC transition, no tree level ⇒ highly suppressed.
- Theoretically predicted [1]:

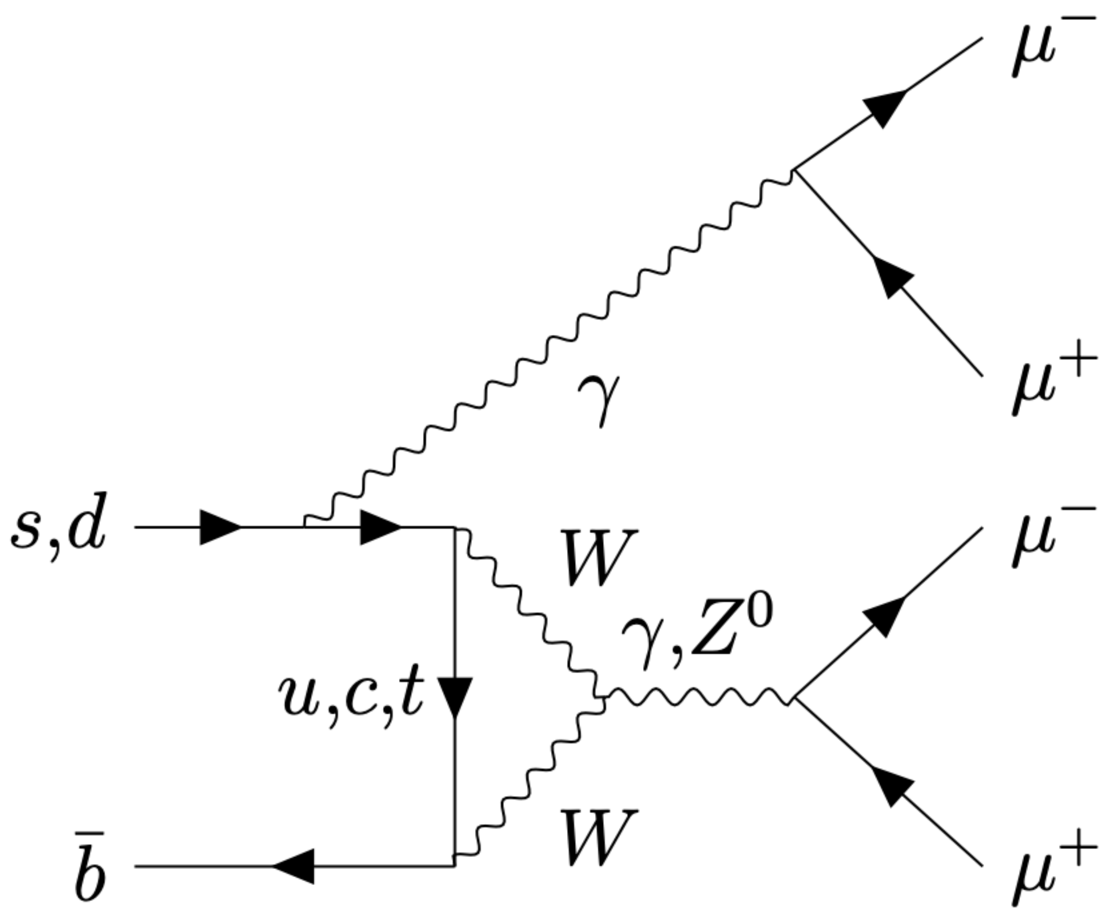
  $\mathscr{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) = (0.4 - 4.0) \times 10^{-12}$

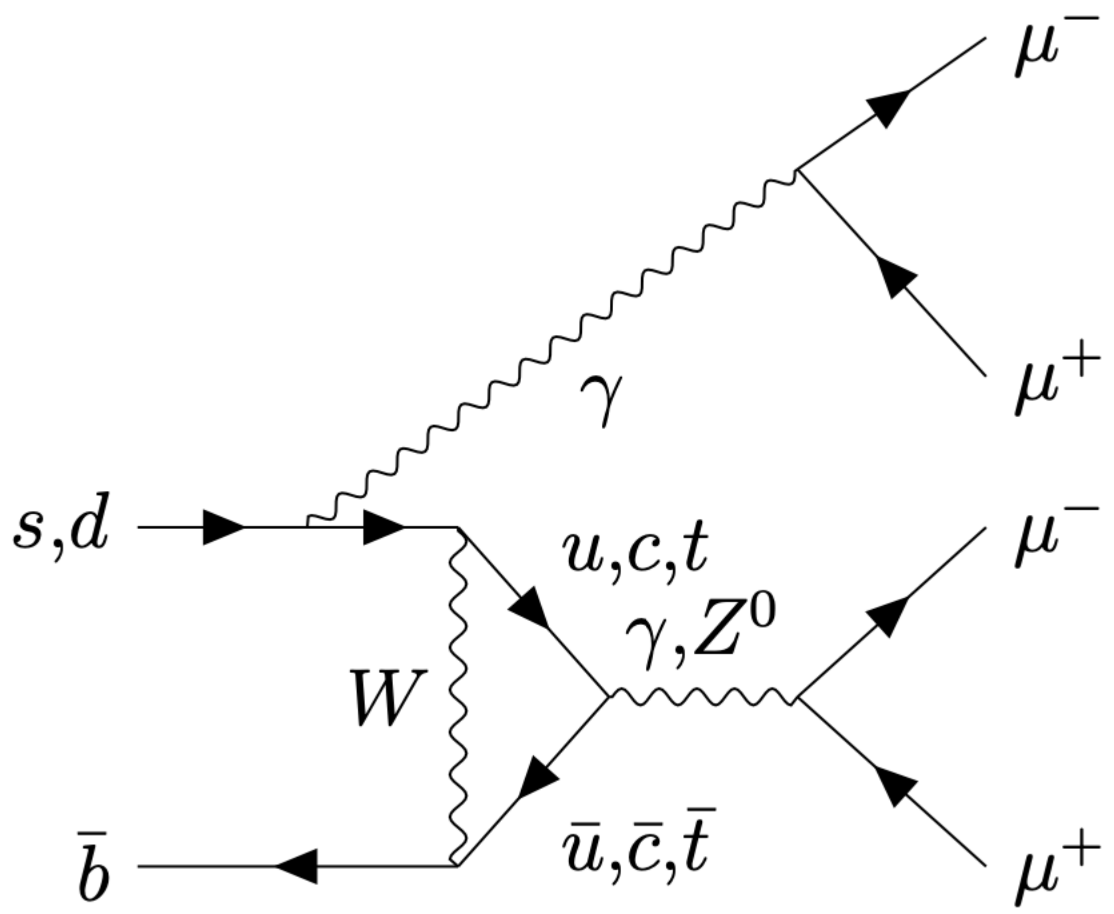
  $\mathscr{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^- = (0.9 - 1.0) \times 10^{-10}$

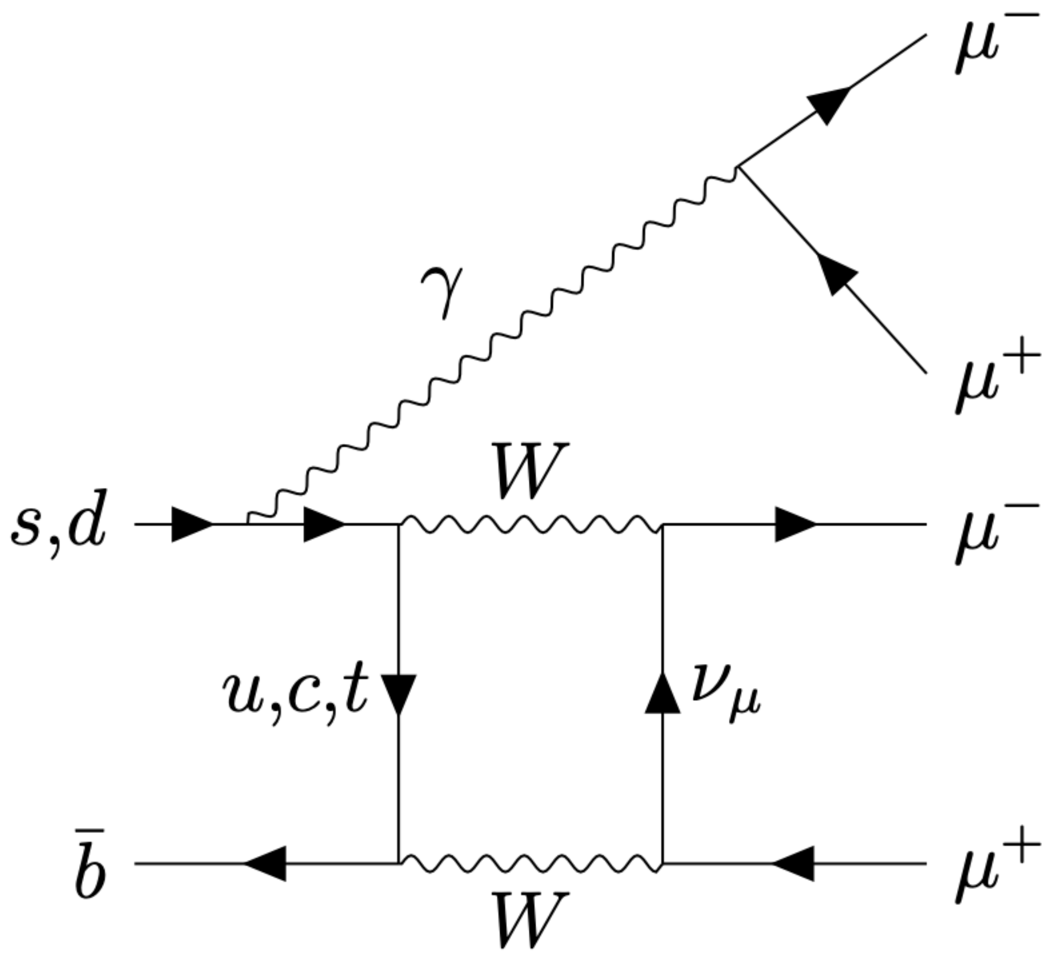
- Sensitive to new physics: MSSM sgoldstino [2].
- Previous LHCb limits with Run 1 data at 95% CL [3]:

  $\mathscr{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10}$

  $\mathscr{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9}$







[1] Phys. Atom. Nucl. **81** (2018) 347 [2] Phys. Rev. **D85** (2012) 077701 [3] J. High Energ. Phys. **2017** (2017) 001

$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2021-039
JHEP 03 (2022) 109

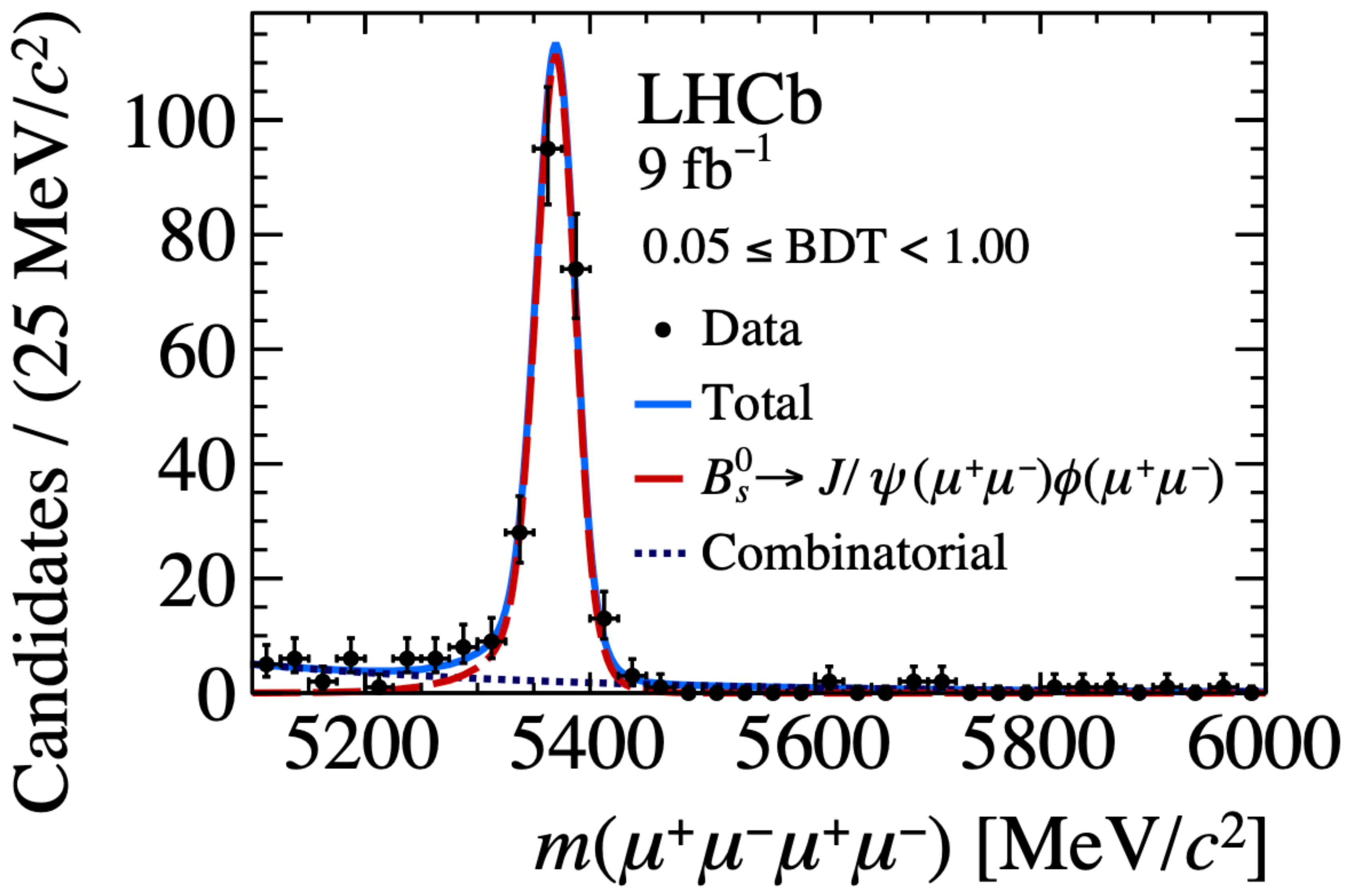
Strategy:

- Three considerations, with specific selection requirements:
  - Direct decay
  - Decay via BSM light scalar a [1,2]
  - Decay via J/ψ [3,4]:

$$\mathcal{B}(B^0 \to J/\psi\ (\mu^+\mu^-)\ \mu^+\mu^-) \sim 10^{-13}$$

$$\mathcal{B}(B^0_s \to J/\psi\ (\mu^+\mu^-)\ \mu^+\mu^-) \sim 10^{-11}$$

- Normalisation channel: $B^0_s \to J/\psi(\mu^+\mu^-)\Phi(\mu^+\mu^-)$.
- Combinatorial bkg = muons that do not all originate from the same b-hadron decay.
- Multivariate classifier to reduce combinatorial bkg.

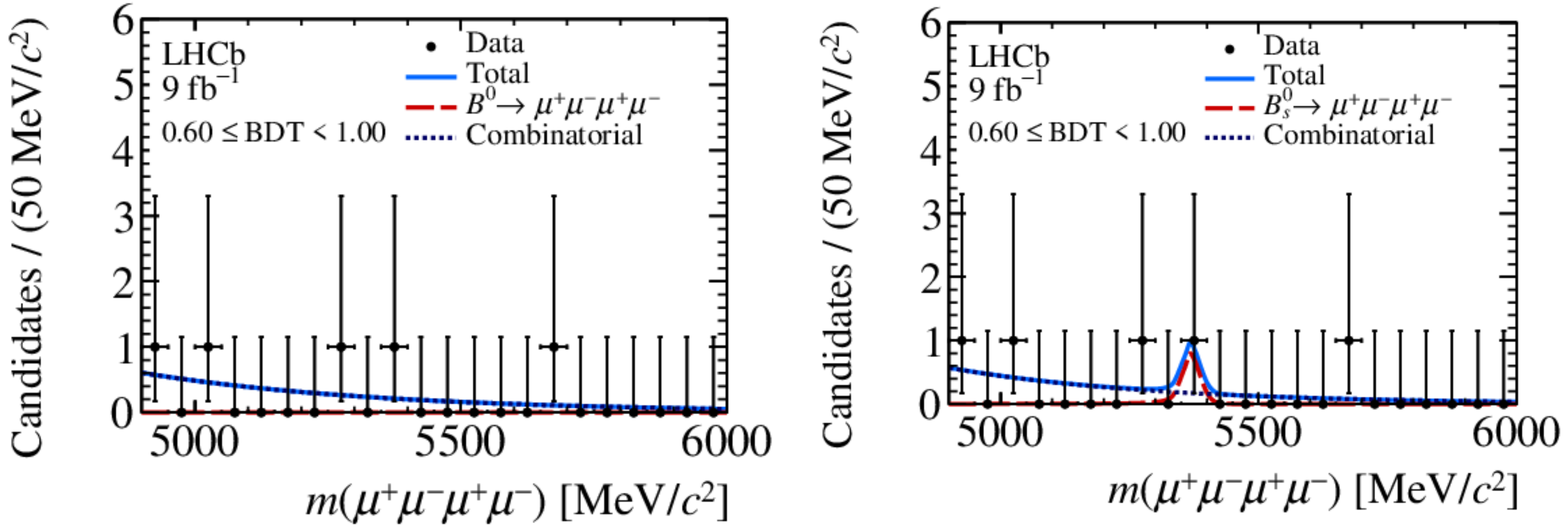


[1] Phys. Rev. Lett. **119** (2017) 031802
[2] JHEP **03** (2019) 008
[3] Nucl. Phys. **B577** (2000) 240
[4] Prog. Theor. Exp. Phys. **2020** (2020) 083C01

$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2021-039
JHEP 03 (2022) 109

Invariant mass of candidates passing the $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ selection in the most sensitive BDT interval:

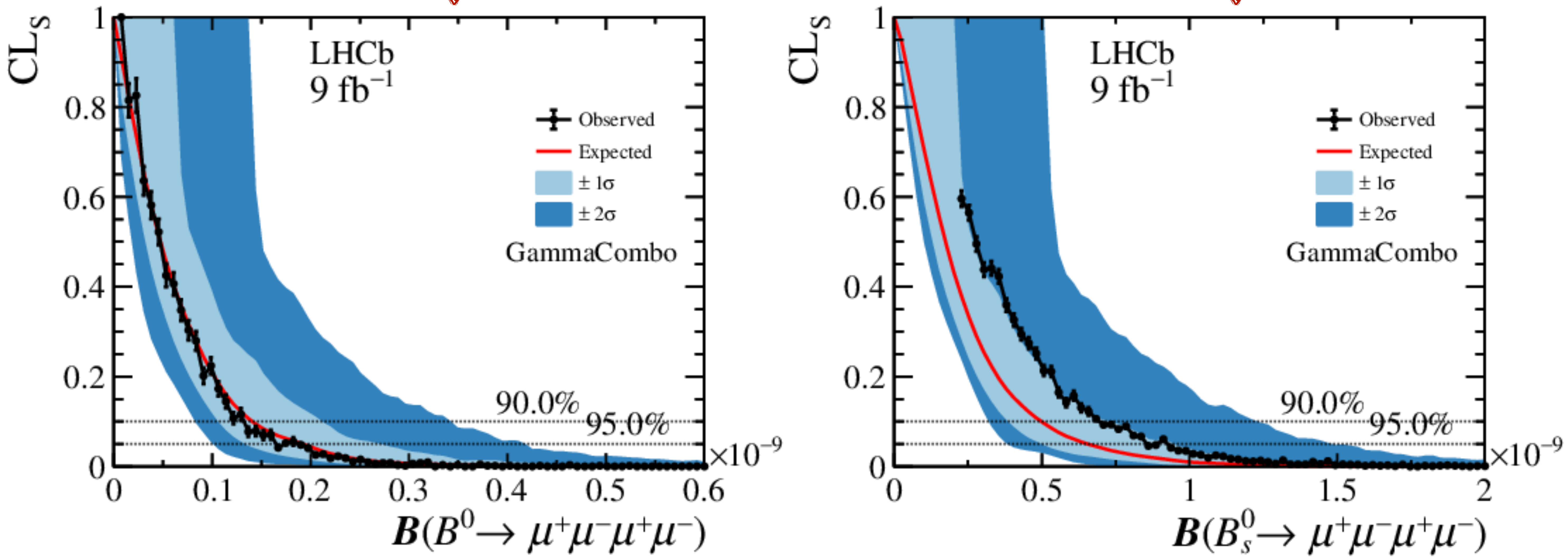


Results:

- Applied Φ and J/ψ vetoes.
- No evidence found of the $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decay.
- Limits at 95% CL:

$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.8 \times 10^{-10}$$

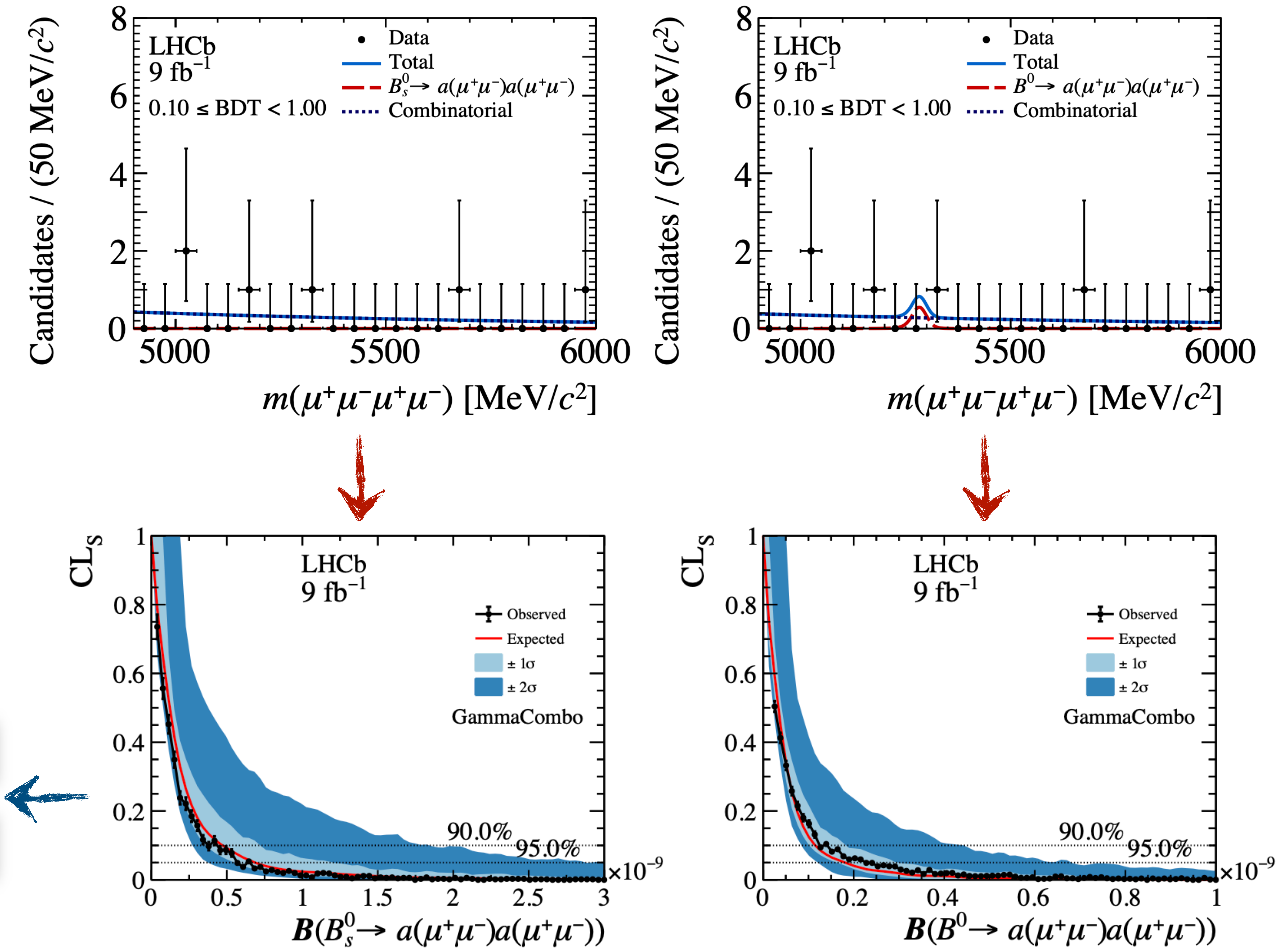
$$\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 8.6 \times 10^{-10}$$



$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2021-039
JHEP 03 (2022) 109

Invariant mass of candidates passing the $B^0 \to a(\mu^+\mu^-)a(\mu^+\mu^-)$ selection in the most sensitive BDT interval:



- a = BSM light narrow scalar resonance. In SM extension involving a new strongly interacting sector.
- Two mutually exclusive pairs of opposite-sign muons satisfying:

$$|q^2_{ij} - q^2_{kl}| < 2\sqrt{\sigma^2(q^2_{ij}) + \sigma^2(q^2_{kl})}$$

- Limits at 95% CL:

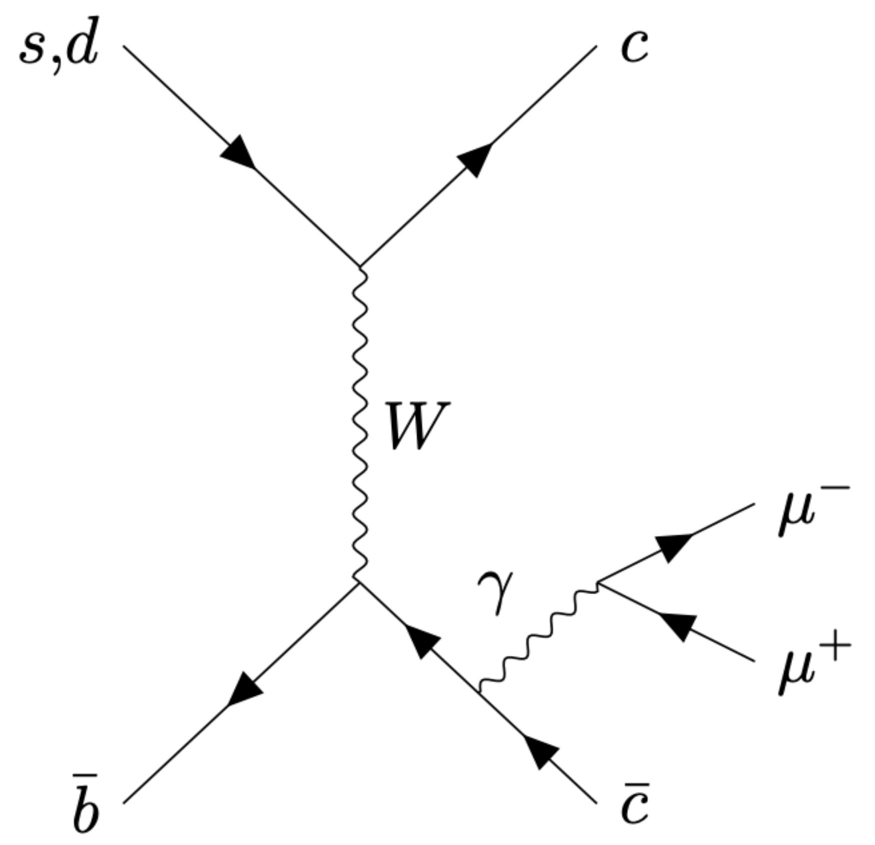
$$\mathcal{B}(B^0 \to a(\mu^+\mu^-)a(\mu^+\mu^-)) < 2.3 \times 10^{-10}$$

$$\mathcal{B}(B^0_s \to a(\mu^+\mu^-)a(\mu^+\mu^-)) < 5.8 \times 10^{-10}$$

$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2021-039
JHEP 03 (2022) 109

- Tree-level $b \to c$ transitions via W exchange:



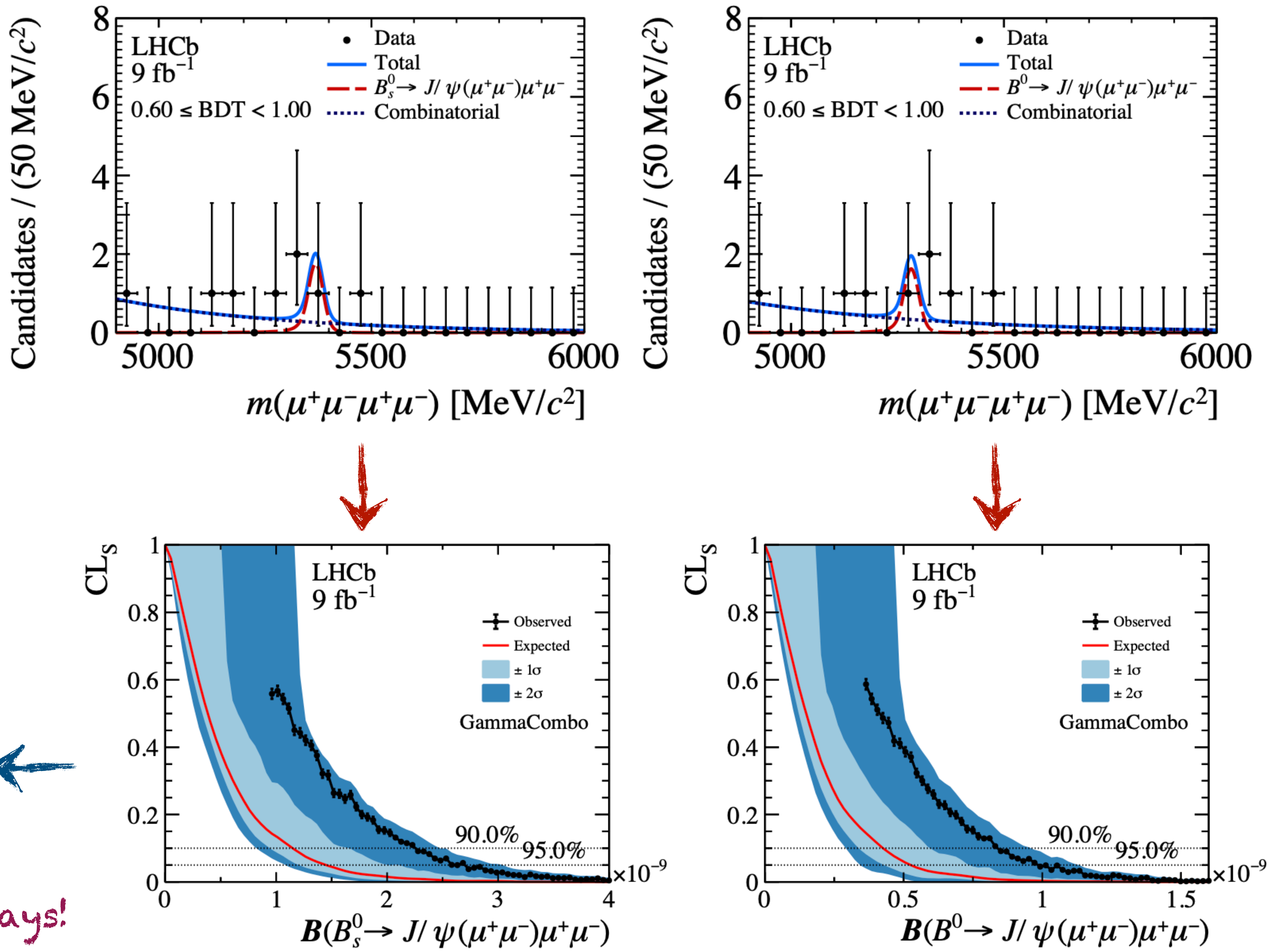
- Limits at 95% CL:

$\mathcal{B}(B^0 \to J/\psi\ (\mu^+\mu^-)\ \mu^+\mu^-) < 1.0 \times 10^{-9}$

$\mathcal{B}(B^0_s \to J/\psi\ (\mu^+\mu^-)\ \mu^+\mu^-) < 2.6 \times 10^{-9}$

Most stringent limits on each of the six decays!

Invariant mass of candidates passing the $B^0_{(s)} \to J/\psi\ (\mu^+\mu^-)\ \mu^+\mu^-$ selection in the most sensitive BDT interval:



$B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$

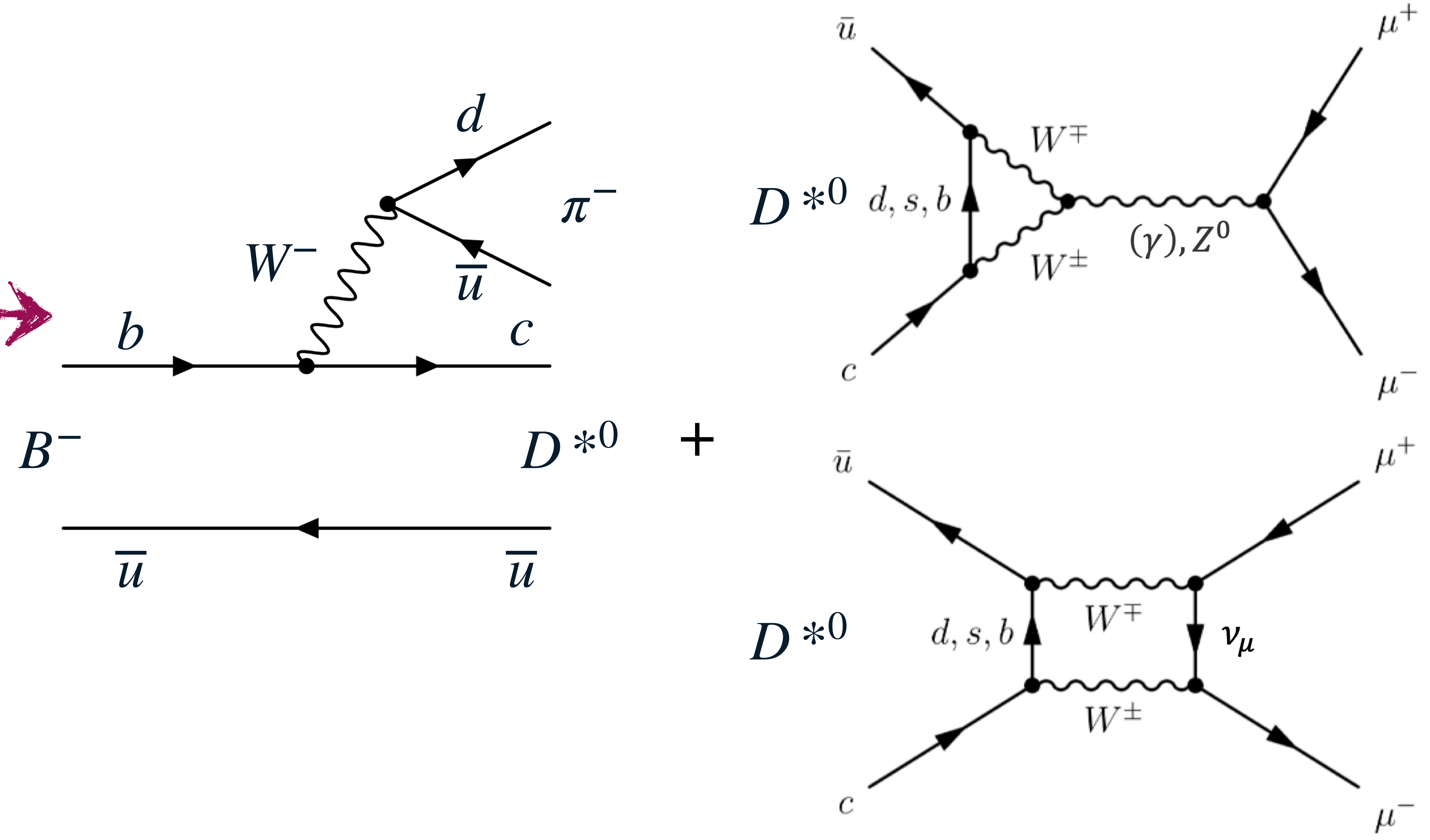
LHCb-PAPER-2023-004
arXiv:2210.10412

First search of a rare charm-hadron decay exploiting production in beauty decays!

Motivation:

- Search for $D^*(2007)^0 \to \mu^+\mu^-$ [1].
- D^{*0} production ($b \to cd\bar{u}$) + $D^{*0} \to \mu^+\mu^-$ decay.
- The B decay allows better bkg. discrimination.
- SM prediction at $\mathcal{O}(10^{-19})$ level [2].
- Potential probe of physics beyond the SM.
- Limit by CMD-3 collaboration at 90% CL [3]:

$$\mathcal{B}(D^{*0} \to e^+e^-) < 1.7 \times 10^{-6}.$$



[1] Eur. Phys. J. **C82** (2022) 459 [2] JHEP **11** (2015) 142 [3] Phys. Atom. Nucl. **83** (2020) 954

$B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$

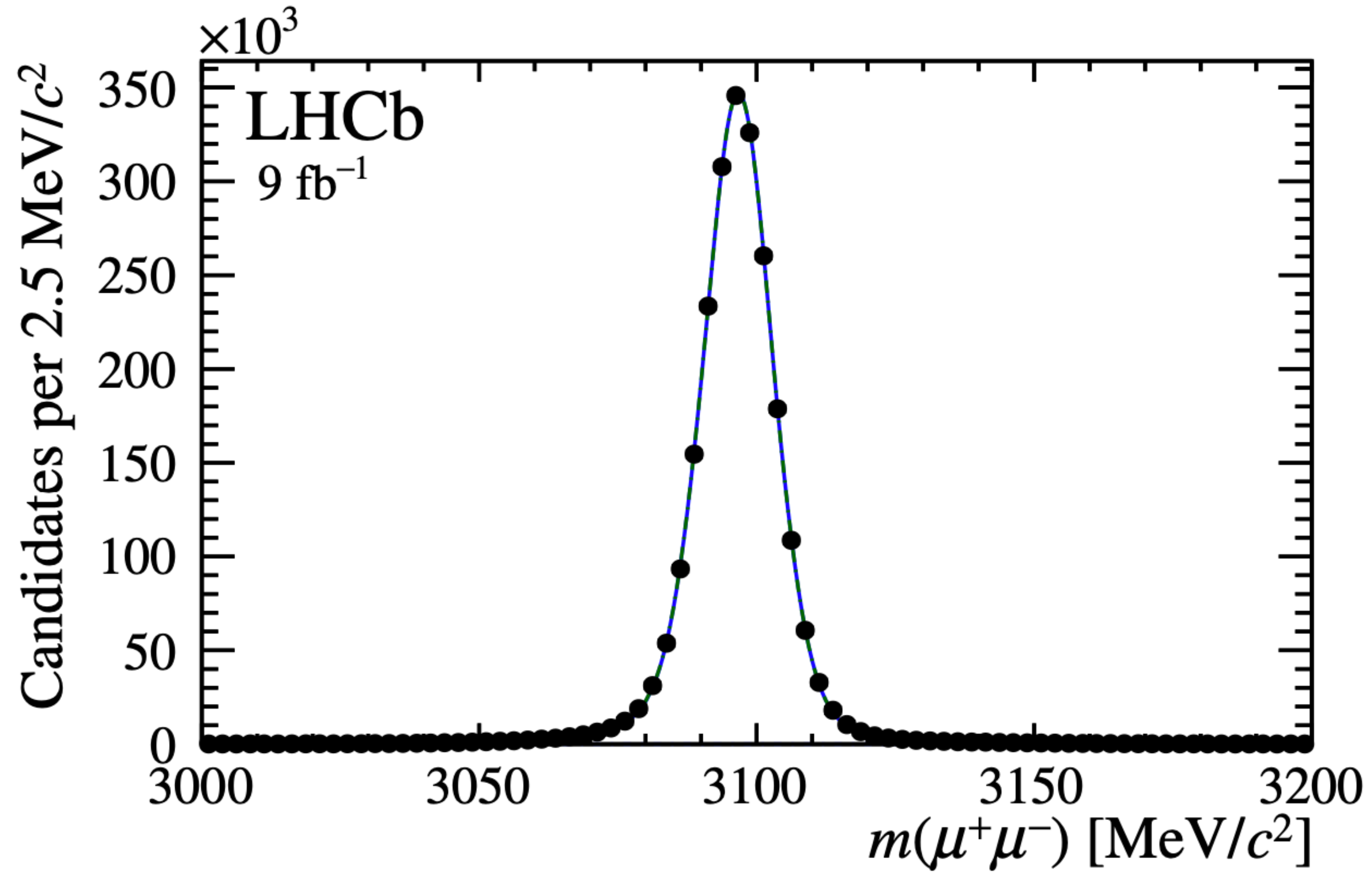
LHCb-PAPER-2023-004
arXiv:2210.10412

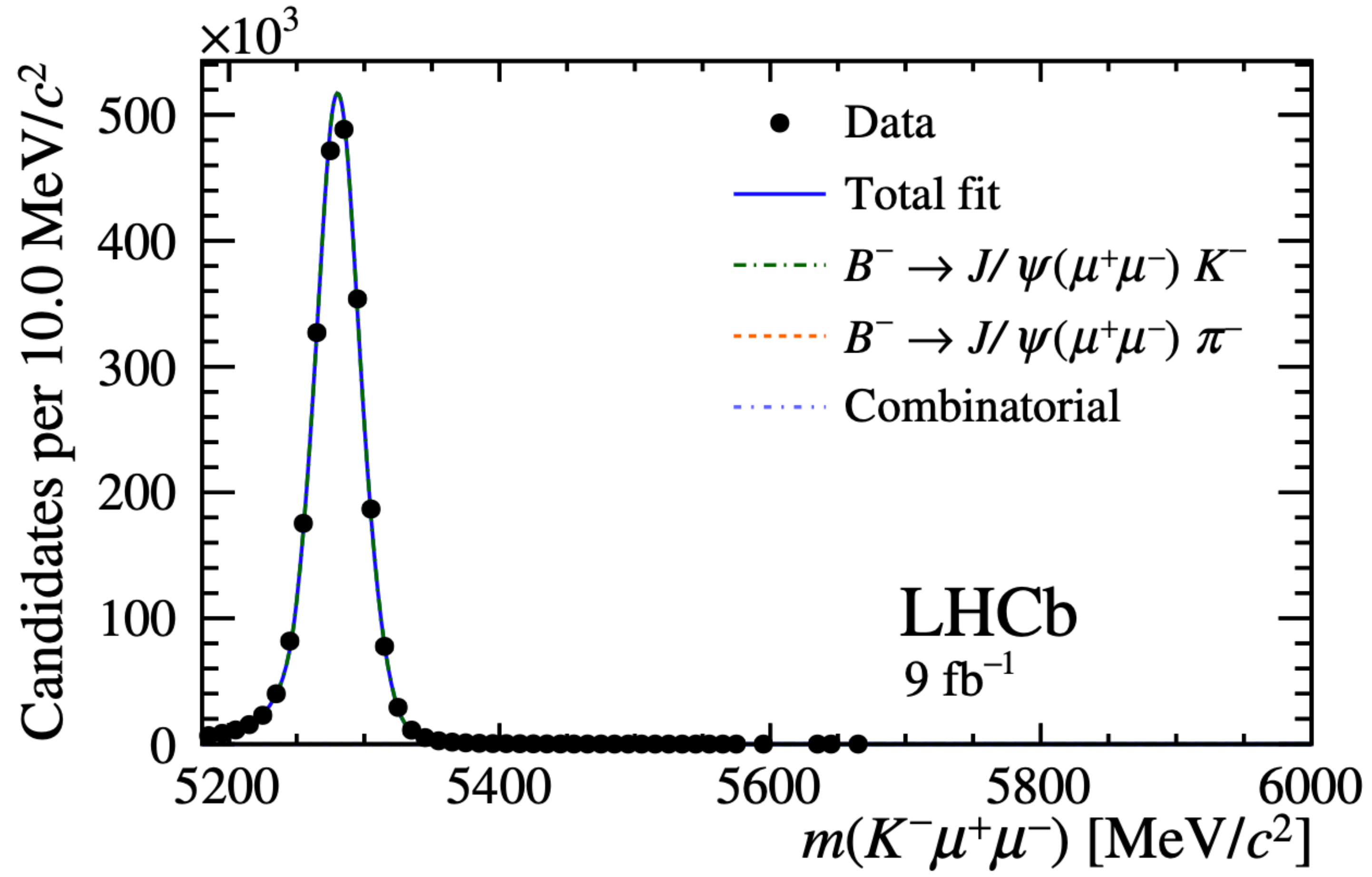
Reconstructed invariant mass distributions for $B^- \to J/\psi(\to \mu^+\mu^-)K^-$ candidates:

Strategy:

- Displace vertex and exclusive final state provide powerful bkg. rejection.
- Use a BDT against combinatorial bkg.
- Use PID info to suppress $K \to \pi$ and $hh \to \mu\mu$ misID bkgs.
- Signal signature = simultaneous peaks in $m(\mu^+\mu^-)$ and $m(\pi^-\mu^+\mu^-)$.
- Normalisation channel $B^- \to J/\psi(\to \mu^+\mu^-)K^-$.

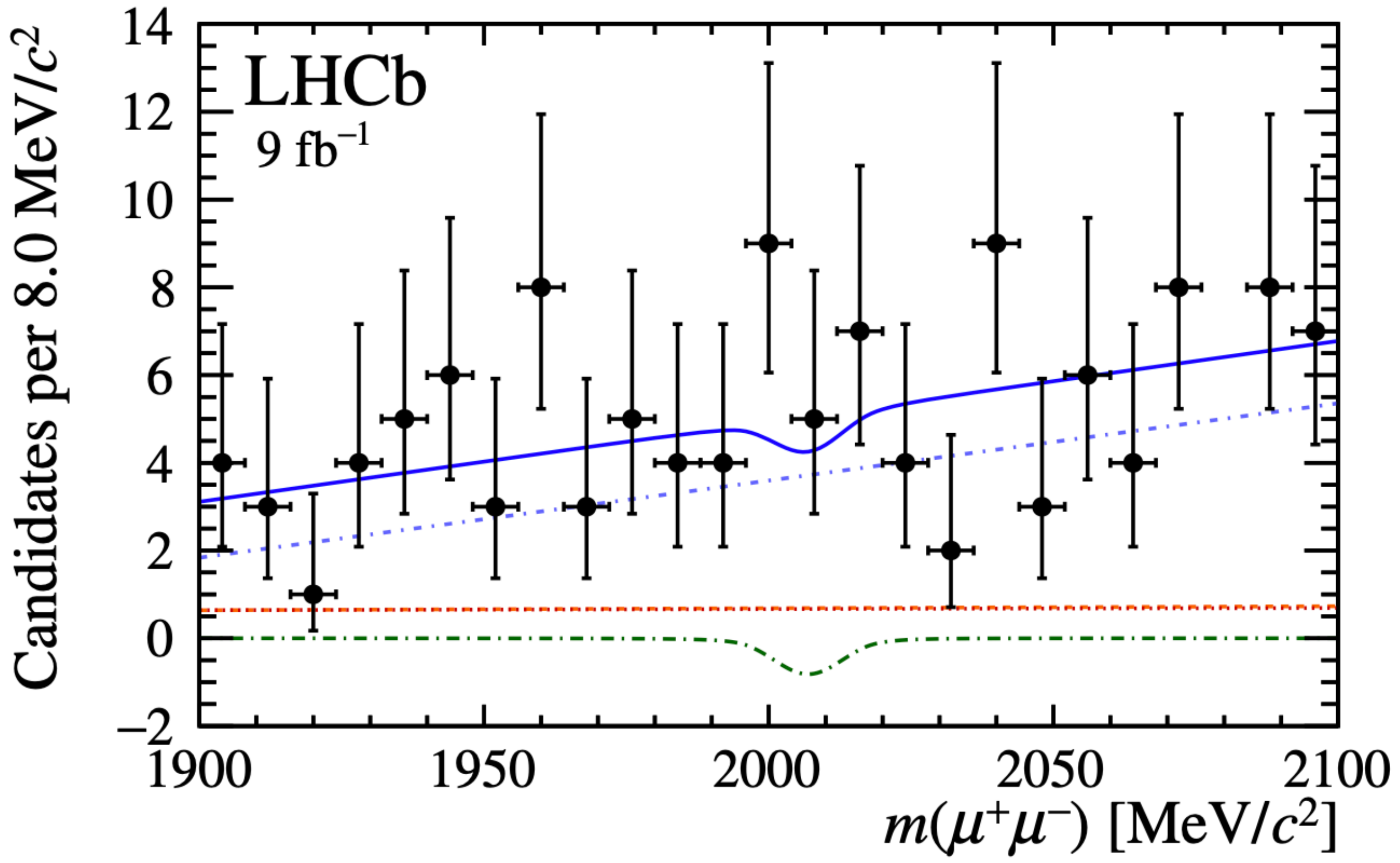
$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = \frac{N_{D^{*0}\pi^-}}{N_{J/\psi K^-}} \cdot \frac{\varepsilon_{J/\psi K^-}}{\varepsilon_{D^{*0}\pi^-}} \cdot \frac{\mathcal{B}\left(B^- \to J/\psi K^-\right)}{\mathcal{B}\left(B^- \to D^{*0}\pi^-\right)} \cdot \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$$

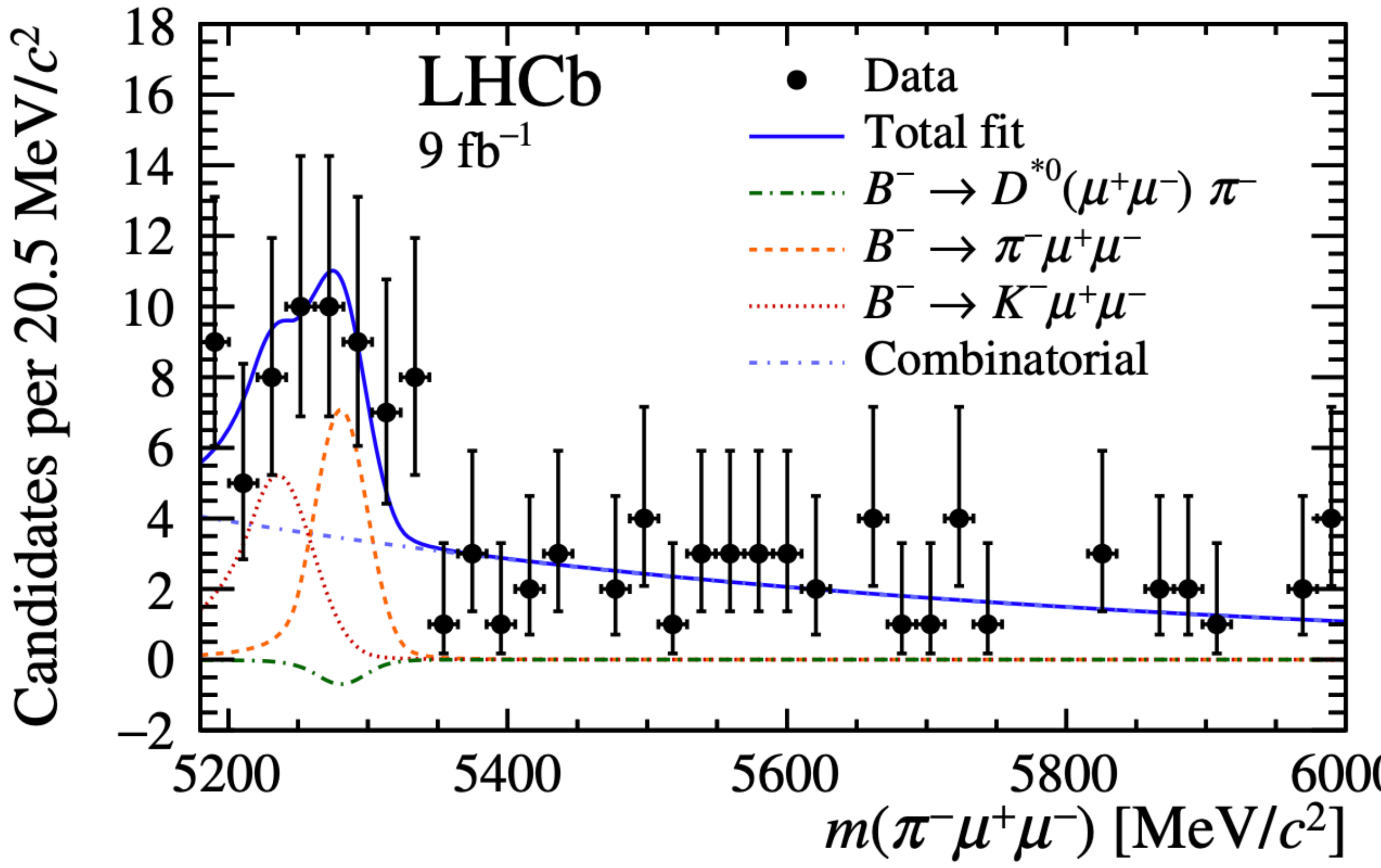




$B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$

LHCb-PAPER-2023-004
arXiv:2210.10412

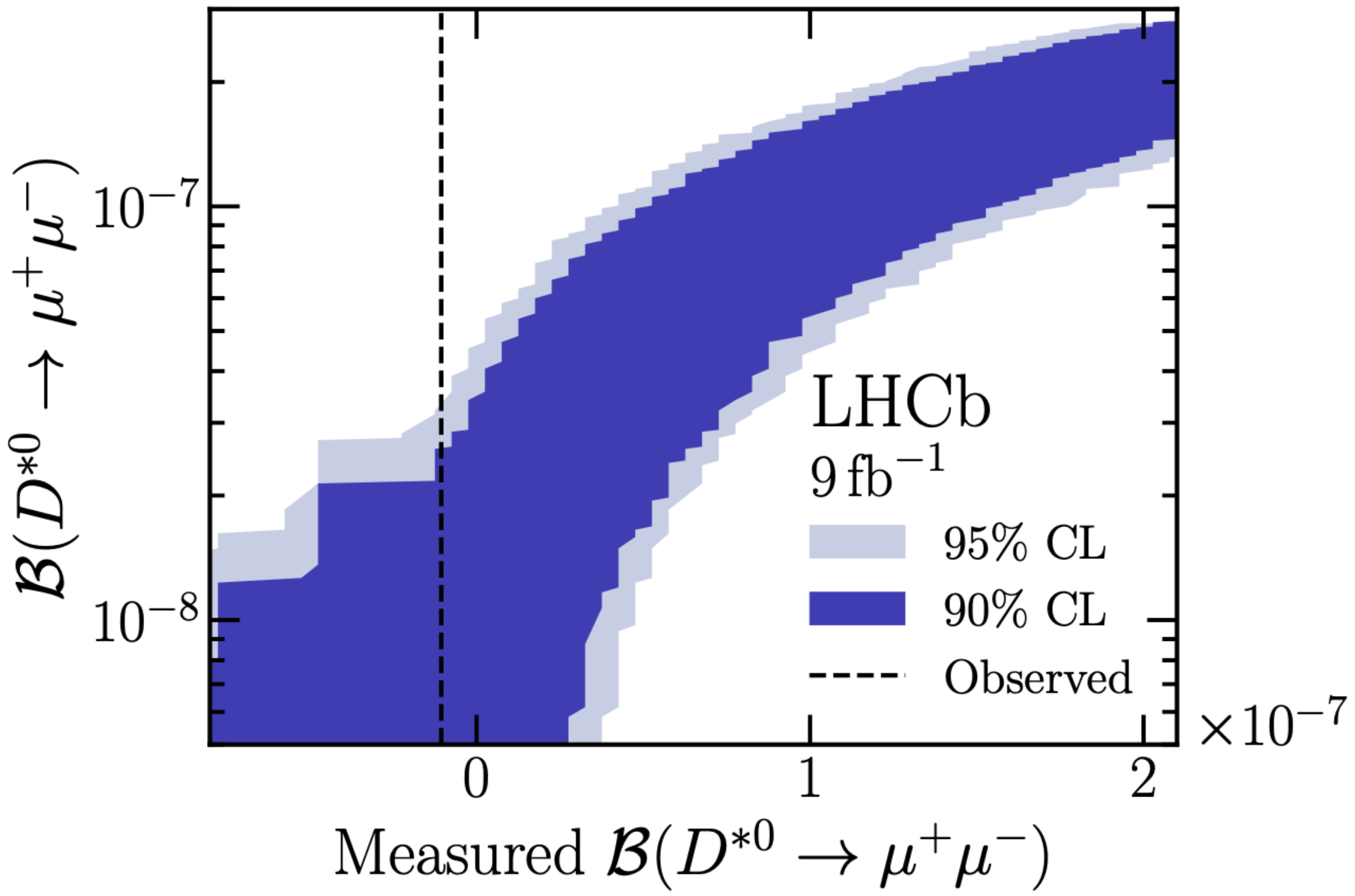




Results:

- First search for a rare charm-meson decay exploiting its production in beauty-meson decays.
- No excess with respect to the background-only hypothesis is observed.
- Upper limits at 90 (95)% CL:

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\ (3.4) \times 10^{-8}$$



Most stringent limit on D^{*0} decays to leptons!

And first limit on D^{*0} to muons!

Conclusions

- In this presentation:
  - $B^0_{(s)} \to p\mu^-$ First time!
  - $B^0_s \to p\bar{p}$ Best limit!
  - $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ Most stringent limits on each of the six decays!
  - $B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$ Most stringent limit on D^{*0} decays to leptons!

Rare B decays are dominated by statistical uncertainties, Run 3 is providing more statistics, and the LHCb upgrade (see presentation) will help us to push the limits of the SM.

New physics can be still hidden in rare B decays!

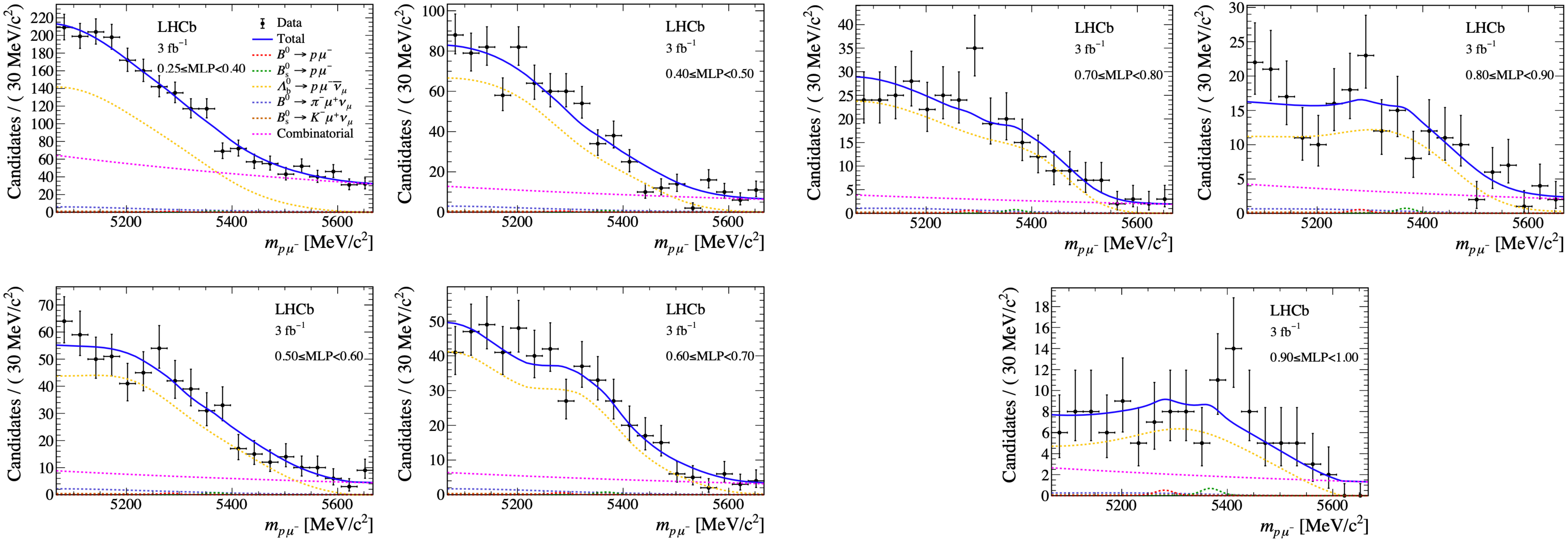
Backup

$B^0_{(s)} \to p\mu^-$

LHCb-PAPER-2022-022

CERN-EP-2022-195

All mass distributions in MLP bins in Run 1:

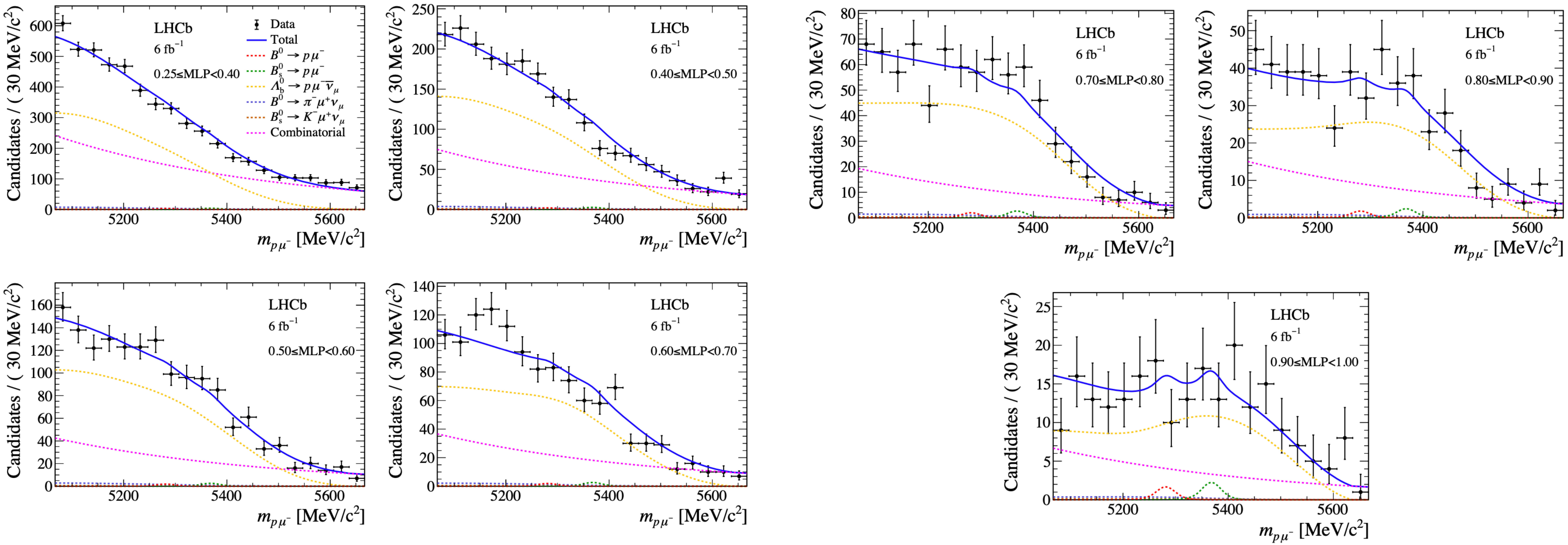


$B^0_{(s)} \to p\mu^-$

LHCb-PAPER-2022-022

CERN-EP-2022-195

All mass distributions in MLP bins in Run 2:



$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2021-039
JHEP 03 (2022) 109

Mass distributions for all BDT bins:

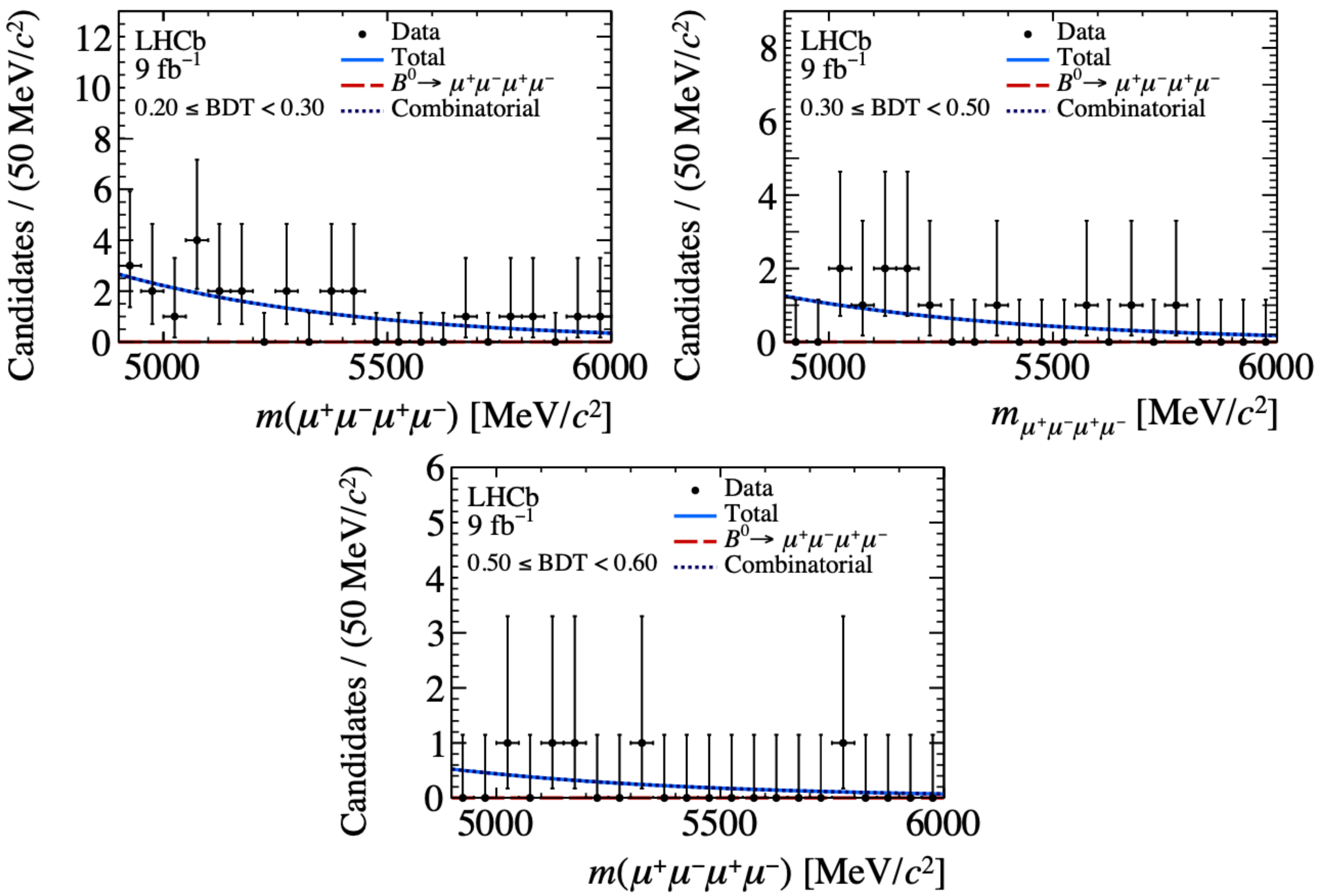


Figure 9: Distribution of the $\mu^+\mu^-\mu^+\mu^-$ invariant mass of candidates passing the $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ selection in (top left) the lowest BDT interval, (top right) the second lowest BDT interval and (bottom) the second highest BDT interval, with the fit models used to determine the branching fraction of $B^0 \to \mu^+\mu^-\mu^+\mu^-$ overlaid.

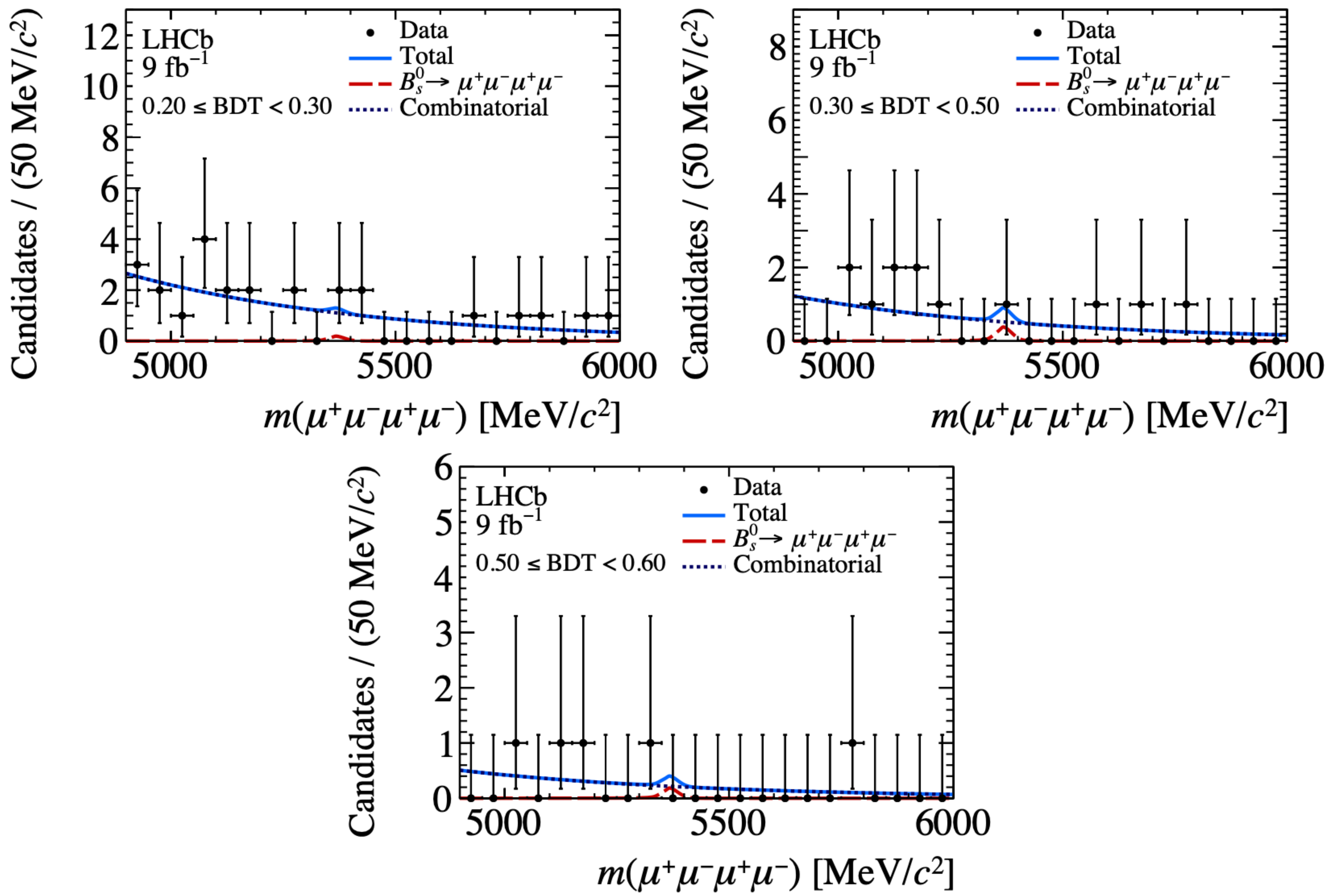


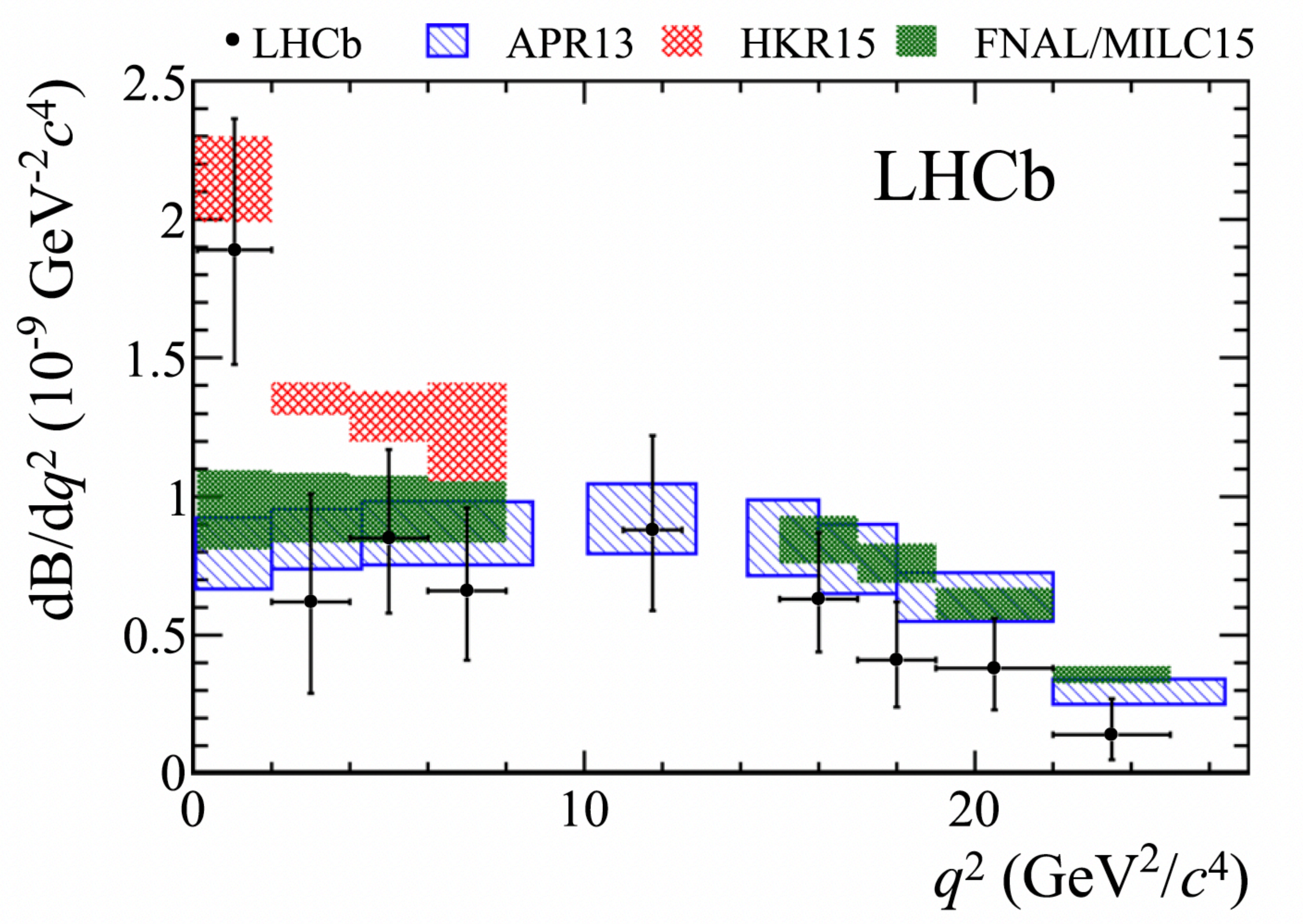
Figure 8: Distribution of the $\mu^+\mu^-\mu^+\mu^-$ invariant mass of candidates passing the $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ selection in (top left) the lowest BDT interval, (top right) the second lowest BDT interval and (bottom) the second highest BDT interval, with the fit models used to determine the branching fraction of $B^0_s \to \mu^+\mu^-\mu^+\mu^-$ overlaid.

$B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$

LHCb-PAPER-2023-004
Submitted to Eur. Phys. J. C.

Differential branching fraction of the $B^+ \to \pi^+\mu^+\mu^-$ decay as a function of q2.

The hashed regions correspond to theoretical predictions.



[1] Eur. Phys. J. **C82** (2022) 459

$B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$

LHCb-PAPER-2023-004
Submitted to Eur. Phys. J. C.

$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = (-1.06 \pm 1.85) \times 10^{-8}$$

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\% \text{ CL}$$

Table 2: Input parameters used in the estimation of the $D^{*0} \to \mu^+\mu^-$ branching fraction. The uncertainties correspond to the statistical and systematic uncertainties added in quadrature.

Parameter	Value
$\mathcal{B}(B^- \to J/\psi K^-)$	$(10.20 \pm 0.19) \times 10^{-4}$ [25]
$\mathcal{B}(B^- \to D^{*0}\pi^-)$	$(4.90 \pm 0.17) \times 10^{-3}$ [25]
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	$(59.61 \pm 0.33) \times 10^{-3}$ [25]
$\varepsilon_{J/\psi K^-}/\varepsilon_{D^{*0}\pi^-}$	1.21 ± 0.03
$N_{J/\psi K^-}$	$(2316 \pm 8) \times 10^3$

Component	Yield
$B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-$	-2 ± 3
$B^- \to \pi^-\mu^+\mu^-$	17 ± 7
$B^- \to K^-\mu^+\mu^-$	17 ± 8
Combinatorial bkg.	90 ± 13

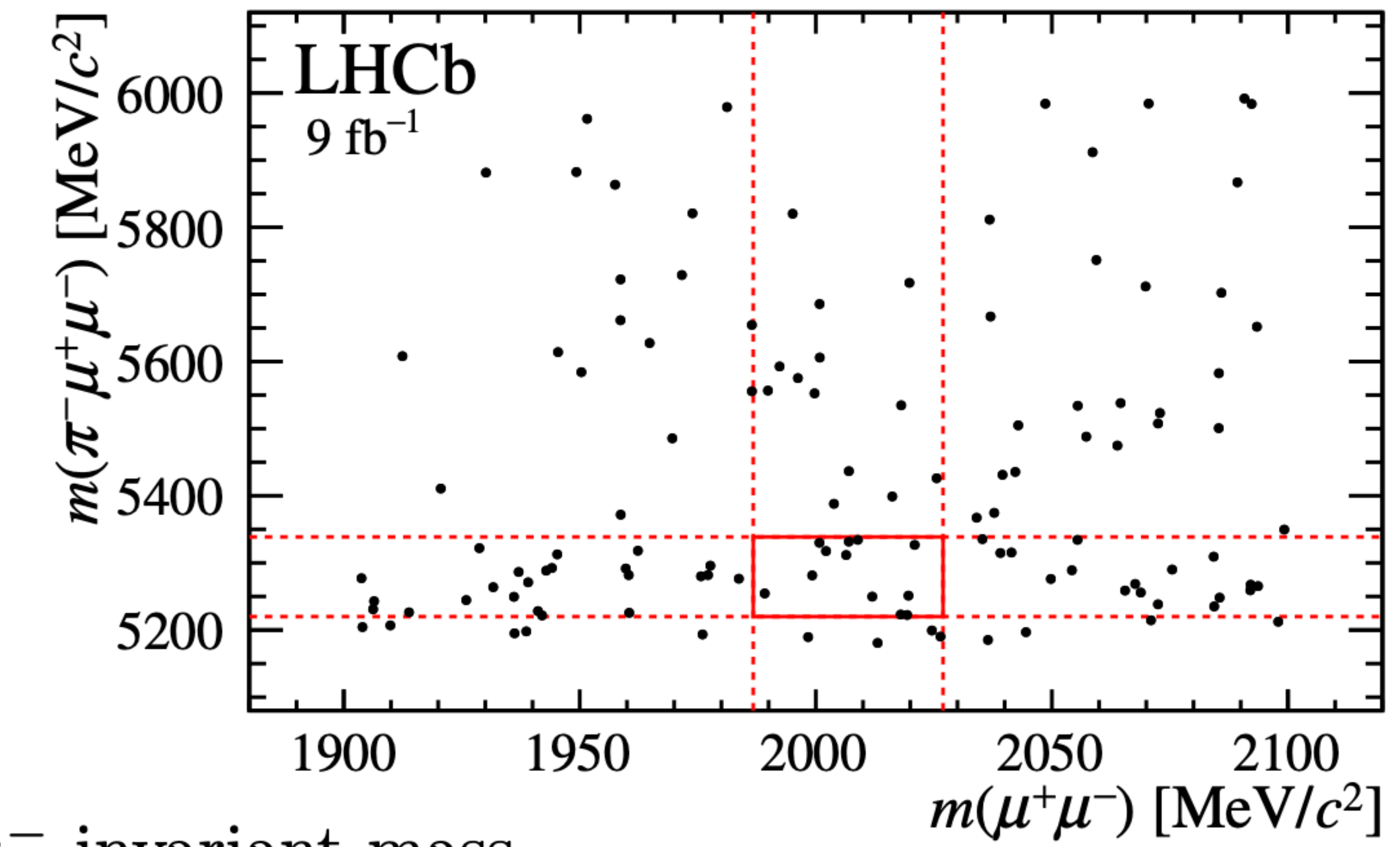
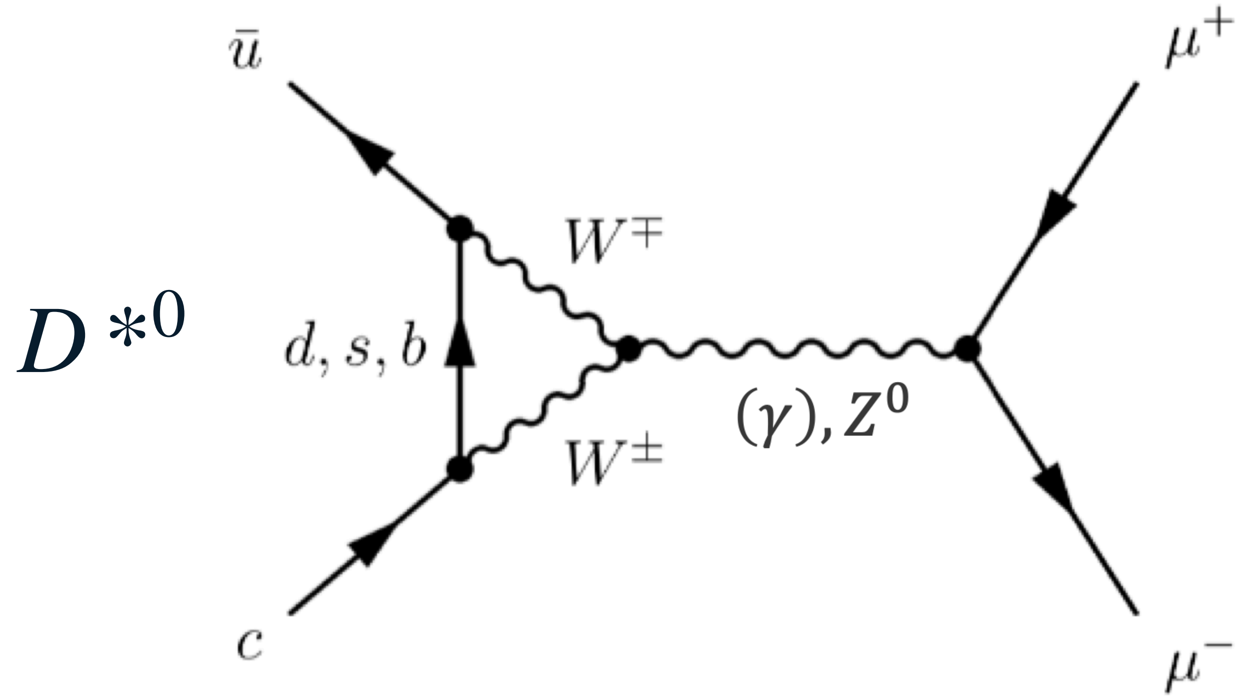


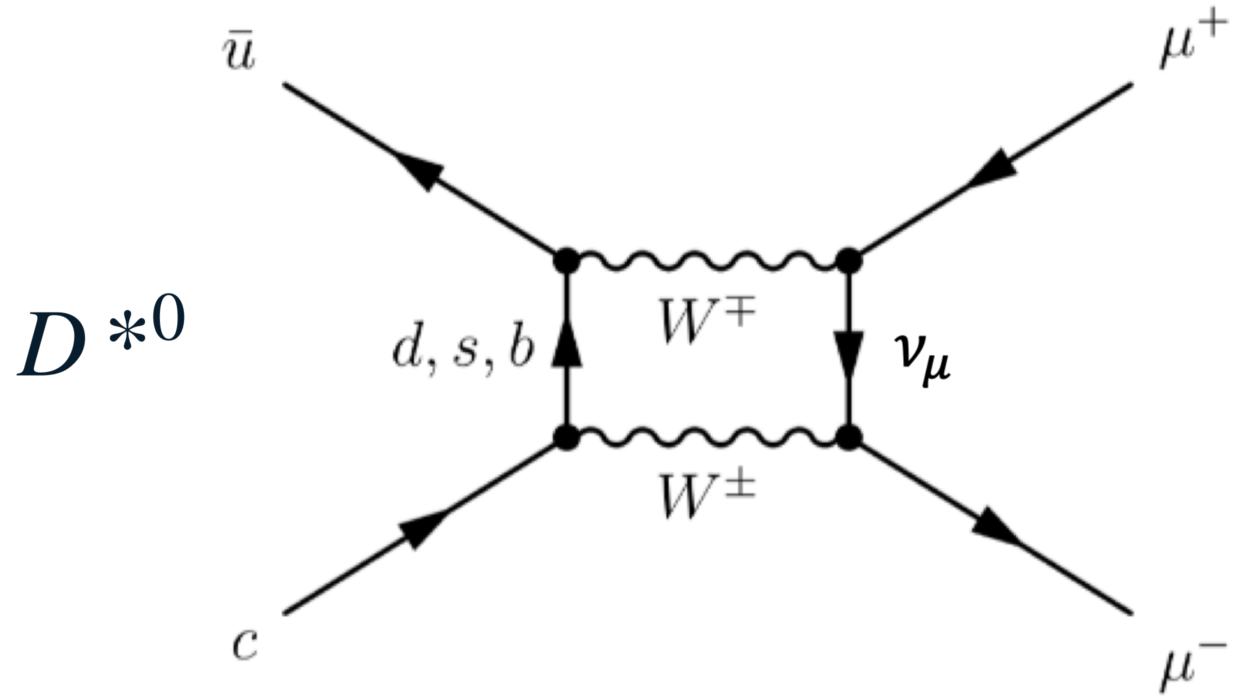
Figure 2: Two-dimensional distribution of $\mu^+\mu^-$ invariant mass versus $\pi^-\mu^+\mu^-$ invariant mass for the selected $B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-$ candidates. The red box corresponds to a range of about $\pm 3\sigma$ around the expected signal peak position in each dimension.

D^{*0} vs. D^0

D^{*0}

spin-1 $\Rightarrow \gamma$ mediator





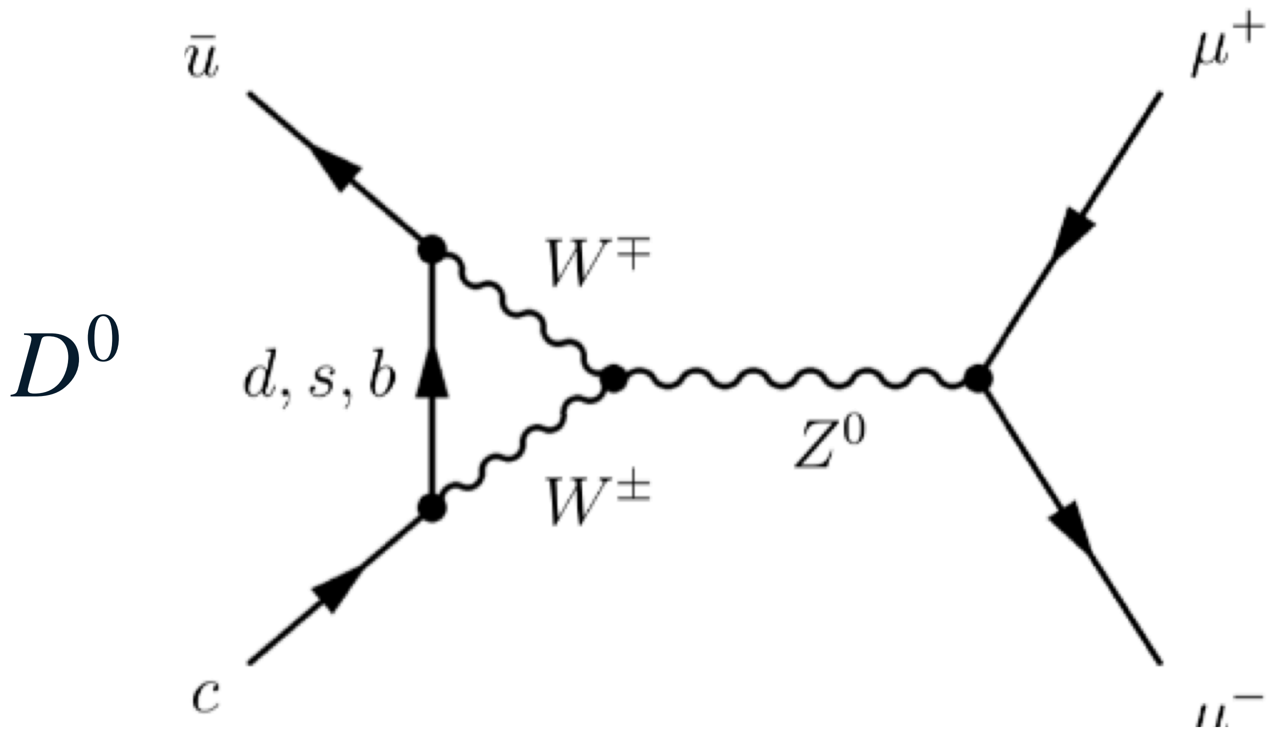
D^0

spin-0 $\Rightarrow$ no γ mediator

Receives two contributions within SM:

Short distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 10^{-18}$ (Z-penguins, W-boxes)

Long distance : $\mathcal{B}(D^0 \to \mu^+\mu^-) < 10^{-11}$ ($D^0 \to \gamma\gamma$ transitions)



$\mathscr{B}(D^0 \to \mu^+\mu^-) < 2.94\ (3.25) \times 10^{-9}$ at 90 (95) % CL

LHCb-PAPER-2022-029