Rare charm and beauty decays at LHCb

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on behalf of the LHCb collaboration

57th Rencontres de Moriond
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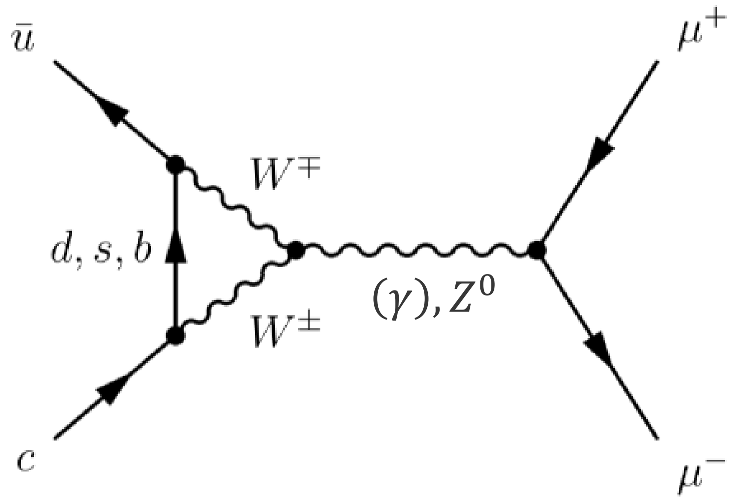
Rare charm and beauty decays

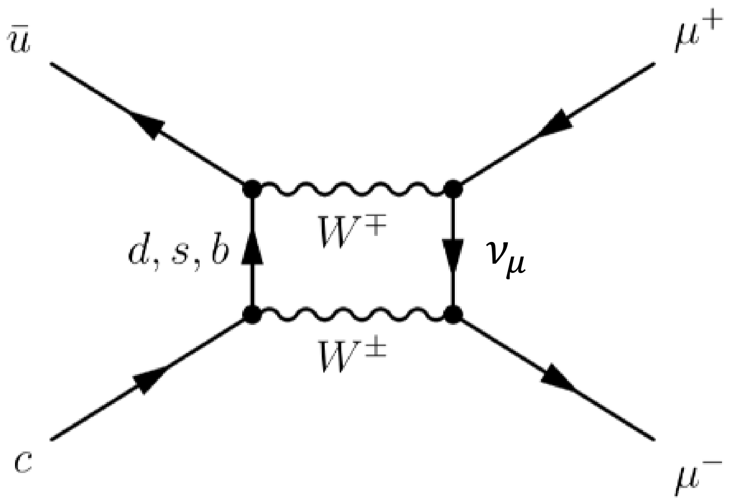
Decays of *c* and *b* hadrons occurring via penguin or box diagrams in the Standard Model

- FCNC processes, suppressed by small size of off-diagonal CKM elements and GIM mechanism
- Sensitive to non-Standard Model contributions
- Offer multiple tests of symmetries of the SM
    - Measurements of angular and CP asymmetries
    - Measurements of lepton flavour universality
    - Searches for extremely rare and forbidden decays

This talk

Example: two possible contributions to $\boldsymbol{D^{(*)0} \rightarrow \mu^+\mu^-}$ decays in the SM





Outline

Recent results exploiting run I + II data set (9fb^{-1}) on searches for the decays

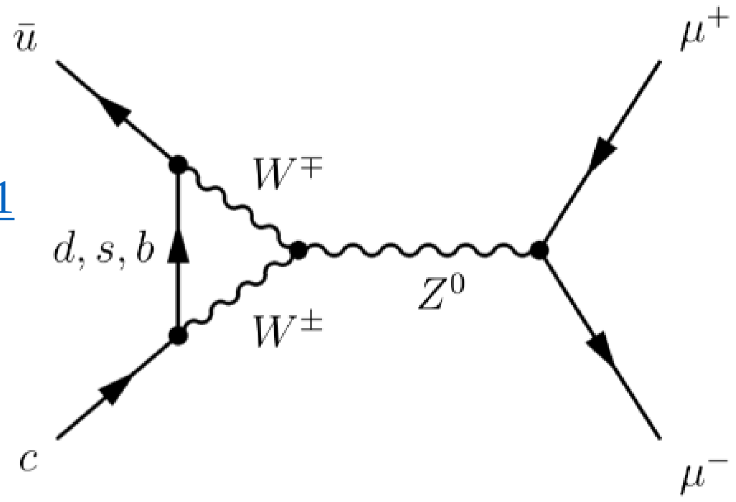
Expected level of suppression

10^{-11}	$D^0 \to \mu^+\mu^-$	LHCb-PAPER-2022-029	Flavour changing neutral currents (FCNC)
10^{-19}	$D^{*0} \to \mu^+\mu^-$ (new!)	LHCb-PAPER-2023-004 (in preparation)	Flavour changing neutral currents (FCNC)
10^{-27}	$B^0_{(s)} \to p\,\mu^-$	LHCb-PAPER-2022-022	Lepton number and baryon number violation (LNV +BNV)
10^{-50}	$B^0 \to K^{*0}\tau^\pm\mu^\mp$	LHCb-PAPER-2022-021	Lepton flavour violation (LFV)

Search for $D^0 \to \mu^+\mu^-$ decays

- FCNC decay with GIM and helicity suppression
- Key in constraining non-SM physics
- Receives two contributions within SM
  - Short distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 10^{-18}$ (Z-penguins, W-boxes) PRD.93.074001
  - Long distance : $\mathcal{B}(D^0 \to \mu^+\mu^-) < 10^{-11}$ ($D^0 \to \gamma\gamma$ transitions)
- Previous upper limit by LHCb (1fb^{-1})
  - $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \cdot 10^{-9}$ at 90% CL PLB.2013.06.37

***Z*-penguin contribution in the SM**



Analysis Strategy

- Reconstruct tagged $D^{*+} \to D^0\pi^+$ decays
- Use a BDT against combinatorial background
- Use PID info to suppress $hh \to \mu\mu$ misID background
- Perform ML fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$

LHCb-PAPER-2022-029

Search for $D^0 \to \mu^+\mu^-$ decays

Signal yield $N_{D^0\to\mu^+\mu^-}$ from fit translated into branching fraction via

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^0\to\mu^+\mu^-}}{\boxed{N_{D^0\to h^+h^-}}} \cdot \boxed{\frac{\varepsilon_{h^+h^-}}{\varepsilon_{\mu^+\mu^-}}} \cdot p \cdot \boxed{\mathcal{B}(D^0 \to h^+h^-)}$$

Efficiency ratio

Norm. BF

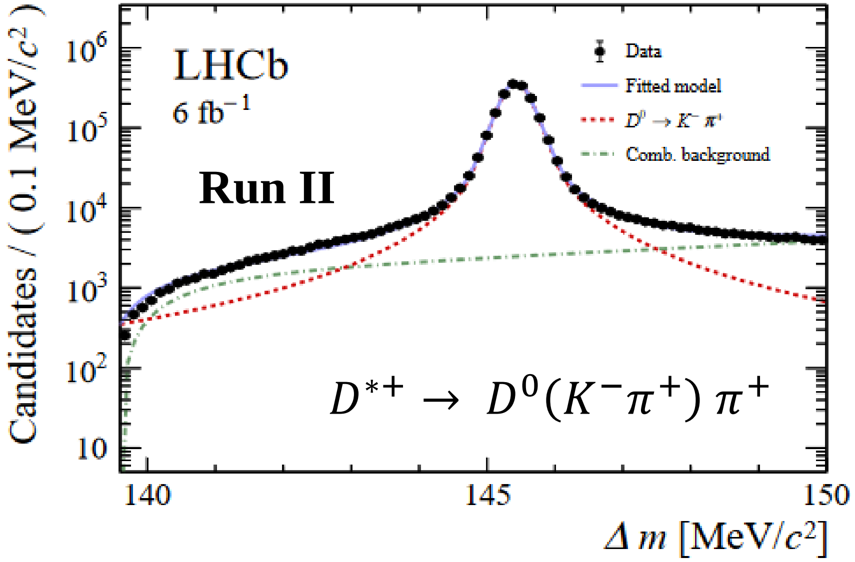
Norm. yield

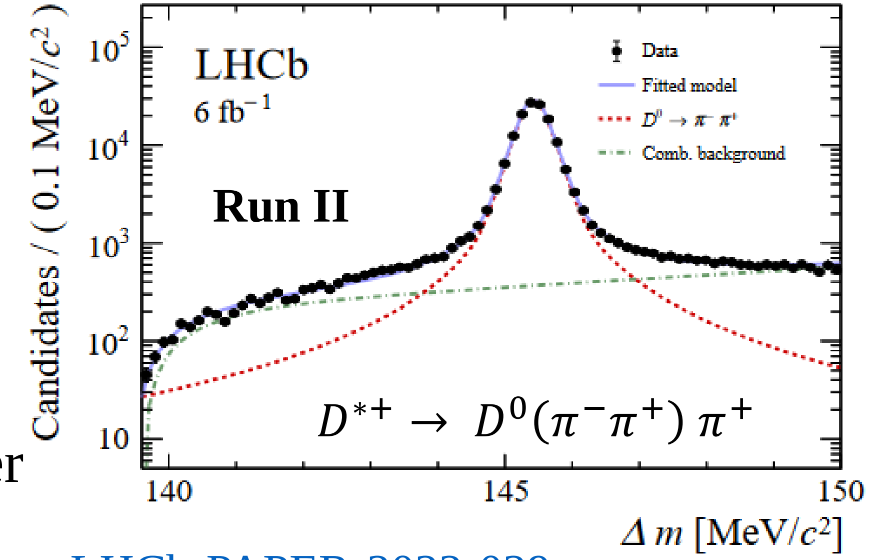
Trigger prescale on norm. mode

$h = K$ or π

- Norm. yield obtained from fit to Δm of $D^{*+} \to D^0(h^-\pi^+)\,\pi^+$ decays
- Efficiencies from simulation corrected for data/MC discrepancies
- Systematic uncertainties associated with normalisation and background model included as Gaussian constraints in signal fit
- Largest systematic originates from the calibration of hadronic trigger

Normalisation mode fits





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Search for $D^0 \to \mu^+\mu^-$ decays

- Signal mode fit performed simultaneously in 3 BDT intervals
- MisID background yields constrained based on simulation and PDG
- Results from fit

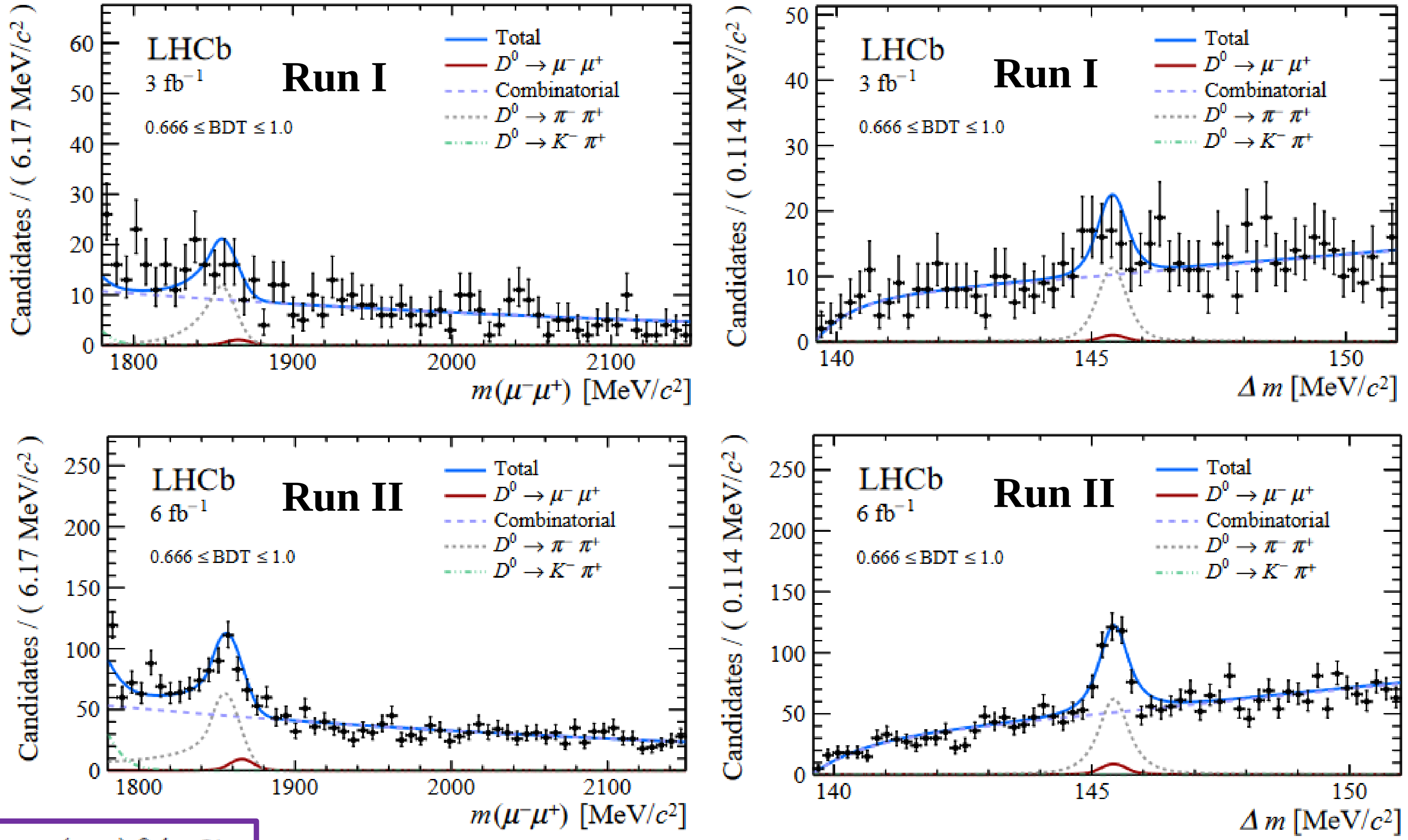
$$N_{D^0 \to \mu^+\mu^-} = 79 \pm 45$$

$$\Downarrow$$

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = (1.7 \pm 1.0) \cdot 10^{-9}$$

$\Rightarrow$ Upper limit on branching fraction based on CLs method

Signal mode fit for most sensitive BDT interval



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

LHCb-PAPER-2022-029

$\Rightarrow$ Improvement by factor ≈ 2 wrt. previous result and most stringent limit of FCNC in charm sector

Search for $D^{*0} \to \mu^+\mu^-$ decays

New!

LHCb-PAPER-2023-004
(in preparation)

- $D^{*0} \to \mu^+\mu^-$ decay probes same operators as $D^0 \to \mu^+\mu^-$ decay

$\Rightarrow$ but not helicity suppressed

- D^{*0} decays strongly $\Rightarrow \mathcal{B}(D^{*0} \to \mu^+\mu^-) \lesssim 10^{-19}$ within SM JHEP11(2015)142
- World's best limit by CMD-3:

$\mathcal{B}(D^{*0} \to e^+e^-) < 1.7 \cdot 10^{-6}$ at 90% CL PAN83.954(2020)

- High production rates of D^{*0} at LHCb

$\Rightarrow$ but bkg. level also high for decays at collision point

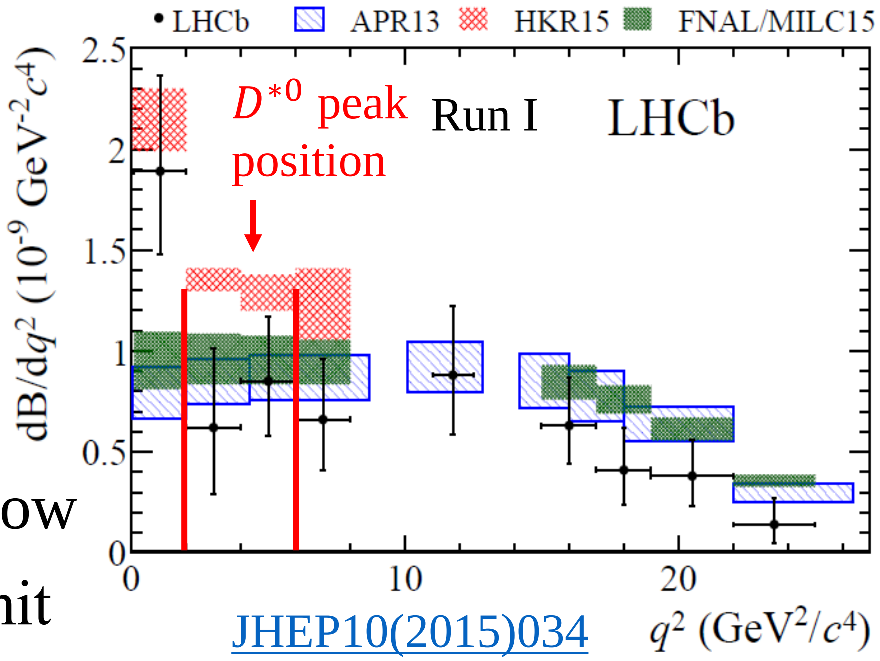
- Most promising approach EPJC82(2022)459

$\Rightarrow$ Search within $B^- \to D^{*0}\pi^-$ decay chain

$\Rightarrow$ Exploit displaced B^- vertex signature to keep bkg. level low

$\Rightarrow$ LHCb run I sensitivity (10^{-7}) better than world's best limit

$B^- \to \mu^+\mu^-\pi^-$ differential BF



JHEP10(2015)034

Search for $D^{*0} \to \mu^+\mu^-$ decays

Analysis Strategy

- Reconstruct $B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-$ decays
- Use a BDT against combinatorial bkg.
- Use PID info to suppress $K \to \pi$ and $hh \to \mu\mu$ misID bkgs.
- Perform simultaneous ML fit to $m(D^{*0})$ and $m(B^-)$
- Signal yield $N_{B^-\to D^{*0}\pi^-}$ from fit translated into BF via

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

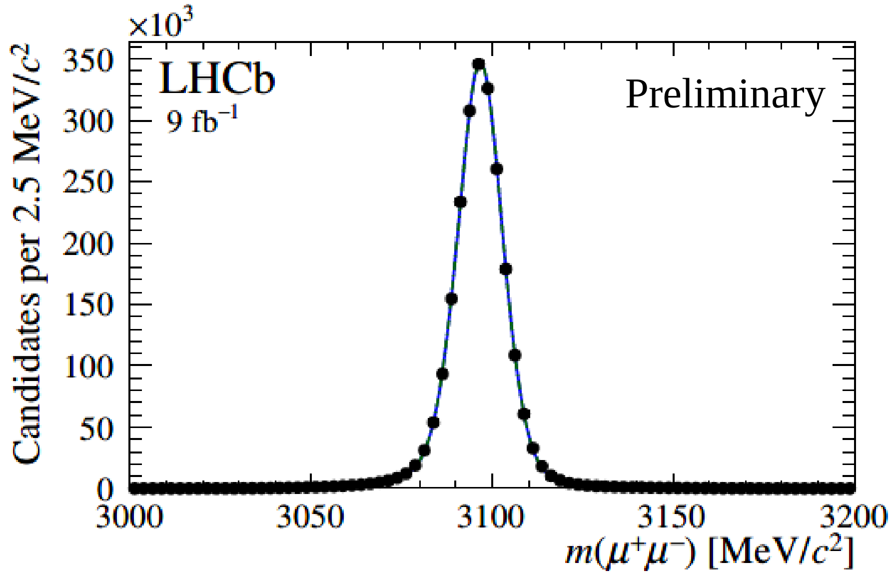
Efficiency ratio

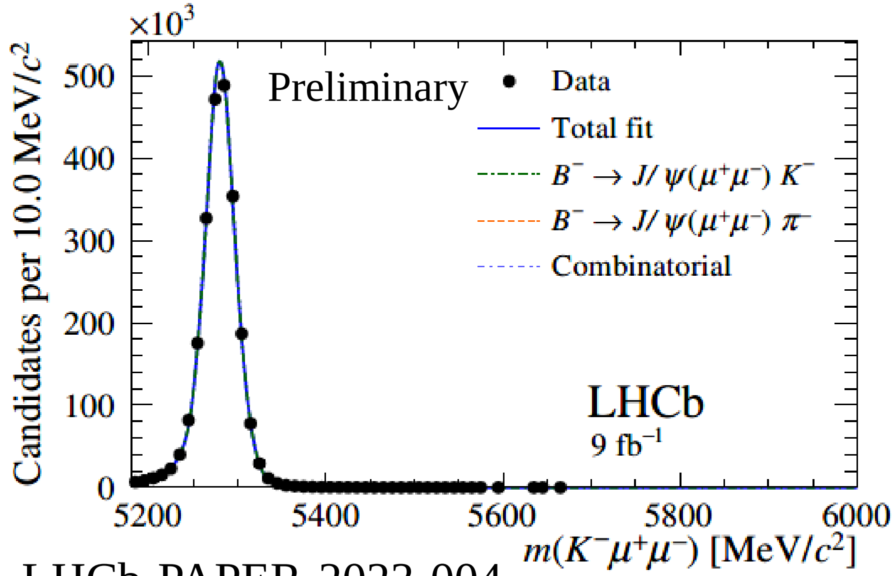
Known BFs

Normalisation yield

- Normalisation yield from fits to $m(J/\psi)$ and $m(B^-)$ of $B^- \to J/\psi(\mu^+\mu^-)K^-$ decays
- Efficiencies from sim. corrected for data/MC discrepancies

Normalisation mode fits





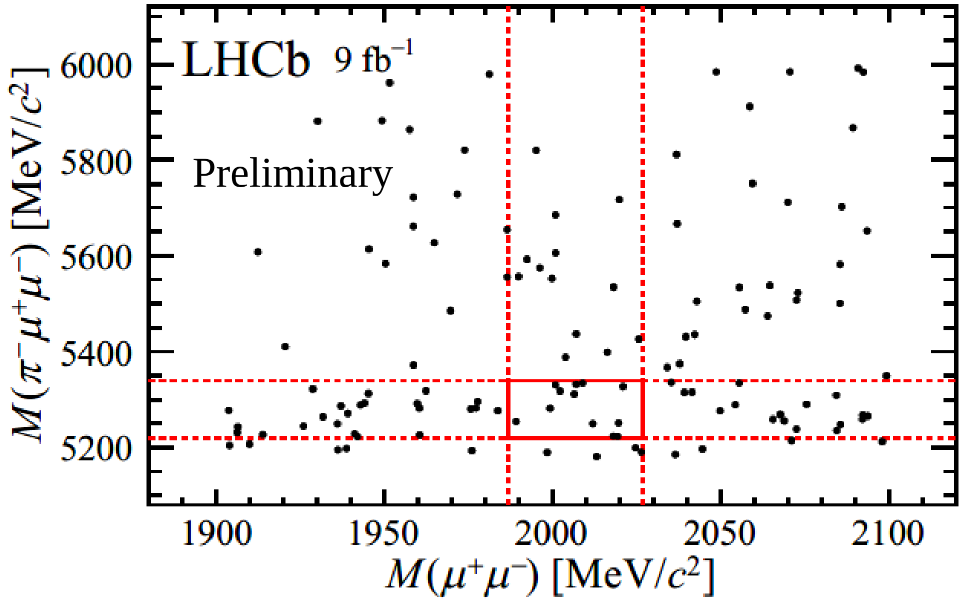
LHCb-PAPER-2023-004
(in preparation)

Search for $D^{*0} \to \mu^+\mu^-$ decays

- Signal mode fit in 1 BDT interval (with max. sensitivity)
- Fit includes non-resonant $B^+ \to \pi^+\mu^+\mu^-$ and misID $B^+ \to K^+\mu^+\mu^-$ decays, and combinatorial bkg.
- Yields for all components vary freely in fit
- Fit converges to a slightly negative signal yield

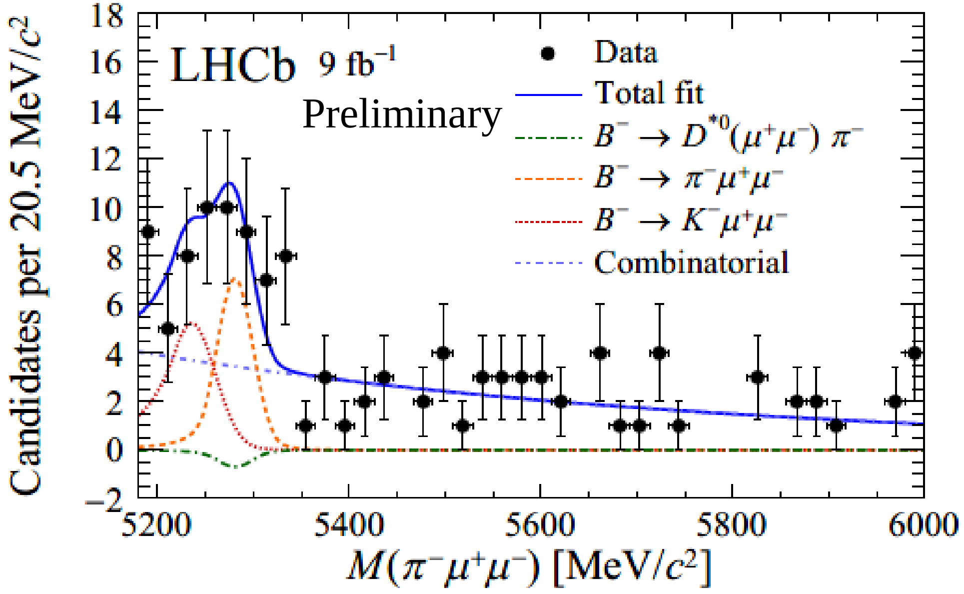
$$N_{B^- \to D^{*0}\pi^-} = -2 \pm 3$$

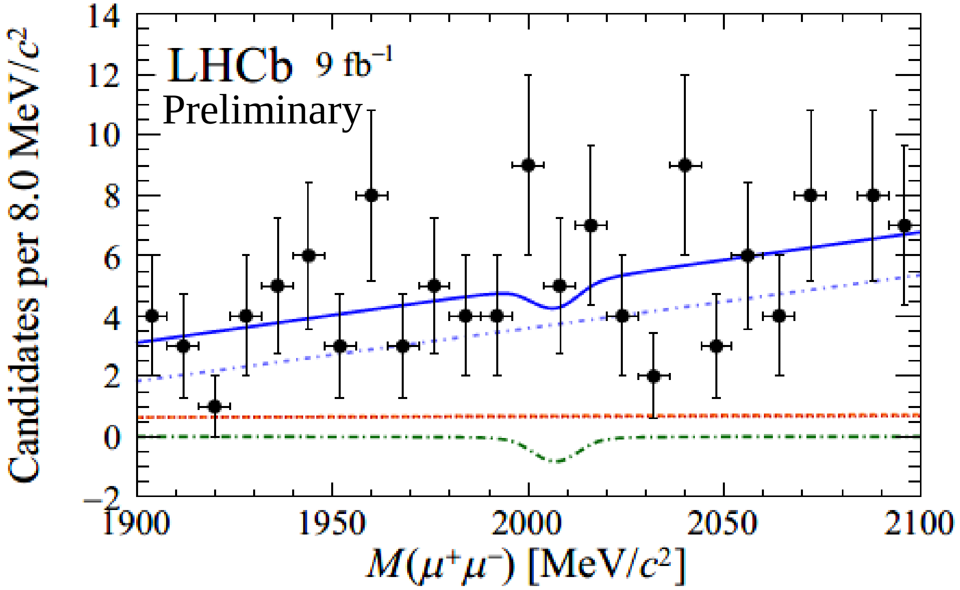
$\Rightarrow$ Attributed to under fluctuation of bkg. in sig. box



LHCb-PAPER-2023-004
(in preparation)

Signal mode fit





Search for $D^{*0} \to \mu^+\mu^-$ decays

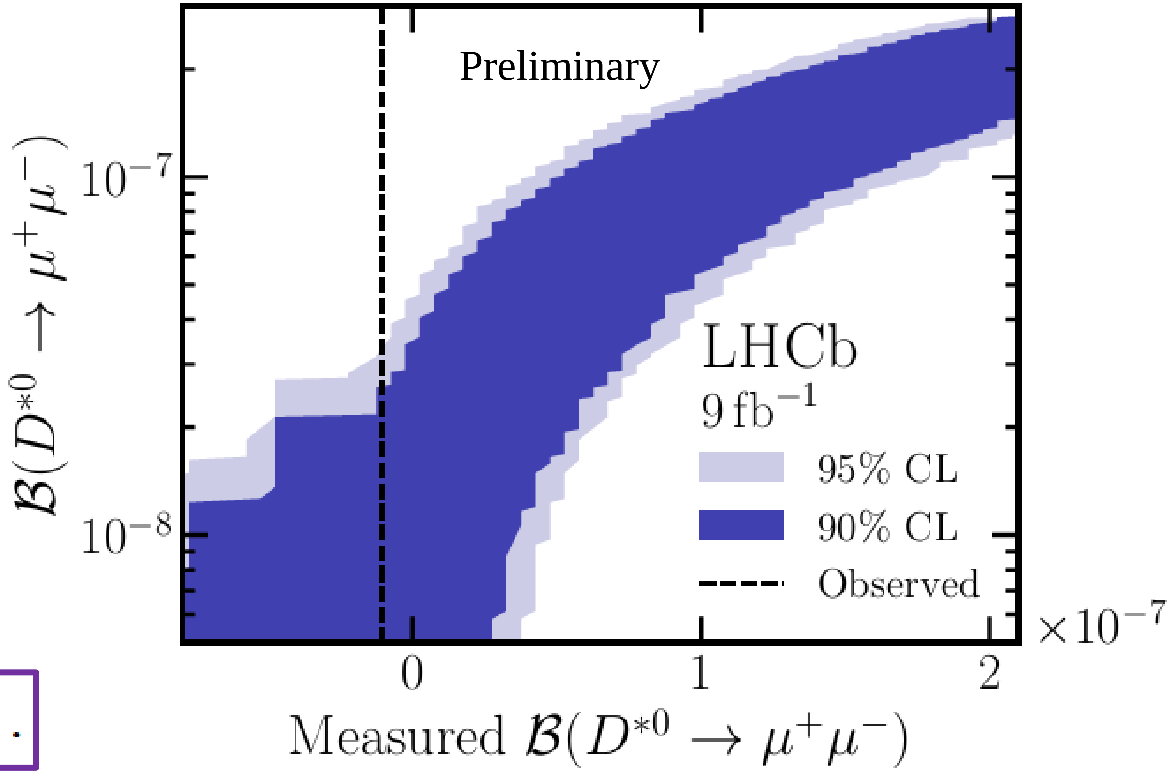
- Systematic uncertainties associated with normalisation, resolution and known BFs included as Gaussian constraints in signal mode fit
- Largest systematic originates from known BFs
- Results from fit to data

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

$\Rightarrow$ Upper limit on branching fraction based on Feldman-Cousins method

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

Confidence belt based on FC prescription



LHCb-PAPER-2023-004 (in preparation)

$\Rightarrow$ Most stringent upper limit on $D^{*0} \to \ell^+\ell^-$ decays

$\Rightarrow$ First search of a rare charm-hadron decay exploiting production in beauty decays

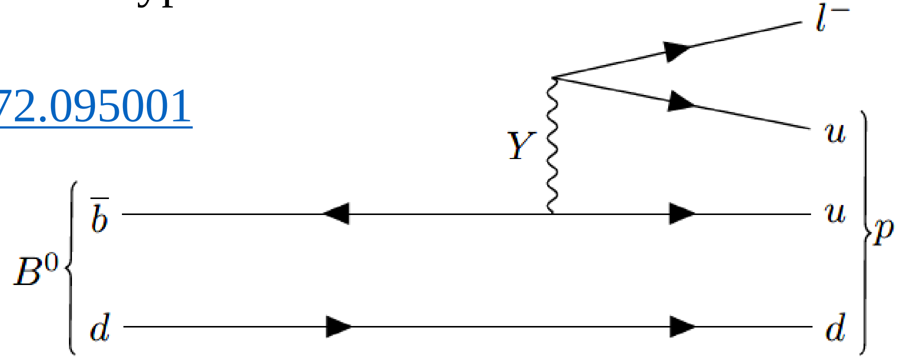
Search for $B^0_{(s)} \to p\,\mu^-$ decays

- Lepton number and baryon number violating decay
- Considering proton decay $\Rightarrow \mathcal{B}(\bar{b} \to uul^-) \lesssim 10^{-27}$ PRD.72.095001

$\Rightarrow$ Far from experimental sensitivity, but search feasible

- First search for this decay

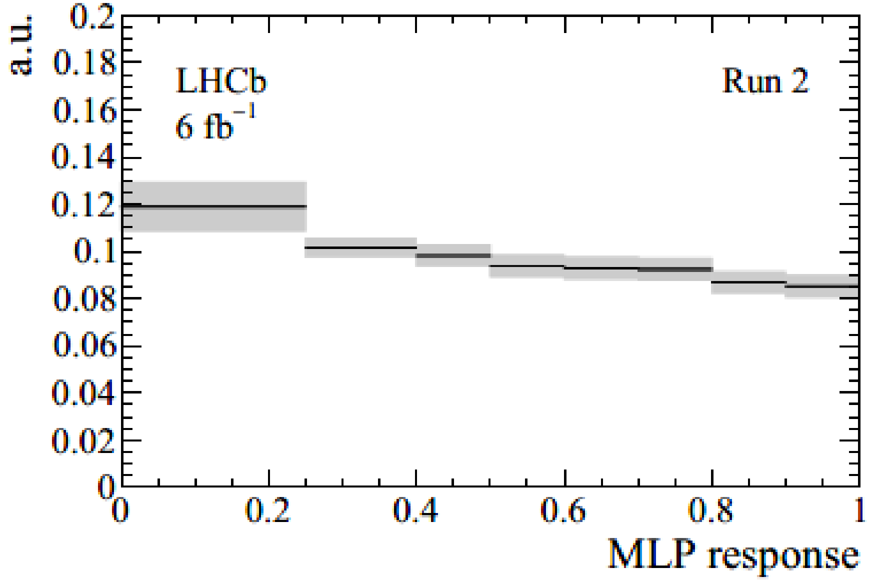
Non-SM contribution mediated by a hypothetical Y boson



Analysis Strategy

- Reconstruct $B^0_{(s)} \to p\,\mu^-$ decays
- Use an MLP against combinatorial background
- Use PID info to suppress $hh \to p\mu$ misID background
- Perform ML fit to $m(p\,\mu^-)$
- Use $B^- \to J/\psi(\mu^+\mu^-)K^-$ as normalisation mode

MLP response for Run II data



LHCb-PAPER-2022-022

Search for $B^0_{(s)} \to p\,\mu^-$ decays

- Signal mode fit performed simultaneously in 7 MLP intervals (least sensitive discarded)
- Semileptonic decays are dominant bkg. source
- Systematic uncertainties on normalisation included as Gaussian constraints in fit
- Results from fit to data

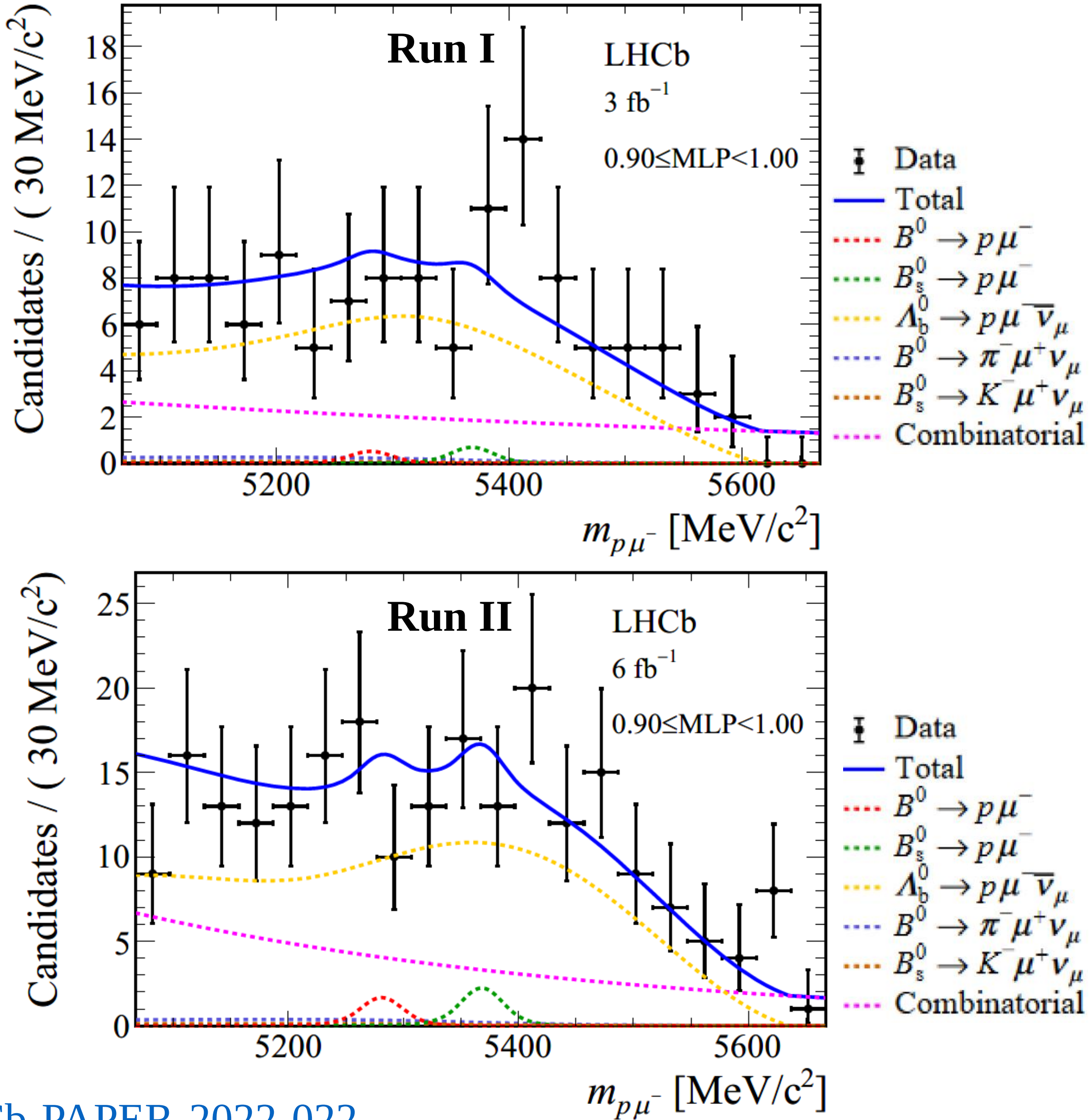
$$\mathcal{B}(B^0 \to p\mu^-) = (0.84 \pm 1.17 \pm 0.57) \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to p\mu^-) = (4.28 \pm 3.99 \pm 2.29) \times 10^{-9}$$

$\Rightarrow$ Upper limits based on CLs method at 90% (95)% CL

$$\mathcal{B}(B^0 \to p\mu^-) < 2.6\ (3.1) \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to p\mu^-) < 12.1\ (14.0) \times 10^{-9}$$

$\Rightarrow$ First upper limits on these decay modes

Signal mode fit for most sensitive BDT interval

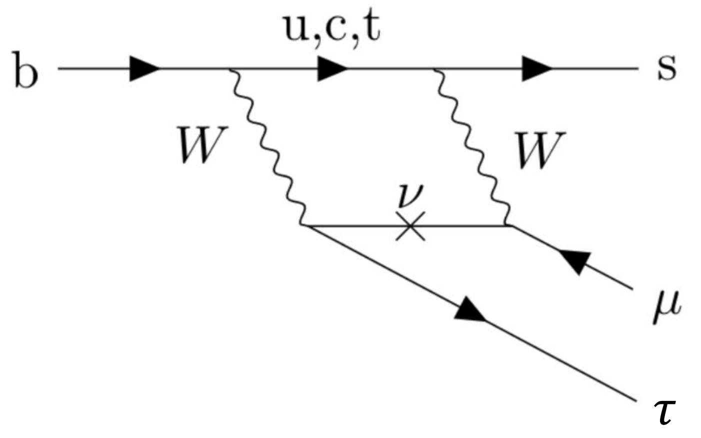


LHCb-PAPER-2022-022

Search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

- Lepton flavour violating decay
- Possible in SM with neutrino oscillation ($\mathcal{B} \lesssim 10^{-50}$)
- First search for this decay

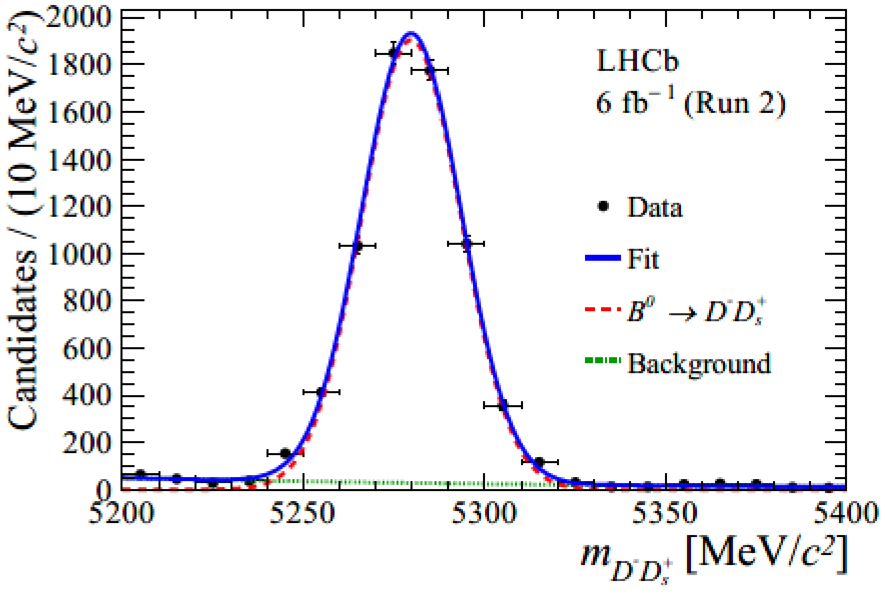
Contribution with neutrino oscillation



Analysis Strategy

- Reconstruct $B^0 \to K^{*0}\ \tau^{\pm}\ \mu^{\mp}$
  $\quad \hookrightarrow K^+\pi^-\ \hookrightarrow 3\pi^{\pm}(\pi^0)\nu_\tau$
- Use a BDT against combinatorial background
- Use a BDT against charmed mesons identified as τ
- Use PID info and veto background from D decays
- Fit to m_{corr} (partially recover missing energy)
- Use $B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)$ as norm. mode

Normalisation mode fit



LHCb-PAPER-2022-021

Search for $B^0 \rightarrow K^{*0}\tau^{\pm}\mu^{\mp}$

- Fit to $m_{\text{corr}} = \sqrt{p_{\perp}^2 + m_{K^*\tau\mu}^2} + p_{\perp}$ → Missing momentum perpendicular to B^0 direction
- Background modelled using control region in data with loosened combinatorial BDT requirement
- Systematic uncertainties on normalisation, bkg. model and BFs included as Gaussian constraints in signal fit
- Largest systematic uncertainty is choice of control region
- No excess observed over background-only hypothesis

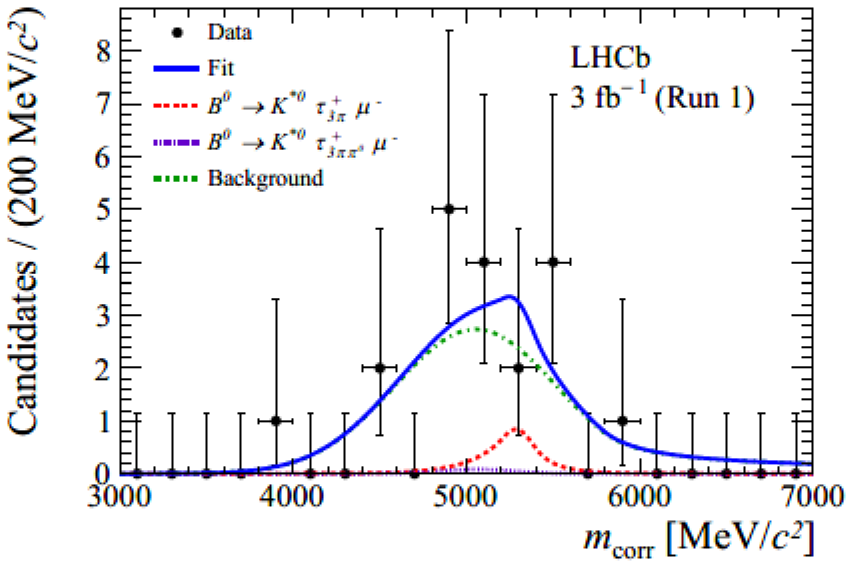
⇒ Upper limits based on CLs method at 90% (95)% CL

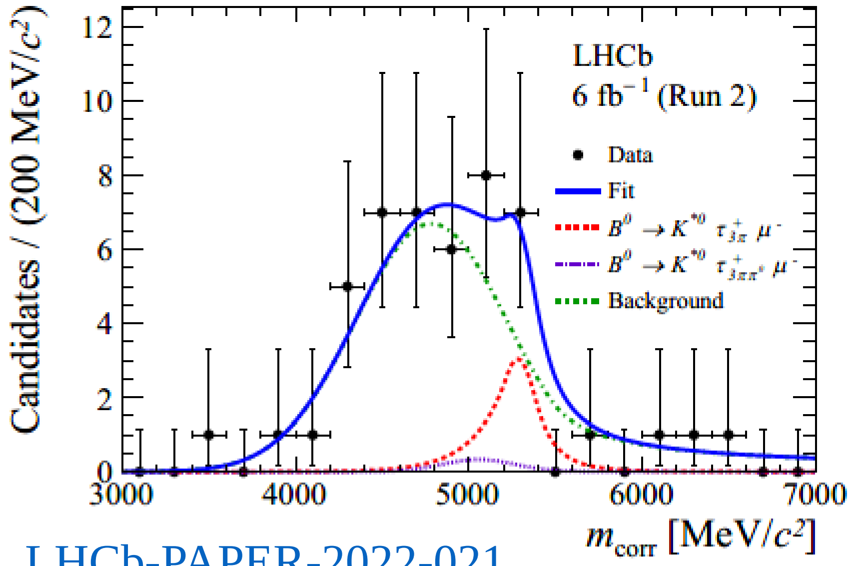
$$\mathcal{B}(B^0 \rightarrow K^{*0}\tau^{+}\mu^{-}) < 1.0\ (1.2) \times 10^{-5}$$
$$\mathcal{B}(B^0 \rightarrow K^{*0}\tau^{-}\mu^{+}) < 8.2\ (9.8) \times 10^{-6}$$

⇒ First upper limits on these decay modes

⇒ Most stringent upper limits on $b \rightarrow s\tau\mu$

Signal mode fit





LHCb-PAPER-2022-021

Summary and outlook

- Extremely rare and forbidden decays offer multiple constraints to non-SM contributions
- All measurements presented in this talk are world's best

$\Rightarrow$ But still a long way to go to get close to SM predictions

- Many new (and update) measurements exploiting run I + II data still to come

$\Rightarrow$ Decays into $e^{\pm} e^{\mp}$ modes, more LFV, LNV and BNV searches, baryonic decays, search for $V \to \mu^+\mu^-$ in B_c^+ decays, …

- LHCb Upgrade I (runs 3 - 4) will continue taking data (expect ~50 fb^{-1} by 2030) and making measurements in the next few years

$\Rightarrow$ Stay tuned!

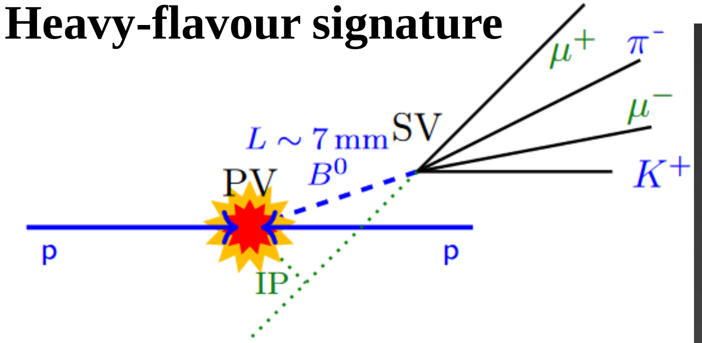
Backup

The LHCb experiment

- Single-arm forward spectrometer optimised for studies of beauty and charm hadrons
- Large cross sections: $\sigma_{b\bar{b}} \approx 280\ (500)\ \mu b$, $\sigma_{c\bar{c}} \approx 1500\ (3000)\ \mu b$ at $7(13)$ TeV

JHEP10(2015)172
JHEP03(2016)159

Heavy-flavour signature



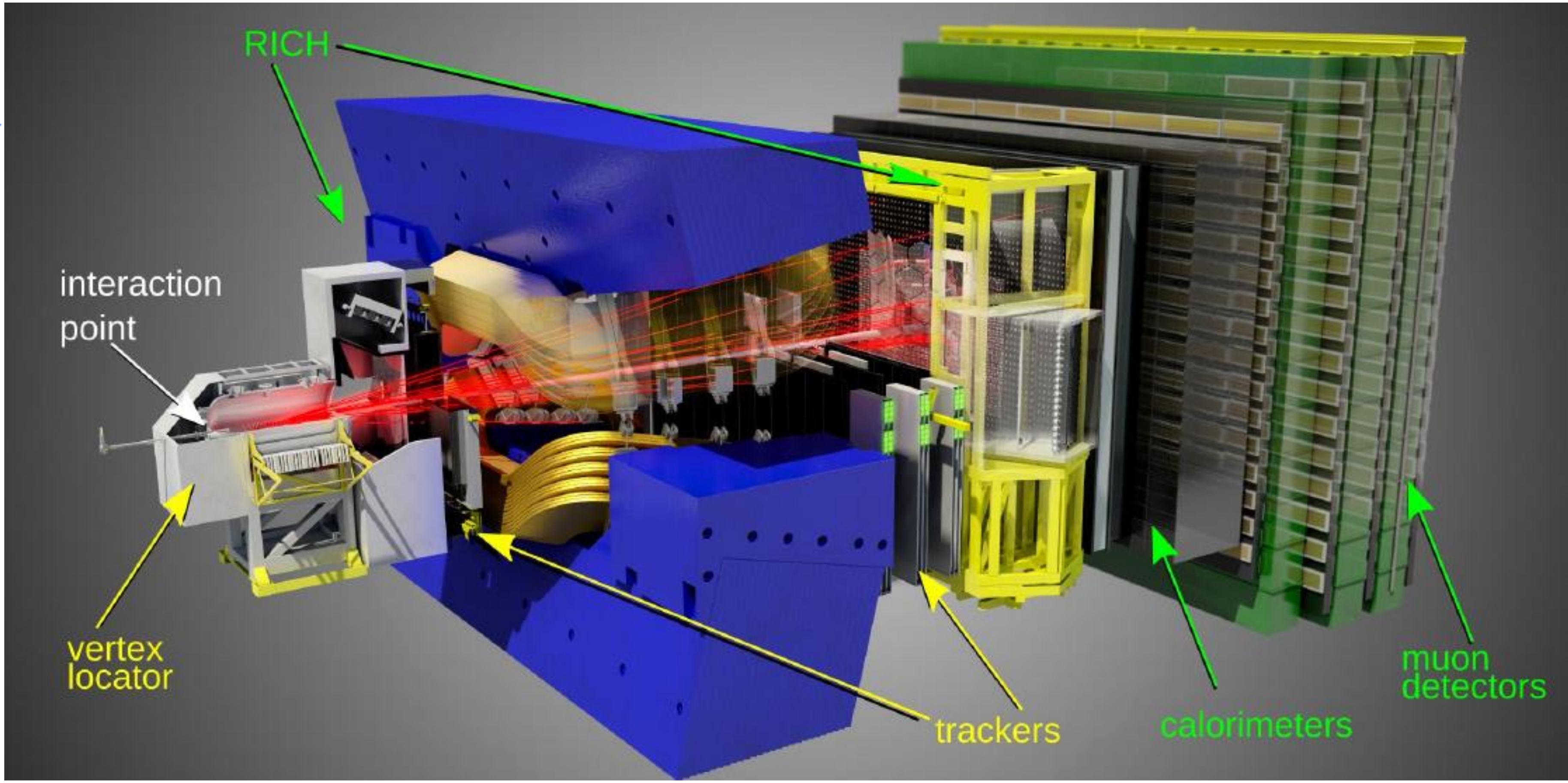
- Excellent IP resolution

$\sim 20\mu m$ to identify B vtx.

- Mom. res. $\frac{\Delta p}{p} = 0.5 - 1\%$
- Particle identification

$\varepsilon_{K\to K} \sim 95\%$ $\varepsilon_{\pi\to K} \sim 5\%$

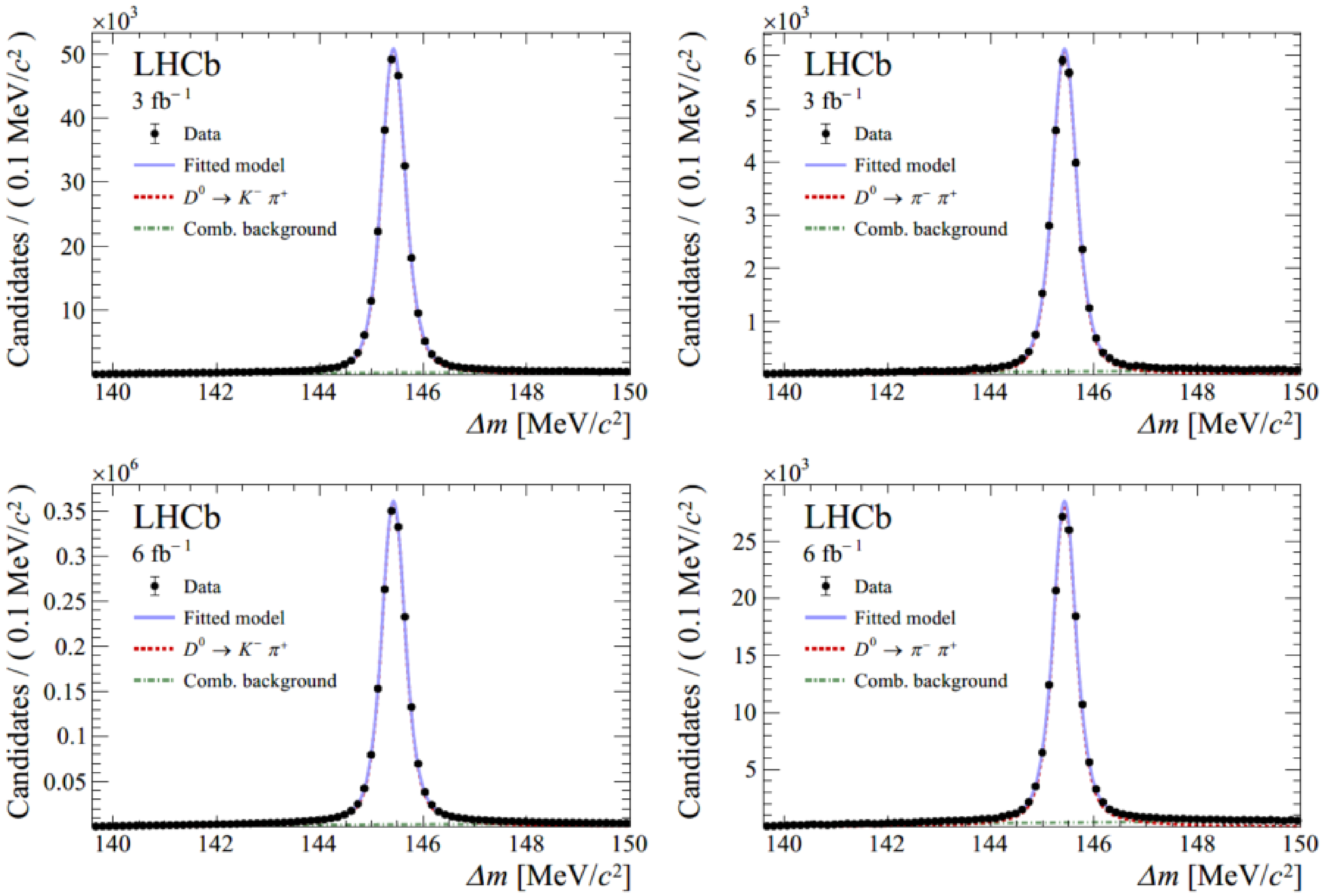
$\varepsilon_{\mu\to\mu} \sim 97\%$ $\varepsilon_{\pi\to\mu} \sim 1 - 3\%$



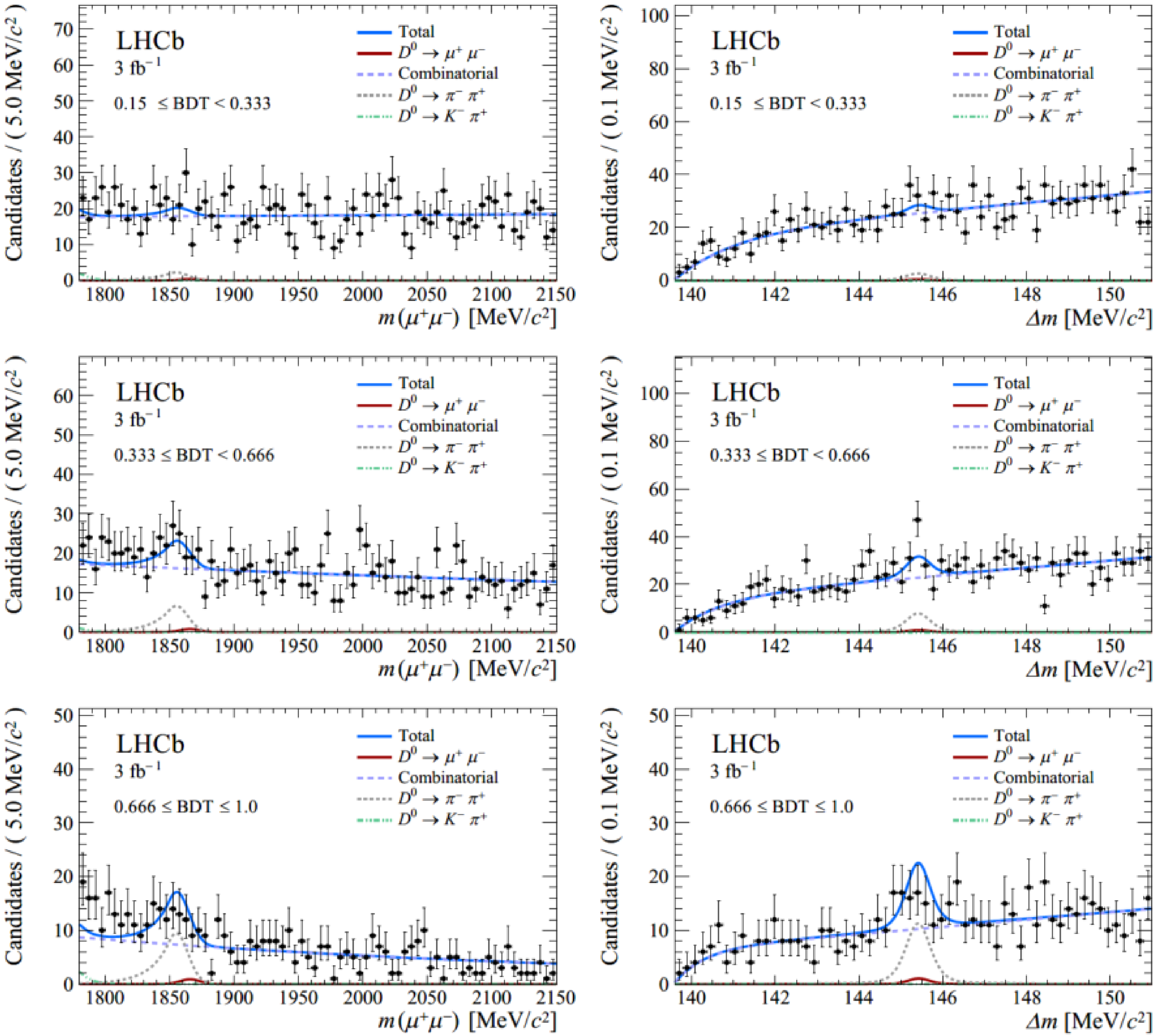
JINST(2008)3S08005

Search for $D^0 \to \mu^+\mu^-$ decays

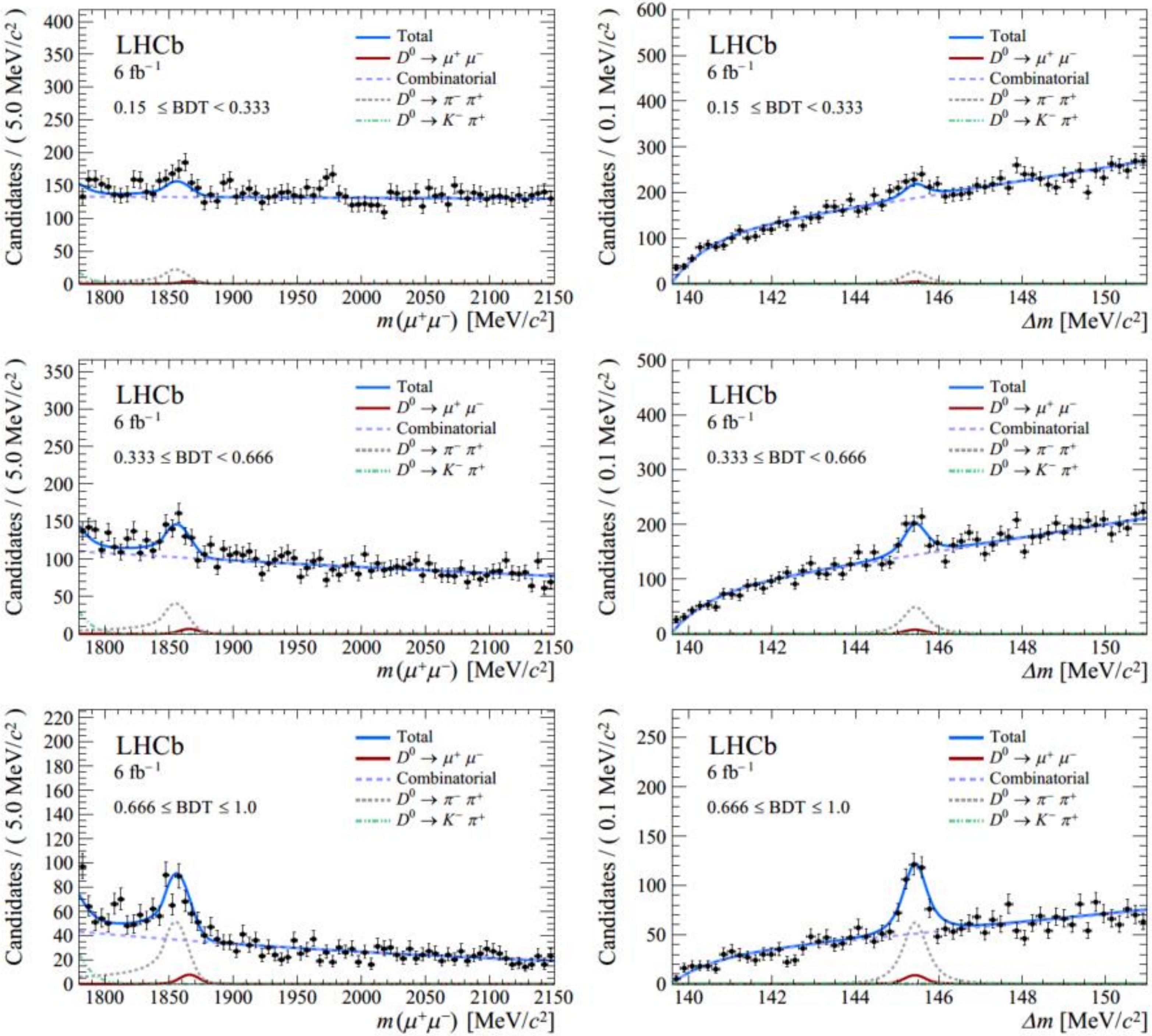
- Normalisation channel fits
- Used also as control channels to study data/MC agreement



- Signal mode fit for all BDT bins using Run I data

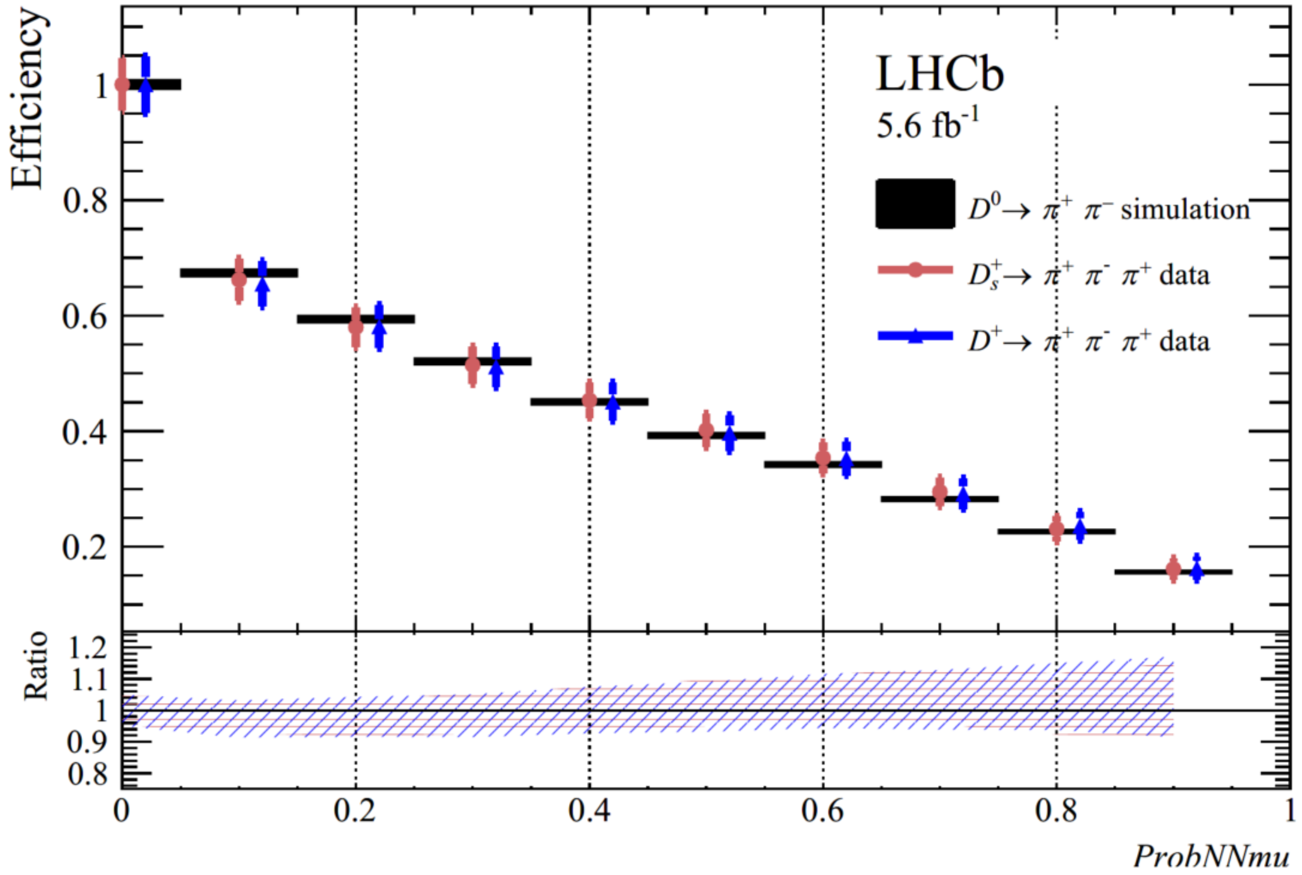


- Signal mode fit for all BDT bins using Run II data



Search for $D^0 \to \mu^+\mu^-$ decays

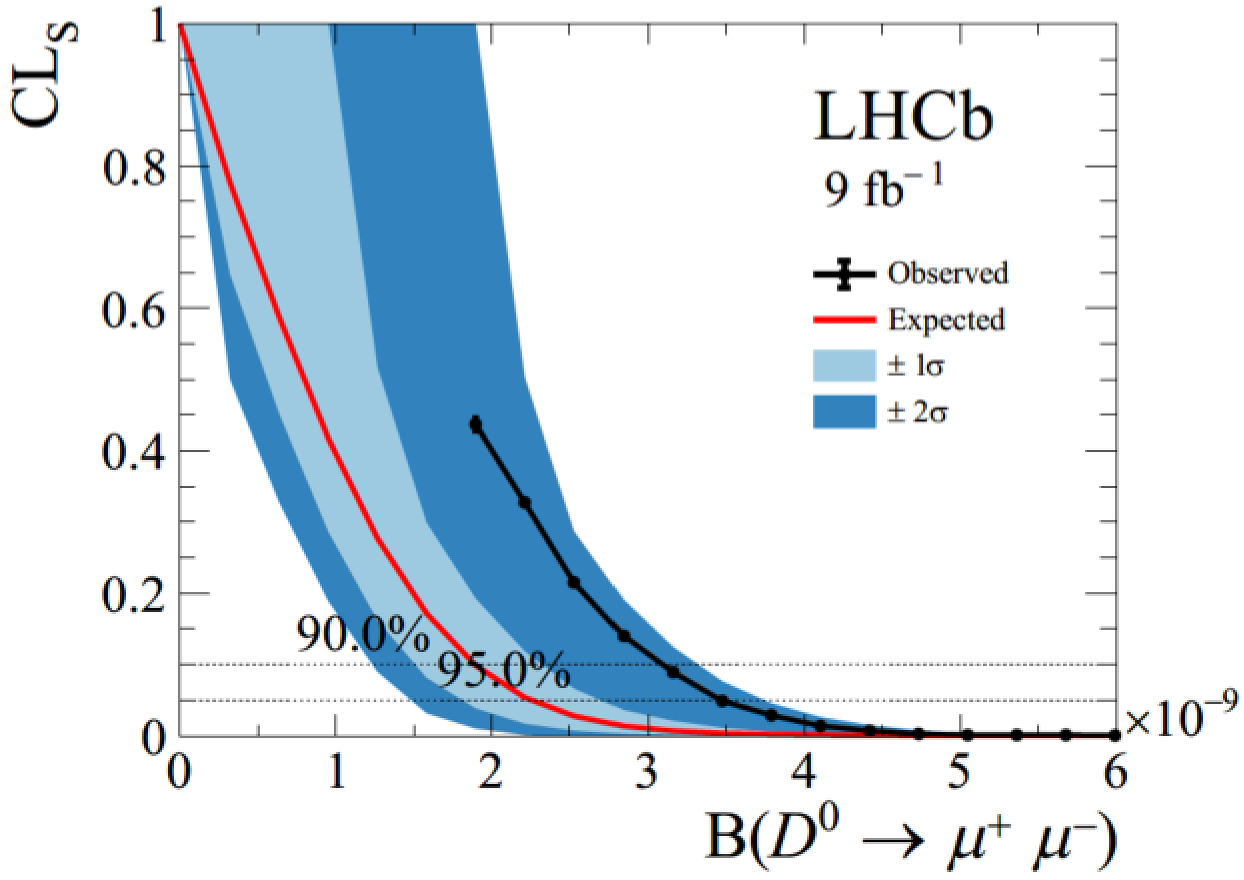
- $\pi \to \mu$ PID efficiency obtained from simulation, cross checked with control samples in data
- Efficiency for two pions to pass the PID requirement (ProbNNmu variable)
- For $D^+_{(s)} \to \pi^+\pi^-\pi^+$ data same-sign pions ($\pi^+\pi^+$) used to avoid contamination from hadronic resonances decaying into $\mu^+\mu^-$.



$\Rightarrow$ Agreement over the full range of the muon identification discriminant variable

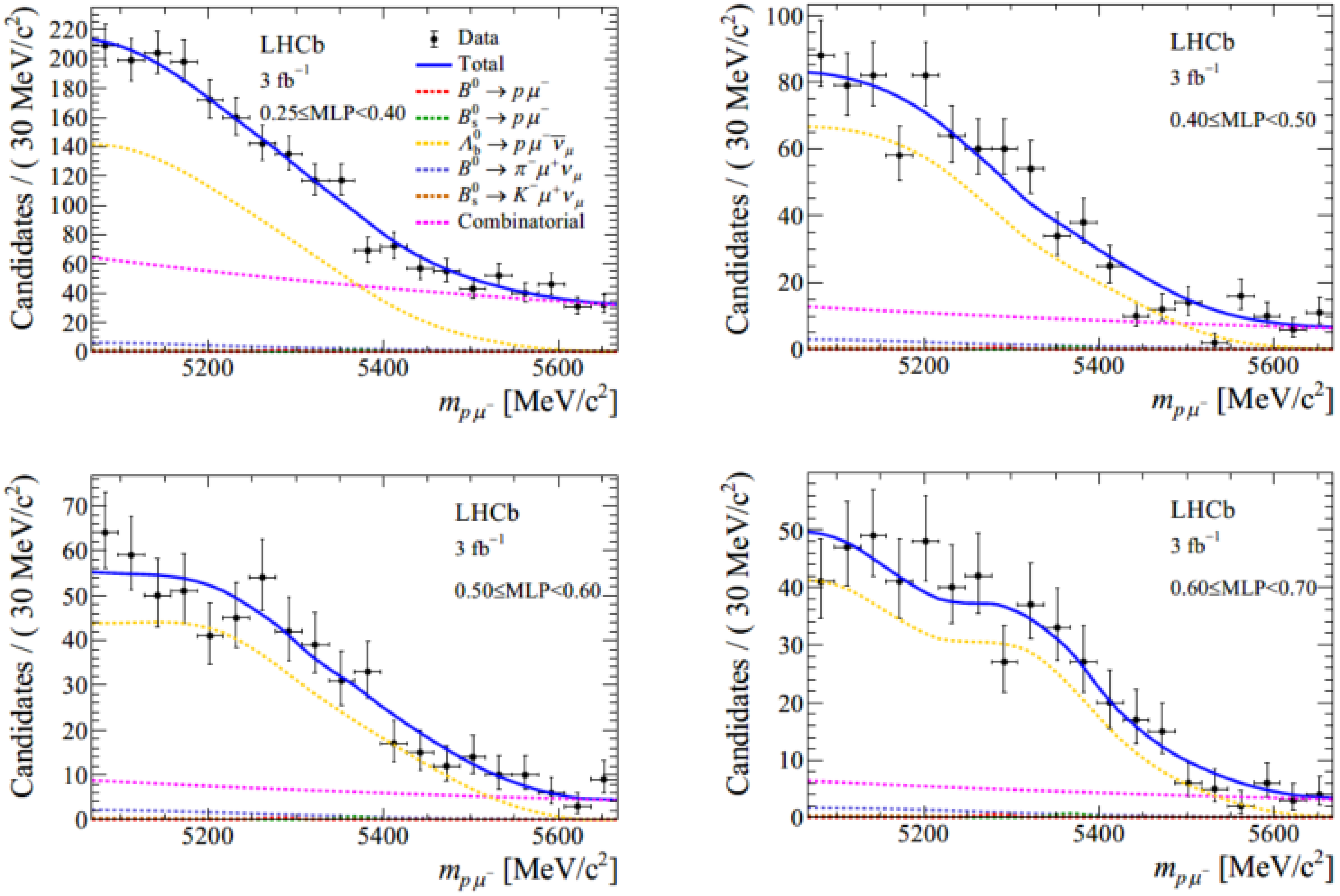
Search for $D^0 \to \mu^+\mu^-$ decays

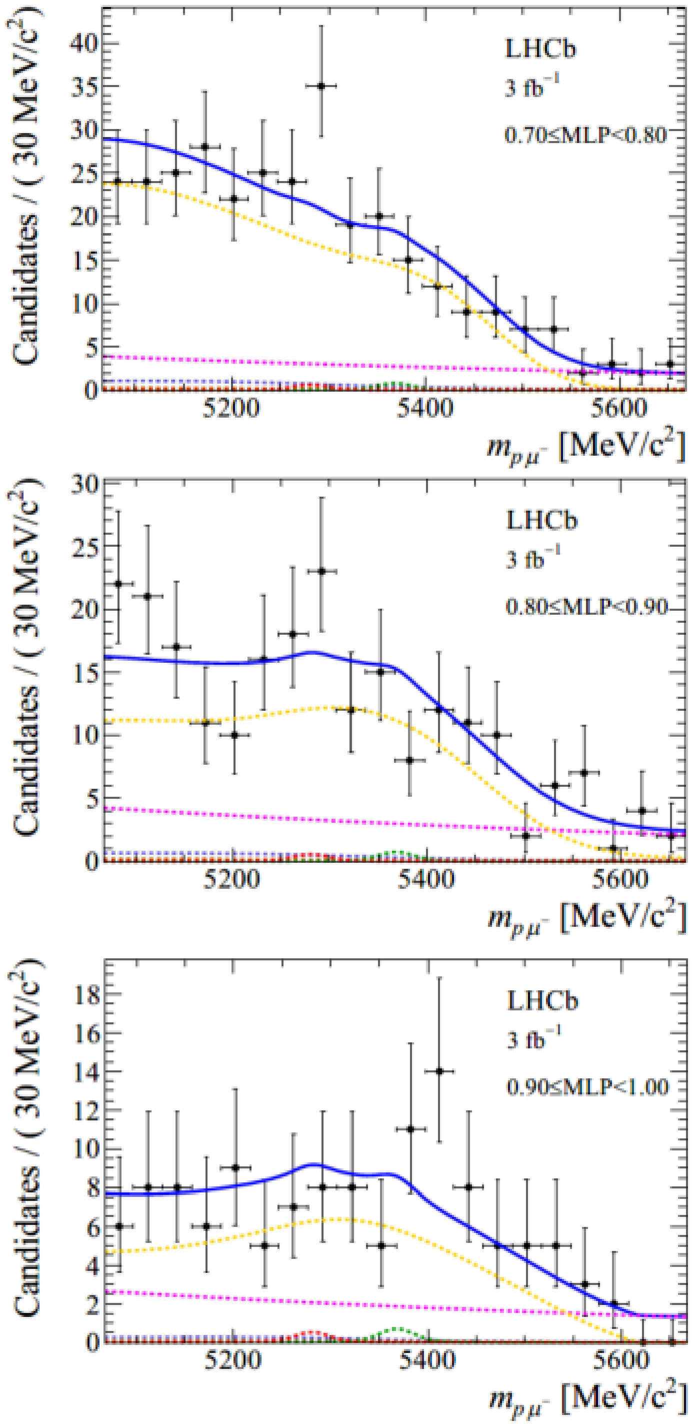
- Results of the CLs scan as a function of the branching fraction



Search for $B^0_{(s)} \to p\,\mu^-$ decays

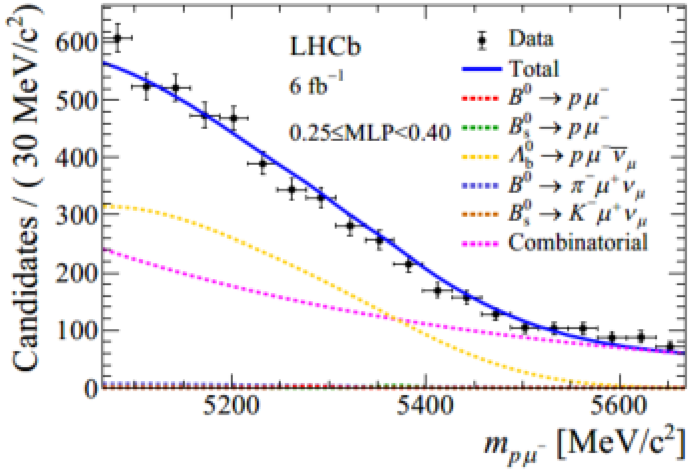
- Signal mode fit for all BDT bins using Run I data

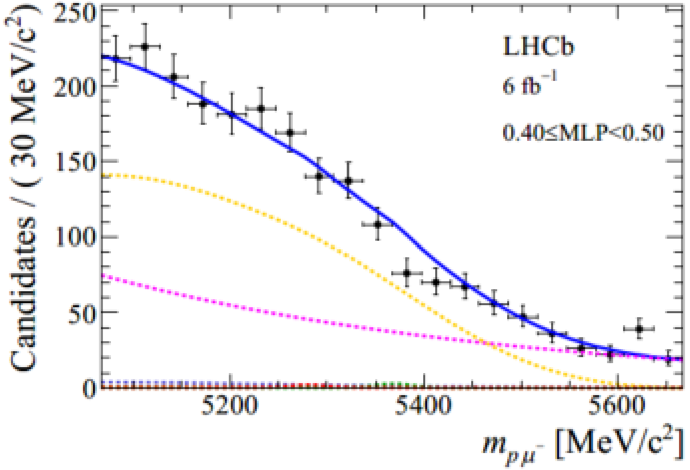


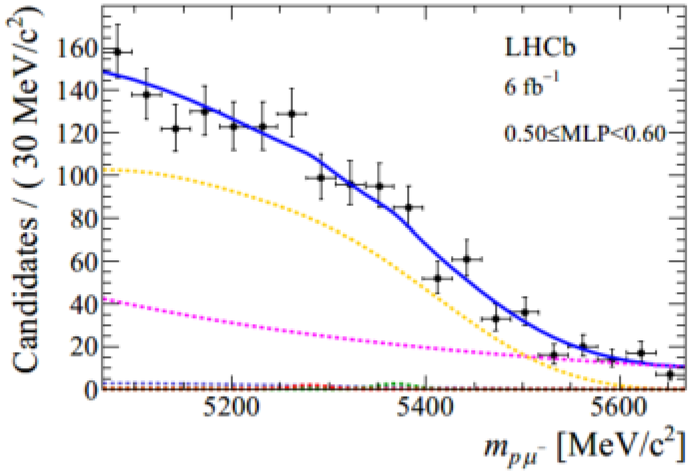


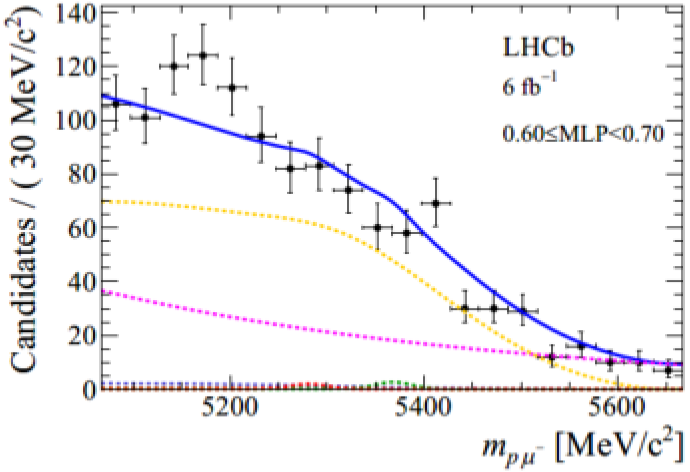
Search for $B^0_{(s)} \to p\,\mu^-$ decays

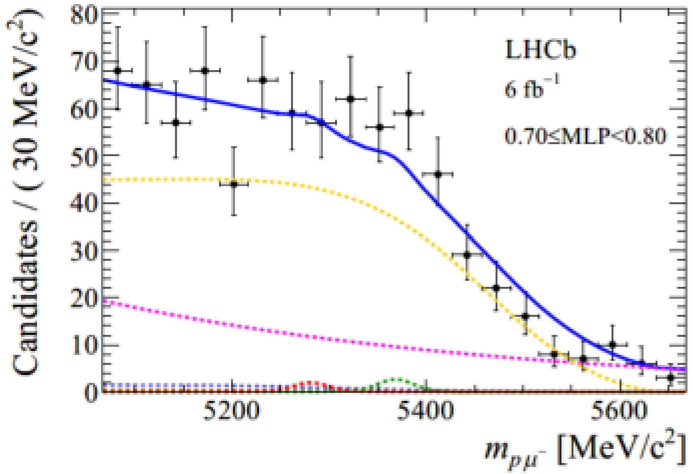
- Signal mode fit for all BDT bins using Run II data

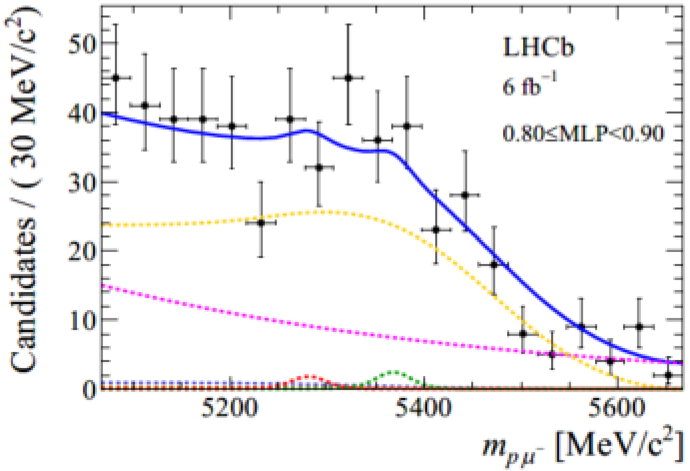


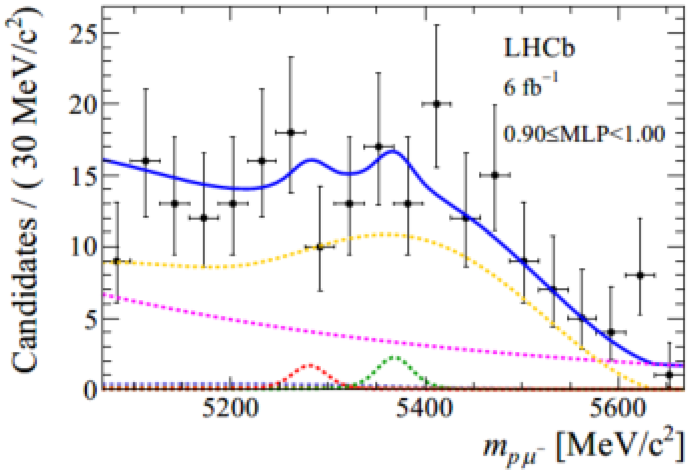






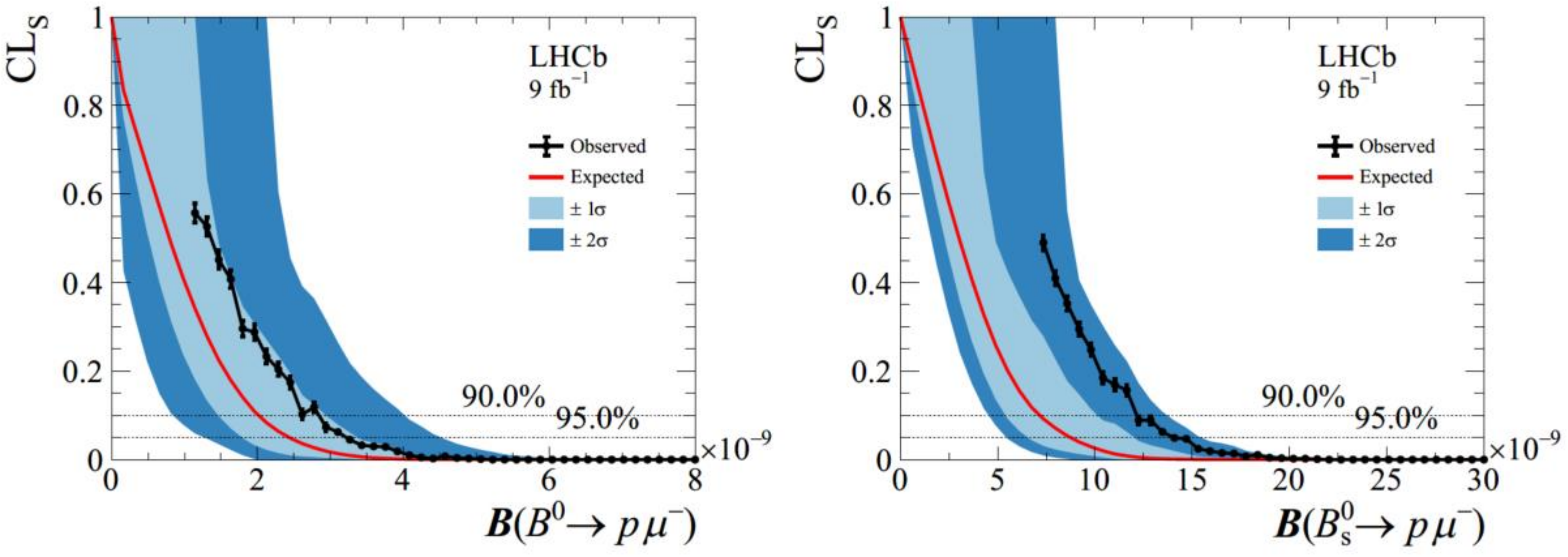






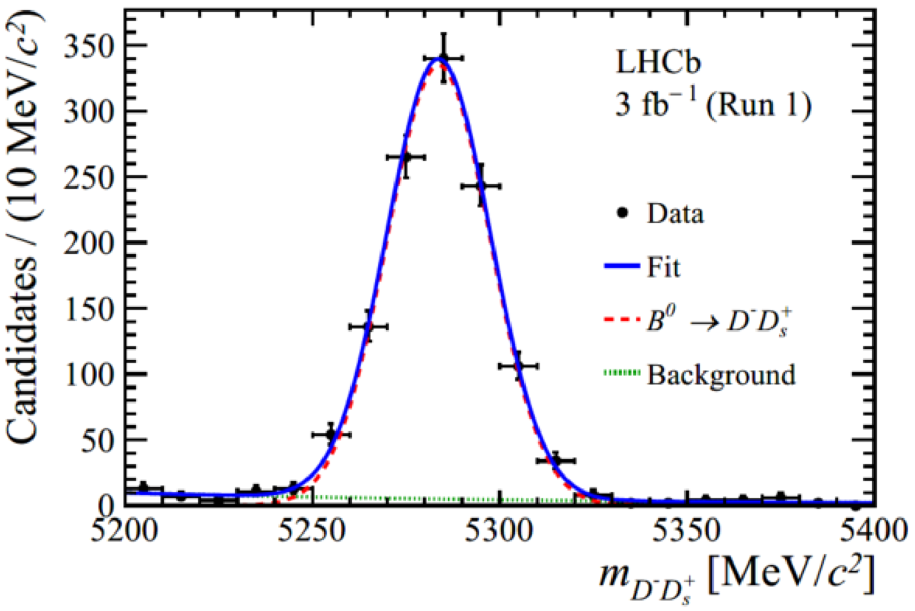
Search for $B^0_{(s)} \rightarrow p\,\mu^-$ decays

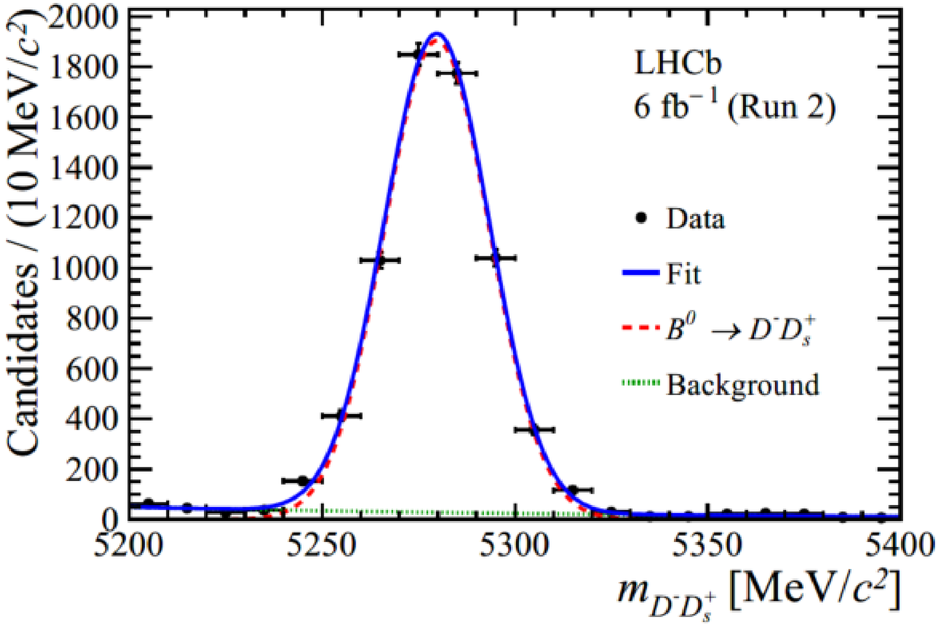
- Results of the CLs scan as a function of the branching fraction



Search for $B^0 \rightarrow K^{*0}\tau^{\pm}\mu^{\mp}$

- Normalisation channel fits
- Used also as control channels to study data/MC agreement

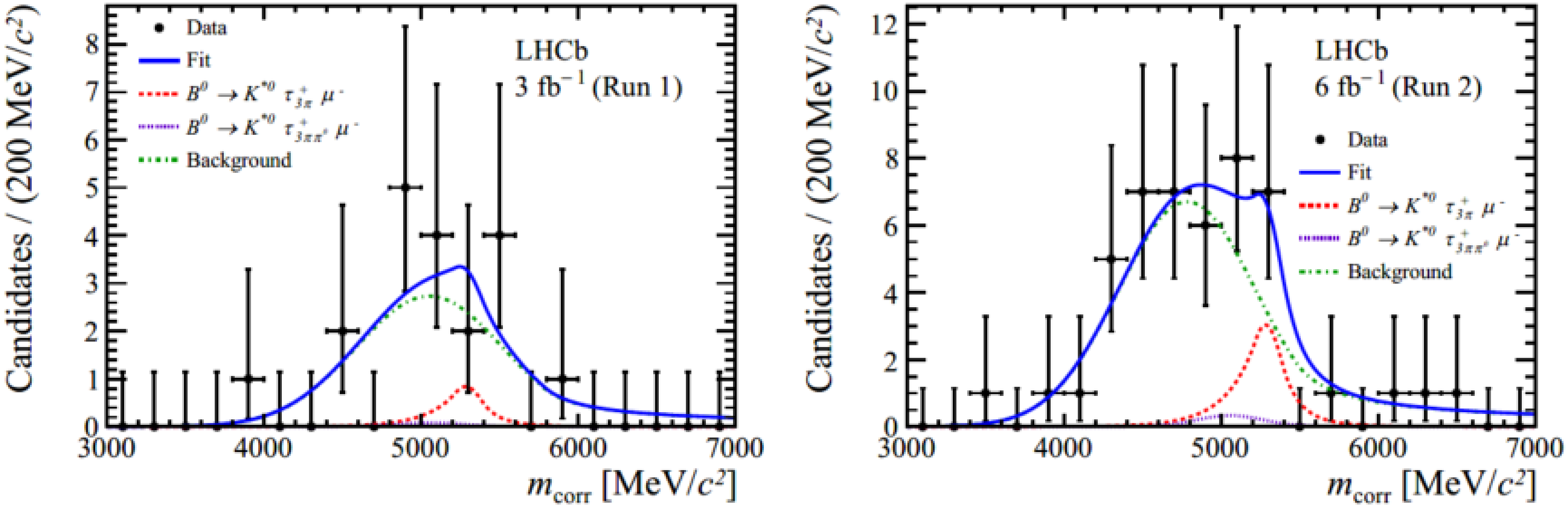




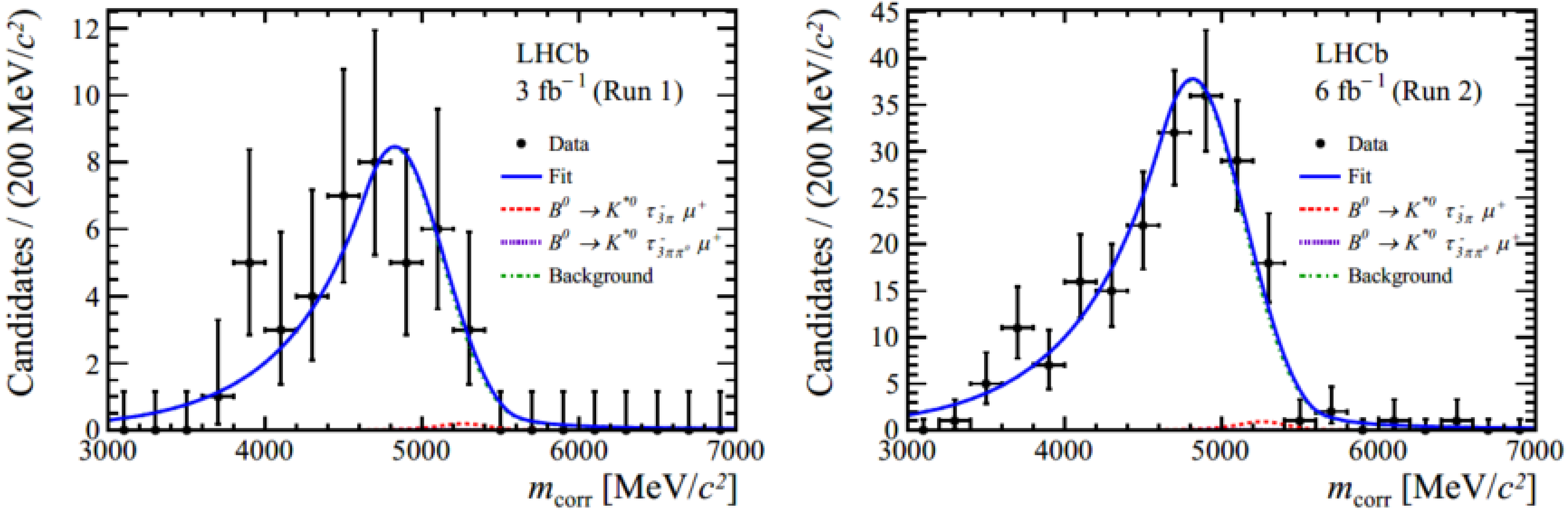
Search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

- Signal mode fit (signal region)

$B^0 \to K^{*0}\tau^{+}\mu^{-}$



$B^0 \to K^{*0}\tau^{-}\mu^{+}$



Search for $B^0 \rightarrow K^{*0}\tau^{\pm}\mu^{\mp}$

- Results of the CLs scan as a function of the branching fraction