Rare and Radiative Decays at LHCb: $B_s^0 \to \mu^+\mu^-\gamma$

Assemblée Générale Enigmass2
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Rare b-hadron decays

Highly **suppressed** in SM:

- Higher orders diagrams
- FCNC box or penguin diagrams
- $b \to sll$

Signal different from SM?

Possible new physics!

Forbidden in SM:

- Lepton Flavour Violating
- Baryon Number Violating
- …

Any signal?

Possible new physics!

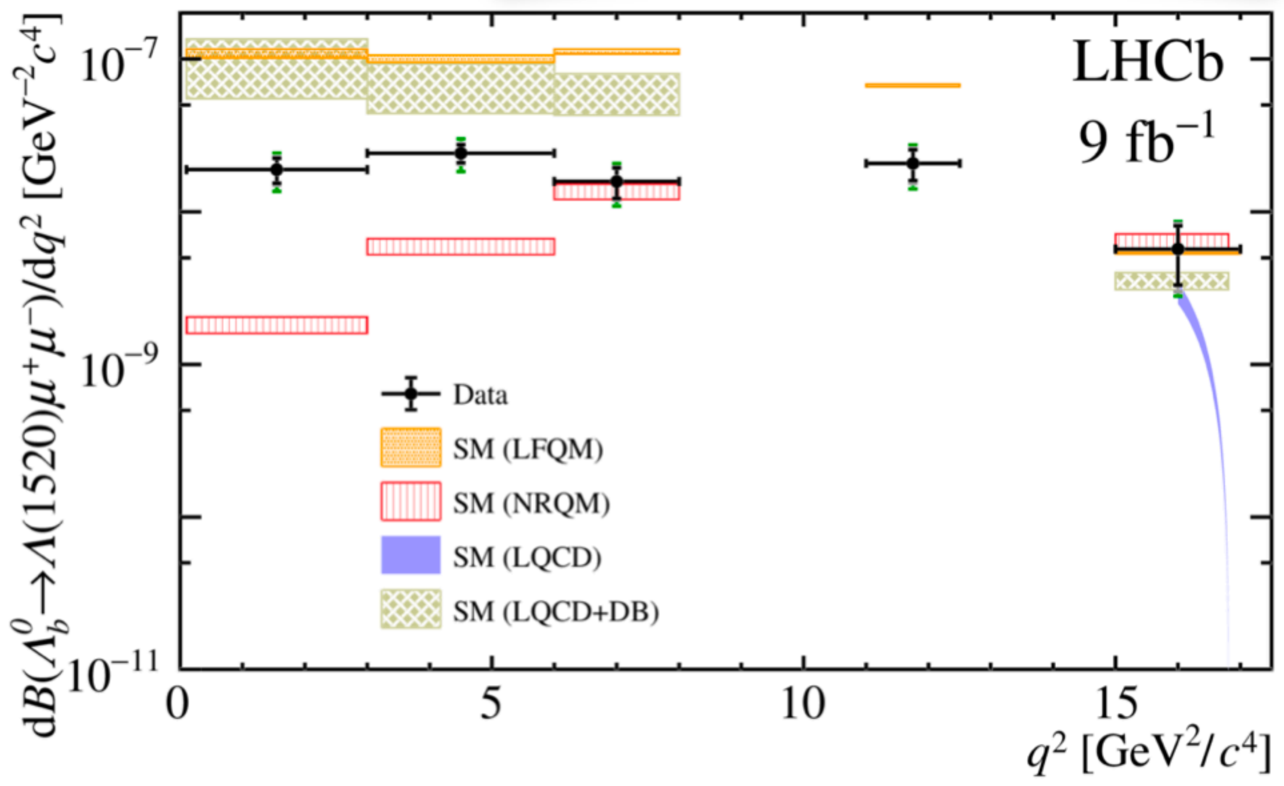
SM = Standard Model

NP = New Physics

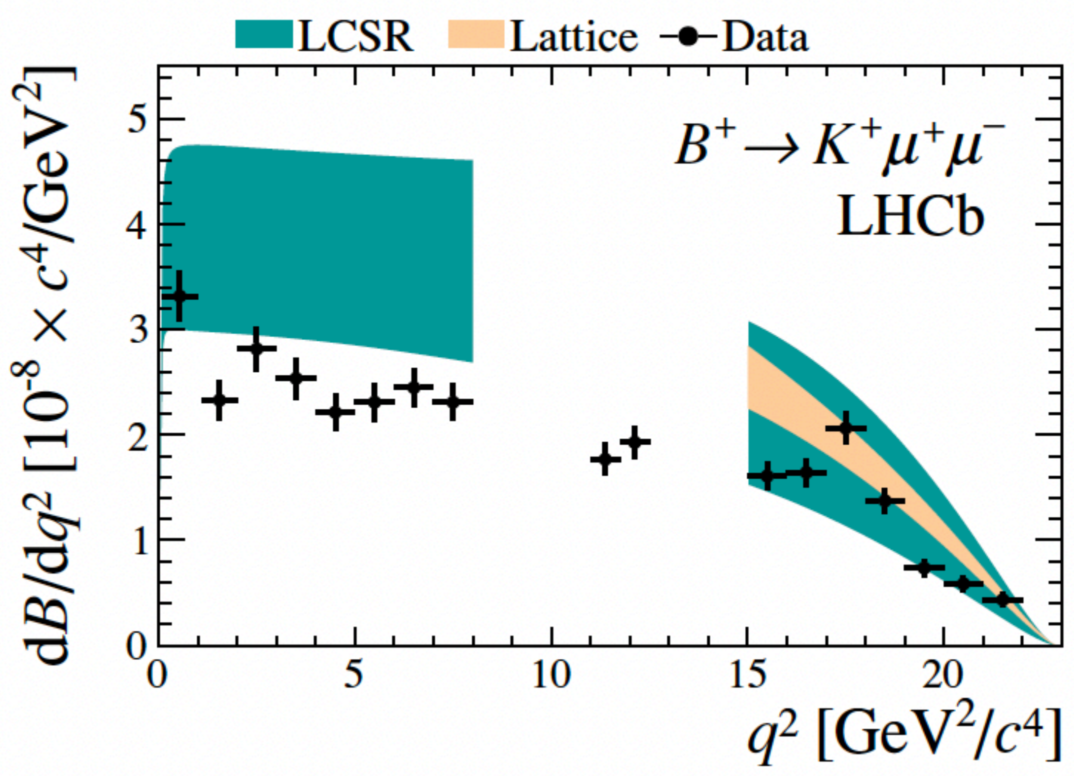
Differential Branching Fractions

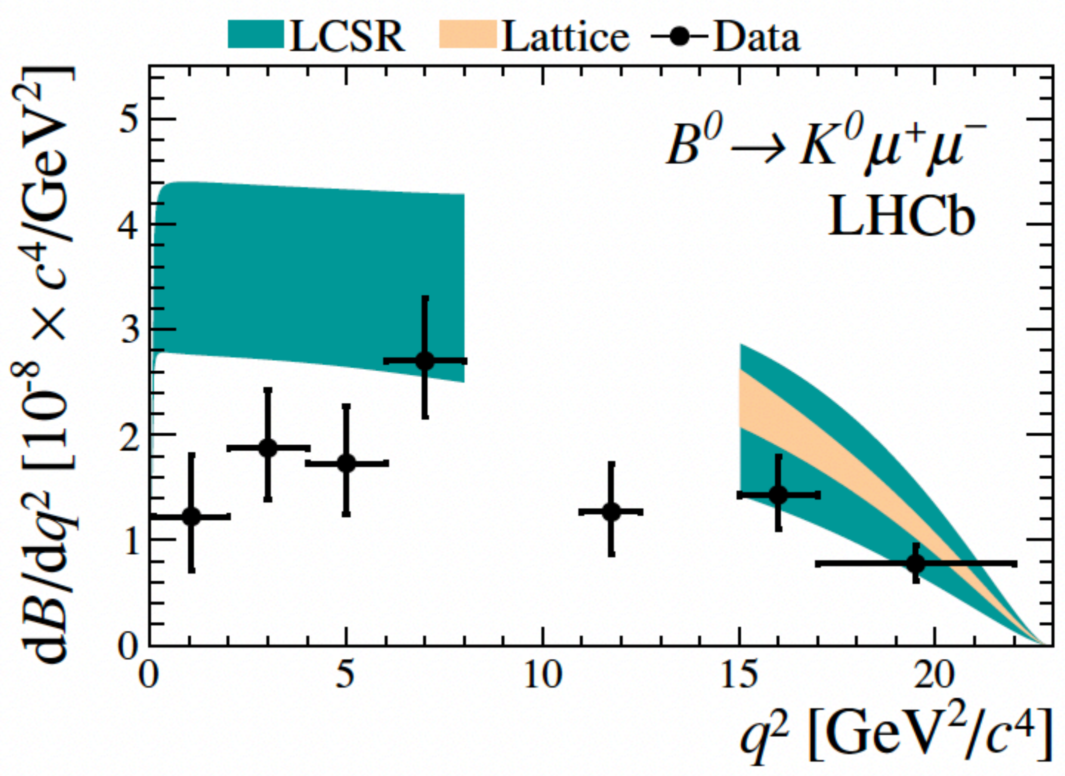
- SM predictions. Large hadronic form factors uncertainties (20-30%).
- ✦ Data. LHCb results.

Phys.Rev.Lett.131(2023)151801

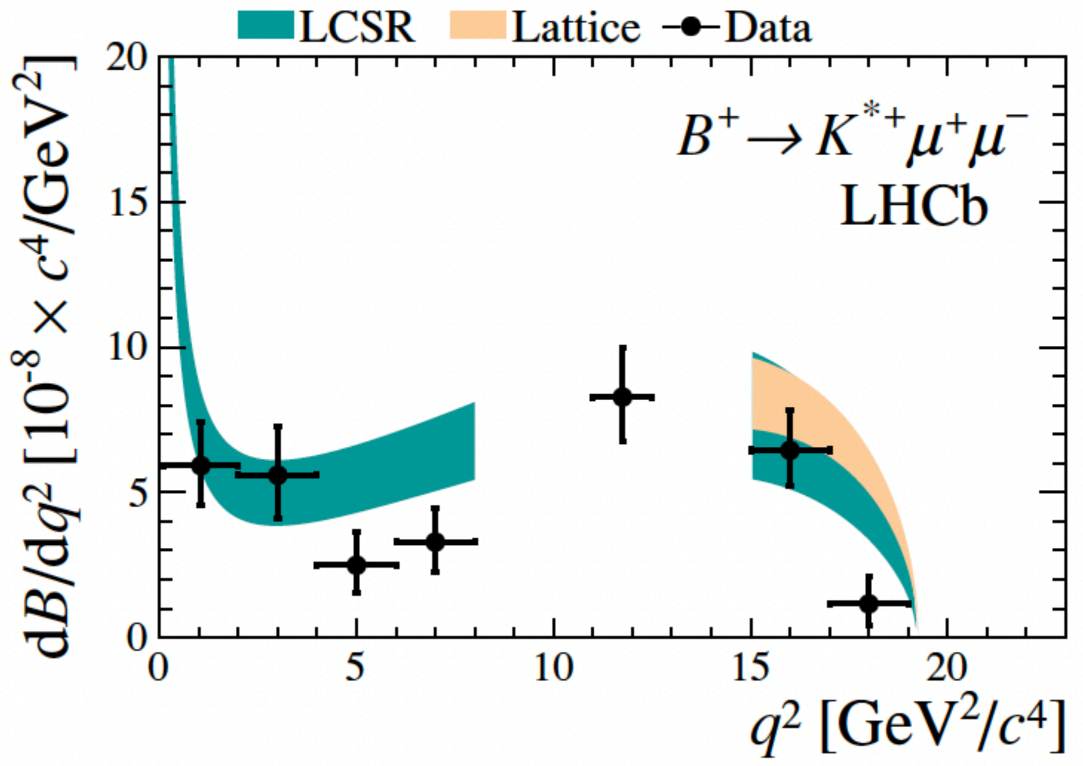


$q^2 = m^2(l^+l^-)$

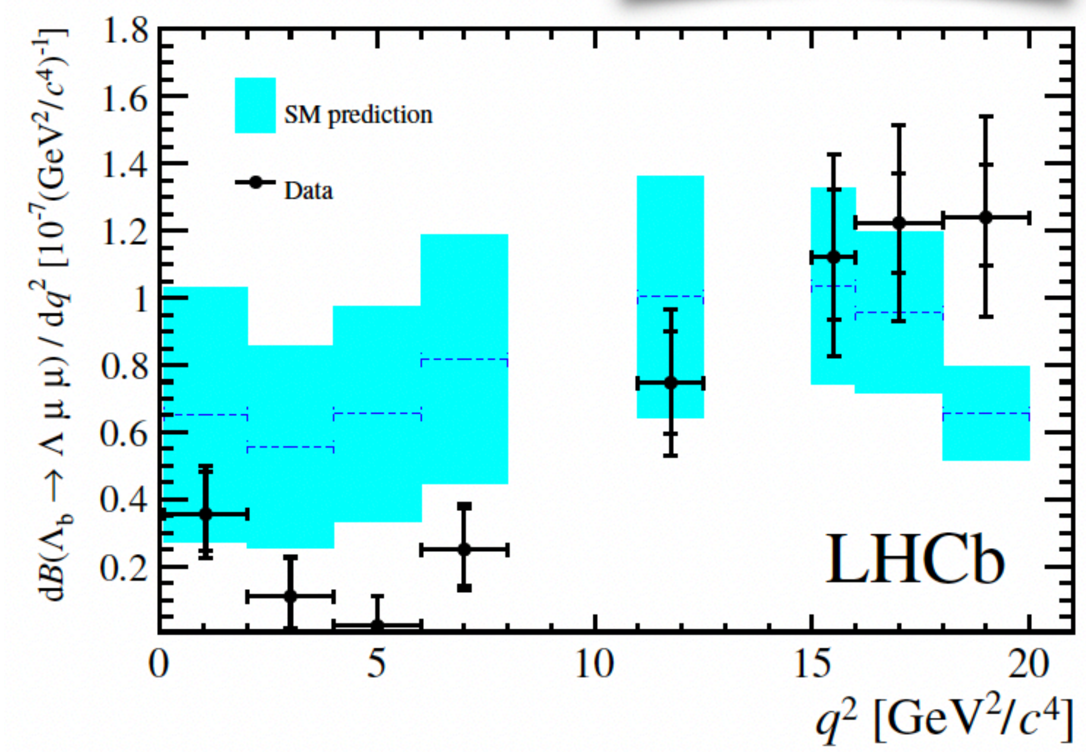




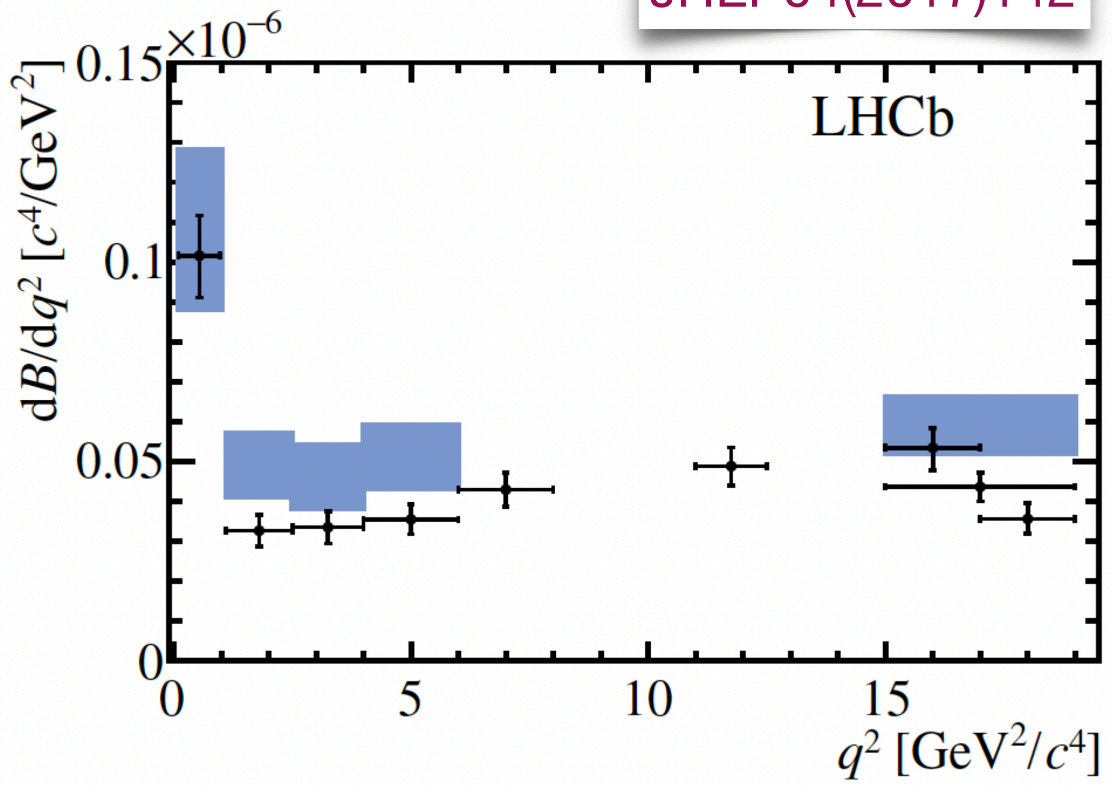
JHEP06(2014)133



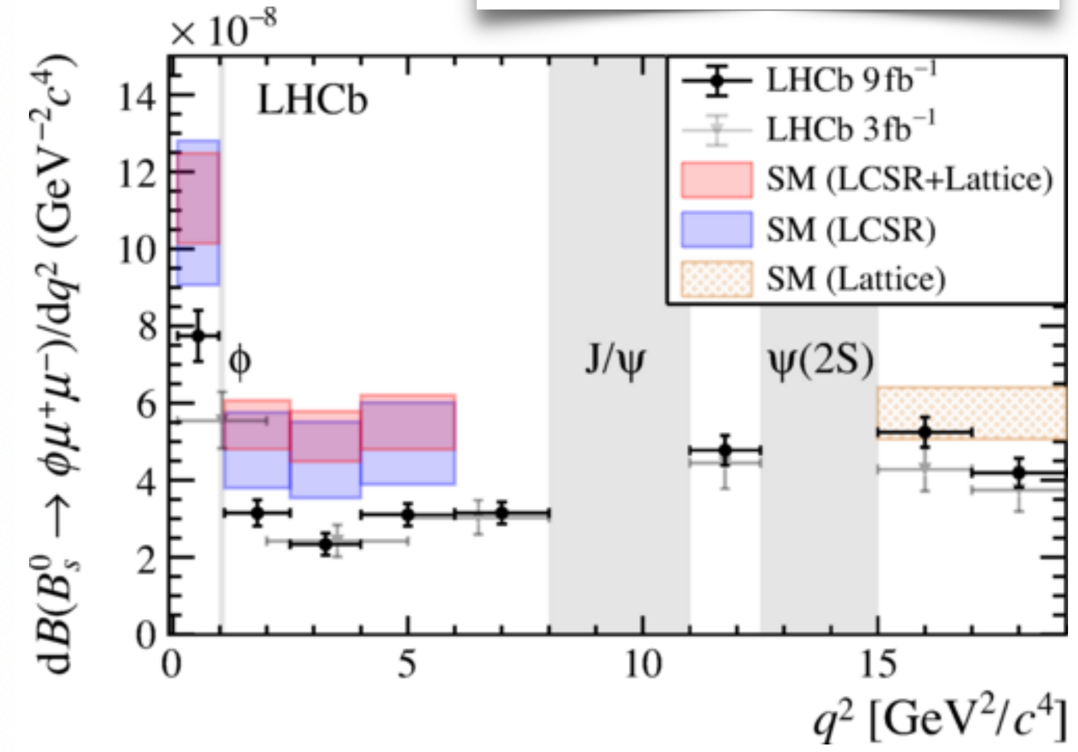
JHEP06(2015)115



JHEP04(2017)142



PRL 127 (2021) 151801



Other observables: angular distributions of the final state particles, relative rates (electron vs muon), etc.

Radiative b-hadron decays

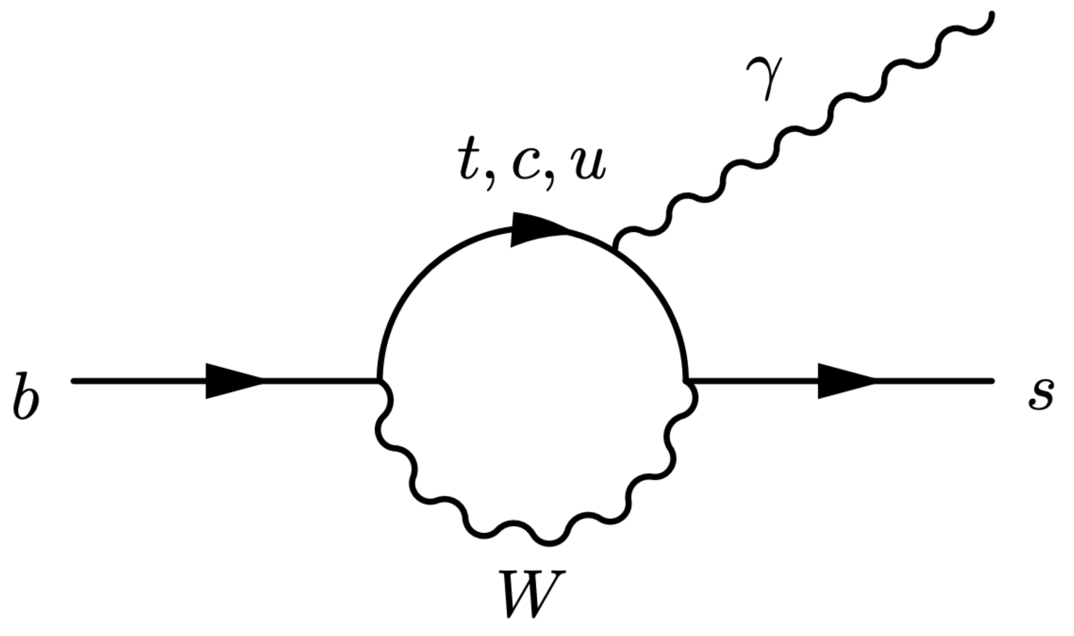
Radiative penguin

The $b \to s\gamma$ transition is a flavour-changing neutral-current process characterised by the emission of a photon (γ).

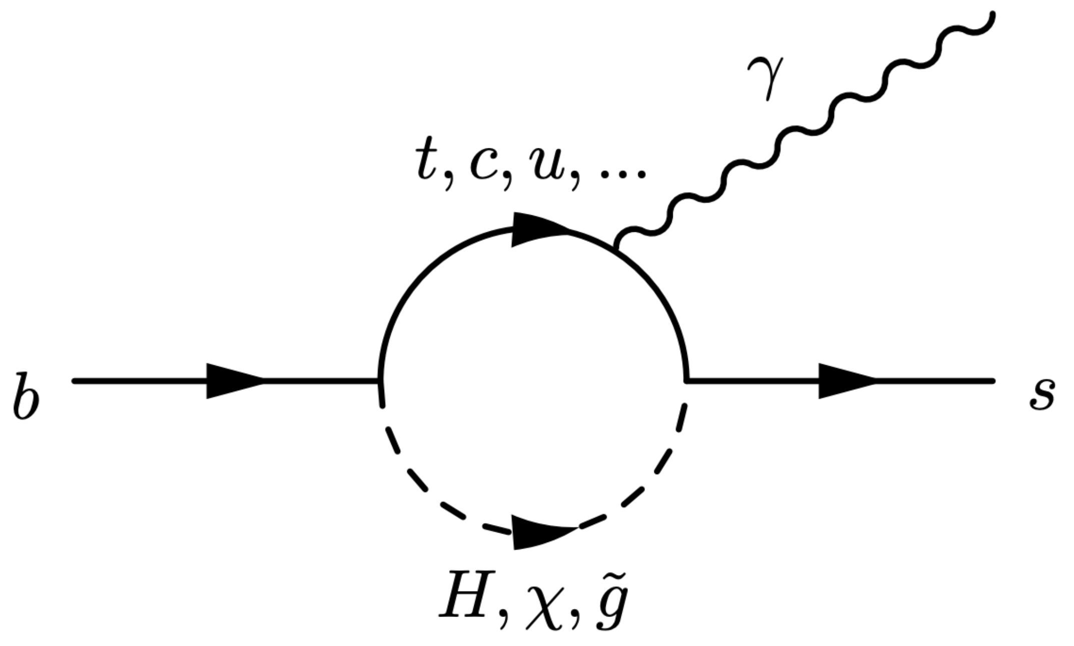
Powerful tool to test the SM, with access to branching fractions, angular and charge-parity-violating observables:

- Possibility of testing the presence of right-handed photons (highly suppressed in the SM).

Standard Model



New Physics



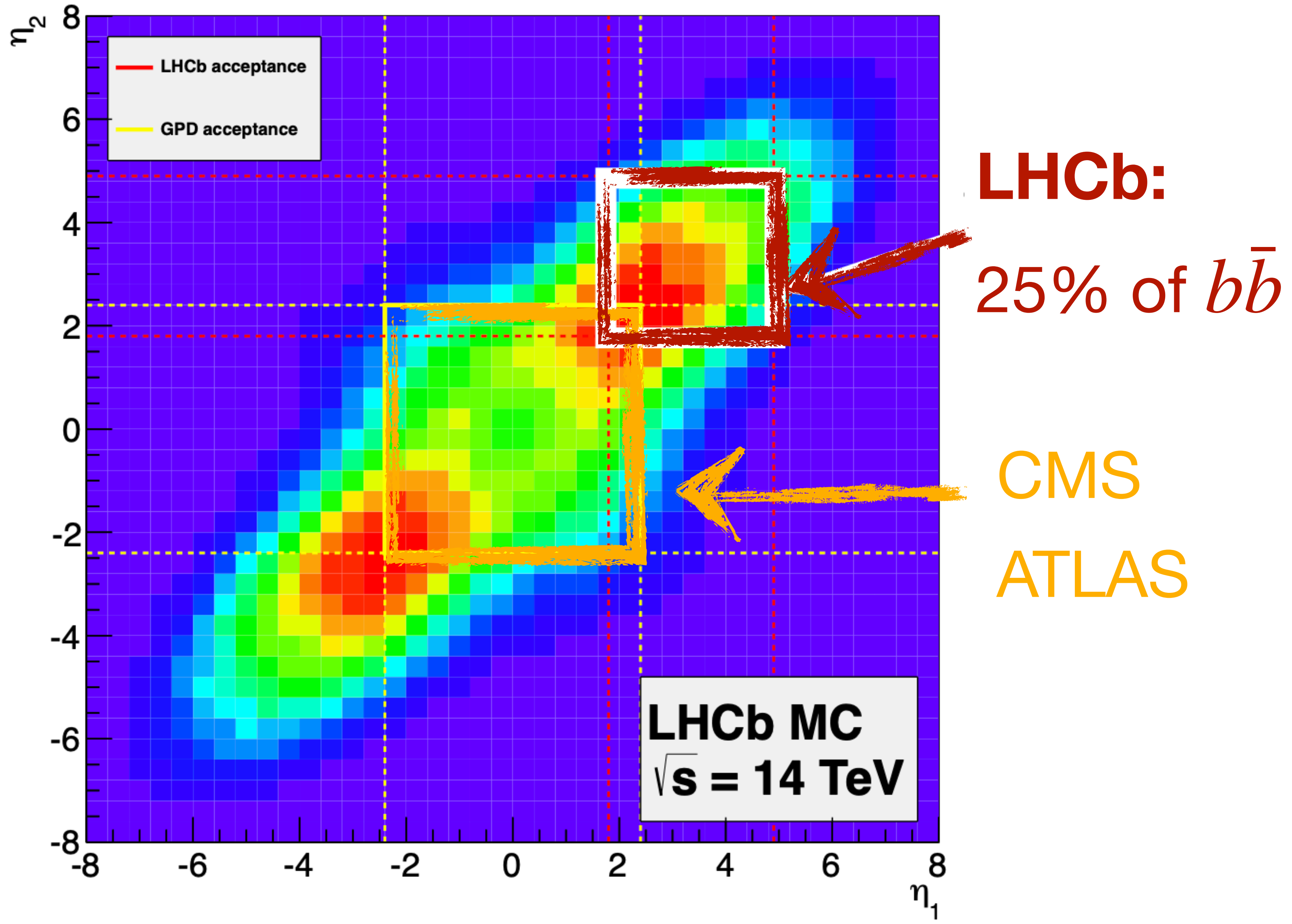
Some LHCb's results on Radiative decays:

- Measurement of CP-Violating and Mixing-Induced Observables in $B_s^0 \to \phi\gamma$ decays Phys. Rev. Lett. 123, 081802
- Measurement of the photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$ decays Phys. Rev. D105 (2022) L051104
- Search for the radiative $\Xi_b^- \to \Xi^-\gamma$ decay JHEP 01 (2022) 069

LHCb detector for b-hadron 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

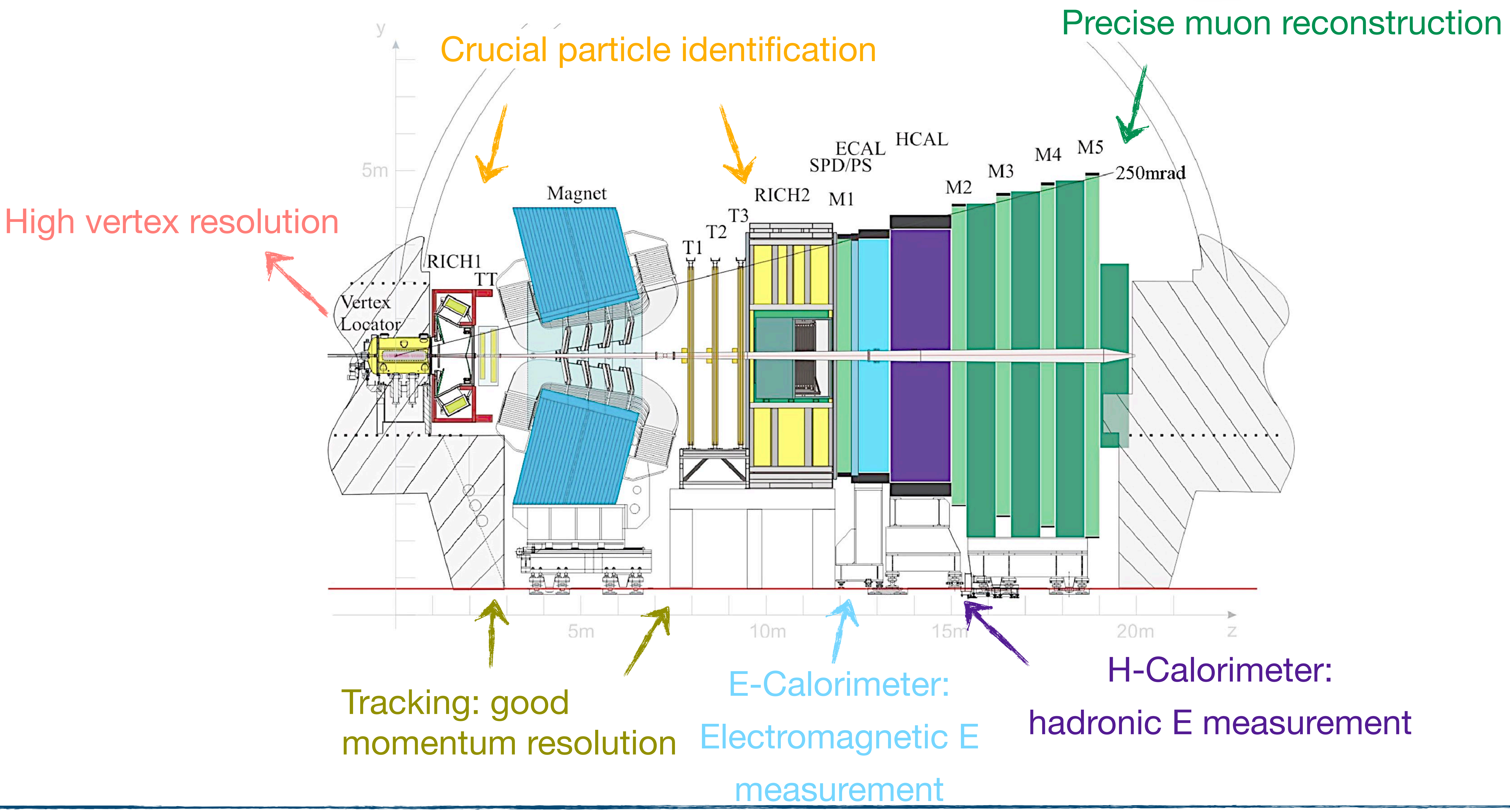
LHCb acceptance $2 < \eta < 5$



LHCb detector for b-hadron decays

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

The LHCb detector is very suitable to search for rare b-hadron decays.



$B_s^0 \to \mu^+\mu^-\gamma$

Rare and radiative !

JHEP **11** (2017) 184

Phys. Rev. D **97**, 053007 (2018)

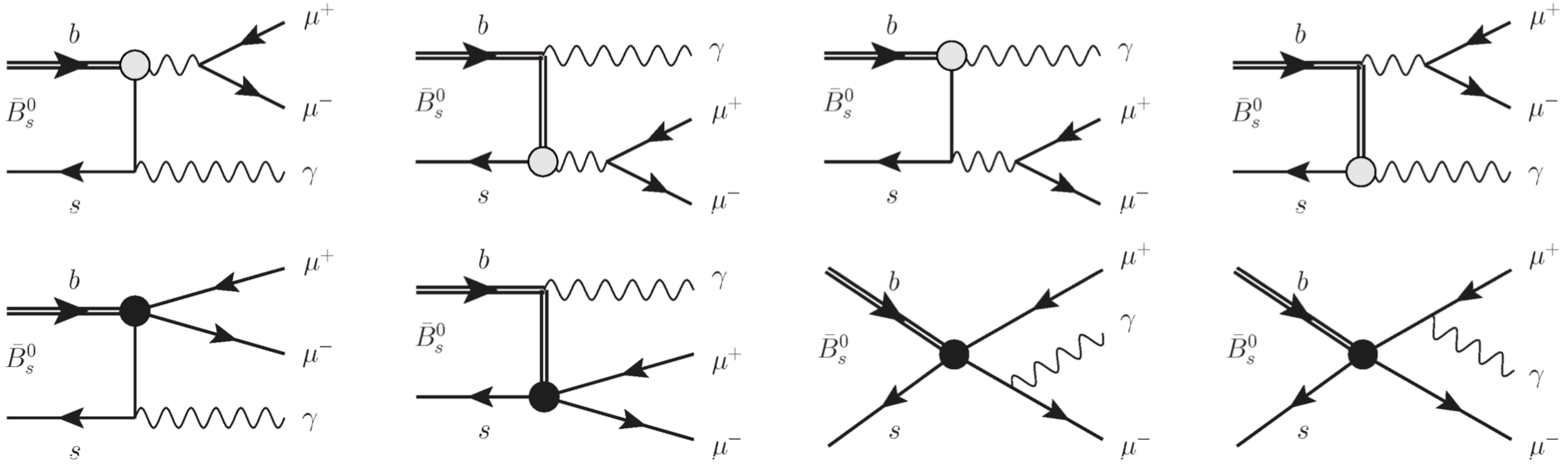
CERN-THESIS-2020-303

$B_s^0 \to \mu^+\mu^-\gamma$ vs. $B_s^0 \to \mu^+\mu^-$

- ➕ Sensitive to a larger set of Wilson coefficients (C_7, C_9, C_{10}) than $B_s^0 \to \mu^+\mu^-$ (C_{10}).
- ➕ The photon lifts the helicity suppression making $\mathscr{B}(B_s^0 \to \mu^+\mu^-) \sim \mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$.

$\mathcal{O}_7^{(\prime)}$

$\mathcal{O}_{9,10}^{(\prime)}$

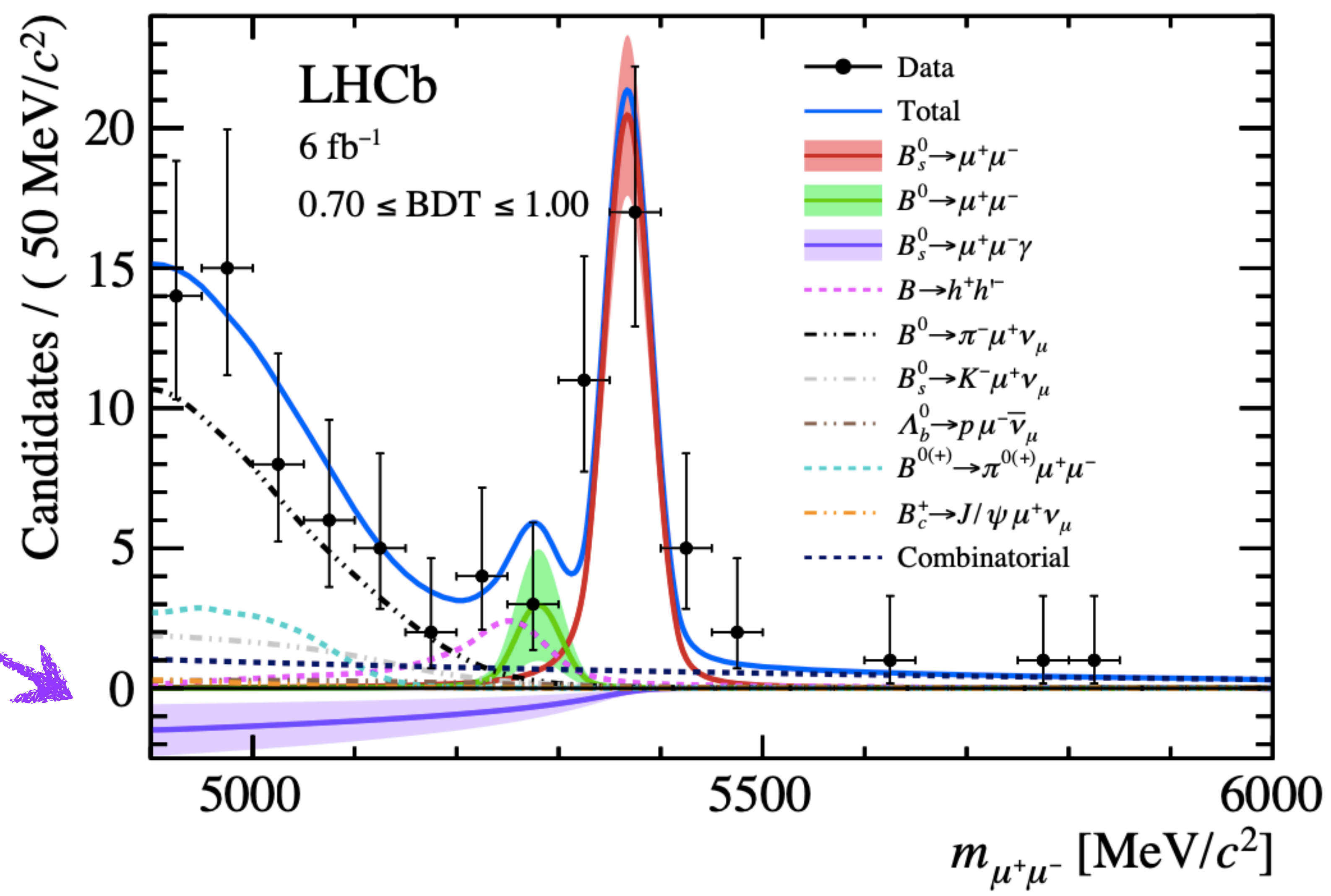


Bremsstrahlung

- ➖ Larger theoretical uncertainties due to the form factors of the $B_s^0 \to \gamma$ transition.
- ➖ Worse mass resolution due to the photon.

Methods

Phys. Rev. D **105** (2022) 012010



Two complementary methods

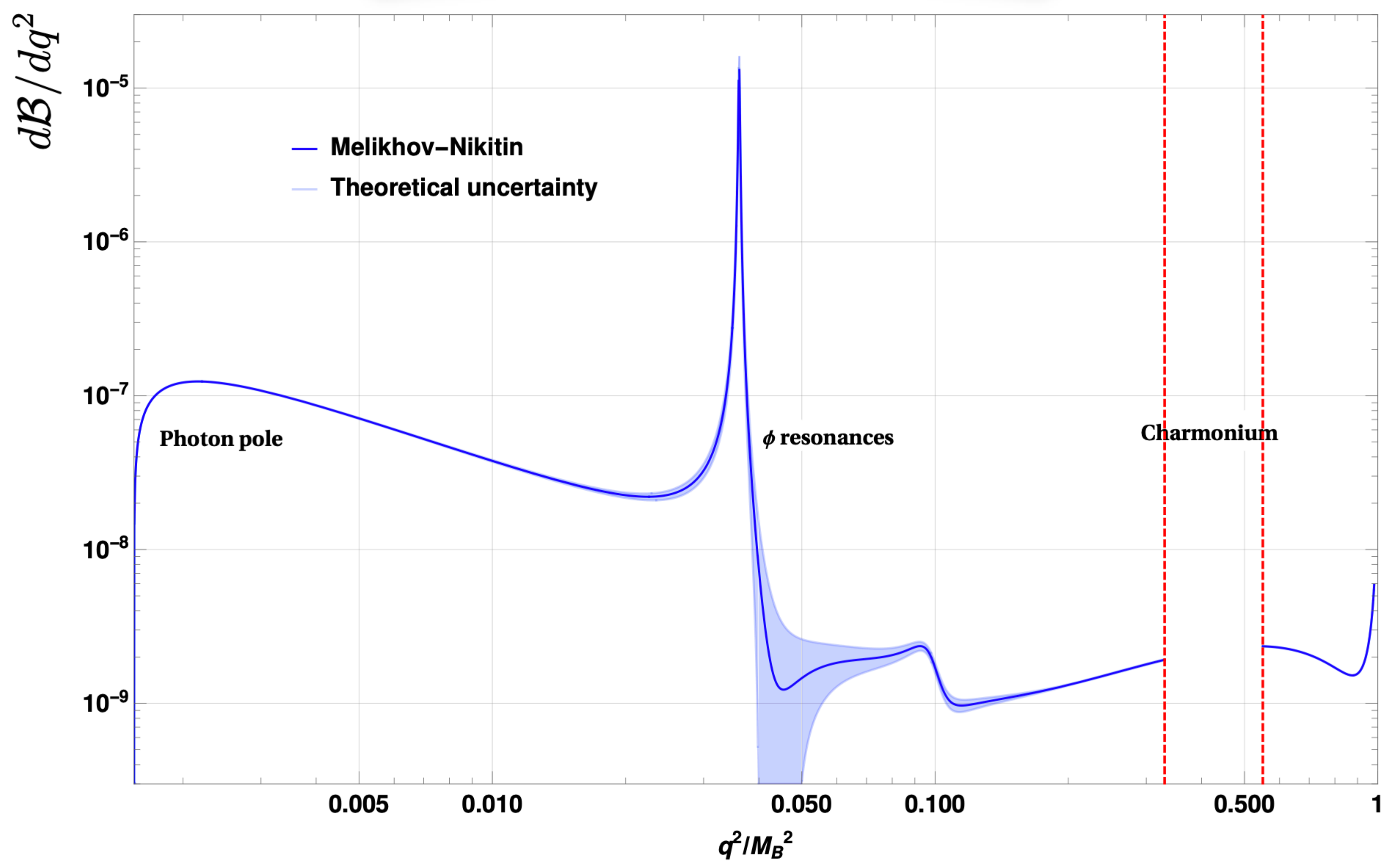
- **Indirect** no photon reconstruction, probing this decay as a background of the $B_s^0 \to \mu^+\mu^-$ process, only sensitive to high q² region:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 2.0 \times 10^{-9} \text{ at 95\% C.L. for } m(\mu\mu) > 4.9 \text{ GeV/c}^2$$

- **Direct** with photon reconstruction (presented today)

First time

Theoretical prediction



Phys. Rev. **D70** (2004) 114028

Low q² region

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < (8.4 \pm 1.3) \times 10^{-9}$$

$$q^2 \in [0.04, 8.64]\ GeV^2/c^4$$

High q² region

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < (8.90 \pm 0.98) \times 10^{-10}$$

$$q^2 \in [15.84, 28.27]\ GeV^2/c^4$$

$$q^2 = m^2(l^+l^-)$$

And first study at low q²

Strategy

$B_s^0 \to \mu^+\mu^-\gamma$

Data: proton-proton collisions recorded by LHCb during Run 2 (6 fb^{-1}).

Blind analysis: to keep the analysis unbiased, the data on the signal mass region is not seen until the full strategy is defined.

If signal is found… measure BR and compare with the SM predictions.

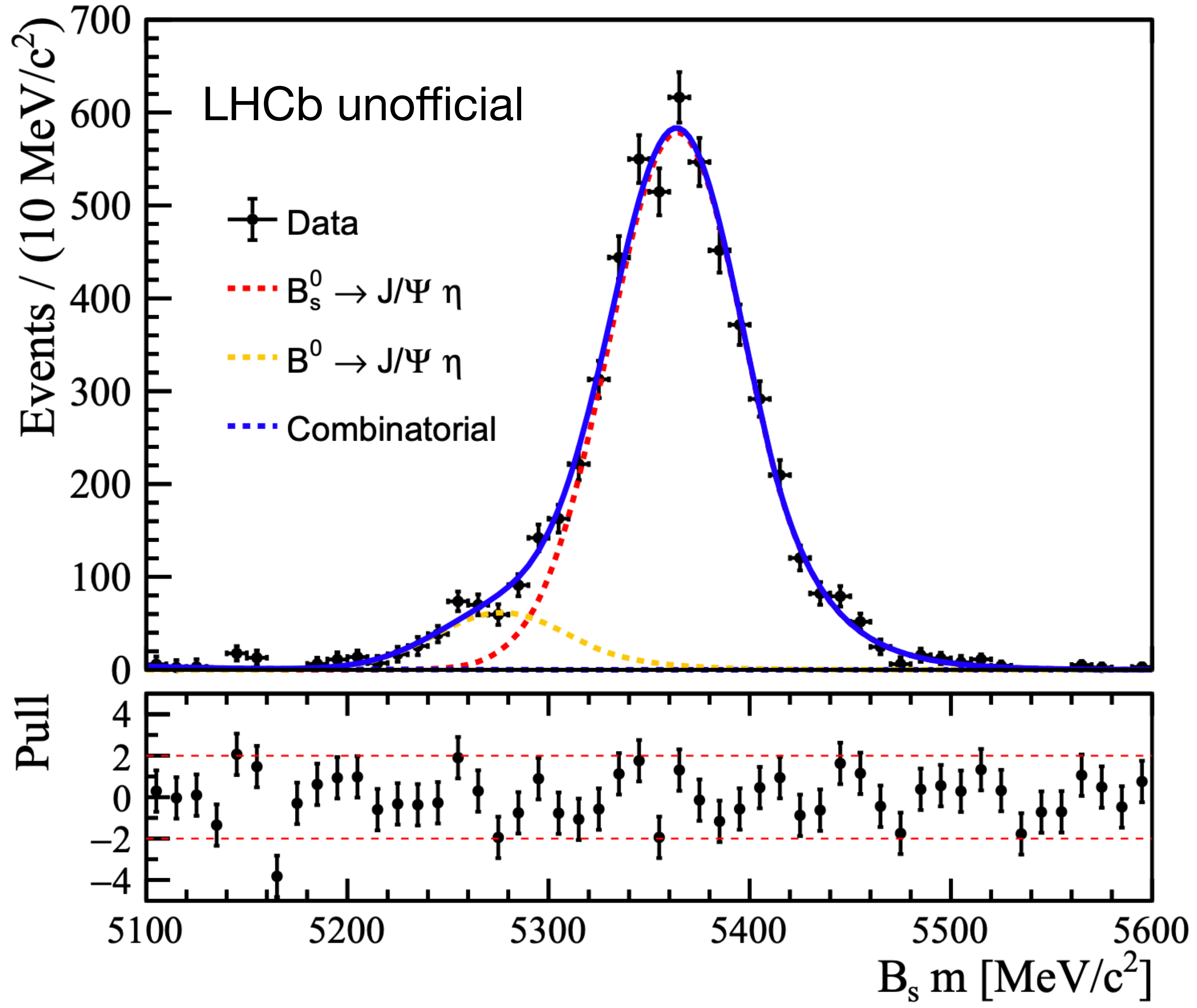
If no signal is seen… compute BR upper limit using CLs method.

Strategy

Normalisation channel

- A well know decay channel
- High statistics
- Good selection efficiency
- Similar final state to the signal: allows uncertainties cancelations
- Chosen channel:

$$B_s^0 \to J/\Psi(\to \mu\mu)\ \eta(\to \gamma\gamma)$$



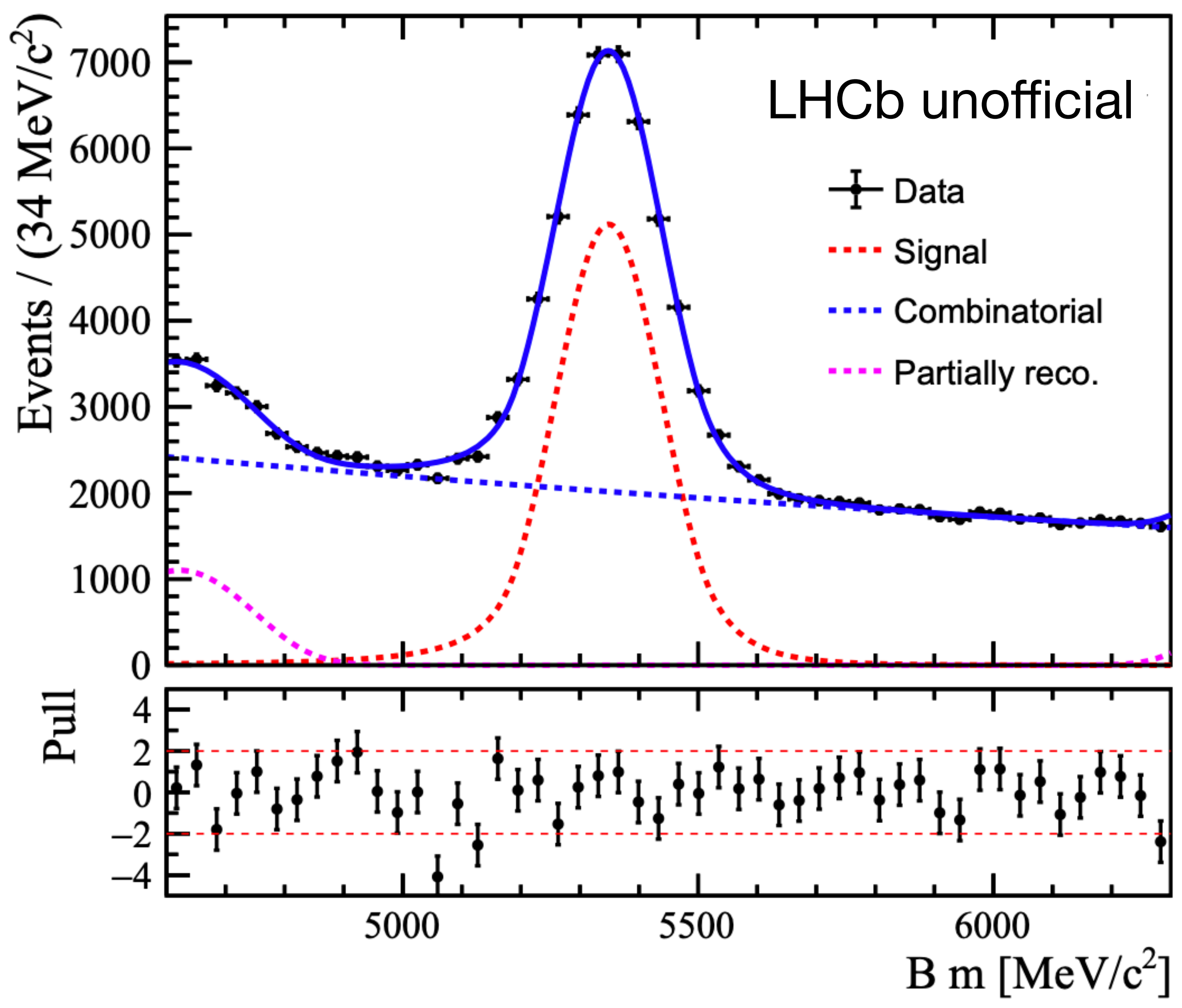
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) = \frac{\mathcal{B}_{\text{norm}}}{N_{\text{norm}}} \times f_{\text{norm}} \times N_{B_s^0 \to \mu\mu\gamma}$$

Strategy

Control channel

- To check the agreement between data and simulation.
- A well know decay channel.
- High statistics.
- Good selection efficiency.
- Similar kinematics: three body decay and low-p_T photons.
- Chosen channel:

$$B_s^0 \to \Phi(\to KK)\ \gamma$$



$B_s^0 \to \mu^+\mu^-\gamma$

Strategy

q² bins

$q^2 = m^2(l^+l^-)$

- **Bin I:** low-q²
- **Bin II:** middle-q²
- **Bin III:** high-q²

Phys. Rev. **D70** (2004) 114028

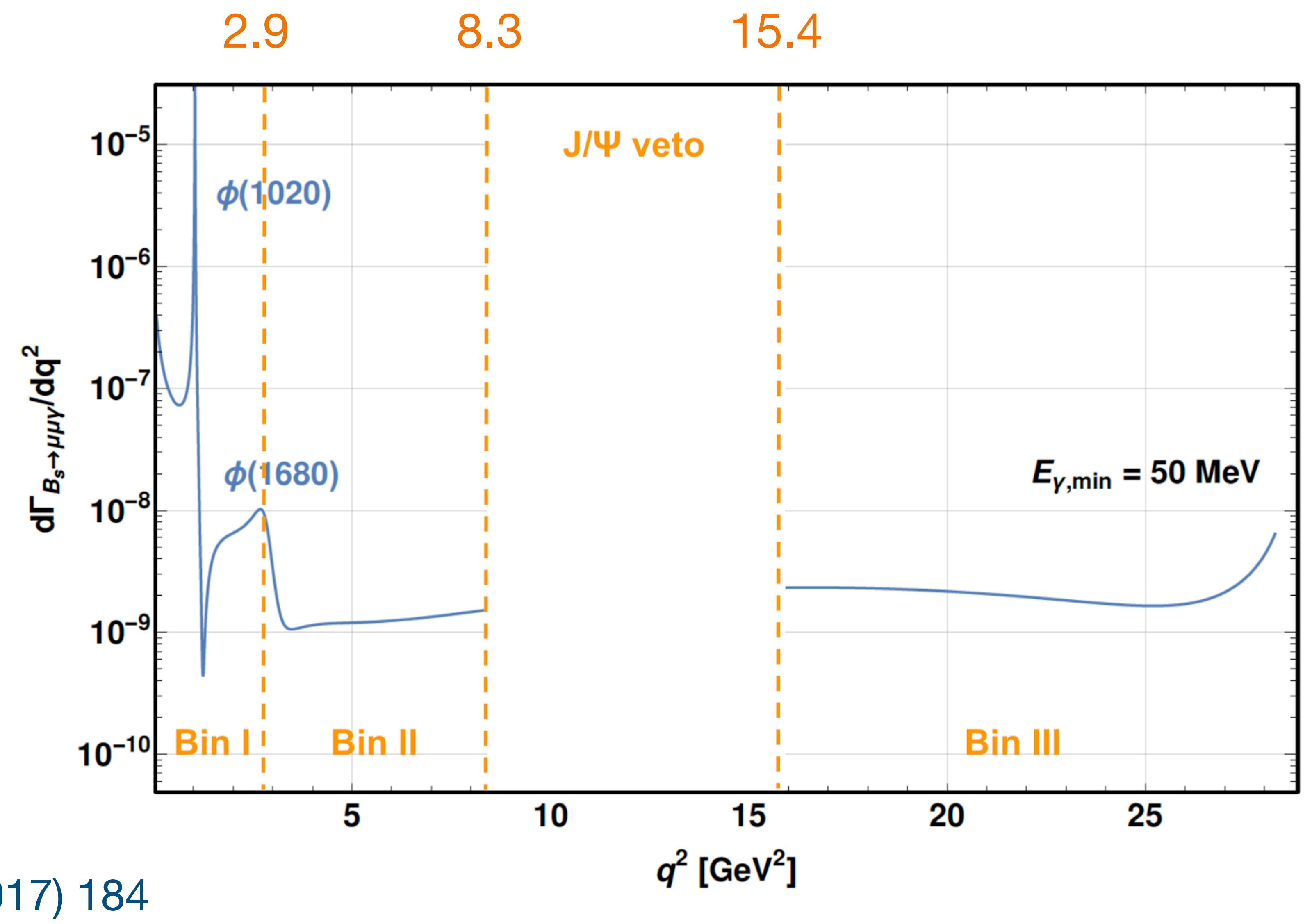
Bin	I	II	III
$10^{10} \times \mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$	82 ± 15	2.54 ± 0.34	9.1 ± 1.1
Fraction of $B_s^0 \to \mu^+\mu^-\gamma$ events	87%	2.7%	9.8%

Bin I is also studied with a veto on the ϕ resonance:

- **Bin ϕ-veto:** low-q² without ϕ

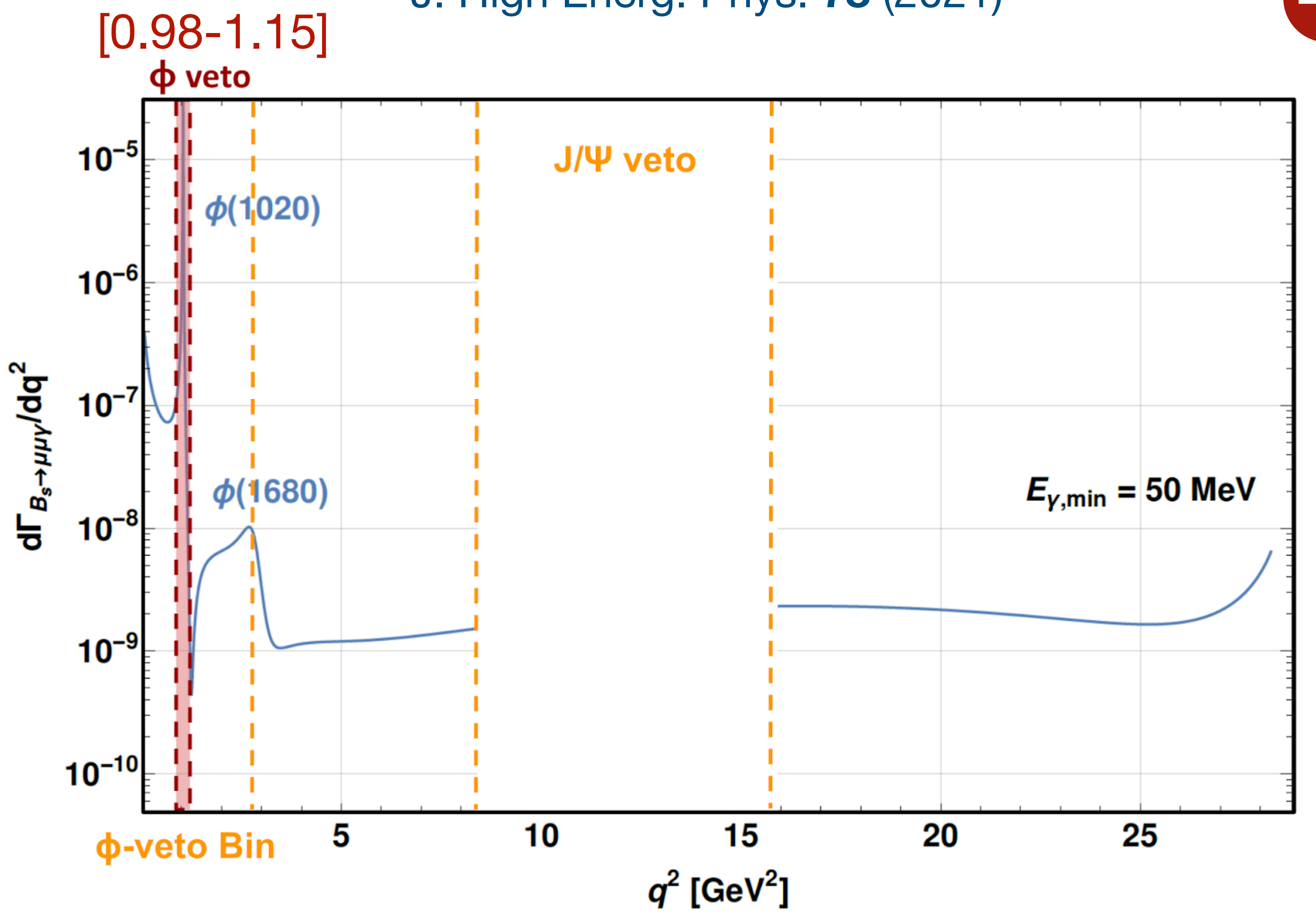
More theoretical interest

Less statistics



JHEP **11** (2017) 184

J. High Energ. Phys. **78** (2021)

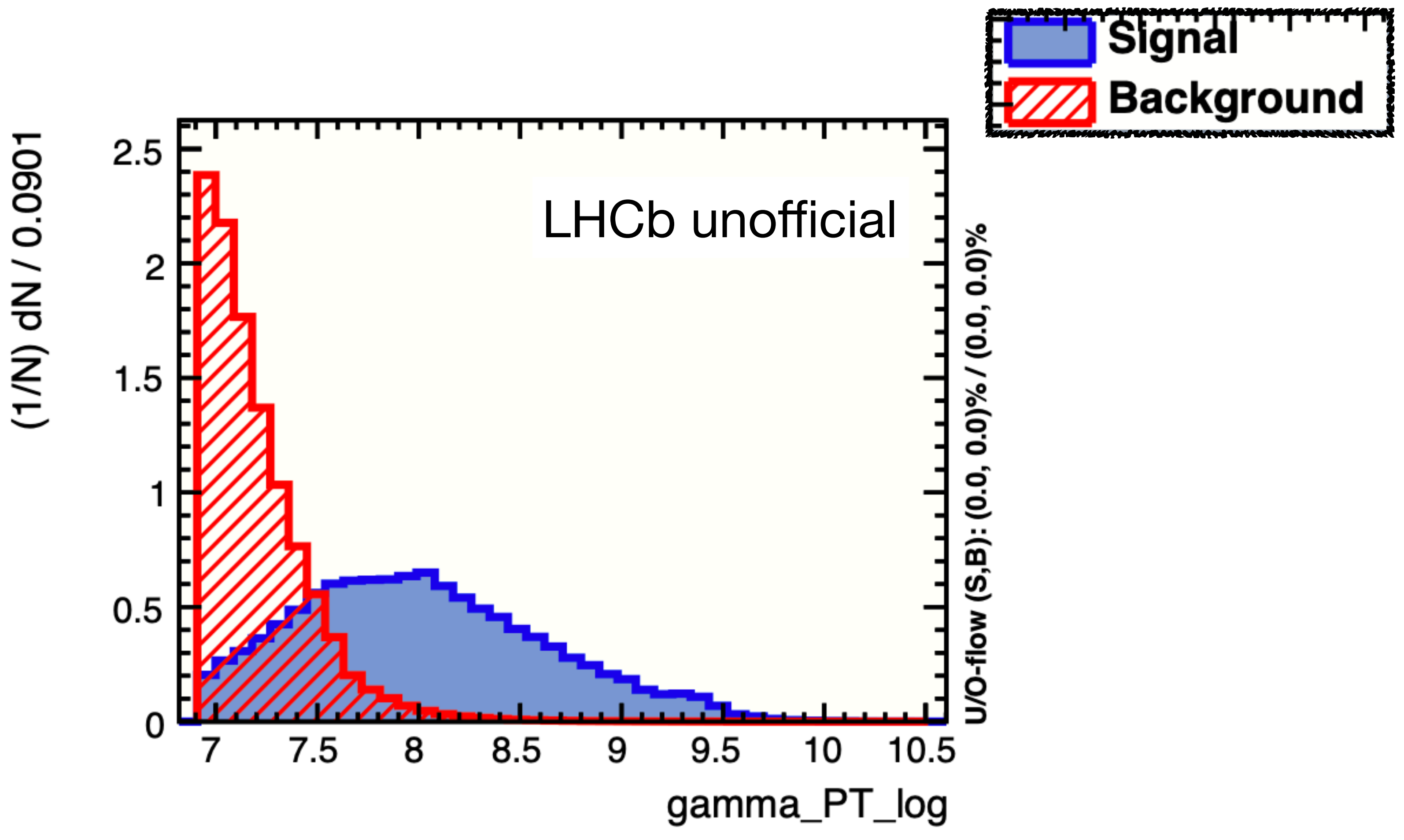


Selection

First BDT

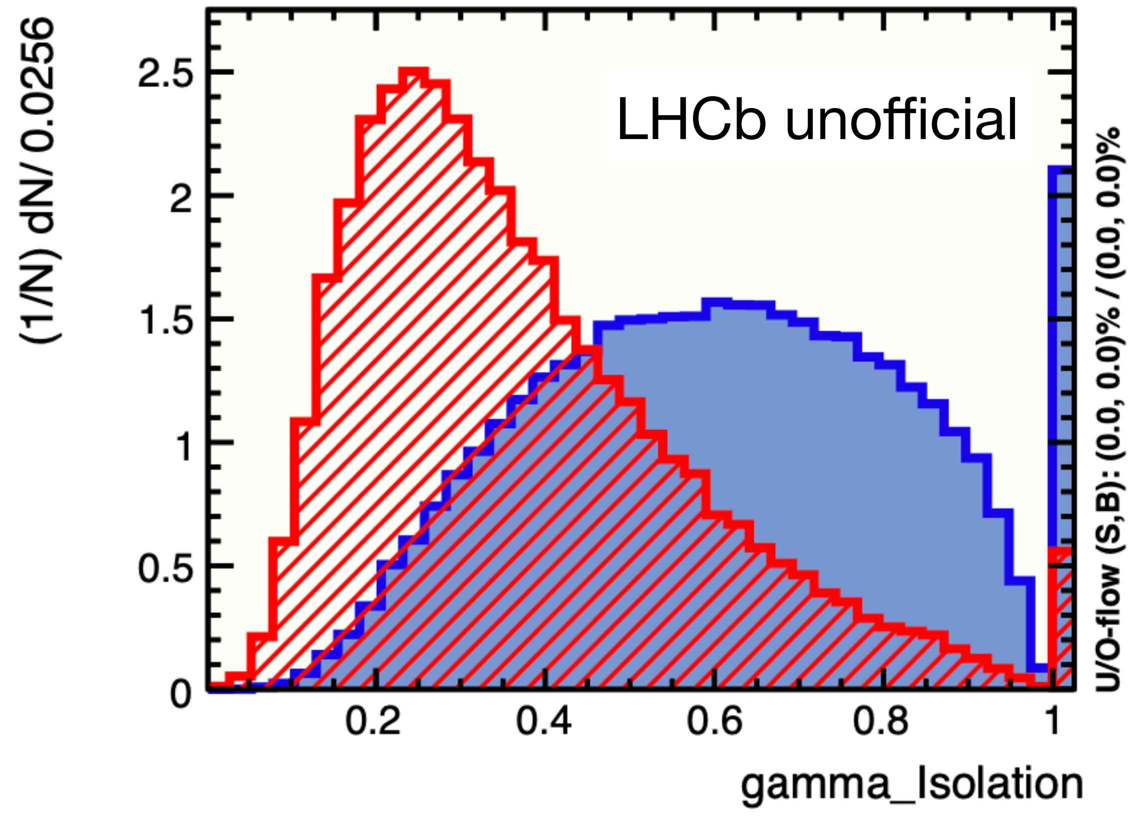
Aim: reduce the combinatorial background using geometrical variables.

Trained in data mass side-bands and background, and signal simulation.



Second BDT

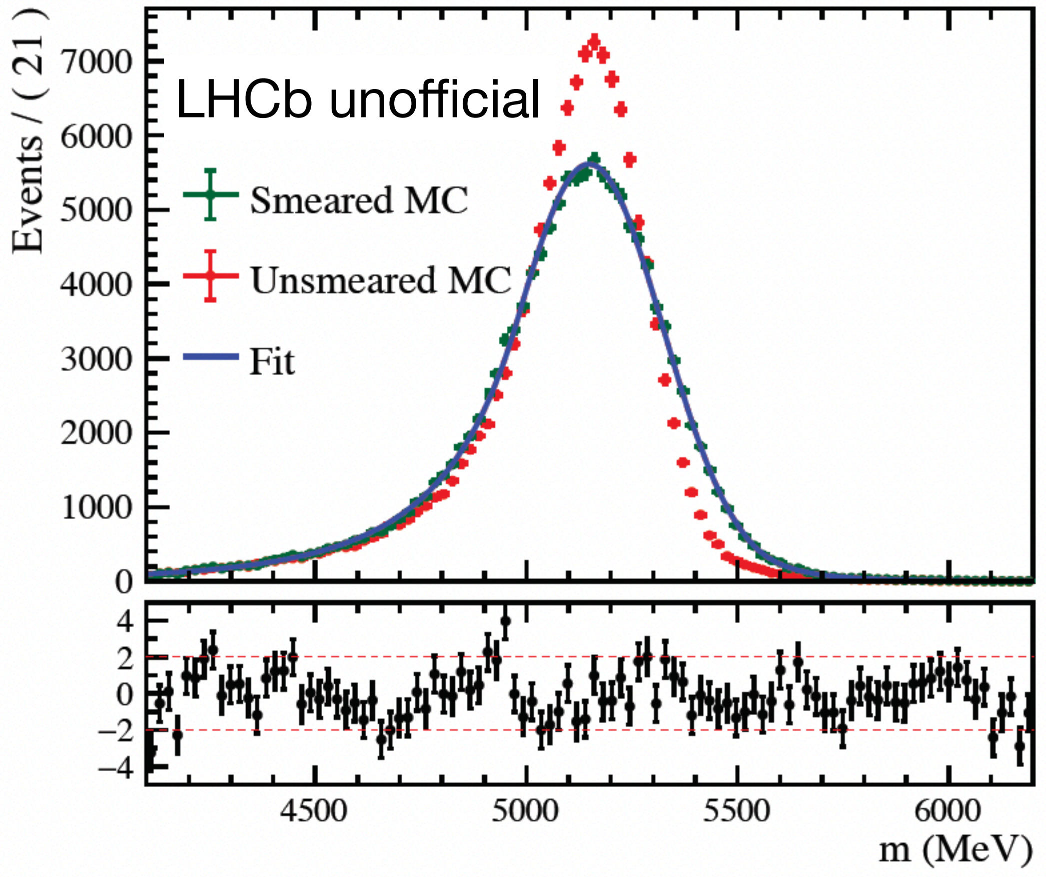
Aim: reduce other backgrounds, exploiting the fact that the signal objects are isolated.



And many others...

Background

Double mis-ID



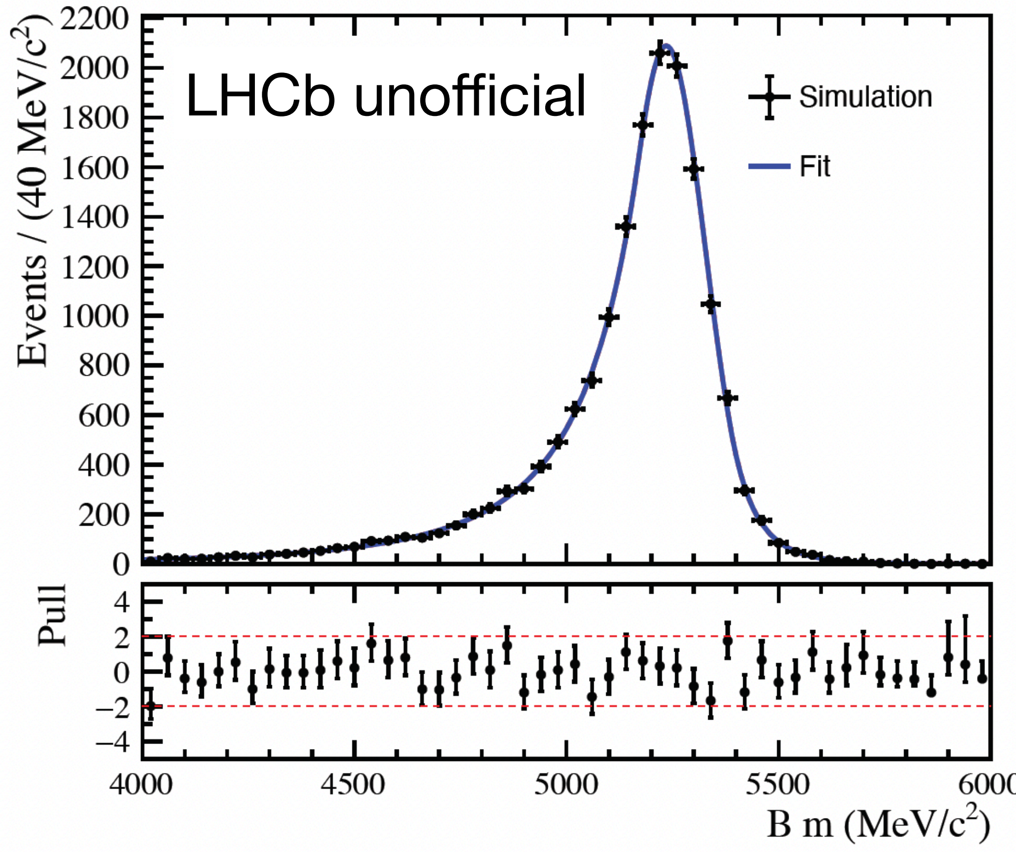
Double misidentification of kaons or pions as muons. Such as:

$$B_s^0 \to \phi(\to KK)\gamma$$
$$B^0 \to K^{*0}(\to \pi K)\gamma$$

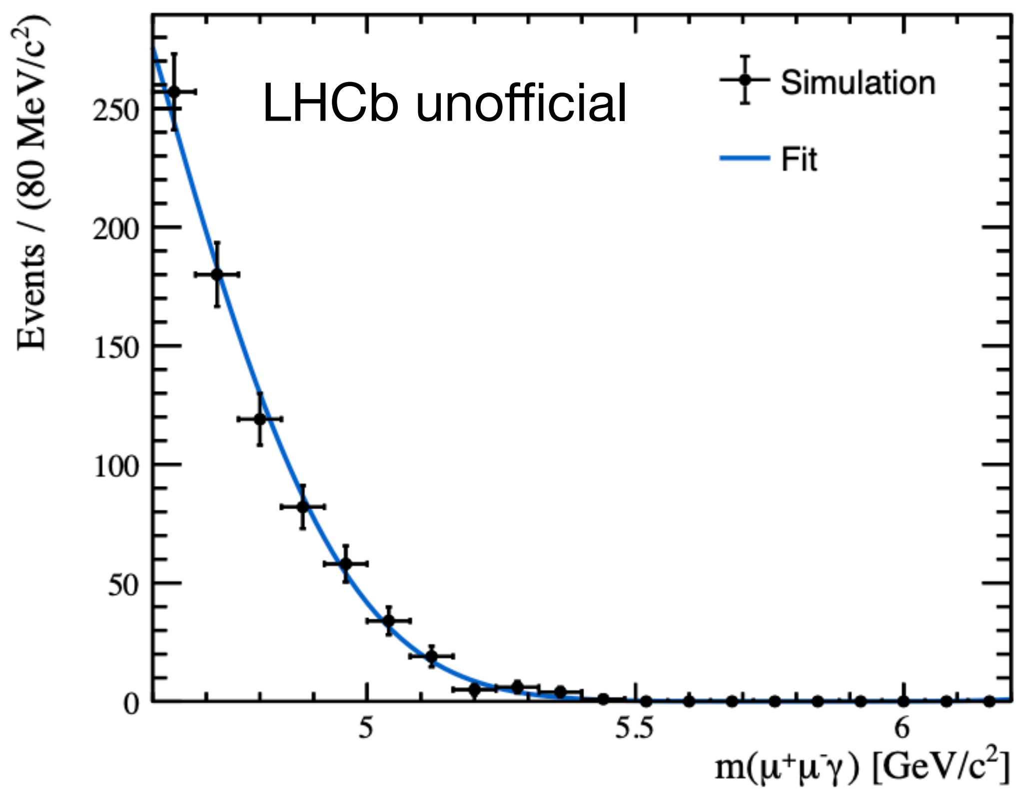
$B^0 \to \mu\mu\pi^0$

If one γ is not reconstructed or both γ's are merge and reconstructed in one.

Low contribution but peaking very close to the signal.



Partially reconstructed

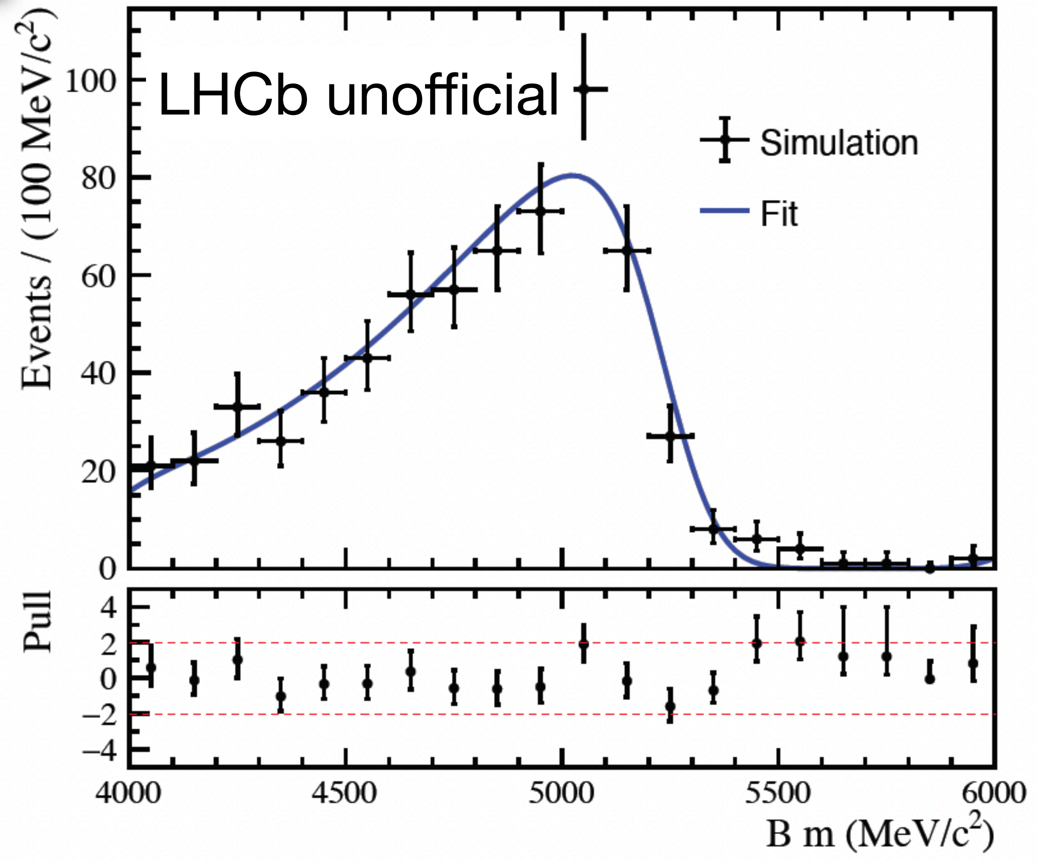


When one particle of the final state is not reconstructed (neutrinos, or by an inefficiency).

A broad peak outside the mass region is expected.

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

Main peaking background in the signal region, but broader than $B^0 \to \mu\mu\pi^0$.



Other backgrounds were studied and estimated negligible

Status

All the ingredients are ready to look for $B_s^0 \to \mu^+\mu^-\gamma$!

Done:

- ☑ Define the selection strategy
- ☑ Train BDTs and optimise cuts
- ☑ Model the backgrounds
- ☑ Calculate the normalisation factor →
- ☑ Mass fits in the sidebands (blinded)
- ☑ Systematics studies

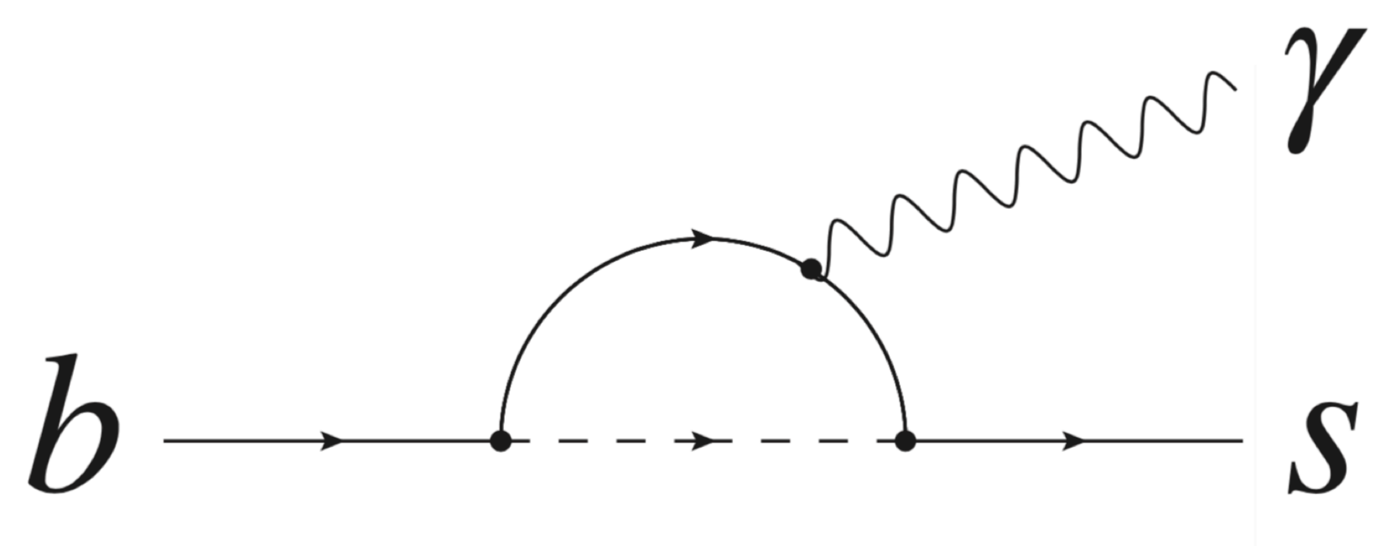
$$f_{\text{norm}} = \frac{\varepsilon^{\text{Acc}}_{\text{Norm.}}}{\varepsilon^{\text{Acc}}_{\text{Signal}}} \times \frac{\varepsilon^{\text{Strip \& Reco}}_{\text{Norm.}}}{\varepsilon^{\text{Strip \& Reco}}_{\text{Signal}}} \times \frac{\varepsilon^{\text{Ch. PID}}_{\text{Norm.}}}{\varepsilon^{\text{Ch. PID}}_{\text{Signal}}} \times \frac{\varepsilon^{\text{N. PID}}_{\text{Norm.}}}{\varepsilon^{\text{N. PID}}_{\text{Signal}}} \times \frac{\varepsilon^{\text{MLPS}}_{\text{Norm.}}}{\varepsilon^{\text{MLPS}}_{\text{Signal}}} \times \frac{\varepsilon^{\text{Trigger}}_{\text{Norm.}}}{\varepsilon^{\text{Trigger}}_{\text{Signal}}} \times \frac{\varepsilon^{\text{MLP}}_{\text{Norm.}}}{\varepsilon^{\text{MLP}}_{\text{Signal}}}$$

Ongoing:

- ☐ Unblinding
- ☐ Measure/Set upper limits of the branching fraction in the different q^2 regions.

Results very soon…

Conclusions



- **Rare** b-hadron decays are excellent opportunities to check the SM and look for NP.
- **Radiative** b-hadron decays provides sensitivity to other NP scenarios, q^2 phase space, observables, etc.
- **LHCb** is the optimal detector to study b-hadron decays.
- The first direct, and first low q^2 search, of the $B_s^0 \to \mu^+\mu^-\gamma$ decay is ongoing.
- Rare b-hadron decays are dominated by statistical uncertainties. The LHC **Run 3** is providing more statistics, and the **LHCb upgrade**, will help us to push the limits of the SM.

Exciting results on the horizon…