Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay at LHCb

INTENSITY frontier GDR-InF

Workshop on radiative leptonic B decays
Marseille
29/02/2024

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agence nationale de la recherche
AU SERVICE DE LA SCIENCE

Rare and radiative *b*-hadron decays

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:

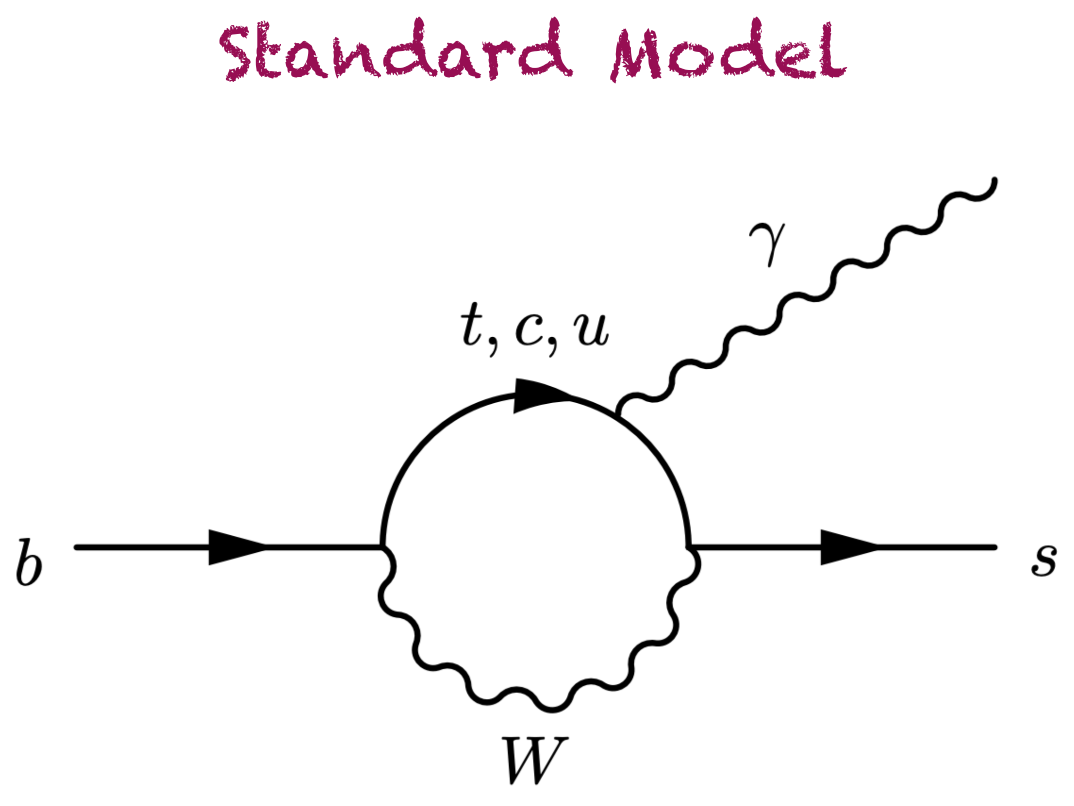
- Possibility of testing the presence of right-handed photons (highly suppressed in the SM).

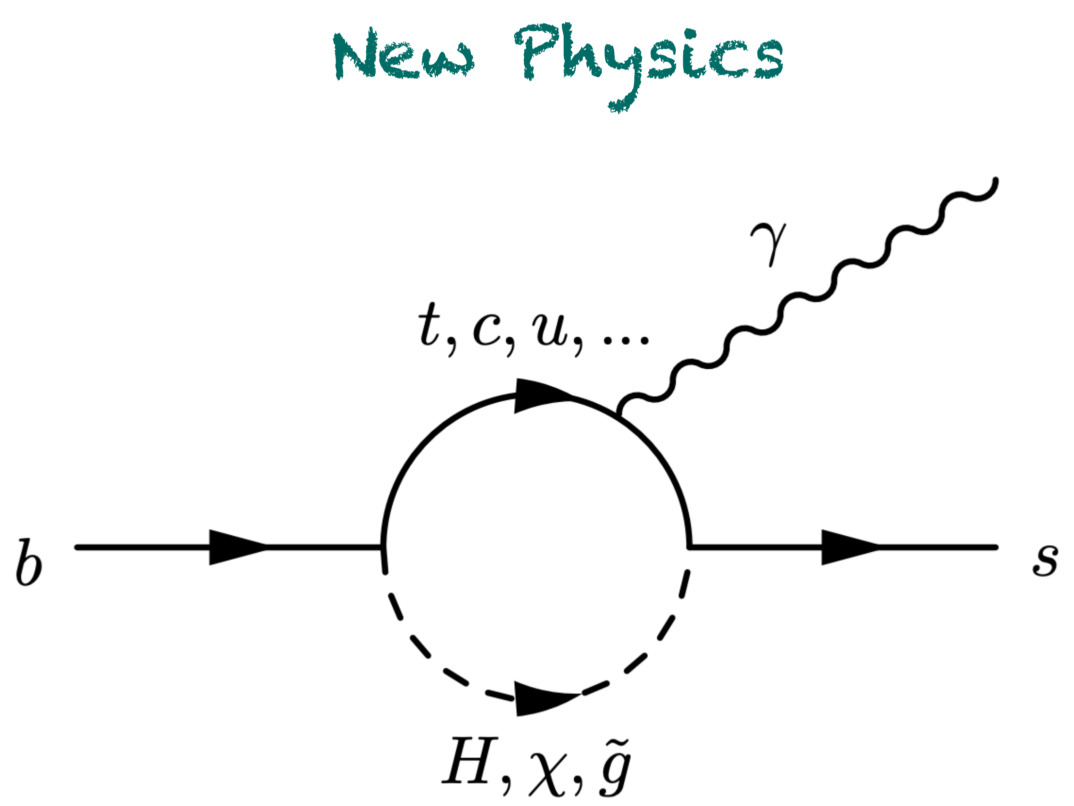
Rare = highly **suppressed** in SM:

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

Signal different from SM?

Possible new physics!





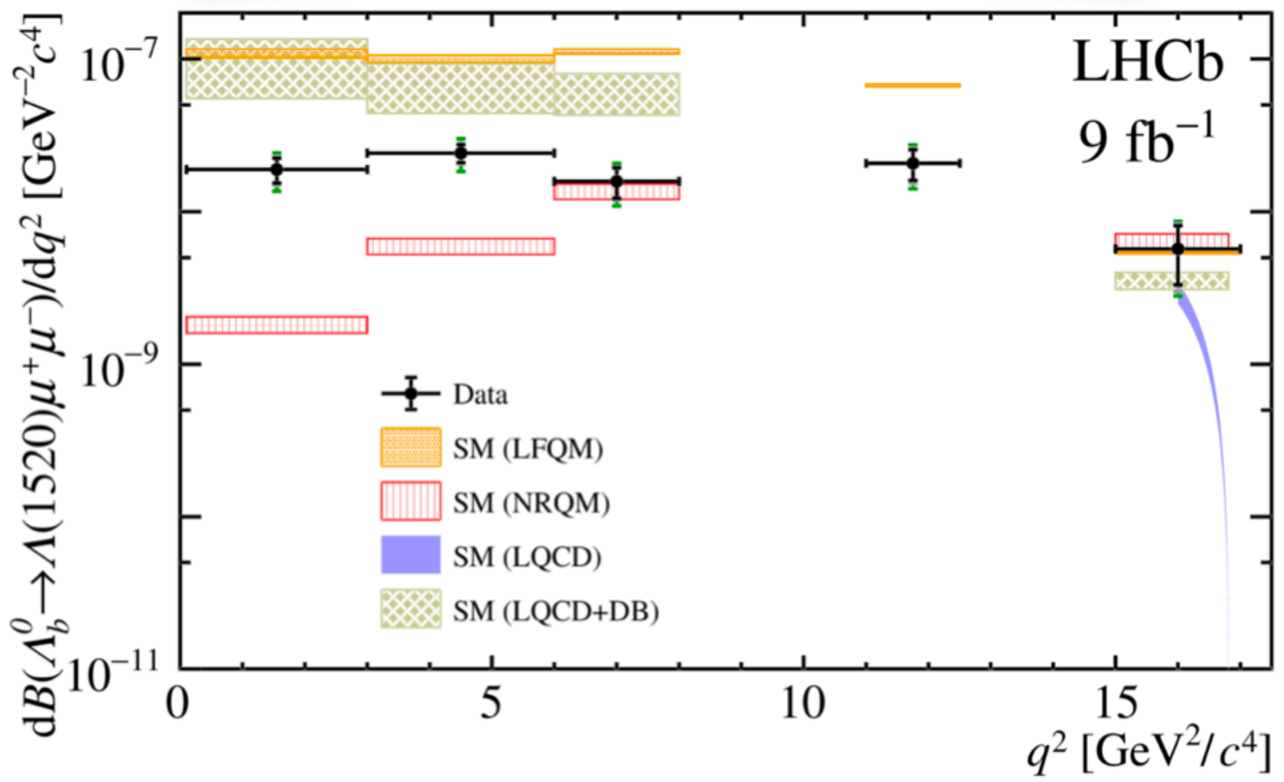
Some LHCb's results on radiative decays:

- 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 [JHEP01(2022)069]

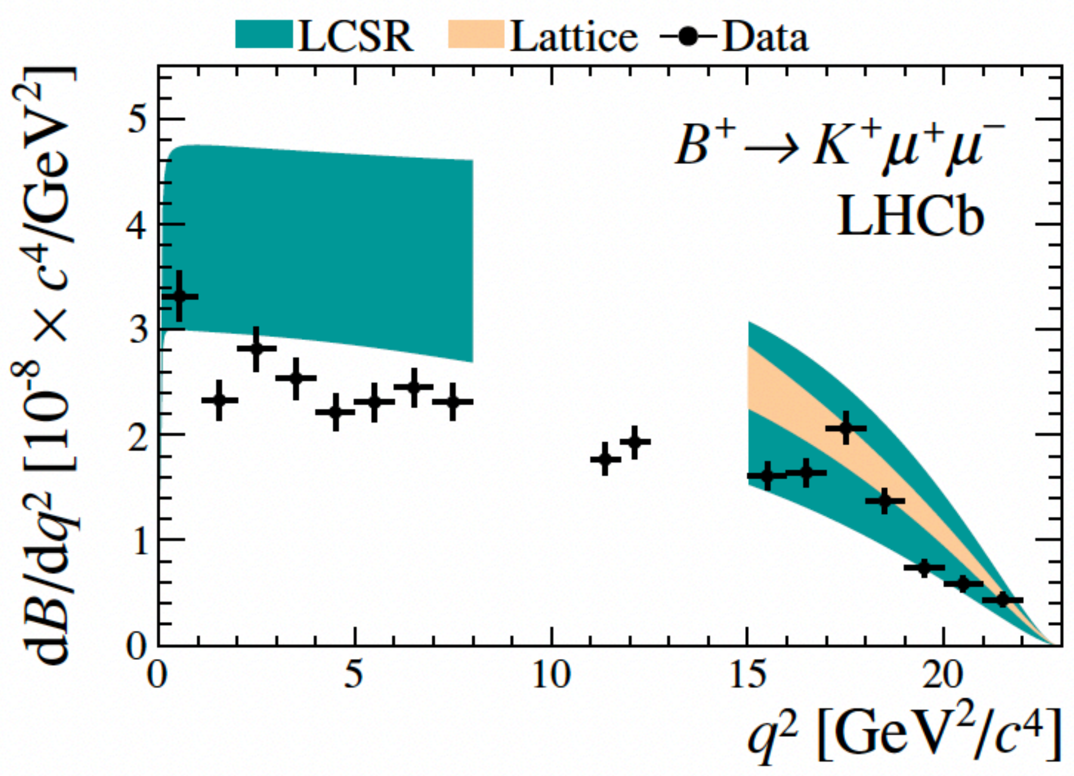
Differential Branching Fractions

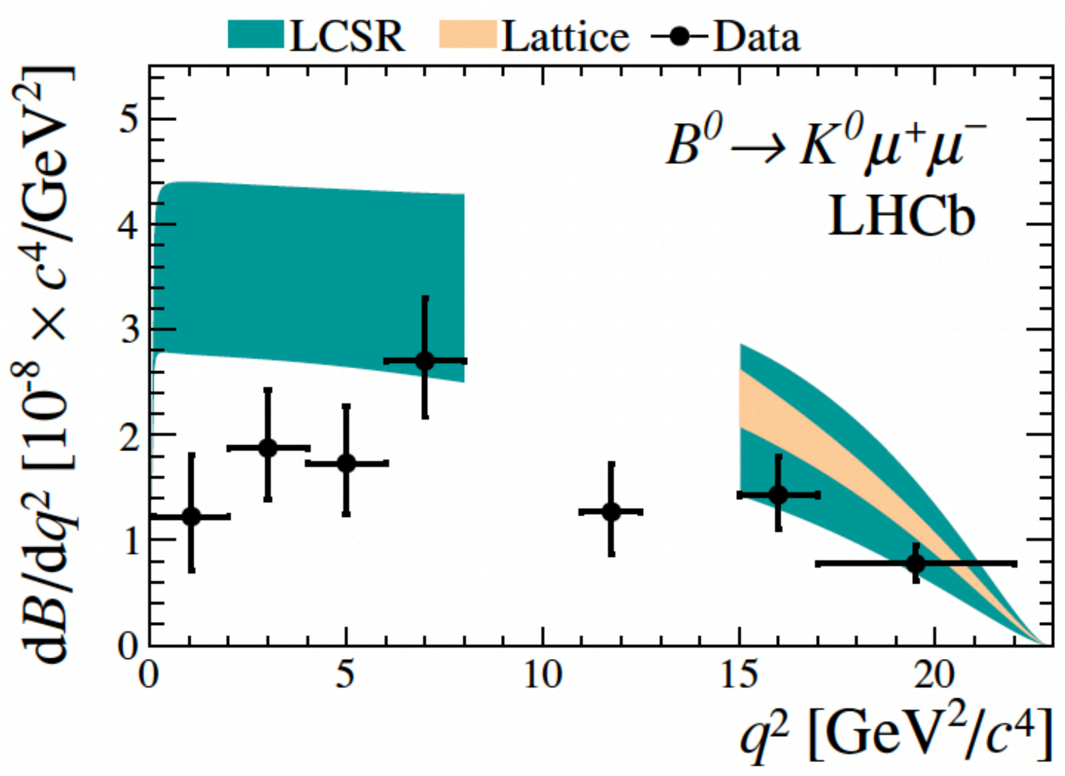
- SM predictions. Large hadronic form factors uncertainties (20-30%).
- Data. LHCb results.

Phys.Rev.Lett.**131**(2023)151801

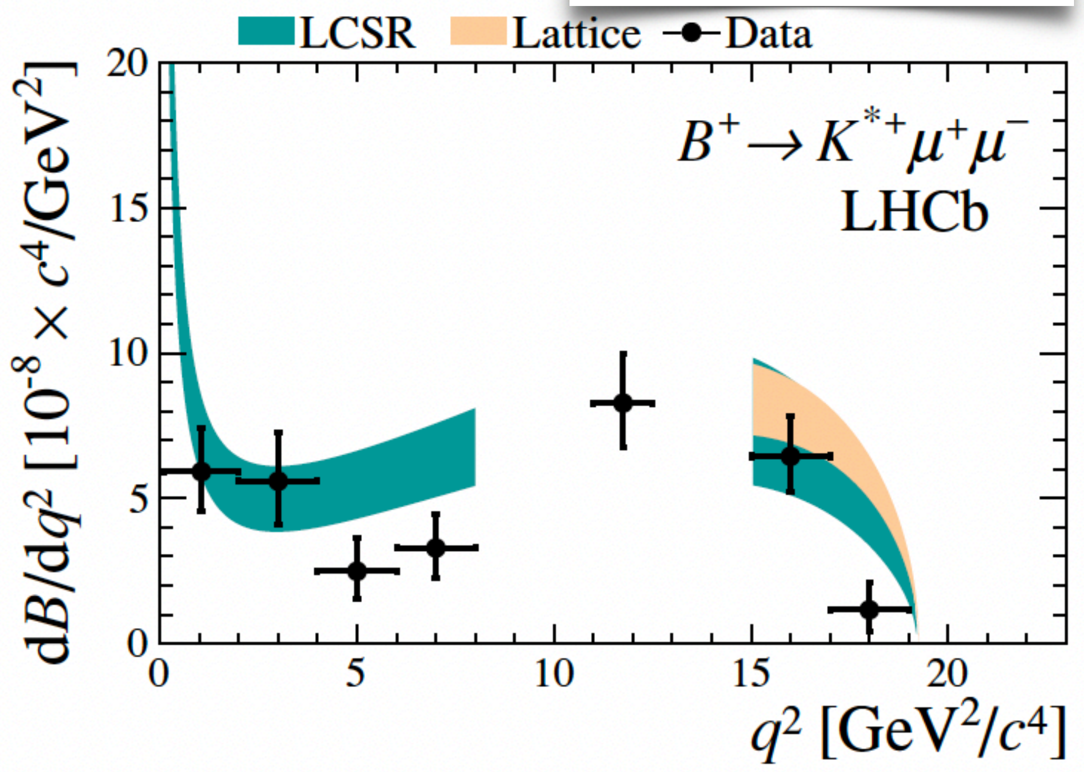


$q^2 \equiv m^2(\mu^+\mu^-)$

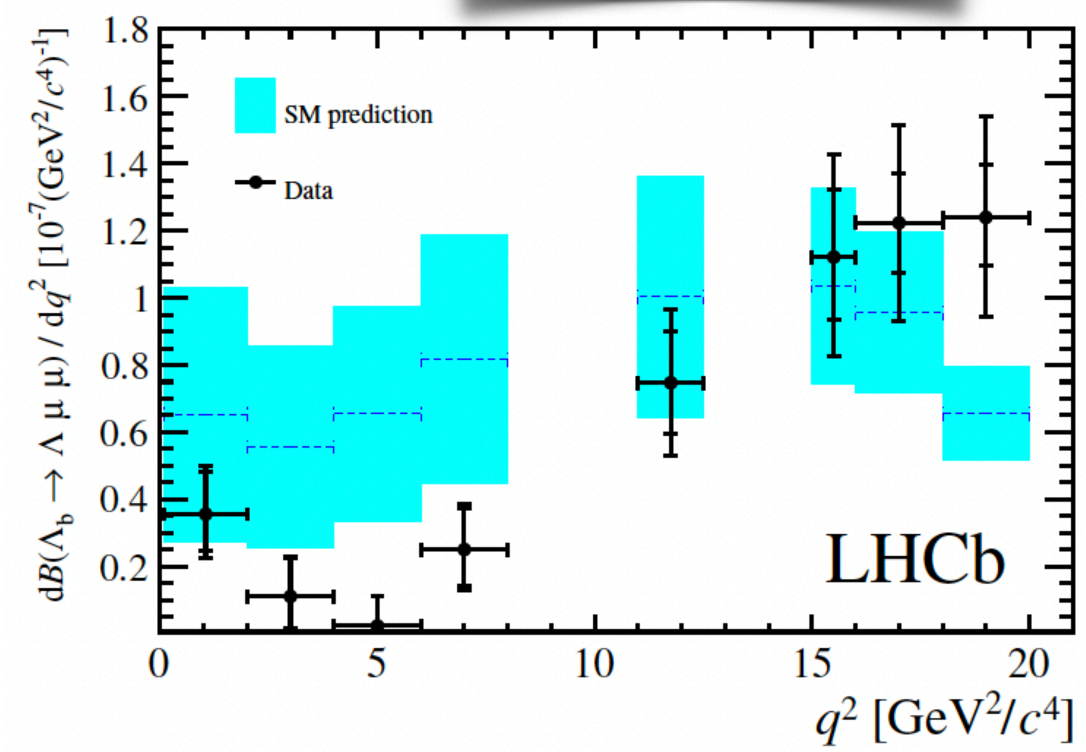




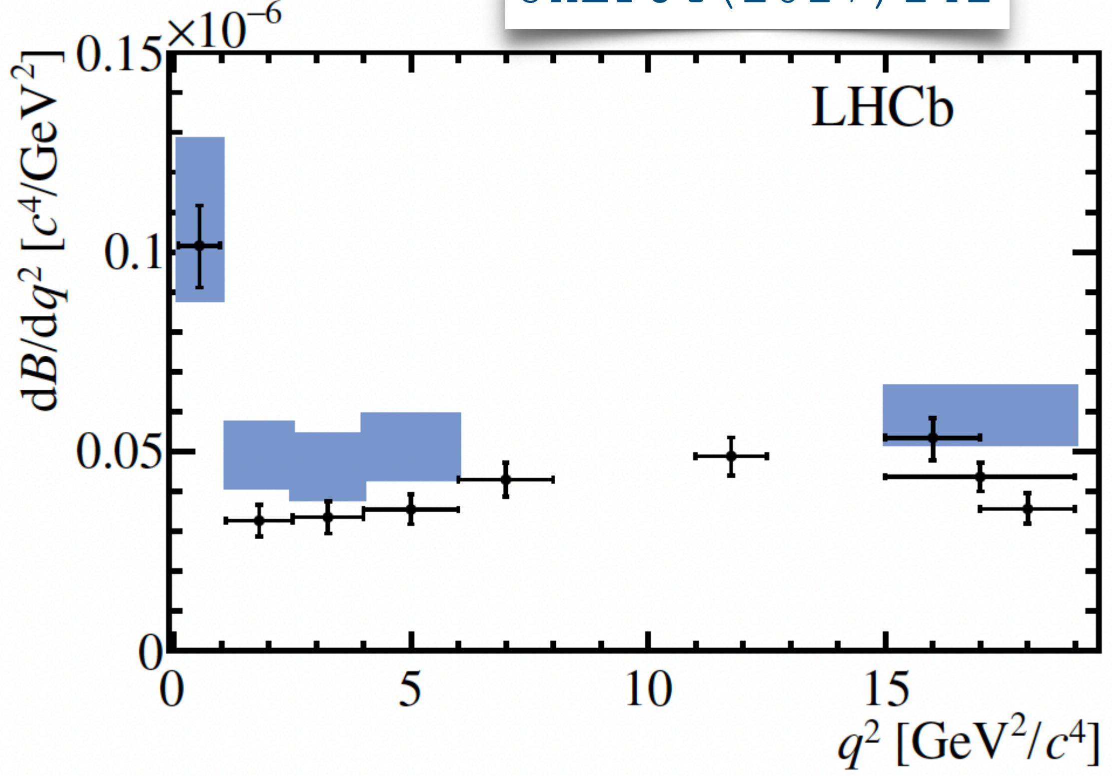
JHEP**06**(2014)133



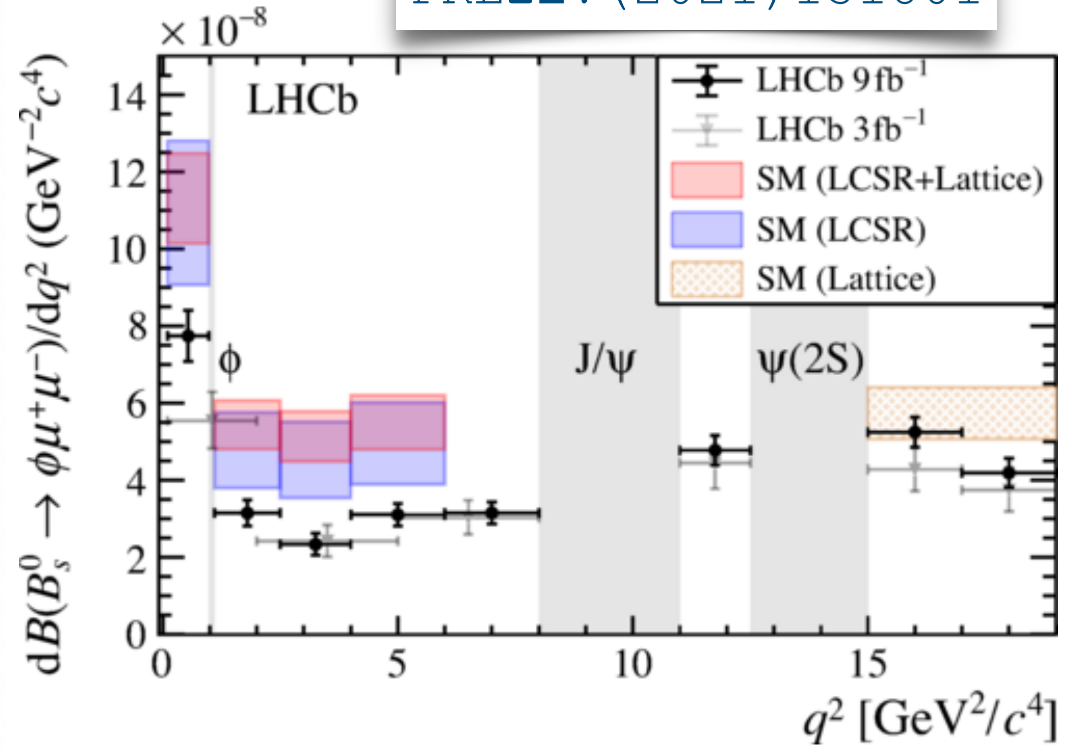
JHEP**06**(2015)115



JHEP**04**(2017)142



PRL**127**(2021)151801



Tensions between experimental result and SM predictions.

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

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

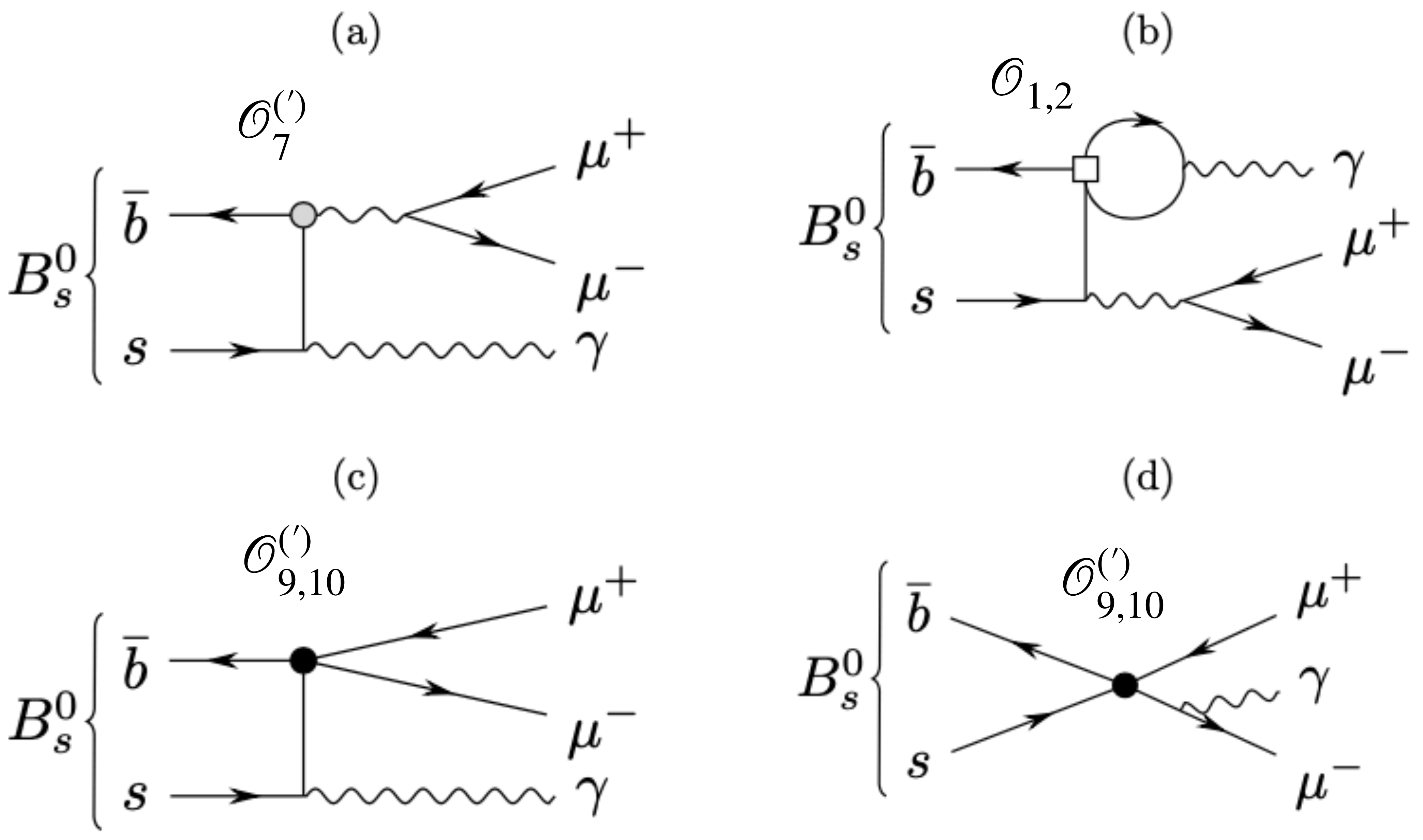
- (+) $B_s^0 \to \mu^+\mu^-\gamma$ decay is sensitive to a larger set of Wilson coefficients ($\mathcal{C}_7$, $\mathcal{C}_9$, $\mathcal{C}_{10}$) than $B_s^0 \to \mu^+\mu^-$ ($\mathcal{C}_{10}$).
  The photon lifts the helicity suppression making $\mathscr{B}(B_s^0 \to \mu^+\mu^-) \sim \mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$.
- (−) Larger theoretical uncertainties due to the form factors of the $B_s^0 \to \gamma$ transition.
  Worse mass resolution due to the photon reconstruction.

Phys.Rev.**D97**,053007(2018)

Physics Letters **B 521** (2001)

JHEP **12** (2021) 008

JHEP **11** (2017) 184

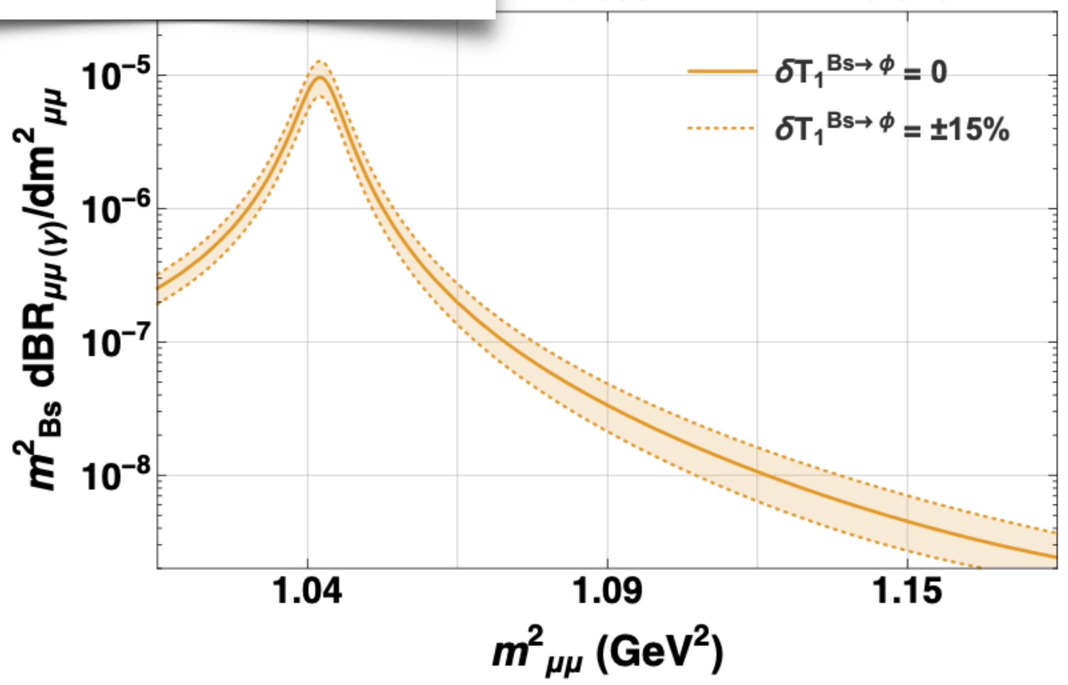


- ○ Electromagnetic-dipole operators
- ● Four-fermion operators
- □ Any four-quark operator

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

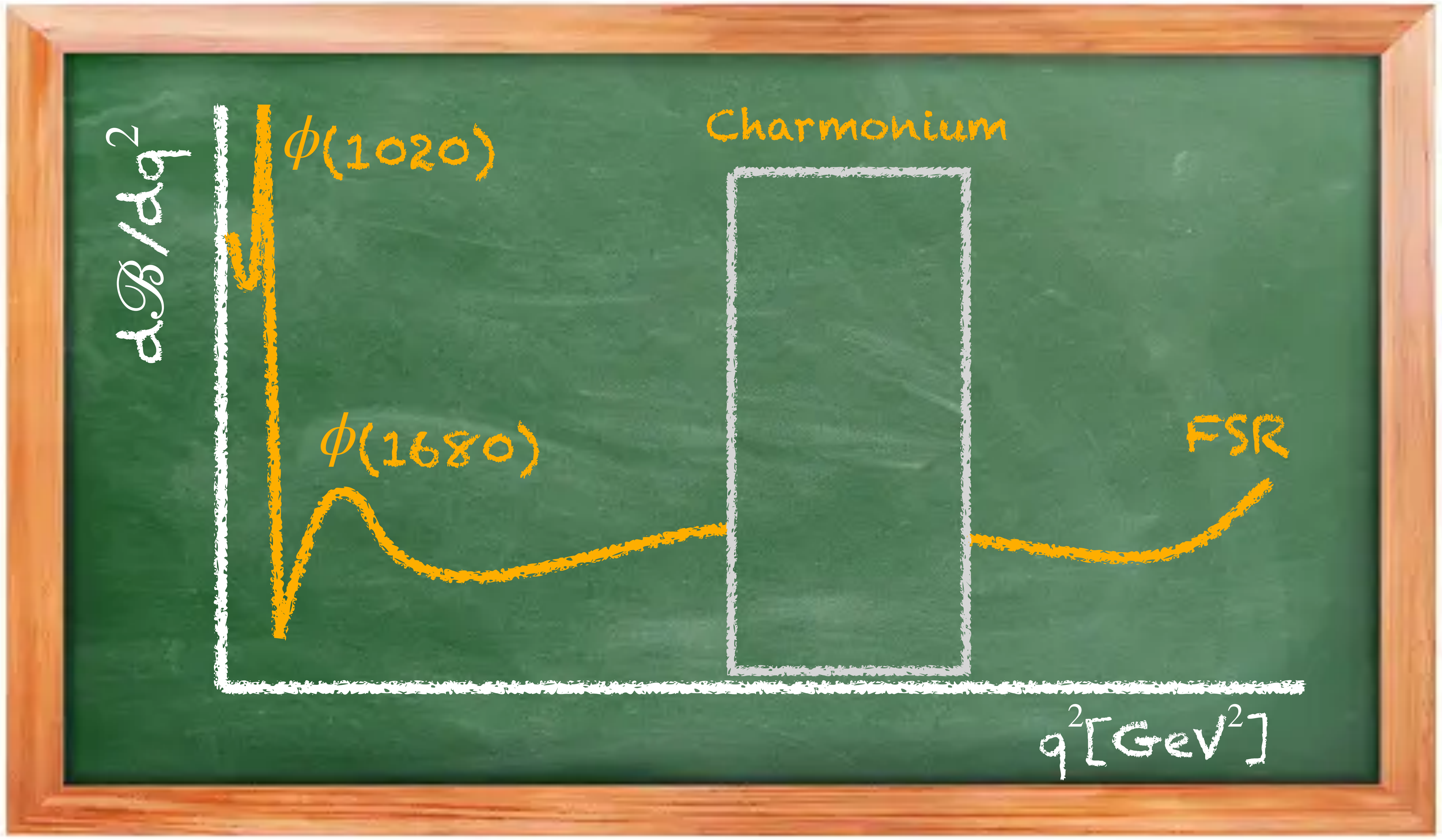
Low q² region

JHEP 11 (2017) 184



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

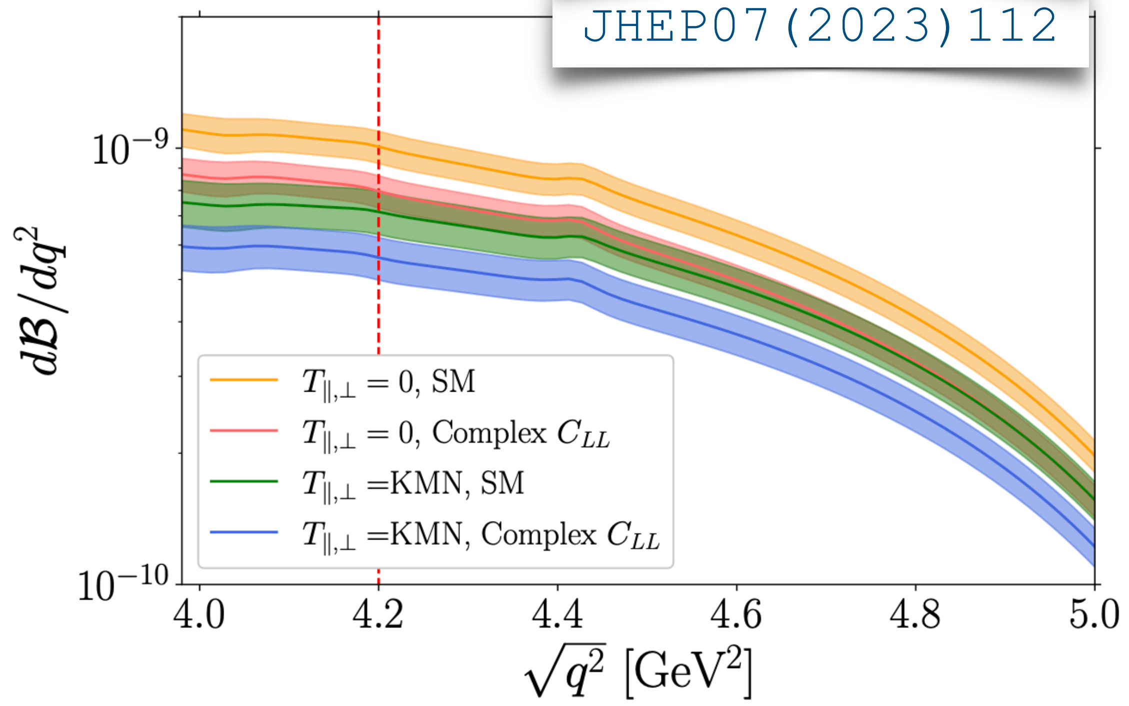
$q^2 \in [0.04,8.64]$ GeV²/c⁴



High q² region

JHEP10(2023)102

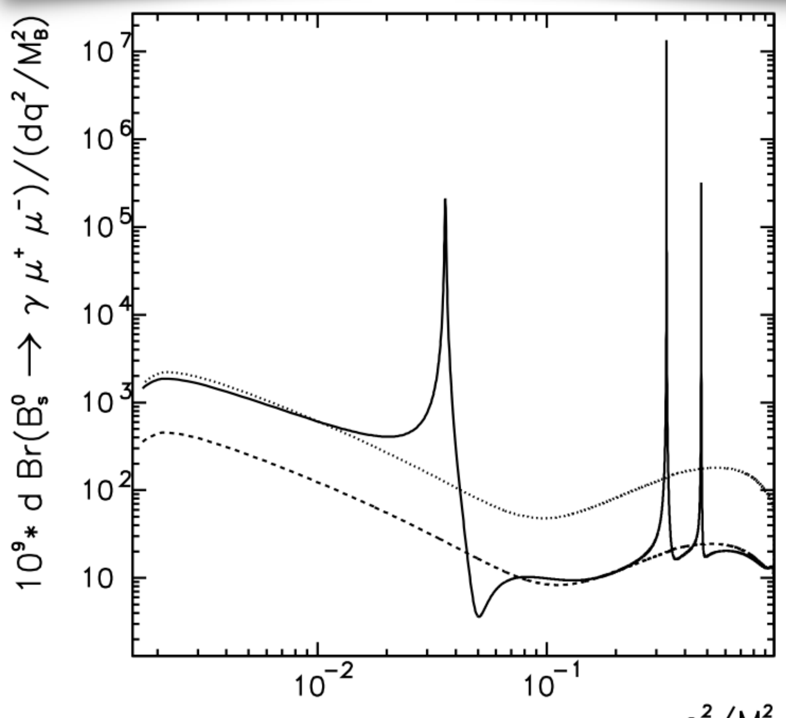
JHEP07(2023)112



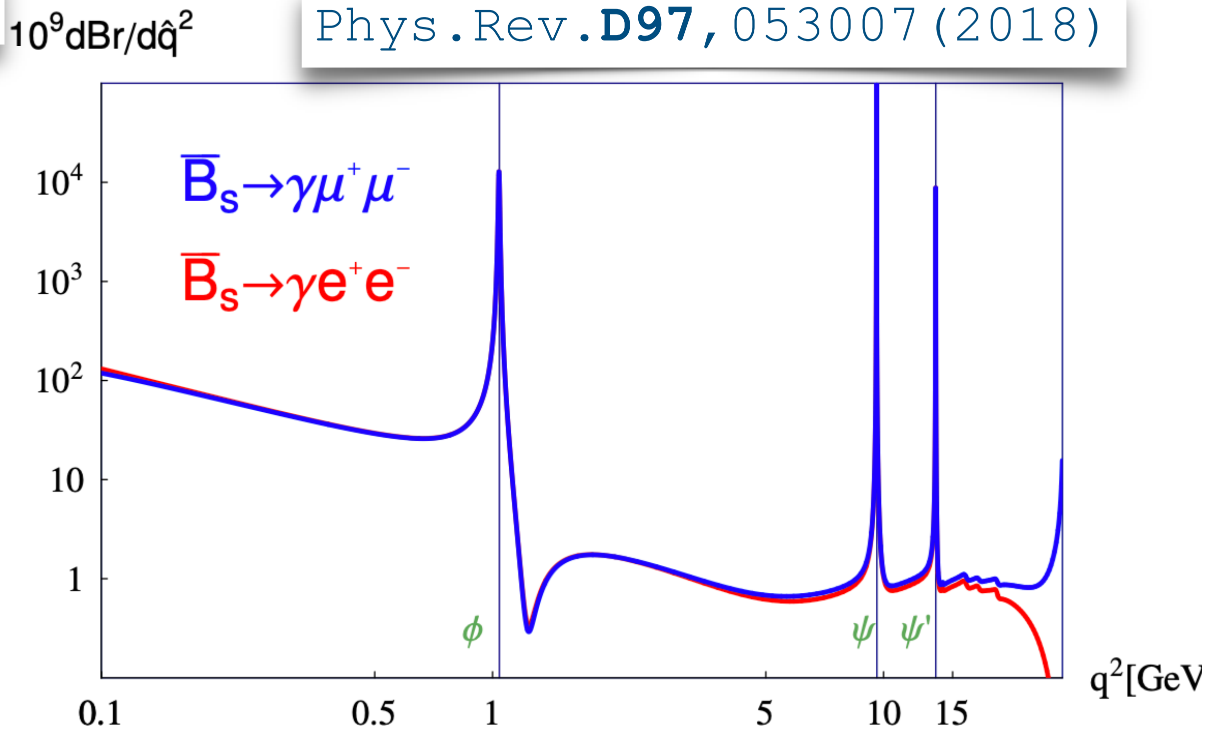
$\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma) = (1.22 \pm 0.14) \times 10^{-10}$

$q^2 \in [17.64,28.80]$ GeV²/c⁴

Phys.Rev.D70,114028(2014)



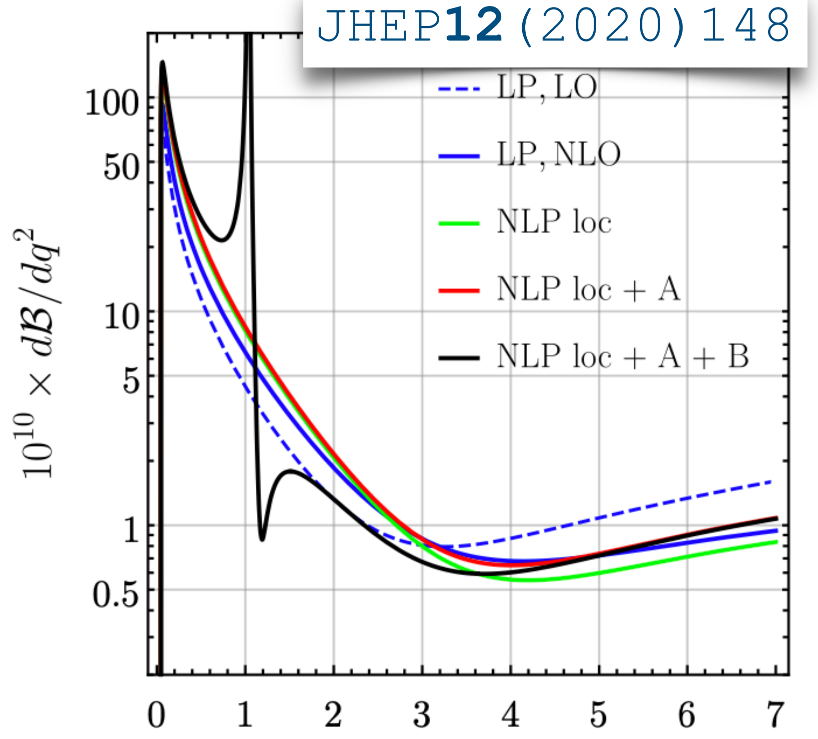
Phys.Rev.D97,053007(2018)



$\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma) = (6.01 \pm 0.08 \pm 0.70) \times 10^{-9}$

$q^2 \in [1,6]$ GeV²/c⁴

JHEP12(2020)148



$\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma) = (1.25 \pm 0.38) \times 10^{-8}$

$q^2 \in [0.04,6]$ GeV²/c⁴

Different theoretical approaches show different estimations of the $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$.
A measurement of the $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$ would test the SM. But an upper limit could also clarify the validity of the different theory approaches.

Methods

Two complementary methods

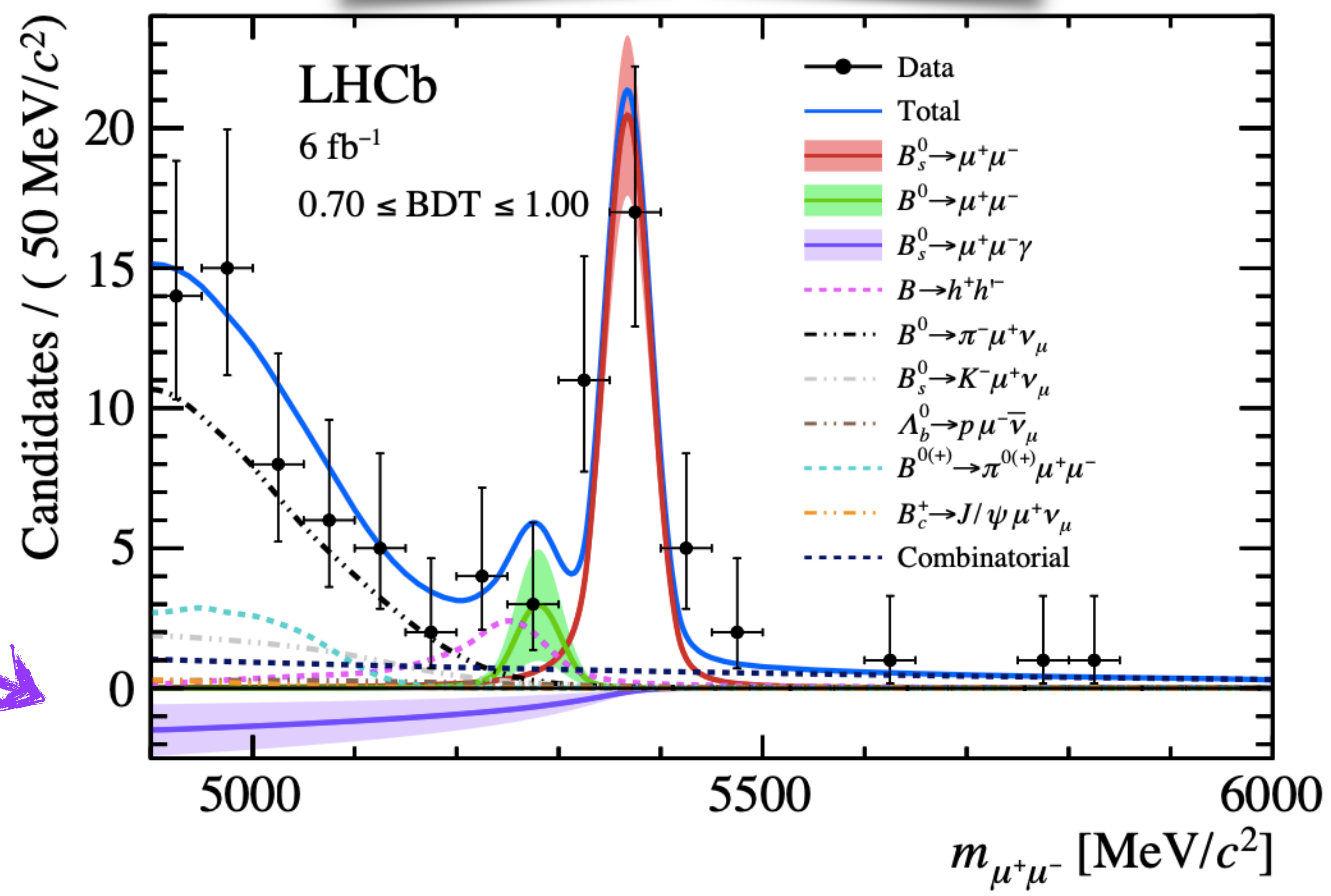
Indirect no photon reconstruction, probing this decay as a background of the $B_s^0 \to \mu^+\mu^-$ process:

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

See next presentation by Camille Normand

Only sensitive to high q^2

Phys.Rev.D105(2022)012010



Direct with photon reconstruction, presented today. First time!

- ➕ Sensitive to low-q^2 region, therefore, to larger set of Wilson coefficients (C_7, C_9, C_{10}).
- ➖ Photon reconstruction worsen the resolution.

And first study at low q^2!

LHCb-PAPER-2023-045
In preparation

Méril Reboud
CERN-THESIS-2020-303

Search by BABAR:

$$\mathcal{B}(B^0 \to \mu^+\mu^-\gamma) < 1.6 \times 10^{-7}$$

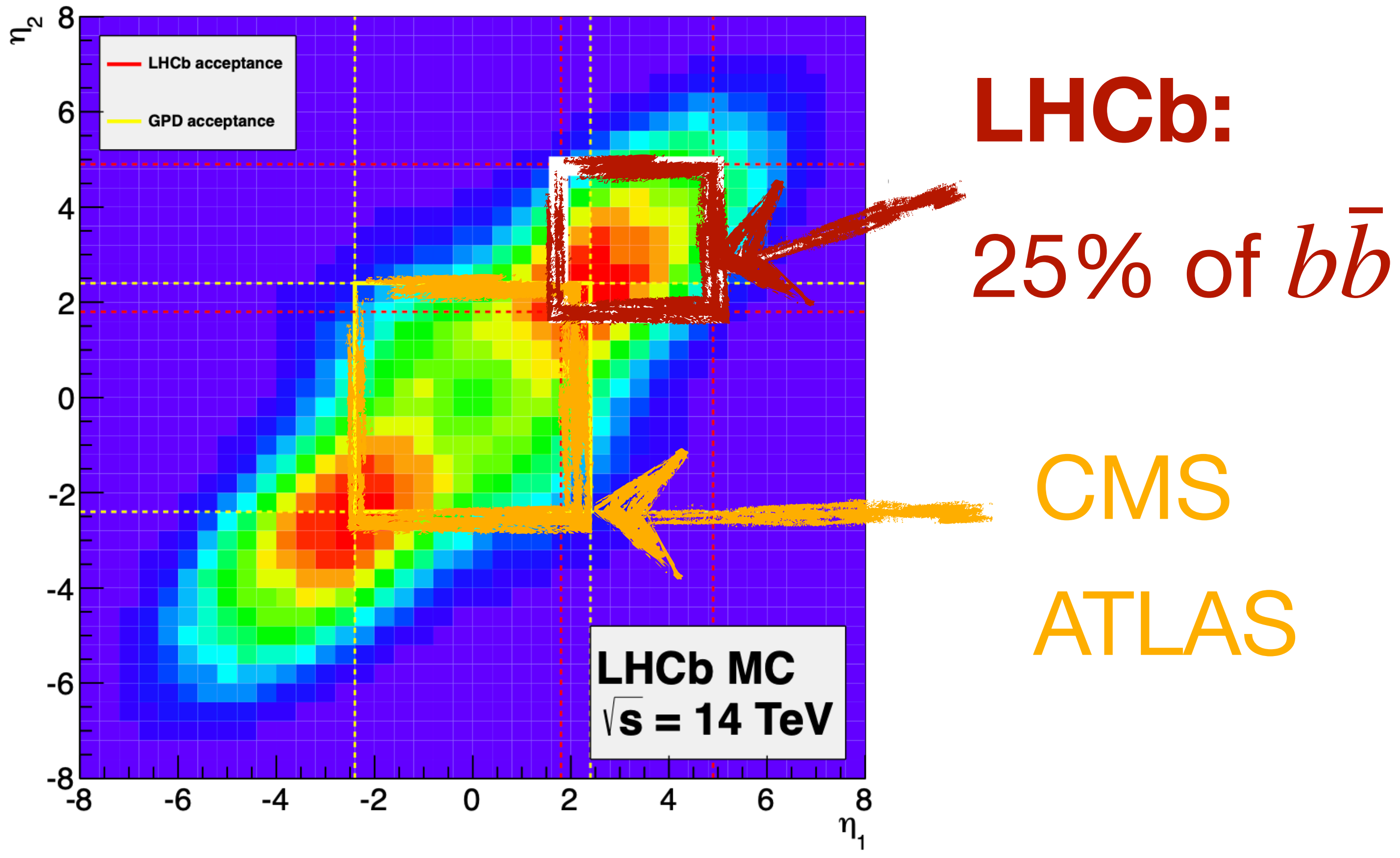
Phys.Rev.D77(2008)011104

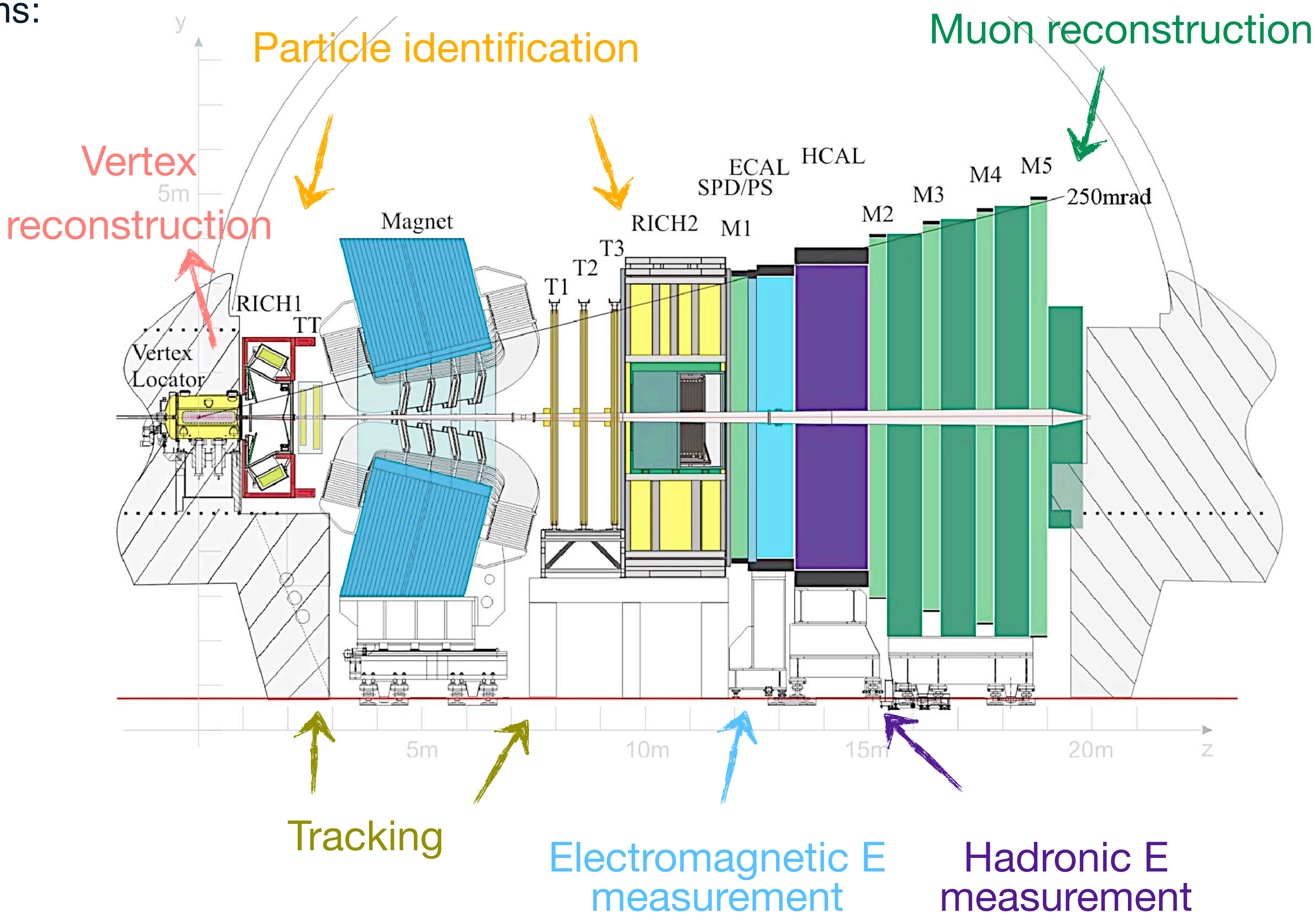
LHCb detector for b-hadron decays

Int.J.Mod.Phys.**A30**,1530022(2015)
CERN-LHCC-2003-030

- 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:





Strategy

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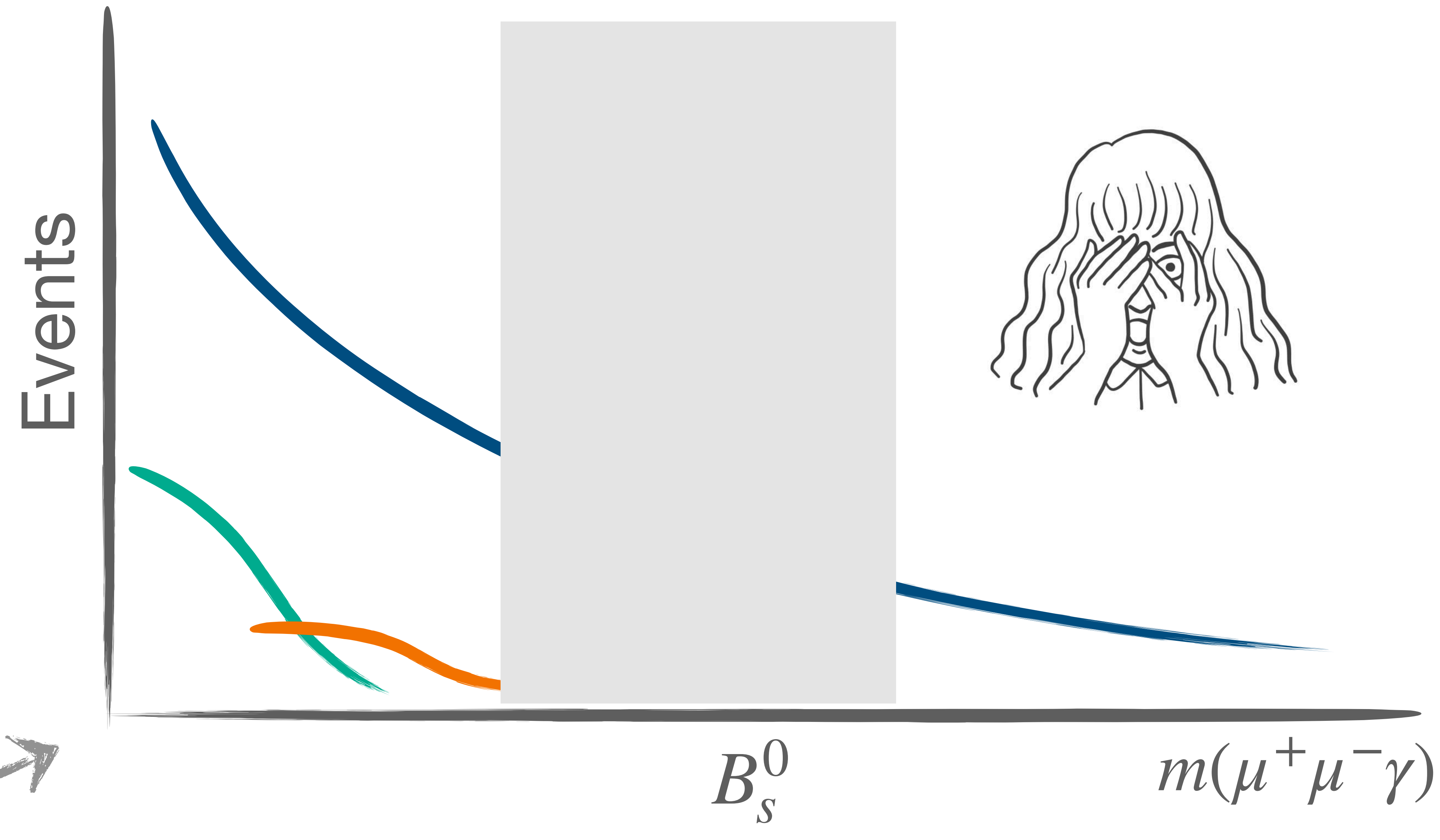
- **Data:** proton-proton collisions recorded by LHCb during Run 2 (5.4 fb^{-1}).
- **Signal simulation:** as theory input the differential branching ratio computed in D.Melikhov N.Nikitin [Phys.Rev.D70(2004)114028]. The implementation of this result is detailed in N.Nikitin,A. Popov,D.V.Savrina [LHCb-INT-2011-011]. + PHOTOS ON for final state radiation.
- **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 $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$ and compare with the SM predictions.

If no signal is seen... compute $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$ upper limit using CLs method.

Strategy

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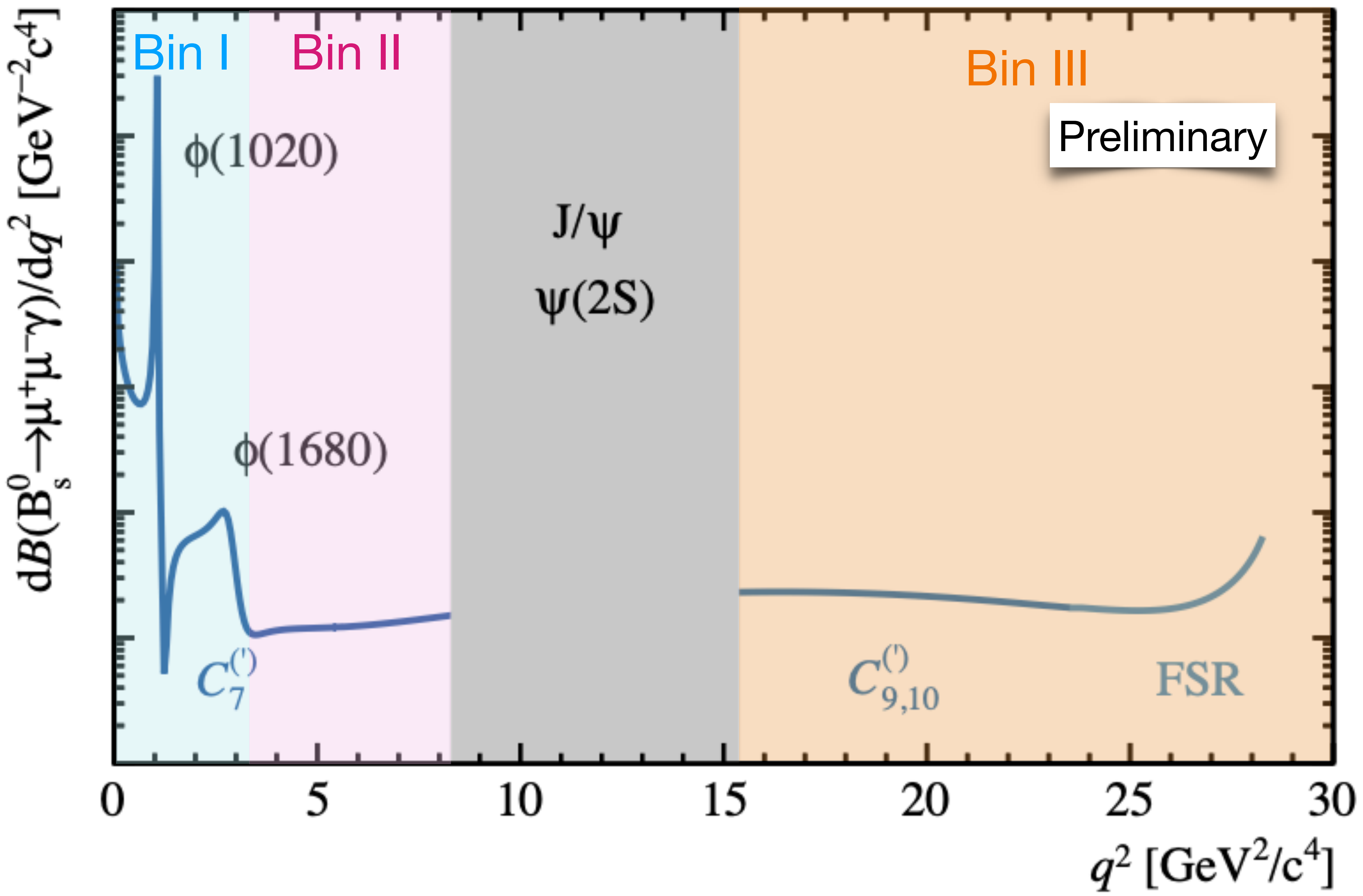
Three q^2 regions:

- Bin I: low-q^2
- Bin II: middle-q^2
- Bin III: high-q^2



Phys.Rev.D70(2004)114028

CERN-THESIS-2020-303

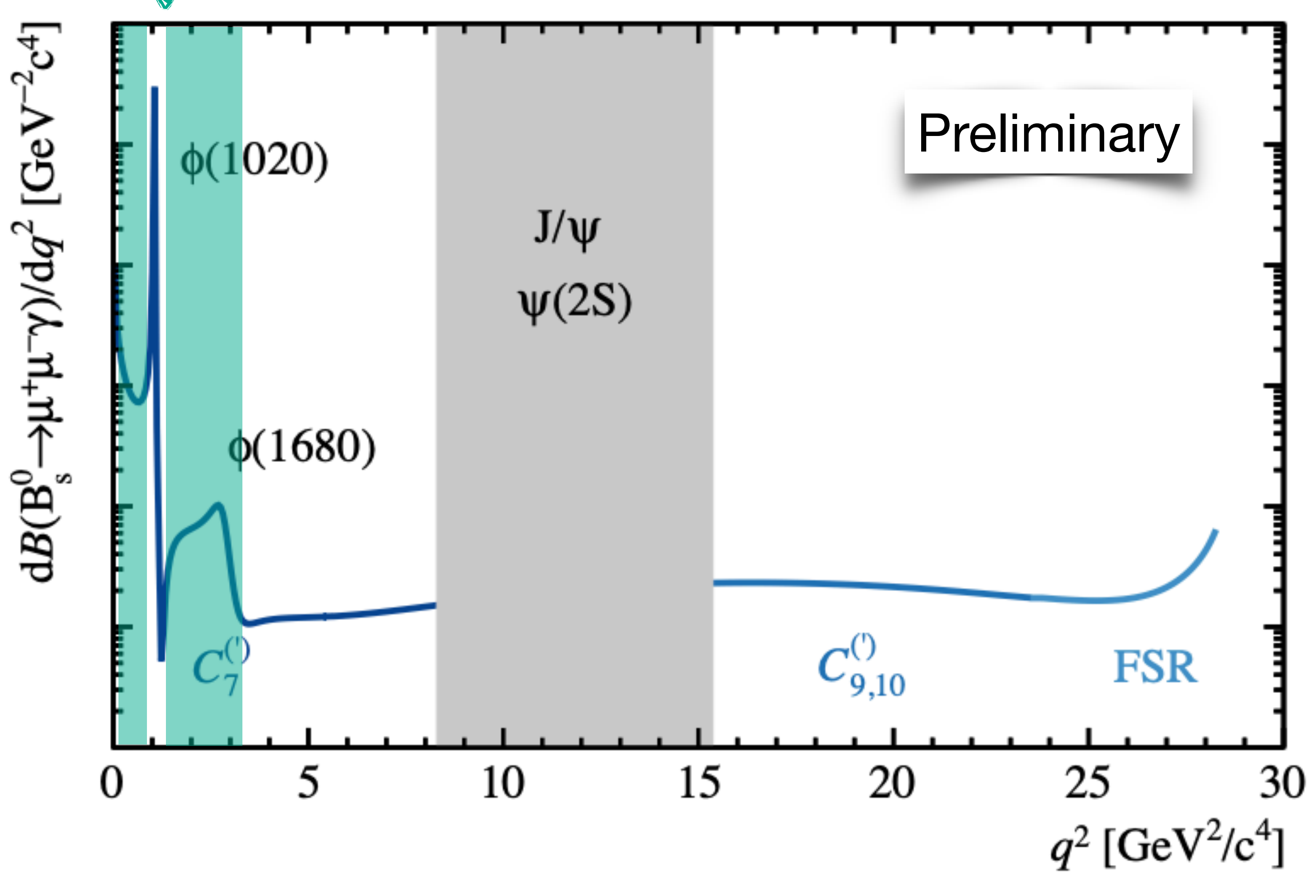
$E_\gamma > 50\mathrm{MeV}/c^2$

FSR = final state radiation

Additionally, Bin I is also studied with a veto on the ϕ-resonance mass:

$m(\mu^+\mu^-)$ = [989.6, 1073.4]MeV/c²

Bin I ϕ-veto: low-q^2 without ϕ region



q^2 bin	I	II	III
q^2 [GeV$^2/c^4$]	$[4\,m_\mu^2, 2.89]$	$[2.89, 8.29]$	$[15.37, m_{B^0_s}^2]$
$m(\mu^+\mu^-)$ [GeV$/c^2$]	$[2\,m_\mu, 1.70]$	$[1.70, 2.88]$	$[3.92, m_{B^0_s}]$
$10^{10}\times\mathcal{B}(B^0_s\to\mu^+\mu^-\gamma)$ [8]	82 ± 15	2.54 ± 0.34	9.1 ± 1.1
Fraction of $B^0_s\to\mu^+\mu^-\gamma$	87%	2.7%	9.8%

Strategy

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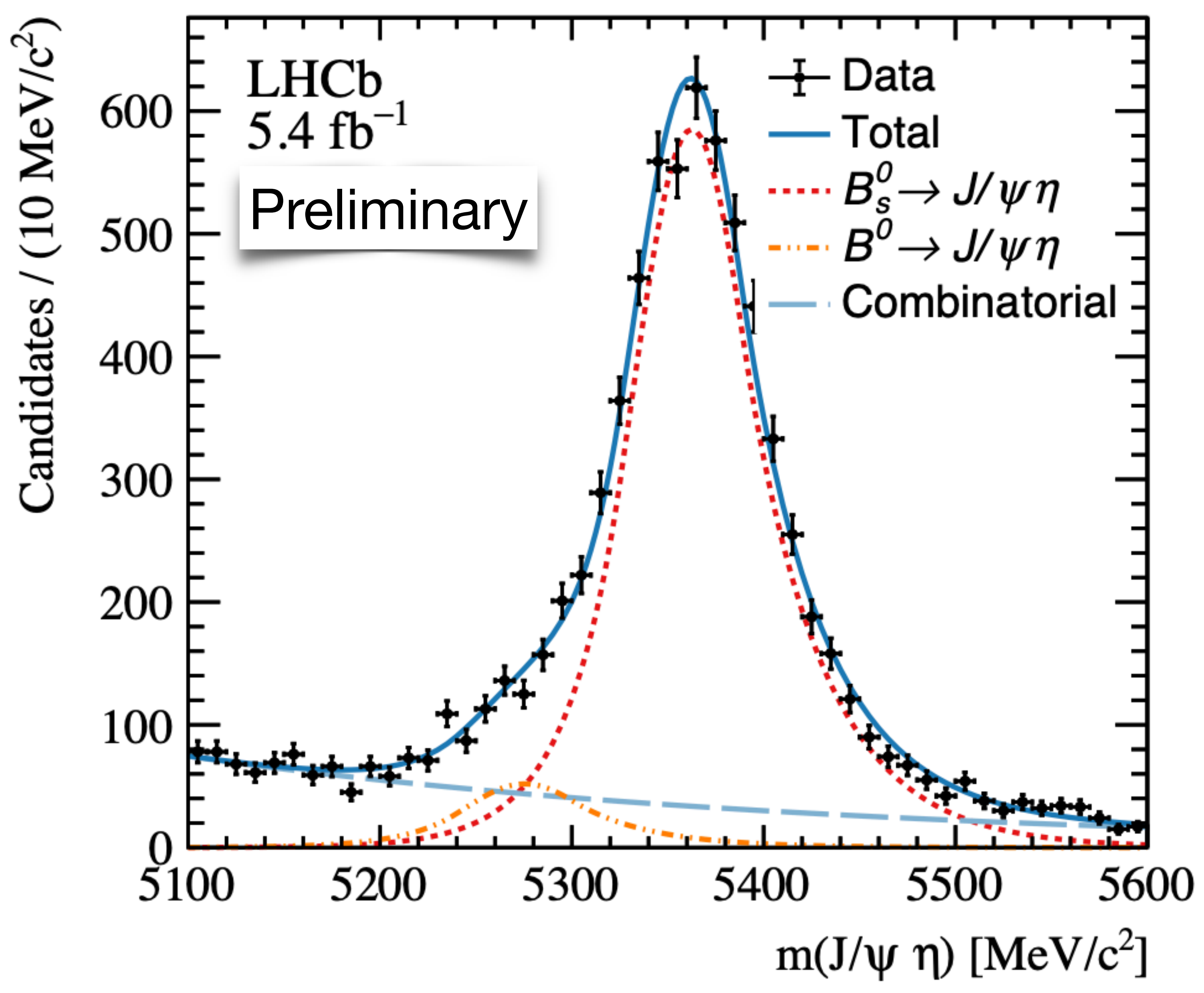
Normalisation channel

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

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



Signal branching fraction to be calculated as:

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

Branching Fraction: from PDG $(9.3 \pm 1.6) \times 10^{-6}$

Efficiencies and its associated syst. uncertainty.

$$\epsilon = \epsilon_{\text{Acceptance}} \times \epsilon_{\text{Preselection}} \times \epsilon_{\mu\text{PID}} \times \epsilon_{\gamma\text{PID}} \times \epsilon_{\text{Trigger}} \times \epsilon_{\text{MLP}}$$

Normalisation yield: from data fit

Strategy

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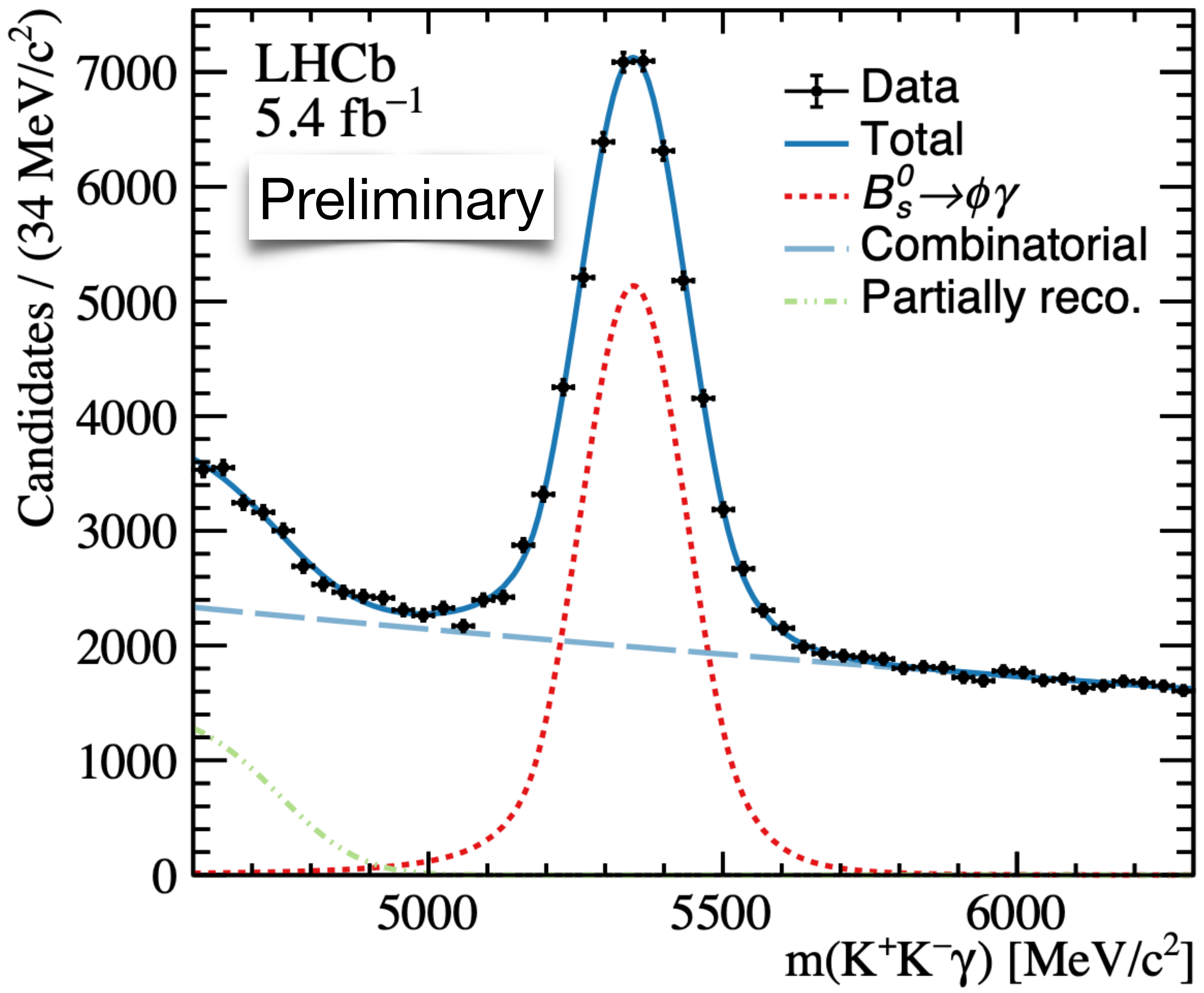
Control channel

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

$$B_s^0 \to \Phi(\to K^+K^-)\ \gamma$$



Selection

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After trigger and basic preselection, $p_T(\gamma) > 1000\mathrm{MeV}/c^2$, candidates must pass a requirement in two MLP classifiers:

First MLP

Aim: reduce the combinatorial background using geometrical and kinematic variables.

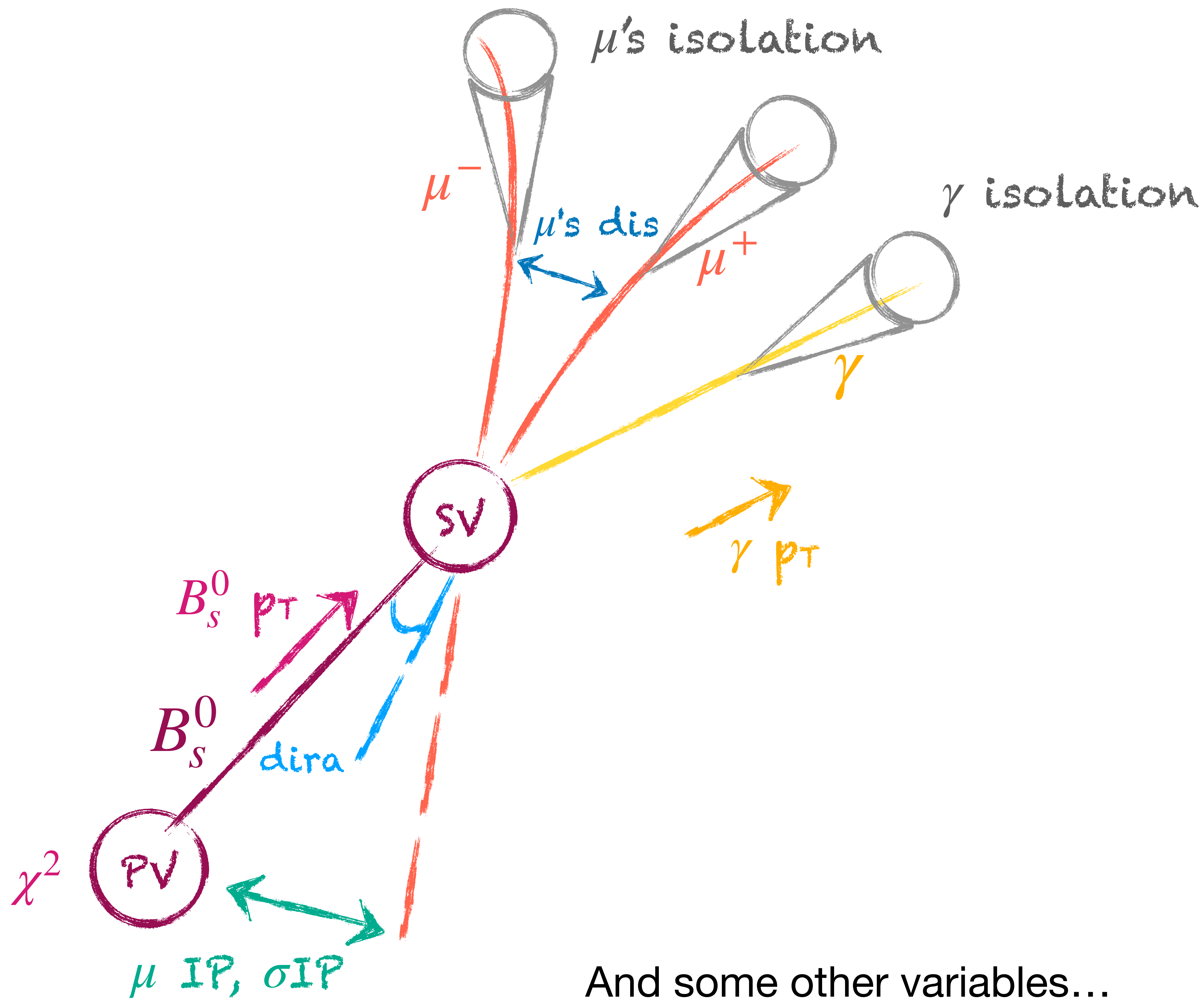
Trained in data mass side-bands and background, and signal simulation.

Second MLP

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

Trained with samples after passing the first MLP.

Optimised cut for each q² bin.



And some other variables…

Background

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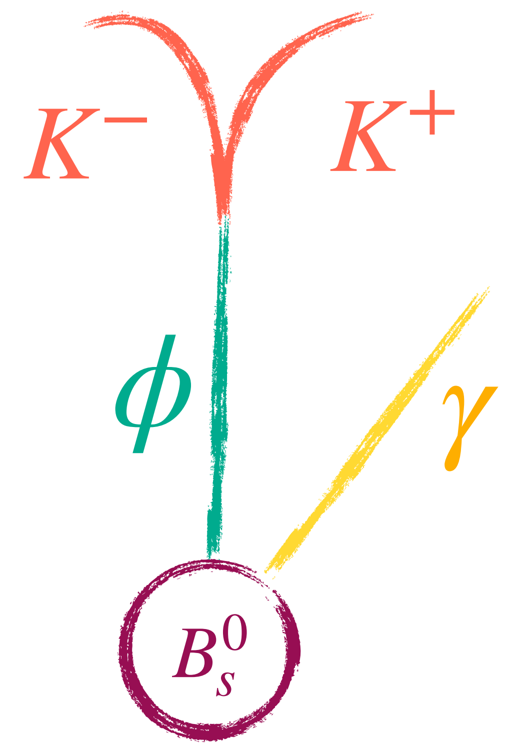
Studied with simulation



Double misID

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

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

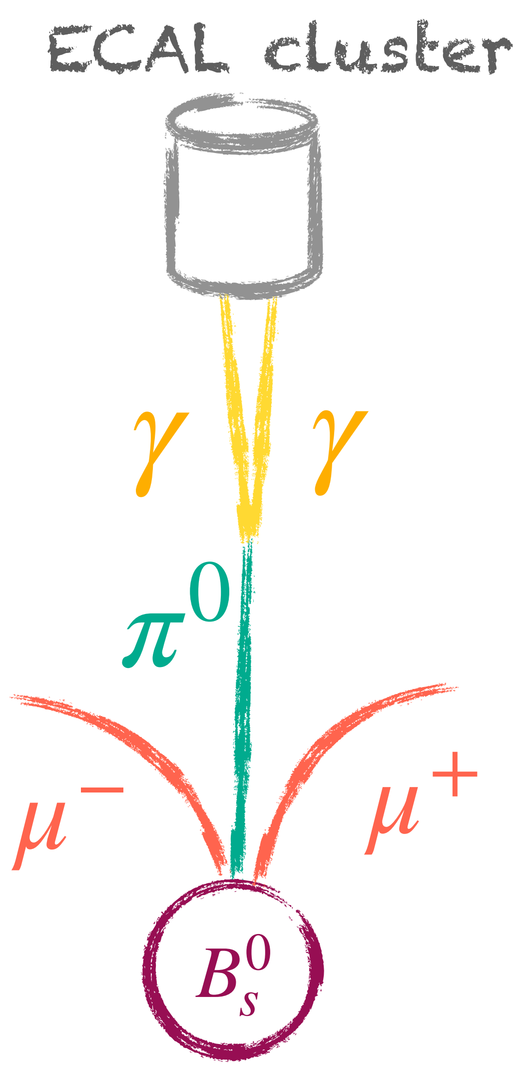
$B^0 \to K^{*0}(\to \pi K)\gamma$

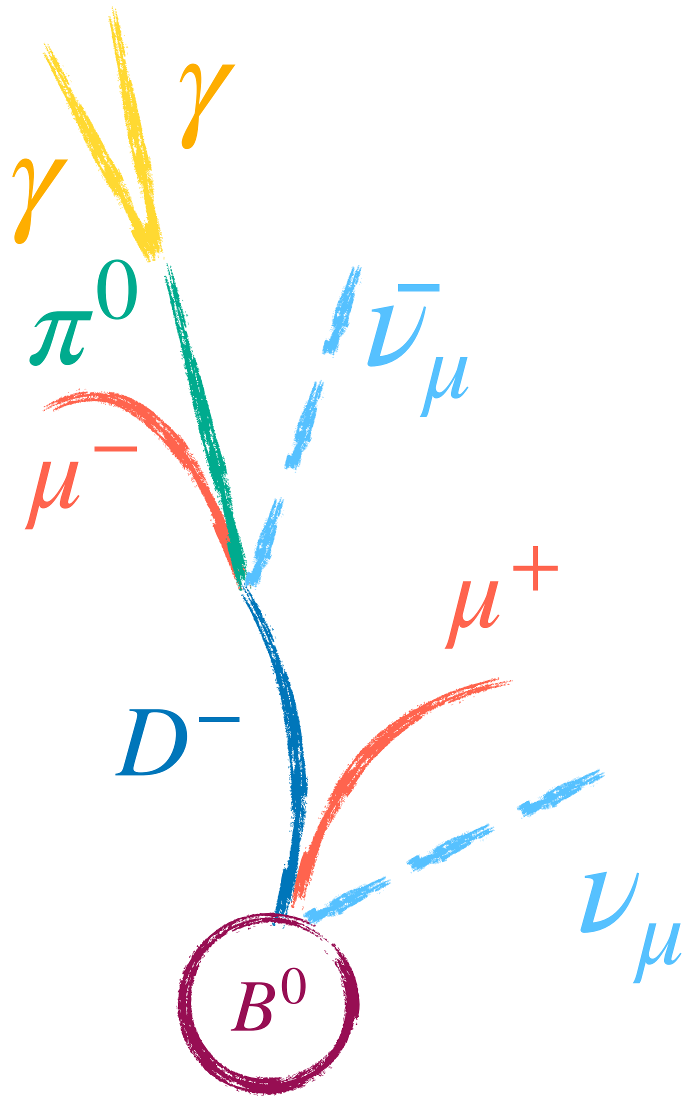
Probability of ~10^{-4} of double misID

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

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.





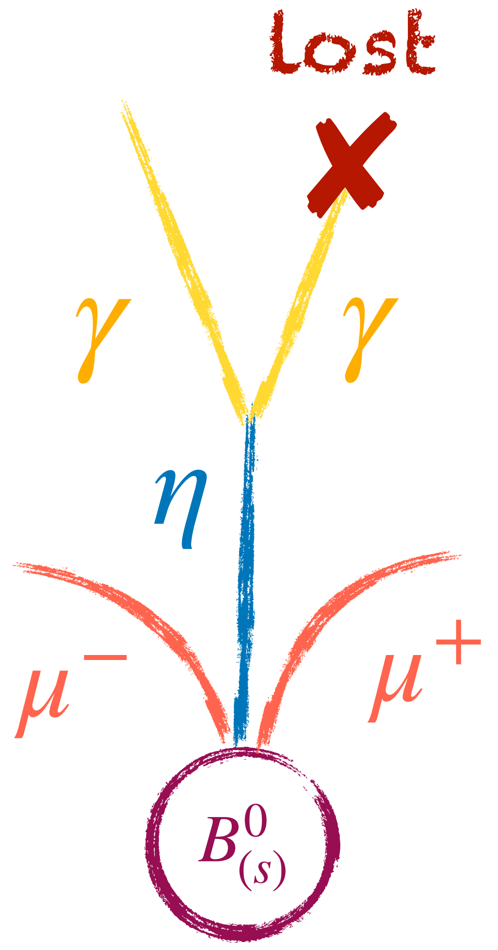
Partially reconstructed

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

A broad peak outside the mass region is expected.

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

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



Other backgrounds were studied and estimated negligible: $B^0 \to \mu\mu\gamma$, $B^0 \to \pi^+\pi^-\pi^0$, $B^{*0} \to B^0\gamma$, $\Lambda_b \to pK\gamma$, etc.

Mass fit

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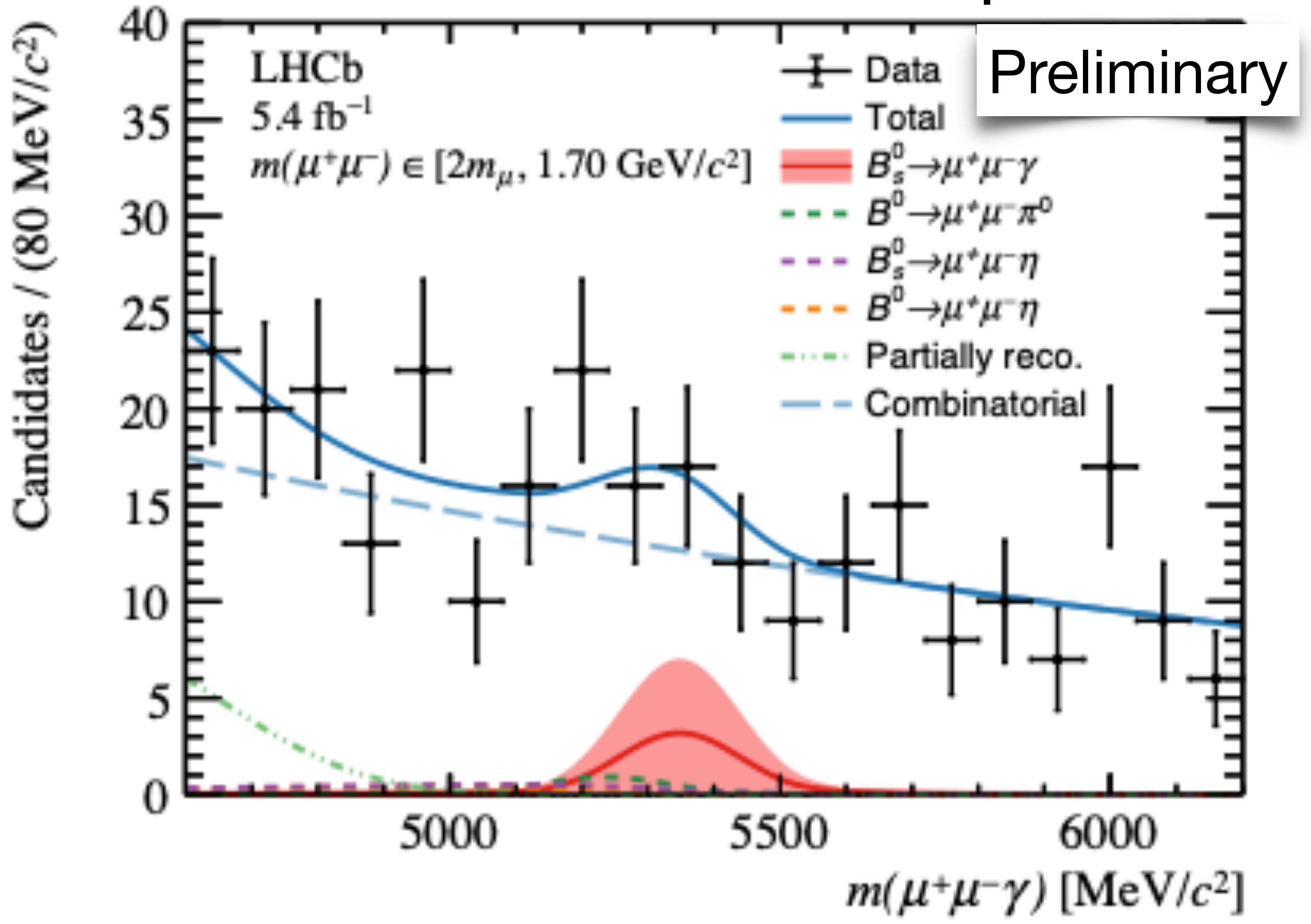
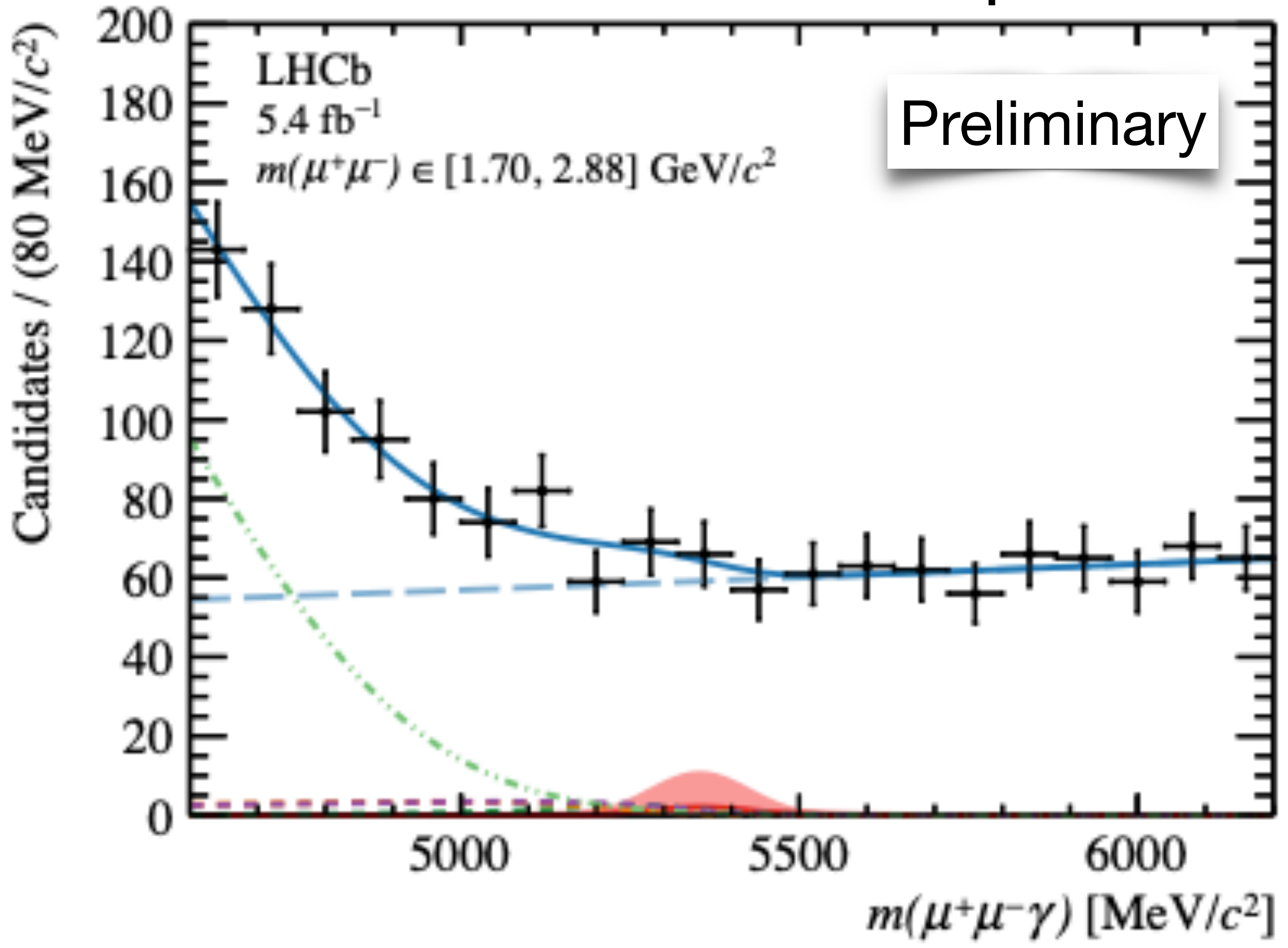
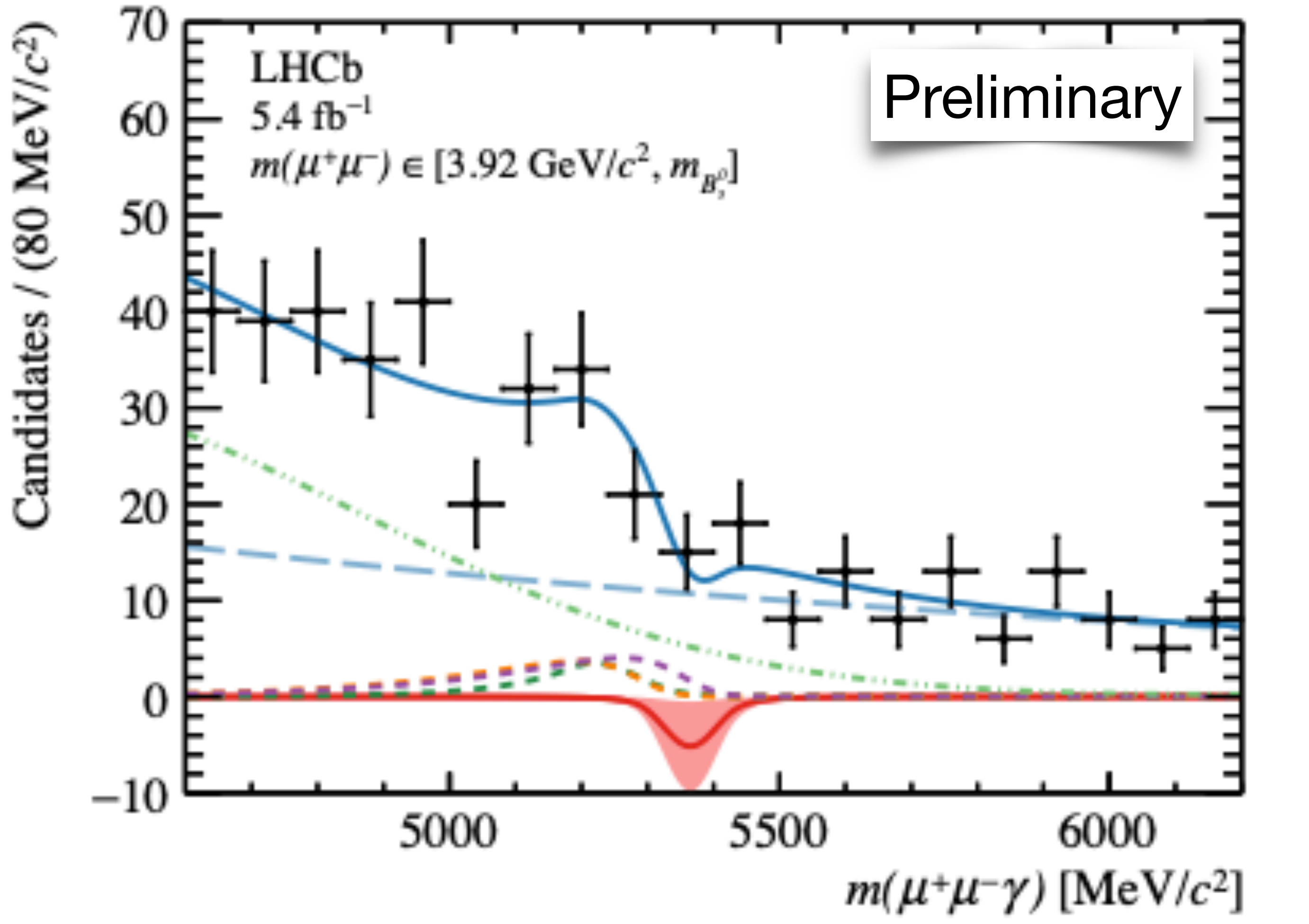
Bin I: low q^2



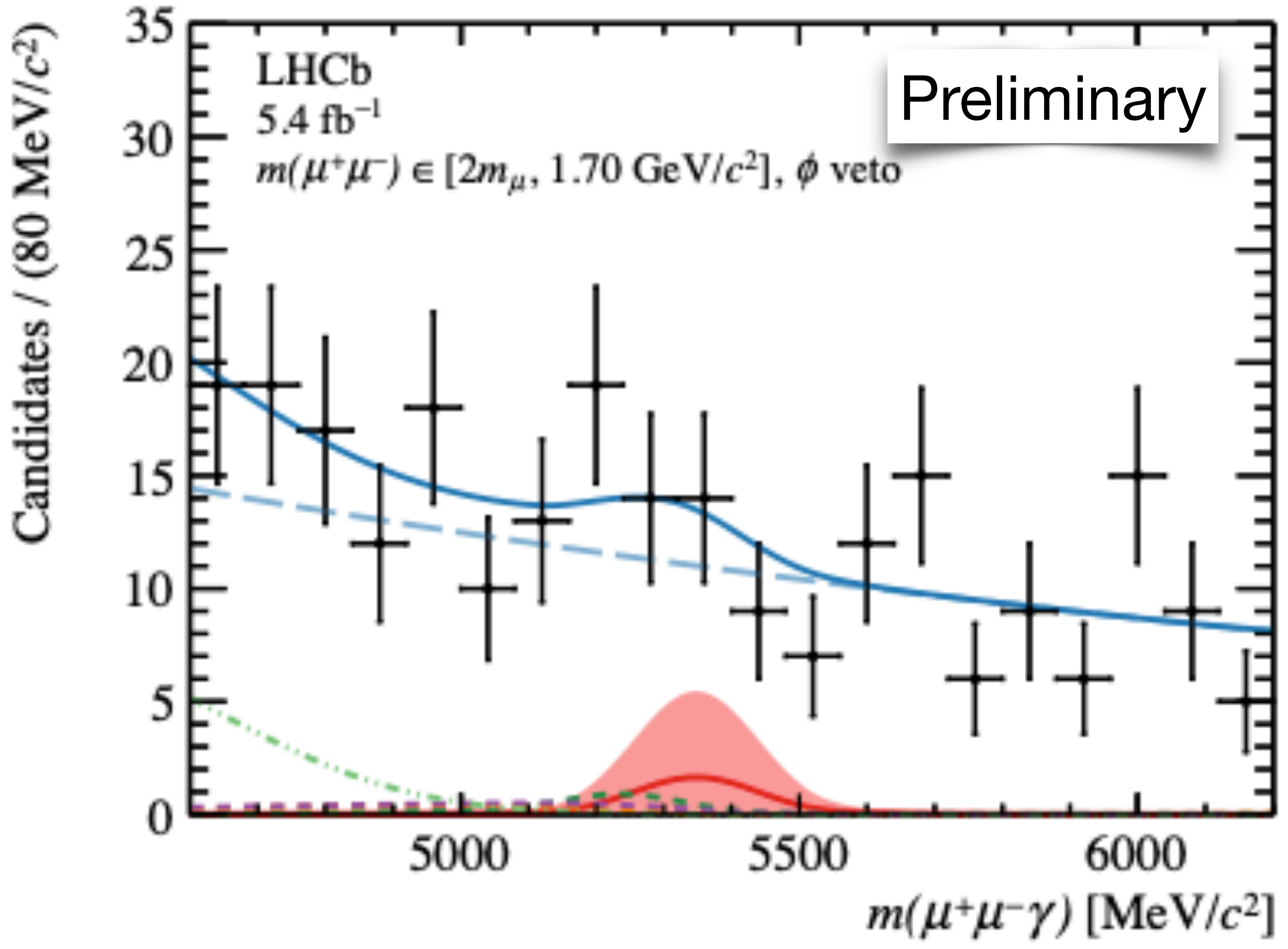
Bin II: medium q^2



Bin III: high q^2



Bin I: low q^2, with ϕ veto



The measured $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$ is not statistically significant in any of the q^2 regions.

They are consistent with the background-only hypothesis at < 1σ level.

$$
\begin{aligned}
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm I} &= (1.34 \pm 1.60 \pm 0.28) \times 10^{-8},\\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm II} &= (0.76 \pm 3.55 \pm 0.30) \times 10^{-8},\\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm III} &= (-2.55 \pm 2.25 \pm 0.41) \times 10^{-8},\\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\rm I,\ \phi\ veto} &= (0.72 \pm 1.56 \pm 0.29) \times 10^{-8}.
\end{aligned}
$$

stat.±syst.

Dominated by statistical uncertainty.

Upper Limits

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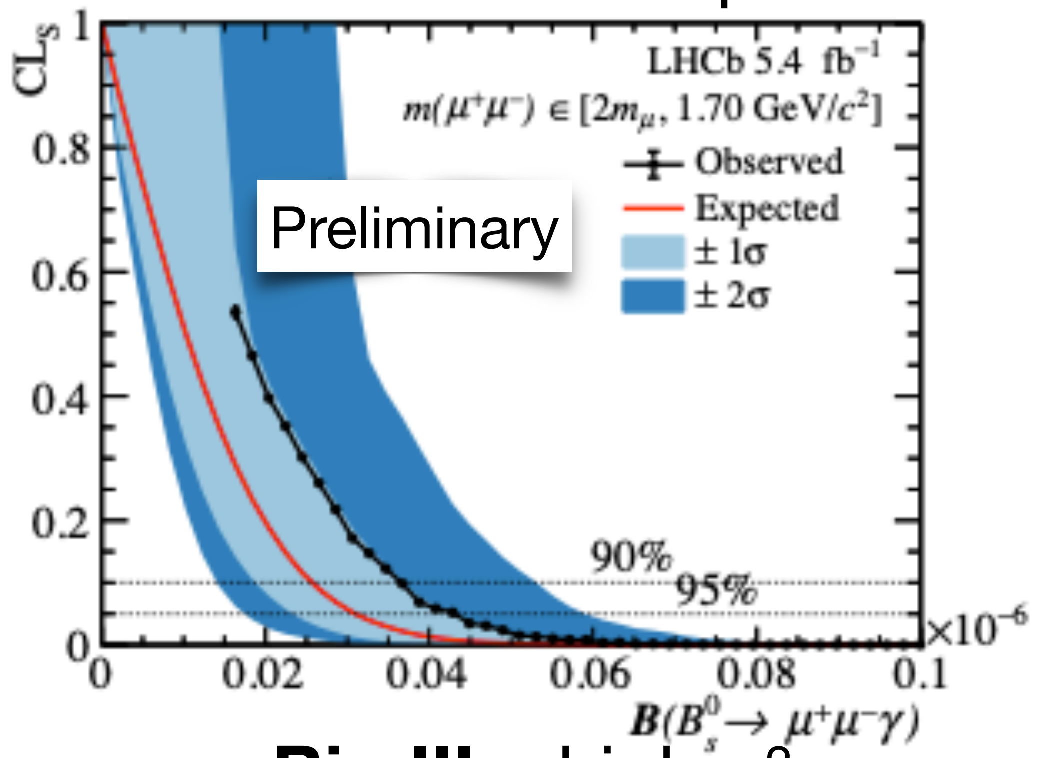
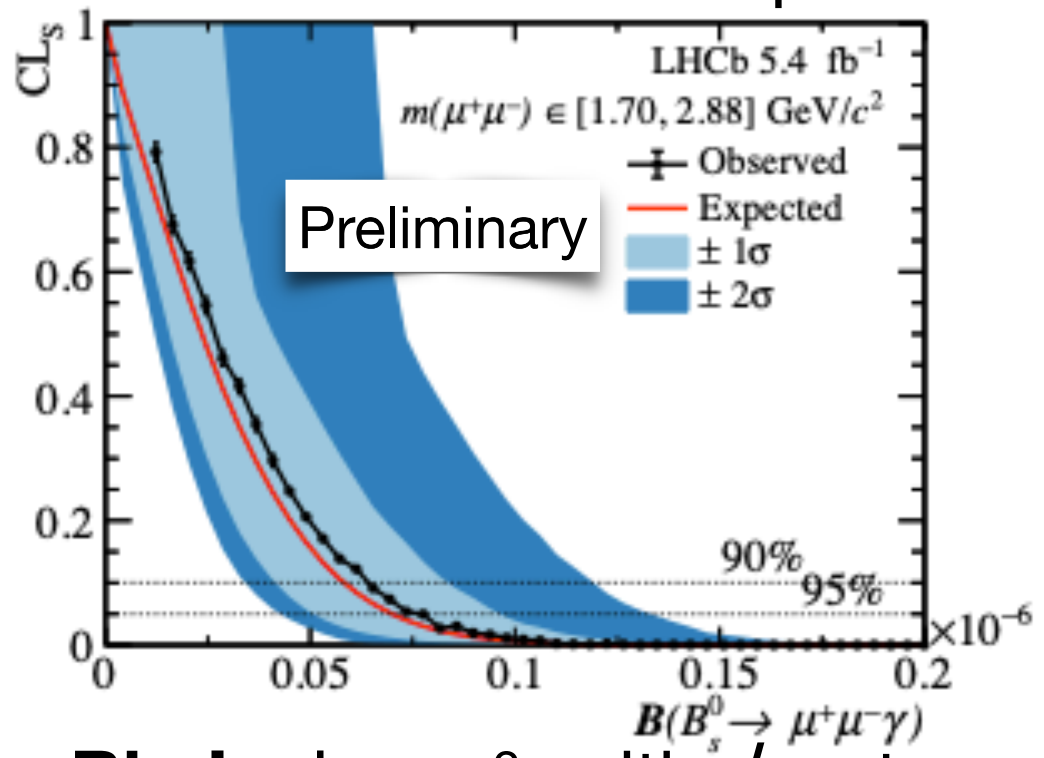
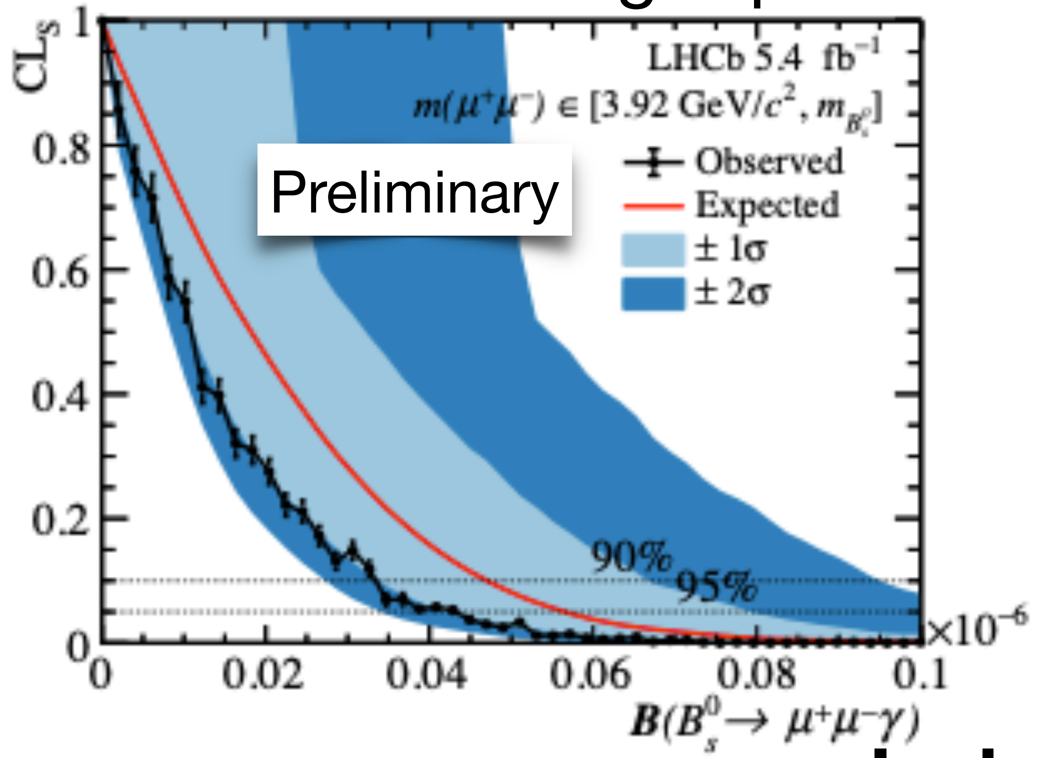
Bin I: low q^2



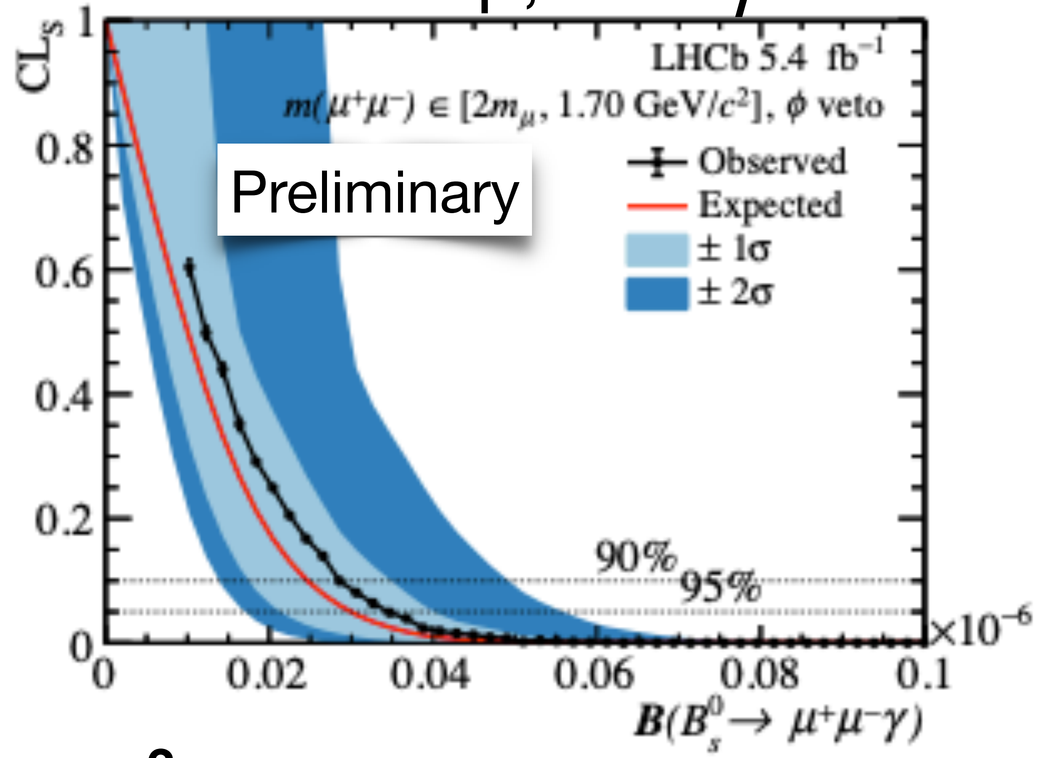
Bin II: medium q^2



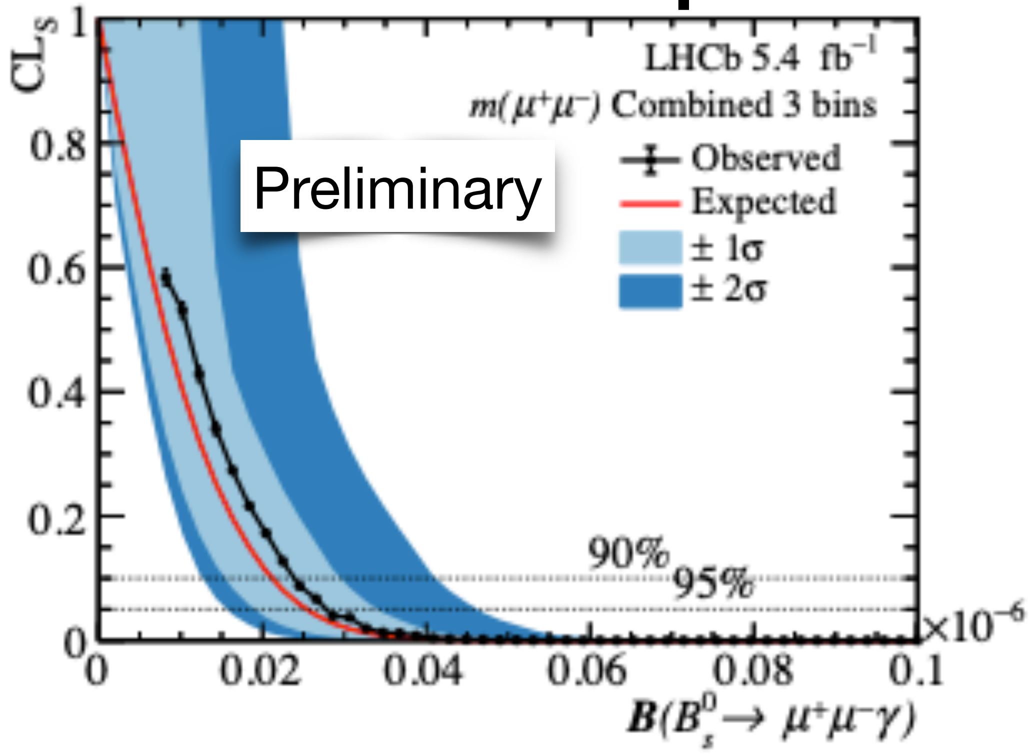
Bin III: high q^2



Bin I: low q^2, with ϕ veto



Inclusive q^2



As no significant excess is observed, upper limits are set on $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)$ using the CL method.

Upper limits on the branching fraction:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\text{I}} < 3.6\,(4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\text{II}} < 6.5\,(7.7) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\text{III}} < 3.4\,(4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\text{I},\,\phi\ \text{veto}} < 2.9\,(3.4) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\text{comb.}} < 2.5\,(2.8) \times 10^{-8},$$

at 90% (95%) CL.

Overview

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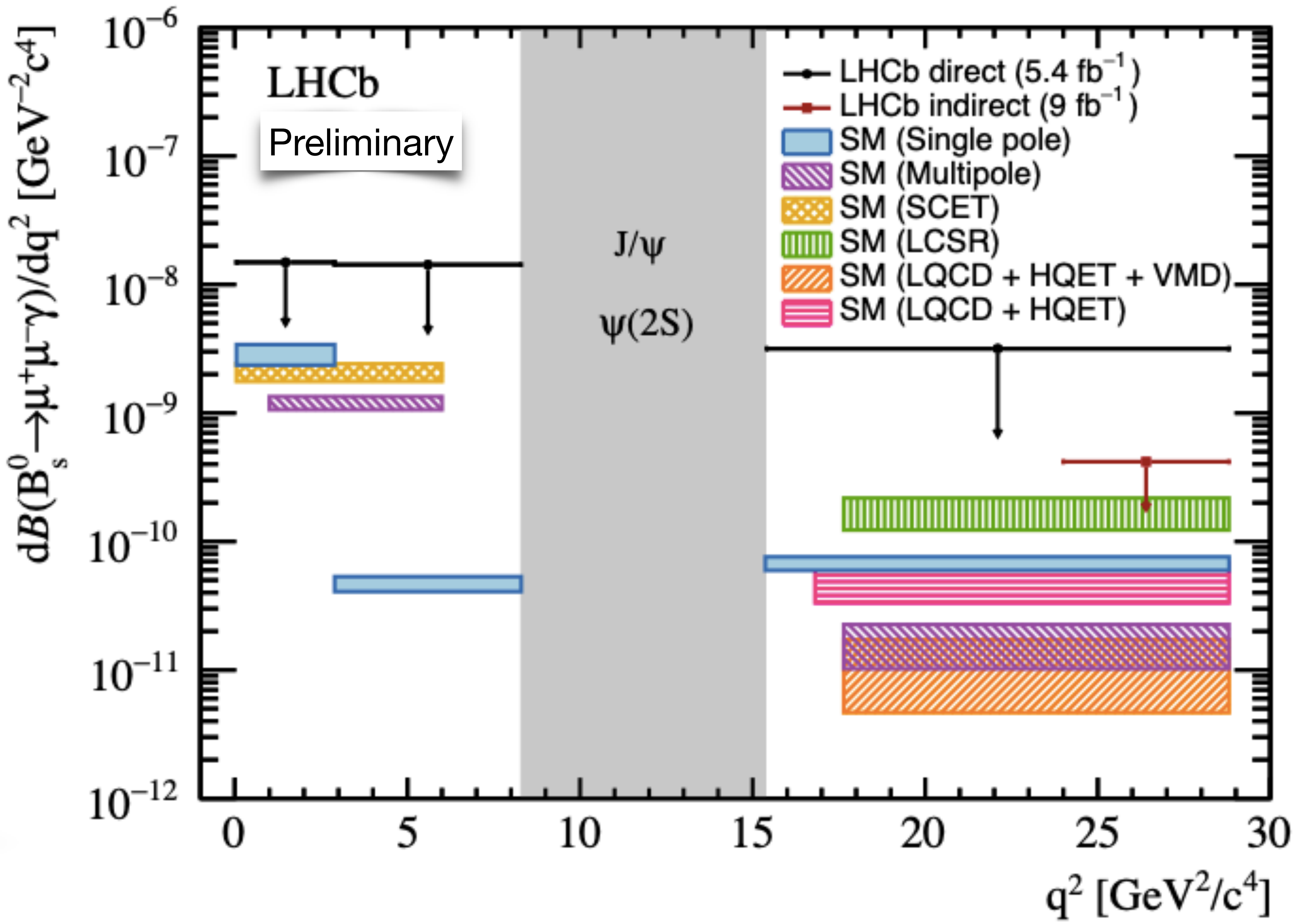
Experimental upper limits in the theoretical context:

- Different approaches to $B_s^0 \to \gamma$ FF's calculation:
  - Different estimates of the $\mathscr{B}$.
- Experimental results are dominated by stat. uncertainties:
  - Run 3 data might be sensitive to different models.
- Indirect method reaches lower ULs.
  - Direct method is sensitive to the full q² spectrum.



- Direct search $B_s^0 \to \mu^+\mu^-\gamma$, these results, at 95% CL. [LHCb-PAPER-2023-045 in preparation]
- Indirect search from $B_s^0 \to \mu^+\mu^-$ decay at LHCb, limit at 95% CL [Phys.Rev.D105(2022)1]
- Single-pole parametrisation [JHEP11(2017)184]
- Multipole parametrisation [Phys.Rev.D97(2018)053007]
- Soft-collinear effective theory [JHEP148(2020)12]
- Light-cone sum rules [JHEP8(2021)12]
- Lattice QCD with heavy quark effective theory, assuming vector meson dominance [JHEP10(2023)102, JHEP7(2023)112]
- Lattice QCD with heavy quark effective theory extrapolation [arXiv:2402.03262]

Conclusions

The **first direct**, and **first low q² search**, of the $B_s^0 \to \mu^+\mu^-\gamma$ decay:

using Run 2 data recorded by the LHCb detector.

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Thank you!