Long exercise B-physics:

Measurement of rare $B_s \to \mu^+\mu^-$ decay

Facilitators: Kai-Feng Chen (Jack), Federica Riti

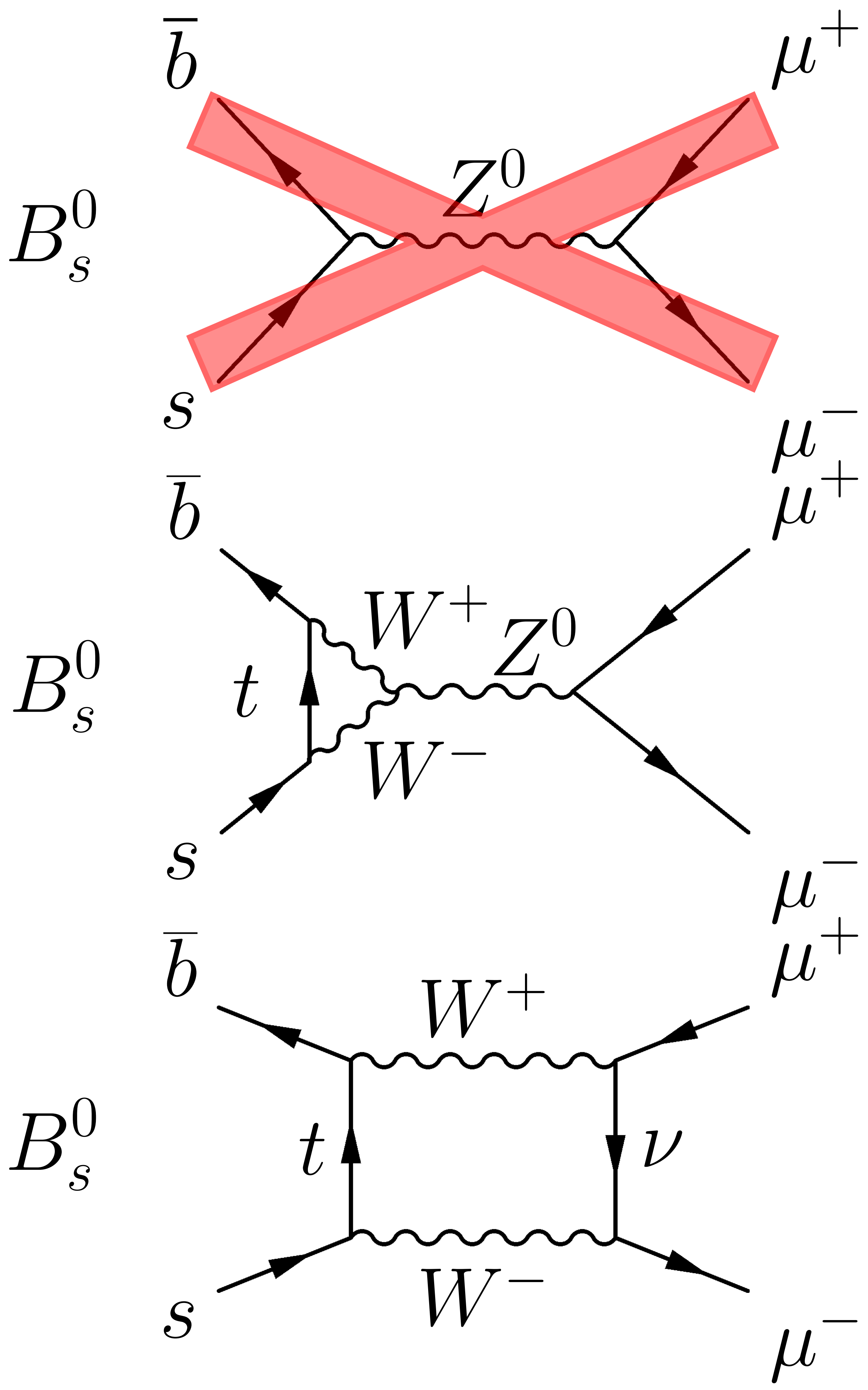
CMS DAS @ CERN 2024, 17–22 Jun 2024

Wednesday 19 June 2024

This presentation is based on Jack BMM5 and Georgios CMSDAS23 slides

Measurement of $B_s^0 \to \mu^+\mu^-$

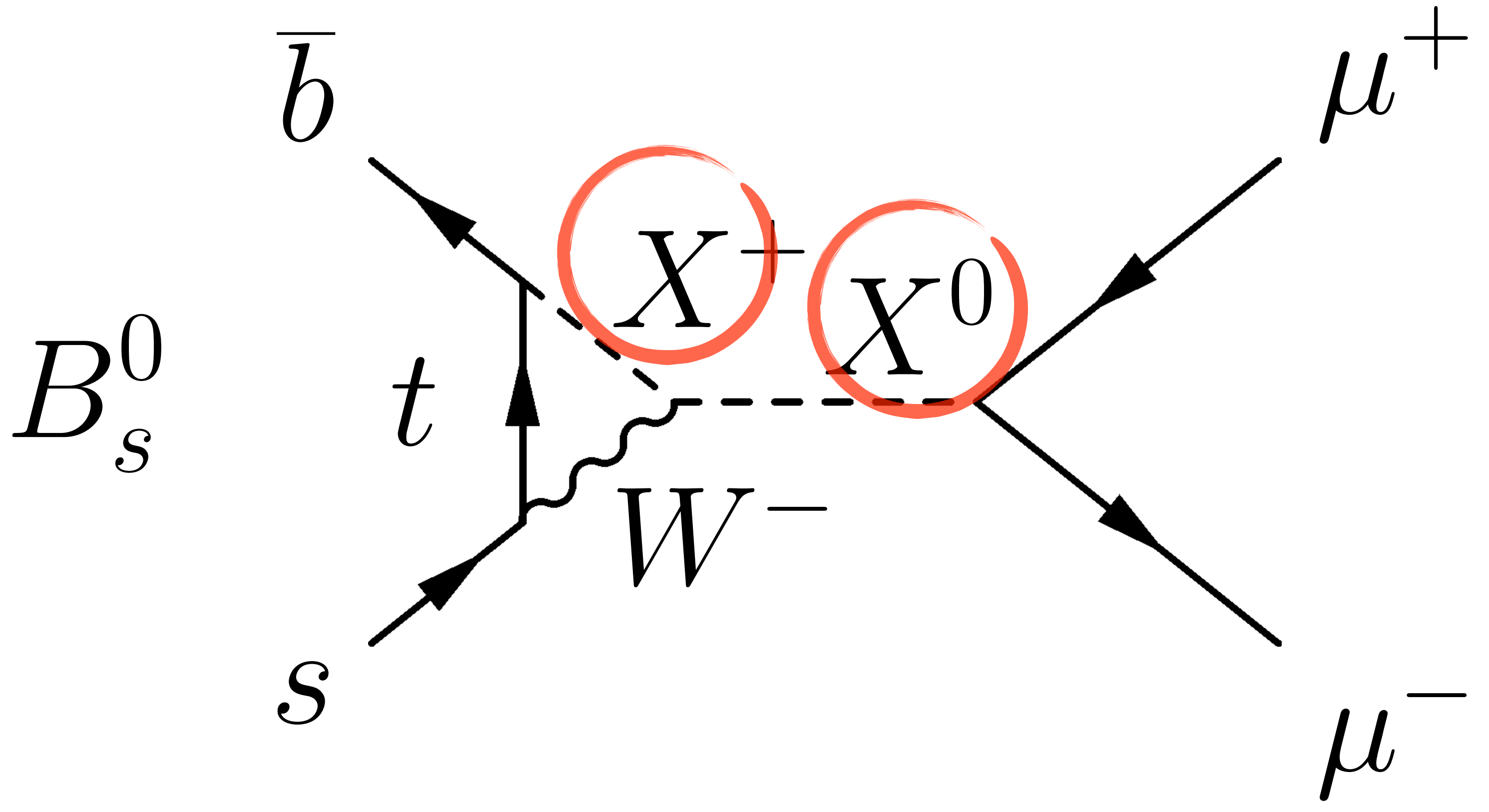
- $B_s^0 \to \mu^+\mu^-$ is a **rare** decay
  - SM theoretical prediction: [JHEP10(2019)232]
    $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$



Why is it highly suppressed in the SM?

- It is a FCNC process, and it only proceeds through Z-penguin & box diagrams (suppressed by $\mathbf{[m_W/m_t]^2}$).
- Cabibbo suppressed: $\mathbf{|V_{tq}|^2}$
- Helicity suppressed: $\mathbf{[m_\mu/m_B]^2}$

Measurement of $B_s^0 \rightarrow \mu^+\mu^-$



- **It is an excellent place to look for new physics!**
  - Loop diagram + Suppressed SM + Theoretically clean
- **Indirect search** for *new* heavy particles
  - *Virtual new particles participate in the loop processes and can increase the $B_s \rightarrow \mu^+\mu^-$ decays rates*

Examples of two possible new physics scenarios:
- **2HDM** (two-Higgs-doublet model)
- **MSSM** (Minimal Supersymmetric Standard Model)

The $B_s \to \mu^+\mu^-$ measurement at the LHC

- Several experiments attempted to measure this decay
  - CDF Collaboration, D0 Collaboration…

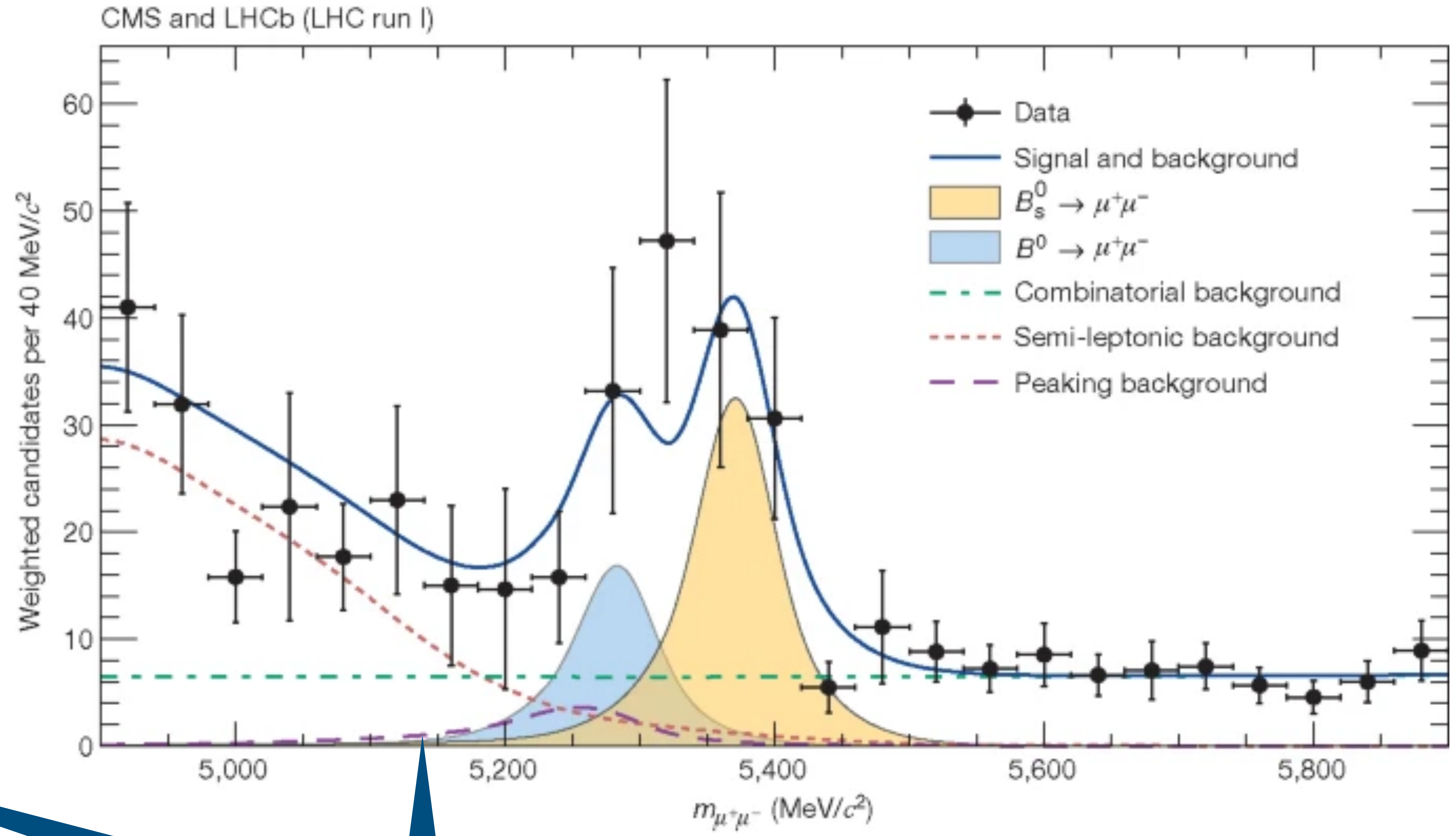
    [Phys. Rev. Lett. 107, 191801] [Phys. Lett. B 693, 539 (2010)]

- **First experimental evidence:**
  - **CMS+LHCb Run1** combination

    6.2σ from SM

    - $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

      [Nature 522, 68–72 (2015)]



First Nature Letter by LHC!

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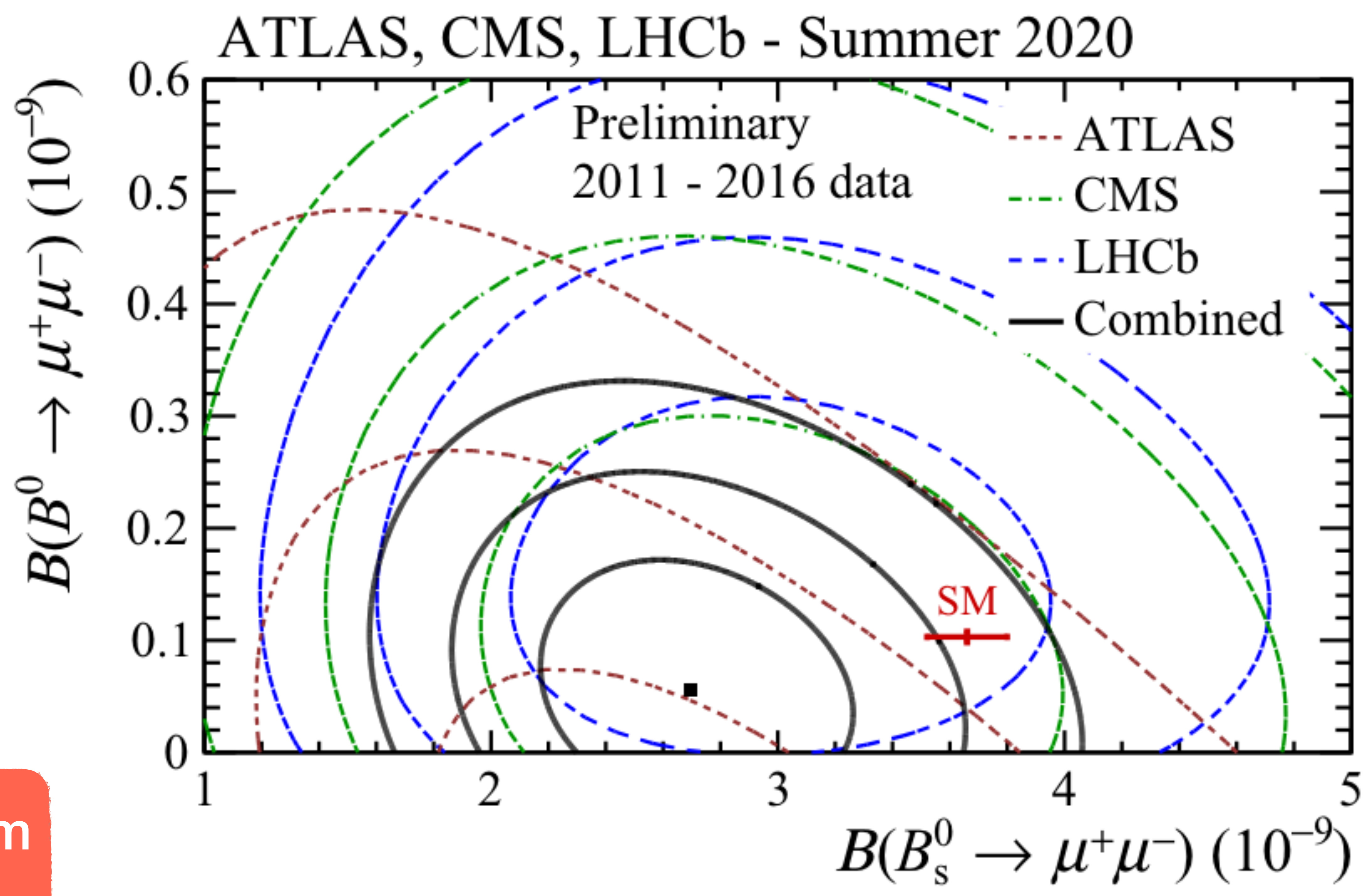
- **ATLAS+CMS+LHCb Run1+2016** combination
    - $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$

      [CMS-PAS-BPH-20-003]

~2σ from SM



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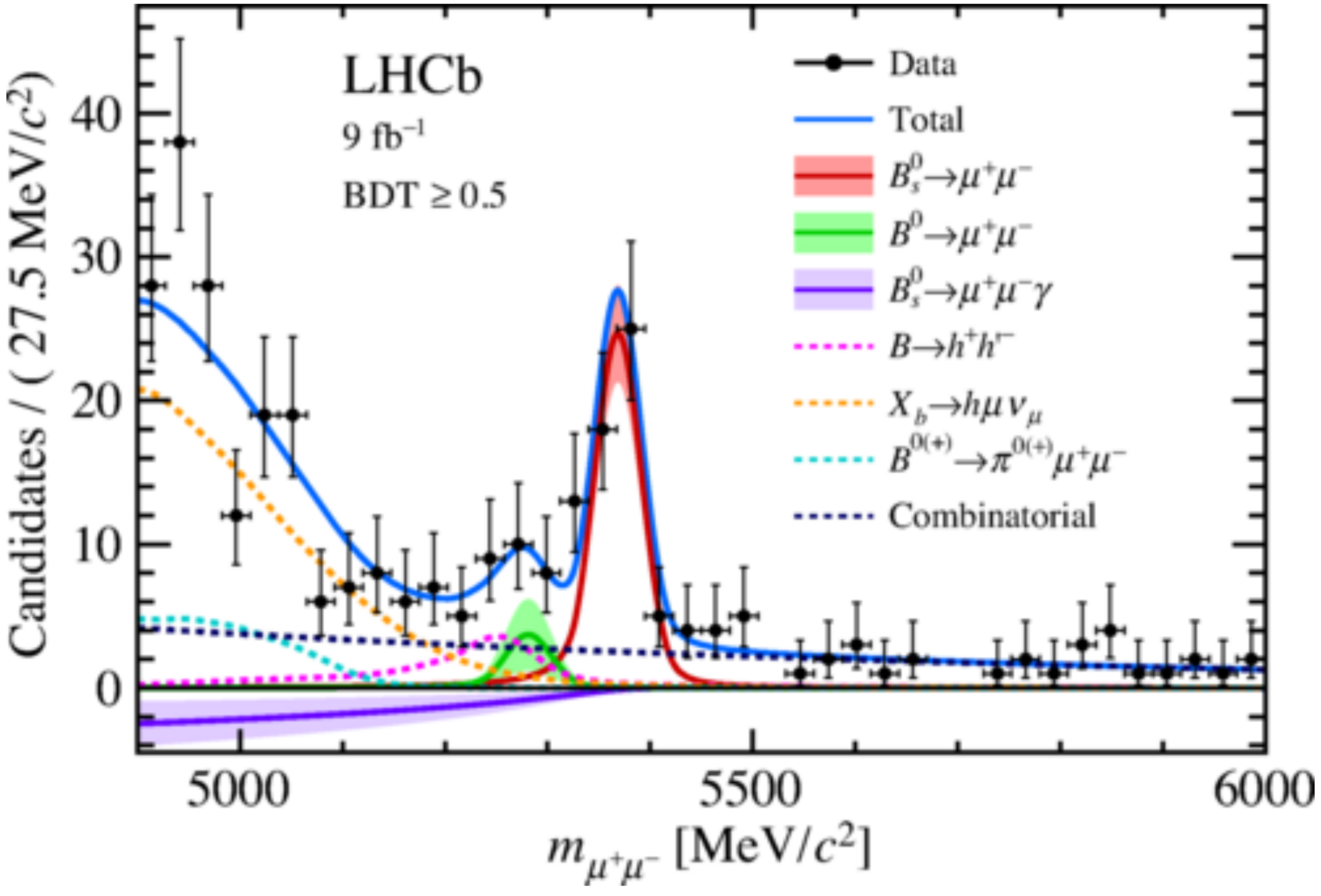
- **LHCb Run1+Run2**
  - $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46\ +0.15}_{-0.43\ -0.11}) \times 10^{-9}$

[Phys. Rev. Lett. 128, 041801]



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Latest CMS full Run2 Analysis: BMM5

$$\mathscr{B}(B_s \to \mu^+\mu^-) = [3.95^{+0.39}_{-0.37}\,(\text{stat})^{+0.29}_{-0.24}\,(\text{syst})] \times 10^{-9}$$

[Phys. Lett. B 842 (2023) 137955]

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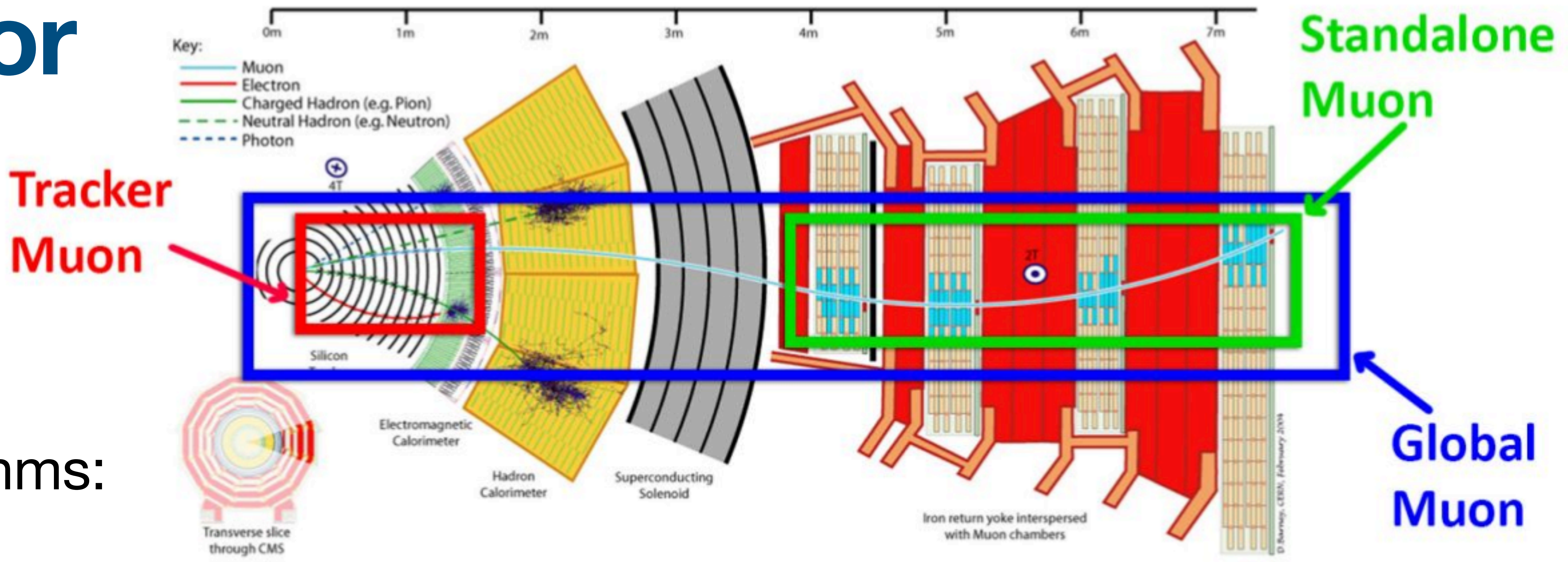
This is the analysis you will try to reproduce!

CMS detector



- Reconstruction algorithms:
  - **Standalone Muons**: reconstructed in muon system only
  - **Tracker Muon**: reconstructed in inner tracker only
  - **Global Muon**: reconstructed in both

- Good dimuon mass resolution ~0.6-1.5%
- Excellent muon identification and ~95% trigger efficiency
- Dedicated muon ID for $B_s \to \mu^+\mu^-$
- Dedicated trigger for this analysis

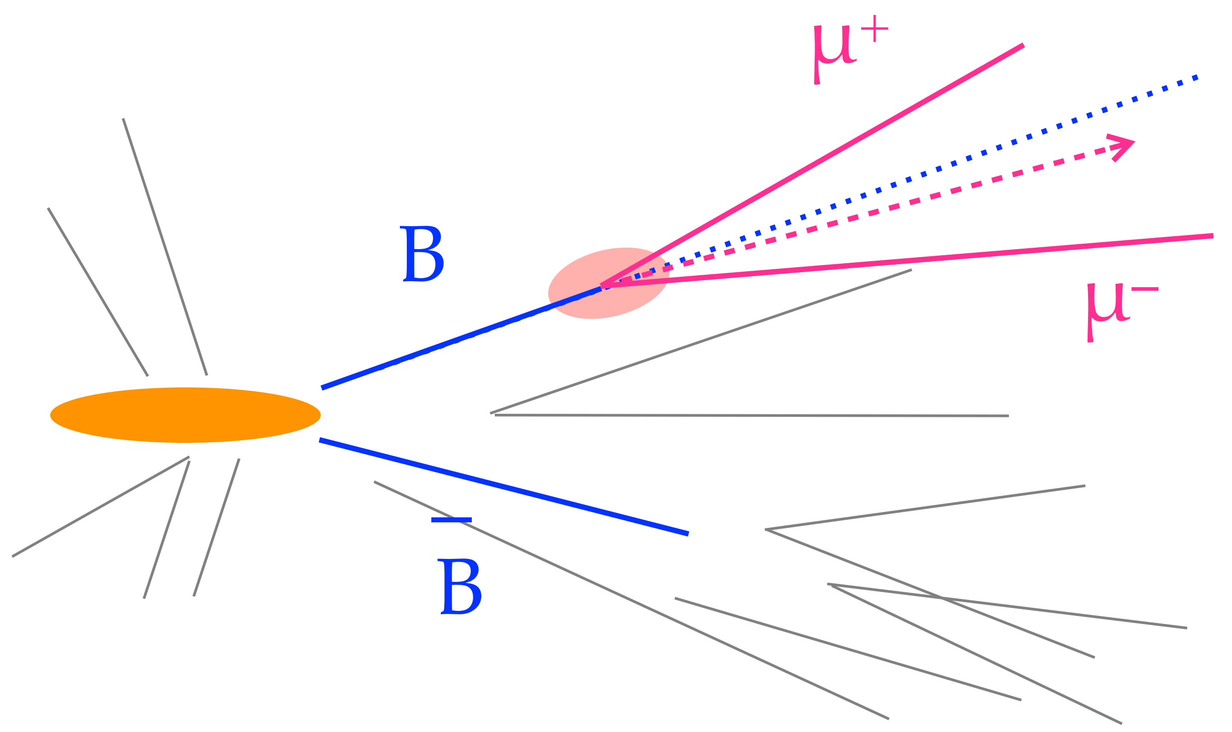
BPH Long Exercise: BMM5 Analysis

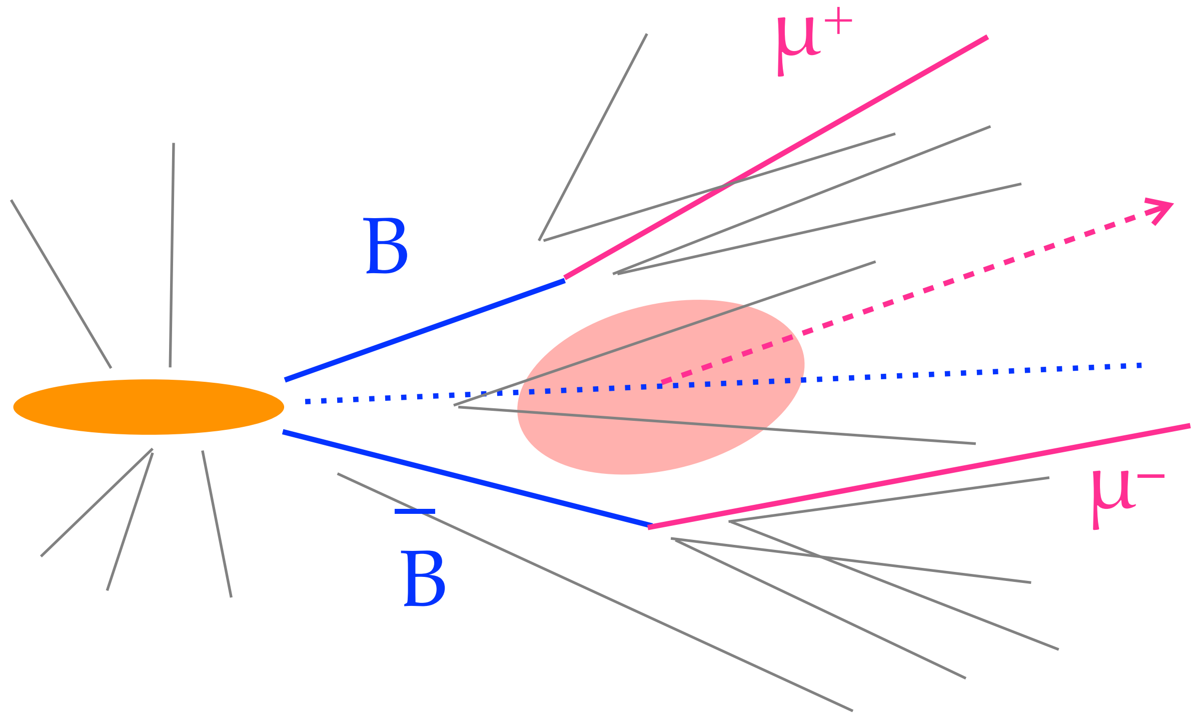
- The BPH long exercise consists into reproducing a slightly simplified version of the latest CMS $B_s \to \mu^+\mu^-$ measurement
  - Using full Run2 dataset = 140 fb^{-1} at 13 TeV
- The exercise instructions can be found in the long-ex-boh-bmm gitLab and in the twiki
- In the following slides we will go through the main steps of the *simplified* analysis together (the BMM5 original analysis is more complex, if interested you can find the details here)

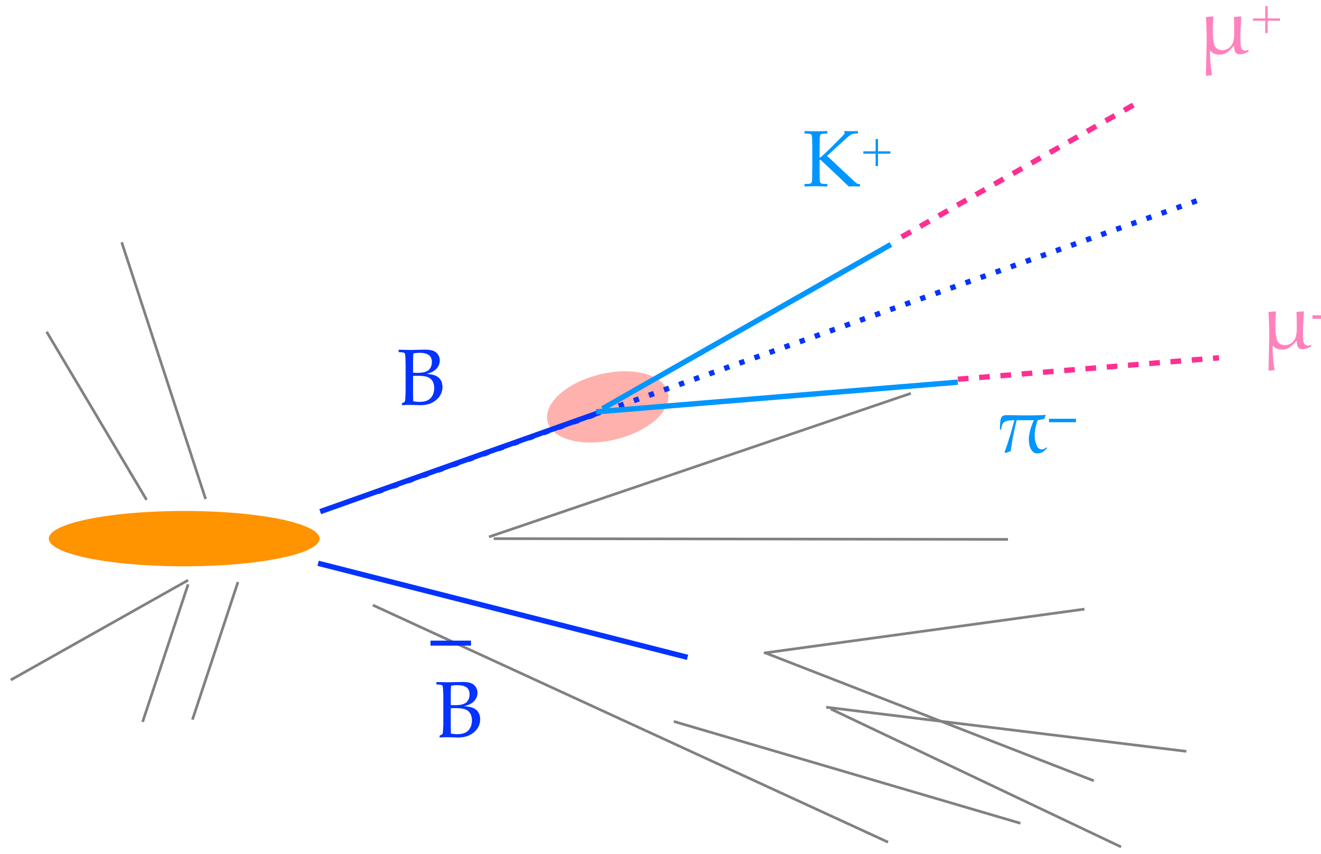
Signal and Backgrounds

- $B_s \to \mu^+\mu^-$ **signal**
  - two muons from one displaced vertex;
  - isolated from other activities;
  - momentum aligned with its flight direction;
  - invariant mass peaking at m(B_s).

- **Background Sources**
  - **Combinatorial background**
    - Two semileptonic B decays
    - One semileptonic B + misidentified hadron
  - **Rare Background** from single B meson decays
    - $B \to K\pi/KK/\pi\pi$ (peaking)
    - $B \to h^-\mu^+\nu, B \to h\mu^+\mu^-$(not peaking)







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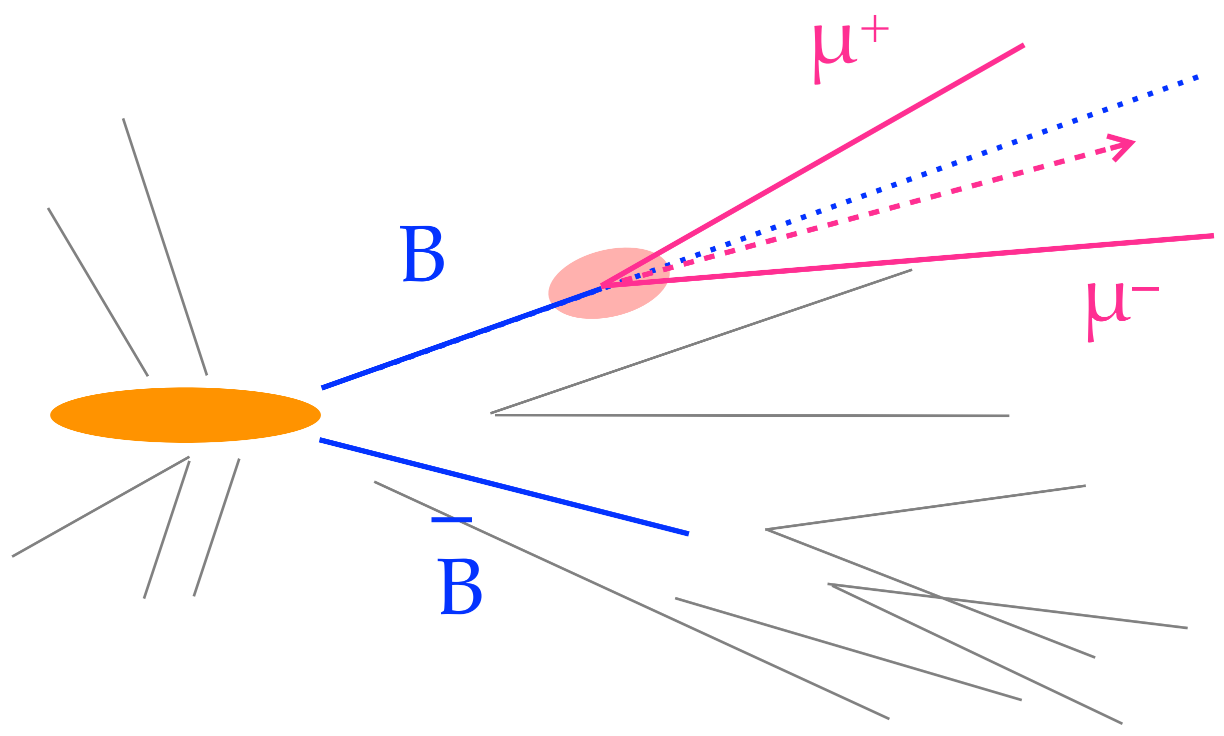

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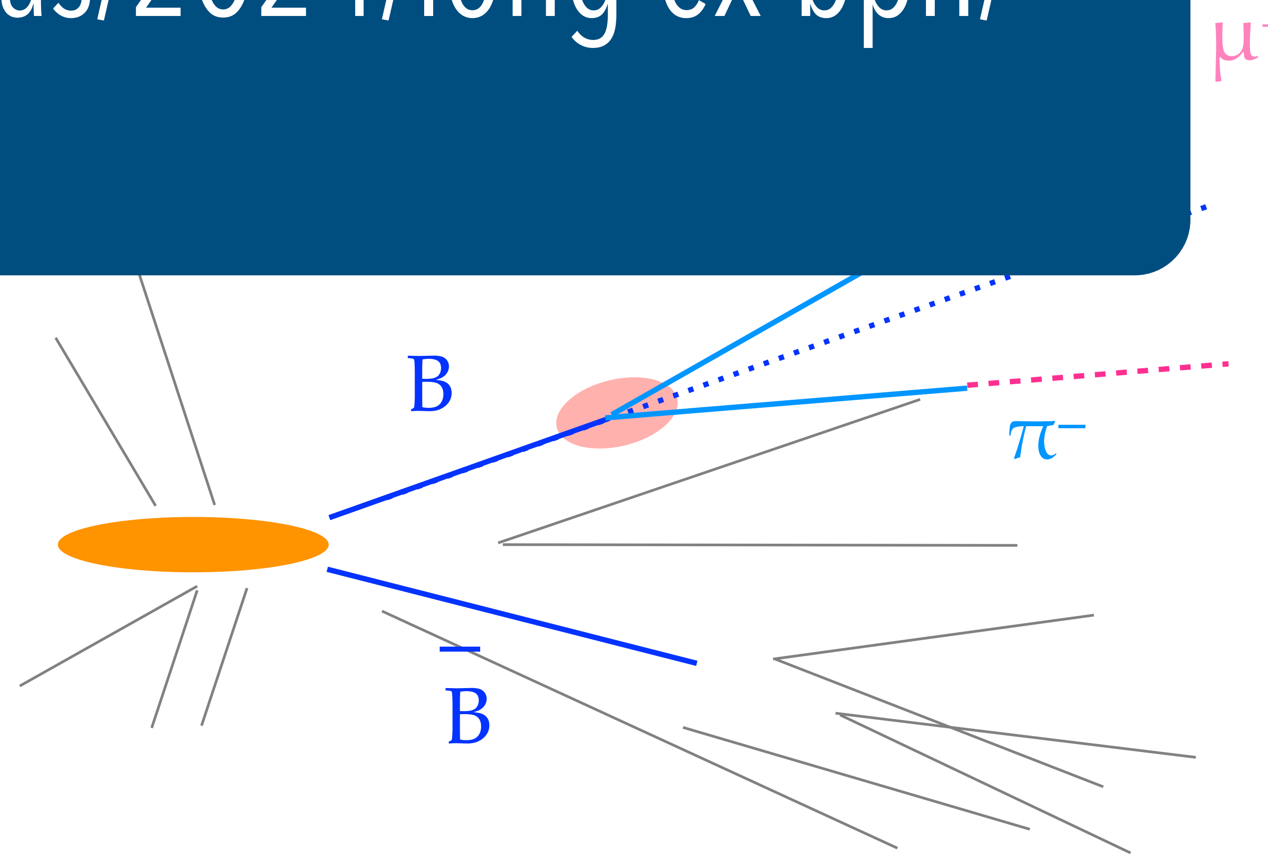
The MC samples for all these decays are provided in /eos/user/c/cmsdas/2024/long-ex-bph/



Analysis Strategy

- **Background suppression** mainly achieved with event classification BDT
- **Signal branching fraction normalisation** achieved with the definition of the normalisation channel $B \to J/\psi K$
- **Simultaneous fit** to $m_{\mu\mu}$ in 8 categories to extract $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
  - 4 eras of data: 2016BF, 2016GH, 2017, 2018
  - 2 channels: central or forward

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+)\mathcal{B}(J/\psi \to \mu^+\mu^-) \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \times \frac{\epsilon_{B^+ \to J/\psi K^+}}{\epsilon_{B_s^0 \to \mu^+\mu^-}} \times \frac{f_u}{f_s}$$

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```
// BF(B+ -> J/psi K+) = (1.010 +- 0.028) E-3 (PDG)
// BF(J/psi -> mu+mu-) = (5.961 +- 0.033) E-2 (PDG)
RooRealVar *BF_bu = new RooRealVar("BF_bu","",1.010E-3 * 5.961E-2);
```

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Final fitted number of signal events

Prefit value set to SM prediction

```
N_bs[idx] = new RooFormulaVar(Form("N_bs_%d", idx), "", "@0*@1*@2*@3/@4/@5",
                              RooArgList(*BF_bs, *N_bu, *fs_over_fu, *Eff_bs, *Eff_bu, *BF_bu));
```

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Number of B candidates from the normalisation channel

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$$\left(\frac{A^{B^+}}{A^{B_s^0}}\right) \times \left(\frac{\epsilon_{trig}^{B^+}}{\epsilon_{trig}^{B_s^0}}\right) \times \left(\frac{\epsilon_{\mu}^{B^+}}{\epsilon_{\mu}^{B_s^0}}\right) \times \left(\frac{\epsilon_{analysis}^{B^+}}{\epsilon_{analysis}^{B_s^0}}\right)$$

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- **Signal branching fraction normalisation** achieved with the definition of the normalisation channel $B \to J/\psi K$
- **Simultaneous fit** to $m_{\mu\mu}$ … $(B_s^0 \to$ …
  - 4 eras of data: 2016B…
  - 2 channels: central or…

Acceptance, trigger and μ efficiencies are provided in the /eos/user/c/cmsdas/2024/long-ex-bph/effyield.csv file

These have to be computed: they depend on the analysis selection!

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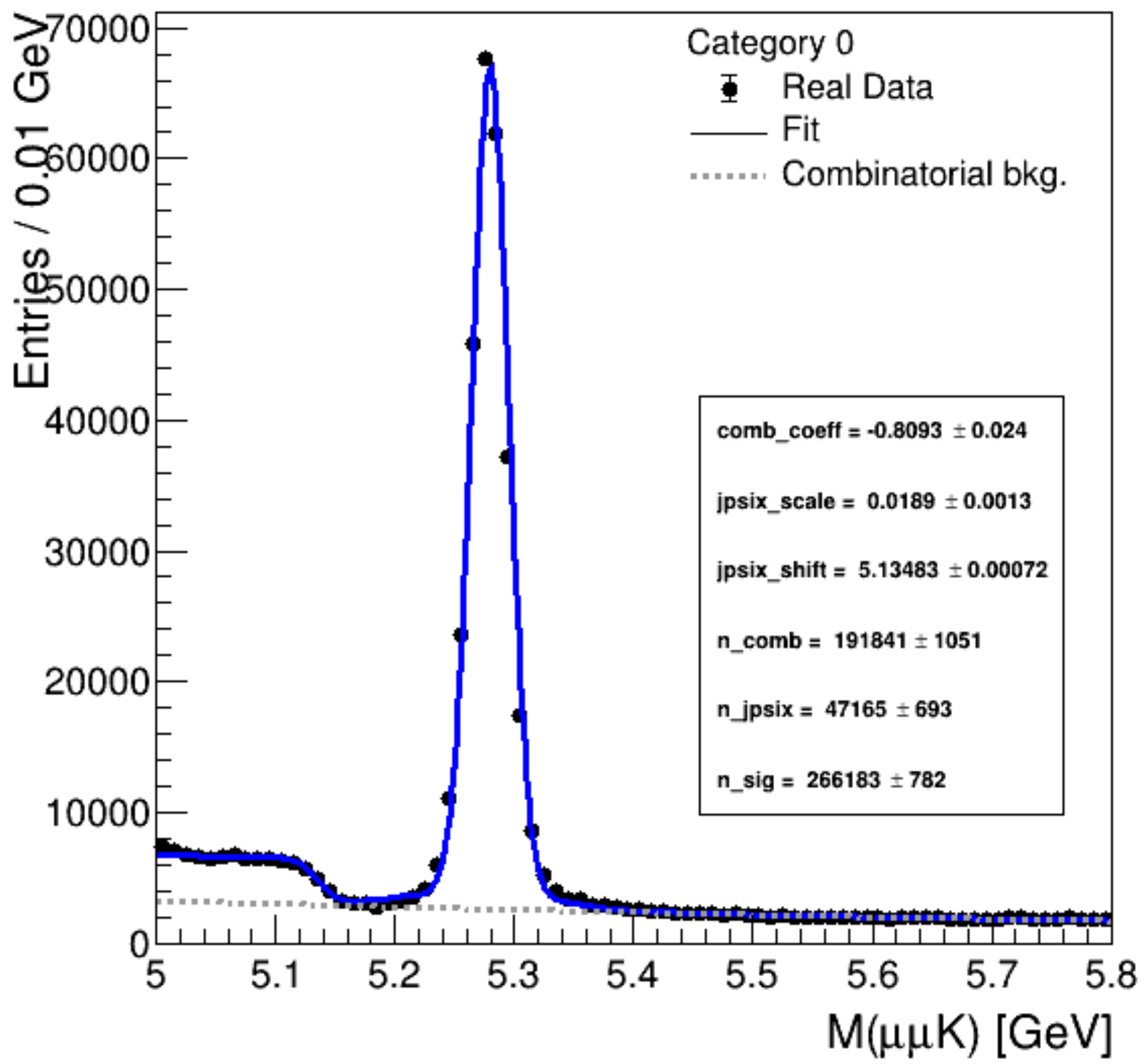
```
// fs/fu = 0.252 +- 0.012 (PDG) +- 0.015 (energy/pt dependence)
RooRealVar *fs_over_fu = new RooRealVar("fs_over_fu","",0.252);
```

External input: ratio of the probabilities for a b-qark to hadronize into a B_s^0 or a B^+

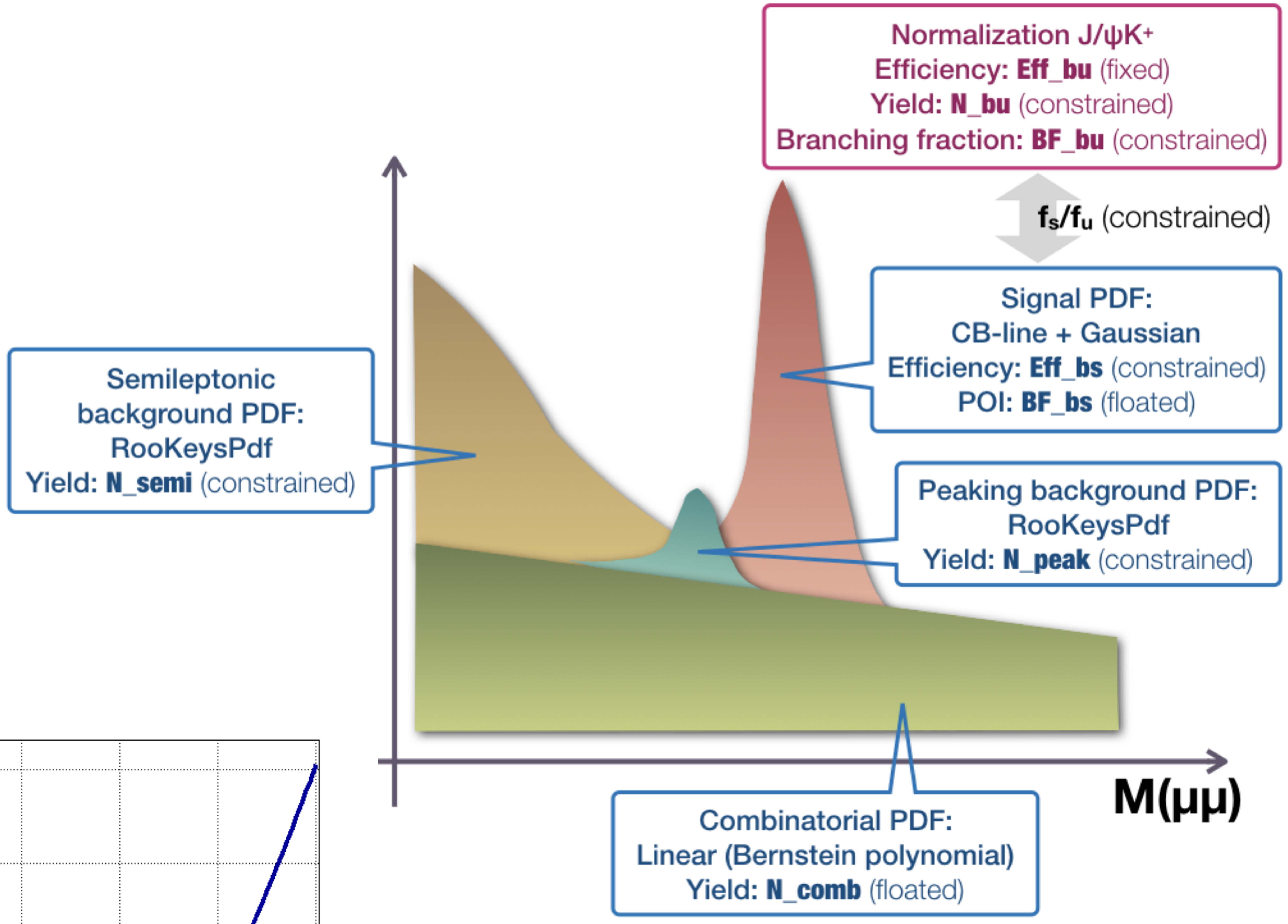
Normalisation Channel

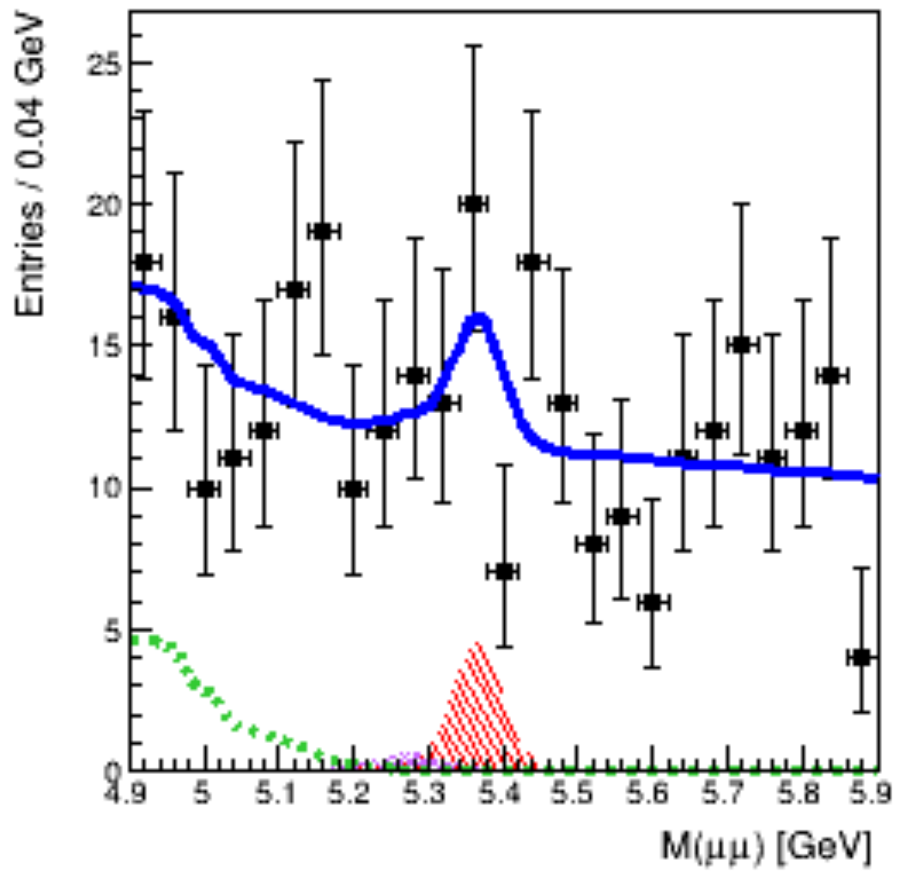
- $B \to J/\psi K$ is the normalisation decay
- **Fit to m($\mu\mu K$)**
  - Double Gaussian for **signal**
  - **Background contributions:**
    - Combinatorial: exponential
    - Partial reconstructed $J/\psi X$: error function

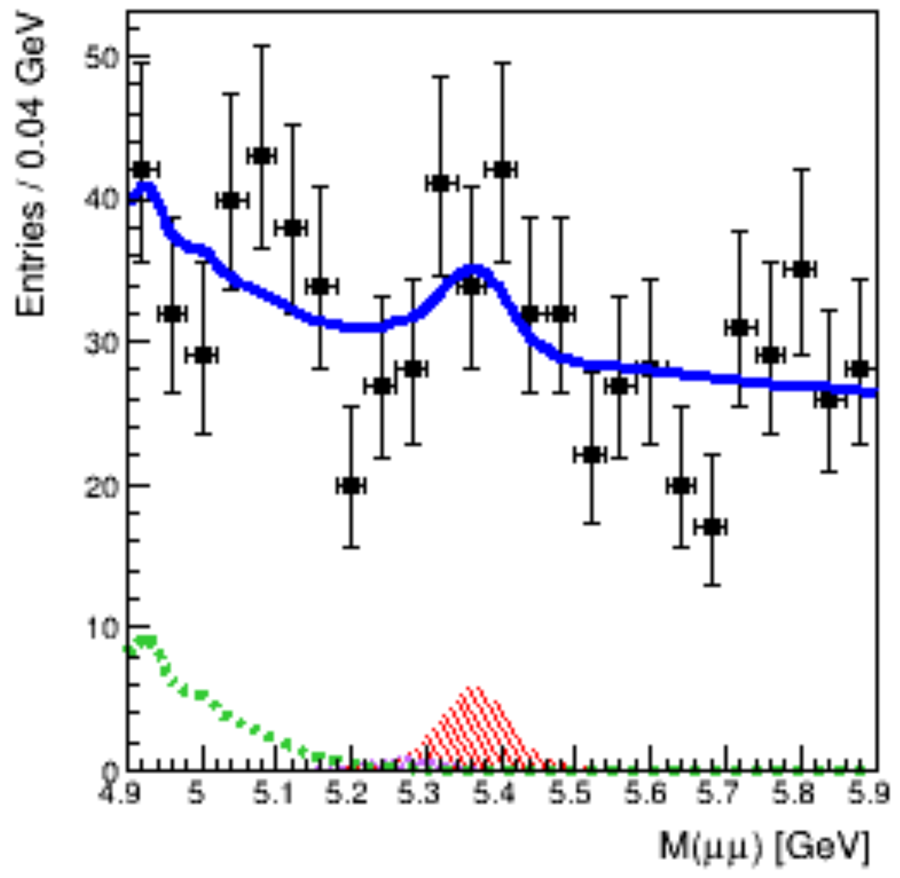


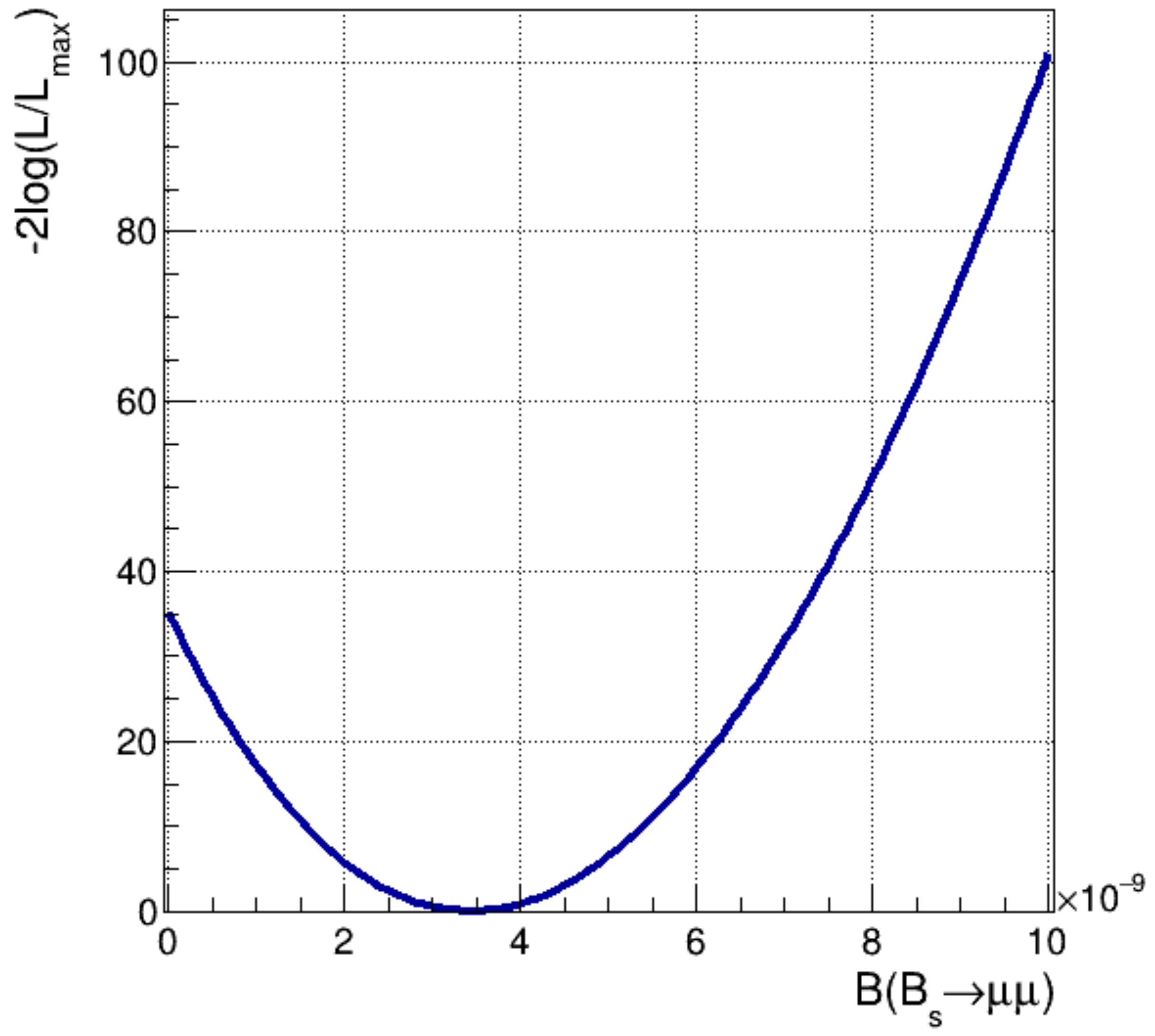
Final Fit Model

- Maximum Likelihood fit combines all the components
- BEFORE looking at the real data, the fit model is studied with the simulation
- The final result is found fitting real data









Tasks

- Follow the instructions for each task in the twiki
- **Work on your code**! The scripts are there to help you, but try by yourself first!
- The goal of the long exercise is to perform the final fit
  - First the blind fit to check that everything is working well
  - Eventually find the $\mathscr{B}(B_s \to \mu\mu)$ from real data (task #7)

Optional Tasks

- If you don't have enough time, you can skip
  - Task #3: verify fs/fu dependence
  - Task #6-4: add systematic uncertainties
    - More specifically you can skip toys with systs

- Task #1: Reconstruction of B mesons
- Task #2: Yield extractions with fits to normalization/control channels
  - Task #2-1: Fit to $B^+ \to J/\psi K^+$ MC
  - Task #2-2: Fit to $B^+ \to J/\psi K^+$ data
  - Task #2-3: Fit to $B^+ \to J/\psi K^+$ data (improved)
  - Task #2-4: Fit to $B^+ \to J/\psi K^+$ data (improved again)
  - Task #2-5: Fit to $B_s \to J/\psi\varphi$ events
- Task #3: Verify fs/fu dependence
- Task #4: Construct signal & background models
  - Task #4-1: Construct peaking background PDF
  - Task #4-2: Construct semileptonic background PDF
  - Task #4-3: Derive signal PDF from MC events
  - Task #4-4: Revisit the normalization channel, $B^+ \to J/\psi K^+$
  - Task #4-5: Store PDF models into RooWorkspace
- Task #5: Optimize BDT thresholds
- Task #6: Put all together -- branching fraction extraction
  - Task #6-1: Construct a (minimal) fitter for all categories
  - Task #6-2: Standard check: profiled likelihood scan
  - Task #6-3: Standard check: statistical tests with toy MC
  - Task #6-4: Systematic uncertainties as constrained nuisances
- Task #7: Fit to the unblind data and produce the results

Organisation

- **Rooms (use CERN Map if in doubt ;) :**
  - 29/1-001 (Wednesday-Friday)
  - 40/5-A01 (Saturday)
- **Timetable** (Indico)
  - Wednesday 9:20 → 12:30
  - Thursday 9:00 → 12:30 + 16:00 → 20:00
  - Friday 9:00 → 12:30 + 13:30 → 20:00
  - Saturday 9:00 →11:35 + 13:00 → 17:00

Work on the exercise

Prepare slides in the morning + presentations and school closing in the afternoon

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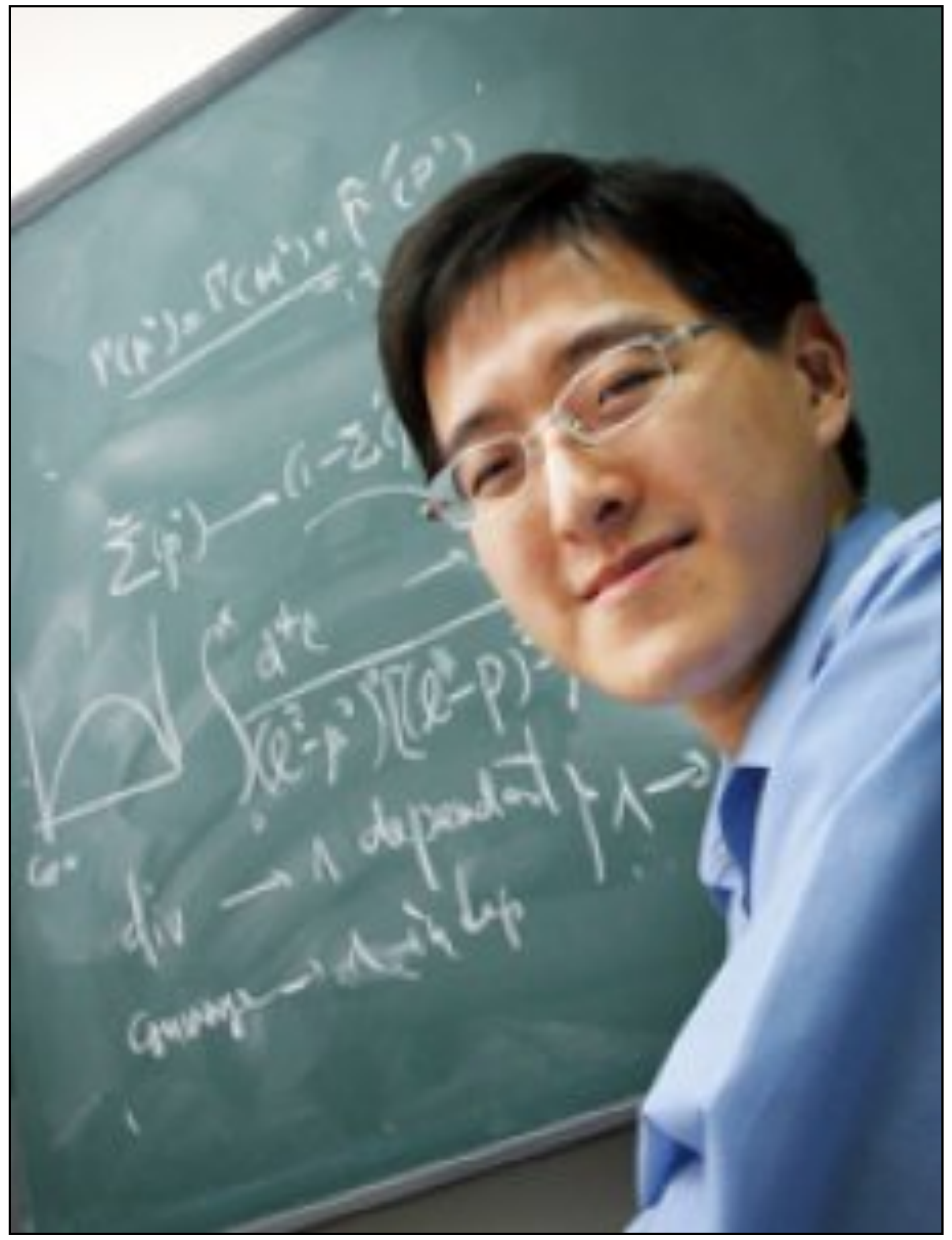
Since R1 closes early, with limited food options in the evening, we propose to go to dinner early (18:30 → 19:30) and continue with the exercise for another hour after dinner (19:30 → 20:30)

Let’s introduce each other!

Who are the facilitators?



- Name: **Kai-Feng (Jack) Chen**.
- Professor in Physics, National Taiwan University, Taipei.
- Ph.D. from the Belle experiment, joined CMS since 2006.
- Detector involvements (together with the whole team): Preshower → Phase-I Barrel Pixel → HGCAL
- Major physics works: Search for new heavy quarks (EXO/B2G), Measurement of $B \to \mu\mu$ (BPH), Search for rare top quark decays and CP violation (TOP).
- Was L2 conveners (BPH, TOP) and L3 conveners (EXO, BPH, PdmV)

Who are the facilitators?

- Name: **Federica Riti**.
- Bachelor and master in Physics in Rome, at Sapienza University
  - Master thesis in the ATLAS experiment
- Got my Ph.D. at ETH Zurich in February 2024
  - I worked in BPH at CMS: tested lepton flavour universality measuring the $R(J/\psi)$ ratio at CMS
  - ECAL detector operations
- I started my Research Fellowship at CERN in March 2024 with the CMS group
  - Soft tau-leptons and BPH measurements
  - Level-1 Trigger upgrade for Phase II

Now it's your turn :)