Moscow International School of Physics 2022
Dubna International Advanced School of Physics

Recent CMS flavor physics results

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Outline

- Why B→μμ? + previous results
- CMS experiment
- Analysis strategy
- Backgrounds
- Event selection
- Results

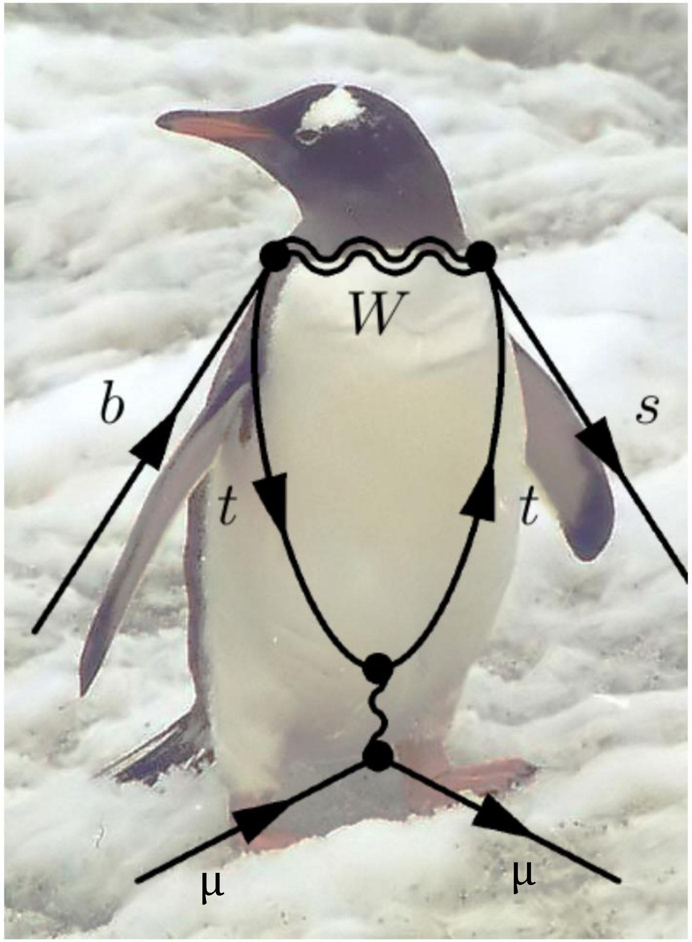
Why B→μμ ?

- The branching fractions of B^0 and $B_s^0 \to \mu\mu$ decays are predicted precisely in the ***SM*** and are very low

$$B(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[Beneke, Bobeth, Szafron, JHEP10(2019) 232]



- The decays also present <u>clean experimental signature</u>

- Any deviations from *SM* would present **a sign of *NP***

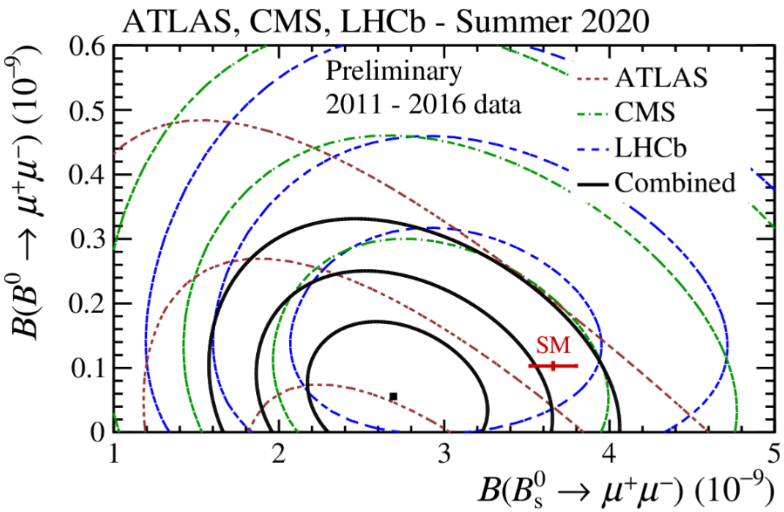
B→μμ: previous results

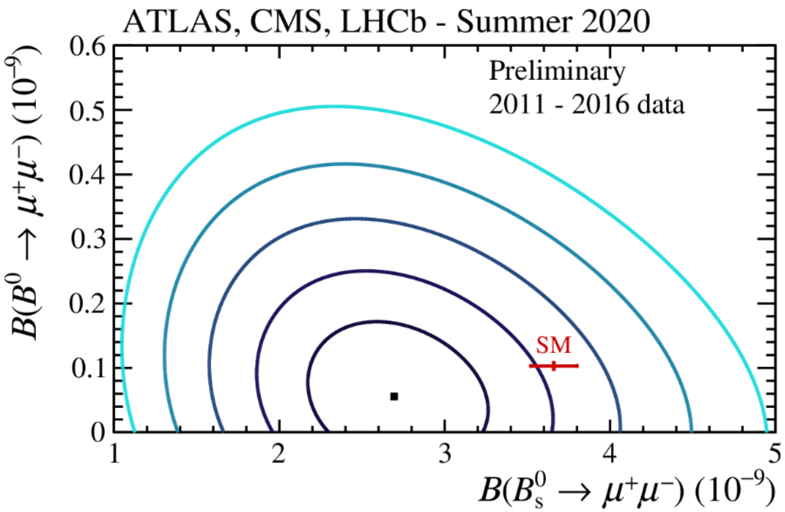
- ATLAS, CMS, LHCb have their results from partial Run-2:
  - ATLAS, 2015+2016 data, combined with Run-1, December 2018
  - CMS, Run-1 + 2016 data, October 2019
  - LHCb, Run-1 + 2016 data, March 2017

- Statistical Combination CMS+ATLAS+LHCb was performed in 2020 *(not published)*

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$$

CMS-PAS-BPH-20-003
ATLAS-CONF-2020-049
LHCb-CONF-2020-002

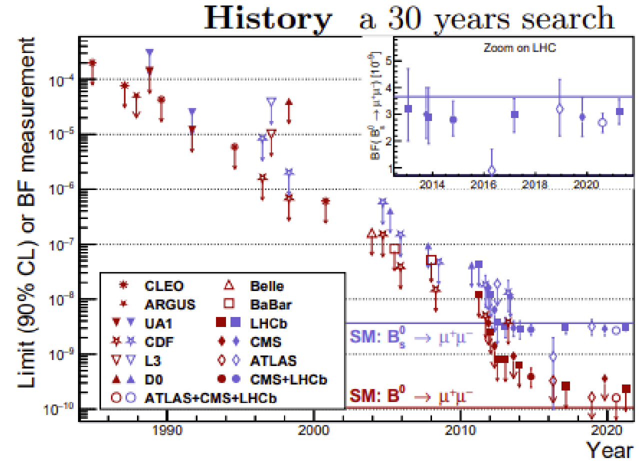




Compatible with SM within 2.1σ

B→μμ

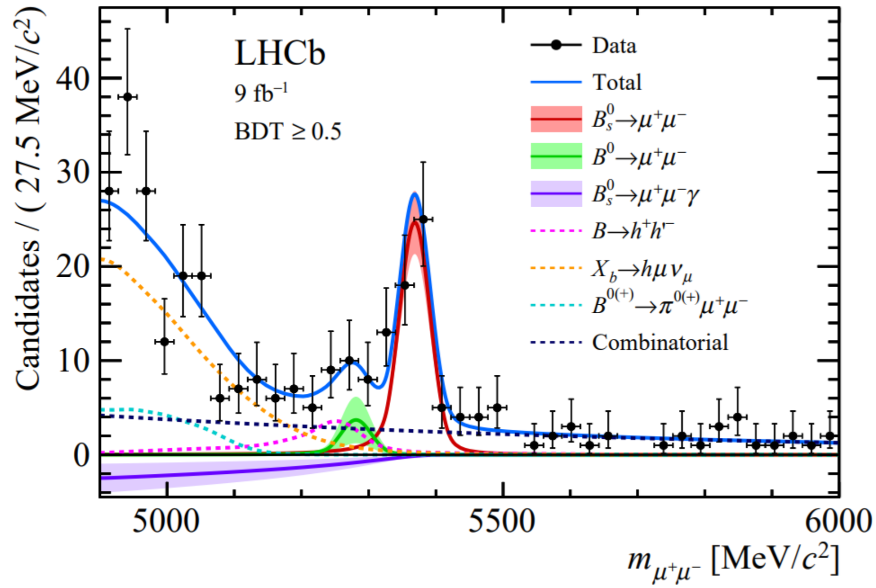
➢ The latest results [until ~2 weeks ago] on 30-year-long search are from LHCb, August 2021, Full Run-1 + Run-2

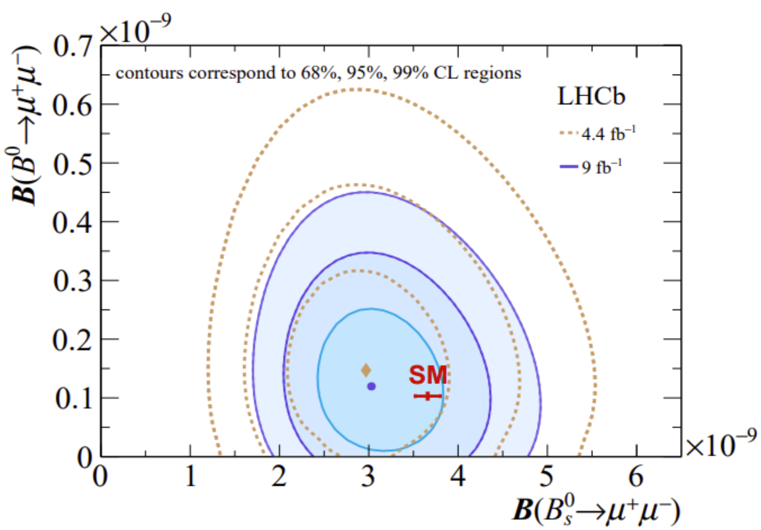


- B_s^0 >10σ, B^0 ~1.7σ

Consistent with SM

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.20\,^{+0.83}_{-0.74} \pm 0.14\right) \times 10^{-10},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ at 95\% CL}$$

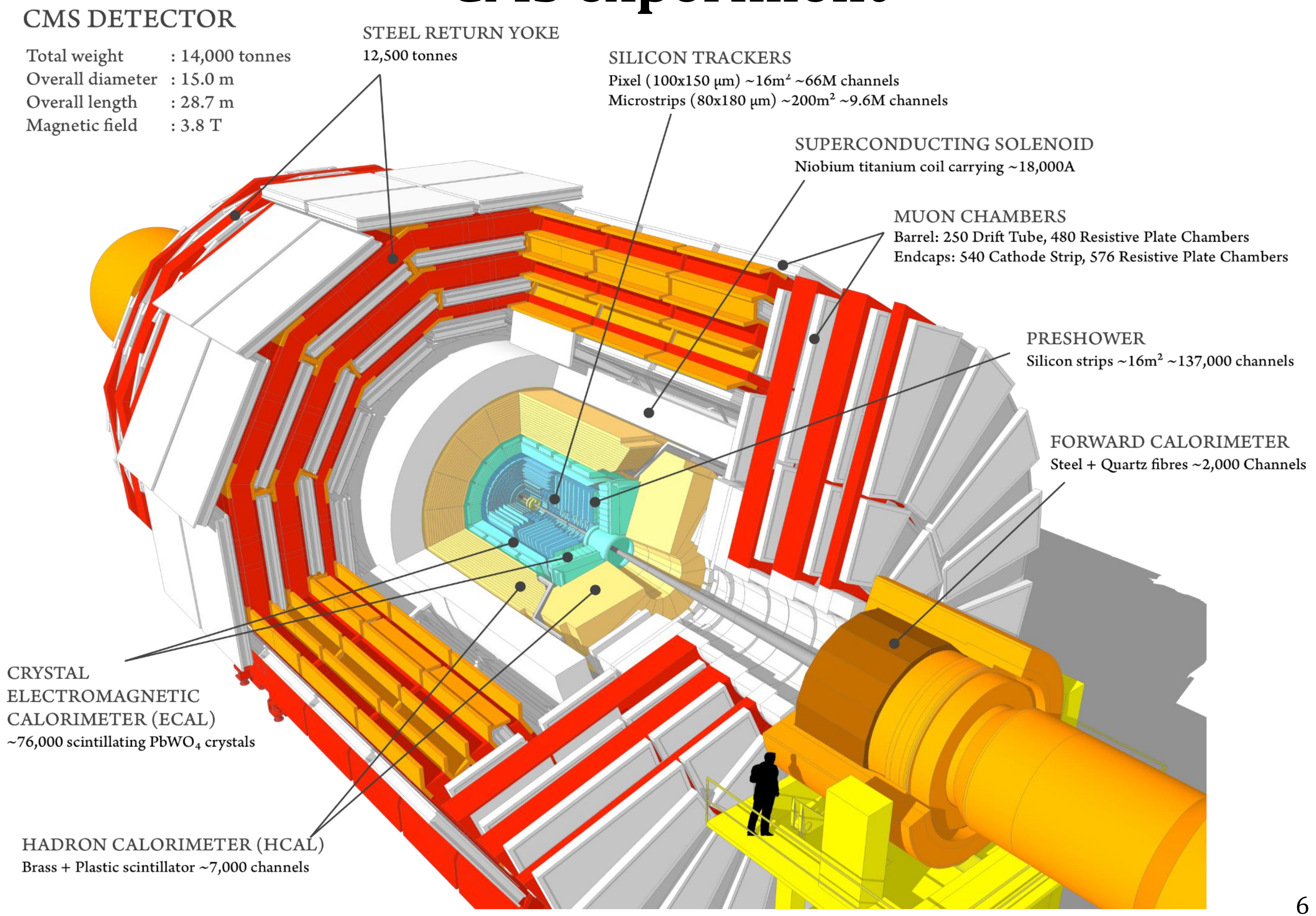




LHCb-PAPER-2021-008, Phys.Rev.D105(2022)012010
LHCb-PAPER-2021-007, Phys.Rev.Lett.128(2022)041801

Papers also reports effective lifetime and $B_s^0 \to \mu^+\mu^-\gamma$

CMS experiment



Analysis strategy

External input, ratio of B_s^0 and B^+ production xsections

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

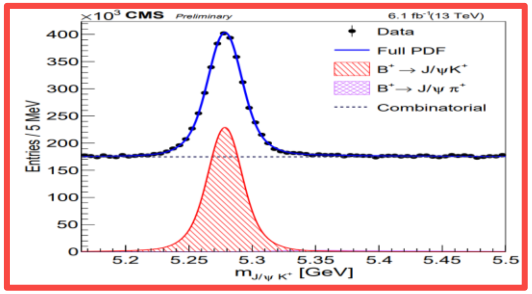
(or $$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to J/\psi\phi)\frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B_s^0\to J/\psi\phi}}\frac{\varepsilon_{B_s^0\to J/\psi\phi}}{\varepsilon_{B_s^0\to\mu^+\mu^-}},$$)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+)\frac{N_{B^0\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}}\frac{\varepsilon_{B^+\to J/\psi K^+}}{\varepsilon_{B^0\to\mu^+\mu^-}}\frac{f_u}{f_d}$$

$\frac{f_u}{f_d} \to 1$ $\sigma(B^+)=\sigma(B^0)$

Branching fractions are measured using the normalization channel **$B^+\to J/\psi K^+$**

- *Most systematic uncertainties cancel in the ratio*



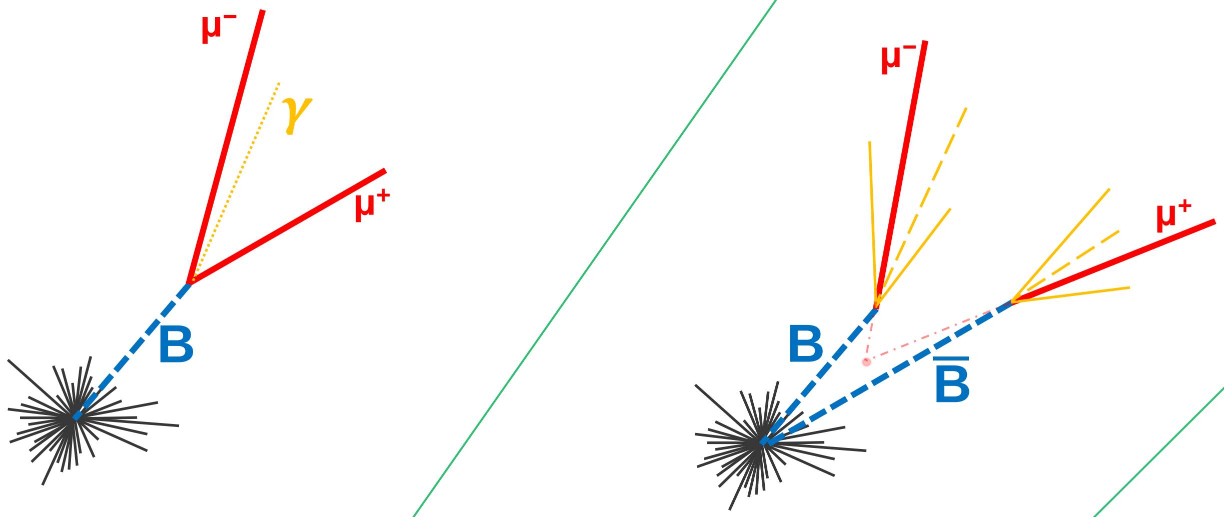
Data are split into 16 = 4*2*2 categories:

- 4 data-taking periods *(2016a, 2016b, 2017, 2018)*
- 2 $|\eta_\mu|$ (muon pseudorapidity) regions
- 2 ranges of MVA discriminator (0.9<MVA<0.99 and 0.99<MVA<1) *- see later*

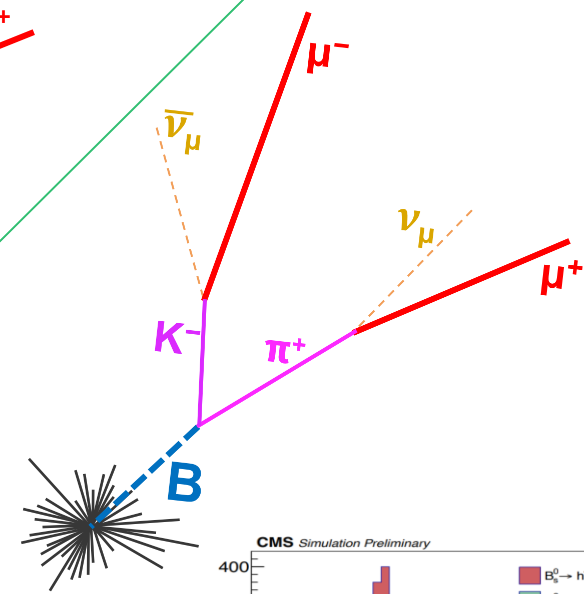
Fitting separately low- and high-sensitivity regions and combining the results yields in a more precise result

Backgrounds

Partially-reconstructed decays

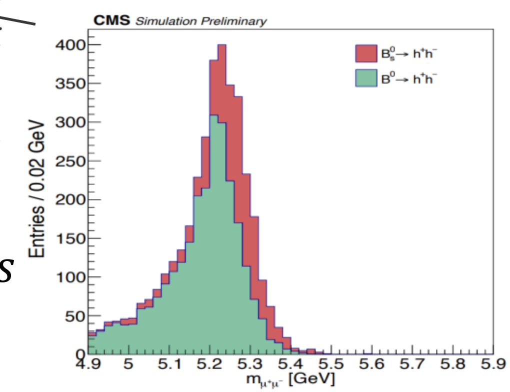


Combinatorial background



Decays in-flight of pions and kaons from **B→hh**, resulting in **double muon fakes**.

- <u>The most complicated bkg!</u> **Looks like signal**
- Reduced with MVA-based muon identification
  - *detecting imperfections in muon trajectory*
  - *Calibrated in data with* φ(1020) → K^+K^- *and* $K^0_S \to \pi^+\pi^-$ *decays*
- Rate is ~comparable to $B^0\to\mu\mu$, and the shape is close to $B^0\to\mu\mu$



Event selection

Selection	$B \to \mu^+\mu^-$	$B^+ \to J/\psi K^+$
B candidate mass [GeV]	[4.90, 5.90]	[4.90, 5.90]
Blinding window [GeV]	[5.15, 5.50]	
$p_{T\mu}$ [GeV]	> 4	> 4
$\lvert\eta_\mu\rvert$	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4
$p_{T\mu\mu}$ [GeV]	> 5	> 7
$\mu\mu$ SV probability	> 0.025	> 0.1
$\mu\mu$ invariant mass [GeV]	[4.9, 5.9]	[2.9, 3.3]
Kaon p_T [GeV]		> 1
Mass-constrained fit probability		> 0.025
2D $\mu\mu$ pointing angle [rad]		< 0.4

Full Run-2 data (140 fb^{-1})

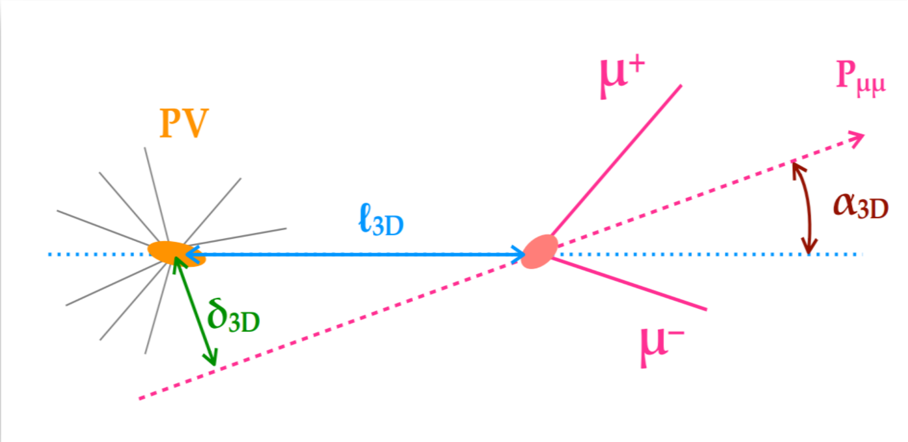
Loose pre-selection before MVA:

Final selection:

<u>MVA trained with XGBoost</u>

(MC for signal, data sidebands for bkg) is used to suppress dominant backgrounds

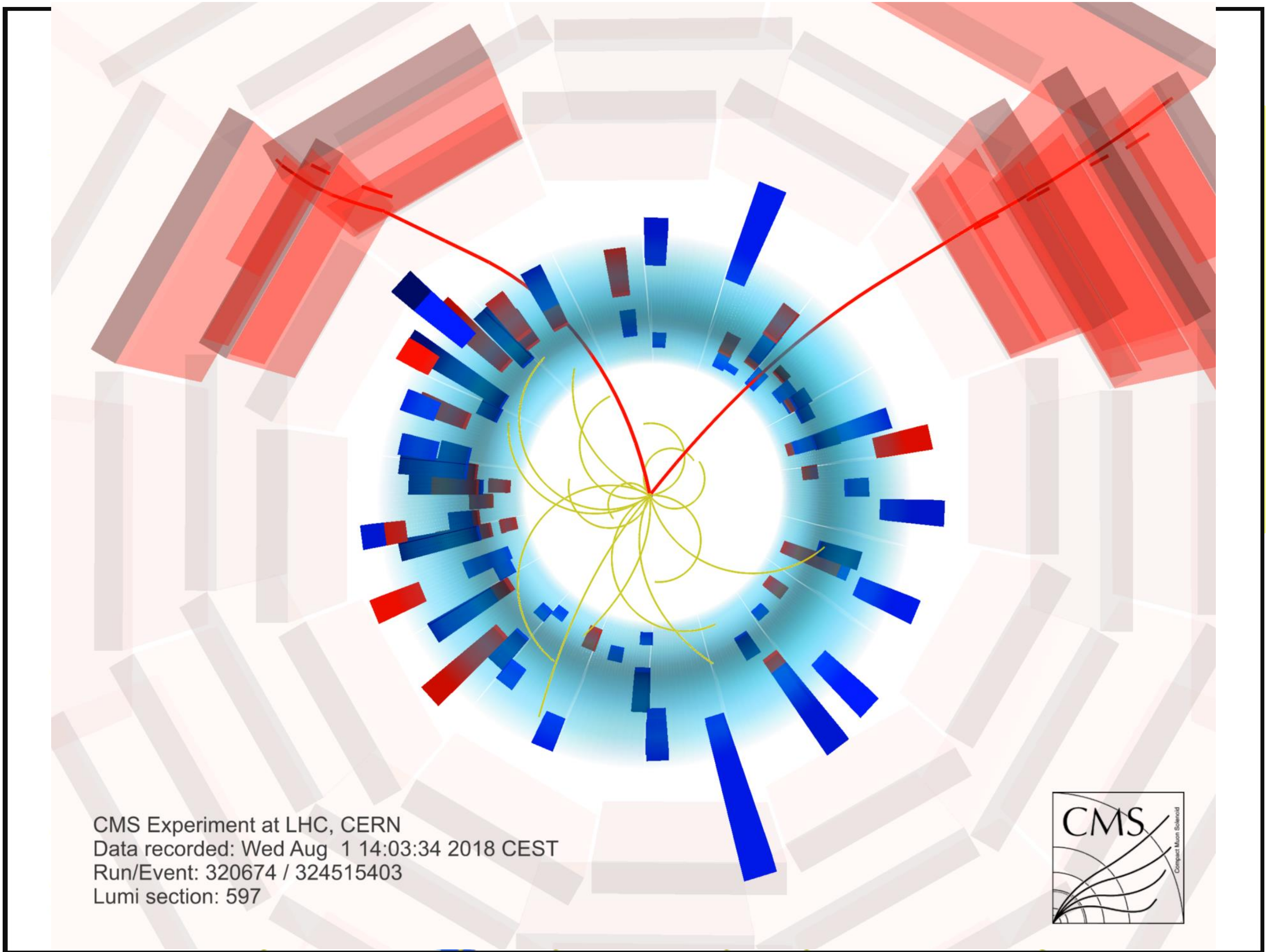
Employed variables identify the **distinct topology of B→μμ decays**

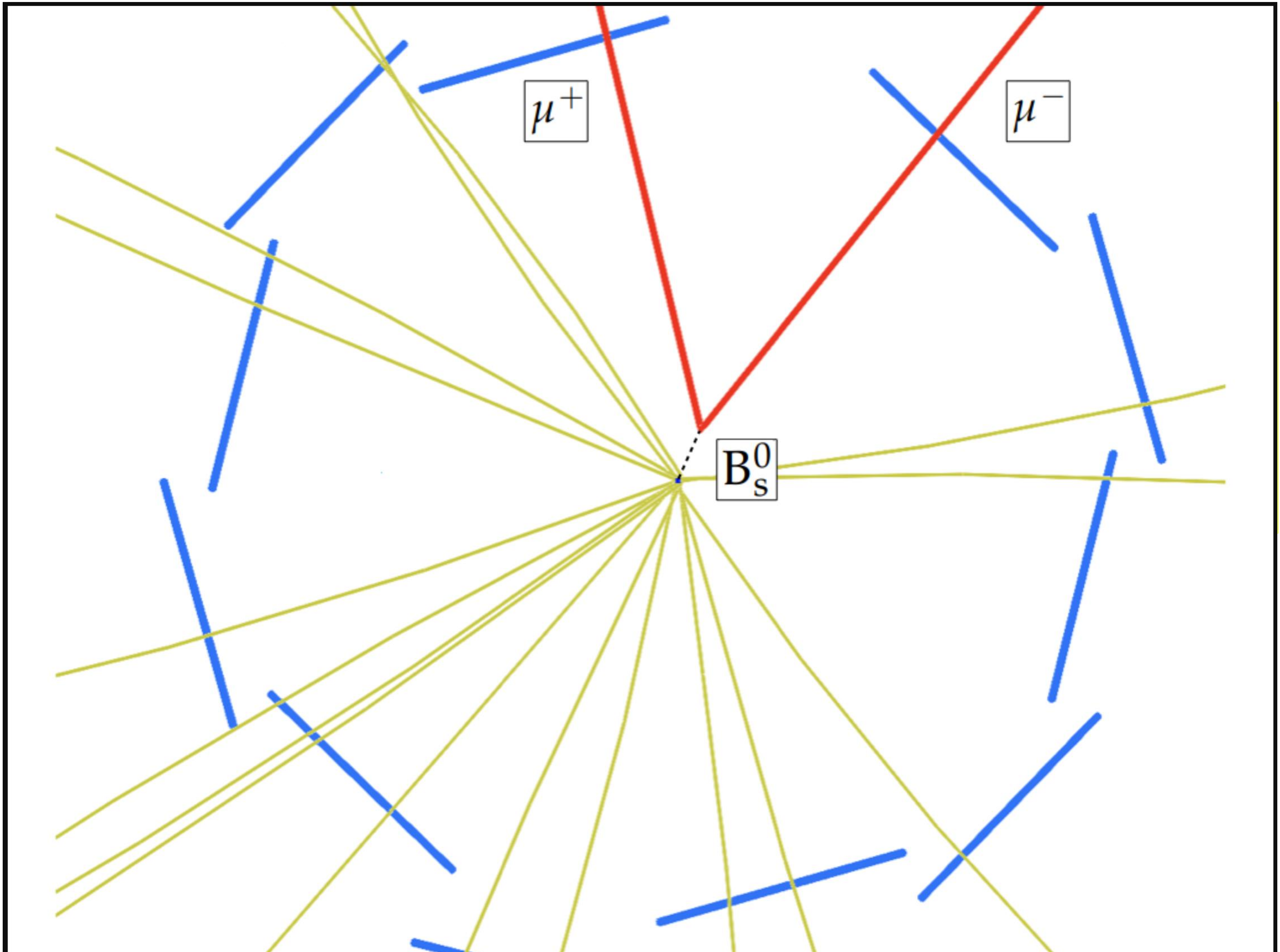


- 2D and 3D pointing angles **α**
- 2D and 3D impact parameter **δ**
- Flight length ***l*** and its significance ***l/σ_l***
- Dimuon vertex quality
- Isolation of muons and the dimuon

Normalization channel $B^+ \to J/\psi K^+$ is used to calibrate MVA with data

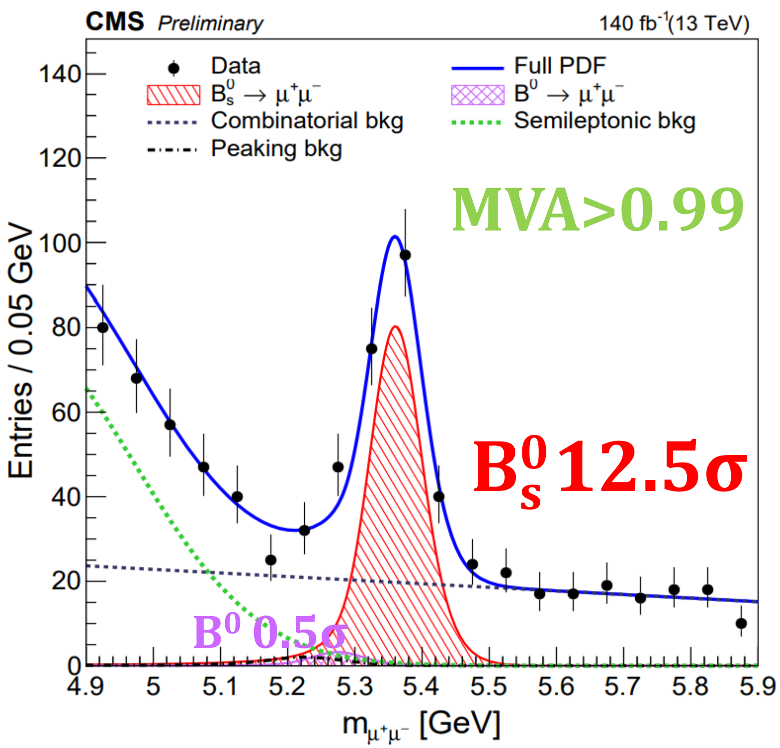
- $p_T(K^+) < 1.5$ GeV and rescaled l/σ_l make a bridge between $B \to \mu^+\mu^-$ and $B^+ \to J/\psi K^+$

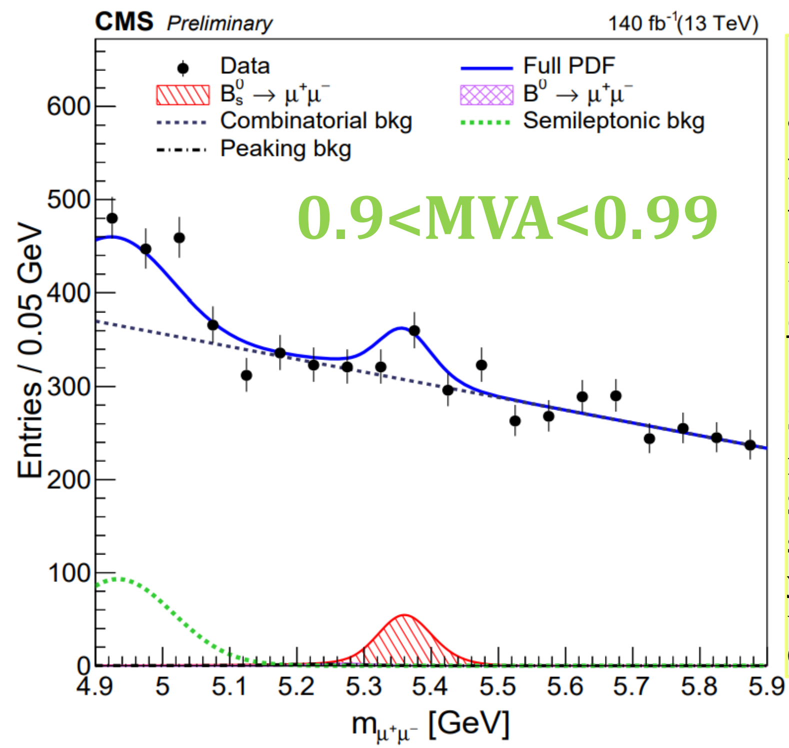

CMS Experiment at LHC, CERN
Data recorded: Wed Aug 1 14:03:34 2018 CEST
Run/Event: 320674 / 324515403
Lumi section: 597
CMS
Compact Muon Solenoid



μ^+
μ^-
B_s^0

Results





2D fit to **mass** and **per-event mass uncertainty** in <u>16 categories</u>

Signal shape fixed to MC
SL and peak. bkg shapes fixed to MC; yields constrained using MC predictions
Comb.bkg. - polynomial

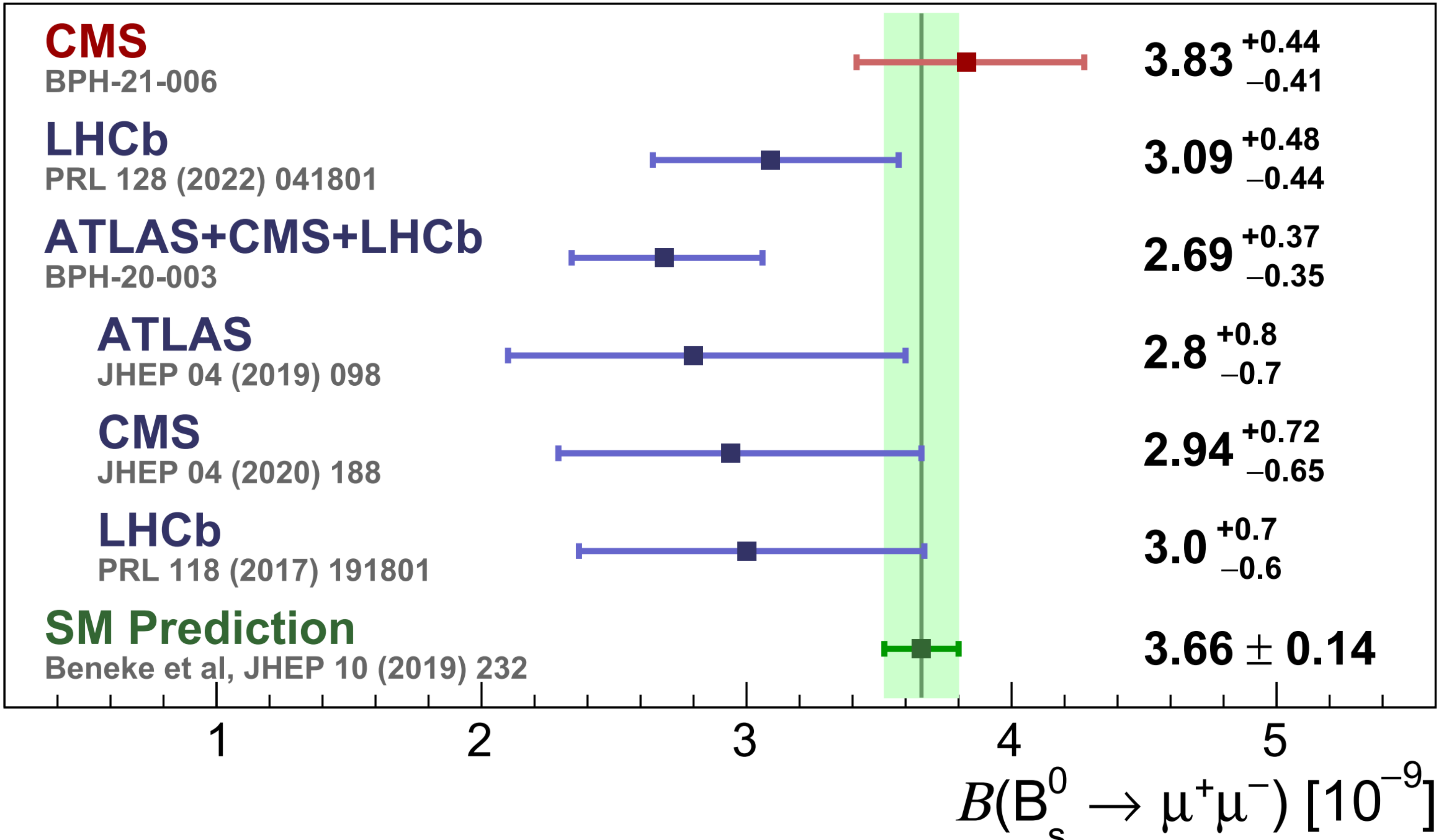
Merged (*2016-2018, both $|\eta_\mu|$ intervals*) projections of the fit and data in 2 MVA ranges

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\,(\text{stat})\,^{+0.08}_{-0.09}\,(\text{syst})\right] \times 10^{-10}.$$

$\mathcal{B}(B^+ \to J/\psi K^+) = (1.020 \pm 0.019) \times 10^{-3}$,
$\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033) \times 10^{-2}$
$f_s/f_u = 0.231 \pm 0.008.$

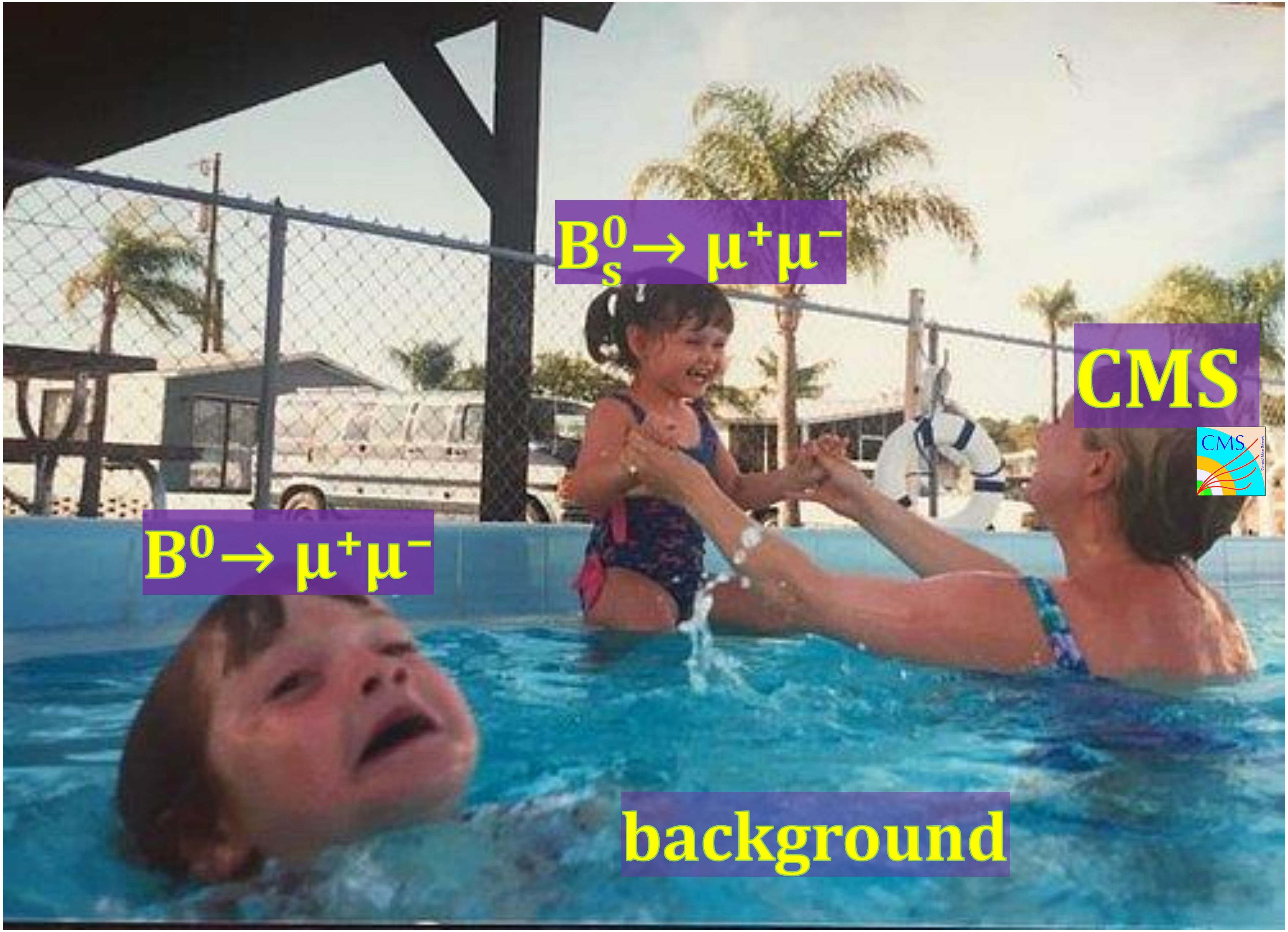
Results for $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$



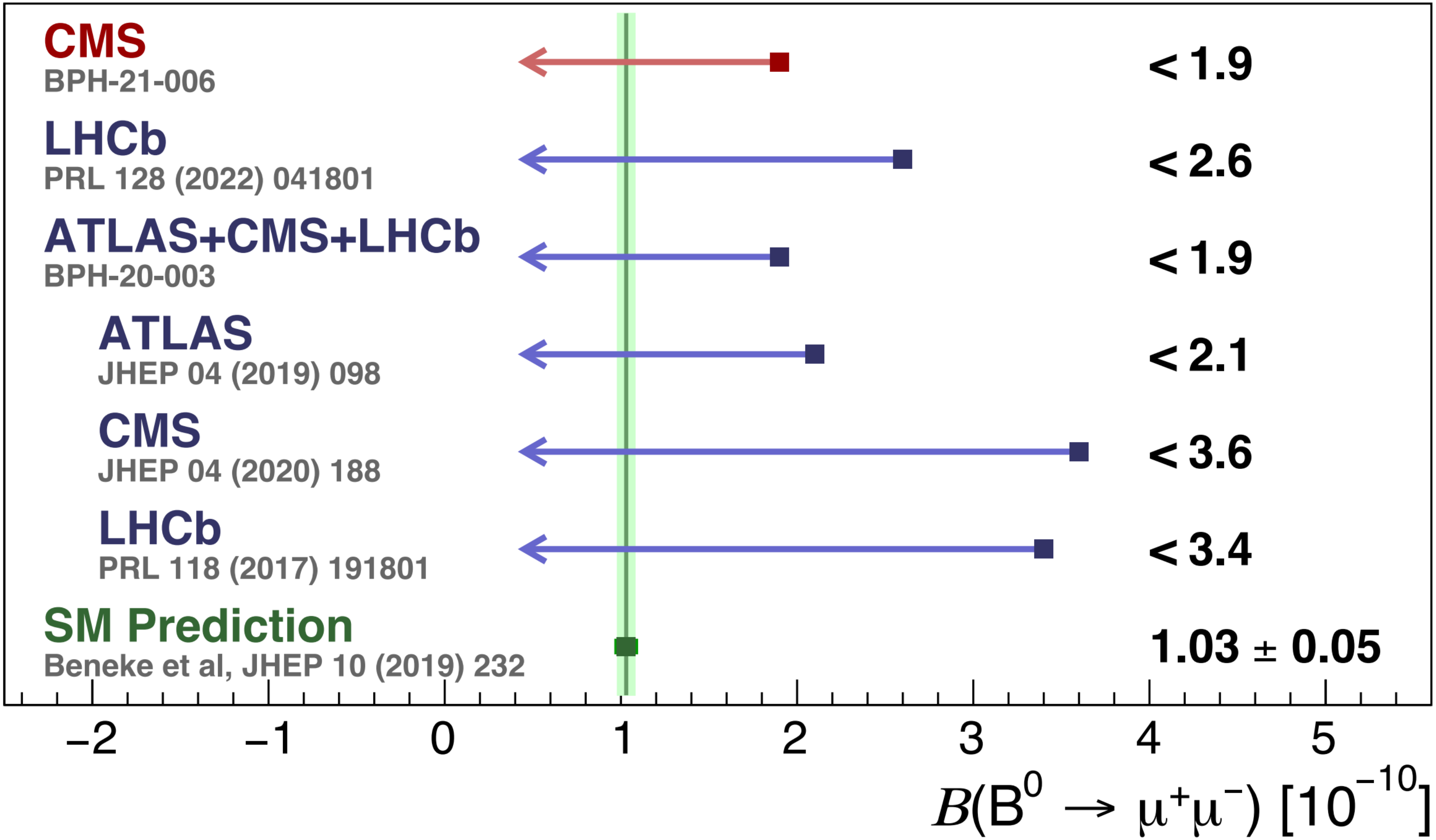
The most precise measurement to date!

Excellent consistency with the SM!

Results (simplified version)



Results for $\mathcal{B}(B^0 \to \mu^+\mu^-)$



The most stringent single-experiment upper limit!

Summary

- A new measurement of $B \to \mu\mu$ decays is performed by CMS
- The result has **world-leading precision and agrees with the SM**
- Measurement of $B_s^0 \to \mu^+\mu^-$ effective lifetime is also reported (see backup)
- Now waiting for ATLAS EXPERIMENT result to perform a full LHC Run-2 combination!

- Run-3 will bring additional sensitivity with improved triggers!
    - Most likely we need to wait until Run-4 to observe $B^0 \to \mu^+\mu^-$

Read more: CMS-BPH-21-006

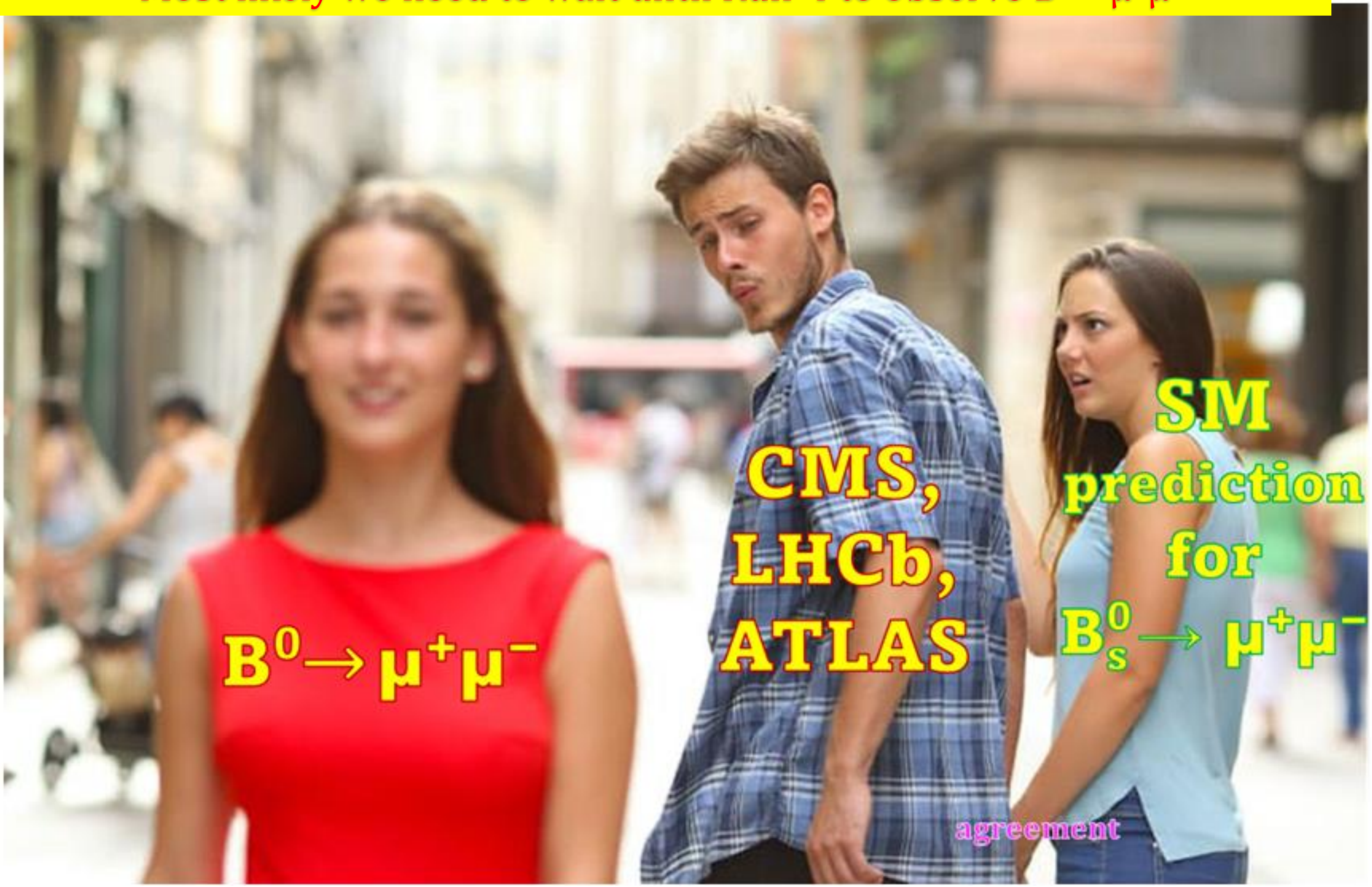
cms.cern/news/new-study-rare-b-meson-decays-two-muons

https://cds.cern.ch/record/2815334/files/BPH-21-006-pas.pdf

Thank you !

Summary

Most likely we need to wait until Run-4 to observe $B^0 \to \mu^+\mu^-$



Thank you !

BACKUP

Systematic uncertainties

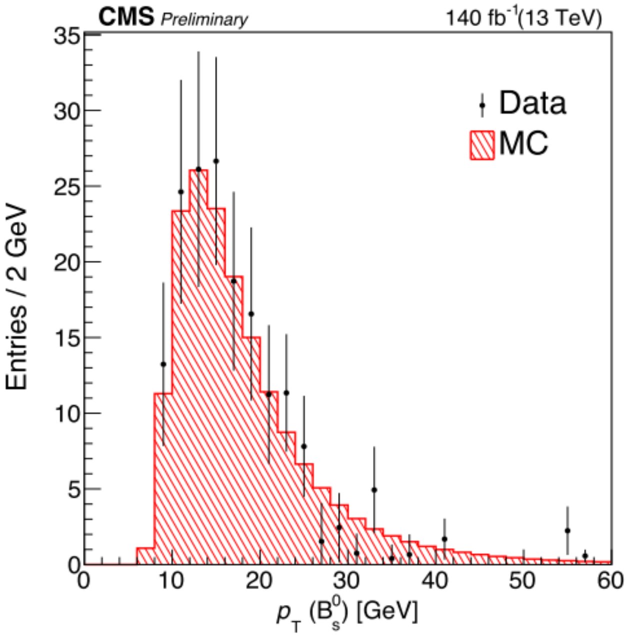
Effect	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
Trigger efficiency	2 – 4%	
Pileup	1%	
Vertex quality requirement	1%	
MVA_B correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
Fit bias	2.2%	4.5%
f_s / f_u - ratio of the B meson production fractions	3.5%	-

- Signal efficiency is correlated with the lifetime
  - Branching Fractions are measured assuming the SM value
  - For alternative lifetime hypothesis scale BF using the following expression

$$\alpha_{BF} = 1.577 - 0.358\,\tau$$

  - τ is in ps

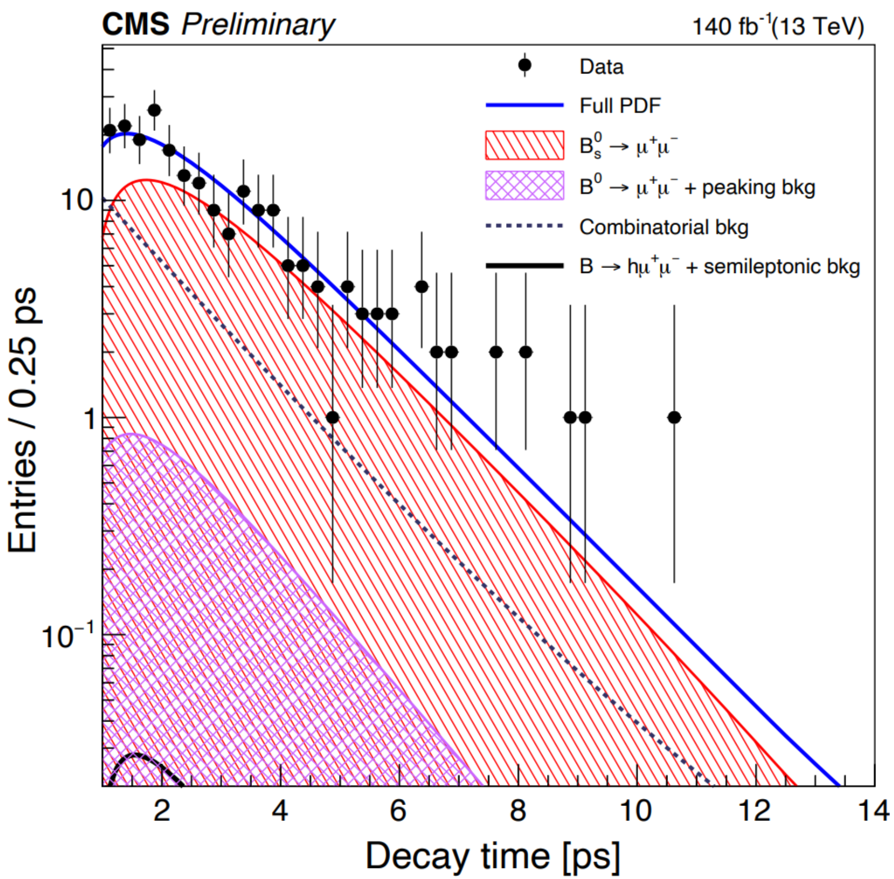
f_s/f_u



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

- f_s/f_u = 0.231±0.008
  - Based on P_T-dependent results from LHCb
    - PRD 104 (2021) 032005
    - Integrate with the effective P_T distribution
  - Previous measurement used 0.252±0.032
- Resulting BF can be rescaled:
  - One can use a different f_s/f_u value
  - Treated as an external uncertainty
    - not as a constrained nuisance parameter

Effective lifetime measurement



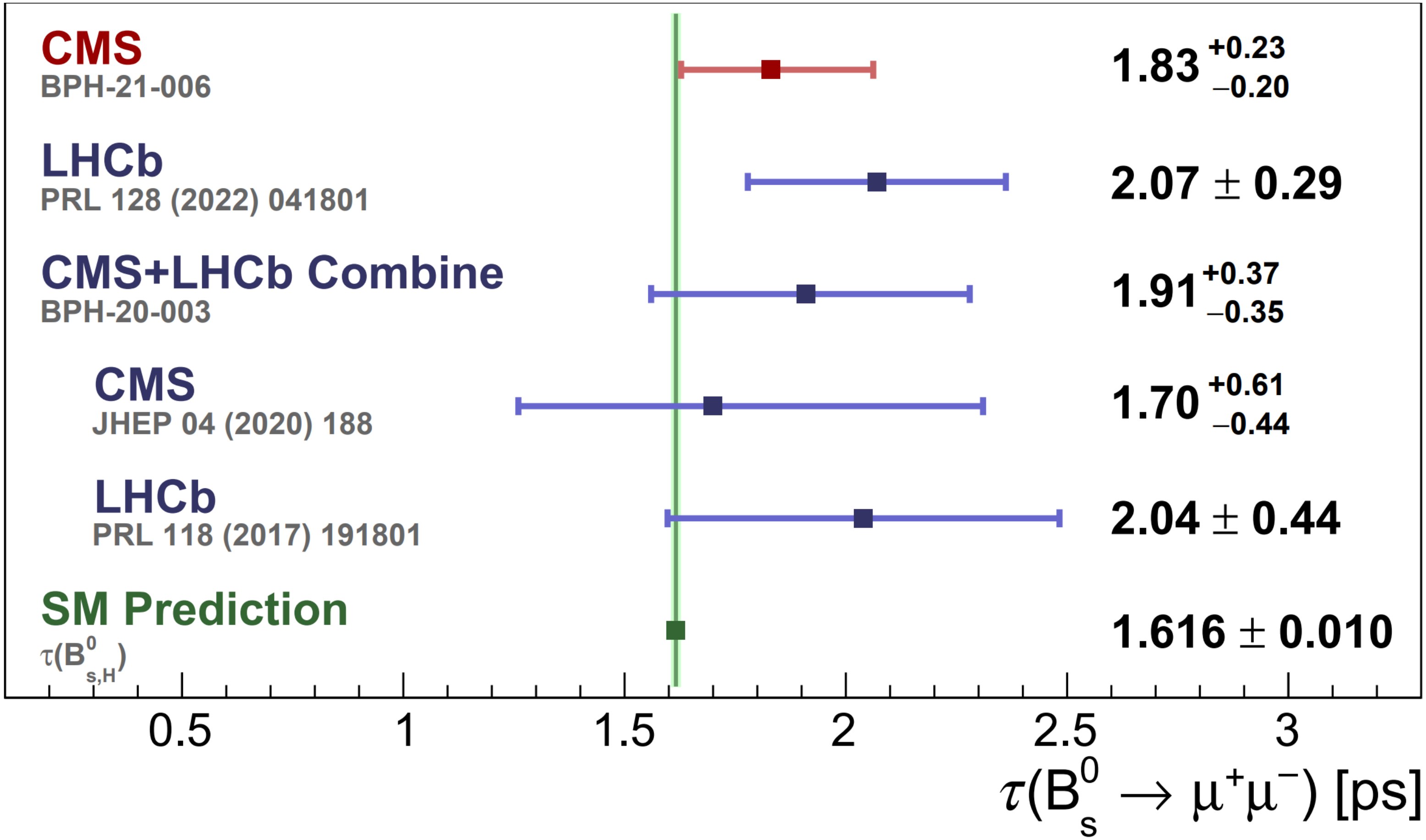
- In the absence of CP violation only the heavy Bs state decays into dimuon
  - Different composition of states may be allowed by New Physics.
- Efficiency correction
  - Decay time efficiency derived from MC
  - Corrected by $B^+ \to J/\psi K^+$ data to mitigate the bias from tight MVA_B requirement.
    - The residual bias and the difference between $B_s \to \mu\mu$ and $B^+ \to J/\psi K^+$ are considered as a systematic uncertainty.

Systematics:

Effect	2016a	2016b	2017	2018
Efficiency modeling	0.01			
Lifetime dependence	0.01			
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Lifetime fit bias	0.04	0.04	0.05	0.04
Total	0.11	0.07	0.05	0.04

Results for effective lifetime

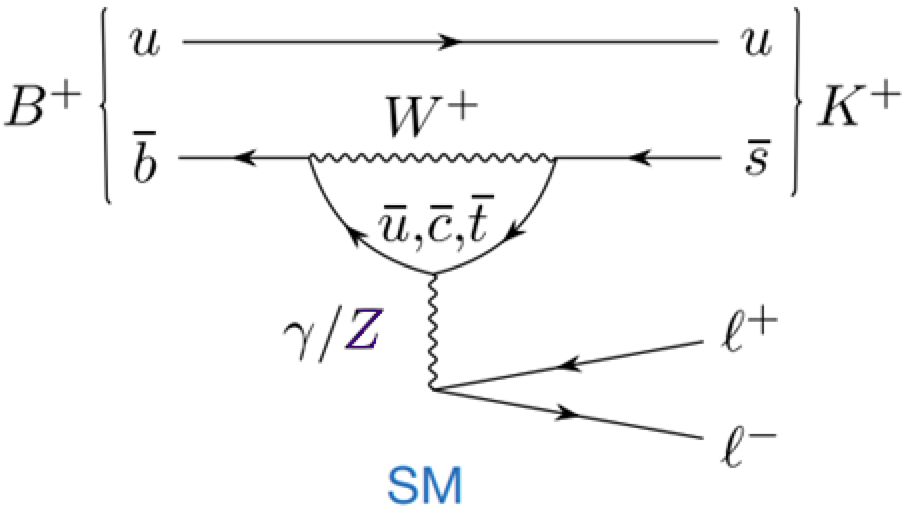
$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\ \text{ps}$$

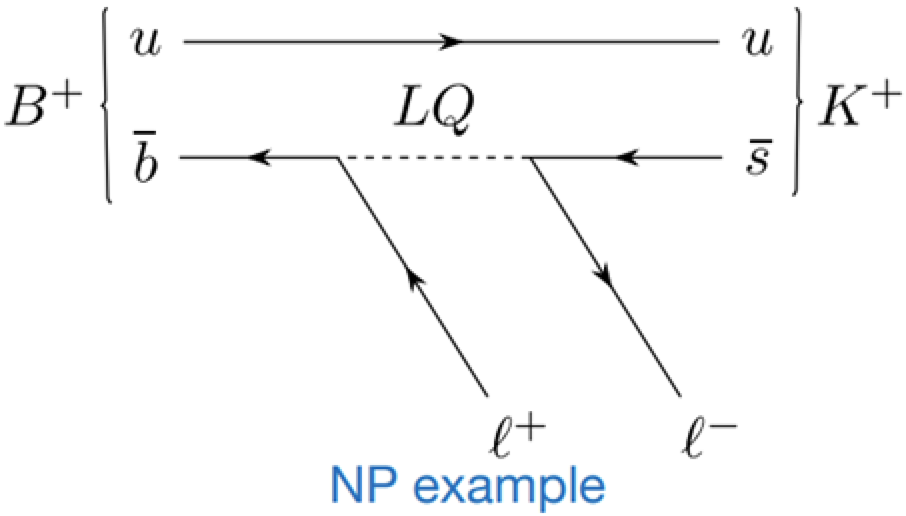


The most precise measurement! In agreement with SM

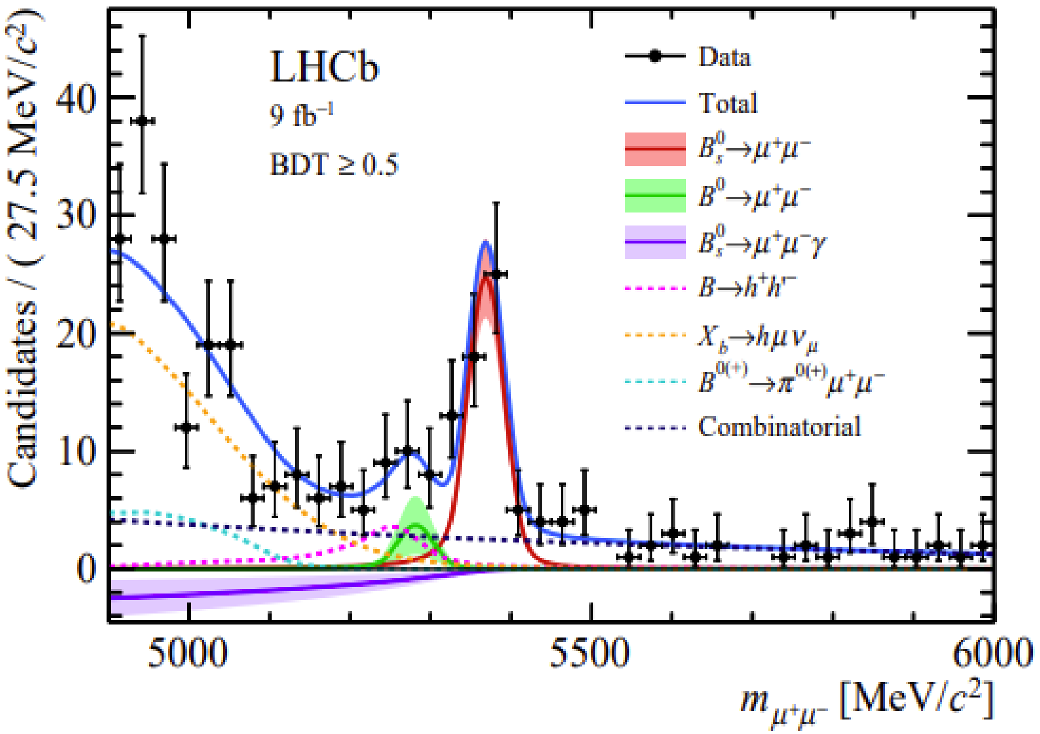
$b \to sll$ as New Physics probes

- $b \to sll$ transitions are precisely predicted by Standard Model
- Processes are rare (loop level, CKM-suppressed)
  → new interactions can be major contribution
- New interactions can have different symmetries from the SM
- NP can modify parameters of angular distributions observed in multibody decays $B \to h\, l^+ l^-$





B→μμ LHCb



- Simultaneous fit in 10 bins
  2 datasets (Run 1, 2) × 5 BDT bins
- External constraints on yield and shape of misidentified backgrounds
- Combinatorial background free
- Signal shapes calibrated and constrained
- All systematic uncertainties directly propagated

$$\mathcal{B}(B_s^0\to\mu^+\mu^-)=\left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right)\times10^{-9}$$

$$\mathcal{B}(B^0\to\mu^+\mu^-)=\left(1.2\,^{+0.8}_{-0.7}\pm0.1\right)\times10^{-10}<2.6\times10^{-10}$$

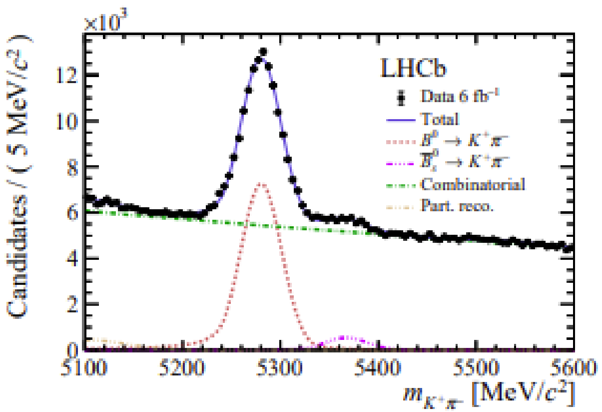
$$\mathcal{B}(B_s^0\to\mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}}=(-2.5\pm1.4\pm0.8)\times10^{-9}<2.0\times10^{-9}$$

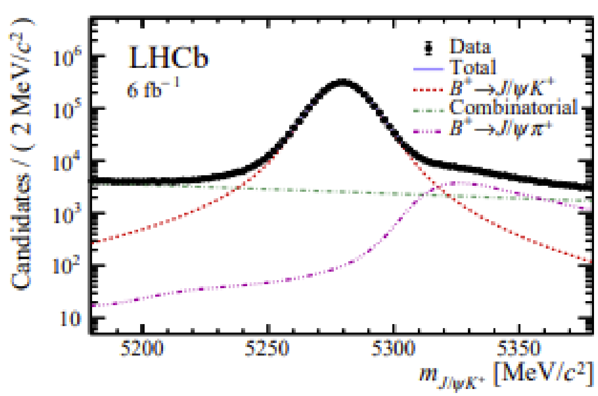
No significant signal for $B^0\to\mu^+\mu^-$ and $B_s^0\to\mu^+\mu^-\gamma$, upper limits at 95%
First world limit on $B_s^0\to\mu^+\mu^-\gamma$ decay
Measured effective lifetime $\tau_{\mathrm{eff}}(B_s^0\to\mu^+\mu^-)=2.07\pm0.29\pm0.03\,\mathrm{ps}$
Consistent at 1.5σ and 2.2σ with the heavy and light B_s^0 eigenstates lifetimes

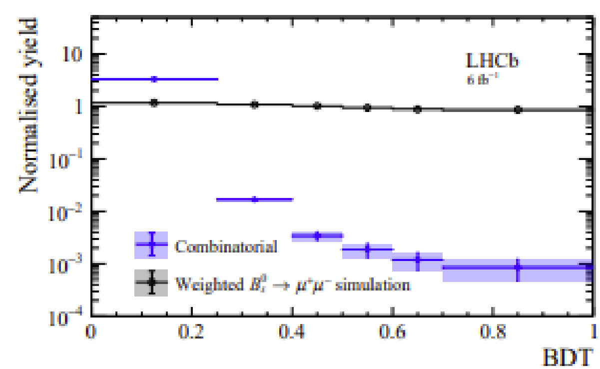
B→μμ LHCb

- Normalised to two channels: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$
- Multivariate operator against combinatorial background
- Tight PID calibrated on data against misID
- Significant improvement in hadronisation fraction $\frac{f_s}{f_d}(13\,\text{TeV}) = 0.2539 \pm 0.0079$ from combined measurement [LHCb-PAPER-2020-046 - PRD 104, 032005 (2021)]

$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \underbrace{\frac{f_{\text{norm}}}{f_{\text{sig}}}}_{\text{Hadronisation fractions}} \overbrace{\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}}^{\text{Efficiencies}} \underbrace{\frac{N_{\text{sig}}}{N_{\text{norm}}}}_{\text{Yields}} \mathcal{B}(\text{norm}) = \underbrace{\alpha_{\text{sig}}}_{\text{Single event sensitivity}} \text{N}_{\text{sig}}$$





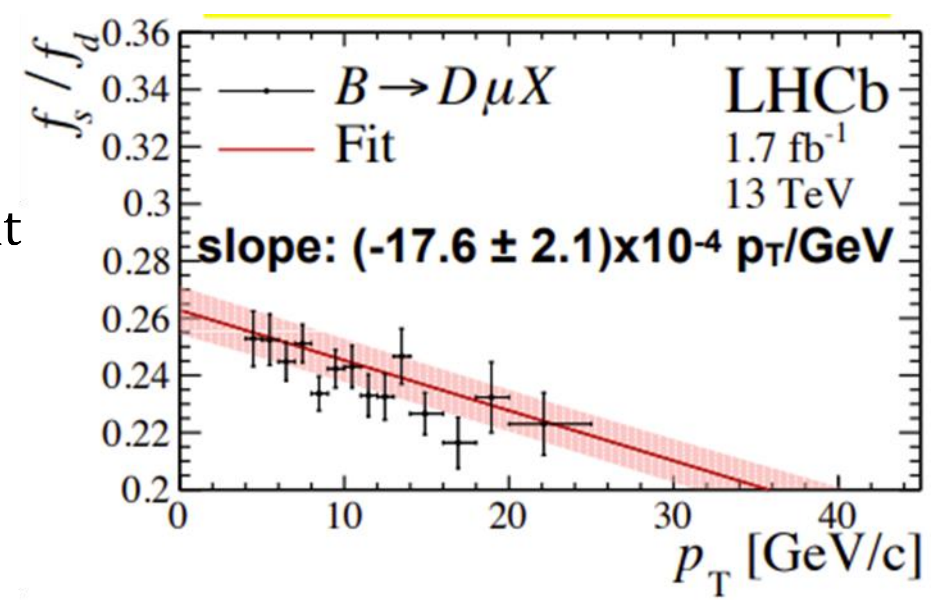


On f_s/f_u and normalization

- LHCb, CMS, ATLAS normalize B_s^0 using the $B^+ \to J/\psi K^+$ decay;
  - LHCb in addition uses $B^0 \to K^+\pi^-$, with low relative weight
- This makes $\boldsymbol{f_s/f_u}$, ratio of B_s^0 and B^+ production, a **crucial ingredient**
- The current 13 TeV LHCb best value is 0.254 ± 0.008 [assuming $f_u = f_d$]

- In CMS, the uncertainty is increased to cover √s and kinematic region dependence
  - Previous CMS result uses 0.015 additional uncertainty, arriving at $f_s/f_u = 0.252 \pm 0.019$
- This 8% of additional uncertainty is one of the leading uncertainties

LHCb-PAPER-2020-046, Phys.Rev.D.104(2021)032005



On f_s/f_u and normalization

- Other possibility is to normalize using the $B_s^0 \to J/\psi\, \varphi$ decay

- Current PDG uncertainty is dominated by LHCb measurement, which is done via $B^+ \to J/\psi\, K^+$ and f_s/f_u, i.e., completely correlated with f_s/f_u

- Belle measurement of $\mathbf{B}(B_s^0 \to J/\psi\, \varphi)$ has ~20% uncertainty

- No B_s^0 decay is measured with a precision of better than 10%
  - Often, the **B** is normalized using f_s/f_d or f_s/f_u

- **The "desired" solution to get out of this vicious circle would be Belle II running on Υ(5S) resonance and precisely measuring absolute B_s^0 branching fractions ☺**

- **With Run-3 data, this normalization channel issue will probably be the leading uncertainty in B($B_s^0 \to \mu\mu$) for CMS & ATLAS**

B→ee, B→ττ

- Similar, from theoretical point of view, rare decays, predicted B are lower (higher) for e (τ) than for μ:

$$\mathcal{B}(B_s^0 \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$
$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

- However, significantly more challenging experimentally
  - *Electrons produce bremsstrahlung radiation in magnetic field, resulting in reduced precision (wide peak)*
  - *Taus quickly decay with 1 or two missing neutrinos per one τ lepton, many decay modes, large backgrounds, very broad peak in m(ττ)*

- With LFU, different NP effects can affect ee, μμ, and ττ modes differently → important to search/study all 3 decay modes!

B→ee, B→ττ

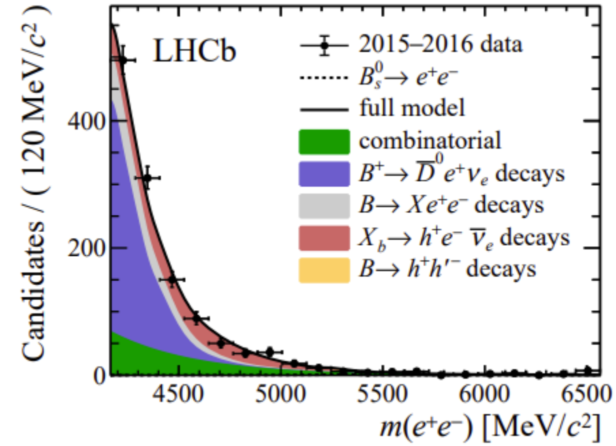
LHCb has performed searches for ee and ττ decays

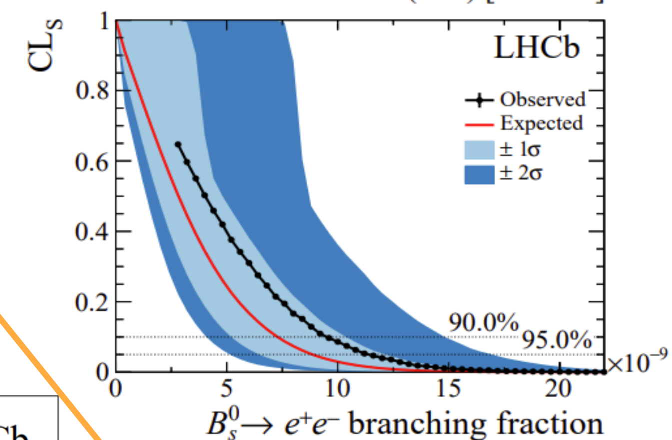
ee: *Run-1+2015+2016*

$$\mathcal{B}(B_s^0 \to e^+e^-) < 9.4\,(11.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to e^+e^-) < 2.5\,(3.0) \times 10^{-9}$$
at 90 (95) % CL

normalized to $B^+ \to J/\psi(ee)\,K^+$

LHCb-PAPER-2020-001, Phys.Rev.Lett.124(2020)211802

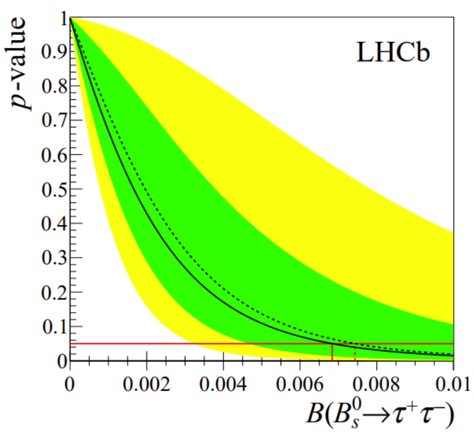


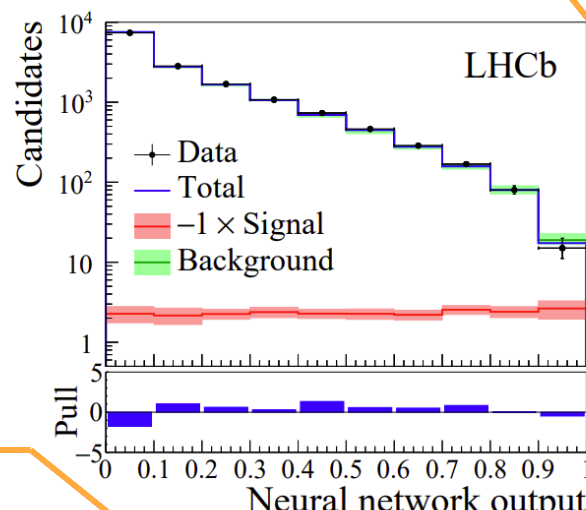


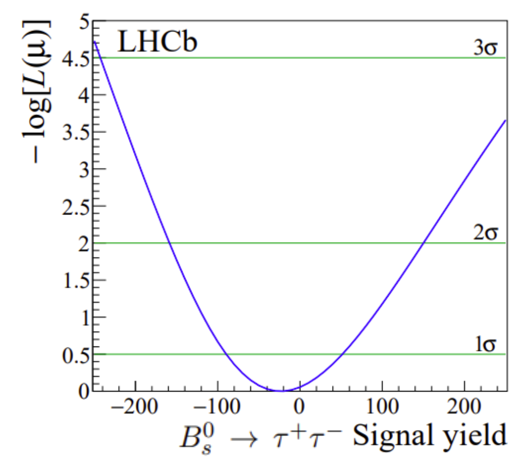
ττ: *Run-1 analysis,* normalized to $B \to DD_s$

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.6\,(2.1) \times 10^{-3} \text{ at } 90\,(95)\% \text{ CL}$$

LHCb-PAPER-2017-003, Phys.Rev.Lett.118(2017)251802



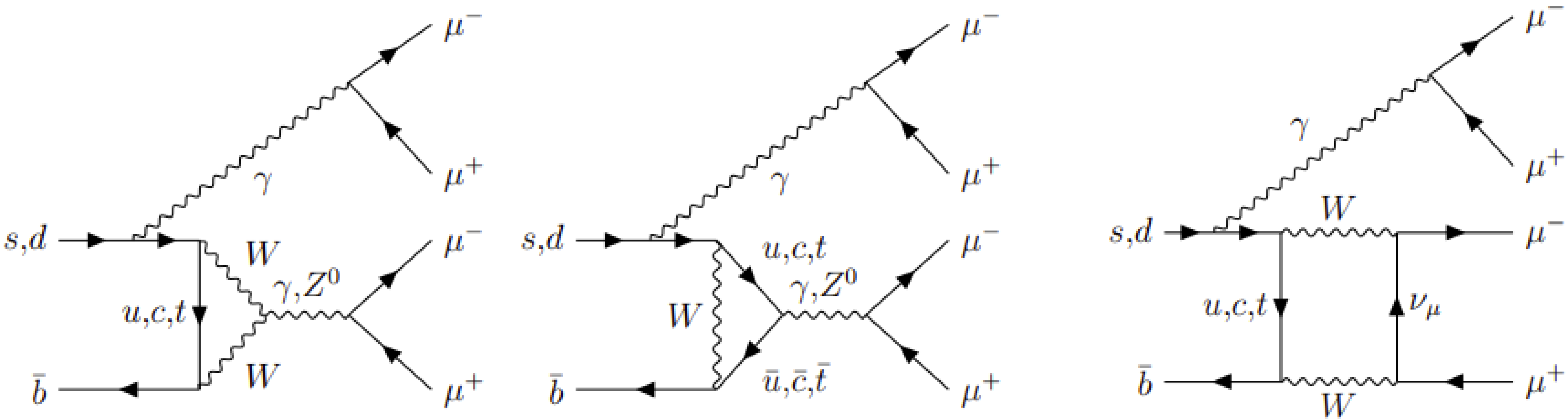




Upper limits many orders of magnitude larger than SM predictions

B→ μμμμ

- If no intermediate resonance, FCNC transitions:

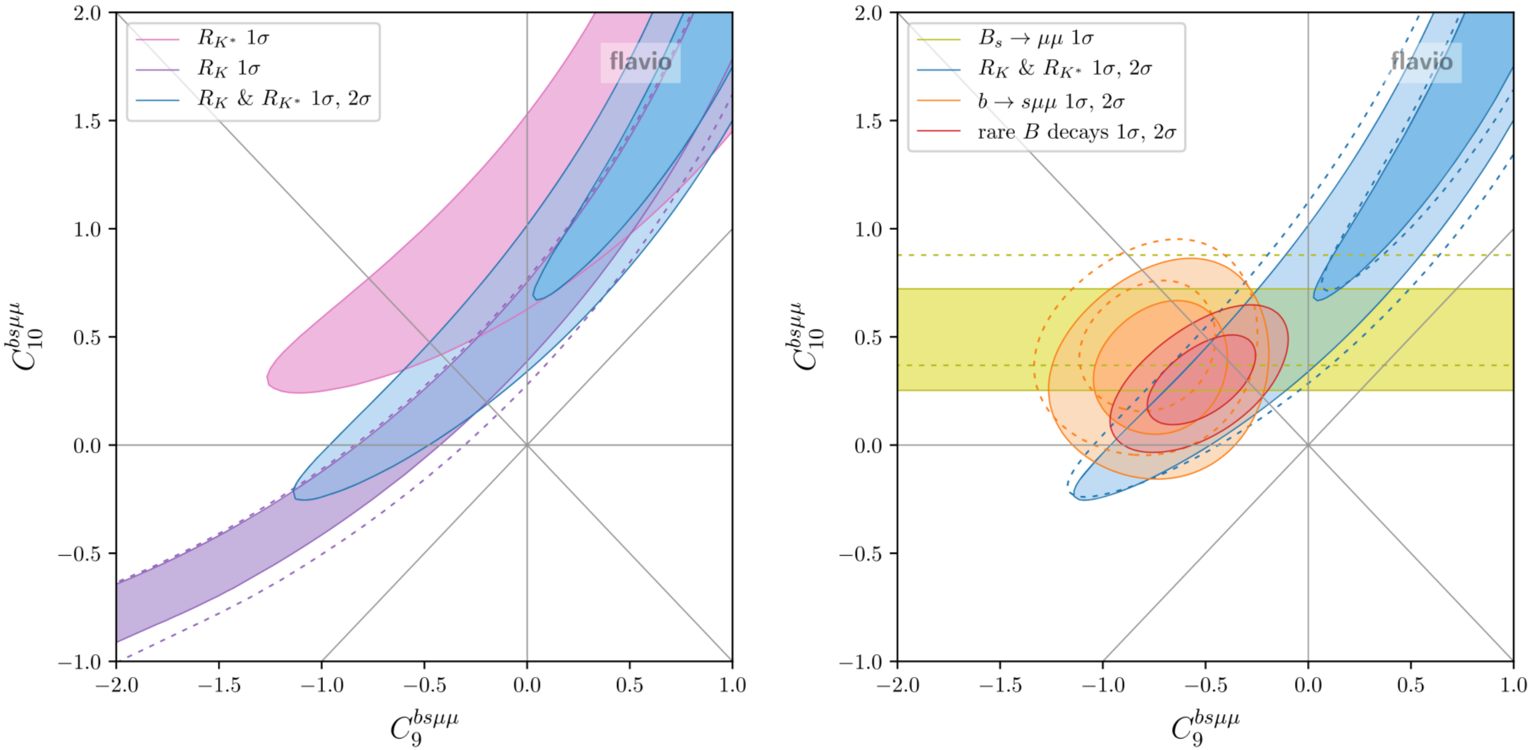


- Very rare in SM:

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) = (0.9 - 1.0) \times 10^{-10}$$
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) = (0.4 - 4.0) \times 10^{-12}$$

- Some SM extensions involve intermediate scalar
  B→aa→4μ with m(a)~1GeV

Tensions in b→*sll* transitions



Eur. Phys. J. C (2021) 81:952

- Multiple discrepancies are observed in b→sℓℓ processes
  - 3.1σ Lepton Flavour Universality violation in R(K) and R(K*)
  - 2-3σ discrepancies in branching fraction and angular observables
- Discrepancies can be described by two 4-fermion contact interaction operators

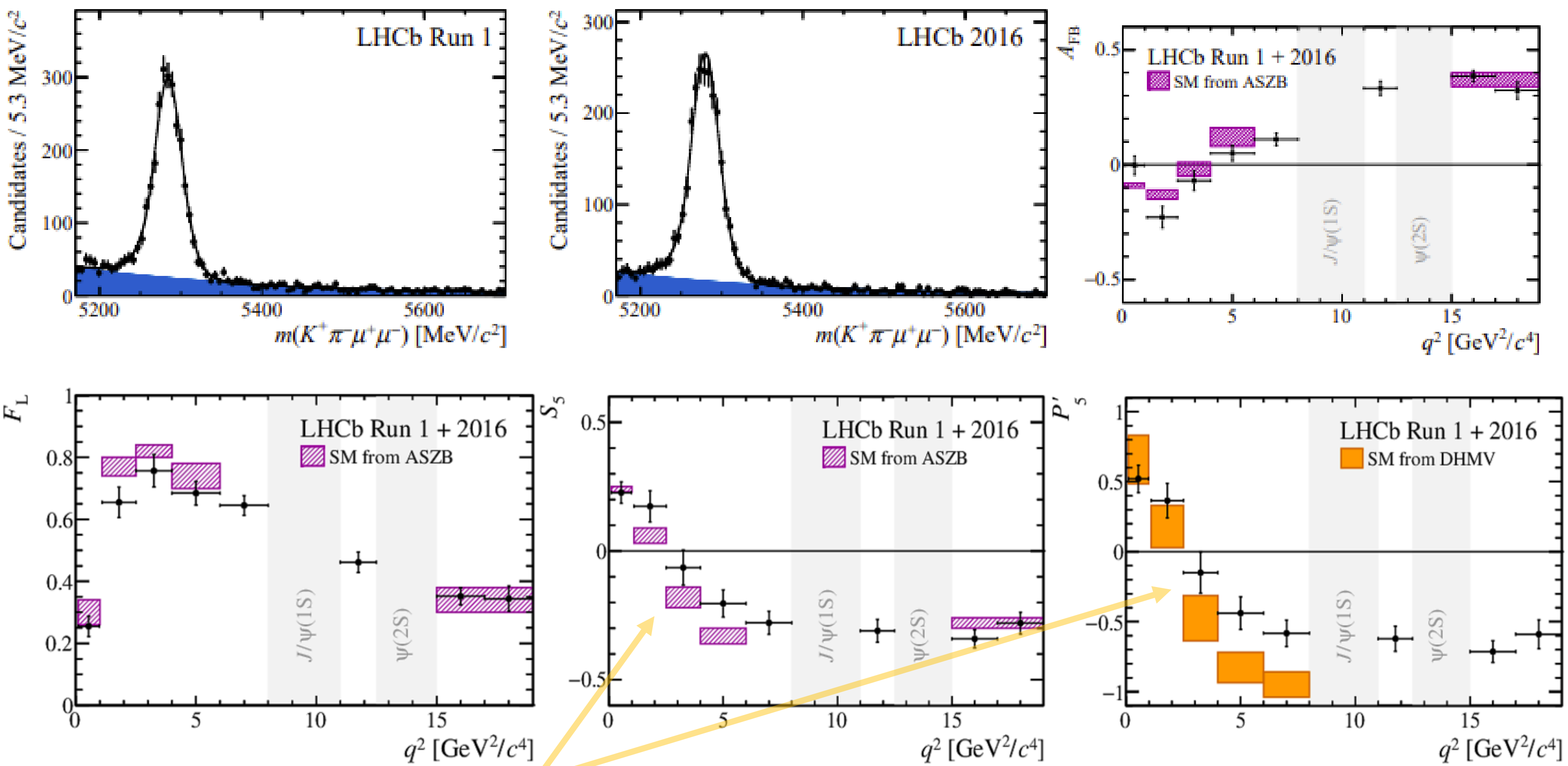
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Angular analyses of *b→sll* transitions

- Many recent results measuring angular parameters and differential branching fractions

$B^0 \to K^{*0}\mu^+\mu^-$, Run-1+2016, ~4500 signal

LHCb-PAPER-2020-002, Phys.Rev.Lett.125(2020)011802



~3σ tension at low q^2 !

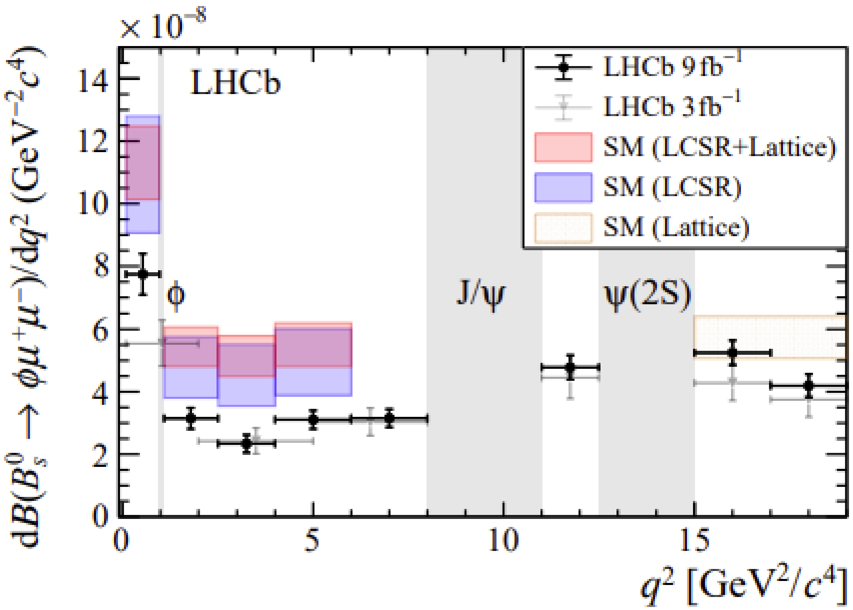
ATLAS and CMS Run-1 results in backup

CMS Run-2 analysis in development

Angular analyses of $b \to sll$ transitions

BF measurement of $\mathbf{B_s^0 \to \phi \mu^+ \mu^-}$ and $\mathbf{B_s^0 \to f_2'(1525) \mu^+ \mu^-}$
LHCb Run-1 + Run-2

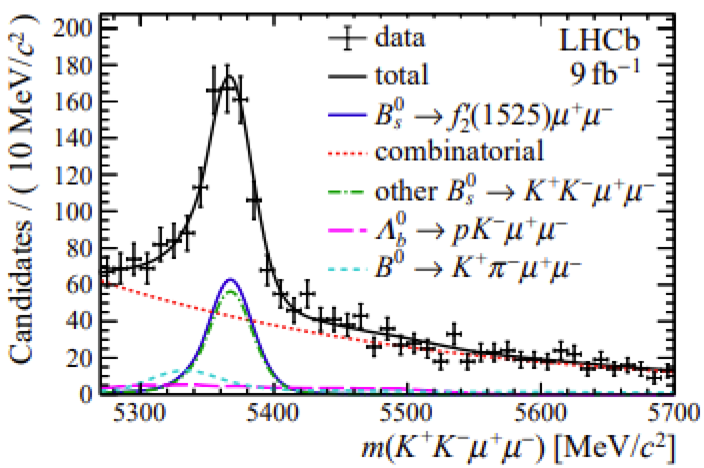
LHCb-PAPER-2021-014, Phys.Rev.Lett.127(2021)151801

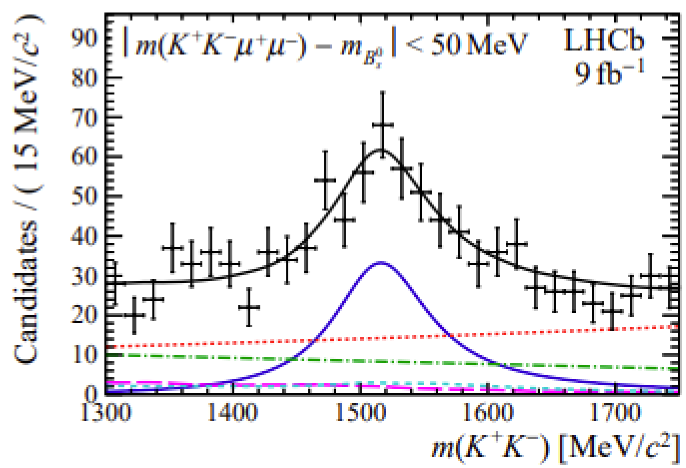


~3.6σ tension w.r.t. SM at low q^2

More details in the parallel talk by Samar N. yesterday

$$\mathcal{B}(B_s^0 \to f_2' \mu^+ \mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$



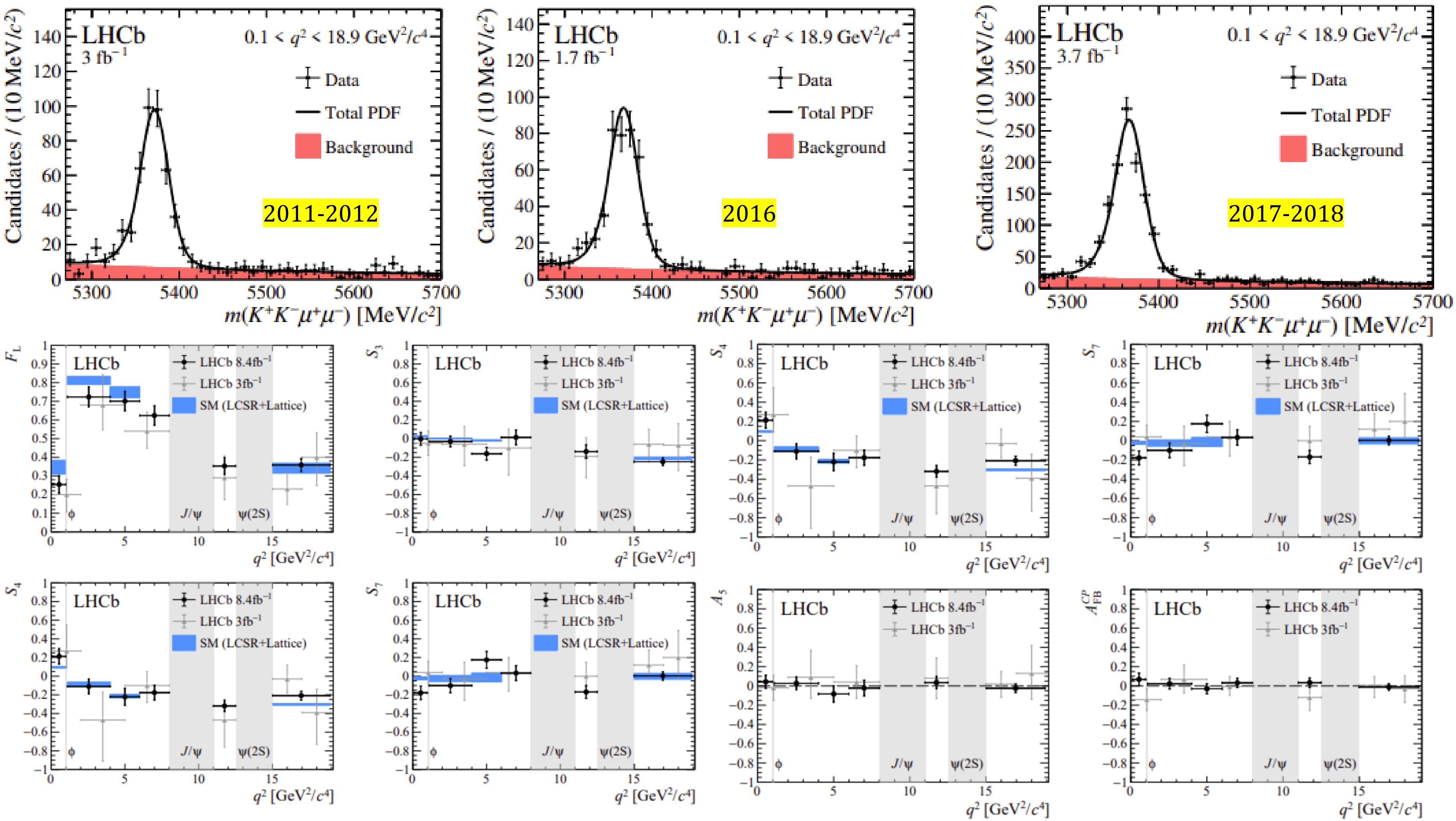


First observation!
BF compatible with SM

Angular analyses of *b→sll* transitions

$B_s^0 \to \phi\mu^+\mu^-$ angular, Run-1+Run-2 (no 2015), ~2000 signal

More details in the parallel talk by Samar N. yesterday



Compatible with SM

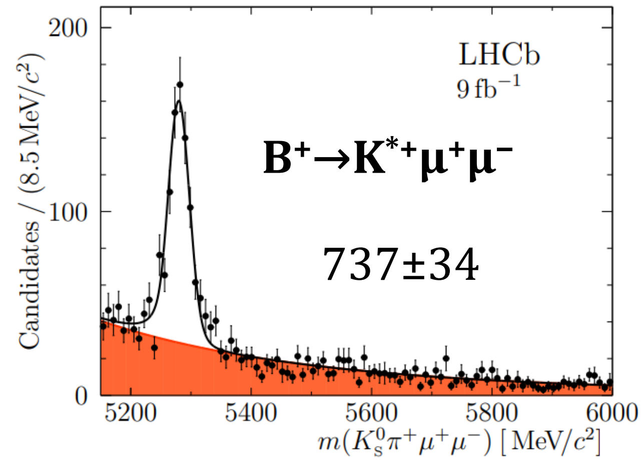
LHCb-PAPER-2021-022, JHEP11(2021)043

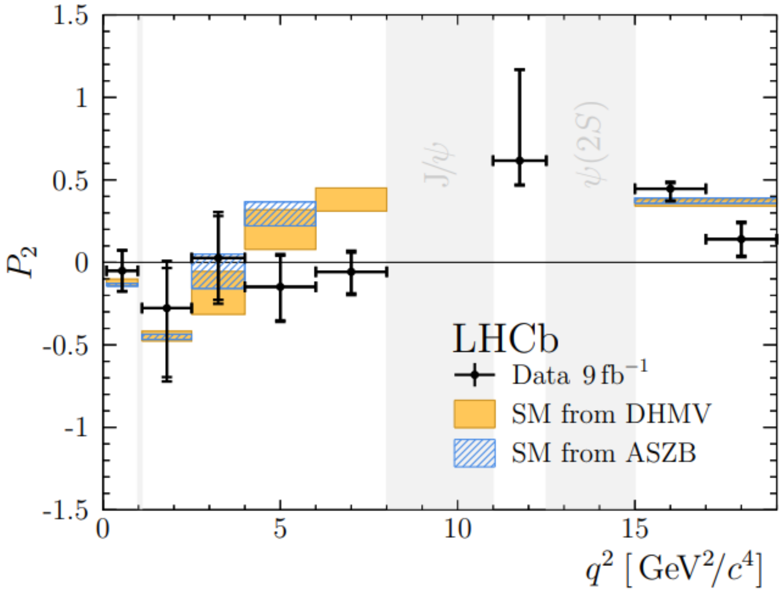
CMS Run-2 analysis in development

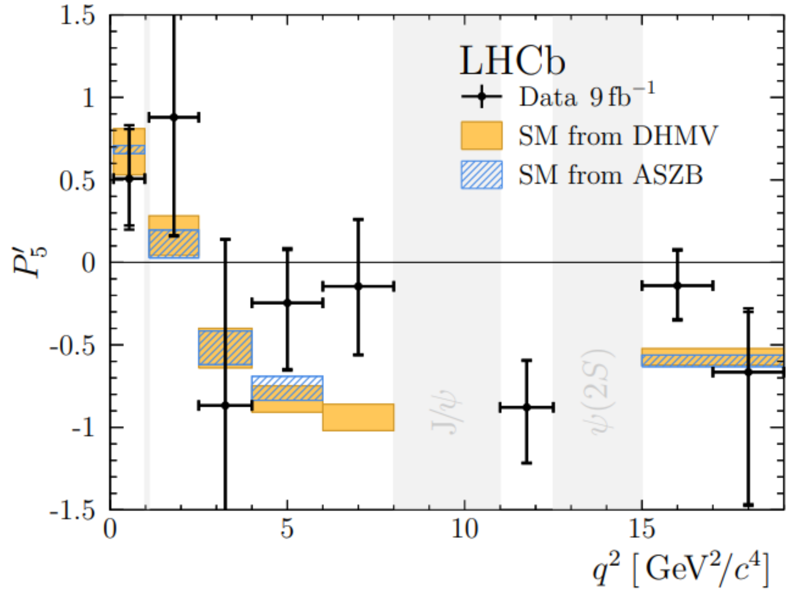
Angular analyses of $b \to sll$ transitions

$B^+ \to K^{*+}\mu^+\mu^-$, ($K^{*+} \to K^0_S \pi^+$) LHCb Run-1 + Run-2, ~90 signal
Lower statistics compared to K^{*0} channel because of K^0_S
Two categories based on K^0_S decay vertex position

Angular analysis, measuring full set of optimized variables,
F_L, S_3, S_4, S_5, A_{FB}, S_7, S_8, S_9, P_1, P_2, P_3, P'_4, P'_5, P'_6, P'_8
in 5 folds of the data, due to limited stat.







3.1σ tension w.r.t SM at low q^2 !

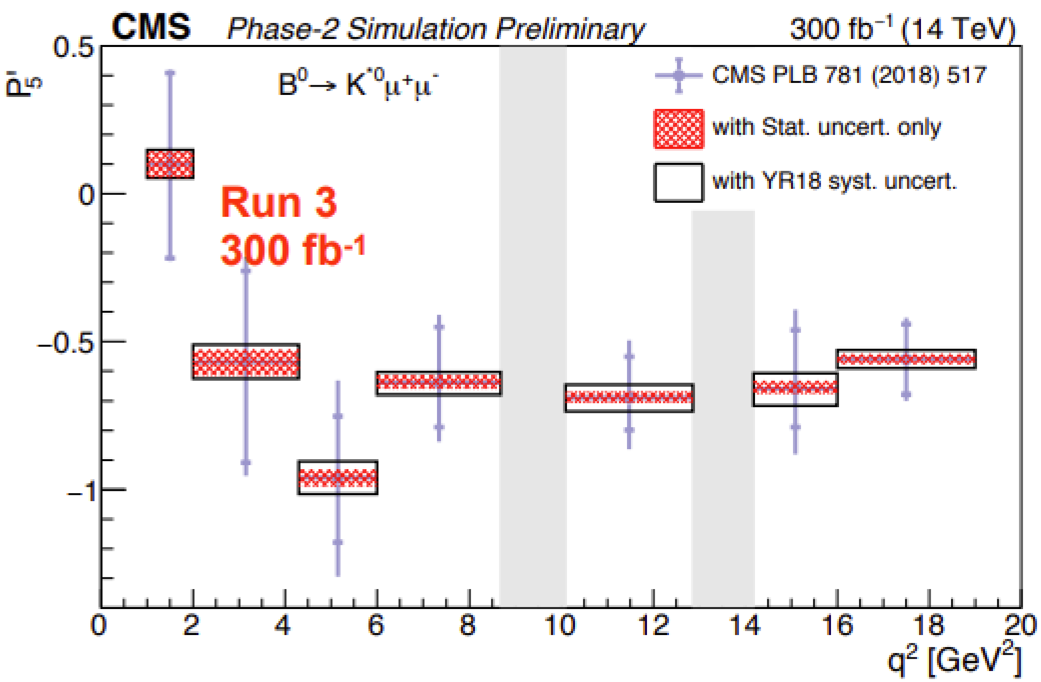
More details in the parallel talk by Samar N. yesterday

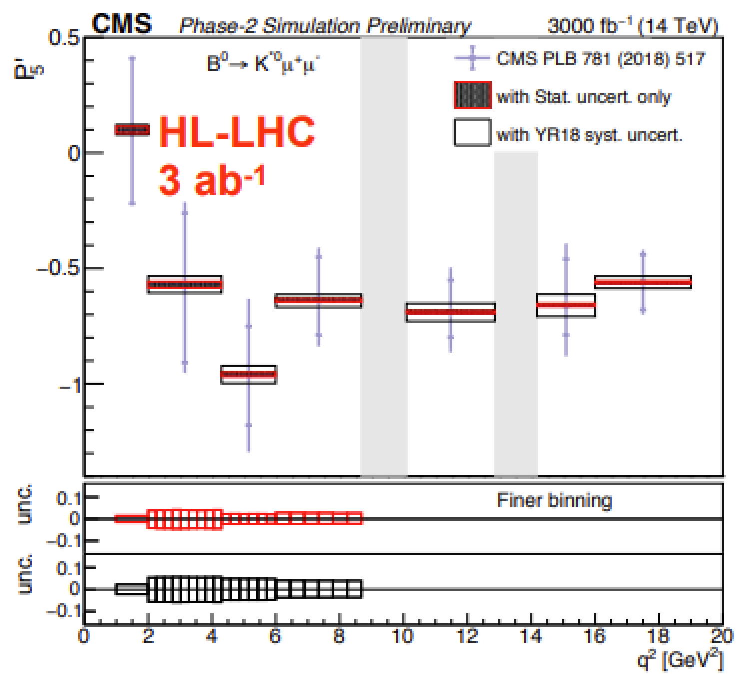
LHCb-PAPER-2020-041, Phys.Rev.Lett.126(2021)161802

P5’ HL-LHC

- Run 3 and HL-LHC projections
  - Up to x15 improvement w/ 3 ab^{-1} compared to the 8 TeV CMS result [PLB 781 (2018) 517]
  - Should be possible to resolve the situation experimentally already in Run 3

CMS PAS FTR-18-033



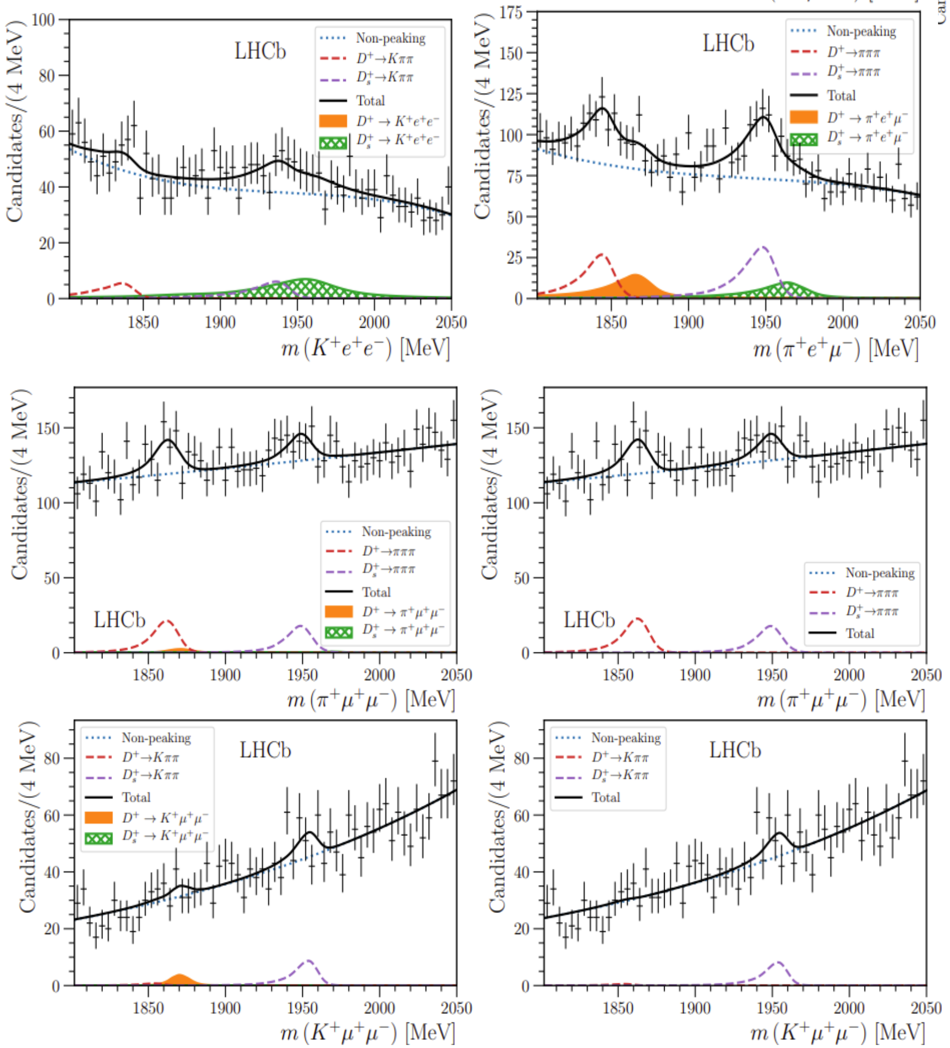


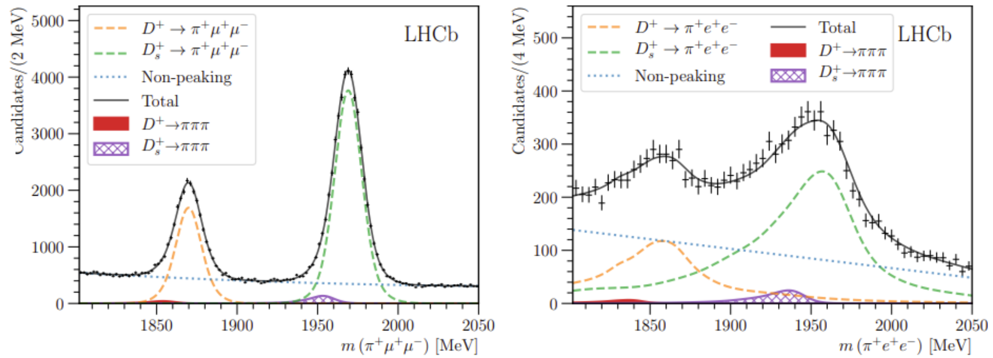
Rare charm decays

LHCb *JHEP* 06 (2021) 044

Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

$$\mathcal{B}_{D^+_{(s)}\to h^\pm \ell^+ \ell^{(\prime)\mp}} = \frac{N_{D^+_{(s)}\to h^\pm \ell^+ \ell^{(\prime)\mp}}}{N_{D^+_{(s)}\to(\phi\to\mu^+\mu^-)\pi^+}} \cdot \frac{\epsilon_{D^+_{(s)}\to(\phi\to\mu^+\mu^-)\pi^+}}{\epsilon_{D^+_{(s)}\to h^\pm \ell^+ \ell^{(\prime)\mp}}} \cdot \mathcal{B}_{D^+_{(s)}\to(\phi\to\mu^+\mu^-)\pi^+}$$



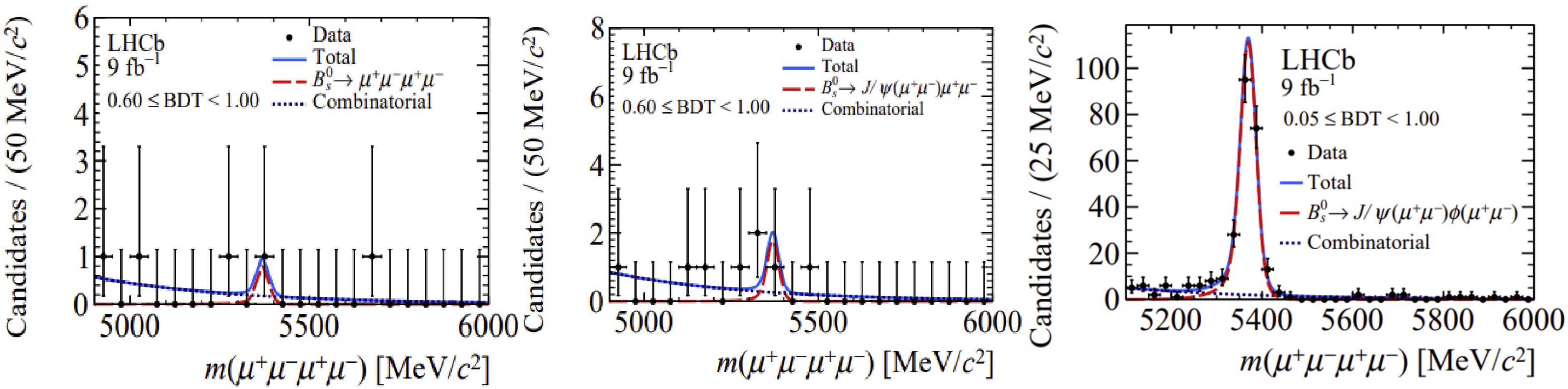


Decay	Branching fraction upper limit $[10^{-9}]$					
	D^+			D_s^+		
	SES	90% CL	95% CL	SES	90% CL	95% CL
$D^+_{(s)}\to\pi^+\mu^+\mu^-$	0.6	67	74	2.4	180	210
$D^+_{(s)}\to\pi^-\mu^+\mu^+$	0.3	14	16	1.8	86	96
$D^+_{(s)}\to K^+\mu^+\mu^-$	1.2	54	61	3.8	140	160
$D^+_{(s)}\to K^-\mu^+\mu^+$	-	-	-	1.2	26	30
$D^+_{(s)}\to\pi^+e^+\mu^-$	0.6	210	230	3.1	1100	1200
$D^+_{(s)}\to\pi^+\mu^+e^-$	0.4	220	220	2.2	940	1100
$D^+_{(s)}\to\pi^-\mu^+e^+$	0.4	130	150	2.0	630	710
$D^+_{(s)}\to K^+e^+\mu^-$	0.7	75	83	3.7	790	880
$D^+_{(s)}\to K^+\mu^+e^-$	0.5	100	110	2.5	560	640
$D^+_{(s)}\to K^-\mu^+e^+$	-	-	-	2.4	260	320
$D^+_{(s)}\to\pi^+e^+e^-$	1.9	1600	1800	8.1	5500	6400
$D^+_{(s)}\to\pi^-e^+e^+$	0.9	530	600	4.1	1400	1600
$D^+_{(s)}\to K^+e^+e^-$	4.4	850	1000	14.8	4900	5500
$D^+_{(s)}\to K^-e^+e^+$	-	-	-	4.1	770	840

B→ μμμμ

- Recent LHCb search uses Full Run1+Run-2 data
- Using $B_s^0 \to J/\psi\varphi \to 4\mu$ for the normalization
- Search also performed for $B_{(s)}^0 \to J/\psi\mu\mu$ decays

LHCb-PAPER-2021-039, JHEP03(2022)109



Upper limits (with excluded known resonance regions) are most stringent to date

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 8.6 \times 10^{-10},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.8 \times 10^{-10},$$
$$\mathcal{B}(B_s^0 \to a(\mu^+\mu^-)\,a(\mu^+\mu^-)) < 5.8 \times 10^{-10},$$
$$\mathcal{B}(B^0 \to a(\mu^+\mu^-)\,a(\mu^+\mu^-)) < 2.3 \times 10^{-10},$$
$$\mathcal{B}(B_s^0 \to J/\psi(\mu^+\mu^-)\,\mu^+\mu^-) < 2.6 \times 10^{-9},$$
$$\mathcal{B}(B^0 \to J/\psi(\mu^+\mu^-)\,\mu^+\mu^-) < 1.0 \times 10^{-9}.$$

m(a)=1GeV, promptly decays

More details in the parallel talk by Christina A. yesterday

$B^0 \to \varphi\mu\mu$

[LHCb-PAPER-2021-042, JHEP05(2022)067]

It proceeds mainly via the color-suppressed penguin annihilation diagrams $\mathcal{O}(10^{-12})$

$\omega - \phi$ mixing can have a sizeble contribution $\mathcal{O}(10^{-10})$

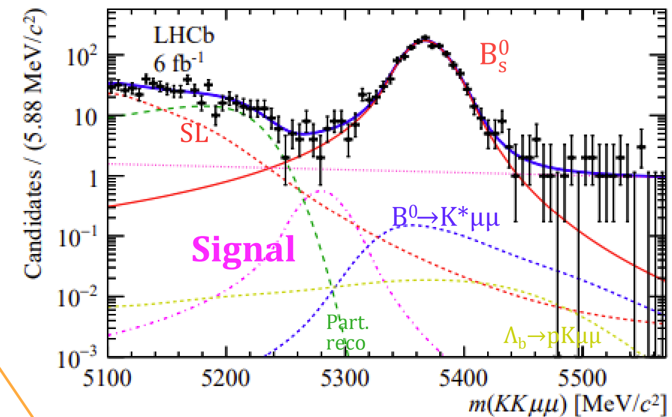
Run 1 + 2 data

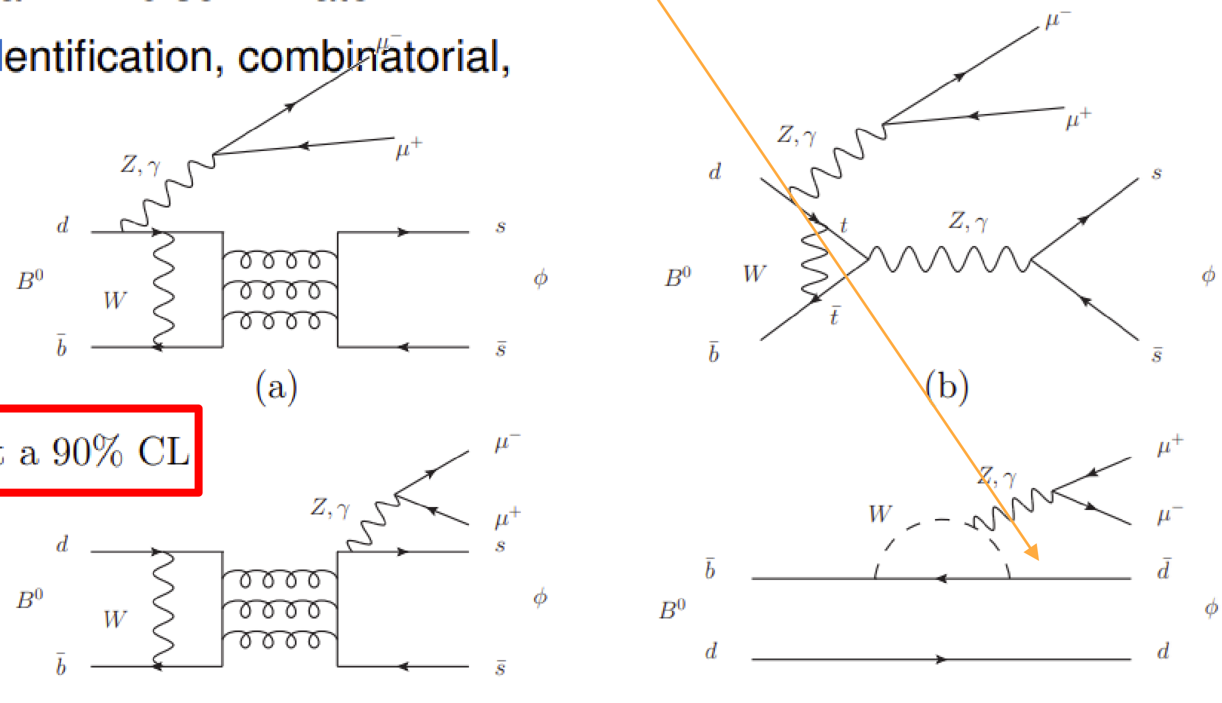
Exclude regions in q^2 corresponding to ϕ, J/ψ and $\psi(2S)$

$B_s^0 \to \phi\mu^+\mu^-$ used as normalisation

$B_s^0 \to J/\psi\phi$ used to develop a MVA discriminator

Dominant backgrounds: misidentification, combinatorial, semileptonic





(a) (b) (c) (d)

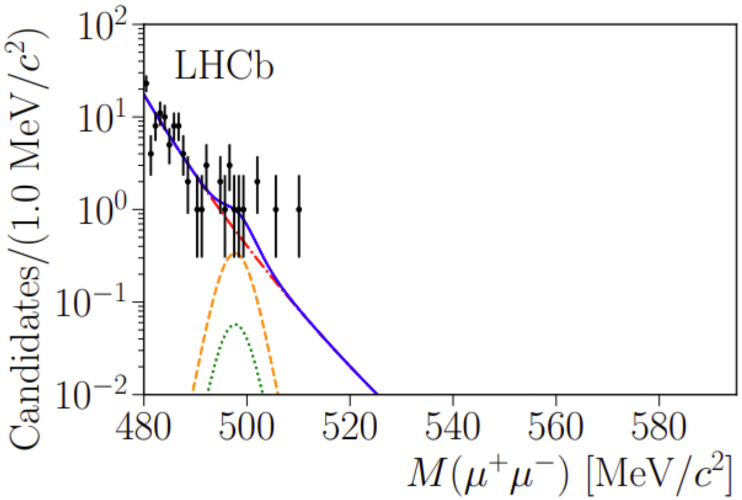
$$\mathcal{B}(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9} \text{ at a } 90\% \text{ CL}$$

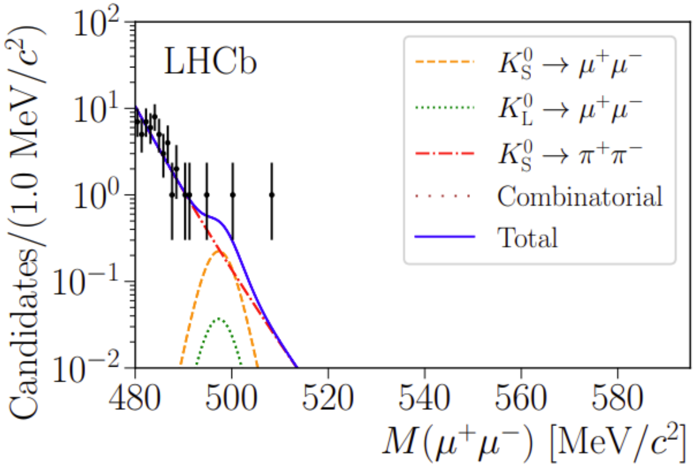
More details in the parallel talk by Christina A. yesterday

$K^0_S \to \mu\mu$

- FCNC process, in SM $\mathcal{B}(K^0_S \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{LD} \pm 0.02_{SD}) \times 10^{-12}$
- Some NP (SUSY/LQ) models modify the **B**
- LHCb performed a search using Run-2 data
- Normalization using decay to $\pi^+\pi^-$
  - This decay is also the main background

LHCb-PAPER-2019-038, Phys.Rev.Lett.125(2020)231801





Statistically combined with Run-1 result upper limit is most stringent to date:

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{ at } 90\% \text{ CL}$$

LFV searches

- Lepton Flavor is conserved in SM to a very good precision

- Observation of LFV process at a rate above SM prediction would immediately point to New Physics contribution

$\tau \rightarrow \mu\mu\mu$

At LHC, two main channels for this search (depending on τ leptons' source):

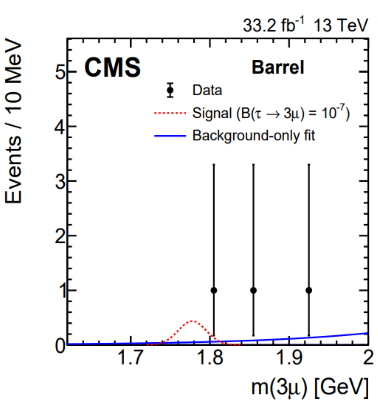
- Heavy Flavor: abundant (especially from D_s^+) but challenging because of very low p_T, forward muons
- $W \rightarrow \boldsymbol{\tau}\nu$: $\sim 10^4$ time less yield, but very clear signature

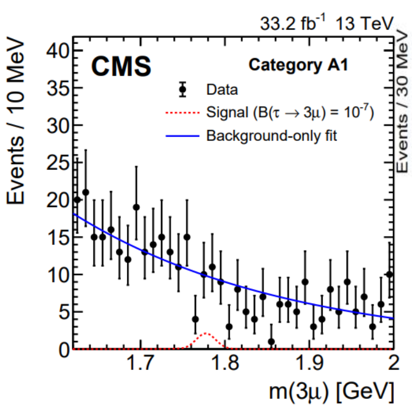
Results from search @LHC: **No evidence** found

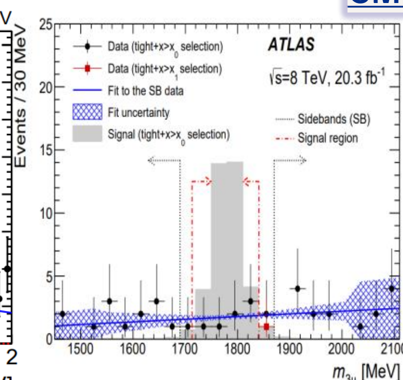
- **LHCb**: **HF** channel, $\mathcal{L} = 3\ fb^{-1}$ — $\mathcal{B}(\tau \rightarrow 3\mu) < 4.6 \cdot 10^{-8}$ at **95% C.L.**
- **ATLAS**: **W** channel, $\mathcal{L} = 20\ fb^{-1}$ — $\mathcal{B}(\tau \rightarrow 3\mu) < 3.8 \cdot 10^{-7}$ at **95% C.L.**
- **CMS**: Both **HF and W** channels, $\mathcal{L} = 33\ fb^{-1}$ — $\mathcal{B}(\tau \rightarrow 3\mu) < 8.0 \cdot 10^{-8}$ at **95% C.L.**

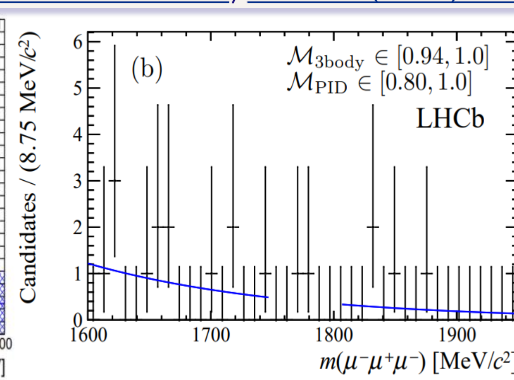
Best UL set by the **Belle** experiment: $\mathcal{B}(\tau \rightarrow 3\mu) < 2.1 \cdot 10^{-8}$ at **95% C.L.**

LHCb-PAPER-2014-052, JHEP02(2015)121
ATLAS-EXOT-2014-14, Eur.Phys.J.C76(2016)5,232
CMS-BPH-17-004, JHEP01(2021)163









CMS Run-2 analysis in development

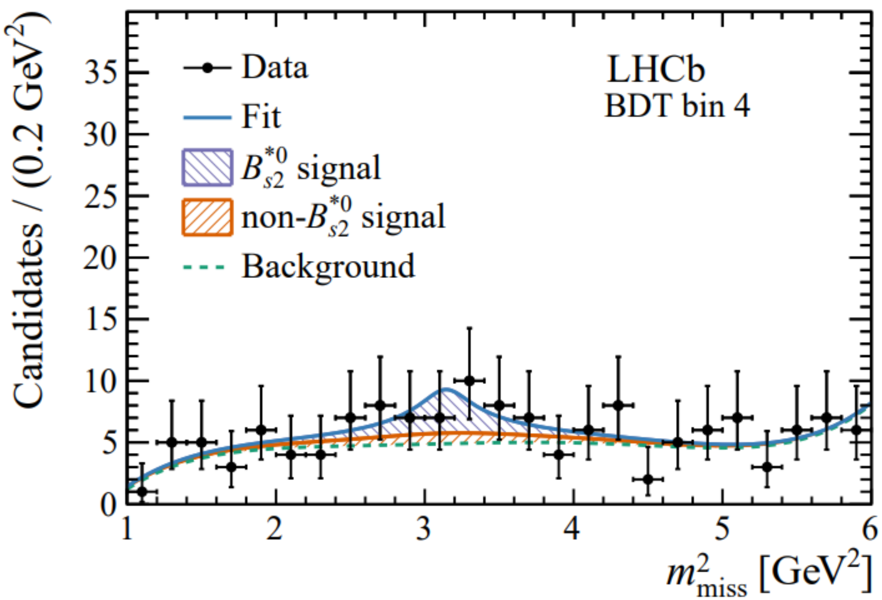
$B^+ \to K^+\mu^-\tau^+$

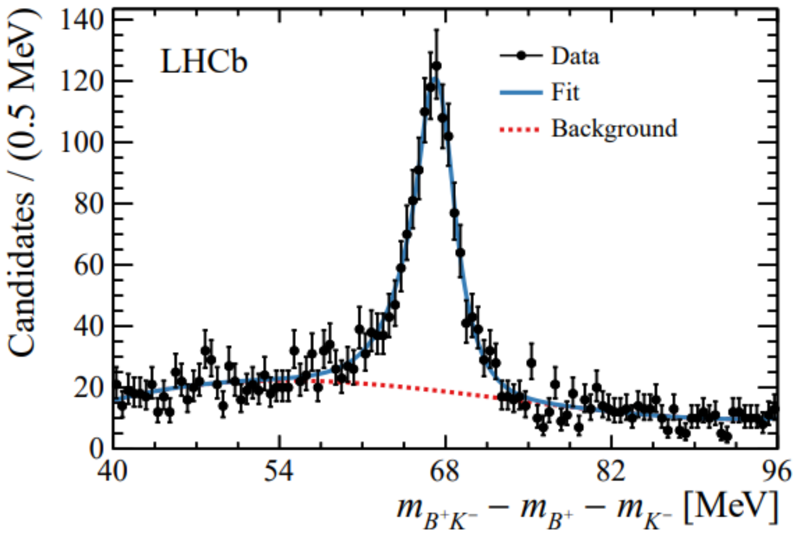
LHCb-PAPER-2019-043, JHEP06(2020)129

LHCb Full Run 1 + Run 2 analysis

Using $B^*_{s2} \to B^+K^-$ decays to tag partially-reconstructed B^+ mesons

Normalization using $B^+ \to K^+\mu^-\mu^+$ (with J/ψ)





$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9 \times 10^{-5} \text{ at } 90\% \text{ CL}$$

Weaker than 2012 BaBar upper limit

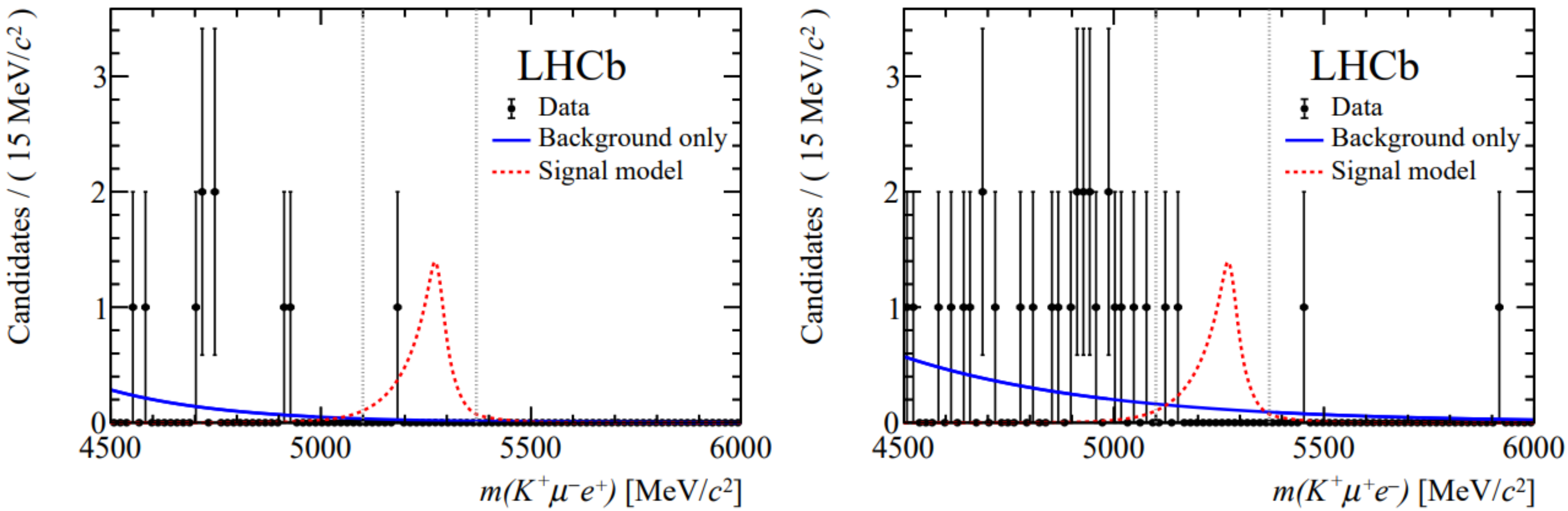
$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 2.8 \times 10^{-5} \text{ at } 90\%$$

More details in the parallel talk by Liang S. yesterday

$B^+ \to K^+\mu^\mp e^\pm$

LHCb-PAPER-2019-022, Phys.Rev.Lett.123(2019)241802

LHCb Run-1 analysis
Normalization using $B^+ \to K^+\mu^-\mu^+$ (with J/ψ)



$$\mathcal{B}(B^+ \to K^+\mu^-e^+) < 7.0\ (9.5) \times 10^{-9}$$

$$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 6.4\ (8.8) \times 10^{-9}$$

World-best limits

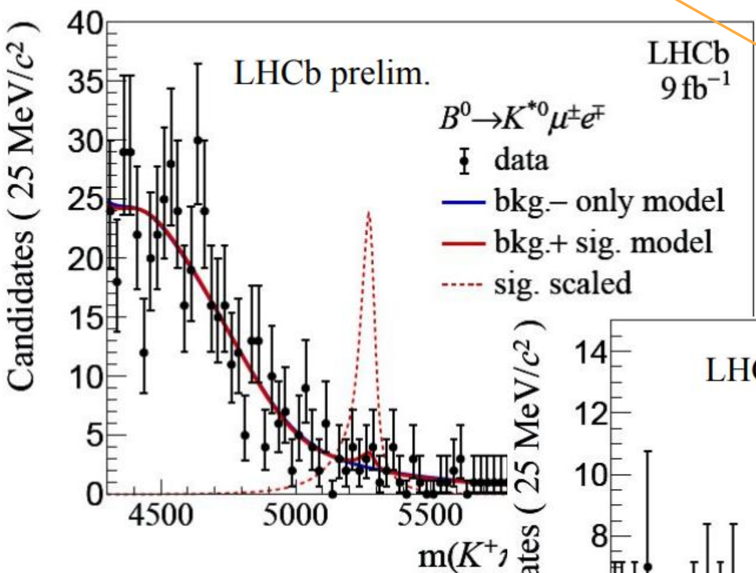
More details in the parallel talk by Liang S. yesterday

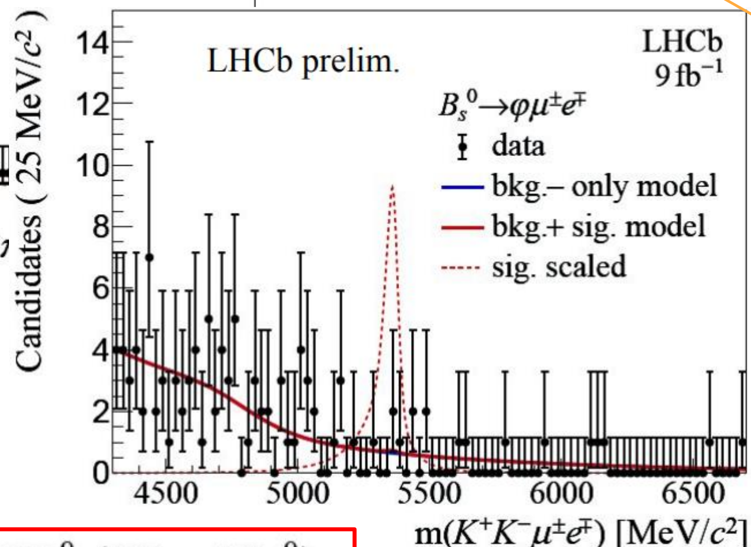
Run-2 analysis ongoing

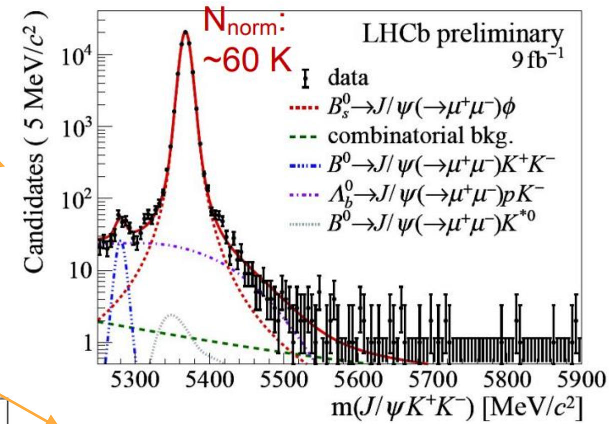
$B^0 \to K^{*0}\mu^{\mp}e^{\pm}$ and $B_s^0 \to \varphi\mu^{\mp}e^{\pm}$

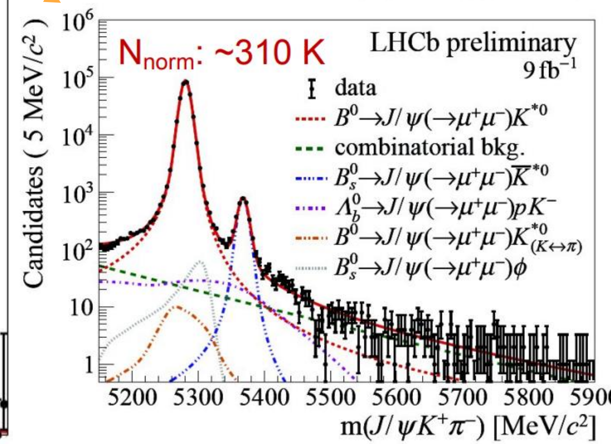
LHCP-PAPER-2022-008, in preparation. Full Run-1 + Run-2 analysis

Normalization using $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\varphi$









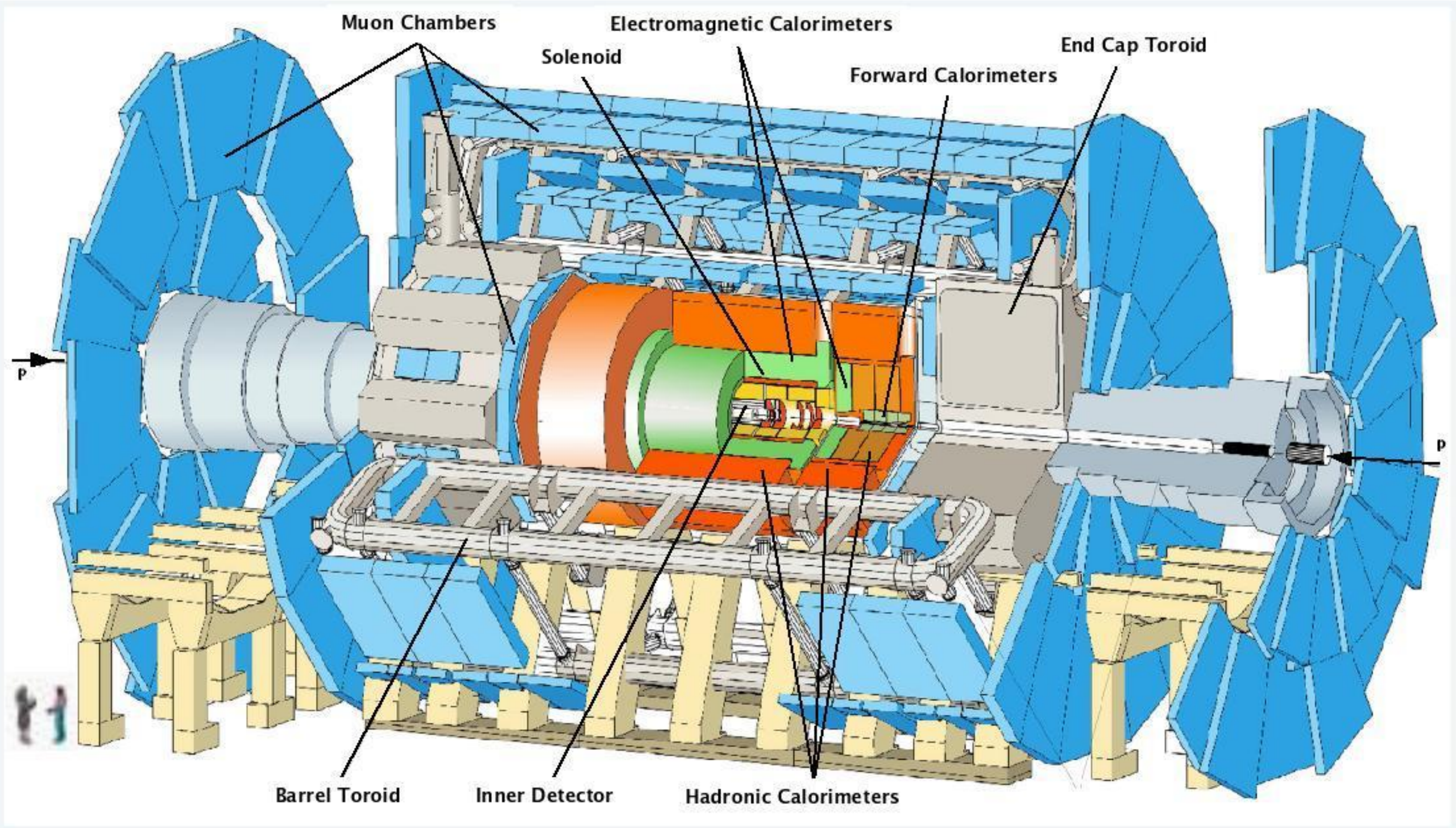
$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}\ (7.0 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.7 \times 10^{-9}\ (7.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 9.9 \times 10^{-9}\ (11.6 \times 10^{-9})$$

$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 15.9 \times 10^{-9}\ (19.4 \times 10^{-9})$$

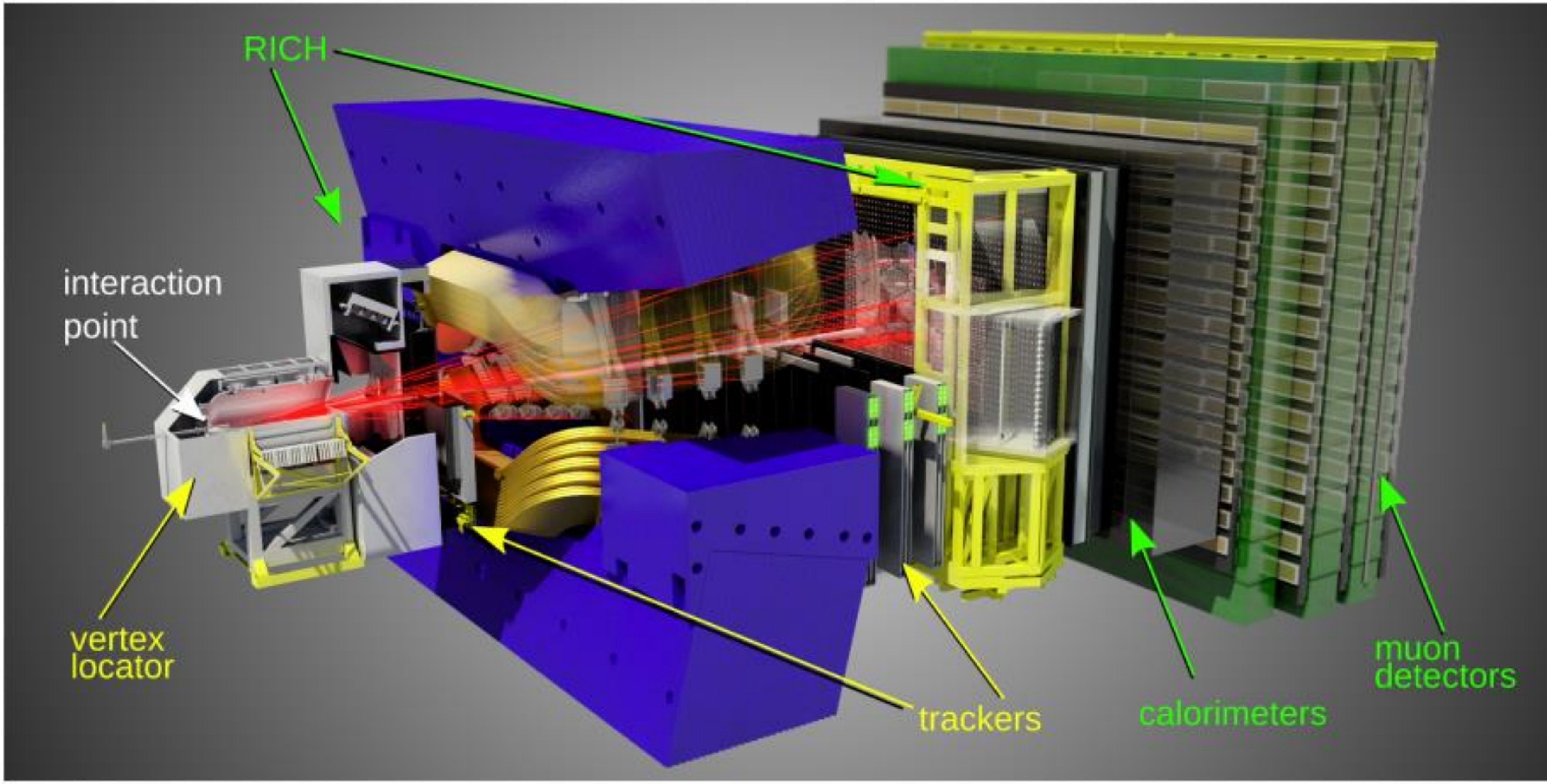
World-best limits

More details in the parallel talk by Liang S. yesterday

ATLAS experiment



LHCb



- pp collisions at $\sqrt{s} = 7, 8, 13$ TeV
- 3 (6) fb^{-1} in Run 1 (Run 2)