University of Colorado Boulder

IASA

H.F.R.I. Hellenic Foundation for Research & Innovation

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b $\rightarrow$ s$\ell\ell$ transitions at CMS

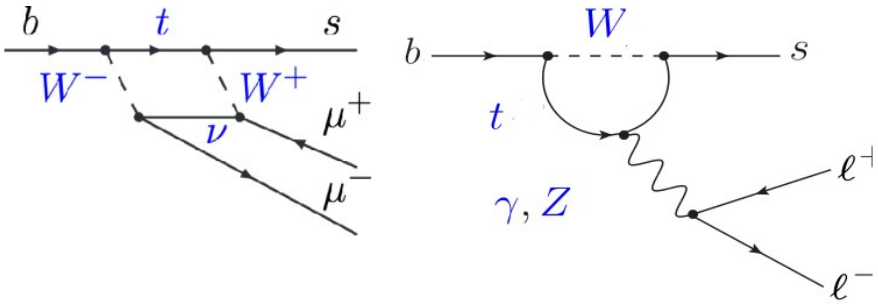
G. Karathanasis on behalf of the CMS Collaboration

EPS-HEP, Hamburg 24/08/2023

Interest in b → $s\ell\ell$ transitions

- Transition in Standard Model (SM):
  - Prohibited at tree level
  - Via loop diagrams (eg penguin, box)
  - Conserve lepton flavour universality
  - Very rare → Weak signals in Beyond SM physics (BSM) might be visible

- Quantities affected by the BSM:
  - Lepton flavour universality (LFU)
  - Branching ratios (BR)
  - Differential BR
  - Angular distributions



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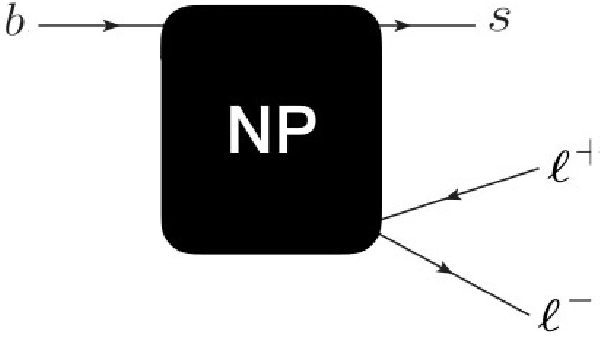
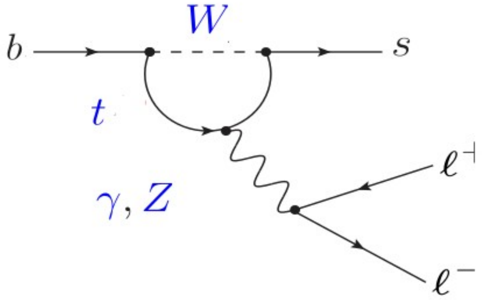
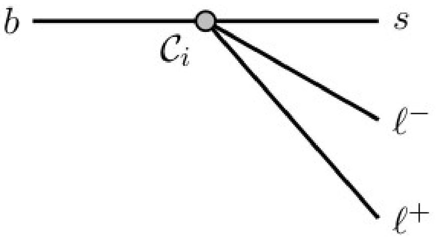


Describing b → sℓℓ with Effective Theory

Full theory



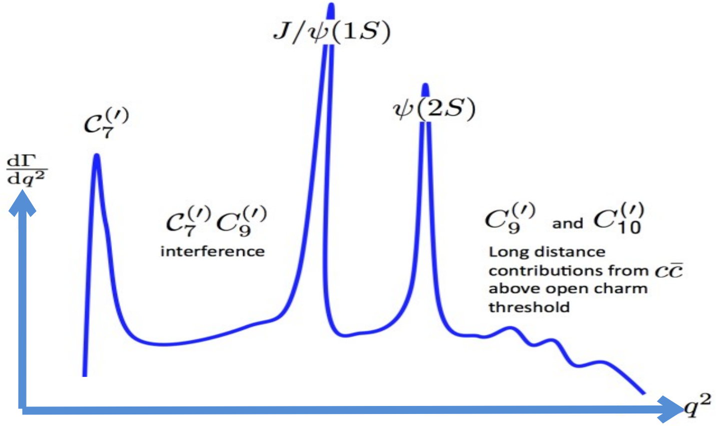
Effective theory



b → s ℓℓ described in model independent effective theory

$$\mathcal{H}_{eff} = \frac{-4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\,\pi^2} \sum_i C_i O_i$$

Wilson coefficients



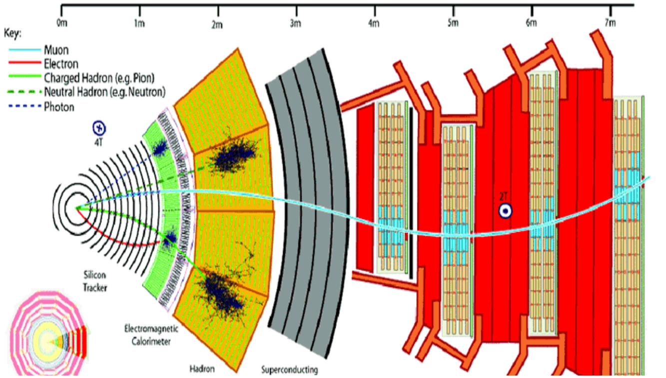
Different $q^2 = m(\ell,\ell)^2$ → different C_i probed

Prediction accuracy

Limitations on predictions:
- BF measurements affected by:
  -- form factors and c-c loops
- Angular distributions affected by:
  -- only c-c loops
- LFU ratios affected by:
  -- neither form factors nor c-c loops

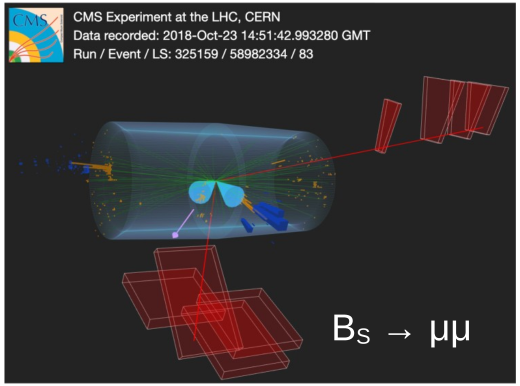
Outline

CMS can probe a wide range of signatures sensitive to New Physics (including the LFU tests)



This presentation reviews some important results:

- **BPH 22 -005** (**new for EPS**):
  - -- Summary of Parking strategy
  - -- LFU test via R_K
  - -- BR of $B \to \mu\mu K$
- **Phys. Let. B 842**:
  - -- BR $B_s \to \mu\mu$ and lifetime measurements
  - -- BR $B^0 \to \mu\mu$ upper limit
- Summary of angular distribution measurements:
  - -- Run 1 results that will be updated shortly



R_K and BR($B \rightarrow \mu\mu K$)

BPH 22 -005

Testing LFU using R_K

To test LFU with minimal theoretical uncertainty, can use the ratio of B → μμK to B → eeK, R_K:

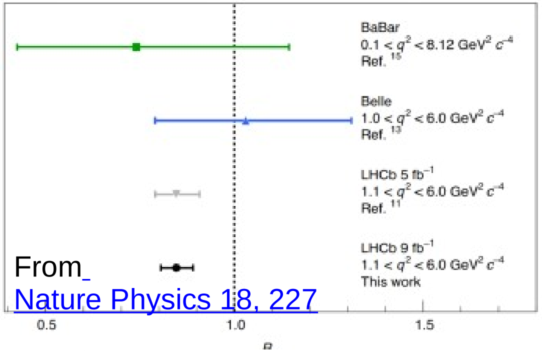
$$R_K = \frac{BF(B \rightarrow \mu\mu K)}{BF(B \rightarrow eeK)}$$

To reduce experimental uncertainties → divide both numerator and denominator with BF(B → J/ψK).

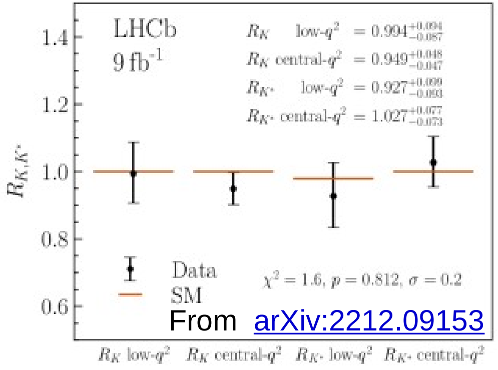
R_K becomes:

$$R_K = \frac{BF(B \rightarrow \mu\mu K)}{BF(B \rightarrow J/\psi K, J/\psi \rightarrow \mu\mu)} \Big/ \frac{BF(B \rightarrow eeK)}{BF(B \rightarrow J/\psi K, J/\psi \rightarrow ee)}$$

Where we "stand"?



From [Nature Physics 18, 227](#)



From arXiv:2212.09153

time

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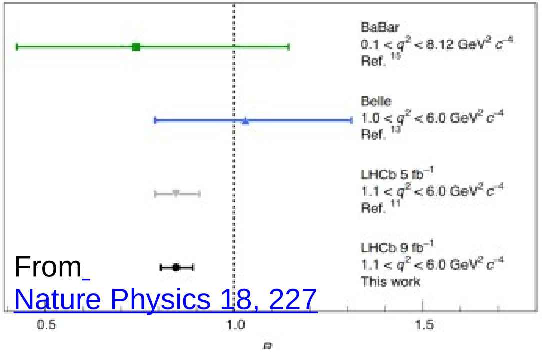

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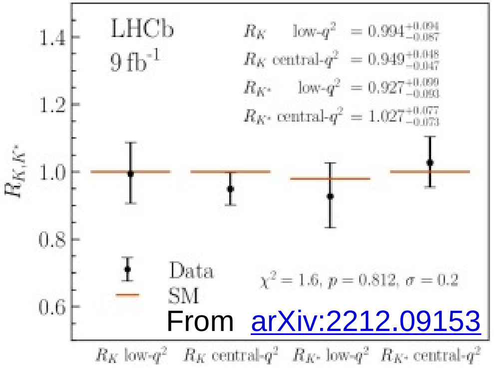

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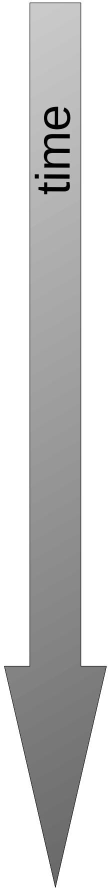
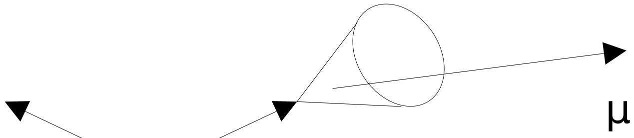


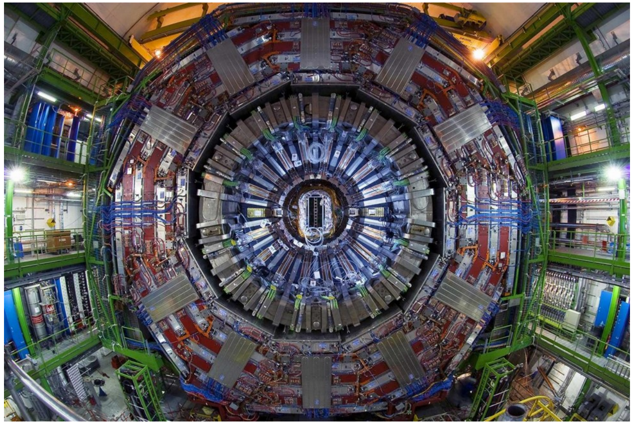
Today: the first R_K result from CMS

B Parking triggering strategy



To collect a sample of eeK with CMS in Run 2:
- **Trigger on one b hadron using muons, leaving the second b hadron completely unbiased**
- μ-based paths to trigger
- Technique known as Tag-and-Probe
- Tag = triggering B

Collisions (p – p) at 40 MHz



L1 Trigger → **HLT Trigger** → **DAQ**

L1 Trigger:
- Single-μ L1 seeds
- η restricted, soft p_T
- Purity in B decays ~30%
- Constant L1 rate

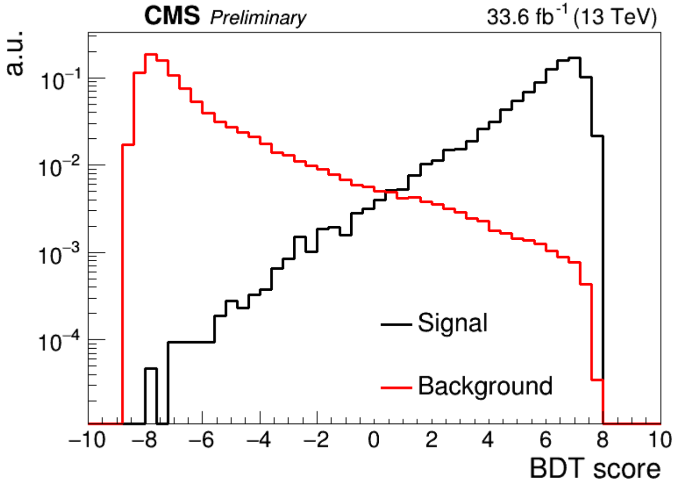
HLT Trigger:
- L1 seeds as inputs
- Refined p_T and d_{xy} cut

DAQ:
- Saved in single copy
- Stored on tape until computing resources available
- Long delay in reconstruction; procedure known as “Parking”

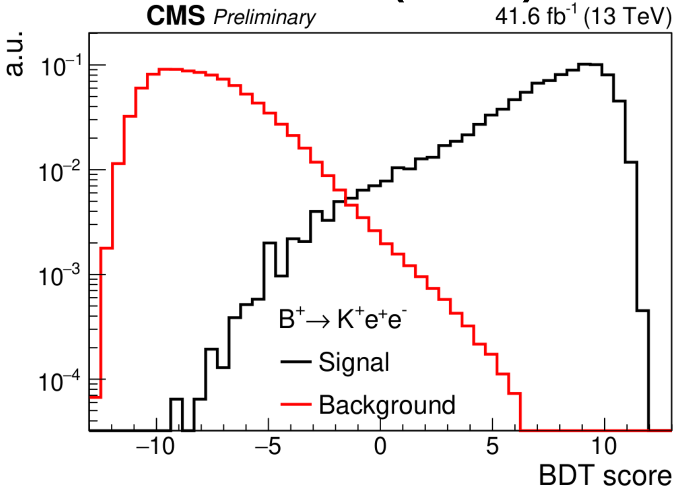
Event selection

- B candidate: created by combining leptons with tracks
- leptons can be: muons, or electrons (includes a dedicated reconstruction for low p_T electrons and the "standard" CMS reco algorithm for higher p_T values)
- Main selection: three BDTs, one for lepton type:
  -- one for μμK, and two for eeK (based on the number of low p_T e)

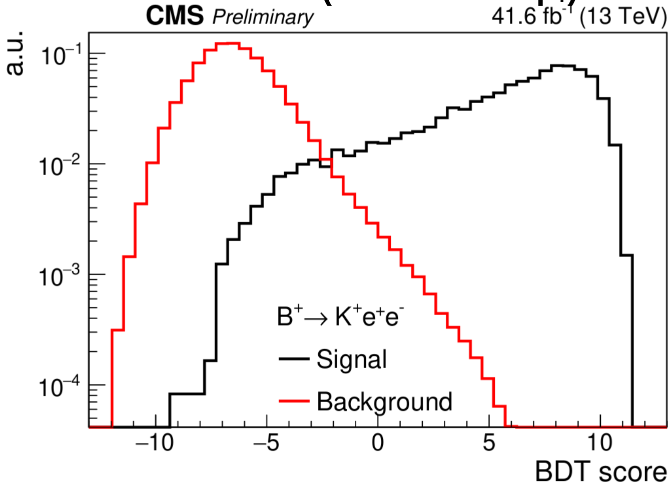
B → μμK



B → eeK (2 std e)



B → eeK (1 std & 1 low p_T)

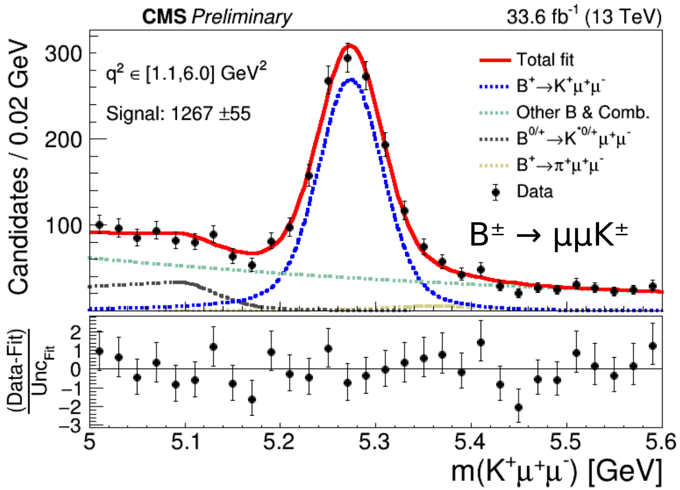


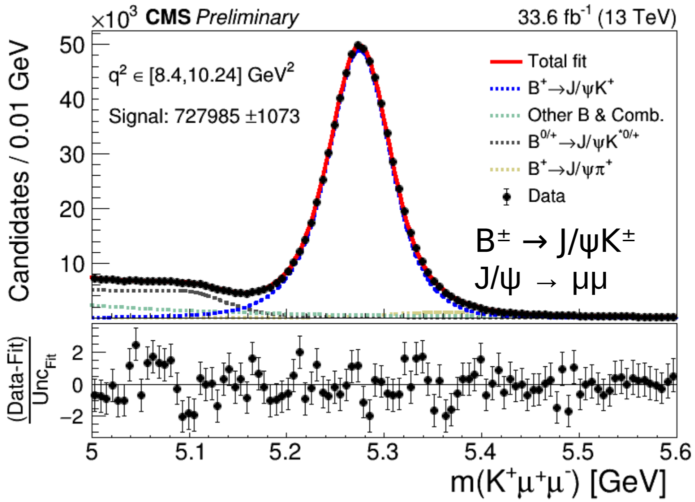
Single-bin mass fits

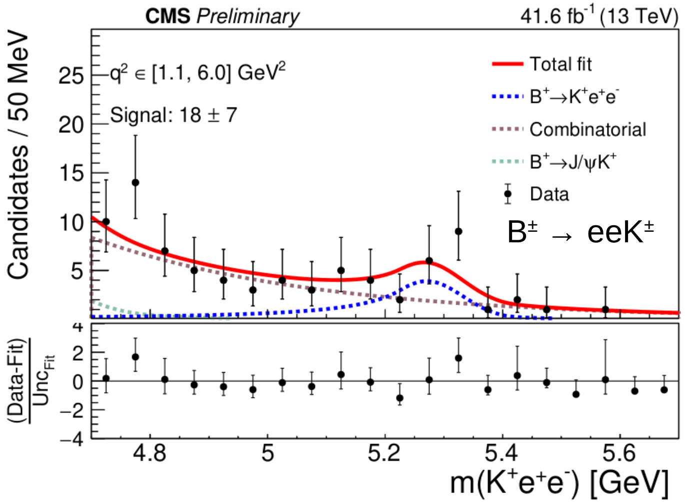
- Analytical functions used for fitting signal and backgrounds

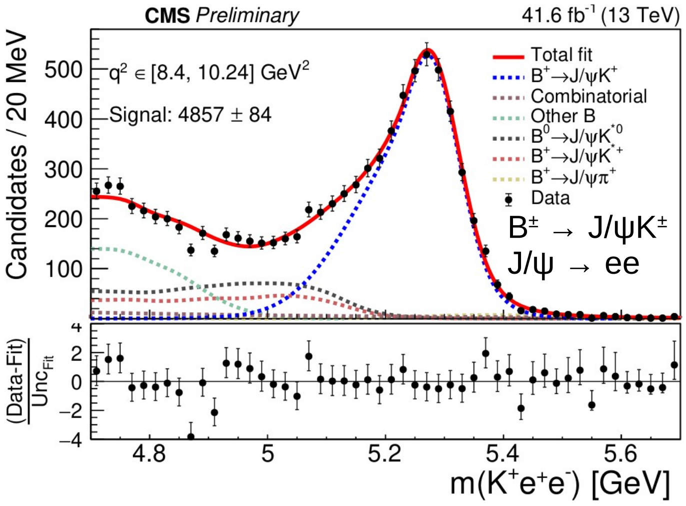
- Signal:
  -- Combination of Gaussians and Double-Sided Crystal Ball functions

-Backgrounds:
  -- B → K*ℓℓ: partial reconstruction of the dominant 4 body decay
  -- Other B: Any other B decay (sequential or J/ψX)
  -- Combinatorial: random combinations of objects from B decays
  -- J/ψK leakage (relevant only in eeK)









BF(B→μμK) and R_K in the low q^2

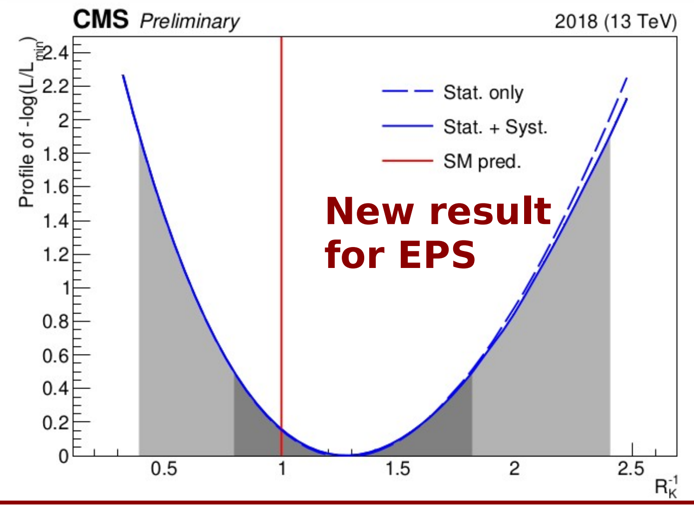
BF(B→ μμK) in full low-q^2 range ($1.1 < q^2 < 6.0$ GeV^2):

BF ($B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$) , $1.1 < q^2 < 6.0$ GeV^2) **New result for EPS**

= (1.242 ± 0.054 (stat) ± 0.011 (MC stat) ± 0.040 (syst)) × 10^{-7}

Can be compared with the predictions of theoretical packages

Package	EOS	Flavio	HEP fit	SuperIso
Prediction [$\times 10^{-7}$]	1.89 ±0.13	1.71 ±0.27	1.98 ±0.73	1.65 ±0.34



Central value and confidence range by minimizing the Likelihood fit function of R_K^{-1}:

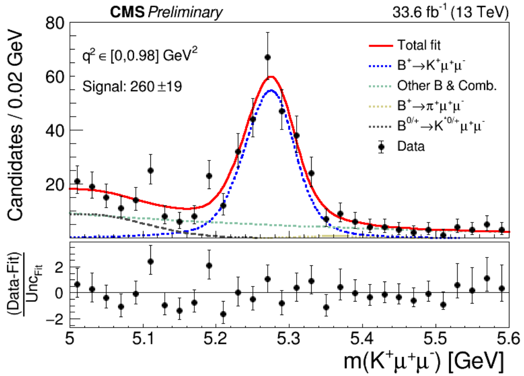
$$R_K = 0.78^{+0.46}_{-0.23}\ (\text{stat})\ ^{+0.09}_{-0.05}\ (\text{syst})$$

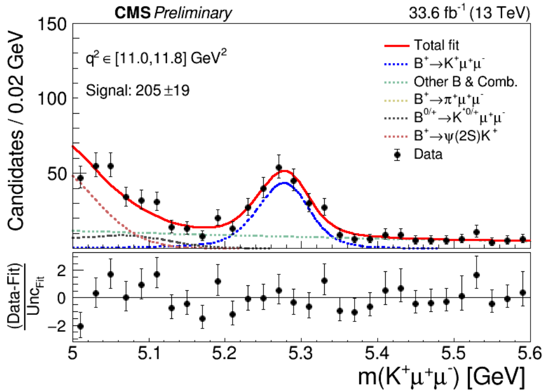
New result for EPS

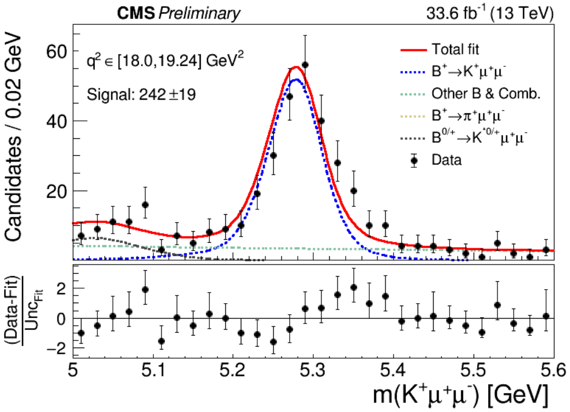
Precision dominated by the low stats of B → eeK

Measurement of differential BF(B → μμK)

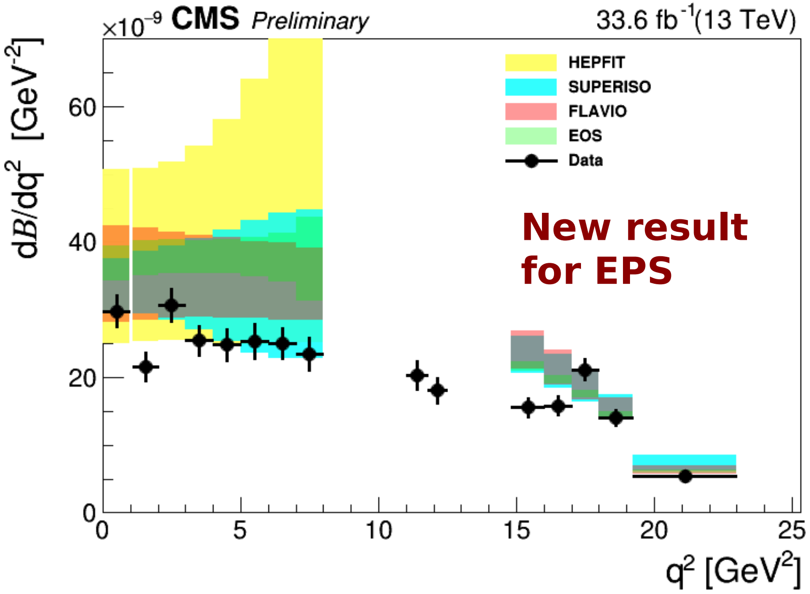
- For differential BR measurement, a fit is performed in all q^2 bins at the same time
- Same functional forms (with different parameters) and event selection as for the BR(B→ μμK) in full low q^2 used







Measurement of dBR/dq^2 and comparison with theory

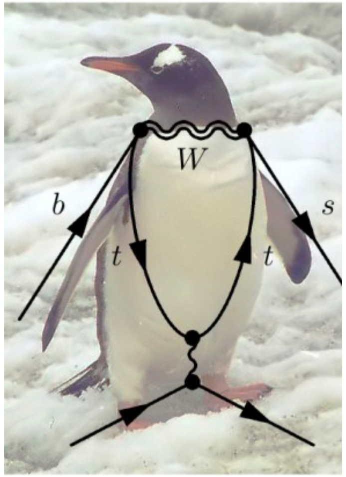


$B_s \to \mu\mu$ & $B^0 \to \mu\mu$

Phys. Lett. B 842

Interest on $B_s \to \mu\mu$ decay

[Phys. Lett. B 842](#)



Searching for $B_s \to \mu\mu$ decay:

- Clean experimental signature
- Precise theoretical calculations
- Deviation of 2.4 σ in BR from the SM prediction in the first "observation" paper
- Sensitive to the value of C_{10} Wilson coefficient

Analysis strategy:

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

0.231±0.008

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

1

BR measured with respect to B → J/ψK decay

Also the B_s effective lifetime is measured in a simultaneous bin in lifetime, mass and lifetime uncertainty

Event selection

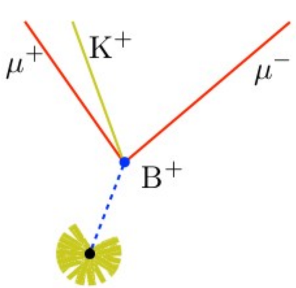
Phys. Lett. B 842

Selection	$B^0_s \to \mu^+\mu^-$	$B^+ \to J/\psi K^+$	$B^0_s \to J/\psi\phi$
B candidate mass [GeV]	[4.90,5.90]	[4.90,5.90]	[4.90,5.90]
Blinding window [GeV]	[5.15,5.50]		
$p_{T\mu}$ [GeV]	> 4	> 4	> 4
$\lvert\eta_\mu\rvert$	< 1.4	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4	> 4
$p_{T\mu\mu}$ [GeV]	> 5	> 7	> 7
$\mu\mu$ SV probability	> 0.025	> 0.1	> 0.1
J/ψ candidate mass [GeV]		[2.9,3.3]	[2.9,3.3]
Kaon p_T [GeV]		> 1	> 1
Mass-constrained fit probability		> 0.025	> 0.025
2D $\mu\mu$ pointing angle [rad]		< 0.4	< 0.4
ϕ candidate mass [GeV]			[1.01, 1.03]

Preselection

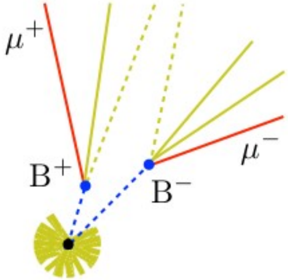
Important backgrounds

Partial B decays



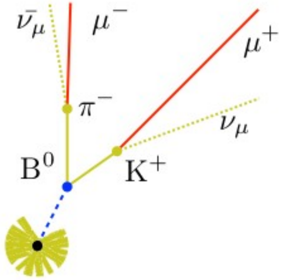
- Found only bellow the B_s mass region

Combinatorial



- Dominant above B_s mass
- Smooth falling distribution

Fake muons



- Peaking in B_s region
- Same magnitude as signal
- Dedicated MVA ID

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[Phys. Lett. B 842]

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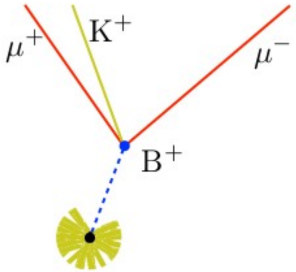

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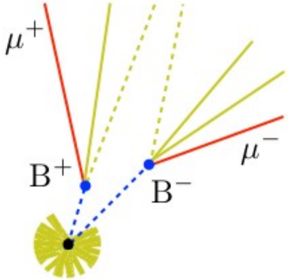

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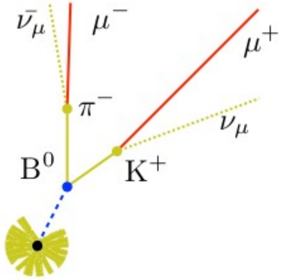

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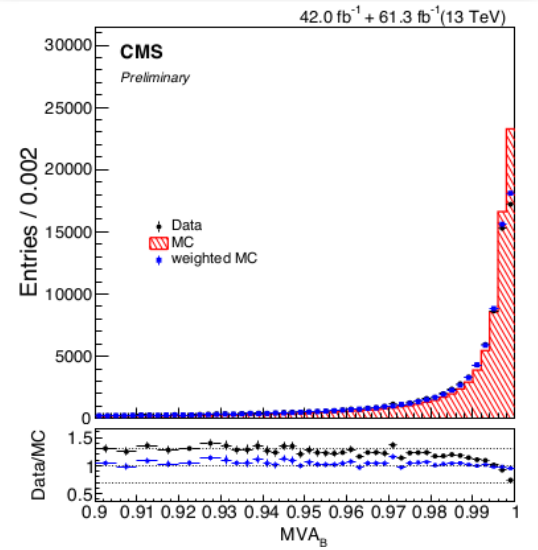

Final selection:
- BDT is used
- 3-fold cross-validation
- Signal from simulation
- Background from data sidebands

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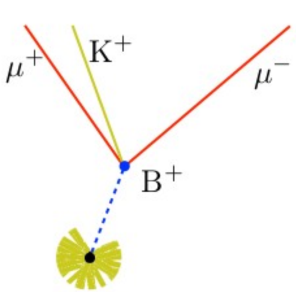

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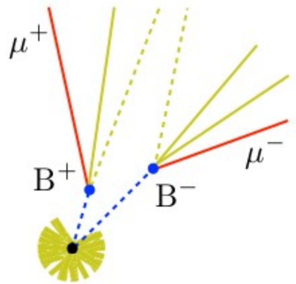

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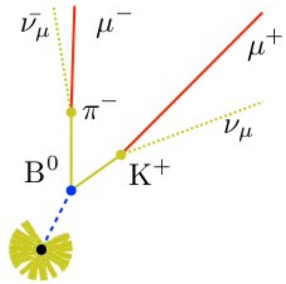

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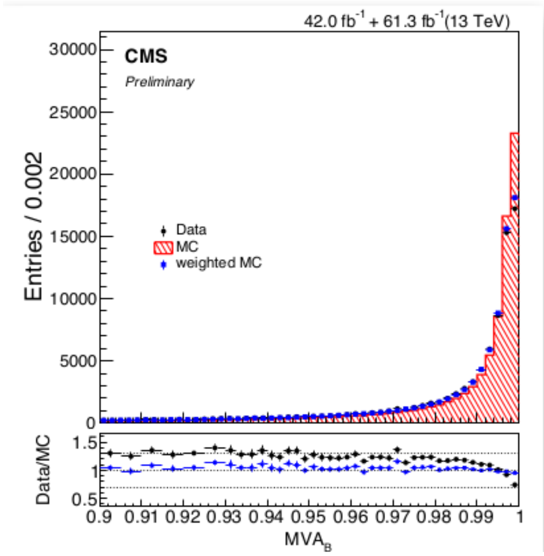
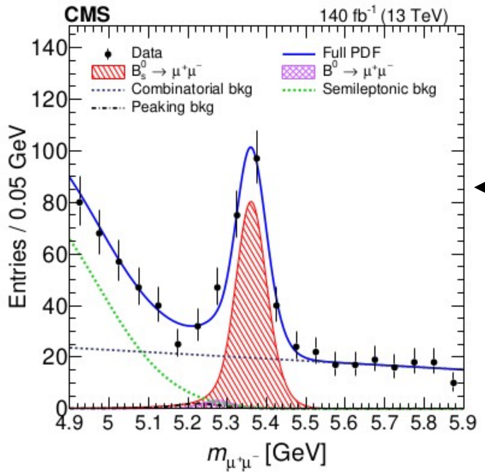


Final selection:
- BDT is used
- 3-fold cross-validation
- Signal from simulation
- Background from data sidebands

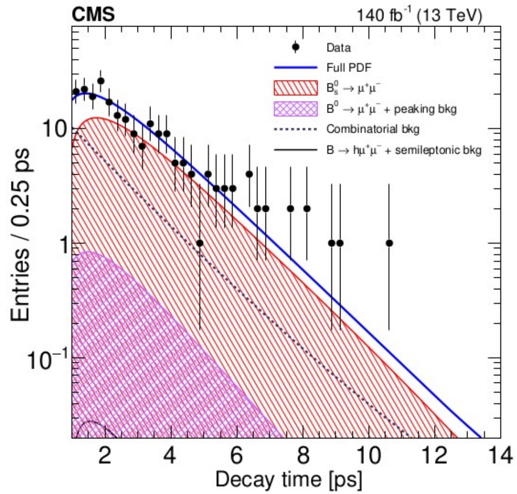
Categorization:
- Two BDT bins: 0.9-0.99 & 0.99-1
- Two |η| regions: 0-0.7 & 0.7-1.4
- Four Data taking eras

16 categories in total



BR measurement:
Simultaneous 2D fit in mass and its uncertainty

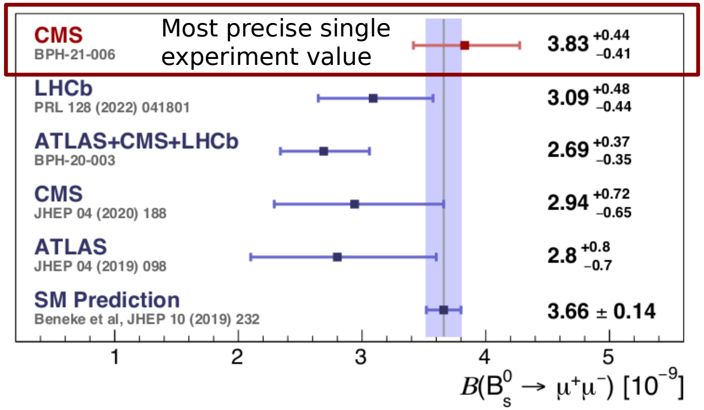
Lifetime measurement:
Simultaneous 3D fit in mass, lifetime and its uncertainty

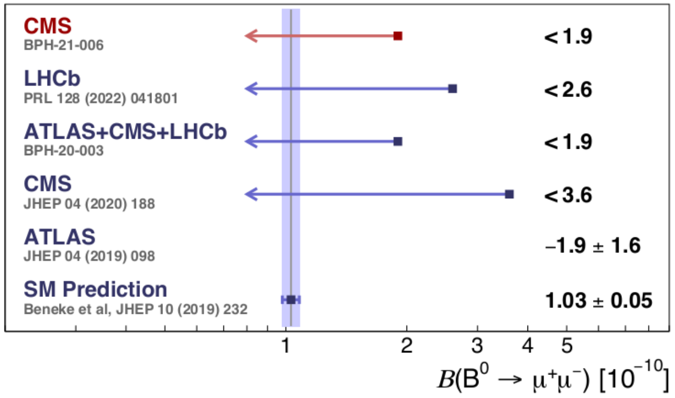


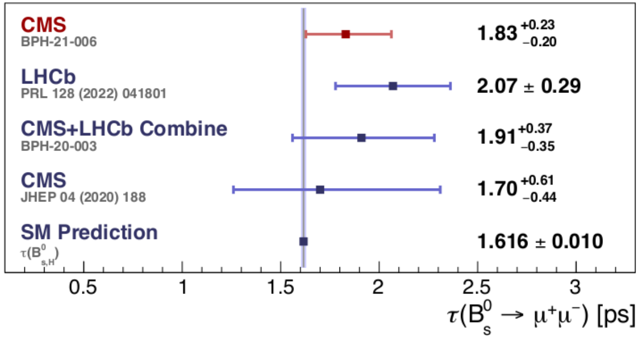
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$$

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







Angular observables

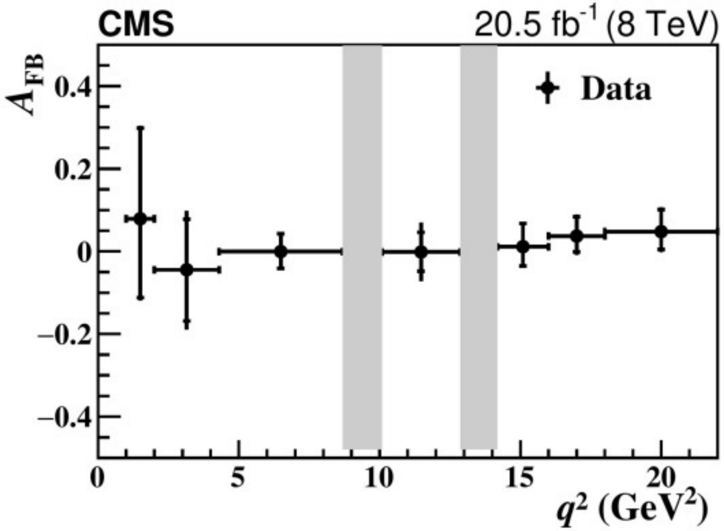
Overview of Run 1 analyses

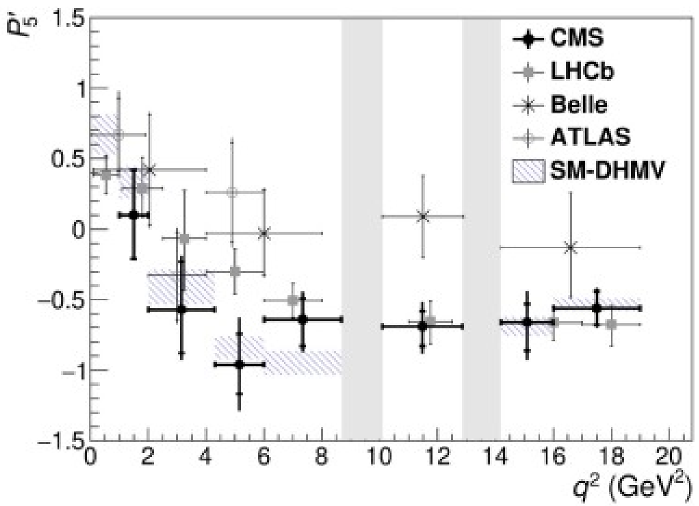
Decay to pseudoscalar: $B^+ \rightarrow K^+\mu\mu$
- Muon direction defines one angular variable
- Allows measuring the muon forward-backward asymmetry

Decay to vector particle: $B \rightarrow K^*\mu\mu$
- Muon direction and K^* polarization define three helicity angles
- Allows measuring a large set of angular parameters, sensitive to Wilson coefficients

Phys. Let. B 753 Phys. Rev. D 98

Phys. Let. B 781 JHEP 124





- Strong legacy on angular distributions measurements
- Statistically limited results
- Updates with Run 2 data coming soon

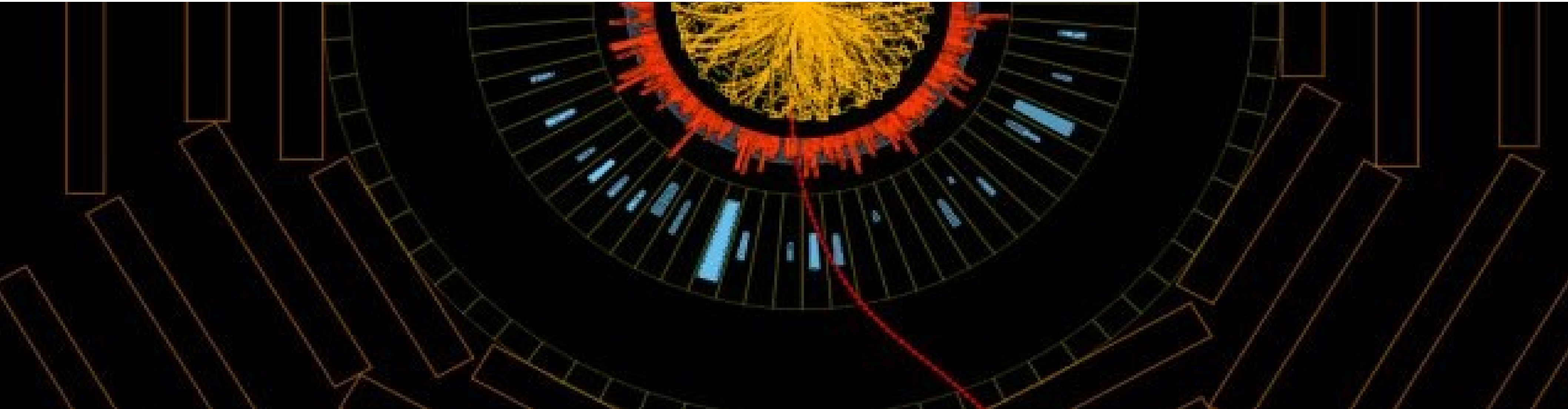
Summary

- CMS pursuing a very ambitious B Physics program
- First R_K result using 2018 data proves the robustness and adaptability of the CMS detector, trigger and software
  - -- We improved triggering strategy in Run 3
  - -- **Expecting large increase in statistics of B → eeK**

Public analysis summary will be posted here: BPH preliminary results

→ ID: BPH 22-005

Stay tuned for more results (soon)!



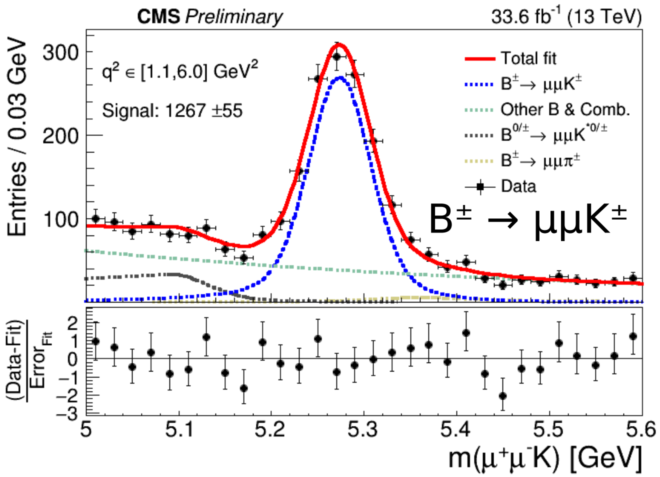
Back up

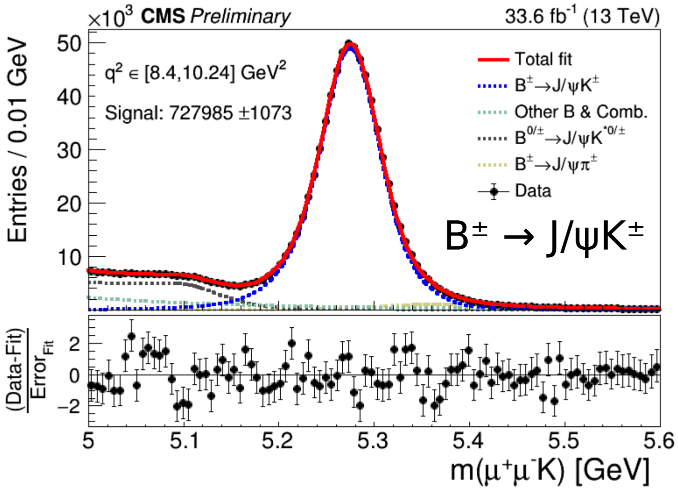
Single-bin mass fits for muon channels

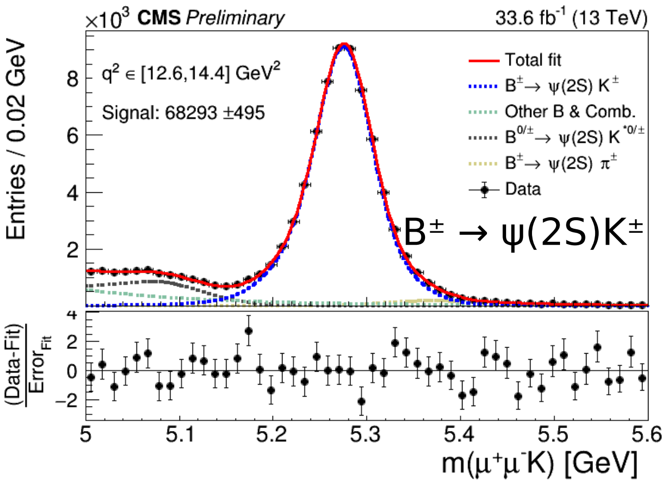
Functions used for each fit component per decay

	$B^{\pm} \rightarrow \mu\mu K^{\pm}$	$B^{\pm} \rightarrow J/\psi K^{\pm}$	$B^{\pm} \rightarrow \psi(2S)K^{\pm}$
Signal	DSCB + Gaussian	Sum of 3 Gaussians	DSCB + Gaussian
Comb & other B	Exponential	Exponential	Exponential
$B^{\pm} \rightarrow K^{*0/\pm}X$	DSCB	DSCB + Exponential	DSCB + Exponential
$B^{\pm} \rightarrow \pi^{\pm} X$	DSCB	DSCB	DSCB

Where X=J/ψ, ψ(2S), μμ





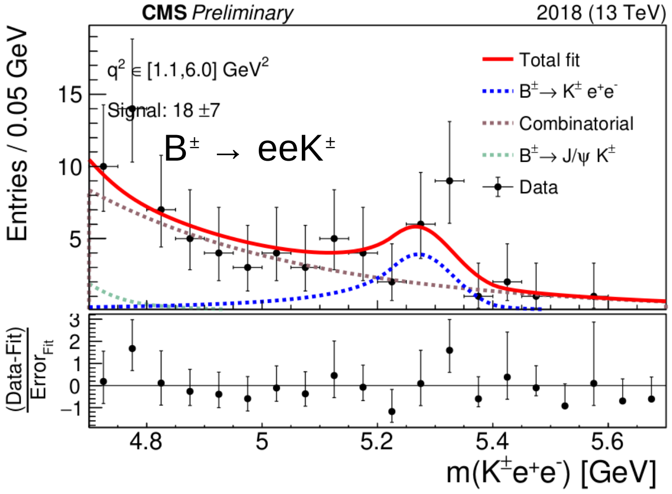


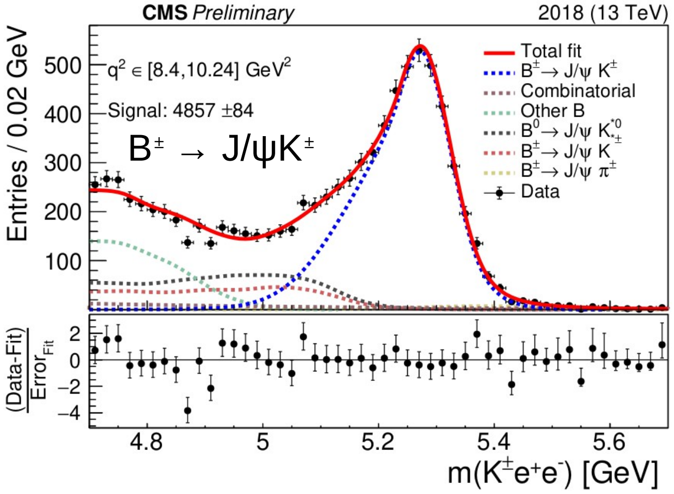
Single-bin mass fits for electron channels

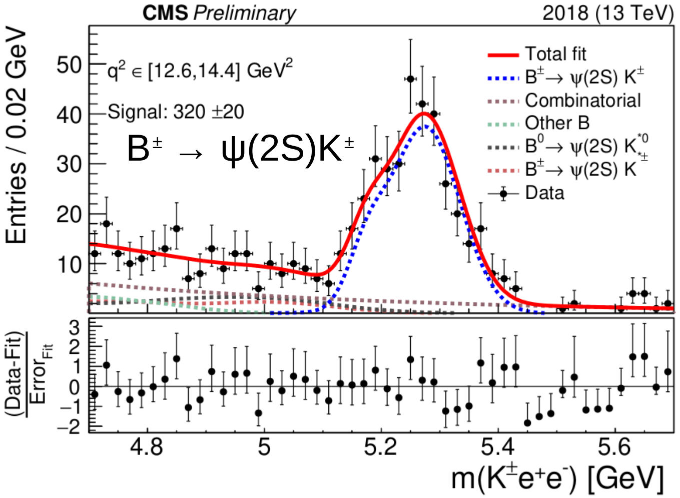
Functions used for each fit component for electron channels

	$B^{\pm} \to eeK^{\pm}$	$B^{\pm} \to J/\psi K^{\pm}$	$B^{\pm} \to \psi(2S)K^{\pm}$
Signal	DSCB	CB + Gaussian	CB + Gaussian
Combinatorial/Other B	Exponential / -	Exponential / KDE	Exponential / KDE
$B^{\pm} \to K^{*0/\pm}X$	-	KDE template	KDE template
$B^{\pm} \to \pi^{\pm} X$	-	CB	-
$B^{\pm} \to J/\psi K^{\pm}$	KDE template	-	-

Where X=J/ψ, ψ(2S), ee

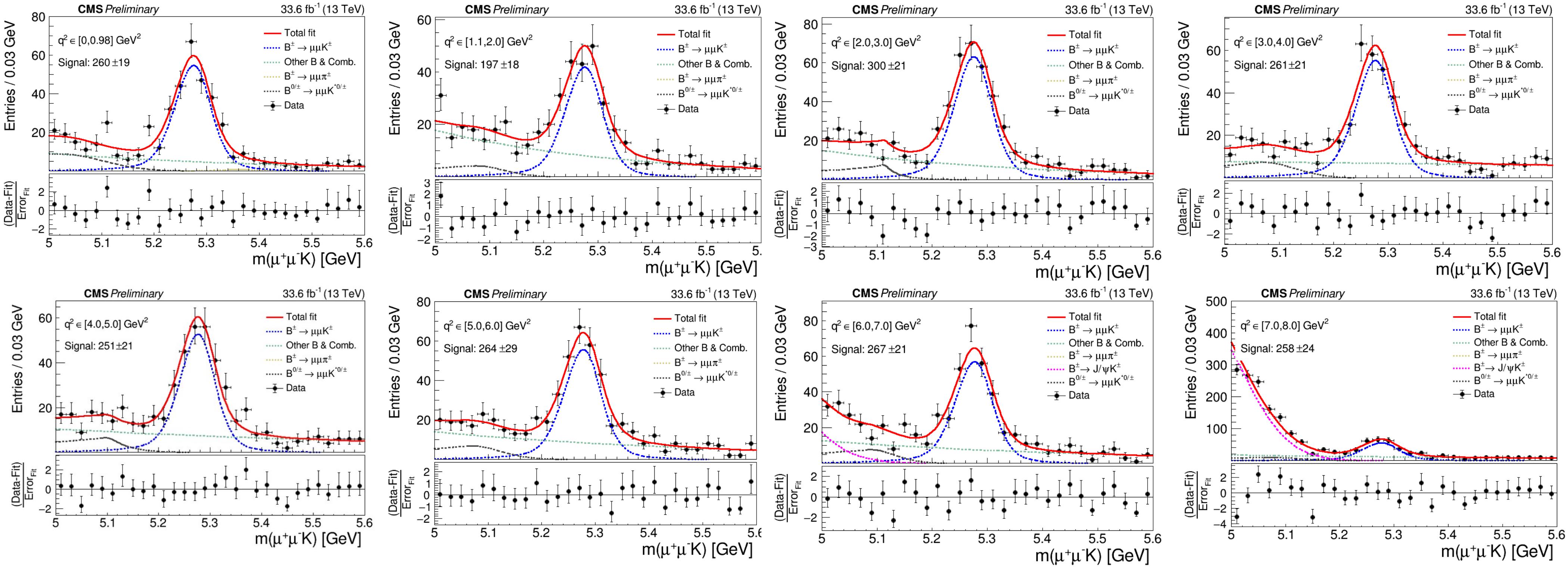






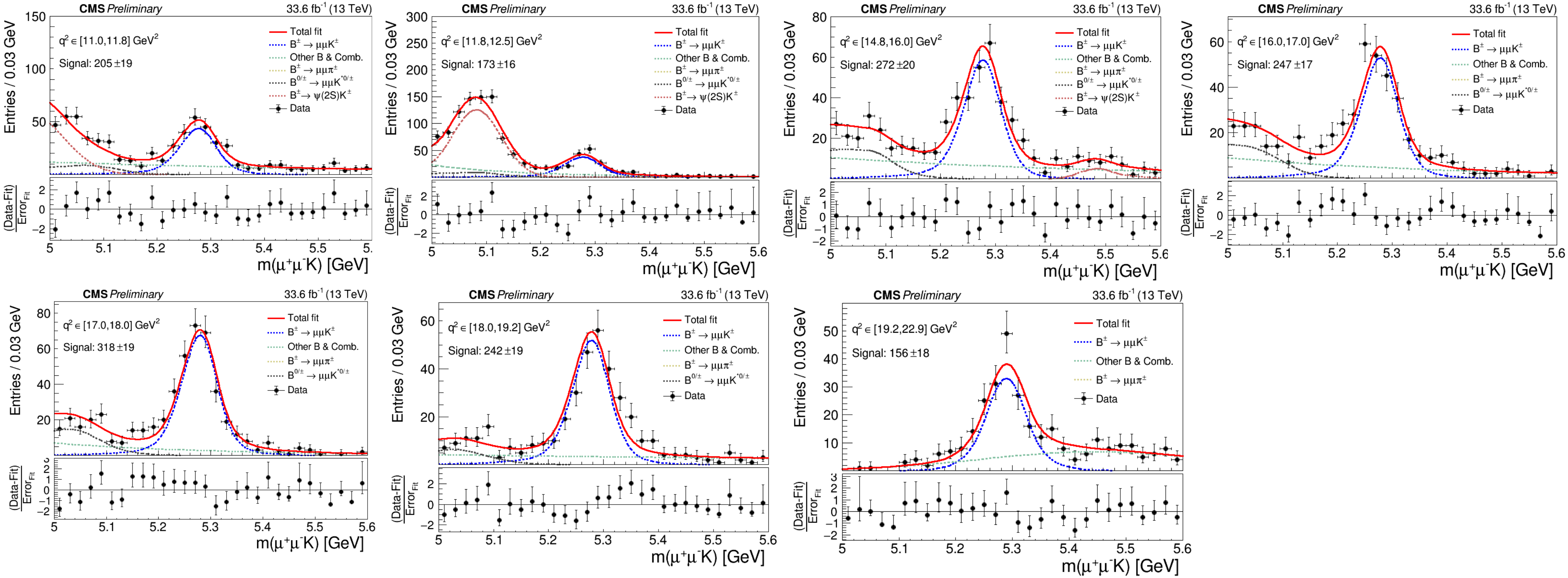
Simultaneous mass fits in q^2 bins

- Same functions as in the single low q^2 fit, but a simultaneous fit is performed in all q^2 bins
- Differences:
  - -- The signal means related across q^2 bins by a linear function with floating slope and intercept
  - -- DCSB in some bins to account for resonant B decays
- Here shown: [0-0.98], [1.1-2], [2-3], [3-4], [4-5], [5-6], [6-7] and [7-8].



Simultaneous mass fit in q^2 bins for μμK

- Here shown: [11-11.8], [11.8-12.5], [14.8-16], [16-17], [17-18], [18-19.2] and [19.2-22.9].

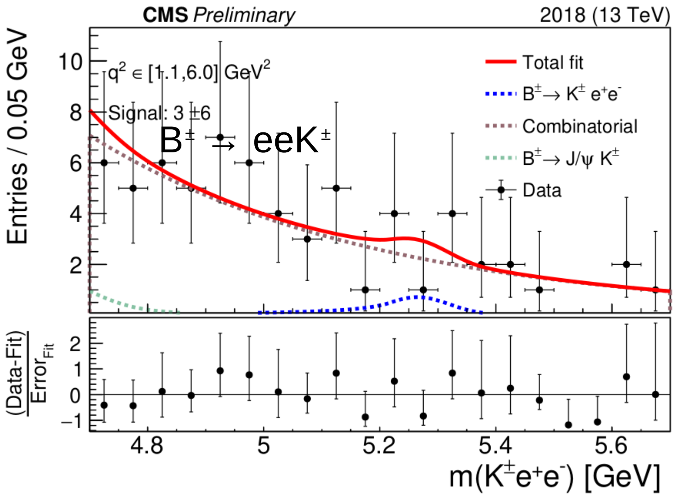


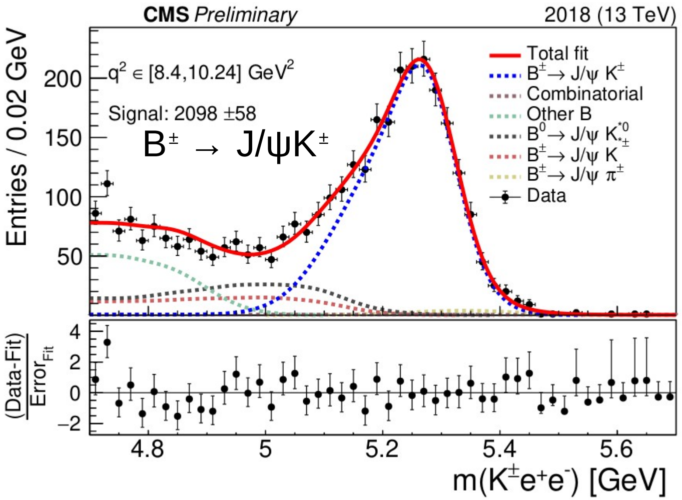
Single-bin mass fits for electron channels

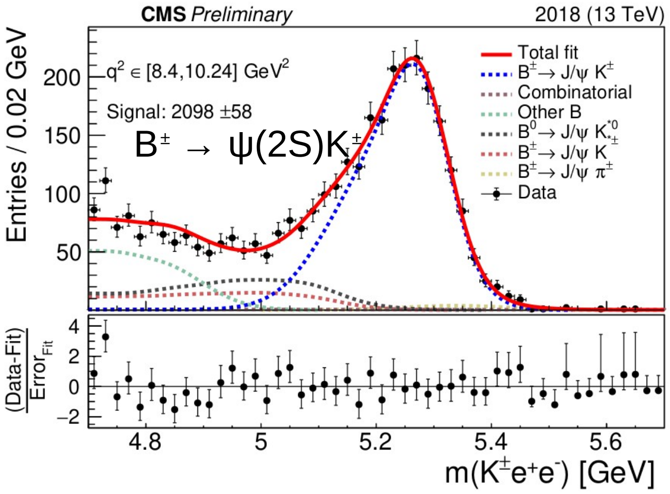
Functions used for each fit component for electron channels with 1 PF & 1 low p_T e

	$B^\pm \to eeK^\pm$	$B^\pm \to J/\psi K^\pm$	$B^\pm \to \psi(2S)K^\pm$
Signal	DSCB	CB + Gaussian	CB + Gaussian
Combinatorial/Other B	Exponential / -	Exponential / KDE	Exponential / KDE
$B^\pm \to K^{*0/\pm}X$	-	KDE template	KDE template
$B^\pm \to \pi^\pm X$	-	CB	-
$B^\pm \to J/\psi K^\pm$	KDE template	-	-

Where X=J/ψ, ψ(2S), ee







Systematic uncertainties

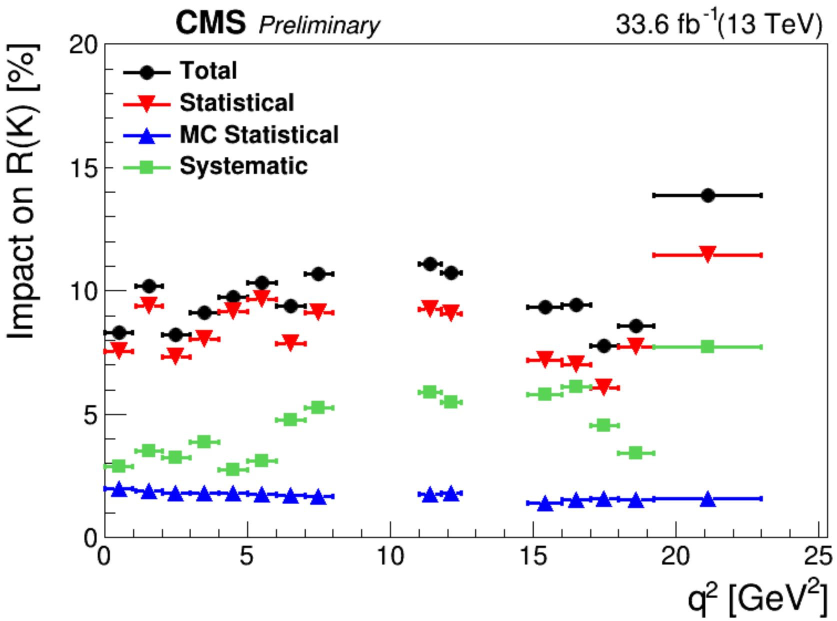
- Systematics are treated as independent between the muon and electron part of R_K
- The total uncertainty of R_K is dominated by the statistical part of electron channels

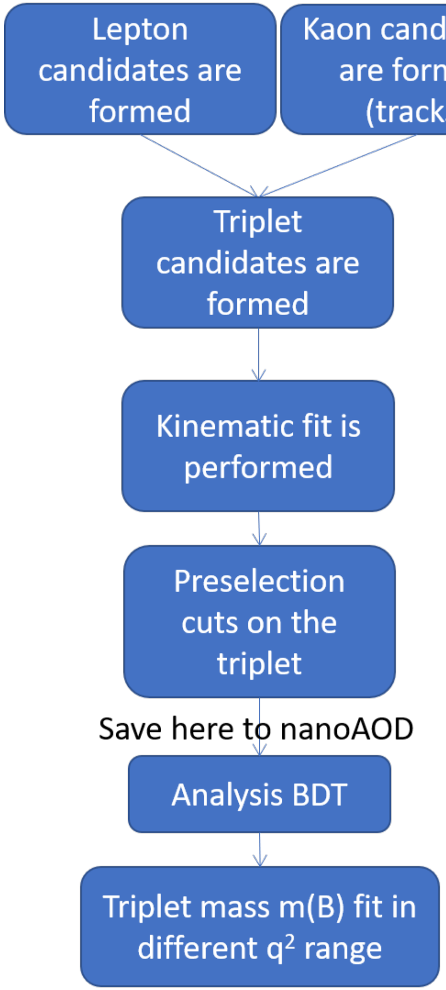
Uncertainties on the muon part **Uncertainties on the electron part**

Source
Backgrou
Trigger tu
Reweight
Backgrou
J/ψ meso
Pileup
Signal sh
Trigger ef
J/ψ reson
Nonresor
Total syst
Statistical
Statistical
Total unc

- Same uncertainty sources considered for the single-bin muon measurement, are evaluated in each q^2 bin

- In all bins: total uncertainty is dominated by the statistical component





A practical problem: Running on 10^{10} events needs a lot of storage, time and computing power

Code strategies:
1) Apply cuts as quickly as possible in every step of the reconstruction
2) Move time consuming processes to the end of the chain

Algorithm:
- Select leptons of opposite sign and create the common vertex
- Combine with a track (Kaon mass assigned)
- Kinematic Fit to a common vertex

Preselection:
- Adaptive grid search approach used
- Cut values are different for μμK and eeK

Preselection for μμK:
- $p_T(B) > 3$ GeV
- Δz(trg μ, track/μ2) < 1.0 cm
- $p_T(track) > 1$ GeV
- $L_{xy}/\sigma > 1$
- cos (α) > 0.90
- Prob > 10^{-5}
- m(K,μ) > 2 GeV [anti-D^0]

Preselection for eeK:
- Δz(trg μ, track/e) < 1.0 cm
- $p_T(e2) > 1.0$ GeV
- cos (α) > 0.95
- Prob > 10^{-5}
- m(K,e) > 2 GeV [anti-D^0]
- $d_{3d} < 0.06$
- ID (e1) > -2
- ID (e2) > 0

Yields

Bin	q^2 range [GeV]	Branching fraction [10^{-8}]
1	0–0.98	2.98 ± 0.25
2	1.1–2.0	2.15 ± 0.22
3	2.0–3.0	3.07 ± 0.25
4	3.0–4.0	2.54 ± 0.23
5	4.0–5.0	2.48 ± 0.24
6	5.0–6.0	2.53 ± 0.26
7	6.0–7.0	2.51 ± 0.23
8	7.0–8.0	2.35 ± 0.25
9	11.0–11.8	2.03 ± 0.22
10	11.8–12.5	1.80 ± 0.19
11	14.82–16.0	1.55 ± 0.14
12	16.0–17.0	1.58 ± 0.15
13	17.0–18.0	2.11 ± 0.16
14	18.0–19.24	1.40 ± 0.12
15	19.24–22.9	0.53 ± 0.07

History of LFU results

(Selected) interesting results of LFU searches:

2013	2014	2017	2022	2022	2022	2023
$R_D = 0.44$ $R_{D^*} = 0.33$	$R_K = 0.74$	$R_{K^*} = 0.69$	$R_K = 0.84$	$R_K = 0.95$ $R_{K^*} = 1.03$	$R_D = 0.44$ $R_{D^*} = 0.28$	$R_K = ?$
Phys. Rev. Lett. 109	Phys. Rev. Lett. 113	JHEP 08, 055	Nature Physics 18, 227	ArXiv: 2212.09152	LHCb-PAPER-2022-039	

R_K : still a very powerful tool to probe LFU

The first R_K result from CMS, today in EPS !

History of LFU results

(Selected) interesting results of LFU searches:

2013	2014	2017	2022	2022	2022
$R_D = 0.44$ $R_{D^*} = 0.33$	$R_K = 0.74$	$R_{K^*} = 0.69$	$R_K = 0.84$	$R_K = 0.95$ $R_{K^*} = 1.03$	$R_D = 0.44$ $R_{D^*} = 0.28$
Phys. Rev. Lett. 109	Phys. Rev. Lett. 113	JHEP 08, 055	Nature Physics 18, 227	ArXiv: 2212.09152	LHCb-PAPER-2022-039

R_K : still a very powerful tool to probe LFU

Signal description

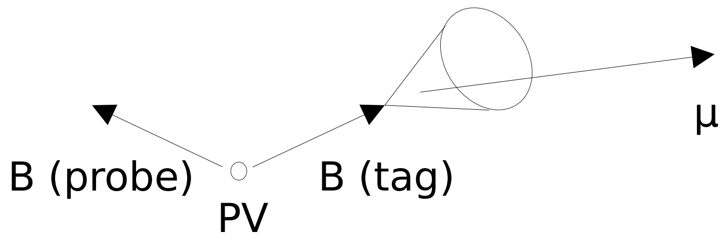
To test LFU with minimal theoretical uncertainty, can use the ratio of B → μμK to B → eeK, R_K:

$$R_K = \frac{BF(B \to \mu\mu K)}{BF(B \to eeK)}$$

To reduce experimental uncertainties → divide both numerator and denominator with BF(B → J/ψK).

R_K becomes:

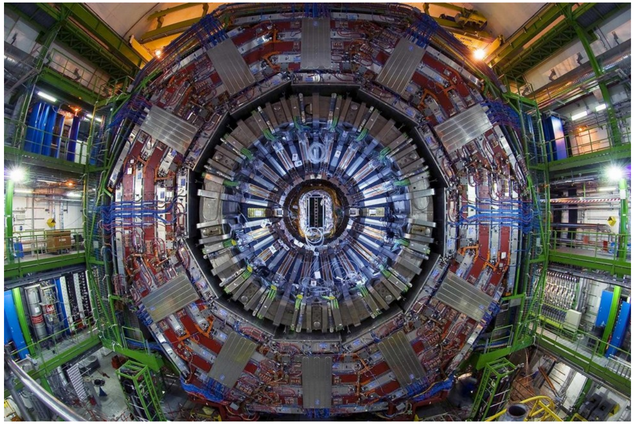
$$R_K = \frac{BF(B \to \mu\mu K)}{BF(B \to J/\psi K, J/\psi \to \mu\mu)} / \frac{BF(B \to eeK)}{BF(B \to J/\psi K, J/\psi \to ee)}$$



To collect a sample of eeK with CMS in Run 2:
- **Trigger on one b hadron using muons, leaving the second b hadron completely unbiased**
- Large probability to for μ in final state
- Use μ-based paths to trigger
- Technique known as Tag-and-Probe
- Tag = triggering B

B Parking trigger

Collisions (p – p) at 40 MHz

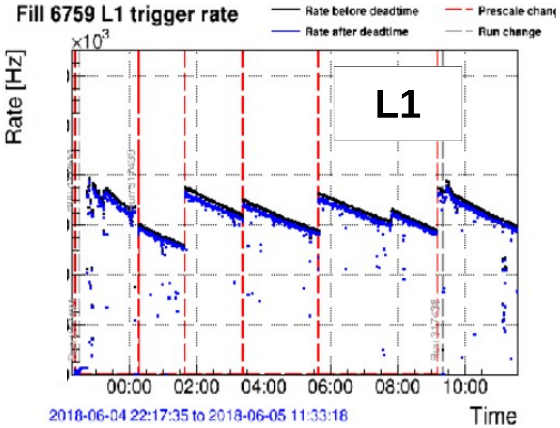


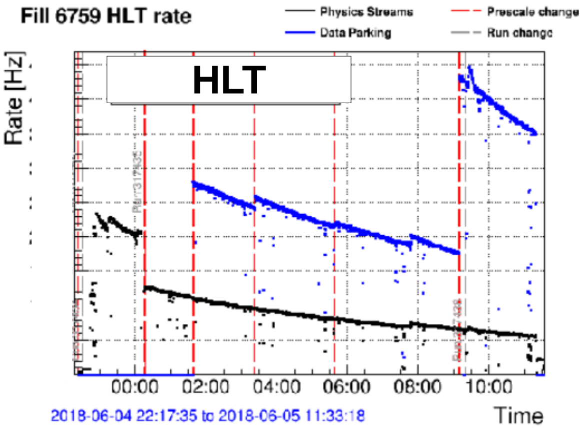
L1 Trigger → **HLT Trigger** → **DAQ**

L1 Trigger
- Single-μ L1 seeds
- η restricted, soft p_T
- Purity in B decays ~30%
- Constant L1 rate

HLT Trigger
- L1 seeds as inputs
- Refined p_T and d_{xy} cut

DAQ
- Saved in single copy
- Stored on tape until computing resources available
- Long delay in reconstruction; procedure known as "Parking"

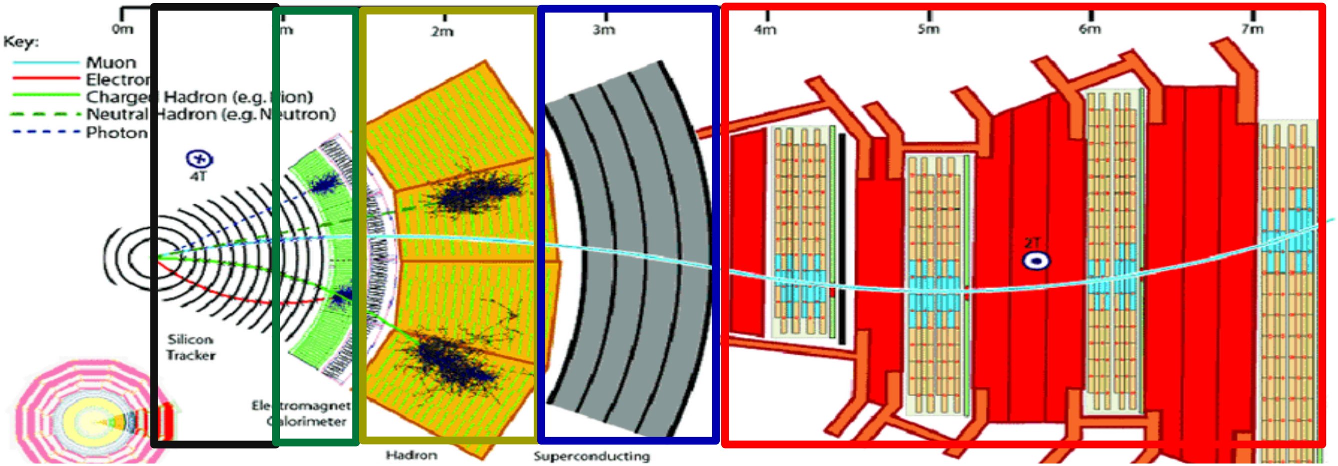




- As luminosity decreases lower p_T seeds enabled
- Tune/optimize paths during data-taking
- **Collected during 2018**

The Compact Muon Solenoid detector

More information in the [TDR]



Tracker:	ECAL:	HCAL:	Magnet:	Muon:
- Pixels in the core - Silicon strips around - In 2017 an extra inner layer added - Total 14(15) layers in Barrel(endcaps) - Reconstructs the trajectory of charged particles - Excellent measurement of position	- Homogeneous calorimiter - Lead tungstate (PbWO) scintillator - 61,200 crystals in barrel - 1,700 crystals in endcap - Measures the energy of e and γ - Very good energy resolution	- Heterogeneous calorimiter - Interleaved heavy material with scintillator layers - Measures the energy of hadrons - Indirect measurement of non-interacting particles (like ν)	- Central device - Large solenoid magnet - Field up to 4T - Bends charged particles to measure their momentum	- Position exploits the penetration of muons - Very clean signatures - Gaseous detectors of three types - Drift tubes (barrel), CSC (endcap), RPC (barrel+endcap)