Exploiting a high-rate trigger strategy at LHC: test of lepton flavor universality in $B \to \ell\ell K$

Georgios Karathanasis, on behalf of the CMS Collaboration

12/01/2023

Outline

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  - R_K definition and previous results
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- B Parking triggering strategy
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  - B candidate reconstruction
  - Selection of B → μμK candidates
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  - Simultaneous mass fit B → μμK in q^2 bins
  - Systematic unc. and corrections
- Results
  - dBF(B → μμK)/dq^2 measurement
  - BF(B → μμK) and R_K in $1.1 < m(\mu\mu)^2 < 6$ GeV^2 measurements

Test of lepton flavor universality in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays

The CMS Collaboration

Abstract

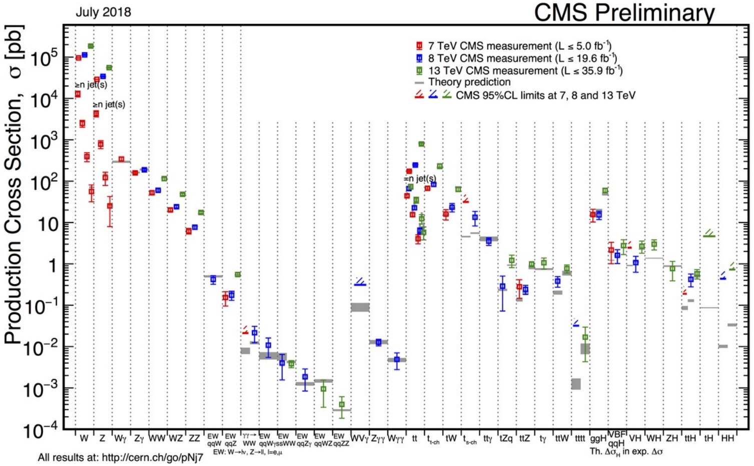
A test of lepton flavor universality in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays, where ℓ is a muon or an electron, as well as a measurement of differential and integrated branching fractions of a nonresonant $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ decay with the CMS experiment at the LHC are presented. The analysis is made possible by a dedicated data set of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded in 2018, using a special high-rate data stream designed for collecting about 10 billion unbiased b hadron decays. The ratio of the branching fractions $\mathcal{B}(B^{\pm} \to K^{\pm}\mu^{+}\mu^{-})$ to $\mathcal{B}(B^{\pm} \to K^{\pm}e^{+}e^{-})$ is measured as a double ratio $R(K)$ of these decays to the respective branching fractions of the $B^{\pm} \to J/\psi K^{\pm}$ with $J/\psi \to \mu^{+}\mu^{-}$ and $e^{+}e^{-}$ decays, which allow for significant cancellation of systematic uncertainties. The ratio $R(K)$ is measured in a range $1.1 < q^2 < 6.0\,\text{GeV}^2$, where q is the invariant mass of the lepton pair, and is found to be $R(K) = 0.78^{+0.47}_{-0.23}$, in agreement with the standard model expectation within one standard deviation. This measurement is limited by the statistical precision of the electron channel. The integrated branching fraction in the same q^2 range of $\mathcal{B}(B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}) = (12.42 \pm 0.68) \times 10^{-8}$ is consistent with the present world-average value and has a comparable precision.

All plots and figures can be found here:

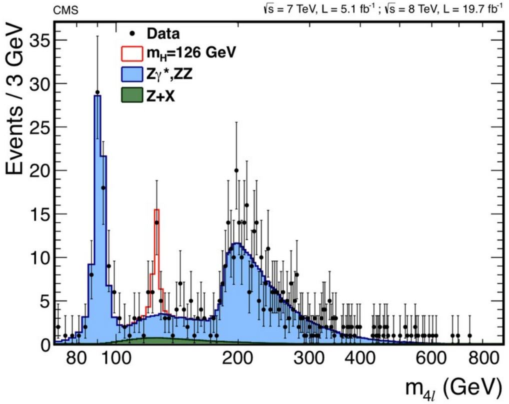
BPH 22-005

Introduction

Standard Model



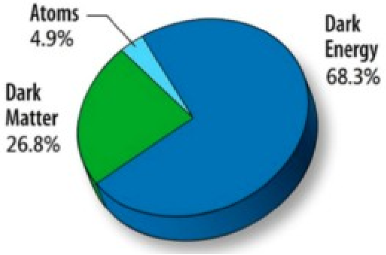
Standard Model (SM):
- Encapsulates everything we know about Nature
- Successfully predicts processes in σ [10^{-3} – 10^{11}] pb
- Discovery of Higgs Boson in 2012 led to extensive search of its properties → (So far) no deviations from SM
- Yet, regarded as an “effective theory”



Not predicted/answered by SM

Hierarchy problem
- New Physics at ~ TeV scale or extremely fine-tuned Higgs mass?

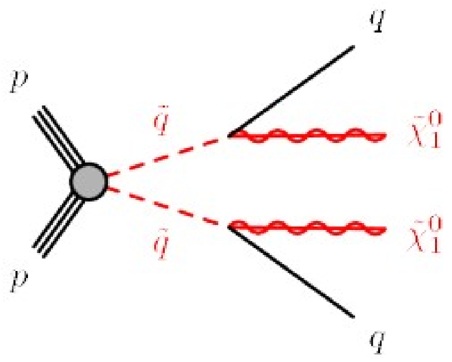
Dark matter problem
- Astrophysical observations indicate 5 times larger mass than visible



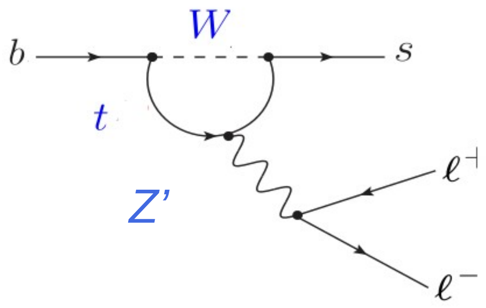
Many more that what can include:
- Neutrino oscillations
- Matter/antimatter asymmetry
-...

Searching for Beyond SM phenomena

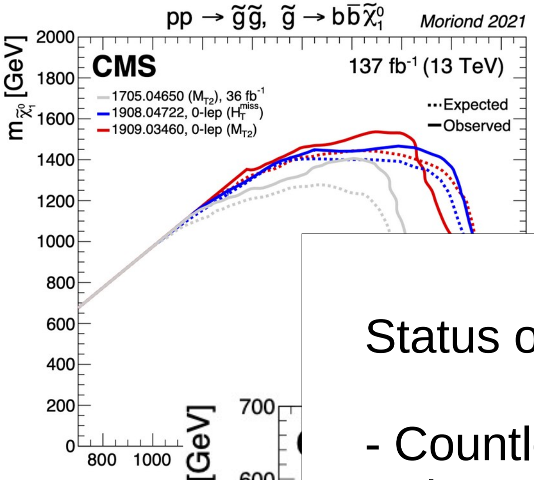
Direct searches:
- New particles are directly produced
- Targets specific Beyond SM (BSM) theory
- (Usually) on-mass shell particles → large signal expected
- Bounded by the center of mass of LHC collisions
- Variety of signatures

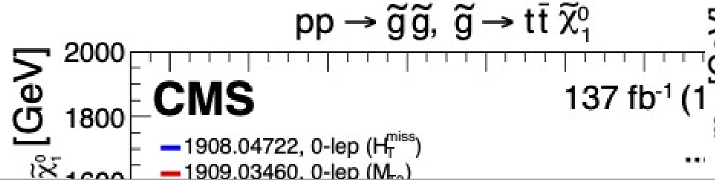


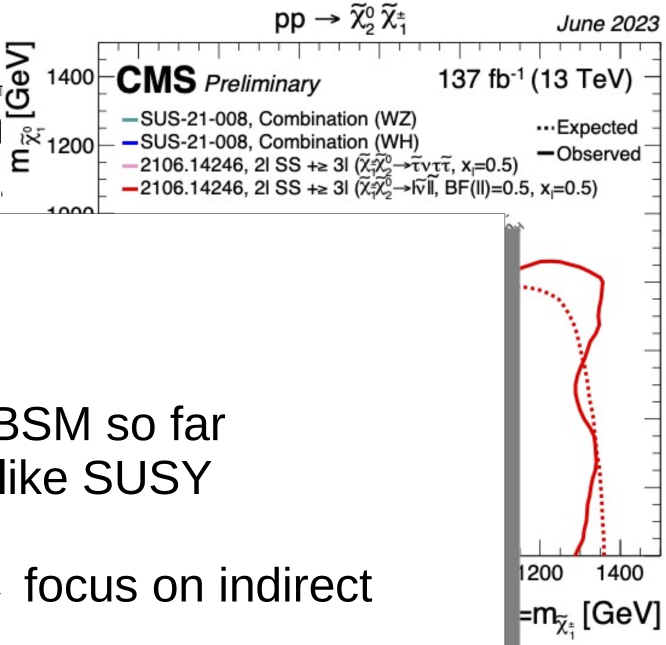
Indirect searches:
- New particles are produced only in loops
- Effects can be explained by many BSM models
- Not bounded by the center of mass of LHC
- Small number of events expected
- Focusing on rare SM signatures where small BSM contributions can be visible.

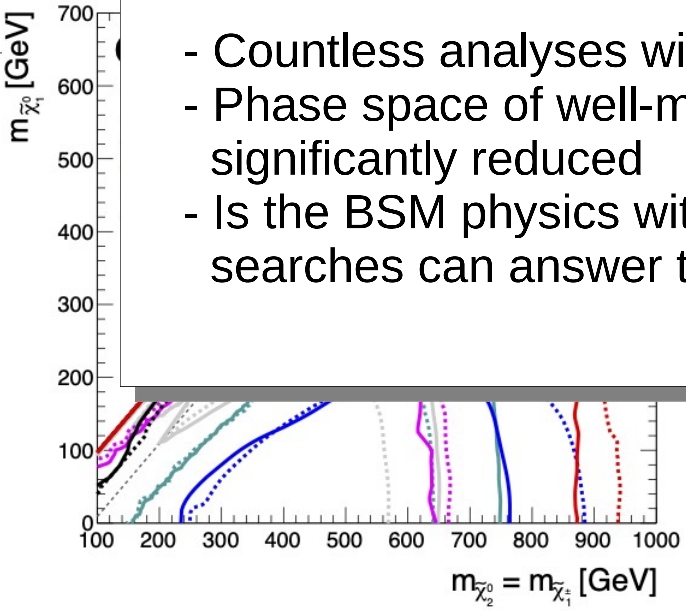


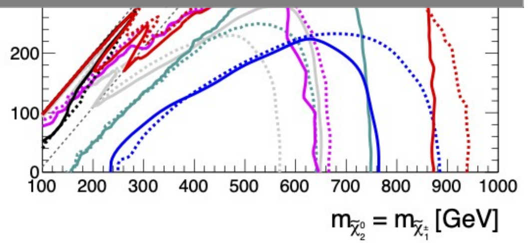
Status of Beyond SM direct searches











Status of direct searches:

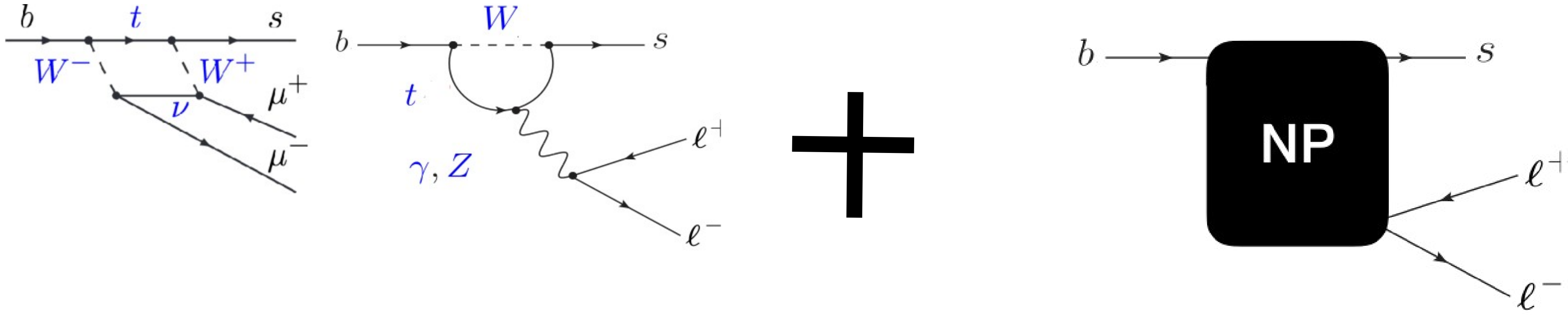
- Countless analyses with no evidence of BSM so far
- Phase space of well-motivated theories, like SUSY significantly reduced
- Is the BSM physics within LHC reach? → focus on indirect searches can answer this

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

- So far no BSM physics has been observed from direct searches
- Rare decays: powerful tool for indirect searches

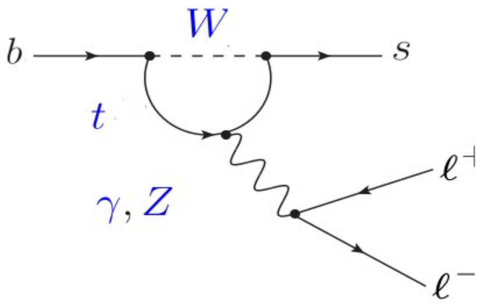
- b→ $s\ell\ell$ transition in the SM:
  - Prohibited at tree level (FCNC)
  - Via loop diagrams (eg penguin, box)
  - Very rare → Weak signals in BSM might be visible

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

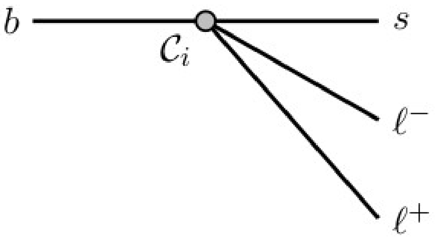


Describing b → sℓℓ with Effective Theory

Full theory



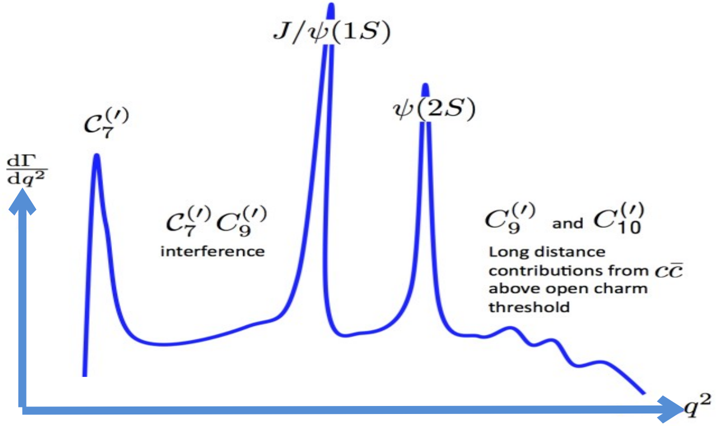
Effective theory



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 SM 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

R_K definition

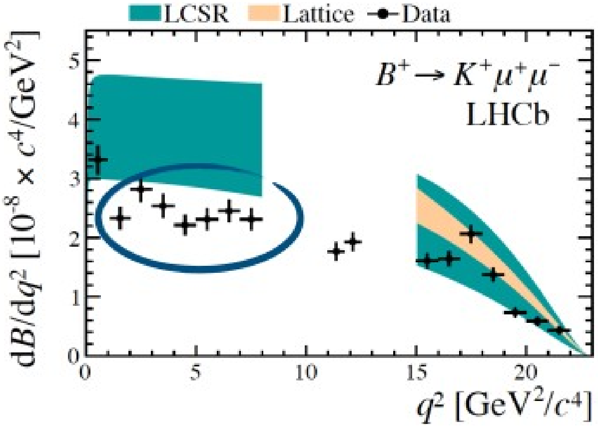
LFU test with minimal theoretical uncertainty via the B → μμK to B → eeK ratio, R_K:

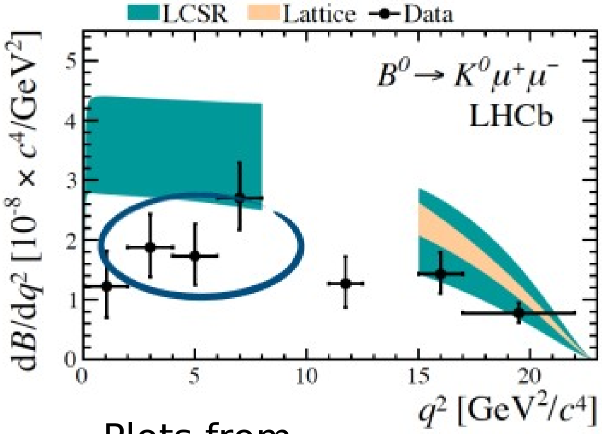
$$R_K = \frac{BF(B \rightarrow \mu\mu K)}{BF(B \rightarrow e e K)}$$

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

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

B Physics anomalies





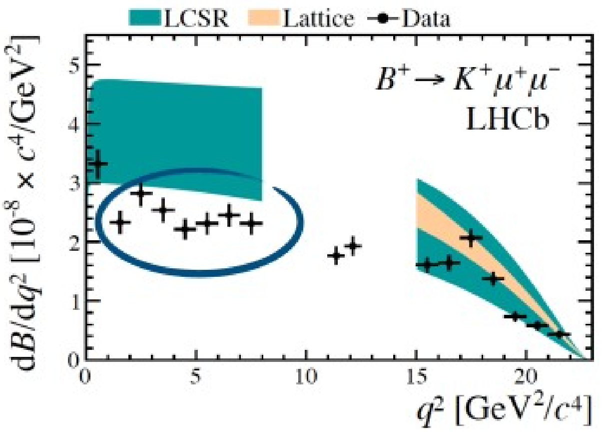
Plots from
JHEP 1406 133

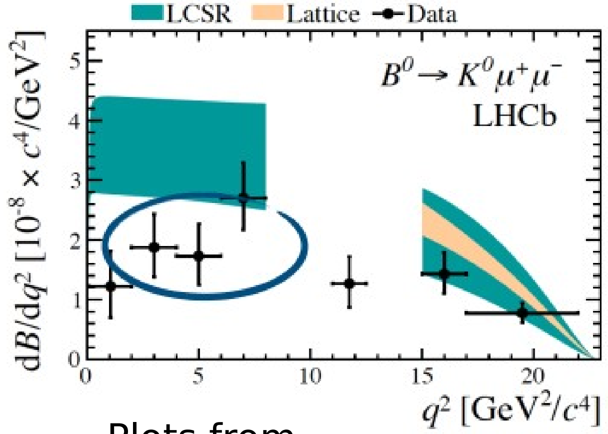
- Deviations of measurements and SM expectations in dBF/dq^2:
  - -- Seen in several channels
  - -- Hadronic form factors have large uncertainties
  - -- BSM effect or common issue of SM expectation?

- Furthermore several angular measurements show ~3σ deviations from SM expectation

- Intriguing pattern

B Physics anomalies





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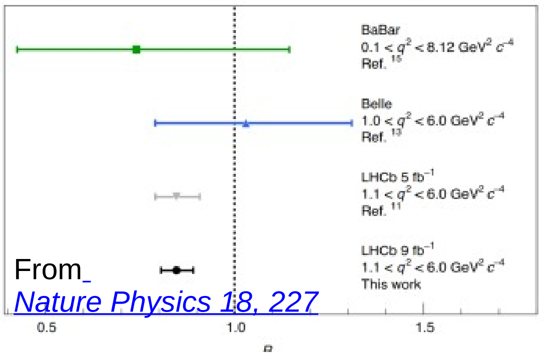
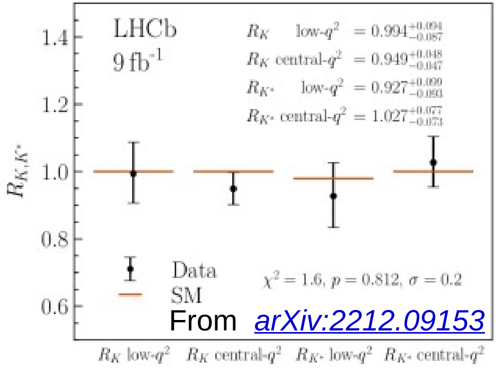
Where we "stand" in R_K?



From Nature Physics 18, 227



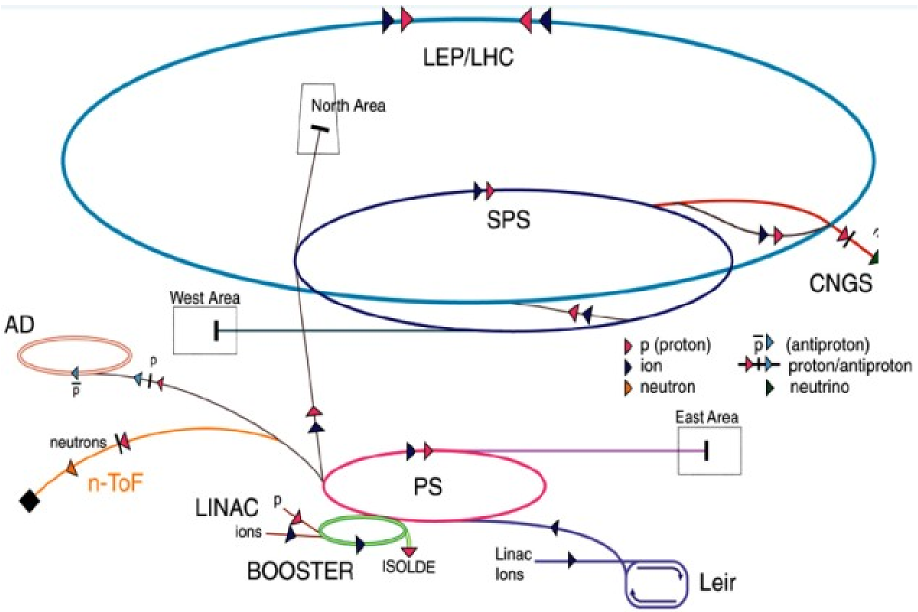
From arXiv:2212.09153

time

Today: the 1st R_K result from CMS using Run 2 data

The Large Hadron Collider

Large Hadron Collider
- Most powerful accelerator
- 27-kilometer ring
- Located in Switzerland & France
- 2 proton beams colliding at 13 TeV
- 4 Interaction points:
    ATLAS, CMS, LHCb, Alice



The Compact Muon Solenoid

Large Hadron Collider
- Most powerful accelerator
- 27-kilometer ring
- Located in Switzerland & France
- 2 proton beams colliding at 13 TeV
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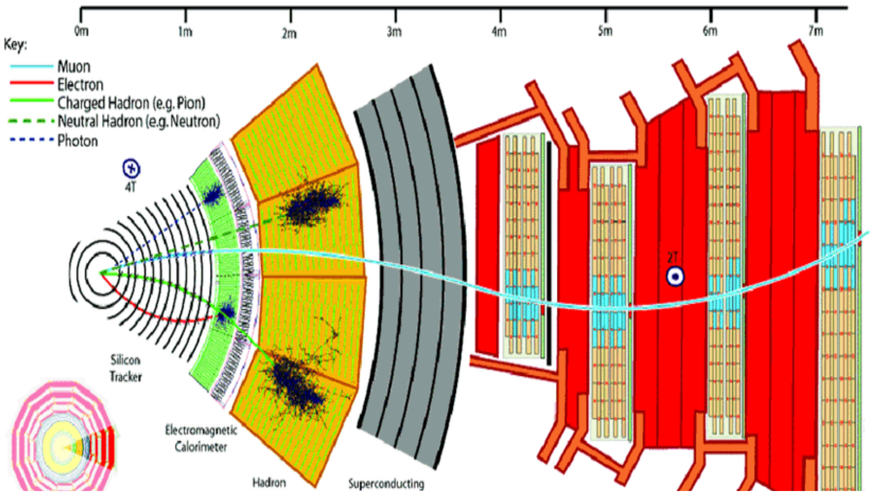
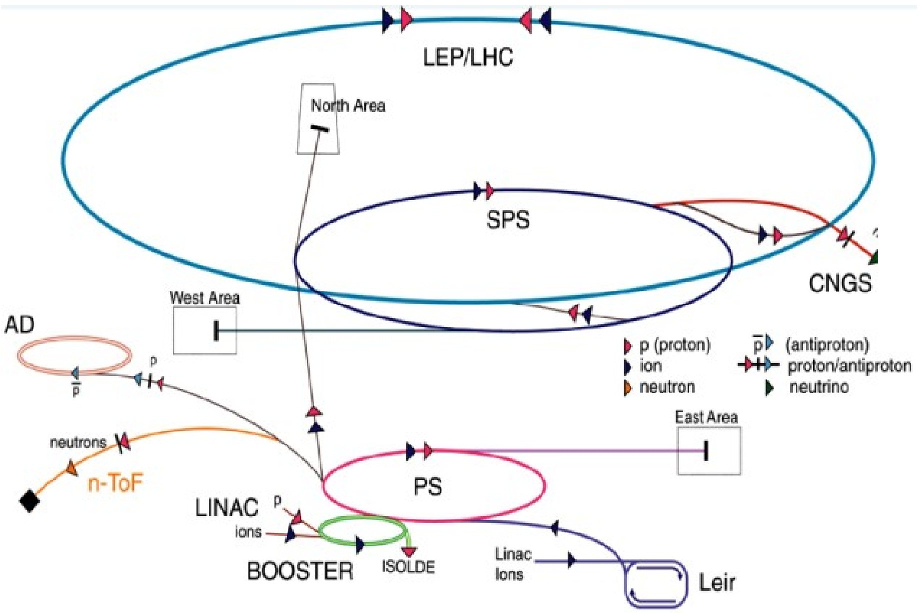


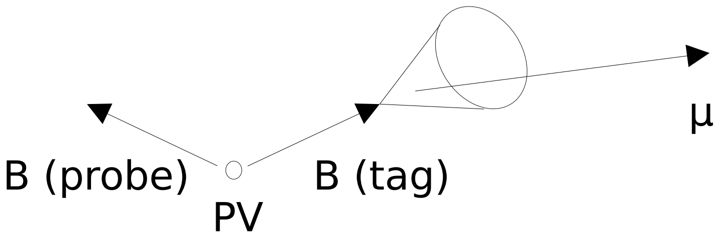


Compact Muon Solenoid
- Located near Cessy
- Magnet generates 3.8 T
- General purpose experiment
- Detectors (from inside out):
  Tracker, electromagnetic calorimeter, hadronic calorimeter, muon chambers

More information in the *TDR*

B – Parking strategy

Motivation



Event collection:
- **Use one b-hadron to trigger, while the other decays freely**
- BF(b → μX) ~20%: large fraction in a very clean object
- Use μ-based paths to trigger
- This technique is known as Tag-and-Probe
- Tag = triggering B

Back-of-the-envelop estimation:

$N = f_B * BF(B \rightarrow eeK) * R_{HLT} * P_{HLT} * T$

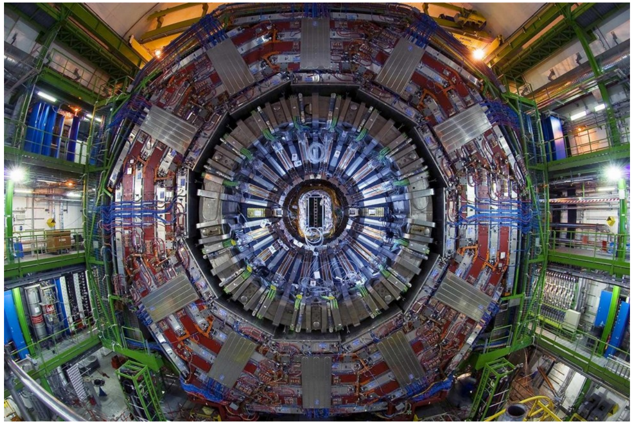
Where:
- N = Produced events
- BF (B → eeK) ~ $O(10^{-7})$
- f_B = B hadron type fraction (0.4)
- R_{HLT} = Trigger rate (~2 kHz)
- P_{HLT} = Trigger purity (~75%)
- T = HLT active time

Aim for **N ~300 events**
=> T = 1.11×10^6 sec

To collect 300 eeK events ~ 10×10^9 B events needed

Implementation

Collisions (p – p) at 40 MHz

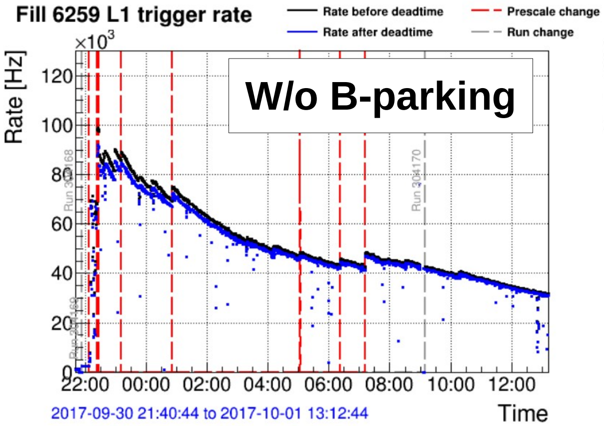


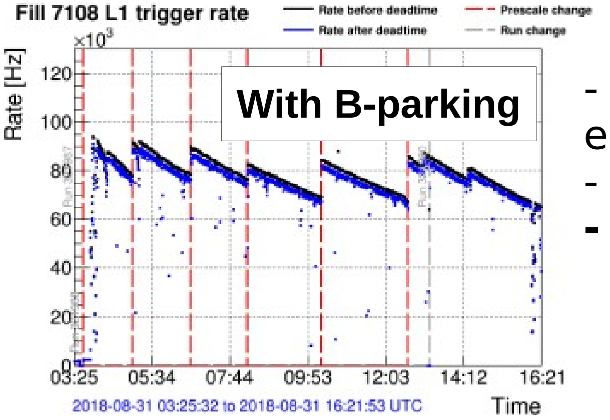
L1 Trigger → **HLT Trigger** → **DAQ**

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”

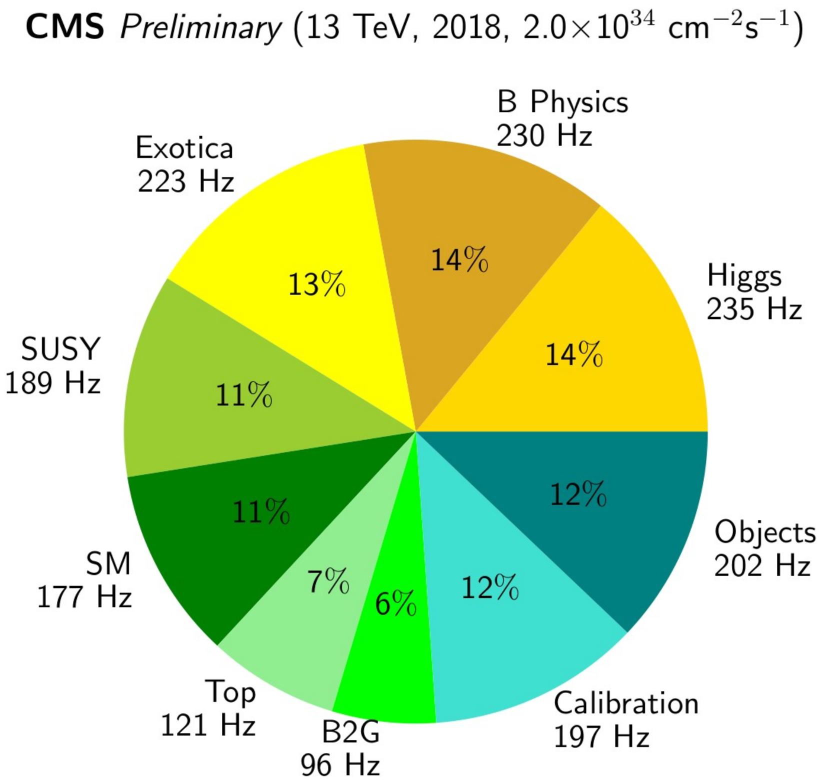




- As luminosity decreases lower p_T seeds enabled
- Tune/optimize paths during data-taking
- **Collected during 2018**

2018 Rate breakdown

“standard CMS menu” HLT rate

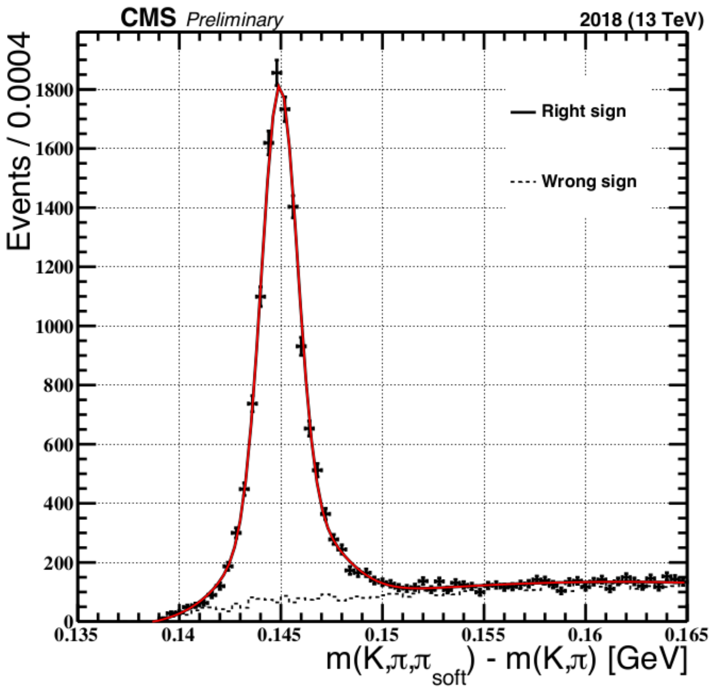


- In 2018 all B Physics rate was coming from muon-based triggers
- With 230 Hz, the number of probe $B \rightarrow eeK$ produced is <30
- Adding acceptance & reconstruction factors, negligible number of events expected
- Using a parking strategy was the only way to measure R_K

Purity in B candidates

- D^0 built by combining tracks of opposite charges, that pass some selection
- D^* built by combining D^0 candidates with a soft track
- Measure P_b for the HLT_Mu9_IP6: μ is required to pass this trigger
- Right Sign, RS: $Q(\mu)\neq Q(\pi_S)$ [Signal] ; Wrong Sign, WS: $Q(\mu)=Q(\pi_S)$ [BKG]
- Plotting $M(K,\pi,\pi_S)-M(K,\pi)$ creates a distinctive peak

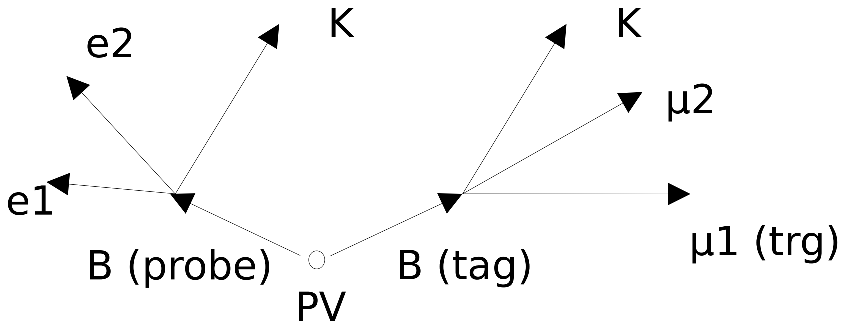
More information in *DP 19-043*



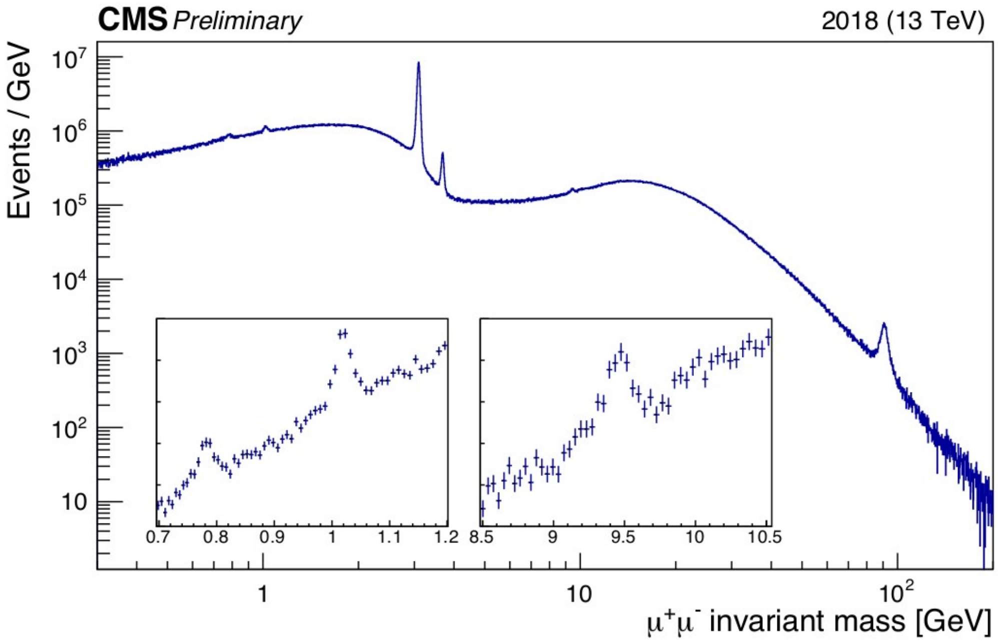
$$P_b = \frac{(N(b\rightarrow\mu))}{(N(\mu))} \quad = \ \dots \implies \boldsymbol{P_b = 0.73}$$

Usage of B Parking sample

- In R_K analysis both B → μμK and B → eeK needed
- B → μμK comes from the "tag B" to improve statistics
- B → eeK from the "probe B"



- B Parking sample: powerful tool used by many analyses
- Single displaced muon trigger: used in Exotic and B physics with muon(s) in final state
- "probe B" used for non-triggered decays



Usage of B Parking sample

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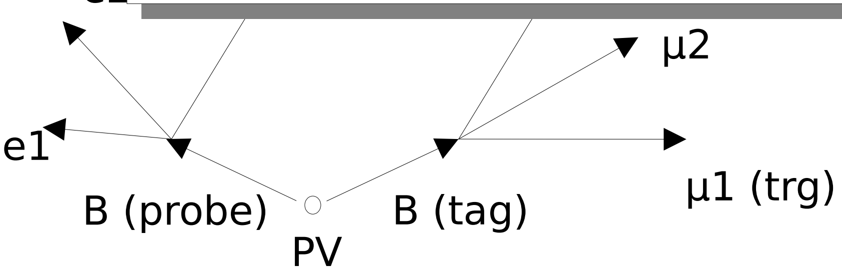
- B → e



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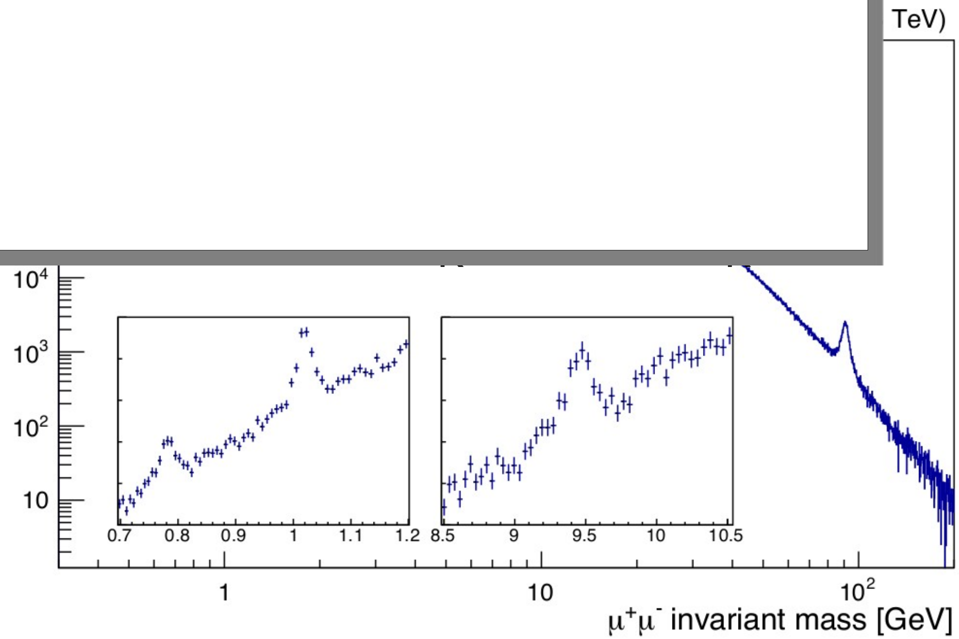
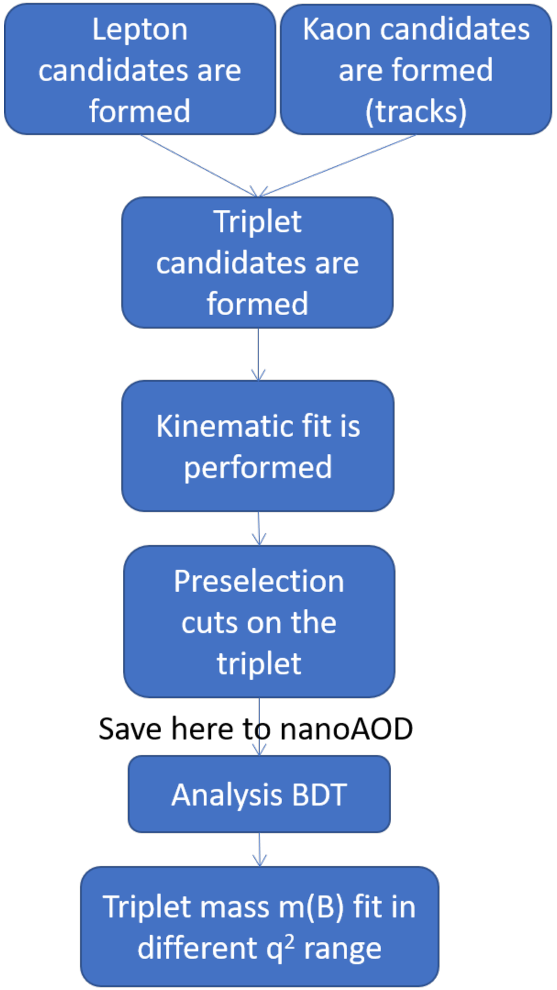


B Parking sample is used for more analysis than R_K:
- R(D)/R(D*) measurement
- CP violation studies
- Exotic searches
- Rare B decays
- Heavy neutrino searches

Main analysis

Analysis overview



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

Analysis framework strategies:
1) Apply preselection cuts as early as possible in the chain
2) Move time consuming processes at the end
3) Modify the precision of ntuple variables to reduce size

Preselection cuts:
- Optimized using using adaptive grid search (back up)

Selection:
- Based on Boosted Decision Trees (BDT) with *XGBoost*

Fits:
- All mass fits are unbinned max likelihood fits, using *RooFit*

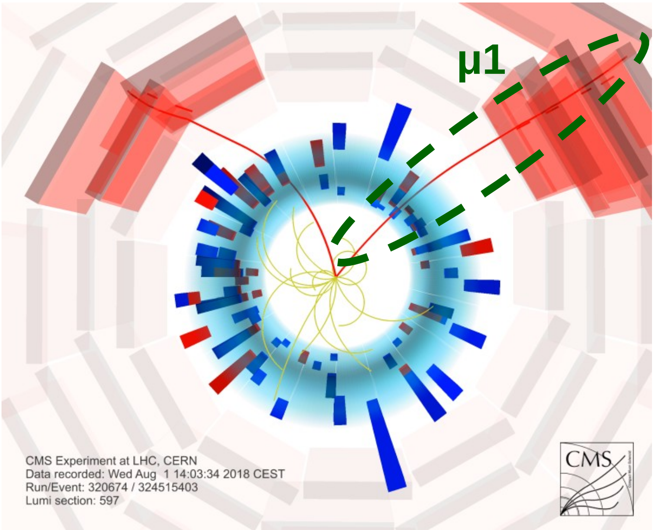
Reconstructing B candidates

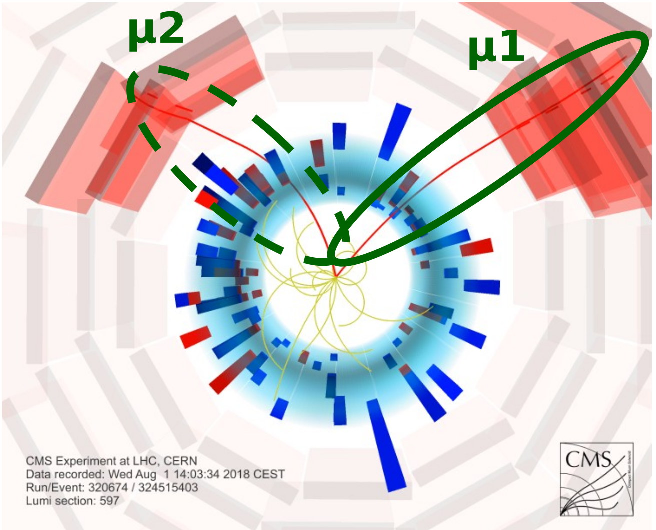
All events are collected by the single μ parking triggers

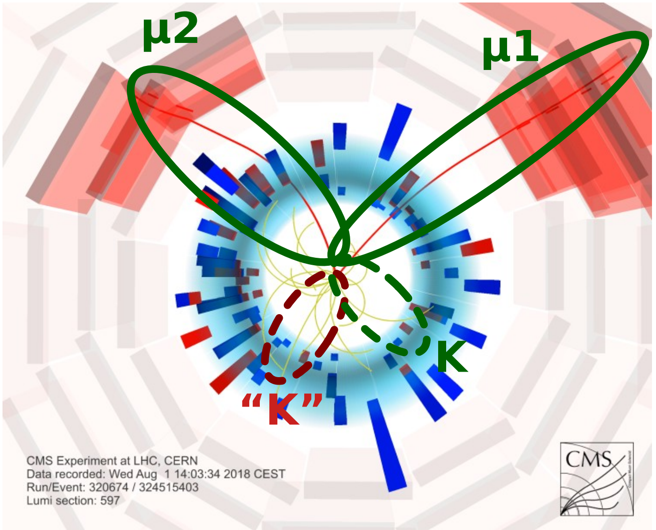
Step 1: Find the triggering muon

Step 2: Select μ close in z to triggering μ → dilepton candidates with m<5GeV

Step 3: Select tracks close to dilepton; assign m(K) and kinematicaly fit to built B candidates



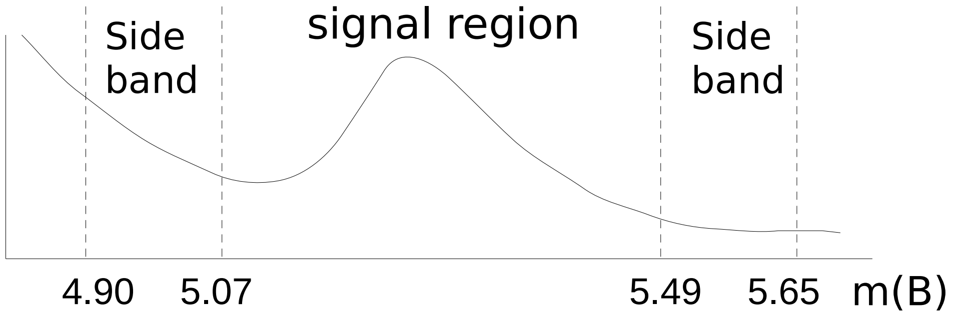




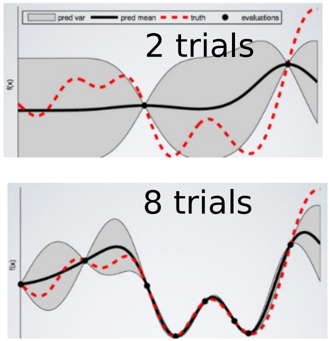
- Events can have more than 1 candidate

BDT optimization strategies

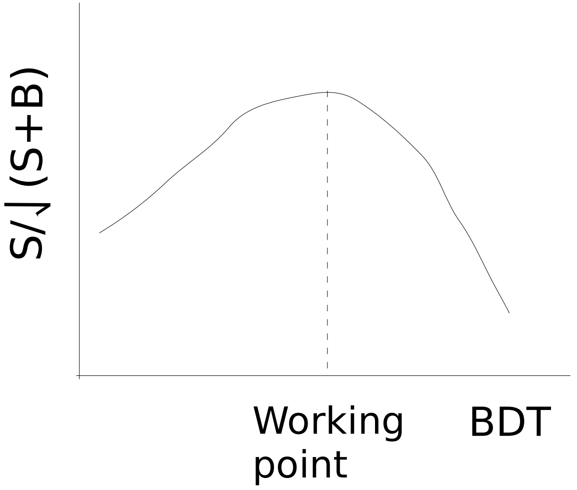
- Main selection based on BDT
  - -- 8-fold cross-validation structure
  - -- Data sidebands as background
  - -- Simulated (MC) B → ℓℓK as signal



- Optimization
  - -- Input variables
  - -- Configuration options (hyperparameters)
  - -- Tested for “mass sculpting”
  - -- Working point defined as the value that Maximizes the S/√(S+B) of the signal



Hyperparameters optimization



Same techniques/methods but different BDTs for μμK and eeK states

Selection of B → μμK candidates

Object selection:

- Muons: Medium ID, $p_T(\mu 1) > 9$ GeV, $p_T(\mu 2) > 2$ GeV and $|\eta|<2.4$
- Tracks: “High purity” ID, $p_T > 1$ GeV and $|\eta|<2.4$

BDT variables

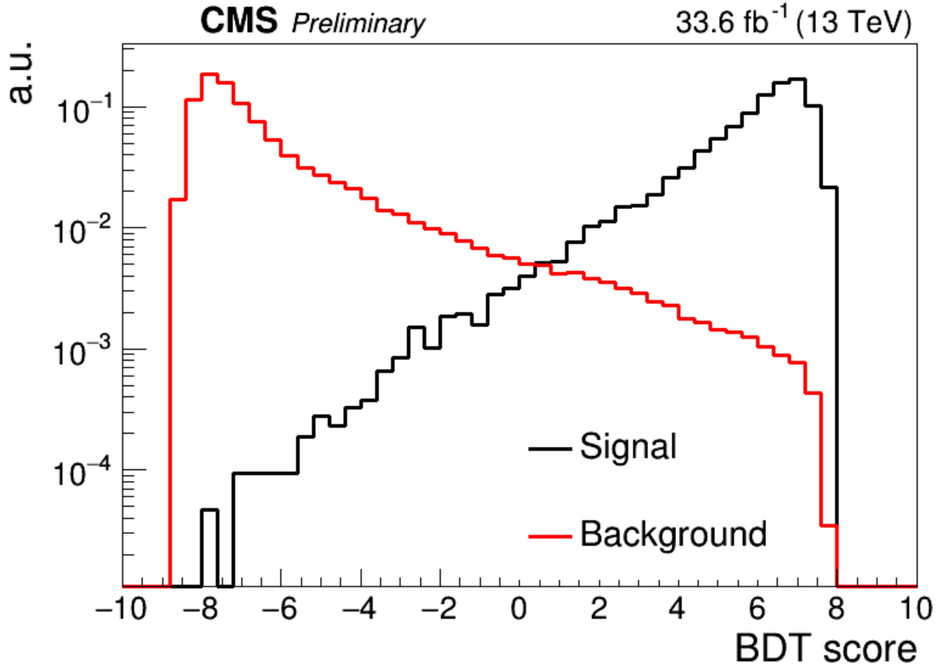
Only on B → μμK BDT:

- $\min \Delta R(\mu, \mathrm{K}^+)$
- $\min \Delta z(\mu, \mathrm{K}^+)$
- $\mathrm{Iso}(\mu_{\mathrm{lead}})$

Common in B → eeK and B → μμK BDTs:

- $\cos \alpha_{3D}$
- $p(\mathrm{B}^+ \text{ vtx})$
- L_{xy}/σ_{xy}
- $p_T(\mathrm{B}^+)$
- $p_T(\mathrm{K}^+)$

BDT discriminant for B → μμK

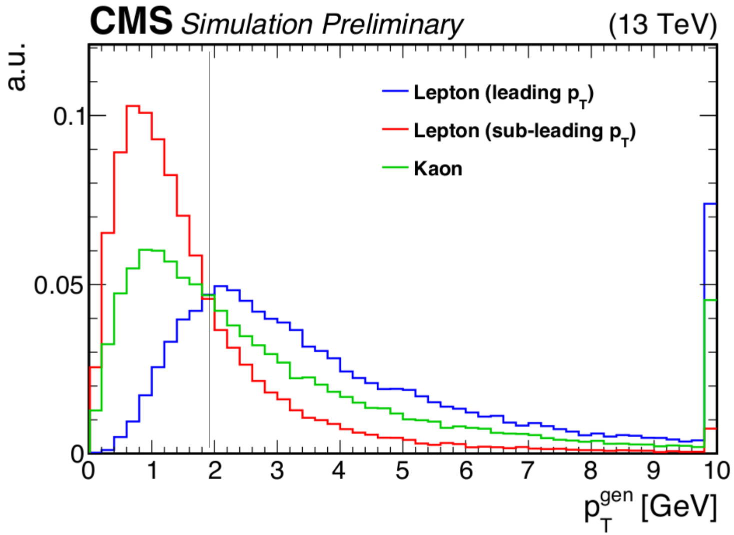


Low p_T electrons

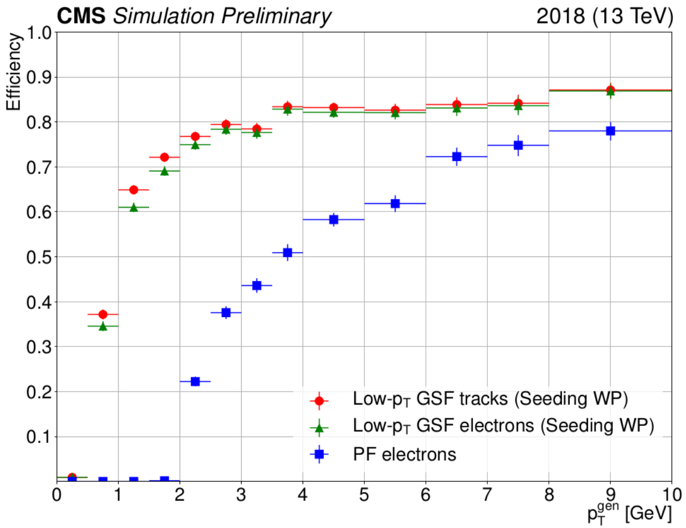
Motivation:
- Most B produce e with p_T<2GeV
- Cannot be reconstructed with the “standard” algo (particle flow, PF)

Low p_T e:
- Tracker seeded
- e candidates identified MVA methods
- Gain in efficiency for $p_T(e)<5$
- **Introducing more background** (including from B decays).

More information in [DP 19-043]



Created a new type of electron the “low p_T” (LP)

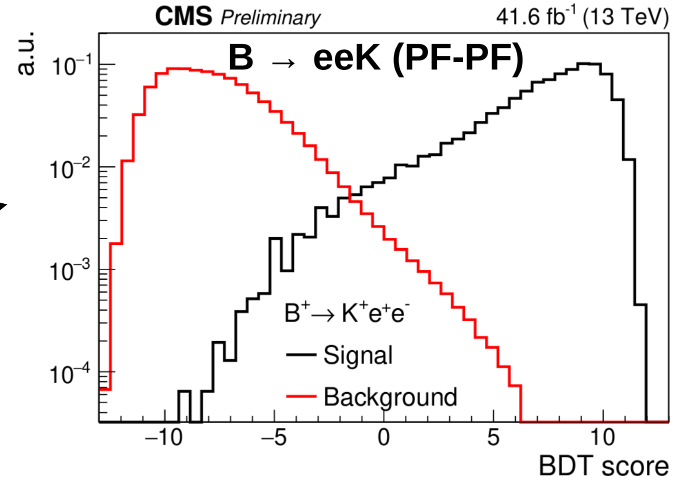


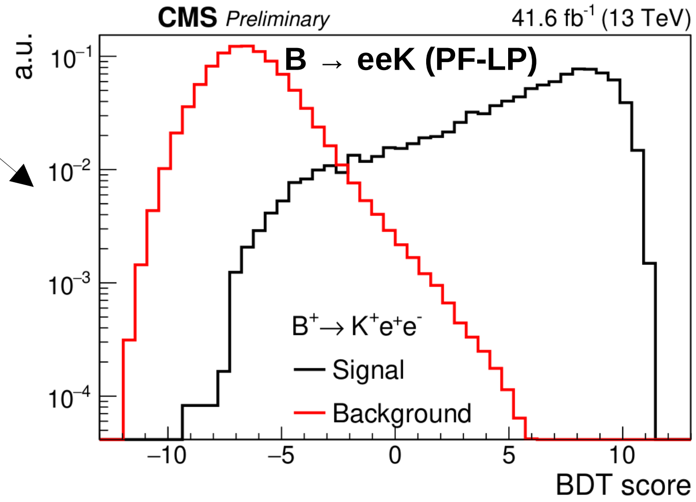
Selection of B → eeK candidates

Object selection:

- Electrons: Candidates with two PF electrons (PF - PF) or one PF and one LP (PF - LP)
- Tracks: Same as in B → μμK case

2 BDTs trained:
one for PF – PF candidates
and one for PF – LP candidates





Variables exclusive to B → eeK BDT

$p_T(e_{1,2})$ $m_{K^+e^+e^-}$

$\Delta z(e_{1,2}, K^+)$

$|d_{3D}(K^+, e^+e^-)| / \sigma_{|d_{3D}(K^+, e^+e^-)|}$

$\Delta R(e^+, e^-)$

$\Delta R(e_{1,2}, K^+)$

$\frac{|\mathbf{p}(e^+e^-)\times\mathbf{r}| - |\mathbf{p}(K^+)\times\mathbf{r}|}{|\mathbf{p}(e^+e^-)\times\mathbf{r}| + |\mathbf{p}(K^+)\times\mathbf{r}|}$

$\mathrm{ID}(e_{1,2})$

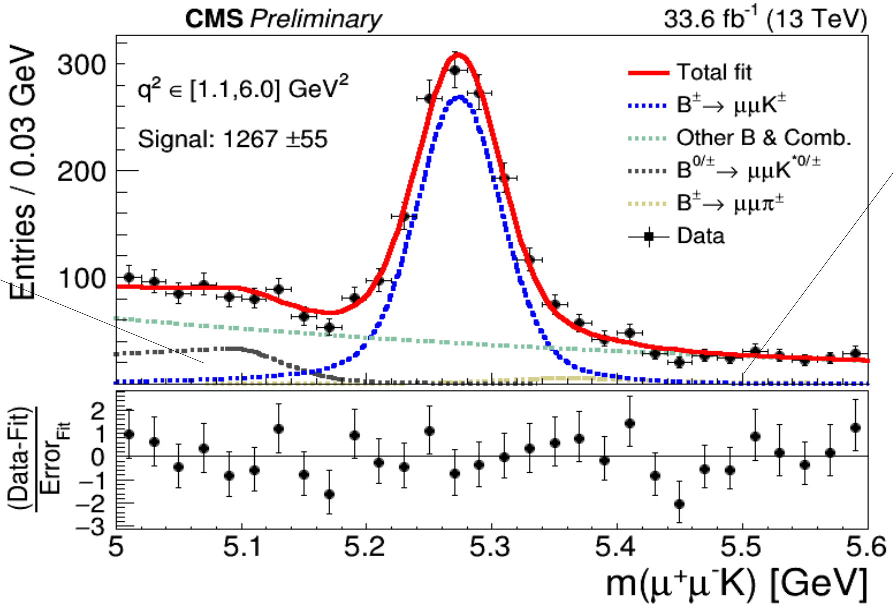
$I^{rel}_{\Delta R=0.4}(e_1/e_2/K^+)$

Background composition

The backgrounds are divided in two categories based on the type:
- Partial B: Candidates from partial reconstruction of B meson decays with many tracks
- Combinatorial: Candidates created with 1 or more objects from pile up/other B

Example using $B^{\pm} \rightarrow \mu\mu K^{\pm}$

Partial B:
- Dominated by $B \rightarrow \mu\mu K^*$
- Lower mass than m(B)



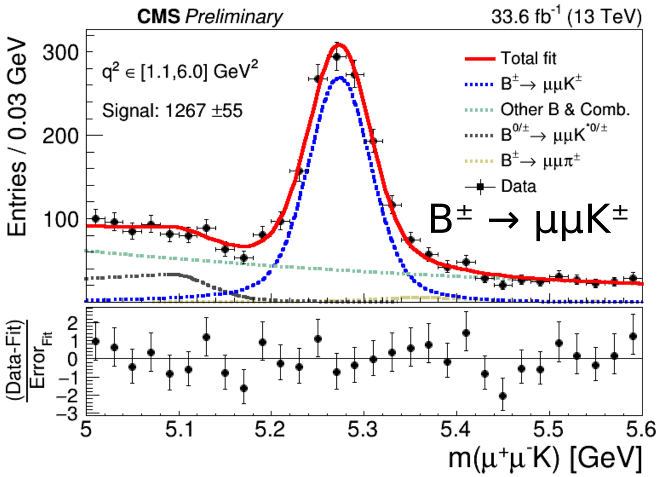
Combinatorial:
- Only background In signal region
- Dominates the high mass sideband
- Studied using B candidates with same sign leptons

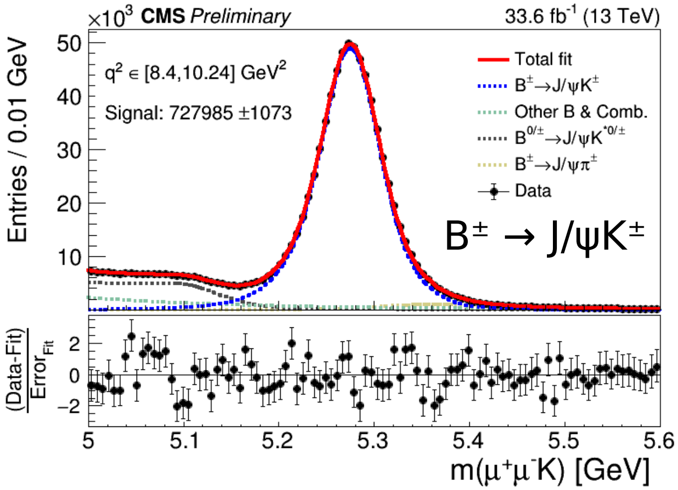
B → μμX mass fits

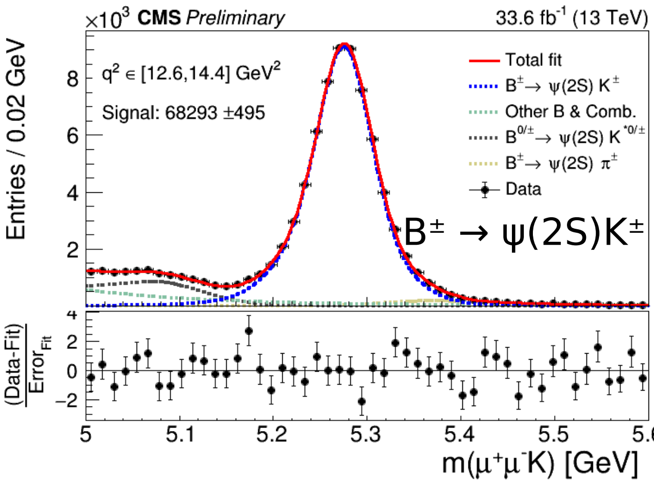
- Analytical functions used for fitting signal and backgrounds

- 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)

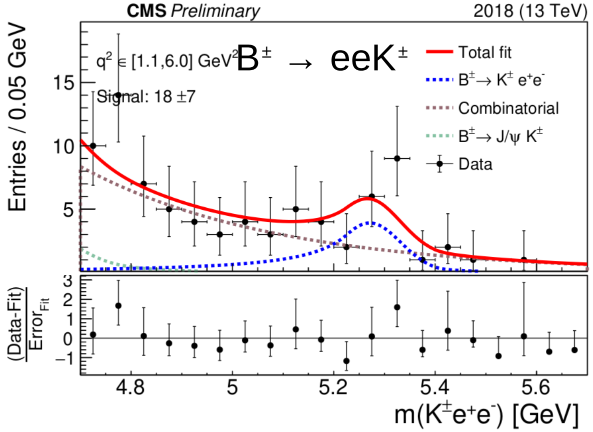


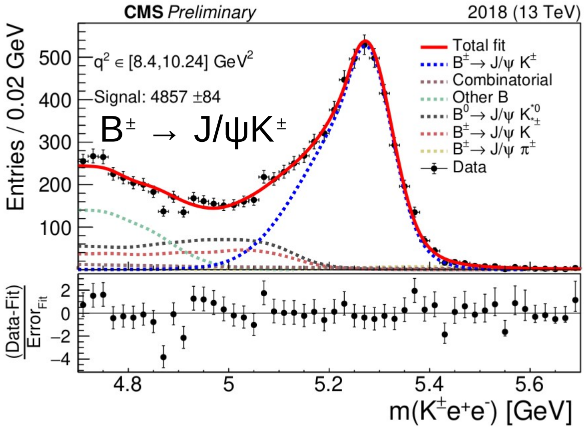


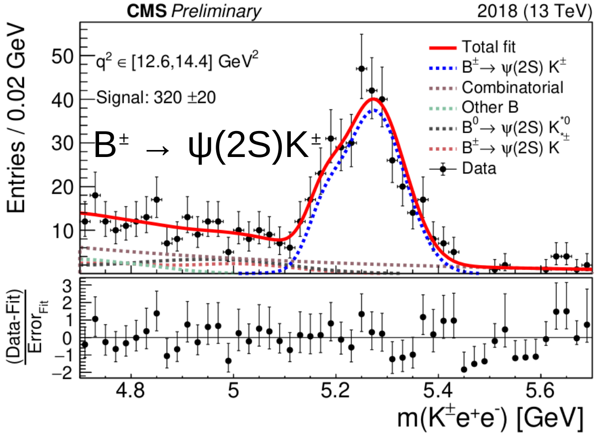


B → eeX mass fits

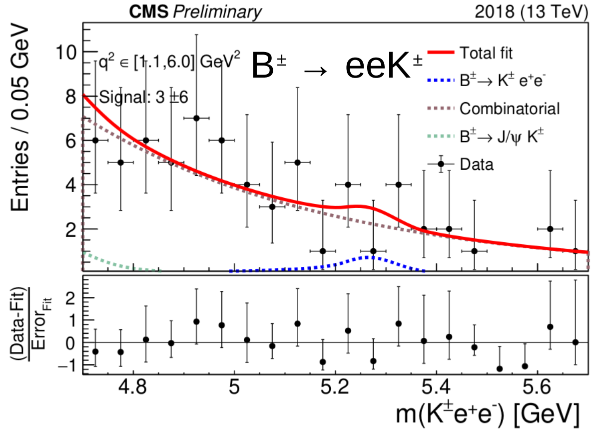
Fits for B candidates built with 2 PF electrons:

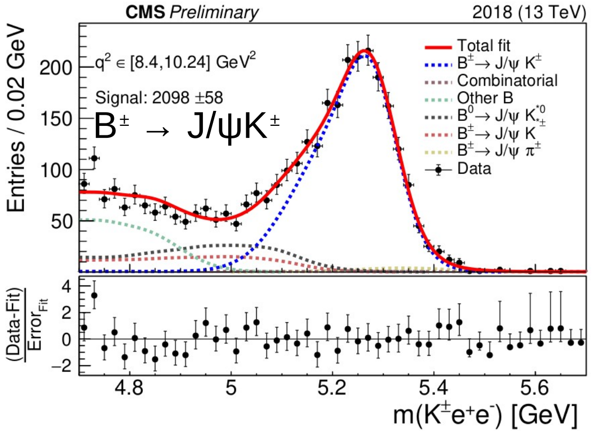


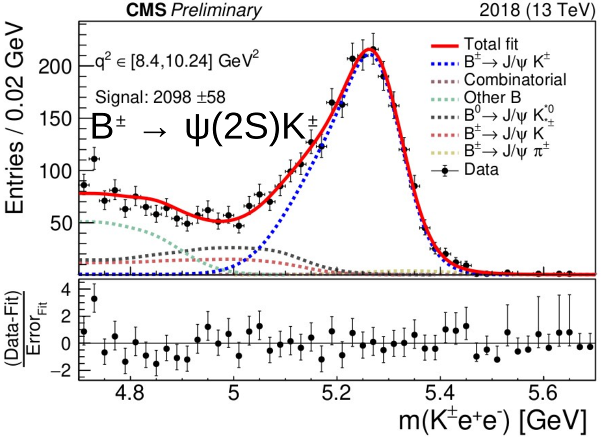




Fits for B candidates built with 1 PF & 1 LP electrons:







B → μμK mass fits in q^2 bins

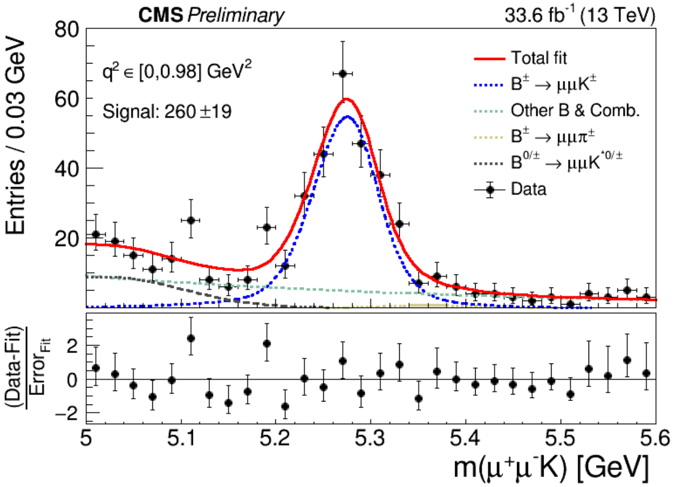
- Since adequate statistics available: differential measurement, dBF/dq2
- Use the same selection and code and instead for a single fit, do a simultaneous fit in q^2 bins
- Result to be compared with several theoretical predictions

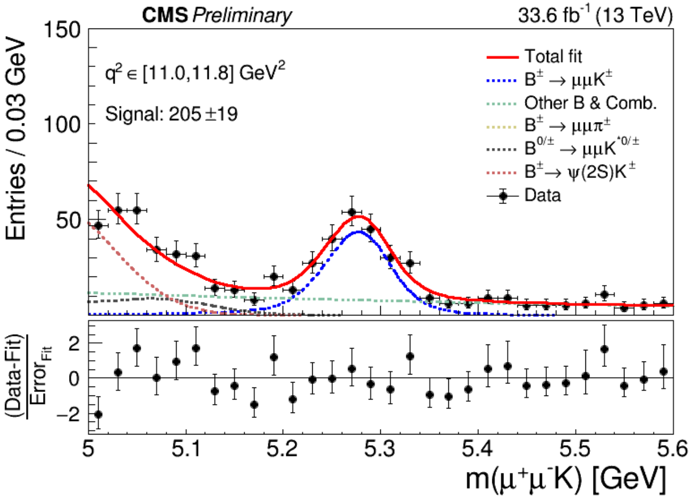
Bin	q^2 range [GeV]
1	0–0.98
2	1.1–2.0
3	2.0–3.0
4	3.0–4.0
5	4.0–5.0
6	5.0–6.0
7	6.0–7.0
8	7.0–8.0
9	11.0–11.8
10	11.8–12.5
11	14.82–16.0
12	16.0–17.0
13	17.0–18.0
14	18.0–19.24
15	19.24–22.9

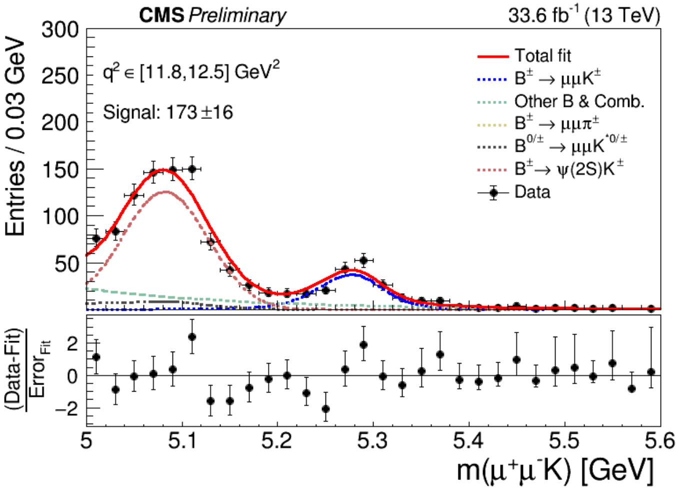
B → μμK mass fits in q^2 bins

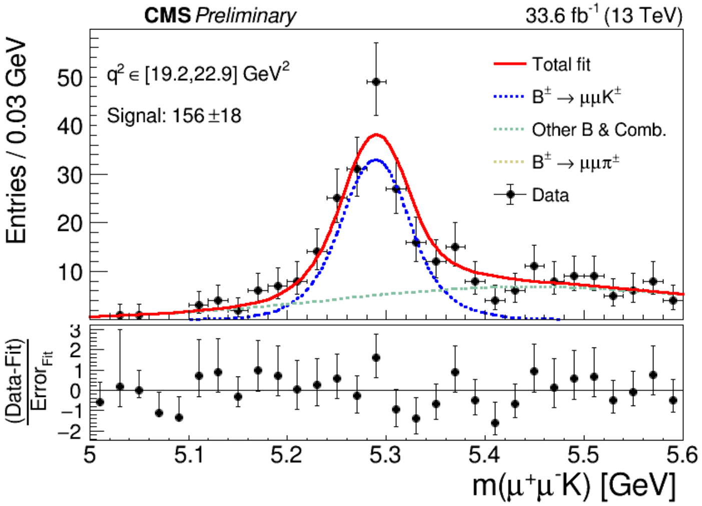
Rest of the fits in back up

Bin	q^2 range [GeV]
1	0–0.98
2	1.1–2.0
3	2.0–3.0
4	3.0–4.0
5	4.0–5.0
6	5.0–6.0
7	6.0–7.0
8	7.0–8.0
9	11.0–11.8
10	11.8–12.5
11	14.82–16.0
12	16.0–17.0
13	17.0–18.0
14	18.0–19.24
15	19.24–22.9









Systematic uncertainties and corrections

- Corrections on MC to account for known disagreements with data:
  -- Trigger response, lepton reconstruction/identification, B p_T spectrum, BDT response

- 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

Source	Impact on the $R(K)$ ratio [%]
Background description, low-q^2 bin	1.75
Trigger turn-on	1.30
Reweighting in p_T and rapidity	0.86
Background description, J/ψ CR	0.64
J/ψ meson radiative tail description	0.48
Pileup	0.38
Signal shape description	0.32
Trigger efficiency	0.16
J/ψ resonance shape description	0.08
Nonresonant contribution to the J/ψ CR	0.07
Total systematic uncertainty	2.5
Statistical uncertainty in MC samples	1.7
Statistical uncertainty	7.5
Total uncertainty	8.1

Uncertainties on the electron part

Source	Impact on the $R(K)$ ratio [%]	
	PF-PF	PF-LP
Signal and background description	5	5
J/ψ event leakage to the low-q^2 bin	4	9
BDT efficiency stability	2	5
BDT cross validation	2	3
Trigger efficiency	1	4
BDT data/simulation difference	1	2
J/ψ meson radiative tail description	1	1
Total systematic uncertainty	7	13
Statistical and total uncertainty	40	200

Systematic uncertainties and corrections

- Corrections on MC to account for known disagreements with data:
  - -- Trigger response, lepton reconstruction/identification, B p_T spectrum, BDT response

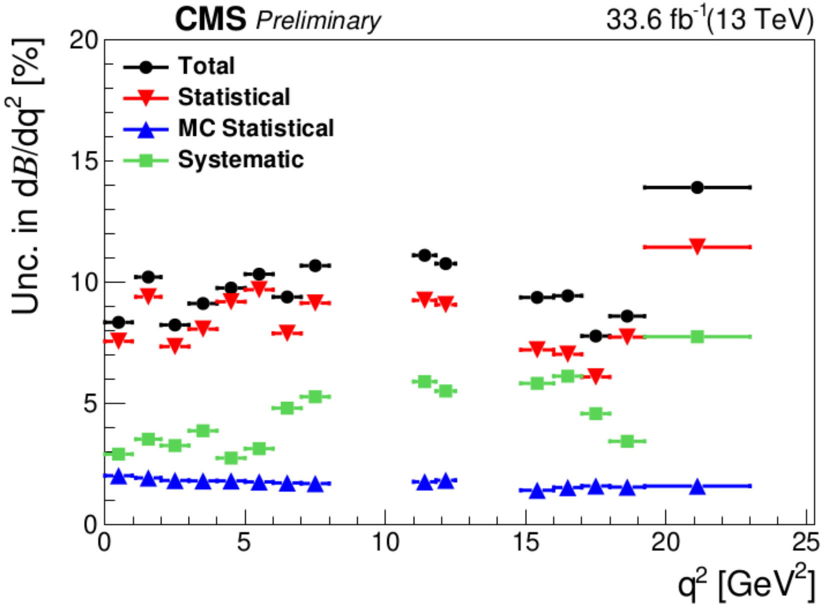
- Systematics are treated as independent between the muon and electron part of R_K
- The total uncertainty of R_K is dominated by the statistical part of electron channels

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



Results

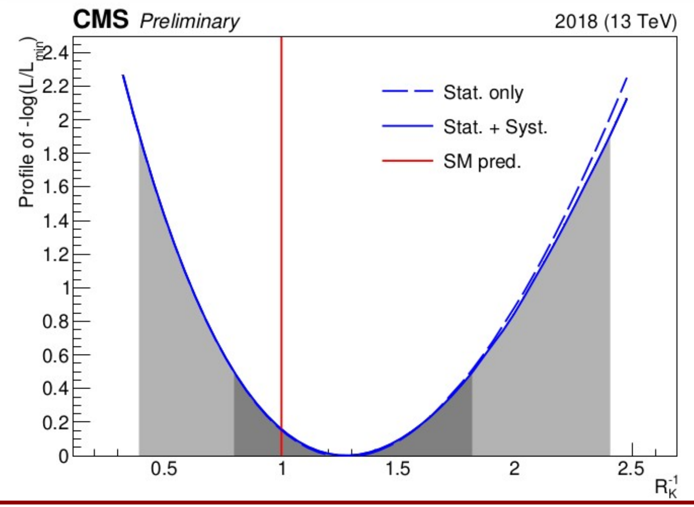
BF(B→μμK) and R_K in the low q^2

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

Can be compared with the various theoretical predictions

Package	EOS	Flavio	HEP fit	SuperIso
Prediction [$\times10^{-7}$]	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}:

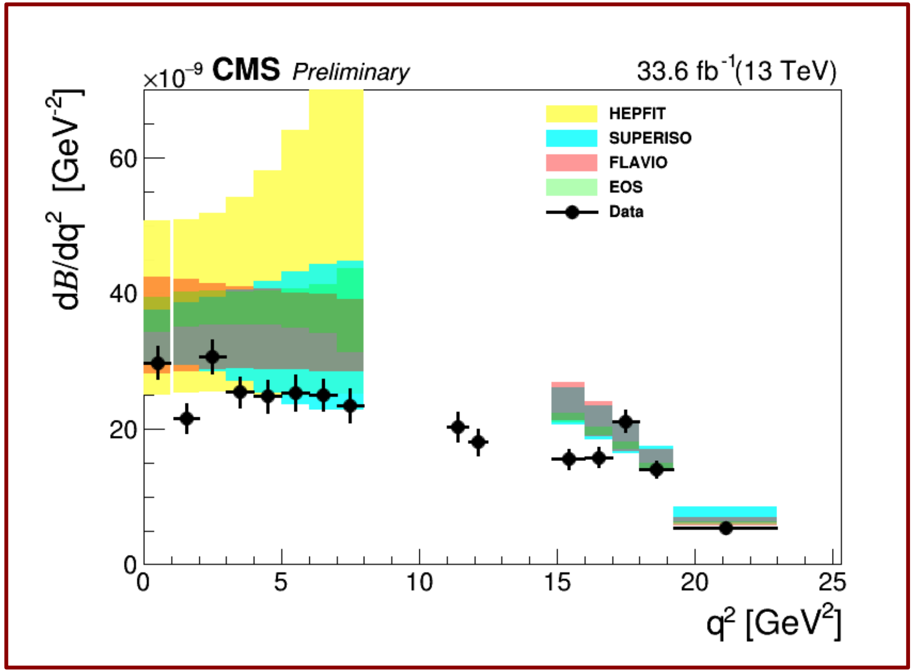
$$R_K = 0.78^{+0.46}_{-0.23}\ \text{(stat)}\ ^{+0.09}_{-0.05}\ \text{(syst)}$$

Precision dominated by the low stats of B → eeK

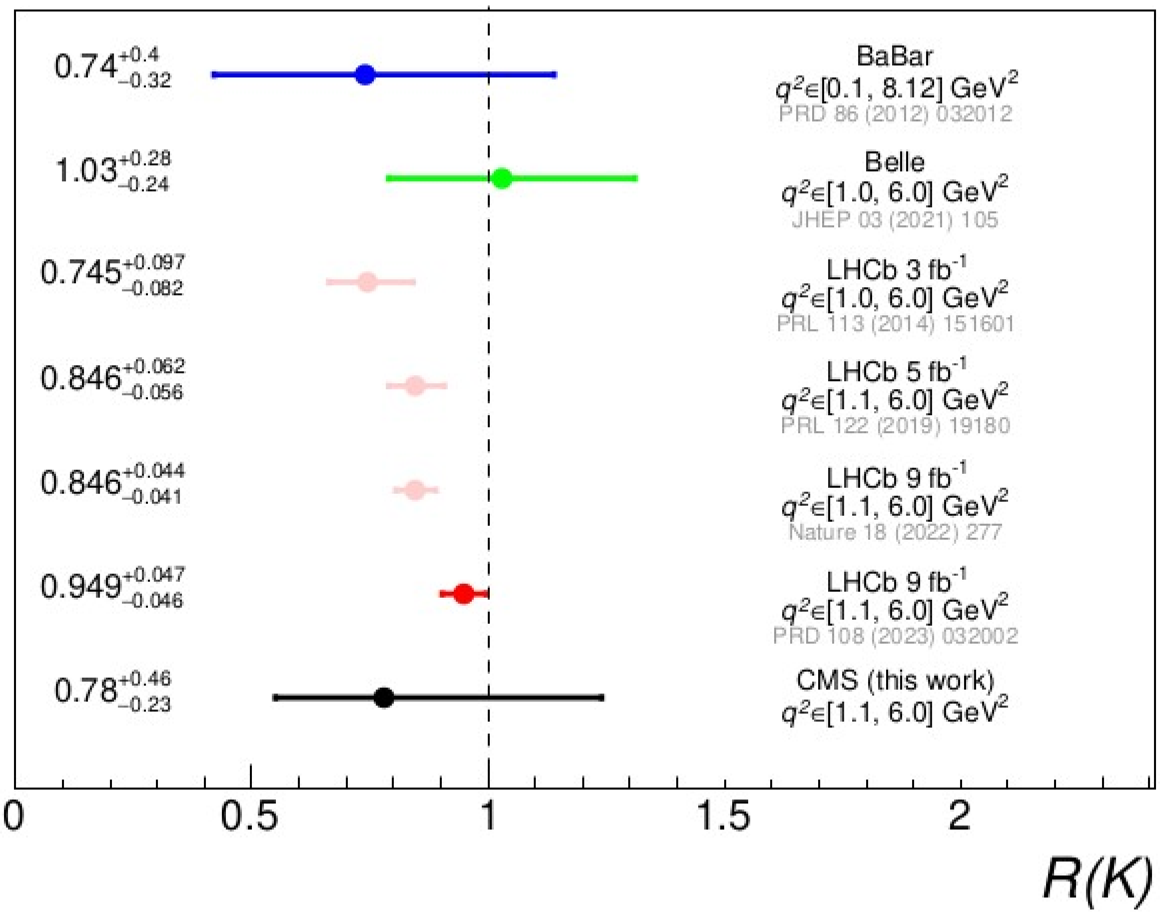
Measurement of differential BF(B → μμK)

- For differential BR measurement, a fit is performed in all q^2 bins at the same time
- Compare measurement with the theoretical predictions in each q^2 bin

Measurement of dBR/dq^2 and comparison with theory



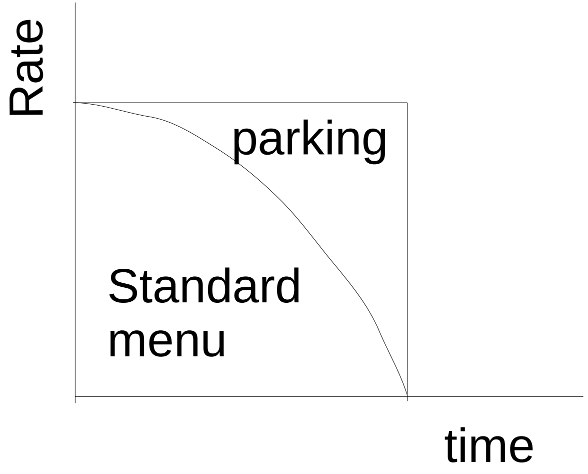
CMS update to the R_K measurement



A look into the (near) future

- Lessons learned from Run 2 (up to 2018):
  - -- Muon channel: high statistics → comparable precision to world average
  - -- Electron channel: low statistics → “penalty” for using the “probe B”

- In Run 3 (after 2022) we improved the strategy:
  - -- Two parking samples used (one for muons/ one for electrons)
  - -- Same strategy of exploiting the unused L1/HLT rate:
    - -- Gradually enabling looser triggers
  - -- Dielectron parking is based on:
    - -- Topological variables
    - -- p_T thresholds
    - -- Sophisticated online ID
    - -- Expecting large increase in stats
    - -- **Analysis is ongoing; first look quite promising**…

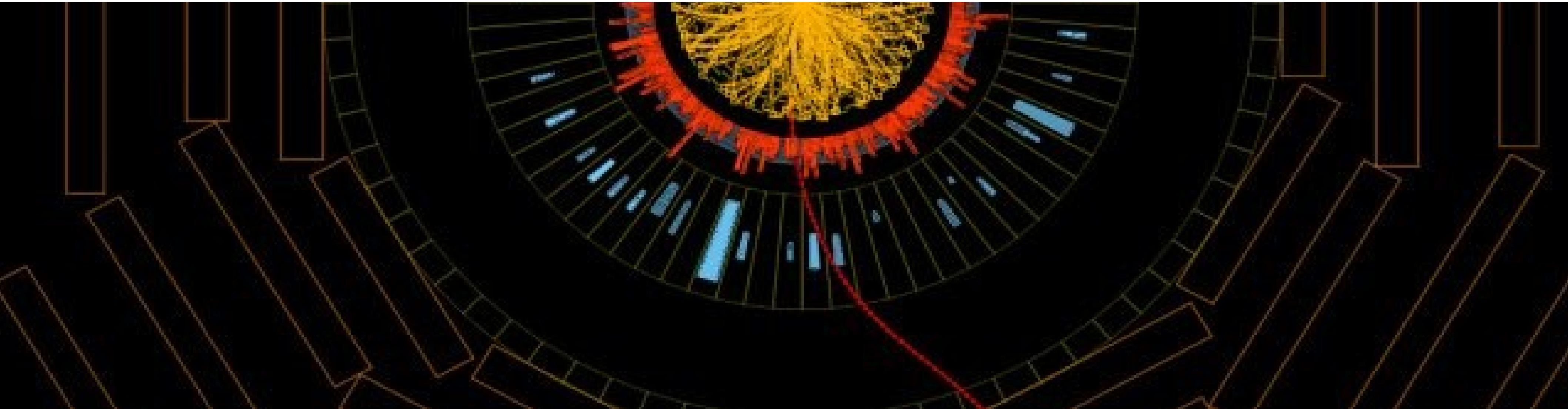


Summary

- CMS pursuing a very ambitious B Physics program
- First RK result using 2018 data demonstrates 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 is posted here: *BPH 22-005*

Stay tuned for more!



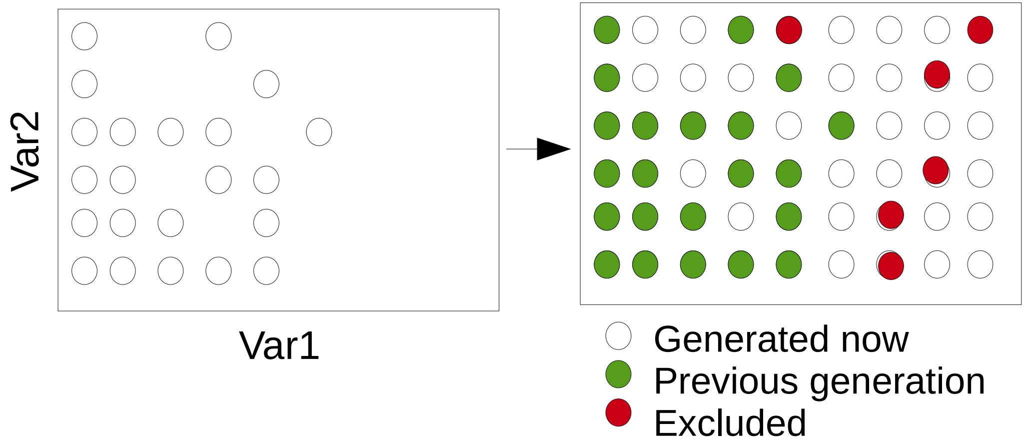
Back up

Preselection

Adaptive grid search:
- Every variable is a dimension
- Scan variables (grid points)
- Take into account previous searches before generating a point
- Find optimal, according to some metric(s)
- Computing resources reduced by ~75% wrt to standard grid search

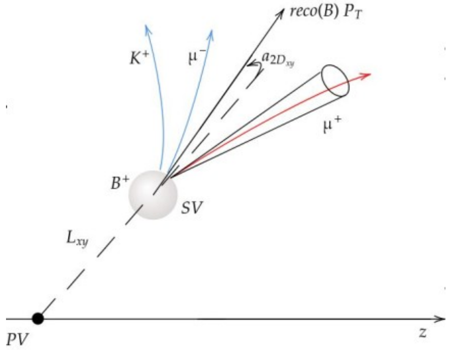
Step1: Generate points

Step2: use previous result to skip useless points



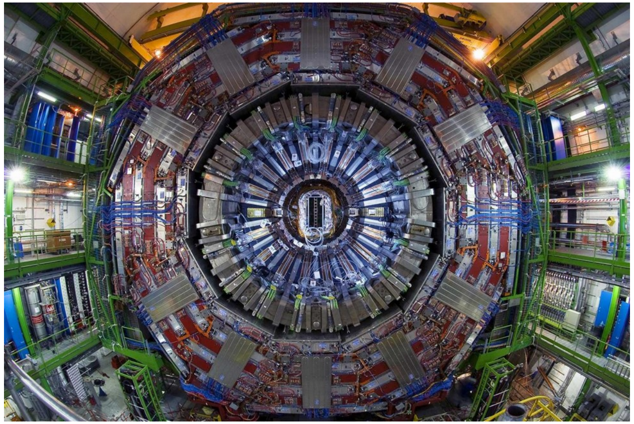
Preselection for μμK:
- $p_T(B) > 3$ GeV
- Δz(trg μ, track/μ2) < 1.0 cm
- p_T(track) > 1 GeV
- $L_{xy}/\sigma > 1$
- cos (α) > 0.90
- Prob > 10^{-5}
- m(K,μ) > 2 GeV [anti-D^0]

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



Implementation

Collisions (p – p) at 40 MHz

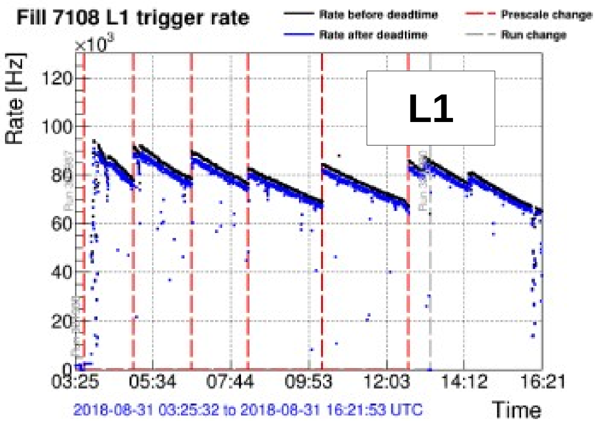


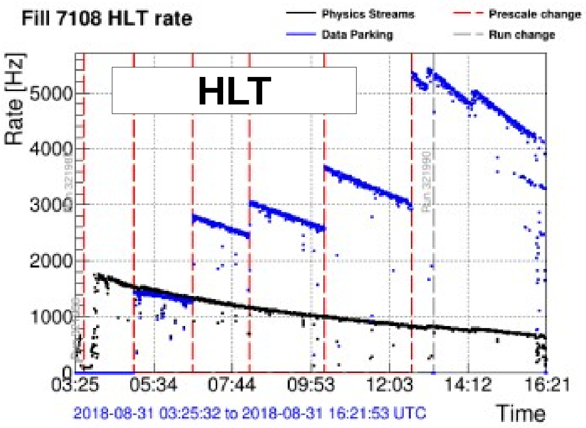
L1 Trigger → **HLT Trigger** → **DAQ**

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

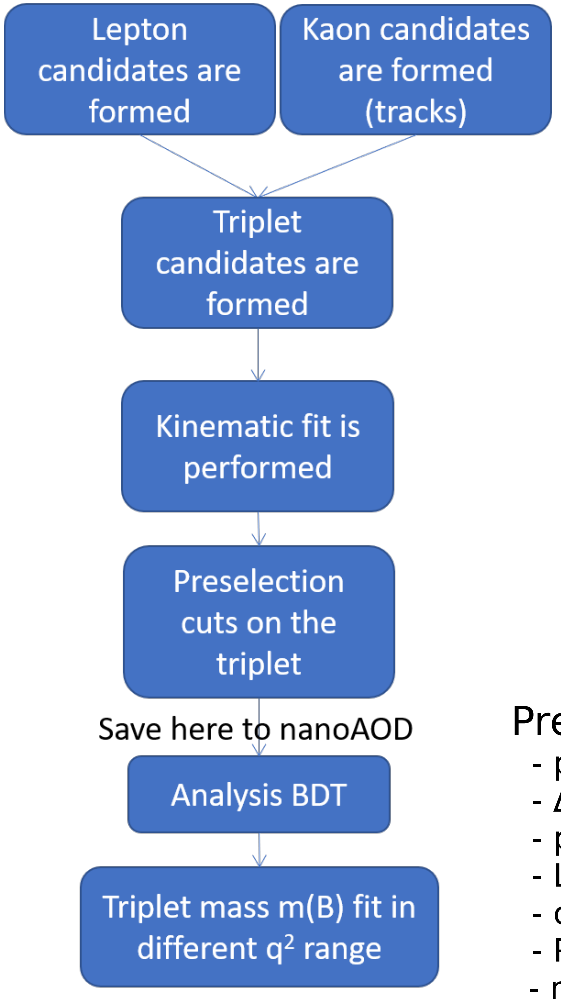
DAQ
- Saved in single copy
- Stored on tape until computing resources available
- Long delay in reconstruction; procedure known as “Parking”





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

B candidate reconstruction



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]

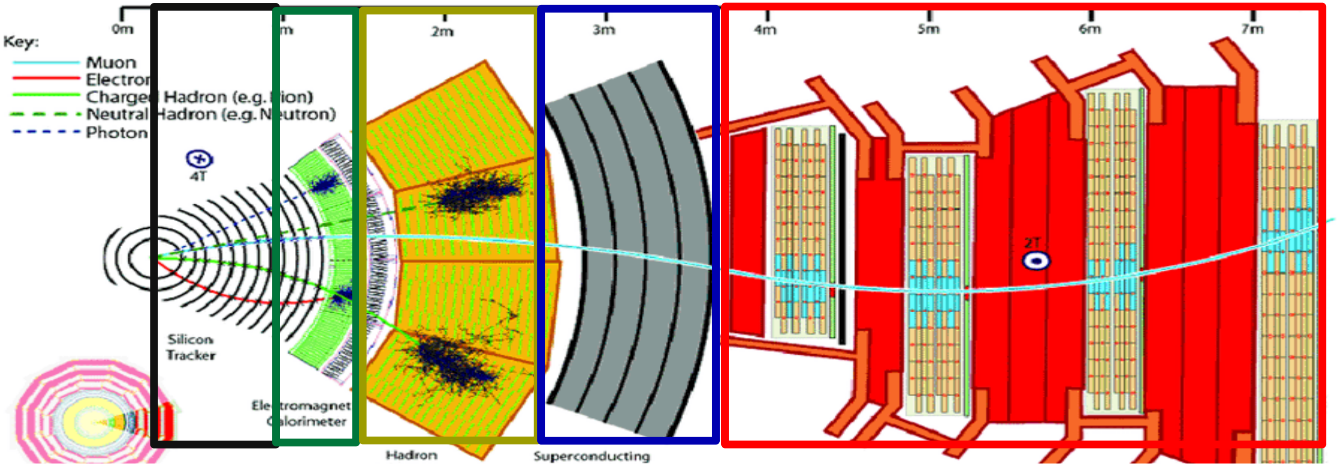
Preselection for eeK:
- Δz(trg μ, track/e) < 1.0 cm
- $p_T(e2) > 1.0$ GeV
- cos (α) > 0.95
- Prob > 10^{-5}
- m(K,e) > 2 GeV [anti-D^0]
- $d_{3d} < 0.06$
- ID (e1) > -2
- ID (e2) > 0

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

The Compact Muon Solenoid detector

More information in the *TDR*



Tracker:
- 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

ECAL:
- 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

HCAL:
- Heterogeneous calorimiter
- Interleaved heavy material with scintillator layers
- Measures the energy of hadrons
- Indirect measurement of non-interacting particles (like ν)

Magnet:
- Central device
- Large solenoid magnet
- Field up to 4T
- Bends charged particles to measure their momentum

Muon:
- Position exploits the penetration of muons
- Very clean signatures
- Gaseous detectors of three types
- Drift tubes (barrel), CSC (endcap), RPC (barrel+endcap)

BDT leplepK common variables

$\cos\alpha_{3D}$	Cosine of the angle between the momentum vector of the B^+ candidate and the vector connecting the PV and SV
$p(B^+ \text{ vtx})$	Probability of the SV kinematic fit
L_{xy}/σ_{xy}	Significance of the SV displacement in the transverse plane with respect to the PV
$p_T(B^+)$	Transverse momentum of the B^+ candidate; in the electron channel it is divided by $m_{K^+e^+e^-}$
$p_T(K^+)$	Transverse momentum of the K^+ candidate; in the electron channel it is divided by $m_{K^+e^+e^-}$

BDT μμK exclusive variables

$\min \Delta R(\mu, K^+)$	$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ distance between the K^+ candidate and the closest muon
$\min \Delta z(\mu, K^+)$	Δz distance between the points of origin of the K^+ candidate and the closest muon along the beam axis direction
$\mathrm{Iso}(\mu_{\mathrm{lead}})$	PF isolation for the p_T-leading muon, defined as a scalar p_T sum all PF candidates, excluding the muon itself, within $\Delta R < 0.4$ of the muon and corrected for PU

BDT eeK exclusive variables

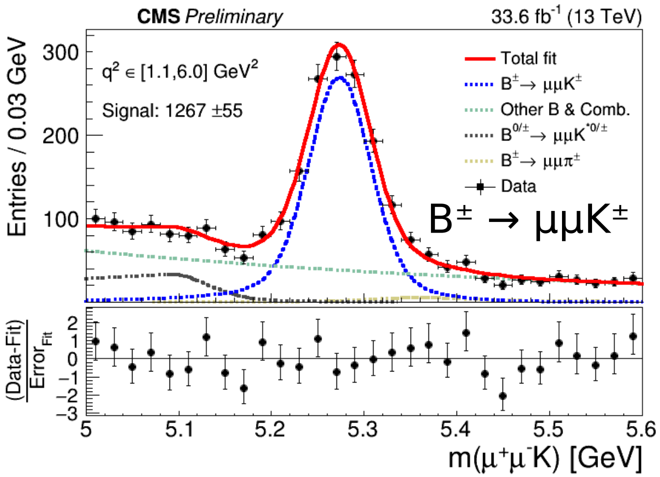
$p_{\mathrm{T}}(\mathrm{e}_{1,2}) m_{\mathrm{K}^+\mathrm{e}^+\mathrm{e}^-}$	Transverse momenta of the two electron candidates, divided by the invariant mass of the B^+ candidate
$\Delta z(\mathrm{e}_{1,2}, \mathrm{K}^+)$	Longitudinal distance between the points of origin of each electron and the kaon
$\lvert d_{3\mathrm{D}}(\mathrm{K}^+, \mathrm{e}^+\mathrm{e}^-) \rvert / \sigma_{\lvert d_{3\mathrm{D}}(\mathrm{K}^+, \mathrm{e}^+\mathrm{e}^-) \rvert}$	Kaon 3D impact parameter significance with respect to the dielectron vertex
$\Delta R(\mathrm{e}^+, \mathrm{e}^-)$	ΔR between the two electrons
$\Delta R(\mathrm{e}_{1,2}, \mathrm{K}^+)$	ΔR between each electron and the kaon
$\frac{\lvert \mathbf{p}(\mathrm{e}^+\mathrm{e}^-) \times \mathbf{r} \rvert - \lvert \mathbf{p}(\mathrm{K}^+) \times \mathbf{r} \rvert}{\lvert \mathbf{p}(\mathrm{e}^+\mathrm{e}^-) \times \mathbf{r} \rvert + \lvert \mathbf{p}(\mathrm{K}^+) \times \mathbf{r} \rvert}$	Asymmetry of the momentum of the dielectron system and that of the K^+ momentum with respect to the B^+ candidate trajectory, where $\mathbf{r}$ is a unit vector connecting the PV and SV
$\mathrm{ID}(\mathrm{e}_{1,2})$	Electron ID BDT score for each of the two electrons
$I^{\mathrm{rel}}_{\Delta R = 0.4}(\mathrm{e}_1/\mathrm{e}_2/\mathrm{K}^+)$	Relative track-based isolation of e_1, e_2, and K^+ candidates, respectively, defined as a scalar p_{T} sum of all additional tracks in a $\Delta R < 0.4$ cone around the candidate, divided by the candidate's p_{T}

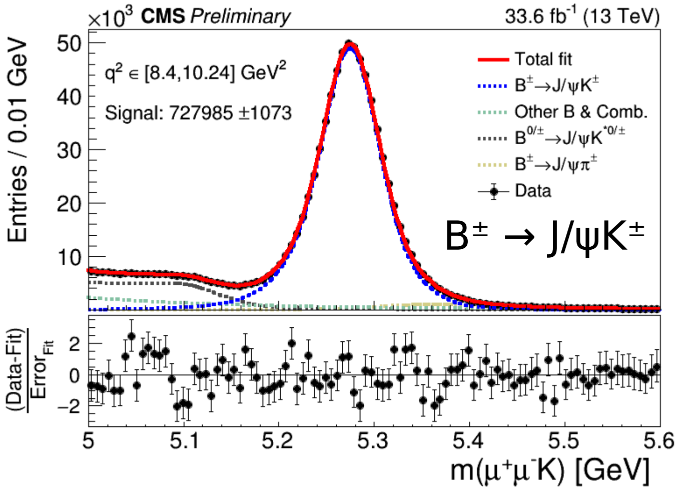
B → μμX mass fits

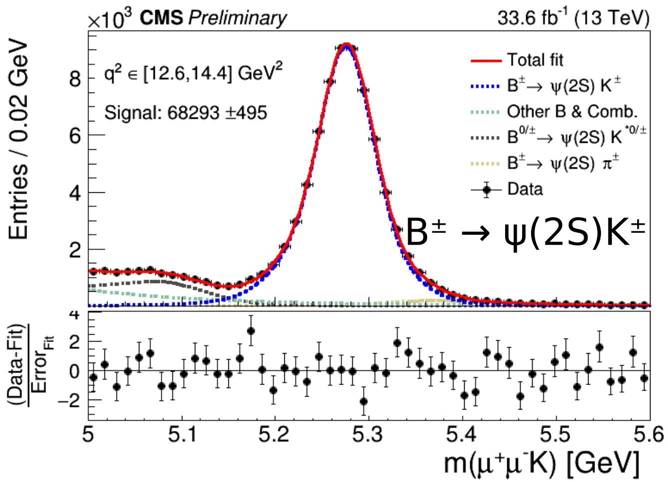
Functions used for each fit component per decay

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

Where X=J/ψ, ψ(2S), μμ   DSCB = Double-Sided Crystal Ball





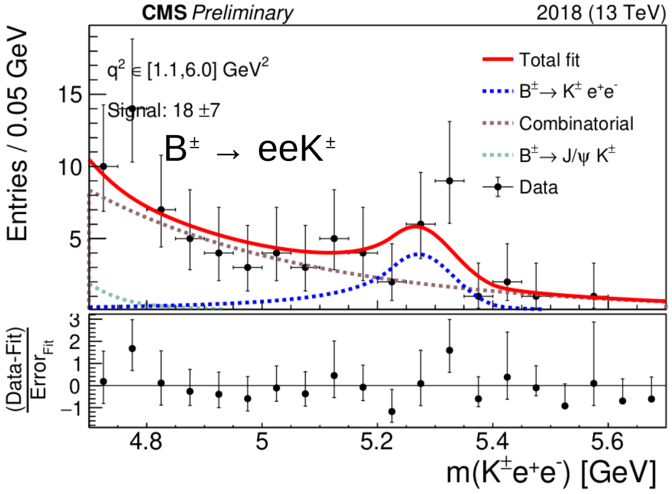


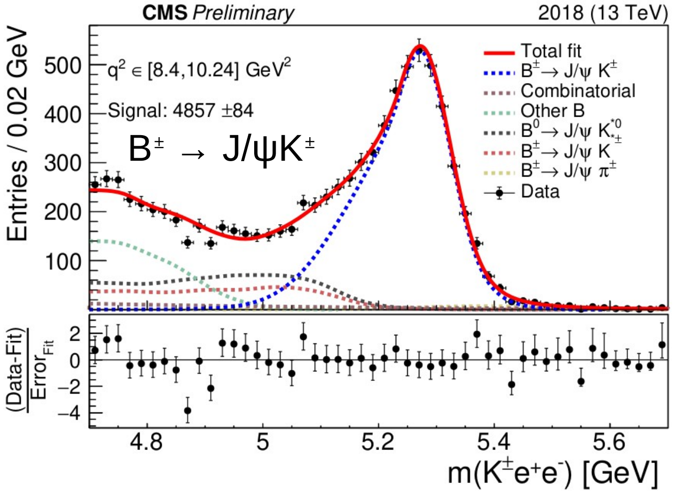
B → eeX mass fits (PF - PF)

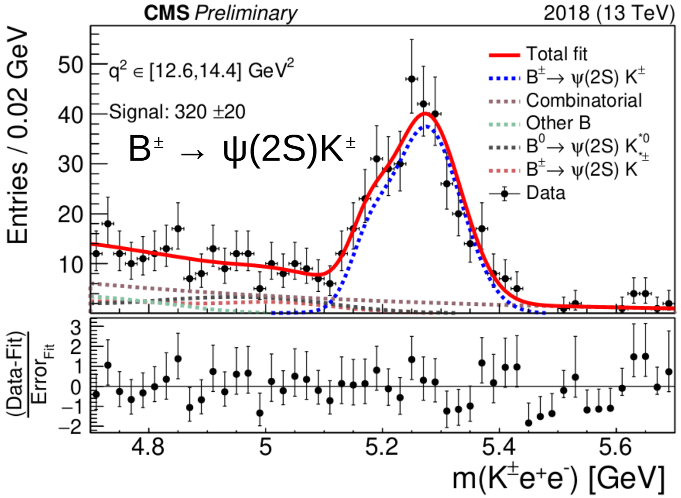
Functions used for each fit component for 2 PF electron channels

	$B^\pm \to eeK^\pm$	$B^\pm \to J/\psi K^\pm$	$B^\pm \to \psi(2S)K^\pm$
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 KDE = Kernel Density Estimator, CB = Crystal Ball, DSCB = Double-Sided Crystal Ball





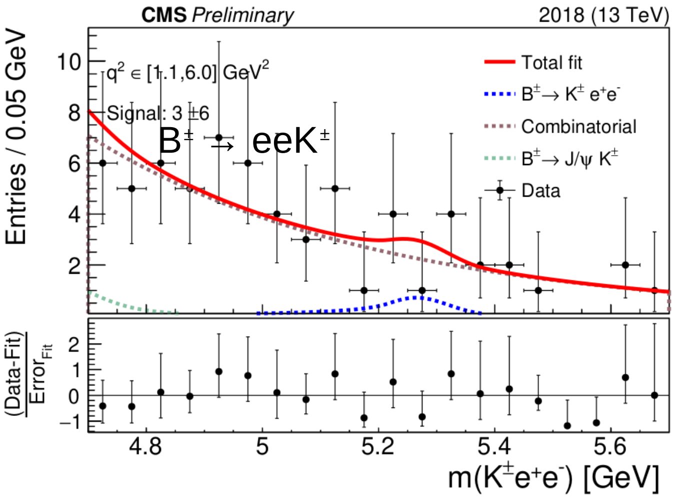


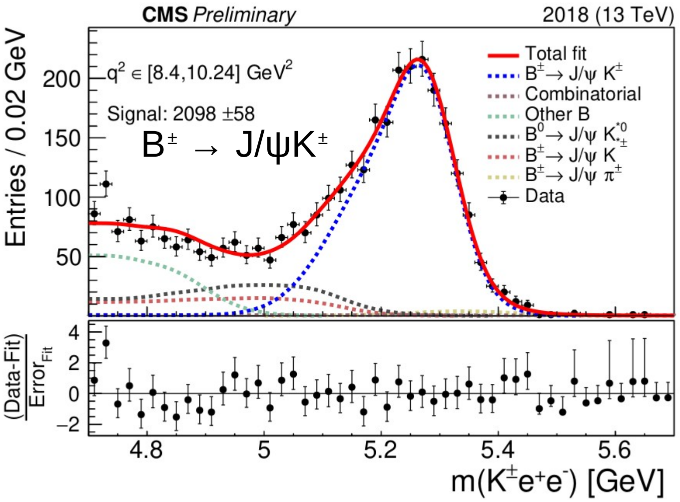
B → eeX mass fits (PF - LP)

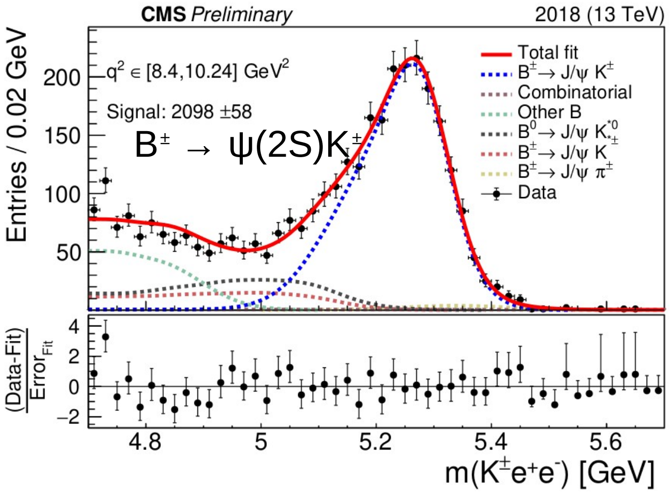
Functions used for each fit component for PF - LP electron channels

	$B^{\pm} \to eeK^{\pm}$	$B^{\pm} \to J/\psi K^{\pm}$	$B^{\pm} \to \psi(2S)K^{\pm}$
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 KDE = Kernel Density Estimator, CB = Crystal Ball, DSCB = Double-Sided Crystal Ball

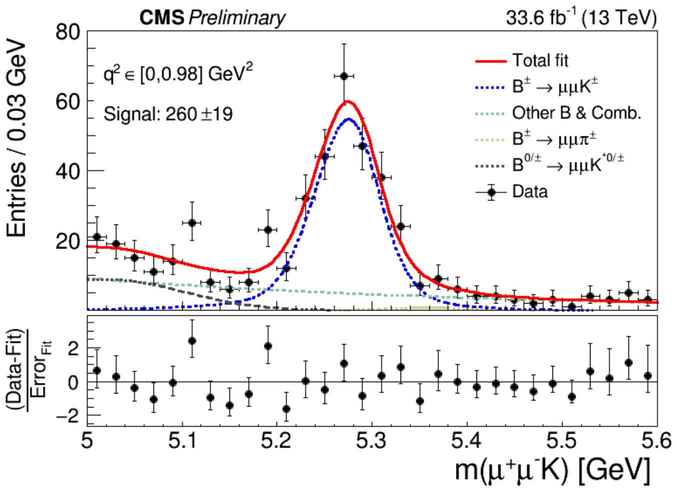


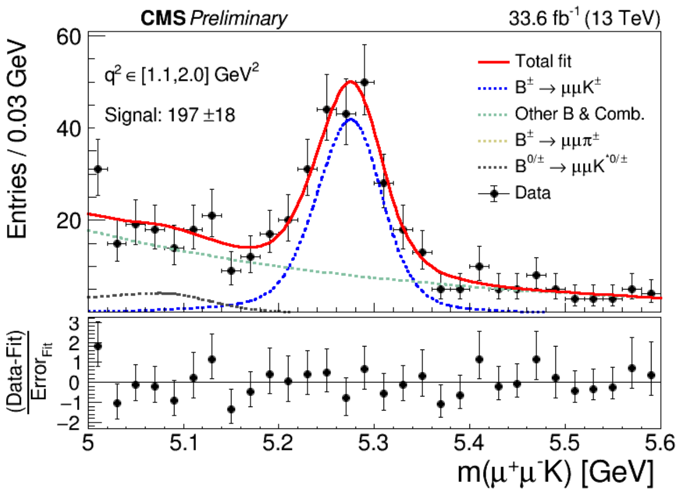


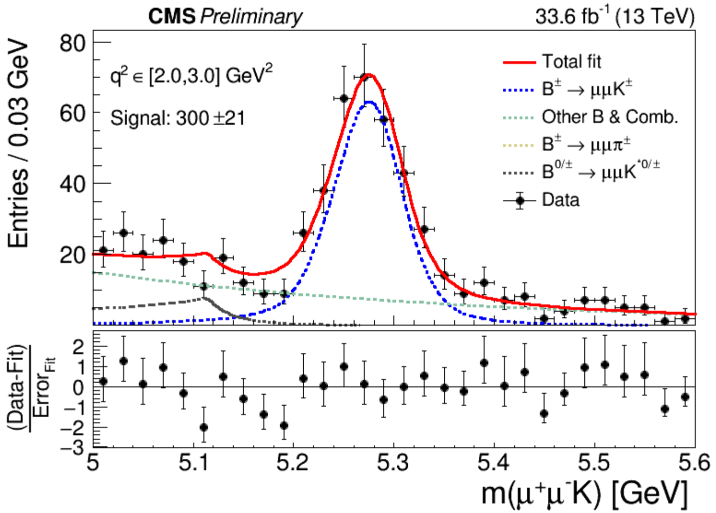


B → μμK mass fits in q² bins

Bin	q^2 range [GeV]
1	0–0.98
2	1.1–2.0
3	2.0–3.0
4	3.0–4.0
5	4.0–5.0
6	5.0–6.0
7	6.0–7.0
8	7.0–8.0
9	11.0–11.8
10	11.8–12.5
11	14.82–16.0
12	16.0–17.0
13	17.0–18.0
14	18.0–19.24
15	19.24–22.9







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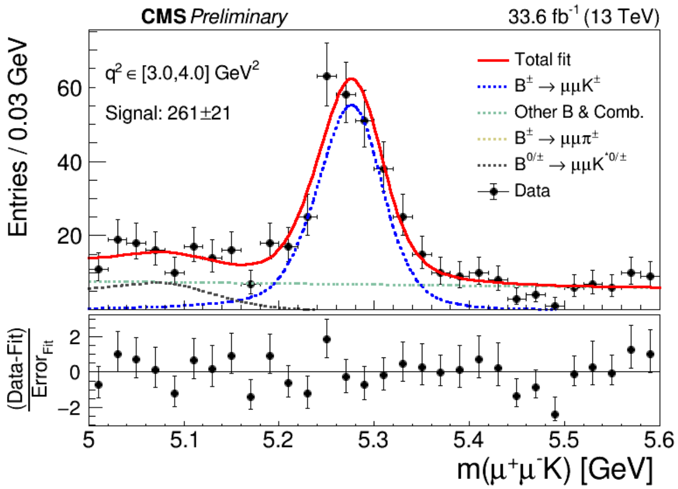

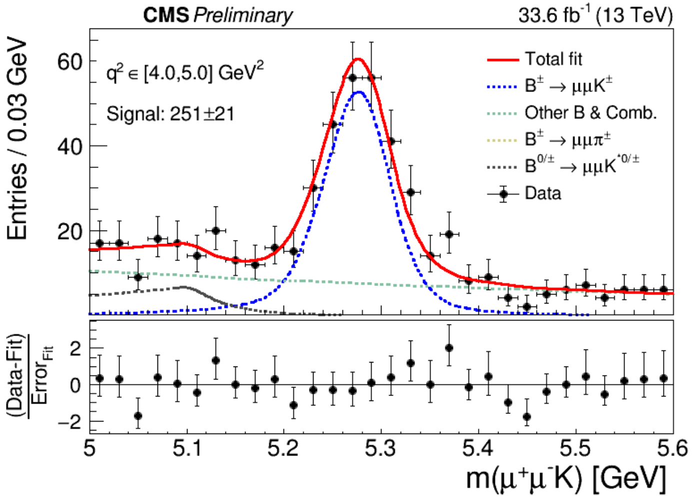

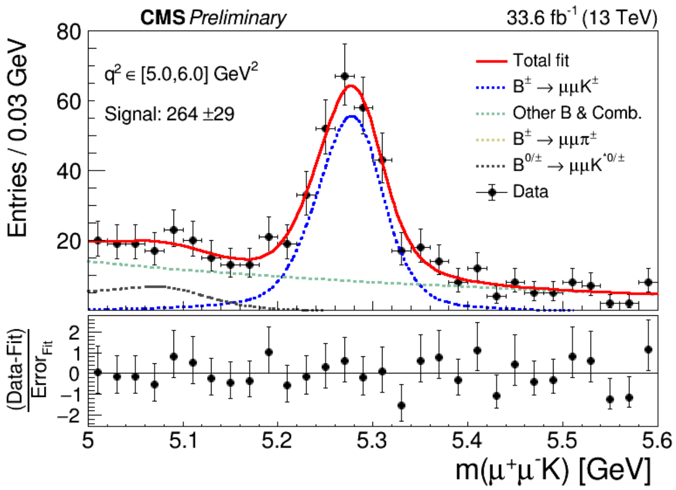

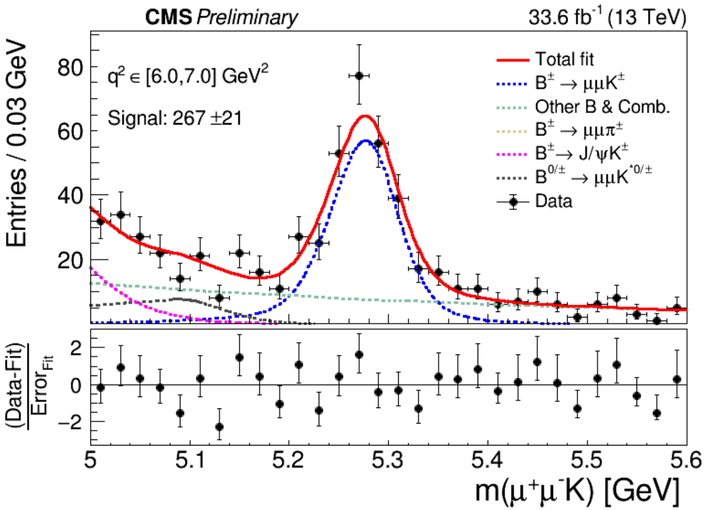

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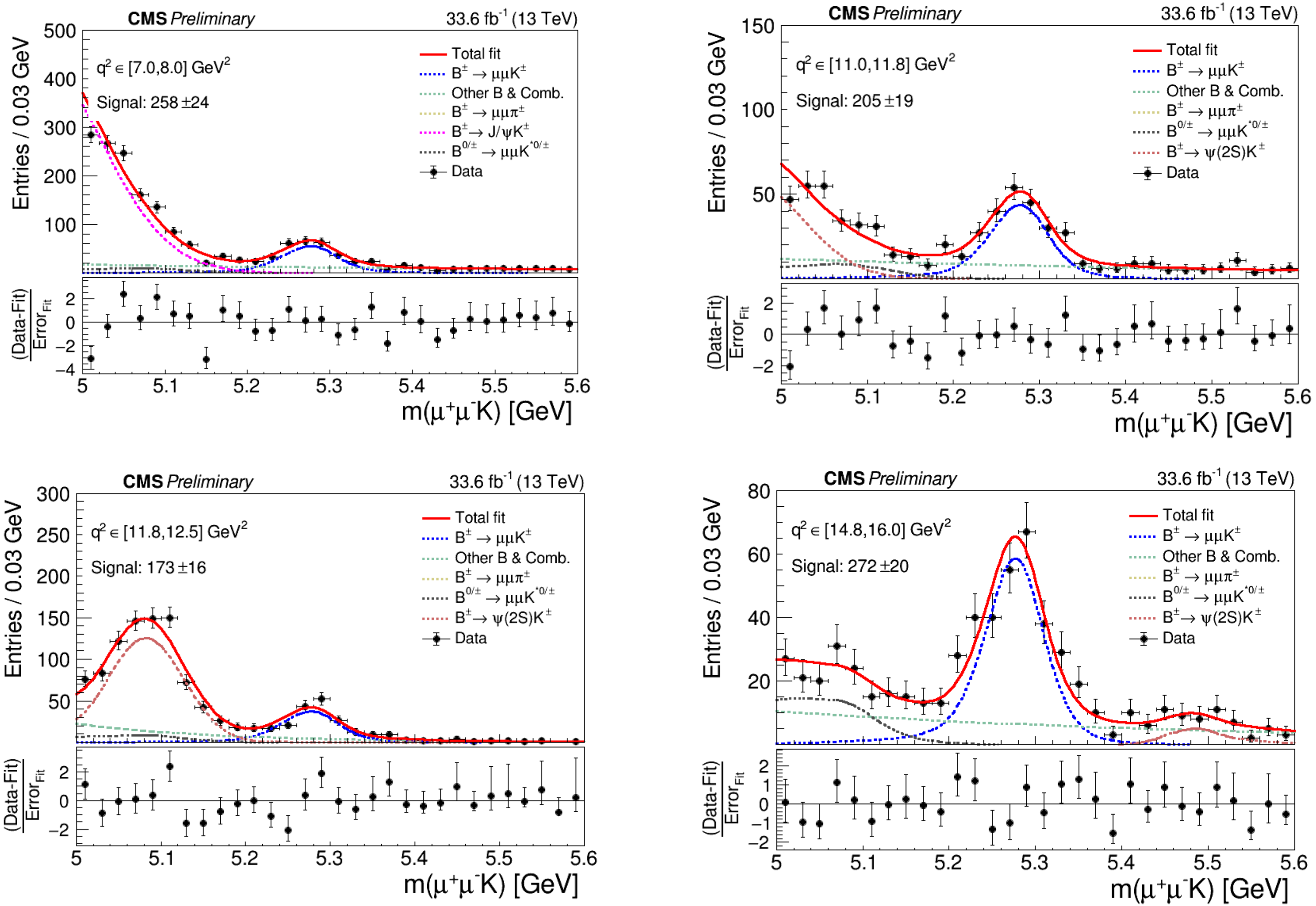

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