University of Ljubljana
Faculty of Mathematics and Physics

IJS

Measurement of the $B^+ \to K^+K^-\ell^+\nu_\ell$ Decay with the Belle Detector

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PhD Thesis Defense

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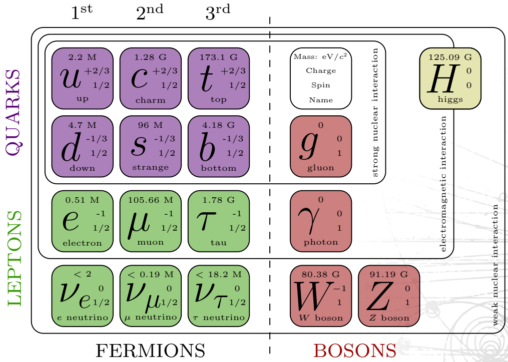
Overview

Introduction I – Standard Model

- The Standard Model (SM) is a basic theory which describes elementary particles and interactions between them
- Quarks: can be grouped into baryons ($q_1q_2q_3$) or mesons ($\bar{q}_1q_2$)
- Focus of this analysis are B mesons: $B^+(\bar{b}u)$

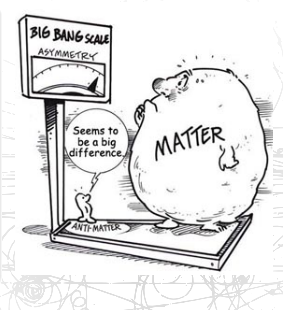


Introduction II – *CP* Violation

- *C* (charge conjugation), *P* (parity) and *T* (time reversal) symmetries were believed to be conserved individually (based on EM interaction, 1954)
- Observation of *P* symmetry violation confused physicists (1956)
- Observation of *CP* symmetry violation confused physicists even more (1964)

CP symmetry? $\rightarrow$ A sort of a "physics mirror", stating that the laws of physics should be the same if observed through said mirror.

- *CP* violation one of the necessary conditions for matter and antimatter asymmetry in the universe
- This analysis is one of the many steps toward a better understanding of our universe

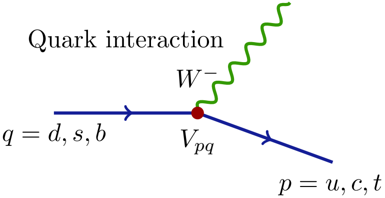


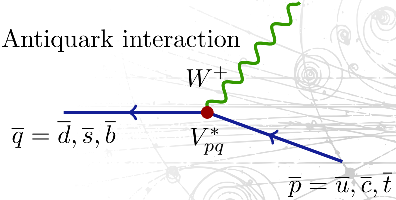
http://pprc.qmul.ac.uk/~still/homepage/Matter_and_Anti-Matter.html

Introduction III – CKM Matrix

- Quarks can transform to other quarks (weak nuclear interaction)
- Transition probabilities are contained in the complex Cabibbo-Kobayashi-Maskawa (CKM) matrix
- CKM matrix is strongly connected to *CP* violation

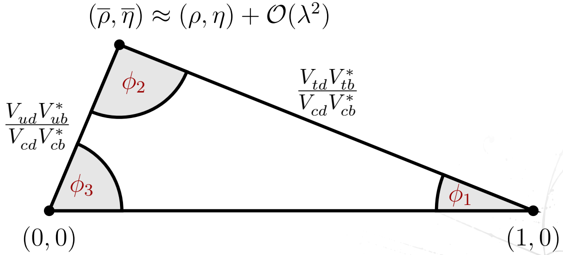
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}, \quad |V_{ij}|^2 \propto q_i \leftrightarrow q_j \ \text{transition probability}$$





Introduction IV – Unitarity Triangle

- The most relevant unitarity condition of the CKM matrix for this analysis is
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



- By measuring the sides and angles of the triangle, we can overconstrain it and check if all the sides meet
- CKM matrix elements are not determined by theory or experiment alone, but by their joint effort

Introduction V – Unitarity Triangle Determination

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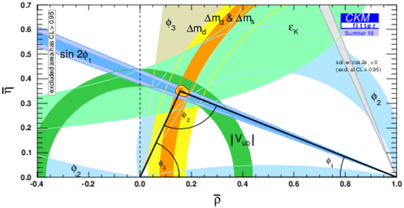
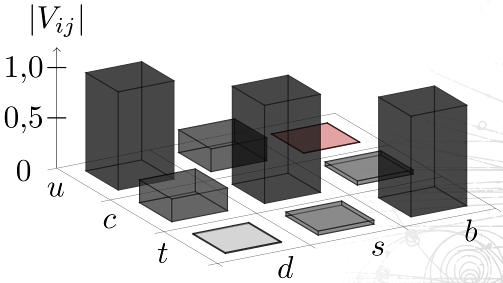


- By measuring the sides and angles of the triangle, we can overconstrain it and check if all the sides meet
- CKM matrix elements are not determined by theory or experiment alone, but by their joint effort
- In this analysis we focus on decays involving V_{ub}

Overview

Motivation I – Why V_{ub}?

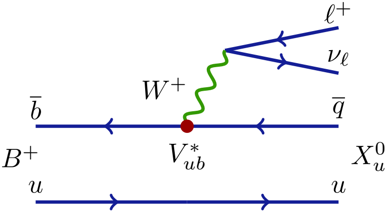
- The magnitude of *CP* violation that we know of is not large enough to account for the matter and antimatter asymmetry
- We are searching for new physics (NP) processes, which are not described by our current model
- $|V_{ub}|$ has the smallest value and the largest uncertainty of all the CKM matrix elements, precision measurements require better accuracy



Motivation II – Why B Mesons?

- B mesons exhibit a rich spectrum of decay modes, out of which many allow the study of the underlying physics processes
- Decays are deeply connected to the CKM matrix

- We focus on the charmless semileptonic B meson decays of the form $B^+ \to X_u^0 \ell^+ \nu_\ell$
- Such decays are used to determine the $|V_{ub}|$ CKM matrix element



Reliable experimental measurements along with precise theoretical calculations enable the determination of the $|V_{ub}|$

$$\mathrm{d}\Gamma \propto G_F^2 |V_{ub}|^2 |L^\mu \langle X_u | \bar{u} \gamma_u \frac{1}{2}(1-\gamma_5) b | B \rangle |^2,$$

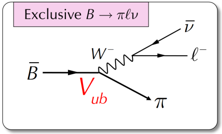
Γ is the decay width, L^μ is the leptonic current and $\langle \dots \rangle$ is the hadronic current.

Motivation III – Why This Analysis?

There are two common methods of $|V_{ub}|$ determination

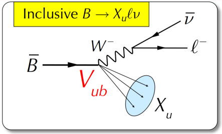
Exclusive

- B decays to a specific hadronic final state X_u (such as π or ρ)



Inclusive

- B meson decays to any hadronic final state X_u



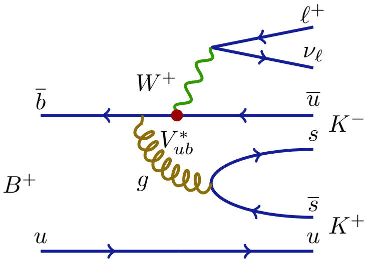
Both methods require different experimental and theoretical approaches, therefore yield largely independent results

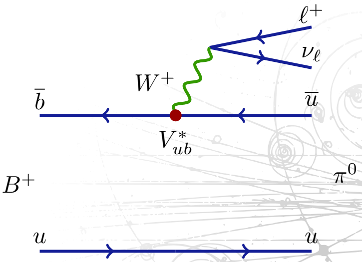
$$|V_{ub}|_{\text{excl.}} = (3.65 \pm 0.09 \pm 0.11) \times 10^{-3},$$
$$|V_{ub}|^{\text{GGOU}}_{\text{incl.}} = \left(4.52 \pm 0.15\,^{+0.11}_{-0.14}\right) \times 10^{-3},$$

However, they agree only at a 3σ level $\rightarrow$ The V_{ub} puzzle

Motivation IV – Why This Decay?

- The decay $B \to KK\ell\nu$ is similar to the $B \to \pi\ell\nu$ decay, so a similar analysis process can be applied
- The decay has not been observed yet
- Kaons ($K^+(u\bar{s})$) are usually present in $b \to c(\to s)$ decays, so a K-veto is used to remove such background cases in inclusive V_{ub} studies
  $\to$ but this is a charmless process ($b \to u$) with kaons in the final state!





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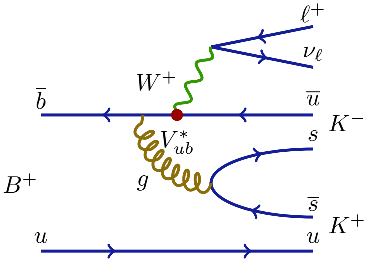

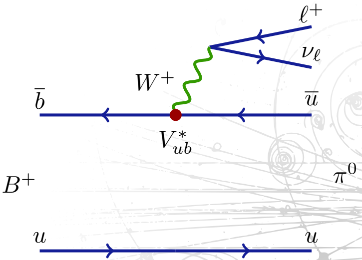

Can change the value of $|V_{ub}|$ with inclusive method!

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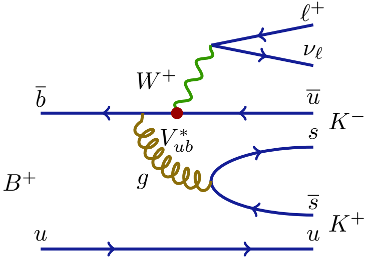
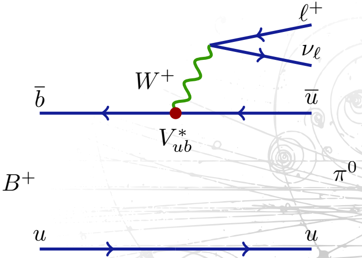


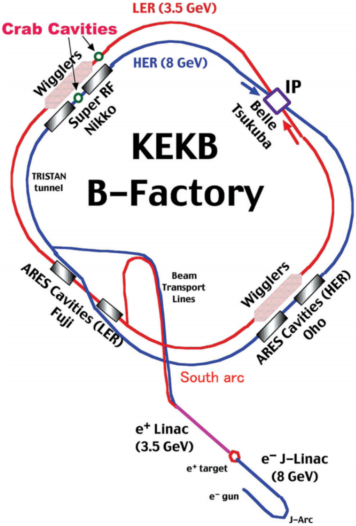


Impact of not taking these decays into account?

Overview

Experimental Setup I – KEKB Accelerator

- Two rings (e^+ and e^-) with a diameter ≈ 1 km
- Particles are produced in events when e^+ and e^- collide
- Energy in the center-of-mass frame is 10.58 GeV
  - corresponds to $\Upsilon(4S)$ meson mass
- B factories are known for mass production of B mesons



Experimental Setup II – Particle Detection

- Event – collision of e^+ and e^-

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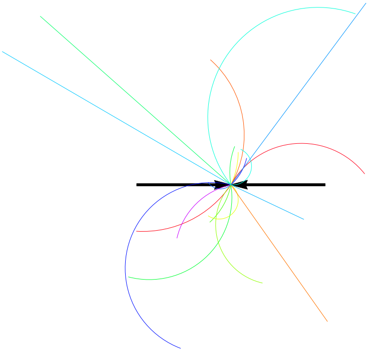
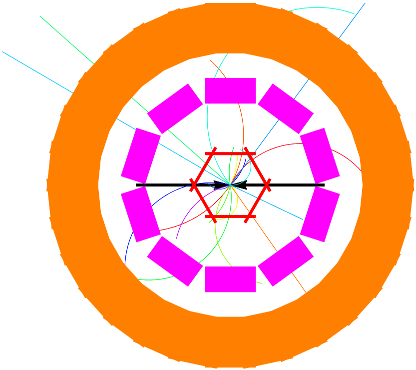


- Event – collision of e^+ and e^-
- Production of new particles

Experimental Setup II – Particle Detection



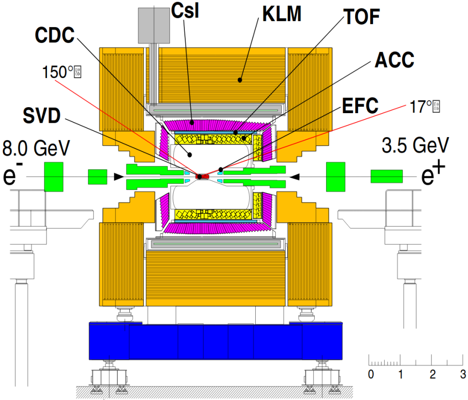
- Event – collision of e^+ and e^-
- Production of new particles
- Detection of final, stable particles

Experimental Setup III – Belle Detector

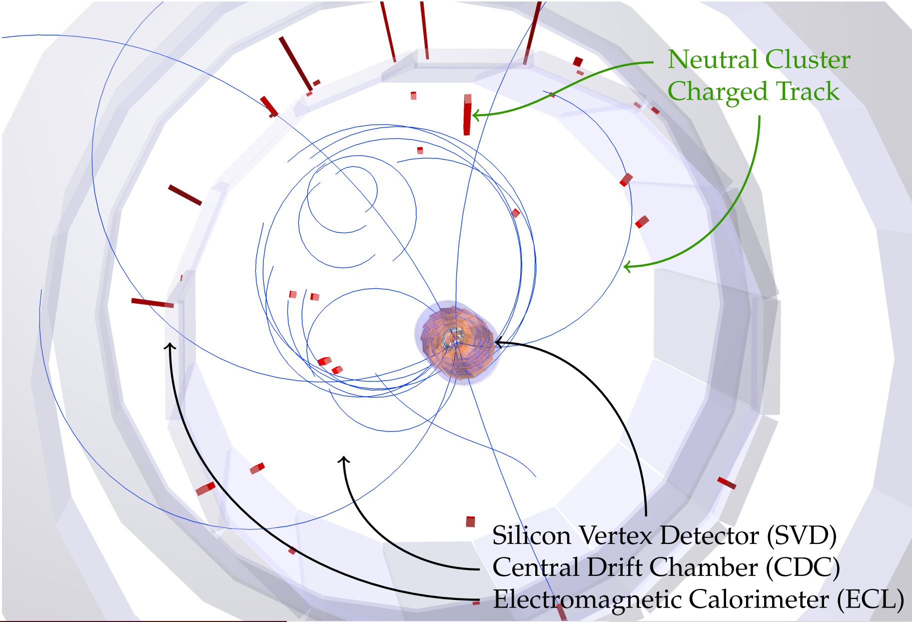
- A cylindrically symmetric magnetic spectrometer
- Wide solid angle coverage ($\sim 92\%$)
- Specialized for e^+e^- collisions
- Constructed from several subdetectors, each with its own purpose

Belle II detector subsystems:

- Decay vertex determination
- Tracking
- Particle identification
- Calorimetry



Experimental Setup III – Belle Detector Subsystems



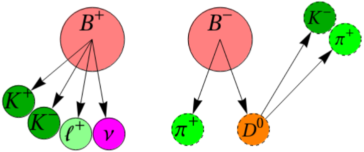
Overview

Analysis I – Method overview

- Initial state well known: $e^+e^- \to \Upsilon(4S)$ @ $E_{CMS} \approx M_{\Upsilon(4S)}$
- $\Upsilon(4S)$ at rest $\to B\overline{B}$
- Kaons K and the leptons e and μ produce tracks $\to$ easily detectable
- Neutrinos ν interact weakly and escape the detector $\to$ missing energy and momentum

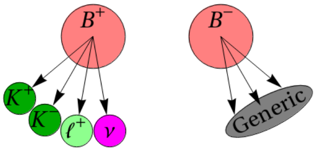
Reconstruction methods

Tagged measurement



Example scheme
of a tagged mode

Untagged measurement



Companion B
not reconstructed

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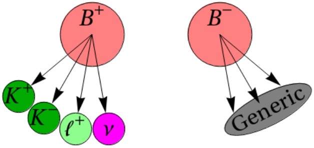
Reconstruction methods

Untagged measurement

We opt for this method $\to$ Neutrino 4-momentum is inferred from missing momentum in event (assuming only 1 neutrino missing)



Companion B not reconstructed

Analysis II – Particle Reconstruction

Part I: Final State Particles (FSP)

- Charged particles like K, e and μ are reconstructed from tracks, a quality selection is performed
- Neutrinos are weakly interacting and escape detection

Part II: FSP Combinations

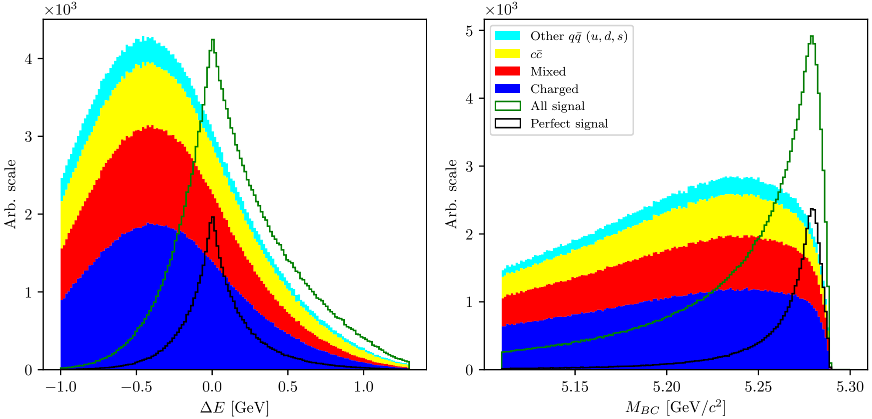
- Combinations of FSP particles KKe and $KK\mu$ represent first B meson candidates with a missing neutrino

Part III: Loose Neutrino Reconstruction

- Rest of Event (ROE) are all the tracks (charged particles) and clusters (neutral particles) which were not used in the reconstruction
- ROE is needed to reconstruct the missing neutrino momentum, where all tracks and clusters from ROE are summed up together

Analysis III – B meson specific variables

$$\Delta E = E_B - E_{CMS}/2, \quad M_{BC} = \sqrt{(E_{CMS}/2)^2 - |\vec{p}_B|^2}$$

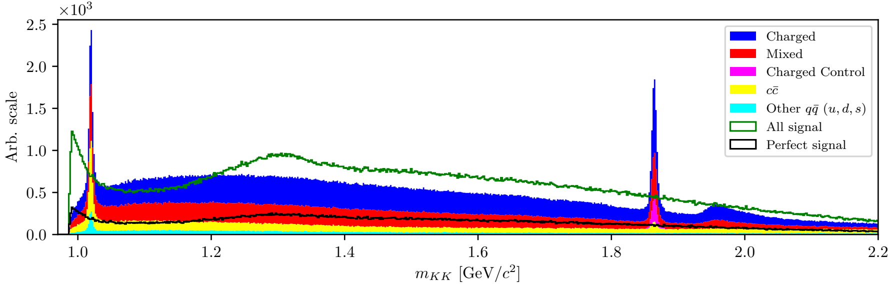


Signal is scaled up. Correctly reconstructed candidates have $\Delta E \approx 0$ and $M_{BC} \approx m_B$

Analysis IV – Control Decay

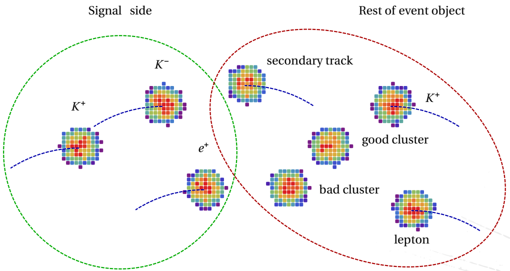
We define a control decay mode, similar to our signal decay mode.

- The decay mode is $B^+ \to \bar{D}^0 \ell^+ \nu$, $D^0 \to K^+ K^-$
- The properties of the control and signal decay are very similar
- Its purpose is to continuously check the consistency between simulation (Monte Carlo or MC) and measured data



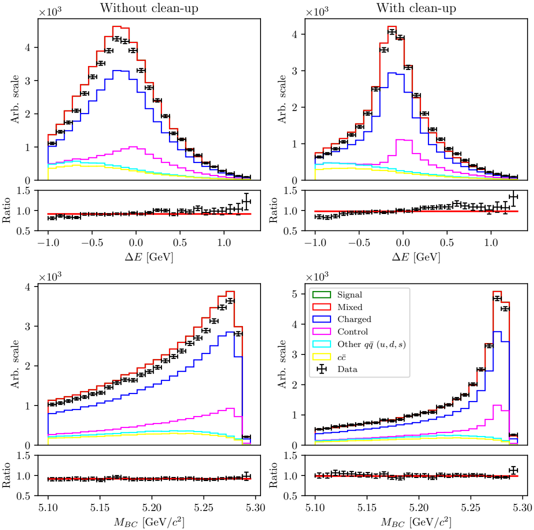
Analysis V – ROE Clean-up

- Rest of Event (ROE) are all the tracks (charged particles) and clusters (neutral particles) which were not used in the reconstruction
- ROE is needed to reconstruct the missing neutrino momentum



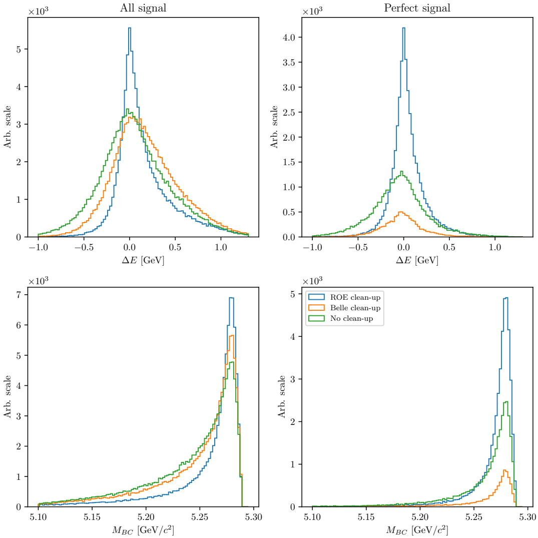
- Why? Extra tracks and clusters should not be taken into account when calculating the neutrino 4-momentum
- How? We apply machine learning in several steps of the ROE clean-up in order to efficiently clean it

Analysis VI – ROE Clean-up Results



- ROE clean-up performs well, distributions are more prominent
- The clean-up procedure does not introduce differences between MC and Data
- The control (and therefore signal) distribution is much more significant after the cleanup
- The charged background more "signal" like because phase-space similar to the one for the control decay

Analysis VI – ROE Clean-up Results



- The procedure **improves the resolution** of signal distribution
- It performs **better** than the standard Belle procedure
- **The efficiency** of perfectly reconstructed signal **increases**

	$\mathcal{E}$	FWHM
Belle	28.5 %	75.0 %
ROE	140.1 %	35.0 %

Perfectly reconstructed signal candidates are signal candidates from events, where all tracks and clusters are accounted for.

Analysis VII – Background Suppression

In order to further suppress various sources of background, we use *machine learning algorithms*:

These algorithms take multiple properties of candidates as input and produce an output variable, similar to a signal probability

Boosted Decision Trees (BDT) algorithms are commonly used in the field

Continuum Suppression

- Events of the form $e^+e^- \to q\bar{q}$, where $q \in [u, d, s, c]$
- Energy and momentum distribution of such events differ from $e^+e^- \to B\bar{B}$ events

$B\bar{B}$ Suppression

- Deeper look into the properties of the signal decay enable separation of signal from other $e^+e^- \to B\bar{B}$ events

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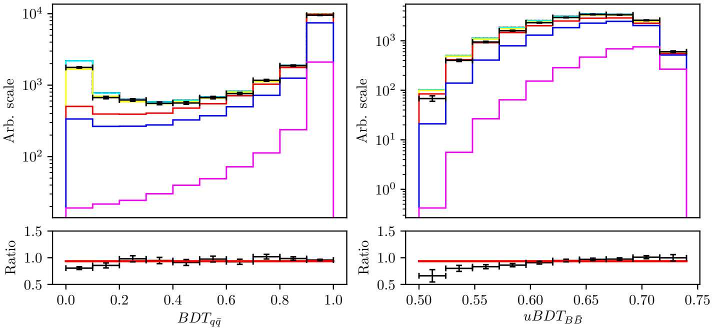
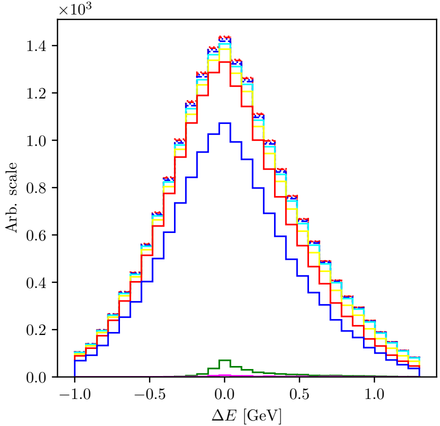


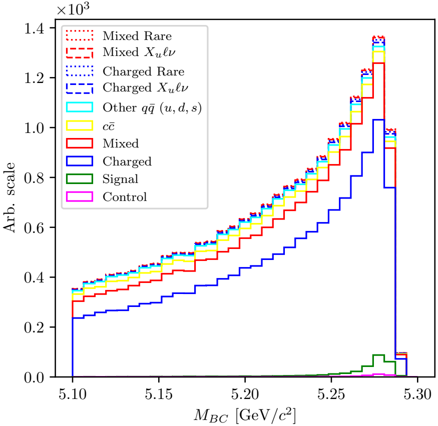
Continuum (left) and $B\bar{B}$ (right) suppression BDT variable. Signal is more likely distributed on the right side of the variables.

Analysis VIII – Final Selection

Sample composition after background suppression:

$$N_{\text{sig}} = 264, \quad \frac{N_{\text{sig}}}{N_{\text{bkg}}} = 1.33$$





Overview

Parameter Extraction I – Fit Method

- Define "templates" which describe distribution shapes (signal, background, . . .)
- For each histogram bin define Poisson probability for it's content w.r.t. the measurement
- Obtain the combination of template yields which maximise the probability

Templates in the signal fit:

- signal
- continuum
- well-defined sources →
- other $B\bar{B}$ background

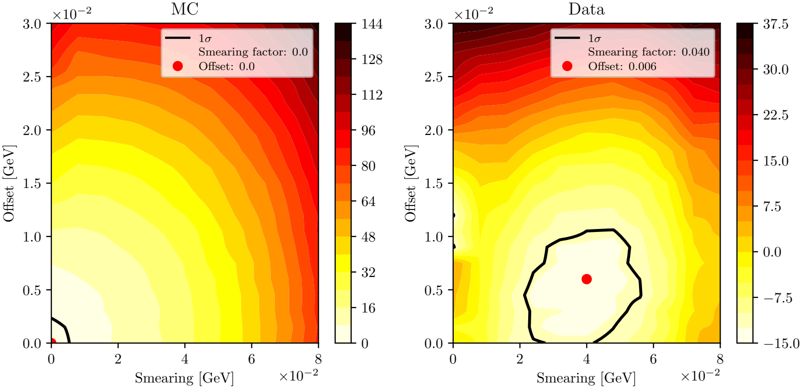
- control decay,
- $B \to \bar{D}^{*} \ell^{+} \nu,\ D^{0} \to K^{-} K^{+},$
- $B \to \bar{D}^{(*)} \ell^{+} \nu,\ D^{0} \to K^{-} \pi^{+},$
- $B \to \bar{D}^{(*)} \ell^{+} \nu,\ D^{0} \to K^{-} K^{+} \pi^{0},\ K^{-} \pi^{+} \pi^{0},$
- $B \to \bar{D}^{(*)} \ell^{+} \nu,\ D^{0} \to K^{-} \ell^{+} \nu,$
- $B^{0} \to D^{(*)-} \ell^{+} \nu,\ D^{+} \to K^{-} K^{+} \pi^{+},\ K^{-} \pi^{+} \pi^{+},$
- other $B \to \bar{D}^{(*)} \ell^{+} \nu$ decays,

Yields of all templates are floated, except in the well-defined cases, where yields are constrained by world measurements.

Parameter Extraction II – Smearing and Offset

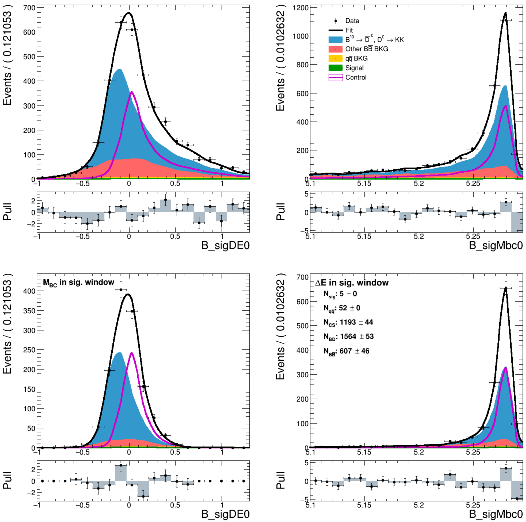
We introduced 2 additional parameters to the ΔE variable:

$$f_{\text{offset}} : x \mapsto x + a, \quad f_{\text{smearing}} : x \mapsto \frac{1}{\sqrt{2\pi\sigma^2}} \mathrm{e}^{-\frac{(x-\mu)^2}{2\sigma^2}},$$



Consistency check on MC, data fit better with introduced parameters:
Smearing: 40^{+15}_{-17} MeV, Offset: $6^{+4.6}_{-6}$ MeV.

Results of the control decay fit to DATA

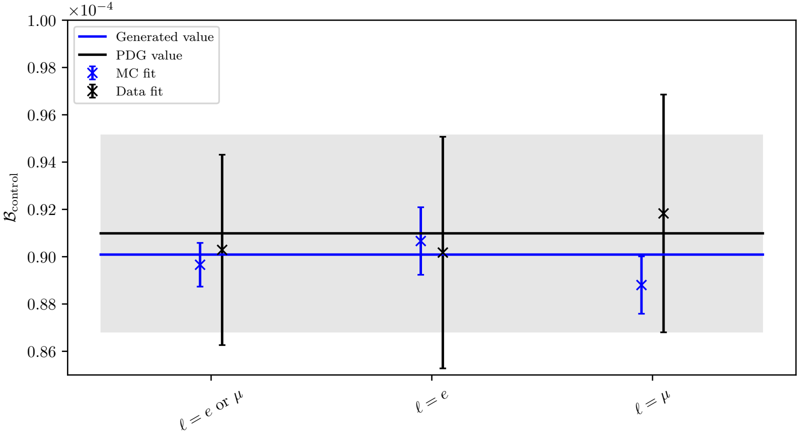


- Templates are appropriately summed to best fit the measurement
- The fit behaves well, no strange artefacts in pulls

pulls ∝ differences between the function and the points

Parameter Extraction III – Control Fit Results

Simulated and measured branching ratio of the control decay for joint and split lepton modes.



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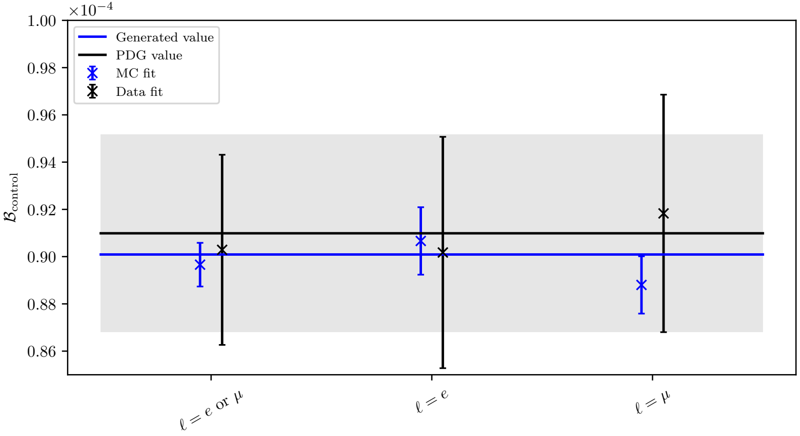
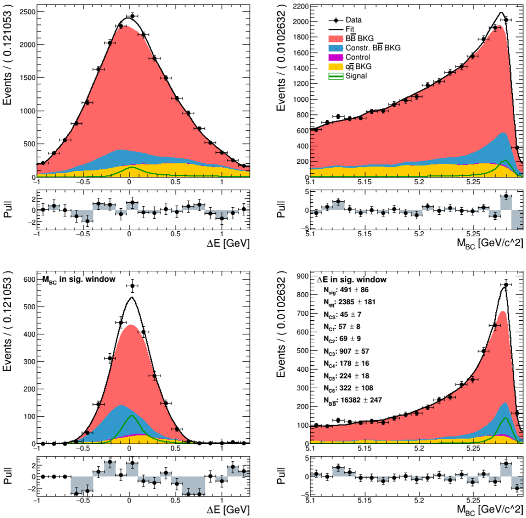


The simulated and measured values of the control decay branching ratio seems to agree well with the generated value and the world average from PDG (`http://pdglive.lbl.gov`).

Parameter Extraction IV – Signal Fit Results

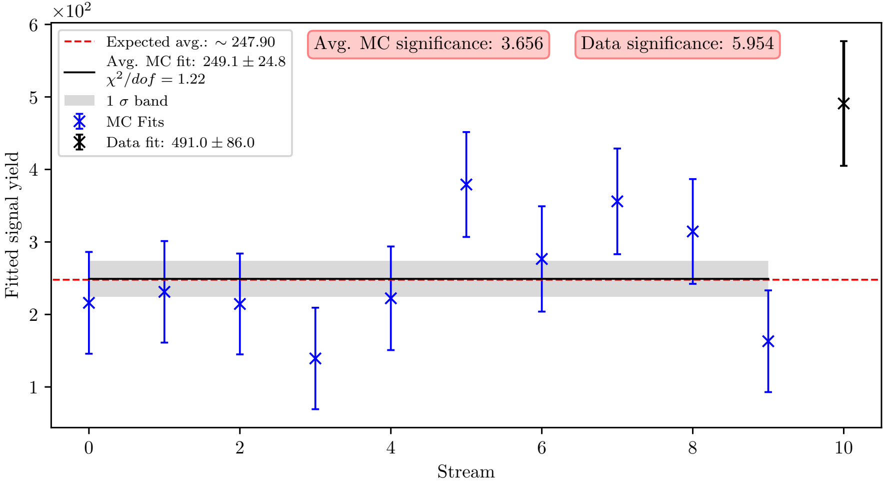
Results of the signal decay fit to DATA



Category	Fit Yield
Signal	491 ± 86
$q\bar{q}$ bkg	2385 ± 181
C_0	45 ± 7
C_1	57 ± 8
C_2	69 ± 9
C_3	907 ± 57
C_4	178 ± 16
C_5	224 ± 18
C_6	322 ± 108
Other $B\bar{B}$ bkg	16382 ± 247

Parameter Extraction IV – Signal Fit Results

Signal fit to measured data and 10 equal samples of simulated data (streams)



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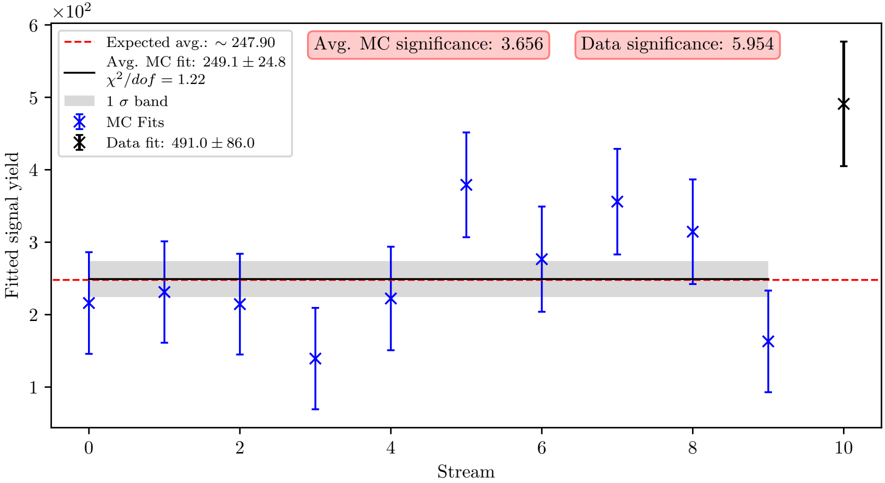
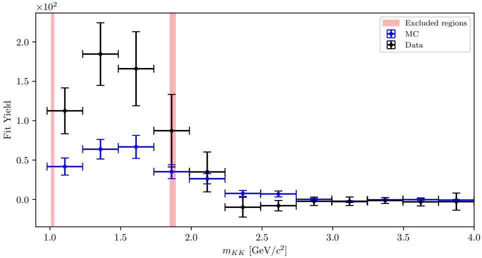
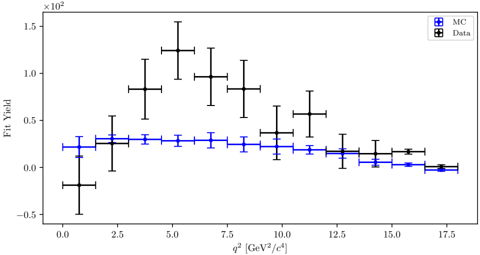


Much more signal in measured data than expected from simulation!

Parameter Extraction V – Signal Distributions



- Invariant mass of two kaons
- Distributions are similar
- Signal much more abundant in DATA



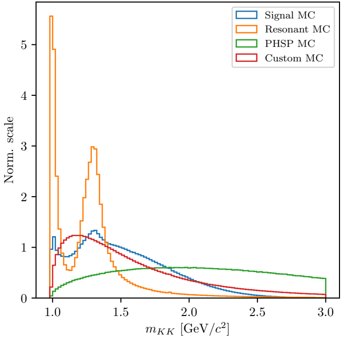
- q is the 4-momentum transferred to the lepton pair
- Distributions are quite different
- Signal much more abundant in DATA

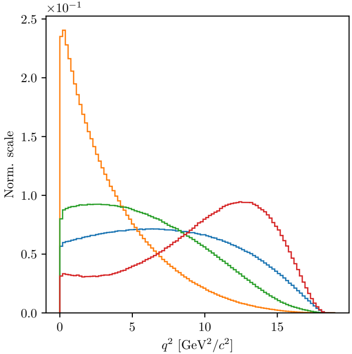
Such measurements help improve future models and minimize difference between data and simulations.

Overview

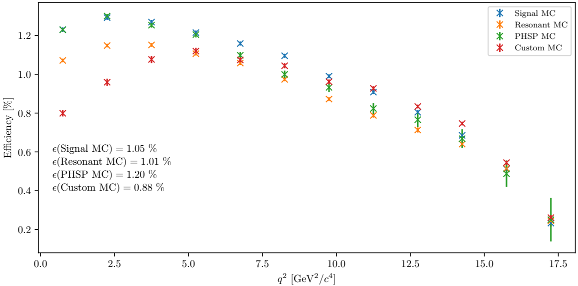
Systematic Uncertainties I – Model Dependency

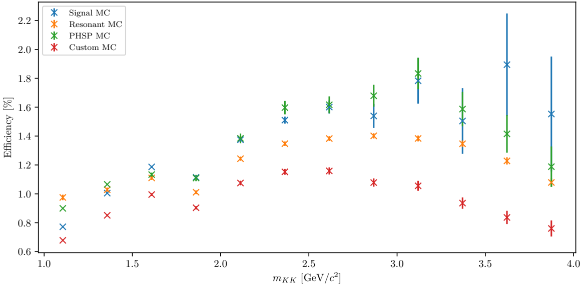
- Largest source of uncertainty in this analysis
- `ISGW2` model for signal decay is not the most reliable, try to not depend on it
- Three additional signal models are used to estimate dependency, used as substitute templates
- Different models have different signal efficiencies





Systematic Uncertainties I – Model Dependency





Systematic Uncertainties II – All Sources

Source	σ	δ [%]
PID	10	2.0
Fit Bias	$^{+7}_{-10}$	$^{+1.5}_{-2.0}$
Gaussian Constraints	26	5.4
Template Smearing	$^{+41}_{-33}$	$^{+8.3}_{-6.7}$
Template Offset	$^{+41}_{-31}$	$^{+8.4}_{-6.3}$
Finite MC Effects	26	5.3
MVA Selection	5	1.0
Model Shape	$^{+45}_{-39}$	$^{+9.3}_{-8.0}$
Model Efficiency	$^{+70}_{-79}$	$^{+14.3}_{-16.2}$
Total	$^{+109}_{-107}$	$^{+22.2}_{-21.9}$

Overview

Results I – Branching Ratio of Signal Decay

Calculated branching ratio from simulated data is:

$$\mathcal{B}^{\mathrm{MC}}(B^+ \to K^+K^-\ell^+\nu) = (1.55 \pm 0.15) \times 10^{-5},$$

And on data, after taking all uncertainties into account:

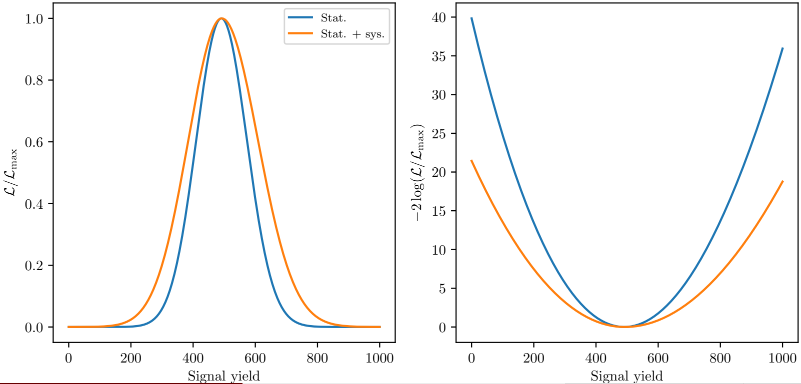
$$\mathcal{B}(B^+ \to K^+K^-\ell^+\nu) = (3.04 \pm 0.51 \pm {}^{+0.67}_{-0.66}) \times 10^{-5},$$

where the first and the last error are statistical and systematic, respectively.

Almost a factor of 2 difference!

Results II – Signal Significance

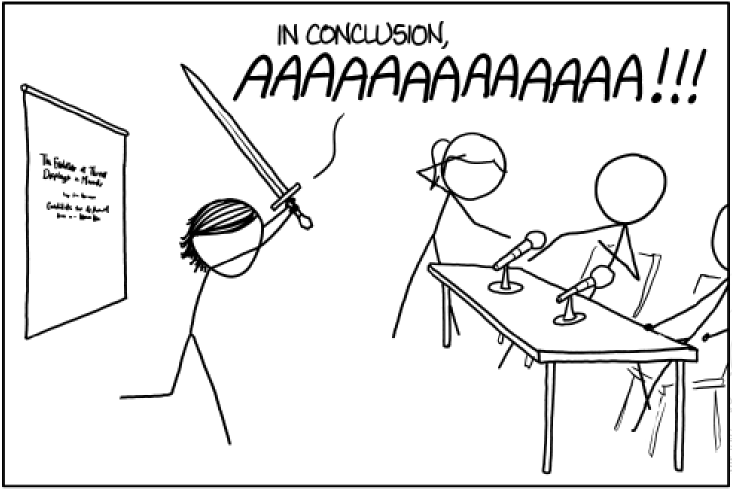
- Profile likelihood gives the value of likelihood at different expected yields of signal, used for significance estimation
- Statistical significance corresponds to 6.3σ
- Systematic uncertainties are incorporated via a convolution
- Overall signal significance $4.6\sigma \rightarrow$ evidence!



Summary

- We present an improvement in the untagged method with the ROE clean-up
- Machine learning algorithms aid substantially in such complex analyses
- The evidence for the decay mode $B^+ \to K^+K^-\ell^+\nu_\ell$ was found
- Further insight into signal distributions helps to improve future simulation models
- **Discarding decays of the form $B \to X_u\ell\nu$ with kaons in the final state might affect the inclusive measurements more than previously believed.**

Thank you!



THE BEST THESIS DEFENSE IS A GOOD THESIS OFFENSE.

https://xkcd.com/1403/

BACKUP

Analysis III – Selection Criteria

Two modes are reconstructed, neutrinos escape detection:
$$B^+ \to K^+K^-e^+ \quad \text{and} \quad B^+ \to K^+K^-\mu^+$$

Selection:

- FSP particles:
  - electrons: $|d_0| < 0.1$ cm, $|z_0| < 1.5$ cm, $p > 0.6$ GeV$/c$, $p_{CMS} \in [0.4,\ 2.6]$ GeV$/c$, $eID > 0.9$,
  - muons:
    $|d_0| < 0.1$ cm, $|z_0| < 1.5$ cm, $p_{CMS} \in [0.6,\ 2.6]$ GeV$/c$, $\mu ID > 0.97$,
  - kaons: $|d_0| < 0.15$ cm, $|z_0| < 1.5$ cm, $p_{CMS} < 2.5$ GeV$/c$, $K/\pi\ ID > 0.6$, $K/p\ ID > 0.1$,
- B meson candidates:
  - standard selection:
    $P(\chi^2,\ DOF) > 6 \times 10^{-3}$, $|\cos\theta_{BY}| < 1.05$, $|m^2_{miss}| < 0.975$ GeV$/c^2$,
  - fit region selection:
    $\Delta E \in [-1.0, 1.3]$ GeV, $M_{BC} \in [5.1, 5.295]$ GeV$/c^2$,
  - signal region selection: $|\Delta E| < 0.126$ GeV, $M_{BC} > 5.271$ GeV$/c^2$,
  - charge categorization: $q_{B^\pm} q_{B^\mp} = -1$.