Search for $B \to 3\mu\nu$ at LHCb

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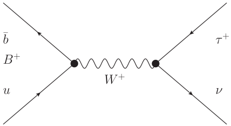
Motivation

- fully **leptonic decays of B^+ mesons** are naturally rare
- branching fractions is proportional to the coupling strength $|V_{ub}|^2$

$B^+ \to \tau^+ \nu_\tau$:



- has precise SM predictions due to absence of hadrons in final state :

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_{\tau^+}^2}{8\pi} \left[1 - \frac{m_{\tau^+}^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_{B^+}$$

- decay rate is helicity suppressed by factor: $(\frac{m_\tau}{m_B})^2$
  $\to$ highly sensitive to BSM particles, such as charged Higgs in 2HDM

Leptonic B decays

$B^+ \to \tau^+ \nu_\tau$

- most precise measurements done by Belle and BaBar:
  Phys. Rev. D92 (2015) 051102, Phys. Rev. Lett. 110 (2013) 131801, Phys. Rev. D88 (2013) 031102(R), Phys. Rev. D81 (2010) 051101(R)
- are consistent with SM predictions of $\mathcal{B}_{SM} = ((144 \pm 31)x10^{-6}$ (HFLAV December 2017)

- $B^+ \to \tau^+ \nu_\tau$ at LHCb ?
  - τ reconstruction very challenging: short lifetime and further decay into neutrinos
  - B vertex reconstruction from only one track highly challenging in busy LHC environment

Leptonic B decays

$B^+ \to \mu^+\nu_\mu$

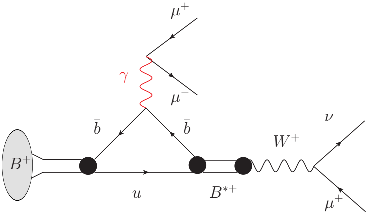
- $B^+ \to \mu^+\nu_\mu$ even further supressed by factor: $(\frac{m_\mu}{m_B})^2$
- measurements performed by Belle and Babar: Phys. Rev. Lett. 121, 031801 (2018), Phys. Rev. D81 (2010) 051101(R)
- also consistent with SM predictions of $\mathcal{B}_{SM} = (3.80 \pm 0.31)x10^{-7}$

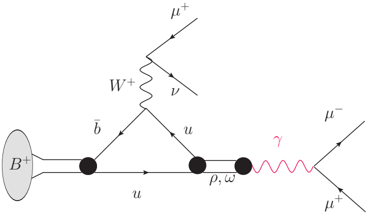
$B^+ \to \gamma\mu^+\nu_\mu$

- adding a photon lifts the strong suppression of the $B^+ \to \mu^+\nu_\mu$ mode
- SM branching fraction of $\mathcal{O}(10^{-6})$ expected
- measurements performed by Belle: Phys. Rev. D 91, 112009 (2015) gives $\mathcal{B}(B^+ \to \gamma\mu^+\nu_\mu) < 3.4 \times 10^{-6}$
- $B^+ \to \gamma\mu^+\nu_\mu$ at LHCb ?
  - μ reconstruction very good
  - but B vertex not further constrained from $\gamma \to$ hard to reconstruct neutrals

$B^+ \to \mu^+\mu^-\mu^+\nu_\mu$

- here photon decays into pair of muons
- very good muon reconstruction
- B vertex well defined from three muon tracks
- gets contributions from $B^+ \to (\gamma* \to \mu^+\mu^-)\mu^+\nu_\mu$ and $B^+ \to (V \to \mu^+\mu^-)\mu^+\nu_\mu$, where V is a vector meson decaying into two muons (ρ, ω)





- recent theoretical calculation based on vector meson dominance predicts $\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) \approx 1.3x10^{-7}$ [Phys. Atom. Nucl. 81 (2018) 34]

$\to$ decay has been never observed before

Analysis Strategy for $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ ★ NEW

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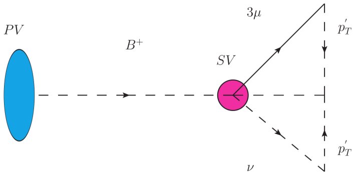
- **dataset**: full Run I (2011+2012) and 2016 $\to$ 4.7 fb^{-1} pp data
- performed blinded analysis
- normalize branching fraction to $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
- reconstruct B meson using **corrected mass** variable:
  $m_{B_{corr}} = \sqrt{m_{3\mu}^2 + p_T'^2} + p_T'$
  with $m_{3\mu}$ is invariant mass of 3 muons,
  p_T' missing momentum transverse to flight direction of B candidate



Selection

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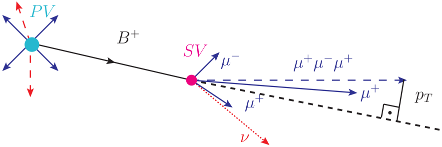
Topology of decay



- select 3 good quality muon tracks originating from the same vertex
- vertex needs to be displaced from primary vertex (PV)
- good trimuon vertex
- B^+ direction points in the same direction as the line from PV to SV
- require that at most one muon station hit is allowed to be shared between the muon candidates

Selection

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Choice of q^2 region

- Two combinations of invariant mass squared are possible with two opposite sign muons
- restrict search into region with $\min(q(\mu^+, \mu^-)) < 960\,\mathrm{MeV}/c^2$
- reduces combinatorial background
- expected signal yield outside of region is minimal
- remove backgrounds from J/ψ and $\psi(2S)$ decays using mass vetos

MC simulation $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ decay

- nominal model: photon pole for one of the muon pair and flat mass distribution for third muon and neutrino
- phase space model for systematic checks
- vector meson dominance (VMD) model as proposed in [Phys. Atom. Nucl. 81 (2018) 34]

Main Backgrounds

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- *combinatorial background:*
  random combinations of 3 muons passing the selection
  $\rightarrow$ reduce it using a region around B mass of [4000-7000 MeV/c^2]
  $\rightarrow$ train **dedicated BDT** to remove it: rejects 99% of combinatorics while 40% efficient on signal

- *Partially reconstructed background:*
  3 muons are correctly identified but additional particles not reconstructed e.g.
  $B^+ \rightarrow D^0(K^+\pi^-\mu^+\mu^-)\mu^+\nu X$
  $\rightarrow$ controlled using simulation

- *other exclusive backgrounds:*
  - $B^+ \rightarrow \pi^+\mu^+\mu^-$ low BF and low misID probability for pion $\rightarrow$ negligible
  - $B^+ \rightarrow K^+\mu^+\mu^-$ corrected mass far away from signal region $\rightarrow$ negligible

MisID background

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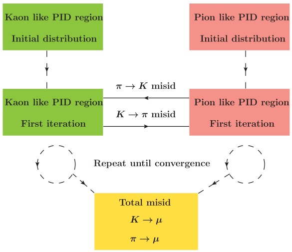
- K, π or p misidentified as muon e.g. cascade decays $B \to D(\to K\mu\nu)\mu\nu$
- estimated from **control sample** in data $\mu\mu hX$:
  - determine different misID rates by splitting into separate 3 PID regions
  - calculate cross feed between them
- probability of K and π passing μ-PID requirements from $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ calibration sample
- misID bkg from protons can be neglected



$\to$ train **dedicated BDT** to remove it:
rejects 94% of misID while 40% efficient on signal

Normalisation to $B^+ \to \mathrm{J}/\psi K^+$

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$$\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) = \mathcal{B}(B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)K^+) \times \frac{\varepsilon(B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)K^+)}{\varepsilon(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)} \times \frac{N(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)}{N(B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)K^+)}$$

- use external $\mathcal{B}(B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)K^+)$ measurement from PDG
- take most efficiencies from MC, PID efficiencies from control data samples:

  $$\frac{\varepsilon(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)}{\varepsilon(B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)K^+)} = 0.37 \pm 0.003$$

  caused by lower dimuon mass and tighter PID requirements
- keep selection as similar as possible to cancel systematic uncertainty of efficiency ratio

Normalisation Fit

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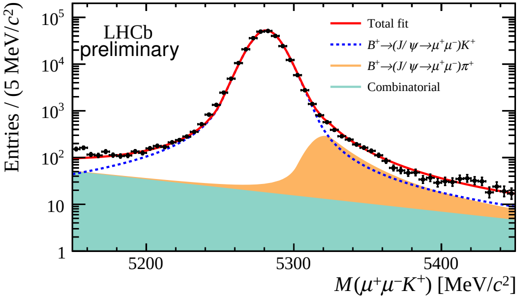

- perform unbinned maximum likelihood fit to $M(\mu^+\mu^-K^+)$
- $\boldsymbol{B^+ \to J/\psi K^+}$: Ipatia function with non-Gaussian tails
- **misID bkg** $B^+ \to J/\psi\pi^+$: Gaussian core with power law tails
- **combinatorial bkg**: exponential function

$\to$ gives $\approx 300k$ $B^+ \to J/\psi K^+$ candidates with 98% purity

Signal Templates

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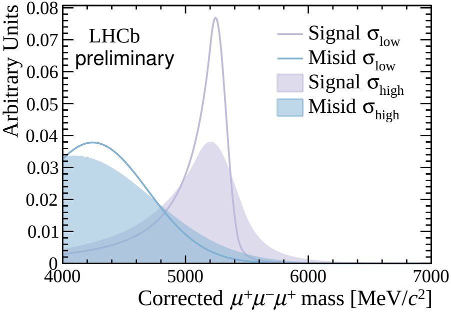
- to improve sensitivity an event-by-event uncertainty on the corrected mass is calculated by propagating the uncertainties of the PV and SV
- data is split into two equally-sized regions with **high and low fractional corrected mass uncertainty**
  $\rightarrow$ improves the branching fraction sensitivity by 11% due to the different signal distribution in the two samples



Signal Fit

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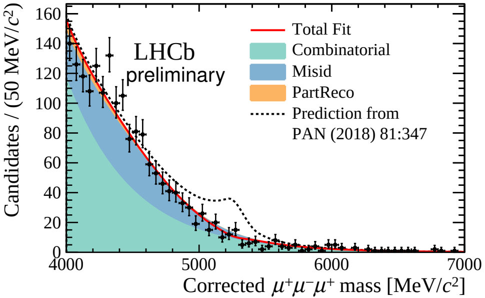

- **signal**: sum of two Gaussian with different power law tails
- **Combinatorial**: exponential function, free slope
- **Misid bkg**: from $\mu^+\mu^- hX$ control sample, shape and yield fitted with Gaussian, power law tail at high corrected mass
- **PartReco**: shape and yield from simulation

- unbinned maximum likelihood fit is performed to the corrected mass
- **signal yield** is slightly negative
  $\rightarrow$ total fit component slightly below sum of the backgrounds
- dashed line shows theoretical prediction of $\mathcal{B}(B^+ \rightarrow \mu^+\mu^-\mu^+\nu_\mu) \approx 1.3x10^{-7}$ [Phys. Atom. Nucl. 81 (2018) 34]

Limit Setting

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- **No significant signal** component, set a limit of 1.4×10^{-8} at 95% confidence level using the CLs method
  (preliminary)
- CLs method uses knowledge that true branching fraction has to be non-negative
- From pseudo-experiments **expected sensitivity** is found to be 2.8×10^{-8}

  $\rightarrow$ present result represents a downward fluctuation $< 2\sigma$

Systematic Uncertainties

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Source	Relative uncertainty [%]
Choice of signal decay model	4.6
Trigger efficiency data/simulation	3.5
Normalisation mode branching fraction	3.0
Kaon interaction probability	2.0
Production kinematics	1.5
Fit bias	1.0
Simulation size	0.8
Total	**7.1**

- **largest systematic** uncertainty due to decay model for the signal channel: replace nominal with phase space model
- **trigger systematic** due to difference between MC and data, evaluated using $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ $\to$ conservative estimate, doesn't take expected cancellation in ratio into account
- difference of modelling of the B^+ production kinematics between signal and normalisation calculated using weights

$\to$ systematic uncertainties added as Gaussian constraints when calculating the limit
$\to$ assumed to be fully correlated between bins of fractional corrected mass error

Conclusion

- Search performed for the rare decay $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ using 4.7 fb^{-1} of proton-proton collision data collected by the LHCb experiment
- No signal is observed for the $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ decay
- Upper limit of $\boldsymbol{\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) < 1.4 \times 10^{-8}}$ at 95% CL is set (preliminary)
- The limit on the branching fraction does not agree with a recent theoretical calculation based on the vector dominance model of $\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) \approx 1.3x10^{-7}$ [Phys. Atom. Nucl. 81 (2018) 34]
- Prospects:
  Statistically limited search, sensitivity scales with $\sqrt{\mathcal{L}}$
  $\to$ either observe decay very soon or set much better limits in Upgrade

$\to$ **Stay tuned!**

Thanks for your attention!

Backup Slides

Main Backgrounds

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combinatorial background:

- random combinations of 3 muons passing the selection
- don't come from same decay chain
  $\rightarrow$ reduce it using a region around B mass of [4000-7000 MeV/c^2]

- train **dedicated BDT** to remove it:
  - trained on signal MC and upper mass sideband $m_{B_{corr}} > 5500\,\mathrm{MeV}/c^2$ data as bkg
  - contains kinematic and geometric properties of B^+ candidate and muon tracks, also multiplicity of event
  - most discriminating variables: isolation of decay vertex, quality of B vertex and muon IPs wrt. PV
  - BDT response optimised by maximising Punzi FOM: $\frac{\epsilon_S}{\sqrt{B}+3/2}$
  - rejects 99% of combinatorics while 40% efficient on signal

MisID background

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- misID background: kaon, pion or proton misidentified as muon
  e.g. cascade decays $B \to D(\to K\mu\nu)\mu\nu$
- estimated from **control sample** in data
  - same selection except reversal of muonID requirement for one track
    $\to$ selects sample of $\mu\mu hX$ candidates in data, with h any hadron
    $\to$ mixture of cascade decays $B \to D(\to h\mu\nu X)\mu\nu$ and combinatorial bkg
  - muon misID rate different for kaon and muon $\to$ hadron species must be determined
  - done by isolating the hadrons into separate hadron PID regions and then take into account cross-feed between the regions:
    $\to$ split $\mu\mu hX$ sample into 3 separate hadron PID regions consistent with the kaon, pion and proton hypotheses
  - Probabilities of identifying the hadrons with a given PID requirement as a fct of p and η of the particle taken from dedicated control samples
- probability of kaon and pion passing muon PID requirements calculated from $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ decays as a calibration sample
- misID bkg from protons can be neglected

$\to$ train **dedicated neural-network** based PID selection to remove it:

- trained on signal MC and $\mu\mu hX$ background in data
- rejects 94% of combinatorics while 40% efficient on signal

Normalisation Fit

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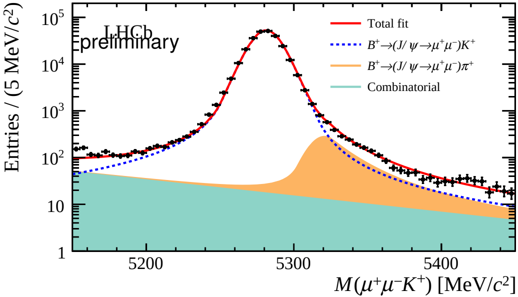

- perform unbinned maximum likelihood fit to $M(\mu^+\mu^-K^+)$
- $\boldsymbol{B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)K^+}$ described by Ipatia function with non-Gaussian tails on both sides, mean and width allowed to vary, all others fixed from simulation
- **misID bkg** $B^+ \to \mathrm{J}/\psi(\to \mu^+\mu^-)\pi^+$ modelled with Gaussian core with power law tails on each side, freely varying mean and with, tail parameters fixed from simulation
- **combinatorial bkg** modelled using exponential function, decay constant allowed to vary in fit

$\to$ gives $\approx 300k$ $B^+ \to \mathrm{J}/\psi K^+$ candidates with 98% purity

Signal Fit

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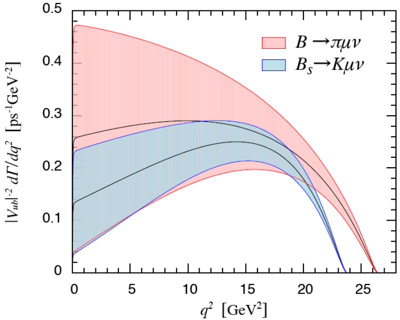
- unbinned maximum likelihood fit is performed to the corrected mass
- **signal shape** is modelled with the sum of two Gaussian functions with different power law tails on each side, determined from simulation
- **combinatorial bkg** modelled using exponential function, slope allowed to vary in fit, parametrisation is verified using simulation
- **Misid bkg** from the $\mu^+\mu^- hX$ control sample, shape and yield fitted with a Gaussian function with a power law tail at high corrected mass
    - parametrisation cross-checked by fitting a sample with looser muonID requirement
    - uncertainties on the associated parameters are propagated to the fit using a multivariate Gaussian constraint
- **partially reconstructed background**: shape and yield taken from simulation.
- Yields are allowed to vary within constraints from a Poisson distribution in the fit

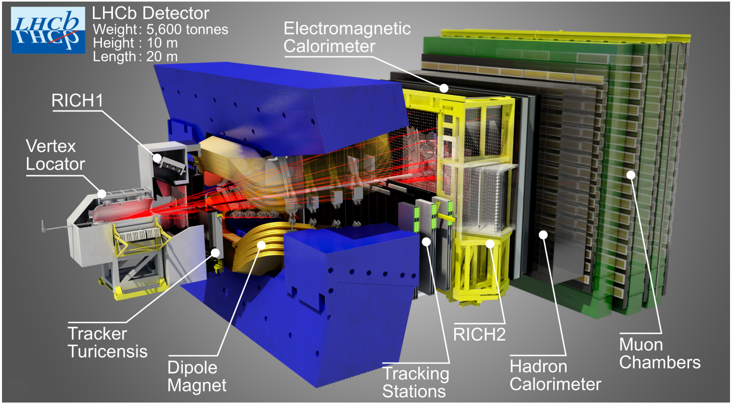
Future plans

- We are working currently on extraction $|V_{ub}|$ exclusively from $B_s^0 \to K^- \mu^+ \nu_\mu$, using normalisation channel of $B_s^0 \to D_s^- \mu^+ \nu_\mu$
- Smaller FF uncertainty expected wrt. $\Lambda_b \to p\mu\nu$: ~3% [Phys. Rev. D 91, 074510 (2015)]
- Production fraction ~10%, smaller compared to Λ_b (~20%)
- More difficult to handle background (Λ_c, D_s, D^+, D^0) w.r.t. Λ_b
- recent results on FFs:
  - from LQCD: Phys. Rev. D 91, 074510 (2015), Phys. Rev. D 90, 054506 (2014) NEW directly on BF ratio: arXiv 1808.09285
  - from LCSR predictions at low q^2: arXiv 1703.04765



LHCb Detector

JINST 3 S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)



- VELO: primary and secondary vertex
- Tracking: momentum of charged particle
- RICHs: particle identification $K^{\pm}$, $\pi^{\pm}$
- MUON: trigger on high p_{T} $\mu^{\pm}$ & PID
- Calorimeter: ECAL and HCAL for γ, $e^{\pm}$ and hadronic energy