Challenges in Semileptonic B decays

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Prospects for exclusive measurements of $|V_{ub}|$ at LHCb

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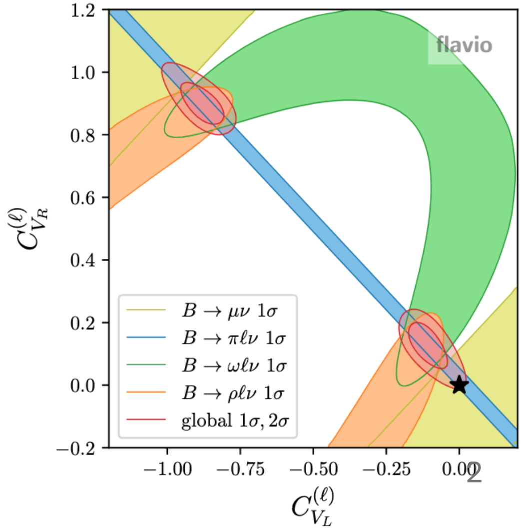
On behalf of the LHCb Collaboration

Introduction

- $b \rightarrow u l \nu$ transitions can serve as a playground for probing EW and strong interactions and to measure the CKM element $|V_{ub}|$.
- Exclusive decays are the best target for LHCb, exploiting large b production at LHC and precise measurement of decay products in the detector.
- Interplay between inclusive and exclusive measurements from different channels can help to best constrain $|V_{ub}|$ value.

- This talk focus: studies on $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ and $B^+ \rightarrow \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$

- Additional interest in $b \rightarrow u l \nu$ transitions for SM tests and searches for New Physics effects, eg. in SMEF analysis (JHEP11(2023)023, JHEP08(2023)063 and others)
    - Future analysis on angular distributions or with $l=\tau$ will also provide valuable inputs.



JHEP11(2023)023

Semileptonic decay reconstruction at LHCb

- B momentum reconstruction in semileptonic decays challenging at LHCb
  - Main production from gluons at LHC → large variation of B momenta
  - LHCb forward acceptance → partial coverage of the complete $b\bar{b}$ event .

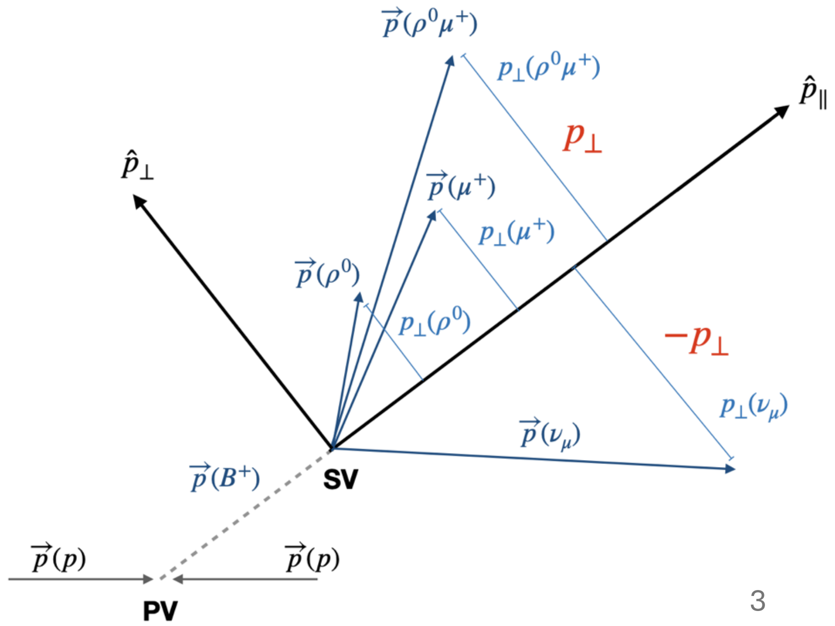
- Using PV to SV direction as B flight direction we get $p_\perp(\nu) = -p_\perp(\text{vis})$
- Adding B mass constraint can solve E-conservation equations with a 2-fold ambiguity
  - Use regression algorithm to pick-up the best solution

[JHEP02(2017)021] and evaluate q^2

$$q^2 = (P_\mu + P_\nu)^2$$

- Use corrected mass as discriminating variable

$$m_{\text{corr}}(B^+) = \sqrt{m_{\text{vis}}^2 + p_\perp^2} + p_\perp$$

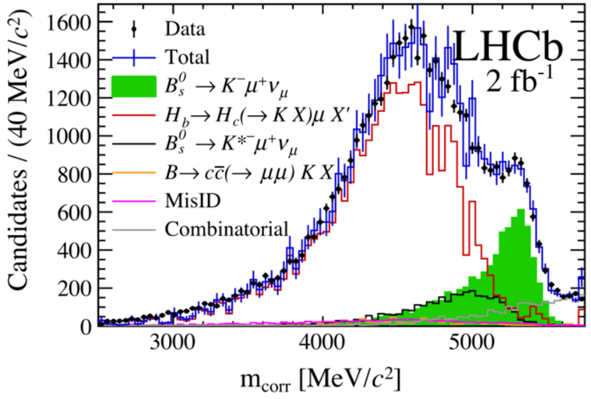


$B^0_s \rightarrow K^- \mu^+ \nu_\mu$

$B^0_s \rightarrow K^- \mu^+ \nu_\mu$

PhysRevLett.126.081804

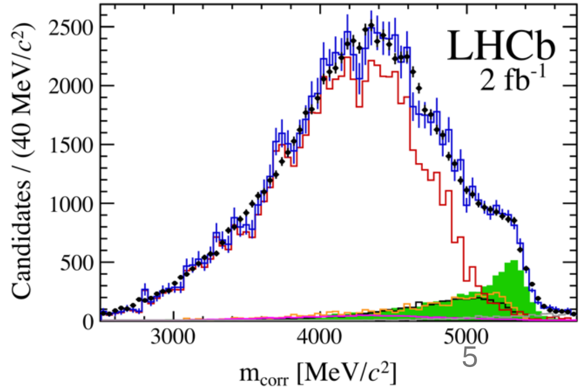
- First observation of the $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ decay performed by LHCb with Run1 data (2fb^{-1})
  PRL126, 081804 (2021)
- $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ yields are normalized to $B^0_s \rightarrow D_s^- \mu^+ \nu_\mu$ and the ratio of branching fractions is measured.



- The signal is split into two q^2 bins ($\gtrless$7 GeV^2/c^4) with similar yields

$$\frac{\mathcal{B}(B^0_s \rightarrow K^- \mu^+ \nu_\mu)_{low\ q^2}}{\mathcal{B}(B^0_s \rightarrow D_s^- \mu^+ \nu_\mu)_{full\ q^2}} = (1.66 \pm 0.08(stat) \pm 0.07(syst) \pm 0.05(D_s)) \times 10^{-3}$$

$$\frac{\mathcal{B}(B^0_s \rightarrow K^- \mu^+ \nu_\mu)_{high\ q^2}}{\mathcal{B}(B^0_s \rightarrow D_s^- \mu^+ \nu_\mu)_{full\ q^2}} = (3.25 \pm 0.21(stat)^{+0.16}_{-0.17}(syst) \pm 0.09(D_s)) \times 10^{-3}$$



$|V_{ub}|/|V_{cb}|$ from $B^0_s \rightarrow K^- \mu^+ \nu_\mu$

PhysRevLett.126.081804

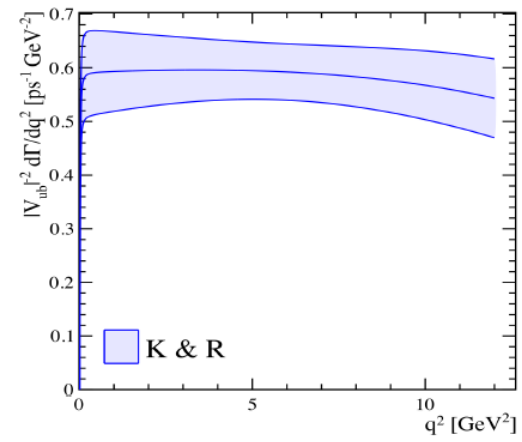
- The ratio is determined from the relation $|V_{ub}|^2/|V_{cb}|^2 = \mathcal{R}_{\mathcal{B}}\mathcal{R}_{FF}$

  where $\mathcal{R}_{\mathcal{B}}$ is the ratio of branching ratios and $\mathcal{R}_{FF}$ the ratio of theoretical decay rates, dependent on form factors, integrated in the appropriate q^2 range.

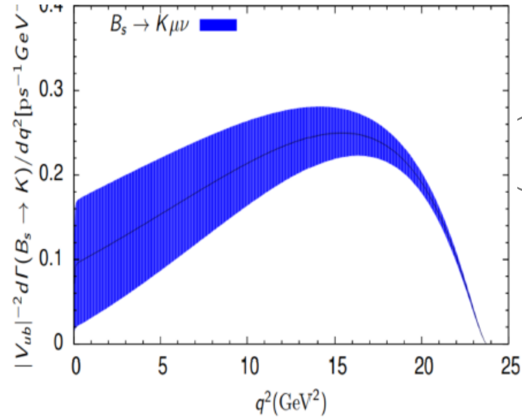
- For $b \rightarrow K$ two different form factors calculations are used, according to their range of best accuracy, LCSR at low q^2 [PRD 100(2019)034501], LQCD at high q^2 [PRD 100(2019)034501]
- For $b \rightarrow D_s$ LQCD FF is used [PRD 101(2020)074513].

$$|V_{ub}|/|V_{cb}|(low\ q^2) = 0.0607 \pm 0.0015(stat) \pm 0.0013(syst) \pm 0.0008(D_s) \pm 0.0030(FF)$$

$$|V_{ub}|/|V_{cb}|(high\ q^2) = 0.0946 \pm 0.0030(stat)^{+0.0024}_{-0.0025}(syst) \pm 0.0013(D_s) \pm 0.0068(FF)$$



JHEP08(2017)112



PRD 100(2019)034501

- Contribution to systematic uncertainty from normalization mode is from 2.8% uncertainty on $\mathcal{B}(D_s \rightarrow KK\pi)$ and 4% from the D_s FF.

- $\mathcal{B}(B_s \rightarrow D_s\mu\nu)$, not used since measured by LHCb with the same data, has a 9.4% uncertainty.

$B^0_s \to K^- \mu^+ \nu_\mu$ systematic unc.

PhysRevLett.126.081804

TABLE I. Relative systematic uncertainties on the ratio $\mathcal{B}(B^0_s \to K^- \mu^+ \nu_\mu)/\mathcal{B}(B^0_s \to D^-_s \mu^+ \nu_\mu)$, in percent.

Uncertainty	All q^2	Low q^2	High q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\text{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	...	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$

Tracking: Hadronic interaction of extra K,π in $D_s \to KK\pi$

q^2 migration: No q^2 unfolding

Fit template: Include background shape, and FF variation in the simulation

- Systematic uncertainties can be reduced with larger datasets and simulation

$B^0_s \to K^- \mu^+ \nu_\mu$ with Run2 data

- New $B^0_s \to K^- \mu^+ \nu_\mu$ analysis with Run2 data ongoing. Use 2016-18 data at $\sqrt{s}$=13 TeV.
- Aim at a measurement of $|V_{ub}|$ independent on $|V_{cb}|$.
- Exploits larger data set (~5x) of data to perform a binned measurement of the branching ratio, in O(10) q^2 bins
- The branching ratio is normalized with a well-known decay mode, chosen as $B^- \to J/\psi(\mu^+\mu^-)K^-$

$$\Delta\mathcal{B}_i = \frac{N_{sig,i}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig,i}} \frac{f_u}{f_s} \mathcal{B}_{norm}$$

$N_{sig,i}$ signal yield in the q^2 bin

N_{norm} normalization yield in the full q^2 range

$\frac{\epsilon_{norm}}{\epsilon_{sig,i}}$ ratio of efficiencies

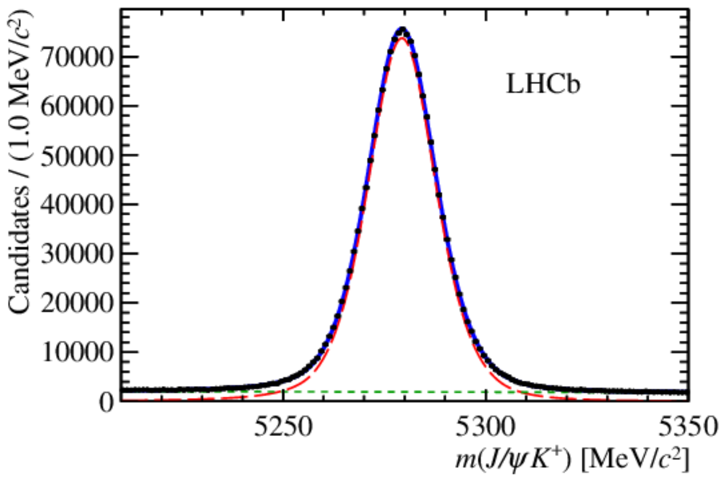
$\frac{f_u}{f_s}$ ratio of B^+ to B^0_s production fractions

$\mathcal{B}_{norm}$ normalization branching ratio

- Signal yields determined from a template fit simultaneous on all q^2 bins.
- q^2 unfolding to obtain signal yields in true bins

$B^0_s \to K^- \mu^+ \nu_\mu$ Normalization

Chosen normalisation mode is $B^- \to J/\psi(\mu^+\mu^-)K^-$



Eur. Phys. J. C 79,8(2019)706

- Very clean and large sample
  - small additional statistical uncertainty
- Same number of tracks and similar topology to signal when one muon is neglected.
  - reduced systematic uncertainty on efficiencies ratio

- Ratio of B_s to B^+ production fractions precisely measured by LHCb [PRD 104, 032005 (2021)] $f_s/f_d = 0.2539 \pm 0.0079$ at 13 TeV
- External systematic uncertainty from normalization will be slightly smaller than in Run1 measurement
  - 1.9% from $\mathcal{B}(B^- \to J/\psi(\mu^+\mu^-)K^-)$, 3.1% from f_s/f_u

$B^0_s \to K^- \mu^+ \nu_\mu$ Background

- Background from physics processes: shape modelled with simulation.

- Main sources are $b \to c$ decays like $H_b \to (H_c \to K^- X)\mu^+\nu_\mu X'$ and $H_b \to c\bar{c}(\mu^+\mu^-)K^- X$ (concentrated in few q^2 bins).
  - Suppressed with multivariate classifier with kinematical and topological variables, trained on simulation.

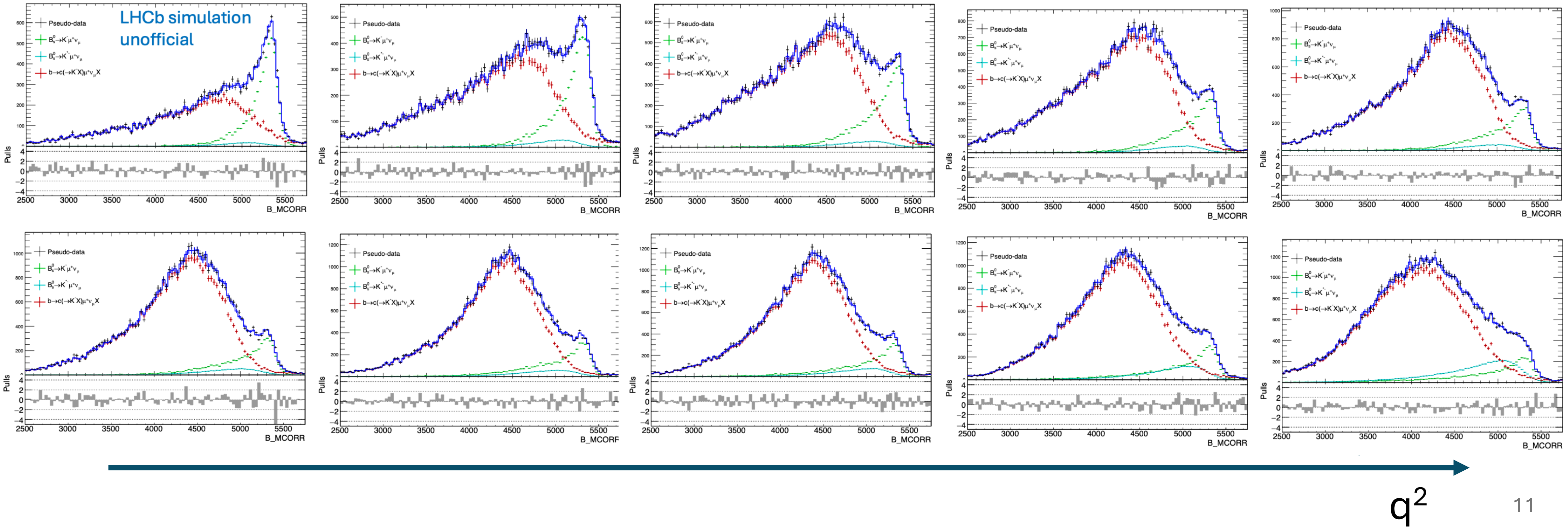
- Contributions from $B^0_s \to (K^{*-} \to K^- \pi^0)\mu^+\nu_\mu$ with $K^*(892)$, $K^*_0(1430)$, $K^*_2(1430)$ with unreconstructed π^0
  - Unmeasured branching fractions
  - Poor knowledge of the expected q^2 shape, additional input would be useful
  - Some separation from signal due to the missing particle
  - Partially suppressed with neutral isolation criteria

- Smaller contributions from random $K^-\mu^+$ combinations and semileptonic decays with mis-identified K^-.
  - Suppressed with multivariate classifier trained on $K^\pm\mu^\pm$ data and PID cuts. Shape modelled with data-driven methods.

$B^0_s \to K^- \mu^+ \nu_\mu$ signal fit

- Maximum-likelihood fit in HistFactory framework.
- Simultaneous in O(10) q^2 bins and three data-taking years. Bins optimization not final.

Toy MonteCarlo with signal and two physics background contributions



Prospects on $|V_{ub}|$ and FF determination in $B^0_s \to K^- \mu^+ \nu_\mu$

- Several FF scheme available to describe signal shape in simulation. Examples:
  - LCSR JHEP 08(2017)112
  - HPQCD 2014 PRD 90(2014)054506
  - RBC/UKQCD PRD 91(2015)074510
  - FNAL/MILC PRD 100(2019)034501

  } Average of 3 LQCD results by FLAG21(Feb 23). BCL extrapolation.
  - RBC/UKQCD update PRD 107 2023)114512 superseeding their previous results, with BGL.
  - Bayesian inference JHEP 12 (2023) 175 with BGL
  - LCSR&LQD combination arXiv:2308.04347, with modified BGL

- Baseline FF to be used not defined yet (FLAG24 average?)
  - Could provide results with different options.
  - Dependence of fitted signal yields on FF reduced using high number of bins (small variation of m_{cor} distribution inside the bin).
  - Dependence of signal efficiency per bin on FF to be detrmined.

- Same FF scheme will be used to fit $\frac{d\mathcal{B}}{dq^2}$ distribution and determine $|V_{ub}|$ via

$$\frac{d\mathcal{B}}{dq^2} = \frac{d\Gamma^0_{sig}}{dq^2} \, |V_{ub}|^2 \, \tau_B$$

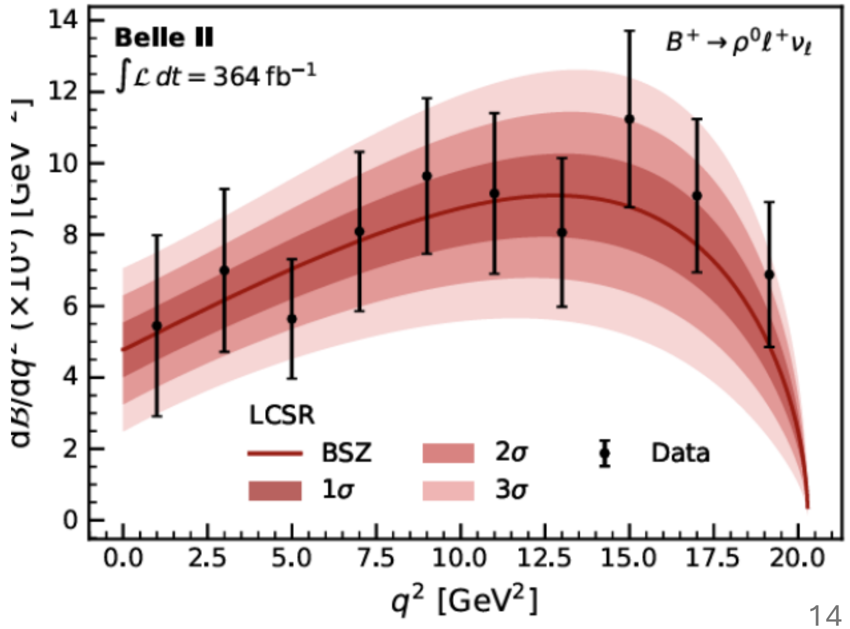
$B^{+} \rightarrow \rho^{0}(\pi^{+}\pi^{-})\mu^{+}\nu_{\mu}$

$B^+ \rightarrow \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$ Introduction

- Branching ratio measured at BFactories. Large discrepancy between BaBar and Belle measurements.
- Preliminary Belle II measurement consistent with Belle.
- A new, precise measurement from LHCb will help to solve the tension.

- The large sample of LHCb data will allow a precise determination of the differential decay rate and a fit to $|V_{ub}|$

Experiment	Branching Ratio (10^{-4})	Stat. (10^{-4})	Syst. (10^{-4})
BaBar [1]	1.00	0.10	0.17
Belle [2]	1.83	0.10	0.10
Belle II 364 fb^{-1} preliminary [3]	1.625	0.079	0.18

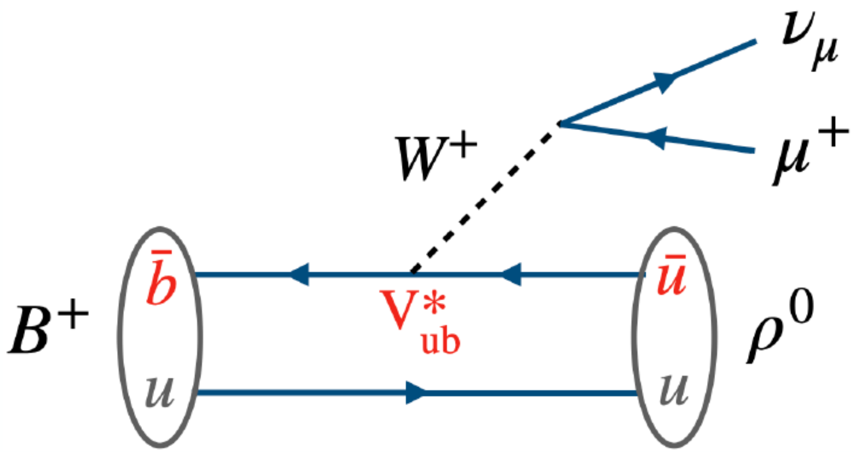


arXiv:2407.17403

1. arXiv:1005.3288/Phys.Rev.D83, 032007
2. arXiv:1306.2781/Phys.Rev.D88, 032005
3. arXiv:2407.17403

$B^+ \to \rho^0 \mu^+ \nu_\mu$ measurement at LHCb

- Goal: measure the differential branching fraction in bins of q^2 and extract the FF
- The ρ^0 decay exclusively via $\rho^0 \to \pi^+\pi^-$
- The branching fraction is measured relative to a normalization decay mode chosen as $B^+ \to \overline{D}^0(\pi^+\pi^-)\mu^+\nu_\mu$



$$\left(\frac{\Delta\mathcal{B}}{\Delta q^2}\right)_i = \frac{N_{sig,i}}{q^2_{max,i} - q^2_{min,i}} \frac{\mathcal{B}_{norm}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig,i}}$$

$N_{sig,i}$ signal yield in the q^2 bin

N_{norm} normalization yield in the full q^2 range

$\frac{\epsilon_{norm}}{\epsilon_{sig,i}}$ ratio of efficiencies

$\mathcal{B}_{norm}$ normalization branching ratio

$B^+ \rightarrow \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$ Normalization

- Normalization mode chosen as $B^+ \rightarrow \overline{D}^0\mu^+\nu_\mu$, $\overline{D}^0 \rightarrow \pi^+\pi^-$

  $\mathcal{B}(B^+ \rightarrow \overline{D}^0(\pi^+\pi^-)\mu^+\nu_\mu = (3.34 \pm 0.14)\ 10^{-5}$ with a 4.2% relative uncertainty

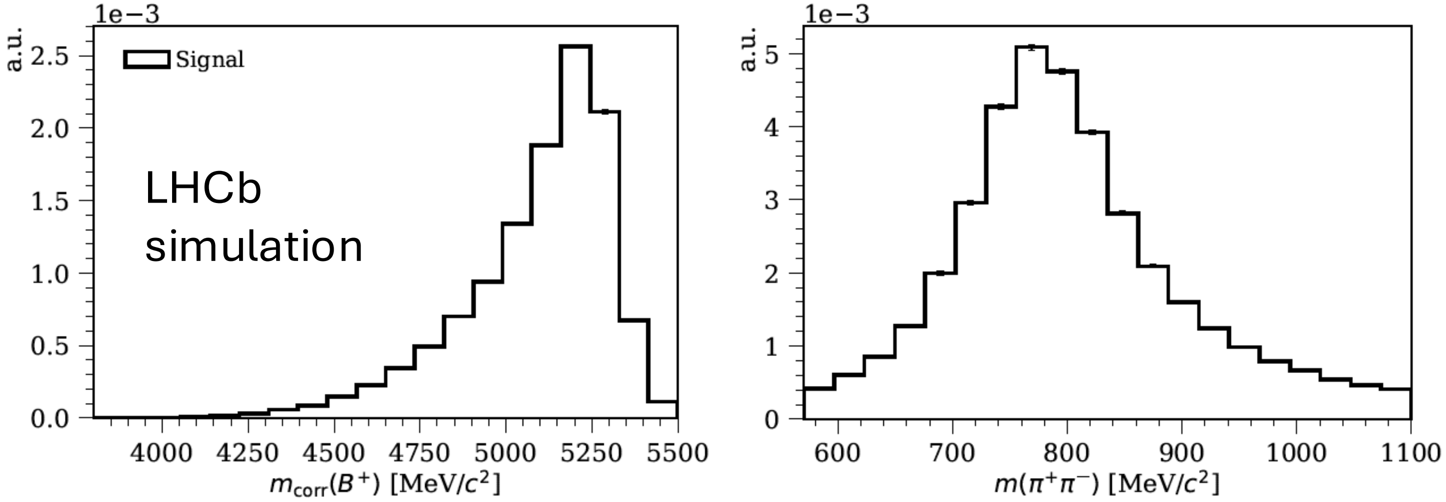
  - Same set of final state tracks to reduce systematic uncertainty in efficiency ratio
- Main physics backgrounds from $B^+ \rightarrow \overline{D}^{*0}\mu^+\nu_\mu$ and $B^0 \rightarrow D^{*-}\mu^+\nu_\mu$ partially reconstructed

- Normalisation yield extracted from a 1D template fit in the full q^2 region.
- Statistical uncertainty from normalization O(3%)

$B^+ \rightarrow \rho^0 (\pi^+\pi^-)\mu^+\nu_\mu$

- Signal yield extracted from a 2D template fit to m_{cor} and $m_{\pi\pi}$ in O(10) non-uniform q^2 bins (approximate same yields).

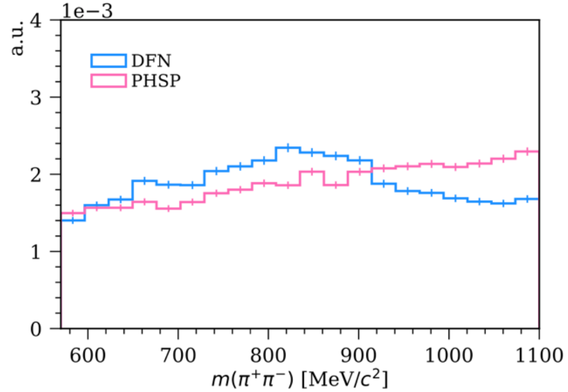
  - two pion mass added as additional discriminating variable against background
- Shapes of m_{cor} and $m_{\pi\pi}$ modelled with templates histograms
- Extended maximum likelihood fit in the HistFactory framework
  - Signal simulated with BCL/BSZ FFs [PRD104,034032 (2021)] and $m_{\pi\pi}$ shape reweighted to include ρ–ω interference



$B^+ \to \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$ Background

- Background from physics processes: modelled with simulation.
  - $B^+ \to D^0(\pi^+\pi^- X^0)\, \mu^+\nu_\mu\, (X)$ with X^0 = one or more neutral particles
  - $B^{+,0} \to X_u \mu^+\nu_\mu$ various charmless semileptonic decays
  - $B^+ \to \pi^+\pi^-\mu^+\nu_\mu$ with non-resonant $\pi^+\pi^-$

    This is the most critical background, having m_{cor} distribution similar to signal and $m_{\pi\pi}$ poorely constrained by external inputs.



$B^+ \to \pi^+\pi^-\mu^+\nu_\mu$ shapes from
DFN/PYTHIA simulation
[JHEP 06 (1999) 017]
Phase-space simulation

- Combinatorial background: modelled with same-sign data.
- MisID background: modelled with data-driven methods.

- Background rejection mainly from multivariate classifiers with isolation variables, trained on simulation.

$B^+ \to \rho^0 \mu^+ \nu_\mu$ $\Delta\mathcal{B}_i$, $|V_{ub}|$ and FF determination

Analysis still blinded. Prospects:

- Expected statistical sensitivity on branching fraction per q^2 bin O(5%-6%), using 2018 data (~ $2fb^{-1}$).
  - Systematic uncertainty O(5%-9%), dominated by uncertainty on $m_{\pi\pi}$ shape of the non-resonant component. External systematic uncertainty 4.2%.
- q^2 unfolding to obtain signal yield in true bins.

- Measurement of $|V_{ub}|$ and FFs from fit to dB/dq^2, following [PRD 104,034032 (2021)]
- Predictions of the FFs $V(q^2)$, $A_1(q^2)$ and $A_{12}(q^2)$ based on light-cone sum rules (LCSR) calculations valid in $q^2 \lesssim 14 GeV^2/c^4$ [PRD 79,013008 (2009)].
- BCL/BSZ parametrisations to extrapolate FFs in the full region [JHEP08,098 (2016)]

Conclusions and outlook

- New measurements of $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ and $B^+ \rightarrow \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$ decays expected from LHCb, with Run2 data.
- Other $b \rightarrow ul\nu$ exclusive analysis on Λ_b and B_c decays under study.
- Run3 data-taking (~9 fb^{-1} expected this year) will provide more data and open the path to improved analyses.
- Input from theory crucial for $|V_{ub}|$ determination.