Searches for $B^+_{(c)} \to \ell^+\ell^-\ell'^+\nu_\ell$ at LHCb

Workshop on radiative leptonic B decays
Marseille
28 February 2024

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Laboratoire de Physique des Hautes Energies

Outlook

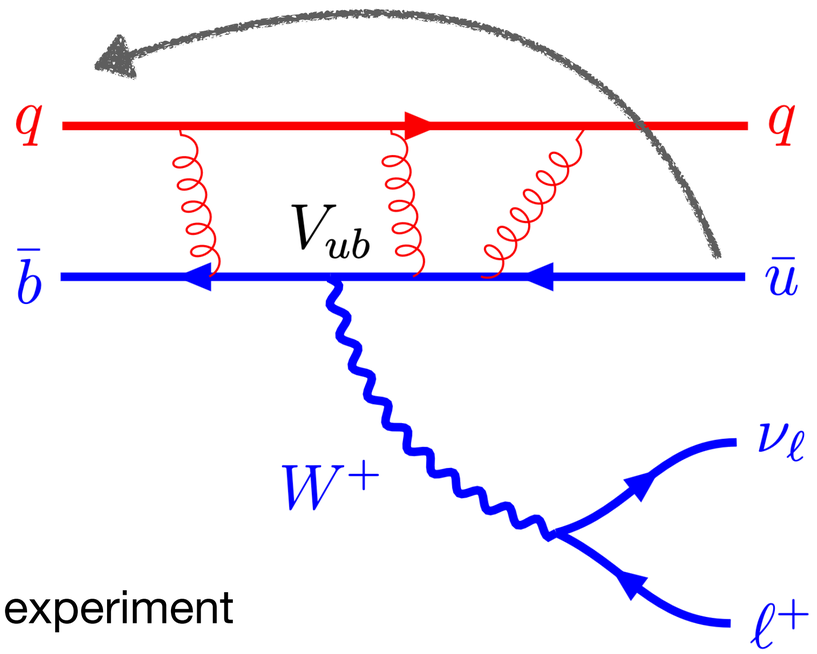
- Motivation for $B^+_{(c)} \to \ell^+\ell^-\ell'^+\nu_\ell$ at LHCb
- $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ published analysis (run 1 + 2016) *Eur.Phys.J.C* 79 (2019) 8, 675
- Updating $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ analysis with run 2
- Sensitivity study of $B^+ \to e^+e^-\mu^+\nu_\mu$
- Conclusion

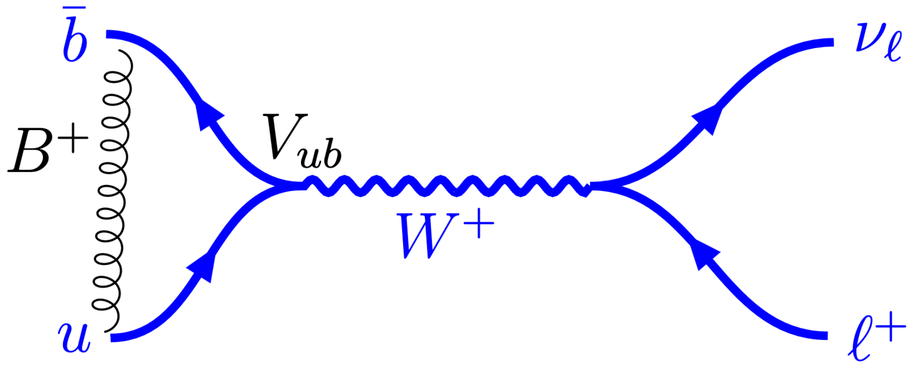
$B^+_{(c)} \to \ell^+\ell^-\ell'^+\nu_\ell$ at LHCb

Motivations

Fully leptonic decays at LHCb

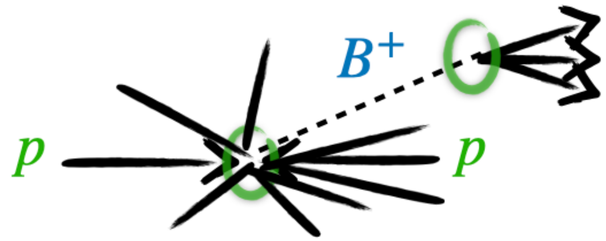
❖ V_{ub} via fully leptonic decays
→ simpler hadronization pattern with only one form factor





❖ LHCb experiment

- ✓ Statistical power thanks to large $\sigma(b\bar{b})$ production
- ✓ Good particle identification and tracking
- ✳ Harsh environment → High track multiplicity
  Rely on displaced B vertex to reduce background to fight noisy environment

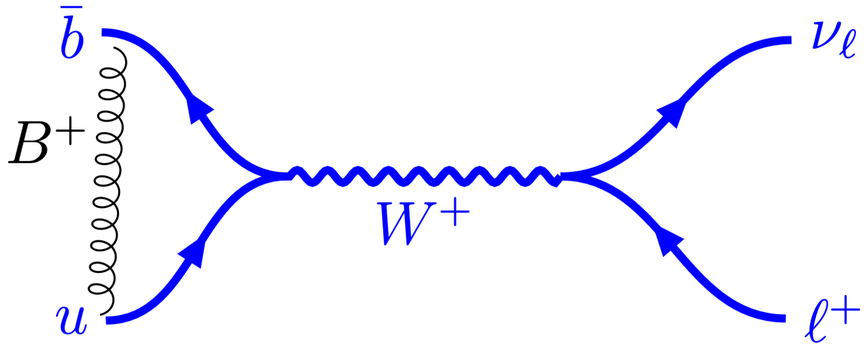


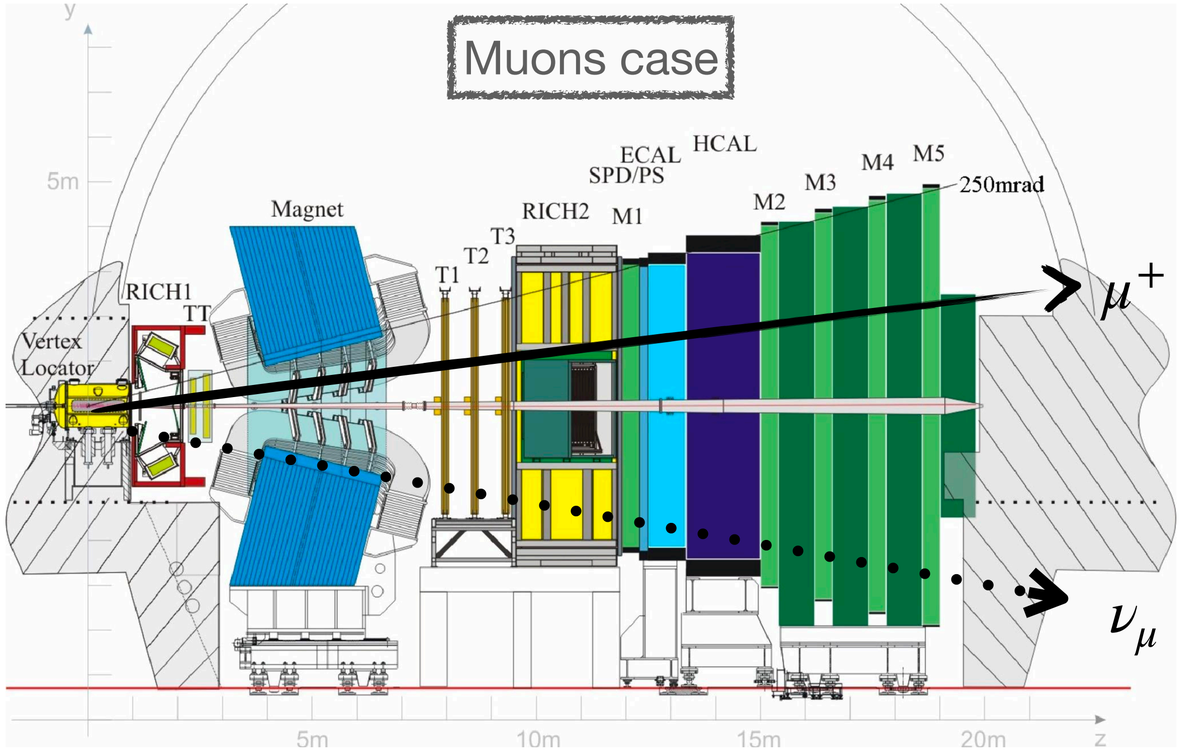
How to use the LHCb experiment ?

❖ One track → very challenging to reconstruct the decay vertex

Helicity suppressed

One track → Challenging





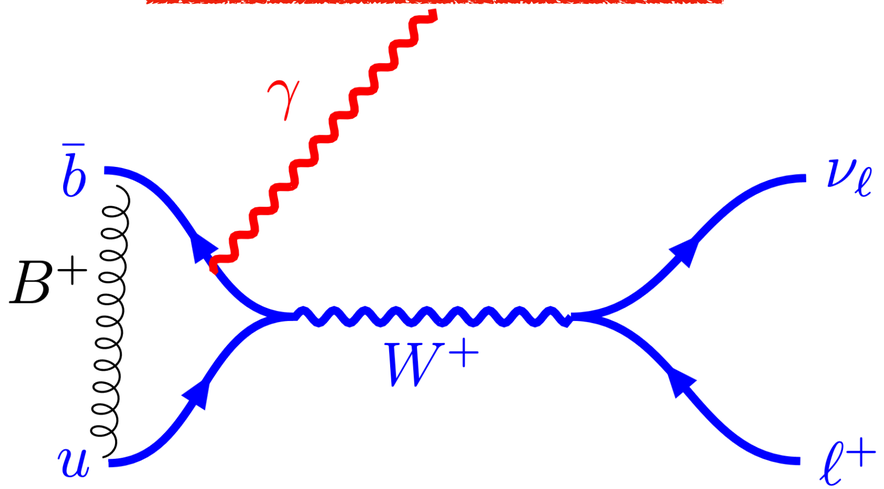
How to use the LHCb experiment ?

- One track → very challenging to reconstruct the decay vertex
- Photon neutral → hard to reconstruct neutral

See previous talk by Fabian Glaser “Prospects for $B_{(c)} \to \mu\nu\gamma$ at LHCb”

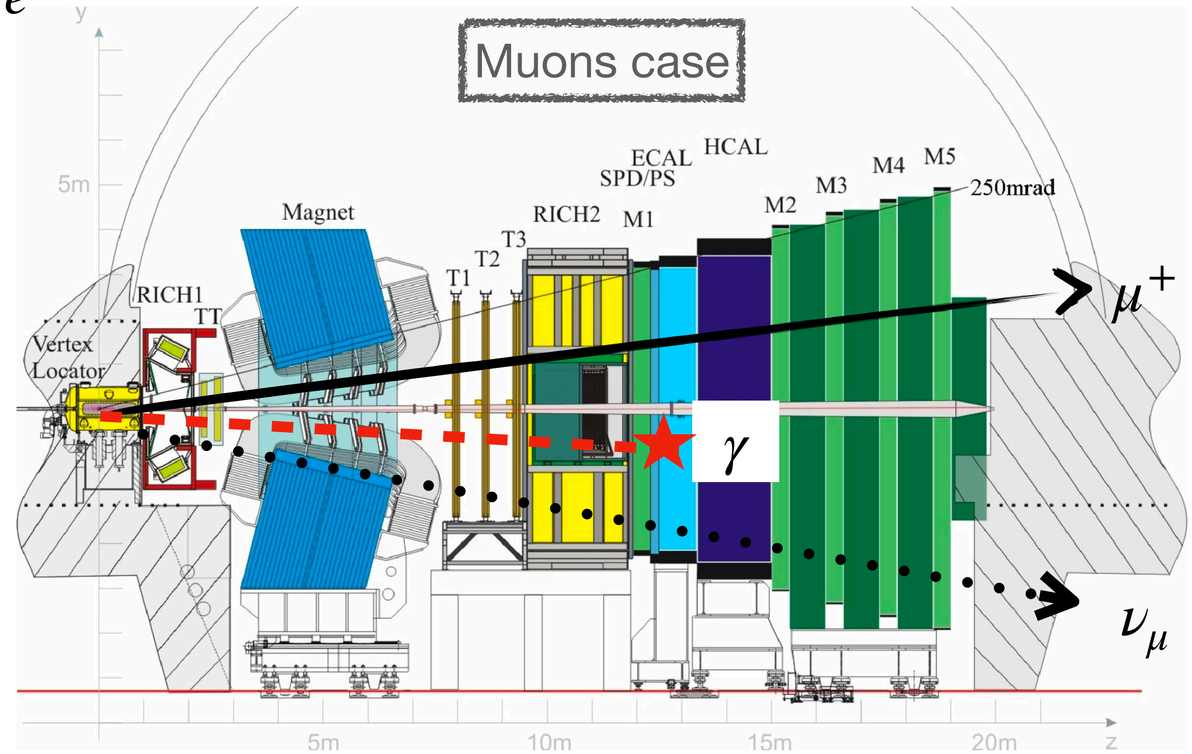
⇒ only use photon interacting with material $\gamma \to e^+e^-$

Photon → hard to handle



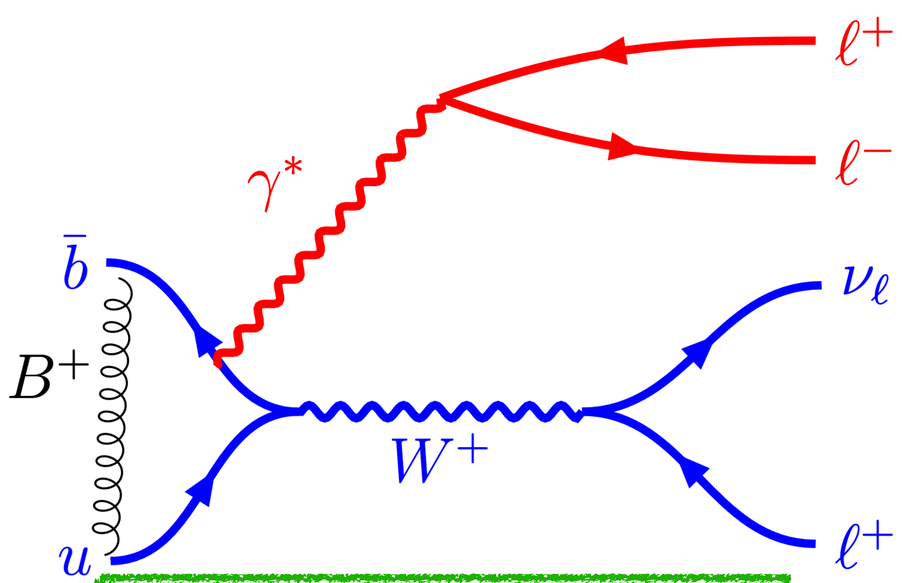
Photon → Helicity suppression lifted

Probing $B \to \gamma$ form factor (LCDA)



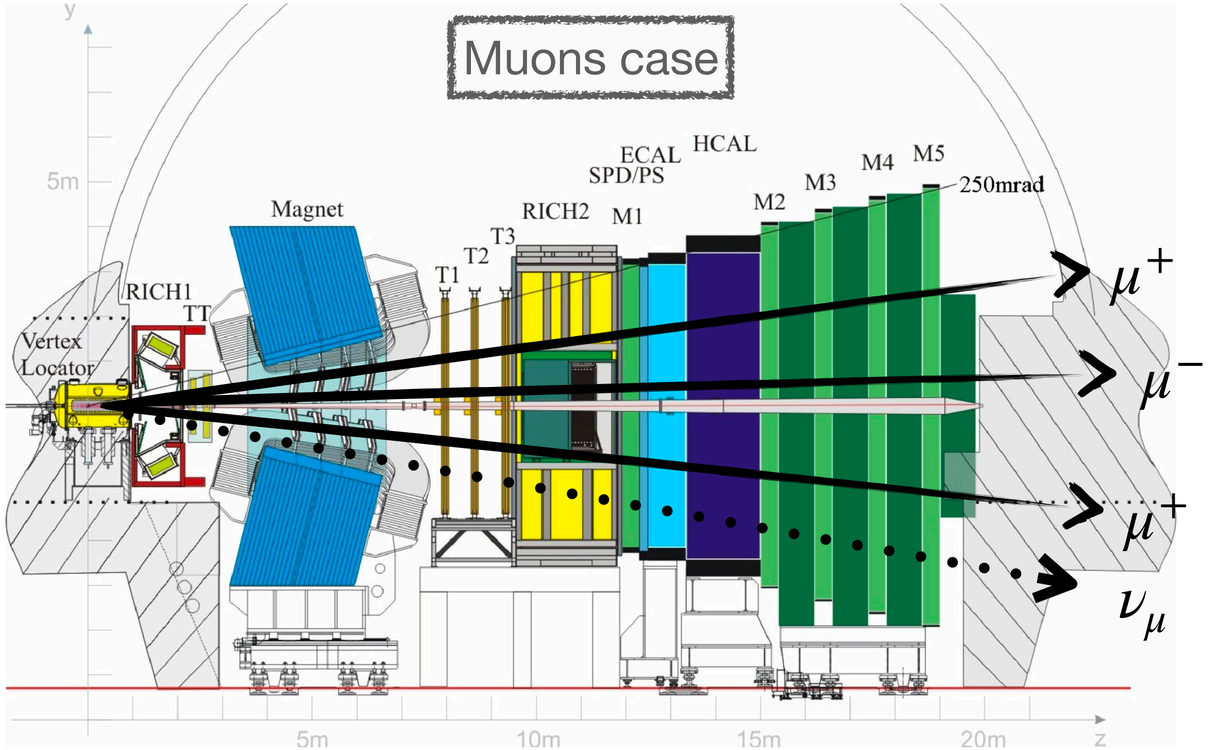
How to use the LHCb experiment ?

- ❖ One track → very challenging to reconstruct the decay vertex
- ❖ Photon neutral → hard to reconstruct neutral
- ❖ Three tracks → Can reconstruct B decay vertex for efficient background rejection



Three tracks → B decay vertex

Probing $B \to \gamma^*$ form factor (LCDA)



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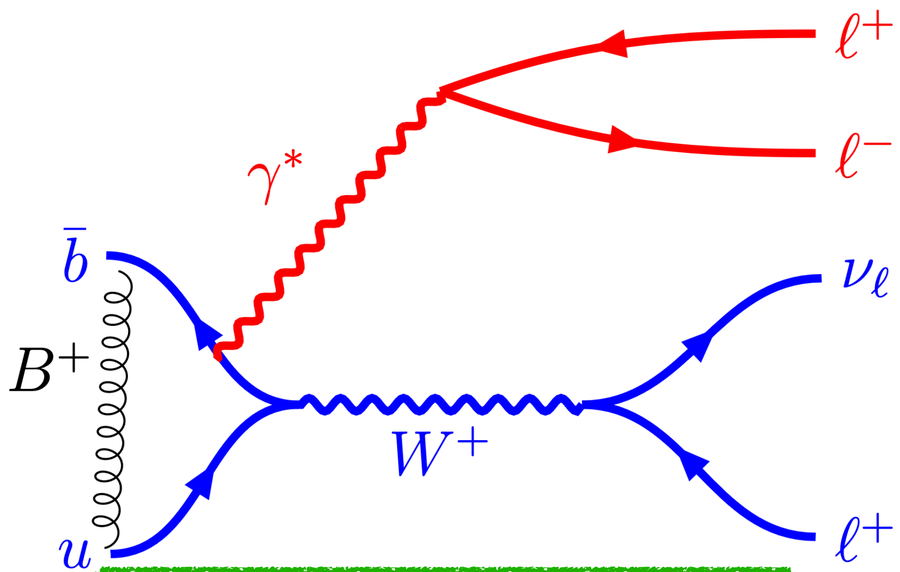

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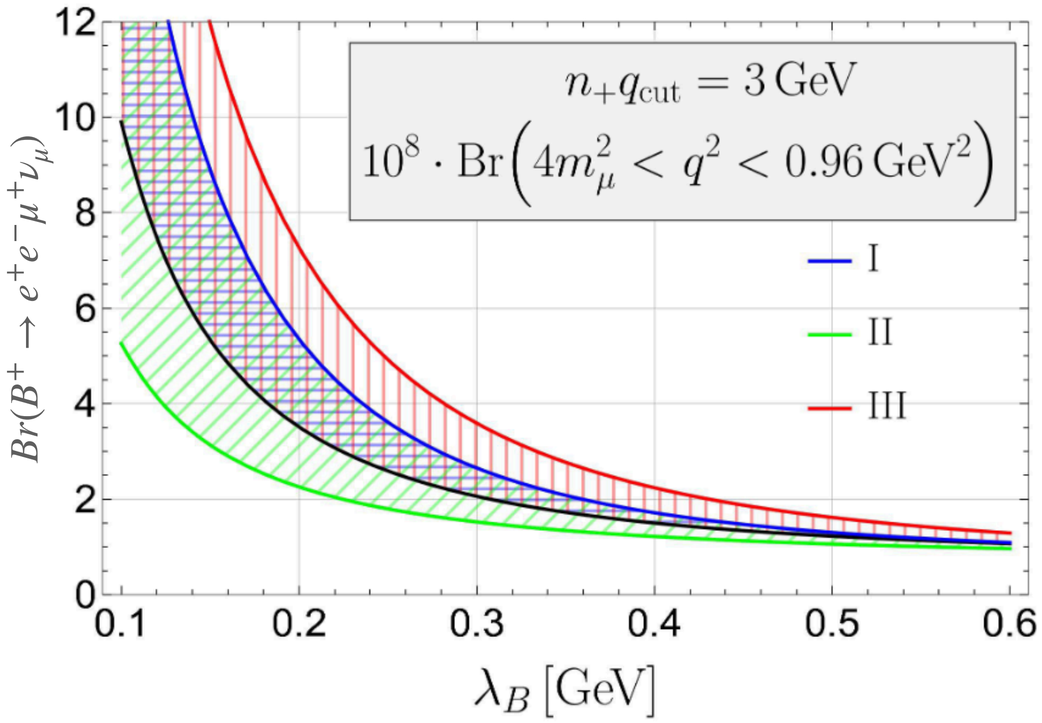
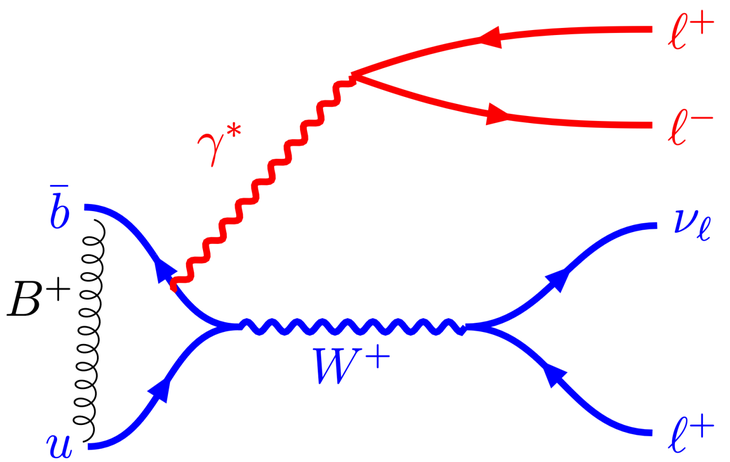
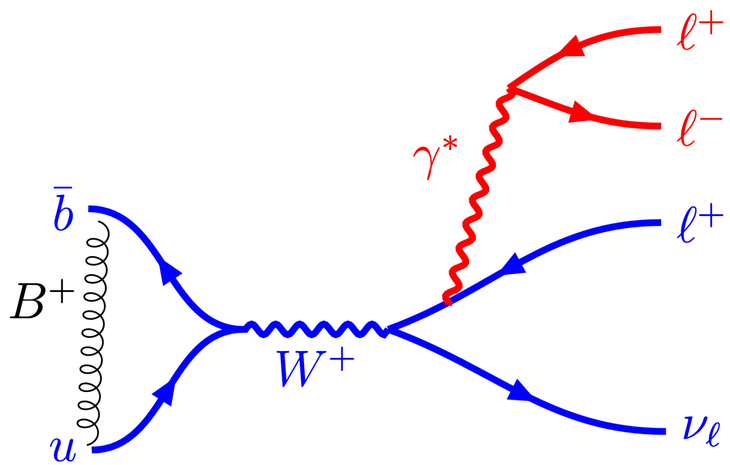


Beneke, Böer, Rigatos, Keri Vos (2021)

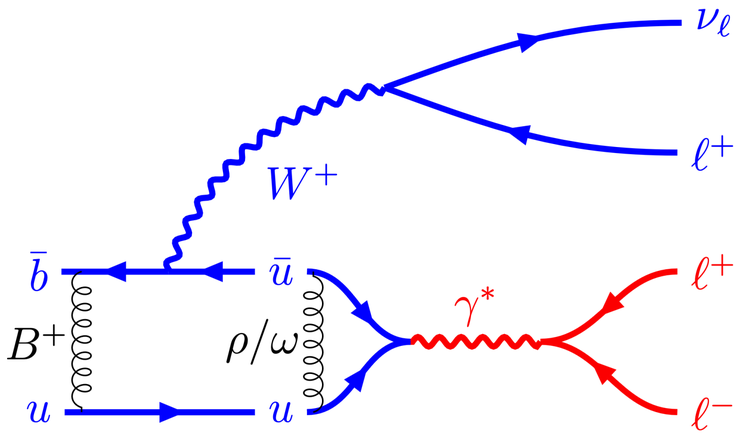
Contribution from photon and vector meson

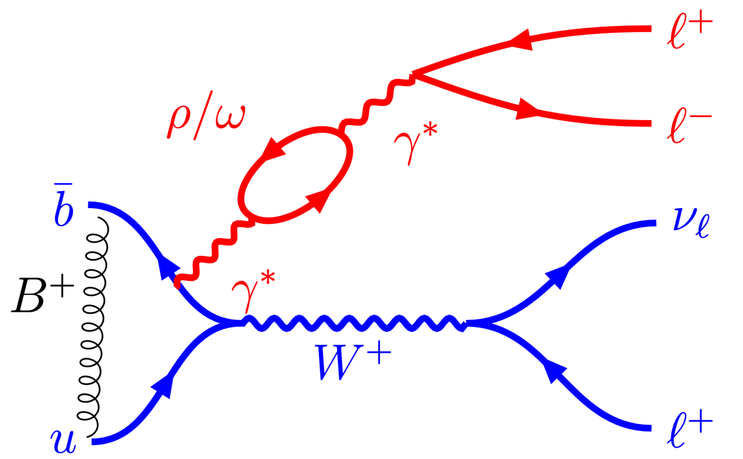
❖ Initial/final state photon





❖ ρ/ω resonance





Current status $B^+_{(c)} \to \ell^+\ell^-\ell'^+\nu_\ell$ of results

	Theory prediction	Experimental measurements
• $Br(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)$	$\approx (3.02^{+0.45}_{-0.25}\vert_{\lambda_B} \pm 0.62\vert_{\text{weak ffs}})10^{-8}$ [1]	$< 1.6 \cdot 10^{-8}$ (95 % CL) [4]
	$\approx (1.54^{+1.34}_{-0.48})\ 10^{-8}$ [2]	
• $Br(B_c^+ \to \ell'^+\ell^-\ell^+\nu_\ell)$	??	??
• $Br(B^+ \to \mu^+\mu^- e^+\nu_e)$	$\approx (3.01^{+0.53}_{-0.19}\vert_{\lambda_B} \pm 0.82\vert_{\text{weak ffs}})10^{-8}$ [1]	??
	$\approx (1.57^{+1.37}_{-0.49})\ 10^{-8}$ [2]	
	$\approx 3.13(42)_N(25)_{V_{ub}} \cdot 10^{-8}$ [3]	
• $Br(B^+ \to e^+e^-\mu^+\nu_\mu)$	$\approx (5.24^{+2.6}_{-1.05}\vert_{\lambda_B} \pm 0.70\vert_{\text{weak ffs}})10^{-8}$ [1]	In progress
	$\approx (2.28^{+2.49}_{-0.86})\ 10^{-8}$ [2]	Sensitivity study from master thesis
	$\approx 3.72(46)_N(30)_{V_{ub}} \cdot 10^{-8}$ [3]	

Getting close

Quite empty

[1] Ivanov, Melikhov (2022) + erratum (2022)
[2] Beneke, Böer, Rigatos, Keri Vos (2021)
(include a cut on n_+q)
[3] Kürten, Zanke, Kubis, van Dyk (2022)
[4] LHCb collaboration (2019)

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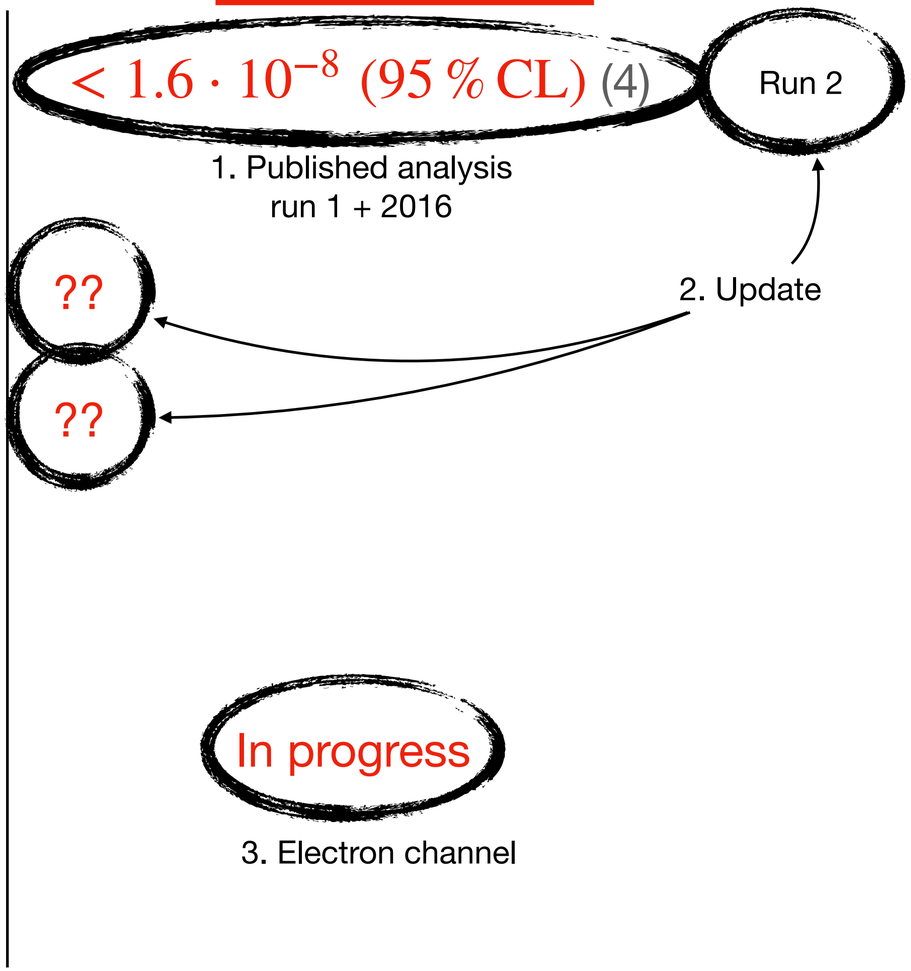
Experimental measurements



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

Published analysis (run 1 + 2016)

"Search for the rare decay $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$" (2019)
arXiv:1812.06004
Eur.Phys.J.C 79 (2019) 8, 675
LHCb collaboration

Inspired from the presentation :
"Search for $B \to 3\mu\nu$ at LHCb" (Svende Braun)
in Heidelberg, CKM 2018, 17-21 September 2018

Analysis strategy

❖ Dataset: Full Run 1 (2011-2012) and 2016
$\rightarrow 4.7\ \mathrm{fb}^{-1}$ pp data

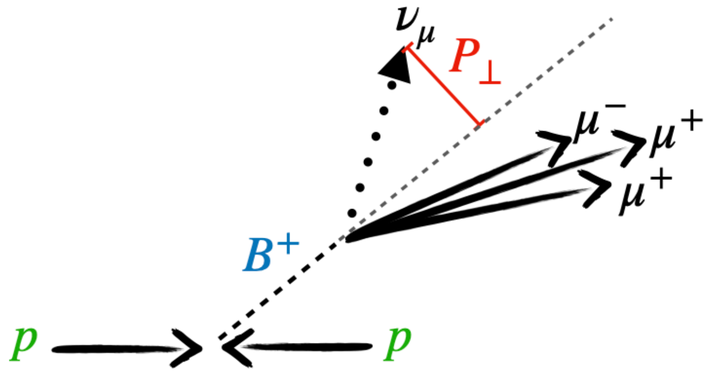
❖ Normalise branching fraction to $B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+$

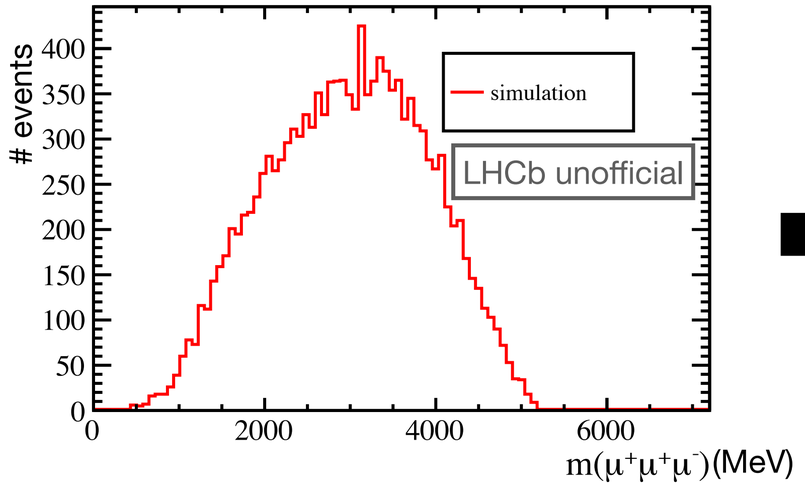
❖ Reconstruct B meson using the corrected mass variable: retrieve information from undetectable neutrino

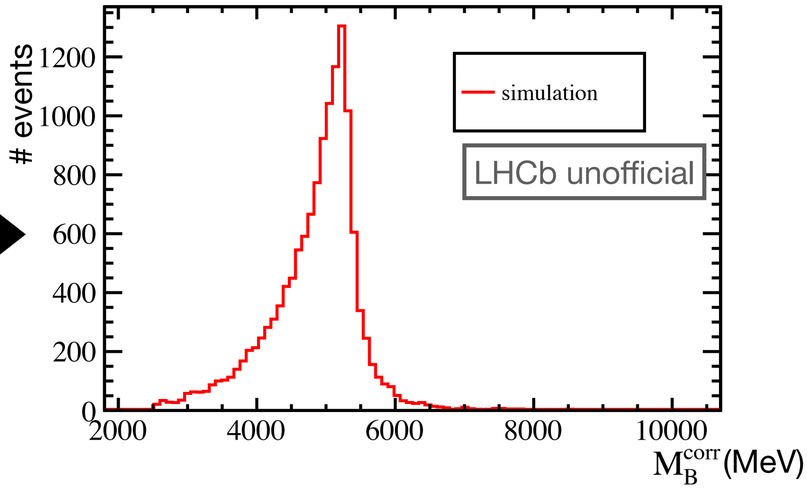
$$M_B^{\mathrm{corr}} = \sqrt{M_{\mu\mu\mu}^2 + P_\perp^2} + P_\perp$$

$\Rightarrow$ Better resolution on signal

❖ Unbinned maximum likelihood fit on M_B^{corr}



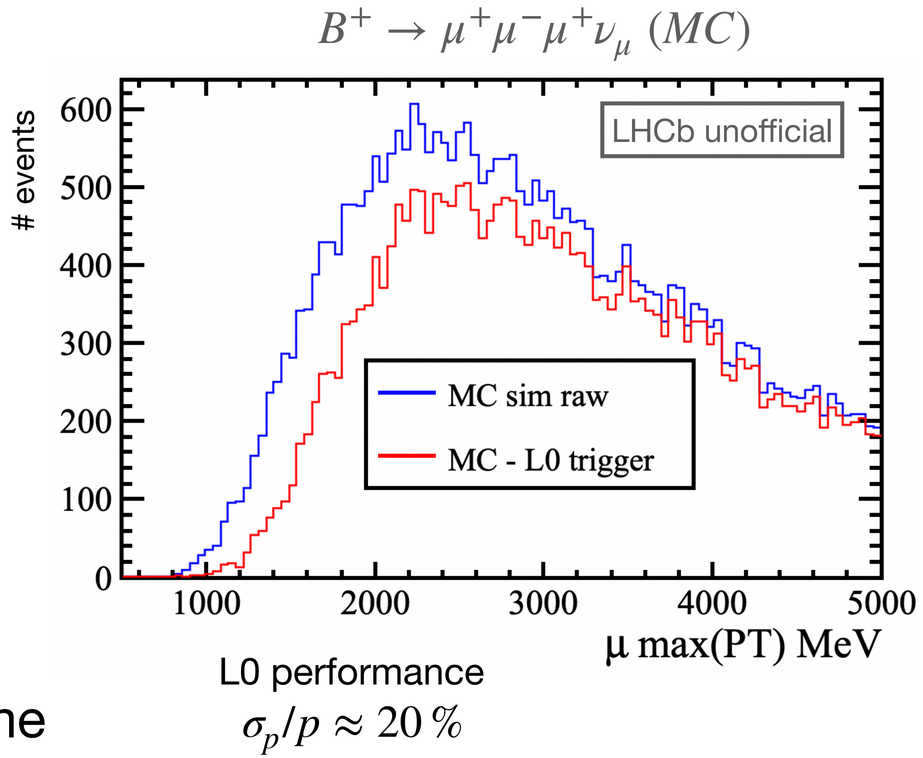




Selection

❖ Selection at each of the three level of the LHCb trigger

- L0 → look for energetic muon ($P_T > 1.3$ GeV)
- HLT1 → good displaced muon track
- HLT2 → displaced B-vertex

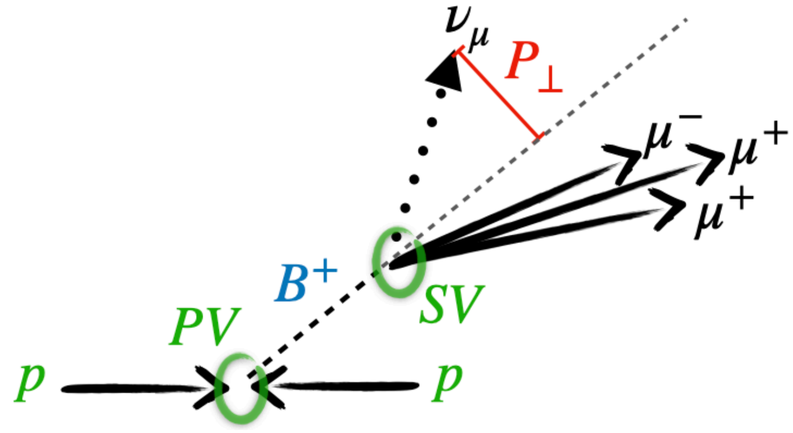


L0 performance

$\sigma_p/p \approx 20\,\%$

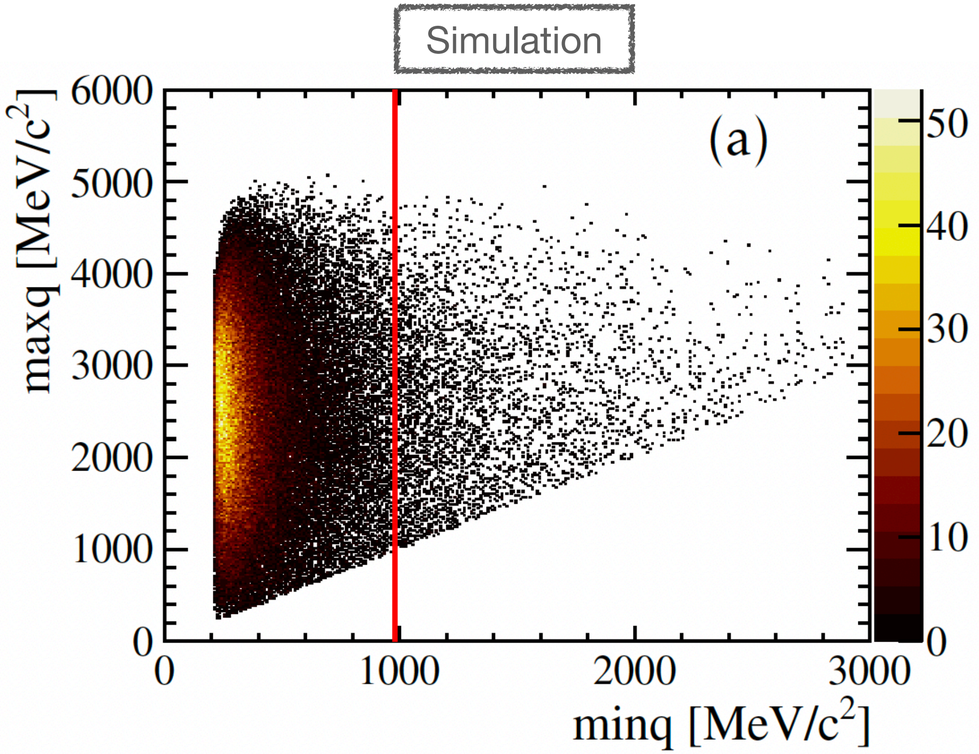
❖ Selection using topology of the decay

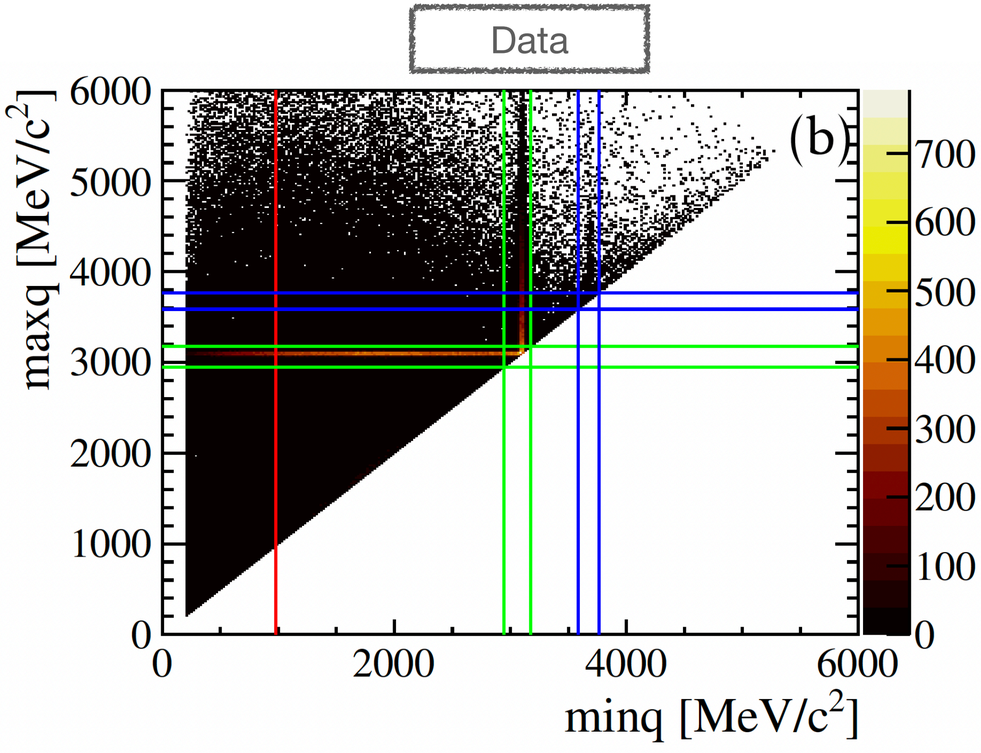
- Select 3 good quality muon tracks originating from the same vertex
- Vertex needs to be displaced from primary vertex
- Require that at most one muon station hit is allowed to be shared between the muon candidates



Selection

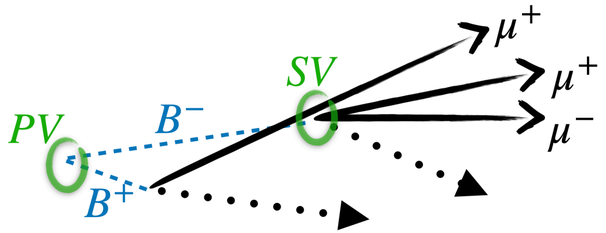
- Choice of q^2 (= $p^2_{\gamma^*}$) region: $min(q(\mu^+, \mu^-)) < 980\ \mathrm{MeV/c^2}$
  - Two possible μ^+ combinations → $min(q(\mu^+, \mu^-))$ most likely to be from photon
  - Expected signal yield outside of region is minimal
  - Reduce combinatorial background
- Remove backgrounds from J/ψ, $\psi(2S)$ resonances using mass vetos



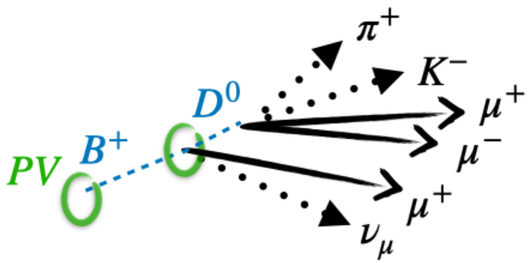


Main background

❖ Combinatorial background
Random combinations of 3 muons passing the selection
→ Reduce by training a dedicated BDT in the region around the B mass $[4000 - 7000\ \mathrm{MeV/c^2}]$
→ rejects 99% of combinatorics while 40% efficient on signal



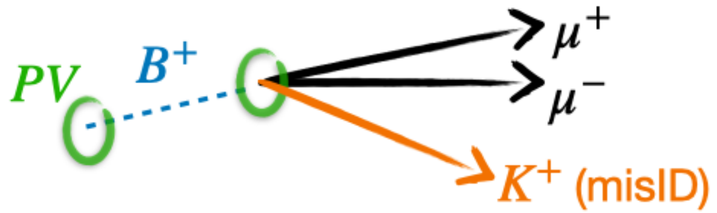
❖ Partially reconstructed background:
3 muons are correctly identified but additional particles not reconstructed
e.g. $B^+ \to (\overline{D}^0 \to K^+\pi^-\mu^+\mu^-)\mu^+\nu_\mu$
→ Reduced through isolation requirements
→ controlled using simulation



❖ Other exclusive backgrounds:

- $B^+ \to \pi^+\mu^-\mu^+$ low Br and low Mis-ID probability for pion → negligible
- $B^+ \to K^+\mu^-\mu^+$ corrected mass far away from signal region → negligible
- $B^0 \to (\eta' \to \mu\mu\gamma)\ (V \to \mu\mu)$ very low $Br \approx 4.5 \cdot 10^{-14}$ → negligible

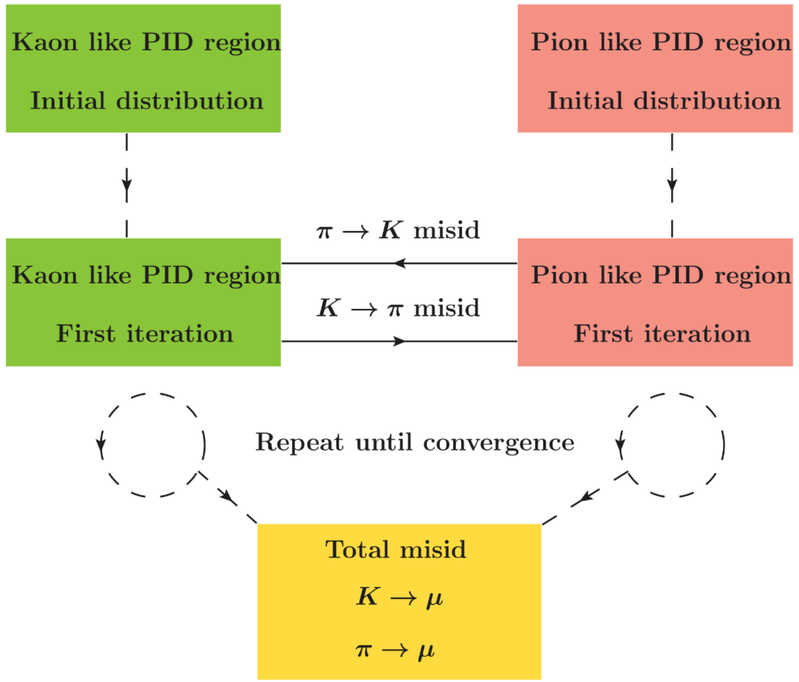
MisID background



- K, π or p misidentified as muon
  e.g. cascade decays $B \to (D \to K\mu\nu)\mu\nu$

- Train a dedicated BDT to remove misID backgrounds
  → rejects 94% of misID while 40% efficient on signal

- 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 background from protons can be neglected

Normalisation to $B^+ \to K^+ J/\psi$

$$Br(B^+ \to \mu^+\mu^-\mu^+\nu) = Br(B^+ \to (J/\psi \to \mu^+\mu^-)K^+) \times \frac{N(B^+ \to \mu^+\mu^-\mu^+\nu)}{N(B^+ \to (J/\psi \to \mu^+\mu^-)K^+)} \times \frac{\epsilon(B^+ \to (J/\psi \to \mu^+\mu^-)K^+)}{\epsilon(B^+ \to \mu^+\mu^-\mu^+\nu)}$$

→ from PDG | Yields → from fits | Efficiencies → from MC

- Normalisation channel with selection as similar as possible
  → cancel systematic uncertainties in the ratio

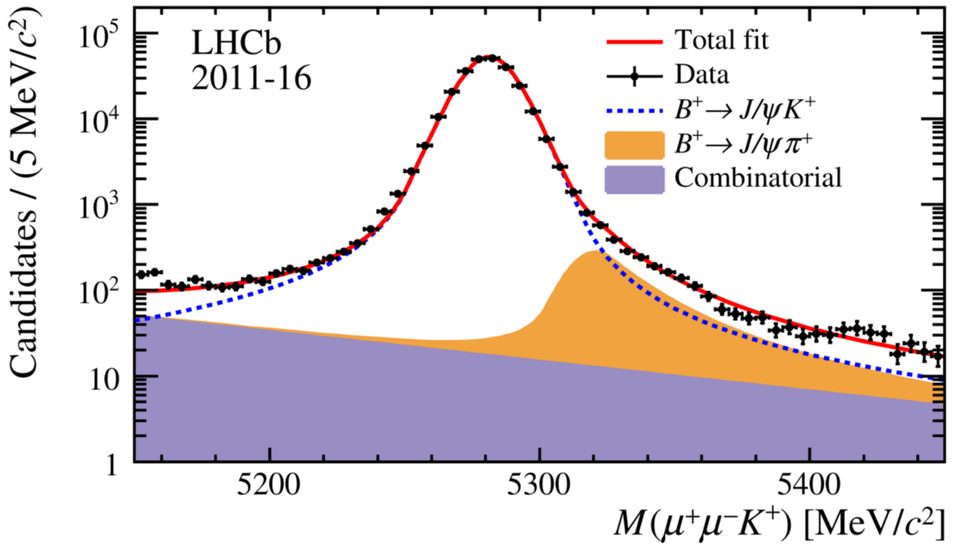
- Yield $N(B^+ \to (J/\psi \to \mu^+\mu^-)K^+)$
  From unbinned maximum likelihood fit of $M(K^+\mu^+\mu^-)$
  → provide $\sim 300\text{k}\ \text{B}^+ \to \mu^+\mu^-\text{K}^+$ candidates with purity 98%

- Efficiencies
  $\epsilon = \epsilon_{acceptance} \cdot \epsilon_{stripping} \cdot \epsilon_{trigger} \cdot \epsilon_{reconstruction} \cdot \epsilon_{selection} \cdot \epsilon_{PID}$
  All from MC, but ϵ_{PID} from control data samples

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

- Caused by lower dimuon mass and tighter PID requirements

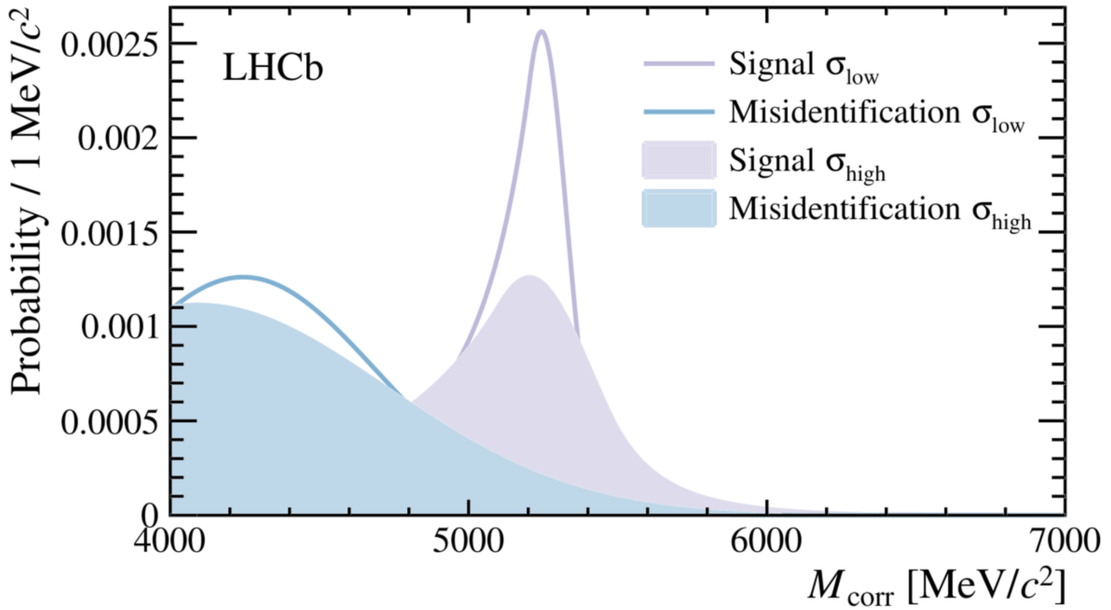
$$N(B \to X) = 2 \cdot \cancel{\sigma_{bb}} \cdot \cancel{f_u} \cdot \cancel{\mathscr{L}} \cdot Br(B \to X) \cdot \epsilon$$



Signal templates

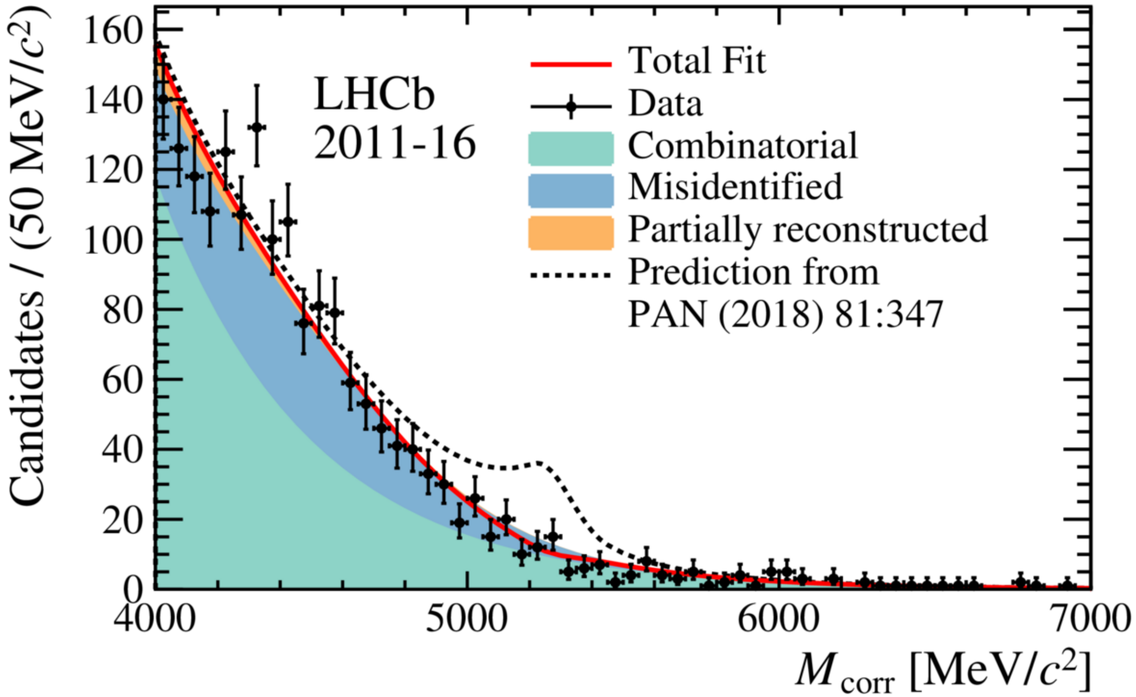
- To improve sensitivity, an event-by-event uncertainty on the corrected mass is calculated by propagating the uncertainties of the PV and SV
- Data is split into two equally-sized regions with high and low fractional corrected mass uncertainty

  → improves the branching fraction sensitivity by 11% due to the different signal distribution in the two samples



Signal fit

- Unbinned maximum likelihood fit is performed to the corrected mass
- Component of the fit:
  - Signal: shape from simulation, free yield
  - Combi.: exponential with free slope and yield
  - MisID: fixed from $\mu^+\mu^- hX$ data control sample
  - Part. Reco.: fixed from simulation



- Result:
  - Signal yield slightly negative → downward fluctuation of 2σ
  - Upper limit of $Br(B^+ \to \mu^+\mu^-\mu^+\nu) < 1.6 \times 10^{-8}$ at 95% using the CLs method

- Largest systematic uncertainty due to decay model for the signal channel
- Dominated by statistical uncertainty

$B^+_{(c)} \to \mu^+\mu^-\mu^+\nu_\mu$

Update with run 2 and improvement

"Search for the rare decay $\boldsymbol{B^+ \to \mu^+\mu^-\mu^+\nu_\mu}$*"*
(in progress)

LHCb collaboration

Updating the $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ result

- Data from full run 2 available at 13 TeV ⇒ larger $\sigma(b\bar{b})$ production

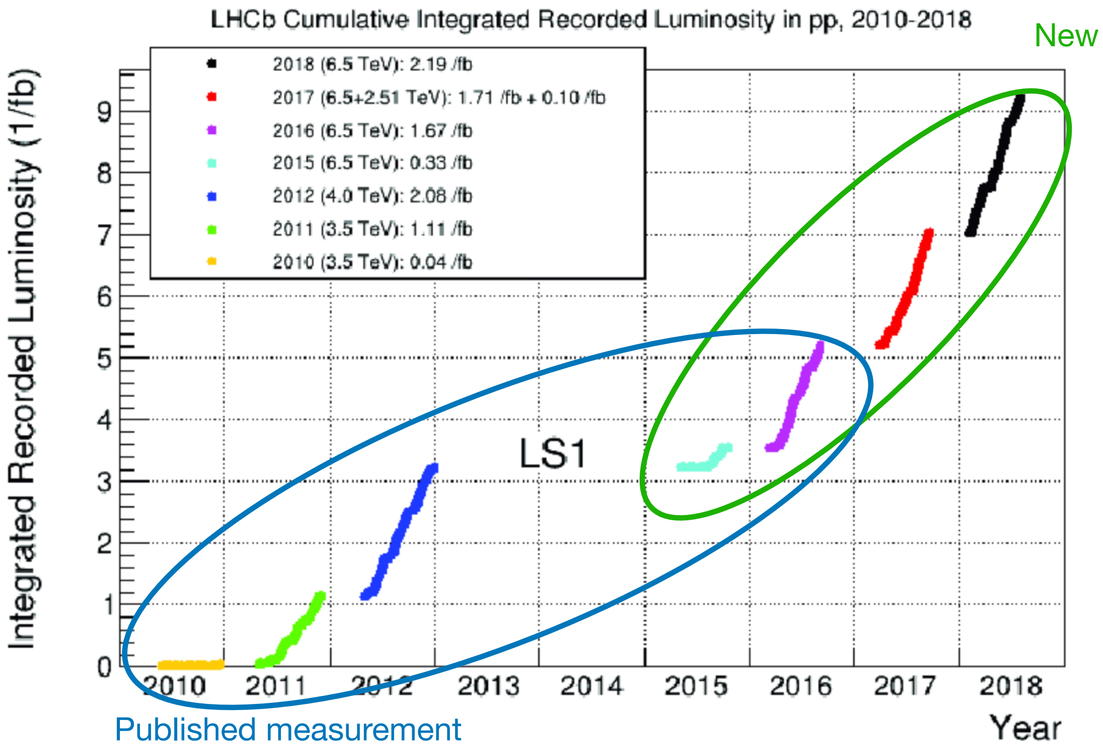
  2016 + New data 2017-2018
  → $5.57\ \text{fb}^{-1}$ pp data

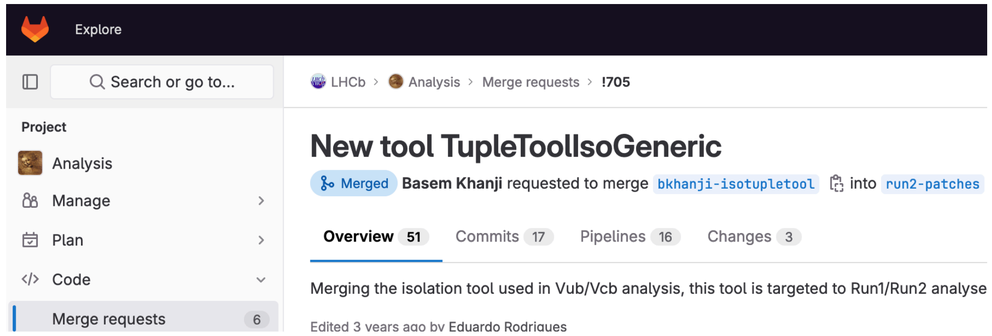
- New analysis tool now available
  → New isolation tool

- Previously, we had a bug in the muon ID impacting 2016 dataset
  → Now fixed for 2017-2018

- Working on a new muon ID tool to treat MisID bkg

- Try to revisit:
  - background estimation with data driven methods
  - Fit logic





Better simulation model

❖ Simulation from published analysis:
suffered from inaccurate decay model for their simulation samples

→ *INSP:* for mass fit shapes and efficiencies (default)

BTOSLLBALL model inspired from $B^+ \to K^{*+}\ell^+\ell^-$ with K^{*+} having W^+ properties

Decay model: B^+ decays into $K^*(\mu^+,\nu_u)\mu^-\mu^+$ using `BTOSLLBALL` decay model and $K^*(\mu^+,\nu_u)$ then decays into $\mu^+\nu_\mu$ using phase space decay model (PHSP). `BTOSLLBALL` decay model [9], is traditionally used for $B \to (K,K^*)l^+l^-$ decay, with the form factor calculations using the light cone QCD sum rule approach.

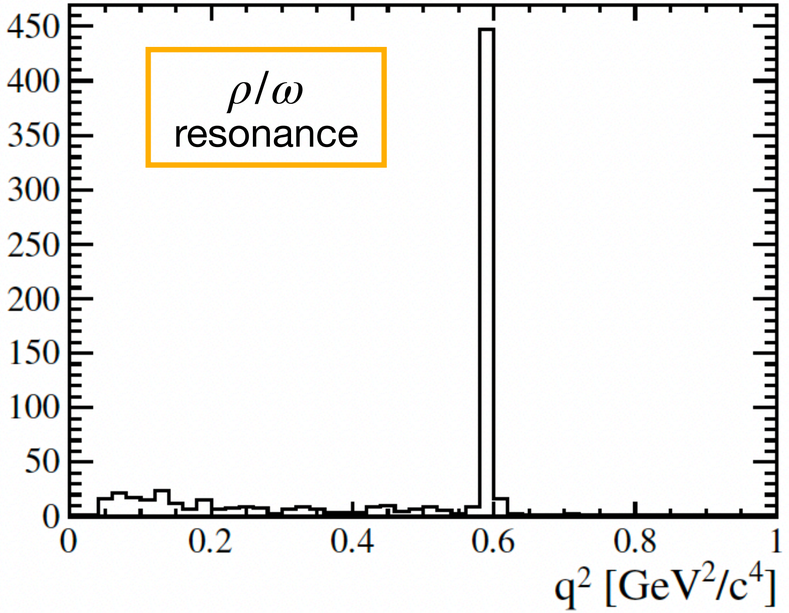
$W^+(\mu^+,\nu_\mu)$ flat distribution

$q^2(\mu^+,\mu^-)$ with photon pole

→ *PHSP:* for alternative efficiencies

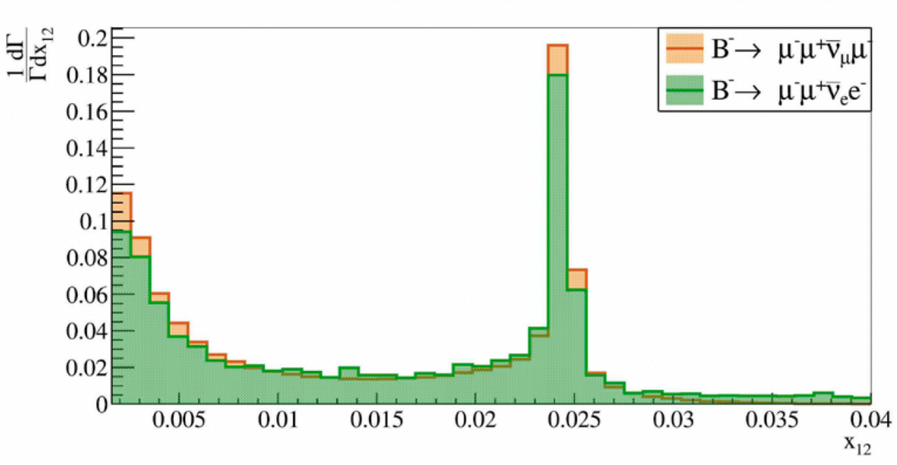
→ *NIKI:* to validate the choice of q^2 region,
Based on VDM model (Nikitin,Danilina, 2017)

Decay model NIKI



Better simulation model

Decay model New NIKI

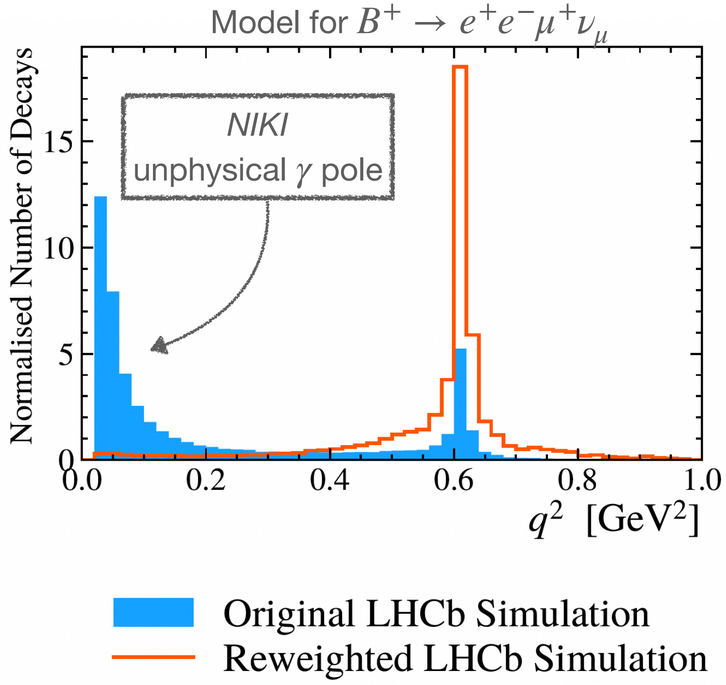


❖ A new version of *NIKI* model is now fully implemented into EvtGen and the LHCb simulation framework (Nikitin,Danilina,Toms, 2019)
→ *New NIKI: BLLNUL* model, used for all fits and efficiencies

❖ But recent decay model for $B^+ \to \ell'^+\ell'^-\ell^+\nu_\ell$ with $\ell \neq \ell'$ (Kürten,Zanke,Kubis,van Dyk, 2023)
→ showing different kinematic features

❖ Possible Strategy:

- Reweight *NEW NIKI* MC simulation to this updated model
  → already performed in $B^+ \to e^+e^-\mu^+\nu_\mu$ analysis
- But need a solution to adapt for $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ with identical leptons
  → Theory guidance welcome
  (would be useful to have a new model in EvtGen)



Other channels

❖ $B_c^+ \to \mu^+\mu^-\mu^+\nu_\mu$

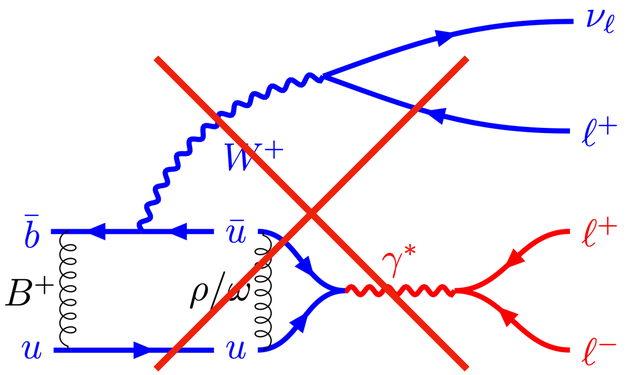
- Present in the same dataset and spectrum as B^+
  → Coming for free !
- 1^{st} important difference: Particle lifetime
  → The stripping selection of the dataset was changed to accommodate for B_c^+
  → Loser cut on the particle flight distance
  → Worse selection efficiencies
- 2^{nd} important difference:
  From naïve prediction $\frac{N(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)}{N(B_c^+ \to \mu^+\mu^-\mu^+\nu_\mu)} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2}\frac{f_u}{f_c} \approx 1.5$
  But no contribution from ρ/ω resonance because of missing u quark
  → expect lower signal yield
- No good model for B_c yet → Theory guidance also welcome

$B^\pm$

Mass $m_{B^\pm} = 5279.34 \pm 0.12$ MeV
Mean life $\tau_{B^\pm} = (1.638 \pm 0.004) \times 10^{-12}$ s
$c\tau = 491.1\ \mu$m

B_c^+

Mass $m = 6274.9 \pm 0.8$ MeV
Mean life $\tau = (0.510 \pm 0.009) \times 10^{-12}$ s



❖ $B_{(c)}^+ \to \mu^+\mu^-e^+\nu_e$

- Analysis started at EPFL (Raphaël Van Laak, Lesya Shchutska, Vitalii Lisovskyi)

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

A first search

"A first search for the rare $B^+ \to e^+ e^- \mu^+ \nu_\mu$*"*
(Master thesis of Tom Wolf)

LHCb collaboration

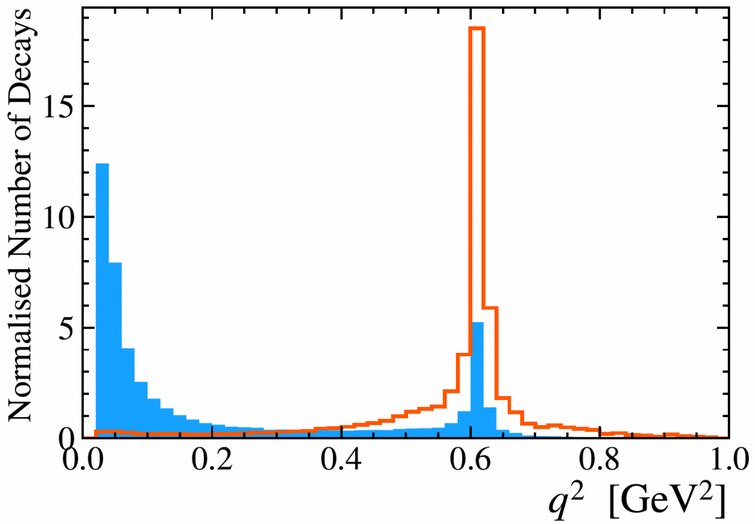
Data and Selection

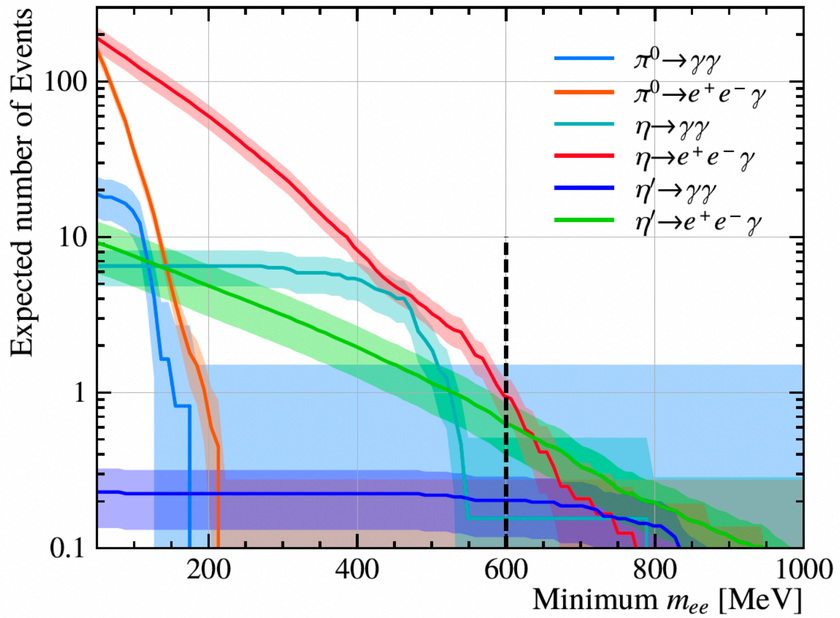
❖ Data: Run 2 data (2016-17-18)

❖ Selection:
→ Similar to $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ published analysis
up to requirements on electrons instead of muons

❖ Simulation:
→ Corrected to a better model via a reweighing of the 5 kinematic quantities (model: *NIKI* → *Kürten et al*)
→ increase the importance of the ρ/ω resonance

❖ Different choice of signal window $m_{ee} \in [600,900]$ MeV
→ focus on the region most sensitive to Br
e.g. the ρ/ω resonance
→ Remove significantly partially reconstructed bkg at low m_{ee}
$B^+ \to (h^0 \to ee\gamma)\mu^+\nu_\mu$ with $h^0 = \pi^0, \eta, \eta'$
→ Remove combinatorial background at high m_{ee}





Status of the work

❖ Backgrounds:

- Partially reconstructed bkg
  → Isolation BDT
- Combinatorial bkg
  → Dedicated BDT trained against same sign data
  Fit ⇒ exponential with free slope an yield
- MisID bkg
  → reduced with PID requirements
  Fit ⇒ shape and yield estimated from $\mu^+\mu^- hX$ data (with possible multiple MisID)
- $B_c^+ \to (J/\psi \to e^+e^-)\mu^+\nu_\mu$ → studied to be negligible
- $B_c^+ \to e^+e^-\mu^+\nu_\mu$ → Naïvely expect small contribution, but no good prediction ?

→ Working point of combined BDT chosen to maximise the fitting procedure, studied with toy models

❖ Signal region still blinded → Sensitivity estimate from toys
⇒ Expected upper limit is extracted from binned maximum likelihood fit performed on toys
⇒ Still ongoing analysis

Conclusion

Conclusion

❖ Fully leptonic decays of B meson
→ allow to use the power of LHCb ! (Statistics and detector performance)
→ study the B meson sub-structure

❖ Current status:

- $Br(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) < 1.6 \times 10^{-8}$ at 95% CL with run 1 (2011-12) and 2016 data
- Update on $Br(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)$ with run 2 → work in progress
- First search for $B_c^+ \to \mu^+\mu^-\mu^+\nu_\mu$ and $B_{(c)}^+ \to \mu^+\mu^-e^+\nu_e$ → work in progress
- First search for $B_c^+ \to e^+e^-\mu^+\nu_\mu$ → work in progress

} Collaboration ongoing

❖ Future:
→ maybe new LFU tests in the future
→ Could try channels with tau leptons

❖ Run 3 of LHCb:
Better efficiencies thanks to fully software trigger ! → good prospect for future analyses


Thank you !
LHCb
YCMM01
UX85

Back up slides

Selection $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ published analysis

Muon Cuts	Mother/CombCut
$\chi^2_{minIP} > 9$	2500 MeV/c^2 $< M_{\mathrm{B_{corr}}} <$ 10000 MeV/c^2
$\Delta LL(\mu - \pi) > 0$	$cos(\theta_B) > 0.999$
$\Delta LL(\mu - K) > 0$	$p_T > 2000$ MeV/c
$P_T > 0$	$\chi^2_{FD} > 50$
$\chi^2_{tr}/dof < 3$	$\chi^2/dof < 4$
$P_{ghost} < 0.35$	0 MeV/c^2 $< M_B <$7500 MeV/c^2

Trigger selection line	2011	2012	2016
Bplus_L0MuonDecision_TOS	0.915	0.895	0.74
Bplus_Hlt1TrackMuonDecision_TOS	0.874	0.929	0.931
Or of HLT2 lines below	0.986	0.987	0.996
Bplus_Hlt2TopoMu2BodyBBDTDecision_TOS	0.859	0.892	0.94*
Bplus_Hlt2TopoMu3BodyBBDTDecision_TOS	0.677	0.76	0.886*
Bplus_Hlt2DiMuonDetachedDecision_TOS	0.809	0.769	0.988
Bplus_Hlt2DiMuonDetachedHeavyDecision_TOS	0.94	0.929	0.99

Idea	Object	Selection Run 1	Selection 2016
J/ψ veto	Dimuon	!(2946.0 MeV/c^2 $<$ | M(μ^+ μ^-) | $<$ 3176.0 MeV/c^2)	!(2946.0 MeV/c^2 $<$ | M(μ^+ μ^-) | $<$ 3176.0 MeV/c^2)
Ψ(2S) veto	Dimuon	!(3586.0 MeV/c^2 $<$ | M(μ^+ μ^-) | $<$ 3766.0 MeV/c^2)	!(3586.0 MeV/c^2 $<$ | M(μ^+ μ^-) | $<$ 3766.0 MeV/c^2)
Clean	Muon	-	`IsMuonTight==1.0`
Clone and ghost	Muon	`Nshared==0`	`Nshared<2`
Bkg Removal	event	Combinatorial BDT selection	Combinatorial BDT selection
Bkg Removal	event	Misid BDT selection	Misid BDT selection
Fit Region	B	4000 MeV/c^2 $< M_{\mathrm{B_{corr}}} <$ 7000 MeV/c^2	4000 MeV/c^2 $< M_{\mathrm{B_{corr}}} <$ 7000 MeV/c^2
Optimize `FOM`	Muon	`Probnnmu`$>$ 0.35	`Probnnmu`$>$ 0.35

Selection $B^+_{(c)} \to \mu^+\mu^-\mu^+\nu_\mu$ run 2

Muon Cuts	Mother/CombCut
$\chi^2_{minIP} > 9$	2500 MeV/c^2 $< M_{\mathrm{B_{corr}}} <$ 10000 MeV/c^2
$\Delta LL(\mu - \pi) > 0$	$DIRA > 0.99$
$\Delta LL(\mu - K) > 0$	$p_T > 2000$ MeV/c
$P_T > 0$	$\chi^2_{FD} > 30$
$\chi^2_{tr}/dof < 3$	$\chi^2/dof < 4$
$P_{ghost} < 0.35$	0 MeV/c^2 $< M_B <$7500 MeV/c^2

Selection	cut
q^2 region	$min\ m(\mu^+\mu^-) <$ 980 MeV/c^2
J/ψ veto	!(2946 MeV/c^2 $<$ m$(\mu^+\mu^-) <$ 3176 MeV/c^2)
$\psi(2S)$ veto	!(3586 MeV/c^2 $<$ m$(\mu^+\mu^-) <$ 3766 MeV/c^2)
muon cleaning	NShared < 2 (3x muons)
muon cleaning	isMuonTight $== 1$ (3x muons)
clone tracks	$\theta(\mu_i\mu_j) > 0.001$ (3x muon pairs)

	Trigger
L0	Bp_L0MuonDecision_TOS Bp_L0DiMuonDecision_TOS
HLT1	Bp_HLT1TrackMuonDecision_TOS Bp_HLT1TrackMVADecision_TOS Bp_HLT1TwoTrackMVADecision_TOS
HLT2	Bp_HLT2TopoMuMu2BodyDecision_TOS Bp_HLT2TopoMuMu3BodyDecision_TOS Bp_HLT2DiMuonDetachedDecision_TOS Bp_HLT2DiMuonDetachedHeavyDecision_TOS

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

Type	Applied on	Requirement
Detector	μ^+	$\texttt{hasMuon} == 1$
	$e^\pm$	$\texttt{hasCalo} == 1$ $\texttt{hasRich} == 1$ $\texttt{InAccECAL} == 1$ $\texttt{region}_{ECAL} \geq 0$ $(x_{ECAL} > 363.3\,\text{mm} \mid y_{ECAL} > 282.6\,\text{mm})$
	general	$\texttt{nSPDHits} < 450$
PIDCalib	μ^+	$p_T \in [1200, 14000]\,\text{MeV}$ $p > 3000\,\text{MeV}$ $\eta \in [1.75, 4.5]$
	$e^\pm$	$p_T \in [500, 14000]\,\text{MeV}$ $p > 3000\,\text{MeV}$ $\eta \in [1.75, 4.5]$
Topological	B^+	$\texttt{DIRA} > 0.995$ $\chi^2_{FD} > 100$ $\chi^2_{DOCA}(\mu^+e^+e^-) < 9$
	dielectron	$\chi^2_{IP} > 40$
Kinematic	$e^\pm$	$p_{T,track} > 200\,\text{MeV}$
	general	$m_{\mu ee} \in [500, 6000]\,\text{MeV}$ $m^2_{miss} \in [-10, 10]\,\text{GeV}^2$ $k^2 > -5\,\text{GeV}^2$
Clone veto	$\mu^+e^\pm$	$\theta(\mu^+, e^\pm) > 5\,\text{mrad}$
Virtual photon requirement	$e^\pm$	$\texttt{VeloCharge} < 1.25$
	dielectron	$FD < 20\,\text{mm}$ $\chi^2_{FD} < 9$
PID	μ^+	$\texttt{PIDmu} > 2$ $\texttt{ProbNNmu} > 0.8$ $\texttt{isMuon} == 1$
	$e^\pm$	$\texttt{ProbNNe} > 0.2$

Applied on	Requirement
B^+	$m_{corr} \in [2500, 10000]\,\text{MeV}$ $m_{\mu ee} \in [0, 7500]\,\text{MeV}$ $\texttt{DIRA} > 0.99$ $p_T > 2000\,\text{MeV}$ $\chi^2_{FD} > 30$ $\chi^2_{vertex}/ndof < 4$
μ^+	$\chi^2_{track}/ndof < 3$ $\text{p}_{ghost} < 0.35$ $\min(\chi^2_{IP}(primary)) > 9$ $\texttt{PIDmu} > 0$ $(\texttt{PIDmu} - \texttt{PIDK}) > 0$
$e^\pm$	$p_T > 200\,\text{MeV}$ $\chi^2_{track}/ndof < 3$ $\text{p}_{ghost} < 0.35$ $\min(\chi^2_{IP}(primary)) > 25$ $\texttt{PIDe} > 2$ $(\texttt{PIDe} - \texttt{PIDK}) > 0$

Trigger	Selected conditions
L0	$\texttt{L0Electron}(e^+, e^-)$ $\texttt{L0Muon}(\mu^+)$
HLT1	`Hlt1TrackMVA Hlt1TwoTrackMVA` `Hlt1TrackMuon`
HLT2	`Hlt2Topo[2,3]Body` `Hlt2TopoMu[2,3]Body`

Muon bug in previous analysis

- Compare track extrapolation with muon hit
  if 2 tracks for one hit:
  -> the closest get the hit
  -> the furthest get an increment in NShared

- Bug 1 (before Run2): Mistake in calculation of compared distance

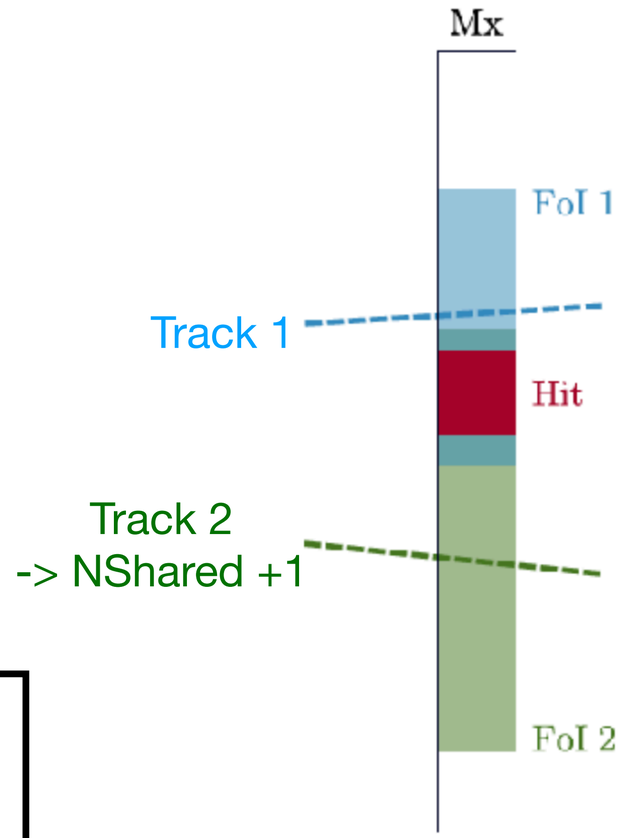
  ➡ Fixed

- Bug 2 (before 2017): Mistake leading to forgetting M5

  ➡ All fixed in 2017 and forward

- Impact:

  - Data and MC are wrong in the same way => negligible effect over ProbNNs.
  - Larger impact on high momentum tracks as those arrive to M5.



- Need to be more studied
  But we might remove the cut and simply put it in the BDT to decide

New muon ID tool

❖ Pair of muon from the photon are quite soft
LHCb standard ID tool less performant at low momentum
ProbNNmu: Neural network to identify μ from other particle
⇒ Aim at creating a new muon ID tool performing better on soft muon

❖ Train a dedicated BDT

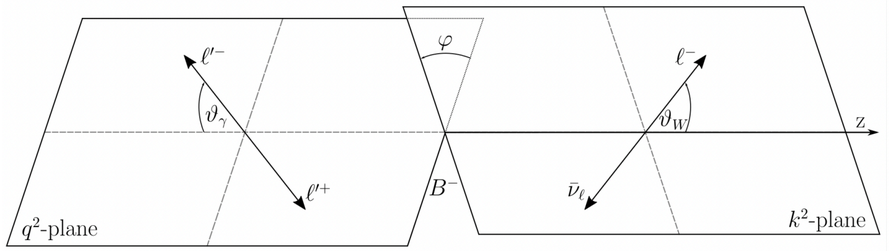
- Samples:
  Data-driven from PID calibration samples for μ, K and π
- Variables: kinematics + PID variables

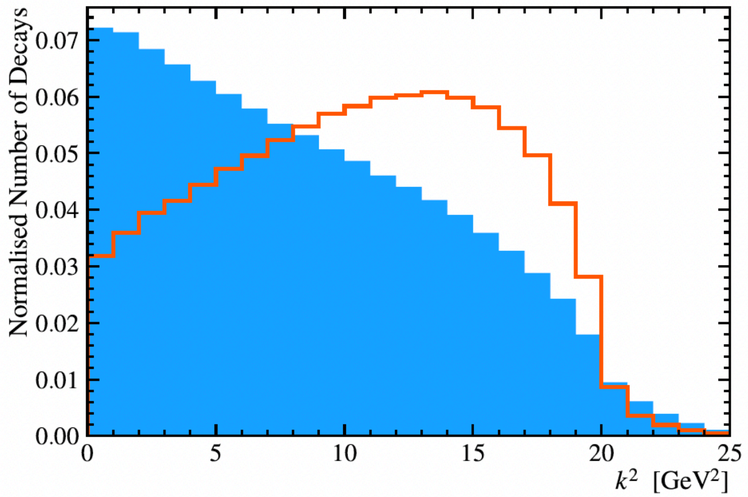
❖ Improving performance compared to *ProbNNmu*

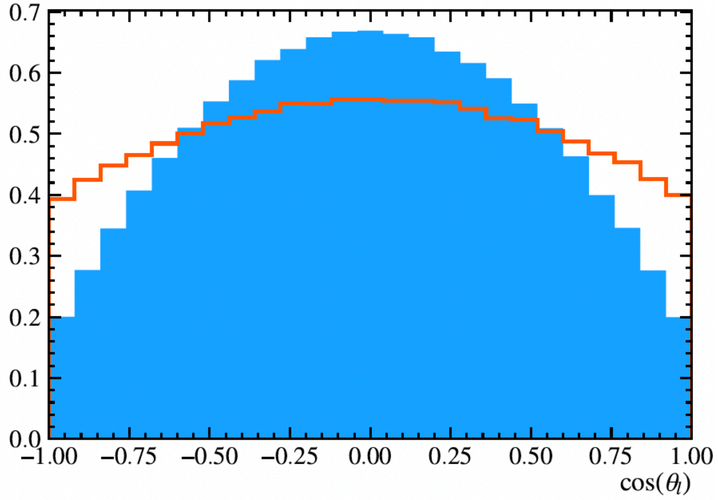
$D_s^+ \to \phi\pi^+$ with $\phi \to \mu^+\mu^-$	Muon sample
$K_S^0 \to \pi^+\pi^-$	Pion sample
$D_s^+ \to \phi\pi^+, \quad \phi \to K^+K^-$	Kaon sample

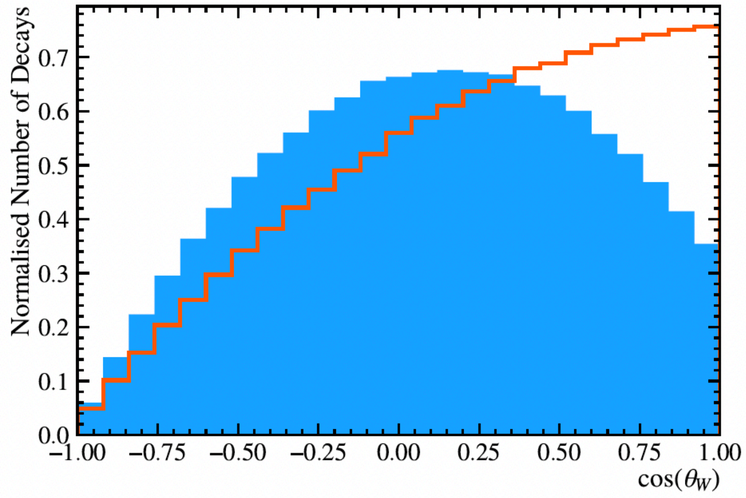
Work performed by Dariia Berezovska
(little project during Master at EPFL)

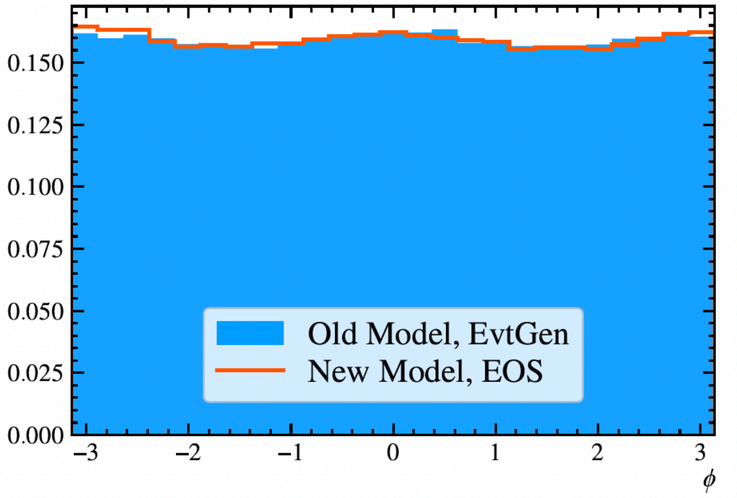
$B^+ \to e^+e^-\mu^+\nu_\mu$ kinematic reweighing on new decay model











$B^+ \to e^+e^-\mu^+\nu_\mu$ kinematic reweighing on new decay model