Semileptonic b→c and b→u decays at LHCb

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On behalf of the LHCb collaboration

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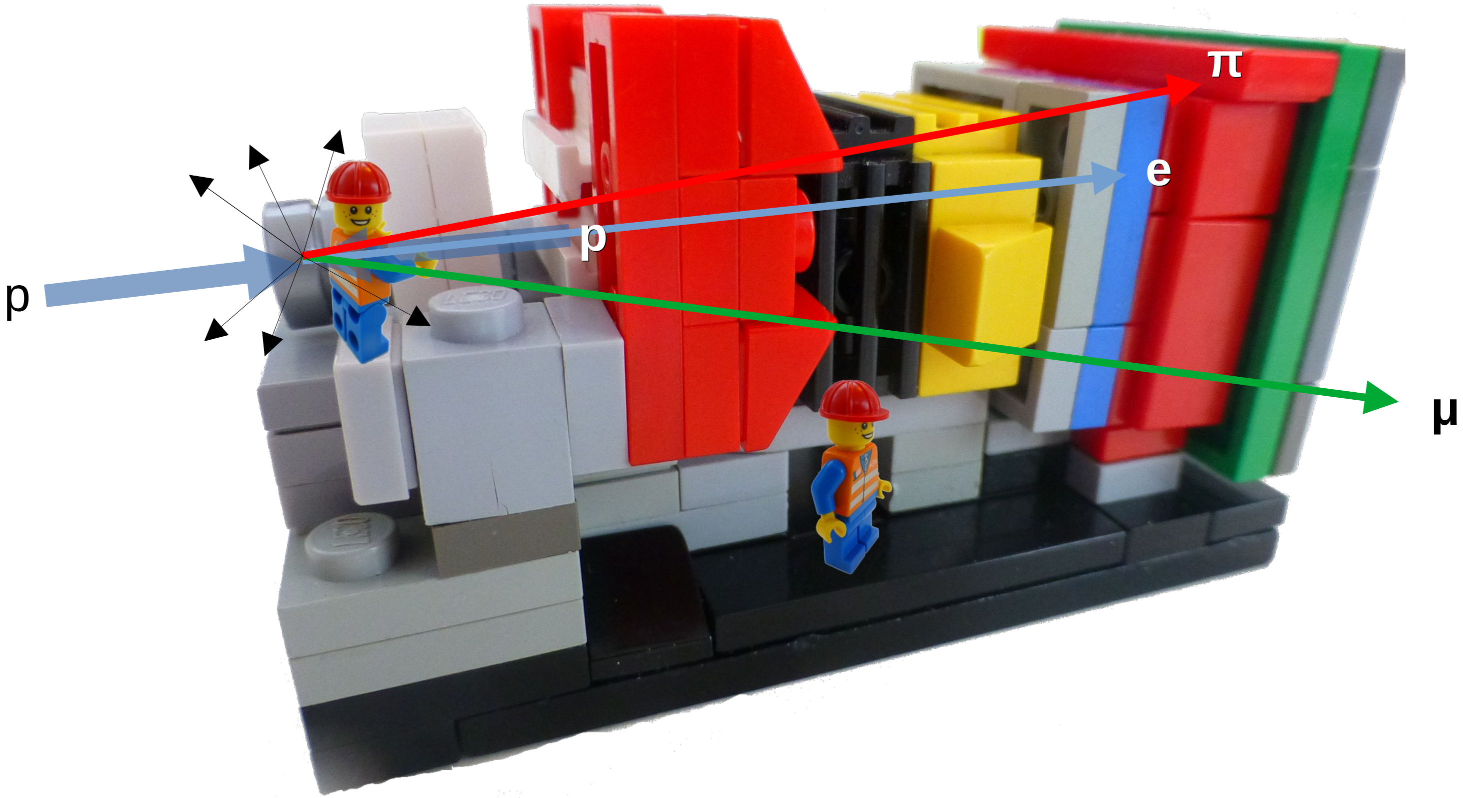
LHCb collision region

- Producing b-hadrons in p-p collisions is very different to a B-factory

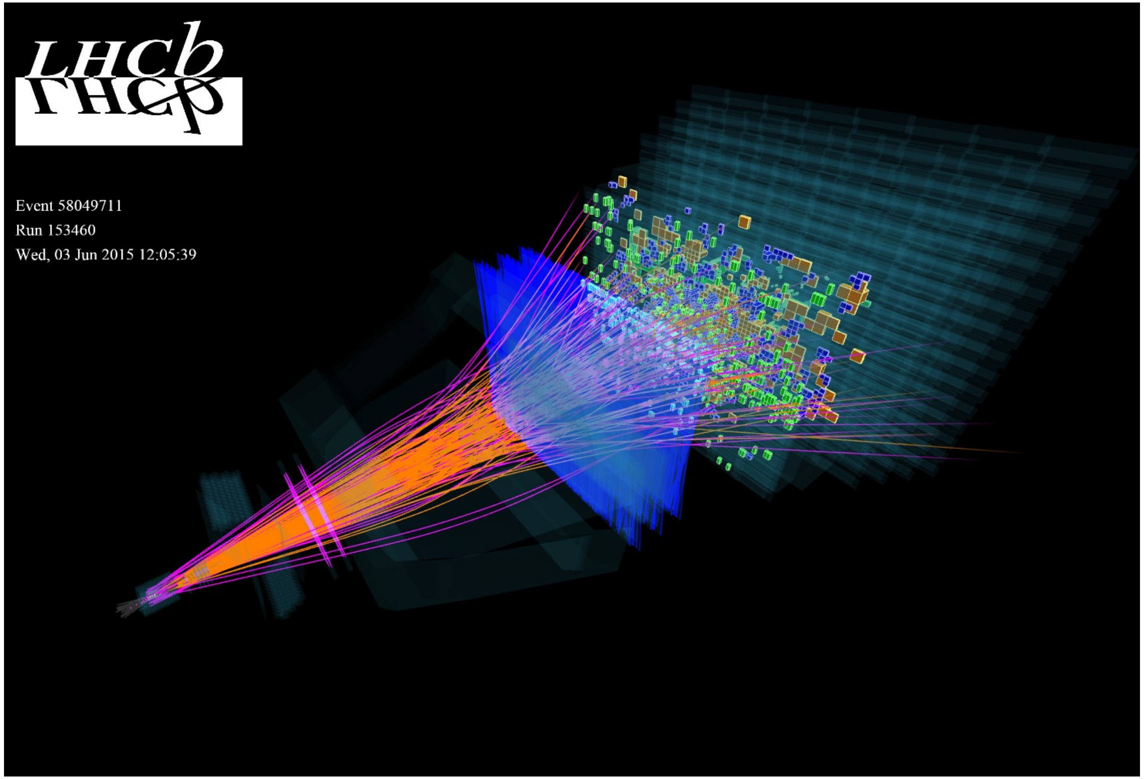


LHCb – the good bits

- All b-hadrons produced (B^+, B^0, Λ_b, B_s, B_c, Σ_b, Ξ_b, …)
- Rates are huge, for 2022-2030 (Upgrade I) about 600 kHz in detector (factor 300 above Super KEKB design)
- Vertex separation is fantastic

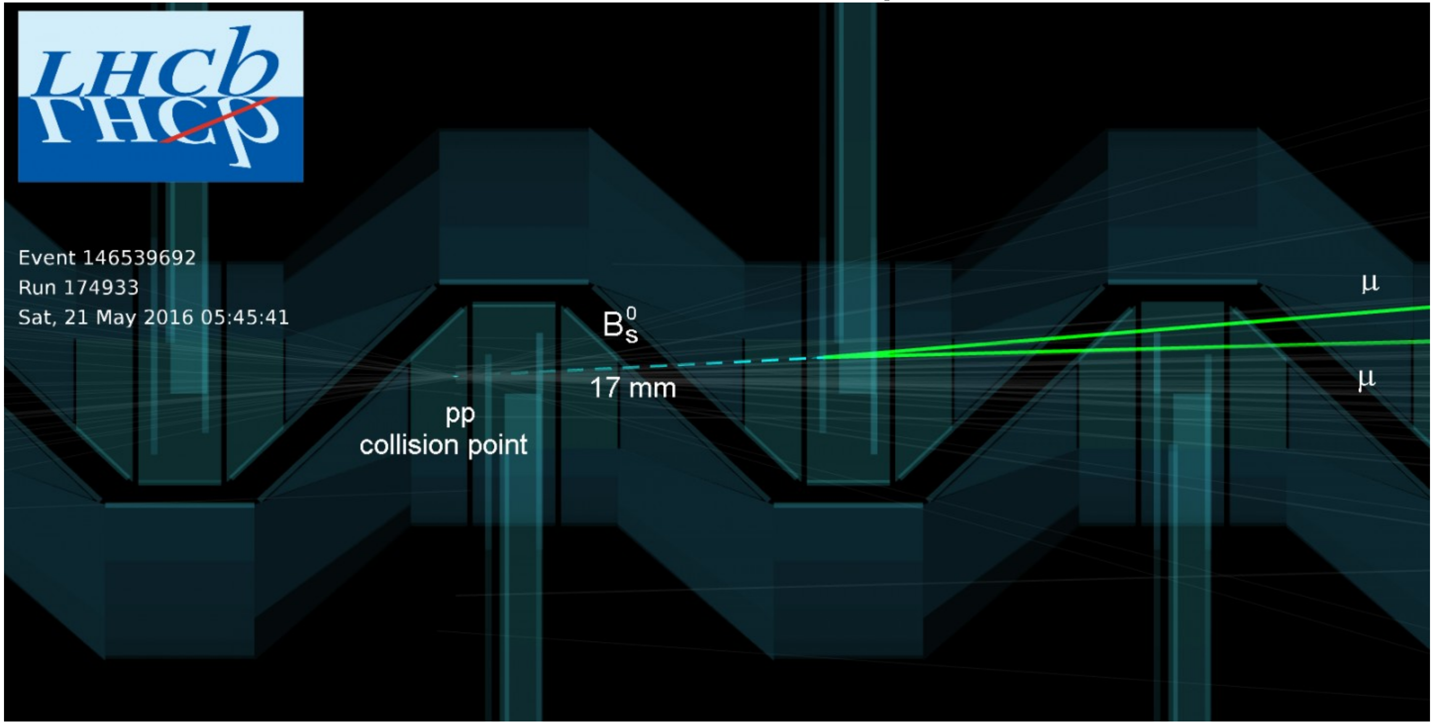
LHCb – the challenges

- The large number of π^0's produced at the PV
- The rates are huge, so trigger has to be very selective
- Flavour tagging is hard as there are many other particles
- With O(100) tracks in each event which have nothing to do with the b-hadron decay, combinatorial background is *a-priori* huge



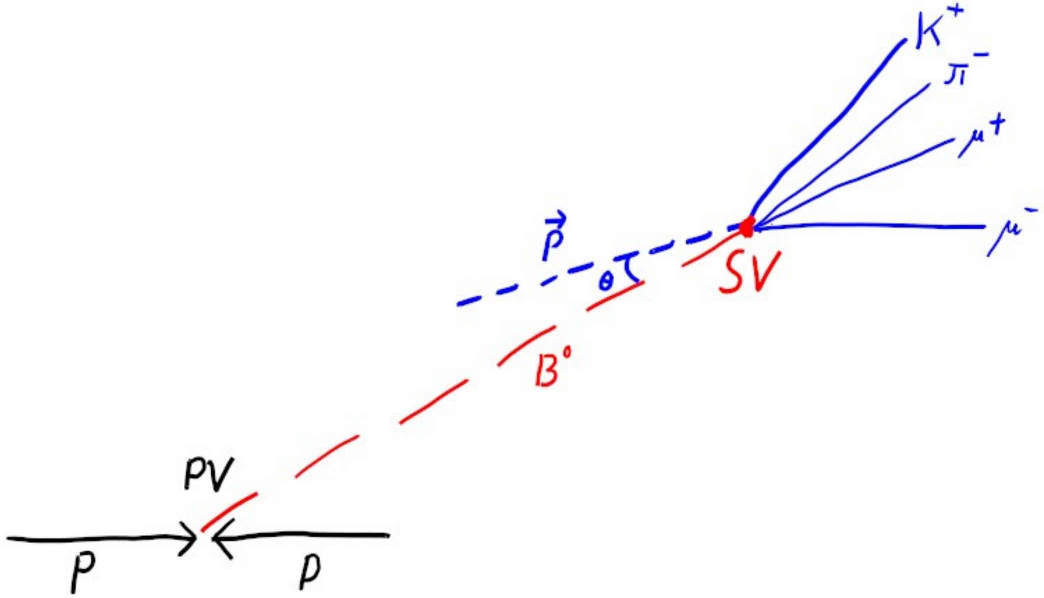
Kill the background

- Detached vertices are tool #1
- The typical b-hadron momentum is around 50 GeV, so γ factor of 10
- The b-hadron will fly O(cm) before it decays
- We have O(100μm) resolution

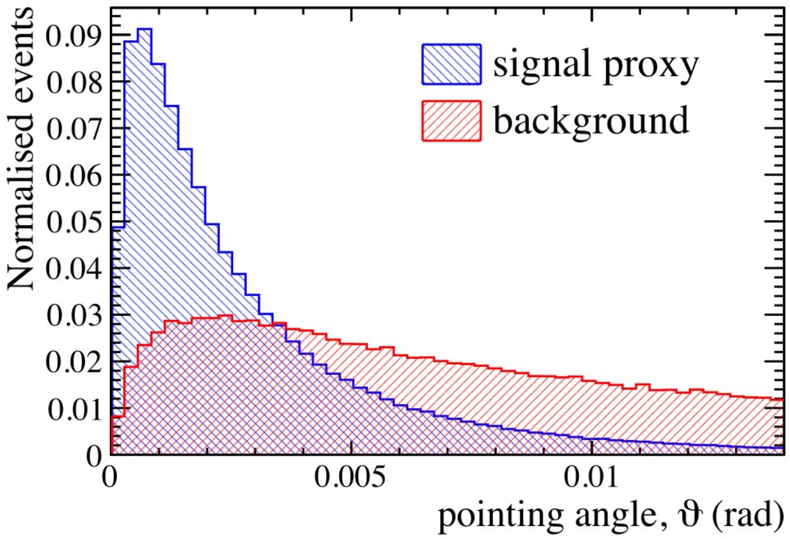


Kill the background

- Tool #2 is pointing
- The decay products of a b-hadron decay should have its momentum vector aligned with vector from primary to secondary vertex



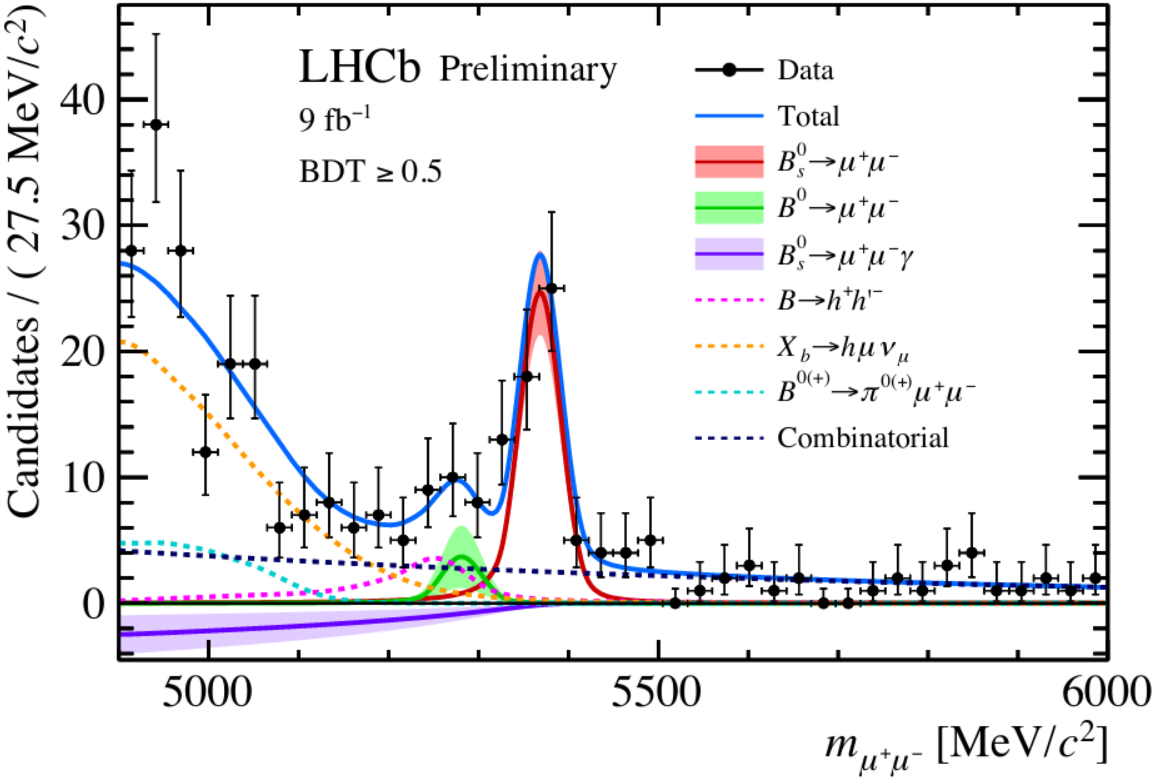
S. Cunliffe, thesis, 2016



Kill the background

- Tool #3 is mass
- The long length of the LHCb spectrometer gives excellent mass resolution
- Reduces combinatorial background under peak
- Allows for clean separation of B^0 and B^0_s

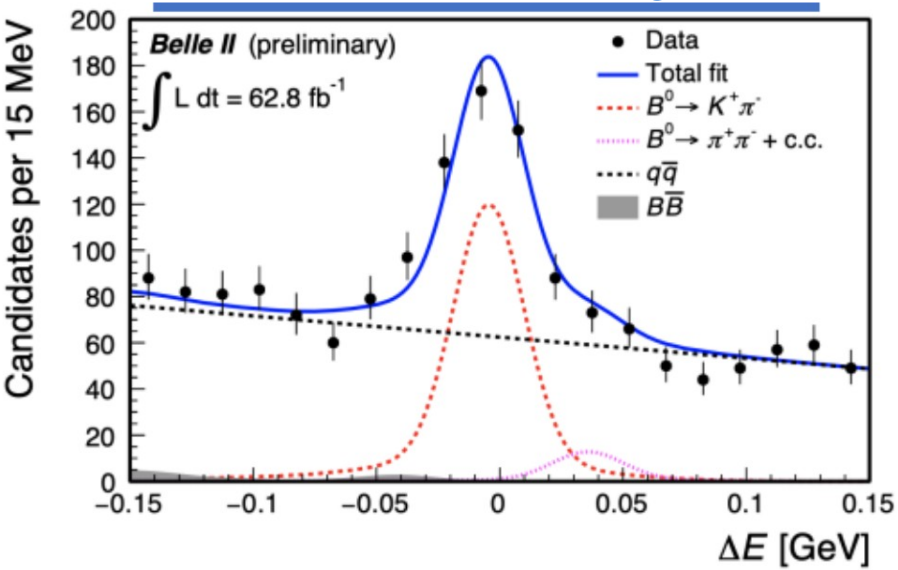
LHCb-PAPER-2021-007



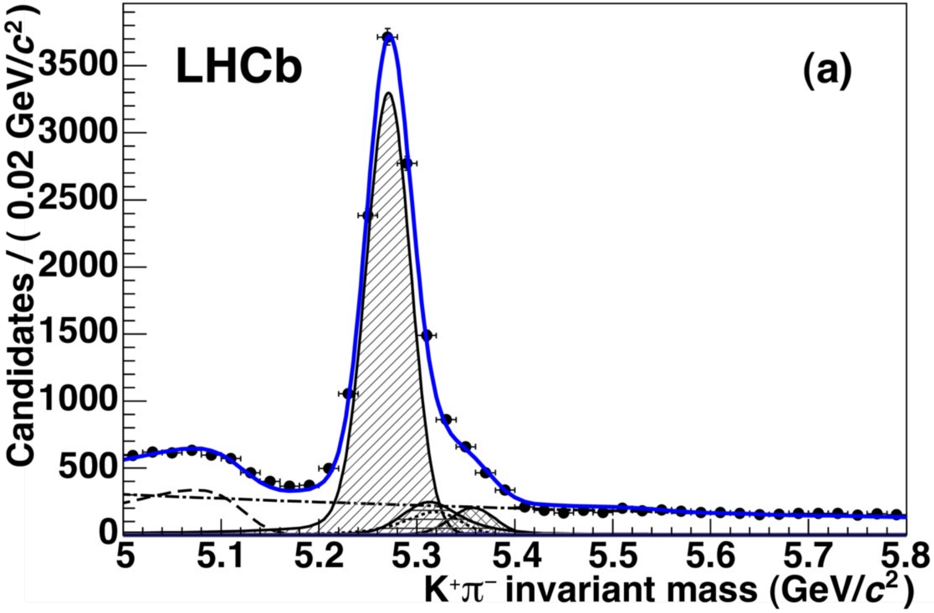
Combinatorial background

- For fully reconstructed final states, the background levels in most LHCb analyses are really low

Belle II @ FPCP 2021



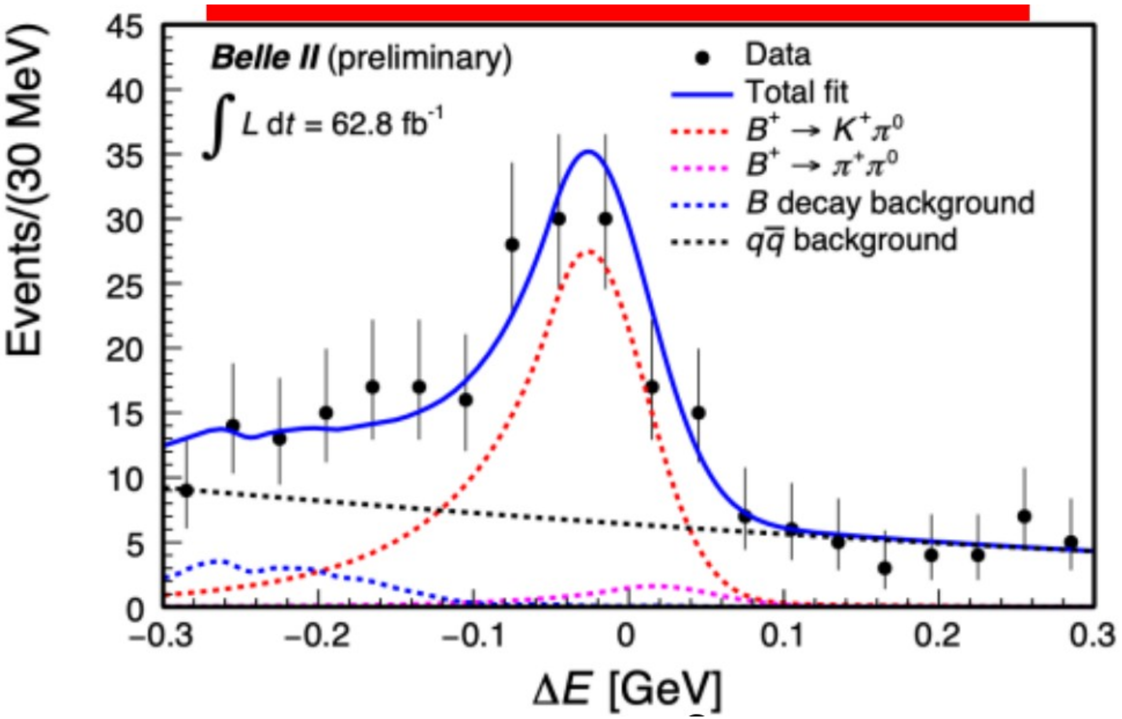
JHEP 10 (2012) 37



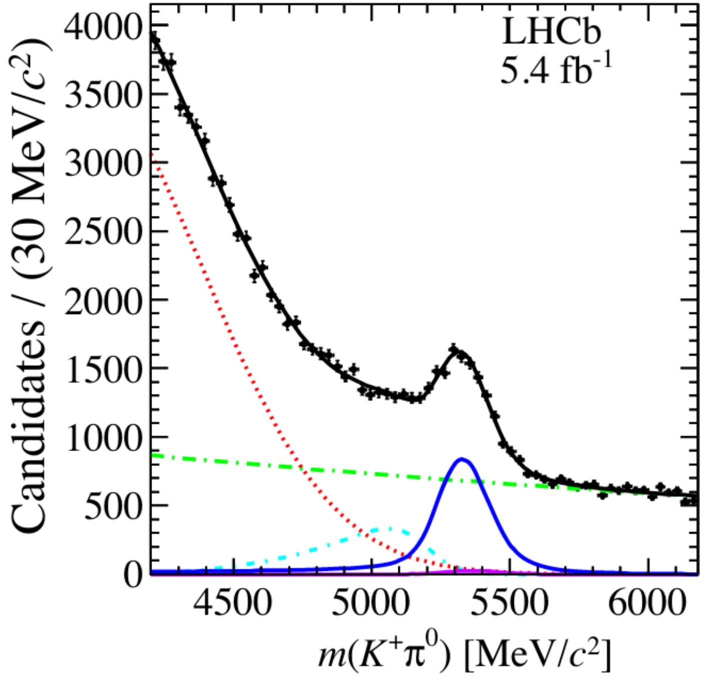
Combinatorial background

- When secondary vertex is no longer there, combinatorial background can still be controlled

Belle II @ FPCP 2021

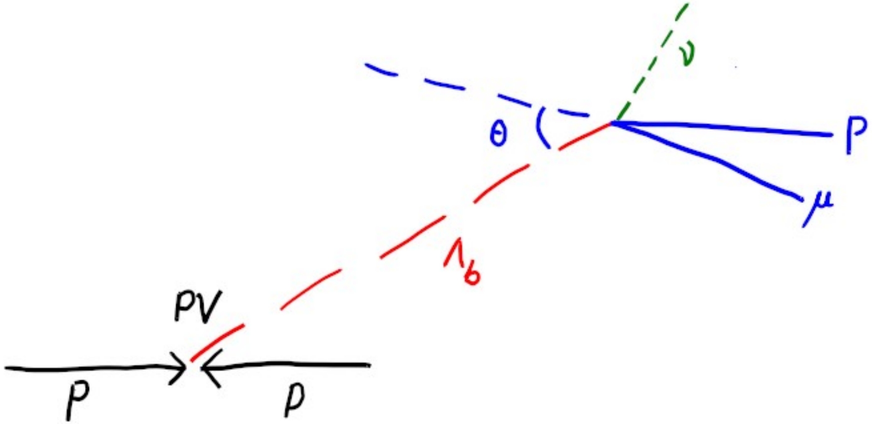


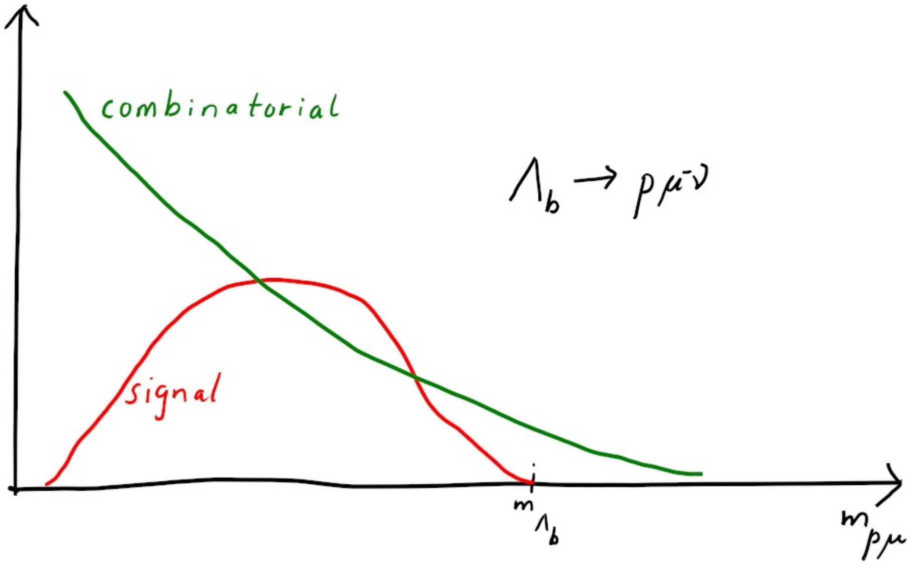
PRL 126 (2021) 091802



Semileptonic decays

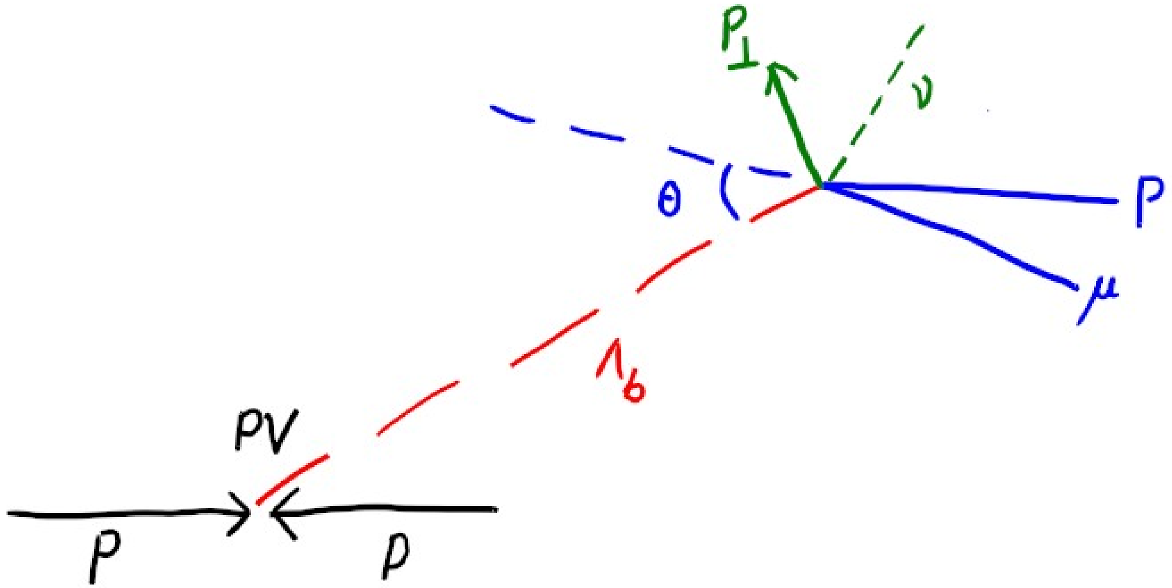
- With a semileptonic decay of the type $h_b \rightarrow h\mu\nu$, we (partially) lose two of the three major tools for background reduction as missing neutrino means that
  - we no longer have the momentum of daughters pointing to the primary vertex
  - the 4-vectors of the daughters do not add up to the b-hadron mass





Corrected mass

- All is not lost as we can combine the pointing and the mass into a single constraint called the *corrected mass*
  - Find the transverse momentum $p_\perp$ required to restore the pointing



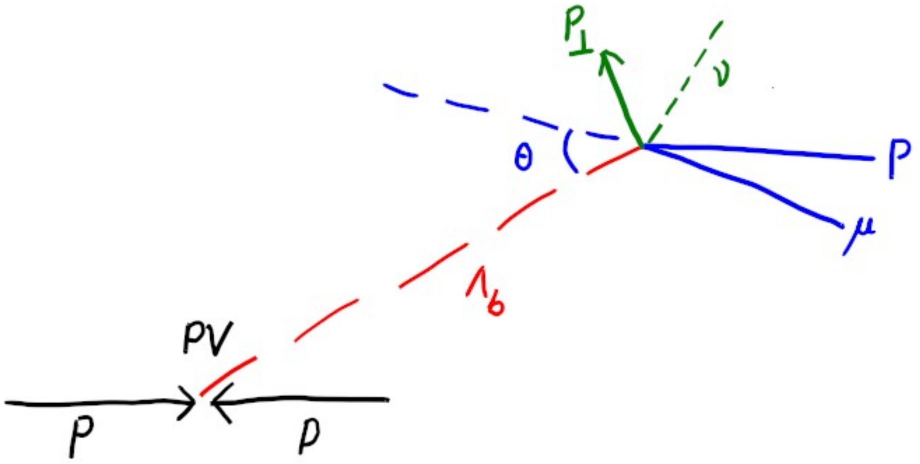
Corrected mass

- Consider the rest frame of the Λ_b

$$m_{\Lambda_b} = E_{p\mu} + E_{\nu}$$
$$= \sqrt{m_{p\mu}^2 + p_\perp^2 + p_\parallel^2} + \sqrt{p_\perp^2 + p_\parallel^2}$$

- Now ignore the unknown $p_\parallel$

$$m_{corr} = \sqrt{m_{p\mu}^2 + p_\perp^2} + p_\perp$$



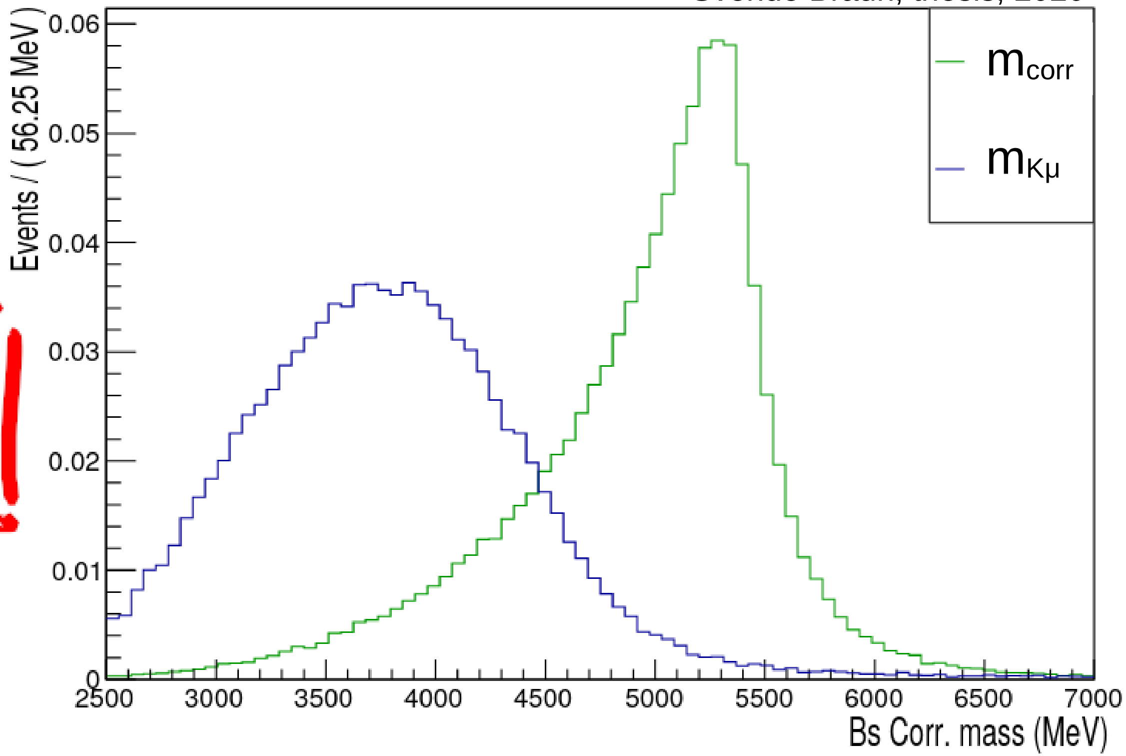
- Ignoring resolution effects, we always have $m_{corr} < m_{\Lambda b}$

Corrected mass

- The corrected mass is not restoring the mass resolution but still gives a peak
- Here illustrated in $B_s \to K\mu\nu$ simulation

$$m_{corr} = \sqrt{m_{p\mu}^2 + p_\perp^2} + p_\perp$$

Svende Braun, thesis, 2020



Corrected mass

- Width of corrected mass peak is affected by primary and secondary vertex reconstructions

$$\sigma^2_{m_{\text{corr}}} = \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{\partial m_{\text{corr}}}{\partial x^i_{\text{PV}}} \frac{\partial m_{\text{corr}}}{\partial x^j_{\text{PV}}} M_{ij} + \sum_{n=1}^{3}\sum_{m=1}^{3} \frac{\partial m_{\text{corr}}}{\partial k^m} \frac{\partial m_{\text{corr}}}{\partial k^n} J_{mn}$$

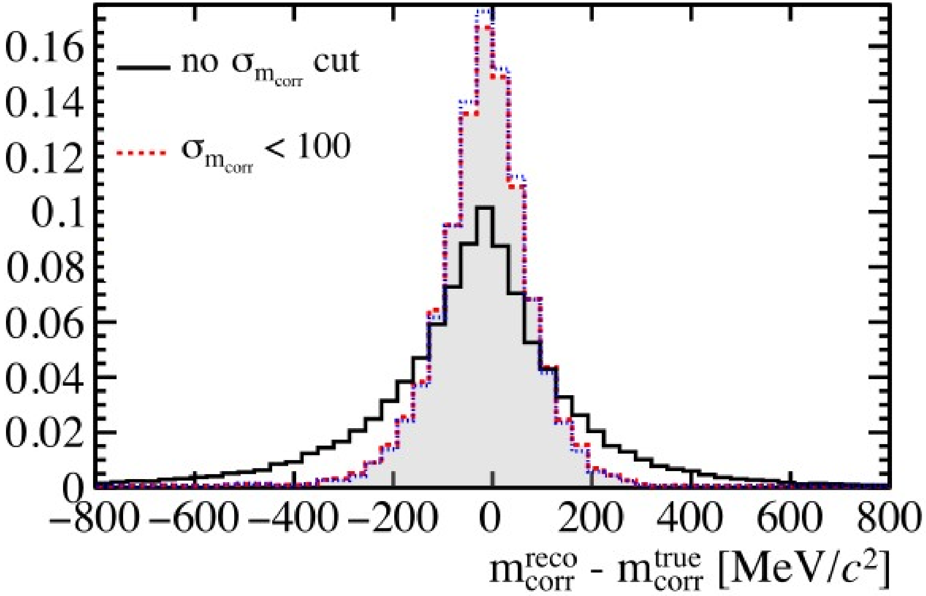
3x3 error matrix of PV

3x3 error matrix of SV

Corrected mass

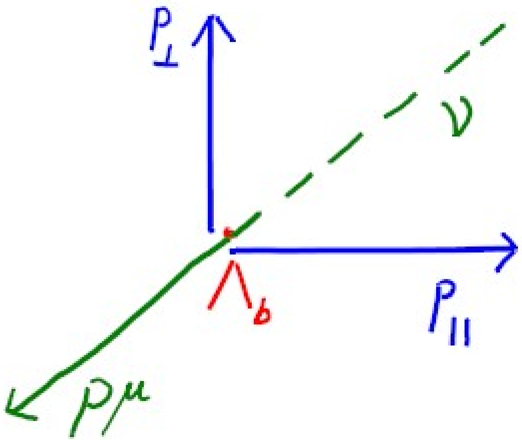
- Width of corrected mass peak is affected by primary and secondary vertex reconstructions

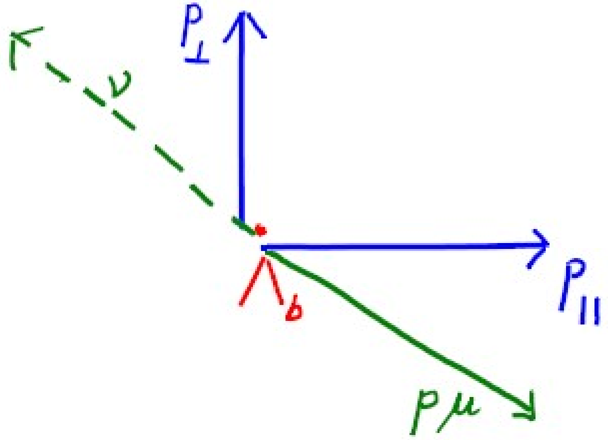
$$\sigma^2_{m_{\rm corr}} = \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{\partial m_{\rm corr}}{\partial x^i_{\rm PV}} \frac{\partial m_{\rm corr}}{\partial x^j_{\rm PV}} M_{ij} + \sum_{n=1}^{3}\sum_{m=1}^{3} \frac{\partial m_{\rm corr}}{\partial k^m} \frac{\partial m_{\rm corr}}{\partial k^n} J_{mn}$$



How to get the kinematics

- Having a signal candidate, we would now like to get the kinematics of the decay
- By now assuming the b-hadron mass, we can calculate $p_{\parallel}$
- 2-fold ambiguity corresponding to if neutrino goes forwards or backwards in b-hadron rest frame

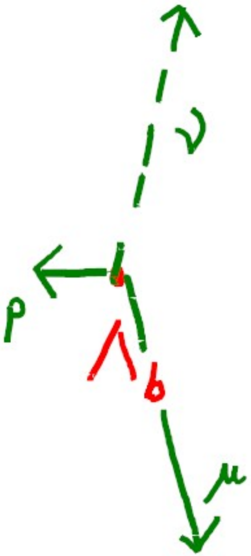




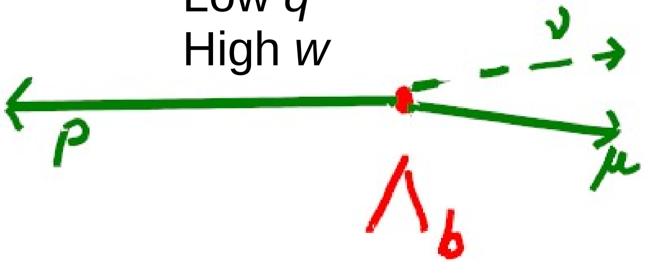
How to get the kinematics

- We use two equivalent variables
  - Recoil energy w – energy of hadronic system in rest frame
  - q^2 – squared mass of $\nu\mu$ lepton system

High q^2
Low w



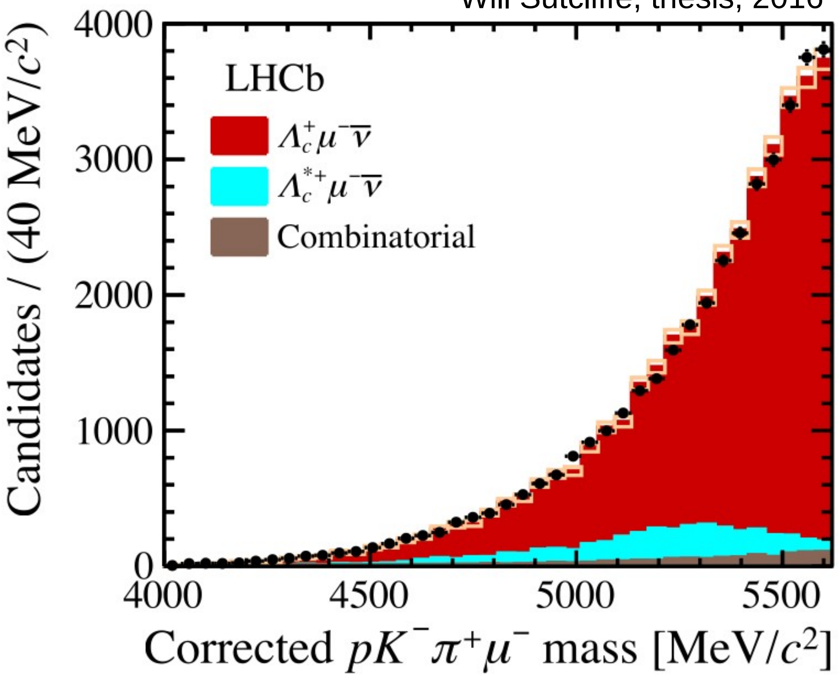
Low q^2
High w



How to get the kinematics

- Unphysical solutions
- The quadratic equation sometimes have two imaginary solutions
  - These correspond to $m_{corr} > m_{\Lambda b}$
  - We can either discard them as unphysical – see $\Lambda_b \to \Lambda_c \mu \nu$ example
  - … or keep them to understand resolution effects

Will Sutcliffe, thesis, 2016

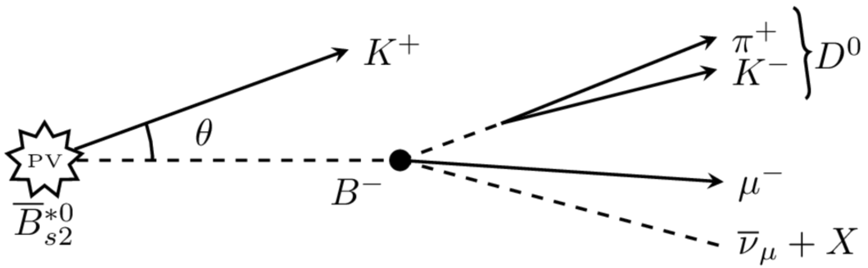


How to get the kinematics

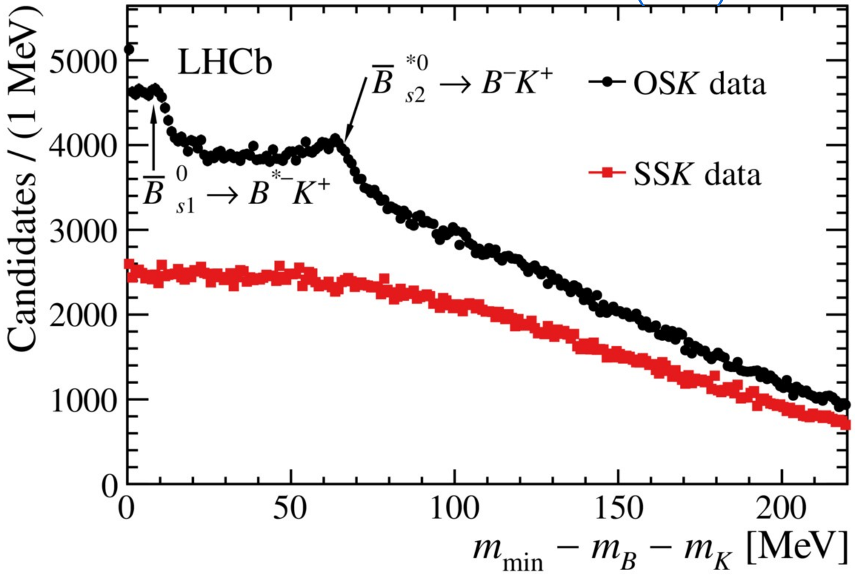
- With two solutions, there are different strategies for going ahead
- Both solutions can be kept in analysis.
  - Great care has to taken with uncertainties as we now get weighted events
  - Might not be optimal
- Always pick the one with smallest or largest q^2
  - This can be the optimal way to reduce systematic uncertainties
- Pick the best one
  - The two solutions result in different *b*-hadron momentum.
  - As we know *b*-hadron spectrum and *b* lifetime, one solution will be more probable

Recover the lost constraint through cascade decays

- Most of us are familiar with using $D^{*+} \rightarrow D^0 \pi^+_s$ decays as a way to reduce background in charm decays and to recover kinematic constraint
- Same trick can be played for *b*-hadrons but works less well



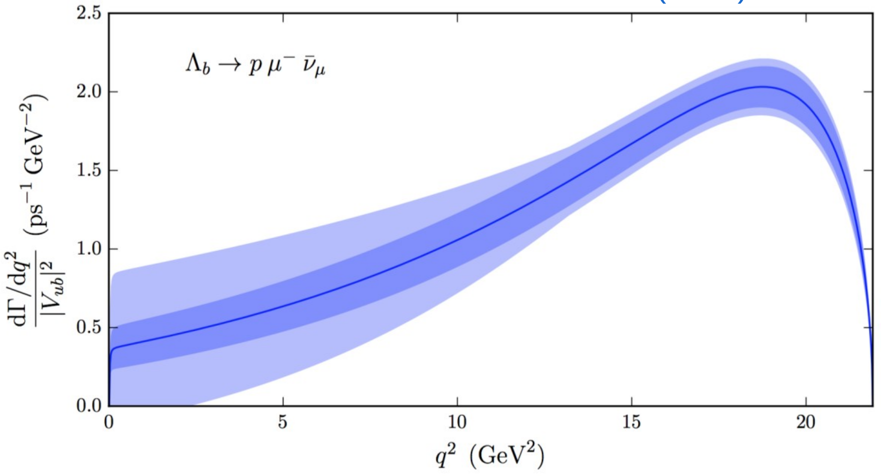
PRD99 (2019) 092009



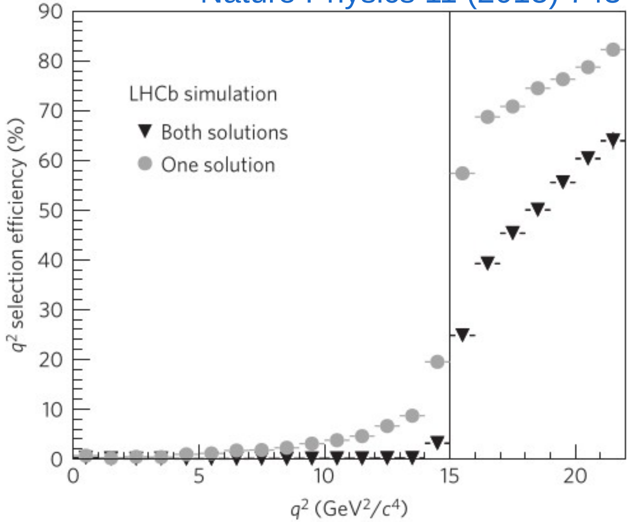
Analyses using the tools at LHCb

- $\Lambda_b \to p\mu\nu$ and $\Lambda_b \to \Lambda_c\mu\nu$ measured to determine $|V_{ub}|/|V_{cb}|$
  - Want to identify candidates with high q^2 (low recoil) where Lattice QCD predictions of form factors are the best
  - Pick only events where the lowest q^2 solution is above 15 GeV^2

PRD92 (2015) 034503



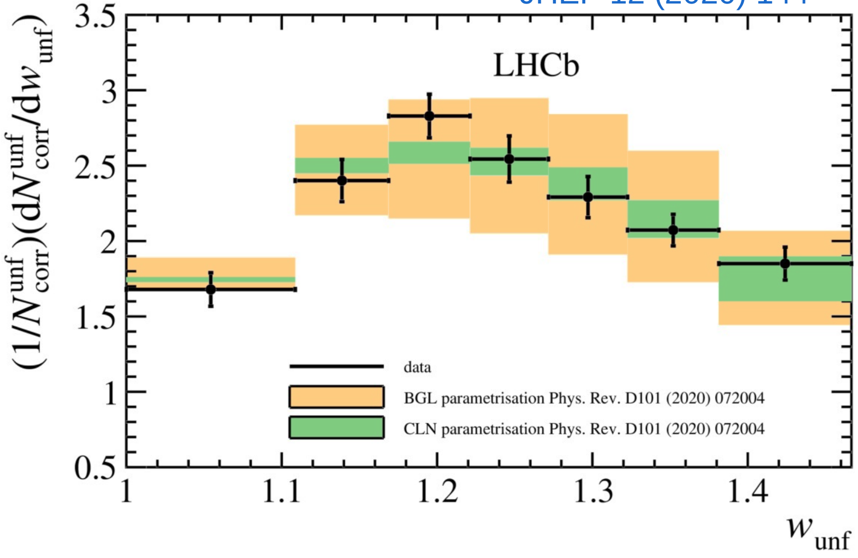
Nature Physics 11 (2015) 743



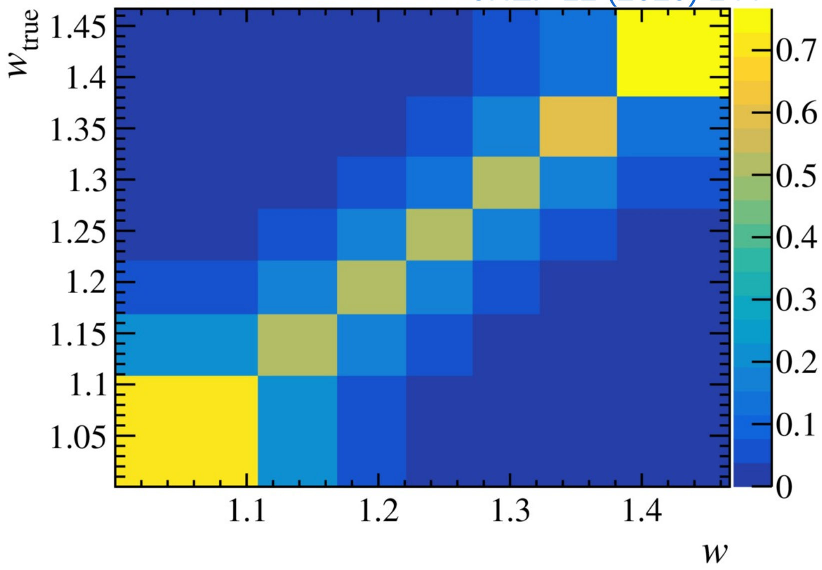
Analyses using the tools at LHCb

- Spectra of $B^0_s \to D_s^* \mu \nu$
  - Machine learning method used to pick correct solution 70% of time
  - Spectra can be unfolded but a remaining correlation between bins is left

JHEP 12 (2020) 144



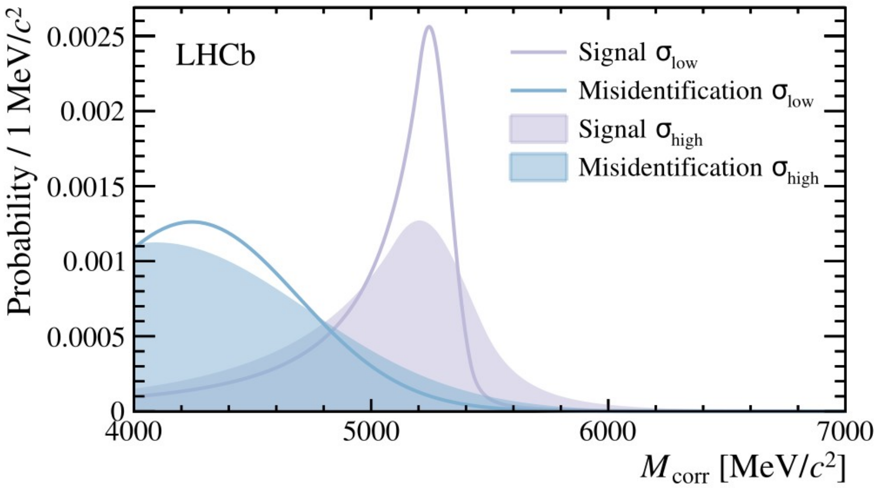
JHEP 12 (2020) 144



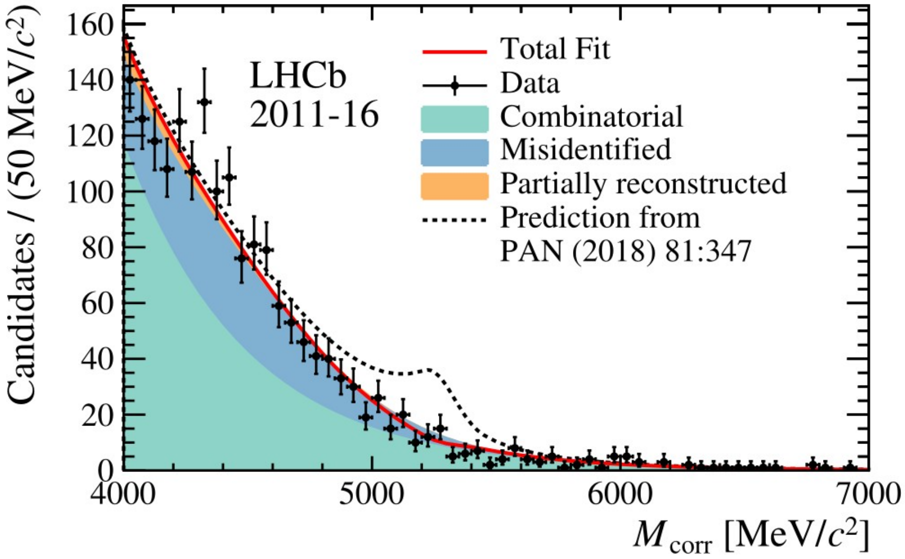
Analyses using the tools at LHCb

- A search has also been perfopmed for the rare decay $B^{+}\to\mu\mu\mu\nu$
  - The use of muon identification, corrected mass and the uncertainty on the corrected mass essential to reduce background
  - Achieves branching fraction limit of 1.8 x 10^{-8}

EPJC 79 (2019) 675



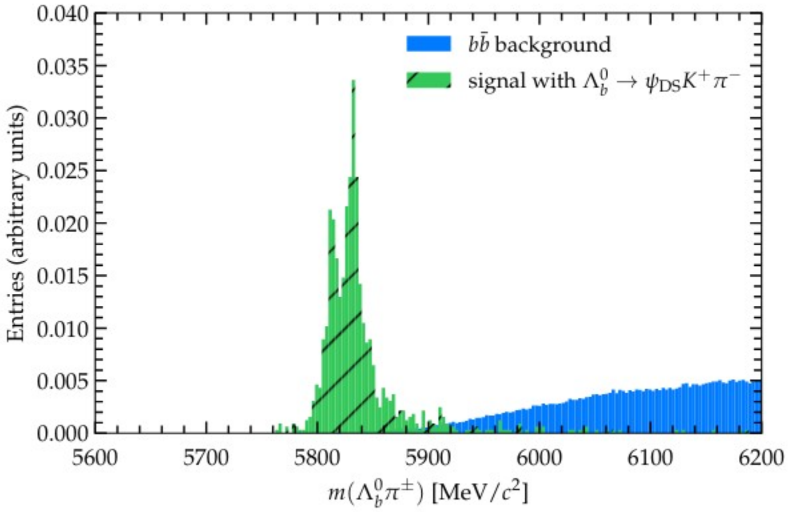
EPJC 79 (2019) 675



What if missing particle is massive

- If we have a single missing particle that is massive, assumption for m_{corr} breaks down
  - Separation less powerful
- The use of cascade decays now becomes essential
  - Idea explored in looking for dark matter candidate
- Method not exploited yet

ArXiv:2106.12870



Conclusion

- Semileptonic $b \to c$ and $b \to u$ decays can be cleanly reconstructed in LHCb with kinematics well determined
- The corrected mass variable is essential for high quality separation of signal and background
- Cascade decays can be utilised but comes at a price of lower efficiency and fake solutions
- Rare decays are possible to search for as well