Studying unique beauty at LHCb

Seminar at TU Dortmund, July 30, 2025

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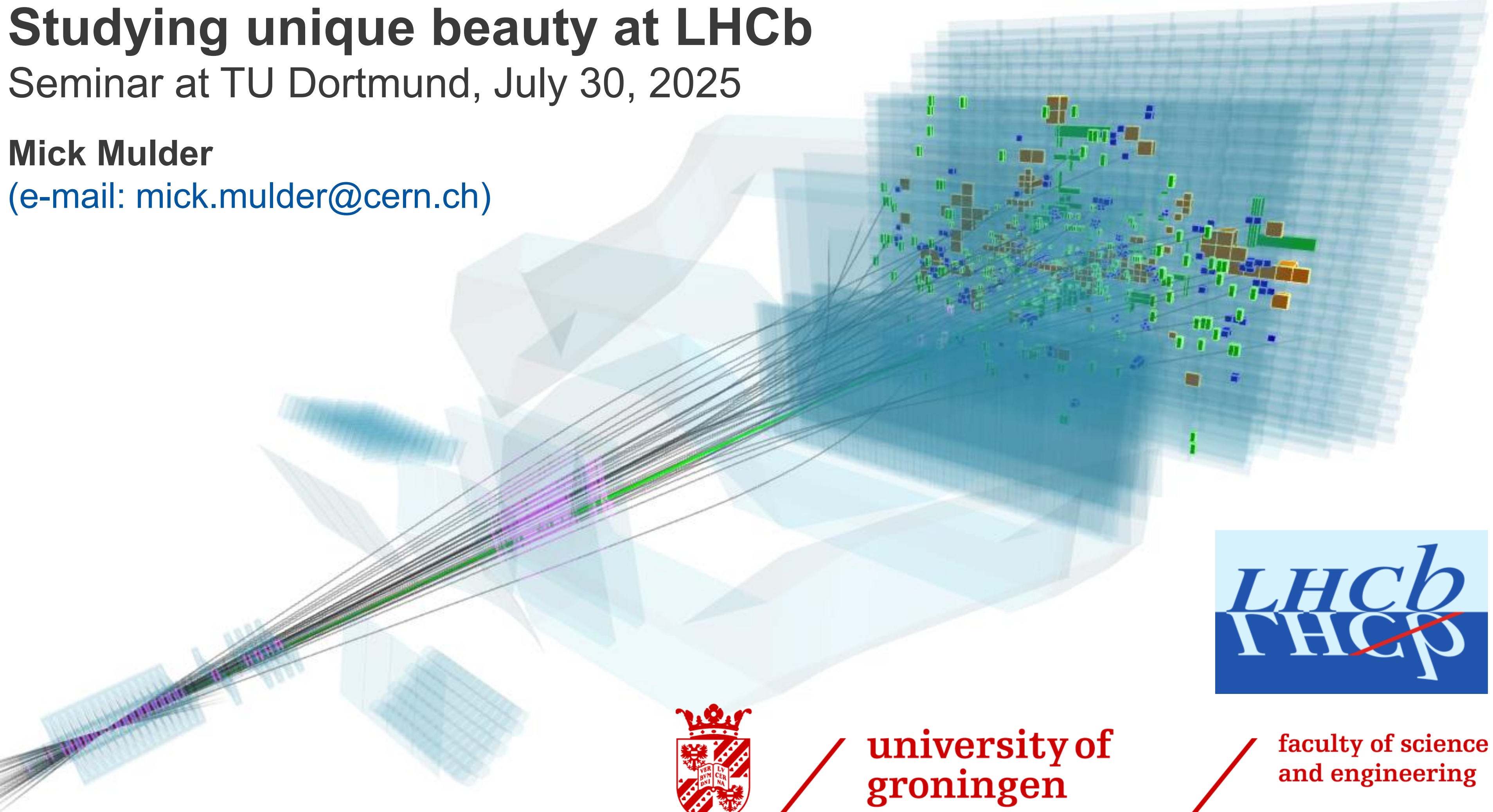

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Unique beauty at LHCb

At LHCb, all kinds of b hadrons are produced abundantly, including Λ_b^0 (udb), B_s^0 ($\bar{b}s$) and B_c^+($\bar{b}c$)

They can give unique insights into the flavour puzzle!

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They can give unique insights into the flavour puzzle!

On the menu today:

- Semileptonic rare decays: $\Lambda_b^0 \to \Lambda^0 \ell^+ \ell^{(\prime)-}$, with $\ell^{(\prime)}$ either μ or e
- Leptonic rare decays: $B_{(s)}^0 \to \mu^+\mu^-$
- “Regular” leptonic decays: $B_{(c)}^+ \to \tau^+\nu$

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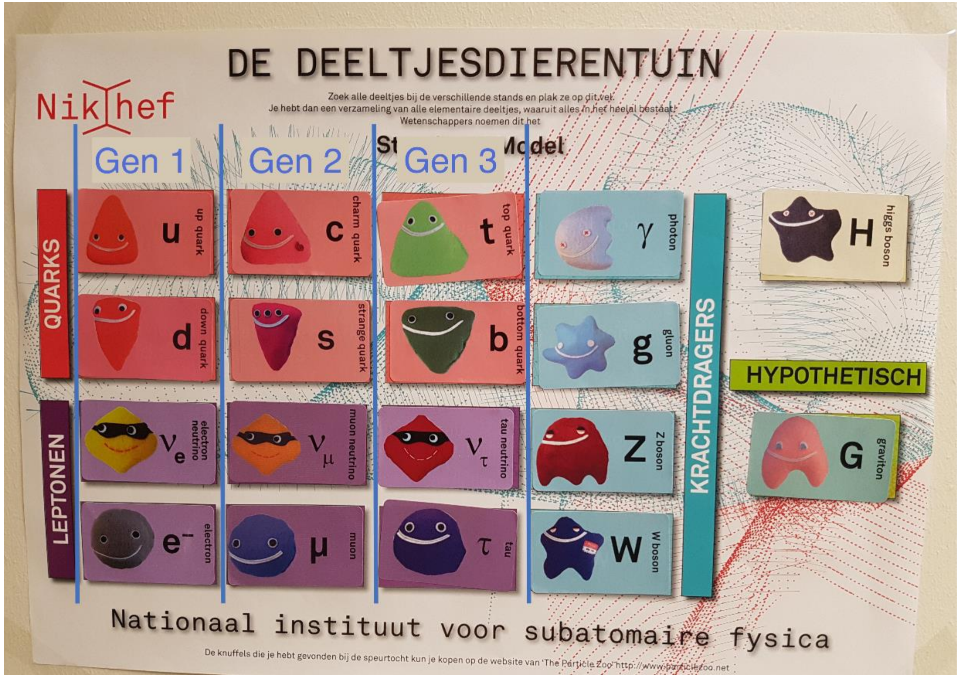
But what is the flavour puzzle?

Flavour puzzle: generations

There are three generations of matter:
Why exactly three?
Perhaps because at least three are needed for CP violation,
i.e. matter-antimatter differences?



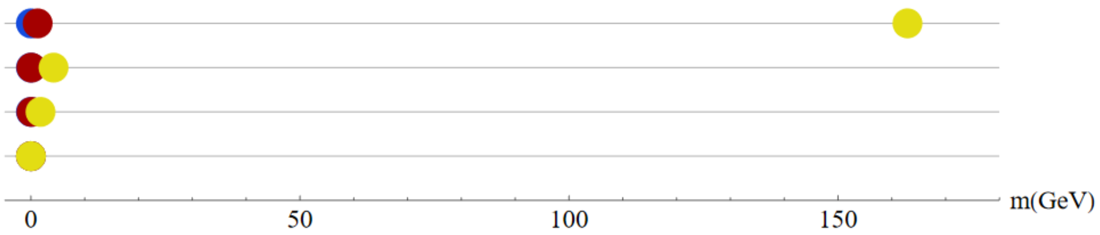
Flavour puzzle: masses

20 out of 26 Standard Model parameters associated with Higgs particle
12 masses, one per fermion

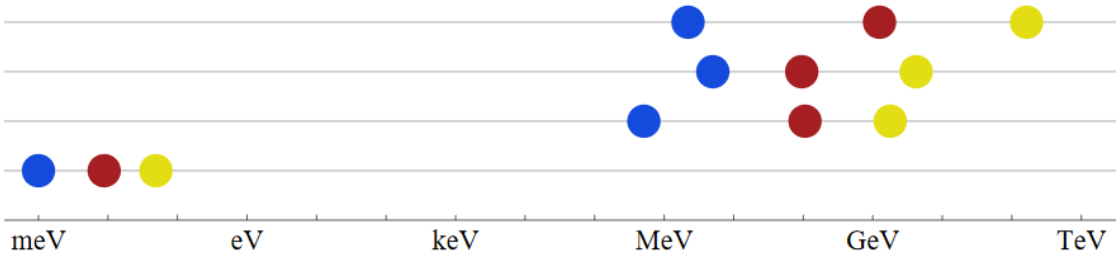
Why are masses so hierarchical for quarks + charged leptons?

Why are neutrino masses so much smaller?

Masses on linear scale for **first**, **second**, **third** gen



Masses on log scale for **first**, **second**, **third** gen

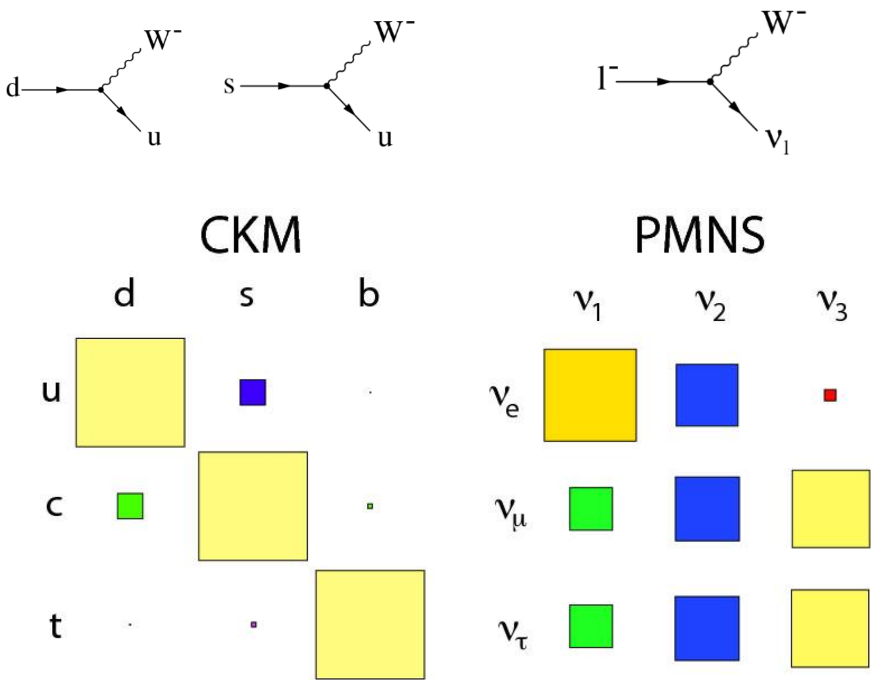


Flavour puzzle: fermion mixing

Quark mixing caused by separate eigenstates for
Higgs, weak interaction →
4 parameters for quarks,
4 parameters for leptons

Why do mixing parameters for quarks look hierarchical and anarchical for neutrinos?

To solve flavour puzzle: study third generation
→ beauty quarks



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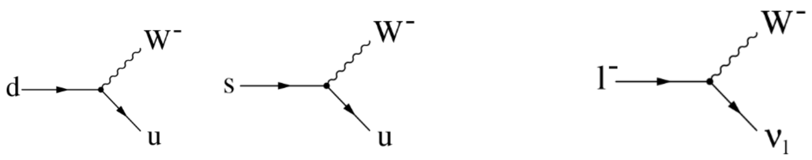
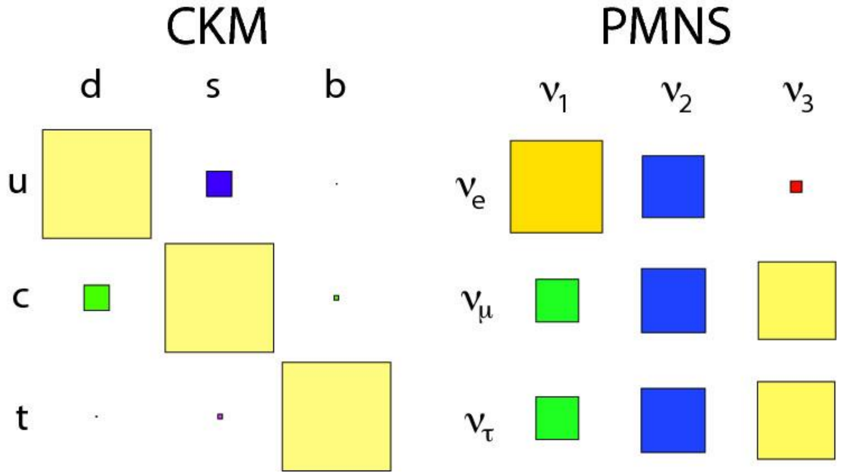
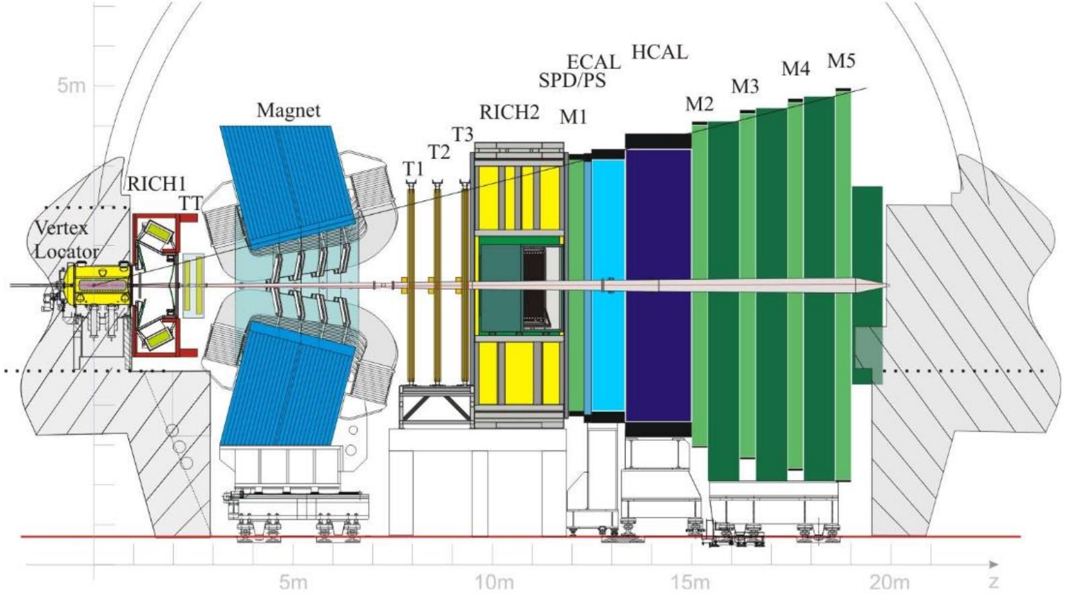
Where to study them? LHCb!





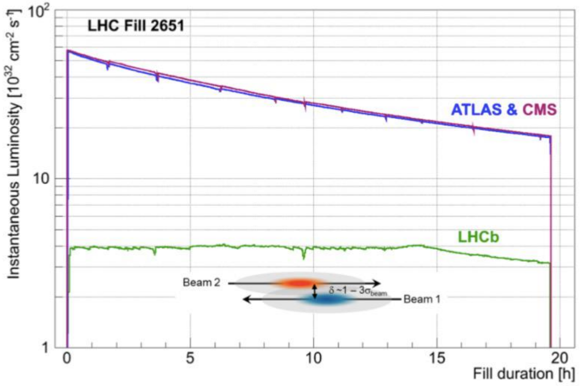
LHCb experiment

- Forward spectrometer at the LHC, optimised for b-hadrons
- $b\bar{b}$ cross section $= 154.3 \pm 1.5$ μb at $\sqrt{s}$ =13 TeV in acceptance $2 < \eta < 5$
- $O(10^5)$ $b\bar{b}$ pairs/s in LHC Run 1 & 2 (and 20 x more $c\bar{c}$)

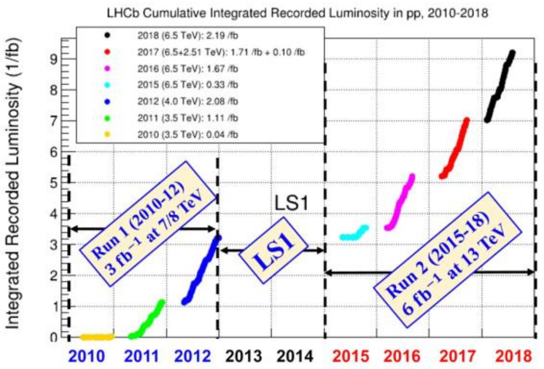


LHCb Run 1 & 2 data taking

- Running with LHC luminosity levelling ($\mathcal{L} = 4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 2x design luminosity)
  → **stable data-taking conditions**
- Corresponds to 1.5 interactions per bunch crossing



- Total of $9\ \mathrm{fb}^{-1}$ collected
  → around $3 \cdot 10^{12}\ \mathrm{b\bar{b}}$ pairs produced!



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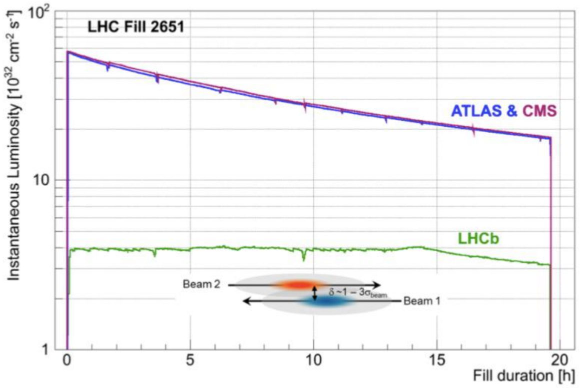

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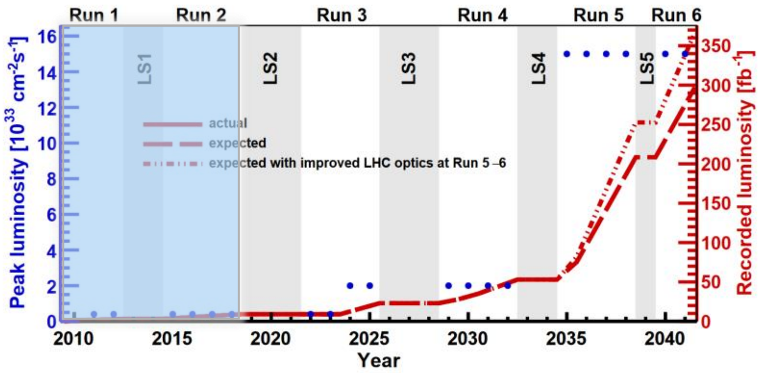
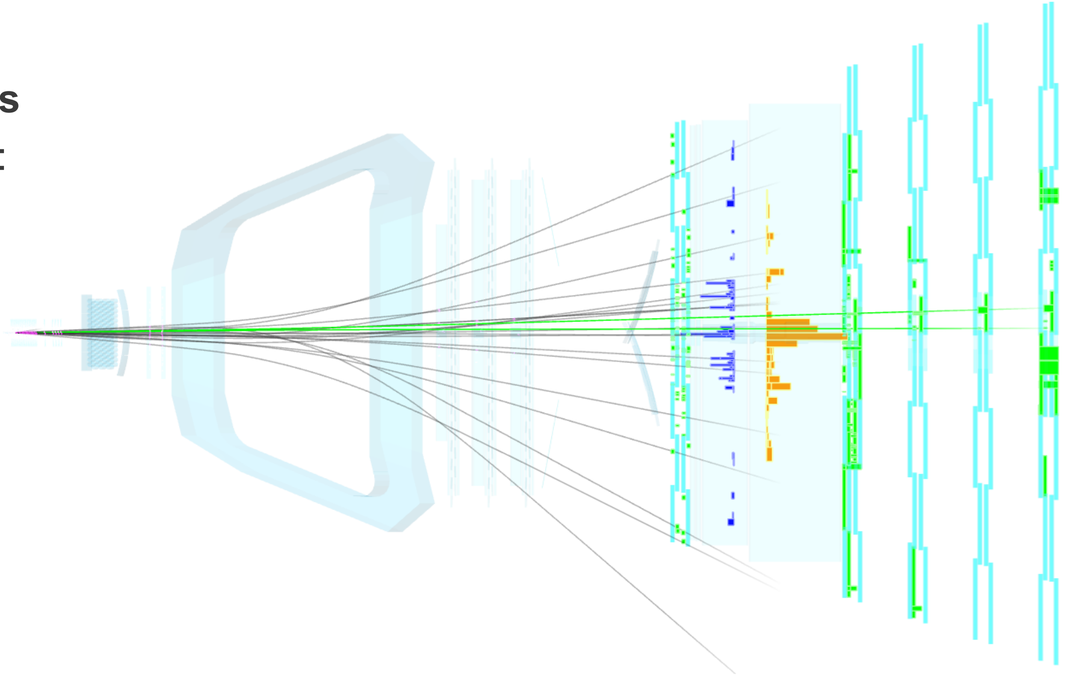
- **Only the beginning!**



LHCb performance

- Very good momentum resolution ($\Delta p/p = 0.5 - 1.0\%$)
  → **Sufficient to separate B_s^0, B^0 decays**
- Excellent charged particle identification:
  μ ID ~ 97 % w. 1-3% $\pi \rightarrow \mu$ mis-id
  e ID ~ 90 % w. ~ 5% $h \rightarrow e$ mis-id
  → **required to reject hadronic B decays & separate π, K, p**



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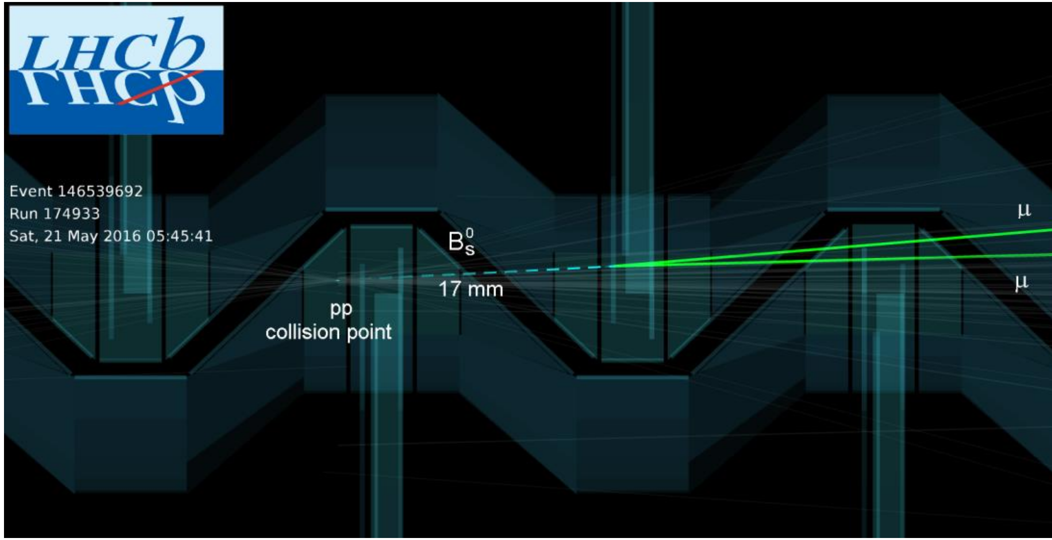
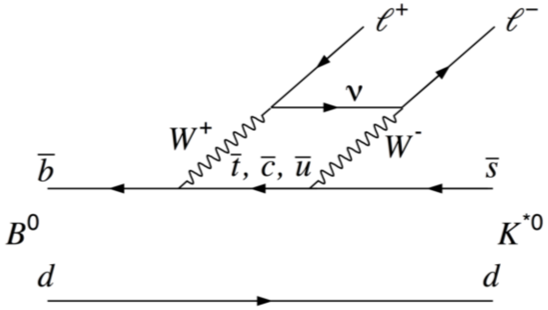
  → **required to reject hadronic B decays & separate π, K, p**
- Clear separation of B hadron decay vertex and pp collision:
  45 fs decay time resolution ≅ 3% of B lifetime
  → **essential to reduce backgrounds**

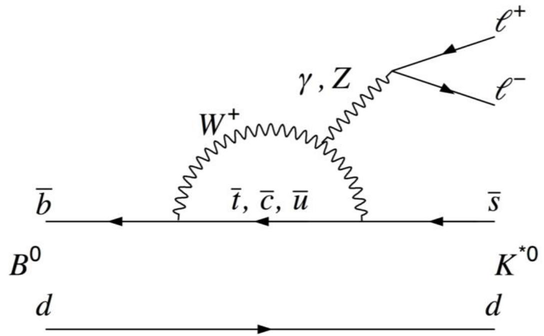


Rare decays

Rare decays: $b \to s(d)\ell\ell$

- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)





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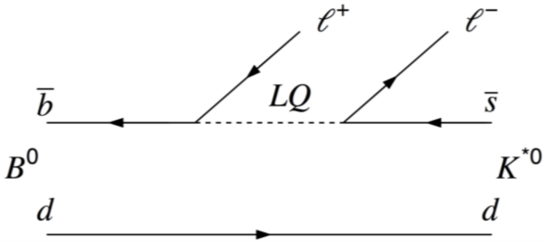
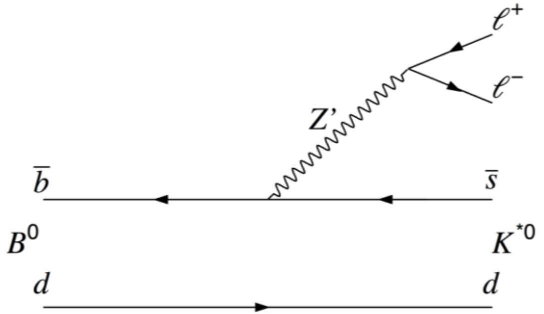
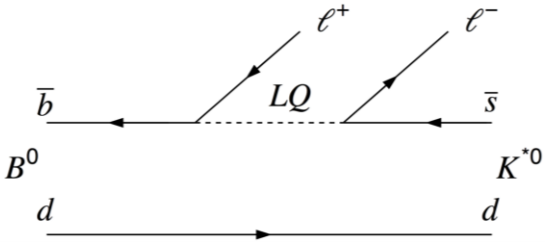
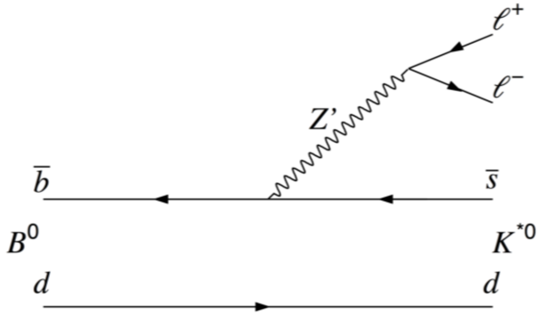




Rare decays: $b \to s(d)\ell\ell$

- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)
- Transition uncommon in Standard Model, **sensitive to small contributions from heavy new particles**!
- Large variety of channels and observables, such as:
  - Branching fractions
  - Angular distributions
  - Lepton universality (e.g. $\Lambda_b^0 \to \Lambda\ell^+\ell^-$) → today
  - Leptonic decays (e.g. $B_s^0 \to \mu^+\mu^-$) → today



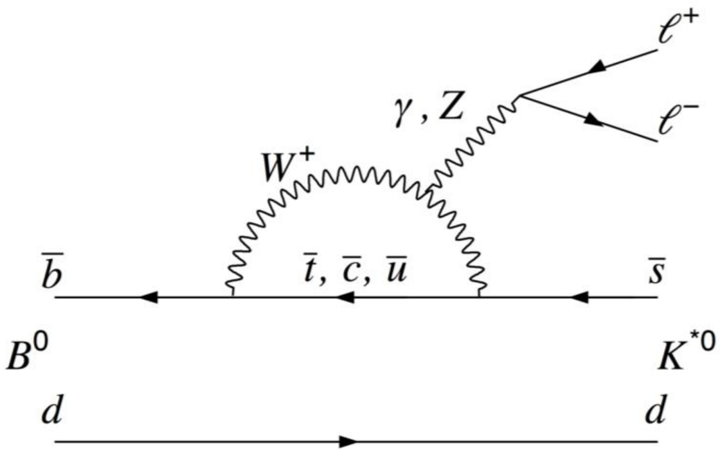


Semileptonic rare decays and $\Lambda_b^0 \to \Lambda \ell^+ \ell^-$

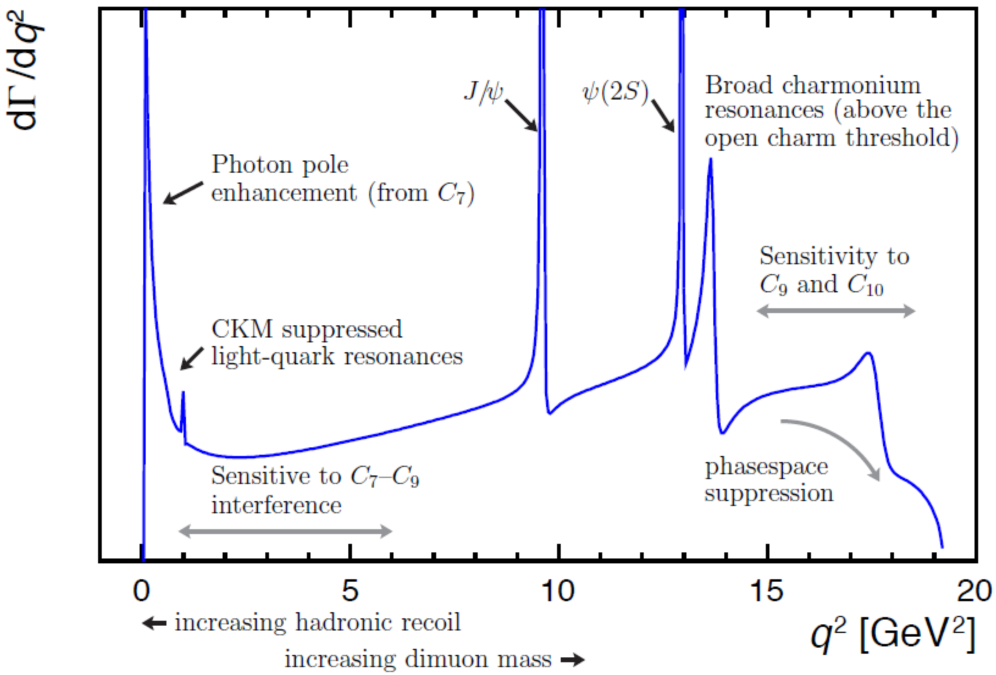
Semileptonic rare decays: q^2

Physics depends on $q^2 = m^2_{\ell\ell}$:

- Resonances (e.g. $J/\psi, \phi$)
- Photon pole at very low q^2
- Vector or axial vector current

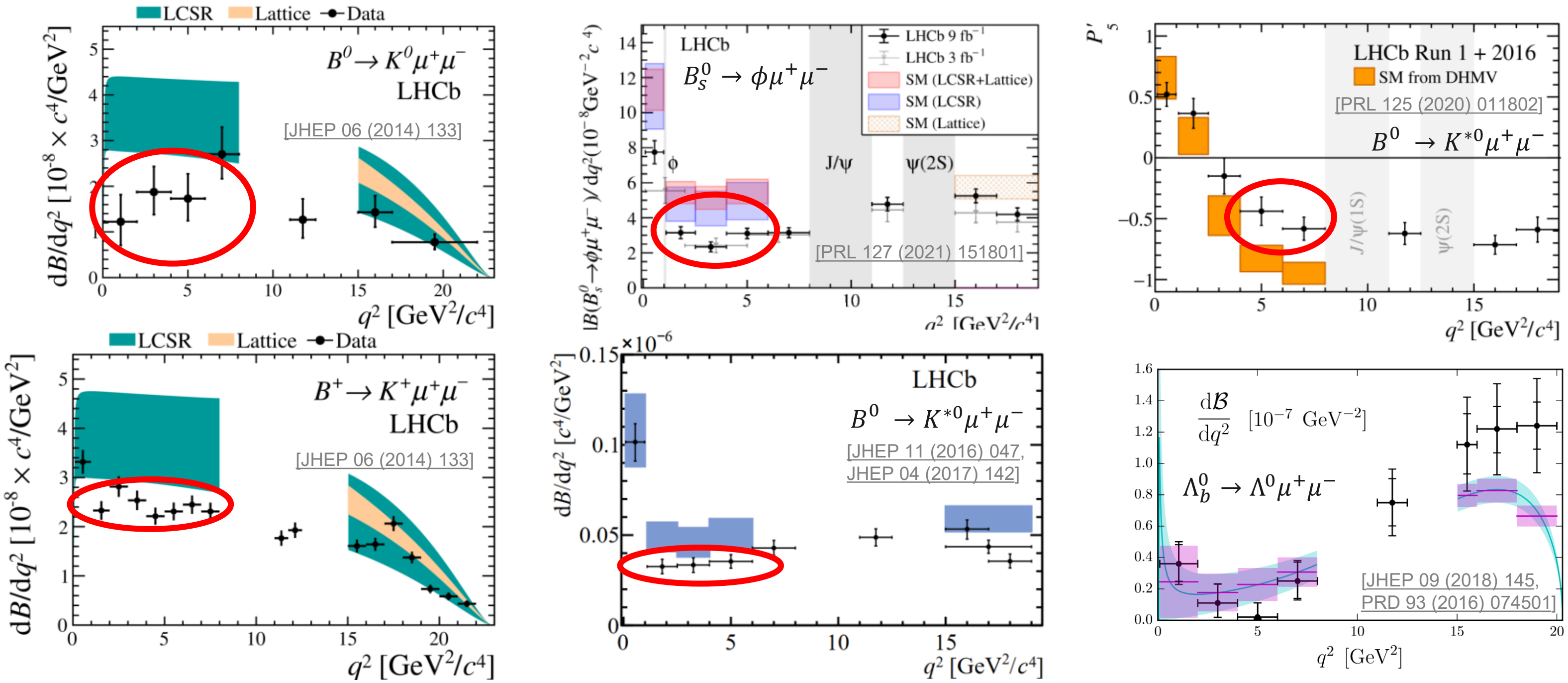


T.Blake et al. arXiv:1606.00916



Semileptonic rare decays: deviations

Measurements of semileptonic rare decays **still deviate** from predictions….



Note: these deviations are consistent (interpreted in EFT framework, see backup)

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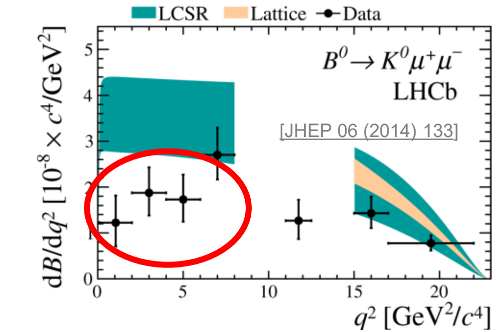
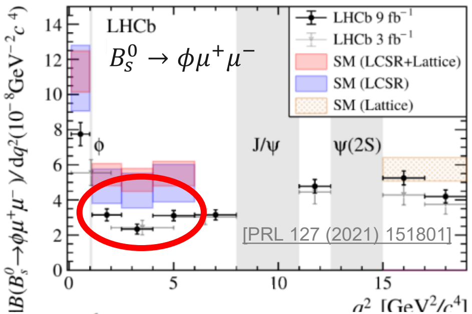
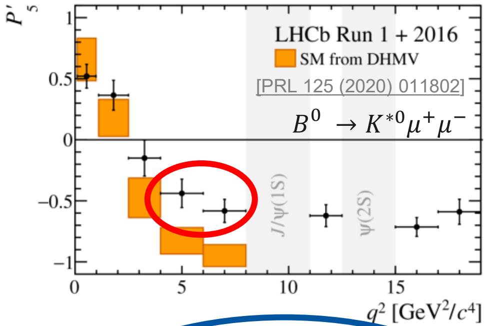
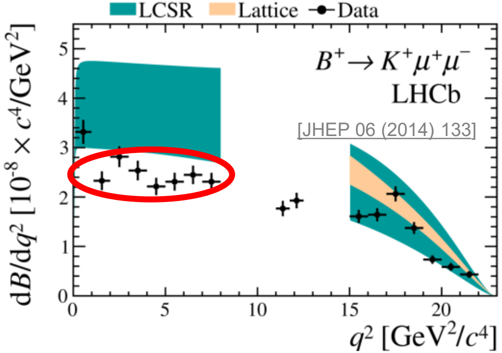
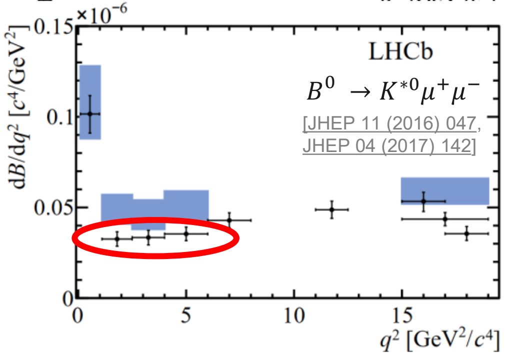
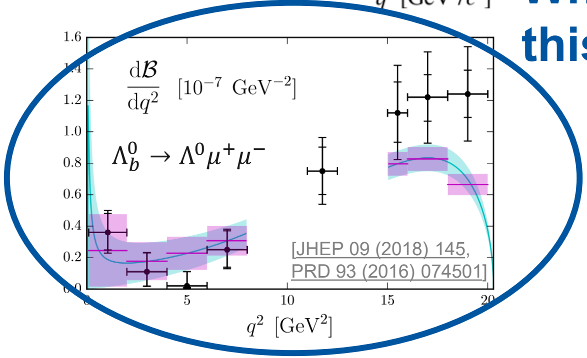










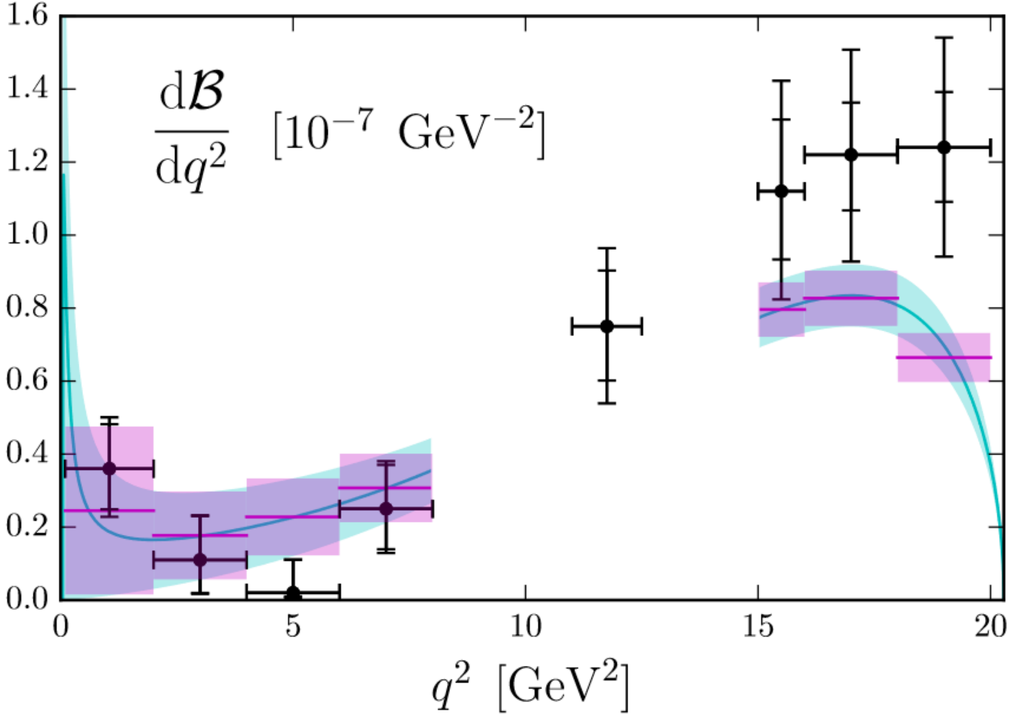


What about this plot?

Note: these deviations are consistent (interpreted in EFT framework, see backup)

Add the $\Lambda_b^0 \to \Lambda^0 \ell\ell'$ system to the mix!

Current knowledge on $\Lambda_b^0 \to \Lambda^0 \ell^+\ell^-$ limited by uncertainty on $\mathrm{BF}(\Lambda_b^0 \to J/\psi\Lambda^0)$ (~20%)



Very interesting laboratory!

- Baryon to baryon transition → polarised states
- The Λ baryon decays weakly: **many observables available, with much cleaner predictions than $B^0 \to K^{*0}\mu^+\mu^-$**
- Competitive with B meson measurements at high q^2

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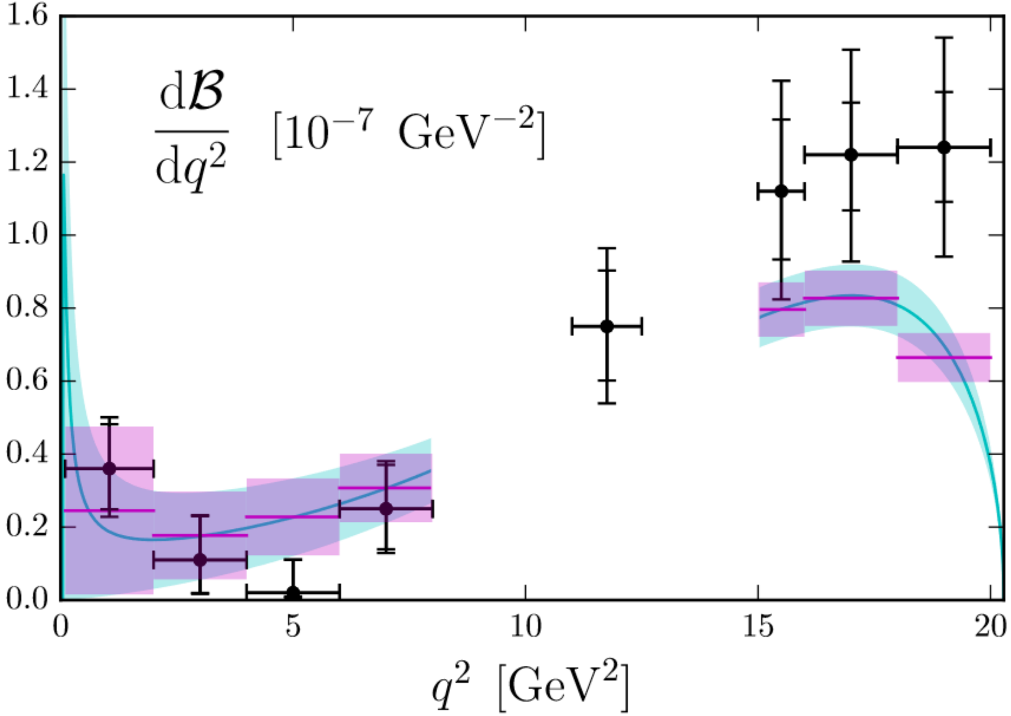


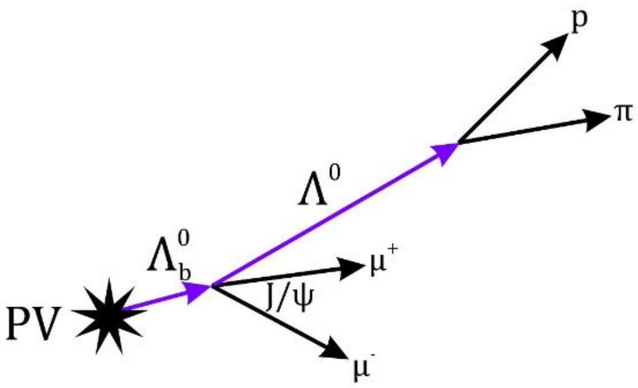
Our group has three goals:

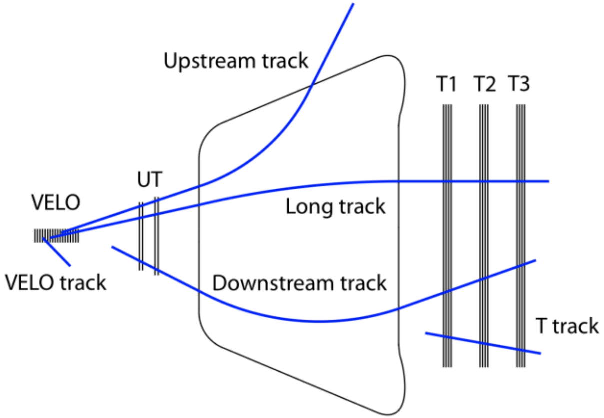
1. Measure $\mathrm{BF}(\Lambda_b^0 \to J/\psi \Lambda^0)$
2. First limit on $\Lambda_b^0 \to \Lambda^0 e^{\pm} \mu^{\mp}$
3. First lepton universality test: $\Lambda_b^0 \to \Lambda^0 e^+ e^- / \Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$

Will briefly discuss 1. and 3. today

Reconstructing $\Lambda_b^0 \to \Lambda^0 \ell \ell'$

- Use Λ^0 with two long tracks (LL) or two downstream tracks (DD)
- Major loss in statistics because of slow decay, challenging to calibrate



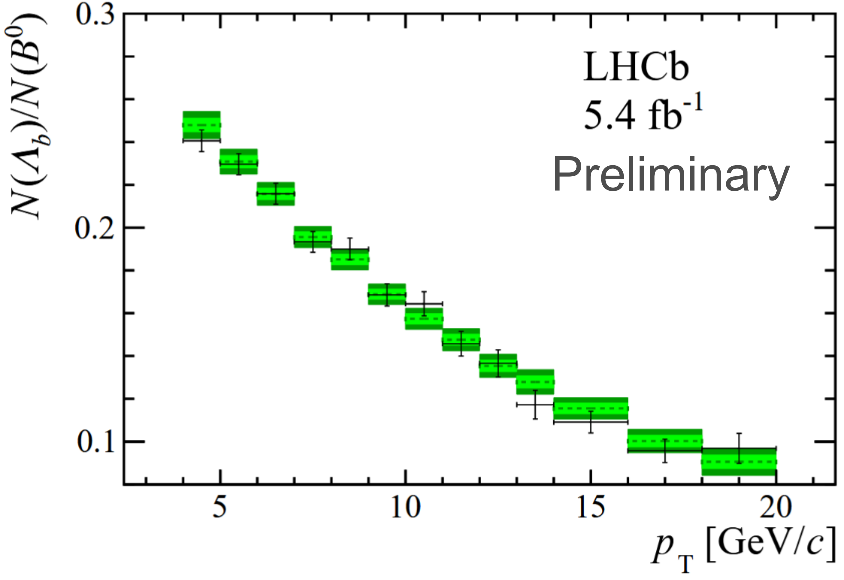


Measuring $\mathrm{BF}(\Lambda_b^0 \to J/\psi\Lambda^0)$

- Use improved determination of Λ_b^0/B^0 production rate $f_{\Lambda_b}^0/f_d$ (7%)
- Experimentally challenging (Λ^0 decays travelling through detector)
- $\mathrm{BF}(\Lambda_b^0 \to J/\psi\Lambda^0) = (3.34 \pm 0.31)\%$,
  reduction of uncertainty by factor 3

- **Unlocks new set of measurements: branching fractions of $\Lambda_b^0 \to \Lambda^0\ell\ell'$**

Recently unblinded results:

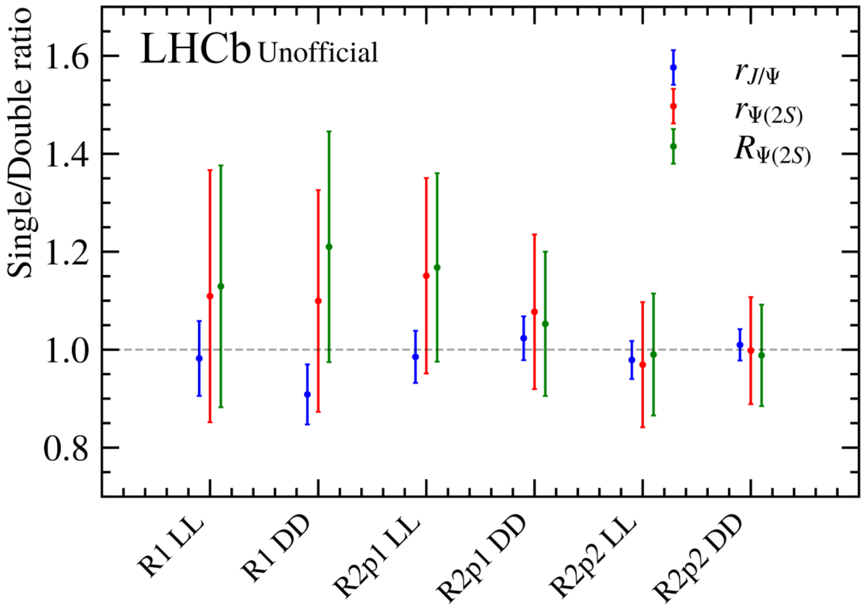


Measuring lepton universality: $R(\Lambda)$

- Precise way to test structure of matter: **lepton flavour universality**
- $R(\Lambda) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda^0 e^+ e^-)} = 1$ (in SM)
- Very challenging: electron momentum is difficult to reconstruct at LHCb
- **Essential: cross-check using more common $\Lambda_b^0 \to J/\psi\Lambda, \psi(2S)\Lambda$ decays, e.g.**

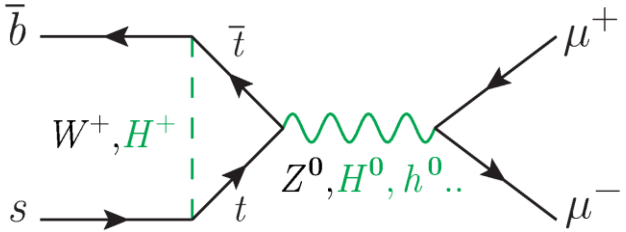
$$r_{J/\psi} = \frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda^0 J/\psi(\to \mu^+\mu^-)\right)}{\mathcal{B}(\Lambda_b^0 \to J/\psi(\to \Lambda^0 e^+ e^-))} = 1$$

- Expected sensitivity of around 16% on $R(\Lambda)$, backgrounds being calibrated

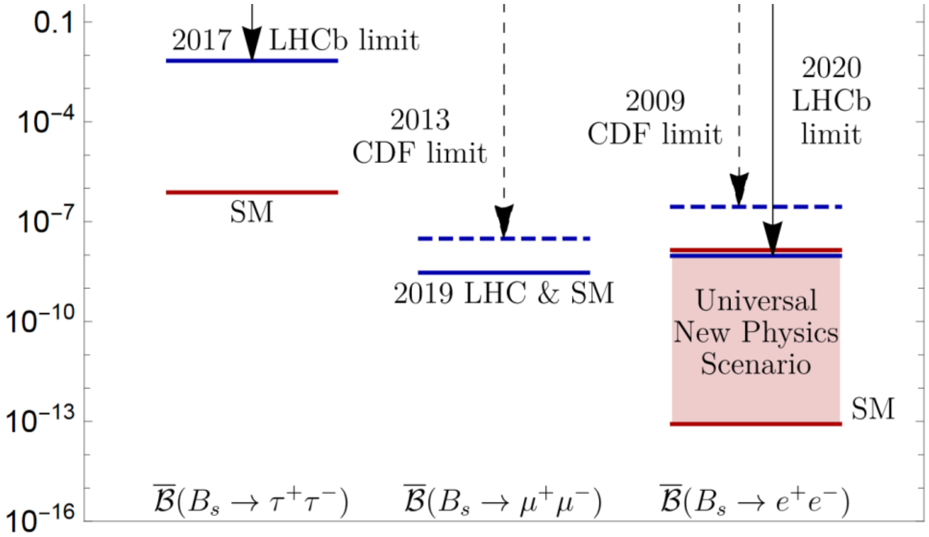


Leptonic rare decays and $B^0_{(s)} \to \mu^+\mu^-$

Leptonic rare decays: $B^0_{(s)} \to l^+ l^-$



- **Precise theory predictions** (decay rate has only ~3% uncertainty)
- **Strong constraints on New Physics**, especially scalar New Physics, due to helicity suppression in SM
- Only $B^0_s \to \mu^+\mu^-$ in current experimental reach



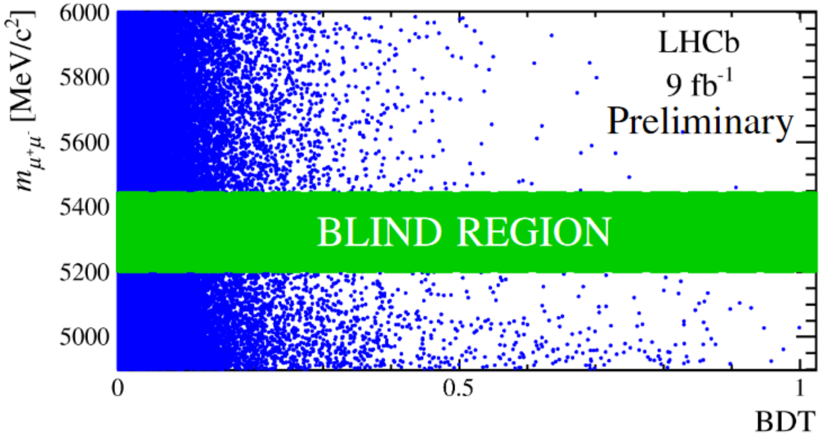
Fleischer et al., JHEP 05 (2017) 156

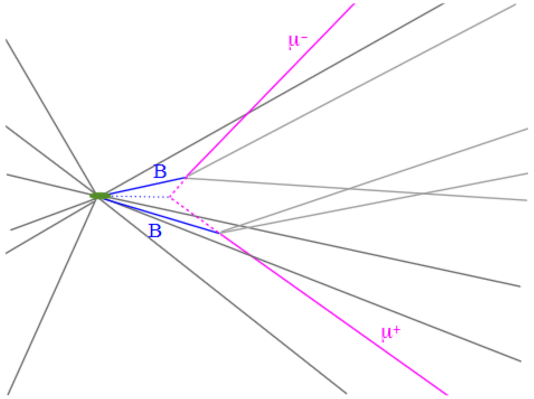
Analysis strategy

- **Similar strategy to previous analysis, strongly improved calibration**
- Use full Run 1 + Run 2 data
- Muon pairs with $m_{\mu^+\mu^-} \in [4.9, 6.0]$ GeV with good displaced vertex
- Signal region blind until analysis is finalised
- Suppress misID with tight Particle ID cut

- Main background: **combinatorial**
- Rejected with multivariate classifier, namely Boosted Decision Tree (BDT)
- **Determine signal from fit to $\mathbf{m_{\mu\mu}}$ and BDT**

[Phys. Rev. D105 (2022) 012010]

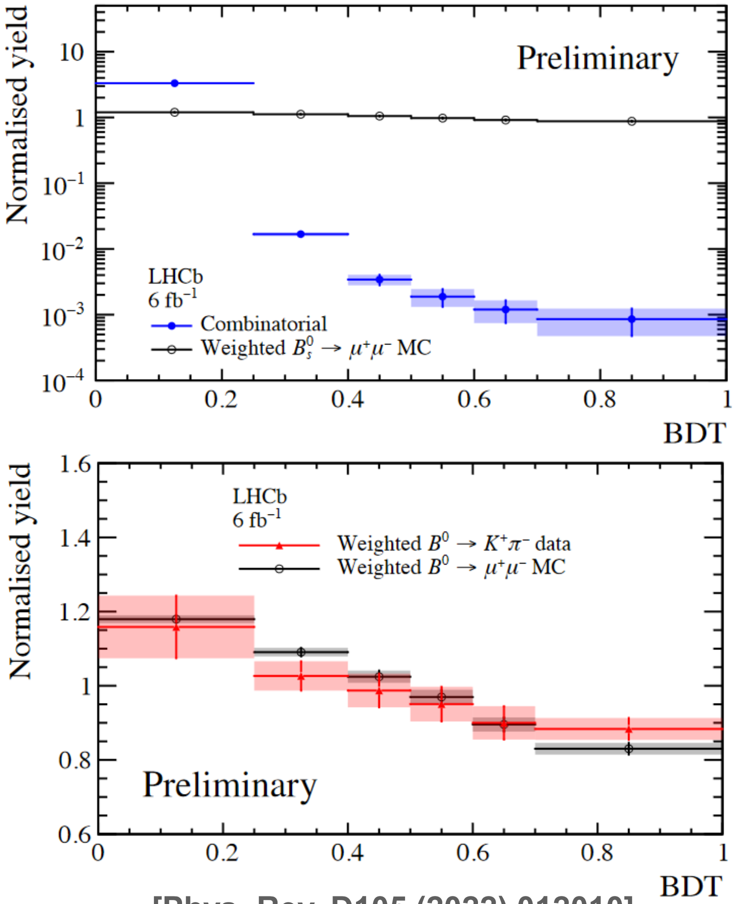




BDT calibration

- Divide fit sample in 6 BDT bins, exclude first bin (too much background)
- Flat for simulated signal before PID and trigger, strongly falling for combinatorial background
- PID, trigger and data-simulation differences can modify the shape

- **New procedure**: simulation samples corrected using data control channels (kinematics, occupancy, PID, trigger)
- Essential: cross-check with $B^0_{(s)} \to h^+h^-$ data!
- **Uncertainty reduced significantly with new procedure**

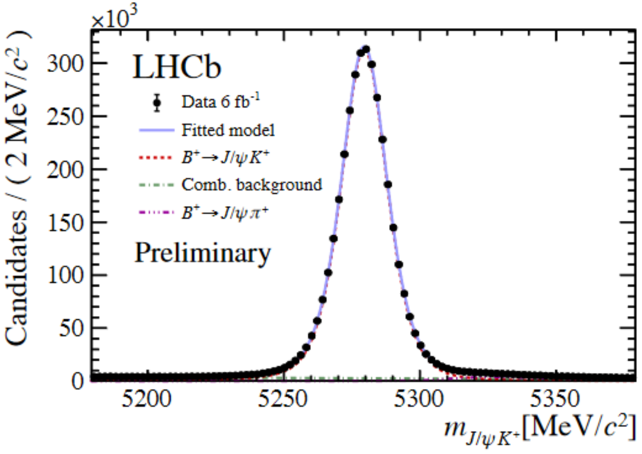


[Phys. Rev. D105 (2022) 012010]

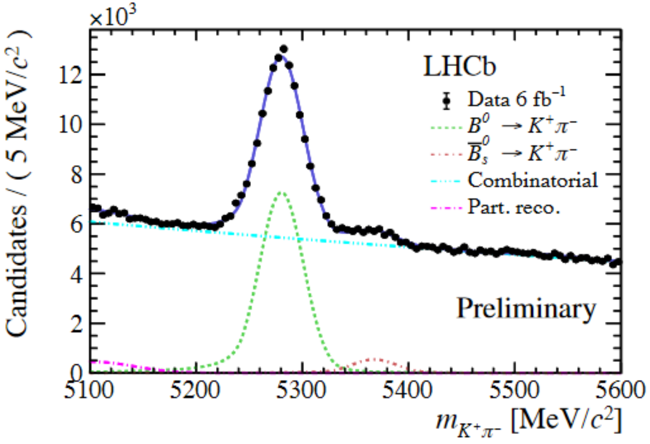
Normalisation: strategy

- Normalise branching fraction to well-known channels
- Use two modes, yields determined from mass fits

$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
Muons in final state: similar trigger, PID



$B^0 \to K^+\pi^-$
Two-body B decay: similar decay topology



[Phys. Rev. D105 (2022) 012010]

Normalisation: results

[Phys. Rev. D105 (2022) 012010]

- Normalisation used to convert yield into BF using

$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \underbrace{\overbrace{\frac{\mathcal{B}_{norm}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{f_{norm}}{f_{d,s}}}^{\alpha_s}}_{\alpha_d} \times N_{B^0_{d,s}\to\mu^+\mu^-}$$

- Normalisation yield and BF
- Signal/normalisation efficiency ratio evaluated from simulation, control channels

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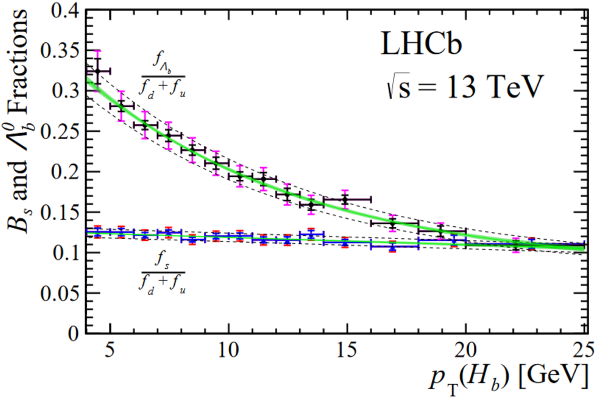
- Normalisation yield and BF
- Signal/normalisation efficiency ratio evaluated from simulation, control channels
- Ratio of hadronisation fractions (for B_s^0): **f_s/f_d from new combination, major reduction in uncertainty**

Intermezzo: f_s/f_d at LHCb

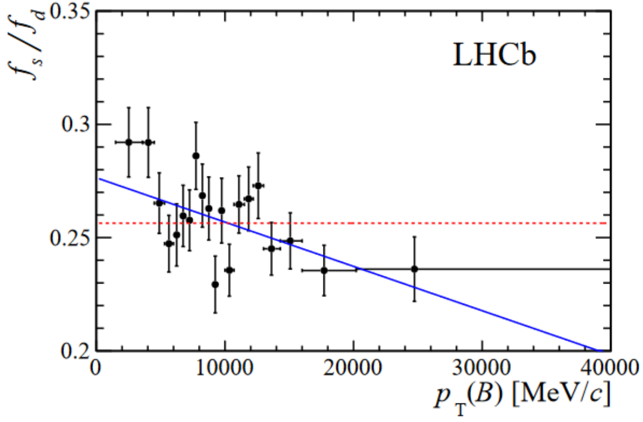
[PRD104 (2021) 032005]

- f_s/f_d = B_s^0/B_d^0 production ratio
  - **Required to measure B_s^0 branching fractions such as $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$**
  - Interesting per se as probe of hadronisation and fragmentation
- **Combine 5 previous measurements** performed at different pp collision energies, versus p_T and η

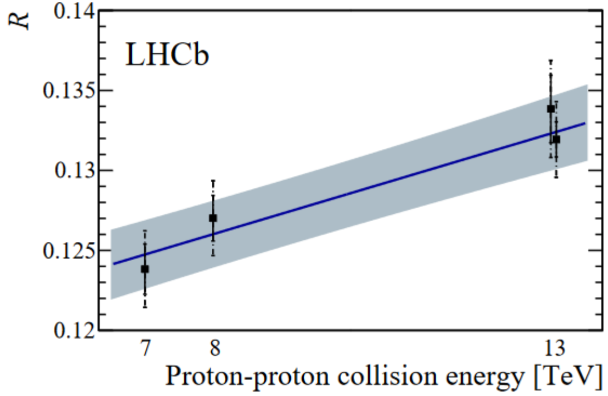
$B \to D\mu X$, 13 TeV



$B \to Dh$, 7 TeV



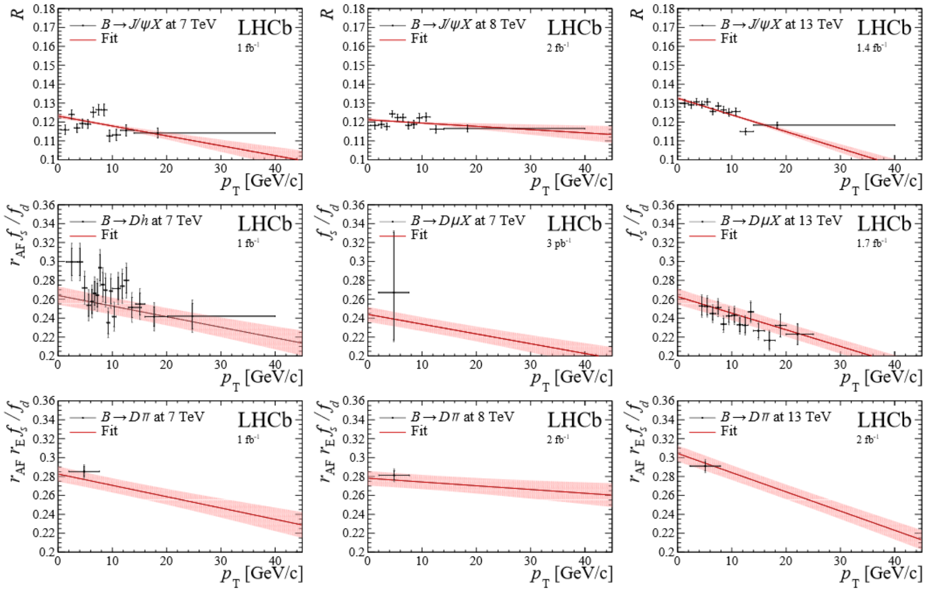
$B \to J/\psi X$, various $\sqrt{s}$



Intermezzo: f_s/f_d at LHCb

[PRD104 (2021) 032005]

- **Complicated analysis,**
  can discuss details if interested
- Observe variation of f_s/f_d with pp collision centre-of-mass energy
- Integrated value in LHCb acceptance:
  $\frac{f_s}{f_d} = 0.2539 \pm 0.0079$
- **Uncertainty reduced by factor two, also applied to previous B_s^0 branching fraction measurements**
- **Essential improvement for future measurements of $B(B_s^0 \to \mu^+\mu^-)$**



[Phys. Rev. D105 (2022) 012010]

Normalisation: results

- Normalisation used to convert yield into BF using

$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \overbrace{\underbrace{\frac{\mathcal{B}_{norm}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}}}_{\alpha_d} \times \frac{f_{norm}}{f_{d,s}}}^{\alpha_s} \times N_{B^0_{d,s}\to\mu^+\mu^-}$$

- Normalisation yield and BF
- Signal/normalisation efficiency ratio evaluated from simulation, control channels
- Ratio of hadronisation fractions (for B_s^0): **f_s/f_d from new combination, major reduction in uncertainty**
- **Signal yields consistent with expected improvement**
- Cross-check: $B(B^0 \to K^+\pi^-)/B(B^+ \to J/\psi K^+)$ consistent w. PDG

Estimated total signal yields (before BDT):

$$N(B_s^0 \to \mu^+\mu^-)_{SM} = 147 \pm 8$$

$$N(B^0 \to \mu^+\mu^-)_{SM} = 16 \pm 1$$

$$N(B_s^0 \to \mu^+\mu^-\gamma)_{SM} \approx 3$$

Backgrounds

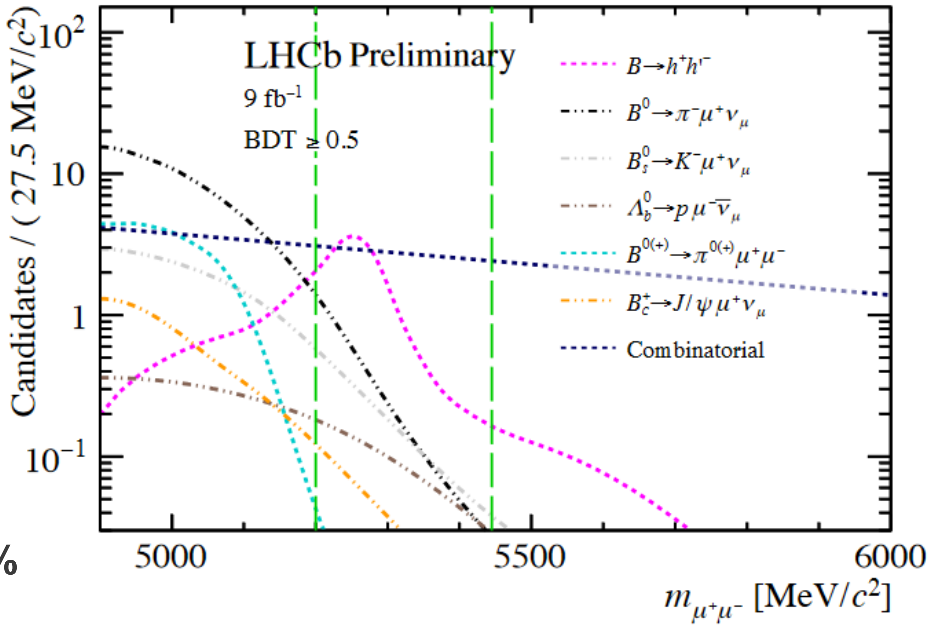
[Phys. Rev. D105 (2022) 012010]

Three types of backgrounds in fit:

1. Combinatorial, over full mass spectrum (free in fit)
2. Mis-identified backgrounds:
   $B^0 \to \pi^- \mu^+ \nu_\mu$, $B_s^0 \to K^- \mu^+ \nu_\mu$,
   $B^0_{(s)} \to h^+ h'^-$, $\Lambda_b^0 \to p \mu^- \overline{\nu_\mu}$
3. Real muons:
   $B^{0/+} \to \pi^{0/+} \mu^+ \mu^-$, $B_c^+ \to J/\psi \mu^+ \nu_\mu$

Calibrate on corrected simulation samples

Cross-check with fit to $B^0_{(s)} \to h^+ h'^-$ data with one hadron mis-identified, consistent within 10%



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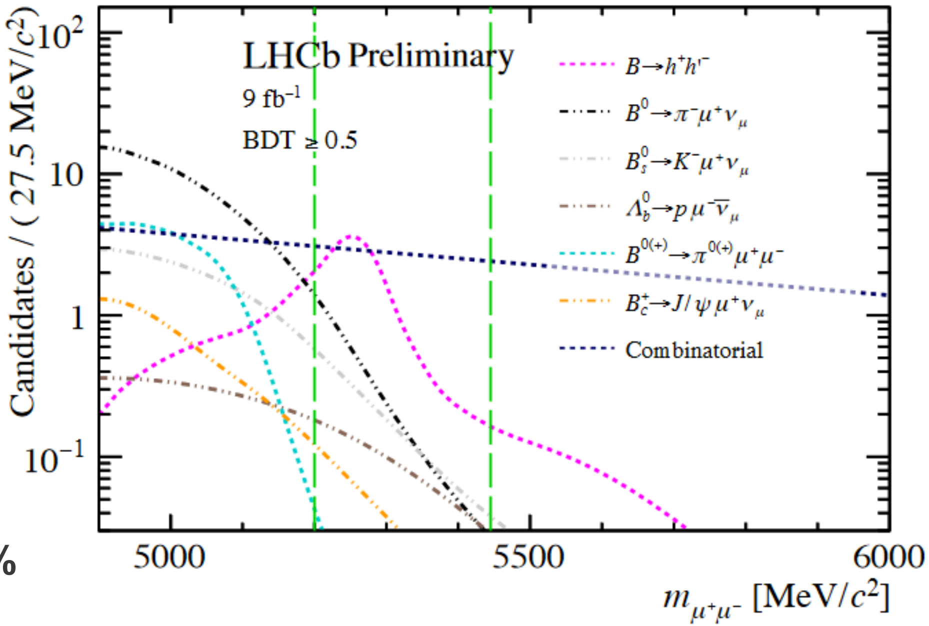
Calibrate on corrected simulation samples

Cross-check with fit to $B_{(s)}^0 \to h^+ h'^-$ data with one hadron mis-identified, consistent within 10%

Everything calibrated? Time to fit!

[Phys. Rev. D105 (2022) 012010]

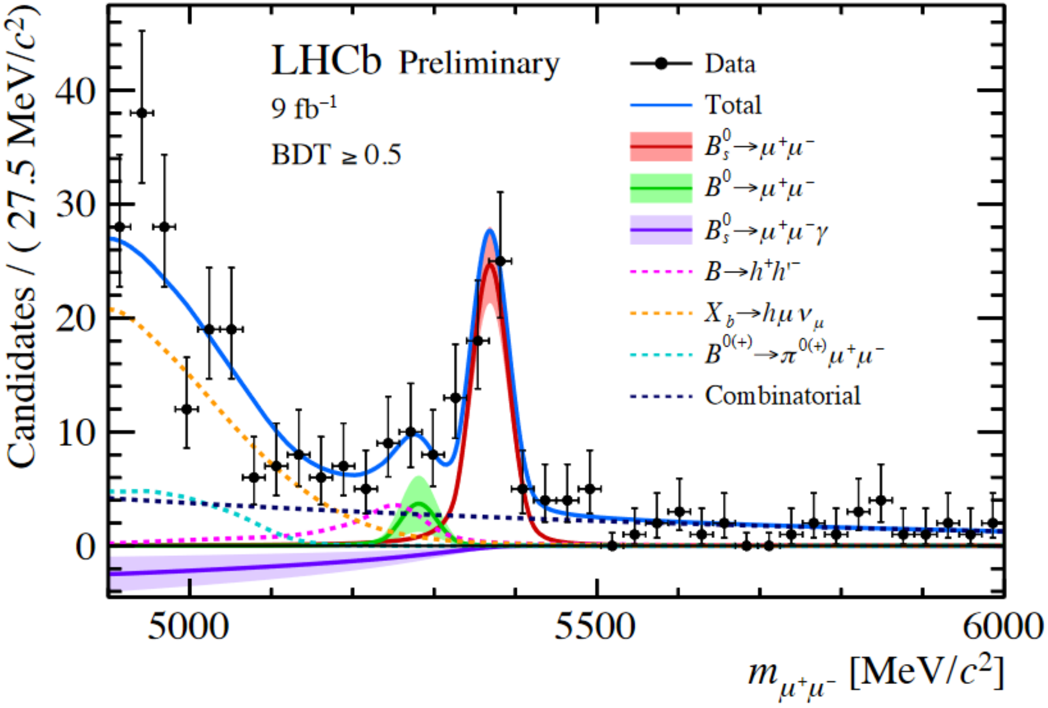


Results

- $\boldsymbol{B(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}}$ **with significance > 10σ**
- **Similar uncertainty to previous LHC combination**

- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background-only at 1.7σ, 1.5σ
- Measurement of $\tau(B_s^0 \to \mu^+\mu^-)$ is testing CP state of decay, but much more data needed…

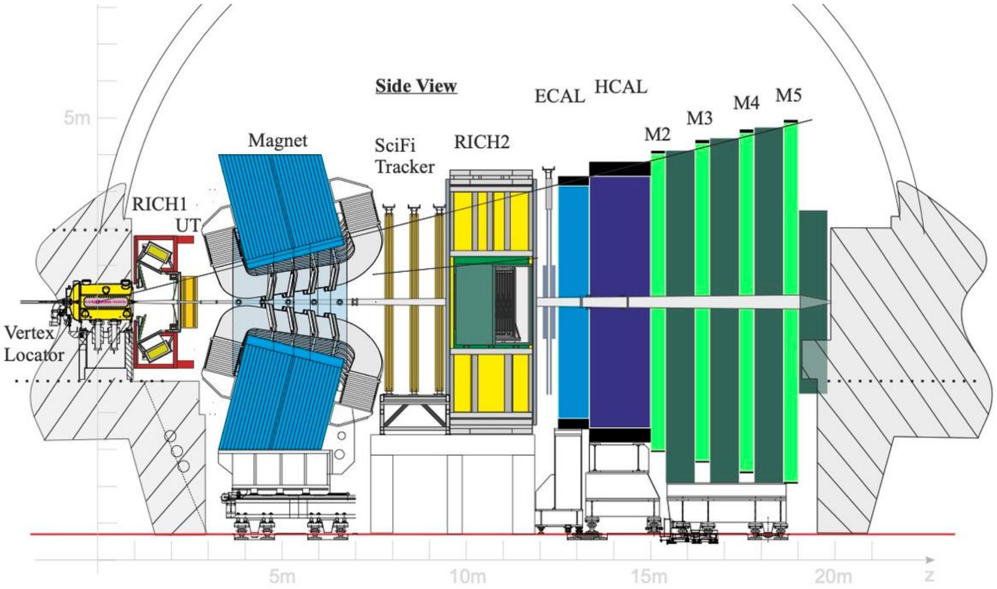
[LHCb-PAPER-2021-007]



New possibilities: LHCb Upgrade I

LHCb Upgrade 1 detector

A whole new detector to take 5-10x more data! (without hardware trigger)



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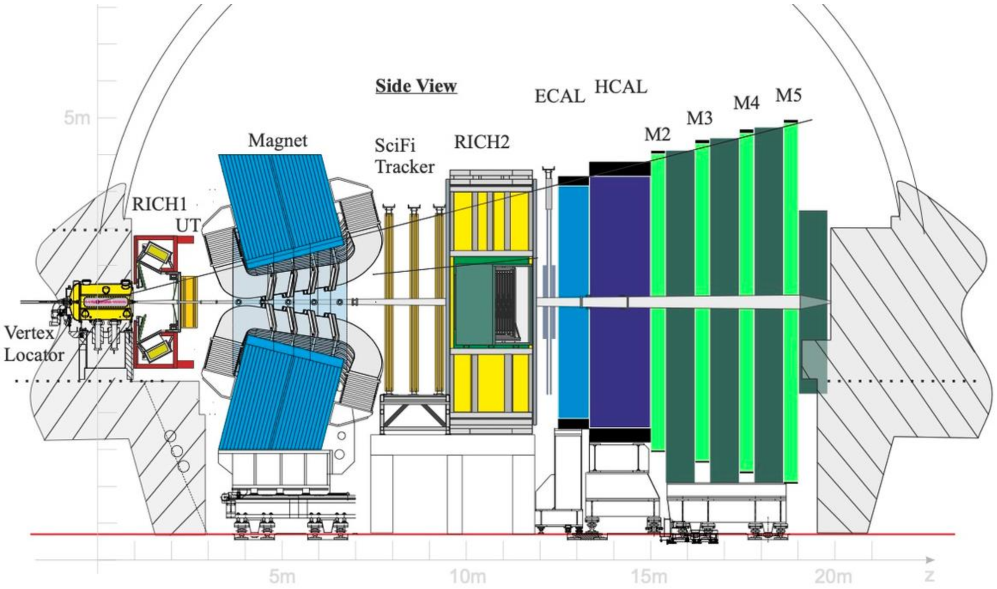
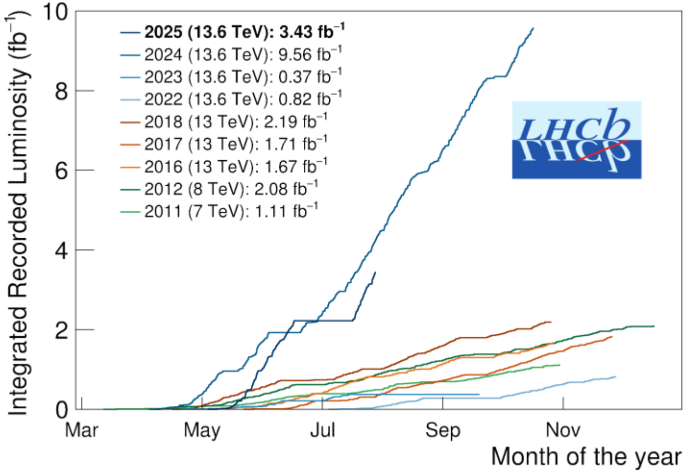
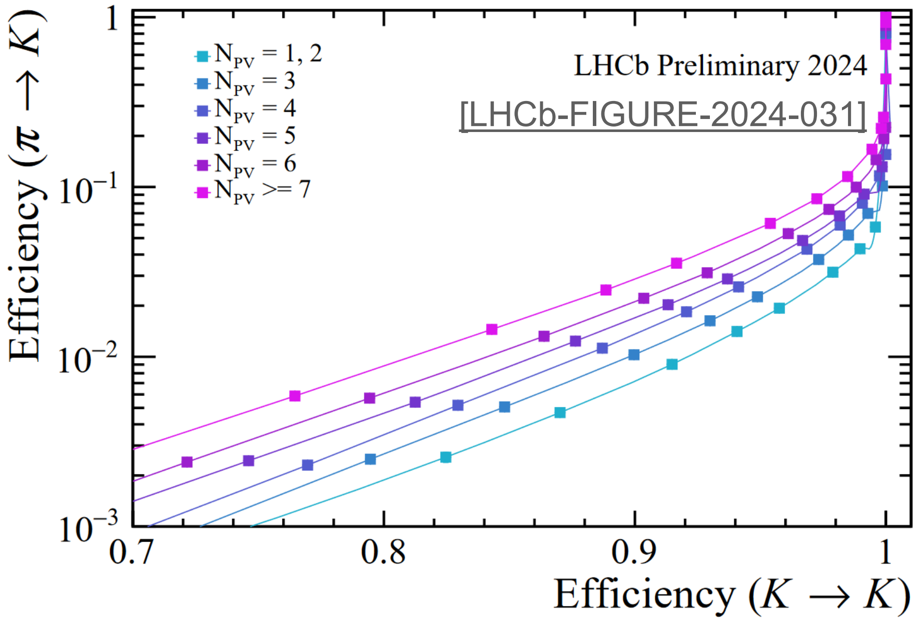
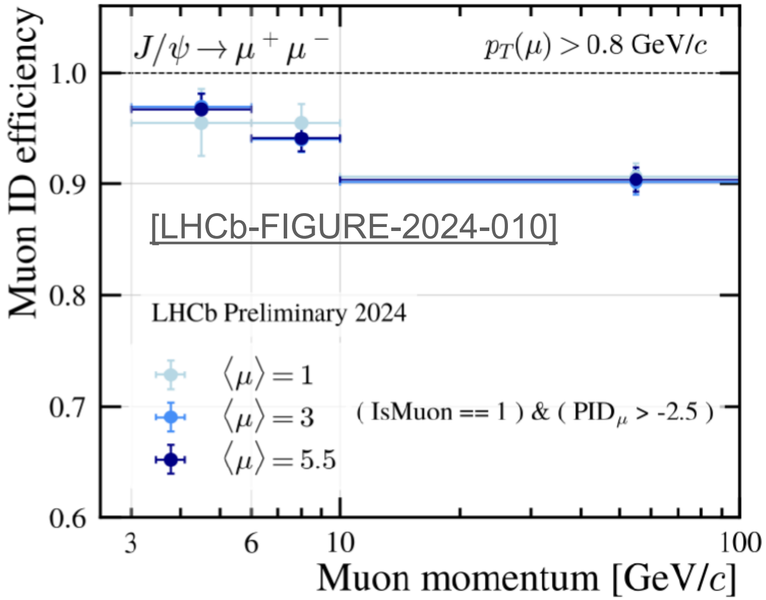




Upgrade performance: particle ID

- Particle ID holding up under harsher Run 3 conditions (to be confirmed in e.g. $B_s^0 \to \mu^+\mu^-$)

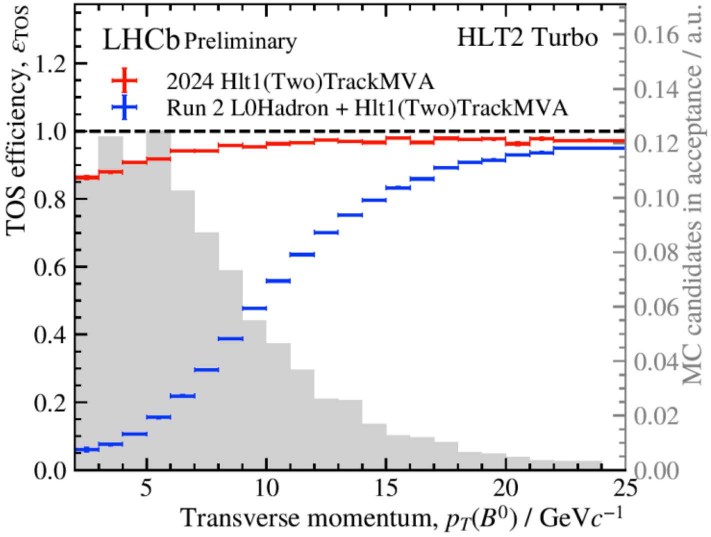




Upgrade performance: trigger

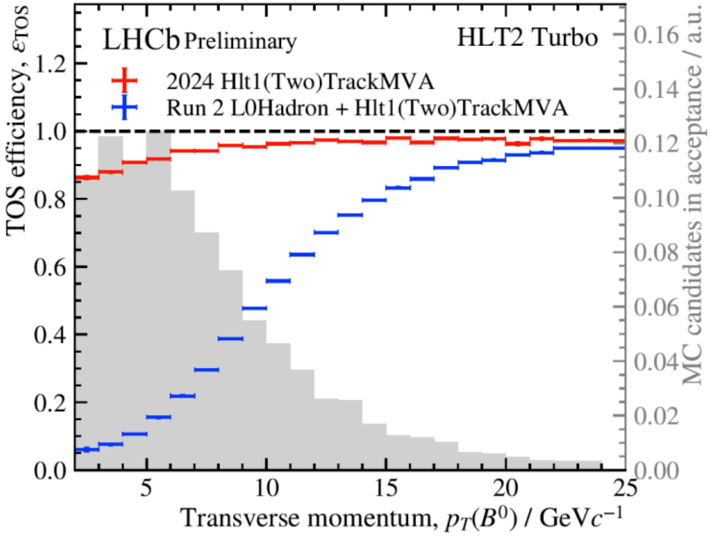
- Trigger performance much better for hadrons…

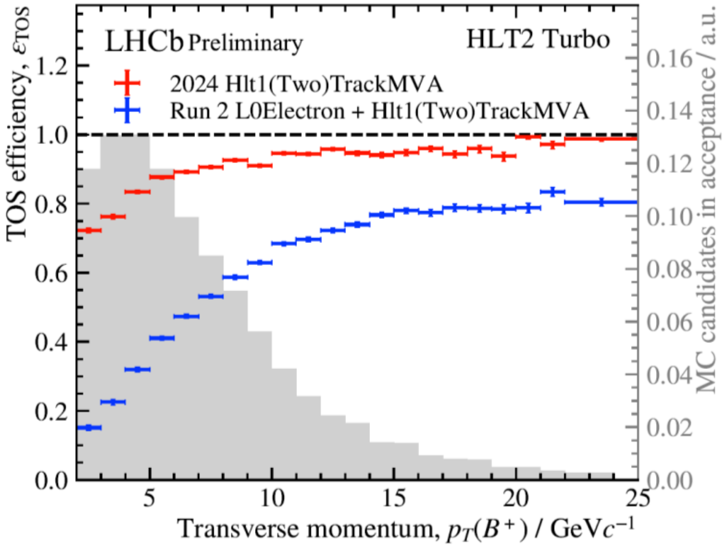
[LHCb-FIGURE-2024-030]



Upgrade performance: trigger

- Trigger performance much better for hadrons… and electrons! (and much easier to calibrate for $B_s^0 \to \mu^+\mu^-$) [LHCb-FIGURE-2024-030]

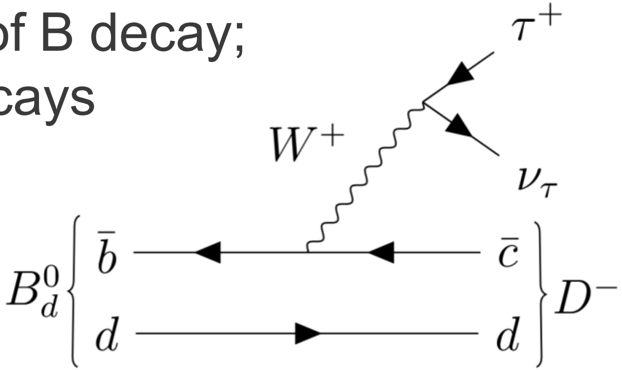




“Regular” rare decays and $B^+_{(c)} \to \tau^+ \nu$

LFU in $b \to c\tau\nu$ transitions

- Semileptonic $\mathrm{b} \to \mathrm{cl\nu}$ is the most common type of B decay; no New Physics expected in tree-level weak decays



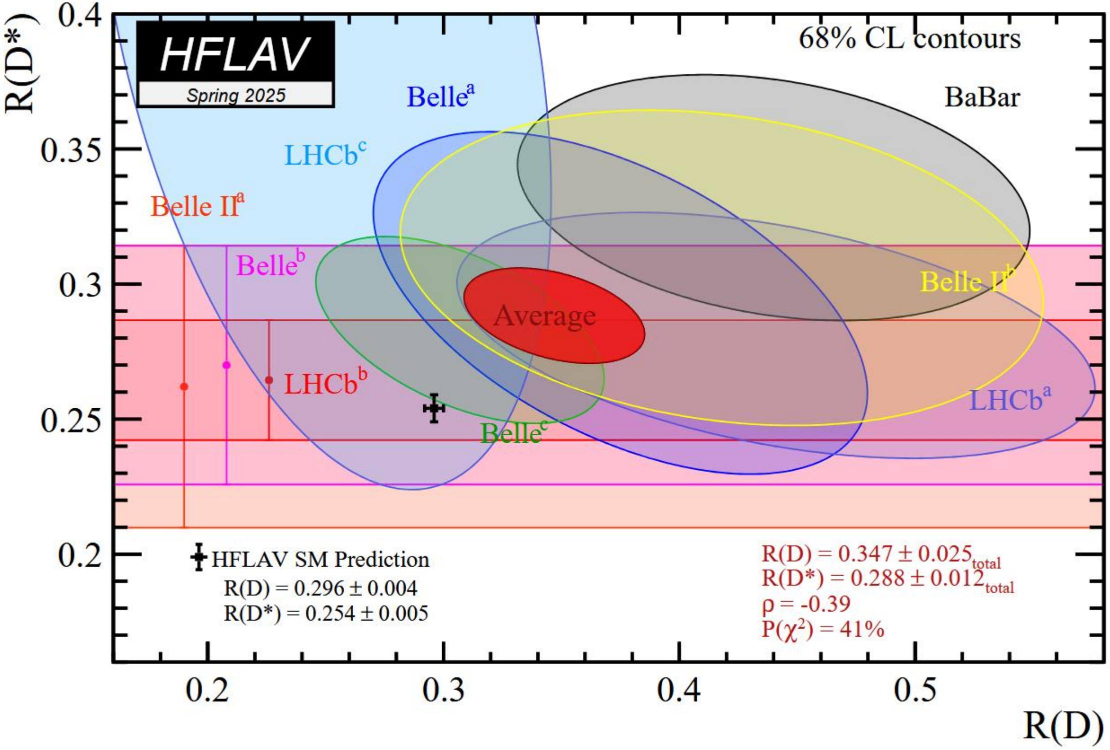
- **Our interest: tests of lepton universality: τ vs. μ, e rates,** precisely predicted in SM

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

- Also here, there are some deviations…

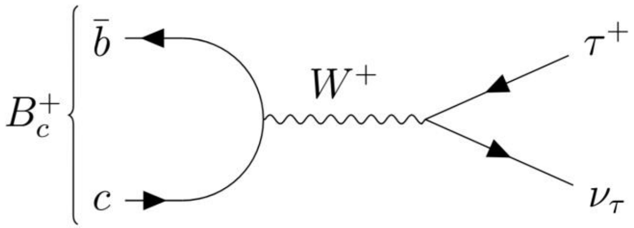
LFU in $b \to c\tau\nu$ transitions: $R(D^{(*)})$

Current tension of around 3.8σ between **measurements** and **SM**



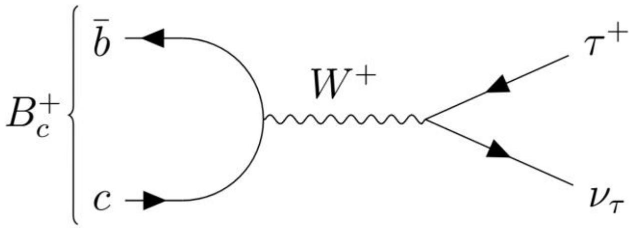
LFU in $b \to c\tau\nu$ transitions: $B_{(c)}^{+} \to \tau^{+}\nu$

- Just as $B_s^0 \to \mu^+\mu^-$, $\boldsymbol{B_c^+ \to \tau^+\nu}$ **is very sensitive to scalar New Physics**
- However, it actually is very common in Standard Model: $\mathcal{B}(B_c^+ \to \tau^+\nu) \approx 2.5\%$
- **No strong constraints available!** (only from lifetime or reinterpretations of LEP measurements)
- New Physics could enhance this decay by an order of magnitude



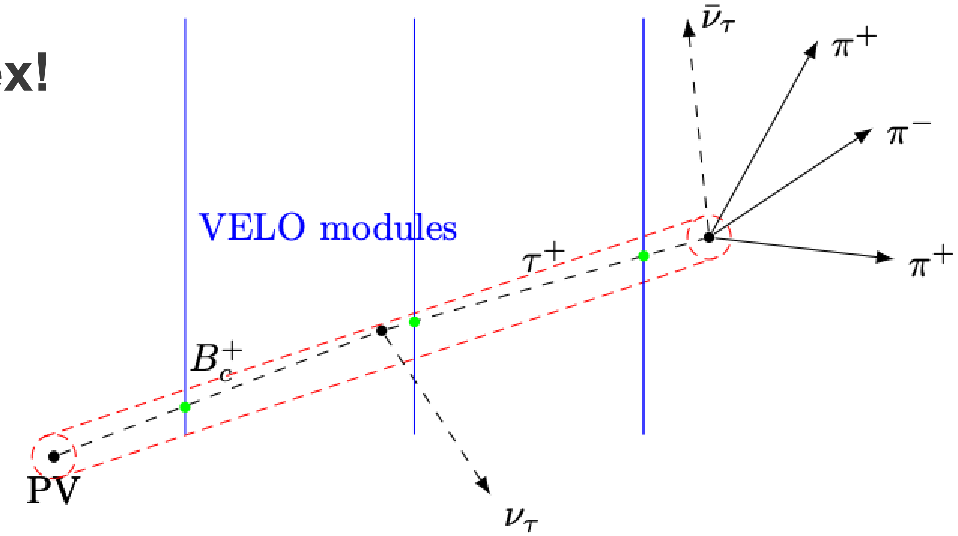
LFU in $b \to c\tau\nu$ transitions: $B^+_{(c)} \to \tau^+\nu$

- Just as $B^0_s \to \mu^+\mu^-$, $\boldsymbol{B^+_c \to \tau^+\nu}$ **is very sensitive to scalar New Physics**
- However, it actually is very common in Standard Model: $\mathcal{B}(B^+_c \to \tau^+\nu) \approx 2.5\%$
- **No strong constraints available!** (only from lifetime or reinterpretations of LEP measurements)
- New Physics could enhance this decay by an order of magnitude
- **So why has it not been studied yet?**



Reconstructing $B^+_{(c)} \to \tau^+ \nu$

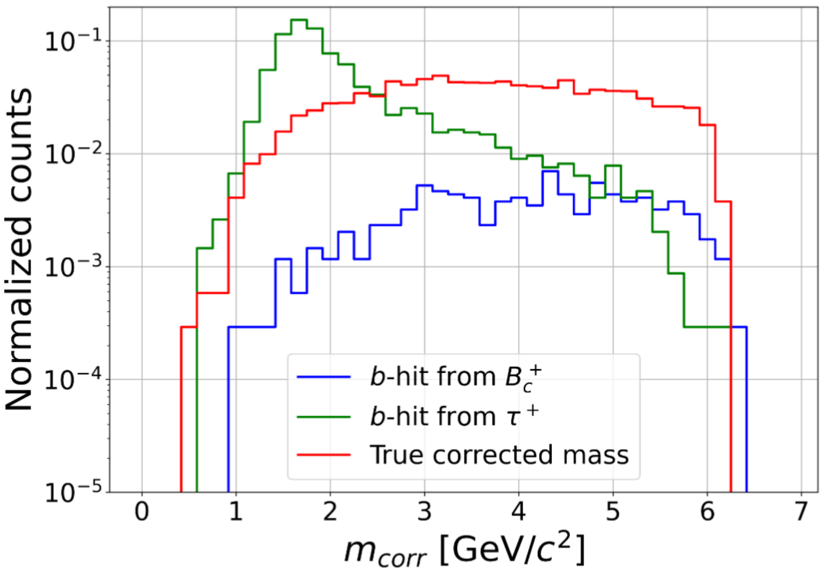
- **Extremely challenging: two neutrinos and no $B^+_{(c)}$ vertex!**
- Use $\tau^+ \to \pi^+\pi^+\pi^-\nu$ decay, to at least have clear τ^+ vertex
- **Our solution: search for hits when $B^+_{(c)}$ decays within VELO, determine "corrected" mass**
- Major increase in background rejection and mass resolution at cost of statistics



Feasibility study

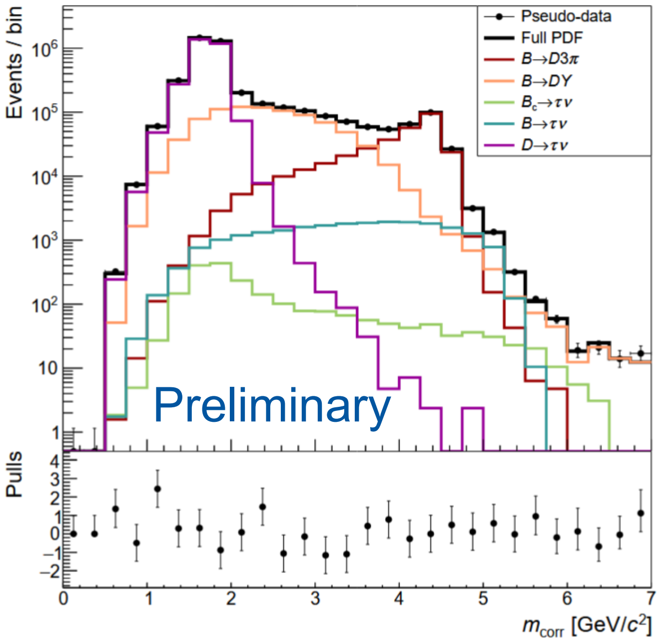
- Simulate LHCb with RapidSim
- Include model of VELO to simulate chance of $B_{(c)}^{+}$ or τ^{+}reaching them
- Simulate all backgrounds with τ or 3π final state
- Train BDT to separate $B_{(c)}^{+} \to \tau^{+}\nu$ from background cocktail
- Perform 2D fit to corrected mass and BDT

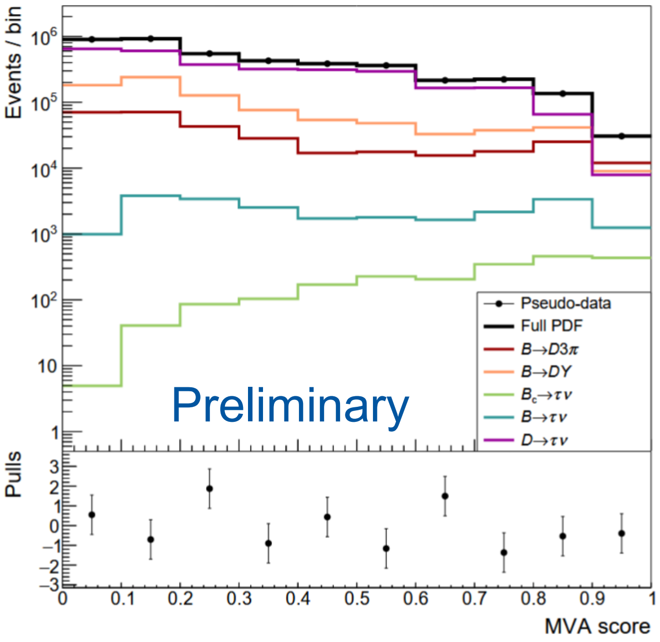
Corrected mass shape $B_c^+ \to \tau^+\nu$



Feasibility study: results

Average significance for $B_c^+ \to \tau^+ \nu$ signal: 4.8 σ with $10\ \mathrm{fb}^{-1}$:
clear potential for discovery of $B_c^+ \to \tau^+ \nu$ with Run 3 data





Conclusions

LHCb performs and is working on unique tests of beauty, such as

- Shedding light on tensions in rare decays with $\Lambda_{\mathrm{b}}^{0} \to \Lambda^{0}\ell^{+}\ell^{(\prime)-}$ system
- Strongly constraining scalar New Physics with $B_{(s)}^{0} \to \mu^{+}\mu^{-}$,
  and soon tightening the screws with LHCb Upgrade data
- A new addition to the family in the LHCb Upgrade era: $B_{c}^{+} \to \tau^{+}\nu$,
  a stringent test of scalar New Physics in the third generation!

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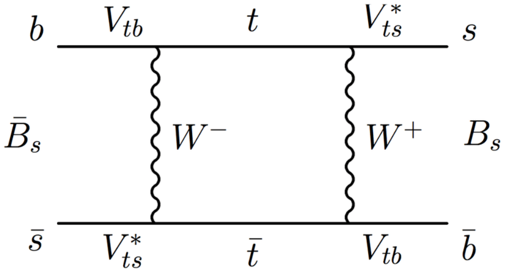
The future is looking bright:
are we closing in on a solution for the flavour puzzle?

Thanks for your attention!

Meson mixing



- Neutral flavoured mesons (K, D, B) only have non-zero quantum numbers that are not invariant for weak interaction!

- Very dependent on meson system
- Described with Hamiltonian, oscillation frequency Δm and lifetime difference $\Delta\Gamma$

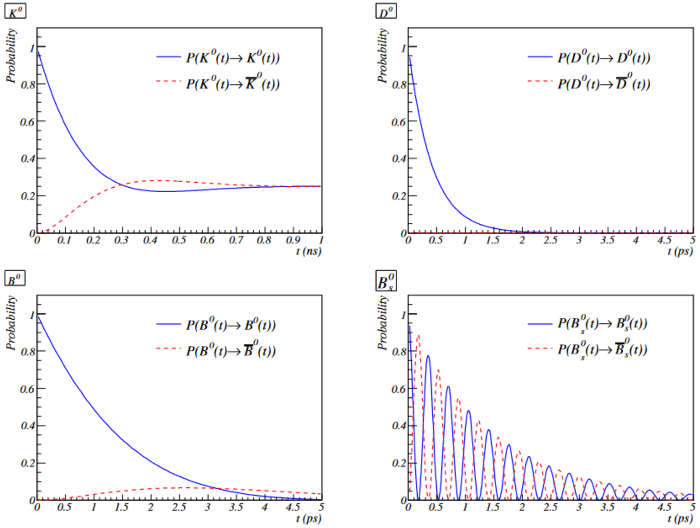
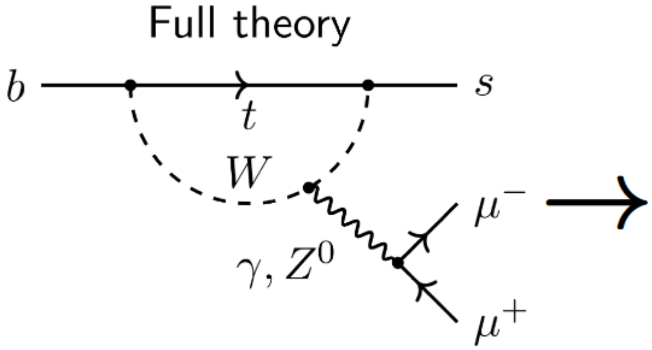
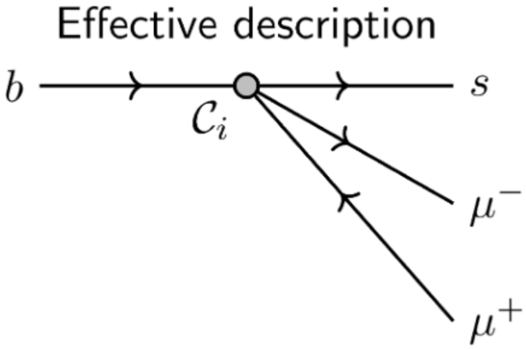


Figure 3.3: *If one starts with a pure P^0-meson beam the probability to observe a P^0 or a $\bar{P}^0$-meson at time t is shown,* $\text{Prob}(t) = \frac{e^{-\Gamma t}}{2}\left(\cosh \frac{1}{2}\Delta\Gamma t \pm \cos \Delta m t\right)$.

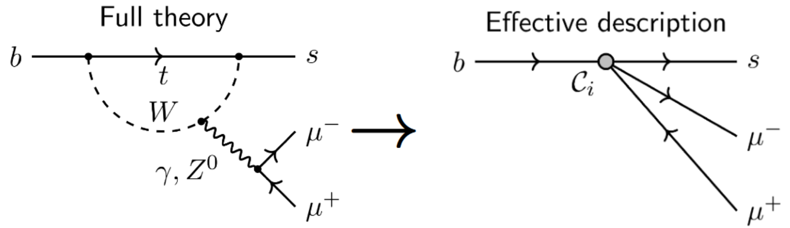
Effective field theory

- Are anomalies consistent with each other?
- **Use effective field theory at B-hadron scale, just like beta decay four-point interaction!**





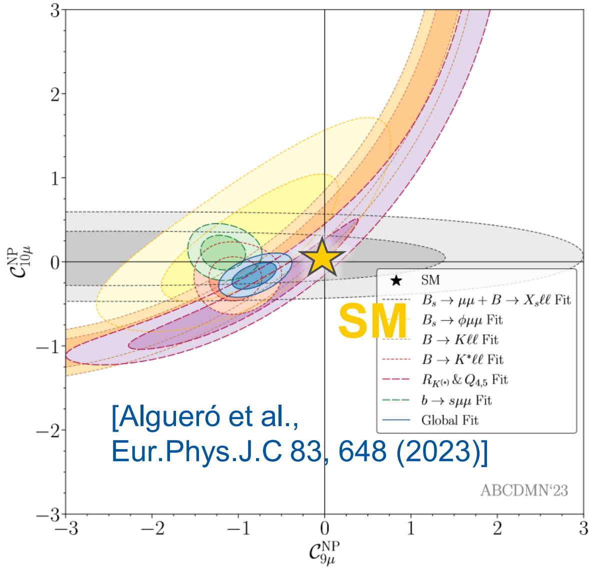
Effective field theory



- An EFT probes different couplings:

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{\rm CKM} \sum_i \mathcal{C}_i \mathcal{O}_i$$

- Fermion operators O_i, Wilson coefficients C_i
- Grouped by leptonic current: (SM,NP)
  - C_7 photon penguin
  - $(C_{10})C_9$ (axial) vector
  - $(C_P)C_S$ (pseudo) scalar
- Note: operators, coefficients with opposite quark current handedness from SM marked with O_i', C_i' (negligible in SM)
- **Global fits indicate consistent deviation: universal reduction in C_9?**

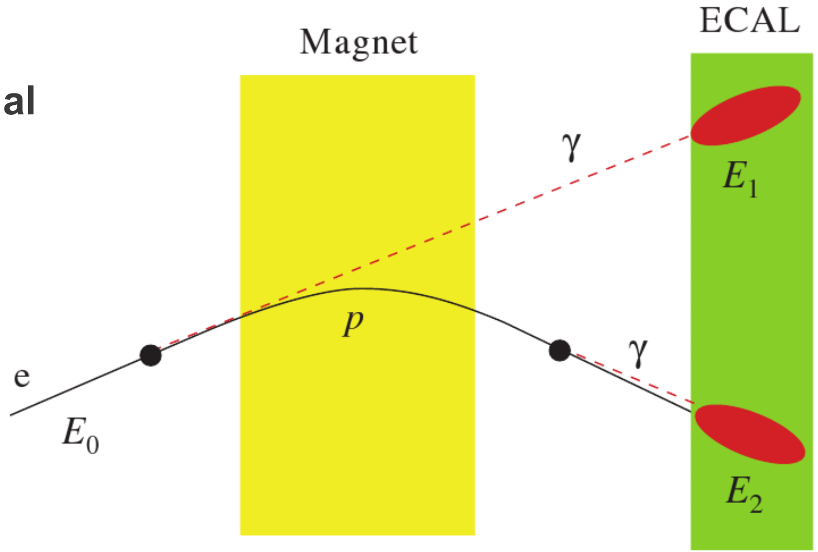


[Algueró et al., Eur.Phys.J.C 83, 648 (2023)]

Measurements with electrons at LHCb

[arXiv:2103.11769]

- **Electrons provide extra challenge in LHCb, because of significant bremsstrahlung in material**
- If bremsstrahlung is emitted before magnet, momentum is underestimated
- Recover bremsstrahlung by searching for photon clusters in calorimeter
- If found, correct electron momentum
- **Still, mass shape worse for electron modes**



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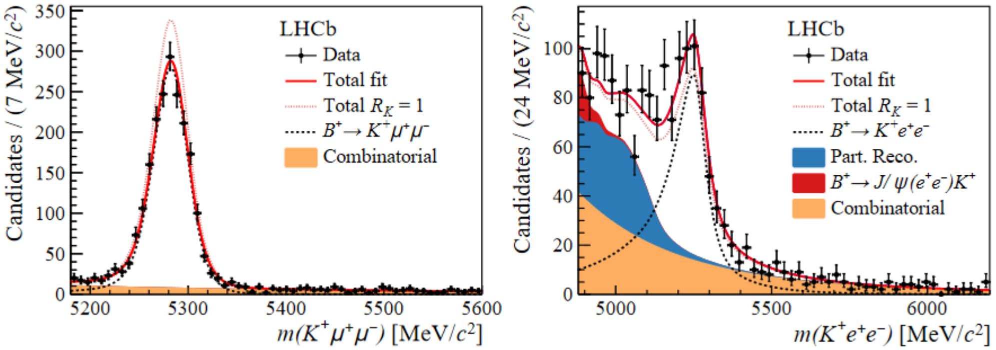
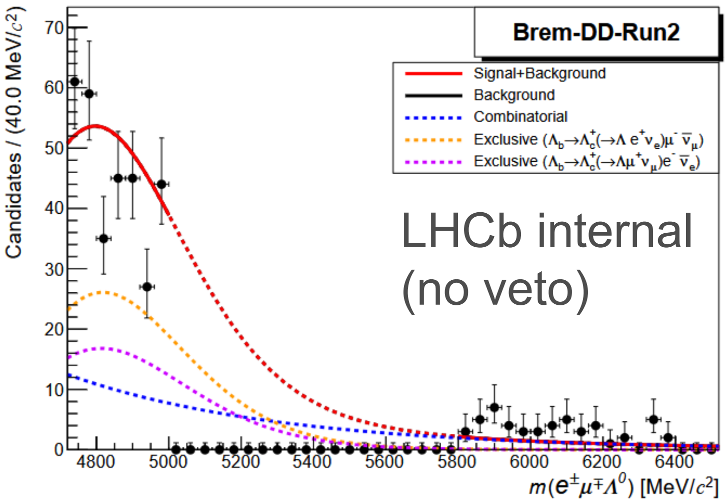
From previous result, LHCb [PRL122(2019)191801]

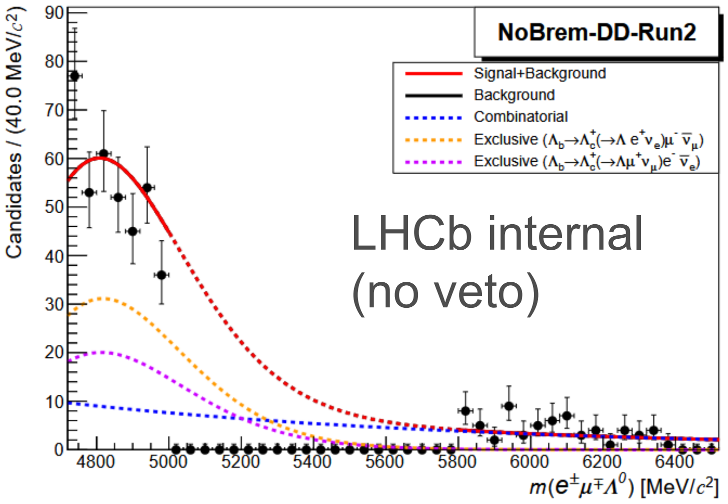


- **Additionally, electrons more difficult for hardware trigger (than muons)**
- Electron sample divided based on hardware trigger category: electron, rest-of-event, or hadron trigger

$\Lambda_b^0 \rightarrow \Lambda^0 e\mu$ analysis status

- Finalising analysis, last ongoing pieces:
  - Rerunning analysis including veto for additional semileptonic background from B^0
  - Expected limit and sensitivity for different decay models
- In end stage of internal review, limited by availability of postdocs





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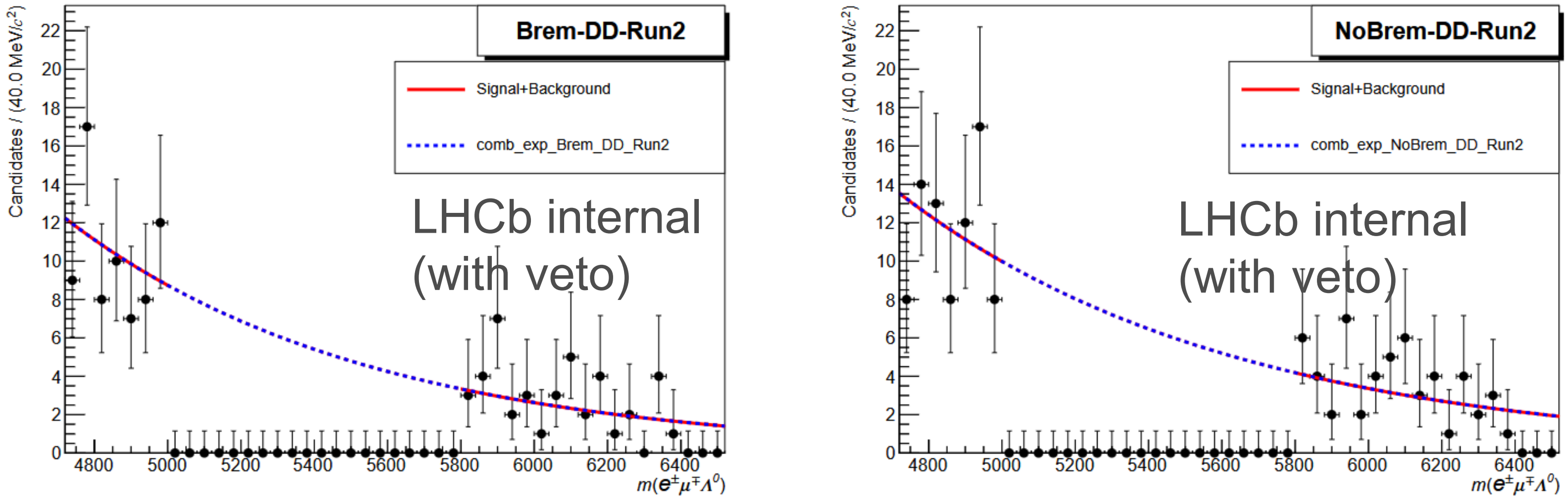
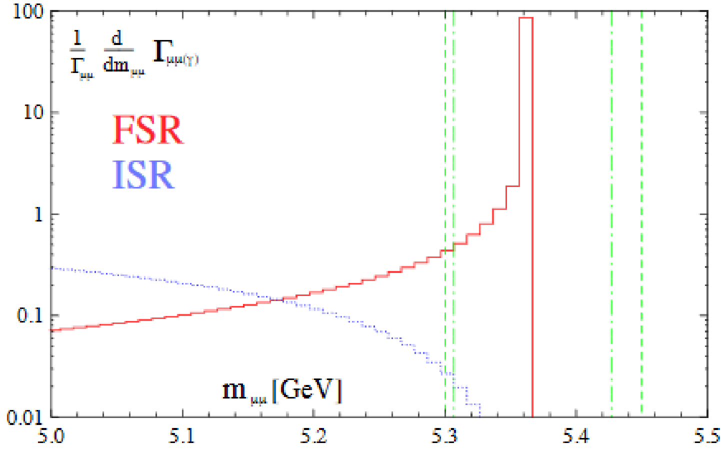


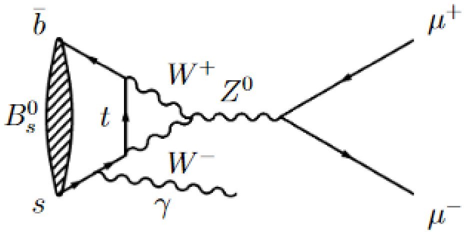
$B^0_{(s)} \to \mu^+\mu^-$ and photon radiation



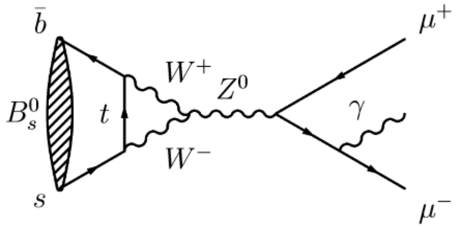
[PRL 112 (2014) 101801]

- Initial State Radiation: photon emitted from quarks, **sensitive to vector and axial vector** here referred to as $B^0_{(s)} \to \mu^+\mu^-\gamma$
- **New observable in this analysis,** without reconstructing photon for $m_{\mu^+\mu^-} > 4.9\ \mathrm{GeV}$
- SM prediction $O(10^{-10})$ [JHEP 11 (2017) 184, PRD 97 (2018) 053007]
- Final State Radiation: soft photons emitted from muons, sensitive to axial vector only, included in $B^0_s \to \mu^+\mu^-$ via PHOTOS

Initial State Radiation

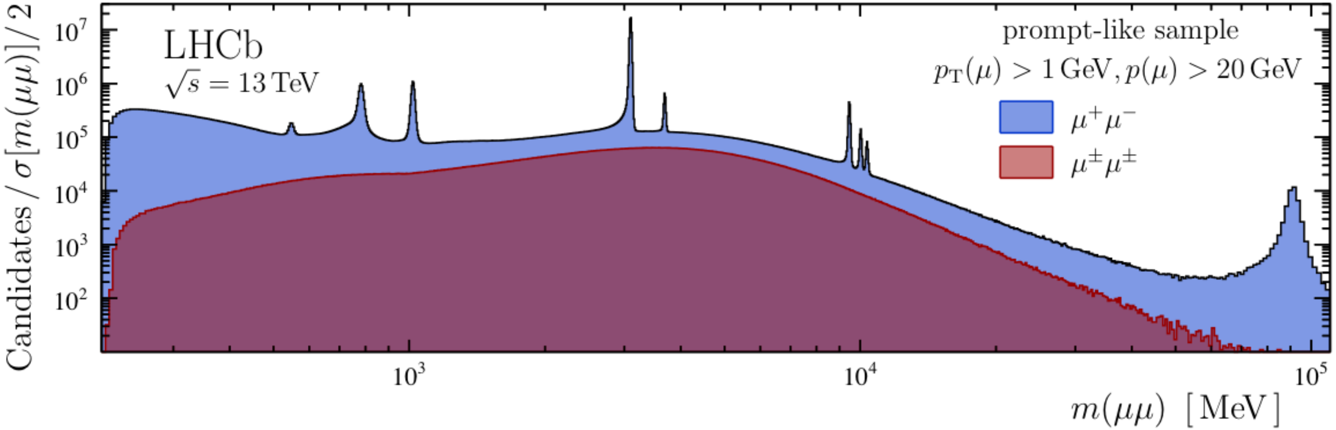


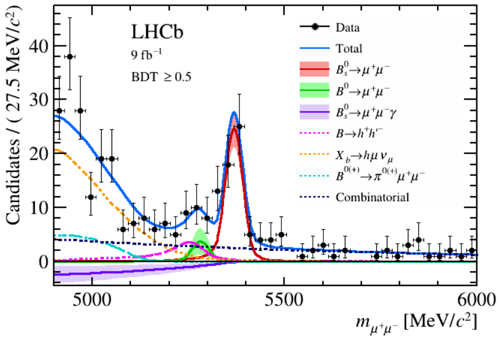
Final State Radiation



Searching for $B_s^0 \to \mu^+\mu^-$

[PRL 120 (2018) 061801]

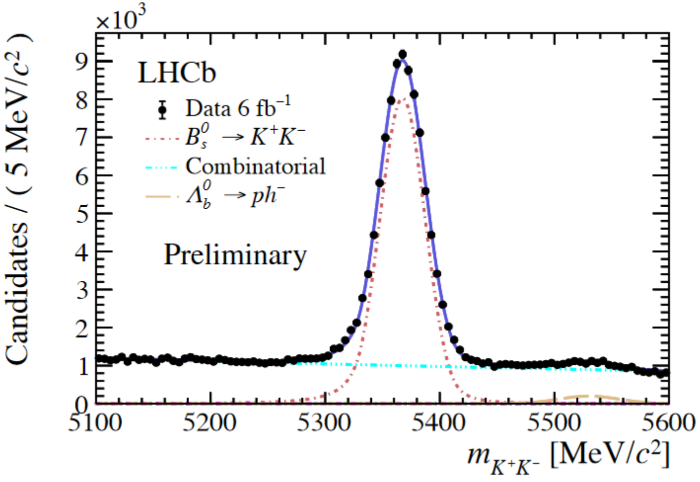


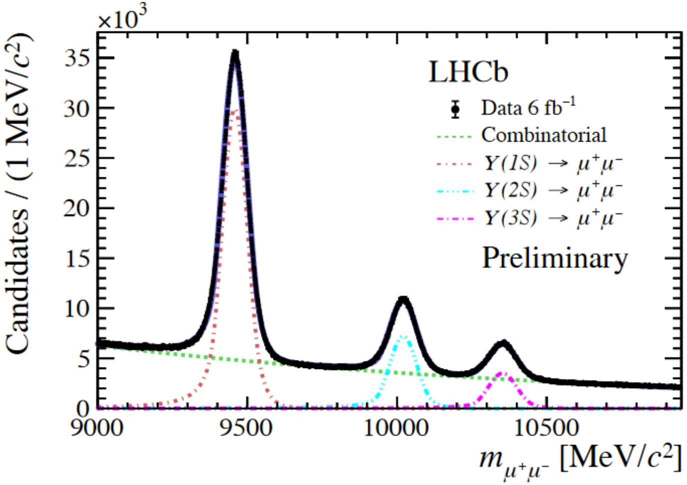


Mass calibration

Mean calibrated from fits to $B^0 \to K^+\pi^-, B_s^0 \to K^+K^-$ data

Resolution calibrated with fits to $J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \to \mu^+\mu^-$ data



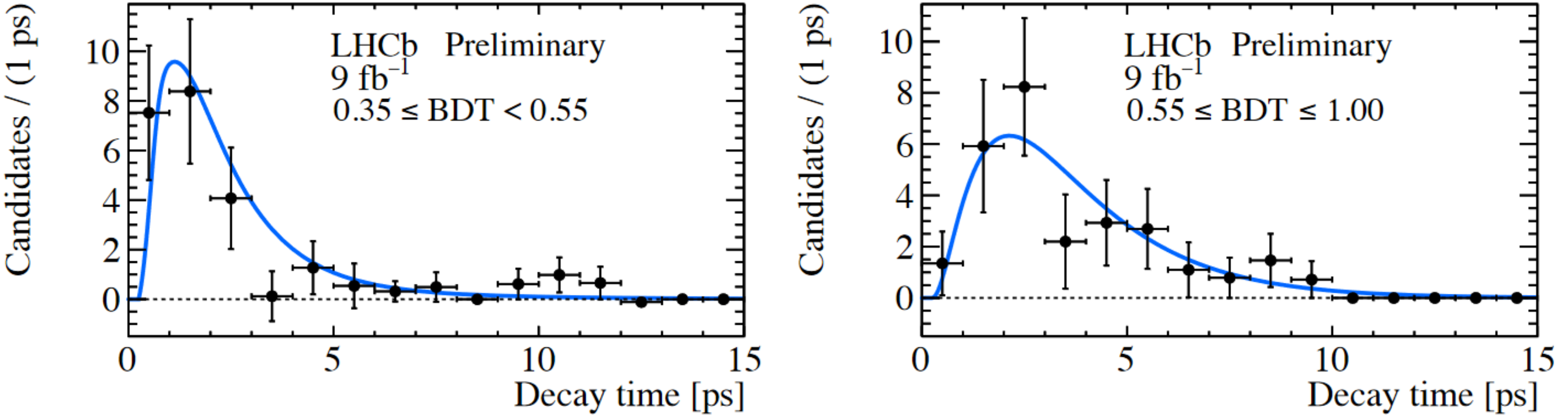


Tail parameters (for FSR) calibrated on smeared simulation
Include correlation of mass shape with BDT

Effective lifetime

[LHCb-PAPER-2021-007]

- $B^0_{(s)} \to \mu^+\mu^-$ decay proceeds through CP-odd state in SM
- CP-even, CP-odd states of B^0_s have different lifetime → **measure effective lifetime τ_{eff} to test CP-even contribution (from scalar NP)**
- $\boldsymbol{\tau\left(B^0_s \to \mu^+\mu^-\right) = 2.07 \pm 0.29 \pm 0.03}$ **ps** (previously $2.04 \pm 0.44 \pm 0.05$ ps)
- 1.5 σ from SM, 2.2 σ away from fully CP-even (extreme non-SM)
  → **More data is needed to constrain the SM here…**

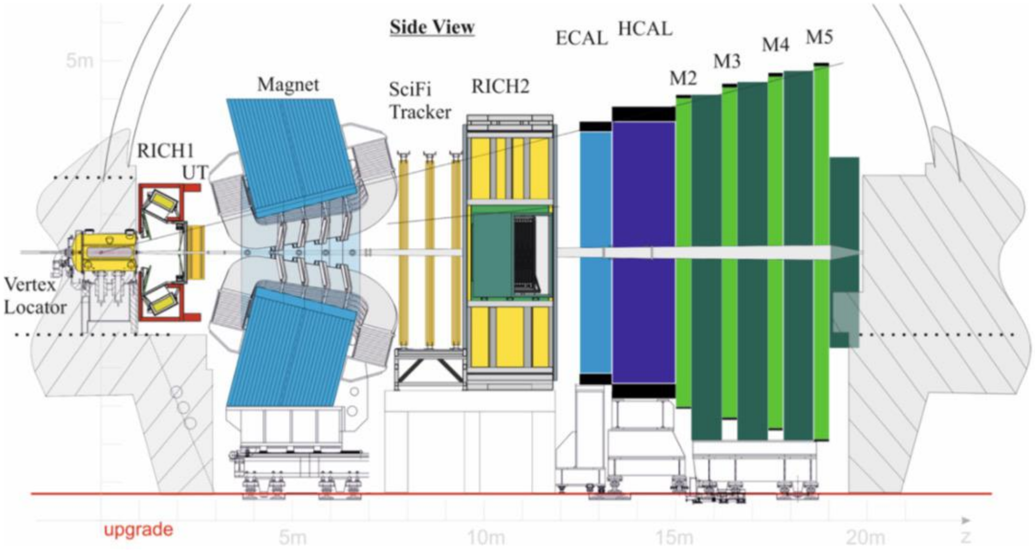


LHCb Upgrade slides

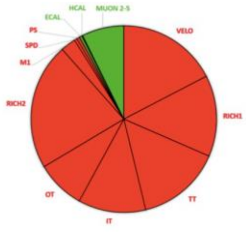
LHCb Upgrade 1 detector

CERN-LHCC-2011-001

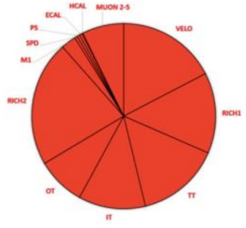
A whole new detector!



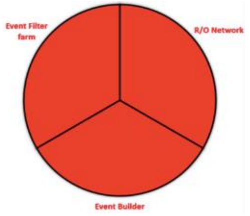
Detector channels



Readout



DAQ



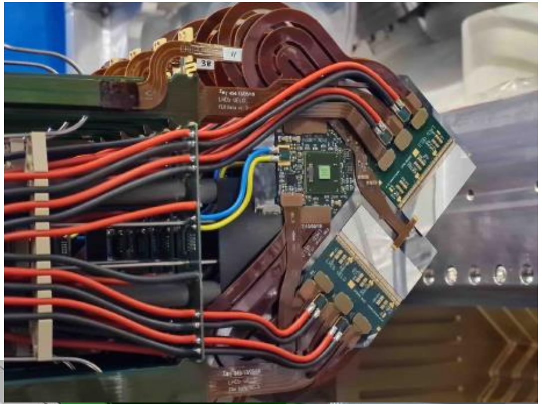
VELO

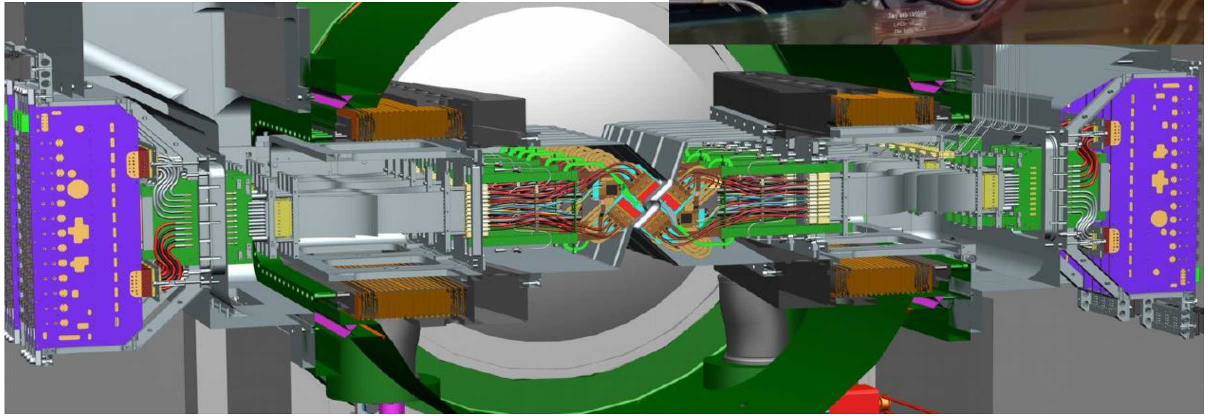
CERN-LHCC-2013-021

New pixel detector (replacing strips)

- Within vacuum of LHC beam pipe; 2 moveable halves (5.1 mm from beam closed, 30 mm open)
- Dedicated RF foil for protection
- Very radiation hard
- Data rate: 3 Tbit/s

Performing well now, after recovery from January 2023 incident





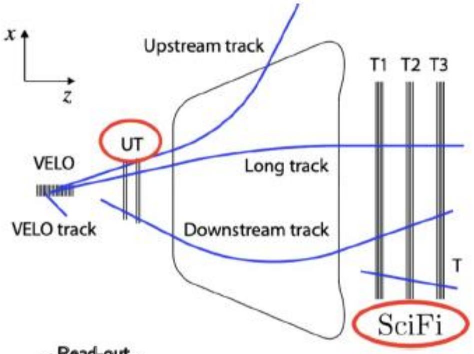
SciFi

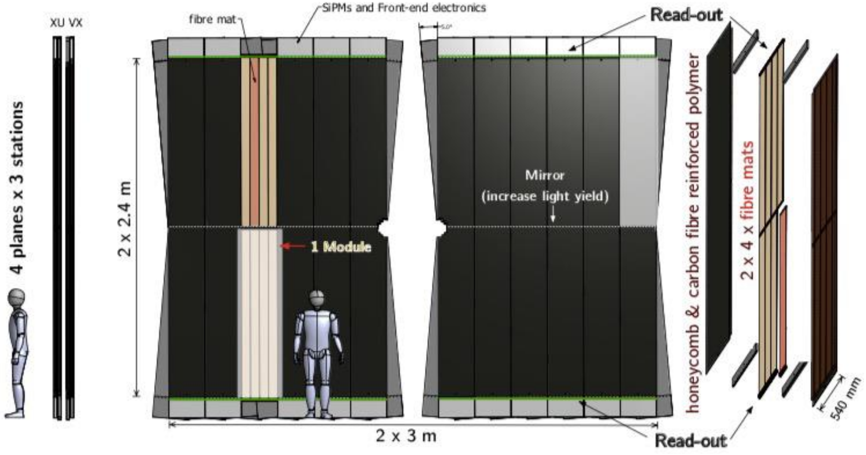
CERN-LHCC-2014-001

Scintillating **Fi**bretracker developed for high occupancy

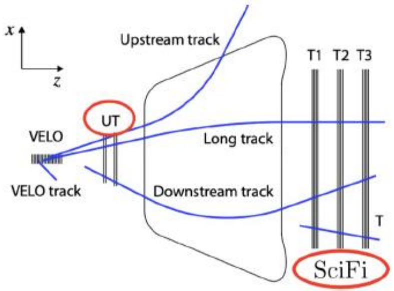
- Spatial resolution 80 μm
- Hit efficiency > 99%

Performing well, with occupancy even higher than in design specifications



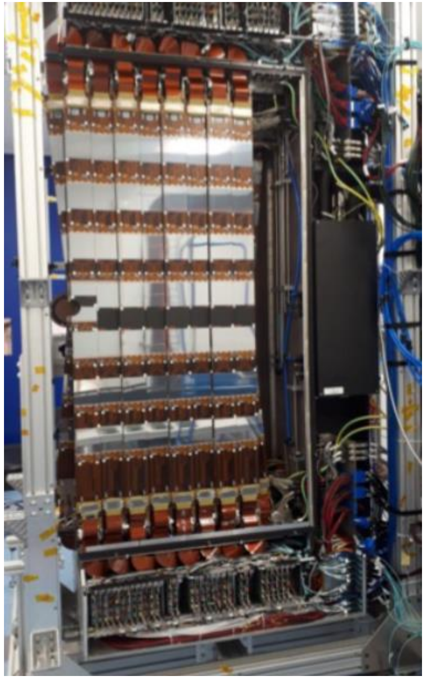


Upstream Tracker



CERN-LHCC-2014-001

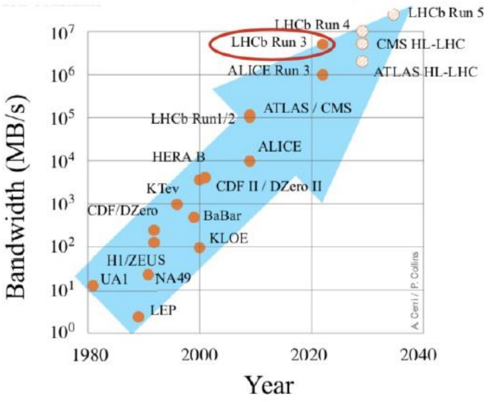
- 4 planes made of **silicon strips** with finer segmentation and improved acceptance
  - Fast pT determination for track extrapolation, reduction of ghost tracks
  - Detect long-lived particles decaying after VELO (K_S^0, Λ^0)
- **Successfully running together with rest of detector**



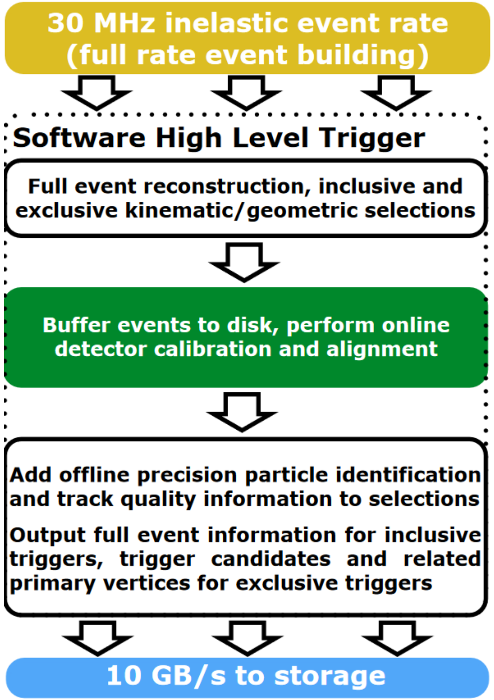
Trigger

CERN-LHCC-2014-016
CERN-LHCC-2020-006

- All subdetectors read out at 30 MHz –
Real Time Analysis with software trigger
- HLT1 reduces 30 MHz to 1 MHz with partial event reconstruction (tracking, vertexing, muon ID), based on GPUs in new data centre
- Calibrate detector in “real-time” such that HLT2 uses best-quality tracking, PID
- Hadronic yield $/\mathrm{fb}^{-1}$ is 2x that of Run 2
- **40 Tbit/s is highest throughput of all LHC**



LHCb Run 3 Trigger Diagram

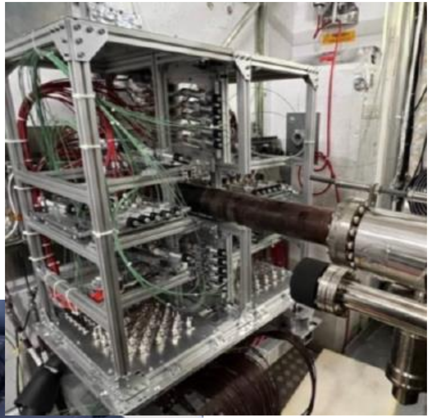


Plume and SMOG

CERN-LHCC-2021-002

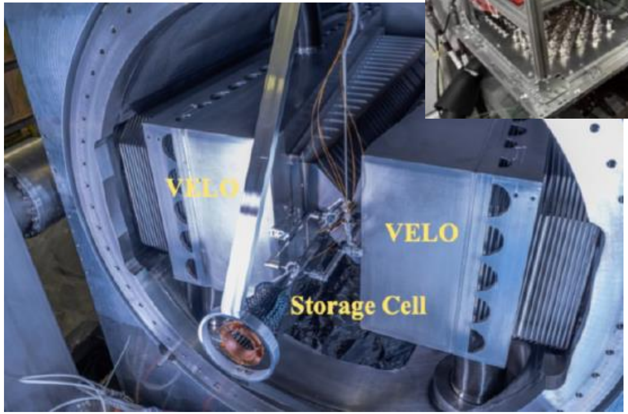
Probe for LUminosity MEasurement (PLUME): new dedicated luminometer

- Quartz tablets + PMTs for online+offline per-bunch luminosity measurement
- **Running continuously, accurate luminosity estimate**



SMOG2 gas system for fixed-target physics

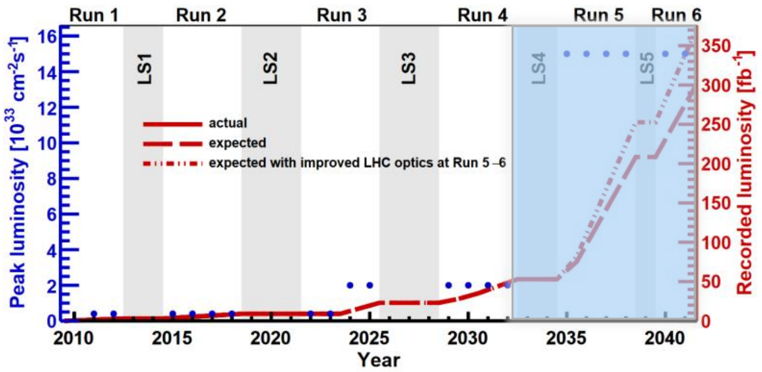
- New storage cell for gas upstream of nominal interaction point
- Gas density increased by up to two orders of magnitude → much higher luminosity
- Gas targets: He, Ne, Ar
  (+ possibly H_2, D_2, N_2, Kr, Xe)
- Simultaneous p-p and p-gas data taking
- **Running smoothly and data taken in parallel**



CERN-LHCC-2019-005

Upgrade 2

Goal: increase of luminosity by factor 7.5; aim for 300 fb-1 after Run 6



Upgrade 2

Goal: increase of luminosity by factor 7.5; aim for 300 fb-1 after Run 6

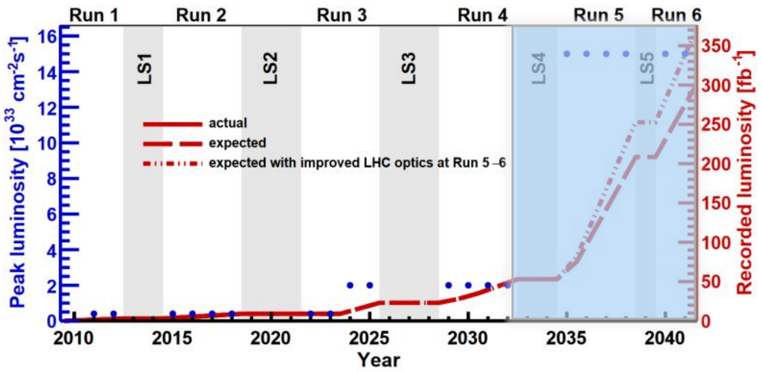
- Will reach unprecedented precision

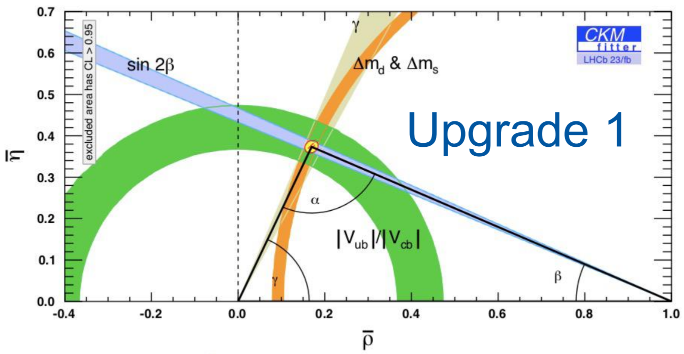
Detector environment will be challenging:

- Pile-up ~40 interactions
- 200 Tb/s of produced data

Detector upgrades: performance in harsher environment

- Better granularity
- Fast timing (~10 ps)
- Radiation hardness





Upgrade 2

Goal: increase of luminosity by factor 7.5; aim for 300 fb-1 after Run 6

- Will reach unprecedented precision

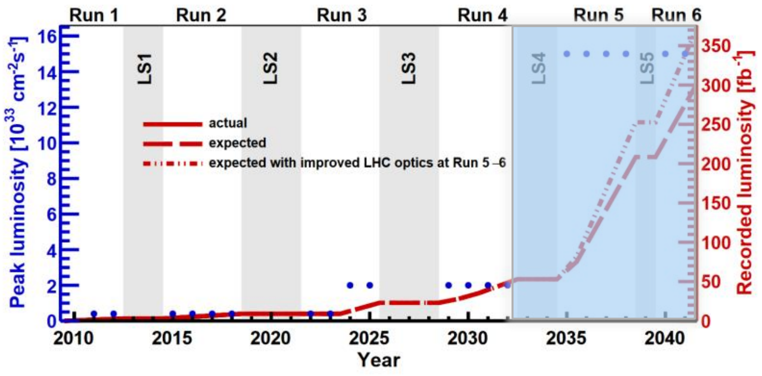
Detector environment will be challenging:

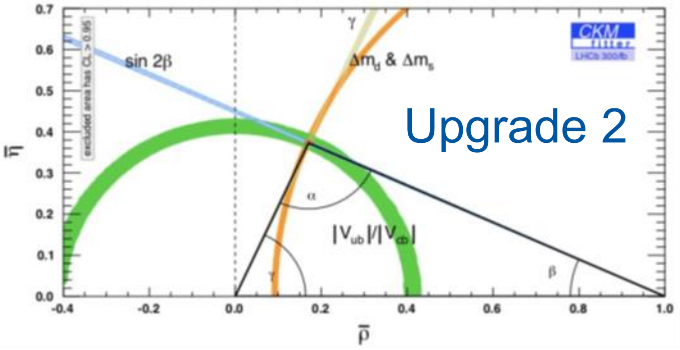
- Pile-up ~40 interactions.
- 200 Tb/s of produced data.

Detector upgrades: performance in harsher environment

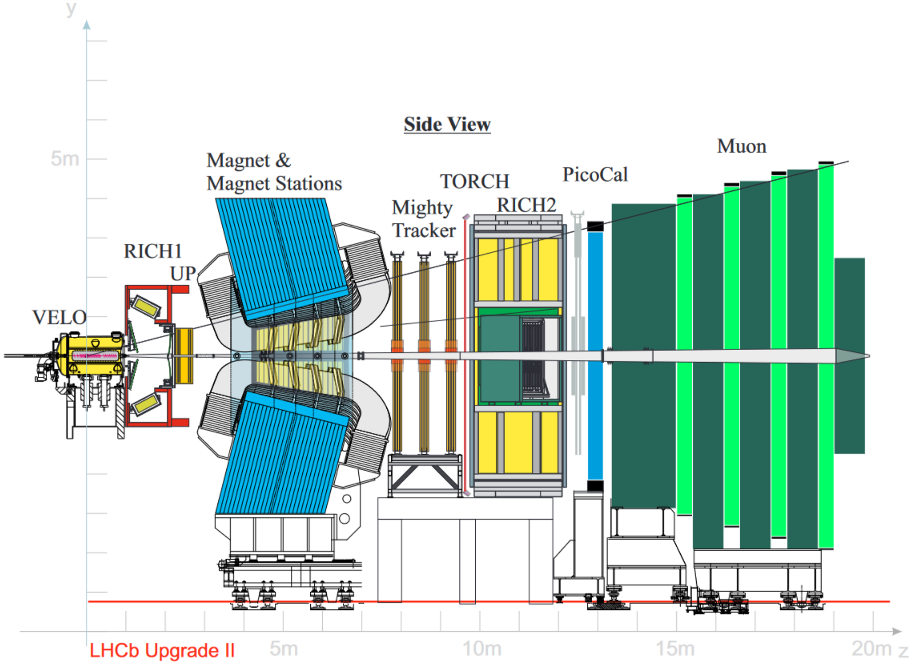
- Better granularity
- Fast timing (~10 ps)
- Radiation hardness

Large step, e.g. in constraining unitarity triangle





LHCb Upgrade 2 detector



Advantages of b-hadrons

- Heaviest quark forming hadrons decaying weakly
- Many possible decay modes,
  and even more observables!
  - Very rich spectrum of possibilities!
  - O(600) modes (incl. searches) for B^+/B^0, O(100) for B_s^0, Λ_b^0
- Weak decay of b-hadron crosses generations:
  - No large branching fractions (largest 5%)
  - Sensitive to small SM and New Physics effects!
- Lifetime and boost at LHCb give decay length of $\mathrm{O}(1\ \mathrm{cm})$; precise lifetime measurement possible