Rare Decays: The Sharpest Tools for New Physics at LHCb

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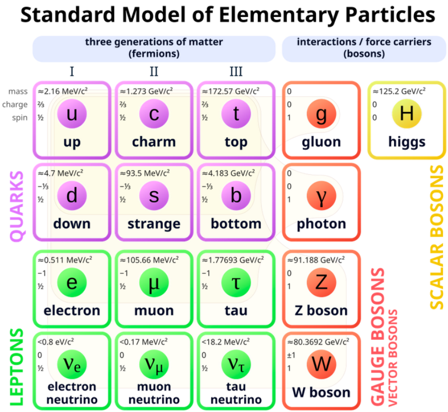
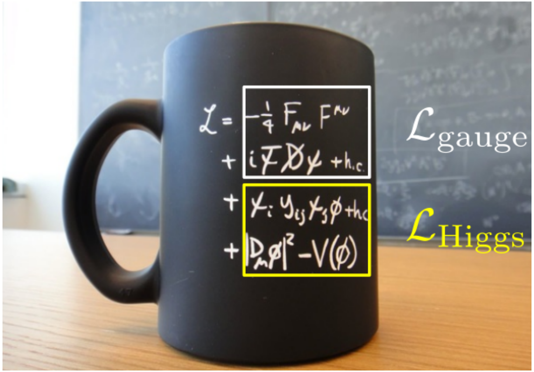
October 2, 2025

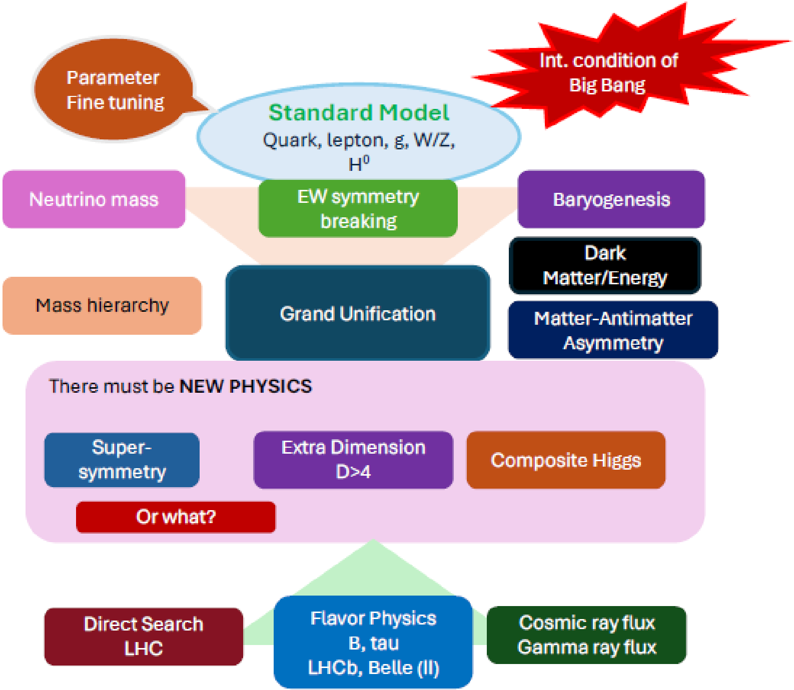
Current Understanding



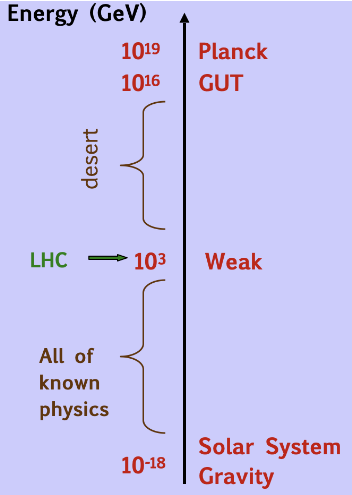


- Fundamental Interactions:
  - Electromagnetic $\rightarrow$ photon (γ) as carrier
  - Strong $\rightarrow$ gluon (g) as the carrier
  - Weak $\rightarrow W^{\pm}, Z^0$ as the carrier
  - Gravity $\rightarrow$ Graviton (?) as the carrier (Not included in the SM)
- $\mathcal{L}_{\text{gauge}} \rightarrow$ mathematically elegant symmetries
  $\mathcal{L}_{\text{Higgs}} \rightarrow$ ad hoc Yukawas

Beyond the Standard Model

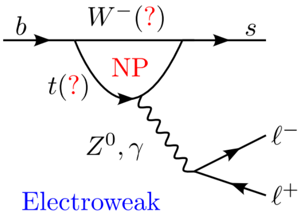


Flavor as a discovery tool



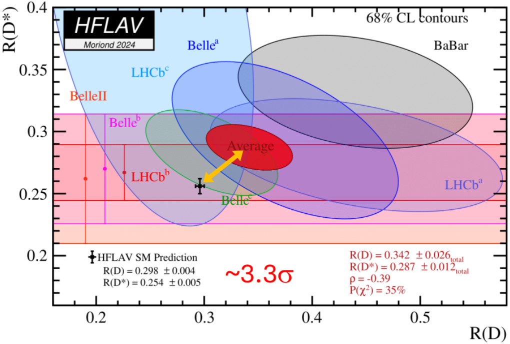
[J. Hewett, LISHEP09]

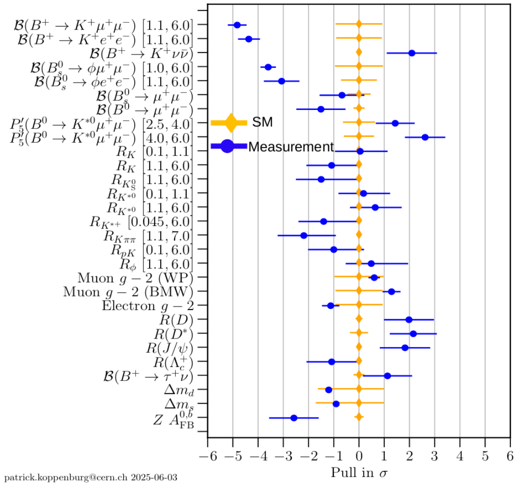
- Long history of flavor as an "indirect" probe for new heavy particles:
  - weak nuclear β decay $\Rightarrow$ heavy W/Z
  - $K^0_L \to$ GIM suppression $\Rightarrow$ charm
  - B^0-mixing at ARGUS $\Rightarrow$ heavy top
  - SM-like $\mathcal{B}(B^0_s \to)$ at the LHC $\Rightarrow$ tight limits on MSSM/SUSY



- Even if $\Lambda_{\rm NP} \gg$ TeV, precision flavor can probe the "desert" via rare loop-mediated processes.

Recent Flavor Anomalies

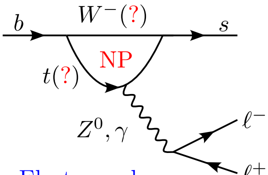




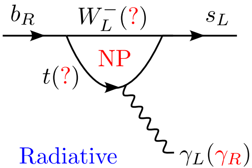
- Tension is at 3.3σ in $b \to c\ell\nu$ transitions
- BR measurements differ from predictions

Rare b-decays

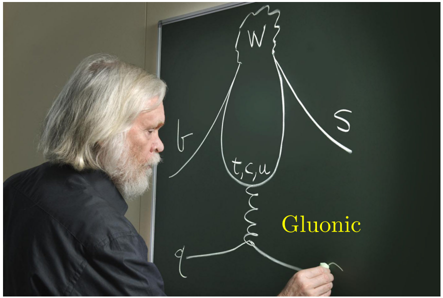
- $b \to s(d)$ flavor changing neutral currents: loop-suppressed in SM.
- New Physics (NP) can enter both at loop- and tree-levels.
- These kinds of rare decays have a long tradition of discovering new things even before doing the actual observations.

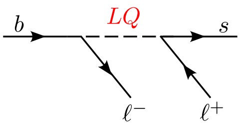


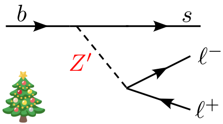
Electroweak



Radiative







EFT tools for rare decays

- Renormalizability requires the $\mathcal{L}_{\text{SM}}$ to have dim $d \leq 4$ operators.
- Eg.: $m_\phi^2 \phi^2$, $m_\psi \overline{\psi}\psi \Rightarrow (m_\phi/E)^2$, (m_ψ/E) UV-safe behavior.
- We can include $d > 4$ operators if we regard the SM as an low energy effective theory. Comes with a cutoff scale, Λ.

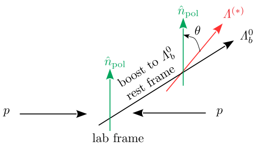
$$\mathcal{L}_{\text{eff}}(x) = \mathcal{L}_{\text{SM}}(x) + \sum_{d>4} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}(x)$$

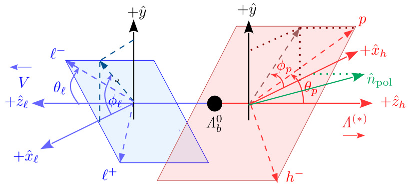
local operators

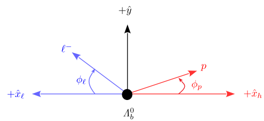
- Amplitudes will have $(E/\Lambda)^{d-4}$ behavior: bad at high-E, but suppressed at $E \ll \Lambda$. Access to heavy (Λ_{NP}) fields from NP.
- Relevant for RD: $d = 6$ operators. $\mathcal{A}_{\text{eff}} \sim \frac{C_{\text{SM}}}{m_W^2} + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$.

Angular analyses as a tool for NP searches

- Huge LHC statistics allow precision measurements of angular observables in $b \to s\ell^+\ell^-$ and $b \to s\vec{\gamma}$. Direct access to $C_i^{\rm NP}$.
- Eg., $\vec{\Lambda}_b^0 \equiv |[ud]\vec{b}\rangle$ reflects the properties of the b-quark, with $[ud]$ as spectator diquark.
- $\vec{\Lambda}_b^0 \to \Lambda^*(\to pK^-)\ell^+\ell^-$: $\{q^2 \equiv m^2_{\ell^+\ell^-}, k^2 \equiv m^2_{pK}\} + \{\theta_\ell, \theta_p, \phi_\ell, \phi_p\}$



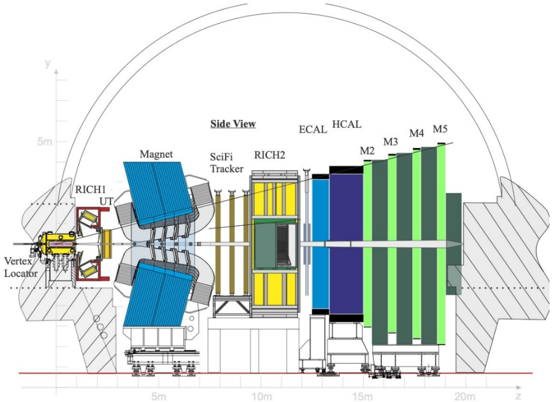


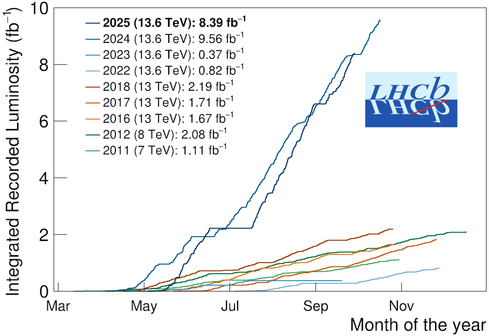


- If Λ_b^0 is unpolarized, $\phi_\ell = 0$, $\chi \equiv \phi_p$. Similar definitions for $B^0 \to K^+\pi^-\ell^+\ell^-$, $B_s^0 \to K^+K^-\ell^+\ell^-$.

LHCb: a discovery tool

[2024 JINST 19 P05065]

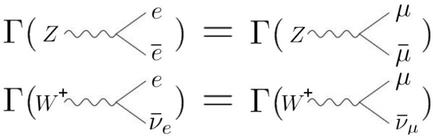




- Single forward-arm spectrometer dedicated to c- and b-physics.
- Major Upgrade-I installed during LS2. Copious Run 3 data taking-ongoing.
- In this talk, I will focus on two rare decay analyses:
  - Electroweak: $\Lambda_b^0 \to pK^-\ell^+\ell^-$ using Run 1+2 (2011-18) data
  - Radiative: triggers and $B_c^+ \to D_s^{*+}(\to D_s^+\gamma)\gamma$ in Run 3 (2024)

Lepton flavor Universality (LFU) in SM

- LFU in the SM: Electroweak couplings of gauge bosons to leptons are independent of their flavor $\rightarrow$



- LHCb is the LFU test industry,
- Thrust has been the ratios:

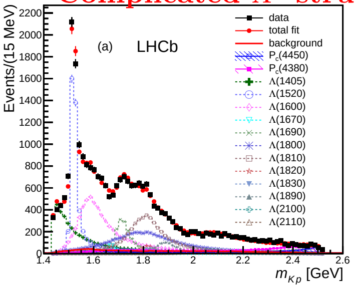
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu \nu_\mu)}, \;\; R(H_s) = \frac{\mathcal{B}(H_b \to H_s \mu\mu)}{\mathcal{B}(H_b \to H_s ee)}$$

$$\text{Where } H_b \in \{B^0, B^+_{(c)}, \Lambda^0_b, B^0_s\},\; H_s \in \{K^{(*)}, \phi, \Lambda^{(*)}\},$$
$$H_c \in \{D^{(*)+,0}, D_s^{(*)+}, \Lambda_c^{(*)-}, J/\psi\}$$

LFUV via angular analysis of $\Lambda_b^0 \to pK^-\ell^+\ell^-$ (Ongoing)

Phys. Rev. Lett. 115, 072001 (2015)

Complicated Λ^* structure

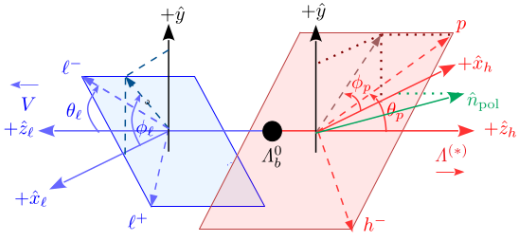


- Wide overlapping resonances is a major complication
- The angular rate for $\Lambda_b^0 \to pK^-\ell^+\ell^-$:

$$\frac{\mathbf{d^4\Gamma}}{\mathbf{dq^2\, d}\cos\theta_\ell\,\mathbf{d}\cos\theta_\mathbf{p}\,\mathbf{d}\chi} = \sum_\mathbf{i} \mathbf{I_i(q^2)f_i}(\theta_\ell, \theta_\mathbf{p}, \phi)$$

- Measure the LFUV observables

$$S_i \equiv \tilde{I}_{i,\mu\mu} - \tilde{I}_{i,ee}$$

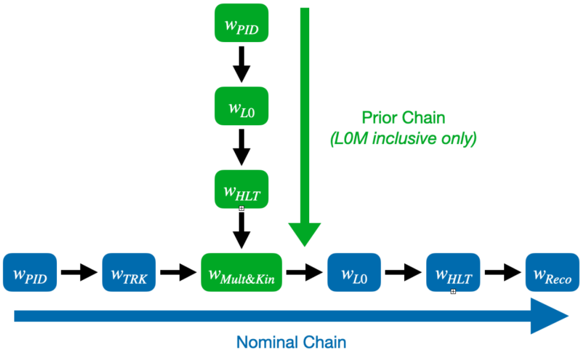


Run 1+2 Analysis Chain $\Lambda_b^0 \rightarrow pK^-\ell^+\ell^-$ (Ongoing)

- Run 1+2 Data and MC samples ✓
- Online-Selections ✓
- Trigger and Pre-BDT selections ✓
- Simulation correction Chain ✓ ← will talk from here
- Combinatorial background suppression by BDT ✓
- Fit to Invariant Λ_b^0 mass (Ongoing)
- Perform Angular analysis
- Systematics calculations and results

Corrections to the simulation

- Data-simulation differences in trigger, kinematic and PID
- Corrections done in two "chains": trigger corrections before (prior) or after (nominal) kinematic corrections.

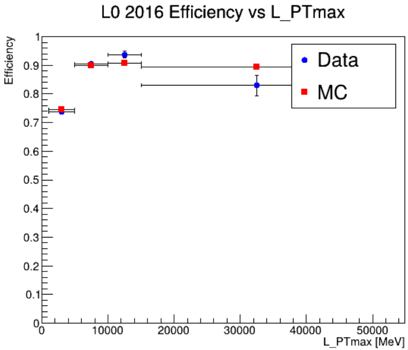


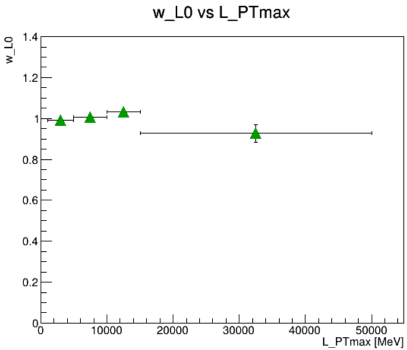
- Following the strategy of other LFUV LHCb analyses, R_{K,K^*} and $R_{K\pi\pi}$.

Corrections to the simulation: L0

LHCb Unofficial

- Example: lepton p_T dependence of the L0 trigger corrections
- Prior chain: $w_{L0} = \frac{\epsilon_{data}}{\epsilon_{MC}}$





Corrections to the simulation: HLT

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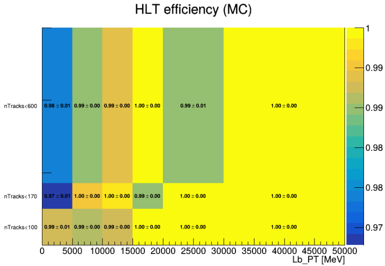
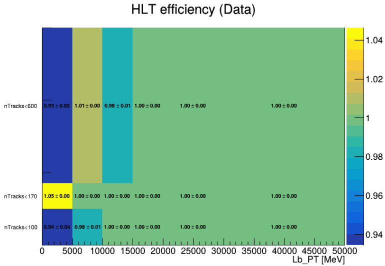
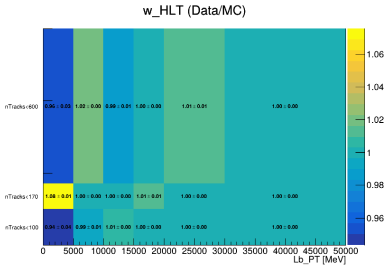
- Prior chain: $w_{HLT} = \frac{\epsilon_{data}}{\epsilon_{MC}}$





- 2D dependence of weights in bins of Λ_b^0 p_T and track multiplicty.



Kinematic variable corrections, $w_{Multi\&kin}$

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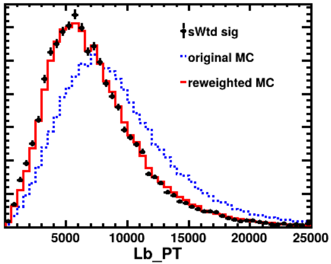
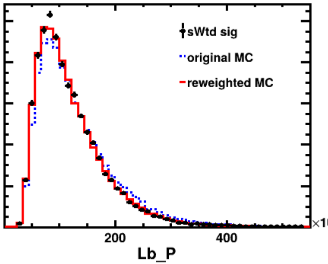
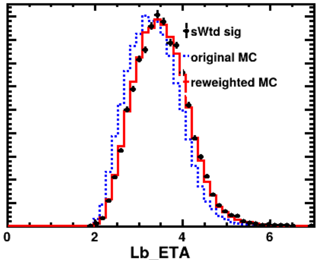
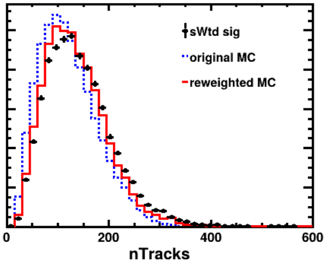
- Use the previously calculated weights
- Correction by a Gradient Boost reweighter
- Separately for each trigger category. Corrections from the resonant channels will be used in both rare and resonant channels.









$w_{Multi\&kin}$ for $\Lambda_b^0 \to pK^- J/\psi(e^+e^-)$

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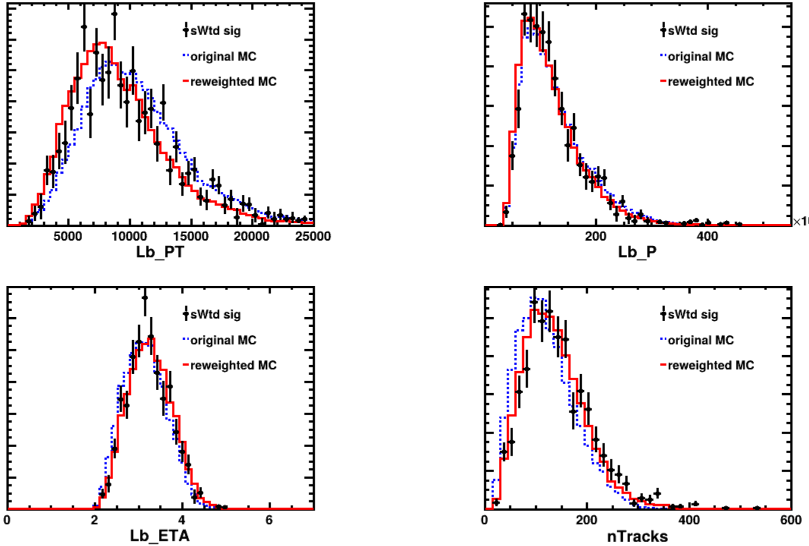

- After this, w_{L0}, w_{HLT} and w_{Reco} are obtained in the nominal chain.

BDT training for $\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-)$

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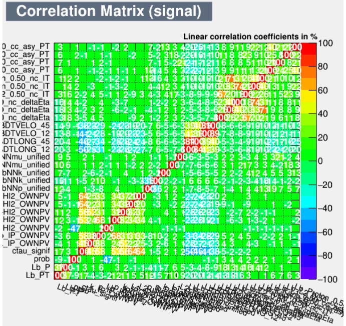
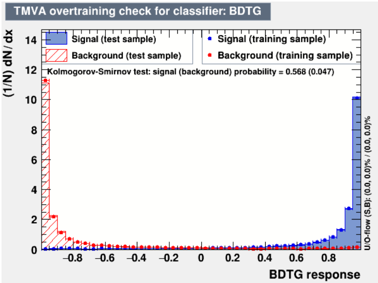
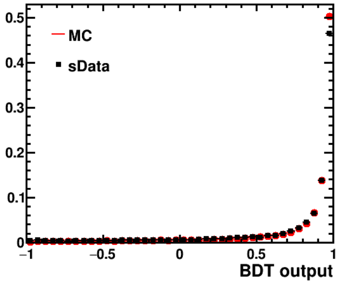
- BDT trained on corrected simulation (signal) and upper-mass sideband $m(pK^-\mu^+\mu^-) > 5800$ data (background proxy).



- BDT includes a large number of kinematic, vertexing, PID, and isolation variables
- Excellent performance and data-simulation agreement





BDT training for $\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-)$

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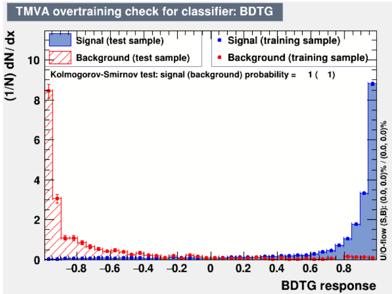
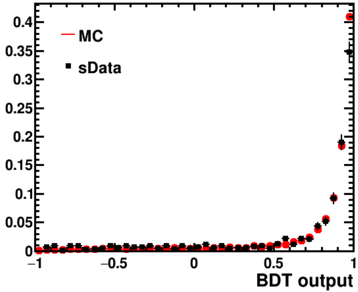
- For ee, due to low statistics, BDT with k-folding and cross-validation



- Good separation and no overtraining despite a large number of variables in the BDT

- Good agreement between corrected simulation and background-subtracted data



- All correlations are preserved between data and simulations

Preliminary resonant channel mass peaks

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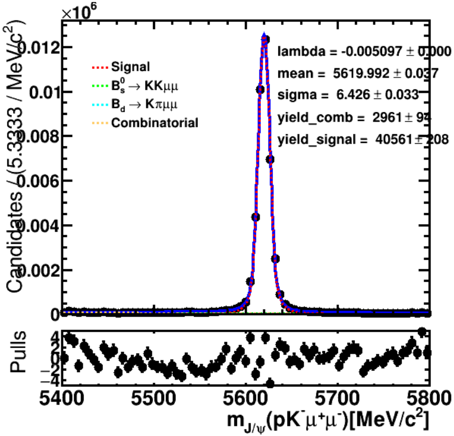
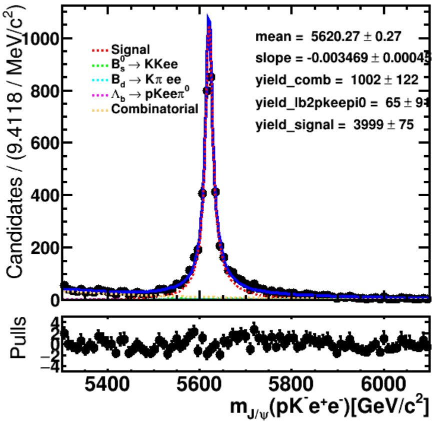
- Checks for Run 2 (2016) for one particular trigger (TOS)

$\Lambda_b^0 \to pK^- J/\psi(\mu^+\mu^-)$



$\Lambda_b^0 \to pK^- J/\psi(e^+e^-)$



Signal yield increased by a factor of 2.3 compared to published R_{pK}

Signal yield increased by a factor of 1.5 compared to published R_{pK}

- Need to understand the large improvement.

Preliminary $\Lambda_b^0 \to pK^-e^+e^-$ fits for 2016 data

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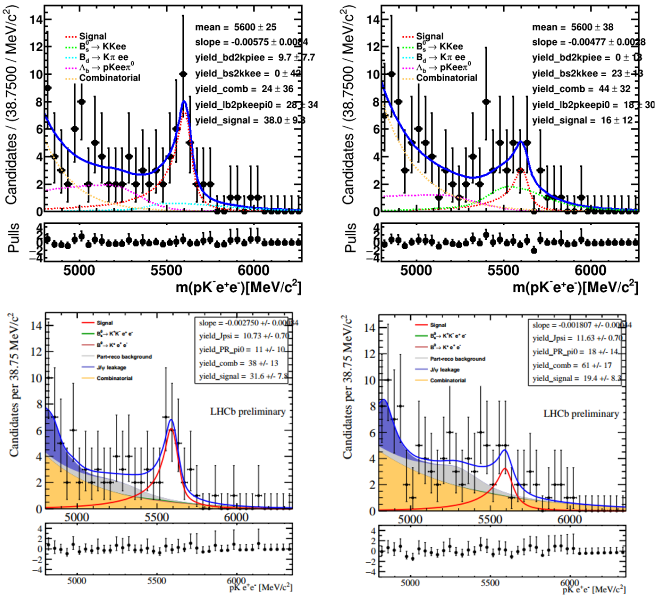
2016 TOS | 2016 TIS



- Showing Run 2 2016 comparisons for different triggers
- Good agreement with the published 2020 R_{pK} paper
- Signal yields are of similar order with the same background
- Ongoing work: better constrain the background components

Ongoing...

- Analysis note is being written at the same time
- Finalizing the mass fits for all the years and rare decays
- Next, perform the angular analysis
- We are working on a phenomenology paper to get the angular observables for any Λ spin.

Run 3

LHCb Run 3 Data Flow

[LHCB-TDR-016]

- Level0 hardware trigger bottleneck removed.

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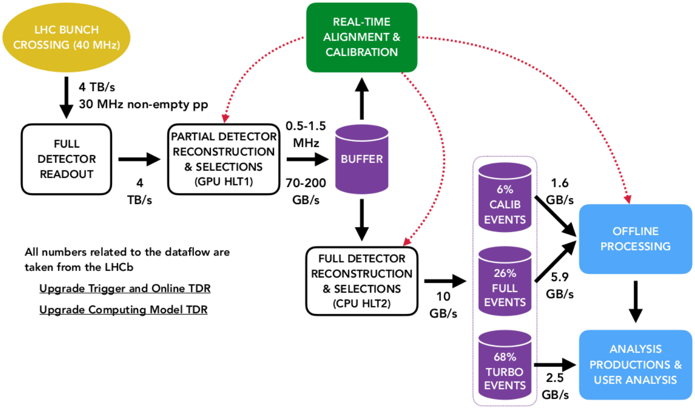

- First time completely software trigger in a high energy experiment!
- I contributed significantly to the HLT2 trigger, which performs the more computationally expensive full reconstruction online during data taking for a specific physics analysis.

Radiative Exclusive HLT2 trigger

LHCb/gitlab/Moore/link

- Built strong radiative program at LHCb in Run 3:
- Designed the following Physics program through HLT2 trigger:

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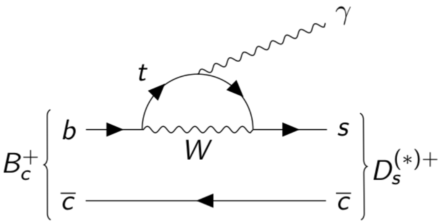
- $B_s^0 \to K^+K^-\gamma$
- $B^0 \to K^+\pi^-\gamma$
- $B^+ \to K^+\pi^+\pi^-\gamma$
- $B^+ \to K^+\phi\gamma$
- $B^0 \to K_s^0\pi^+\pi^-\gamma$
- $B^0 \to K_s^0\phi\gamma$
- $B^+ \to K^+\omega(\pi^+\pi^-\pi^0)\gamma$
- $B^0 \to K_s^0\omega(\pi^+\pi^-\pi^0)\gamma$

- $B_s^0 \to K_s^0K^+\pi^-\gamma$
- $\Lambda_b \to K_s^0 p\pi^-\gamma$
- $\Lambda_b \to pK^-\gamma$
- $B^0 \to \pi^+\pi^-\gamma$
- $B_c^+ \to D^*(2010)^+\gamma$
- $B_c^+ \to D_s^{*+}\gamma$
- $B^+ \to K^+\eta(\pi^+\pi^-\pi^0)\gamma$
- $B^0 \to K_s^0\eta(\pi^+\pi^-\pi^0)\gamma$

- The data collected with these triggers will lead to at least **10 publications**.

Radiative B_c^+ decays

- B_c meson contains two heavy quarks, b and c $\rightarrow$ Large number of decay modes.

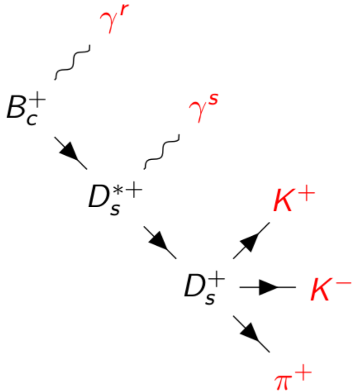


Loop diagram

- B_c can decay radiatively as $B_c^+ \rightarrow D_s^+\gamma$ and $B_c^+ \rightarrow D_s^{*+}[D_s^+\gamma]\gamma$
- Together with the EPFL group, we have started looking at $B_c^+ \rightarrow D_s^{*+}\gamma$ decays.
- Never Searched experimentally
- Theoretically expected BF:$\sim \mathcal{O}(10^{-5})$

Rare $B_c^+ \to D_s^{*+}[D_s^+\gamma]\gamma$

- Only possible at LHCb
- Opportunity to study radiative transitions in the B_c sector
- Many B_c^+ in Run 3
- Challenges:
  - D_s flies, B_c vertex is not reconstructible. Similar to $\Lambda_b^0 \to \Lambda\gamma$
  - 2 photons final state
  - 1 soft photon (γ^s); introduces lots of background, photon identification challenging at low PT



Preliminary mass peaks

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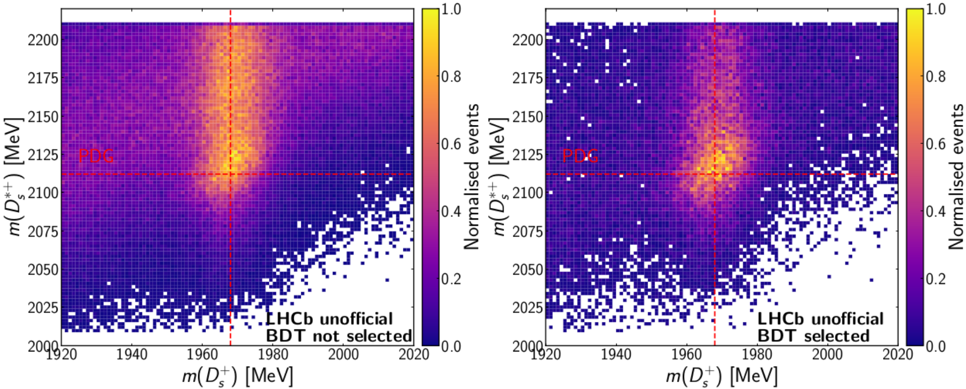
- Samuël Bakker, EPFL project student, looked at 2024 data



- There are D_s^{*+} and D_s^+ mass peaks in data.
- Next, we will study the misidentified and peaking backgrounds

Neutral PID calibration at LHCb

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LHCb-INT-2025-002

- Identification of photons and neutral pions at LHCb is key to several physics analyses.
- Designed LHCb Calo. triggers.
- Decay channels used (large branching fraction) for calibration:

$$B^0_{(s)} \to K^{*0}/\phi\gamma$$
$$D^{*+} \to D^0[K^+\pi^- \pi^0]\pi^+$$
$$D_s^{*+} \to D_s^+ \gamma$$
$$\eta \to \mu^+\mu^- \gamma$$
$$D^+_{(s)} \to \eta^{'}[\pi^+\pi^- \gamma]\pi^+$$

- Calibration will be used by the whole LHCb collaboration

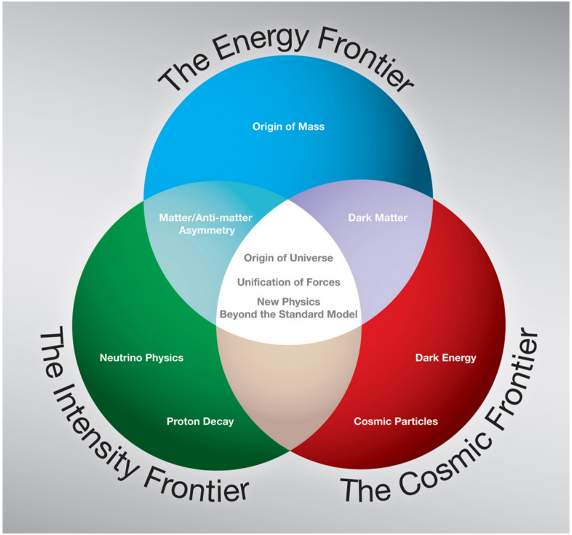
Future Plans

- The journey at LHCb has been exciting, received the YSF grant at La Thuile, Italy, for EMTF work
- Recently won the EKOP scholarship in Hungary (additional support to exceptional researchers)
- After finishing the $\Lambda_b^0 \to pK^-\ell^+\ell^-$ analysis, I plan to focus on radiative decays
- First searches of decays like $B_c^+ \to D_s^{*+}\gamma$, $\Lambda_b \to K_s^0 p\pi^-\gamma$, $B^0 \to K_s^0\pi^+\pi^-\gamma$ would be the immediate thrust
- Observation of these decays will open new avenues for TDCPV, photon polarization study
- I would also be interested in contributing to LHCb Upgrade II.

Conclusion

- Study of rare decays is absolutely crucial for new Physics search
- Designed RD HLT2 trigger lines and also added new Semileptonic and B2OC trigger lines
- Also, contributed as RD RTA liaison for 2025 data taking
- $\Lambda_b^0 \to pK^-\ell^+\ell^-$, planning to enter into RC by the end of this year

The Three Frontiers



- At the intensity frontier, rare decays of subatomic particles like b meson, d meson, τ lepton are studied. Their probability of occurrence is very small.
- We compensate for that by having high luminosity, a large number of these particles being produced.

Reduce Combinatorial backgrounds by BDT

List of variables used for BDT training:

- $p_T(\Lambda_b^0)$
- $p(\Lambda_b^0)$
- χ^2_{DTF} prob
- ctau_signif
- k_IP_OWNPV, p_IP_OWNPV
- Lb_IPCHI2_OWNPV, p_IPCHI2_OWNPV, k_IPCHI2_OWNPV, L1_IPCHI2_OWNPV,L2_IPCHI2_OWNPV
- p_ProbNNp, p_ProbNNk, k_ProbNNk
- L1_ProbNNmu, L2_ProbNNmu,

Isolation variables:

- Lb_TRKISOBDTLONG_12, Lb_TRKISOBDTLONG_45
- Lb_TRKISOBDTVELO_12, Lb_TRKISOBDTVELO_45
- Lb_L2_0.50_nc_deltaEta, Lb_Kaon_0.50_nc_deltaEta, Lb_Proton_0.50_nc_deltaEta
- Lb_L2_0.50_nc_IT, Lb_Proton_0.50_nc_IT, Lb_Kaon_0.50_nc_IT

Triggers

Mutually exclusive L0-Hardware Triggers:

- TIS: `L0Hadron_TIS` (`Lb`) || `L0Muon_TIS` (`Lb`) || `L0Electron_TIS` (`Lb`)
- MTOS: `L0Muon_TOS` ($\mu 1, \mu 2$) && `!TIS(Lb)`
- ETOS: `L0Electron_TOS` ($e1, e2$) && `!TIS(Lb)`

After that, further software-level triggers HLT1 and HLT2 are being applied.

Basis of local operators for $b \to s$ penguins

- $(V-A)$ LH operators consistent with SM symmetries:

$$\mathcal{O}_1^u = (\bar{s}\gamma_\mu T^a P_L u)\,(\bar{u}\gamma^\mu T^a P_L b)$$

$$\mathcal{O}_2^u = (\bar{s}\gamma_\mu P_L u)\,(\bar{u}\gamma^\mu P_L b)$$

$$\mathcal{O}_1^c = (\bar{s}\gamma_\mu T^a P_L c)\,(\bar{c}\gamma^\mu T^a P_L b)$$

$$\mathcal{O}_2^c = (\bar{s}\gamma_\mu P_L c)\,(\bar{c}\gamma^\mu P_L b)$$

$$\mathcal{O}_3 = (\bar{s}\gamma_\mu P_L b)\sum_q (\bar{q}\gamma^\mu q)$$

$$\mathcal{O}_4 = (\bar{s}\gamma_\mu T^a P_L b)\sum_q (\bar{q}\gamma^\mu T^a q)$$

$$\mathcal{O}_5 = (\bar{s}\gamma_\mu\gamma_\nu\gamma_\rho P_L b)\sum_q (\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho q)$$

$$\mathcal{O}_6 = (\bar{s}\gamma_\mu\gamma_\nu\gamma_\rho T^a P_L b)\sum_q (\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho T^a q)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

$$\mathcal{O}_8 = \frac{g_s}{16\pi^2} m_b (\bar{s}\, T^a \sigma_{\mu\nu} P_R b) G^{a\mu\nu}$$

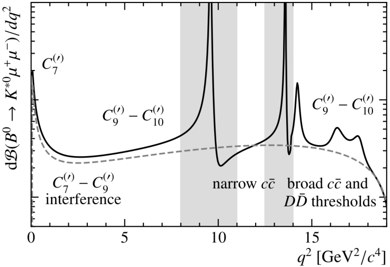
$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

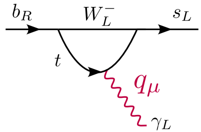
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- $\mathcal{O}_{1,2}$ (4-quark tree), $\mathcal{O}_{3-6}$ (4-quark penguins), $\mathcal{O}_8$ (gluon penguin)

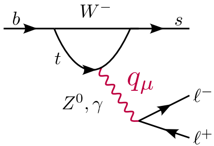
The three dominant contributions

- The dominant $\mathcal{O}_{7,9,10}$ contributions, as a function of q^2:





$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$ photon



$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$ vector

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$ axial-vector

- The primed terms are the RH (quark) operators, suppressed in the SM, but can be enhanced in NP scenarios.

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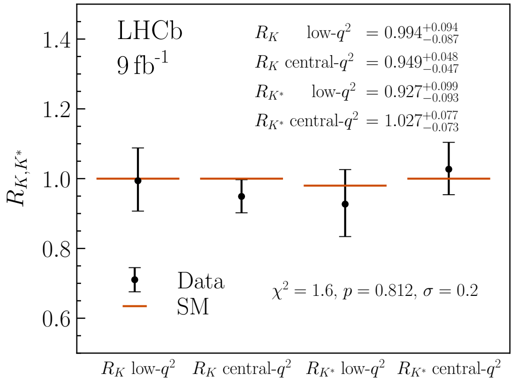

Compatible to the SM

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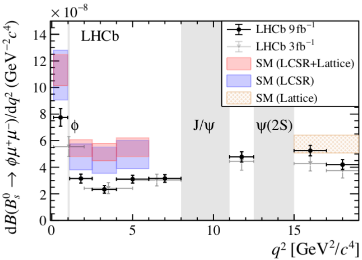

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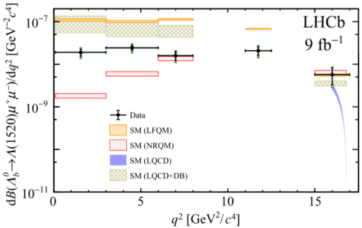
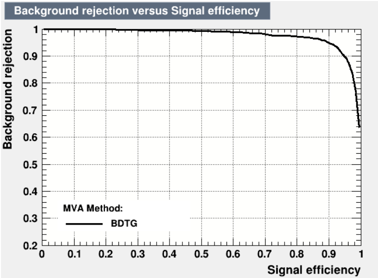


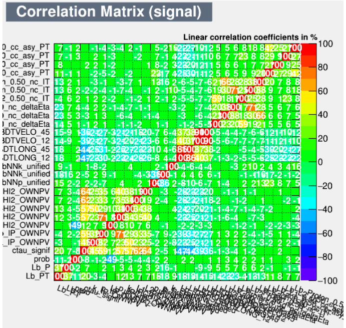
BR measurements differ from predictions

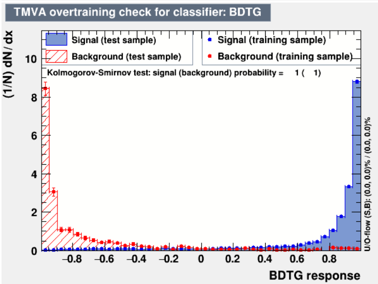
BDT training for $\Lambda_b^0 \to pK^- J/\psi(e^+e^-)$

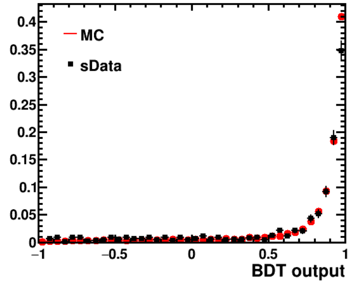
LHCb Unofficial

- For the electron case, due to low statistics, BDT k-folding with cross-validation is being used.

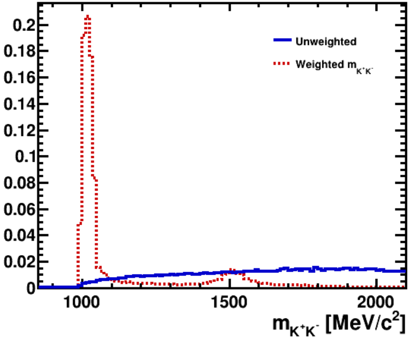


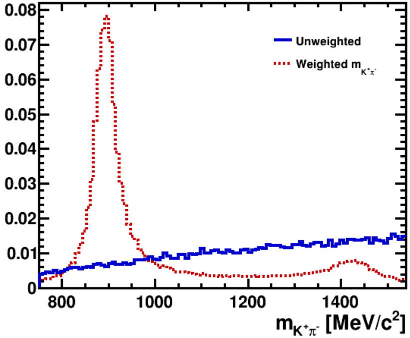






Background Shapes in MC





- Background samples were generated with flat in m_{KK} and $m_{K\pi}$.
- m_{KK} and $m_{K\pi}$ shapes are corrected.
- Get the expected yield =