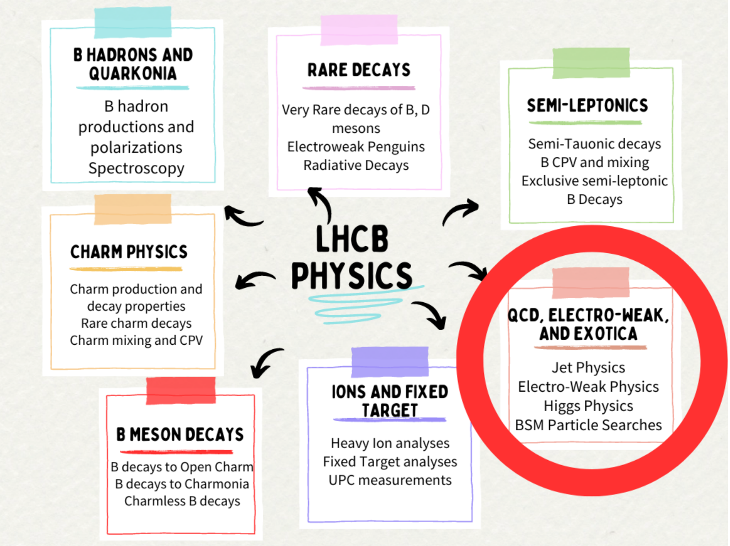
QCD, ElectroWeak physics, and searches for exotic signatures in the forward region at LHCb

Nate Grieser, on behalf of the collaboration

03-04-2025

The LHCb Physics Program



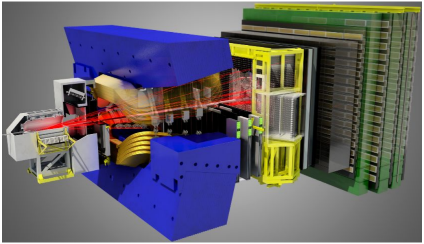
QEE Publications Page

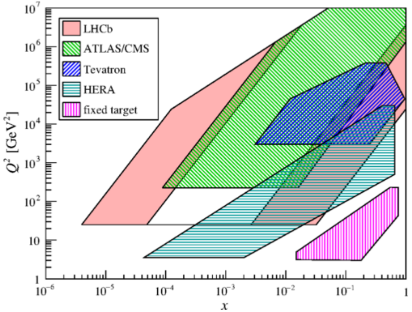
LHCb Detector Overview

JINST 3 (2008) S08005

→ LHCb Strengths of Design:

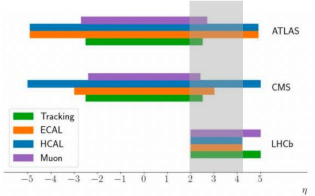
- Long tracking distances for improved flavour physics
- Ring-Imaging Cherenkov (RICH) detectors for particle identification (PID)





PRD 93, 074008 (2016)

- Forward design allows for LHC-unique coverage of low- and high-x partons



Precisely Measuring Electro-Weak Theory: A probe of New Physics

Choice of three free parameters of electroweak theory:

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

A lot of recent activity on this front with numerous collaborations producing interesting measurements of dependent values

$\rightarrow$ Measured values deviating from prediction can give evidence of new physics in the higher order corrections (Δr)

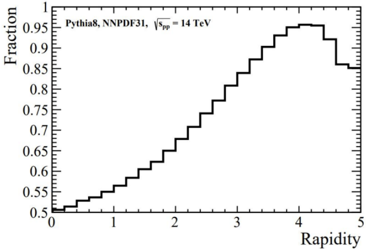
Measurement of the Effective Leptonic Weak Mixing Angle — JHEP 12(2024)026

Significant probe of EW theory; relation of U(1) and SU(2) gauge couplings

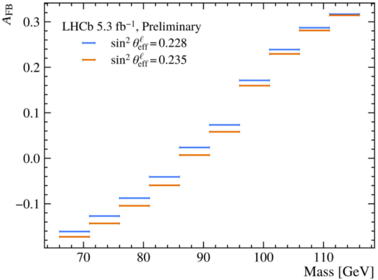
$$\sin\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$$

q–$\bar{q}$ differences at high-x and low-x has significant sculpting of Z relations to initial-state partons

Fraction of events with Z in line with initial-state quark ↓



LHCB-PUB-2018-013



↑ Extract $\sin\theta_W$ using A_{FB}:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

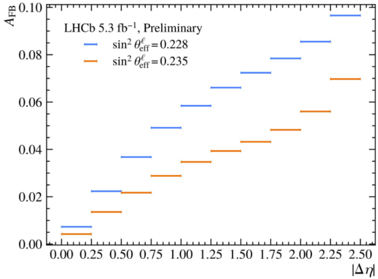
Mass dependent $\sin\theta_W$ no sensitivity

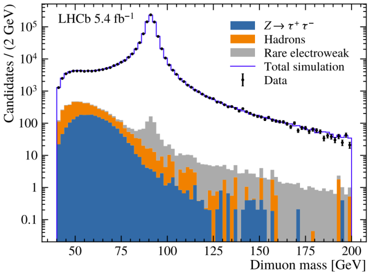
Measurement of the Effective Leptonic Weak Mixing Angle JHEP 12(2024)026

Separate events at large and small $cos\theta^*$ to increase sensitivity

$$\frac{d\sigma}{dcos\theta^*} \propto 1 + cos^2\theta^* + \frac{8}{3} A_{FB} cos\theta^*$$

Bin the measurement of A_{FB} in $\Delta\eta$ of the muons shows significant sensitivity to $\sin\theta_W$ ↓



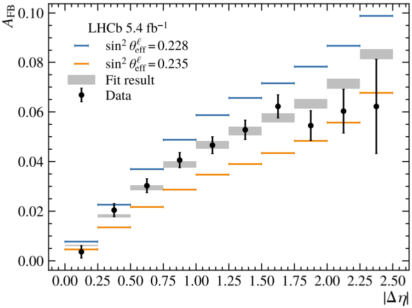


↑ Can use single, large window mass bin due to very pure signal selection

$$66\text{GeV} \leq M_Z \leq 116\text{GeV}$$

Measurement of the Effective Leptonic Weak Mixing Angle — JHEP 12(2024)026

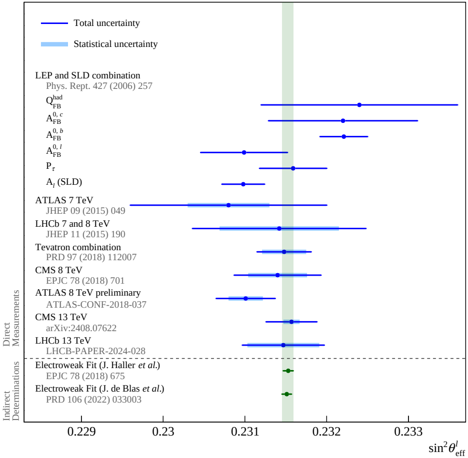
Results: $\sin\theta^{\ell}_{\text{eff}} = 0.23152 \pm 0.00044\ (\text{stat.}) \pm 0.00005\ (\text{syst.}) \pm 0.00022\ (\text{theory})$



Stats are significant limitation in the most sensitive bins

→ Look out for Run 3!

No deviation from SM observed

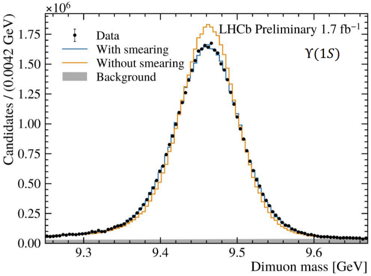


Measurement of Z Boson Mass

LHCB-PAPER-2025-008 (Preparation)

Goal: Further probe of EW theory by measuring m_Z with a dimuon mass distribution
Clean signal selection → Precision to come from calibrations!

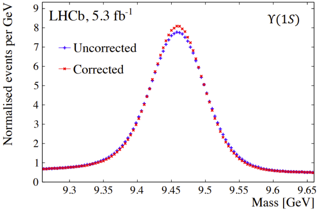
$\Upsilon(1S) \to \mu^+\mu^-$ as calibration channel for both data ↓ and MC →

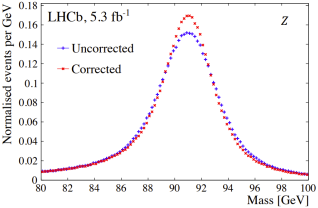


→ Full detector response is dominant systematic

JINST 19 P03010

Data correction with pseudo-mass method

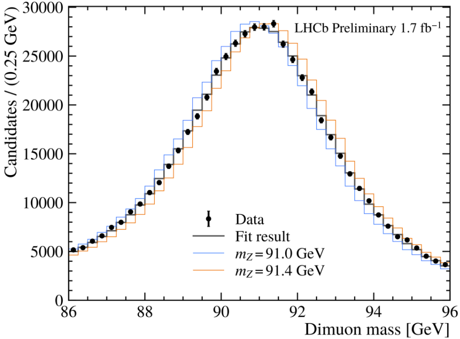




Measurement of Z Boson Mass

LHCB-PAPER-2025-008 (Preparation)

Mass Extraction: Simple fit to the dimuon mass spectrum following all calibrations



Analysis using 2016 dataset

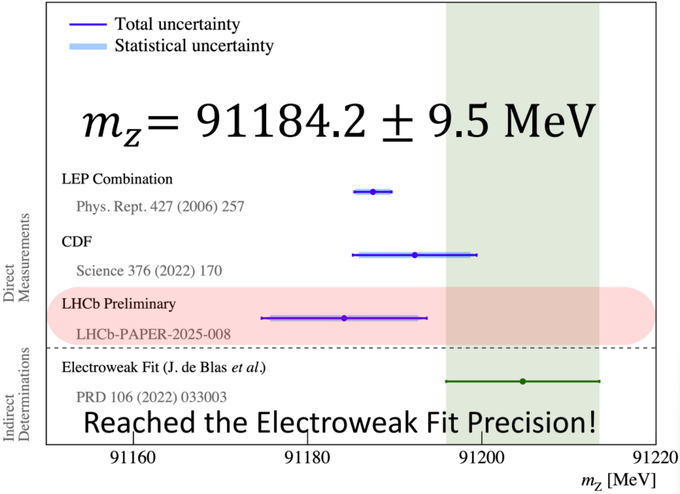
- Binned χ^2 fit used to extract mass value
- Simulation taken from PowHeg with NLO-QED predictions
- Analysis statistically limited
  - Full Run 2 to follow

Source	Size [MeV]
Momentum calibration	4.1
Signal QED corrections	0.8
Parton distribution functions	0.7
Detection Efficiency	0.1
Statistical uncertainty	8.5
Total	**9.5**

Measurement of Z Boson Mass

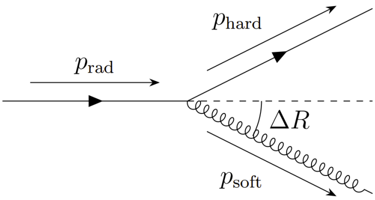
LHCB-PAPER-2025-008 (Preparation)

Results: First dedicated measurement of m_Z at the LHC



Dead Cone Effect and Lund Jet Plane

LHCB-PAPER-2025-010 (Preparation)



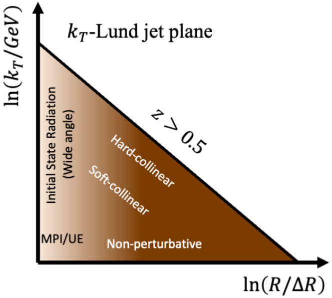
Jet substructure observables sensitive to dead cone effect:

$$z = \frac{p_T^{\rm soft}}{p_T^{\rm soft} + p_T^{\rm hard}}$$

$$k_T = p_T^{\rm soft} \cdot \Delta R$$

Dead Cone Effect: Suppression of collinear radiation around quarks during parton shower

$$\theta_q = \frac{m_q}{E_q}$$



J. Phys. G: Nucl. Part. Phys. 17 1602

Phys. Rev. D 99 (2019) 074027

Lund Jet Plane Measurement

LHCB-PAPER-2025-010 (Preparation)

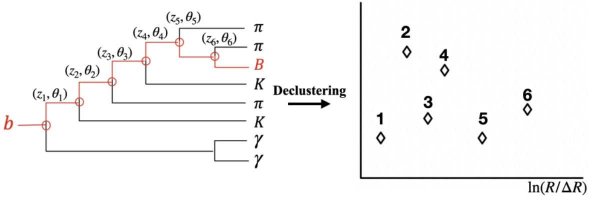
Analysis Goal: Measure and compare LJP of light-quark-enriched and *b*-quark jets

Light-jet-enriched selection:

1. m_Z window: $60 < m_{\mu^+\mu^-} < 120$ GeV
2. $\mu^\pm$ acceptance: $p_T^\mu > 20$ GeV ; $2.0 < \eta^\mu < 4.5$
3. Jet acceptance: $20 < p_T^{\text{jet}} < 100$ GeV ; $2.5 < \eta^{\text{jet}} < 4.0$

***b*-tagged jet selection:**

1. Identified $B^\pm$ mesons: $B^\pm \to J/\psi(\to \mu^+\mu^-)K^\pm$
2. 5.24 GeV $< m_{B^\pm} < 5.31$ GeV
3. Jets must pass Winner-Take-All algorithm tag requirement JHEP10 (2022) 158

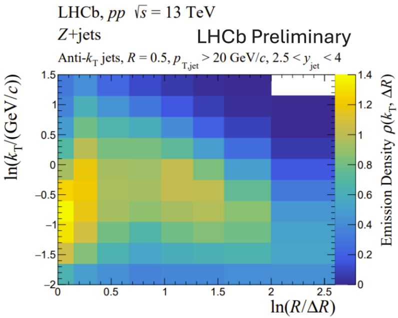


→ **Populate LJP using de-clustering of jet constituents**

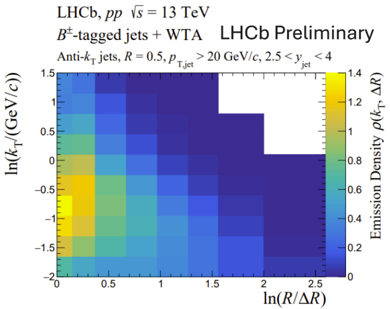
Lund Jet Plane Measurement

LHCB-PAPER-2025-010 (Preparation)

Results: **First direct observation of dead cone effect in B jets**



Wide Angle Emission → Small Angle Emission

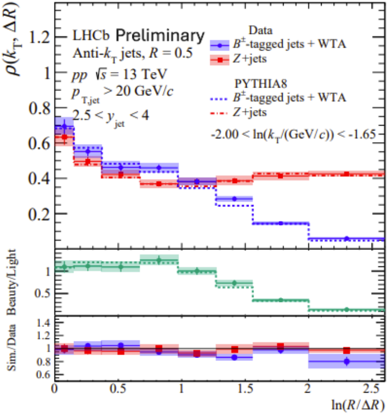


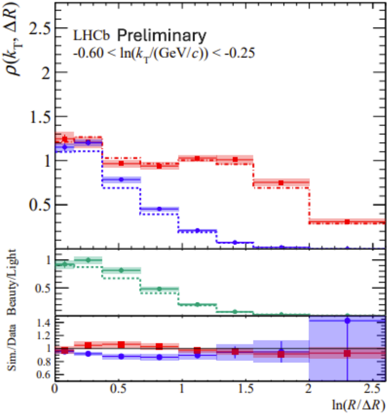
Wide Angle Emission → Small Angle Emission

Lund Jet Plane Measurement

LHCB-PAPER-2025-010 (Preparation)

Results: **First direct observation of dead cone effect in B jets**



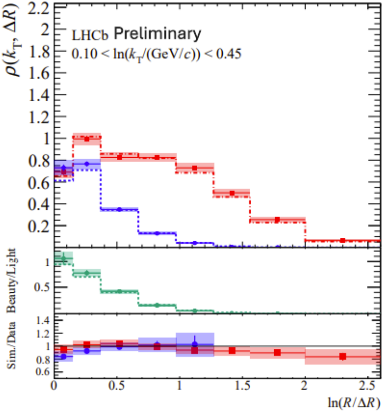


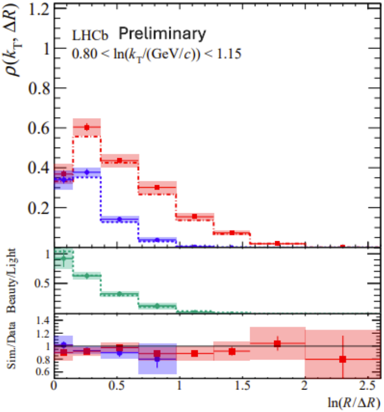
→ Horizontal Projections of k_T LJP from **nonpertubative** regime

Lund Jet Plane Measurement

LHCB-PAPER-2025-010 (Preparation)

Results: **First direct observation of dead cone effect in B jets**

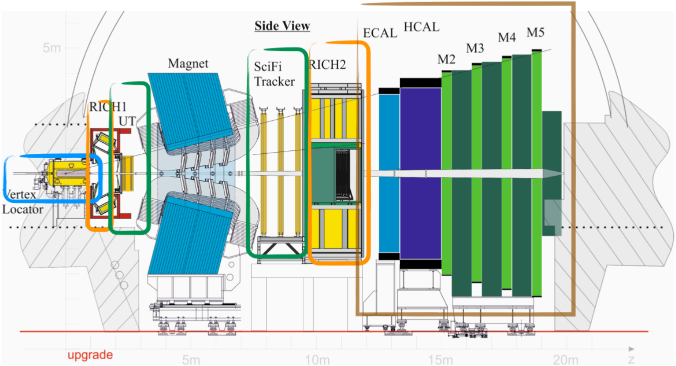




$\rightarrow$ Horizontal Projections of k_T LJP from **perturbative** regime

LHCb Upgrade 1

JINST 19 (2024) 05, P05065

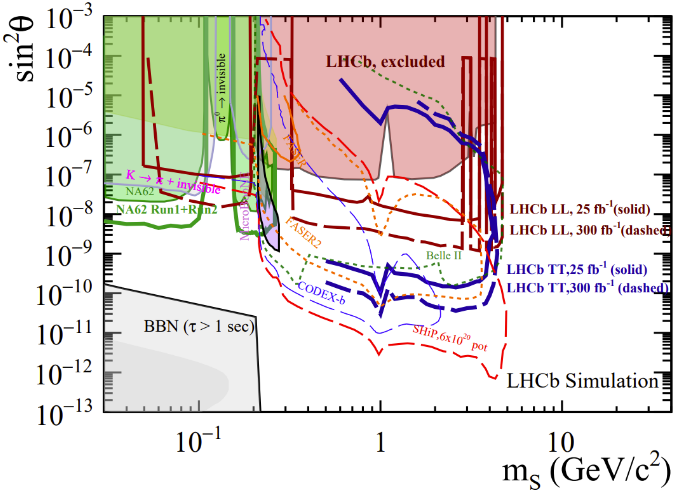


→ LHCb detector went through significant upgrade during LS2

Forward detector allows for unique exotic search applications with Run 3 data

Expected Coverage of Portal Scalars

LHCB-FIGURE-2025-001



→ Application of Sci-Fi only tracks gives significant sensitivity increase!

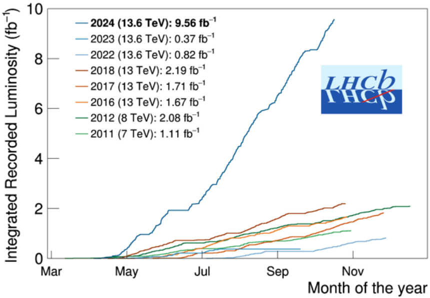
QEE at LHCb – Now and Onto Run 3

LHCb QCD, Electro-Weak, and Exotics continues to provide profound results to our understanding of the Standard Model

- Complementary measurements of electro-weak properties
- Furthering our understanding of QCD with jet substructure measurements
- Using unique detector design and cutting-edge technologies to search for exotic BSM signatures

$\rightarrow$ LHCb Run 3 will offer a unique environment for forward physics at the LHC and is already underway

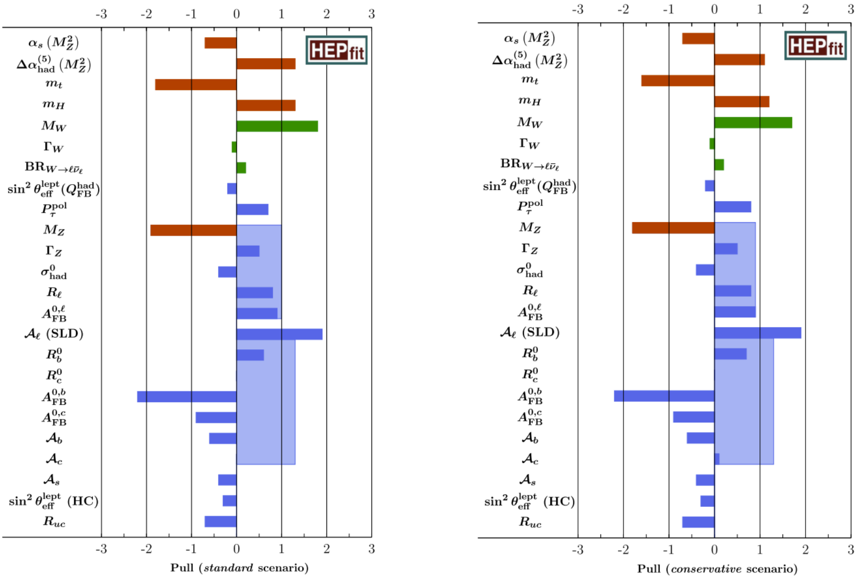
- Forward fiducial region with relatively low pile-up
- Expected luminosity **above 30 fb**$^{-1}$ $\rightarrow$ More opportunities!
- Malleable fully software-based trigger



BACKUP

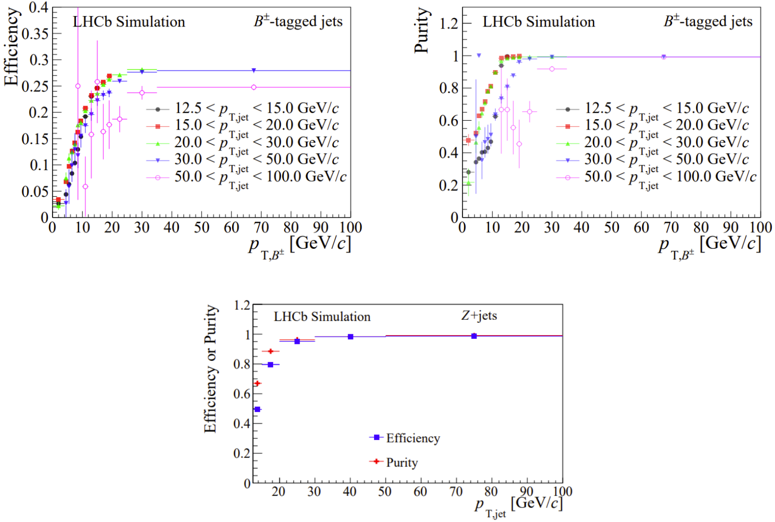
Measurement of Z Boson Mass

Phys. Rev. D. 106 (2022) 033003



Lund Jet Plane Measurement

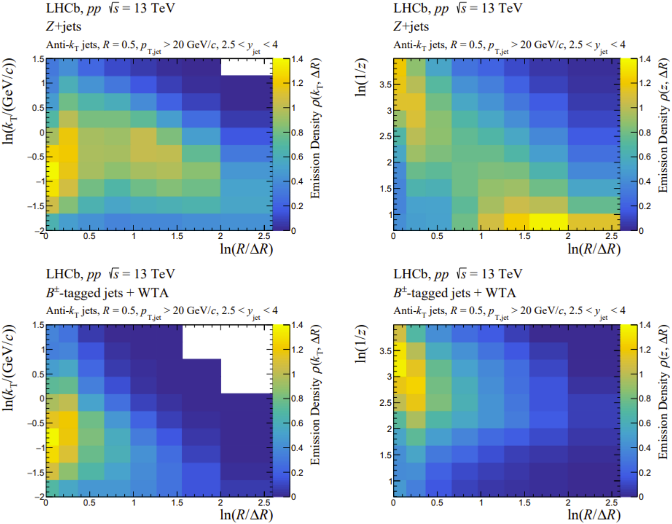
LHCb PRELIMINARY



Lund Jet Plane Measurement

LHCb PRELIMINARY

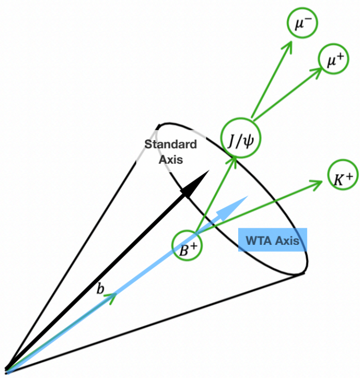
Results: First direct observation of dead cone effect in B jets



Winner-Take-All Tagging

JHEP10 (2022) 158

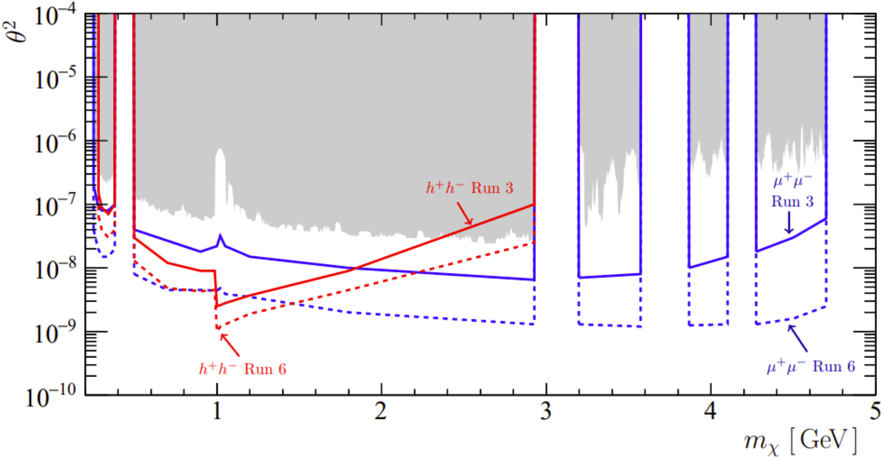
1. Recluster jet using Cambridge-Aachen algorithm
2. Pseudo-jet p at each recluster of the two daughters
3. Pseudo-jet direction along higher p_T daughter
4. WTA Tag Criteria: WTA axis matches heavy-flavour direction



→ Ensures fair comparison between light and heavy-flavour LJP

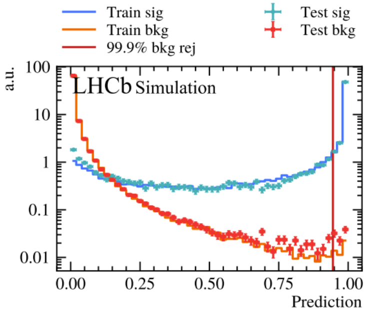
Expected Coverage of Portal Scalars

arXiv.2203.07048



Classical Search Approach – Neural Network

LHCb-FIGURE-2024-015



Neural Networks require defined signal model:

$H \rightarrow AA \rightarrow 4\tau$;

$\tau \rightarrow \pi\pi\pi$

$\rightarrow$**Limitations!**

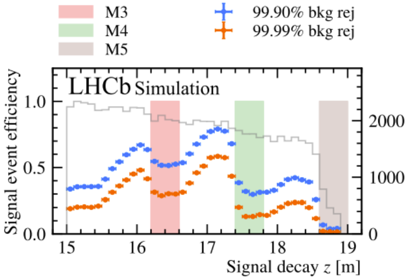
What if reality is different than the model used to train?

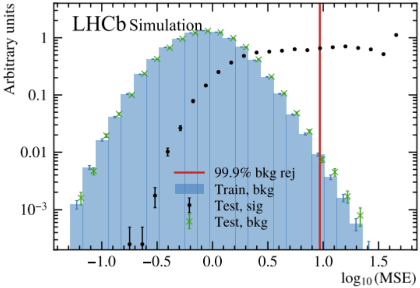
Background-Only Training – Auto Encoders

LHCb-FIGURE-2024-015

Auto Encoders serve as classifiers only training on the background-only hypothesis

Versatile!





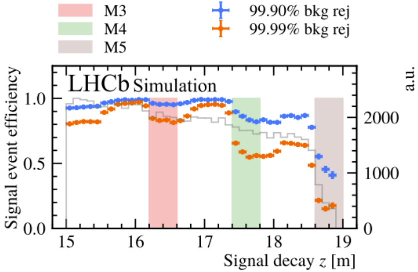
↑ Separation of signal (anything **not** expected) from background (data) comes from minimization of reconstruction error

Penalizing Performance – Normalised Auto Encoders

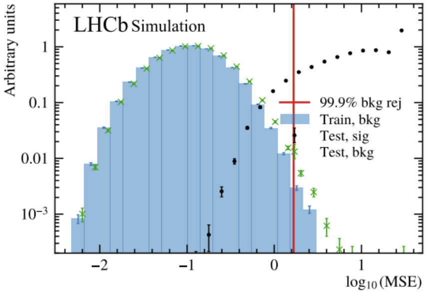
LHCb-FIGURE-2024-015

Auto Encoders can be too good at reconstructing **Anything**, like our anomalies..

Normalised Auto Encoders!



Constructed by sampling reconstructible space outside of min-bias concentration



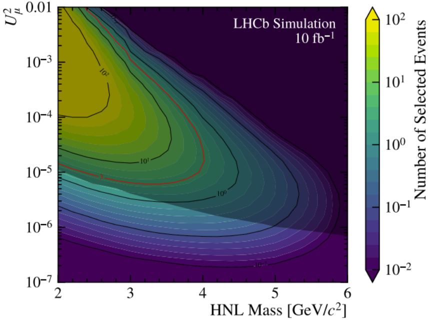
← ↑ Significant improvement in performance

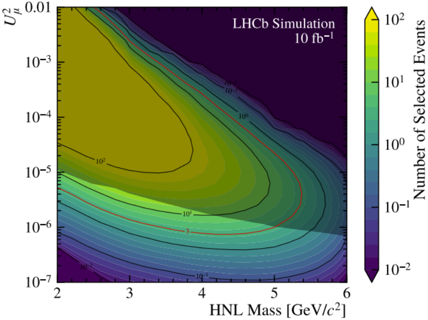
→**Limitations!**

Need stable detector performance, or need to retrain classifier

Expected Coverage of HNLs at LHCb

LHCB-FIGURE-2025-001





$\rightarrow$ Application of Sci-Fi only tracks gives significant sensitivity increase!