Beyond Flavour: Exploring unique measurements of QCD, Electro-Weak, and Exotica (QEE) with the LHCb detector

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Summary

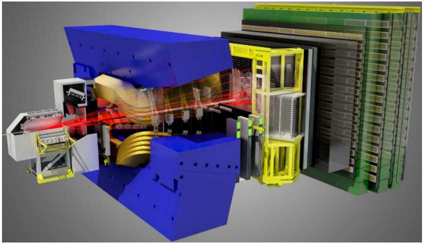
- The LHCb detector is more than a flavour experiment, providing complementary precision measurements of Electro-Weak (EW) parameters
- The LHCb detector provides unique probes into QCD, making use of it's excellent particle identification abilities
- The LHCb detector's unique geometry allows for searches of Long-Lived Particles (LLPs) and other GeV-scale exotic particles
- Exciting future advancements to LHCb ECal, led by US-LHCb colleagues, will greatly improve the scope of the LHCb QEE physics program

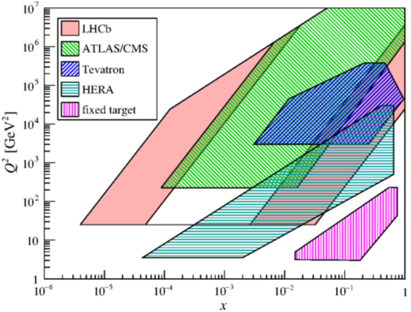
LHCb Detector Overview

JINST 3 (2008) S08005

→ LHCb Strengths of Design:

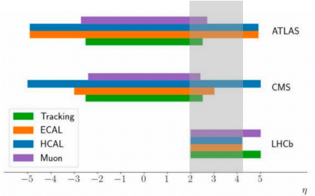
- Long tracking distances for improved flavour physics
- Ring-Imaging Cherynkov (RICH) detectors for particle identification (PID)





PRD 93, 074008 (2016)

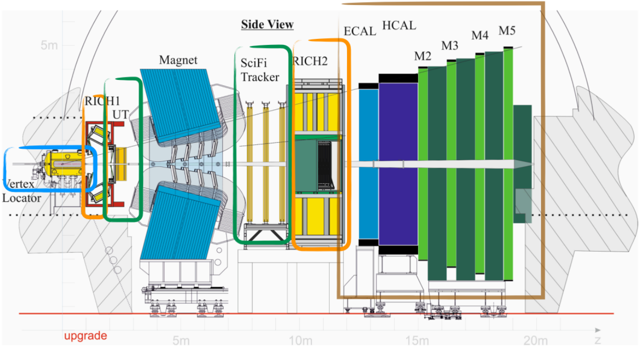
- Forward design allows for LHC-unique coverage of low- and high-x partons



LHCb Upgrade I

arXiv:2305.10515

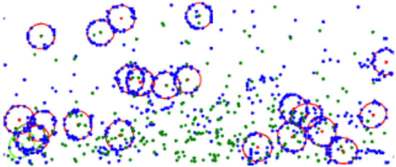
Significant upgrades to the LHCb detector were made during the recent LHC LS2



- New Vertexing Detector → Closer to beam; Silicon pixels improve IP resolution
- New PID detector → New photon detectors and improved readout
- New tracking system → Silicon strip UT for improved tracking granularity; Fibre tracking for high particle density momentum resolution
- New Readout Systems
- *BONUS* : New GPU-based trigger

LHCb RICH System - Concept Overview

- Charged particles passing through a medium faster than the speed of light (in the same medium) emits a cone of light
- Different dense gases are used for this medium
- The cone shape is a function of the velocity
- Combining the velocity with the momentum measurements, one can extract the exact mass of the particle to use in particle identification (PID).

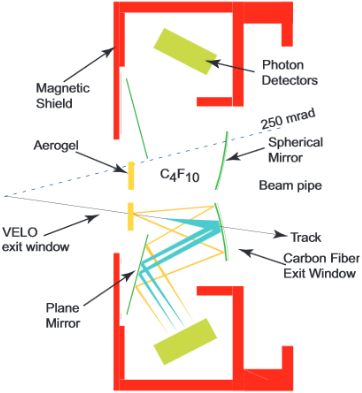


LHCb RICH System - Making the Emissions

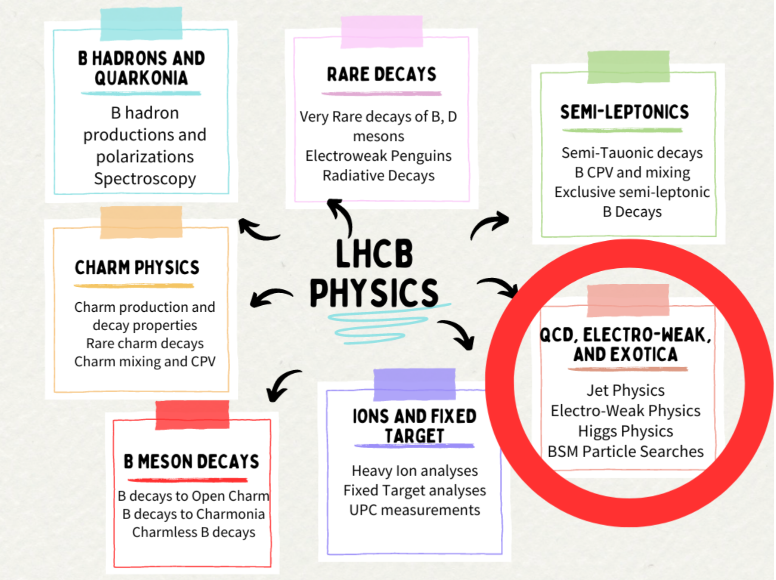
- LHCb utilizes two RICH detectors: one before the magnet (RICH-1), and one beyond the magnet and tracking stations (RICH-2)
  - RICH-1 uses a combination of silica aerogel and C4F10 gas radiators (targeting low and medium momentum particles)
  - RICH-2 uses a CF4 gas radiator (targeting high momentum particles)

- RICH1 makes use of a carbon-fibre reinforced polymer (CFRP) mirrors to reduce the amount of scattering of charged particles

- RICH2 uses glass mirrors because they are downstream the tracking stations.



The LHCb Physics Program



The QEE Group – Cleaning Up the Rest

The QEE Group: All of the forward physics that isn't covered by the rest of the groups

- The analysis group is split further into two subgroups:
  1. Fundamental Standard Model Interactions
  2. Beyond Standard Model Searches
- SM $\rightarrow$ Electro-weak, Higgs, Top, Jet Physics
- BSM $\rightarrow$ LLPs, Dark Photons, Light Scalars, ...

Physics Analysis Groups (PAGs)

BPH: B Physics and Quarkonia
Conveners (email): C. Rovelli (ROMA), D. Kovalskyi (MIT)
Public page

SMP: Standard Model Physics
Conveners (email): A. Gilbert (LLR), M. Pellicioni (TORINO)
Public page

TOP: Top Physics
Conveners (email): J. Kieseler (KIT), A. Grohsjean (HAMBURG)
Public page

HIG: Higgs Physics
Conveners (email): A. De Wit (LLR), E. Di Marco (ROMA)
Public page

SUS: Searches for new physics in final states with Unbalanced pT and Standard objects
Conveners (email): M. Masciovecchio (UCSD), C. Caillol (CERN)
Public page

EXO: Searches for Exotica
Conveners (email): L. Soffi (ROMA), C. Pena (FNAL)
Public page

B2G: Searches for Beyond SM particles decaying to top quarks and Higgs and Gauge bosons
Conveners (email): L. Gouskos (CERN), A. Reimers (UZH)
Public page

HIN: Heavy-Ion Physics
Conveners (email): G. Krintiras (KANSAS), J. Wang (CERN)
Public page

Covering a broad area of topics with a very small team

Ability to provide complementary (EW, Higgs, Jet) and unique (Jet, BSM) measurements and analyses to the LHC community

Analyses Covered in this Seminar

Electro-Weak Precision Measurements:

- TODAY: Measurement of the W boson mass with the LHCb detector
- Additionally: Weak Mixing Angle, Z-mass measurement, W Helicity Measurement, W cross section, ...

QCD Probes with Jet Physics:

- TODAY: Z Bosons Produced in Association with Charm
- TODAY: Charged Hadron Distributions in Z-tagged Jets
- TODAY: Search for $H \to b\bar{b}$ and $H \to c\bar{c}$
- Additionally: Lund Jet Plane, Jet Substructure measurements, Hadronic W decays, ...

Beyond Standard Model Searches:

- TODAY: Search for heavy neutral leptons in $W^{\pm} \to \mu^{+}\mu\pm jet$ decays
- Additionally: Dark photons, axion-like particles (ALPs), sexaquark search, Dark Matter searches, ...

TODAY: Prospects for the future

Measurement of the W Boson Mass

JHEP 01 (2022) 036

Mass of the W boson is one of three free parameters of electroweak theory:

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

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

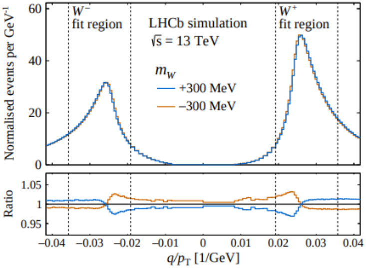
$\rightarrow$ A lot of recent activity on this front with numerous collaborations producing interesting measurements

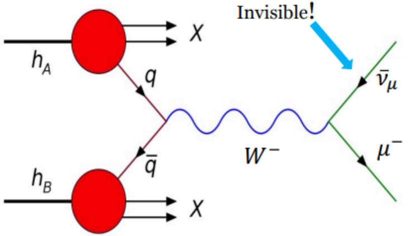
Measurement of the W Boson Mass

JHEP 01 (2022) 036

Analysis Strategy: Select well-isolated muons, performing significant momentum calibrations to ensure precision

The analysis uses q/p_T^{μ} to allow for visualization of all muons with $p_T > 24$ GeV $\downarrow$



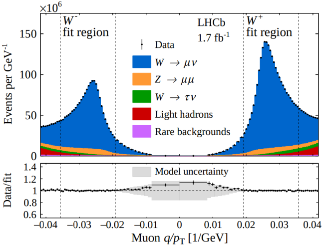


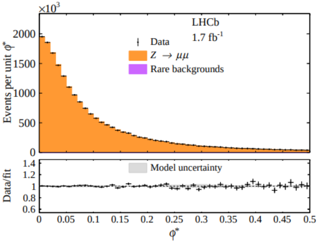
Calibrations of p_T^{μ} are carried out using $\Upsilon(1S) \to \mu\mu$ and $J/\Psi \to \mu\mu$ channels, validated with $Z \to \mu\mu$ distributions

Measurement of the W Boson Mass

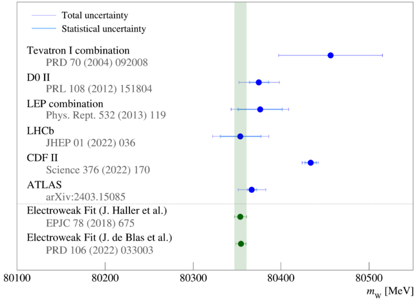
JHEP 01 (2022) 036

Results: $m_W = 80354 \pm 23\,(\text{stat.}) \pm 10\,(\text{exp.}) \pm 17\,(\text{theory}) \pm 9\,(\text{PDF})$ MeV





← Current analysis based only on 1/3 of LHCb Run-2 dataset (2016), with simultaneous
fit to muon q/p_T and ϕ^* of Z candidates



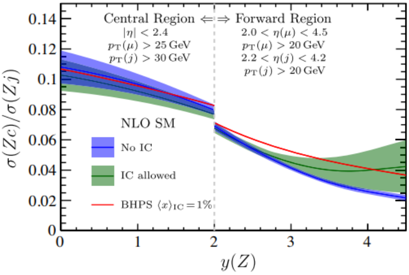
PDF uncertainties are anti-correlated between central and forward measurements
→ Significant contribution to global fits!

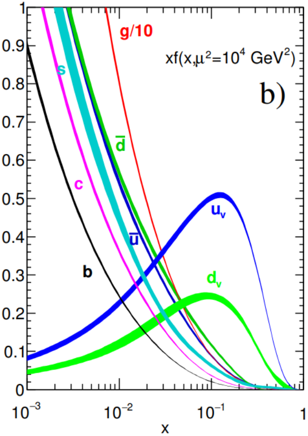
Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Study of the proton wave function has been a topic for discussion for many years $\rightarrow$ Does the proton wave function contain a a valence-like charm contribution beyond the $g \rightarrow c\bar{c}$ perturbative gluon radiation?

1. Intrinsic charm (IC) will manifest in the proton wave function as $|uudc\bar{c}\rangle$
2. Forward coverage of LHCb detector provides unique probe to proton pdf

$\downarrow$

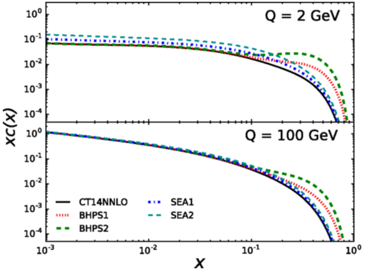


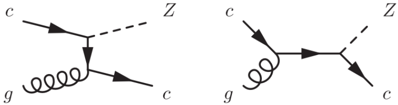


Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Analysis Strategy: Use jets produced in association of a Z boson to study the intrinsic charm production

Forward production of Zc allows to specifically probe high-x of the proton PDF ↓





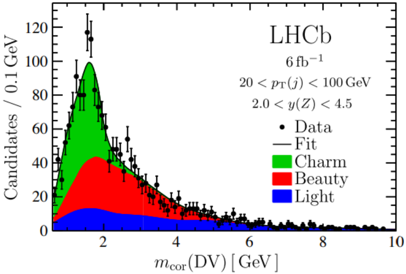
Analysis is made differentially in y_Z bins, with charm-jet yields caclulated in p_T^j bins

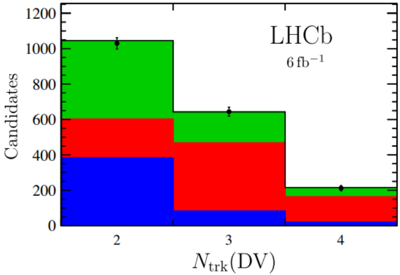
Result is given as the ratio of yields of Zc to total Zj yield:

$$R_c^j \equiv \frac{N(c\text{−}tag)}{\epsilon(c\text{−}tag)N(j)}$$

Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Charm Tagging: c-jets defined as jets containing long-lived c hadron with $p_T^h > 5$ GeV





Displaced Vertex (DV) jet properties are used to extract c-jet yields

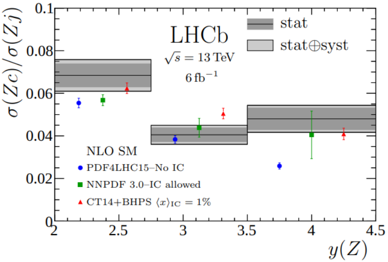
$\rightarrow$ Efficiencies vary as function of $p_T^{c-\mathrm{jet}}$, roughly around 25%

Z Bosons Produced in Association with Charm PRL 128, 082001 (2022)

Results: R_c^j measurements show consistency with valence-like intrinsic charm theory
Conclusions on the p wave function can be drawn with inclusion in global PDF analyses

- Systematics dominated by c-tag procedure, arising from tag-and-probe method scale factor calculations
  - c-tagging efficiency and $Z + c$ yield are highly correlated $\longrightarrow$ taken into account in the systematic calculation
- Theoretical predictions allowing IC are limited due to very little data available to constrain the charm PDF in this region
  - Fixed values of IC contribution reduces this uncertainty and has strong agreement with R_c^j measurement

Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%



Charged Hadron Distributions in Z-tagged Jets

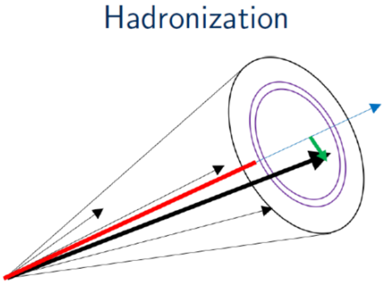
PRD 108, L031103 (2023)

Observing quarks and gluons in isolation is impossible → Must relate quark-gluon degrees of freedom to observables of bound state hadrons

1. Parton Distribution Function (PDF) – The nucleus hard-scatter part, The momentum the partons carry
2. Fragmentation Functions (FF) – The long-range hadronization part, The momentum the hadrons carry

FF and PDFs must be constrained by experimental measurements, used to tune MC generators

1. Jet Fragmentation Functions (JFFs) – Provide probe of FFs using jet substructure



Motivation: Set constraints on fragmentation functions and parton distribution functions of pp hard-scatter factorization, providing tuneable feedback to MC generators

Charged Hadron Distributions in Z-tagged Jets

PRD 108, L031103 (2023)

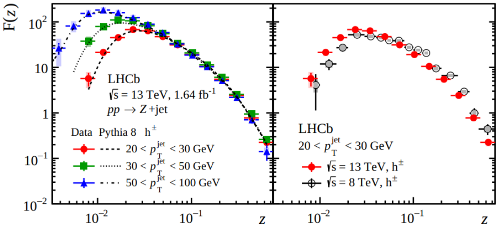
Analysis Strategy: Use jets produced in association with Z boson to study JFF parameters $\rightarrow$ Jets contain identified charged hadrons

Two observables employed to study the longitudinal and transverse contributions:

1. $z = \frac{\mathbf{p}_{\text{had}} \cdot \mathbf{p}_{\text{jet}}}{|\mathbf{p}_{\text{jet}}|^2}$
2. $j_T = \frac{|\mathbf{p}_{\text{had}} \times \mathbf{p}_{\text{jet}}|}{|\mathbf{p}_{\text{jet}}|}$

Event selection follows closely the Z-production measurement

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 ; $2.5 < \eta^{\text{jet}} < 4.0$



Inclusive measurement of the observable yields in differential p_T^{jet} bins shows agreement with theory and previous 8 TeV LHCb analysis

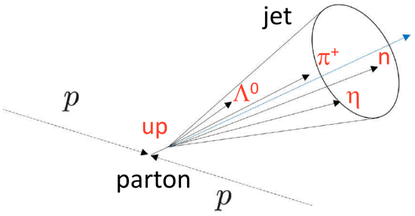
Yields are defined as:

$$f(z, j_T) = \frac{1}{N_{\text{Z+jet}}} \frac{\mathrm{d}N_{\text{had}}(z, j_T)}{\mathrm{d}z\mathrm{d}j_T}$$

Charged Hadron Distributions in Z-tagged Jets

PRD 108, L031103 (2023)

Identifying the Hadrons: Identification of the charged hadrons is performed using the RICH systems

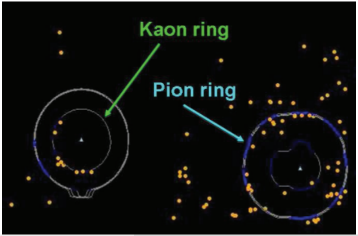


Connecting the dots:

1. Connect initial state (parton) to final state (hadron) using jets
2. Connecting initial flavor (parton) to final flavor (hadron)

The speed of the particle can be calculated from the angle of emission of the photon:

- $cos\theta_c = \frac{c}{nv}$
- The radius then gives an accurate measurement of θ_c: $r = f\theta_c$

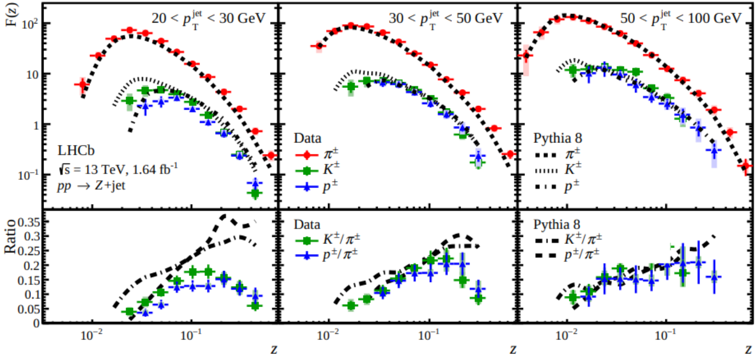


Charged Hadron Distributions in Z-tagged Jets

PRD 108, L031103 (2023)

Results: Integrated differential distributions for both z and j_T show similar behavior between the two consider centre-of-mass energies

Significant overestimation of heavier charged particles (kaons and protons) relative to pions is shown in low jet p_T

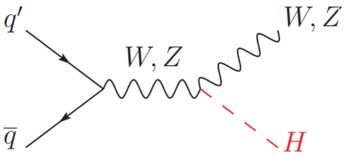


$\rightarrow$ Information can be used to tune MC generation of identified charged particles

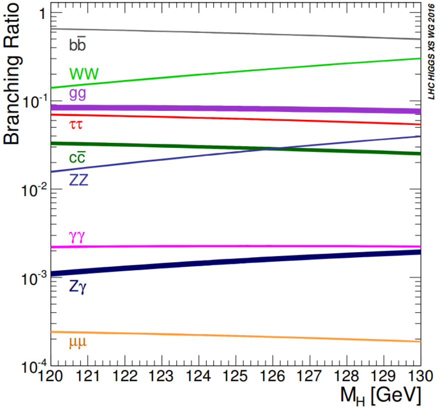
Search for $H \to b\bar{b}$ and $H \to c\bar{c}$

JINST 10 P06013

Branching fractions of $H \to b\bar{b}$ and $H \to c\bar{c}$ are well defined within the SM
$\to$ Deviation from these values can be evidence of new physics



$H \to b\bar{b}$ has been observed by ATLAS and CMS, and evidence of $H \to c\bar{c}$ is just around the corner using VH production
$\to$ *Goal* : Perform complementary measurement in the forward region, utilizing LHCb's excellent flavour abilities

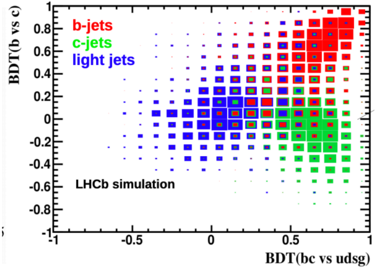


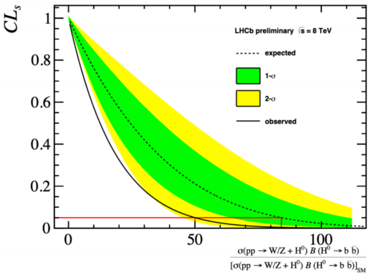
Search for $H \to b\bar{b}$ and $H \to c\bar{c}$

JINST 10 P06013

Analysis Strategy: Associated production of Higgs with Vector bosons (ZH, WH), identifying the flavoured Higgs decays with jet-tagging algorithms

- *VH* channel allows for a cleaner signal sample over selecting the full QCD background spectrum
  Tradeoff→ loss of stats
- First analysis with Run 1 is made using a BDT for jet selections ↓





- Results of Run 1 analysis of $H \to b\bar{b}$ far from SM limits:

$$\mu^b \leq 50 \cdot \mu^b_{SM};\ \mu^c \leq 6400 \cdot \mu^c_{SM}$$

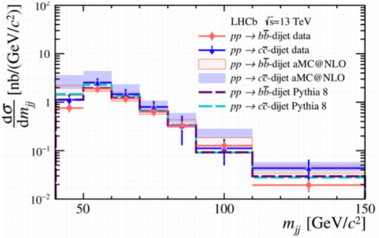
$\to$ Significantly stats limited

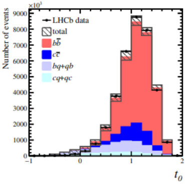
Search for $H \to b\bar{b}$ and $H \to c\bar{c}$

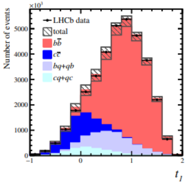
JHEP 02 (2021) 023

Moving Forward: Study the QCD ($b\bar{b}, c\bar{c}$) background to move from the VH mode to ggF/VBF single Higgs production modes (much higher XSec)

- Lower m_{jj} are accessible compared to ATLAS/CMS
- Simultaneous fit to two MVA discriminators is used to get flavour composition of sample ↓







- Differential cross section in m_{jj} is reported for $b\bar{b}$ and $c\bar{c}$
  - First at hadron collider for $c\bar{c}$

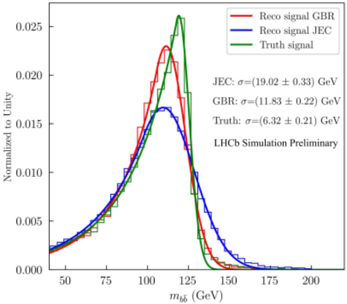
Uncertainties on experimental results show tightening over prediction → Improve background uncertainties for Hbb/Hcc

Search for $H \to b\bar{b}$ and $H \to c\bar{c}$

LHCB-FIGURE-2023-029

Modern analyses require modern solutions: Perform model-independent analysis requiring only 2 final-state jets using advanced techniques

- Specialized jet energy correction (JEC) is needed for jets originating from heavy flavour quarks $\to$
- Targeted gradient-boosted regression (GBR) technique is used for JEC $\downarrow$



Why do heavy flavour jets have different JEC?

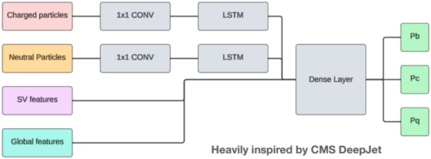
- b and c containing hadrons often decay semileptonically, producing a lepton and a neutrino
- Neutrinos only interact via weak force, allowing them to escape our detectors without a trace
- Missing energy from neutrinos then corresponds to a degradation of the energy resolution

Search for $H \to b\bar{b}$ and $H \to c\bar{c}$

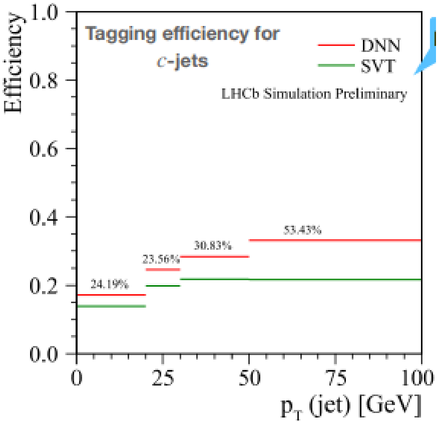
LHCB-FIGURE-2023-029

Modern analyses require modern solutions: Heavy-Flavour jet tagging done with Deep Neural Networks to greatly increase the selection efficiency

- Provides significant improvement over previous Secondary-Vertex tagging (SVT) by removing dependency on SV reconstruction efficiency →
- Takes 400 jet observables as inputs, utilizing information from jet constituents and sub-structure information
- Single DNN : P_b, P_c, P_q



Heavily inspired by CMS DeepJet



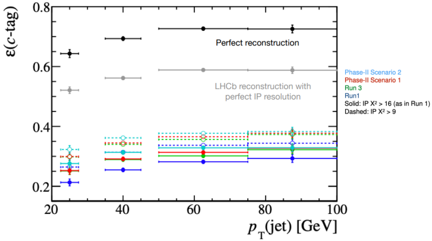
Search for $H \to b\bar{b}$ and $H \to c\bar{c}$

LHCB-PUB-2018-009

Prospects of the future: Leveraging the improvements planned for the LHCb detector, significant gain on sensitivity can be achieved

LHCb expects 300 fb^{-1} by the end of Run 5, allowing for more sensitivity:

- Statistical extrapolation only ends up with $\mu^c \leq 44 \cdot \mu^c_{SM}$
- Loosening criteria c-tagging reaches charmed di-jet efficiency of 35%
- VELO improvements provide absolute 5% charm-tagging efficiency increase per jet
- Continuing improvements of b and c tagging techniques (Graph Neural Nets?) provide further possible improvements



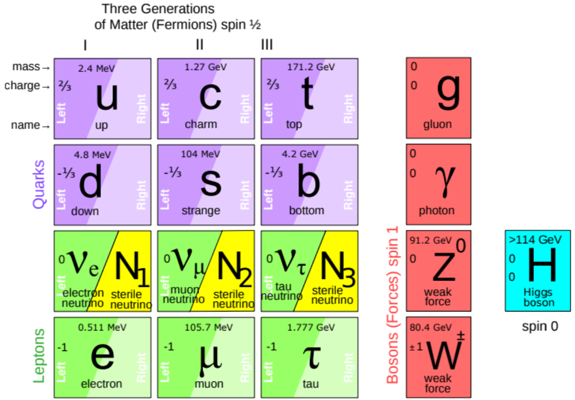
What if we have a perfect detector..?

Where will we end up in the future?

Search for heavy neutral leptons in $W^{\pm} \to \mu^{+}\mu^{\pm} jet$ decays

EPJC (2021) 81:248

Small-ness of neutrino masses is addressed with models introducing sterile, right-handed neutrino states, referred to as Heavy Neutral Leptons (HNLs)



HNLs Could Explain:

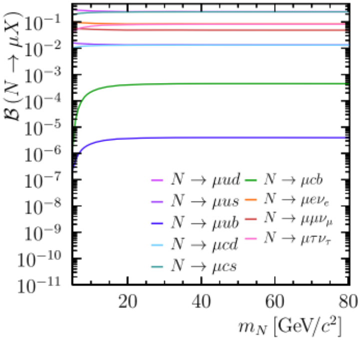
1. Origin of neutrino mass
2. Matter-Antimatter asymmetry
3. Dark Matter candidates

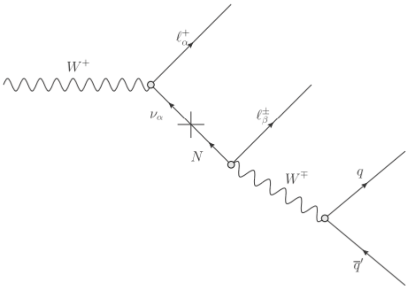
Search for heavy neutral leptons in $W^{\pm} \to \mu^+\mu^{\pm} jet$ decays

EPJC (2021) 81:248

How do we see HNLs: Search for the prompt production of a heavy neutrino with a muon in W boson decays

- The mixing diagram produces final observables of 2 muons and jets →
- HNL branching fraction to different fermions is mass dependent ↓





$$\mathcal{B}(W \to \mu N) = \mathcal{B}(W \to \mu\nu) \left|V_{\mu N}\right|^2 \times \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right)$$

Search for heavy neutral leptons in $W^{\pm} \to \mu^{+}\mu^{\pm} jet$ decays

EPJC (2021) 81:248

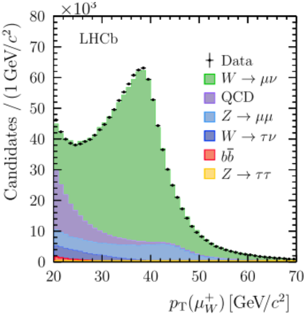
Analysis Strategy: Select events with W boson signature, while also containing HNL candidates

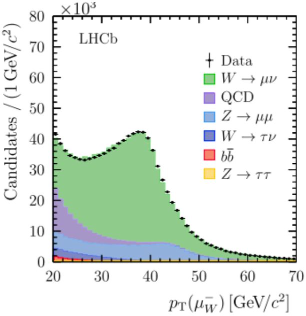
Selecting the muons:

1. High-momentum muon μ_W with $p_T > 20$ GeV
2. Low-momentum muon μ_N with $p_T > 3$ GeV
3. 20 GeV $< M_{\mu\mu} <$ 70 GeV to avoid Z mass window

Building the HNL Candidate:

1. Select jets with $p_T > 10$ GeV; combine with μ_N
2. $M_{HNL} <$ 70 Gev; $p_T^{HNL} > 10$ GeV





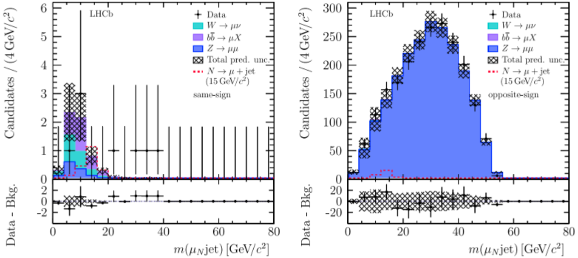
$W \to \mu\nu_\mu$ decay is used for normalization channel in order to determine the branching fraction

$$\mathcal{B}(N \to \mu\,\text{jet})\,|V_{\mu N}|^2 = \frac{N_{\text{sig}}}{N_{\text{norm}}}\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}\left(1-\frac{m_N^2}{m_W^2}\right)^{-2}\left(1+\frac{m_N^2}{2m_W^2}\right)^{-1}$$

Search for heavy neutral leptons in $W^{\pm} \to \mu^{+}\mu^{\pm} jet$ decays

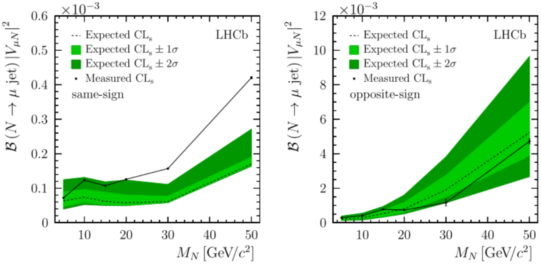
EPJC (2021) 81:248

Results: No evidence of signal is observed $\rightarrow$ CL$_s$ upper limits are calculated



Simultaneous fits of the HNL mass $m(\mu_N\text{jet})$ in same sign and opposite sign regions to extract signal yield

First BF limits are provided for same-sign and opposite-sign modes independently
$\rightarrow$ Statistically limited, pushing towards most stringent world limits with run 3+4



Current Detector – Where Are the Electronic Modes?

Currently the LHCb detector faces some significant difficulties in the field covered by the QEE physics program:

- Detector was primarily designed for excellent tracking and particle identification, with calorimetry complementing the low-mass bulk of the physics program
- Higher p_T (EW scale) electrons are limited by E-Cal cell saturation, not allowing for precision reconstruction of electronic modes of gauge boson decays

$\rightarrow$ "Light" at the end of the tunnel:
Upgrade-II E-Cal is expected to allow similar reconstruction precision of high-p_T electrons as current muon reconstruction

Future Prospects of the HL-LHC LHCb Detector for W/Z

arXiv:1808.08865

Availability of electronic modes at the EW scale, along with a significant increase in luminosity will allow some considerable future studies at LHCb

$\rightarrow$ **What is envisioned:**

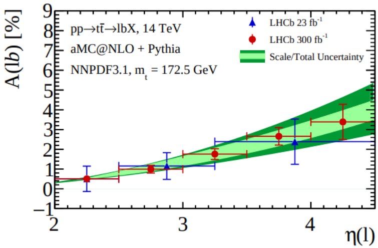
- Differential Z boson production, along with $Z+$ heavy flavour measurements
  $\rightarrow$ Set important constraints on out-of-reach x–Q^2 phase-space
- Measurement of $\sin^2\theta_W^{eff}$ from forward-backward asymmetries in Z boson production
  $\rightarrow$ Increased precision to probe LEP/SLD tensions
- Precision measurement of the W mass
  $\rightarrow$ Increased statistical precision to complement the ATLAS/CMS combination for an even further precise world average measurement
- $\gamma+$ charm and beauty associated productions
  $\rightarrow$ Further probe the intrinsic charm and beauty contributions providing access to the high-x portion of PDFs

Future Prospects of the HL-LHC LHCb Detector for Top

arXiv:1808.08865

Top quark measurements at LHCb have been significantly limited by statistics for Run 1 and Run 2

Including electronic mode allows for studies of single-top production (importantly top asymmetry) in forward region ↓



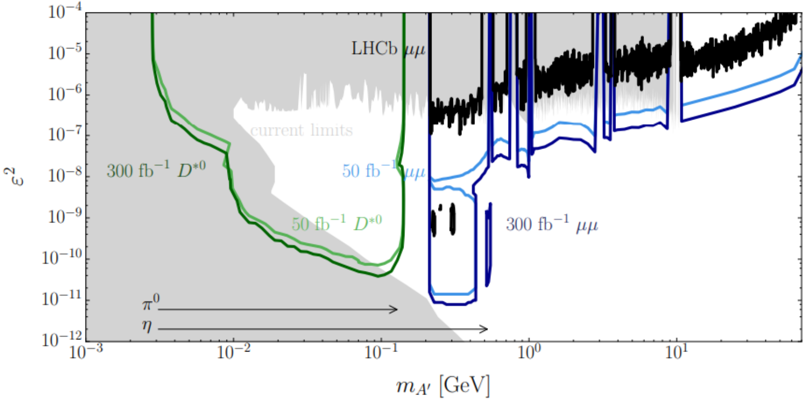
final state	current	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$	$< x >$
ℓb	220 [414]	54k	117k	830k	0.295
$\ell b\bar{b}$	24 [415]	8k	17k	130k	0.368
μeb	38 [416]	1k	2k	12k	0.348
$\mu eb\bar{b}$	-	120	260	1.5k	0.415

↑ Top pair production will also see a great increase in precision, allowing for a significant improvement on gluon PDF at large-x

Future Prospects of the HL-LHC LHCb Detector for BSM

arXiv:1808.08865

Dark Photon searches are poised to improve significantly on current world limits



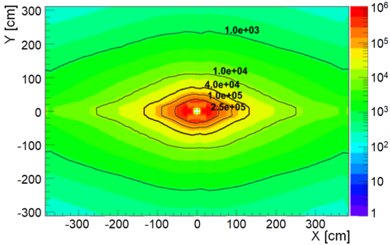
Green bands and black arrows show stretch of e/γ modes to cover gaps of current muonic modes

Planned Upgrade II Improvements of ECal

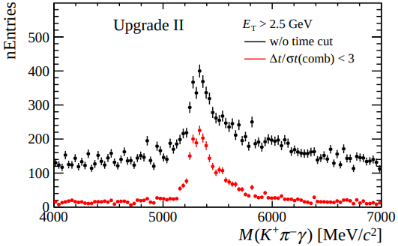
LHCB-TDR-023

Challenge: Maintain energy resolution and reconstruction efficiencies like run1/2 in a high pile-up/radiation environment
Achievable? $\rightarrow$ Granularity and precision timing needed!

Utilize different technologies in different regions to account for expected radiation doses ↓



Spaghetti Calorimeter Inner;
Shashlik Outer



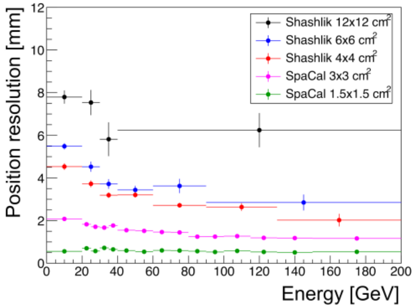
Timing capabilities has significant impact on photon-containing modes often used in QEE-BSM searches

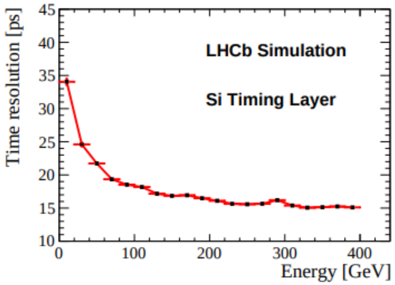
Planned Upgrade II Improvements of ECal

LHCB-TDR-023

Bump up the energy: ECal upgrade also has expectations to greatly in improve the resolution of high energy electrons and photons

SpaCal + Shashlik calorimeter design gives mm resolution in central regions ↓





↑ Timing resolutions show excellent behavior out to EW scale energies

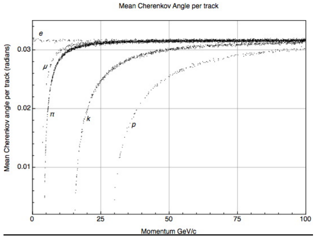
What To Walk Away With

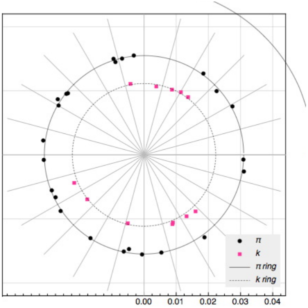
- LHCb has a thriving forward physics group spanning large areas of SM physics topics
- LHCb's long arm design allows for interesting and unique BSM searches in the GeV scale
- Many analyses in the group are statistically limited $\rightarrow$ expect huge gains from increase Run 3 and 4 luminosity!
- Future upgrades, especially ECal, will greatly expand the reach of the QEE physics program

BACKUP

LHCb RICH – Some Math on It

- The speed of the particle can be calculated from the angle of emission of the photon:
  - $cos\theta_c = \frac{c}{nv}$
- At high momentum, multiple photons can be emitted, allowing for an even more precise calculation of θ_c
- The emissions of the photons can occur at any point along the trajectory, forming a light-cone in the detector
  - The radius then gives an accurate measurement of θ_c: $r = f\theta_c$
- The precision of the RICH detectors can be defined as such:
  - $\sigma_m = \frac{\sigma}{\sqrt{N}}$, $N = \frac{N_c q^2 sin^2(\theta_c)}{1-n^{-2}}$





LHCb RICH System - Online Visualization

- Significant amount of work is put into the monitoring to evaluate numerous alignment issues.
- Timing alignment, mirror alignment, magnetic corrections, gas property measurements, and HPD calibration are all closely monitored during run time
- Calibrations are performed on a run-by-run basis to correct for any changes in the above alignments