LHCb η acceptance in Upgrade II

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Upgrade II Tracking Workshop

6th – 7th March 2024

Institute of Physics

THE UNIVERSITY of EDINBURGH

LHCb

Reducing acceptance in high-η

- Why would we?
  - High-η tracks have largest occupancy and is the most challenging part for tracking
    - Tracks at low angle traversing a large amount of material (high ghost rate)
    - η coverage and r-z footprint of VELO highly related
    - Mechanical constraints from closing to beampipe for UT/MT
  - We want to match acceptances between subdetectors

    We need to align between the sub-detectors and take into account what coverage we need from physics

Matt Needham, 110th LHCb week

- We want to know - how would reducing acceptance affect the physics from LHCb?

Previous study from 2021

Detector level consideration

- **Before magnet**, high-η region impact **radiation and rate constraints**.
  - UT HV(LV)-CMOS options radiation hardness limit translate to 4.85(4.95)
  - RICH1 covers $\eta < 4.4$ (beam-pipe at 25mrad).
  - VELO at high-η has poor z-pointing, larger T.o.F, having to go toward SB would imply larger z to cover high-η.
- **After magnet, less impact** because the magnet swipe
  - RICH2 acceptance and SciFi/MT hole correspond to $\eta < 4.9$
  - MUON inner angular accept. at 16 mrad ($\eta < 4.85$)
  - CALO inner hole covers $\eta < 4.6 - 4.8$ @ U2 ($\sim$ 40% energy from neutrals)

Channel	η <4.85	η <4.7	
$B_s^0 \to \mu^+\mu^-$ [muon]	0.15%	0.8%	
$B^0 \to K^* e^+ e^-$ [elect]	0.2%	0.6%	same for comb and part. reco
$B_s^0 \to D_s^- \pi^+$ [hadr]	0.4%	1.3%	w/o sel. 1.1%, 2.9%
$B \to D^{*+} \tau_h^-$ [high mult]	0.2%	0.6%	similar loss for the 6 tracks
$B_s^0 \to K^+ K^-$ [high pt]	0.05%	0.2%	w/o PID 0.4%, 1.5%
$D^{*+} \to D^0(K_s\pi\pi)\pi^+$ [low pt]	0.5%	1.2%	Background 1.1%, 2.3%

Small efficiency loss in B and D decays

QEE: not considering effective detector acceptance <1% - 7% loss

- Studied relative loss at generator level wrt. $2 < \eta < 5$

Channel	η <4.85	η <4.7
$H \to cc$ [jets]	0.2%	1.1%
$Z \to \mu^+\mu^-$ [very high pt]	5.1%	7.7%
$W^+ \to \mu^+\nu$ [very high pt]	0.7%	1.7%

assuming detector effective acceptance is already around 4.8 – closer to what's observed with B/D decay

- Reduction of the η coverage shows little impact on signal efficiency

  Effective acceptance already smaller than $2 < \eta < 5$
  Should we align PID and tracking coverage?
  What should we consider as specification?

- S/B seems to degrade at high-η

  $\rightarrow$ some work started to **understand combinatorics increase at U2**

- Beyond the high-η issue we **should investigate the S/B situation in U2**:
  - at detector level we target same signal (track) efficiency and same background (track) retention.
  - what is the impact on detector perf. of trying to achieve same S/B (which is to some extent assumed in LOI)?
  - or: "does same performance than U1 at particle level allows to do physics at U2?"

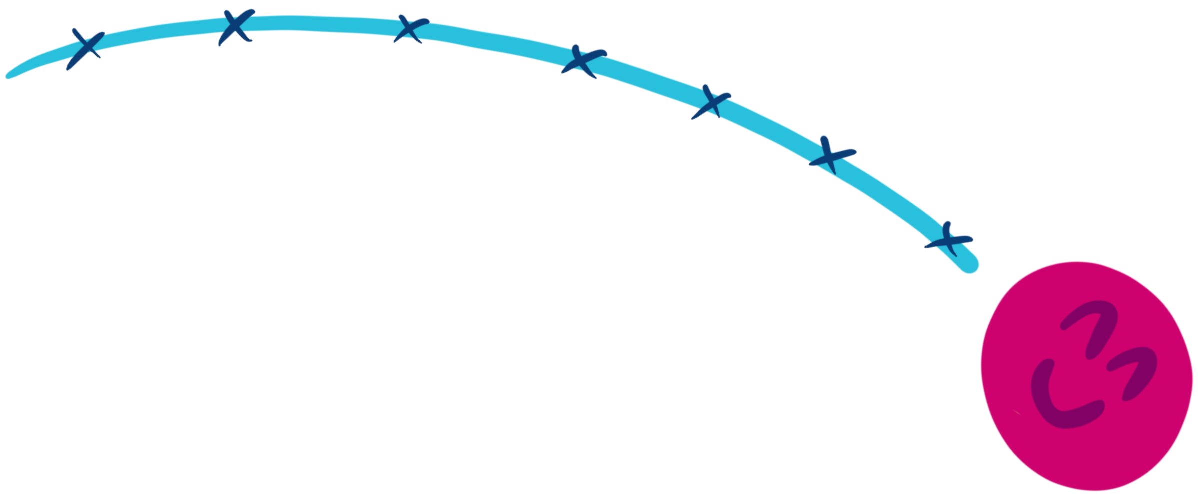
- Lower η_{max} does not really have impact as down scaling option:

  $\rightarrow$ in most of the case $\eta_{max} < 5$ already.

- **Could be limiting for Velo and UT** (depends on next 2-3 years R&D outcome)

Victor Coco

Small efficiency loss in B and D decays

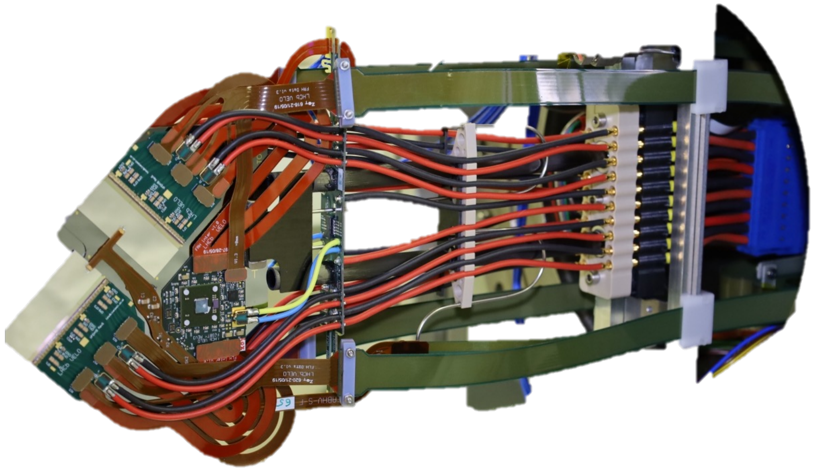


Subdetectors

What acceptance are we working towards? Does a smaller acceptance provide flexibility for detector design?

The VELO

- Current VELO covers up to $\eta = 5$
- In U2, the most relief comes from reducing to a coverage up to $\eta = 4.8$
- Between 4.7 and 4.8, relaxes (z, R) positions of modules – can spare modules and gives freedom to move in R if radiation hardness not met



Jianchung Wang

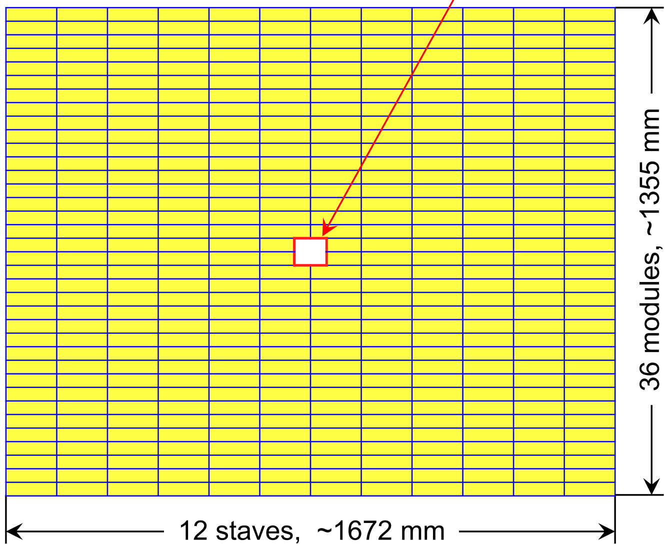
The UT

U2 UT Geometric Configuration

A box corresponds a 7×2-chip module

Chip size ~ 2×2 cm^2

Beam hole inactive area (±39mm) × (±37mm)



- The U2 UT has 4 detector planes, at Z similar to the current UT. The number of planes may be reduced to 3, pending further studies.
- A plane has 12 staves, covers ~1672 mm in the X direction, with 2 mm overlaps.
- A stave has 36 modules, covers ~1355 mm in the Y direction.
- A module consists of 7×2 sensor chip. In the outer regions of each plane dual-modules are used for efficient IpGBT.
- The central 4×4 chips are removed for beam pipe, covers (±39mm)×(±37mm).
- In total: 4 layers, 48 staves, 1728 modules, 24128 chips.

5/3/2021 7

Maximum radius from beampipe – 53.7mm

First station at 2317.5mm

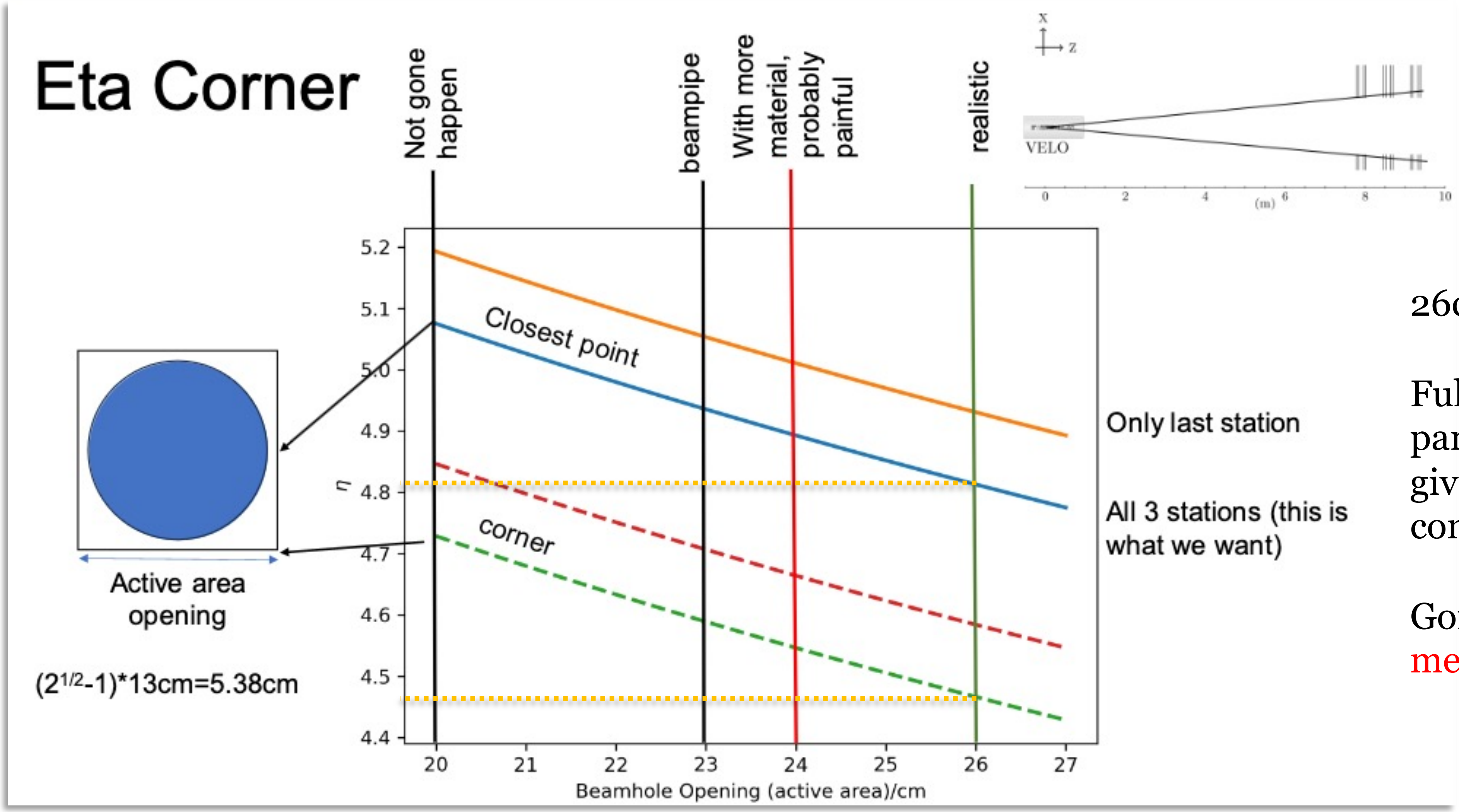
100% efficiency up to 4.46

Minimum radius from beampipe – 37mm

Partial efficiency up to 4.83

the central modules can be re-arranged for a different hole size matched with the radiation resistance and rate requirements

The Mighty Tracker



26cm scenario most likely

Full coverage up to **4.4** with partial coverage up to **4.8** given from mechanical constraints

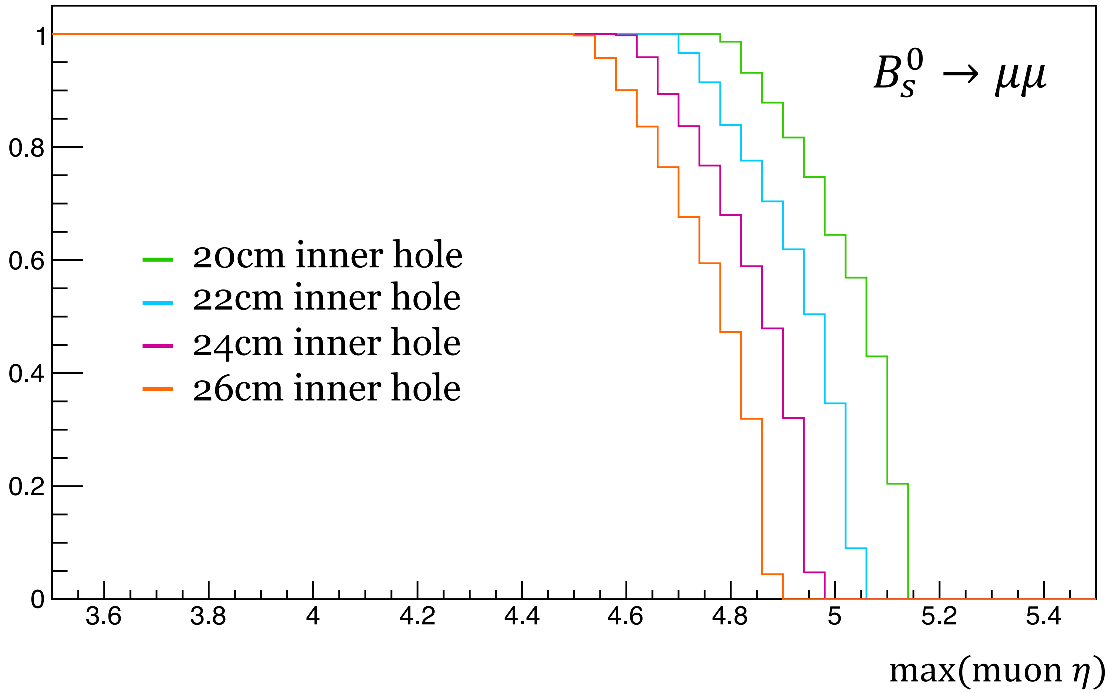
Going up to 4.9 would be mechanically challenging

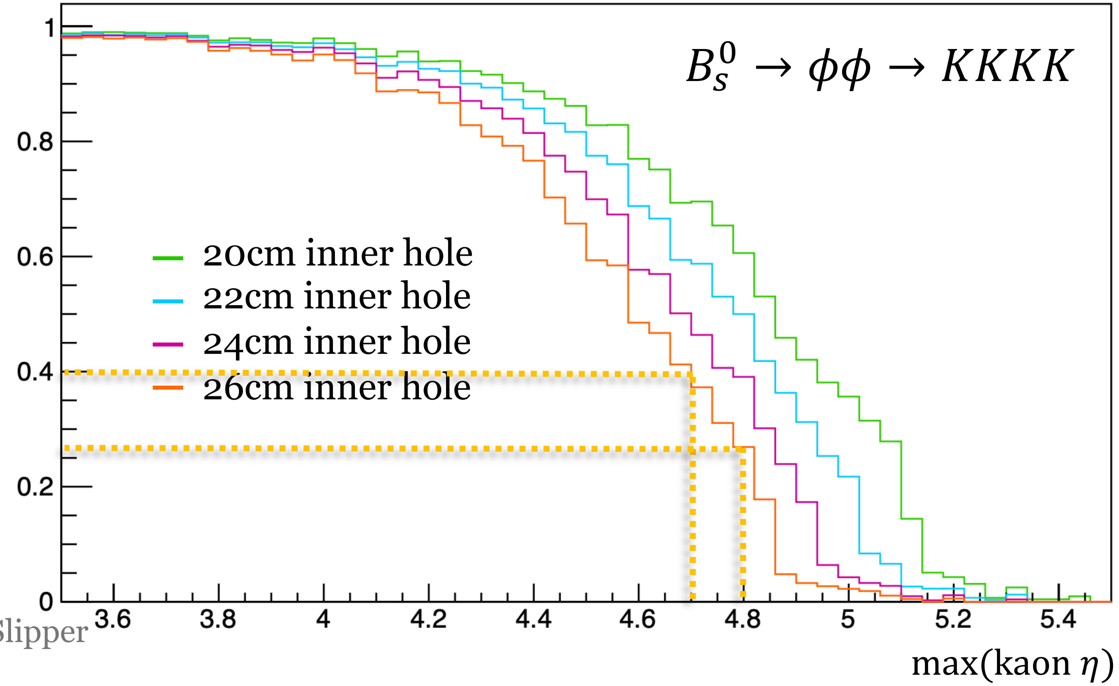
The Mighty Tracker

$$\epsilon = \frac{N_{\text{inside}}^{X\text{cm}}}{N_{\text{inside}}^{0\text{cm}}}$$

X = 20, 22, 24 and 26

- 26cm beam pipe hole – orange line
- This is max(η) at production before the magnet
- Using RapidSim with U2 momentum smearing, and a single magnet kick model to understand which tracks are not inside the MT

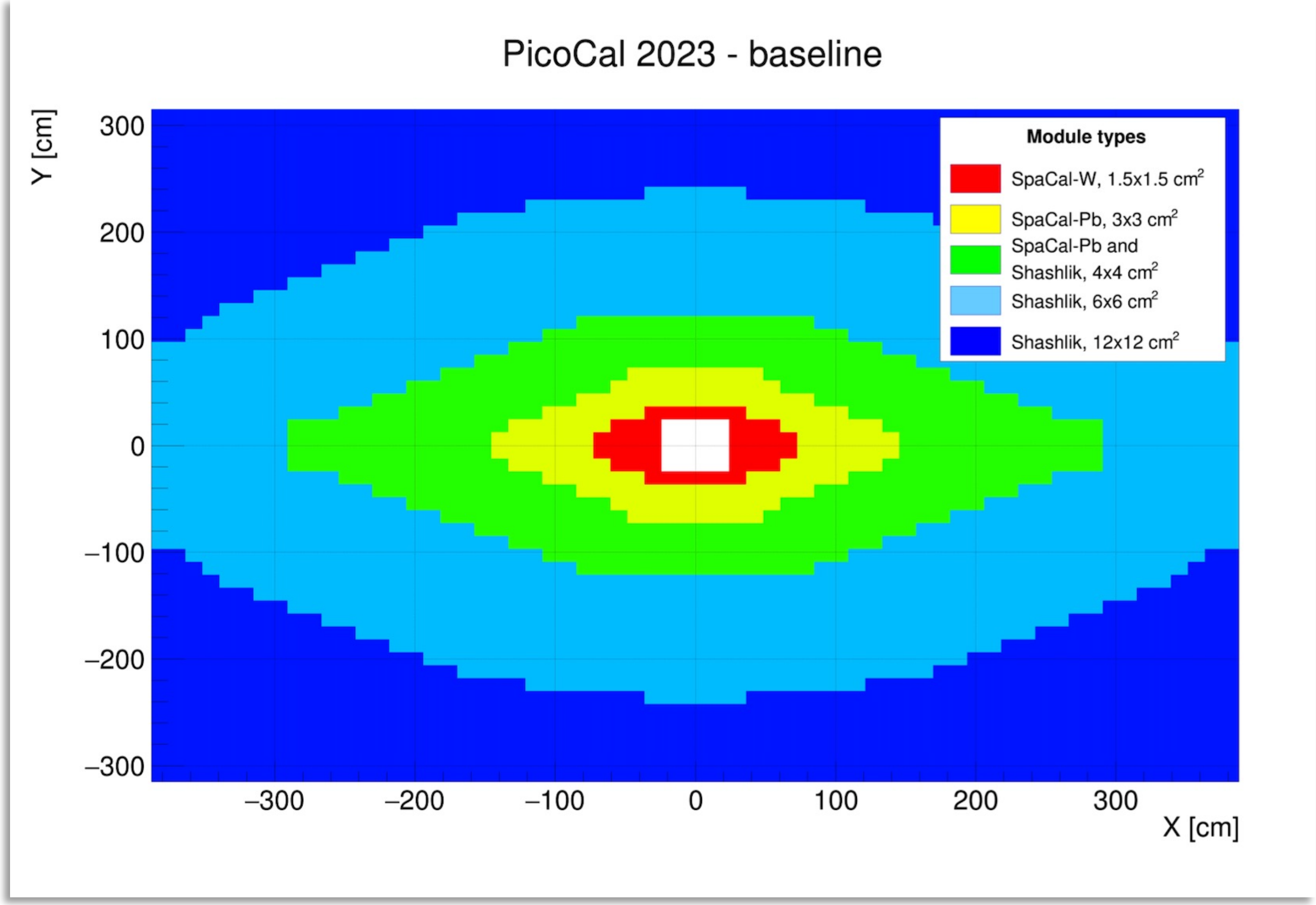




CALO

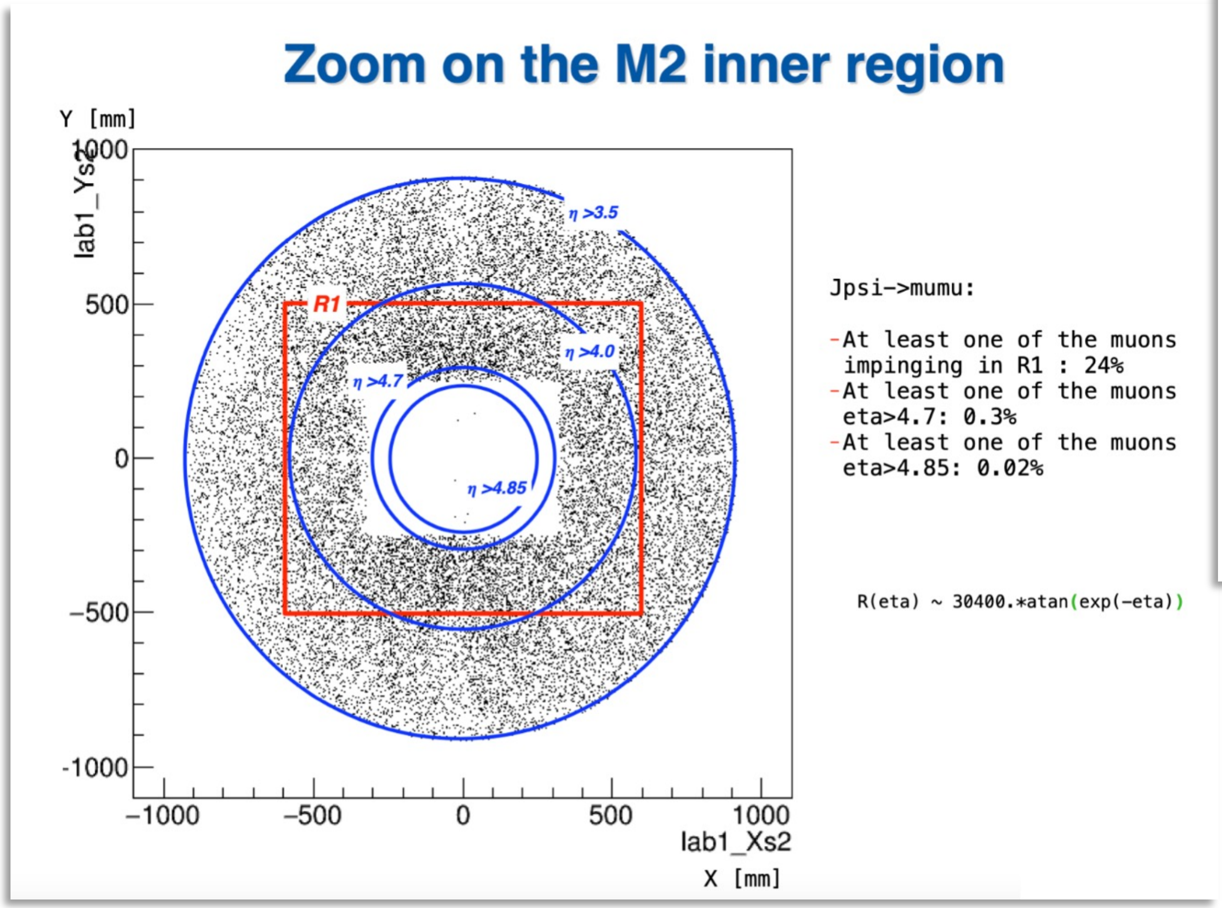
Beam hole of the ECAL is 4x4 modules
(or 48 x 48 cm²) at 12.6 meters.

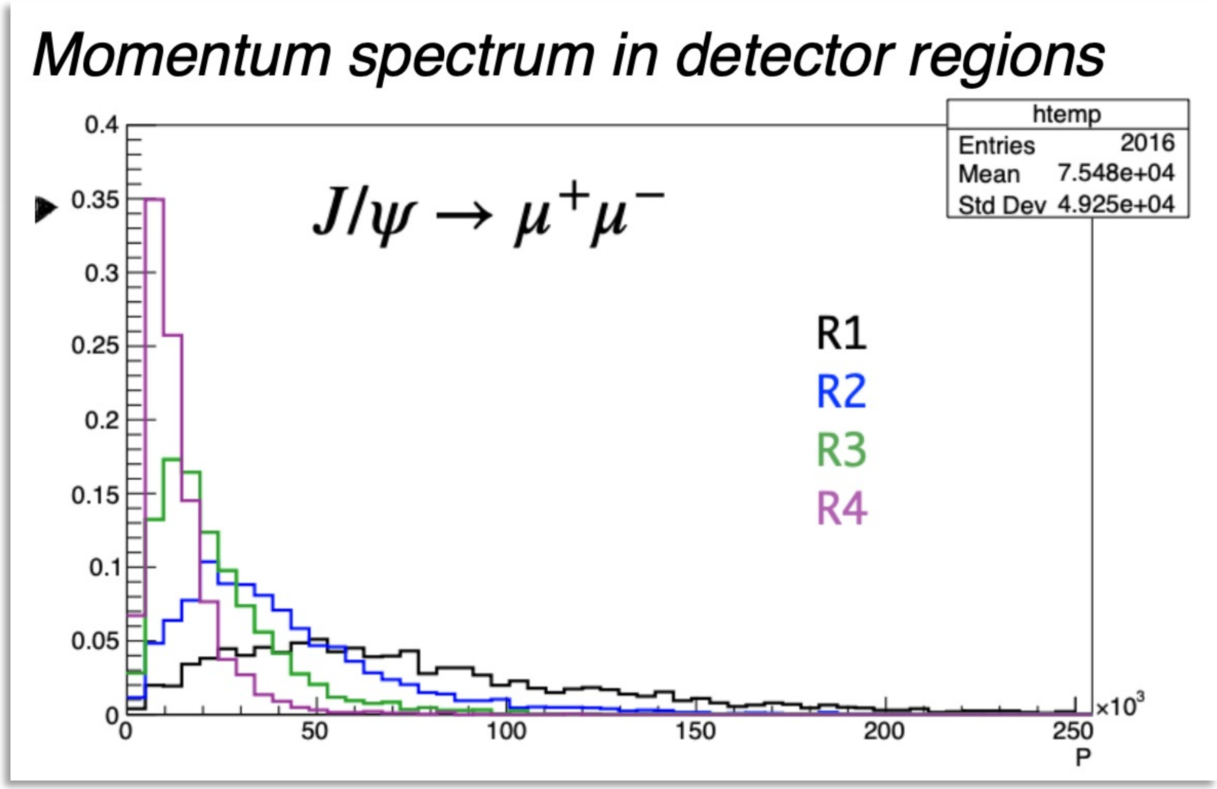
For straight lines (e.g. photons), this corresponds to 1.1 - 1.5 degrees or an eta range of **4.3 – 4.7**



Barbara Sciascia, Matteo Palutan

The Muon stations





Present acceptance is **4.7** (**4.85**) in horizontal (vertical) planes with no plans to reduce the acceptance (**full coverage 4.4**)

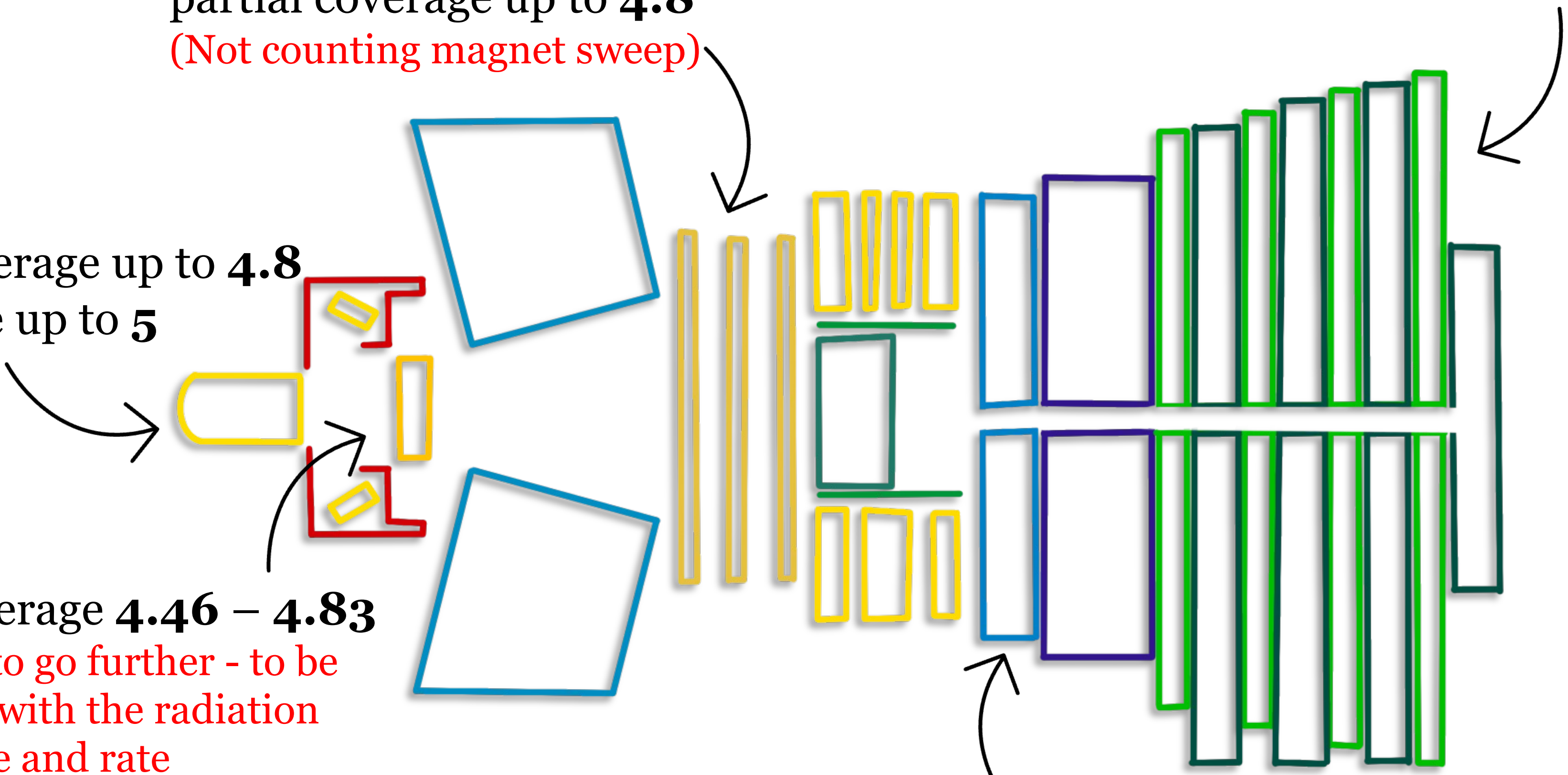
M2 may be reduced, but M3-5 will still cover the acceptance

Summary of acceptances

Muons: full coverage up to **4.4**
partial coverage **4.7** (**4.85**) horizontal (vertical)
(Not counting magnet sweep)

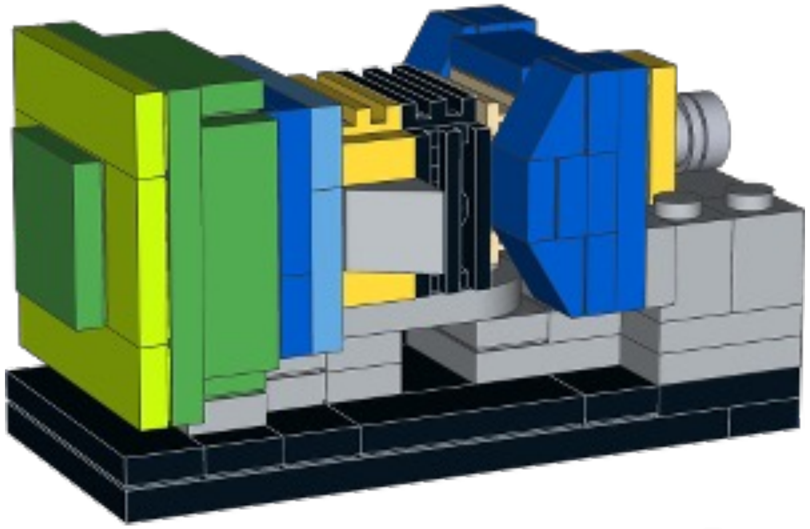
Mighty Tracker: full coverage up to **4.4**
partial coverage up to **4.8**
(Not counting magnet sweep)

VELO: full coverage up to **4.8**
partial coverage up to **5**



UT: coverage **4.46** – **4.83**
Possible to go further - to be matched with the radiation resistance and rate requirements

ECAL: coverage **4.3** – **4.7**
(Not counting magnet sweep)



Physics cases and LHCb's uniqueness

Want to understand how a reduction in high-η acceptance will affect our physics programme

Claire Pouvré, Sara Celani

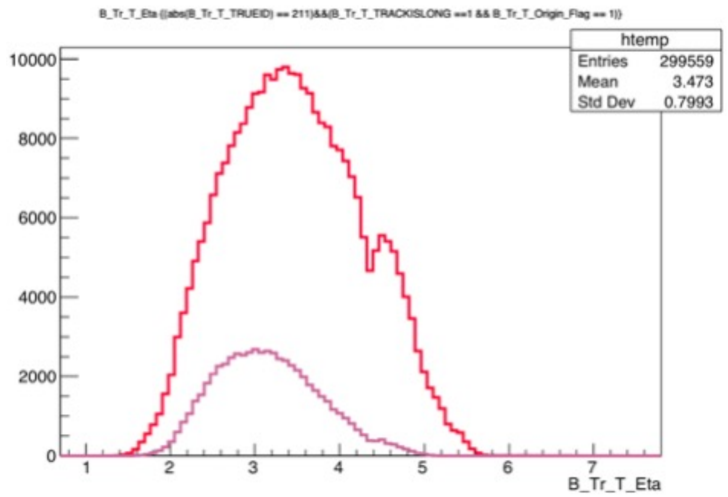
Flavour tagging perspective

- Tracks from B – population at high η – hadronization giving low–angle tracks

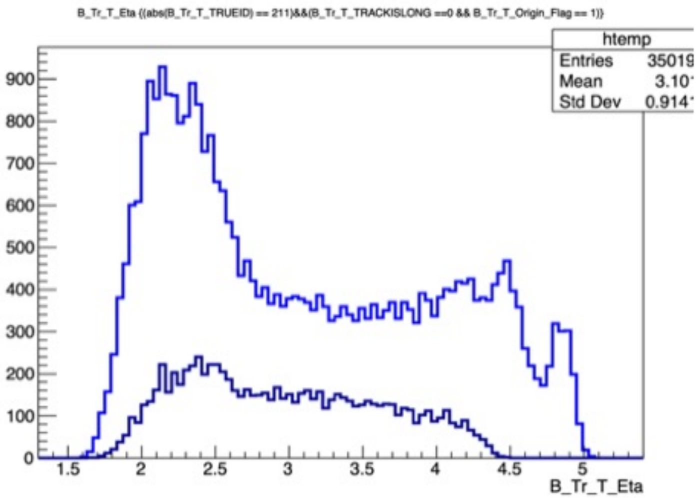
Plots of same-side fragmentation pions

$B^0 \to D^- \pi^+$ and $B_s \to D_s\, \pi$ MC
2024 nominal conditions
preselection: Run 2 preselection

Long tracks, before and after preselection



Upstream tracks, before and after preselection



Claire Pouvré, Sara Celani

Flavour tagging perspective

$B^0 \to D^- \pi^+$ and $B_s \to D_s\, \pi$ MC 2024 nominal conditions
preselection: Run 2 preselection

		Same-side fragmentation tracks		Opposite-side decay tracks	
		before presel	**after presel**	**before presel**	**after presel**
LONG	**> 4.7**	7.5%	2.1%	4.5%	2.2%
	> 4.8	5.5%	1.2%	2.8%	1.0%
UPSTREAM	**> 4.7**	5.3%	2.2%	4.4%	4.8%
	>4.8	3.4%	1.5%	2.8%	3.1%

High-η tracks may be powerful

Not clear how these affect tagging performance

Would require a major study

Melissa Cruz Torres, Ozlem Ozcelick,
Peilian Li, Stefano Perazzini,
Resmi Puthumanaillam,
Wenbin Qian

BnoC, B2CC and B2OC

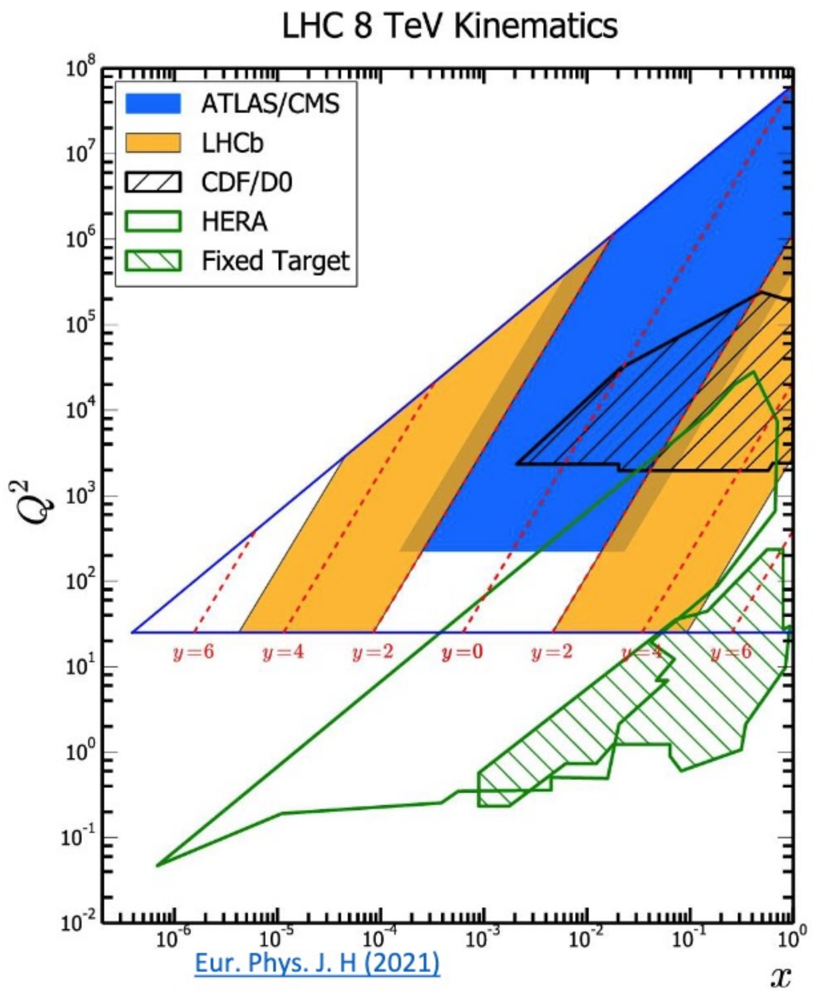
- Concerns raised about the affect this could have on flavour tagging (discussed in prev. slides)
- Main charge asymmetry in the RICH from particles going into beampipe after T stations and before RICH2
  - High momentum and high rapidity tracks
  - Could be worth to check the effect of reducing the acceptance

Do not foresee it will affect these programs apart from loss efficiencies

B&Q

- Reducing inner acceptance reduces uniqueness of production in low x, high Q^2

- Central Exclusive Production – HeRSChel physics motivation
  - Is this something we can still consider at high pileup?



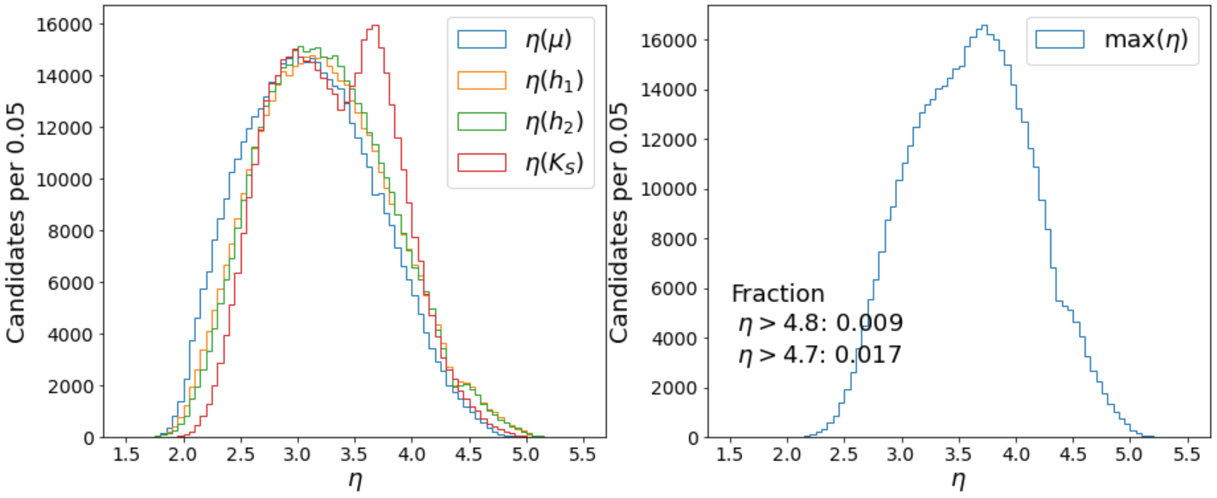
Saliha Bashir – Hadron Production at LHCb Experiment

Marco Gersabeck, Nathan Jurik, Guilia Tuci,
Jairus Patoc, Federico Betti, Tommaso Pajero

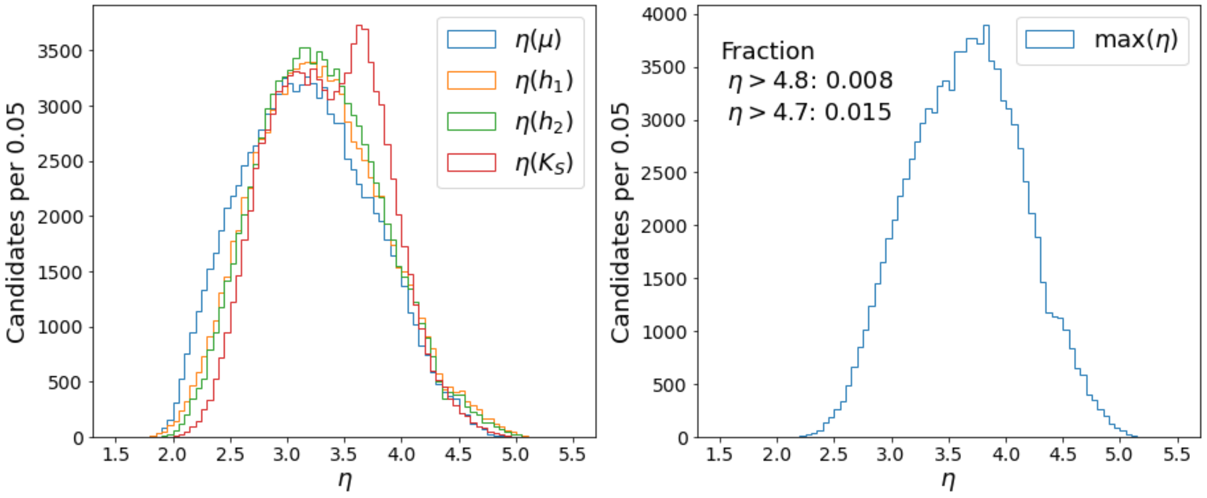
Charm

$D^0 \to K_S\pi^+\pi^-$ with a combination of long and downstream K_S^0 candidates, and offline selection applied on top of trigger requirements for Run 2 data:

D^0 tagged with semimuonic B decays



D^0 doubly tagged with semimuonic B decays into D^{*+}



The plots are prepared using the pseudorapidity of the K_S^0 rather than those of its decay products, but this is not expected to be the limiting factor in the precision of the study.

Marco Gersabeck, Nathan Jurik, Guilia Tuci,
Jairus Patoc, Federico Betti, Tommaso Pajero

Charm

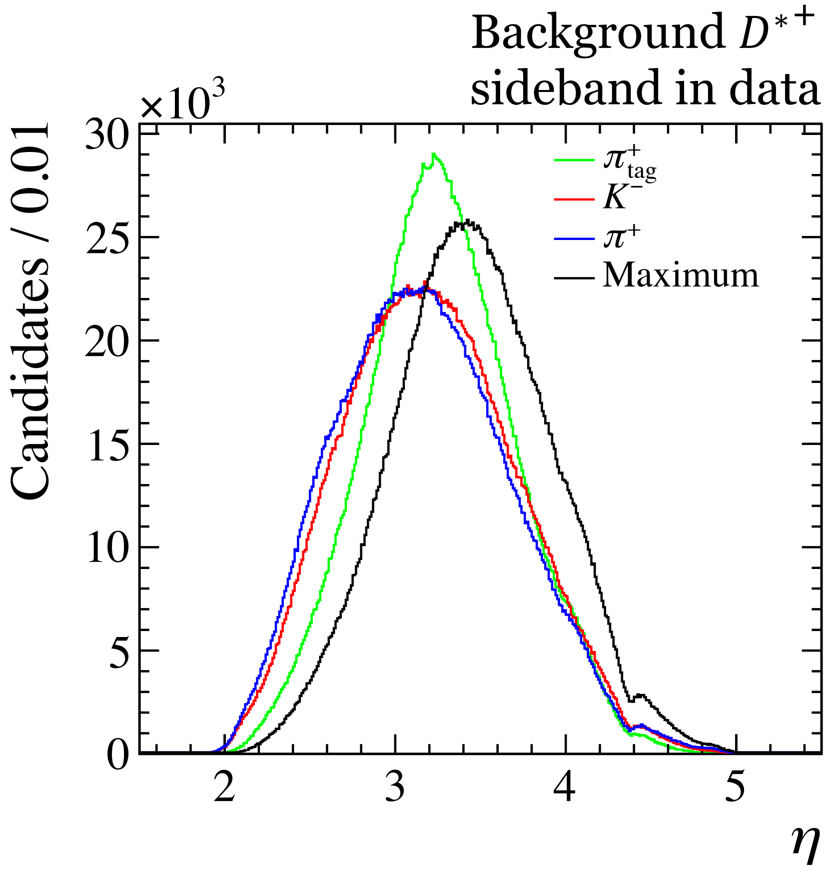
- Some CP violation measurements applied $\eta \in [\,2\,, 4.2\; - 4.3\,]$ in Run 2 – the material budget and consequently the detection asymmetries outside of this range were significantly larger
- For measurements which did not apply η selections, like ΔA_{CP}, the efficiency loss is at most **0.4%** on $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, so negligible.
- WS/RS ratio in $D^0 \to K^{\pm}\pi^{\mp}$ decays after the offline selection:

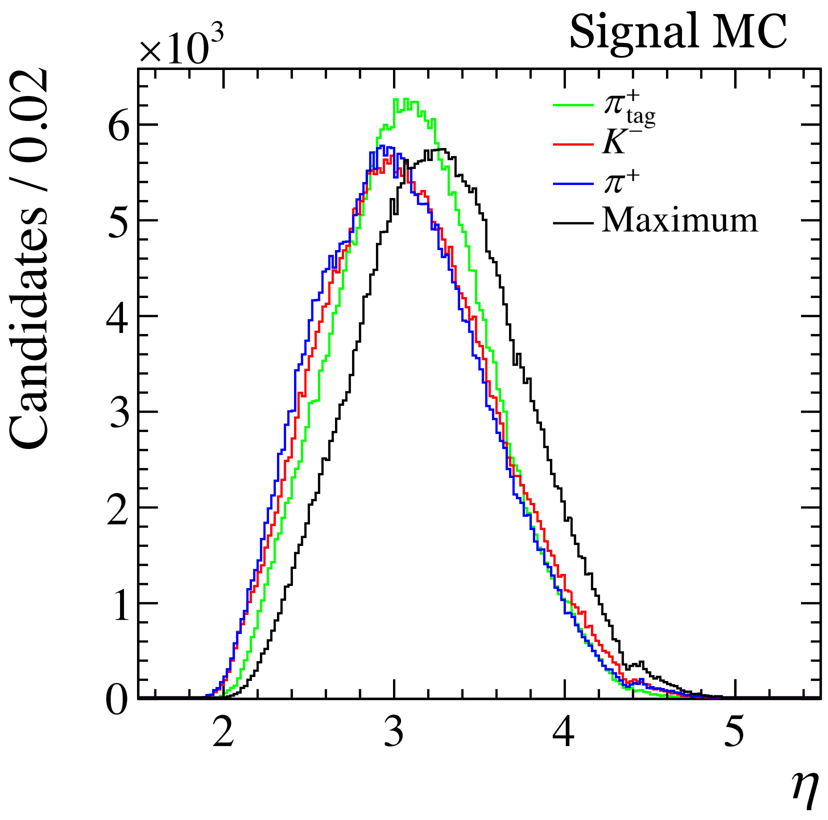
	$\eta < 4.7$	$\eta < 4.8$	$\eta < 4.85$
Signal	**0.15%**	**0.07%**	**0.04%**
Background	**0.44%**	**0.22%**	**0.14%**

Marco Gersabeck, Nathan Jurik, Guilia Tuci,
Jairus Patoc, Federico Betti, Tommaso Pajero

Charm

- WS/RS ratio in $D^0 \to K^{\pm}\pi^{\mp}$ decays after the offline selection:





"unless we get much better tracking efficiency and PID at high η, cutting at 4.7 doesn't harm us at all"

Marco Gersabeck, Nathan Jurik, Guilia Tuci,
Jairus Patoc, Federico Betti, Tommaso Pajero

Charm

- For $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$, the fraction of signal candidates passing the trigger and offline selections in Run 2 that are rejected by the requirement $\eta < 4.8(4.7)$ *is* $\mathbf{7.8(8.3)}\%$
  - Similar expected for $D^0 \rightarrow K^+K^-\pi^+\pi^-$ and $D^0 \rightarrow K^\pm\pi^\mp\pi^+\pi^-$

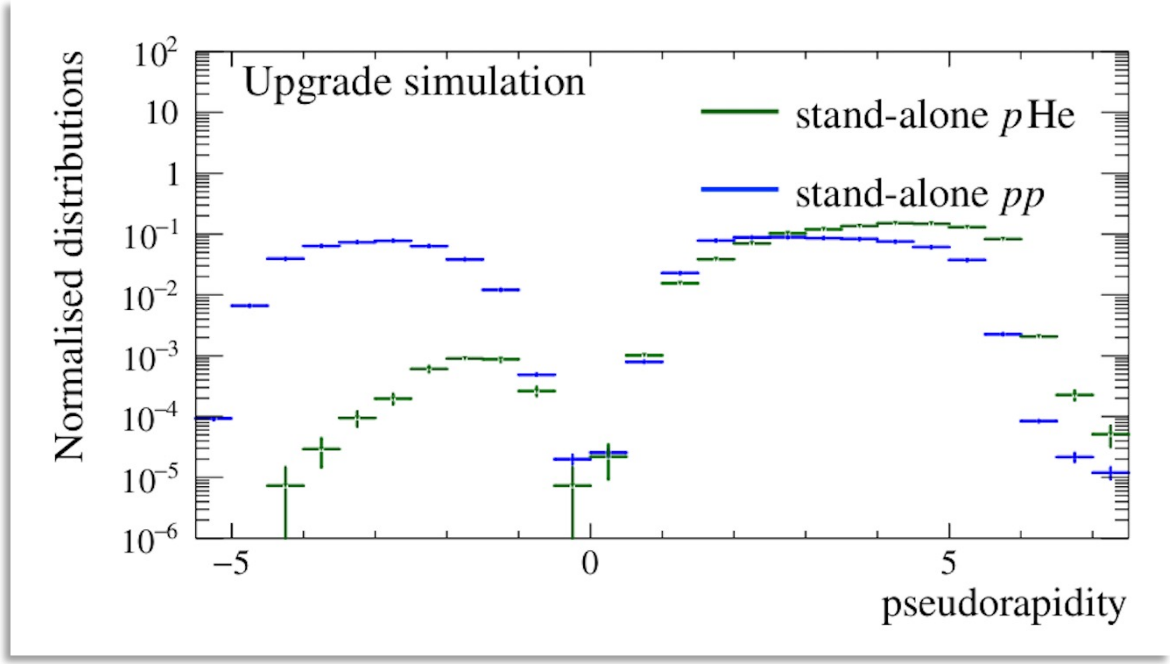
TO BE CHECKED (decrease looks bigger than expected)

- Based on studies for the measurement of CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ decays (Fig. 9 LHCb-INT-2023-003), current HLT1 line for K_S^0 particles looks only for candidates in the range $\eta \in [\,2\,, 4.2\,]$ to improve the S/N ratio

Saverio Mariani, Thomas Boettche, Matt Durham

Ions and fixed target

- For some analyses, cuts at eta = 4.8
- Last pseudorapidity decimals are removed to avoid border effects – will reducing our inner acceptance shift these border effects?
- Parasitic fixed-target - LHCb pseudorapidity coverage is shifted and tracks have a lower aperture with respect to *pp*
  - The more we cut, the more we lose



IONS + FIXED TARGET

Qualitative, not quantitative

Federico Redi, Hang Yin,
Andrii Usachov

QEE - Muons

- Only went as far as $\eta = 4.5$ in Run-1 and Run-2
- The forward region provides crucial inputs for the Global Fit of proton parton distribution functions (PDFs) - very high and very low x regions ATLAS and CMS cannot reach
- The very large η region is needed for W mass and precision EW measurements – combining LHCb results with that from ATLAS and CMS could reduce the PDFs uncertainty
- Need sufficient inter-sub-detector redundancy to measure reconstruction efficiencies – in Run-1 and Run-2 lack the necessary redundancy to measure tracking efficiencies effectively
- The $W \rightarrow \mu\nu$ measurements needs an additional 1/2 isolation cone (0.2 extra) for events in detector boundary regions for Muon isolation

Qualitative, not quantitative

Federico Redi, Hang Yin,
Andrii Usachov

QEE - electrons

- Electron acceptance is limited to around $\eta = 4.2$ in Run-1 and Run-2
- To enhance electron and photon studies, a larger acceptance of the electromagnetic calorimeter is crucial

QEE - BSM

- Long lived particle (LLP) studies benefit from extended acceptance
  - Enhance our ability to explore exotic Higgs decays and other phenomena
- Muon stations serve as a subdetector for LLP studies
  - Forward region is crucial for these studies.
  - Ongoing studies on muon showers are included in the Run 3 program

QEE

Qualitative, not quantitative

Federico Redi, Hang Yin,
Andrii Usachov

QEE – jets

- Jet reconstruction limited to **4.2** due to ECAL and HCAL size constraints - expanding the ECAL acceptance essential for accurate jet reconstruction
- Wider tracking acceptance enhances our capabilities in studies of jets substructure
  - Jets with larger cone size of $R \sim 0.8$ valuable for studying boosted objects and gluon splitting to $\bar{c}c$ and $\bar{b}b$ pairs
- Final η bin (from **3.5 to 4.5**) provides important information for $Z + c$ jet measurement
- Top quarks in LHCb produced from qg and qq (ATLAS/CMS primarily gg) – LHCb forward region plays role in testing QCD calculations
- LHCb has better sensitivity for top charge asymmetry measurement, **especially $\eta > 4$,** compared to ATLAS and CMS

Anna Lupato, Abhijit Mathad, Marta Calvi

Semileptonics

- Reduction in high η values is not seen as a significant issue
- Decrease in η could lead to shape variations within the phase space of the decay of interest, which necessitates further investigation.
- For angular analyses, the efficiency variation across the phase space is of concern, and reduced acceptance could lead to significant shape variations. This aspect requires detailed study on an analysis-specific basis.

It is expected that the MC samples will accurately capture variations.

Renato Quagliani,
Ulrik Egede

Rare decays

From local tests over Run-1/-2 sample with Muon in final states

- $B^0 \rightarrow K^* \mu\mu$ after pre-selection

	$\eta < 4.7$	$\eta < 4.8$
$(0.1 < q^2 < 8.0)$	**86%**	**91%**
$(11.0 < q^2 < 12.5)$	**88%**	**93%**
$(15.0 < q^2 < 20.0)$	**87%**	**92%**

- $B^0 \rightarrow K^* \mu\mu$ after pre-selection

	$\eta < 4.7$	$\eta < 4.8$
Before reconstruction	**87%**	**87.7%**
After reconstruction and prelim. selections	**98.3%**	**99.2%**

For same CALO/RICH acceptances, similar cuts as Run-1/-2

Cutting at $\eta < 4.X$ not so bad for electrons

Material budget and bremsstrahlung more relevant

Renato Quagliani,
Ulrik Egede

Rare decays

- Will need to assess the muon decays $K_S \to \mu\mu$ and $B_s \to \mu\mu$
- Impact on these decays correlated to expected changes in Muon momentum acceptance
  - Particular attention needed concerning muon station design and shielding combined to the trackers for high momentum tracks
  - High momentum $B_s \to \mu\mu$ can be studied with Renato's parameterization tool

Renato Quagliani,
Ulrik Egede

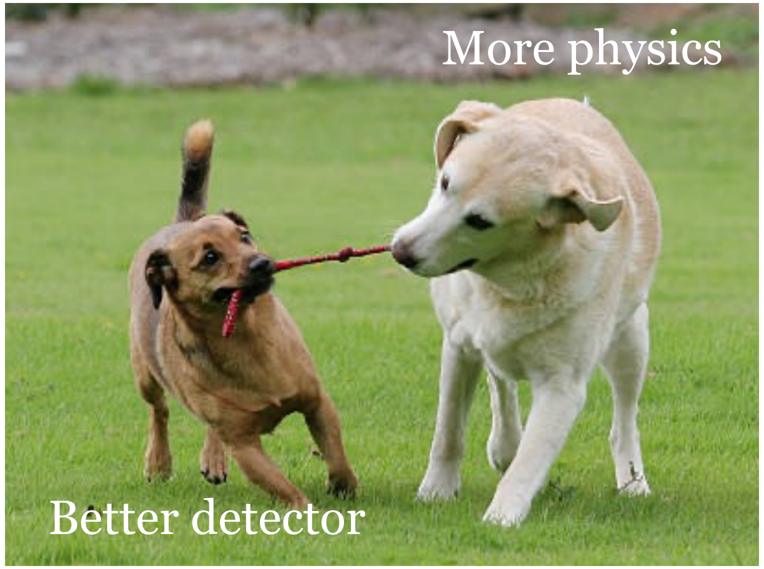
Rare decays

- Probably for soft muons/hard muons we will have different effects when correlated with the muon shielding acceptance.

- For electrons, losses due to material budget more relevant than anything else together with the 'necessary' acceptances needed to be made to have a good PID on particle [RICH/CALO].

Summary

- From the detector design point of view, **going to 4.7 provides relief**, but of course we do not get this for free
- Lose efficiency, bring edge effects closer by reducing our inner acceptance, impact fixed target experiments, reduce LHCb's unique acceptance…
- However, we want RICH, CALO and Muon station acceptances to match tracking acceptance too
  - CALO - **4.3** – **4.7**
  - Muon – full coverage **4.4**
    horizontal **4.7** (vertical **4.85**)



Take-home message and open questions…

- Deciding a benchmark on the acceptance not an easy task…
- Modest impact in most channels reducing acceptance to **4.7**
  - Is 4.7 enough for the cases that rely on high η? E.g., QEE jet studies
- Muon inner acceptance 4.4 full coverage
- CALO inner acceptance 4.3 – 4.7

} Do we need to go further than these?

- Are high η tracks key to flavour tagging?

Thank you to everyone who provided input for these slides!

Everyone's notes here!