Finding a Normalisation Channel for $B_c^+ \rightarrow \tau^+ \nu_\tau$

Student: Max Wiegertjes

Supervisor: Mick Mulder

rijksuniversiteit groningen

Van Swinderen Institute

Nikhef

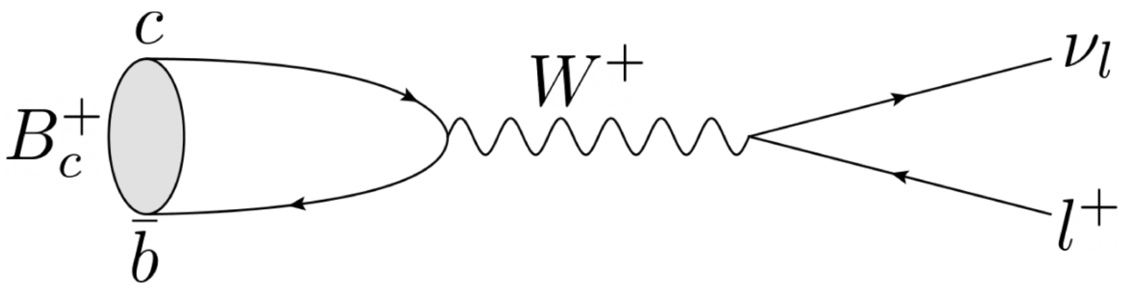
LHCb

Talk Outline

1. Normalising $B_c^+ \to \tau^+\nu$
2. Simulated Data
3. Sneak Peek: 2024 data!

Why $B_c^+ \rightarrow \tau^+ \nu_\tau$?

- No experimental data
- Sensitive to LFU violations
    - Up to 18-30 times SM for pseudoscalar
- Similar process to R(D)



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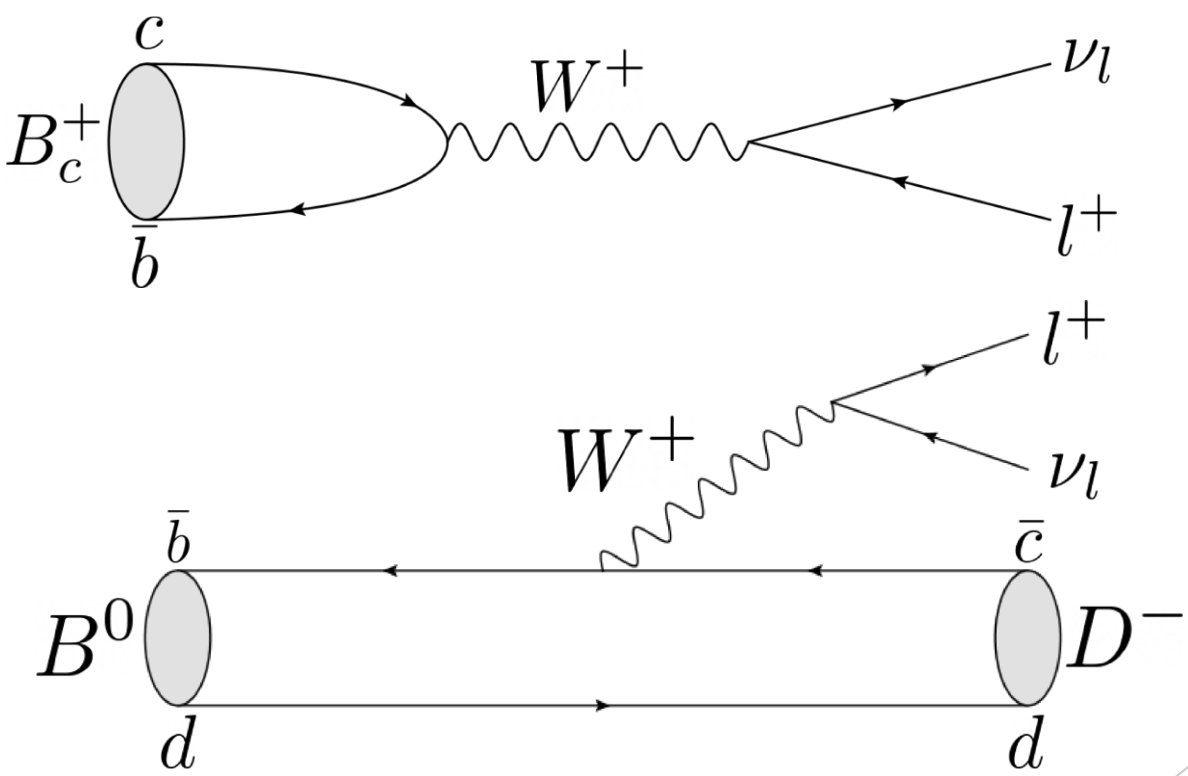
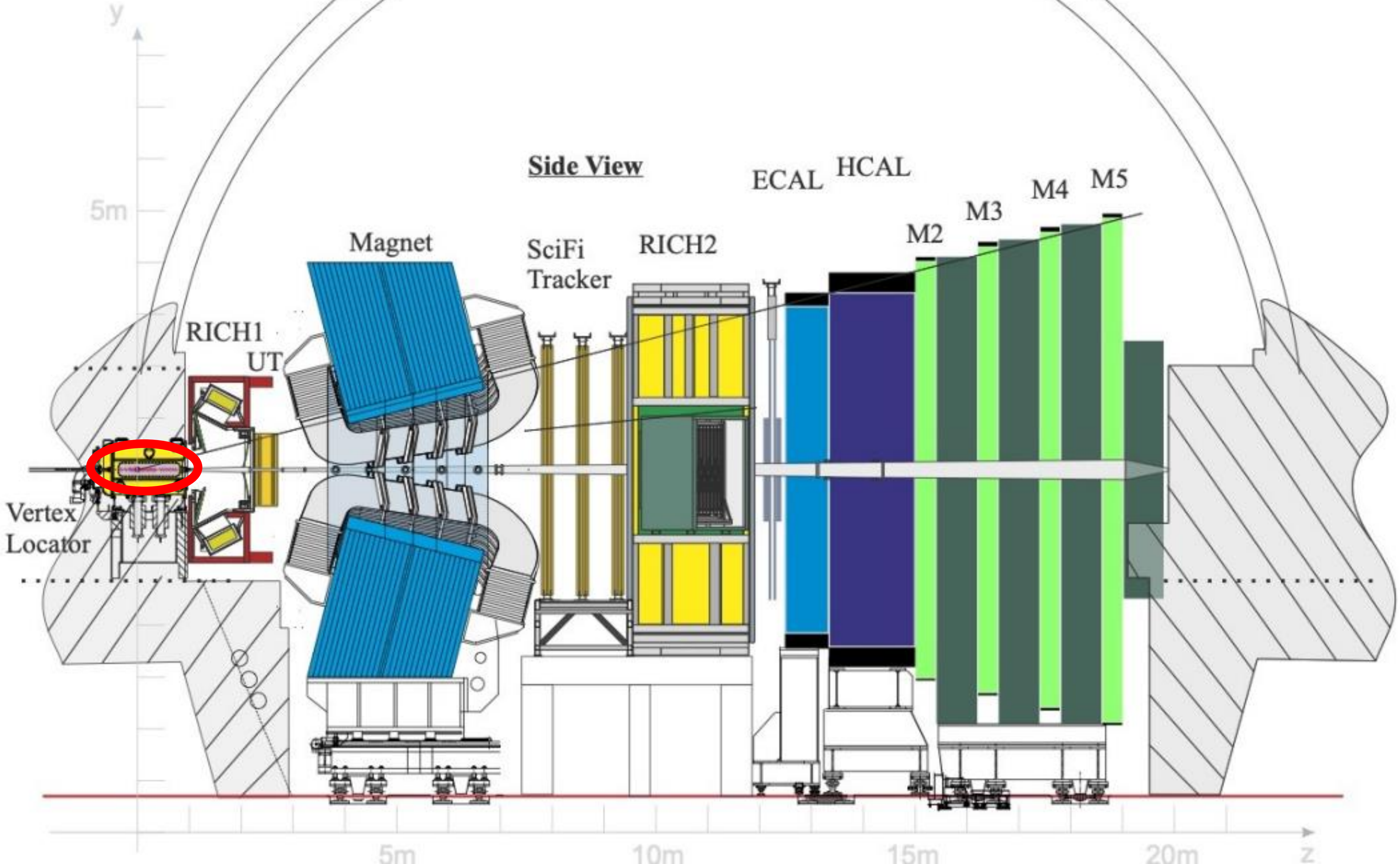
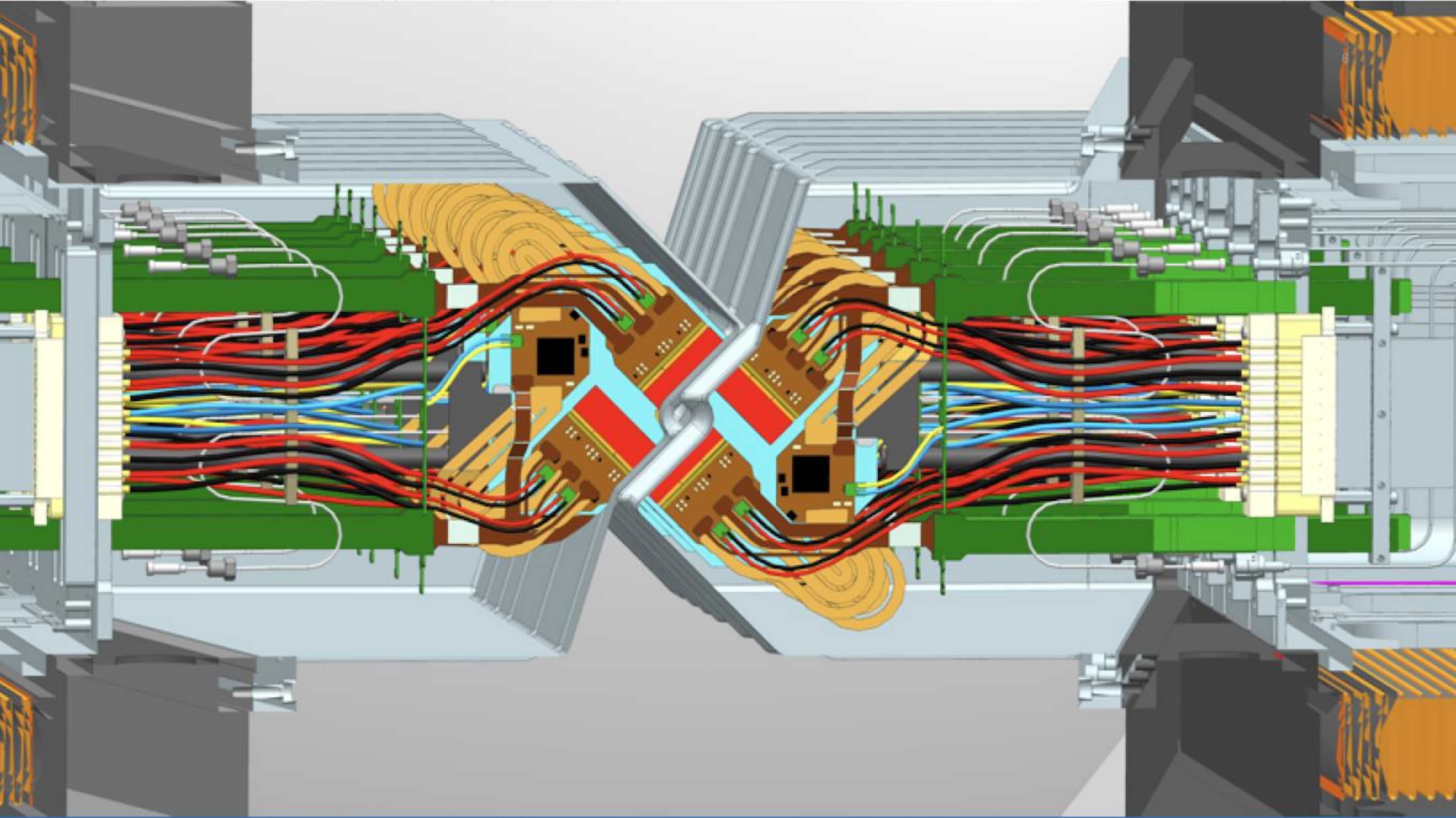
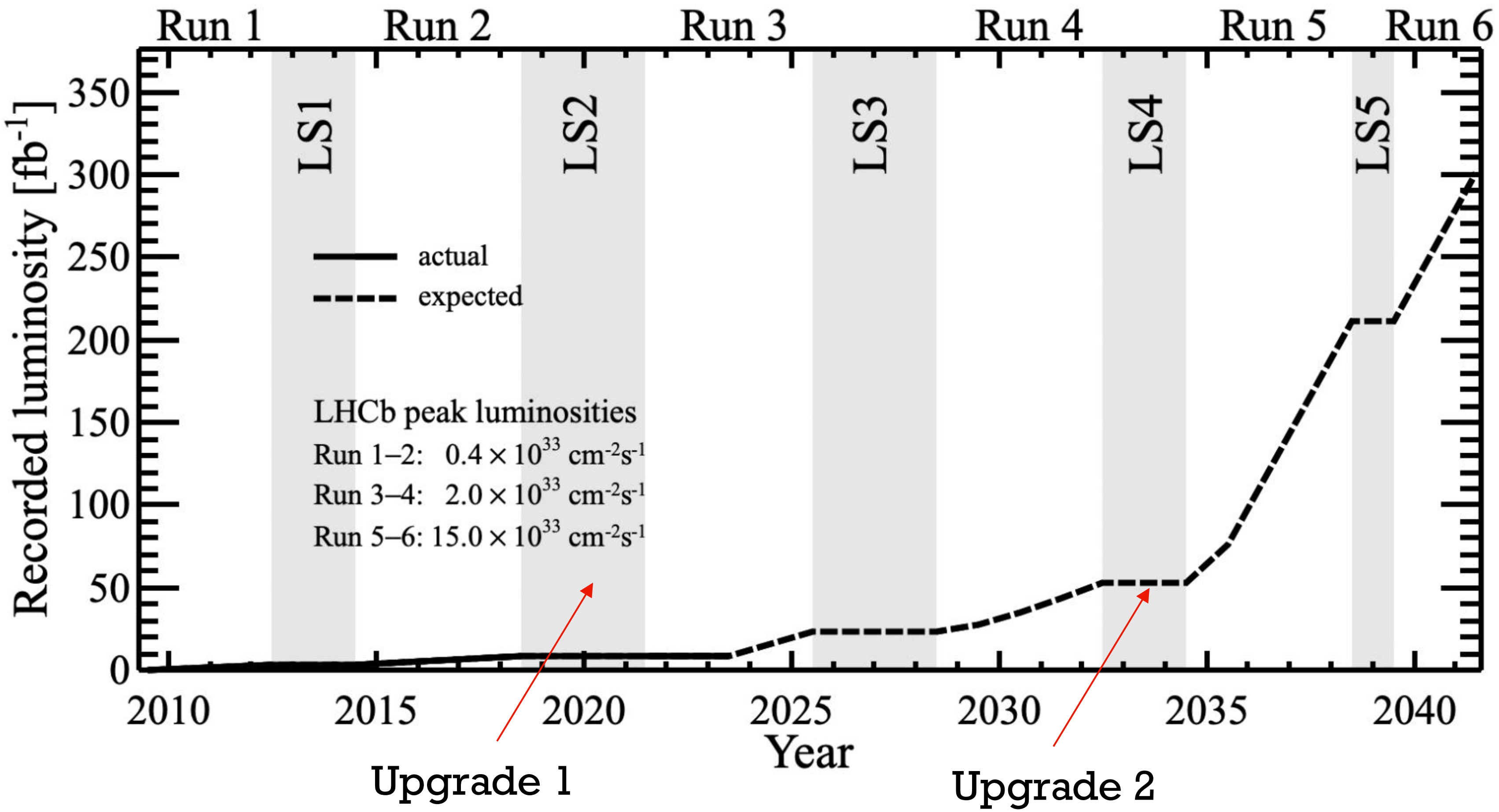


The LHC*b* detector







Runs of Data Taking

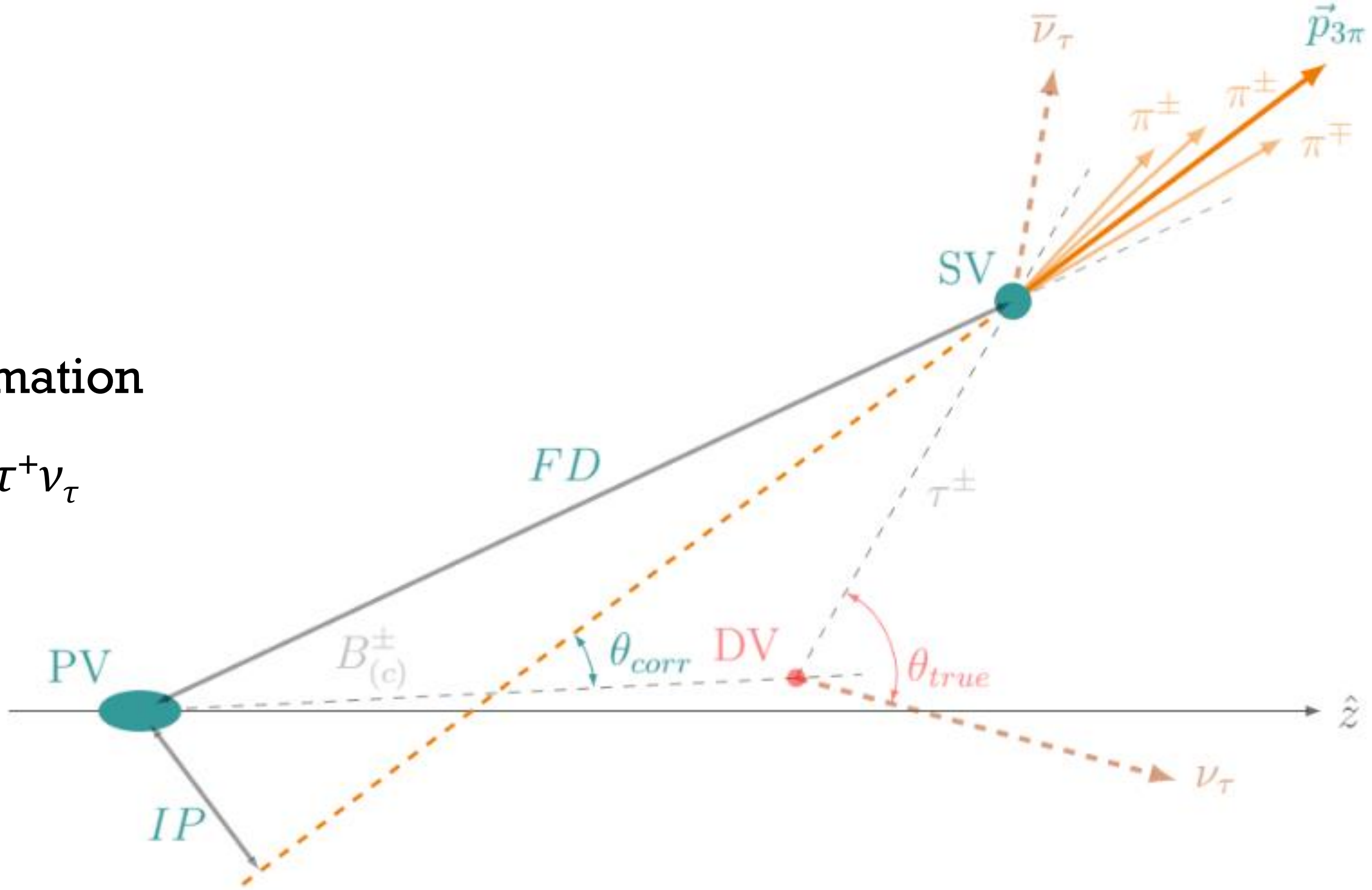
Reconstructing $B_c^+ \rightarrow \tau^+ \nu_\tau$

- Trigger line
- $\tau \rightarrow 3\pi\nu$ sub-decay
- Problems:

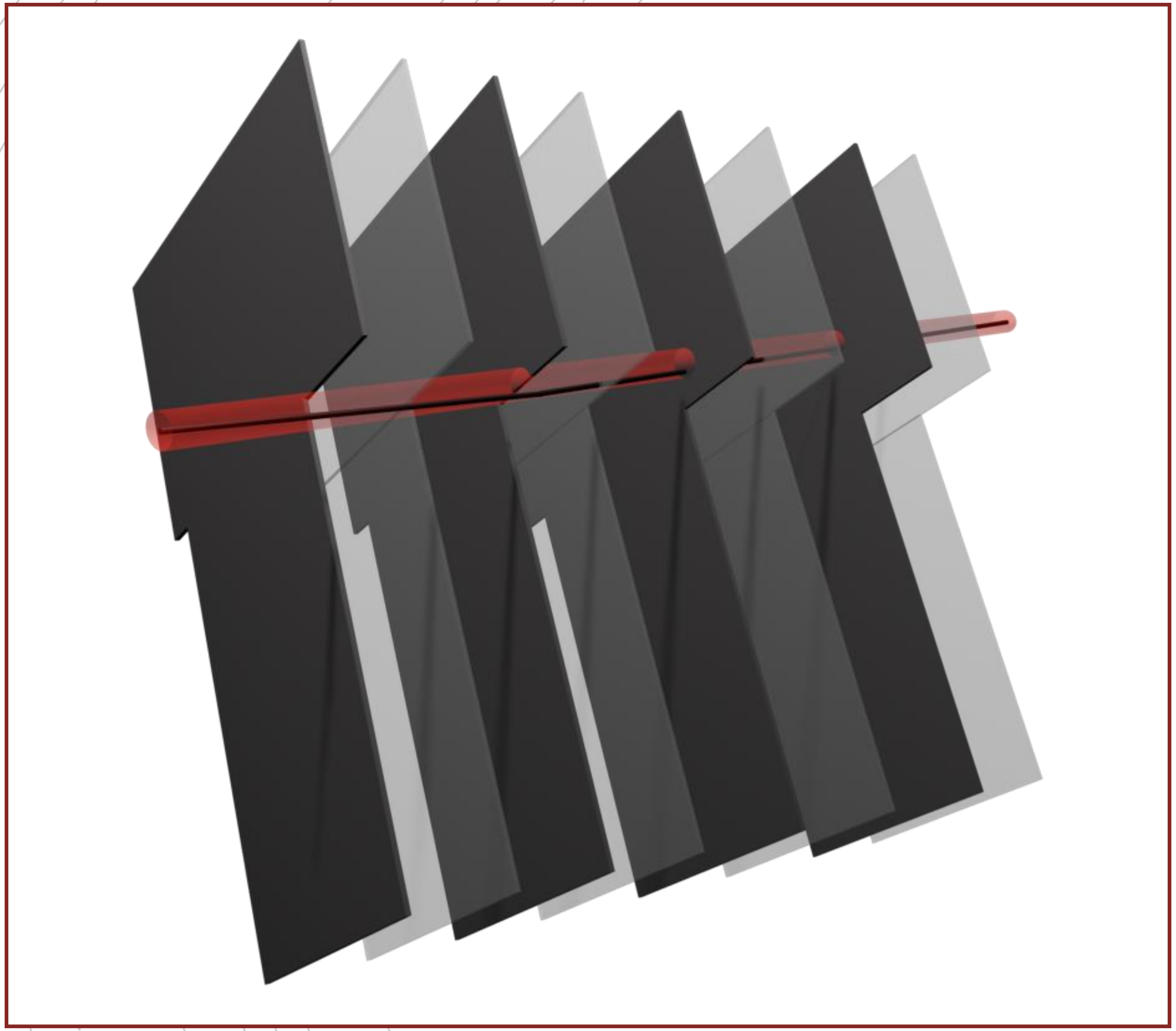
  Neutrinos carry vital information

  Pions do not identify $B_c^+ \rightarrow \tau^+ \nu_\tau$

$$m_{\text{corr}} = \sqrt{m_{3\pi^2} + |\vec{p}_{3\pi\perp}|^2} + |\vec{p}_{3\pi\perp}|$$



J. De Jong (2022)



B-Tracking

- Use direct hits in the VELO
- Search in PV-TV cylinder
- Assume first hit from B_c

Finding a Normalisation Channel

- Report value as a ratio relative to another decay mode

$$\mathcal{R} = \frac{\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)}{\mathcal{B}(\mathrm{norm.})} = \frac{\sigma_N}{\sigma_{B_c^+}} \frac{\epsilon_N}{\epsilon_{B_c^+ \to \tau\nu_\tau}} \frac{\mathcal{N}(B_c^+ \to \tau^+\nu_\tau)}{\mathcal{N}(\mathrm{norm.})}$$

- Choose decay to minimize systematic uncertainty
- Considerations:
  - Sufficient yield
  - Similar reconstruction

To B+ or not to B+?

Bc:
- \+ Cross-section ratio drops out
- \- Statistics becomes an issue, especially with B-hit
- \- Branching fractions poorly understood

B+:
- \+ Abundant
- \+ Branching fractions well understood
- \- Cross-section ratio poorly determined

$$\frac{f_c}{f_u + f_d} \cdot \mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu}) = (7.36 \pm 0.08 \pm 0.30) \cdot 10^{-5}$$

(LHCb 2019) $\mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu}) = (1.95 \pm 0.46)\%$

My Work

- Selecting normalisation mode candidates
- LHC*b* MC samples
- RapidSim vs LHCb MC
- Estimating efficiencies

Run 1 results

- Scaled to 41 fb^{-1} for Run 4

Decay Mode	Rec. Yield
$B^+ \to D^-\pi^+\pi^+$	1.18×10^6
$B^+ \to J/\psi K^+$	8.49×10^5
$B_c^+ \to J/\psi\mu^+\bar{\nu_\mu}$	4.63×10^5
$B_c^+ \to J/\psi\pi^+$	7.28×10^4
$B_c^+ \to J/\psi D_s^+$	699

RapidSim Simulations

- Hit-filtering with MD's script

Decay Mode	ϵ_{velo}	VELO-hit Yield
$B^+ \to D^-\pi^+\pi^+$	0.0073	1321300
$B^+ \to J/\psi K^+$	0.00194	209000
$B_c^+ \to J/\psi\mu^+\nu_\mu$	1.34×10^{-5}	241
$B_c^+ \to J/\psi\pi^+$	1.24×10^{-5}	15
$B_c^+ \to J/\psi D_s^+$	2.18×10^{-4}	24
$B_c^+ \to \tau^+\nu_\tau$	1.17×10^{-4}	3381
$B^+ \to \tau^+\nu_\tau$	0.00254	45500

Efficiency Analysis

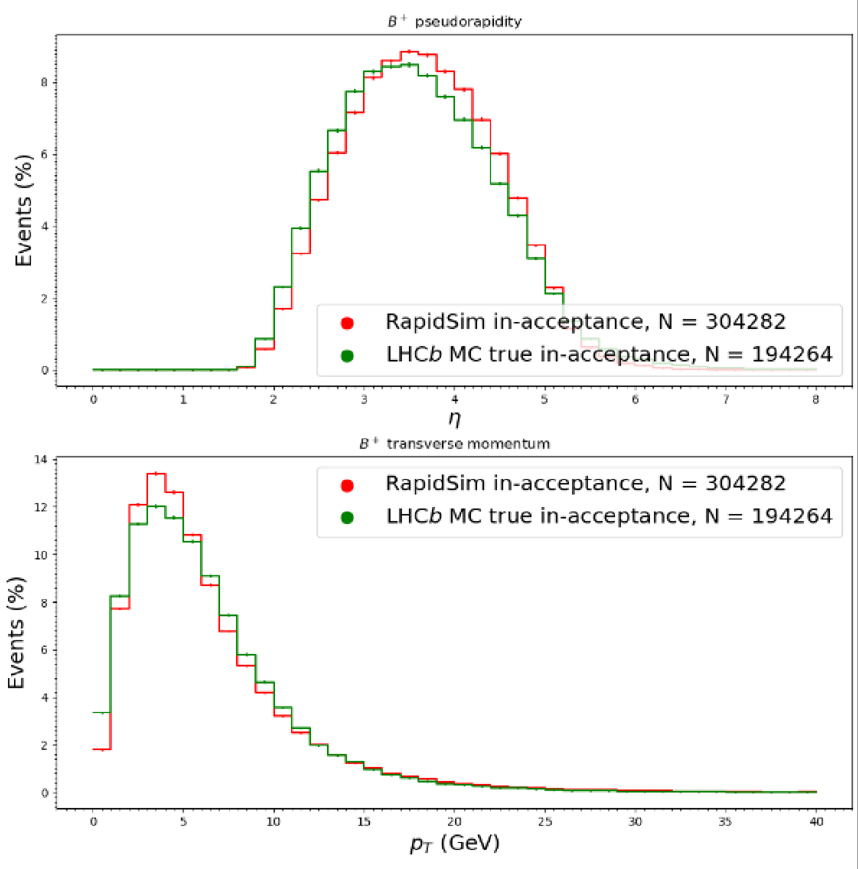
Split into sub-efficiencies:

$$\epsilon_{total} = \epsilon_{Acc} \times \epsilon_{\tau cuts} \times \epsilon_{HLT2} \times \epsilon_{sensor} \times \epsilon_{hit}$$

Cuts on true data   Reconstruction   B-tracking

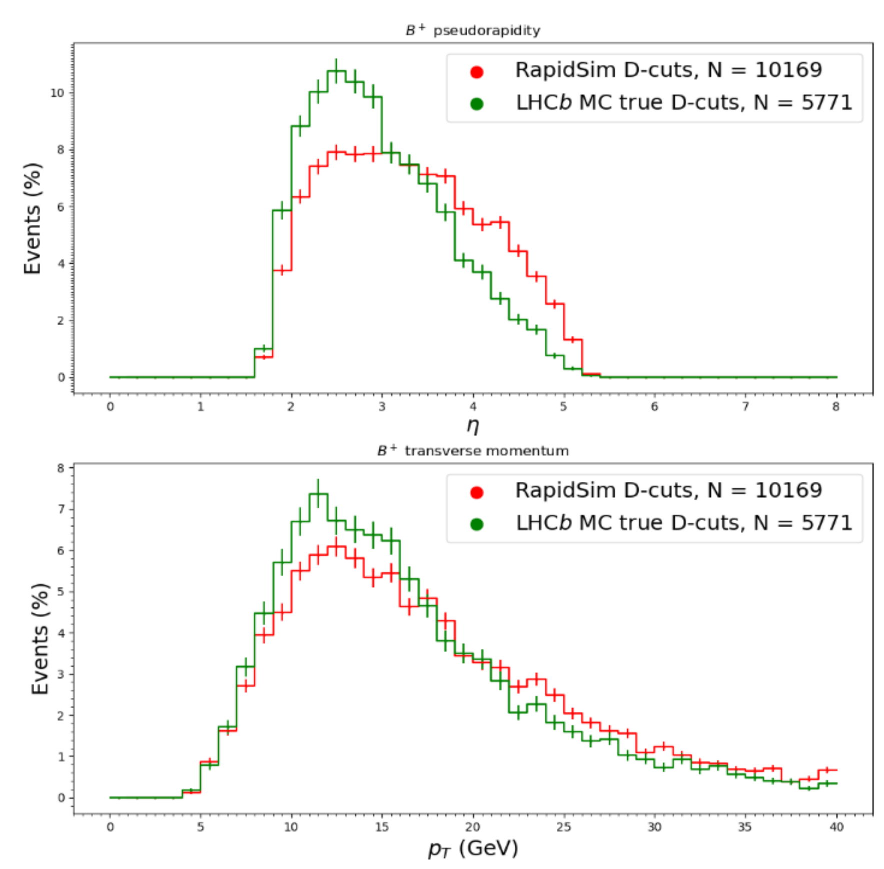
- Acceptance: daughters in 1.595979 < eta < 5.298309
- Tau/D cuts: transverse fd > 4mm & PT > 5 GeV
- HLT2: PID, vertex, mass cuts, etc.
- Sensor Crossing: VELO sensor in PV-TV cylinder
- VELO hit: Actual VELO hit

Comparing LHCb MC with RapidSim

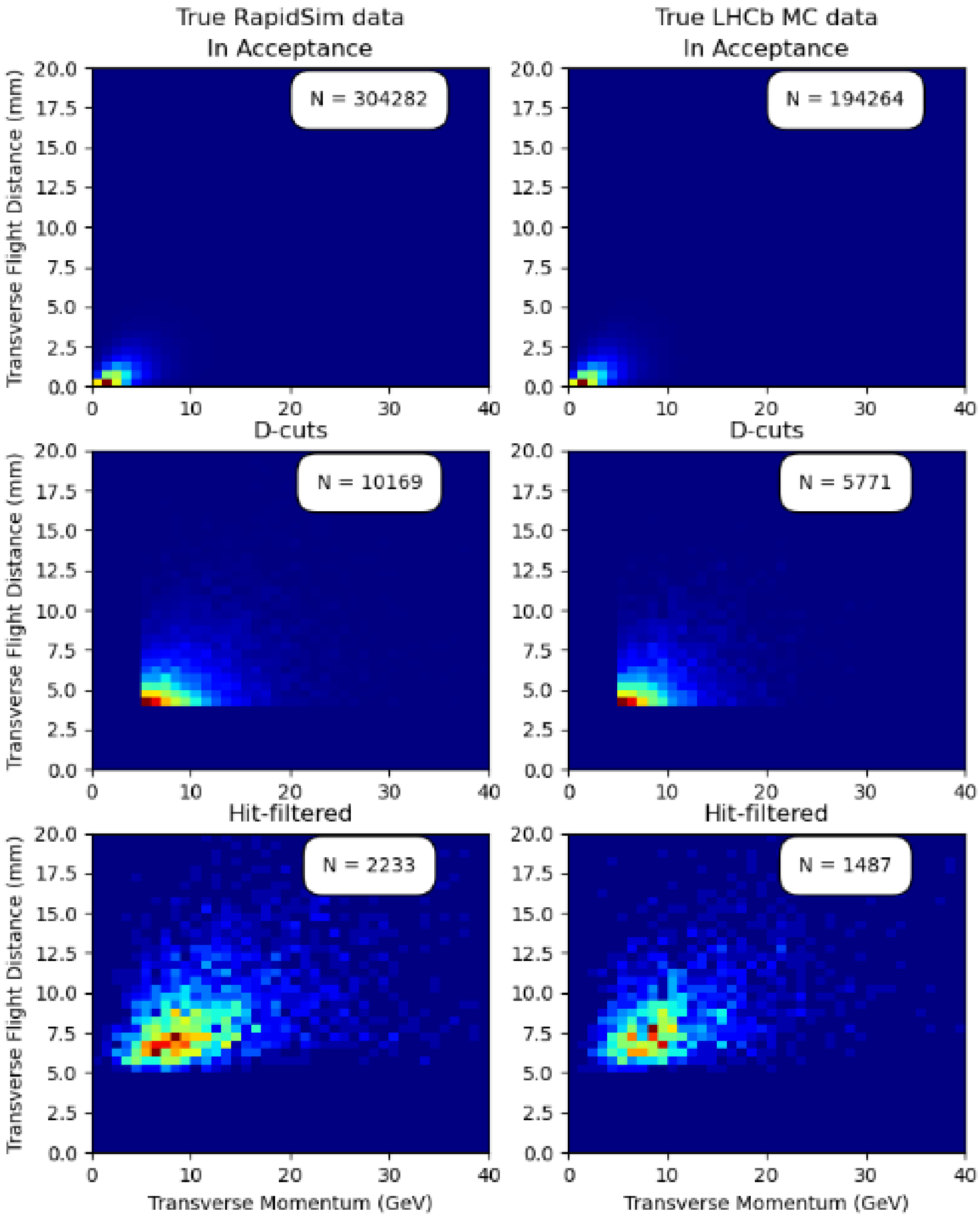


Before cuts

$B^+ \to D^-\pi^+\pi^+$



After cuts



	$B^+ \to \tau^+\nu_\tau$ RapidSim	LHC*b* MC	$B^+ \to D^-\pi^+\pi^+$ RapidSim	LHC*b* MC
τ/D cuts	$1.217 \pm 0.017\,\%$	$1.097 \pm 0.023\,\%$	$3.342 \pm 0.034\,\%$	$2.971 \pm 0.040\,\%$
VELO-hit	$20.49 \pm 0.70\,\%$	$17.74 \pm 0.97\,\%$	$21.96 \pm 0.51\,\%$	$25.77 \pm 0.75\,\%$
Cumulative	$0.2494 \pm 0.0078\,\%$	$0.195 \pm 0.098\,\%$	$0.734 \pm 0.016\,\%$	$0.765 \pm 0.020\,\%$

The Efficiencies

	Yield	Sub-Efficiency	Cumulative
In Acceptance	194264	-	-
D cuts	5771	0.02971 ± 0.00040	0.02971 ± 0.00040
HLT2	707	0.1225 ± 0.0049	$(3.64 \pm 0.14) \times 10^{-3}$
HLT2 + Sensor	213	0.301 ± 0.024	$(1.096 \pm 0.075) \times 10^{-3}$
VELO Hit	166	0.780 ± 0.081	$(8.54 \pm 0.66) \times 10^{-4}$

$B^+ \to D^- \pi^+ \pi^+$

$B^+ \to \tau^+ \nu$

	Yield	Sub-Efficiency	Cumulative
In Acceptance	203973	-	-
τ cuts	2238	0.01097 ± 0.00023	0.01097 ± 0.00023
HLT2	1053	0.471 ± 0.018	$(5.16 \pm 0.16) \times 10^{-3}$
HLT2 + Sensor	182	0.173 ± 0.014	$(8.92 \pm 0.66) \times 10^{-4}$
VELO Hit	115	0.631 ± 0.075	$(5.63 \pm 0.53) \times 10^{-4}$

$$\frac{\delta\mathcal{R}}{\mathcal{R}} = \sqrt{\frac{\delta(\frac{\sigma_{B^+}}{\sigma_{B_c^+}})^2}{(\frac{\sigma_{B^+}}{\sigma_{B_c^+}})^2} + \frac{\delta\epsilon^2_{B_c^+\to\tau^+\nu}}{\epsilon^2_{B_c^+\to\tau^+\nu}} + \frac{\delta\epsilon^2_{\text{norm.}}}{\epsilon^2_{\text{norm.}}} + \frac{\delta\mathcal{N}(B_c^+\to\tau^+\nu)^2}{\mathcal{N}(B_c^+\to\tau^+\nu)^2} + \frac{\delta\mathcal{N}(\text{norm.})^2}{\mathcal{N}(\text{norm.})^2}}$$

Estimating Total Uncertainty

Lower limit:
No contribution from efficiencies

Upper limit:
These efficiencies with no cancelations

Factor	Value	Uncertainty	Relative
$\sigma_{B^+}/\sigma_{B_c^+}$	7.56×10^{-3}	1.81×10^{-3}	23.9%
$\epsilon_{B^+\to\tau^+\nu_\tau}$	5.63×10^{-4}	0.53×10^{-4}	9.4%
$\epsilon_{B^+\to D^-\pi^+\pi^+}$	8.54×10^{-4}	0.66×10^{-4}	7.7%
$\epsilon_{B_c^+\to\tau^+\nu_\tau}$	2.59×10^{-5}	0.24×10^{-5}	9.4%
$\mathcal{N}(B^+\to\tau^+\nu_\tau)$	154574	393	0.25%
$\mathcal{N}(B^+\to D^-\pi^+\pi^+)$	16271	128	0.79%
$\mathcal{N}(B_c^+\to\tau^+\nu_\tau)$	427	21	4.9%

$$\frac{\delta\mathcal{R}}{\mathcal{R}} = \sqrt{\frac{\delta(\frac{\sigma_{B+}}{\sigma_{B_c^+}})^2}{(\frac{\sigma_{B+}}{\sigma_{B_c^+}})^2} + \frac{\delta\epsilon^2_{B_c^+\to\tau^+\nu}}{\epsilon^2_{B_c^+\to\tau^+\nu}} + \frac{\delta\epsilon^2_{\text{norm.}}}{\epsilon^2_{\text{norm.}}} + \frac{\delta\mathcal{N}(B_c^+\to\tau^+\nu)^2}{\mathcal{N}(B_c^+\to\tau^+\nu)^2} + \frac{\delta\mathcal{N}(\text{norm.})^2}{\mathcal{N}(\text{norm.})^2}}$$

δR/R = 24.3-27.2 %

$B+ \to D^-\pi^+\pi^+$

δR/R = 24.4-27.8 %

$B+ \to \tau^+\nu$

Factor	Value	Uncertainty	Relative
$\sigma_{B^+}/\sigma_{B_c^+}$	7.56×10^{-3}	1.81×10^{-3}	23.9%
$\epsilon_{B^+\to\tau^+\nu_\tau}$	5.63×10^{-4}	0.53×10^{-4}	9.4%
$\epsilon_{B^+\to D^-\pi^+\pi^+}$	8.54×10^{-4}	0.66×10^{-4}	7.7%
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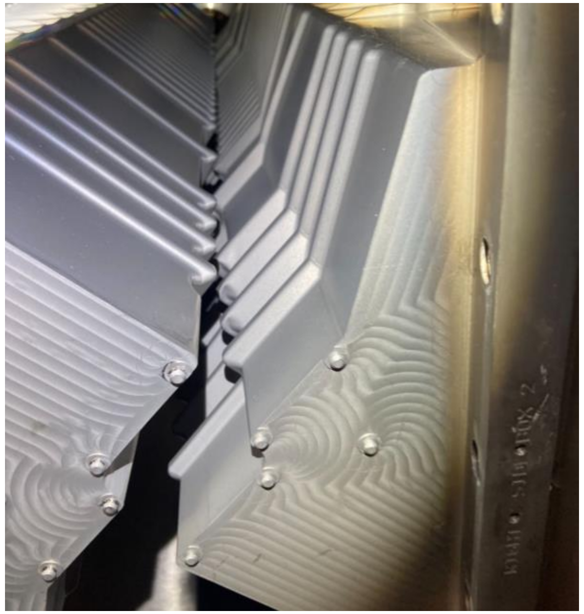
2023 vacuum incident

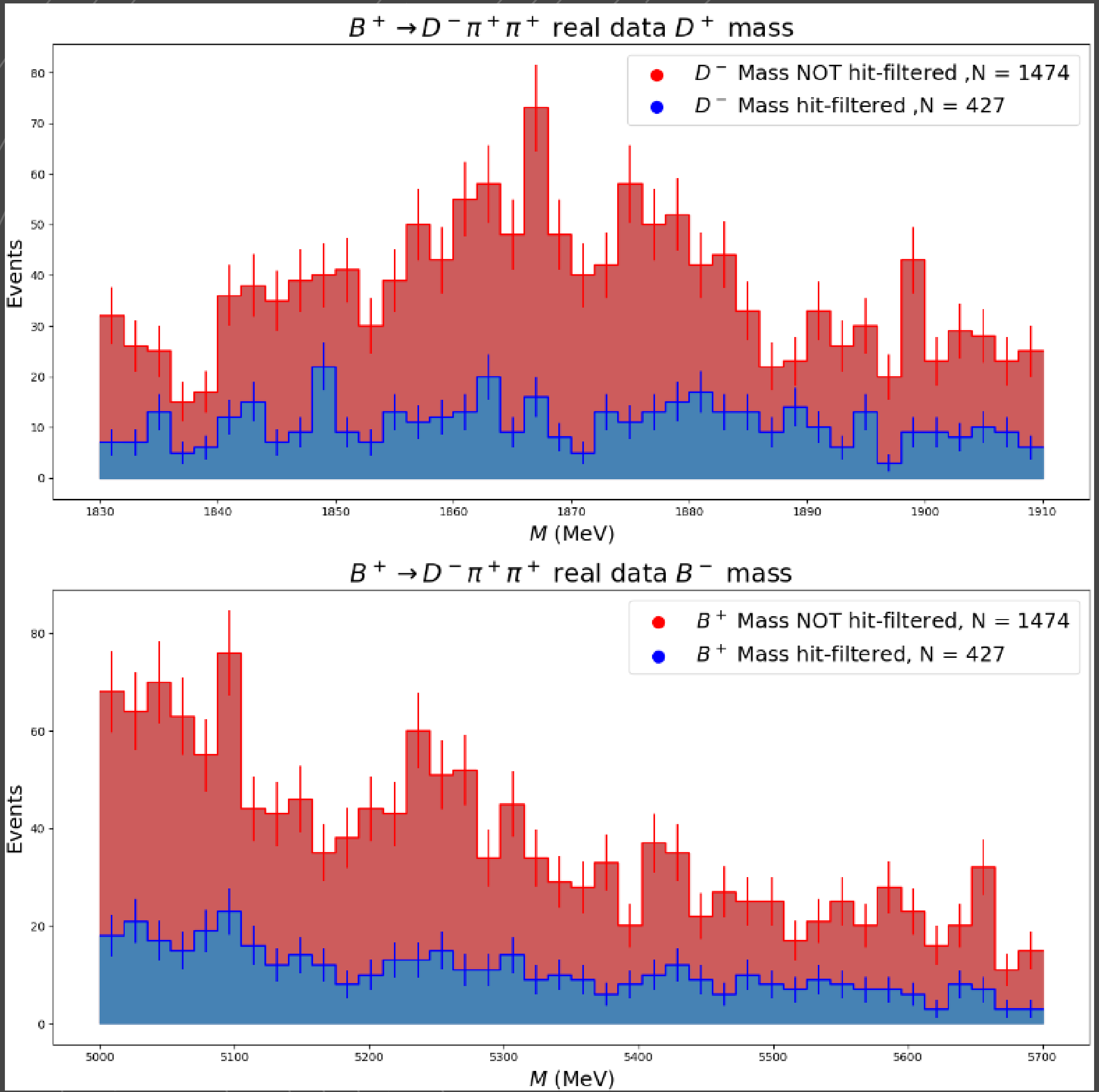
- VELO RF foil deformed

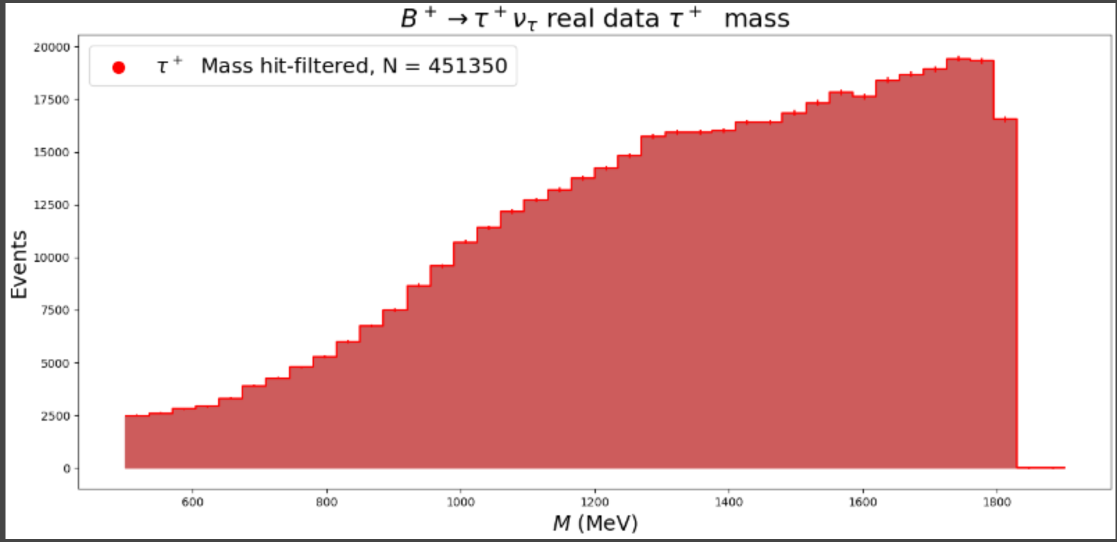
2024 Data

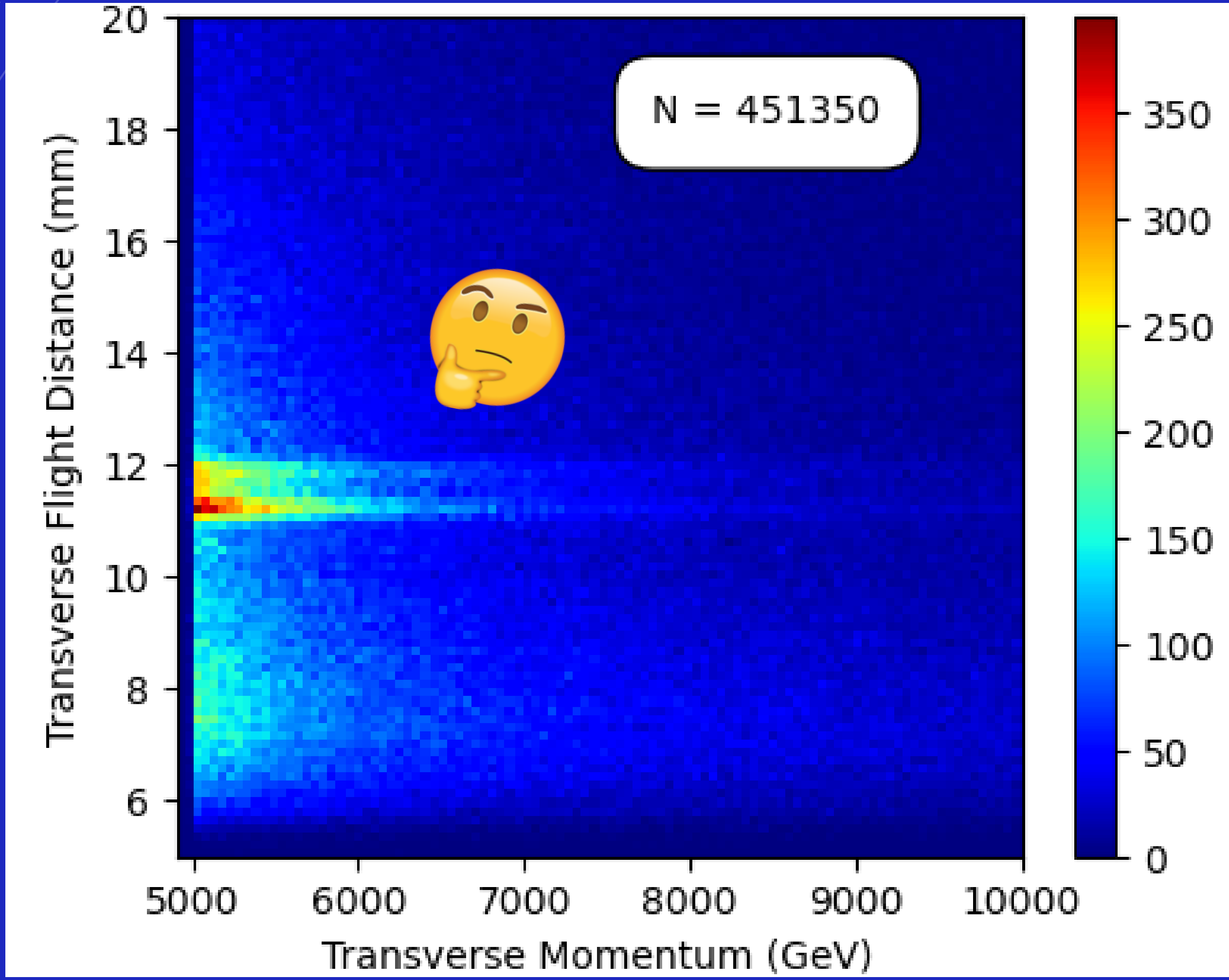
- $B^+ \to \tau^+\nu$ and $B^+ \to D^-\pi^+\pi^+$ lines now implemented
- 8 pb-1 of data

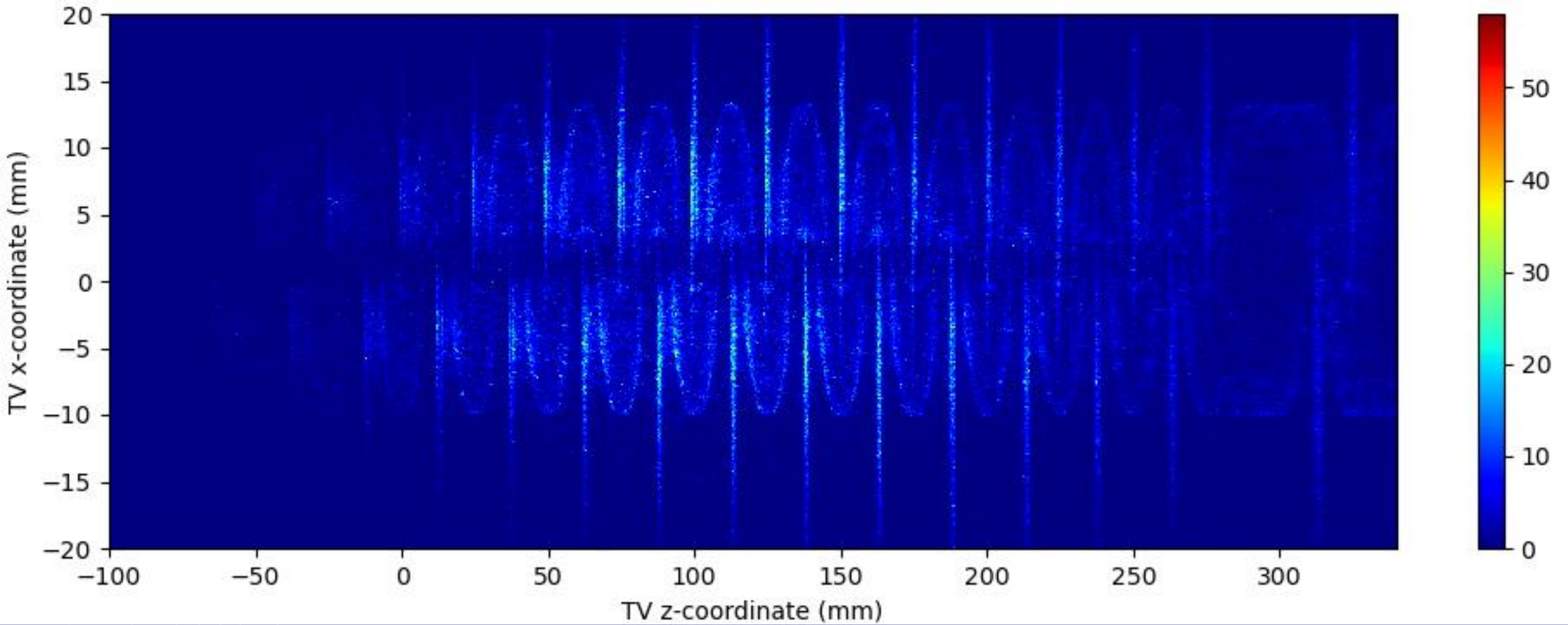


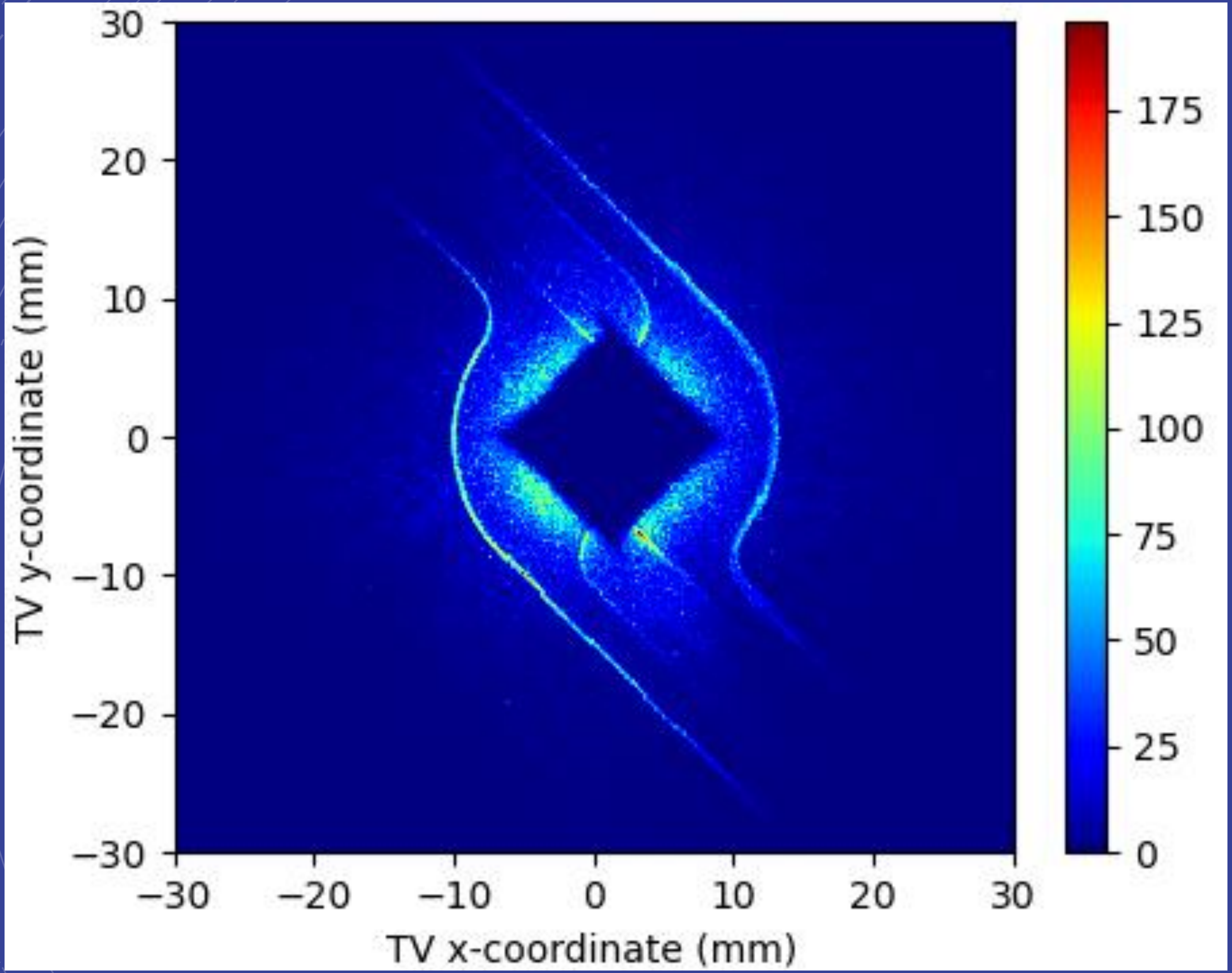
Real Data

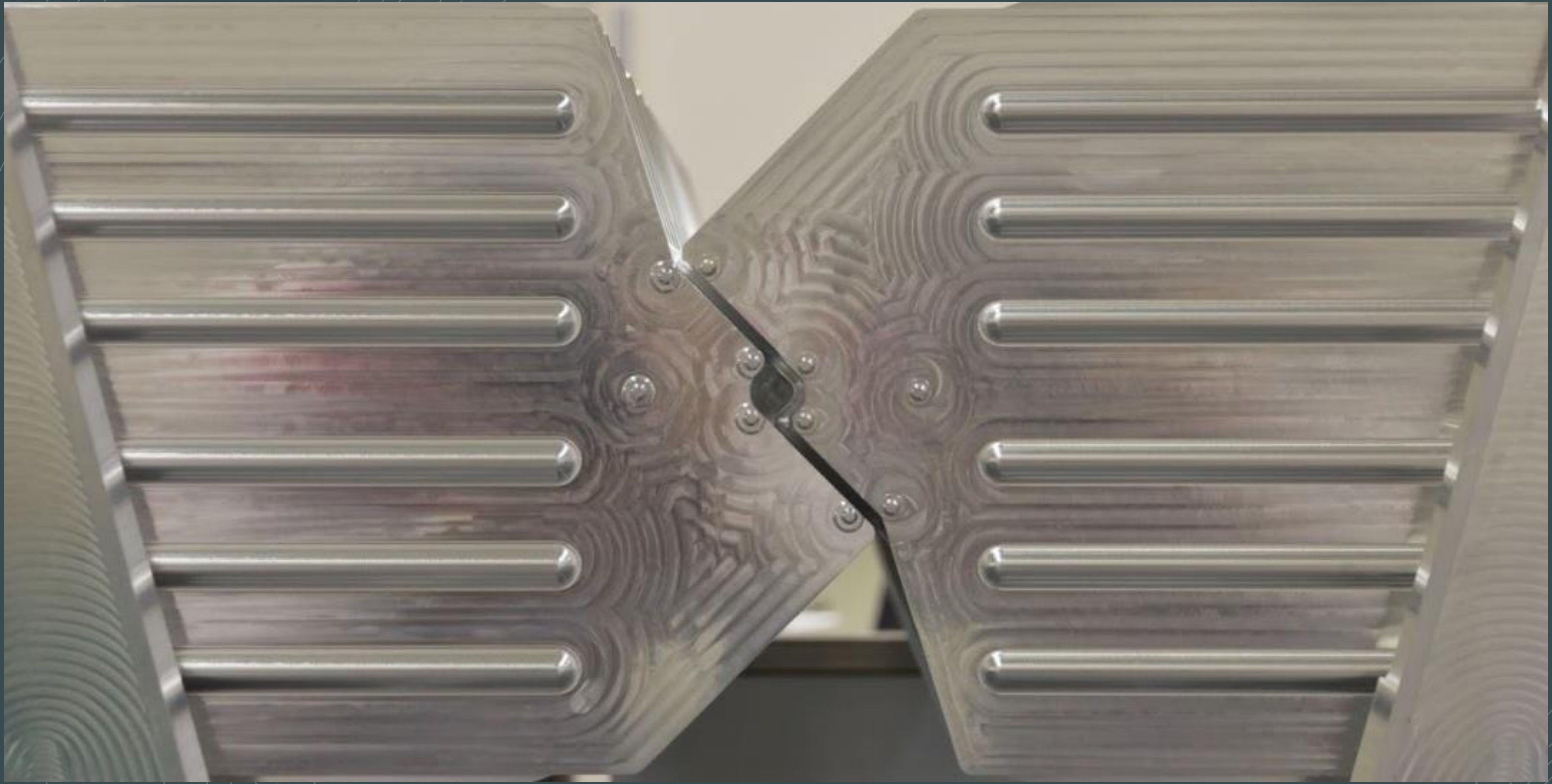

$B^+ \to D^- \pi^+ \pi^+$ real data D^+ mass
D^- Mass NOT hit-filtered ,N = 1474
D^- Mass hit-filtered ,N = 427
Events
M (MeV)
$B^+ \to D^- \pi^+ \pi^+$ real data B^- mass
B^+ Mass NOT hit-filtered, N = 1474
B^+ Mass hit-filtered, N = 427
Events
M (MeV)


$B^+ \to \tau^+ \nu_\tau$ real data τ^+ mass
τ^+ Mass hit-filtered, N = 451350
Events
M (MeV)


N = 451350
Transverse Flight Distance (mm)
20
18
16
14
12
10
8
6
5000
6000
7000
8000
9000
10000
Transverse Momentum (GeV)
350
300
250
200
150
100
50
0


TV x-coordinate (mm)
20
15
10
5
0
−5
−10
−15
−20
−100
−50
0
50
100
150
200
250
300
TV z-coordinate (mm)
50
40
30
20
10
0


30
20
10
0
−10
−20
−30
TV y-coordinate (mm)
−30
−20
−10
0
10
20
30
TV x-coordinate (mm)
175
150
125
100
75
50
25
0



K. Akiba & W. Hulsbergen (2024)

Conclusions

- $B^+ \longrightarrow D^- \pi^+ \pi^+$ is an adequate normalisation channel
- RapidSim VELO-hit efficiencies are good enough for feasibility study
- LHCb MC samples small after HLT2 + VELO-hit
  - $B_c^+ \longrightarrow \tau^+ \nu$ simulation would be nice
- Real data shows high amount of material interactions

Outlook

- More MC data needed!
- What's going on with these backgrounds?
- More detailed efficiency analysis