Muon Upgrade 2

Scenarios & performance studies

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on behalf of the MUON group
6th workshop on LHCb Upgrade 2
Barcelona, 30/03/2023

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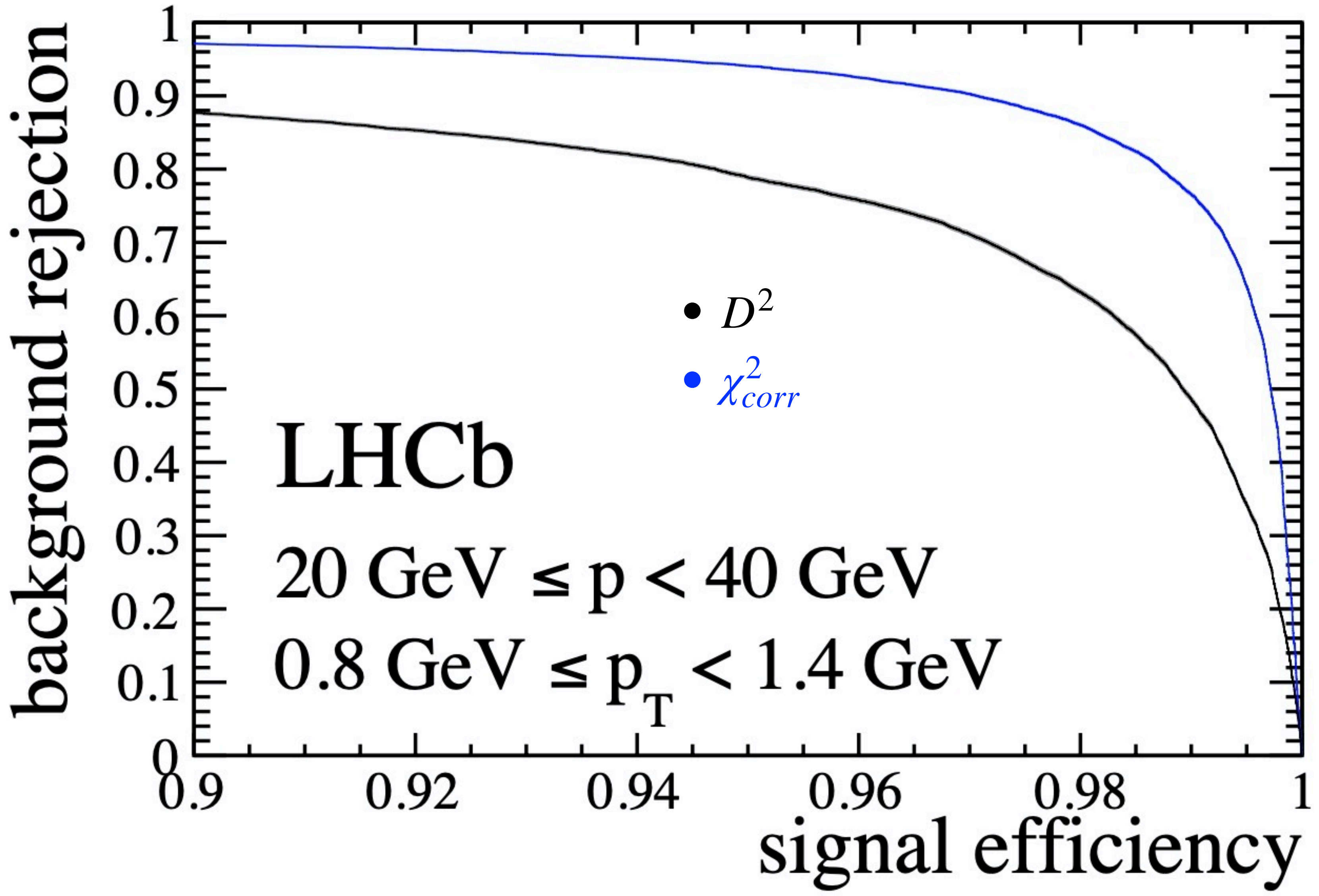
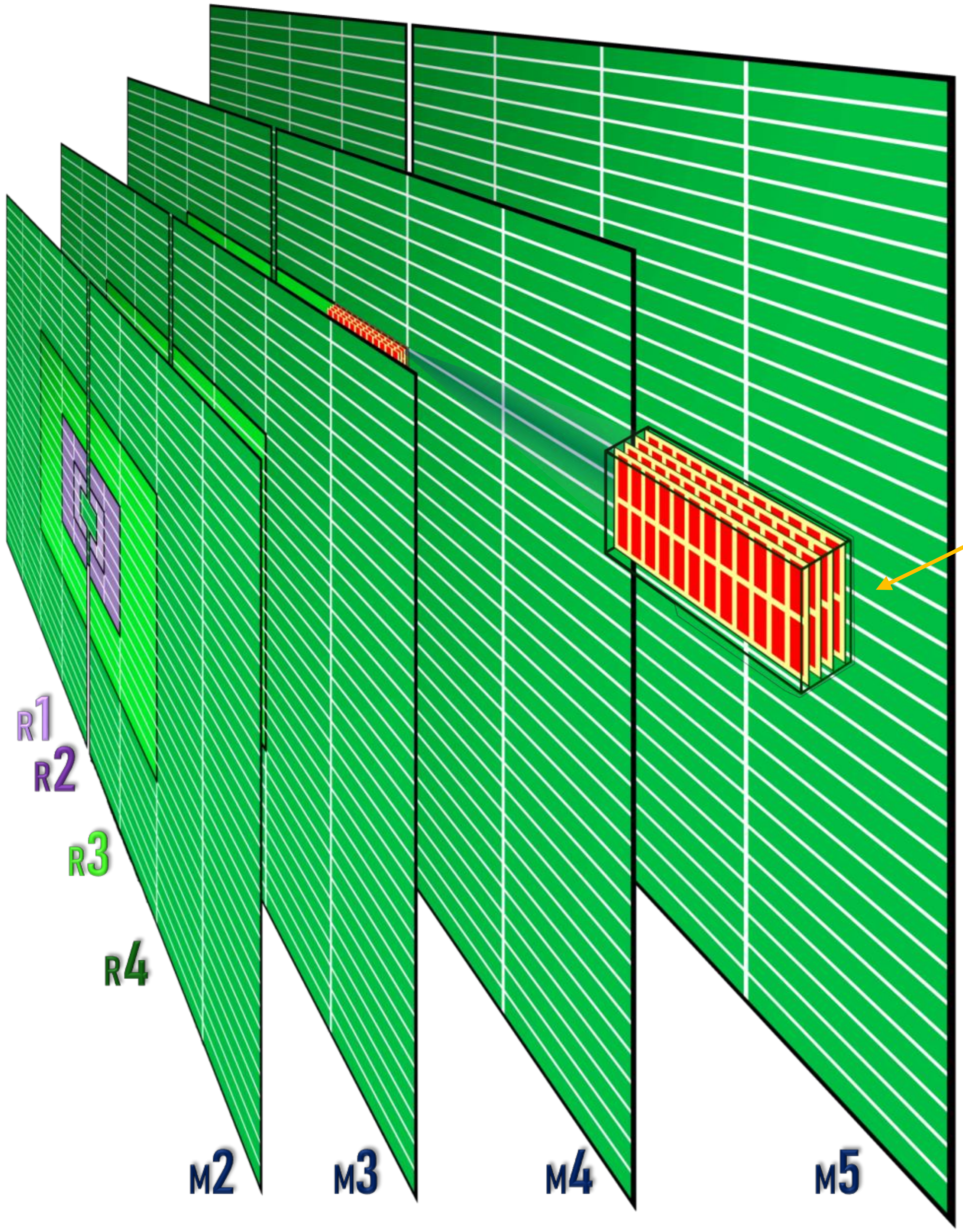
The MUON detector

- The MUON detector is made up of four stations (M2-M5), divided into four regions (R1-R4) from the beam pipe. Between the stations are three 80-cm thick iron absorbers that filter muons.
- Each station is equipped with 4-gap MWPCs
- Coincidence of hits btw stations (isMuon) can be used with ~100% muon efficiency to reduce the hadron misID at the 10^{-2}-10^{-3} level depending on the particle type and momentum
- This performance is enhanced with the D^2 (Run 2) and χ^2_{corr} (Run 3) variables (more in the following)

[JINST 15 (2020) T12005]





4-gaps MWPC of region R3M4

Challenges and solutions

[LHCb-INT-2020-007] [LHCB-U2-FTDR]

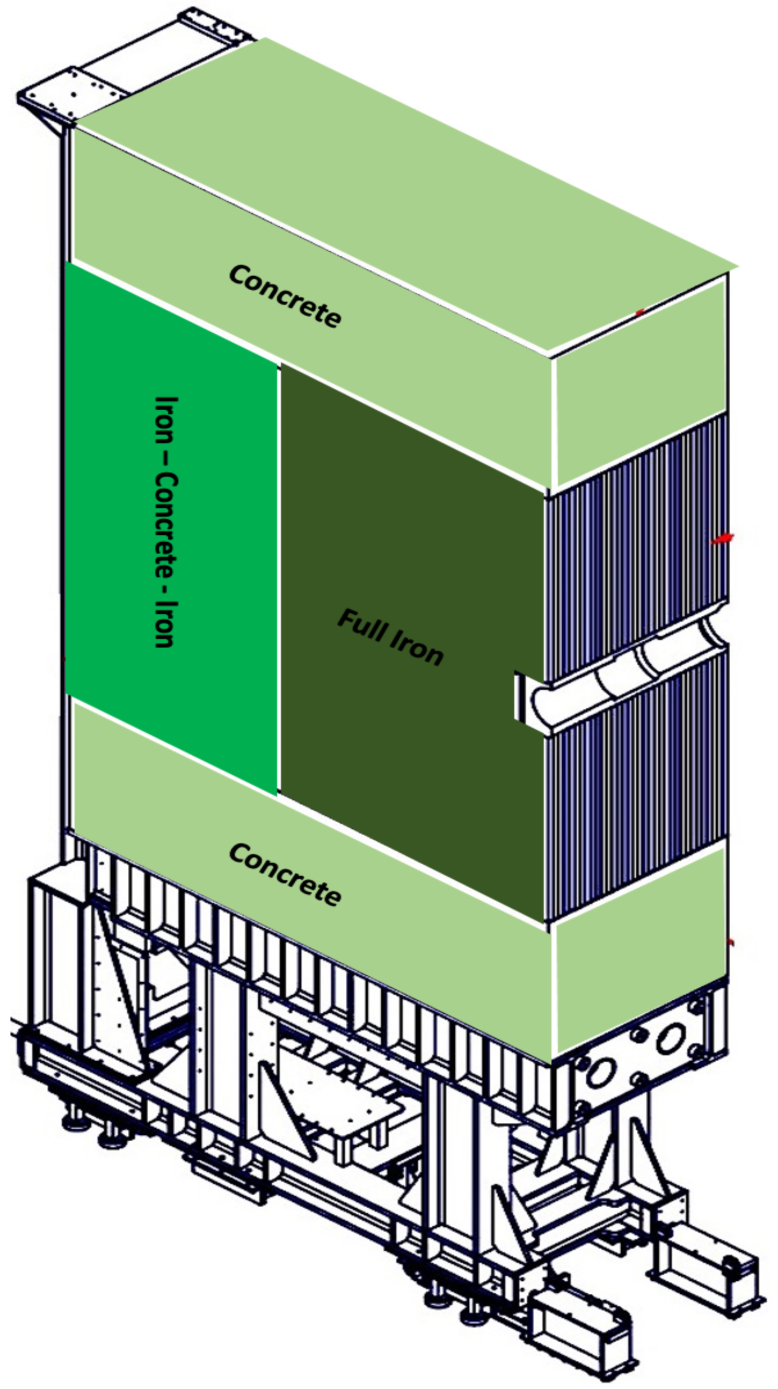
- Challenge: maintain current MUON performance at U2!
- Limiting factors:
  - FEE deadtime for muon efficiency
  - High misID due to increased combinatorial rate & particle flux
- Three “handles” to solve it: improved granularity, new electronics and additional shielding
- Solutions proposed in the FTDR, currently under scrutiny:
  - R1-R2 (rates up to 1 MHz/cm^2):
    - μ-Rwell detectors w small pads → dedicated talk by E. Santovetti
  - R3-R4 (rates $\lesssim$ 50 KHz/cm^2):
    - Keep most of the present MWPC and read them at their full granularity (i.e. no pad grouping to form logical channels)
    - Expected aging @ Run 6 in the outer regions already achieved at the end of Run 2 on M2R1 chambers, with no efficiency loss
    - Expect to replace some MWPCs with high granularity ones
    - Back-up solution: use RPCs / scintillating tiles
  - Increased number of channels & new FEE across the whole detector

MUON U2 detector granularity

	# of chambers	Pad size cm×cm	
M2R1	12	0.9×0.9	μRWell
M2R2	24	0.9×1.8	
M3R1	12	1.0×1.0	
M3R2	24	1.0×1.9	
M4R1	12	1.1×1.0	
M4R2	24	1.1×2.1	
M5R1	12	1.2×1.1	
M5R2	24	1.2×2.2	
M2R3	72	2.5×12.5	MWPCs
M2R3n	40	2.5×6.3	
M2R4	128	5×25	
M3R3	64	2.7×13.5	
M3R4	176	5.4×27.0	
M4R3	48	5.8×14.5	
M4R4	192	5.8×29.0	
M5R3	48	6.2×15.5	
M5R4	192	6.2×31.0	
Total	1104		

Shielding

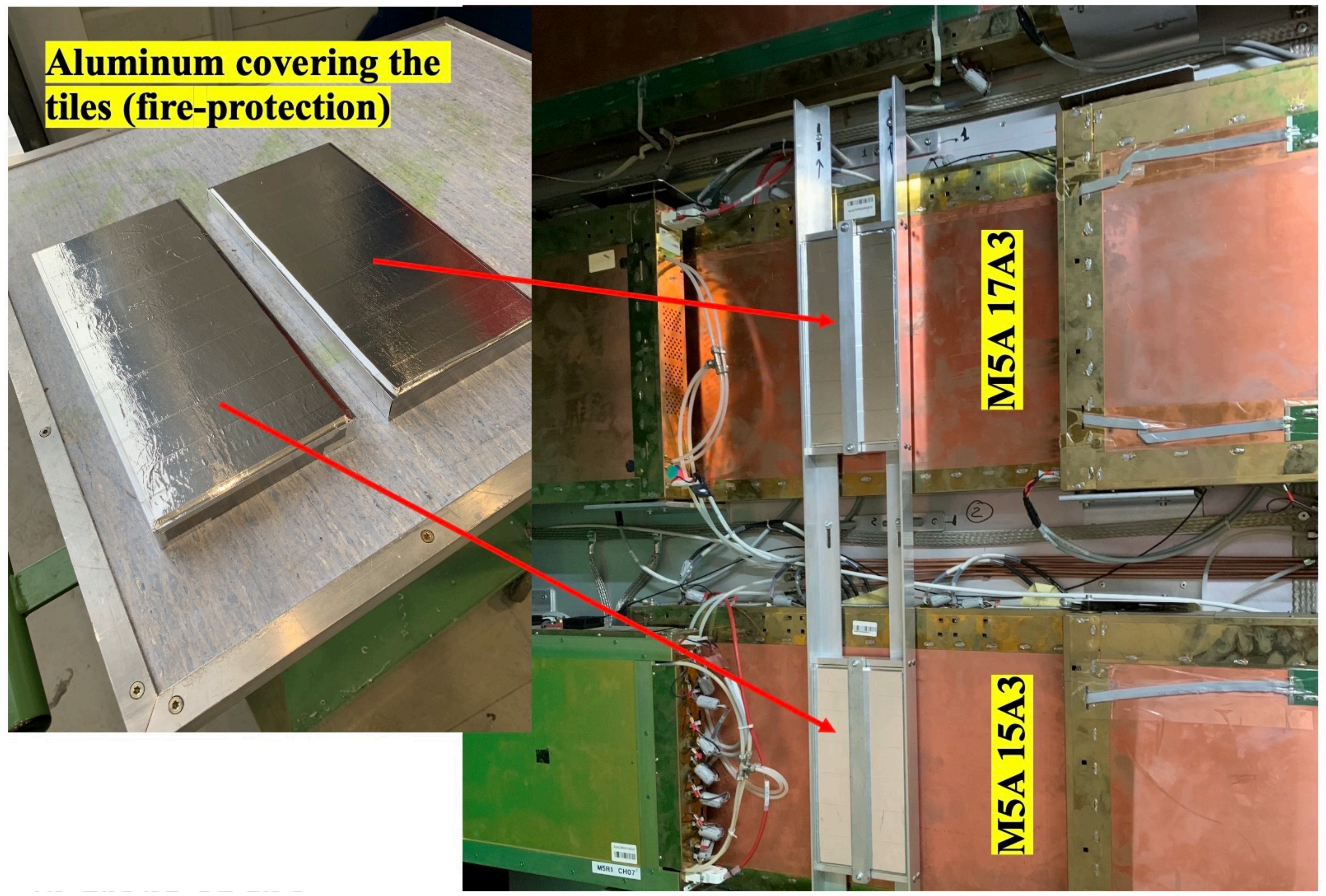
- To mitigate the high particle flux on M2, we're studying the possibility of replacing HCAL (1.7m, $5.6\lambda_I$) with a passive shielding:
  - R1-R3: full iron, $10.1\lambda_I$
  - Median plane: iron/concrete/iron sandwich, $6.2\lambda_I$
  - Top and bottom: concrete, $4\lambda_I$
- Rate reduction M2R1:-42% M2R2:-69% M2R3:-64%
- Negligible muonID efficiency loss is evaluated from simulated $K_s^0 \to \mu^+\mu^-$ events (Run 2 conditions):



[LHCb-INT-2019-008]

	HCAL	Shielding
1μ, all regions	$97.5 \pm 0.2\%$	$97.7 \pm 0.2\%$
R1	$93.1 \pm 0.9\%$	$93.4 \pm 0.8\%$
R2	$98.2 \pm 0.3\%$	$98.7 \pm 0.2\%$
R3	$99.1 \pm 0.2\%$	$97.4 \pm 0.3\%$
R4	$96.9 \pm 0.4\%$	$98.8 \pm 0.2\%$
2μ, all regions	$94.8 \pm 0.4\%$	$95.4 \pm 0.3\%$

- Additional shielding studies are ongoing, e.g. Mirrobor against thermal neutrons

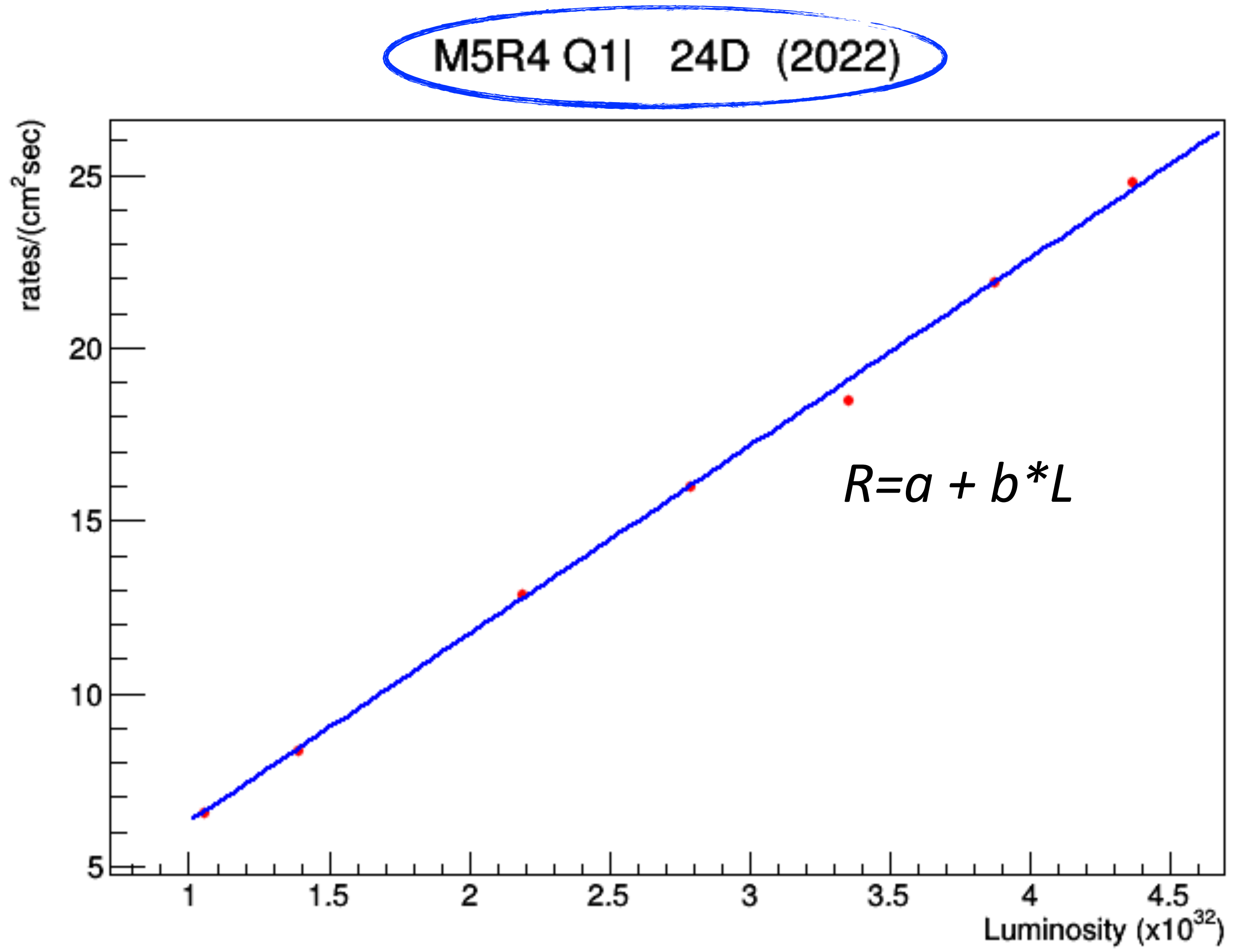


Estimate of U2 particle rates

- In 2022, we repeated a rate measurement campaign with new data → this is crucial to understand the details of the shielding & FEE requirements
- For the extrapolation to U2 luminosity we used:
  - Luminosity scans, e.g. FILL8212 with 7 lumi points taken on 09/2022
  - At each point we recorded FEE scaler counts for each physical channel across the whole detector
  - Chamber rates (avg. of channels) are linearly extrapolated to $\mathscr{L} = 1.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Extra shielding material installed during LS2 is accounted for in data (HCAL-M2 beam plugs + tungsten)

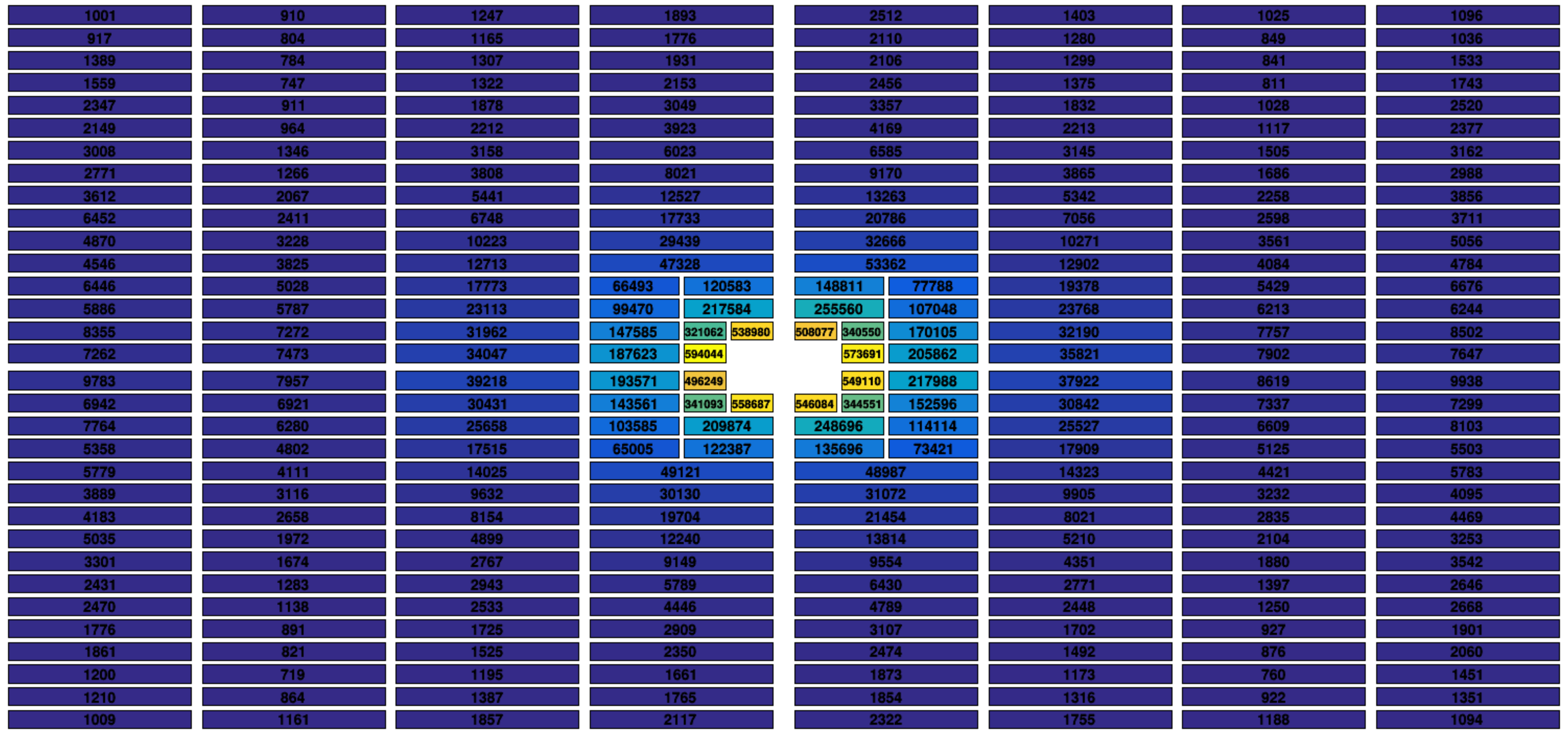
Protons colliding per bunch (μ real):

$\mu = 1.10$	• $L = 1.05\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\mu = 1.45$	• $L = 1.39\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\mu = 2.29$	• $L = 2.19\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\mu = 2.92$	• $L = 2.79\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\mu = 3.50$	• $L = 3.35\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\mu = 4.05$	• $L = 3.87\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\mu = 4.56$	• $L = 4.36\mathrm{x}10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



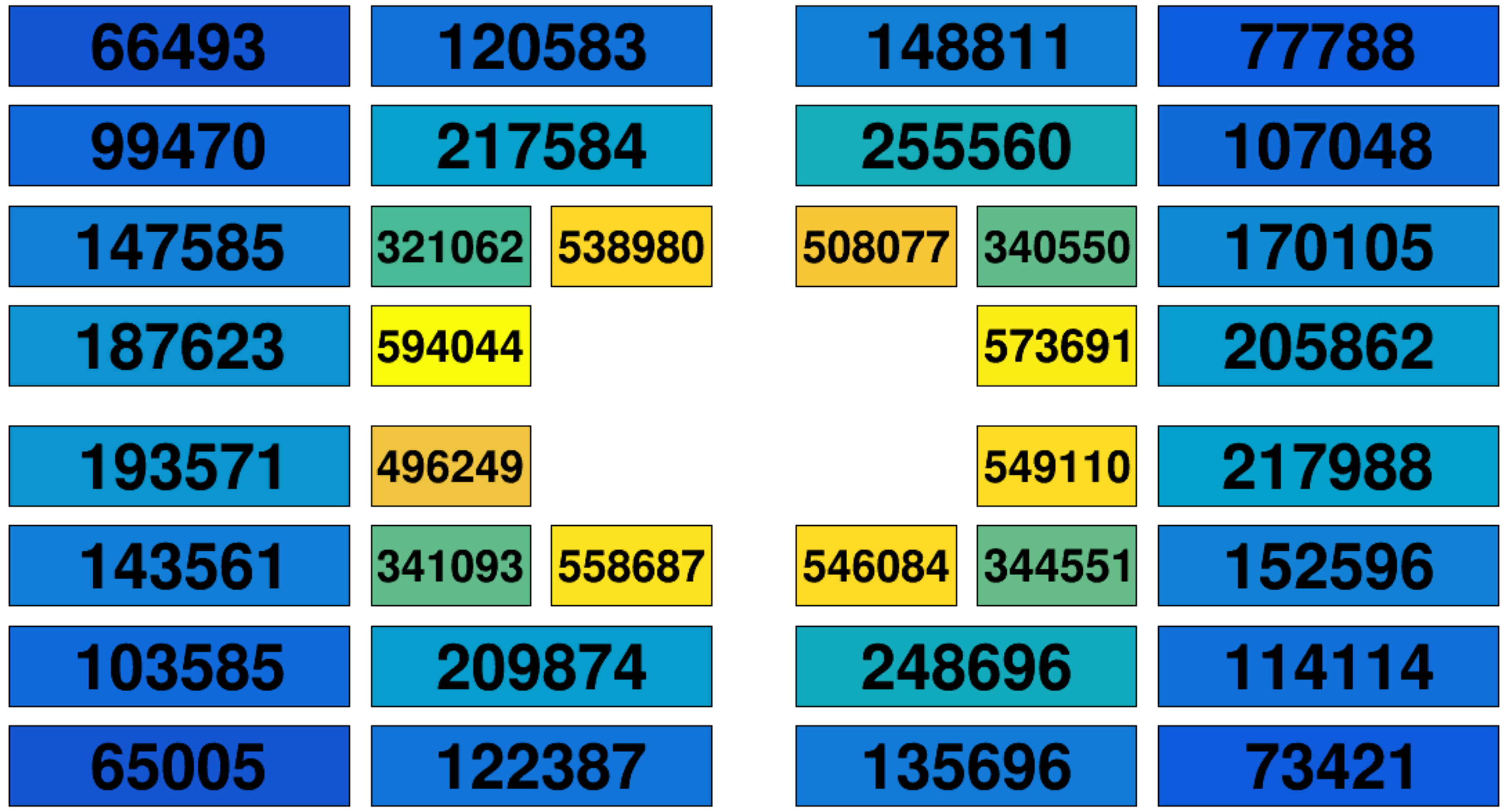
Results (with present detector)

Chamber rates on M2 (Hz/cm²)



1001	910	1247	1893	2512	1403	1025	1096
917	804	1165	1776	2110	1280	849	1036
1389	784	1307	1931	2106	1299	841	1533
1559	747	1322	2153	2456	1375	811	1743
2347	911	1878	3049	3357	1832	1028	2520
2149	964	2212	3923	4169	2213	1117	2377
3008	1346	3158	6023	6585	3145	1505	3162
2771	1266	3808	8021	9170	3865	1686	2988
3612	2067	5441	12527	13263	5342	2258	3856
6452	2411	6748	17733	20786	7056	2598	3711
4870	3228	10223	29439	32666	10271	3561	5056
4546	3825	12713	47328	53362	12902	4084	4784
6446	5028	17773	66493 120583	148811 77788	19378	5429	6676
5886	5787	23113	99470 217584	255560 107048	23768	6213	6244
8355	7272	31962	147585 321062 538980	508077 340550 170105	32190	7757	8502
7262	7473	34047	187623 594044	573691 205862	35821	7902	7647
9783	7957	39218	193571 496249	549110 217988	37922	8619	9938
6942	6921	30431	143561 341093 558687	546084 344551 152596	30842	7337	7299
7764	6280	25658	103585 209874	248696 114114	25527	6609	8103
5358	4802	17515	65005 122387	135696 73421	17909	5125	5503
5779	4111	14025	49121	48987	14323	4421	5783
3889	3116	9632	30130	31072	9905	3232	4095
4183	2658	8154	19704	21454	8021	2835	4469
5035	1972	4899	12240	13814	5210	2104	3253
3301	1674	2767	9149	9554	4351	1880	3542
2431	1283	2943	5789	6430	2771	1397	2646
2470	1138	2533	4446	4789	2448	1250	2668
1776	891	1725	2909	3107	1702	927	1901
1861	821	1525	2350	2474	1492	876	2060
1200	719	1195	1661	1873	1173	760	1451
1210	864	1387	1765	1854	1316	922	1351
1009	1161	1857	2117	2322	1755	1188	1094

Chamber rates on M2R1-R2 (Hz/cm²)



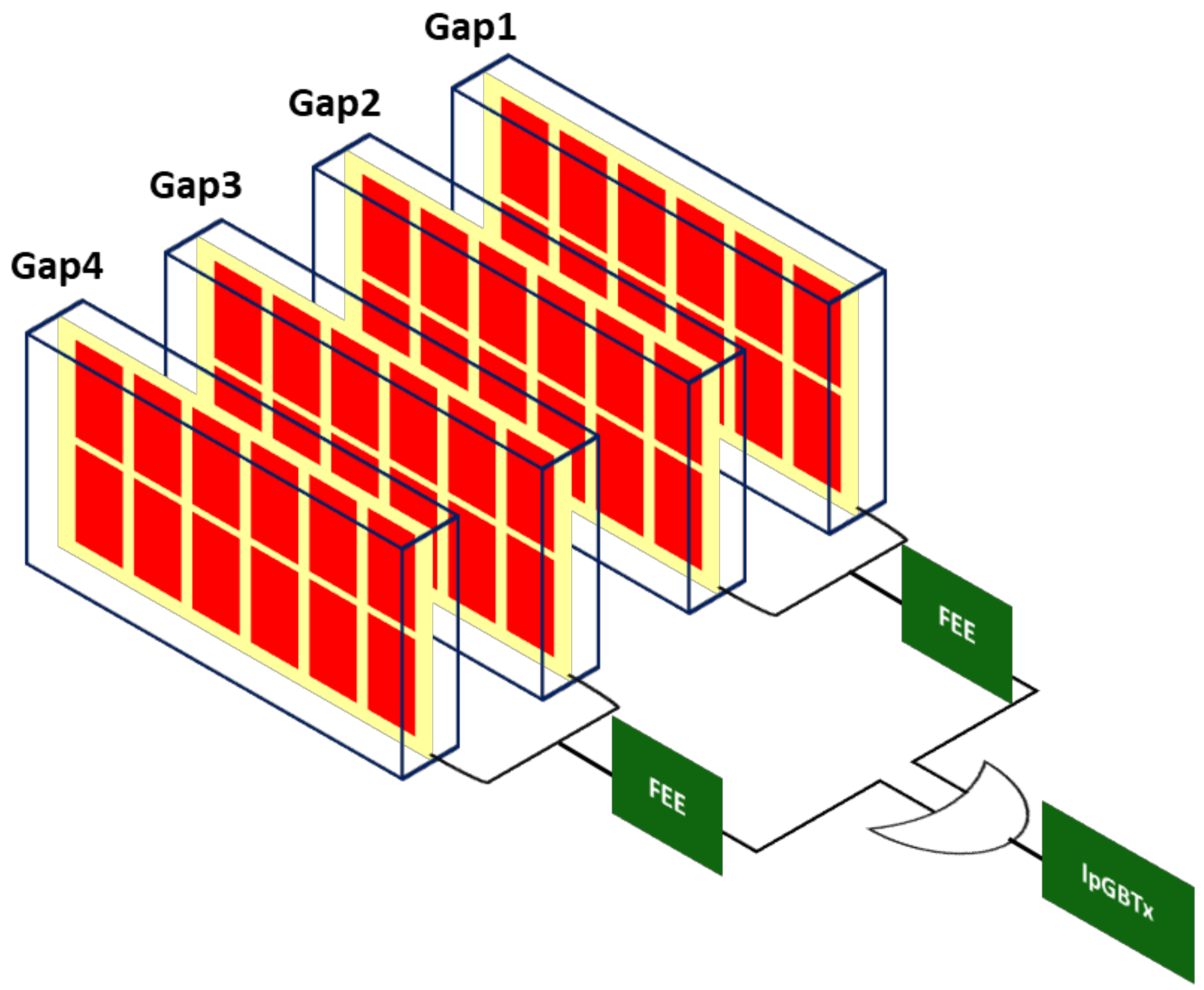
66493	120583	148811	77788
99470	217584	255560	107048
147585	321062 538980	508077 340550	170105
187623	594044	573691	205862
193571	496249	549110	217988
143561	341093 558687	546084 344551	152596
103585	209874	248696	114114
65005	122387	135696	73421

- Maximum rate per region (black) and the mitigation effect of the shielding (-> red) (kHz/cm²)

Maximum chamber rate (kHz/cm²)				
	M2	M3	M4	M5
R1	594.0 -> 344.5	274.5	203.5	232.7
R2	255.6 -> 79.2	64.2	34.1	39.0
R3	53.4 -> 19.2	8.9	6.2	8.9
R4	9.9	3.0	1.7	6.8

Rates: harder than it looks!

- Currently, there’s one FEE channel per bi-gap, made of two physically OR-ed gaps. The two FEE outputs are further OR-ed.
- However, reading each gap individually reduce the rate significantly and is desirable for U2
- To investigate different readout schemes, we measured bi-gap and quadri-gap rates, and also split:
  - Uncorrelated rate (U): due to random hits in each gap
  - Correlated rate (C): due to muons / tracks, or in general time-correlated hits



Measured f_C values

	M2	M3	M4	M5
R1	0.08	0.05	0.12	0.10
R2	0.10	0.08	0.14	0.14
R3	0.16	0.22	0.34	0.33
R4	0.33	0.46	0.51	0.32

- The fractions of correlated hits (f_C) have been measured on data
- The single-gap rate is thus made up of $R_1 = R_{1U} + R_C$, where $R_C = R_4 \times f_C$
- This distinction is important because the deadtime-induced inefficiency for a given readout depends differently on these two components. For example if we read 4 gaps individually:

$$1-\epsilon = \frac{R_{true}\times\delta}{1+R_{true}\times\delta} = R_{obs}\times\delta$$

$$1-\epsilon^{gap}_{uncorr} = R_{1U}\times\delta \rightarrow 1-\epsilon^{cham}_{uncorr} = \underline{(1-\epsilon^{gap}_{uncorr})^4}$$

Uncorrelated inefficiency is negligible

$$1-\epsilon^{gap}_{corr} = R_4\times f_C\times\delta \rightarrow 1-\epsilon^{cham}_{corr} = \underline{1-\epsilon^{gap}_{corr}}$$

Correlated inefficiency dominates!

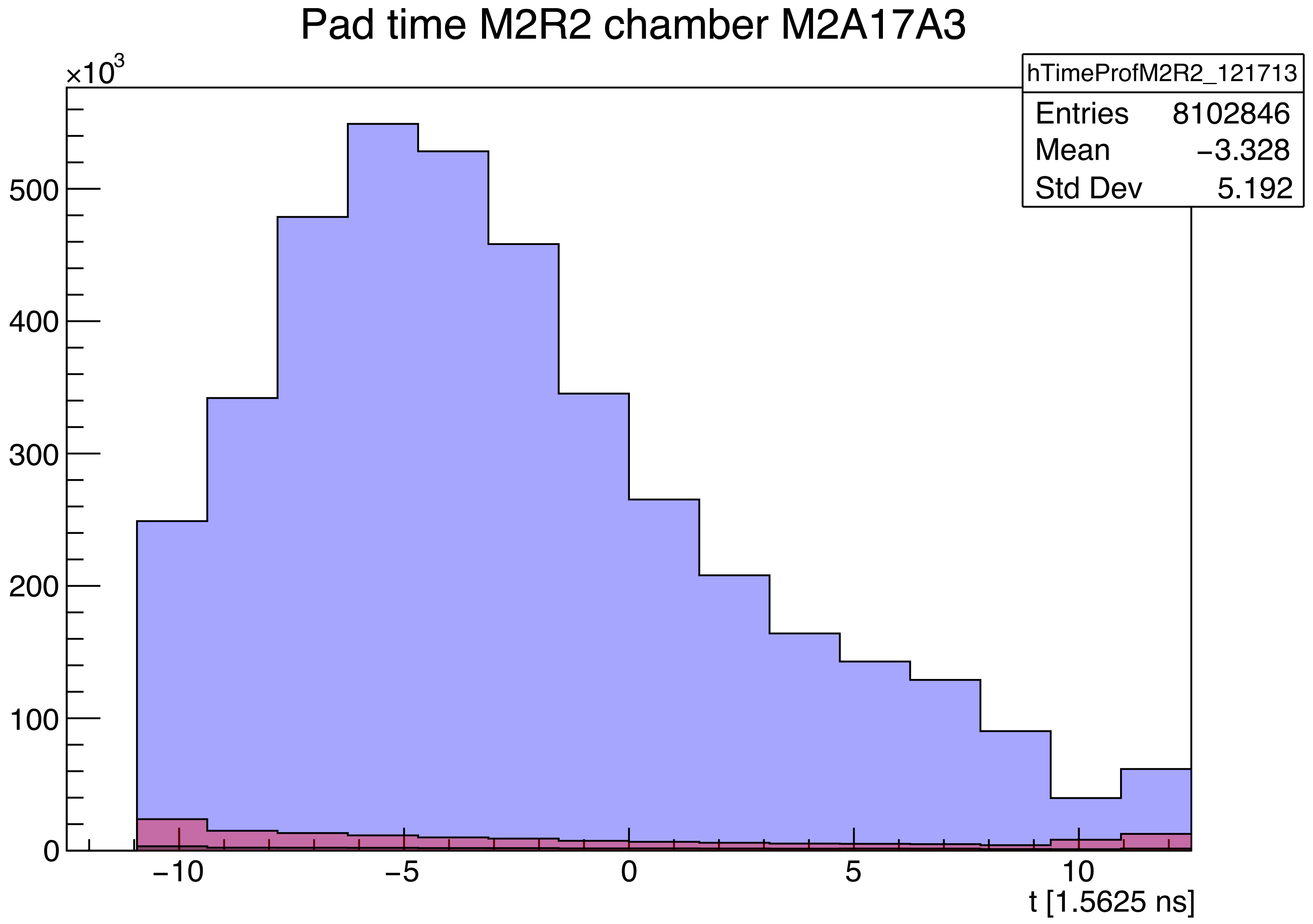
Deadtime inefficiency: a toy MC

- The previous formulas are valid only when the time distribution of the hits is uniform, but at LHC:

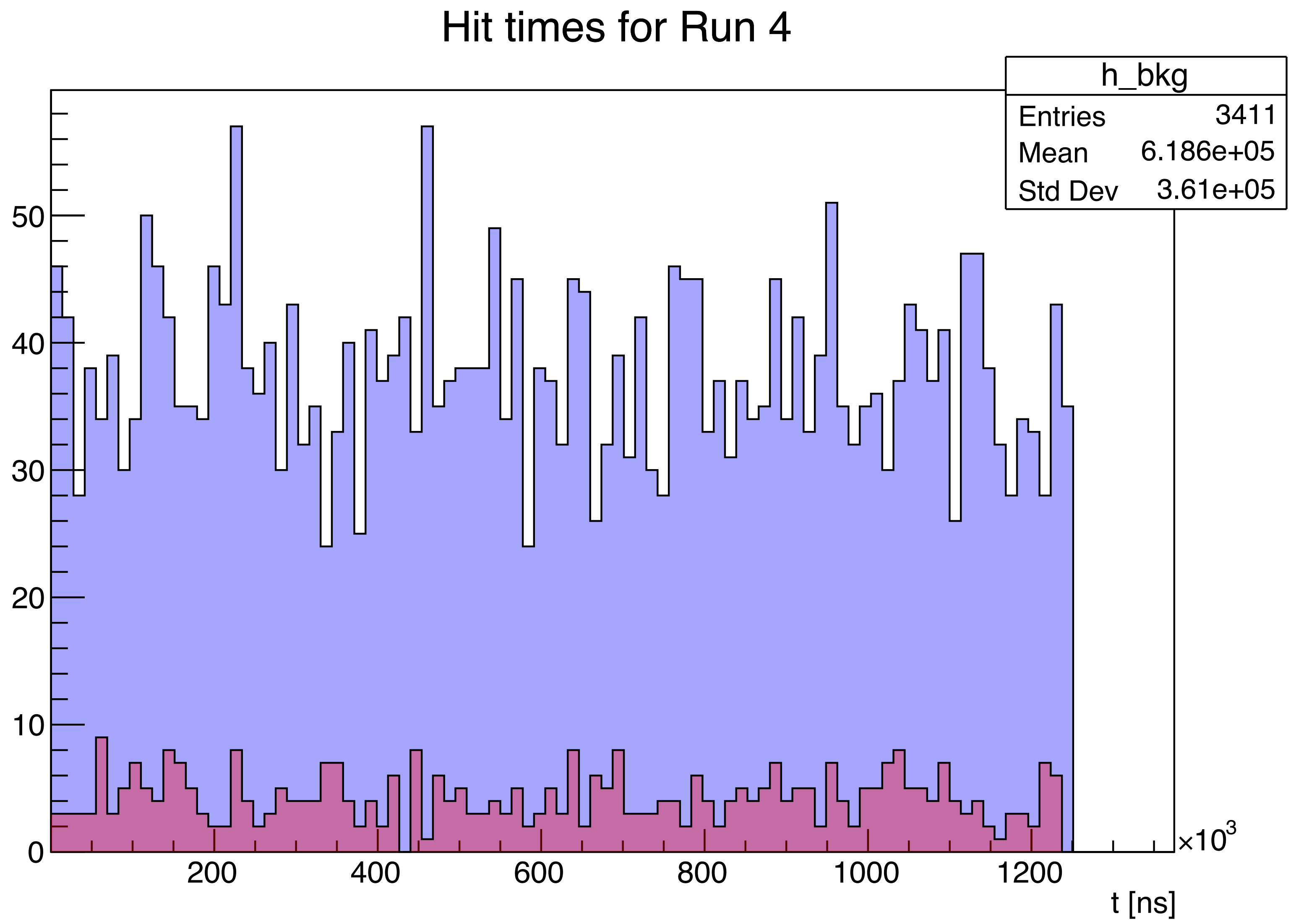
1. the hits are produced in bunches
2. background and muon hits have different time distributions → we are interested in muon inefficiency
3. deadtime fluctuates

→ we developed a Monte Carlo simulation to validate the formulas

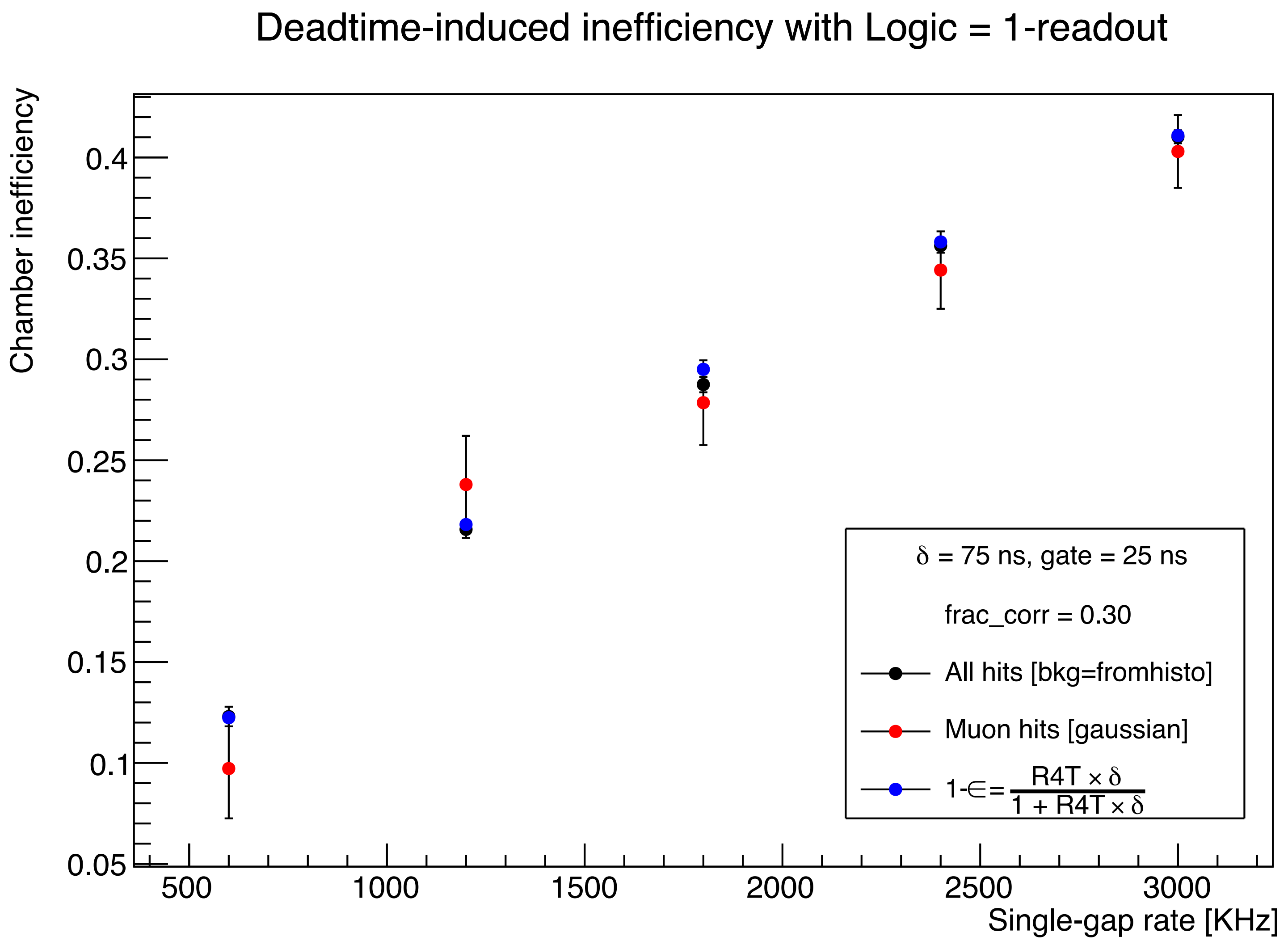
- Background time distributions are generated from measured TDC spectra for each chamber (superposition of 3 consecutive BX)



- Muon hits (pink) are generated with Gaussian times (correlated). However, if the number of hits (per muon channel) is low in each BX, a long train of BX looks ~ uniform in time

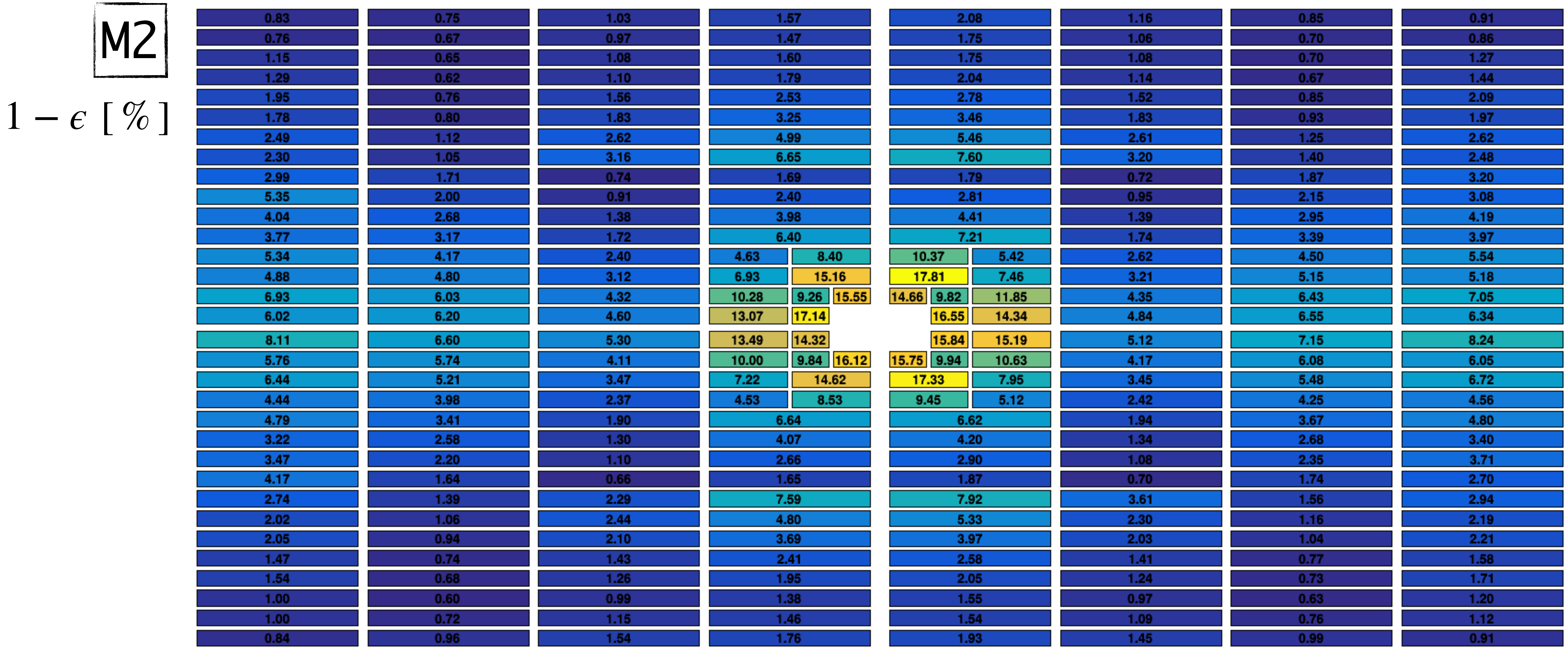


- In fact, the simulated muon inefficiency (red points) matches the formula (blue points), for 1-gap, 2-gap and 4-gap readouts



Deadtime inefficiency maps

- Now that we trust the formulas, we can map the (correlated part of) deadtime-induced inefficiency
- Conservatively assuming $\delta = 100\ \mathrm{ns}$: these values have been measured on data across the whole detector and found to be in the range 75-100 ns with the present FEE [JINST (2016) 11 P04010]
- M2 especially crucial due to high rates, here shown for the worst case i.e. <u>current MWPCs & no shielding</u>:



0.83	0.75	1.03	1.57	2.08	1.16	0.85	0.91
0.76	0.67	0.97	1.47	1.75	1.06	0.70	0.86
1.15	0.65	1.08	1.60	1.75	1.08	0.70	1.27
1.29	0.62	1.10	1.79	2.04	1.14	0.67	1.44
1.95	0.76	1.56	2.53	2.78	1.52	0.85	2.09
1.78	0.80	1.83	3.25	3.46	1.83	0.93	1.97
2.49	1.12	2.62	4.99	5.46	2.61	1.25	2.62
2.30	1.05	3.16	6.65	7.60	3.20	1.40	2.48
2.99	1.71	0.74	1.69	1.79	0.72	1.87	3.20
5.35	2.00	0.91	2.40	2.81	0.95	2.15	3.08
4.04	2.68	1.38	3.98	4.41	1.39	2.95	4.19
3.77	3.17	1.72	6.40	7.21	1.74	3.39	3.97
5.34	4.17	2.40	4.63 8.40	10.37 5.42	2.62	4.50	5.54
4.88	4.80	3.12	6.93 15.16	17.81 7.46	3.21	5.15	5.18
6.93	6.03	4.32	10.28 9.26 15.55	14.66 9.82 11.85	4.35	6.43	7.05
6.02	6.20	4.60	13.07 17.14	16.55 14.34	4.84	6.55	6.34
8.11	6.60	5.30	13.49 14.32	15.84 15.19	5.12	7.15	8.24
5.76	5.74	4.11	10.00 9.84 16.12	15.75 9.94 10.63	4.17	6.08	6.05
6.44	5.21	3.47	7.22 14.62	17.33 7.95	3.45	5.48	6.72
4.44	3.98	2.37	4.53 8.53	9.45 5.12	2.42	4.25	4.56
4.79	3.41	1.90	6.64	6.62	1.94	3.67	4.80
3.22	2.58	1.30	4.07	4.20	1.34	2.68	3.40
3.47	2.20	1.10	2.66	2.90	1.08	2.35	3.71
4.17	1.64	0.66	1.65	1.87	0.70	1.74	2.70
2.74	1.39	2.29	7.59	7.92	3.61	1.56	2.94
2.02	1.06	2.44	4.80	5.33	2.30	1.16	2.19
2.05	0.94	2.10	3.69	3.97	2.03	1.04	2.21
1.47	0.74	1.43	2.41	2.58	1.41	0.77	1.58
1.54	0.68	1.26	1.95	2.05	1.24	0.73	1.71
1.00	0.60	0.99	1.38	1.55	0.97	0.63	1.20
1.00	0.72	1.15	1.46	1.54	1.09	0.76	1.12
0.84	0.96	1.54	1.76	1.93	1.45	0.99	0.91

Deadtime inefficiencies & µRWell

[JINST (2016) 11 P04010]

- As $1 - \epsilon \propto R$, the effect of the shielding is the same shown for the rates in → slide#6
- Instead, here the current MWPCs are compared to µRwell chambers, which have smaller readout pads:

Current pads (black) -> muRwell pads (red) in mm²

Reg / Sta	M2	M3	M4	M5
R1	38x31 -> 9x9	41x34 -> 10x10	29x36 -> 11x10	31x39 -> 12x11
R2	76x31 -> 9x18	82x34 -> 10x19	58x73 -> 11x21	62x77 -> 12x22
R3	25x125	27x135	58x145	62x155
R4	50x250	54x270	58x290	62x309

Maximum deadtime inefficiency % HCAL - MWPC

	M2	M3	M4	M5
R1	17.14	6.65	7.50	8.66
R2	17.81	4.62	5.69	7.34
R3	7.21	1.72	3.49	5.68
R4	8.24	3.37	2.30	8.55

Maximum deadtime inefficiency % HCAL - µRWELL

	M2	M3	M4	M5
R1	1.18	0.48	0.79	0.95
R2	1.22	0.32	0.31	0.41
R3	7.21	1.72	3.49	5.68
R4	8.24	3.37	2.30	8.55

Moving to high-granularity µRWell chambers

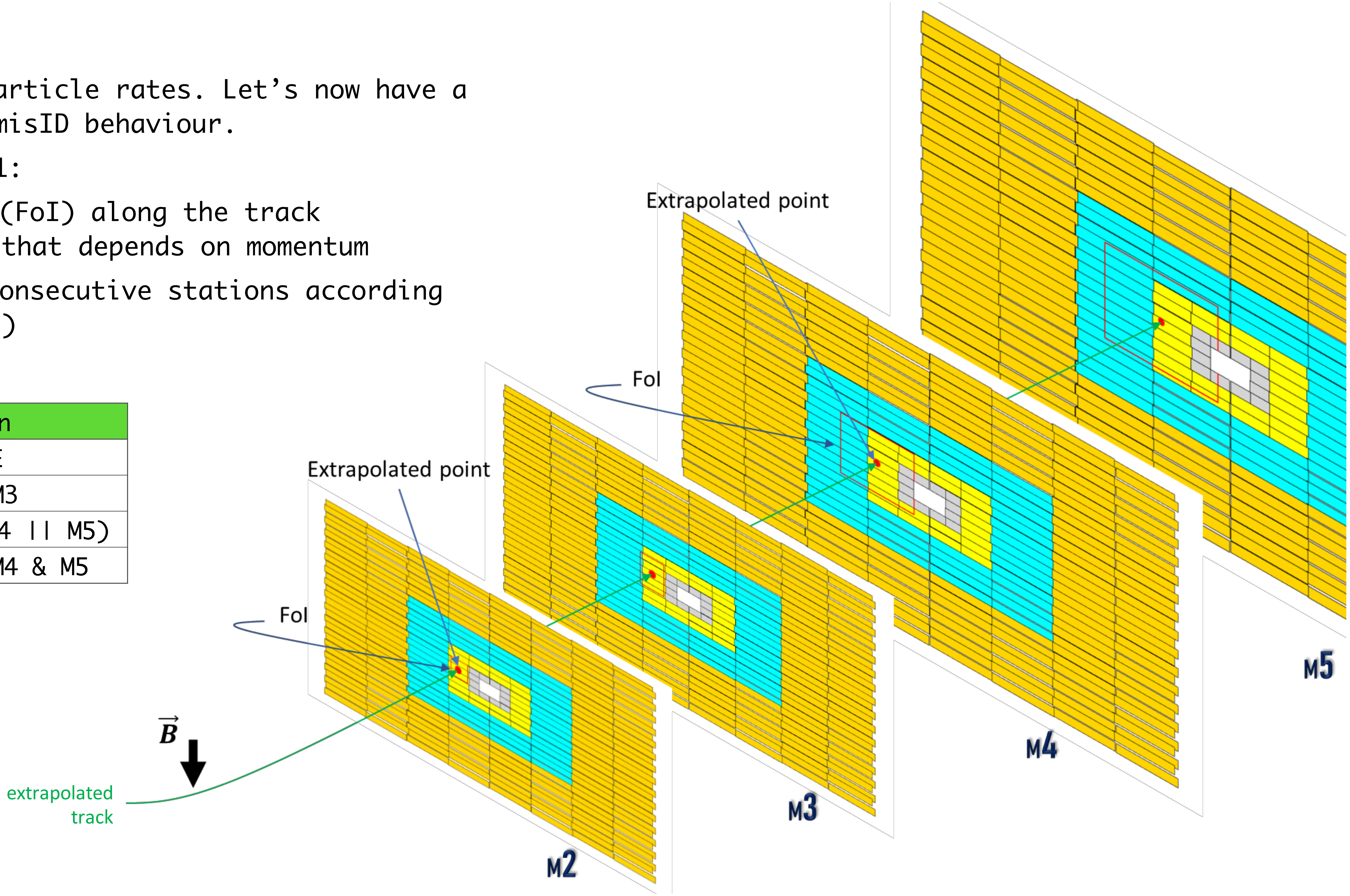
- High inefficiencies are strongly mitigated in R1-R2 with µRwell chambers
- Some high values remain in R3-R4, where MWPCs have large pads

Muon identification: principles

- Previous slides focus on particle rates. Let’s now have a look at muonID and hadron misID behaviour.
- Our basic algorithm at HLT1:

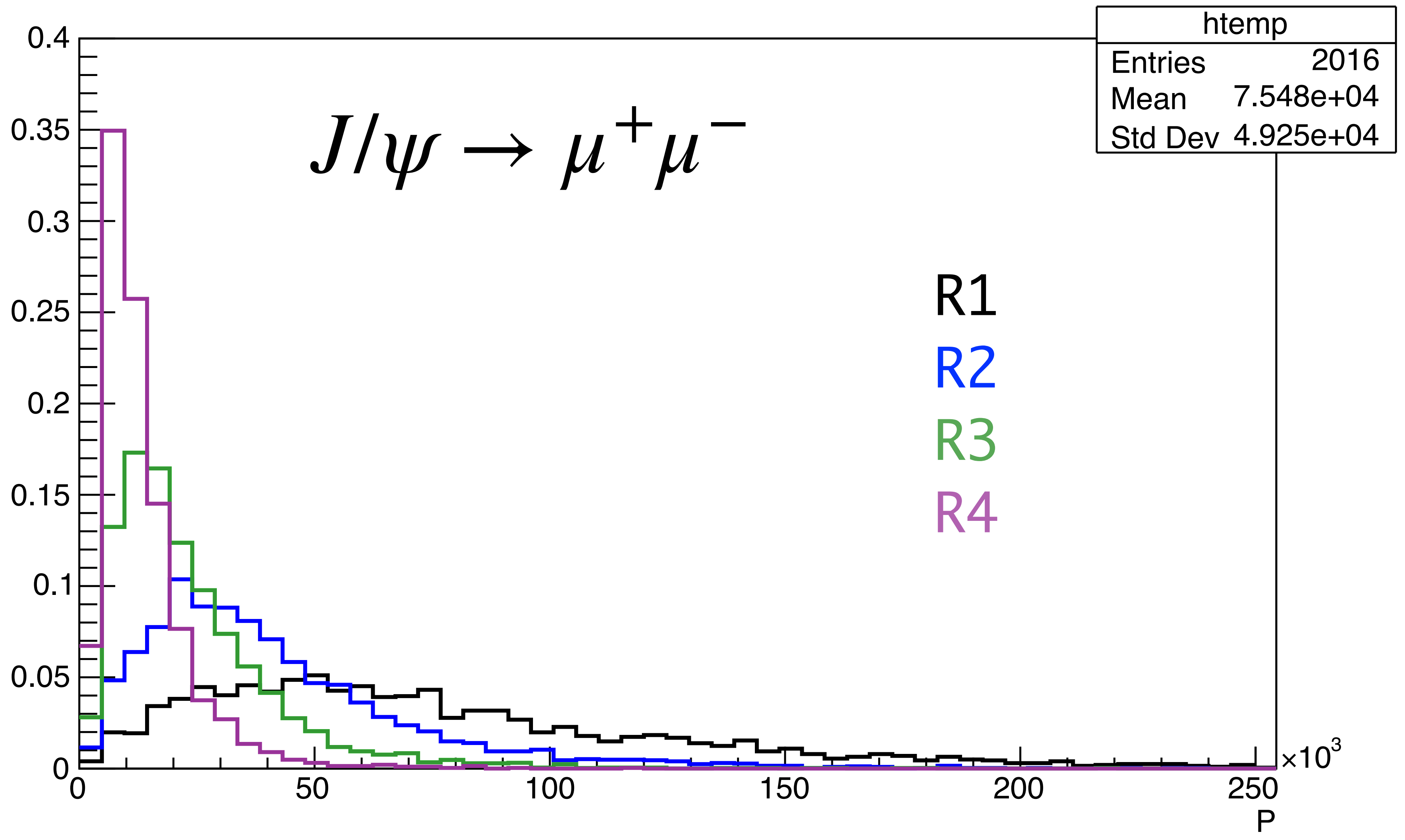
1. Open a Field of Interest (FoI) along the track extrapolation, with a size that depends on momentum
2. Ask for hit presence in consecutive stations according to track momentum (“isMuon”)

Momentum (GeV)	isMuon
p < 3	FALSE
3 < p < 6	M2 & M3
6 < p < 10	M2 & M3 & (M4 || M5)
p > 10	M2 & M3 & M4 & M5



MuonID: testing performance

- Different regions of the MUON detector are impacted differently by new detectors and shielding
  → high momentum tracks more likely fall into inner regions
- The impact of all the quoted effects is therefore evaluated on the muonID efficiency for benchmark channels



1. Deadtime-induced inefficiency → per-chamber maps from previous slides are applied to channel kinematics
2. Shielding in place of HCAL → rate reduction M2R1:-42% M2R2:-69% M2R3:-64%
3. Improved granularity on R1-R2. As per Table in → slide#10
4. Removal of the M2 station, a possibility if highly inefficient

Momentum (GeV)	isMuon w/o M2
p < 3	FALSE
3 < p < 6	M3
6 < p < 10	M3 & (M4 || M5)
p > 10	M3 & M4 & M5

→ the aim is to check the impact of dropping M2 from the present algorithm, not a proposed algorithm for U2!

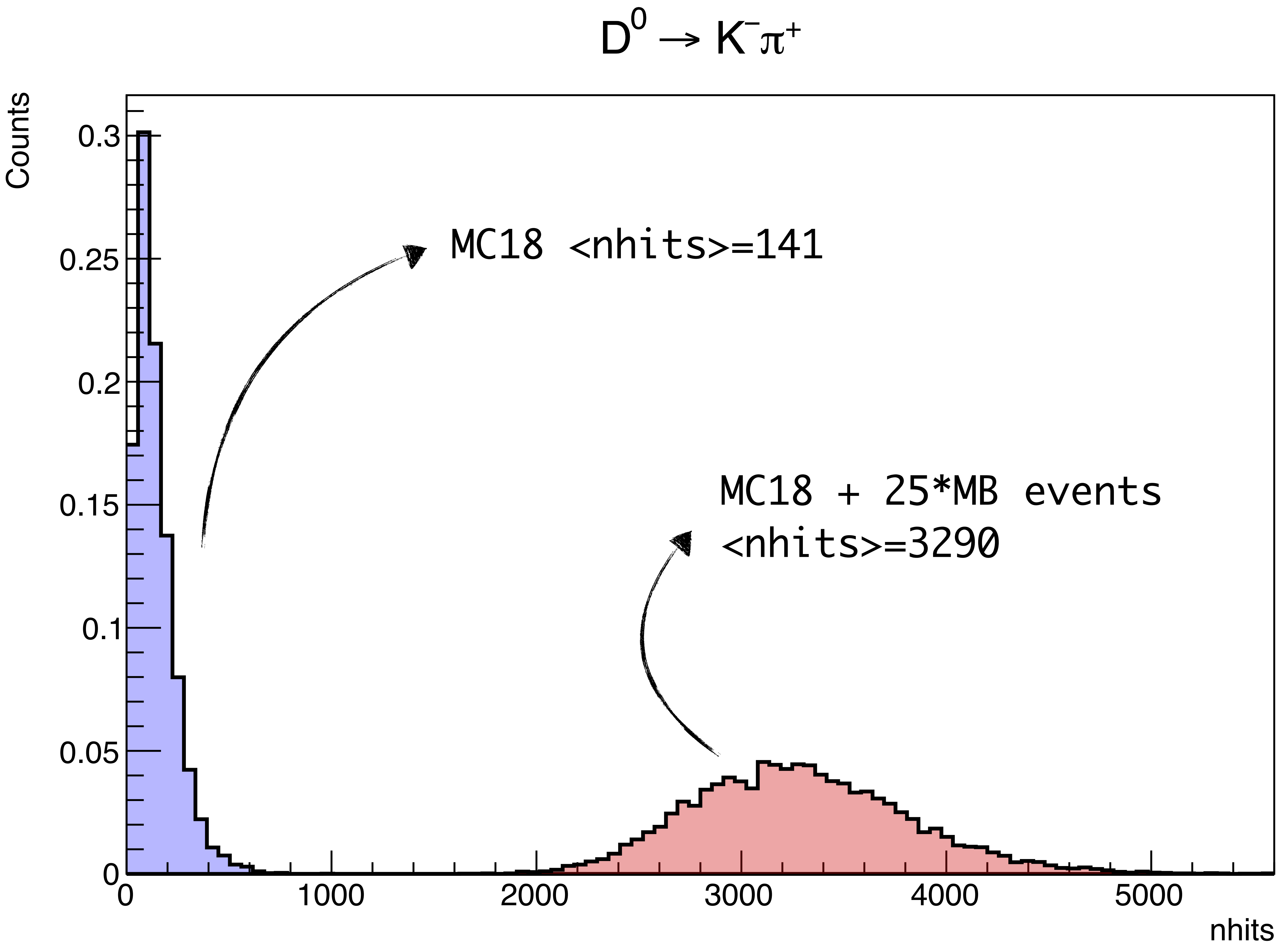
MuonID: results on physics channels

	$B_s^0 \to \mu^+\mu^-$		$D^0 \to \mu^+\mu^-$		$K_s^0 \to \mu^+\mu^-$		$B_s^0 \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$	
Scenario	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)
HCAL	24.7 %	10.3 %	25.9 %	9.4 %	20.0 %	8.4 %	24.9 %	9.5 %
SHIELD	19.0 %	8.6 %	19.4 %	7.6 %	13.9 %	6.3 %	18.7 %	7.8 %
w/o M2	13.4 %	6.0 %	13.7 %	5.3 %	8.3 %	3.2 %	13.1 %	5.3 %

- The simulated event is considered lost if one+ muon does not pass the isMuon selection
- M2 removal seems more effective than the shielding in mitigating the deadtime inefficiency, but the misID must be kept under control

MisID: dealing with lots of hits

- No U2 simulation available → emulate the increased occupancy by superimposing minbias data to $J/\psi \to \mu^+\mu^-$ (muonID) or $D^0 \to K^-\pi^+$ (misID) simulated events
- Superimpose 25 minbias events from data (PU=1.5) to each simulated event (PU=2) to emulate PU=40



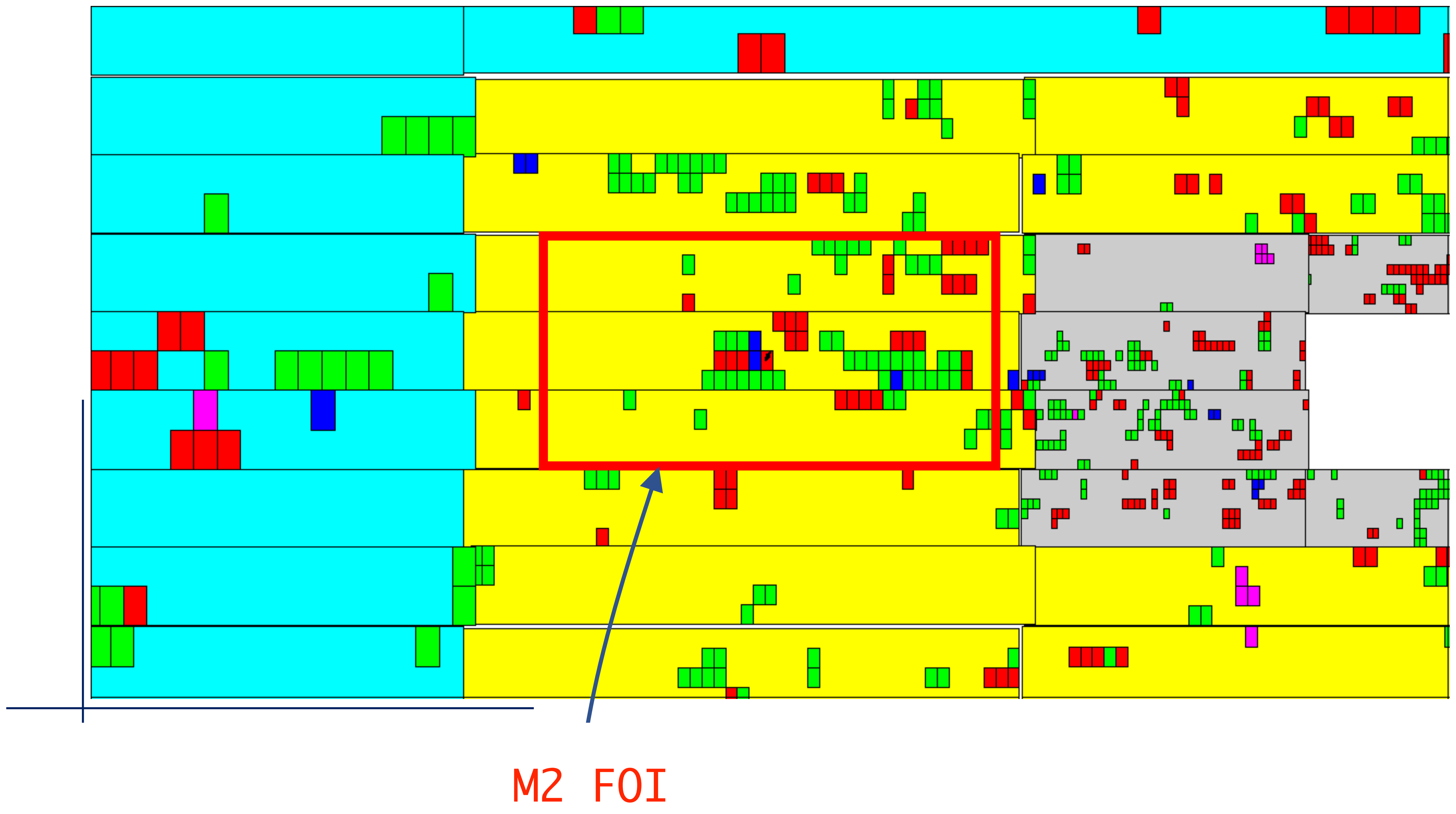
- Background hit composition is inspected via low-energy simulation

🟦 Logical pads fired by muons with E > 3GeV

🟪 Logical pads fired by muons with E < 3GeV

🟩 Logical pads fired by electrons

🟥 Logical pads fired by other particle

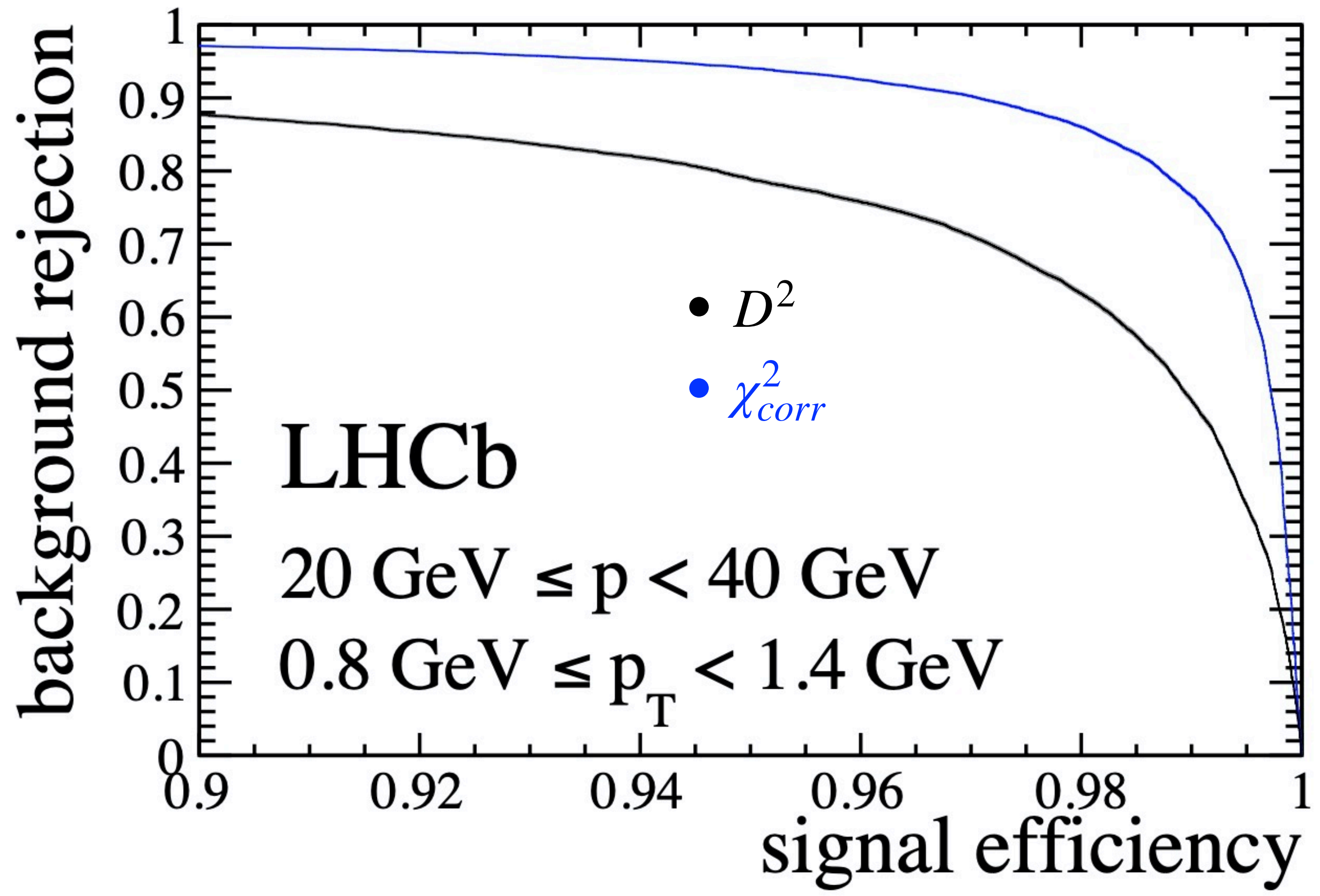


Pushing current algorithms

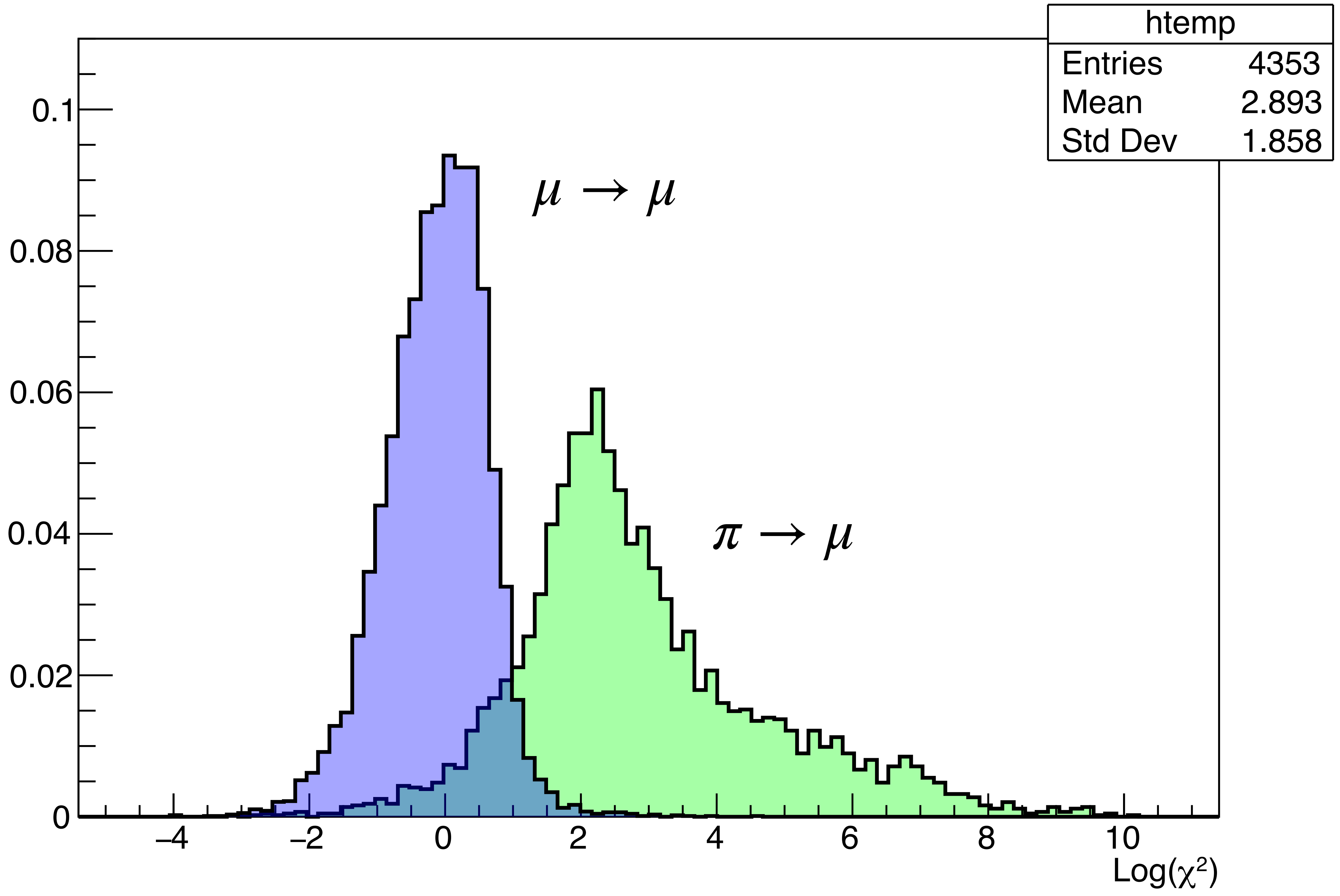
- To cope with the higher misID in Run 3 wrt Run 2, we developed the $\chi^2_{\rm corr}$ algorithm: how does it perform on U2 data?
- Muon track from $J/\psi \to \mu^+\mu^-$, pion track from $D^0 \to K^-\pi^+$ MC after isMuon
  → $\chi^2_{\rm corr}$ still doing its job with U2 occupancy!

D^2 : spatial residuals
$\chi^2_{\rm corr}$: including hit correlations & multiple scattering
→ more details in the backup

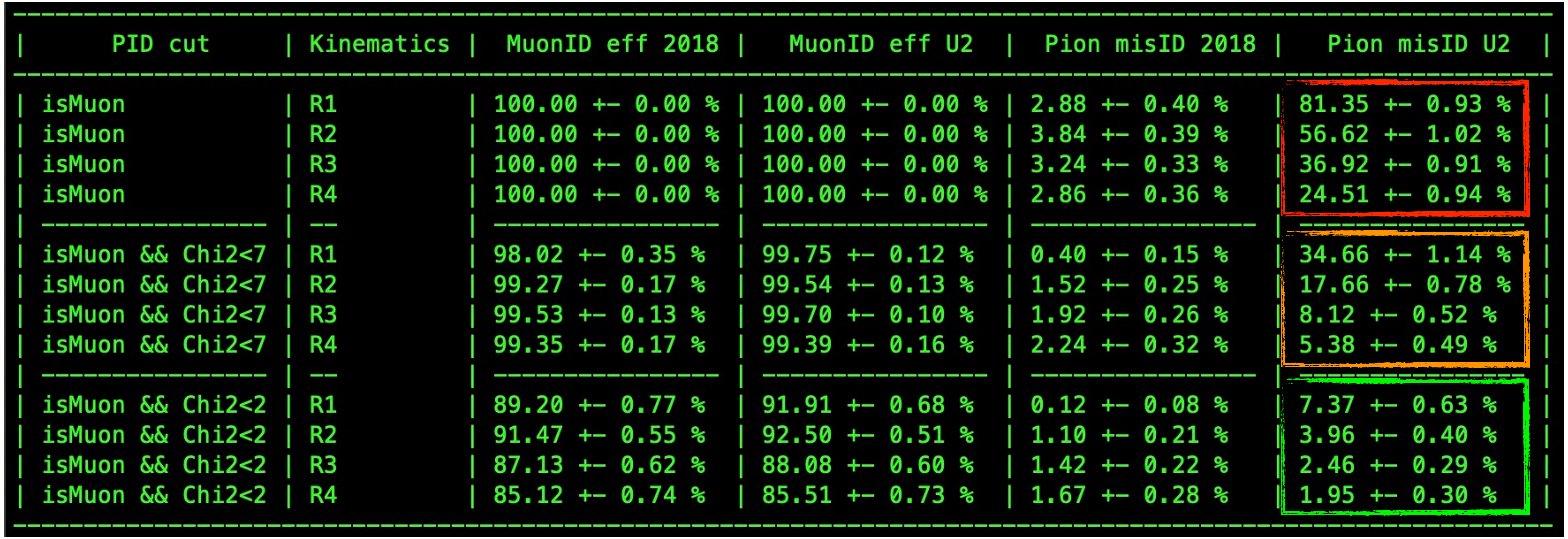
[JINST 15 (2020) T12005]



muon vs protons after isMuon
2016 data with <nPV>=3



MisID vs region: three working points



```
--------------------------------------------------------------------------------------------------------------------
|      PID cut       | Kinematics |  MuonID eff 2018 |   MuonID eff U2   |  Pion misID 2018 |   Pion misID U2   |
--------------------------------------------------------------------------------------------------------------------
| isMuon             | R1         | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 2.88 +- 0.40 %   | 81.35 +- 0.93 %  |
| isMuon             | R2         | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 3.84 +- 0.39 %   | 56.62 +- 1.02 %  |
| isMuon             | R3         | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 3.24 +- 0.33 %   | 36.92 +- 0.91 %  |
| isMuon             | R4         | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 2.86 +- 0.36 %   | 24.51 +- 0.94 %  |
| ----------------   | --         | ---------------- | ---------------- | ---------------- | ---------------- |
| isMuon && Chi2<7   | R1         | 98.02 +- 0.35 %  | 99.75 +- 0.12 %  | 0.40 +- 0.15 %   | 34.66 +- 1.14 %  |
| isMuon && Chi2<7   | R2         | 99.27 +- 0.17 %  | 99.54 +- 0.13 %  | 1.52 +- 0.25 %   | 17.66 +- 0.78 %  |
| isMuon && Chi2<7   | R3         | 99.53 +- 0.13 %  | 99.70 +- 0.10 %  | 1.92 +- 0.26 %   | 8.12 +- 0.52 %   |
| isMuon && Chi2<7   | R4         | 99.35 +- 0.17 %  | 99.39 +- 0.16 %  | 2.24 +- 0.32 %   | 5.38 +- 0.49 %   |
| ----------------   | --         | ---------------- | ---------------- | ---------------- | ---------------- |
| isMuon && Chi2<2   | R1         | 89.20 +- 0.77 %  | 91.91 +- 0.68 %  | 0.12 +- 0.08 %   | 7.37 +- 0.63 %   |
| isMuon && Chi2<2   | R2         | 91.47 +- 0.55 %  | 92.50 +- 0.51 %  | 1.10 +- 0.21 %   | 3.96 +- 0.40 %   |
| isMuon && Chi2<2   | R3         | 87.13 +- 0.62 %  | 88.08 +- 0.60 %  | 1.42 +- 0.22 %   | 2.46 +- 0.29 %   |
| isMuon && Chi2<2   | R4         | 85.12 +- 0.74 %  | 85.51 +- 0.73 %  | 1.67 +- 0.28 %   | 1.95 +- 0.30 %   |
--------------------------------------------------------------------------------------------------------------------
```

isMuon:
unfeasible

loose χ^2 cut:
not bad

hard χ^2 cut:
close to Run 2 misID
but loose some muons

- Can reduce the background by a factor 3-5 with negligible efficiency loss (orange), or achieve ~15x reduction with order 10% muon loss (green). Encouraging results for future algorithms!
- We're considering muon-only information: global PID will perform better
- No shielding is being considered: will ~halve the R1-R2 rate → this roughly means halving the misID but the physics needs to be fully simulated

MisID: fully data-driven

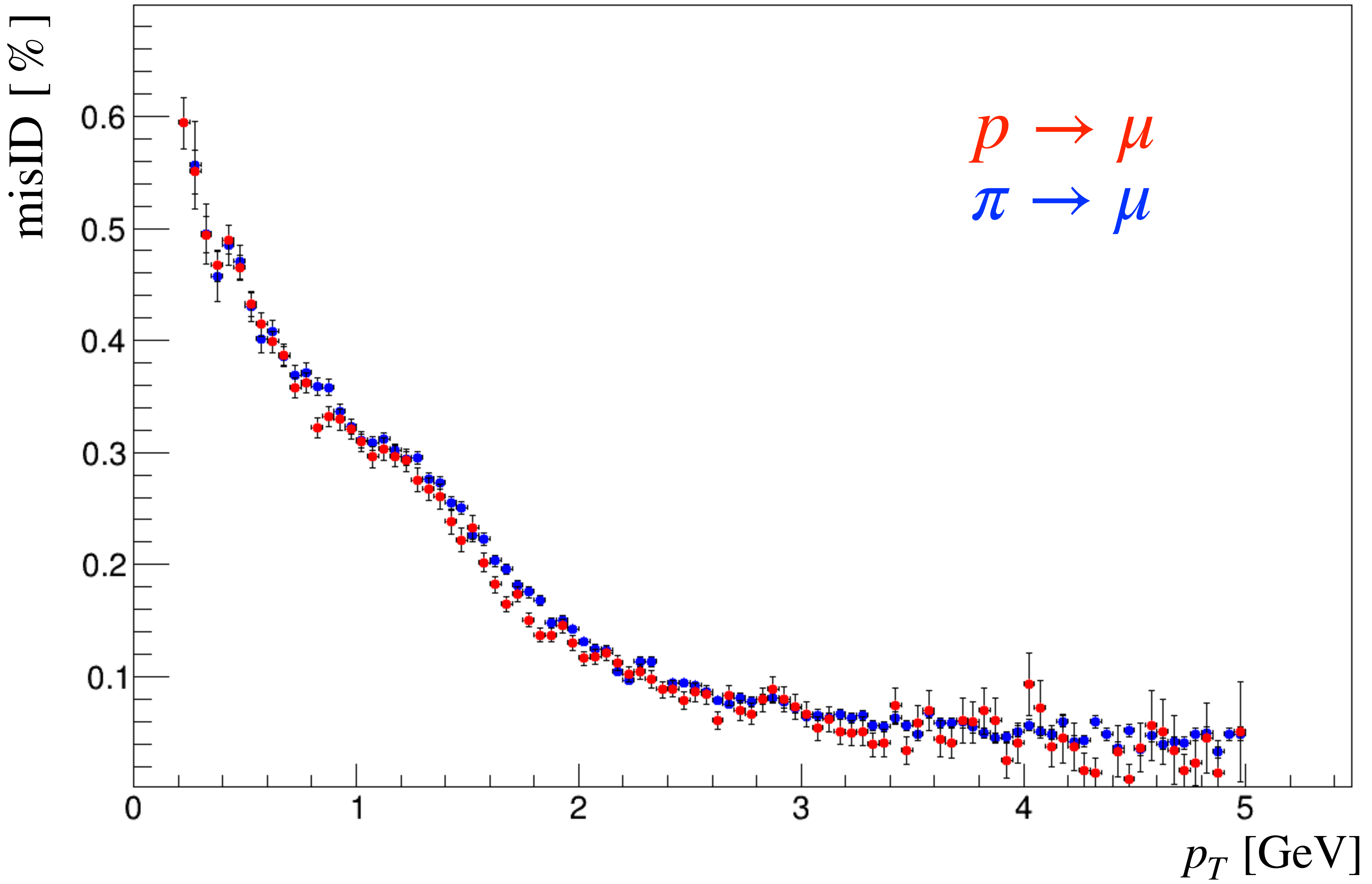
- MisID is also tested on U2 environment from the superposition of 2016 TurCal events
- $J/\psi \to \mu^+\mu^-$, $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda \to p\pi^-$ data, background subtraction via sPlot
- Working point for this study:
  - $p > 10$ GeV (always 4 station coincidence & few decays in flight)
  - requiring crossed hits only (no more x,y strip readout at U2)
  - isMuon w 20% smaller FOI
- Result: <muon efficiency> = 93.1%, <pion misID> = 14.3 %, <proton misID> = 23.6%
- χ^2 improves the muonID similarly to what seen on MC+MinBias data, but mind the occupancy:

- Superimposing 15 events: <N>= 2800

χ2<	1	2	3	4	5	6	7	8	9	nocut
Muon efficiency	36.0	64.5	78.0	83.6	86.4	88.2	89.2	89.9	90.2	91.3
Pion misID	0.29	0.84	1.4	2.1	2.8	3.4	4.1	4.7	5.3	11.0

- Superimposing 20 events: <N>= 3700

χ2<	1	2	3	4	5	6	7	8	9	nocut
Muon efficiency	37.0	67.8	79.7	85.4	88.3	89.5	90.5	91.1	91.5	93.1
Pion misID	0.36	1.2	2.2	3.3	4.3	5.4	6.4	7.3	8.1	14.3



Conclusions & prospects

- Muon detector operated with excellent performance for 10+ years, some chambers still suitable for U2!
- In the FTDR we concentrated on U2 rate studies, now we are converging towards muonID performance determination with a µRwell+ MWPC detector
- This aims at finalising the detector layout, namely:
    - replace HCAL with a passive shielding
    - design additional shielding against low energy background
    - M2 removal?
- Promising results are emerging, but full simulation is required to optimise the shielding & maximise muonID performance
- Good results from existing algorithms encourage future developments

backup

MuonID operators in Run 3

[JINST 15 (2020) T12005]

- In Run 3, x2 increased rate of misID background is expected wrt Run 2, so we developed two new operators:
- The sum of squares of the spatial residuals (D^2) neglects hit correlations between muon stations:

$$D^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\frac{x^i_{\text{closest}} - x^i_{\text{track}}}{\text{pad}^i_x}\right)^2 + \left(\frac{y^i_{\text{closest}} - y^i_{\text{track}}}{\text{pad}^i_y}\right)^2\right]$$

- The χ^2_{corr} accounts for correlations via a covariance matrix V

$$\chi^2_{\text{CORR}} = \delta\overrightarrow{x}^T \mathrm{V}_x^{-1}\delta\overrightarrow{x} + \delta\overrightarrow{y}^T \mathrm{V}_y^{-1}\delta\overrightarrow{y}$$

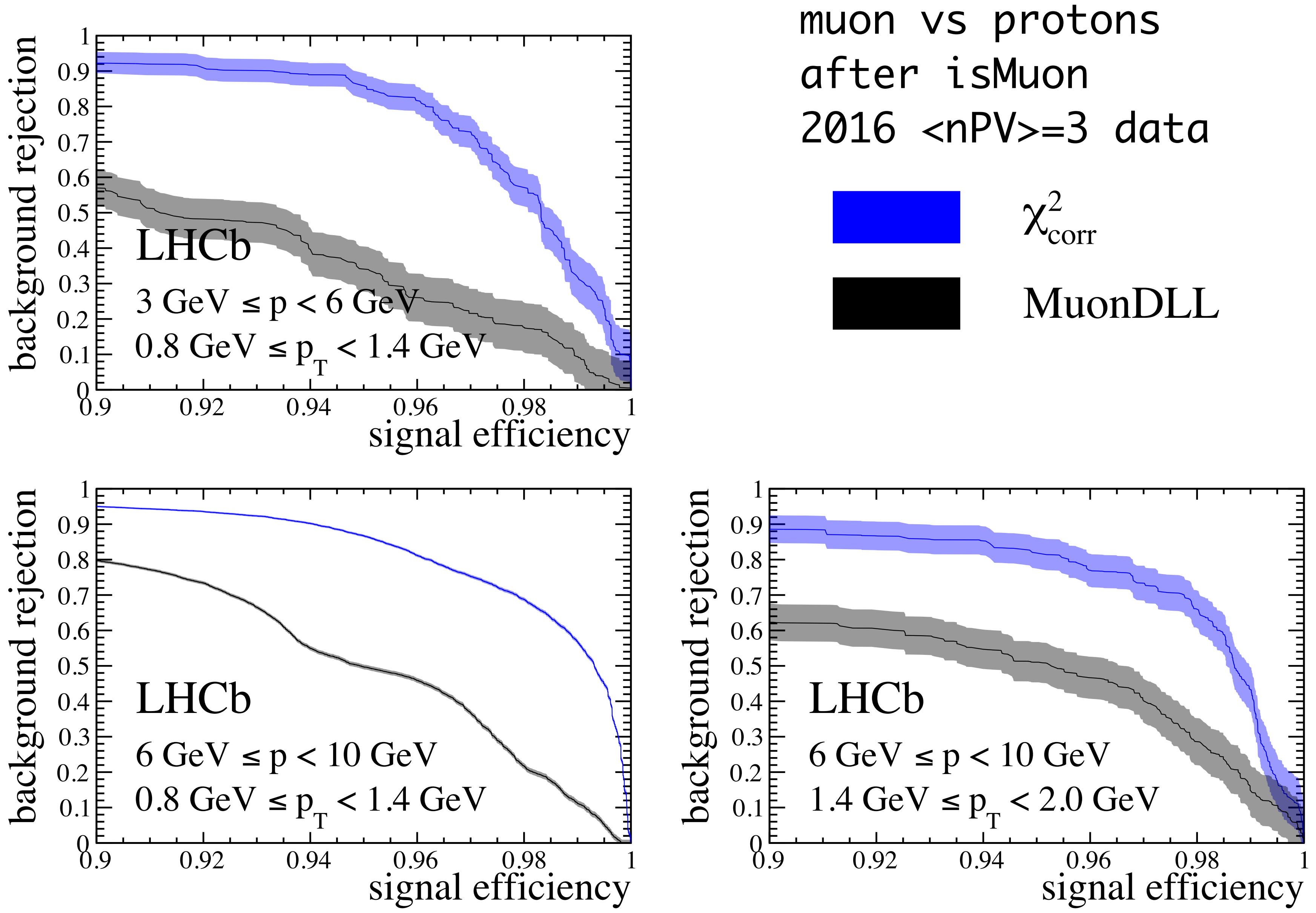
which is made by the sum of the spatial residuals (on the diagonal)

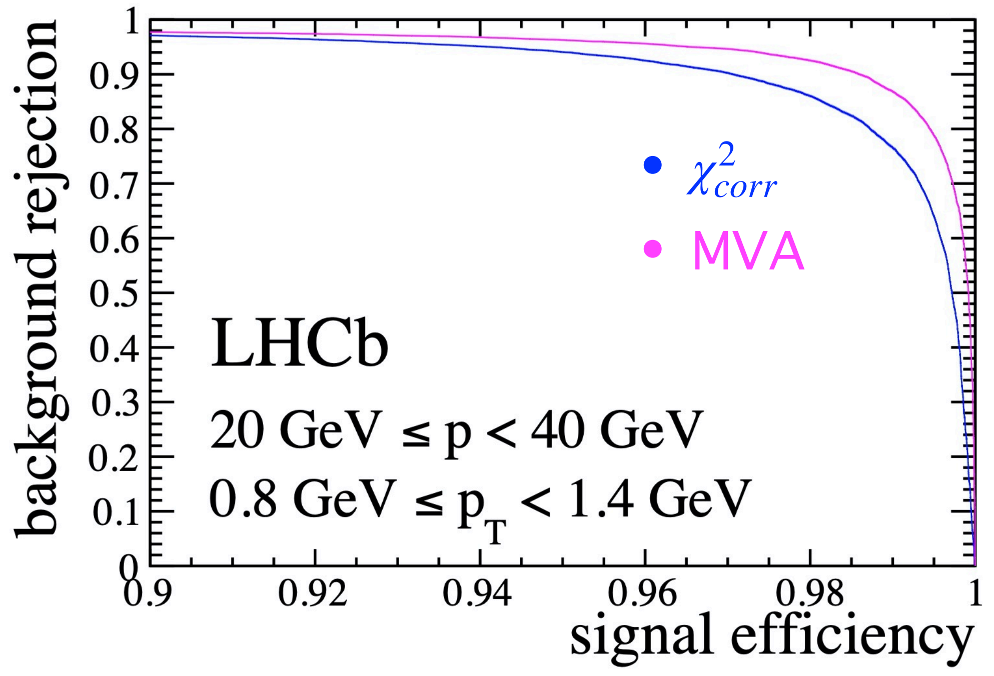
$$\mathrm{V}^{\text{RES}}_{jj} = \sigma^2_{\text{RES},j} \qquad \sigma_{\text{RES},j} = \text{pad}^j_{x,y}/\sqrt{12}$$

and the matrix of MS deviations experienced in the absorbers:

$$\mathrm{V}^{\text{MS}}_{jk} = \sum_{z_i<z_j,z_k}(z_j-z_i)(z_k-z_i)\sigma^2_{\text{MS},i} \qquad \sigma_{\text{MS},i} = \frac{13.6\text{MeV}}{\beta cp}q\sqrt{\Delta z_i/X_0}$$

- χ^2_{corr} gives much better performance on high-multiplicity data on top of the isMuon selection across the whole momentum spectrum
- Even better performance is achieved with Catboost MVA using MUON features

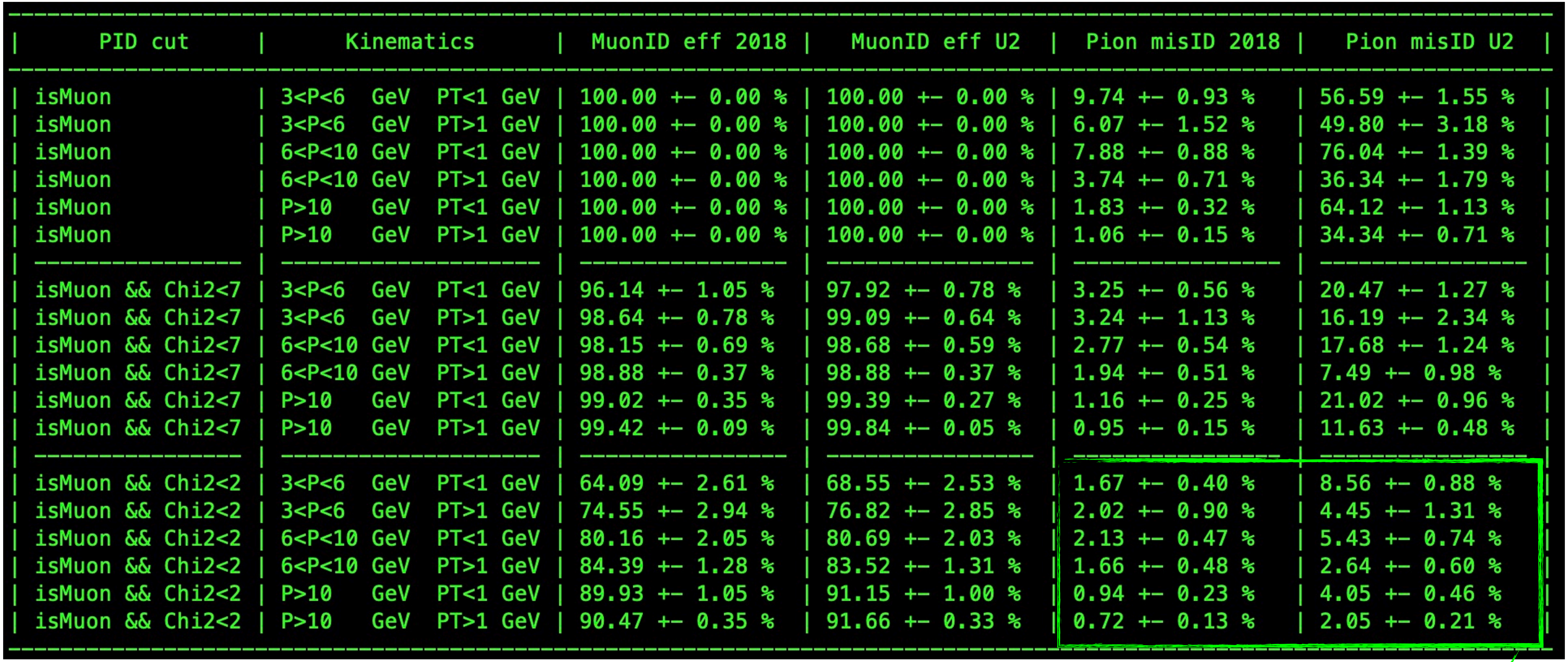




MuonID: physics channels

		$B_s^0 \to \mu^+\mu^-$		$D^0 \to \mu^+\mu^-$		$K_s^0 \to \mu^+\mu^-$		$B_s^0 \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$	
Scenario	Momentum (GeV)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)
HCAL	3<p<6	0.1 %	0.07 %	0.2 %	0.1 %	3.1 %	2.9 %	0.4 %	0.3 %
	6<p<10	0.4 %	0.3 %	0.9 %	0.7 %	4.3 %	2.4 %	1.1 %	0.8 %
	p>10	24.3 %	9.9 %	24.9 %	8.7 %	12.9 %	3.1 %	23.6 %	8.5 %
	TOTAL	24.7 %	10.3 %	25.9 %	9.4 %	20.0 %	8.4 %	24.9 %	9.5 %
SHIELD	3<p<6	0.1 %	0.06 %	0.1 %	0.1 %	2.6 %	2.5 %	0.3 %	0.2 %
	6<p<10	0.3 %	0.3 %	0.7 %	0.5 %	2.4 %	1.5 %	0.8 %	0.7 %
	p>10	18.6 %	8.2 %	18.6 %	7.0 %	9.1 %	2.4 %	17.7 %	6.9 %
	TOTAL	19.0 %	8.6 %	19.4 %	7.6 %	13.9 %	6.3 %	18.7 %	7.8 %
no M2	3<p<6	0.02 %	0.01 %	0.03 %	0.02 %	0.8 %	0.8 %	0.1 %	0.1 %
	6<p<10	0.1 %	0.1 %	0.2 %	0.1 %	0.9 %	0.5 %	0.2 %	0.1 %
	p>10	13.3 %	5.9 %	13.5 %	5.1 %	6.7 %	1.8 %	12.8 %	5.1 %
	TOTAL	13.4 %	6.0 %	13.7 %	5.3 %	8.3 %	3.2 %	13.1 %	5.3 %

MisID vs momentum: three working points



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------------------------------------------------------------------------------------------------------------------------
|     PID cut        |       Kinematics       | MuonID eff 2018 |  MuonID eff U2  | Pion misID 2018 |  Pion misID U2  |
------------------------------------------------------------------------------------------------------------------------
| isMuon             | 3<P<6  GeV  PT<1 GeV | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 9.74 +- 0.93 %   | 56.59 +- 1.55 % |
| isMuon             | 3<P<6  GeV  PT>1 GeV | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 6.07 +- 1.52 %   | 49.80 +- 3.18 % |
| isMuon             | 6<P<10 GeV  PT<1 GeV | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 7.88 +- 0.88 %   | 76.04 +- 1.39 % |
| isMuon             | 6<P<10 GeV  PT>1 GeV | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 3.74 +- 0.71 %   | 36.34 +- 1.79 % |
| isMuon             | P>10   GeV  PT<1 GeV | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 1.83 +- 0.32 %   | 64.12 +- 1.13 % |
| isMuon             | P>10   GeV  PT>1 GeV | 100.00 +- 0.00 % | 100.00 +- 0.00 % | 1.06 +- 0.15 %   | 34.34 +- 0.71 % |
| ------------------ | ---------------------- | ---------------- | ---------------- | ---------------- | ---------------- |
| isMuon && Chi2<7 | 3<P<6  GeV  PT<1 GeV | 96.14 +- 1.05 %  | 97.92 +- 0.78 %  | 3.25 +- 0.56 %   | 20.47 +- 1.27 % |
| isMuon && Chi2<7 | 3<P<6  GeV  PT>1 GeV | 98.64 +- 0.78 %  | 99.09 +- 0.64 %  | 3.24 +- 1.13 %   | 16.19 +- 2.34 % |
| isMuon && Chi2<7 | 6<P<10 GeV  PT<1 GeV | 98.15 +- 0.69 %  | 98.68 +- 0.59 %  | 2.77 +- 0.54 %   | 17.68 +- 1.24 % |
| isMuon && Chi2<7 | 6<P<10 GeV  PT>1 GeV | 98.88 +- 0.37 %  | 98.88 +- 0.37 %  | 1.94 +- 0.51 %   | 7.49 +- 0.98 %  |
| isMuon && Chi2<7 | P>10   GeV  PT<1 GeV | 99.02 +- 0.35 %  | 99.39 +- 0.27 %  | 1.16 +- 0.25 %   | 21.02 +- 0.96 % |
| isMuon && Chi2<7 | P>10   GeV  PT>1 GeV | 99.42 +- 0.09 %  | 99.84 +- 0.05 %  | 0.95 +- 0.15 %   | 11.63 +- 0.48 % |
| ------------------ | ---------------------- | ---------------- | ---------------- | ---------------- | ---------------- |
| isMuon && Chi2<2 | 3<P<6  GeV  PT<1 GeV | 64.09 +- 2.61 %  | 68.55 +- 2.53 %  | 1.67 +- 0.40 %   | 8.56 +- 0.88 %  |
| isMuon && Chi2<2 | 3<P<6  GeV  PT>1 GeV | 74.55 +- 2.94 %  | 76.82 +- 2.85 %  | 2.02 +- 0.90 %   | 4.45 +- 1.31 %  |
| isMuon && Chi2<2 | 6<P<10 GeV  PT<1 GeV | 80.16 +- 2.05 %  | 80.69 +- 2.03 %  | 2.13 +- 0.47 %   | 5.43 +- 0.74 %  |
| isMuon && Chi2<2 | 6<P<10 GeV  PT>1 GeV | 84.39 +- 1.28 %  | 83.52 +- 1.31 %  | 1.66 +- 0.48 %   | 2.64 +- 0.60 %  |
| isMuon && Chi2<2 | P>10   GeV  PT<1 GeV | 89.93 +- 1.05 %  | 91.15 +- 1.00 %  | 0.94 +- 0.23 %   | 4.05 +- 0.46 %  |
| isMuon && Chi2<2 | P>10   GeV  PT>1 GeV | 90.47 +- 0.35 %  | 91.66 +- 0.33 %  | 0.72 +- 0.13 %   | 2.05 +- 0.21 %  |
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- Largest misID increase at U2 is concentrated at low momentum → the impact is channel-dependent