LHCb Prospects on FCNC for Run3 and beyond

Particularly relevant detector upgrades for FCNC

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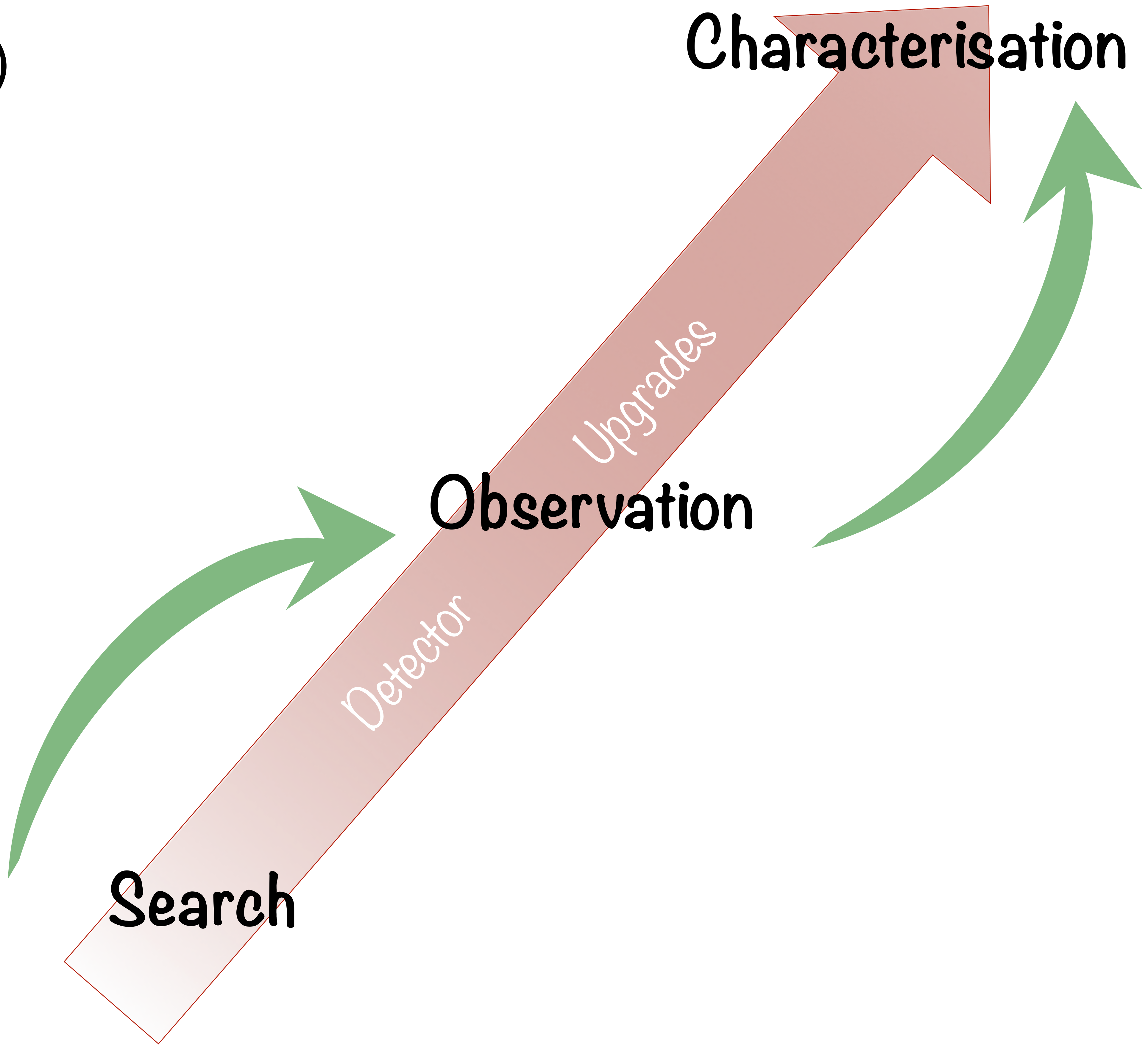
On behalf of the LHCb collaboration

Implications Workshop
27th October 2023

The physics case in a nutshell

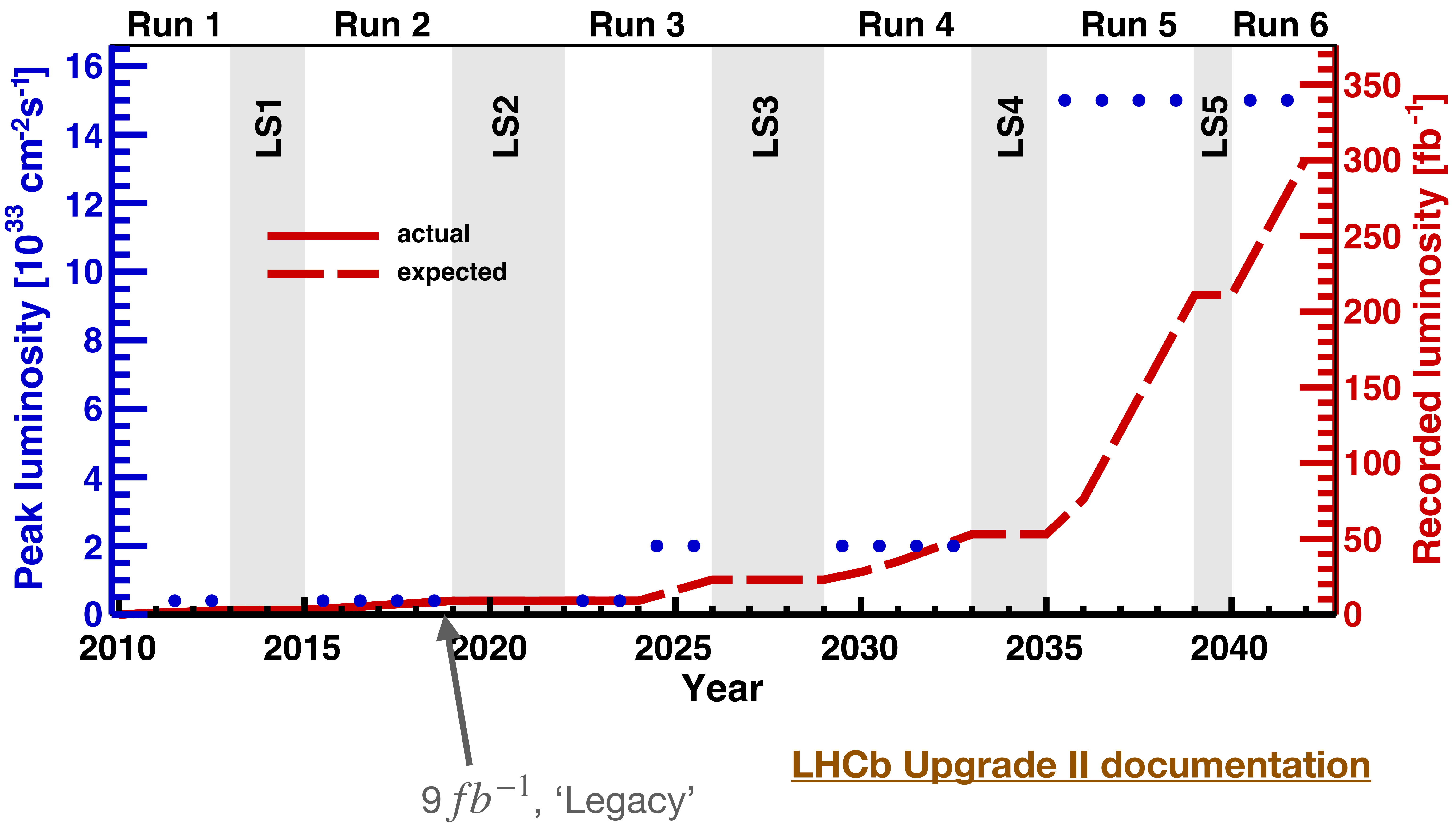
- As we have seen from the previous talks:
  - Final states with hadron + 2 leptons ($B^0 \to K^*\mu\mu$ and friends)
  - Purely leptonic final states ($B_s^0 \to \mu\mu$)
  - Photon polarisation: real photon or very low $q^2(ee)$
  - Rare charm ($D^0 \to \mu\mu$)
- *R* measurements dominated by low yield in the electron mode
- Effort in using data-driven methods and extracting as much information from the data itself.
- Many searches attempted and ongoing for even rarer processes:
  - Only limits available for $K_s^0 \to \mu\mu$, $B_s \to ee$, $K_s/B_s \to \mu\mu\mu\mu$

➡**Consistent statistics limitations.**



Increasing the data sample

- Main factor in Run 2: higher $\sqrt{s} \rightarrow$ higher $\sigma_{bb} \rightarrow$ more data
- After Run 2: increase the instantaneous luminosity → more collisions per bunch crossing
  - While keeping the performance!
- Going beyond that: improve selection efficiencies
  - Improve trigger efficiencies
  - Increase acceptance (instrument new regions of the detector)



LHCb Upgrade II documentation

Increasing the data sample

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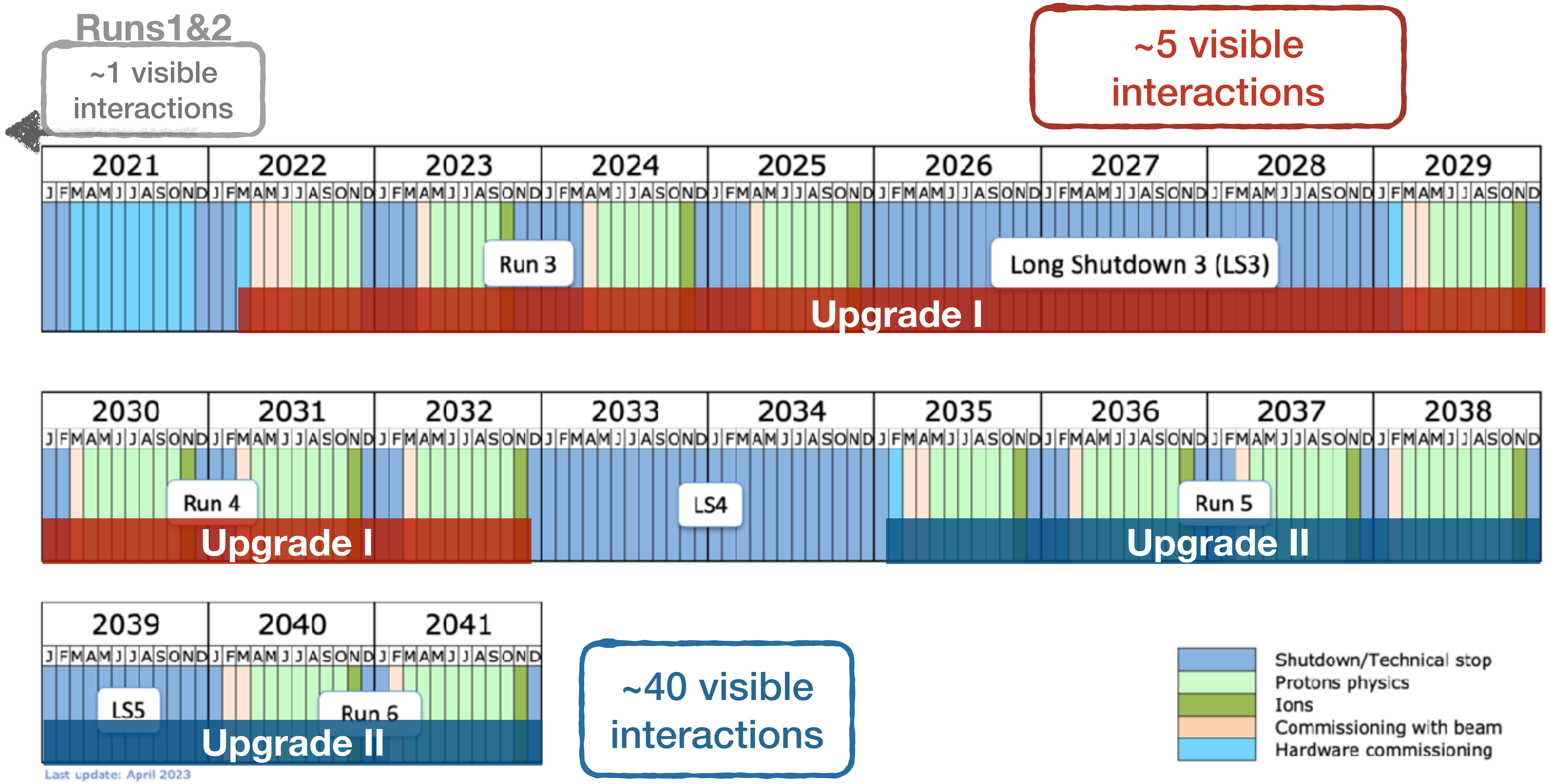


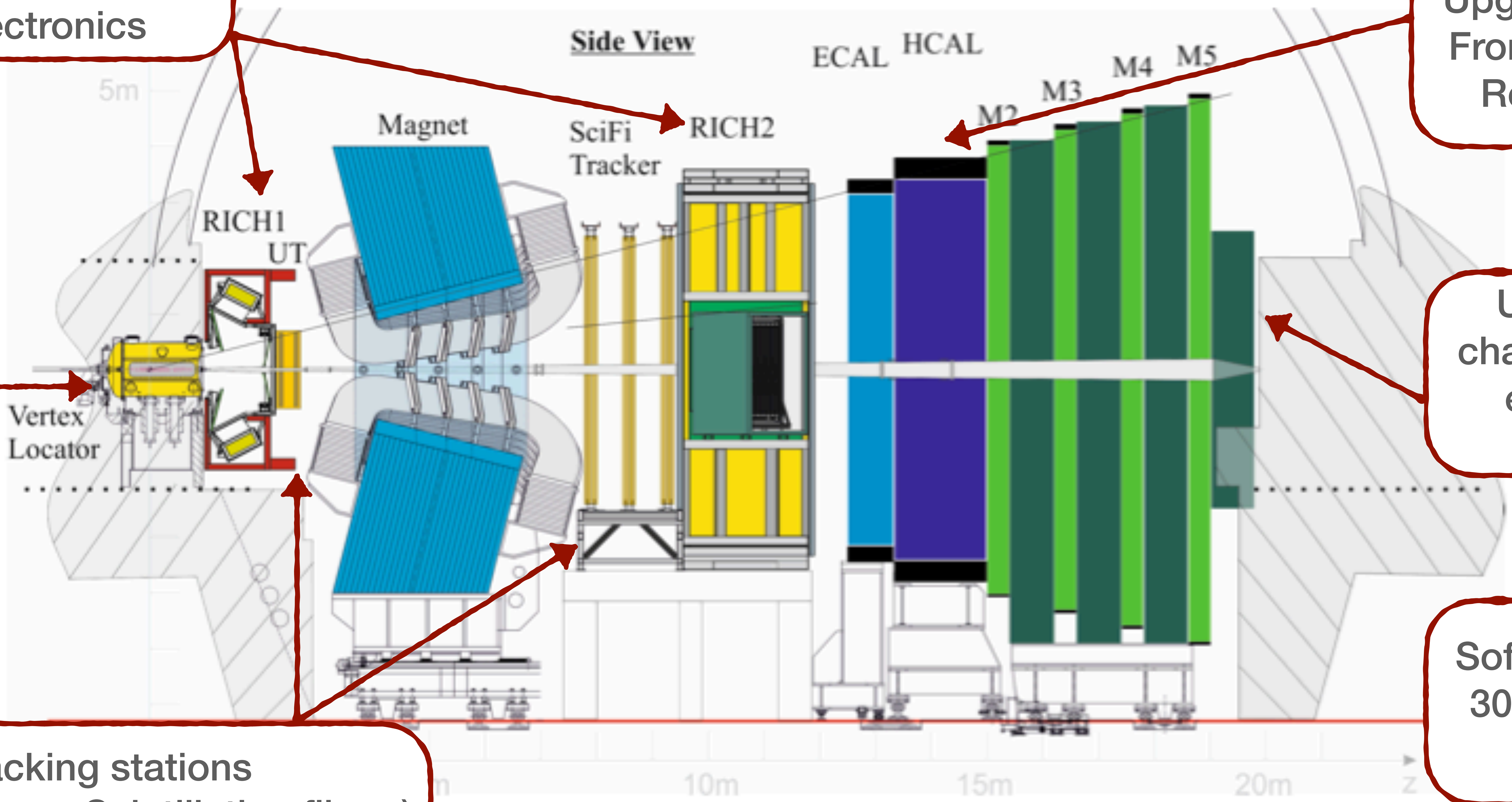
LHC schedule

The LHCb detector in Upgrade I (now)

New RICH PMTs
New electronics

Upgraded Calorimeter
Front-End electronics
Removed SPS/PS

New VELO
Pixels

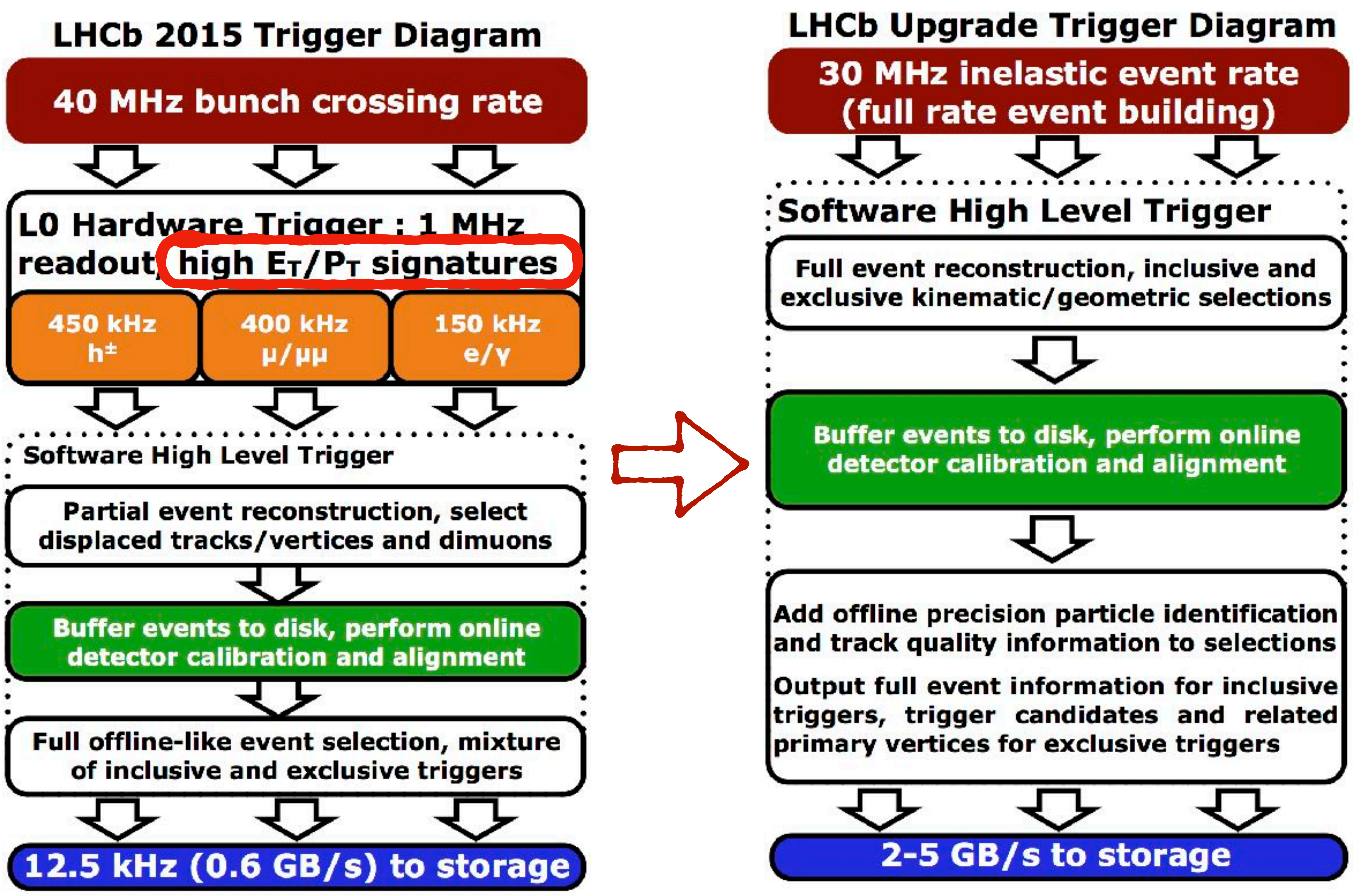


Upgraded muon
chambers Front-End
electronics, M1
removal

Software only trigger
30 MHz processing

New Tracking stations
(Silicon Microstrips + Scintillating fibres)

New trigger scheme



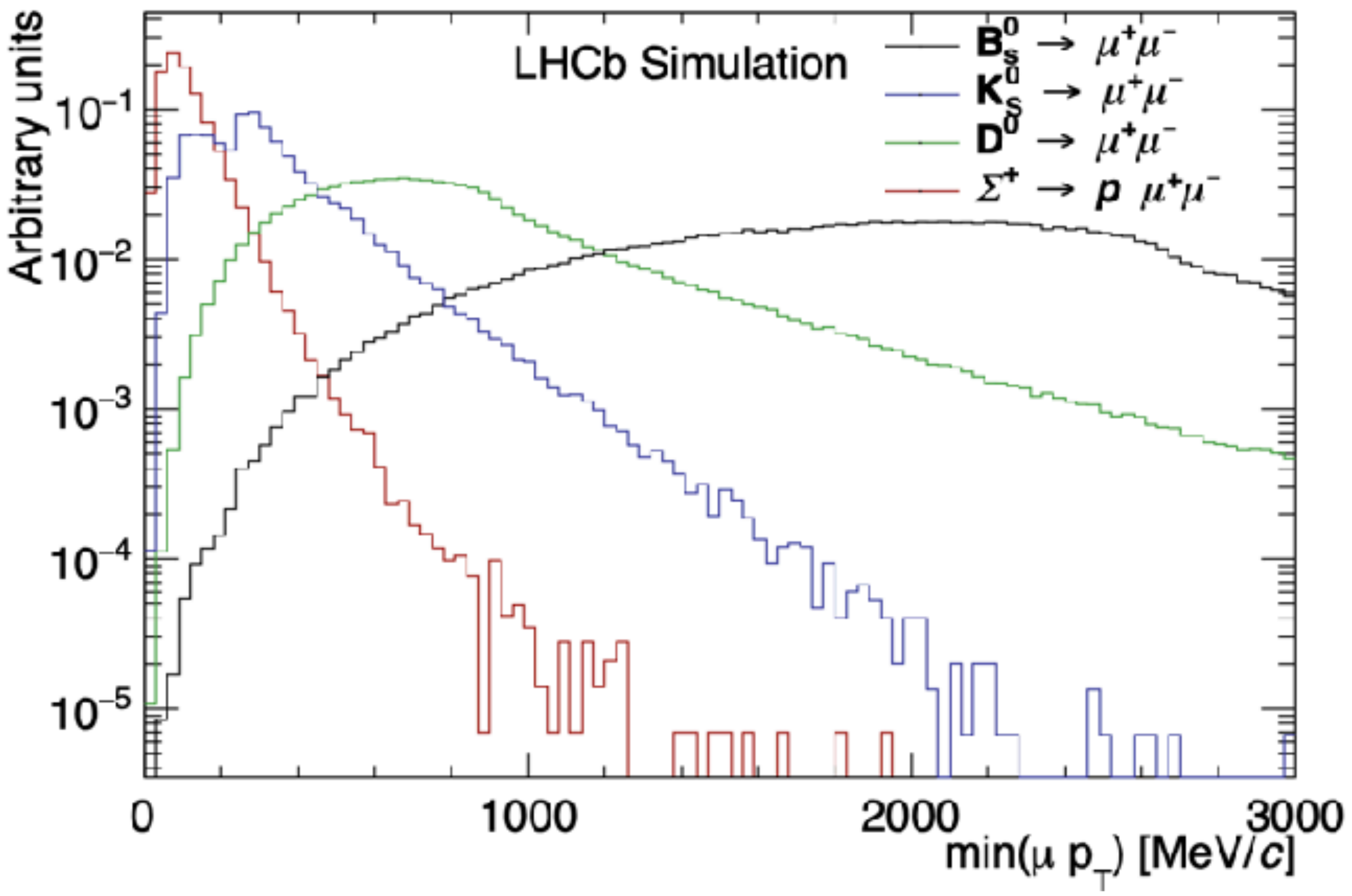
- **Removal of the Level-0 hardware trigger**:
  - much softer p_T requirements. **Quick gain**: soft muons from charm, taus or strange decays and channels with electrons in final state.
- **Run 2 experience**:
  - It is possible to apply online alignment and calibration
  - 'Offline' quality at HLT2 level → **sophisticated (and *flexible*) selections** earlier on gaining up to a factor 2 in fully hadronic final sates

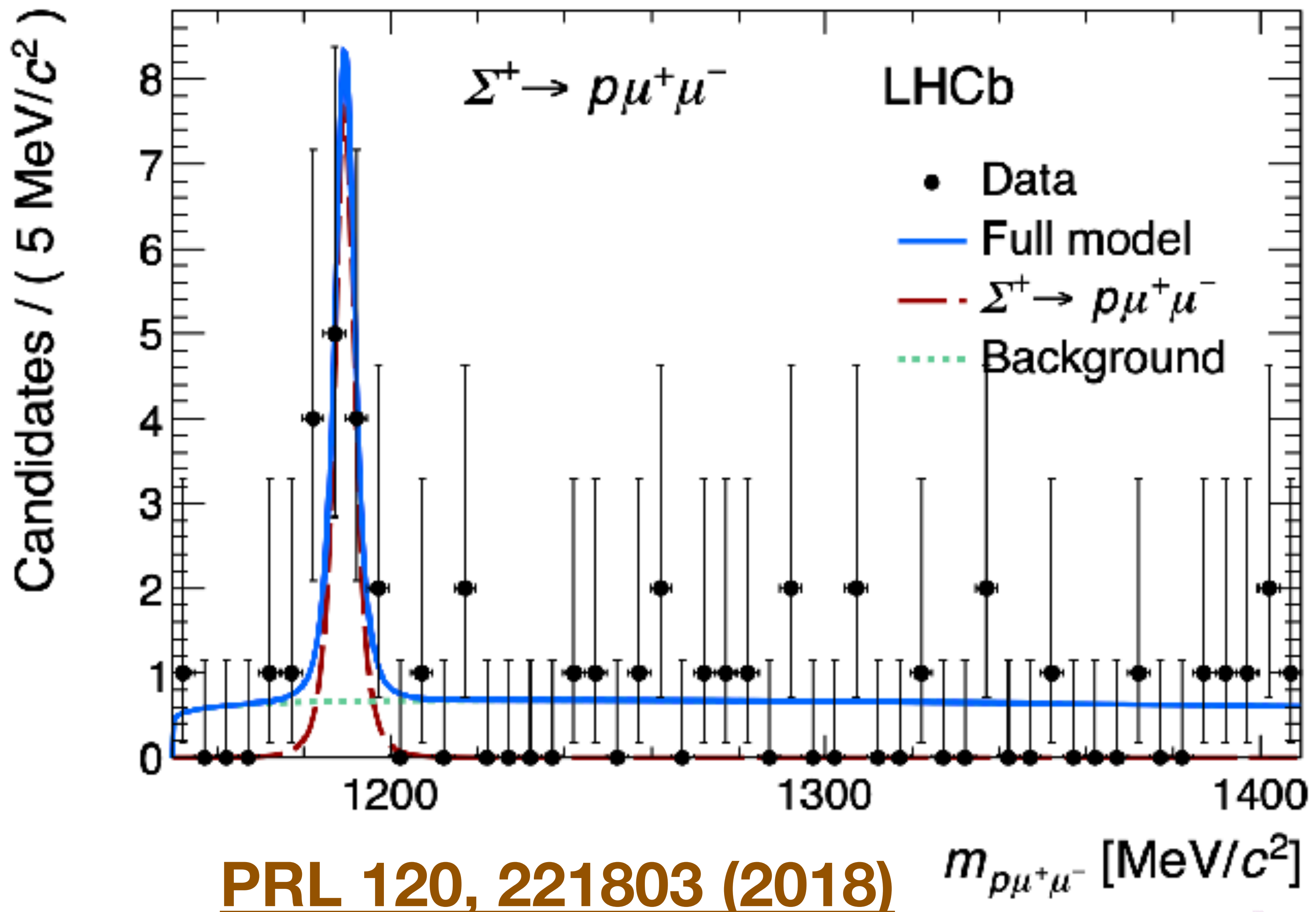
Trigger schemes

Impact: Rare kaon decays

LHCb-PUB-2017-023

- A **clear winner in the changes to the trigger** scheme
  - Dedicated HLT2 lines since Run 2 $\varepsilon \sim 1-2\,\% \rightarrow 18\,\%$ (in dimuons)
  - Typical p_{T} ranges: B physics 1-2GeV, strange physics: <0.1 GeV, removal of L0 hardware trigger brings back most of the signal region
- Several analyses published and ongoing in LHCb:
  - **Rarer modes** ($K_s^0 \rightarrow \mu\mu, K_s^0 \rightarrow \mu\mu\mu\mu,\ \ldots$) **not observed yet** (Run 2 data samples analysed)
  - $\Sigma^+ \rightarrow p\mu\mu$ (4.1σ evidence with Run 1 data) → achieve observation and investigate full differential decay rate.





PRL 120, 221803 (2018)

Impact: Rare charm decays

- **General gain in acceptance** from the **removal** of the (harsh) **L0 trigger** requirements.
  - Better kinematic overlap of different modes (reduced systematics)
- Dedicated new trigger lines for better mis-ID control ($\pi \to \mu$)

Much better efficiency to be expected on **multi-body charm** decays (even softer p_{T} spectra)

- Potential new limits on branching ratios* Upgrade 1, 2022-2030, and Upgrade 2, 2030+:

Mode	Run1-2 (1-9 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^0 \to \mu^+\mu^-$	~~6.2×10^{-9}~~ 3.1×10^{-9}	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	6.7×10^{-8}	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	2.6×10^{-8}	10^{-8}	3×10^{-9}
$\Lambda_c^+ \to p\mu^+\mu^-$	9.6×10^{-8}	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e^\pm\mu^\mp$	1.3×10^{-8}	10^{-9}	4.1×10^{-9}

A.Contu - Towards ultimate precision in Flavour Physics, Durham (2-4 April 2019)

- Statistical precision* on asymmetries:

Mode	Run1-2 (1-9 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$		0.2 %	0.08 %
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	~~3.8 %~~ 2%	1 %	0.4 %
$D^0 \to K^-\pi^+\mu^+\mu^-$		0.3 %	0.13 %
$D^0 \to K^+\pi^-\mu^+\mu^-$		12 %	5 %
$D^0 \to K^+K^-\mu^+\mu^-$	~~11 %~~ 6%	4 %	1.7 %

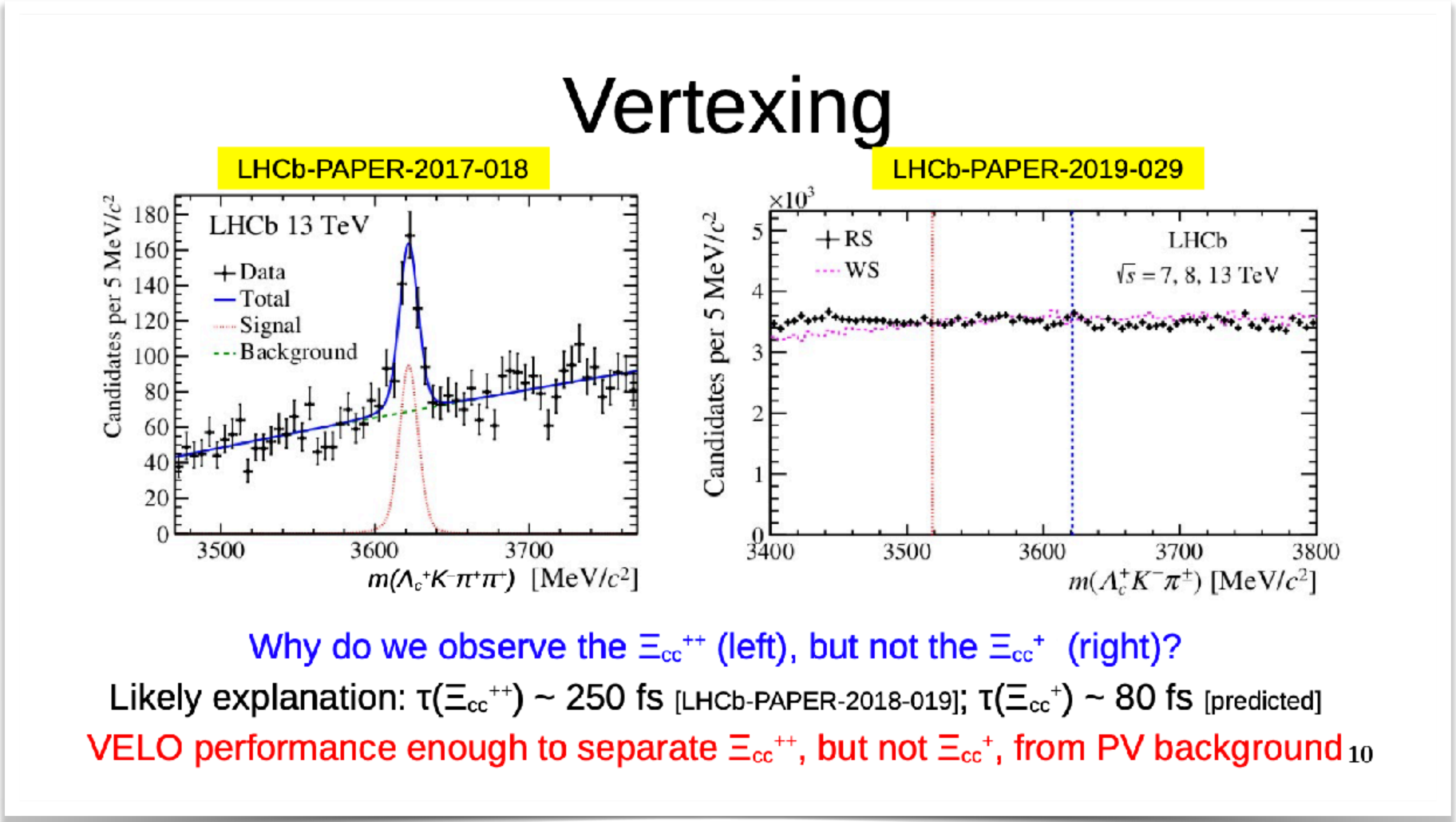
A.Contu - Towards ultimate precision in Flavour Physics, Durham (2-4 April 2019)

D. Unverzagt @Charm23

Relevance of vertexing

Upgraded VELO:

- Expected to **improve the decay time resolution** (σ_t) by a 10% factor (w.r.t. Runs1&2)
- Nominal position for **sensors at ~5.1mm from the collision** region (closer than before)
- Better track/vertex association → reduced combinatorial backgrounds

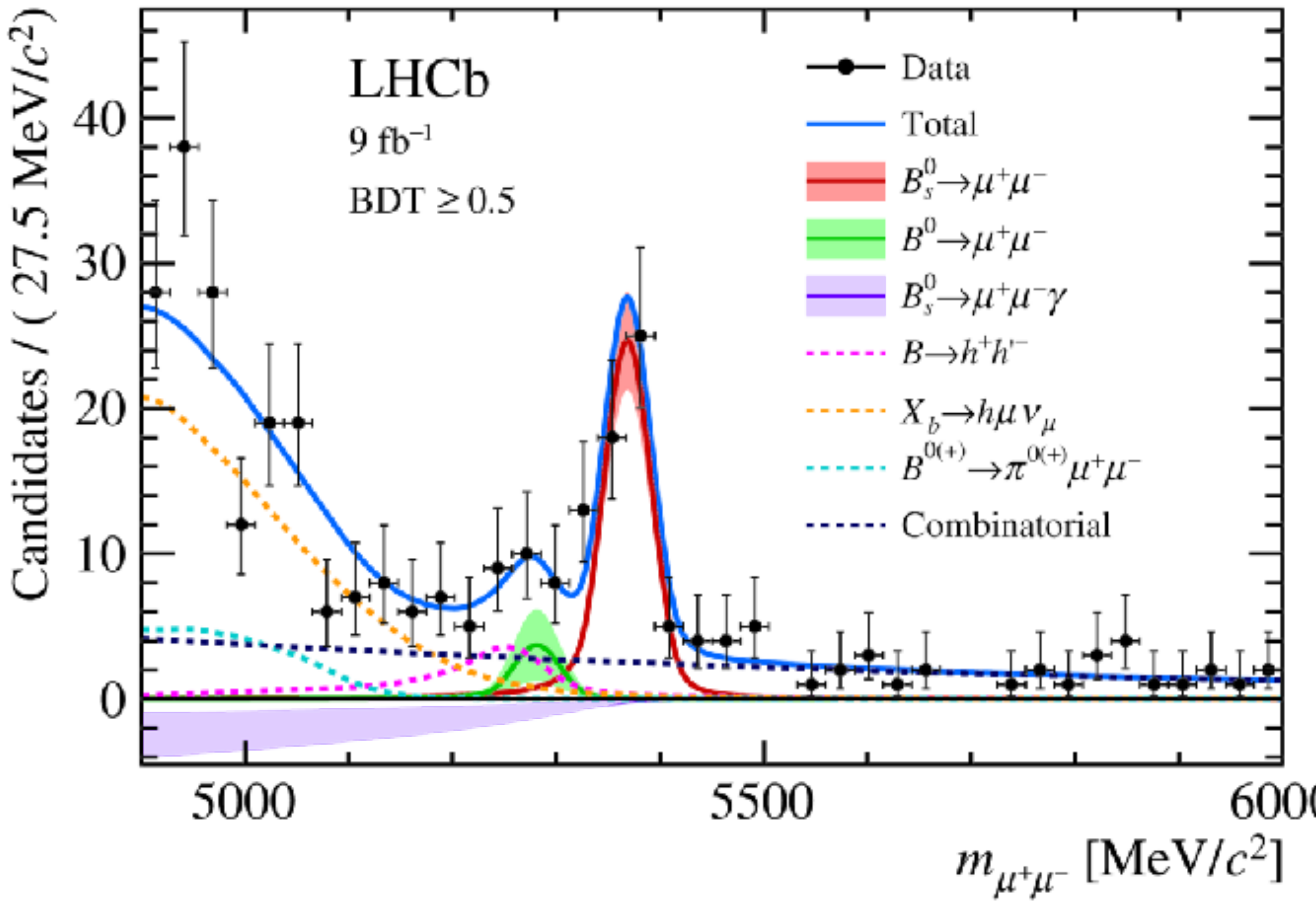


T. Gershon @ UpgradeII workshop

Very rare lands: $B_{(s)} \to \mu\mu$

- **Well stablished B_s mode**, next milestones:
  - $\mathcal{B}(B^0 \to \mu\mu)/\mathcal{B}(B_s^0 \to \mu\mu)$
  - Effective lifetime and time-dependent CP asymmetry
  - $\mathcal{B}(B_s^0 \to \mu\mu\gamma)$
- The combinatorial background is the main factor to be kept under control:
  - ✓ Improved vertexing
  - ✓ Improved momentum estimation from the tracking system (→ better mass resolution)
- **Developments on flavour-tagging** will be needed to increase its performance.
- Based on current results, f_s/f_d could be leading the uncertainty after the data sample collected with the Upgrade II detector
  - Further improvements (beyond $\sqrt{N}$) will be needed on this front

PHYS. REV. LETT. 128, (2022) 041801



FTDR-LHCbUII,LHCC 2021-012

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69% [40, 41]	41%	27%	11%
$S_{\mu\mu}\ (B_s^0 \to \mu^+\mu^-)$	—	—	—	0.2

Electrons in Run 3

- x5 visible interactions → x5 tracks: Run 3 has a harsher environment.
  ⚠ Hand-wavy math

✓ **Improved vertexing and tracking**, better efficiency expected in track matching

✓ **Removal of hardware trigger**: large efficiency increase

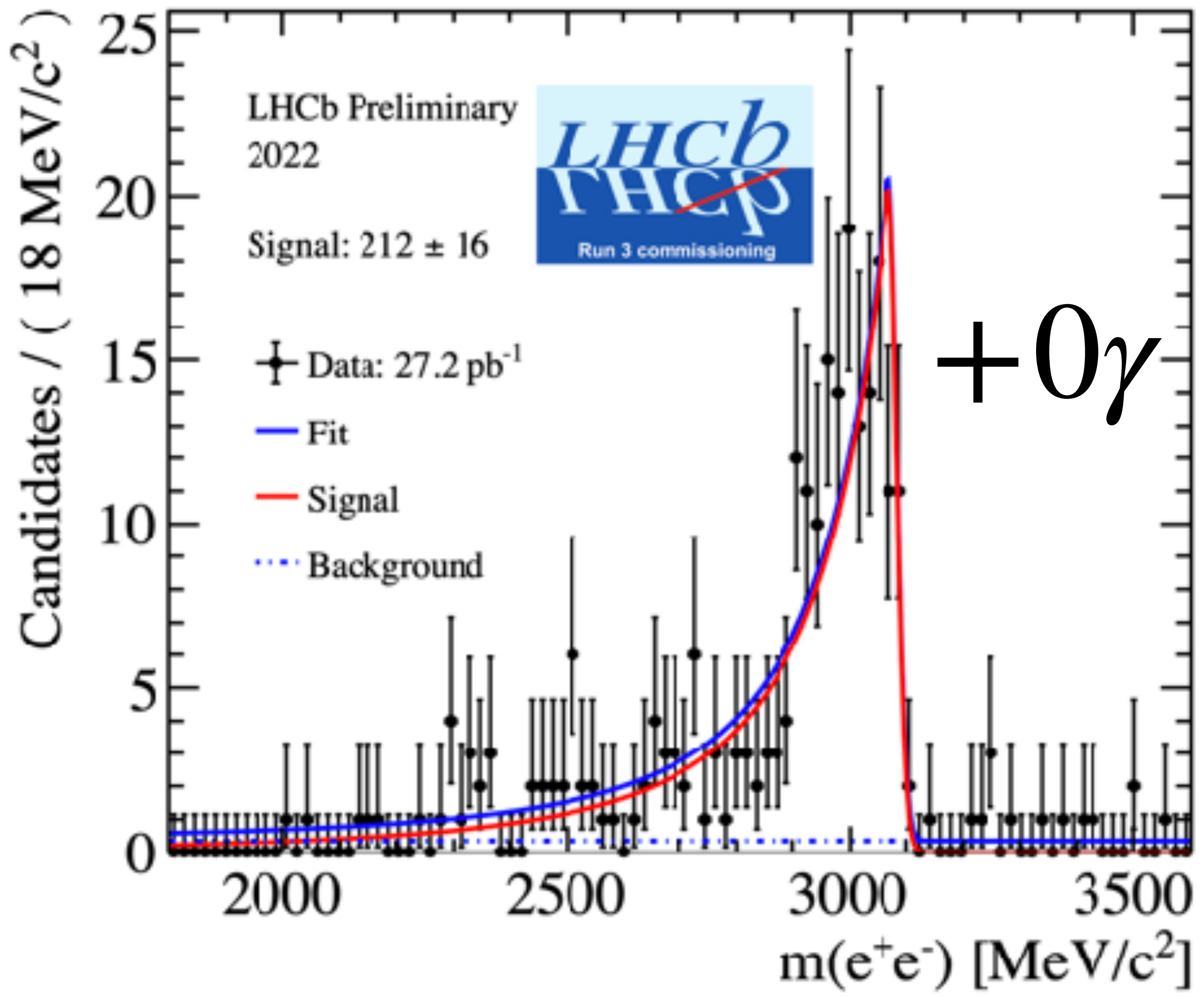
  ✓ Extra: better kinematic overlap with the muon samples (better control of the systematics in ratios)

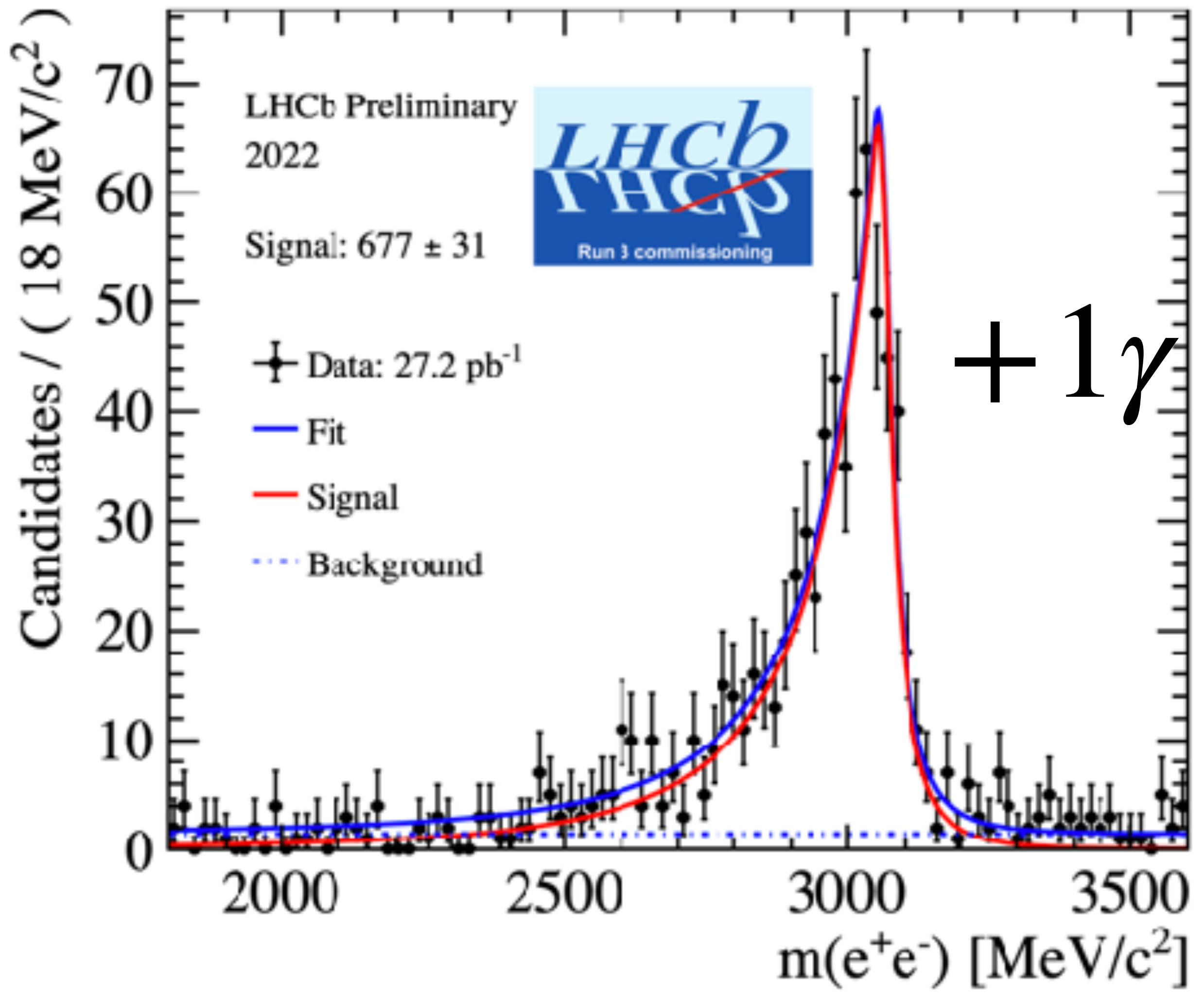
◉ Larger occupancy implies larger backgrounds in a busier calorimeter

  ◉ Momentum and mass resolution with Bremsstrahlung recovery become more challenging

  ✓ Brem. recovery algorithms have been re-written and improved to help coping

✓ Quicker access to higher level information to make selections more efficient





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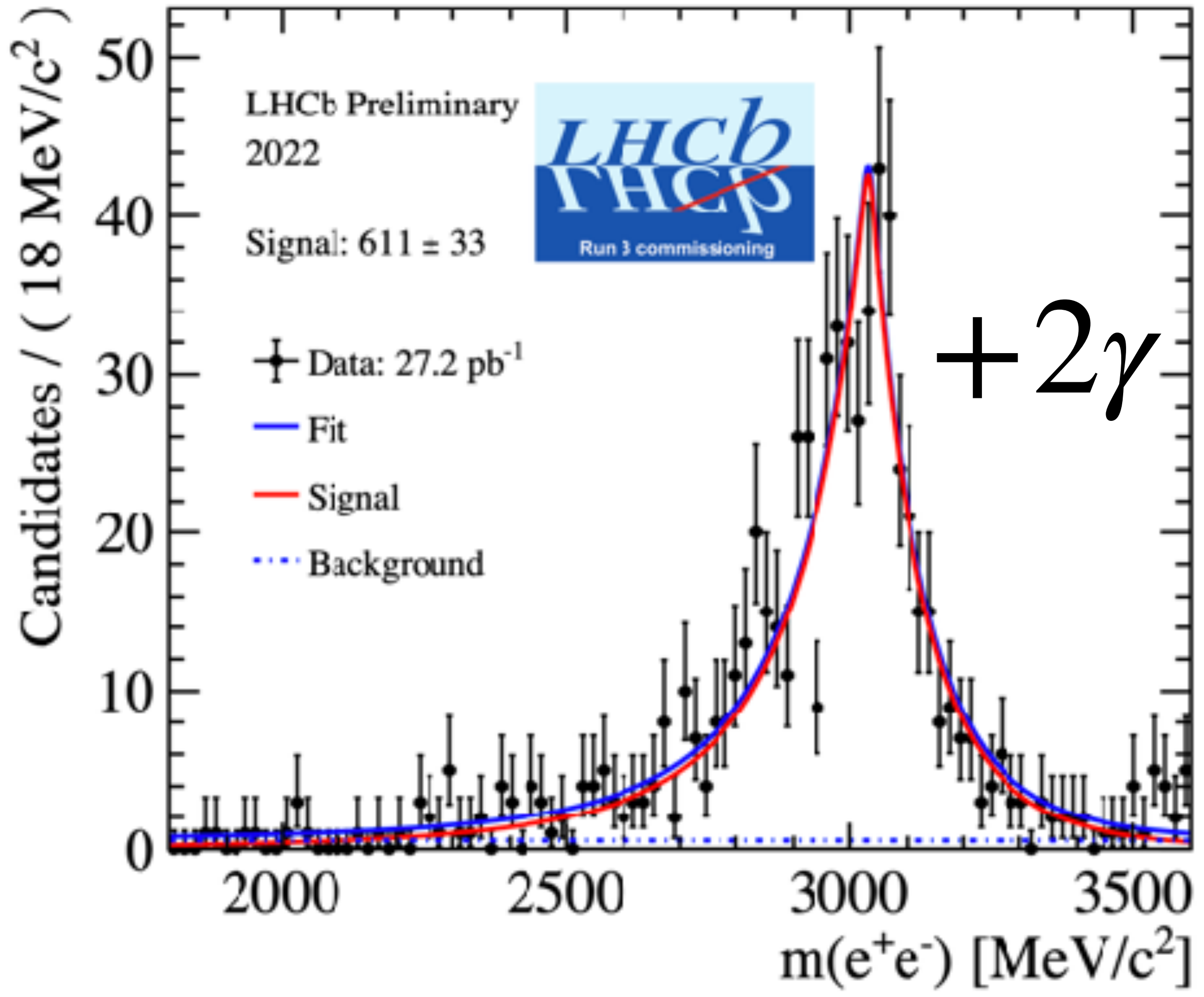


Good qualitative behaviour of Brem. Recovery in early 2022 commissioning data!

Taking a turn to radiative

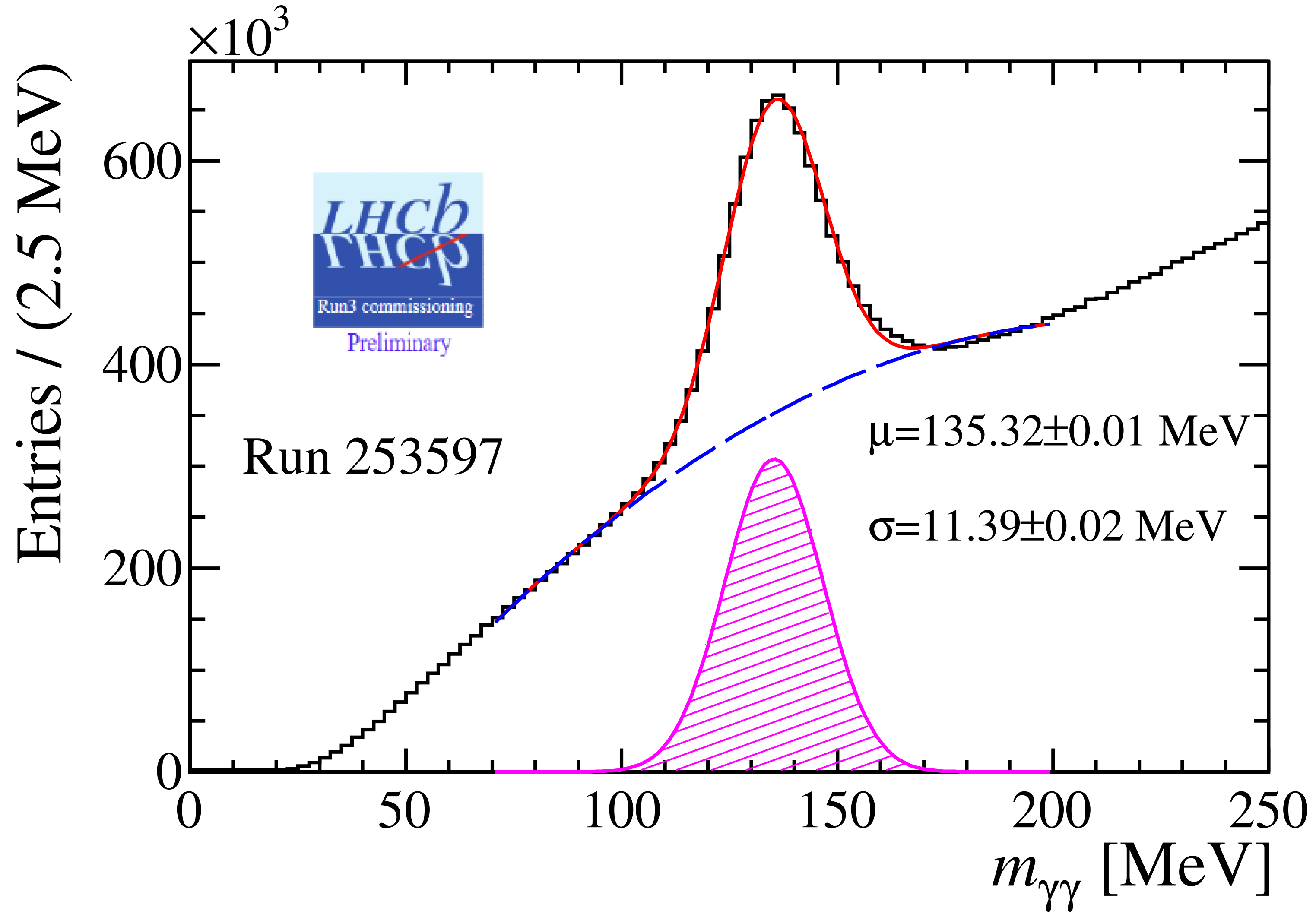
[LHCb-FIGURE-2022-019](#)

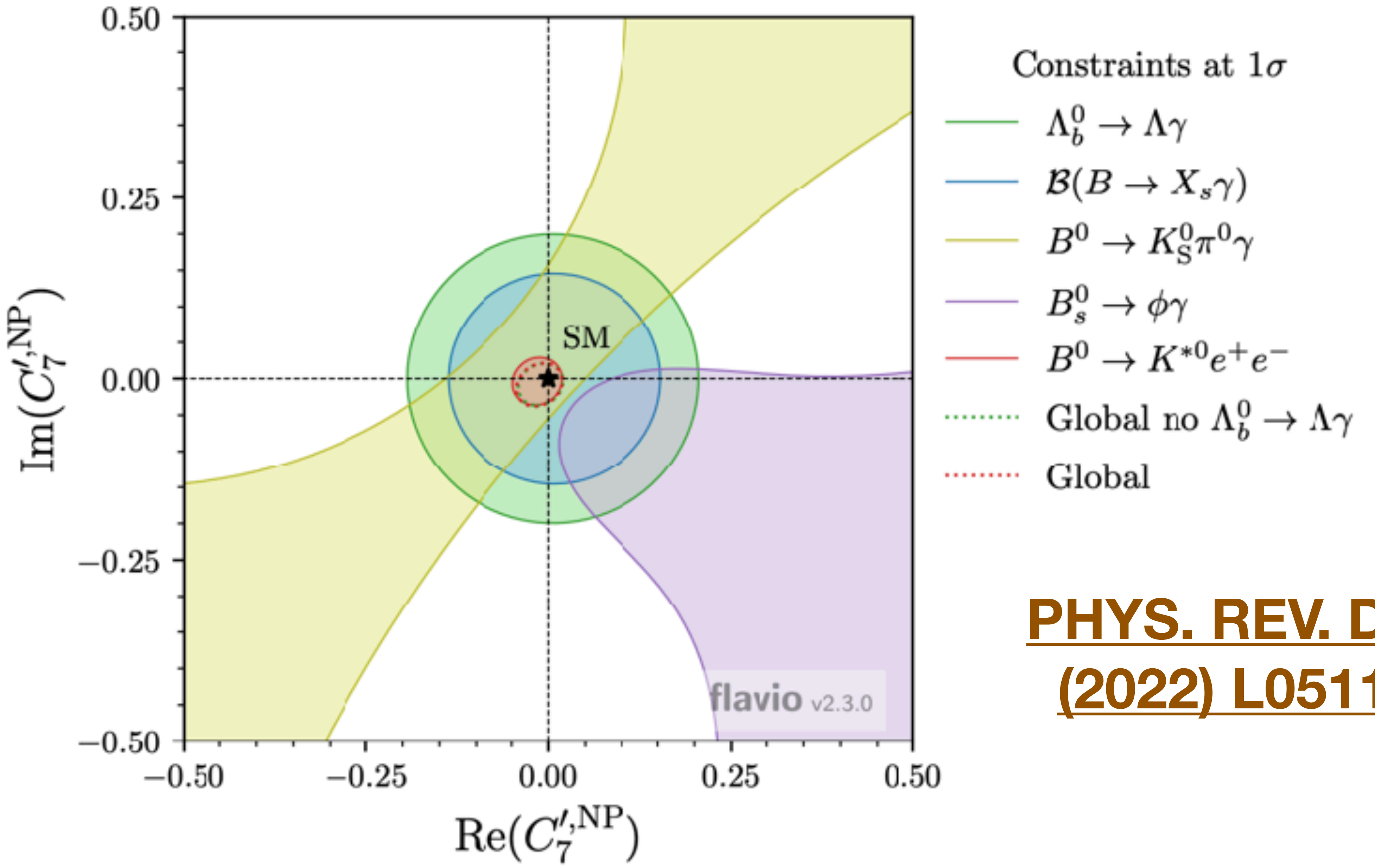
- Similar set of Pros and Cons as electrons → **higher level quantities to be optimised** to recover efficiencies

- Benefits from larger samples and potencial for large impact:

  - $\mathrm{Im}\,\mathrm{C}_7^{\mathrm{eff}}$: time integrated CP asymmetry, $A_{CP}(B^0 \to K^*\gamma) \sim 2\mathrm{Im}\mathrm{C}_7^{\mathrm{eff}}\mathrm{Im}\Delta\mathrm{C}_7$

  - C_7': currently dominated by $B^0 \to K^* e^- e^+$, but nice complementarity with other modes and the direct determination of the photon polarisation





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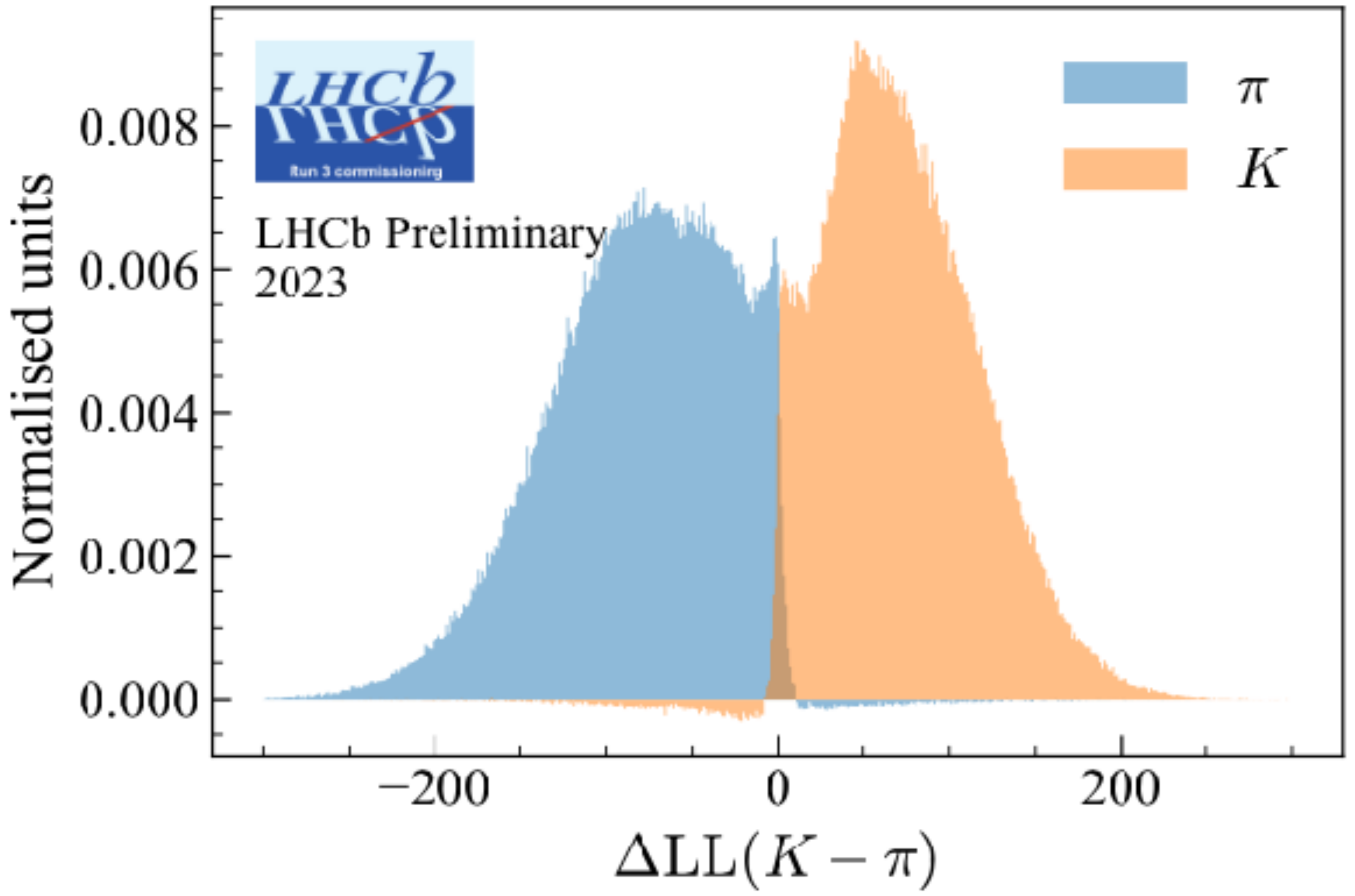
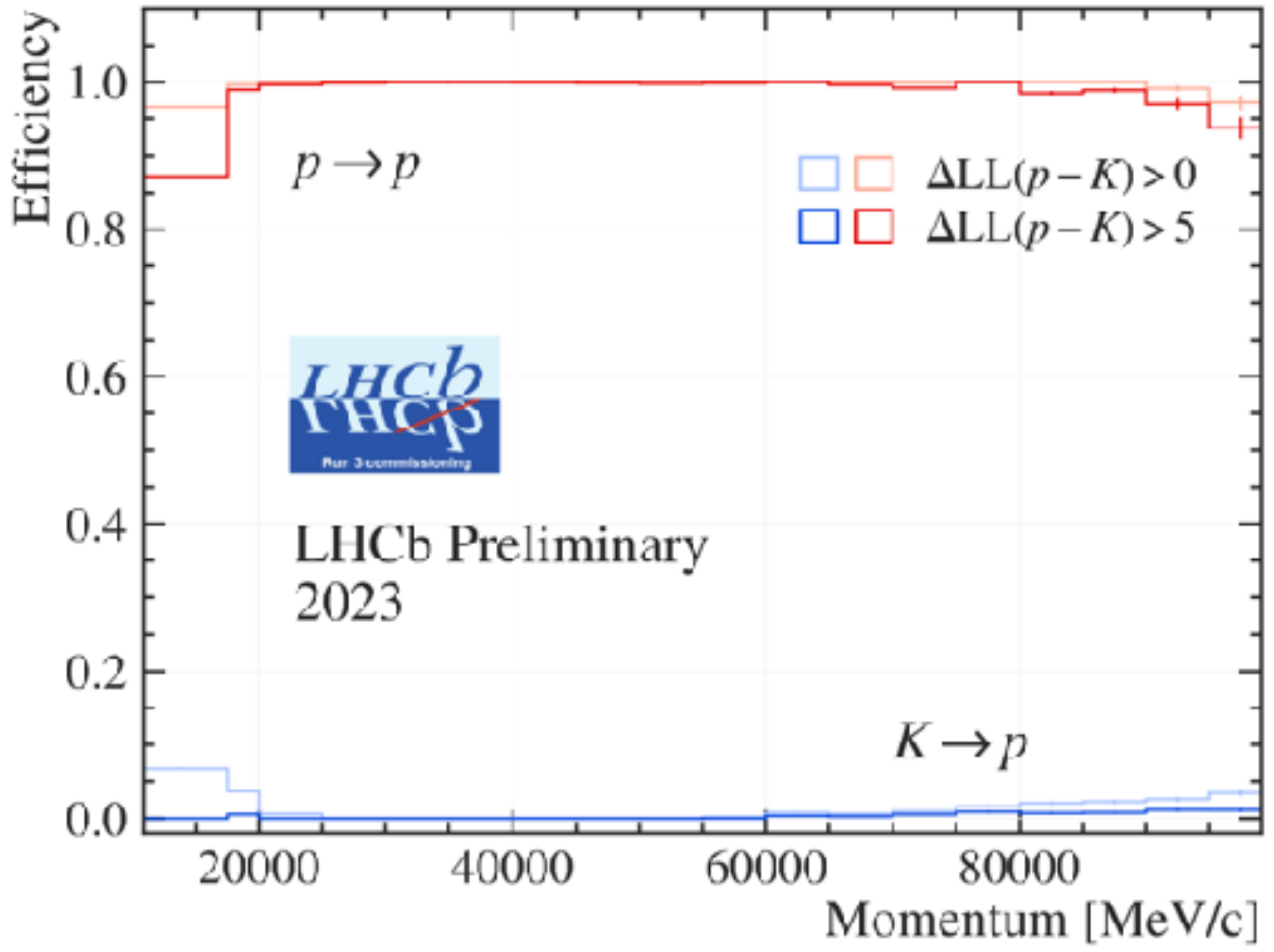
(*) C_7^{eff}:regularisation scheme independent redefinition of C_7

[JHEP 04 (2017) 027](#)

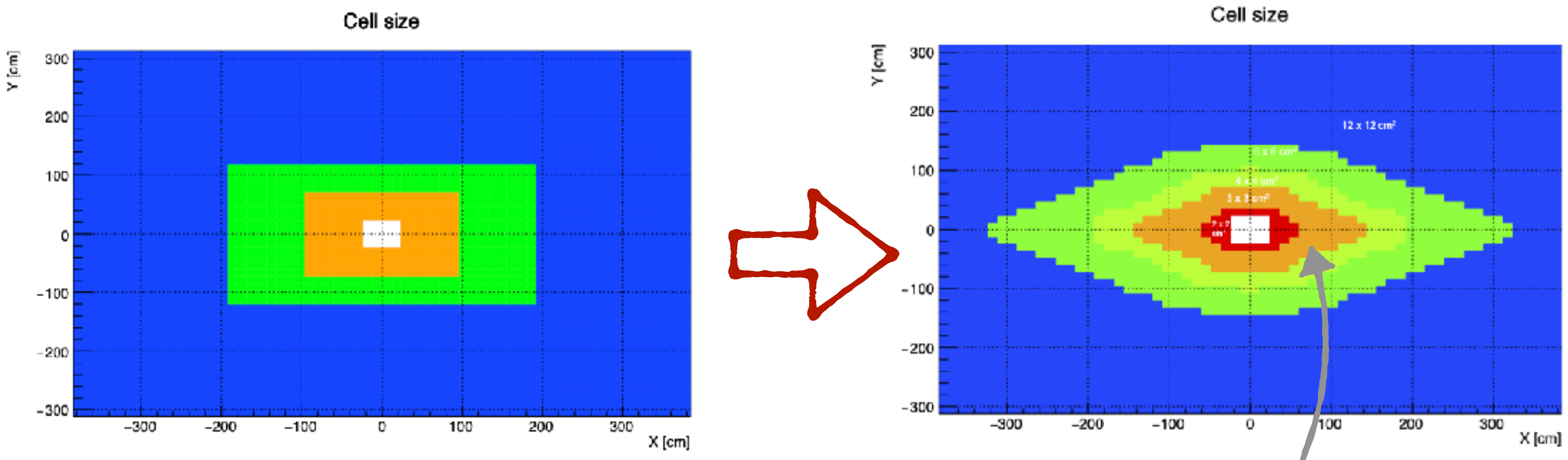
Particle Identification

LHCb-FIGURE-2023-023





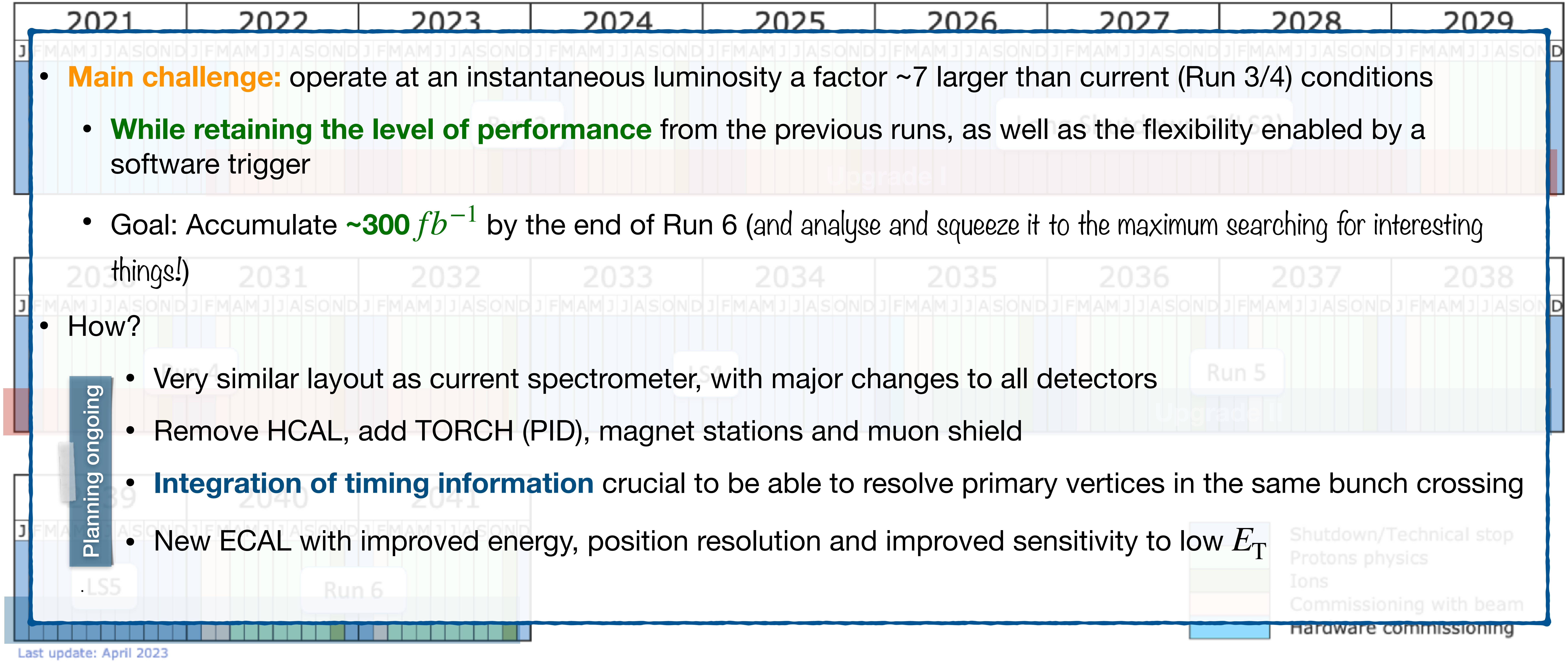
- PID achieved by combining information from several systems
  - Expressed as differences in log-likelihood: $\Delta LL(K) = \log(\mathrm{K}) - \log(\pi)$
  - Preliminary Run 3 results show very good performance
- **Enhancements proposed for LS3** (between Runs 3&4)
  - **Charged PID (RICH)**: new electronics, allowing for **photon time-of-arrival measurement** (enhance photon/track matching)
  - **Neutral PID (ECAL)**: **replacement of the inner section** (cope with radiation damage) with **higher granularity** modules and re-arrangement of the basic geometry (better matching occupancy)



LHCB-TDR-024

~1/3 of the π^0/γ produced from B's are reconstructed here

Looking further ahead: Upgrade II



- **Main challenge:** operate at an instantaneous luminosity a factor ~7 larger than current (Run 3/4) conditions
  - **While retaining the level of performance** from the previous runs, as well as the flexibility enabled by a software trigger
  - Goal: Accumulate **~300 fb^{-1}** by the end of Run 6 (and analyse and squeeze it to the maximum searching for interesting things!)
- How?
  - Very similar layout as current spectrometer, with major changes to all detectors
  - Remove HCAL, add TORCH (PID), magnet stations and muon shield
  - **Integration of timing information** crucial to be able to resolve primary vertices in the same bunch crossing
  - New ECAL with improved energy, position resolution and improved sensitivity to low E_T

LHC schedule

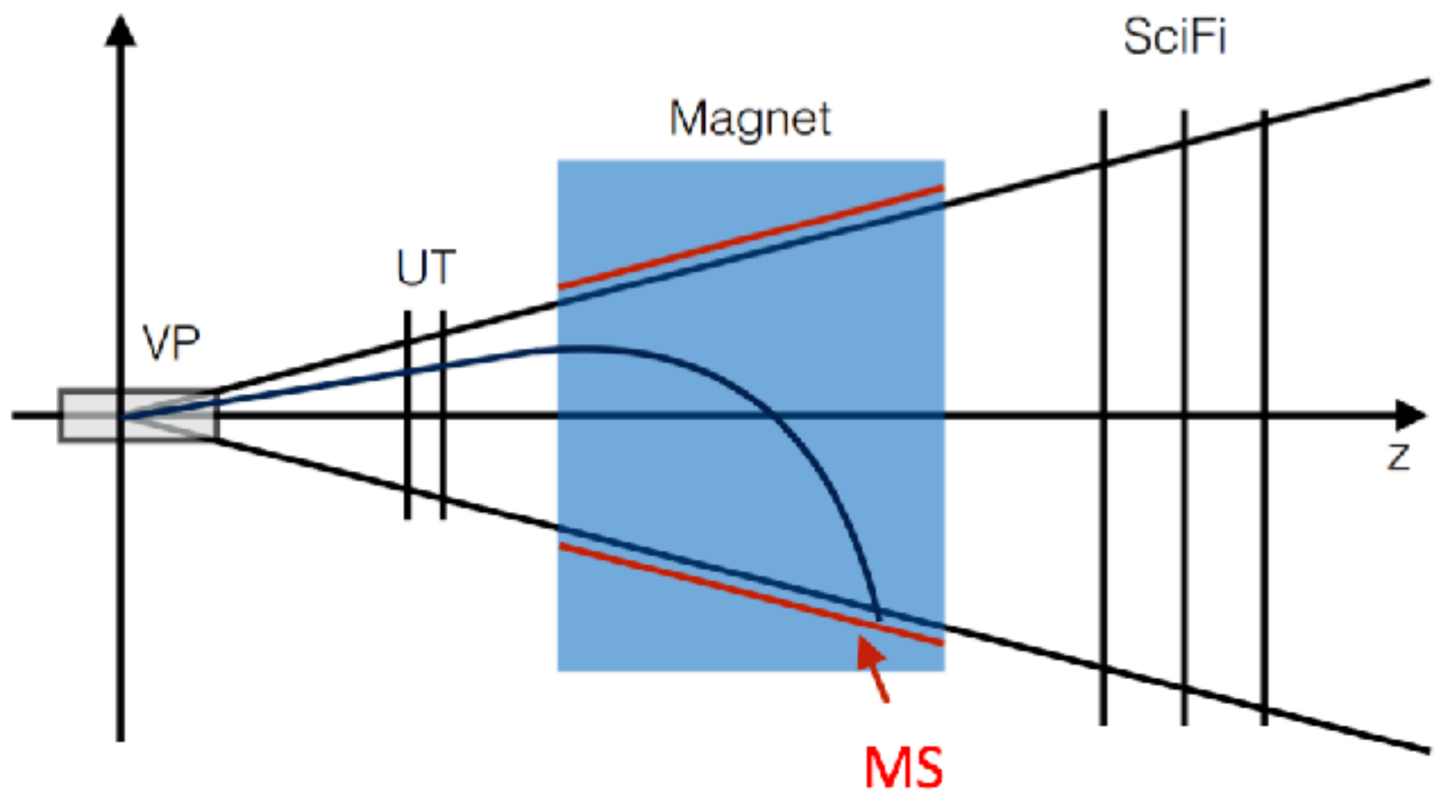
Low momentum gains: Magnet tracking stations

- Proposed scintillating-based tracking subsystem inside the magnet to measure the position and direction of particles hitting the magnet side walls

  ➡ Significantly enlarge the phase space with high precision tracking (in the low momentum region)

Table 3.9: Tracking efficiency relative to VELO+UT tracking efficiency.

channel	≥8 SciFi hits	SciFi+MS hits	gain
$\gamma \to e^+e^-$ ($p_{T,\gamma}$ >10 MeV/c)	0.245	0.98	4.1
$\rho^0 \to \pi^+\pi^-$	0.530	0.780	1.5
$K^0_S \to \pi^+\pi^-$	0.384	0.720	1.9
$K^{*0} \to K^\pm\pi^\mp$	0.479	0.704	1.5
$D^{*+} \to D^0 + \pi^\pm$ ($\pi^\pm$ in MS)	0.33	0.67	2.0
$D^{*0} \to D^0 + e^+e^-$ (e^+e^- in MS)	0.22	0.66	3.0
$D^+_s \to D^0 + K^+$ (K^+ in MS)	0.74	0.89	1.20
$\chi_{c1}(3872) \to J/\psi + \pi^+\pi^-$ ($\pi^+\pi^-$ in MS)	0.51	0.73	1.43
$B^+ \to (J/\psi \to e^+e^-\gamma)\, K^+$	0.70	0.83	1.3
$\Omega^{*0}_c(3067) \to (\Xi^+_c pK^-\pi^+)\, K^+$	0.63	0.80	1.27
$B^+ \to (\bar{D}^0 \to (K^0_S \to \pi^+\pi^-)\, \pi^+\pi^-)\, K^+$	0.34	0.56	1.7
γ+pomeron $\to J/\psi \to e^+e^-$	0.57	0.69	1.18
γ+pomeron $\to \rho^0 \to \pi^+\pi^-$	0.39	0.58	1.49
$\gamma + \gamma \to e^+e^-$	0.008	0.03	3.8



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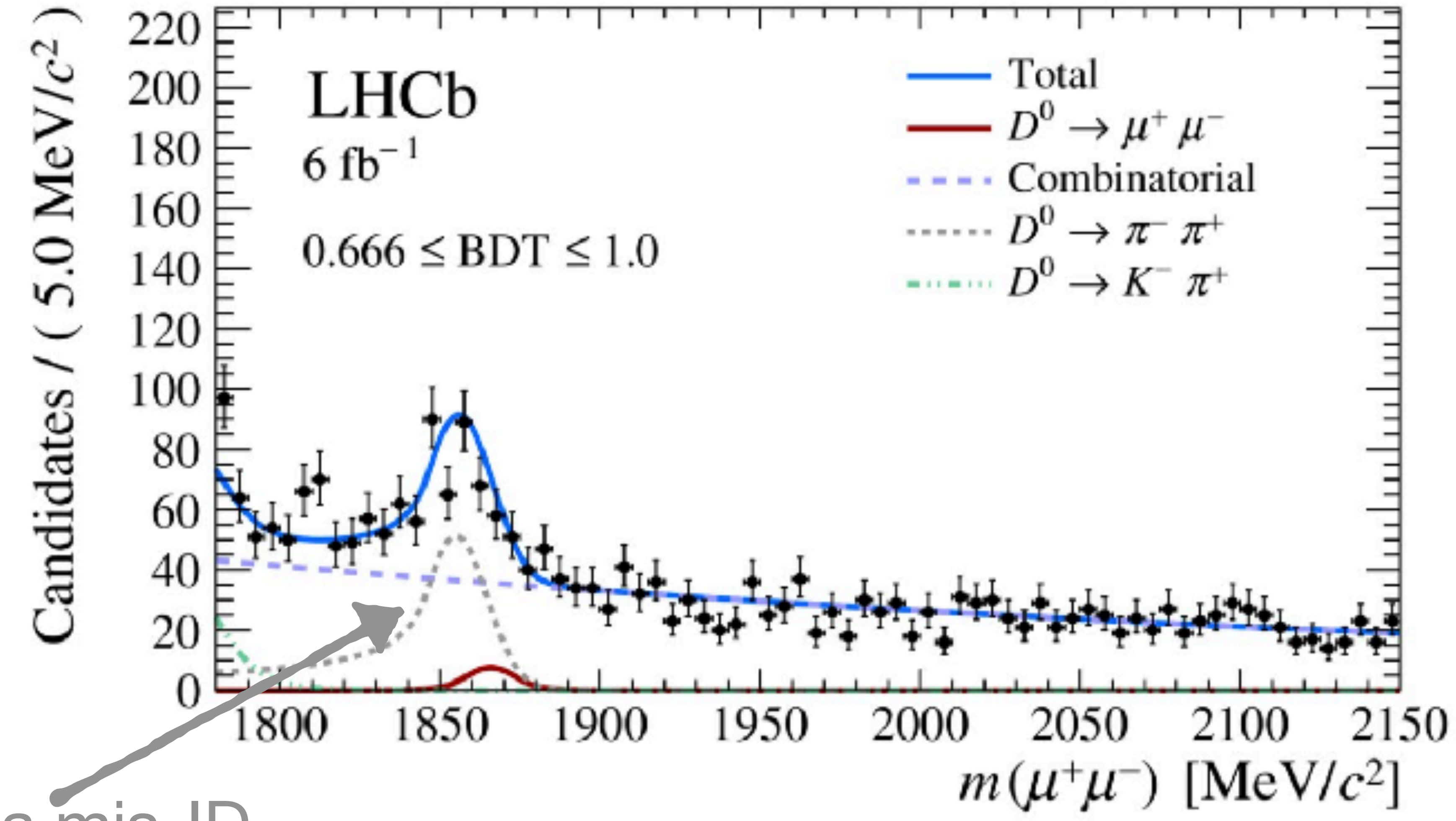
Not an exhaustive list...

And with even *more* data...

- **Time-dependent angular analysis of rare modes** ($B_s^0 \to \phi\mu\mu$, $B^0 \to \rho\mu\mu$) should become feasible (~400 events in Run1 for $B_s^0 \to \phi\mu\mu$) → current estimate is for these to still be statistically limited after Run 6
- **Branching ratio measurements of very rare modes $b \to d\ell\ell$, $c \to u\ell\ell$, strange physics**
  - PID (cross-feed backgrounds) and mass resolution must be kept extremely performant
- **Branching ratio and CP violation measurements in $b \to d\gamma$, $b \to s\gamma$** transitions: large gain expected from an ECAL with better spatial segmentation

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900

LHCB-PUB-2018-009

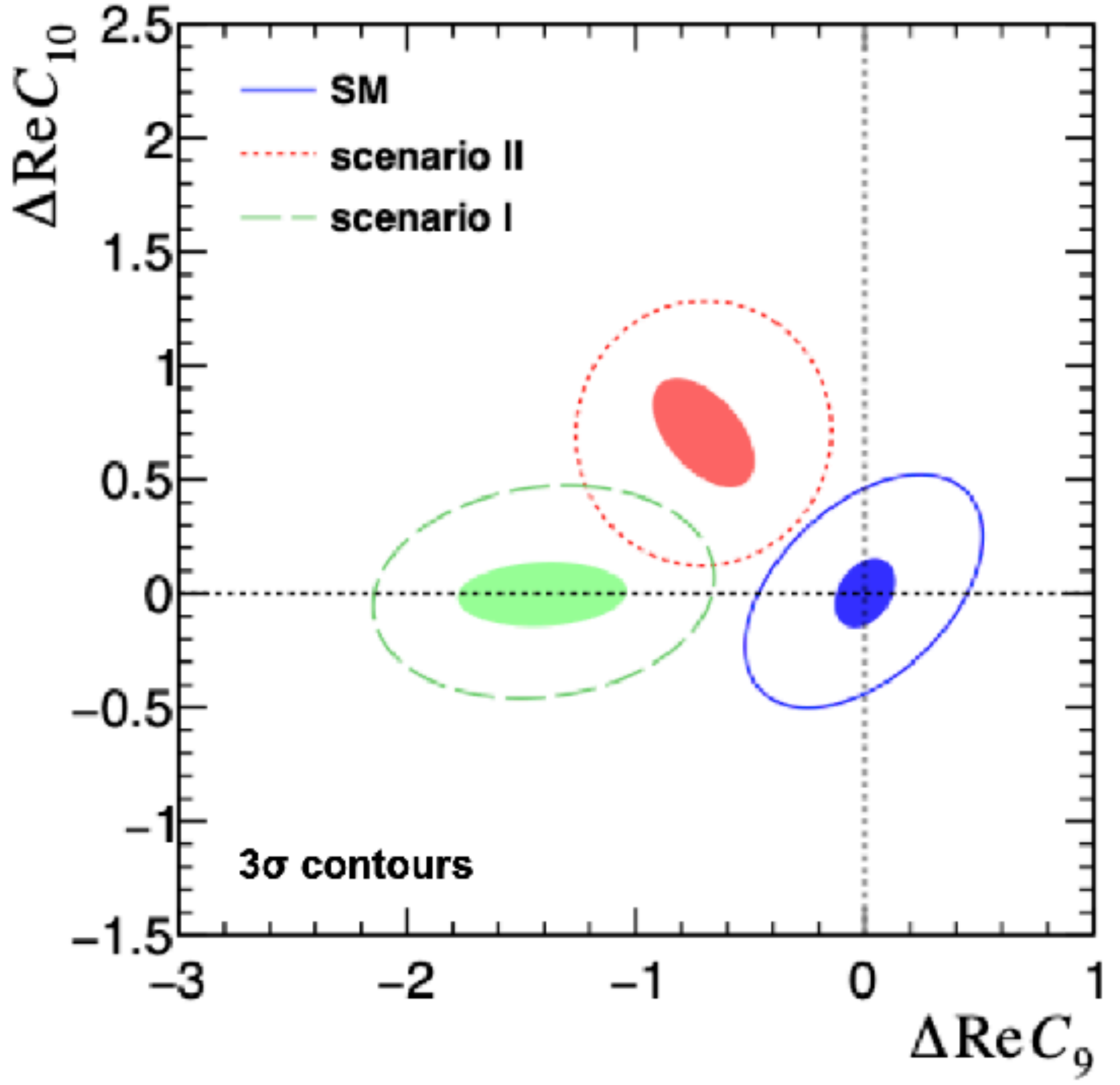


That's a mis-ID background!

LHCB-PAPER-2022-029

Landscape with $300fb^{-1}$

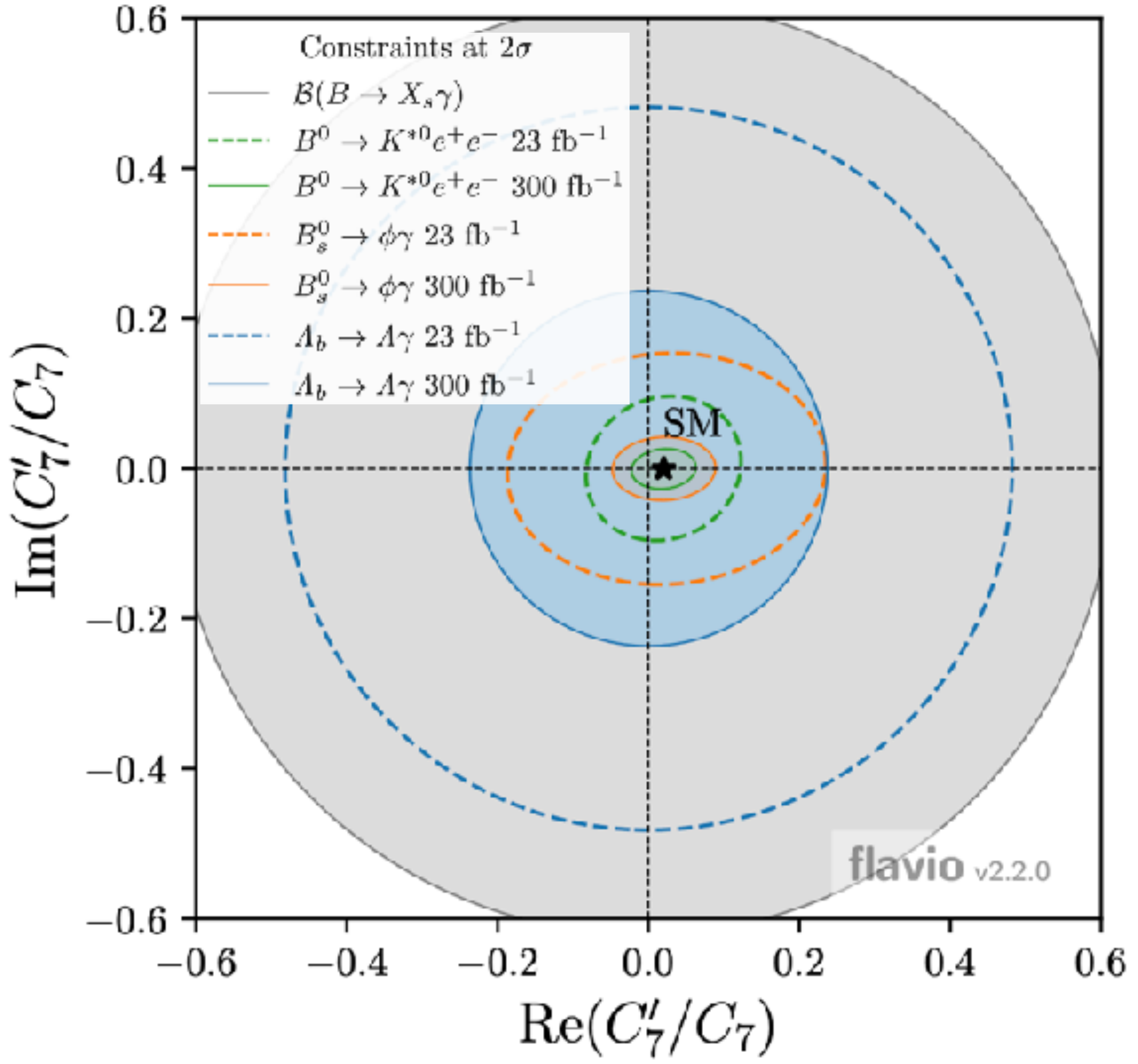
Comparison of the angular distributions between electrons and muons → **distinguish between NP scenarios**



Lines: Run3
Shaded areas: Upgrade II

LHCB-PUB-2018-009

Gains on electrons (measurements with converted photons) and better neutral PID → **high precision SM test**



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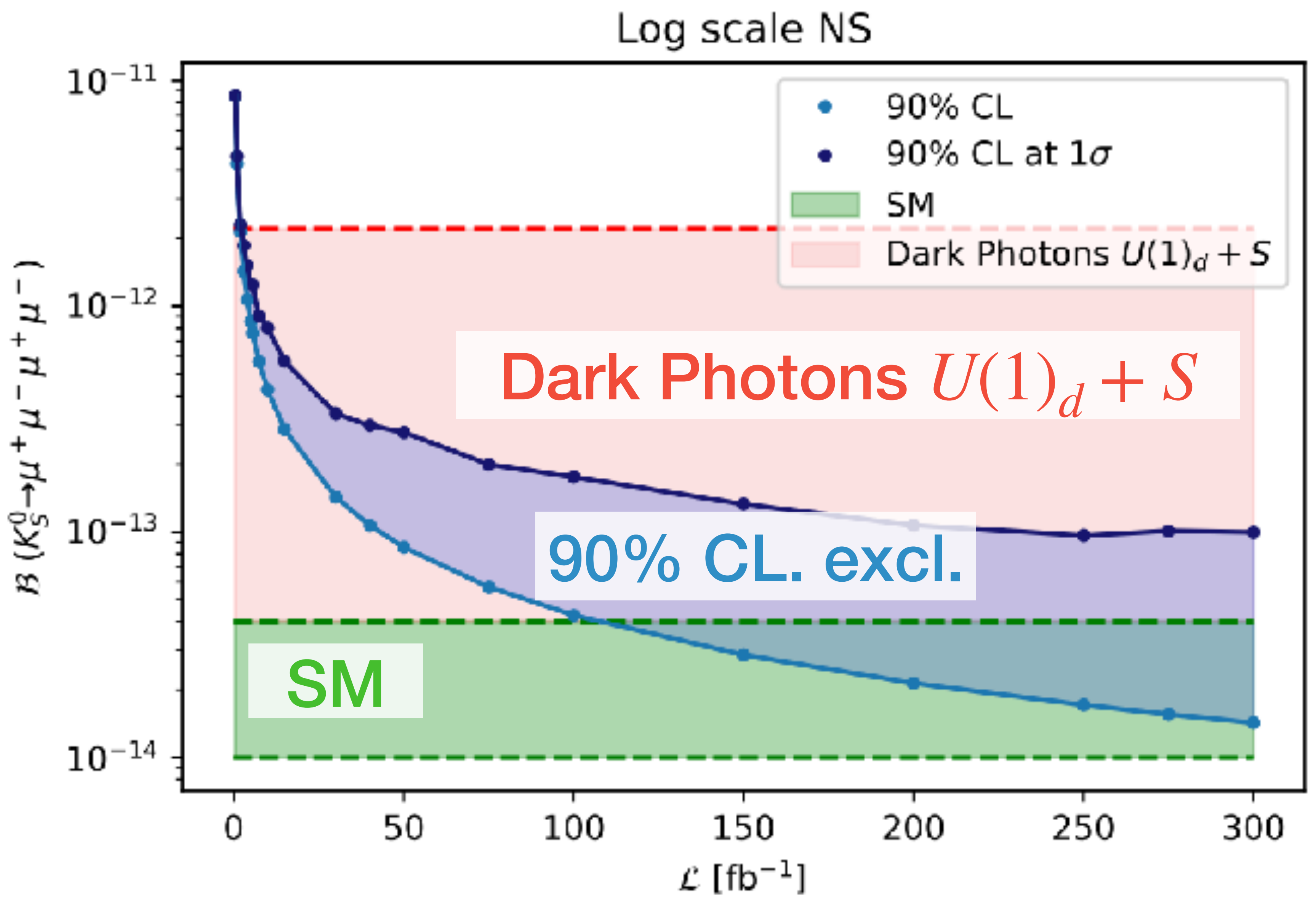
Strange physics: K_s^0 mode unique to LHCb, sensitivity on K_L^0 mode might still compete with dedicated kaon experiments (HIKE Phase 2 if approved)



D. Martinez Santos @Kaon22

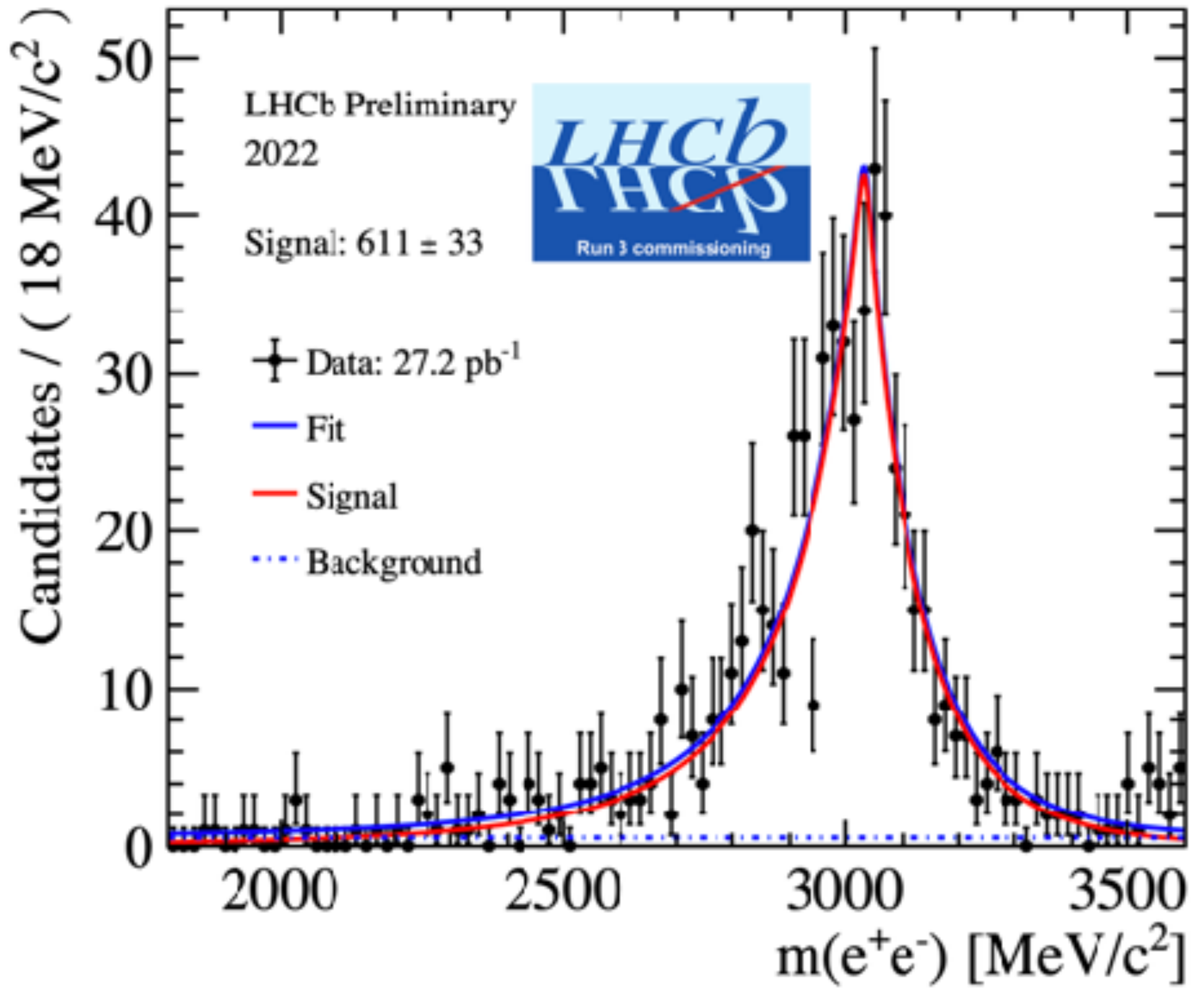
Conclusions

✳ Many LHCb results on FCNC are **limited by analysed sample sizes**

- Upgrade I will allow to push some boundaries, but rarer modes and differential BR measurements still expected to be statistically limited by the end of Run 4
- With **enough data** and **good analysis and interpretation** of it, we will be able to disentangle its different contributions and, hopefully, **understand them at a fundamental level.**

➡**Keep working** on squeezing the available data and on detector upgrades and technologies that will allow for the **best possible physics outputs**

Looking good!



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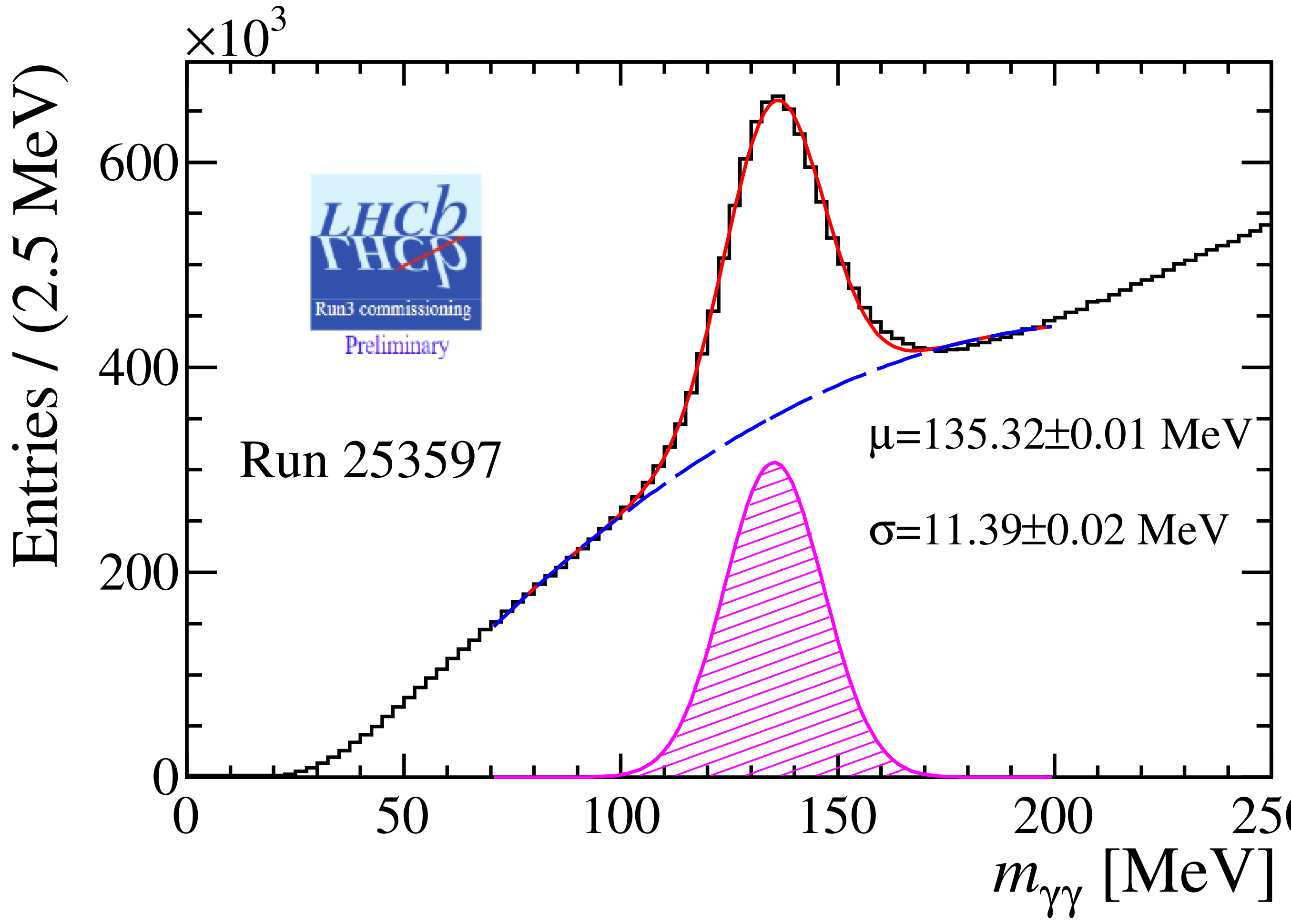
LHCb-FIGURE-2022-019



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