Prospects for the LHCb experiment*

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On behalf of the LHCb collaboration

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Beyond the flavour anomalies workshop

Siegen, 11.04.2024

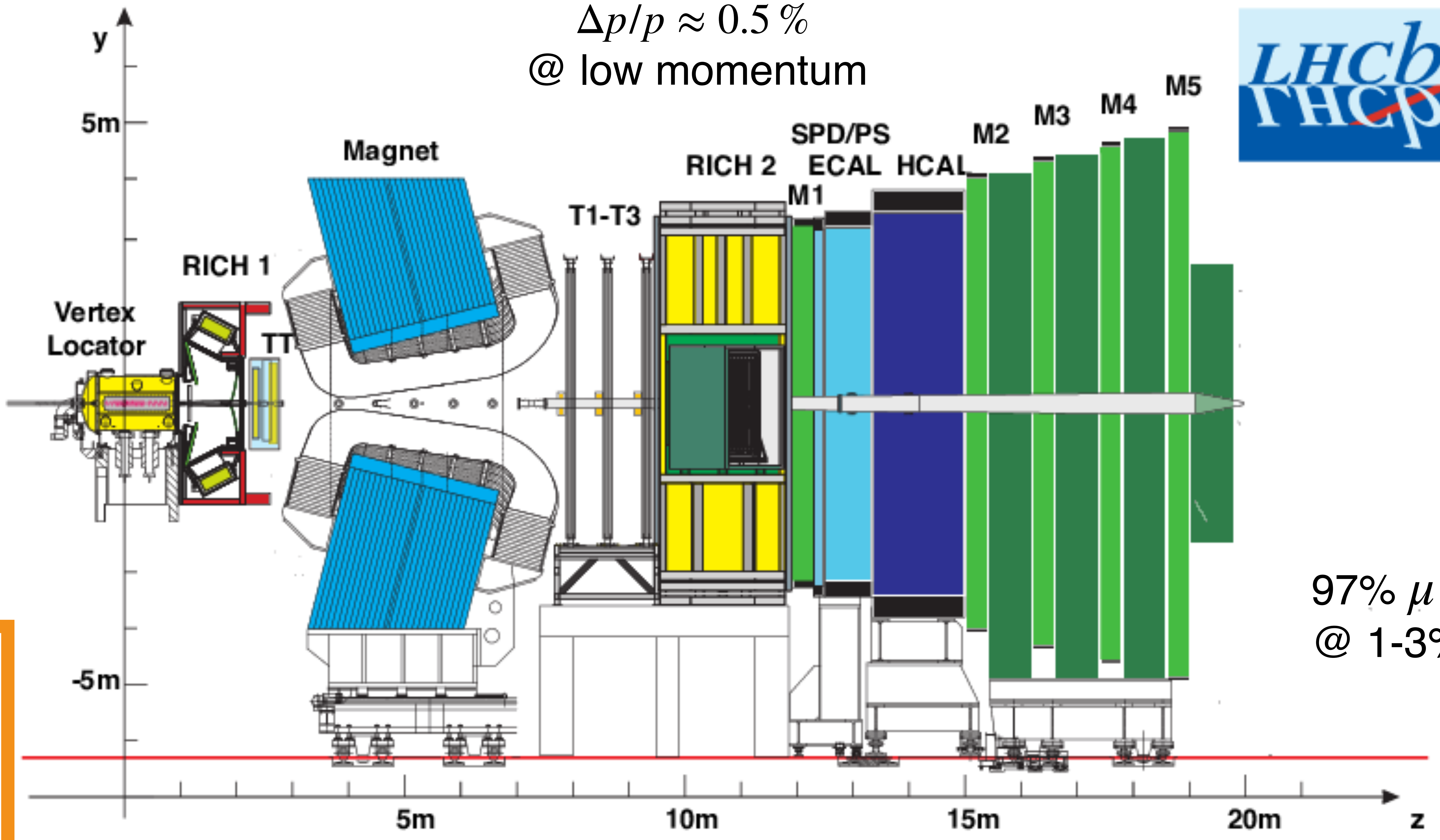
*Or: where to expect the next surprising developments?

LHCb in Run 1&2

Collected $9\,\mathrm{fb}^{-1}$ in 2011-2018
@ 7,8,13 TeV

$\sigma_{IP} \approx 20\mu$m
@ high p_T

$\Delta p/p \approx 0.5\,\%$
@ low momentum



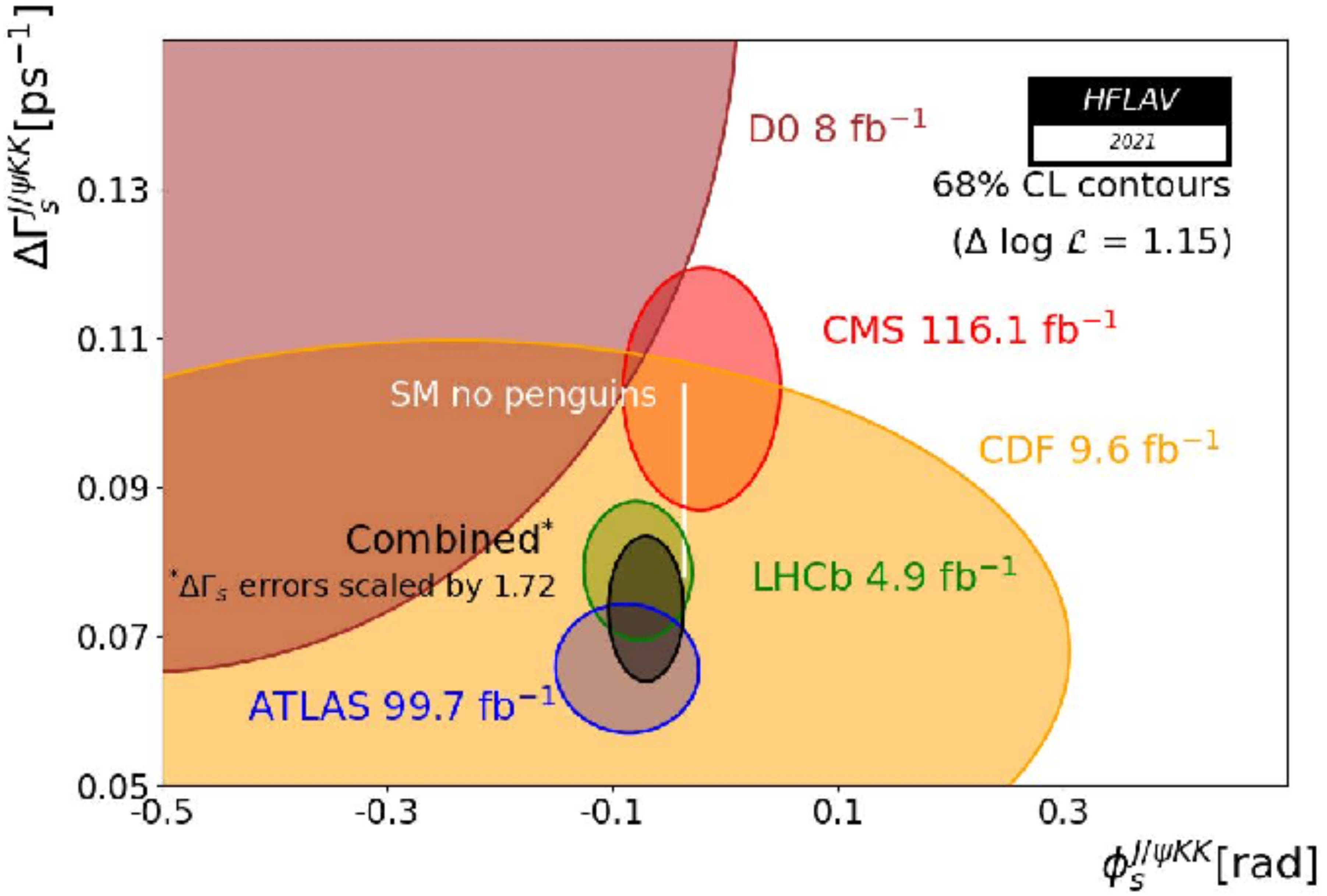
97% μ ID
@ 1-3% pion misID

Designed for CPV and rare decay measurements in beauty and charm

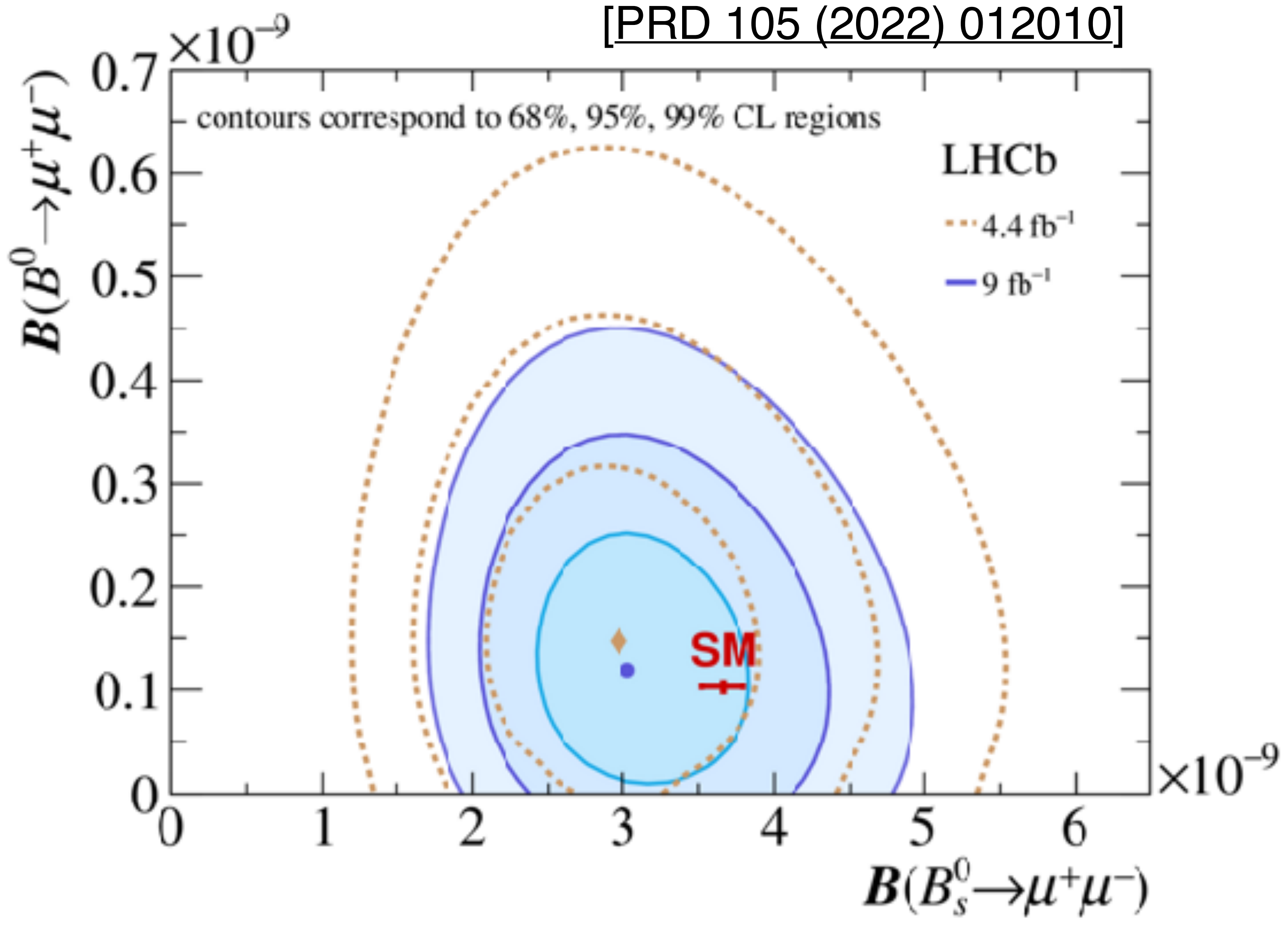
→ Now multipurpose flavour factory (and much more)

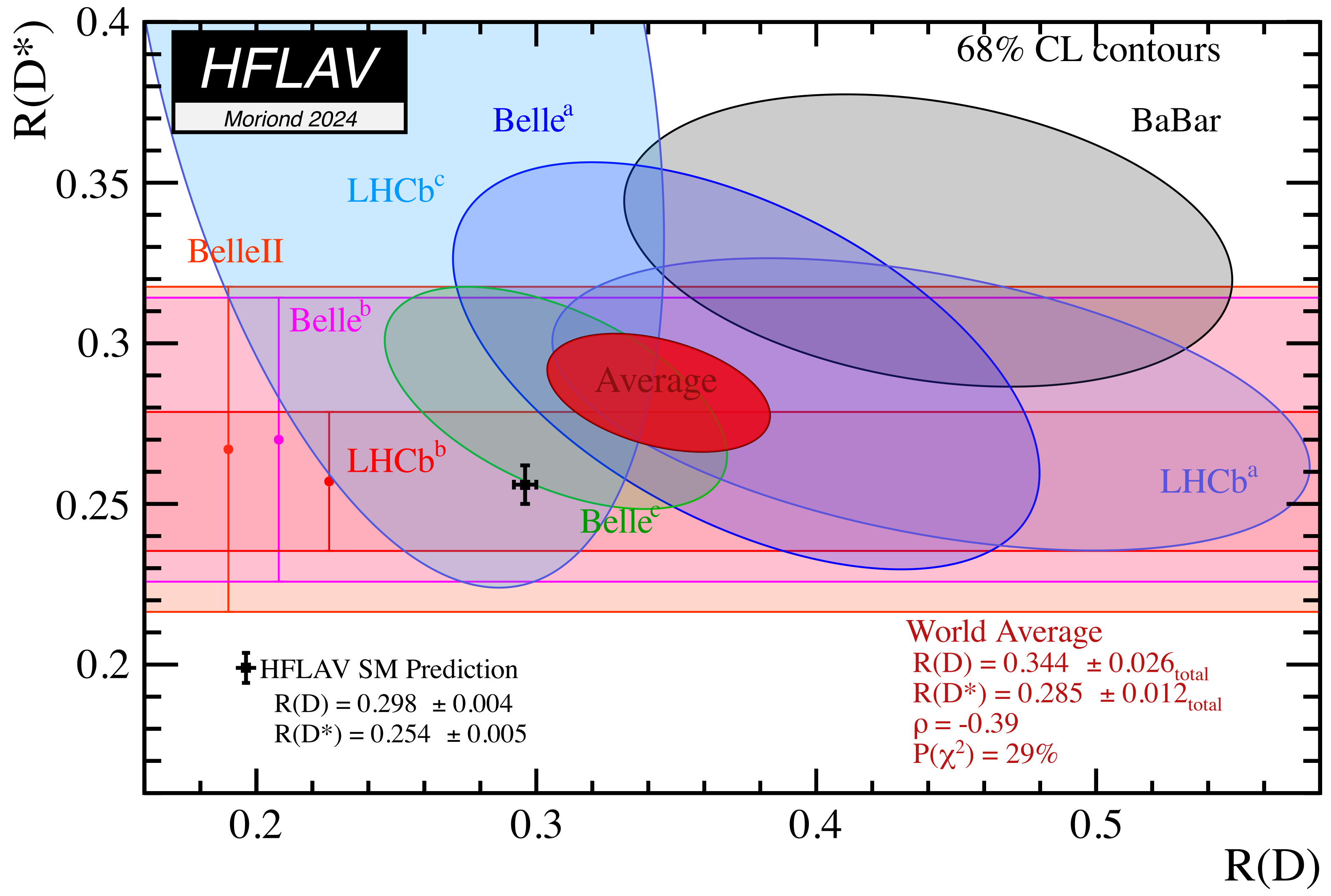
[IJMP A 30 (2015) 1530022]

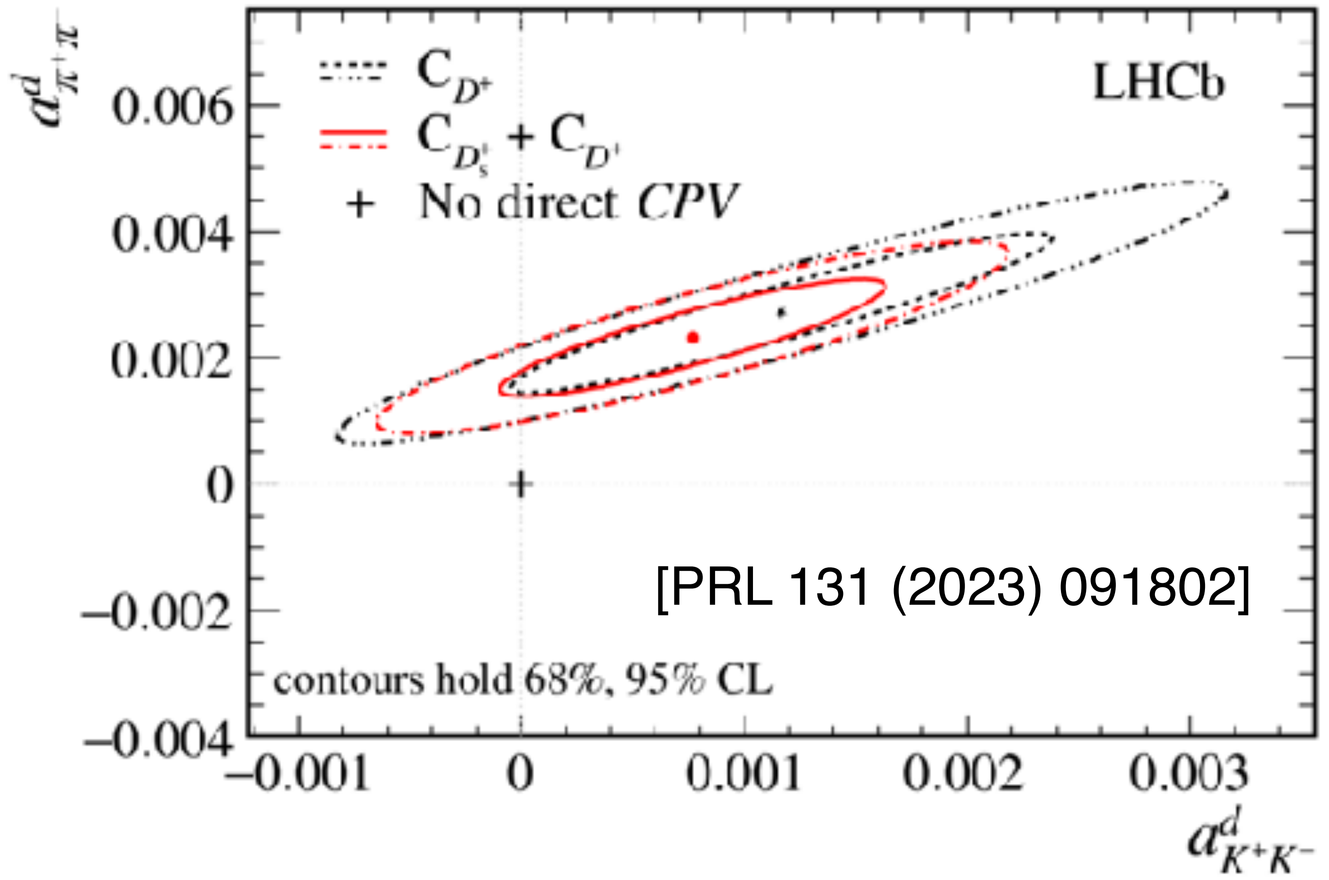
LHCb harvest of Run 1&2



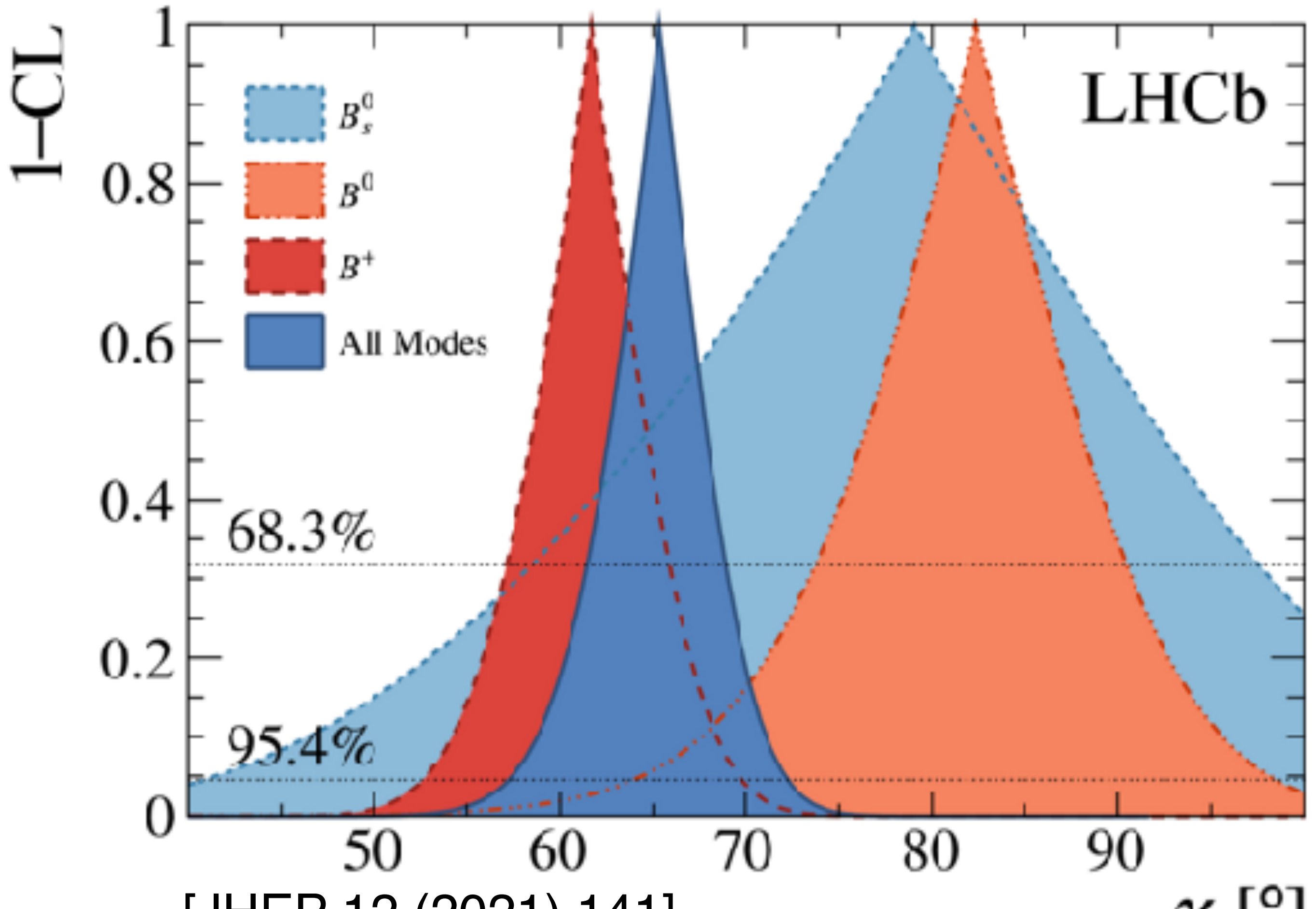
[PRL 128 (2022) 041801]
[PRD 105 (2022) 012010]



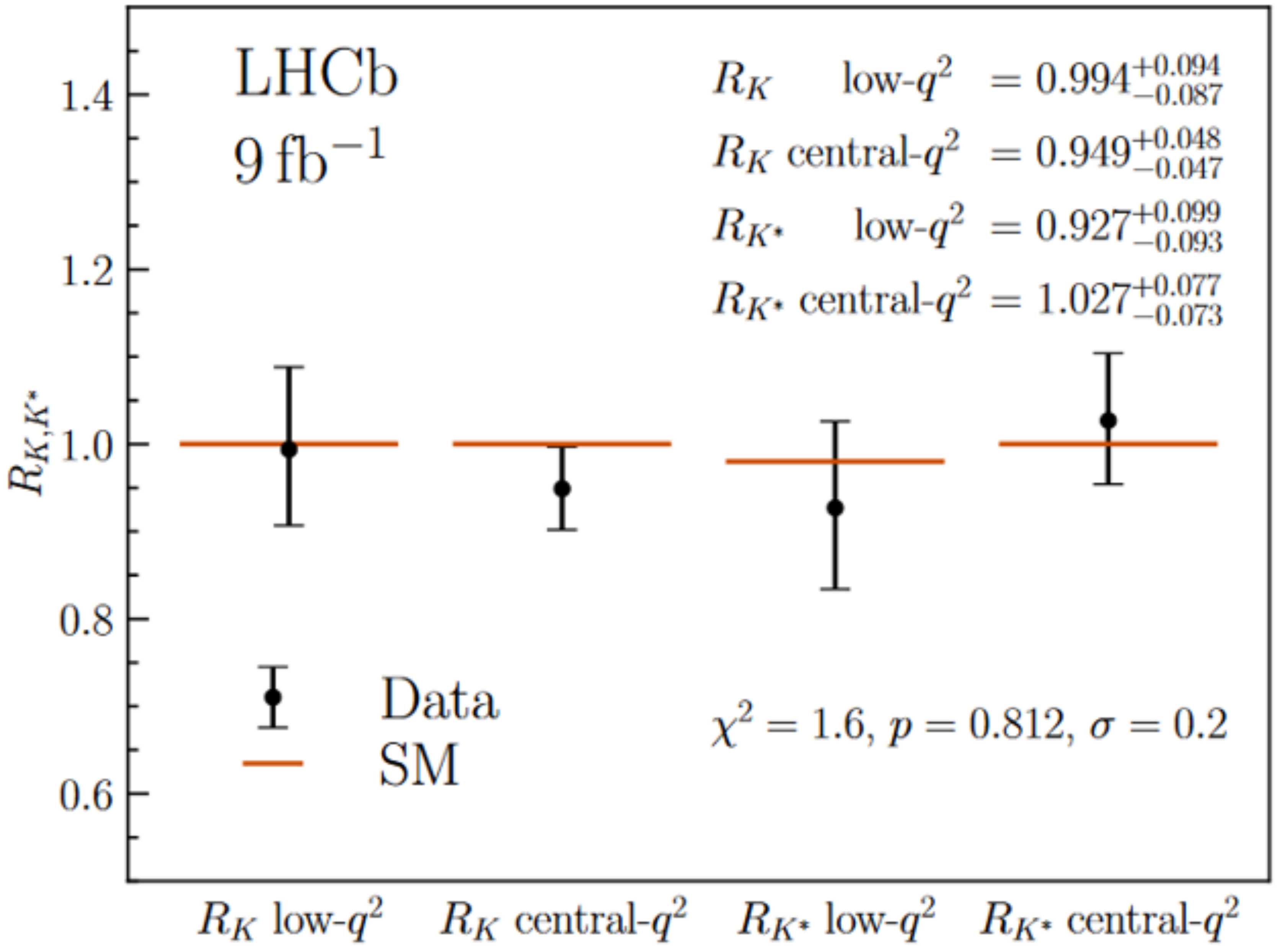




[PRL 131 (2023) 091802]



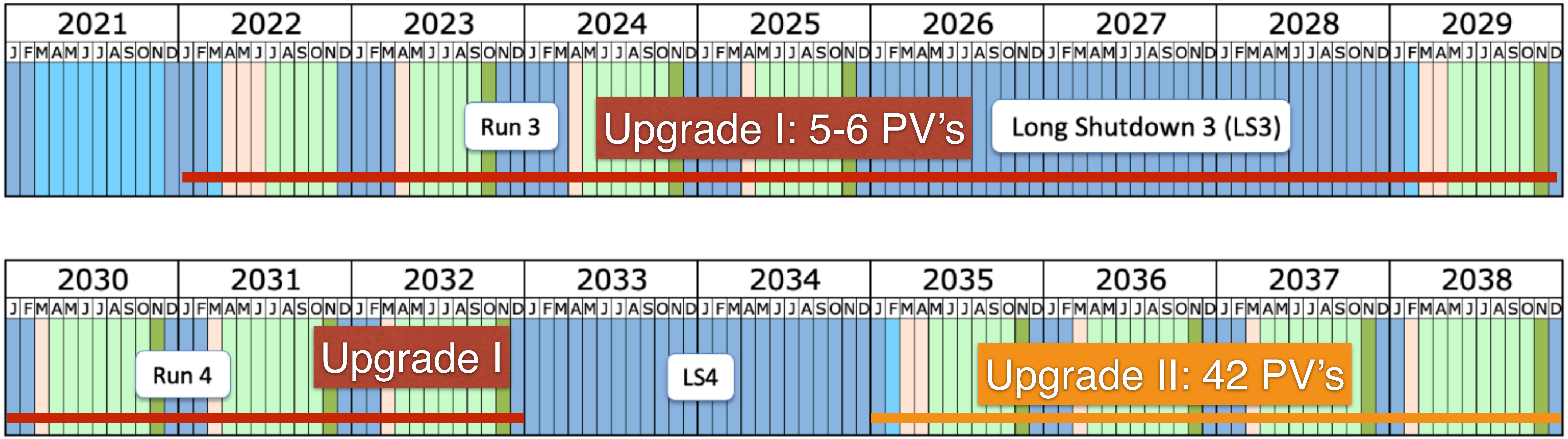
[JHEP 12 (2021) 141]

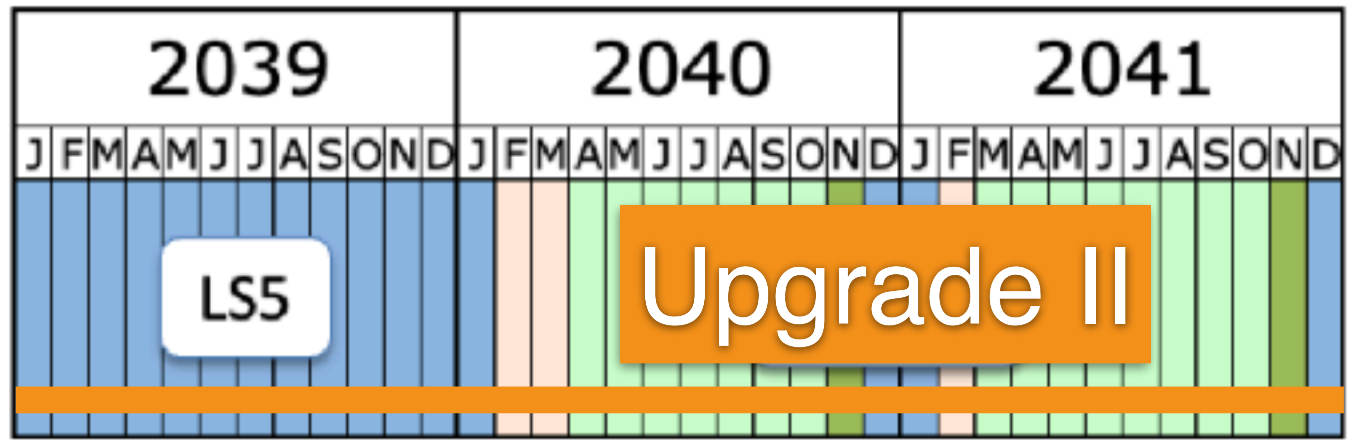


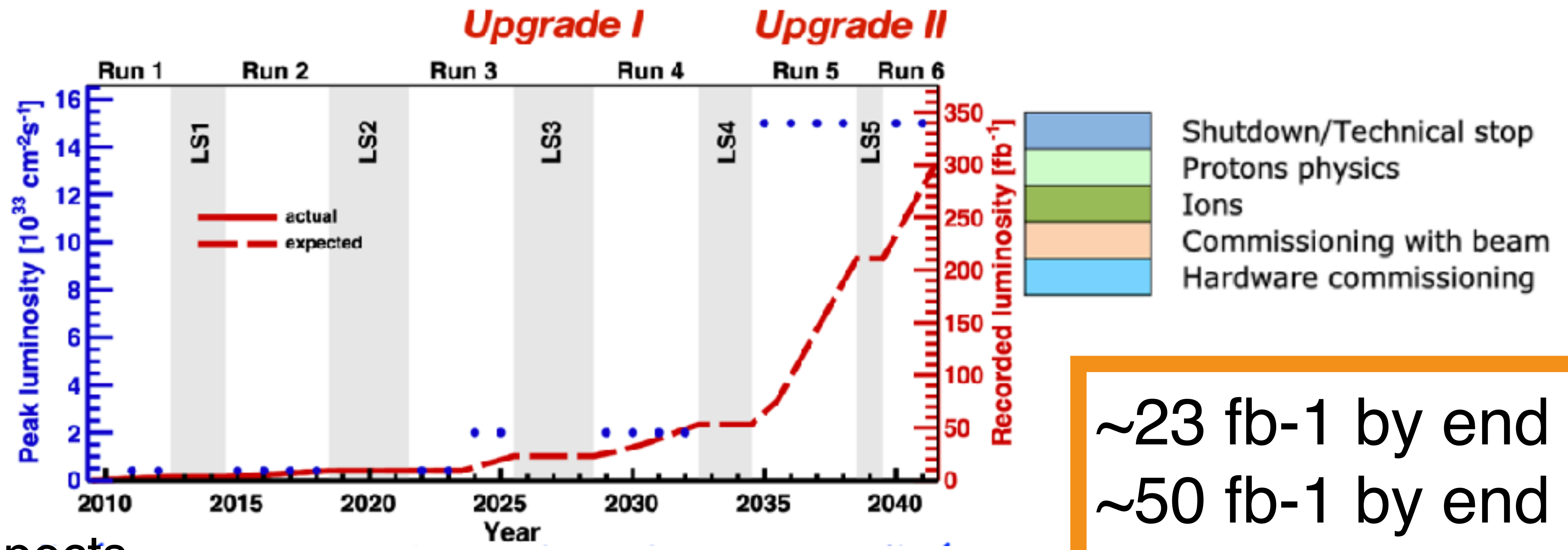
[PRL 131 (2023) 051803]
[PRD 108 (2023) 032002]

LHC time line

LHC schedule







Increase inst. luminosity
@ **similar or better performance!**

LHCb Upgrade II prospects

~23 fb-1 by end of Run 3
~50 fb-1 by end of Run 4
~300 fb-1 by end of Run 5/6

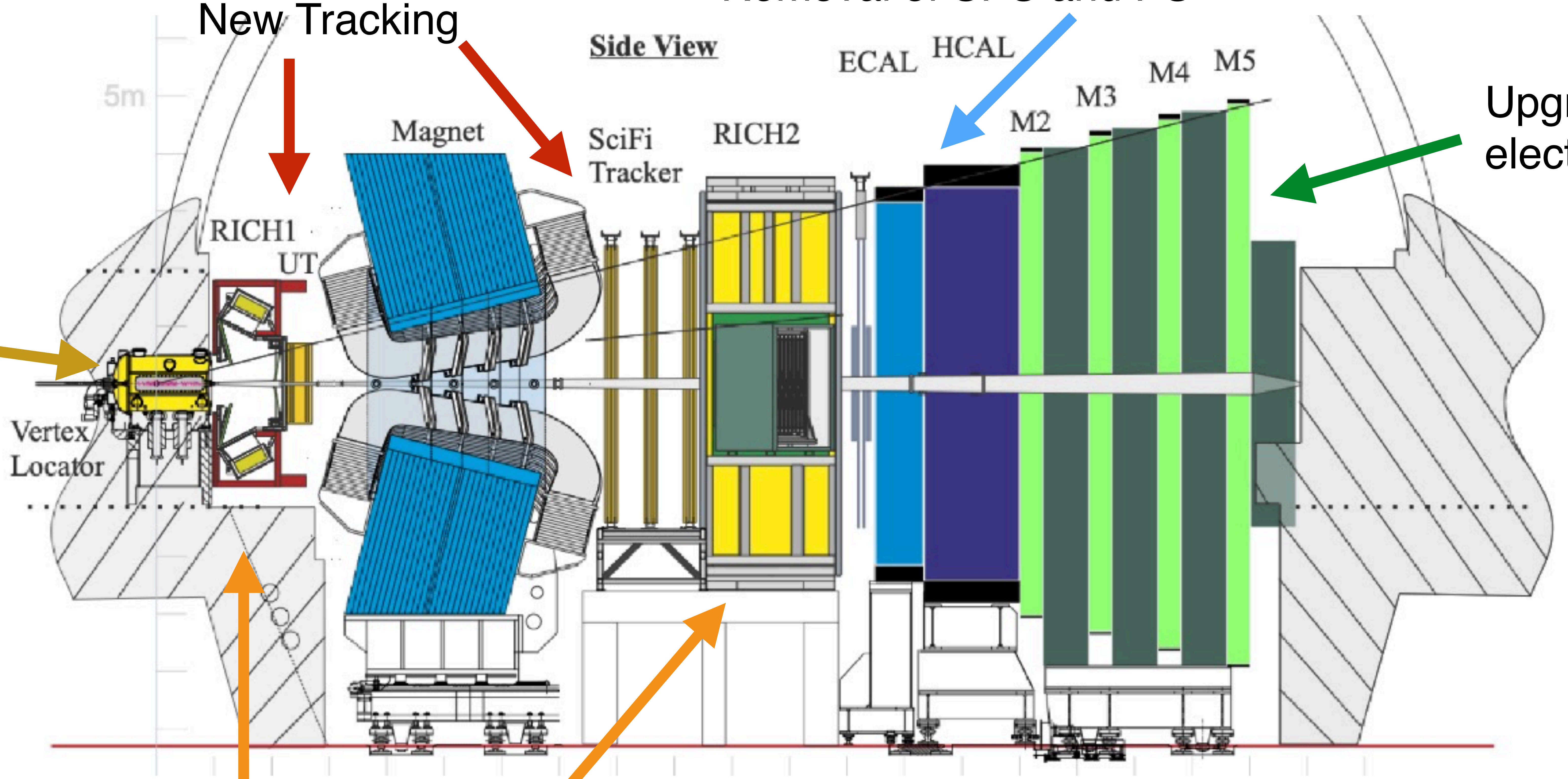
LHCb detector in Run 3&4

New front-end electronics,
Removal of SPS and PS

New Tracking

Upgrade Muon front-end electronics

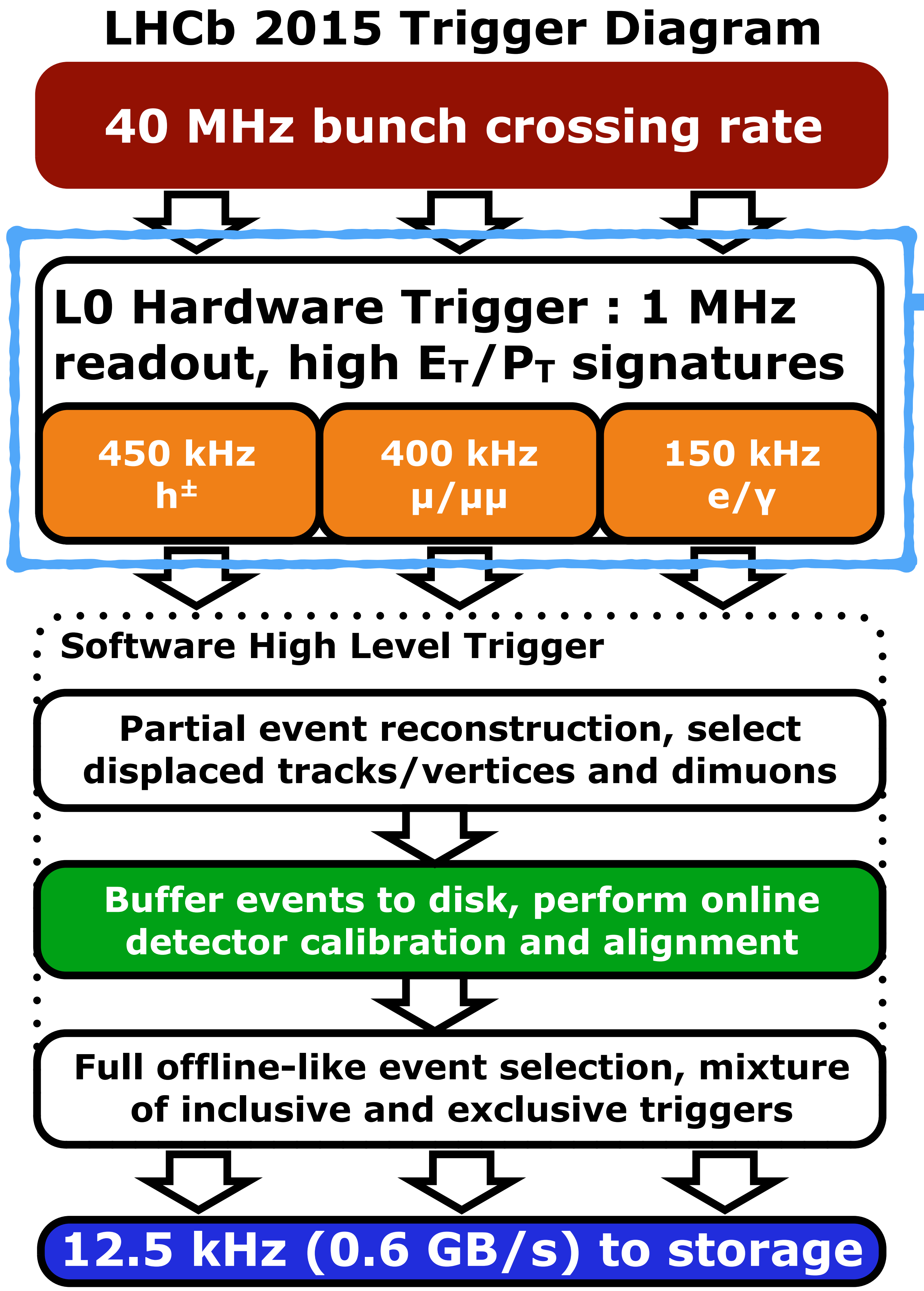
New VELO:
Nominal sensor position @ 5.1 mm (before: 7mm) from collision region
→ improved vertexing!



New RICH PMT's and electronics

LHCb Upgrade I

LHCb trigger in Run 3&4

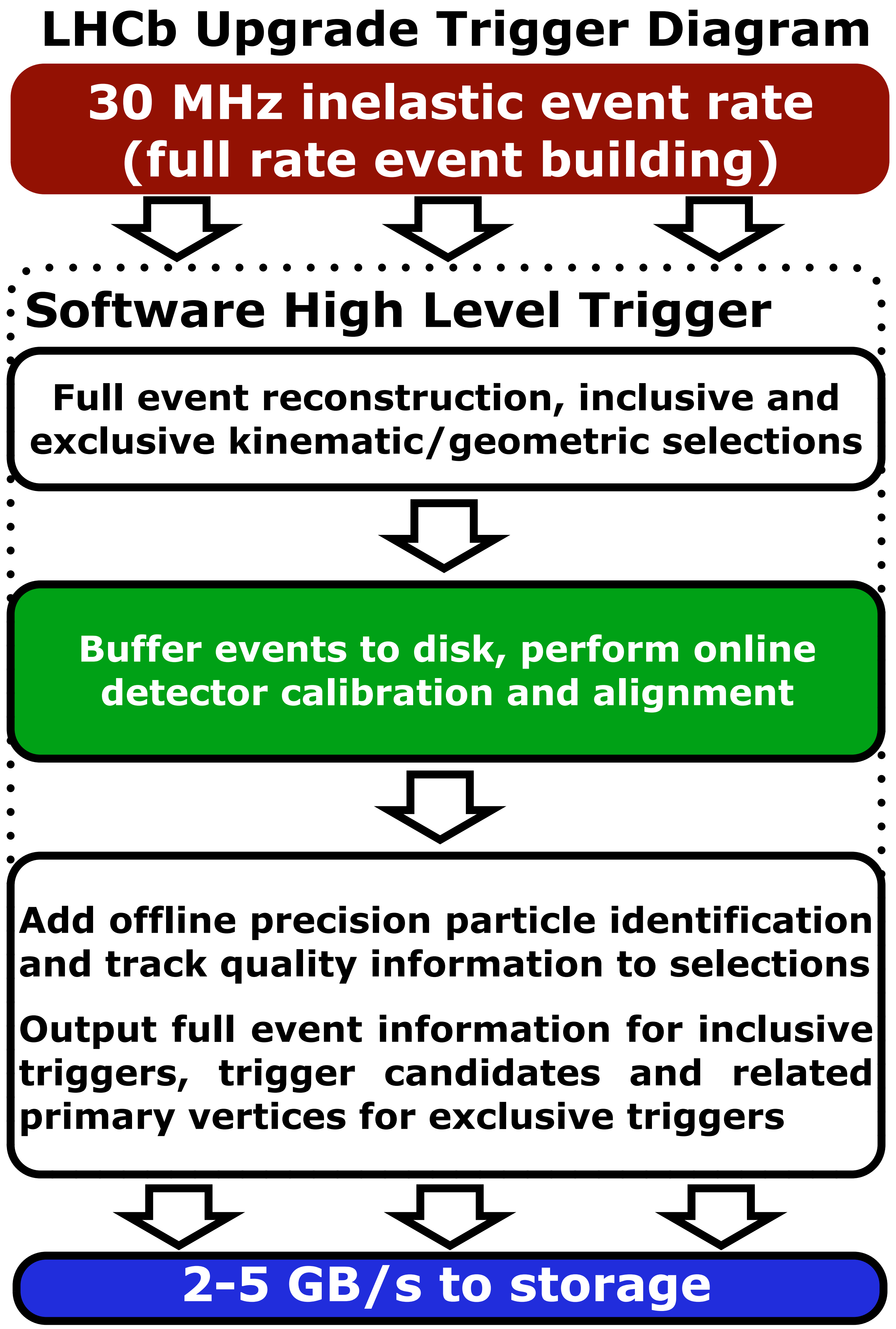


Removal of L0 hardware trigger

Two-staged high-level trigger: HLT 1 (GPU) and HLT2 (CPU)

Full software trigger allows

- More flexible selection with softer p_T requirements
  → benefit to soft muons from charm, tau, strange
  → benefit with electrons in final state
- Offline quality HLT2 trigger allows sophisticated selections → gain of up to $\times 2$ in fully hadronic final states



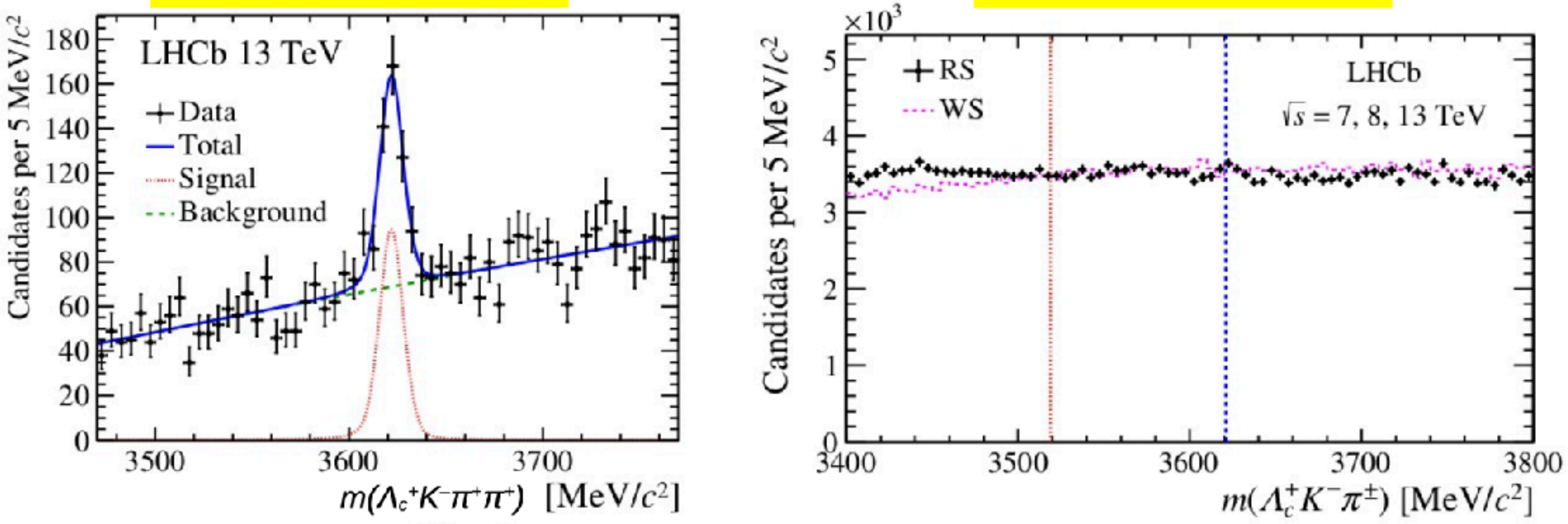
Trigger schemes

The importance of vertexing

- Expect to improve decay time resolution σ_t by 10% wrt Run 1/2
- Nominal sensor position at ~5.1 mm from interaction region (before 7.5 mm)
- Better track-vertex association → reduce random track combinations

Vertexing

LHCb-PAPER-2017-018 LHCb-PAPER-2019-029



Why do we observe the Ξ_{cc}^{++} (left), but not the Ξ_{cc}^{++} (right)?

Likely explanation: $\tau(\Xi_{cc}^{++})$ ~ 250 fs [LHCb-PAPER-2018-019]; $\tau(\Xi_{cc}^{+})$ ~ 80 fs [predicted]

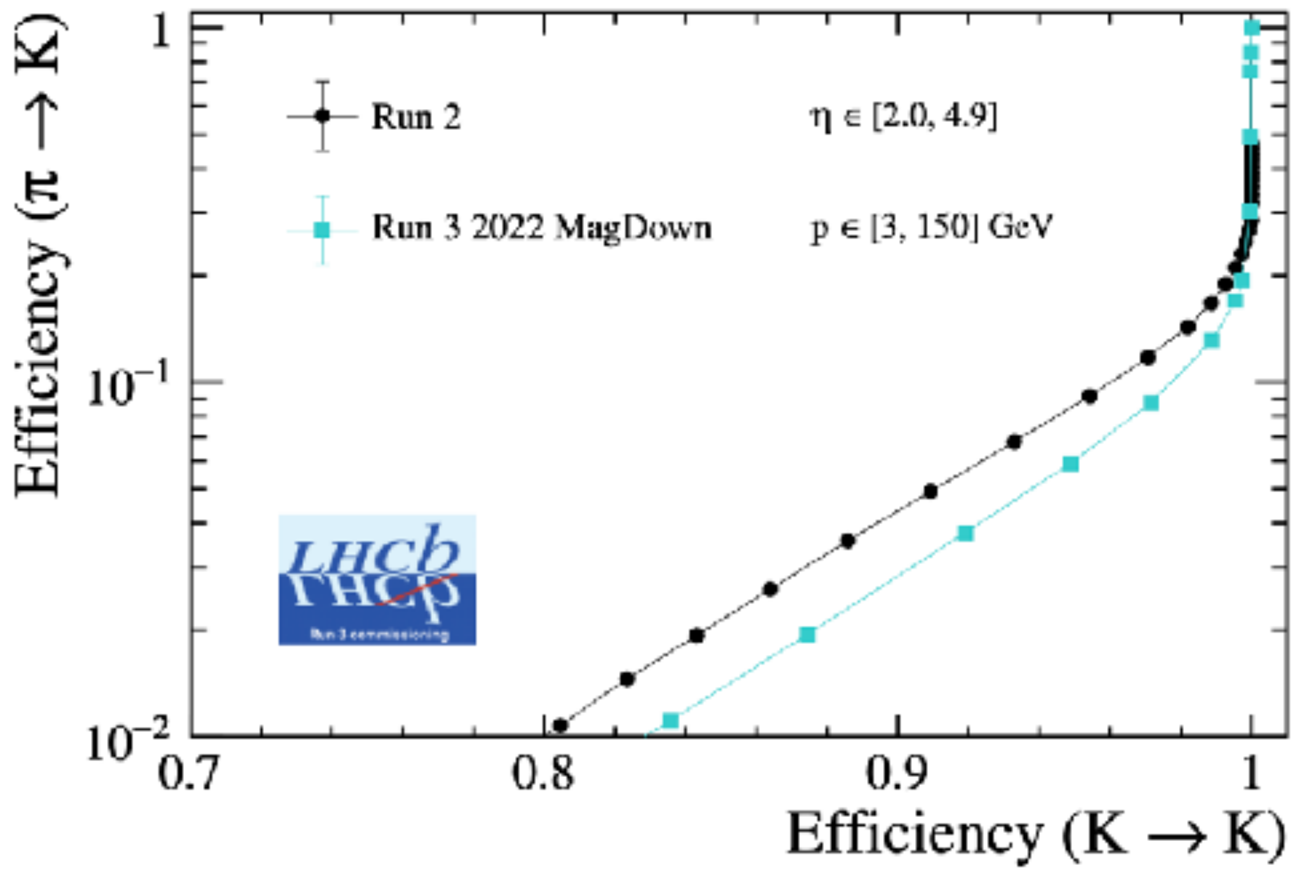
VELO performance enough to separate Ξ_{cc}^{++}, but not Ξ_{cc}^{+}, from PV background

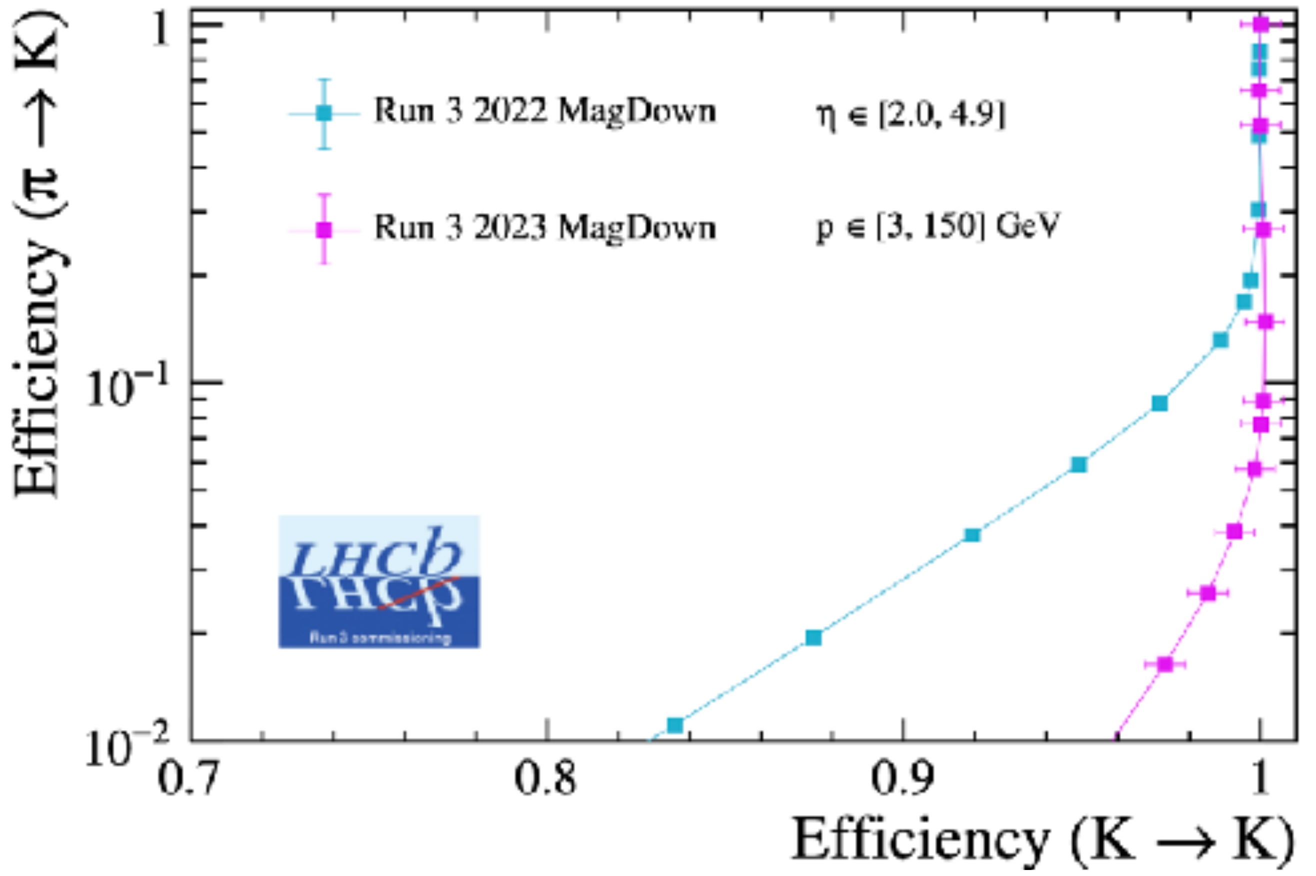
T. Gershon @ LHCb U II workshop

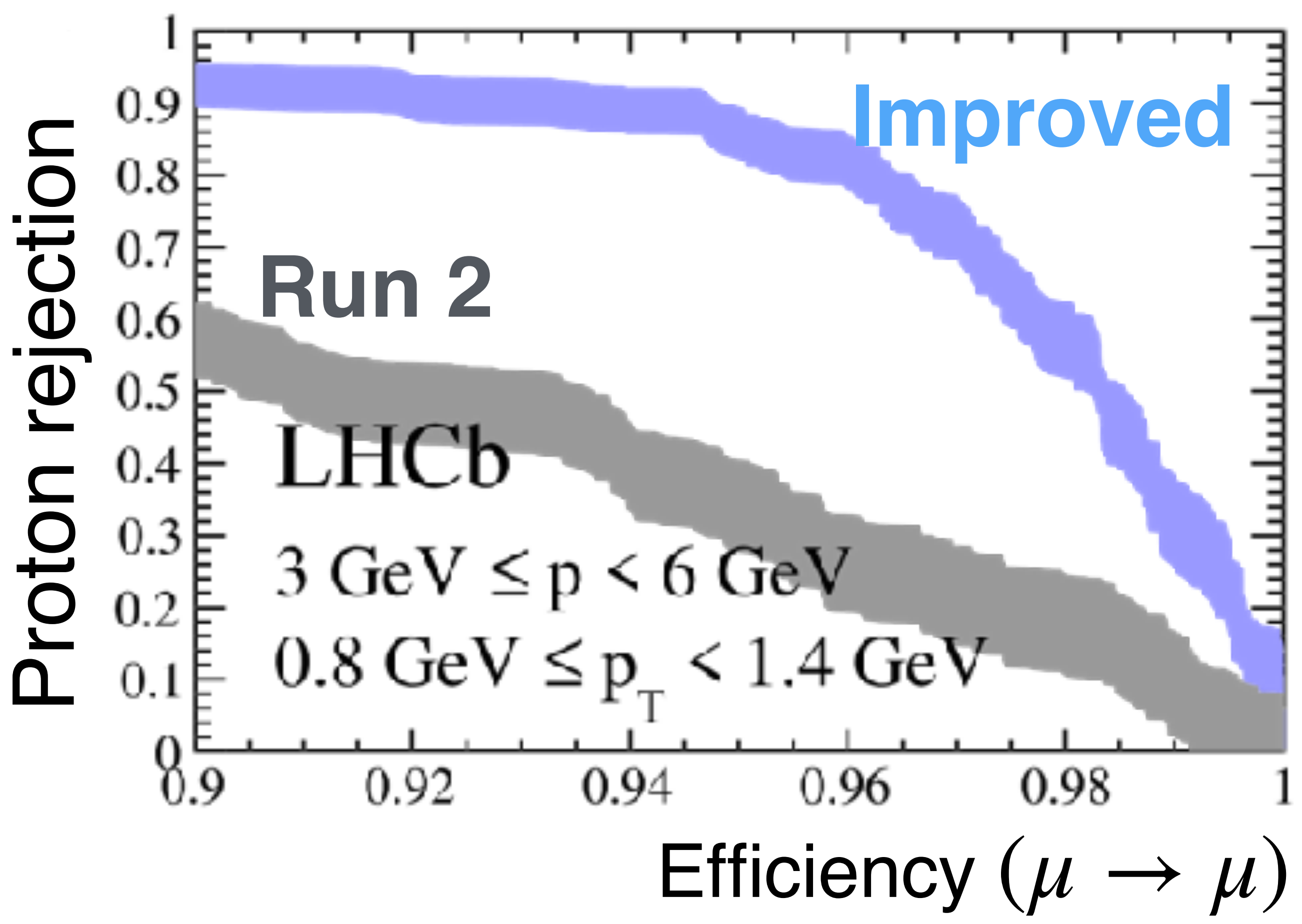
Particle identification performance in Run 3

- Achieve excellent hadron identification → important for background reduction, but also crucial for flavour tagging
- Good photon calibration
- More performant lepton identification at trigger level → more efficient trigger selection

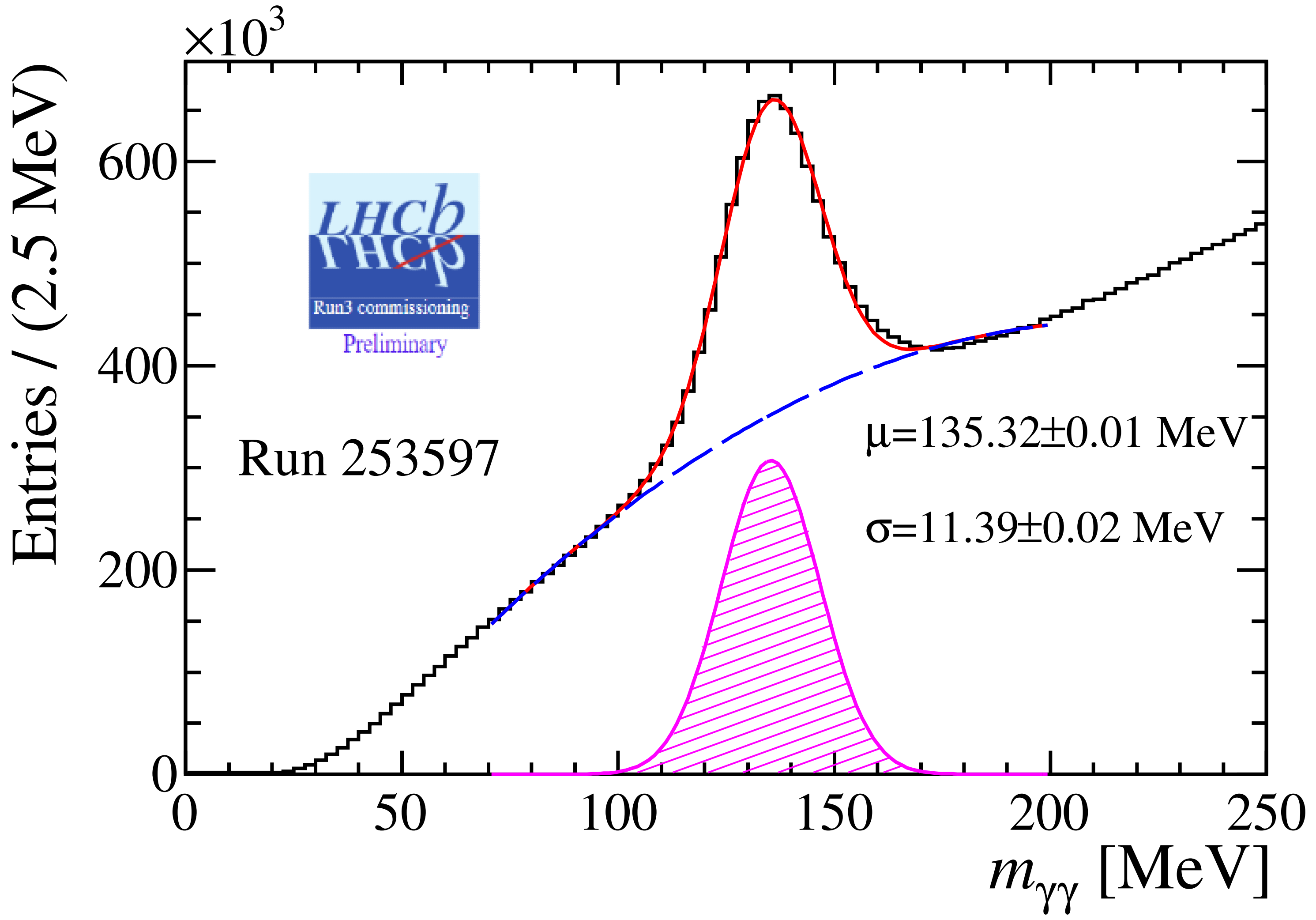
[LHCb-FIGURE-2023-019]







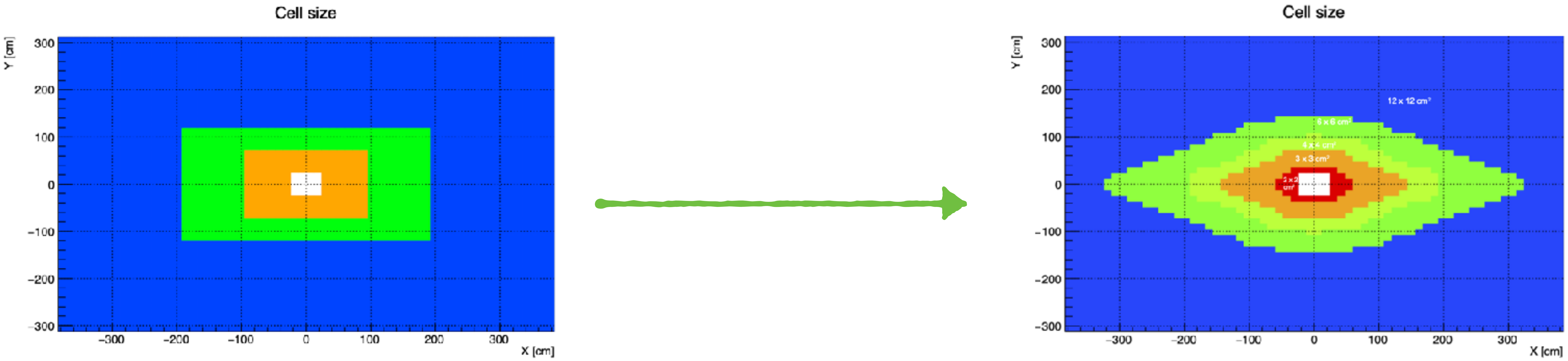
[JINST 15 (2020) T12005]



[LHCb-FIGURE-2022-019]

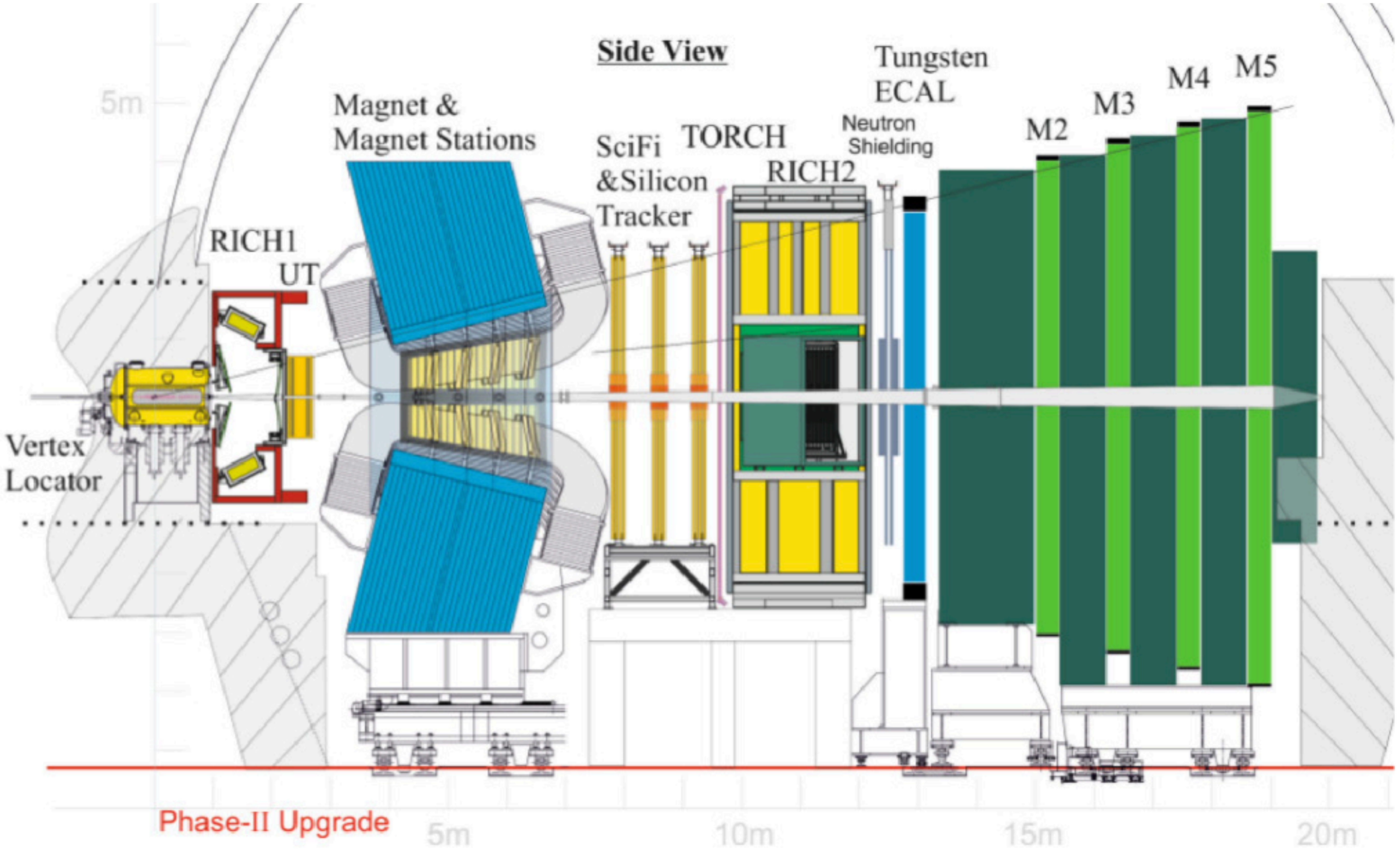
Enhancements for Run 4 (>2029)

- Improved Charged PID (RICH): new electronics that allows photon time-of-arrival measurement → better photon-track matching
  - Relevant for suppressing backgrounds with misidentified particles
  - Also important for flavour tagging
- Improved neutral PID (ECAL): replace inner section (radiation damage) with higher granularity and different basic geometry that better matches occupancy



LHCb in Run 5&6 - another fully new detector

- Expect to cope with Pile-Up of ~42 PV's
  →High timing resolution to resolve PV's
- Replace almost all sub detectors
  - Biggest challenge: occupancy
  - Main tracker out of silicon and fibres
  - More fine-grained calorimeter
  - New Muon system
- New detectors to improve performance
  - Magnet stations for soft tracks
  - TORCH for improving PID performance
  - Neutron shield to increase ECAL performance
  - New ECAL



LHCb Upgrade II prospects

Clear winner: rare charm and tau decays

- Gain in acceptance from L0 removal
- Better kinematic overlap between modes helps with systematics
- Dedicated new selections for better misID control ($\pi \to \mu$)

- Rare tau decays like $\tau \to \mu\mu\mu$ receive boost from new trigger scheme
  - Removal of L0
  - Improved muon identification at HLT1 level will help improve statistics
  - UII with improved calorimetry will help control $D_s^+ \to \eta(\to \mu^+\mu^-\gamma)\mu^+\nu$

- 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)

Slides of D. Unverzagt, Charm23

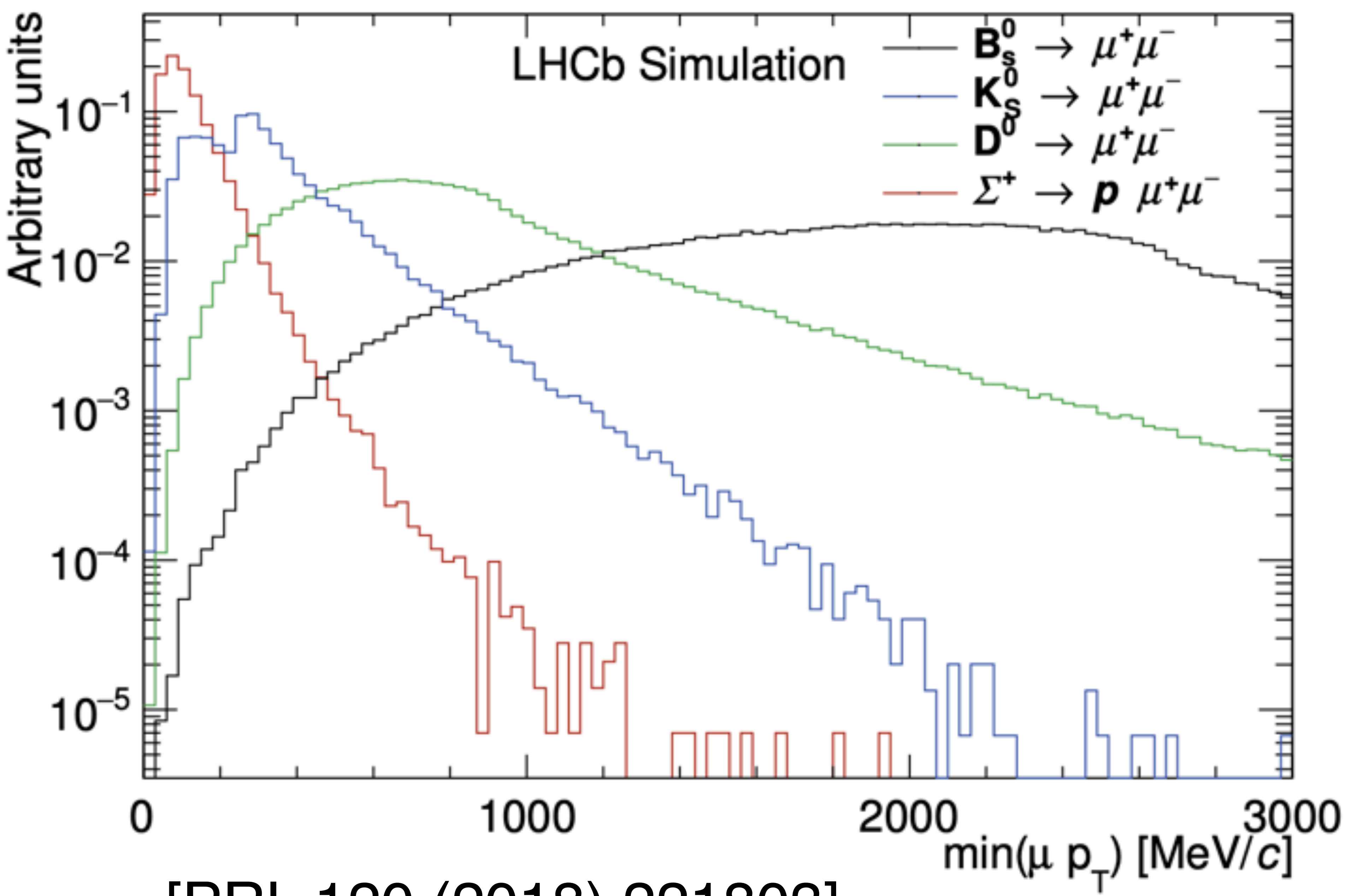
$\mathscr{B}(\tau^\pm \to \mu^\pm\mu^-\mu^+) < \mathcal{O}(10^{-9} - 10^{-8})$ in upgrades
Competitive to Belle II, probing relevant NP region

LHCb Upgrade II prospects

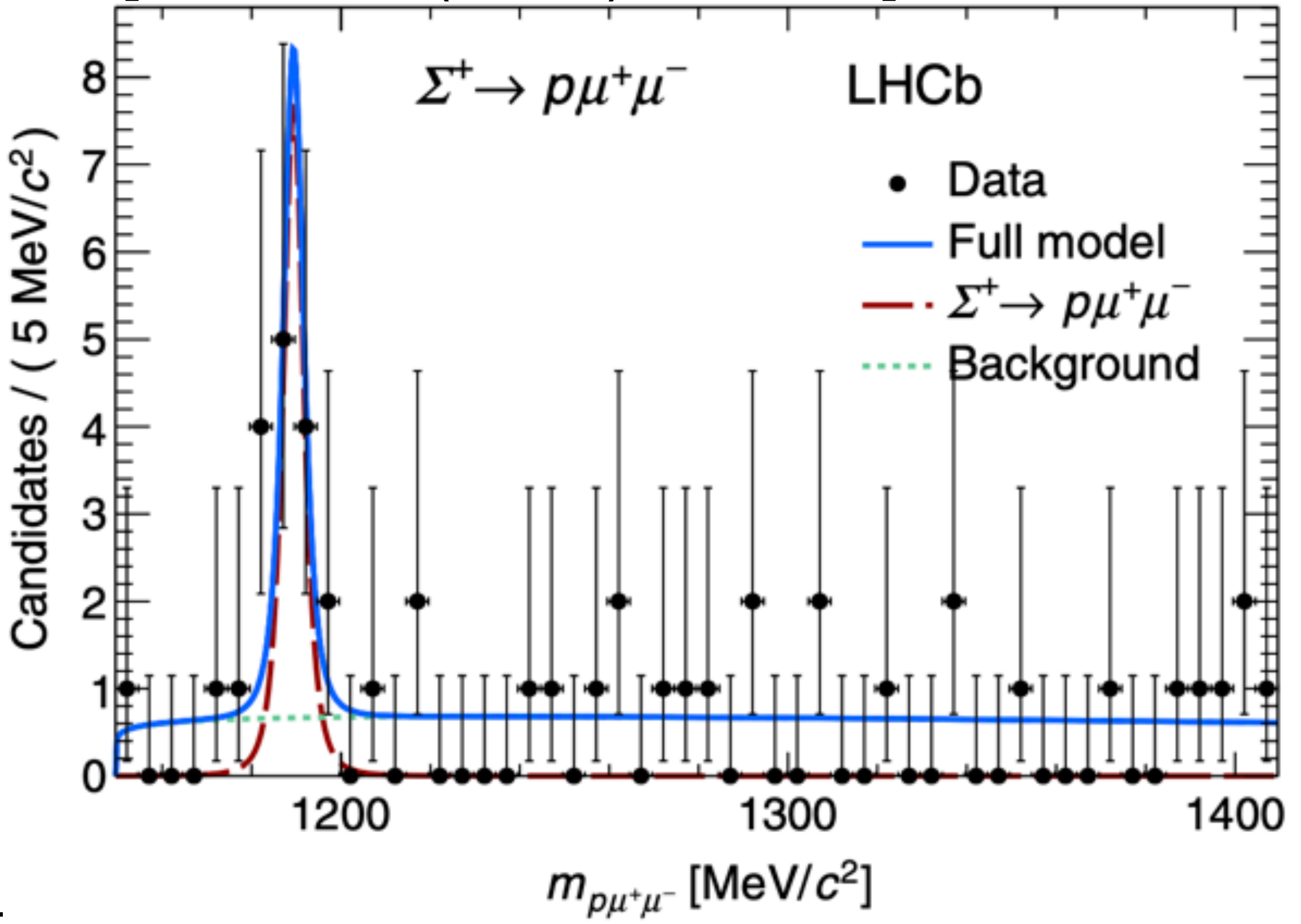
Clear winner: rare strange decays

- Typical $p_T < 0.1$GeV, while B physics ~1-2 GeV
  - Significant gain by L0 removal
- Started with $K^0_\mathrm{S} \to \mu^+\mu^-$
  - Dedicated HLT1 and HLT2 lines since Run 2
  - Being exploited with $K^0_\mathrm{S} \to \mu^+\mu^-\mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$...
- Large sample of strange mesons and baryons ready to be analysed [JHEP 05 (2019) 048]
  - $K^0_\mathrm{S} \to 2\ell, 4\ell$, $K^0_\mathrm{S} \to \pi^0\mu^+\mu^-$, strange baryon decays
  - Unique role as high-yield kaon experiment after stop of NA62!
  - Can learn from $K^0_\mathrm{S} \to \mu^+\mu^-$ and write more dedicated triggers
  - Large lifetime allows to use tracking for charged LLP's! [LHCb-DP-2023-004]

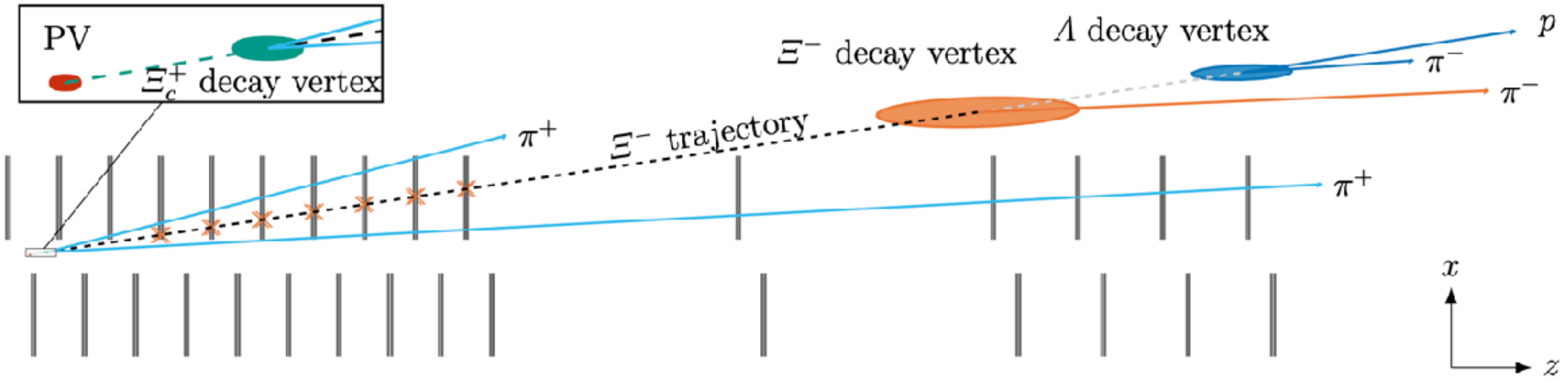
[LHCb-PUB-2017-023]



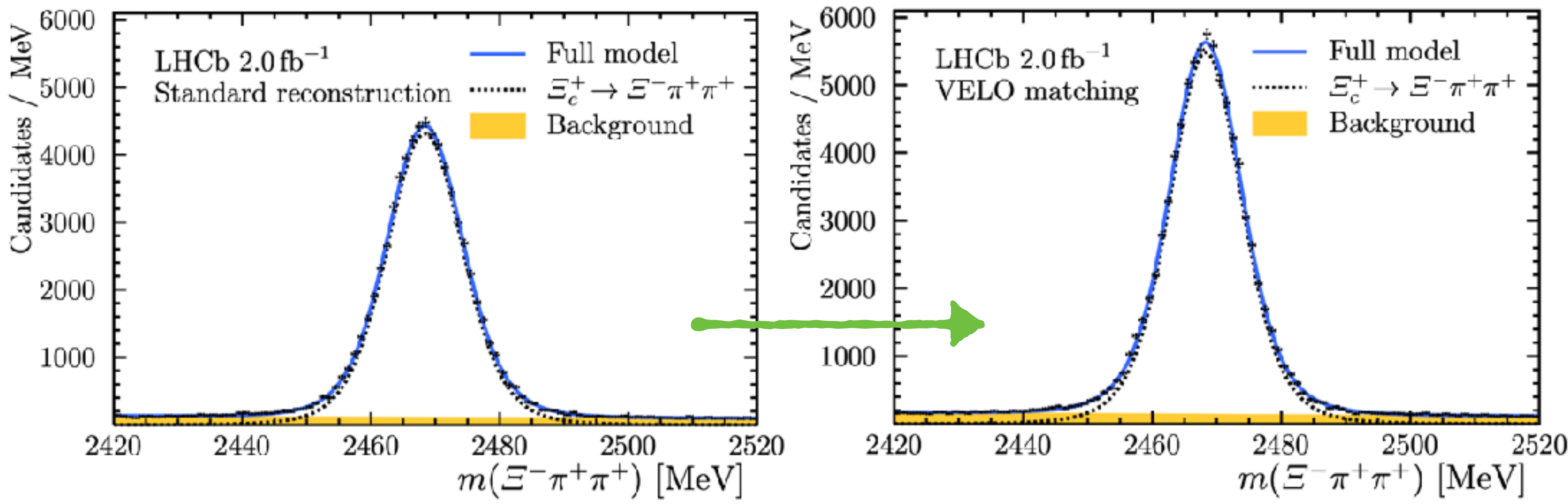
[PRL 120 (2018) 221803]



Charged long-lived particle tracking [LHCb-DP-2023-004]



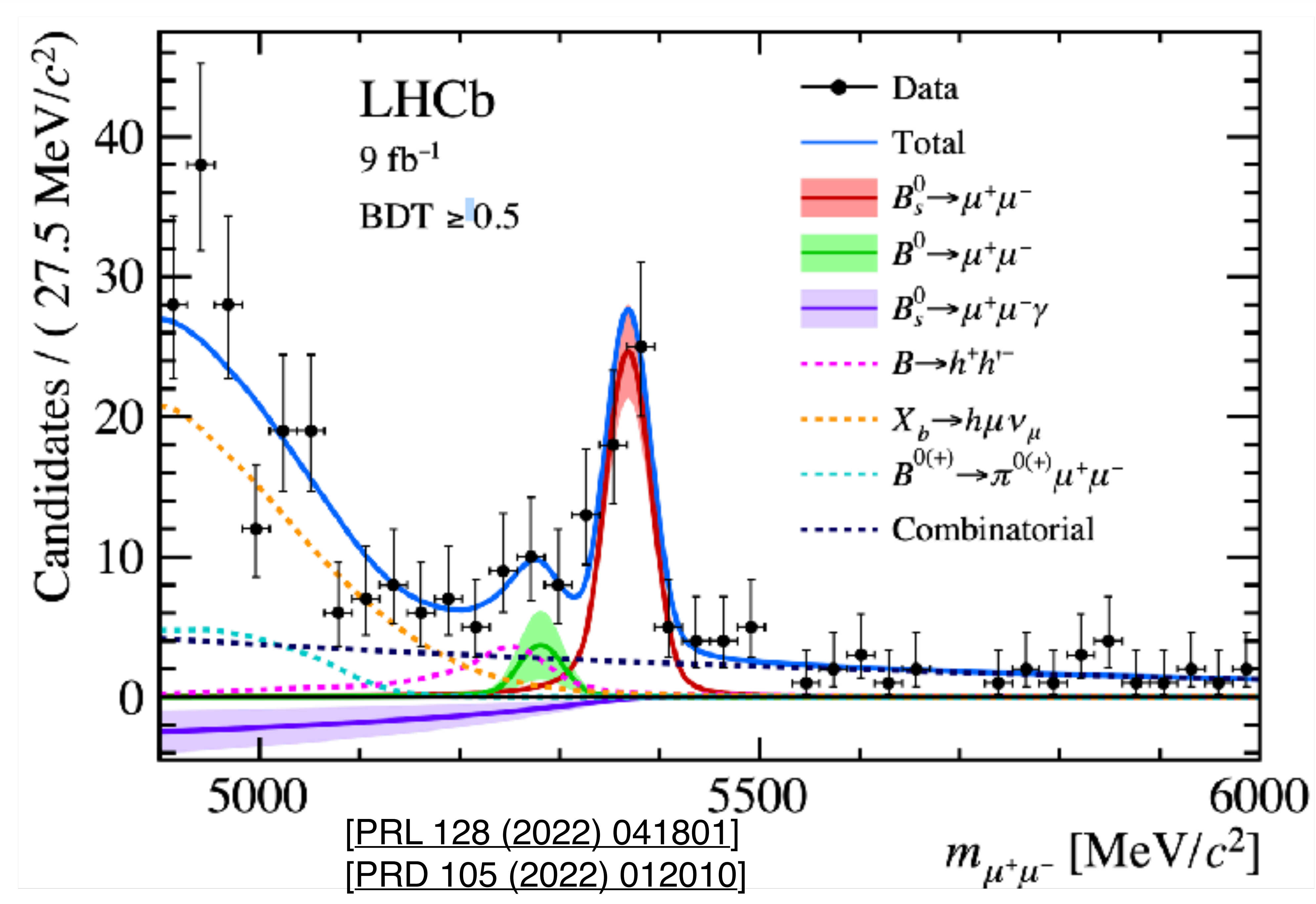
- Look for VELO stub to associate to the collision vertex and decay vertex of long-lived particles
- Case: $\Xi_c^+ \to (\Xi^- \to (\Lambda \to p\pi^-)\pi^-)\pi^+\pi^-$
- Shown to improve efficiency and resolution (and thus purity) of benchmark mode
- Implemented in the Run 3 trigger
- Potential for $\Sigma^+ \to p\ell^+\ell^-$ and $K^+ \to \pi^+\pi^-\pi^+$ (kaon mass), but also potentially enables new modes with neutrals in the final state



What to expect from $B^0_{(s)} \to \mu^+\mu^-$?

Sensitivity @23fb-1 (300fb-1) from statistical scaling:
$\sigma(\mathcal{B}(B^0_s)) \approx 0.3(0.16) \times 10^{-9}$
$\sigma(\mathcal{B}(B^0)/\mathcal{B}(B^0_s)) \approx 34(10)\,\%$
$\sigma(\tau_{\mu\mu}) \approx 8(2)\,\%$
$\sigma(S_{\mu\mu}) < 0.2 \,@\, 300\,\mathrm{fb}^{-1}$

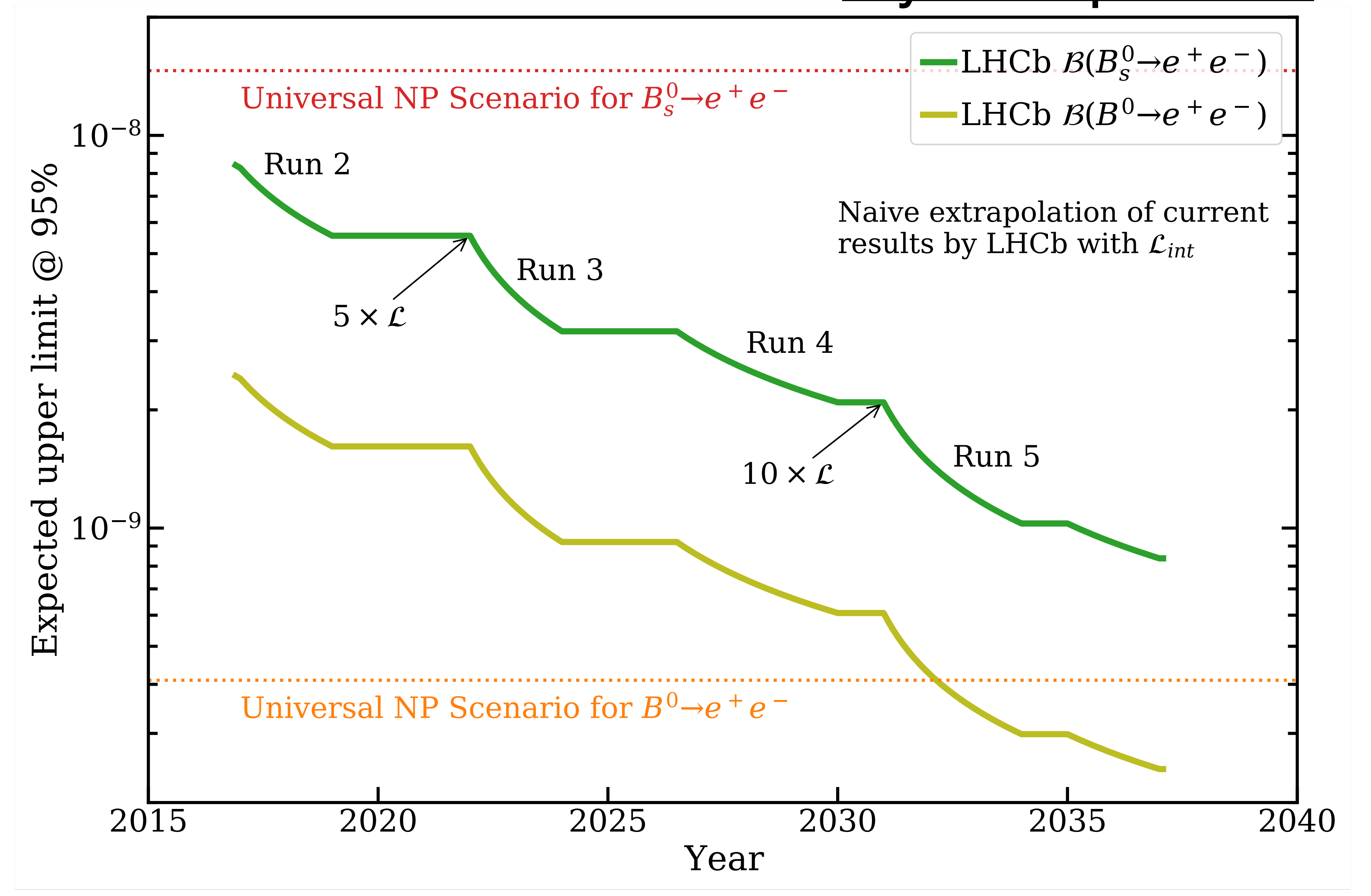
- Entering precision measurements for $B^0_s \to \mu^+\mu^-$
  - Can expect >1.5x improvement in Run 3 for branching fraction and effective lifetime
  - Hunt for $B^0 \to \mu^+\mu^-$
  - First measurements of time-dependent CPV parameter $S_{\mu\mu}$ in becomes possible
  - NEW: $B^0_s \to \mu^+\mu^-\gamma$ @ high q^2
  - Improvements beyond $\mathcal{L}$
    - Improved momentum=mass resolution: move from 22 MeV to 18.5 MeV
    - Vertex resolution improves control of combinatorial
- Experimental challenges:
  - Muon idententification
  - Flavour tagging performance



[PRL 128 (2022) 041801]
[PRD 105 (2022) 012010]

What to expect from other $B^0_{(s)} \to \ell^+\ell^{(\prime)-}$ and LFV?

My extrapolation



- Electron and tau performance enhanced wrt Run 1&2
  - No L0 throttling for electrons and hadrons
  - Gain of ~30% efficiency in Run 3
  - τ reconstruction relies on vertex quality $\rightarrow$ improvements expected
- Important di-tau analyses
  - No free lunch, potential ML improvements
  - Understanding of $\tau \to 3\pi$ important
- New $e\tau$-operators explored:
  - Mass resolution similar between $\mu\tau$ and $e\tau$ final states
  - Can constrain new parameter spaces
  - Studies with Run 2 ongoing

Expected limits @50fb-1 (300fb-1)

$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 1.3(0.5) \times 10^{-3}$

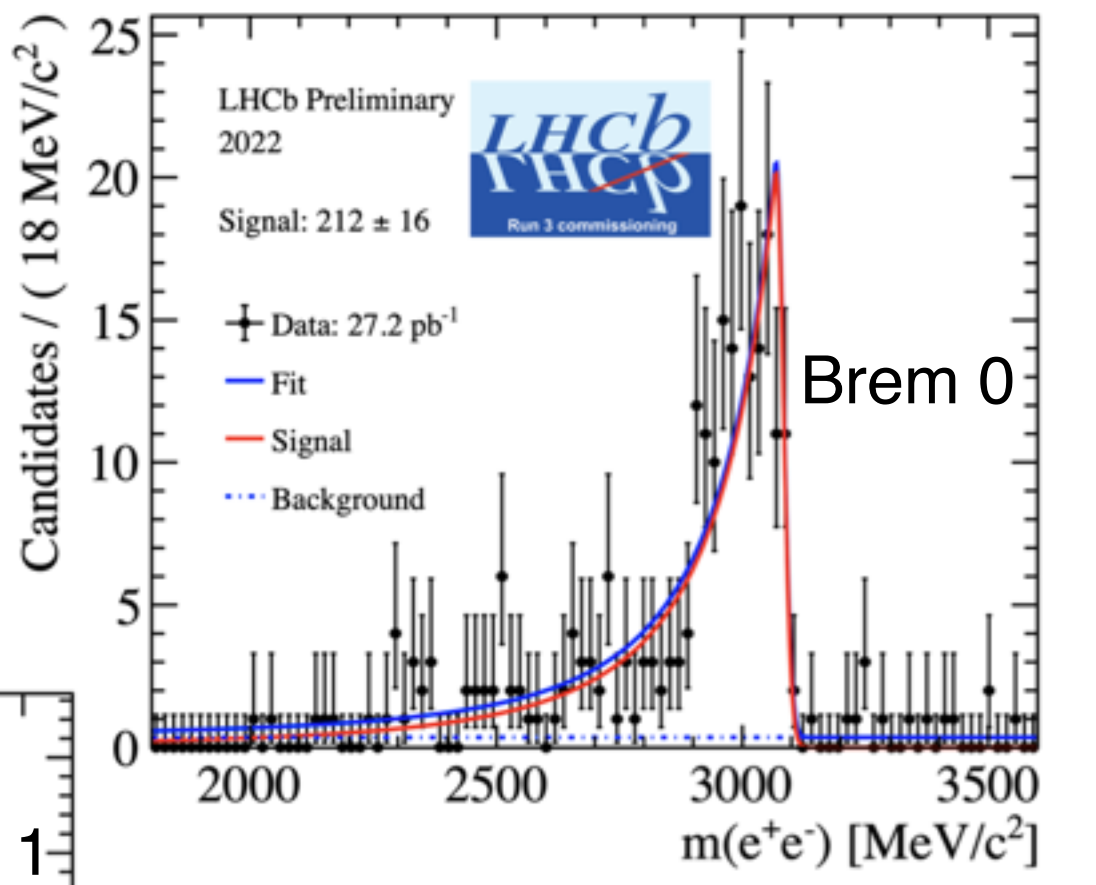
$\mathcal{B}(B^+ \to Ke\mu) < O(10^{-9}(10^{-10}))$

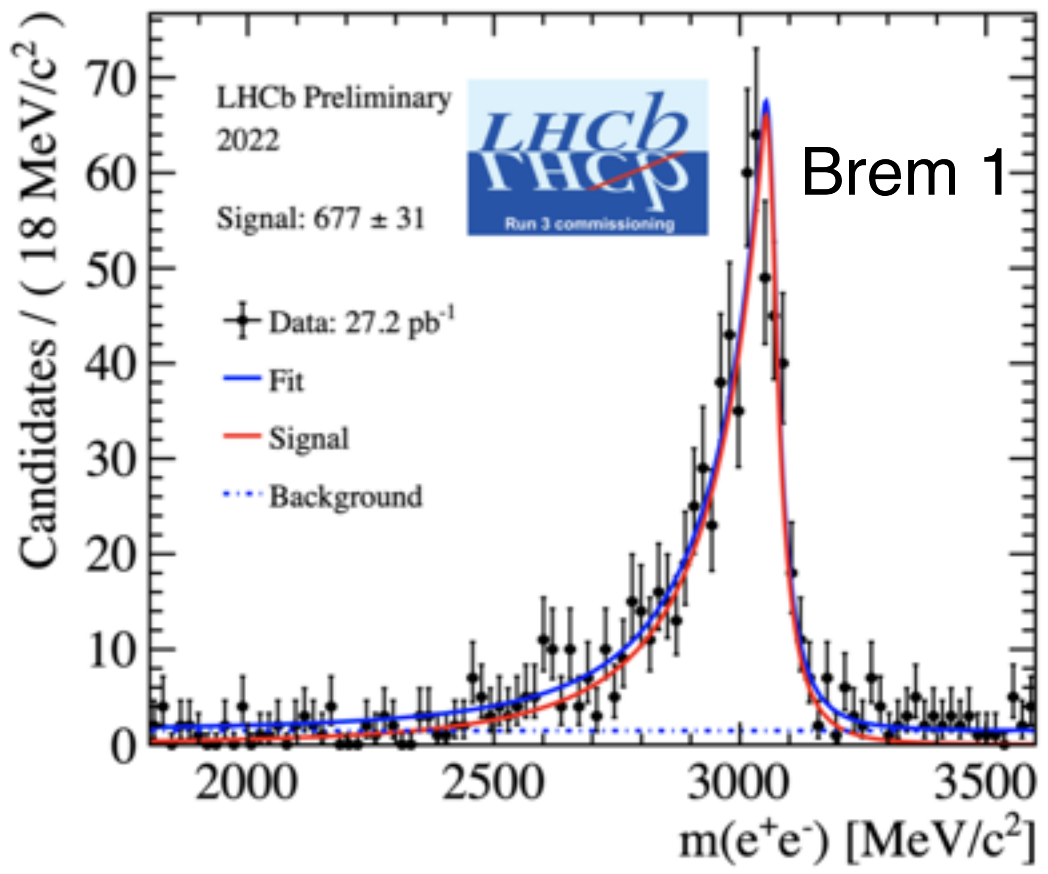
$\mathcal{B}(B^+ \to K\tau\mu) < O(10^{-6}(10^{-7}))$

LHCb Upgrade II prospects

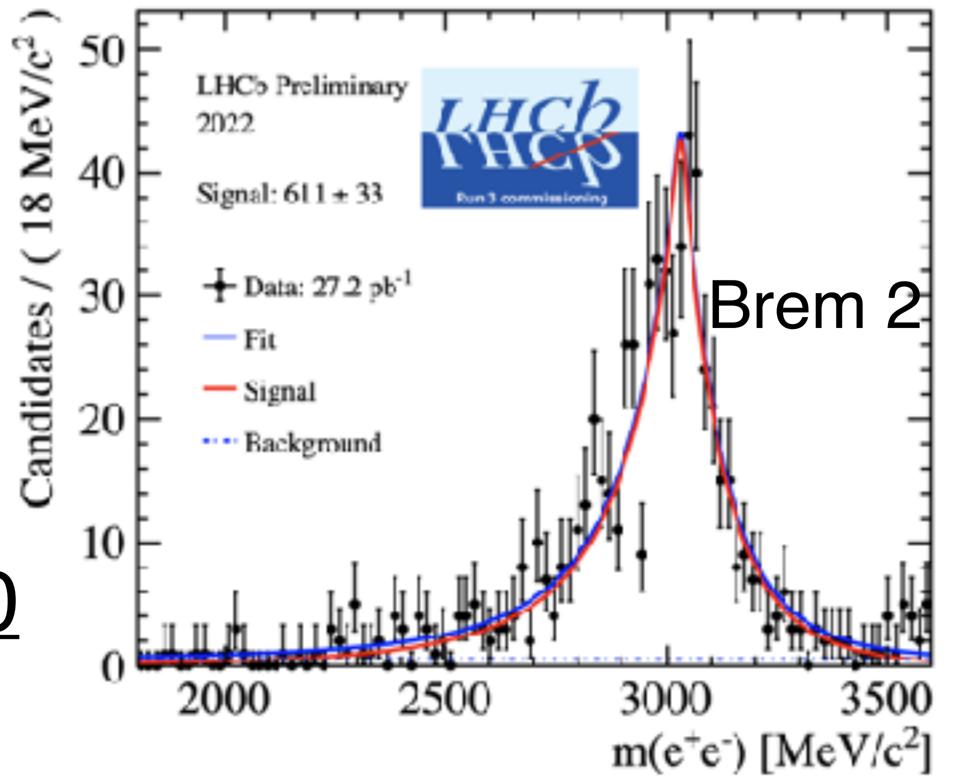
What to expect from $B \to X\ell\ell$ decays

- $b \to s\mu^+\mu^-$ differential branching fractions and angular analyses will be pinned down to maximum precision
  - Lively debates about interpretation with lots of theory input
  - Add differential angular analyses
- Electrons catching up
  - Adapted bremsstrahlung algorithm
  - Will be possible to perform similar measurements as with muons → lepton universality at high granularity, Q5 etc…
- At the same time investigate $b \to d\ell\ell$ (competition from Belle II)
- Perform time-dependent angular analyses in $B_s^0 \to \phi\ell\ell$, $B^0 \to K_S^0\ell\ell$, $B^0 \to \rho\ell\ell$
- Sparsely probed: baryonic transitions
  - Theoretically difficult
  - But access to potentially different phenomena
- Also $b \to s\gamma$ decays will benefit from improved ECAL





Brem proportions improved!



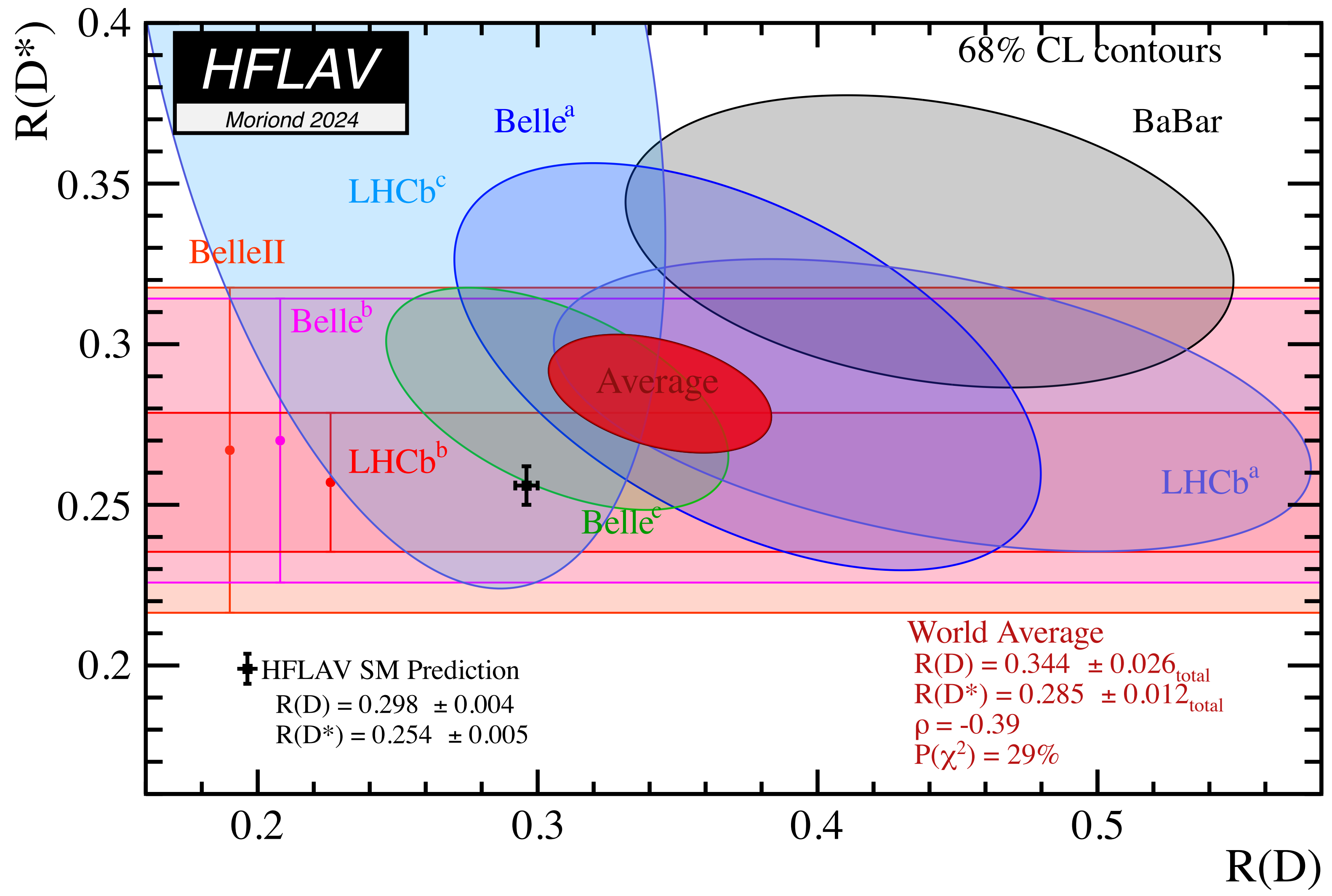
LHCb-FIGURE-2023-010

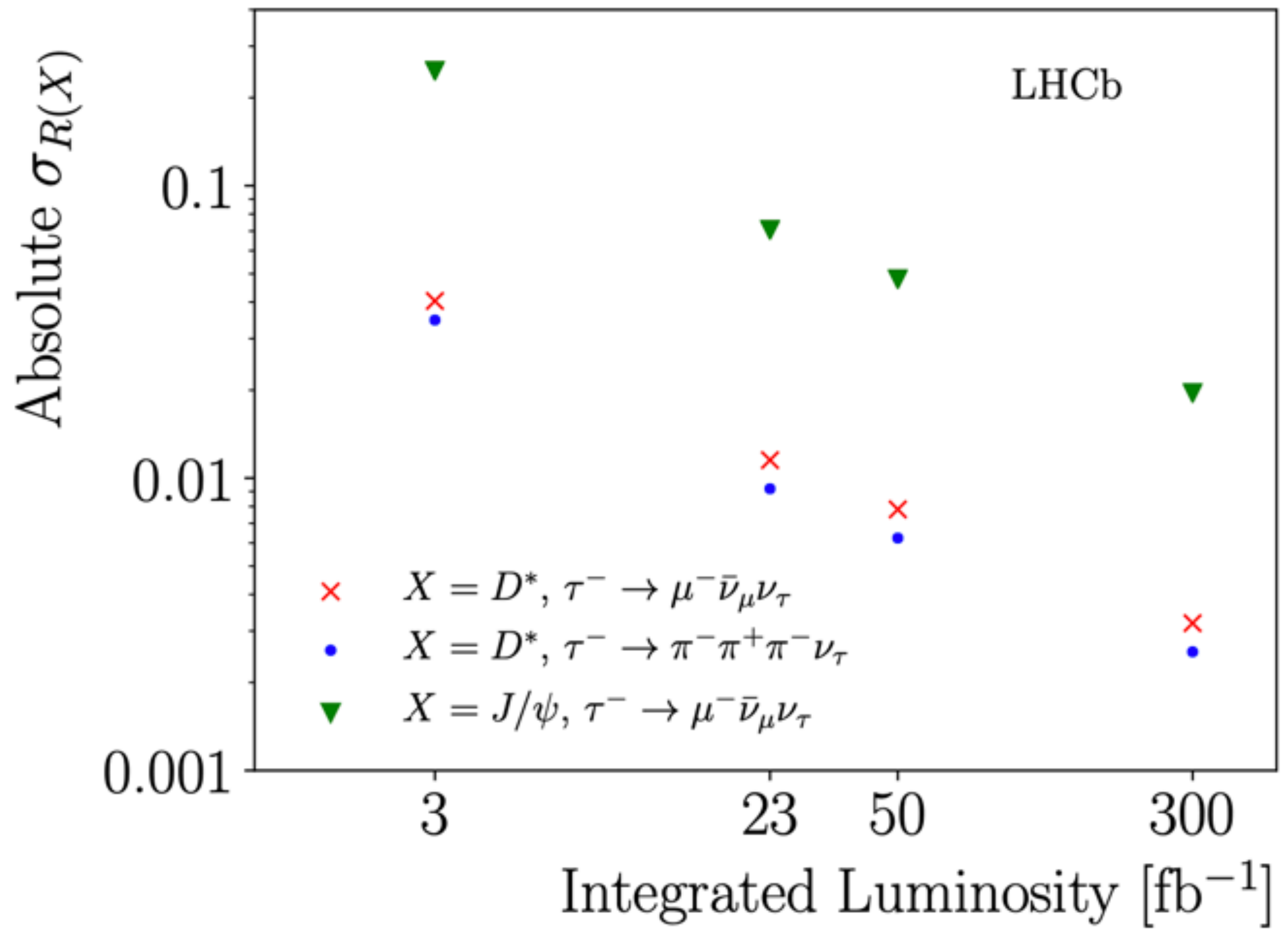
Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20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

LHCb Upgrade II prospects

RD/RDstar puzzle

- Highly complex analyses
- Large systematics
- Run 3+ offer
  - More data to accurately model the background
  - Improved systematics - scale with luminosity
  - Tailored selections for control modes to better study data-simulation differences
  - Remove dependency on $B^0 \to D^{*-}\pi^+\pi^-\pi^+$
  - Plethora of channels to clearly characterise the puzzle
  - Move to q^2-differential measurements



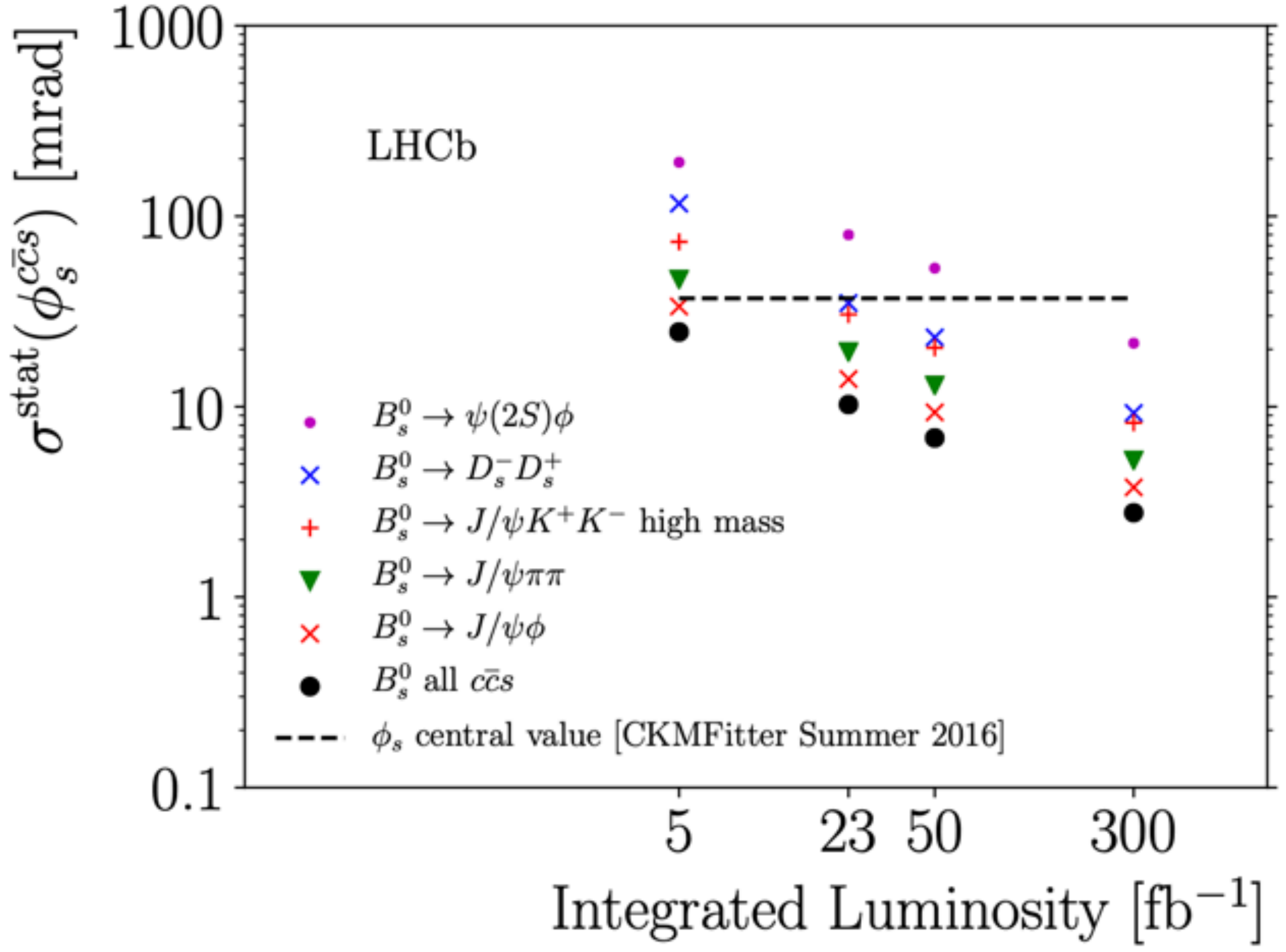


LHCb Upgrade II prospects

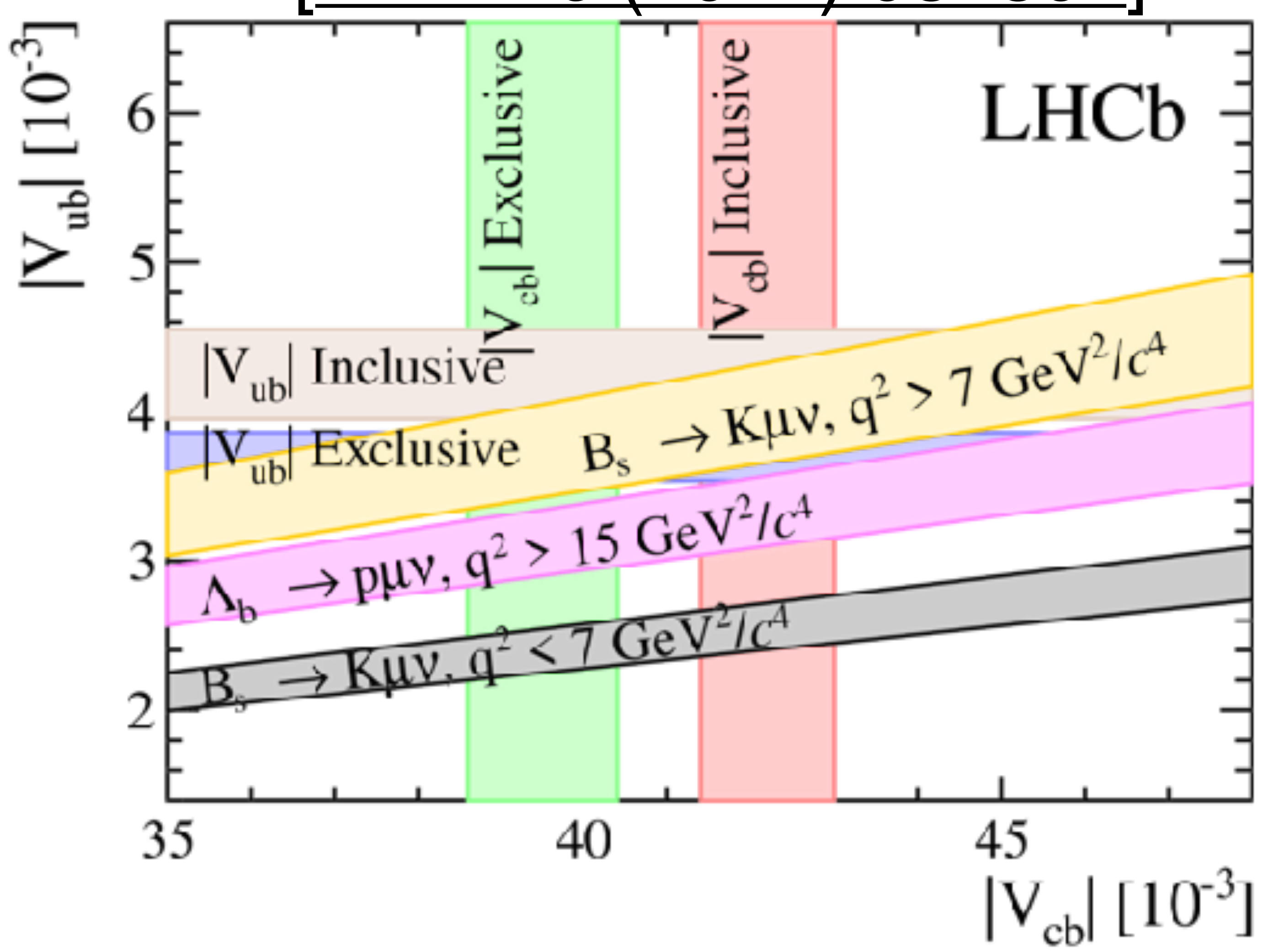
LHCb Upgrade II prospects

CKM puzzles

- Measurements of CKM-angles
  - Delivered most precise β, γ, ϕ_s measurements
  - Gain statistics in fully hadronic modes
  - Will gain in precision from adding more channels
  - Also crucial: vertexing precision
  - In development: inclusive flavour tagging
- Long-standing issue between exclusive and inclusive Vub/Vcb determination
  - Important ingredient - CKM triangle, RD/RDstar, …
  - More insight from q^2-dependent analyses
  - New purer modes like $B_c^+ \to D^0\mu^+\nu, B^+ \to \mu^+\mu^-\mu^+\nu$ will become accessible



[PRL126 (2021) 081804]



Expect to reach uncertainties of ~0.5% @300fb-1

Conclusion

- LHCb shaped the field of flavour physics
- Now taking luminosity data for Run 3
  - First performances promising, first analyses taking shape
  - Sustaining core program, but special enhancements:
    - Soft kinematics: multi-body decays, charm, strange
    - Electrons and muons now kinematically more similar
    - Vertexing improvements yield better suppression of random track combinations
- Broad program, progressing on all fronts - even input from Run 1&2 analyses still to come
- LHCb unique for $B_c^+, B_s^0, \Lambda_b^0, \ldots$
- Innovative ideas to open new avenues
  - VELO tracking of charged LLP's
  - Inclusive flavour tagging
- Let's see whether there is a prince behind the frog…