UNIVERSITY OF CAMBRIDGE

LHCb

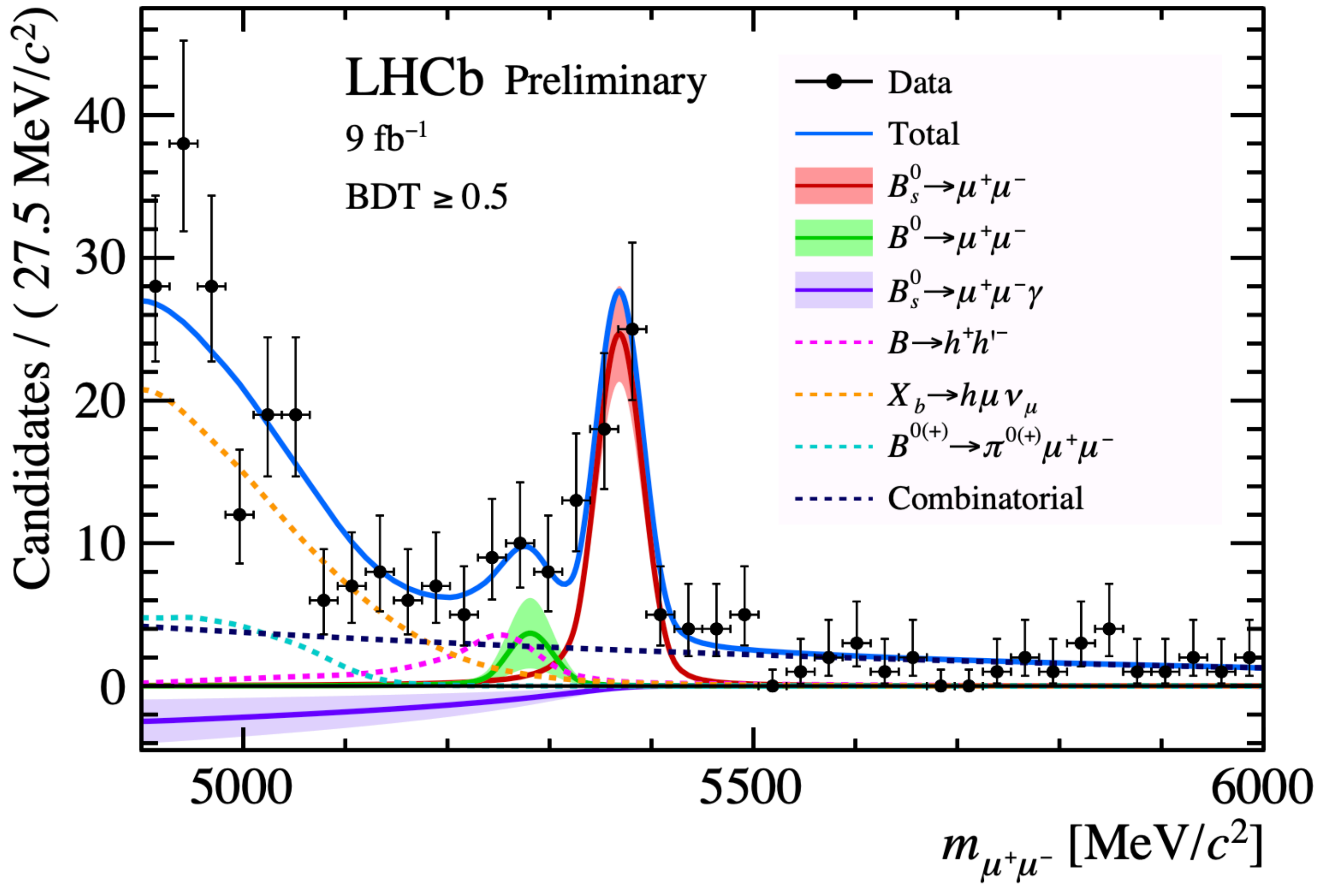
What will Run 3 change for LHCb?

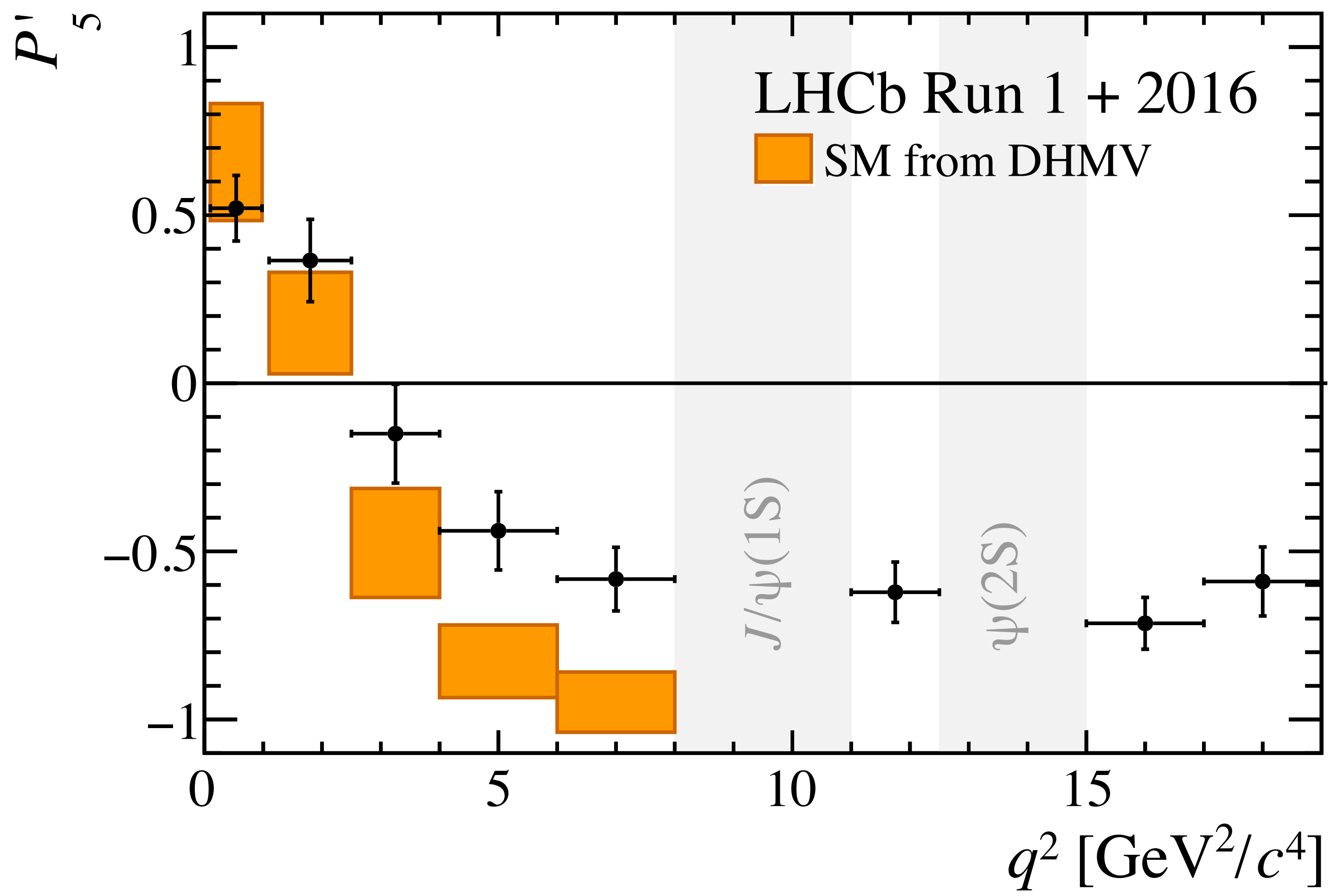
Beyond the Flavour Anomalies III

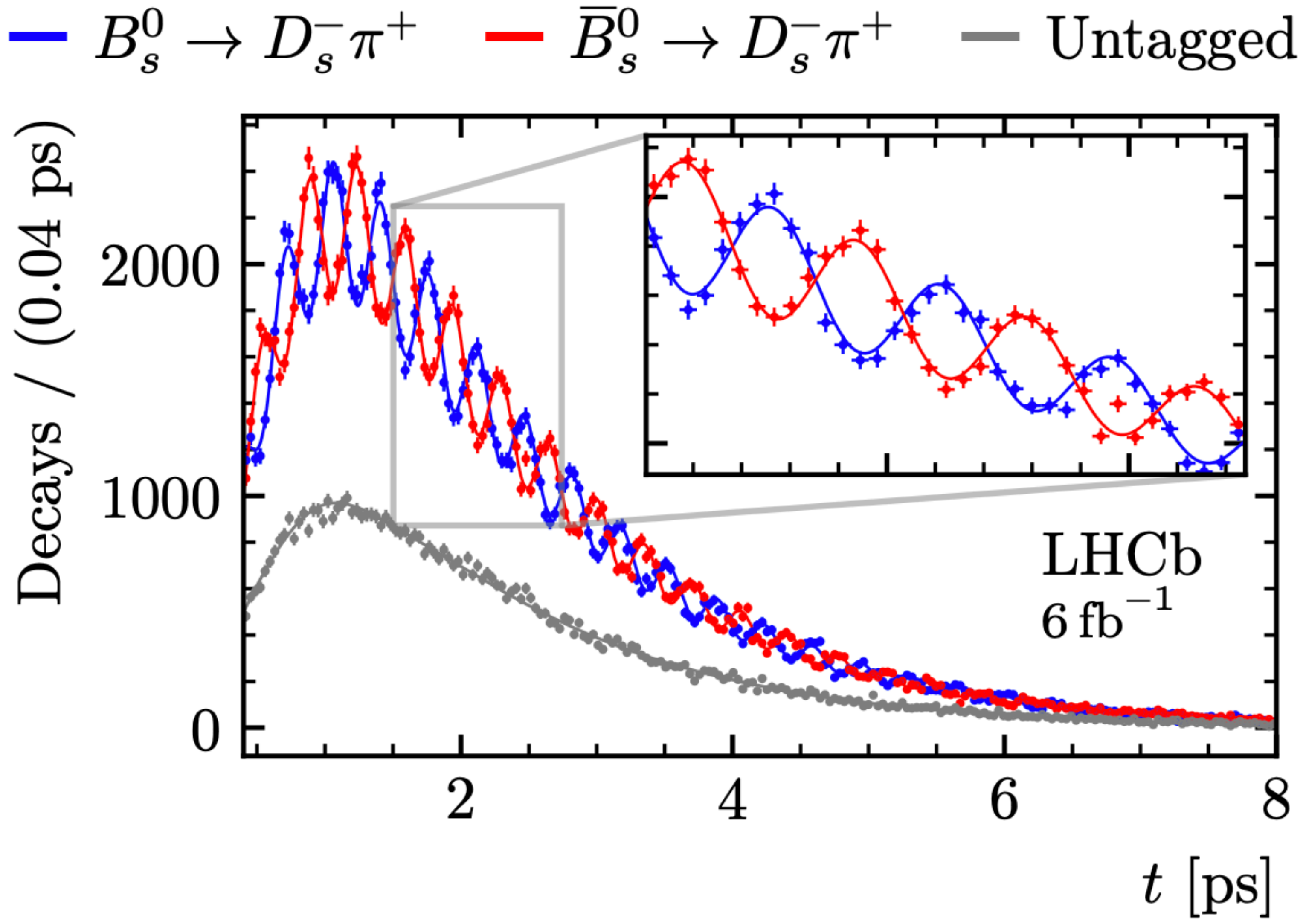
Paula Alvarez Cartelle

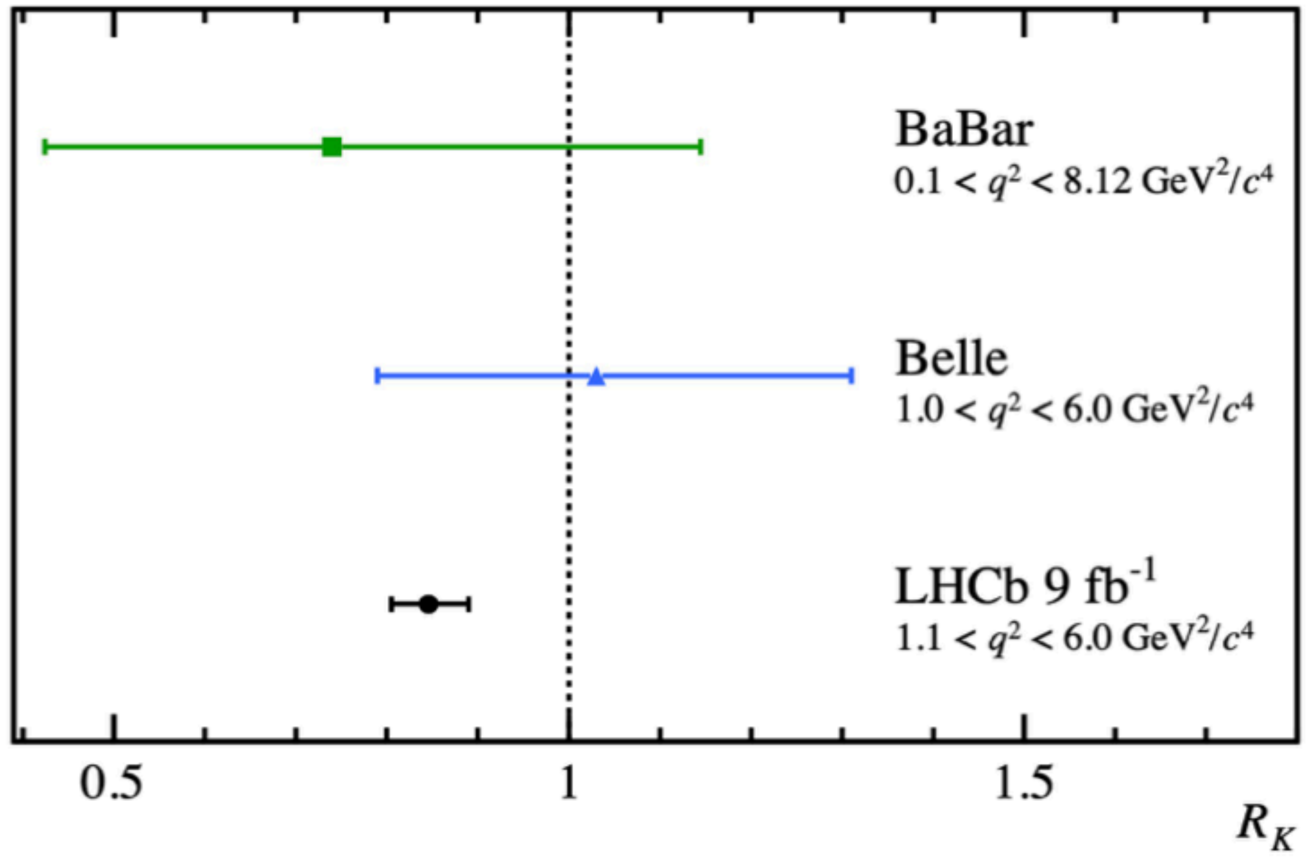
April 2022

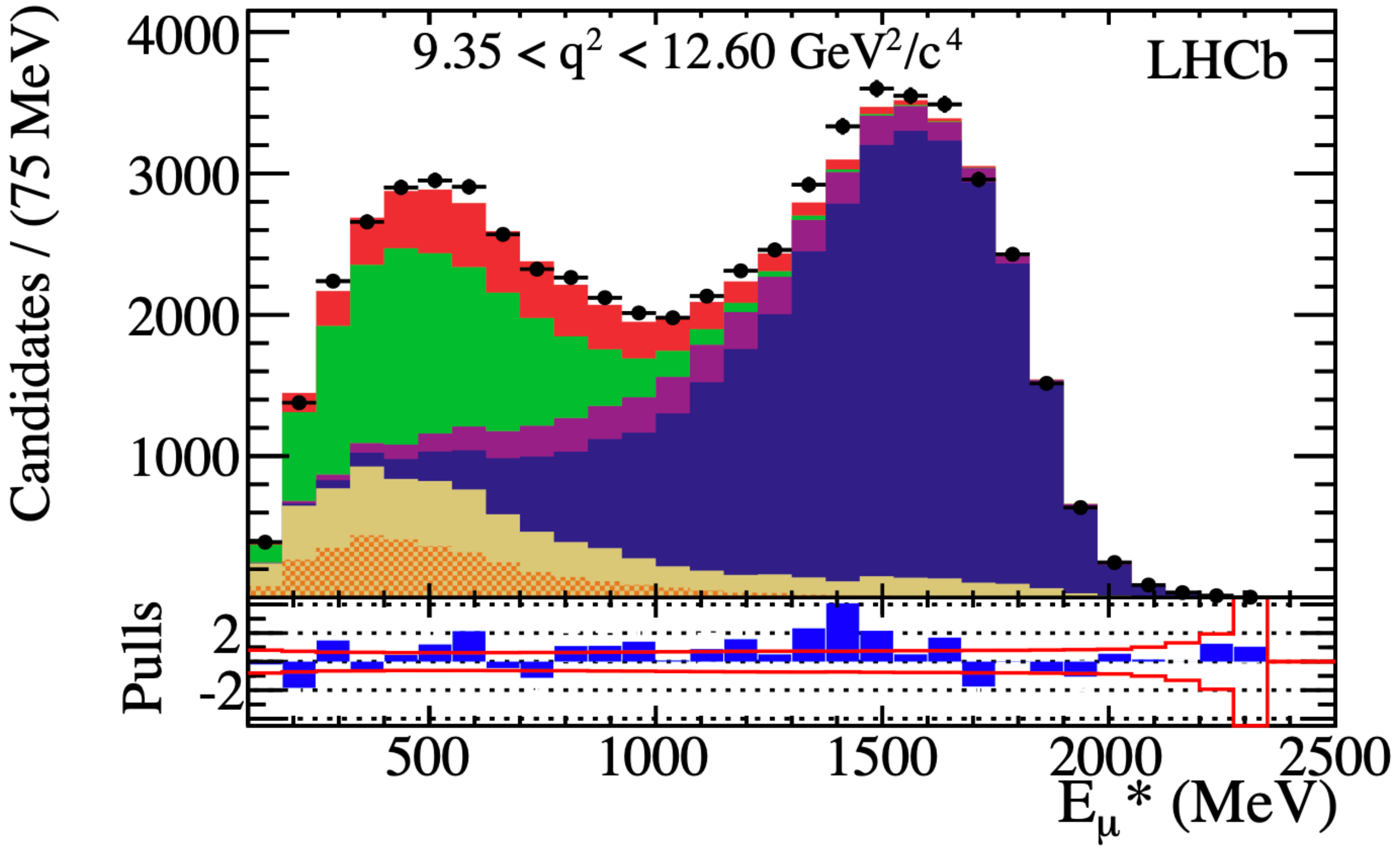
LHCb - Run1 and Run2



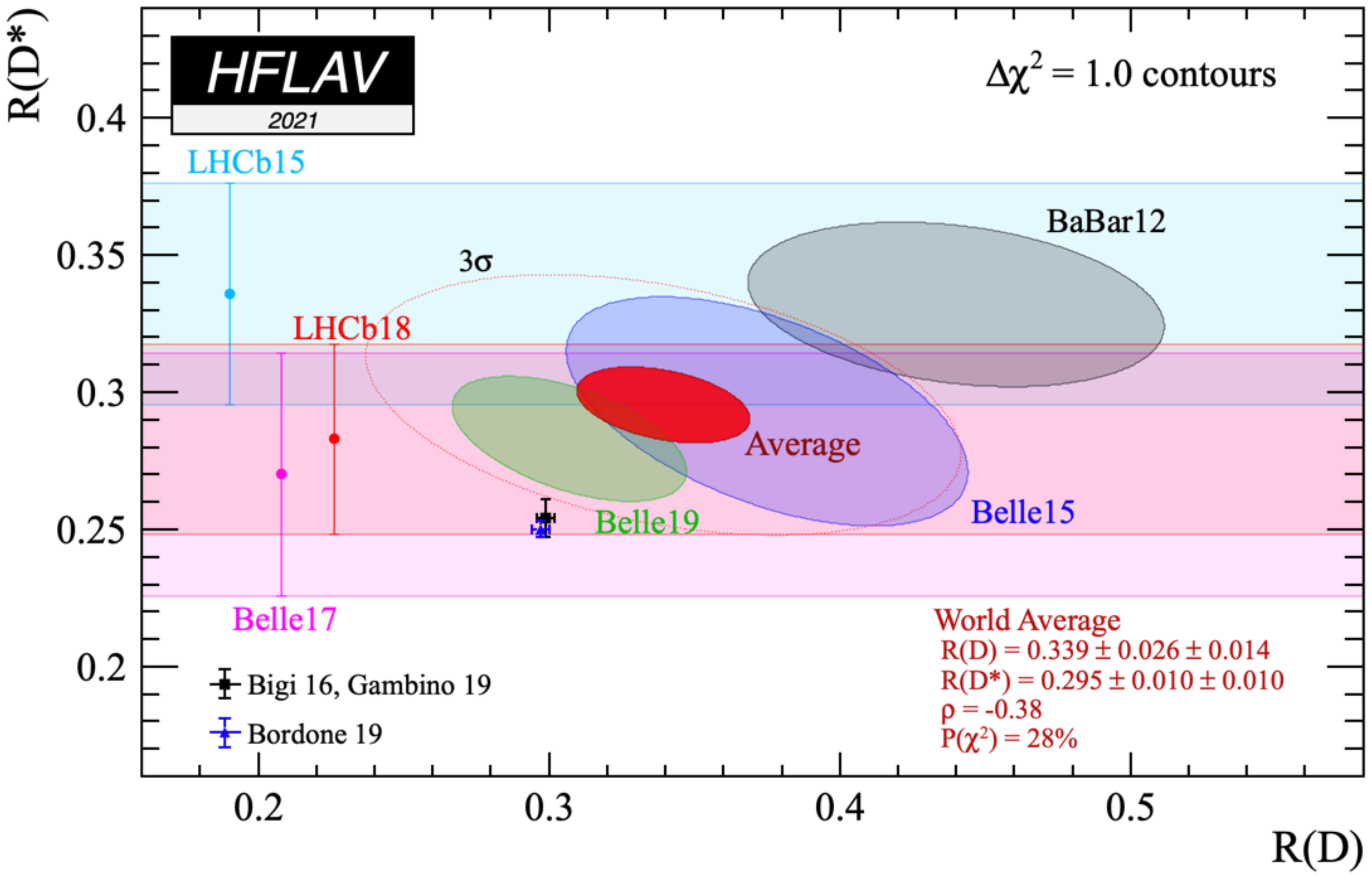


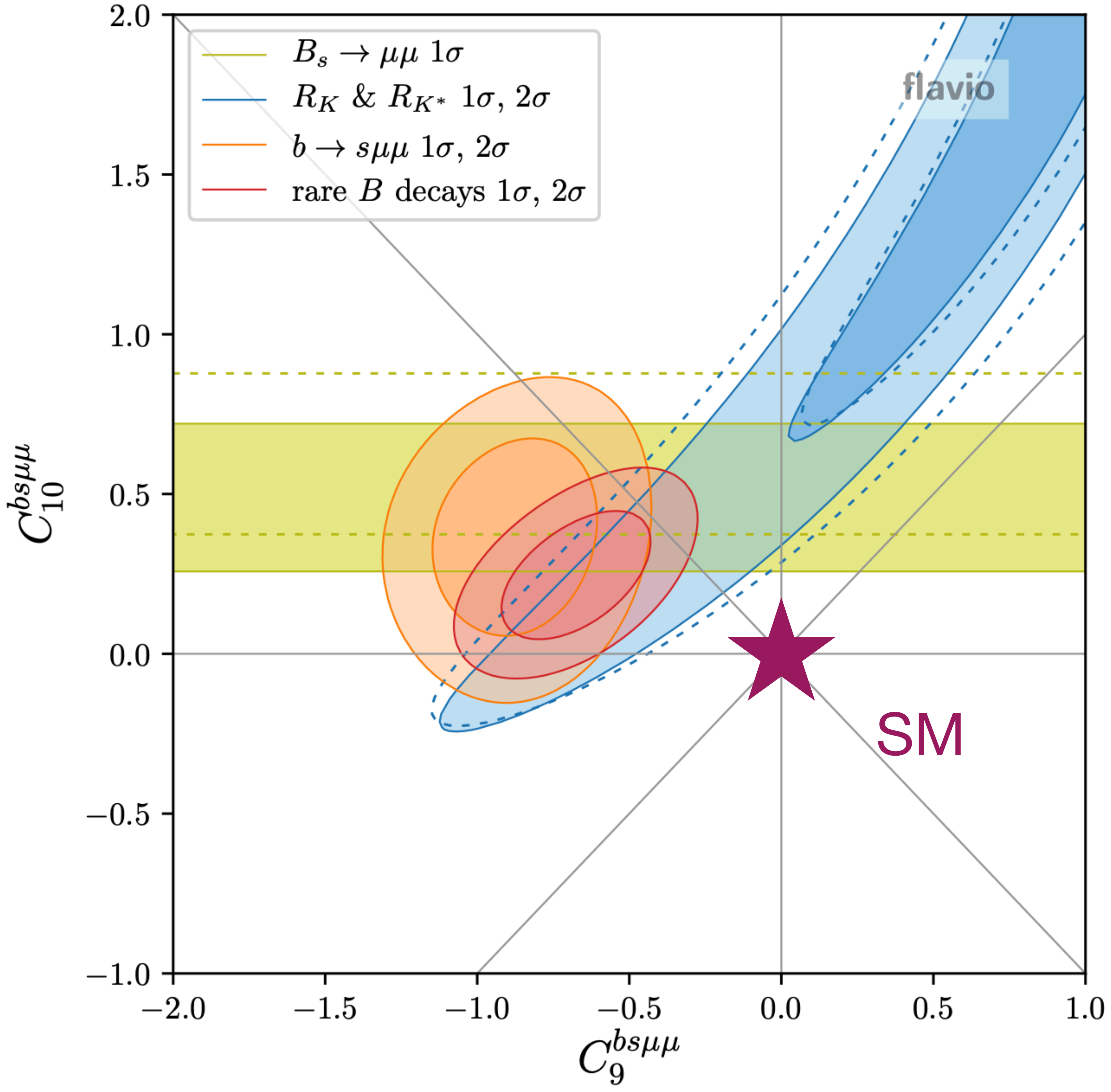






LHCb - Run1 and Run2





[W. Altmannshofer et al., arXiv:2103.13370 *]

Critical to improve the precision in all of these measurements to clarify this picture

[* Similar fits by Algueró et al: arXiv:2104.08921, Hurth et al: arXiv:2104.10058, Ciucchini et al: arXiv:1903.09632, Kowalska et al: arXiv:1903.10932, Geng et al arXiv:2103.12738 and many others]

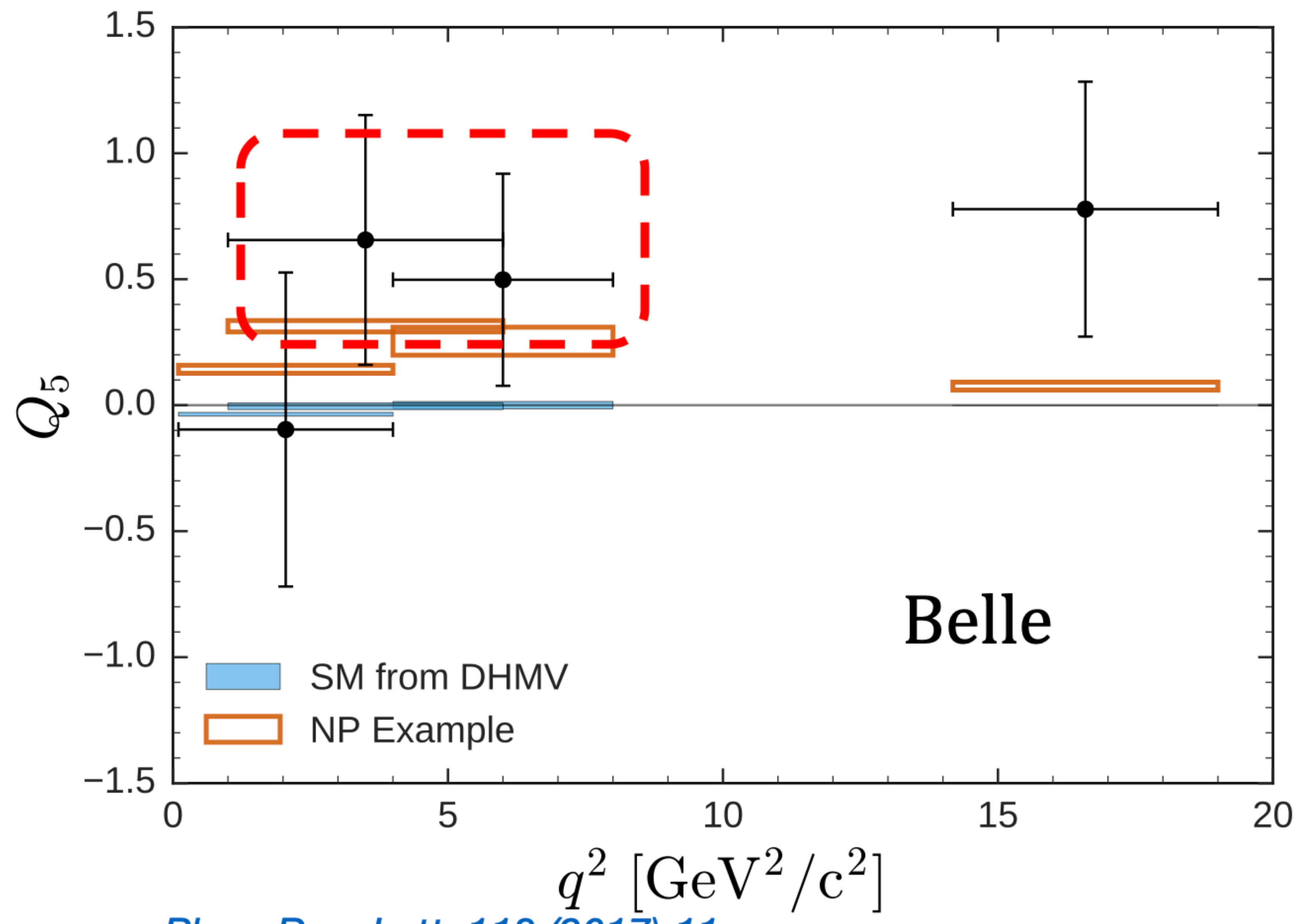
LHCb - Run1 and Run2

[LHCb, arXiv:1808.08865]

R_X precision	$9\,\text{fb}^{-1}$
R_K	0.043
$R_{K^{*0}}$	0.052
R_ϕ	0.130
R_{pK}	0.105
R_π	0.302

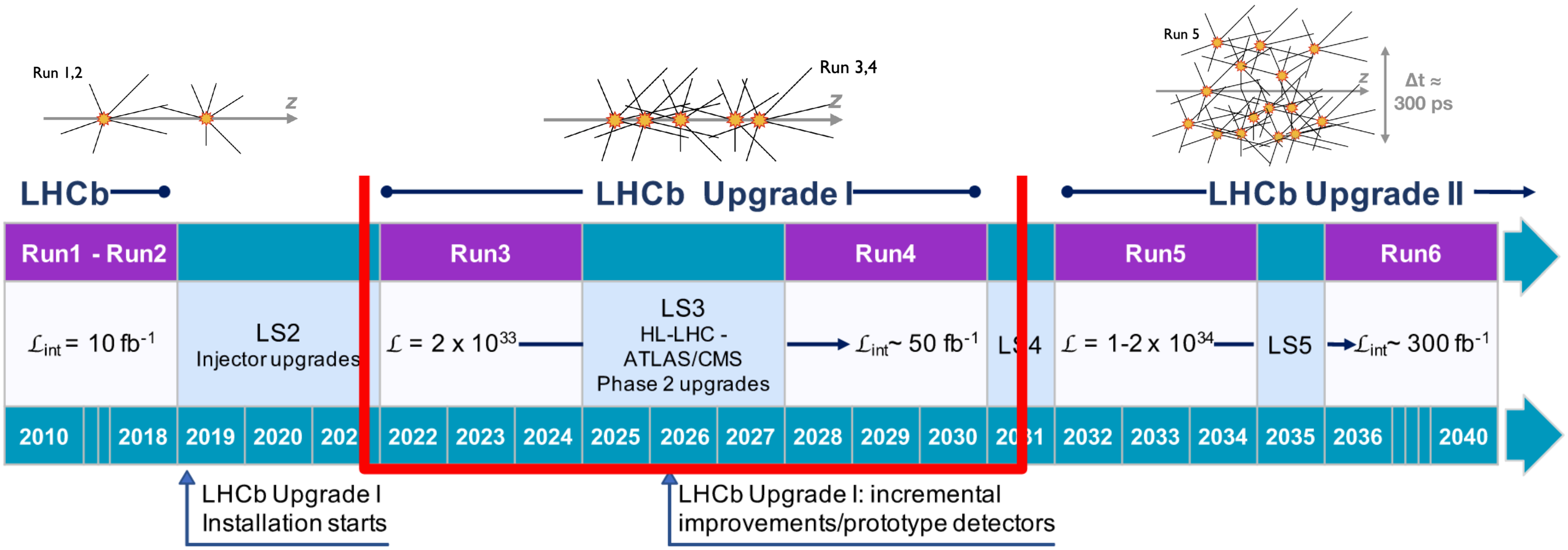
Many results still to come from Run1+2 data

- LFU test in different channels/kinematic regions
  [$R_{K^{*0}}$, R_ϕ, high-q^2, R(D), …]
- Angular observables of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ decays
  [observables, parametric hadronic contributions…]
- Searches for $b \to s\tau\tau$ processes and LFV involving τ's



Phys. Rev. Lett. 118 (2017) 11

What next?

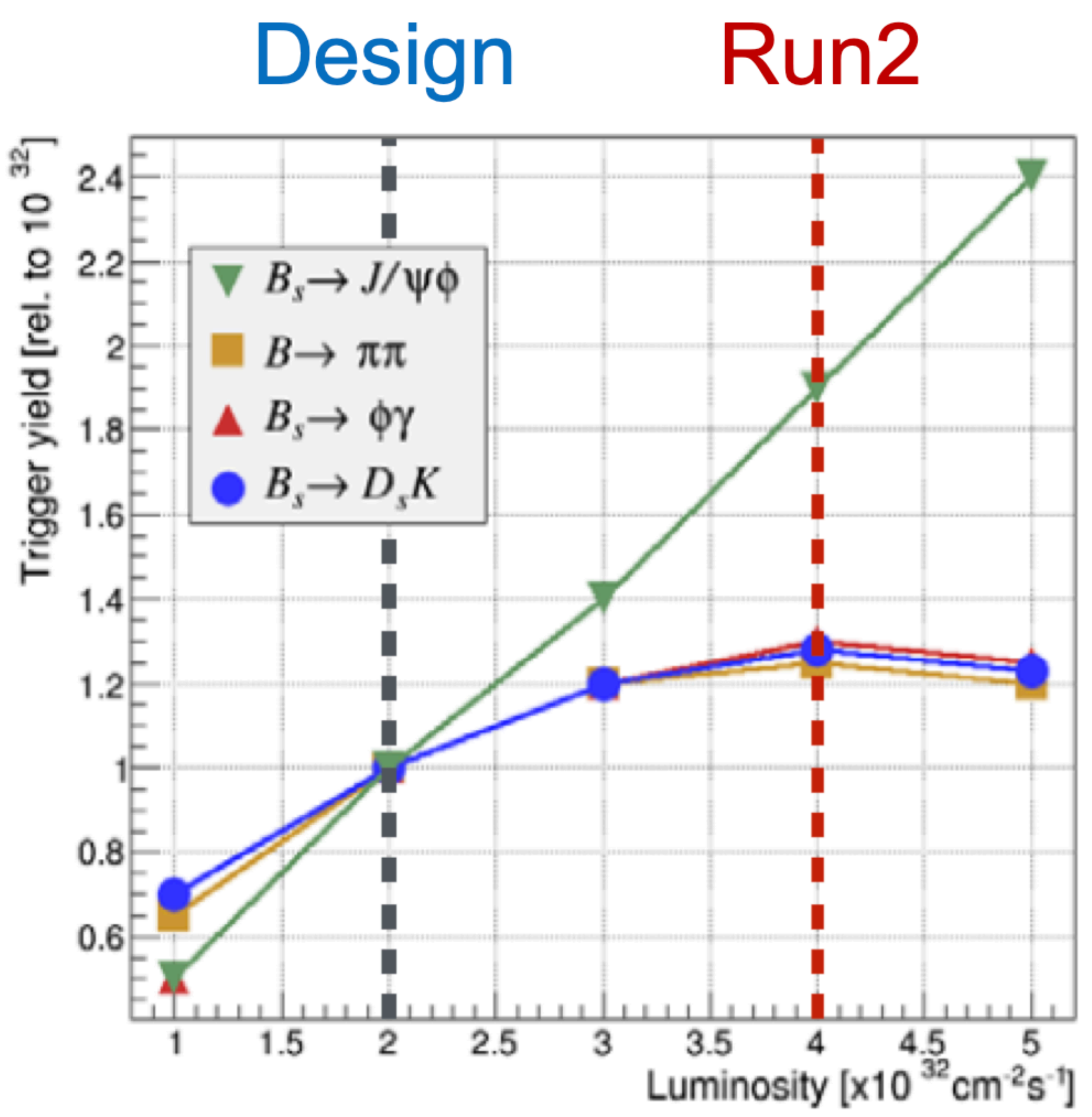


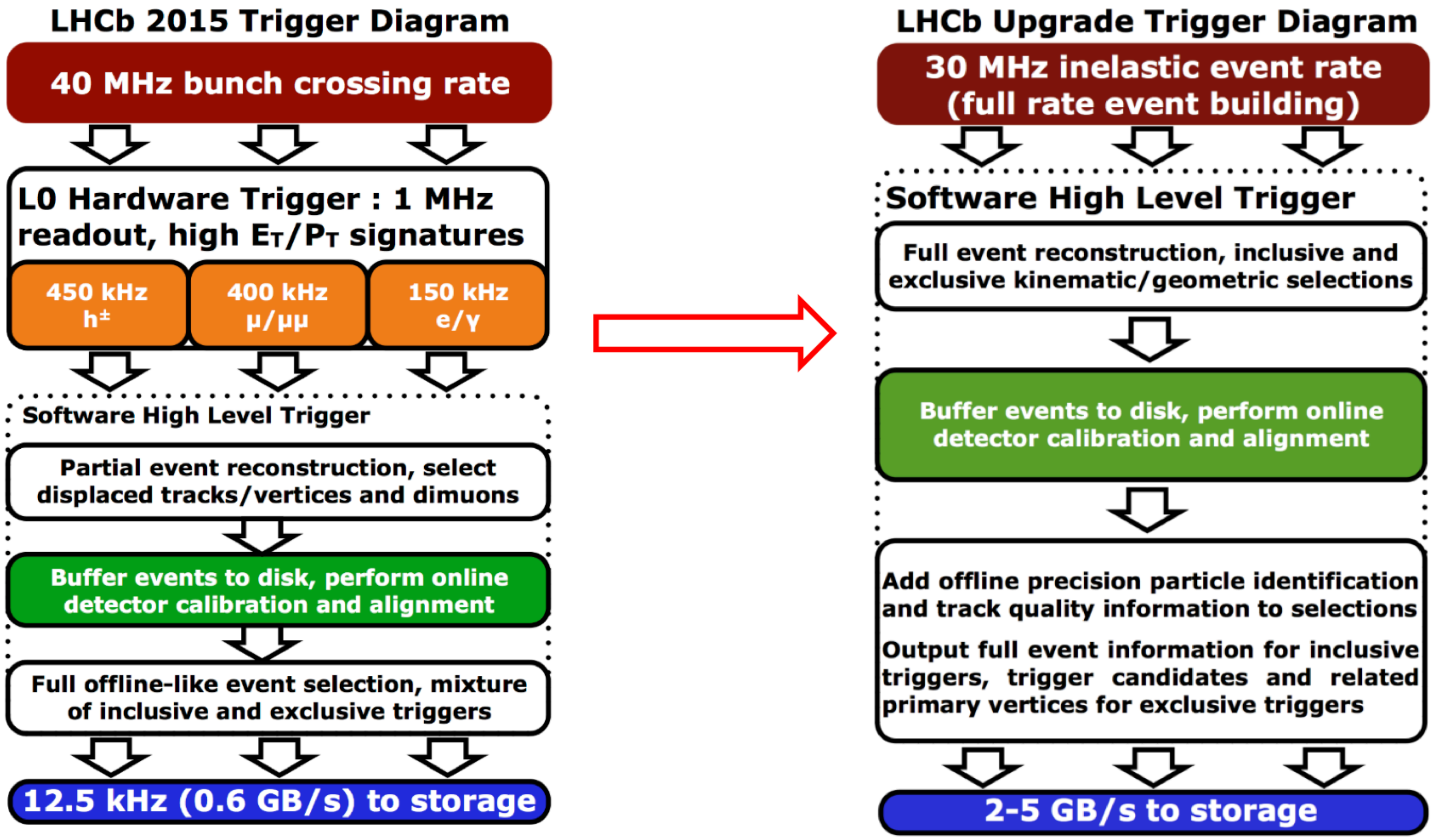
- **LHCb Upgrade I for Run3 and Run4** ($\mathscr{L} \sim 2 \times 10^{33}\ s^{-1} cm^{-2}$)
  - Large detector upgrade, trigger-less readout and full software trigger
  - Goal is to keep the excellent performance of Run1&2 in a more challenging environment
- LHCb Upgrade II to fully profit from HL-LHC ($\mathscr{L} \sim 2 \times 10^{34}\ s^{-1} cm^{-2}$)
  - Novel technologies and timing information to deal with the pile up in the HL-LHC

LHCb Upgrade I

Going Trigger-less & fully software

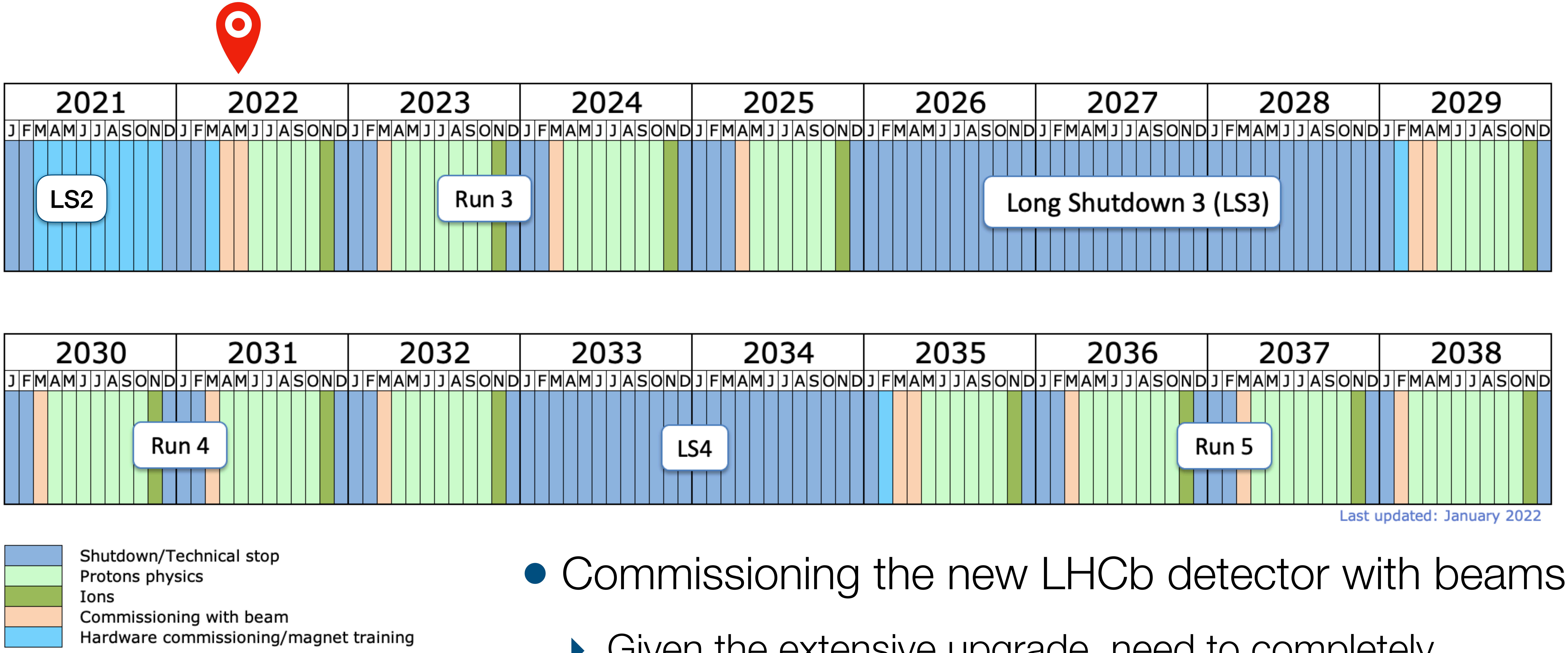
Remove limitations from the hardware trigger, to fully profit from the higher luminosity





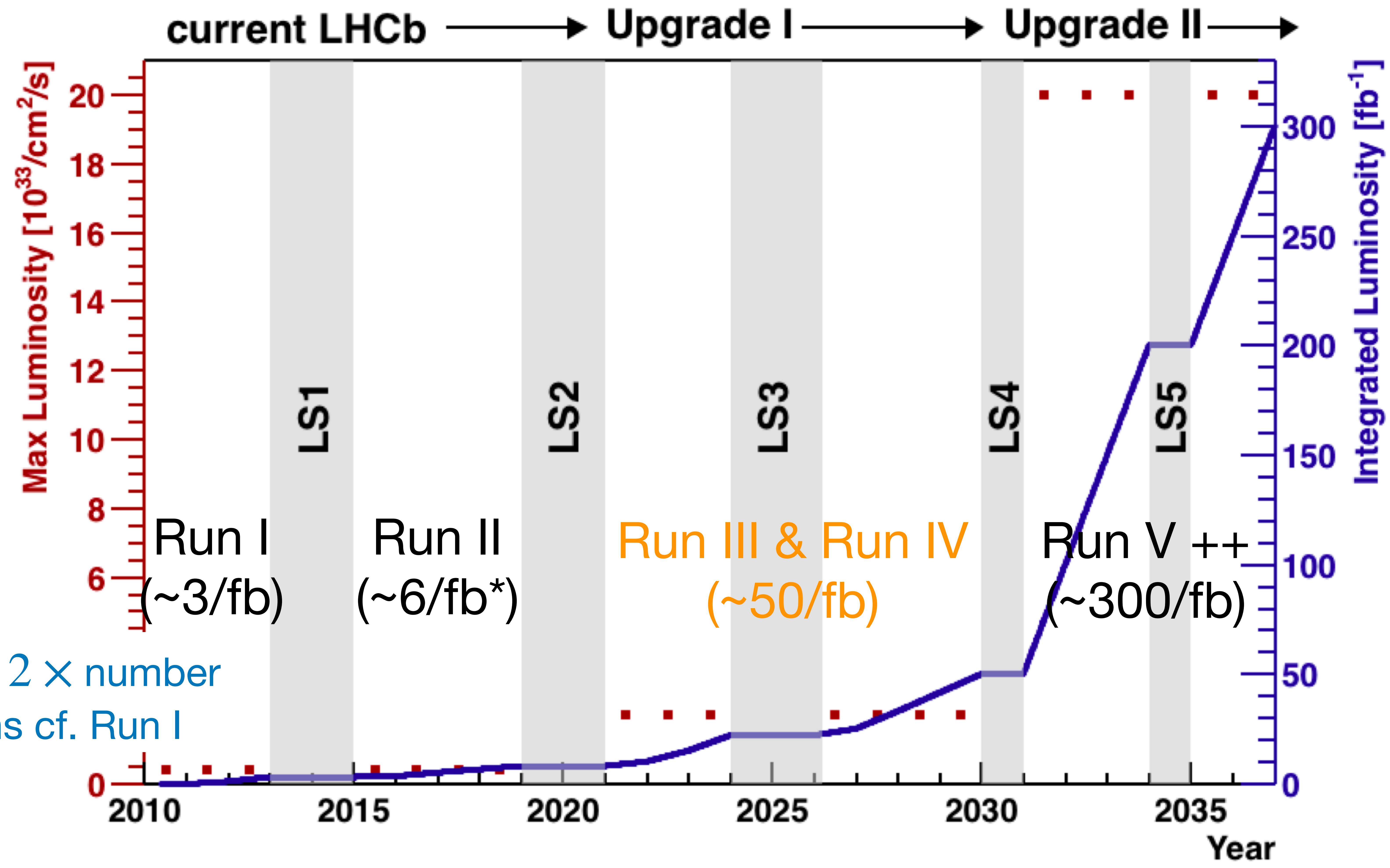
Collect data at 5x the rate for di-muon channels and 10x the rate for hadronic channels

LHC schedule



- Commissioning the new LHCb detector with beams
  - Given the extensive upgrade, need to completely characterise the new detector

Expected data samples



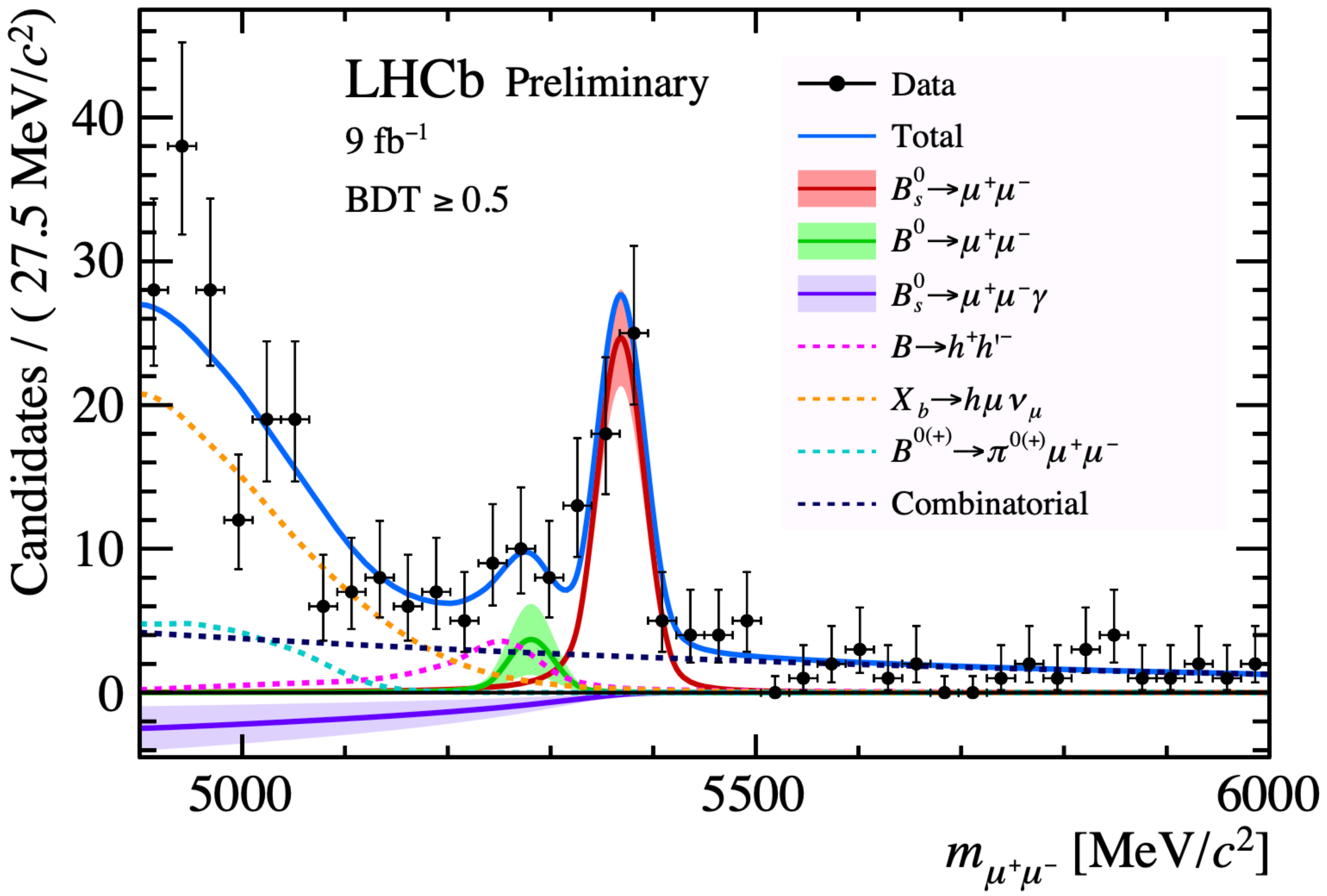
* Increased $\sqrt{s} \Rightarrow \sim 2 \times$ number of b- and c- hadrons cf. Run I

$B^0{}_{(S)} \rightarrow \mu^+\mu^-$

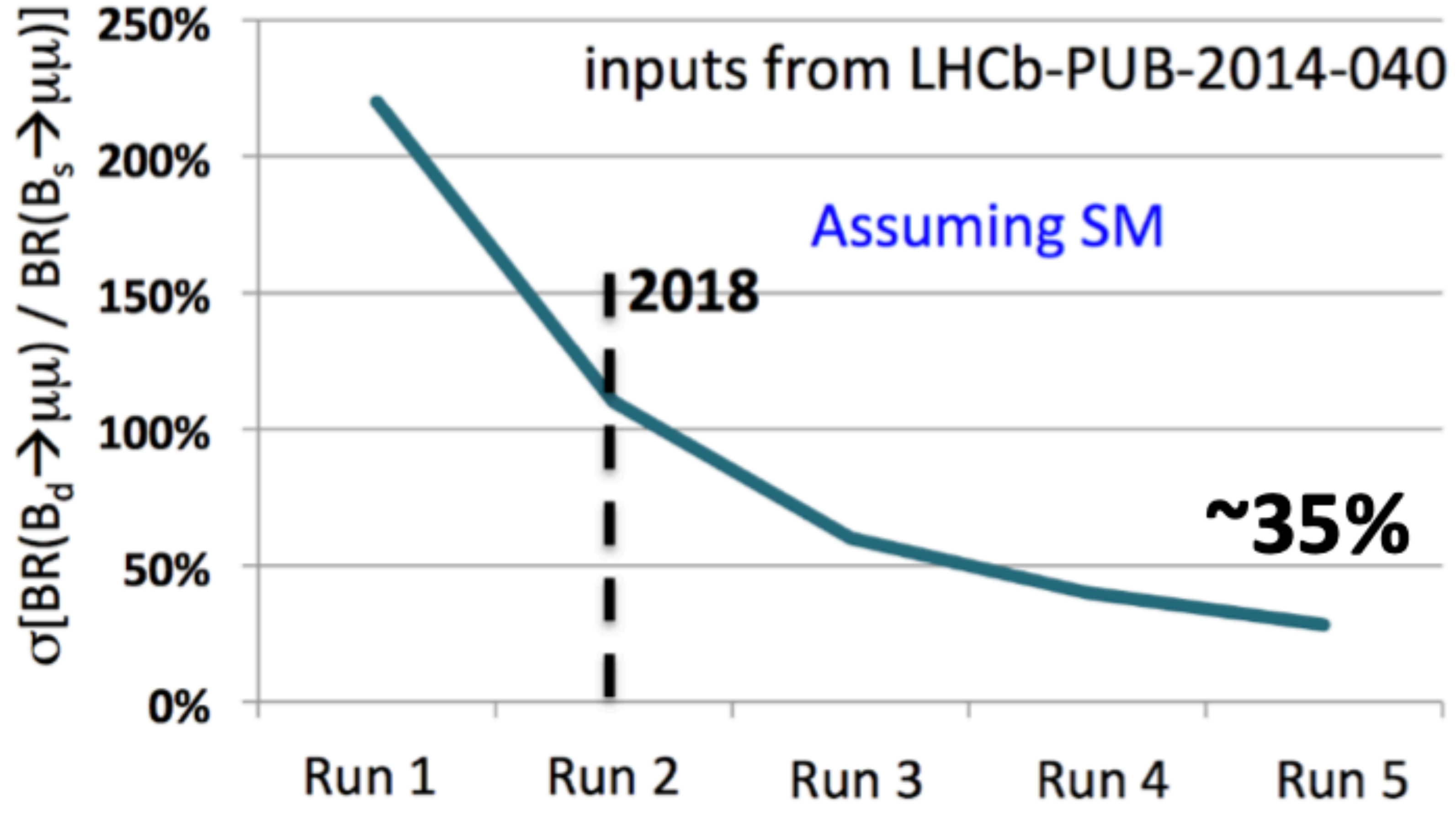
- Full Run1+2 LHCb sample

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09\ ^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (95\,\%\,\mathrm{CL})$$

- Will be still statistically dominated until end of Run4
  - 50/fb: O(6%), 300/fb: O(3%)
- Main BR systematics now from f_s/f_d (3%) [LHCb, arXiv:2103.06810]
- Maybe first evidence for $B^0 \to \mu^+\mu^-$ with 50/fb (1.7σ at Run1+2)



[PRL 128, (2022) 041801]

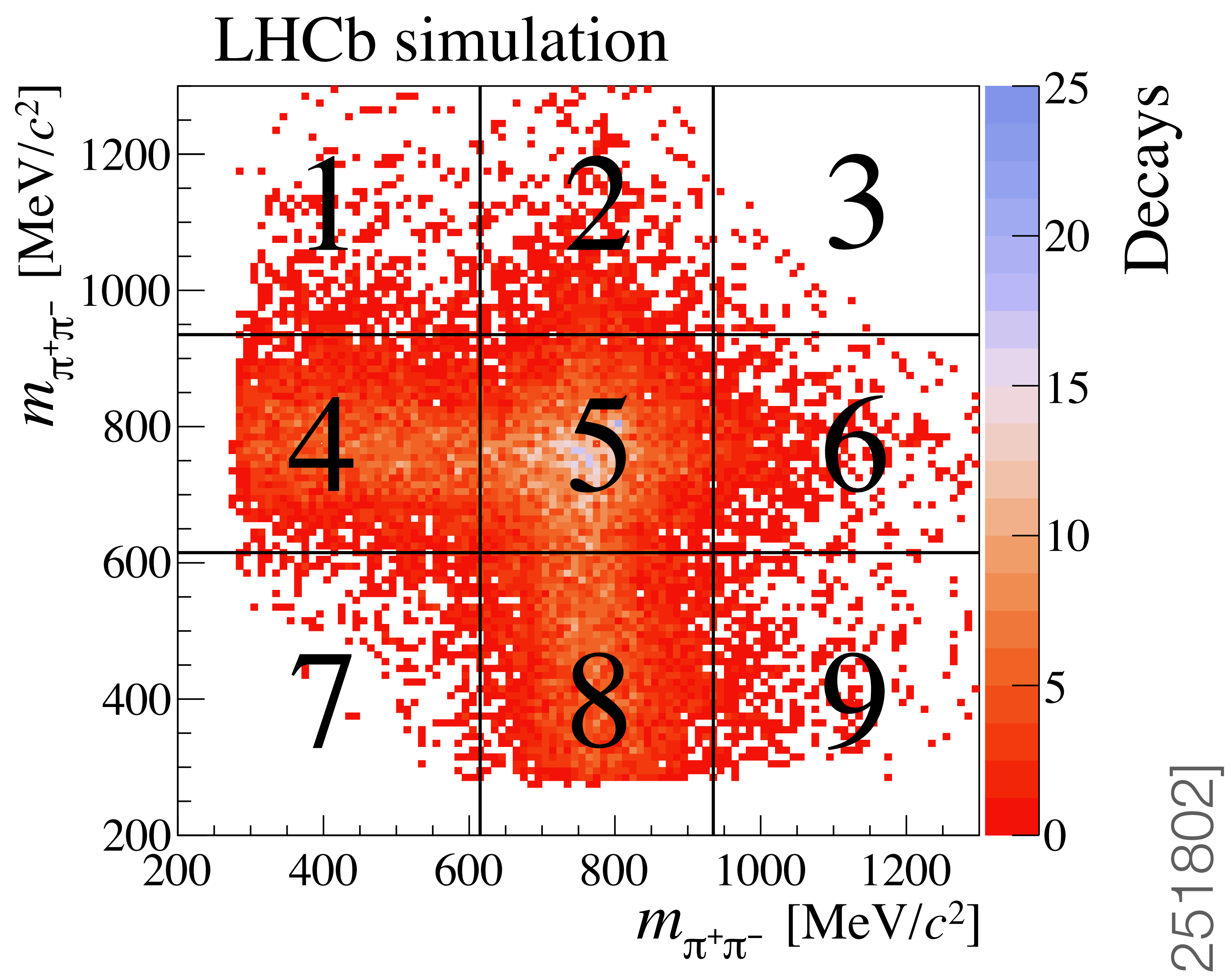


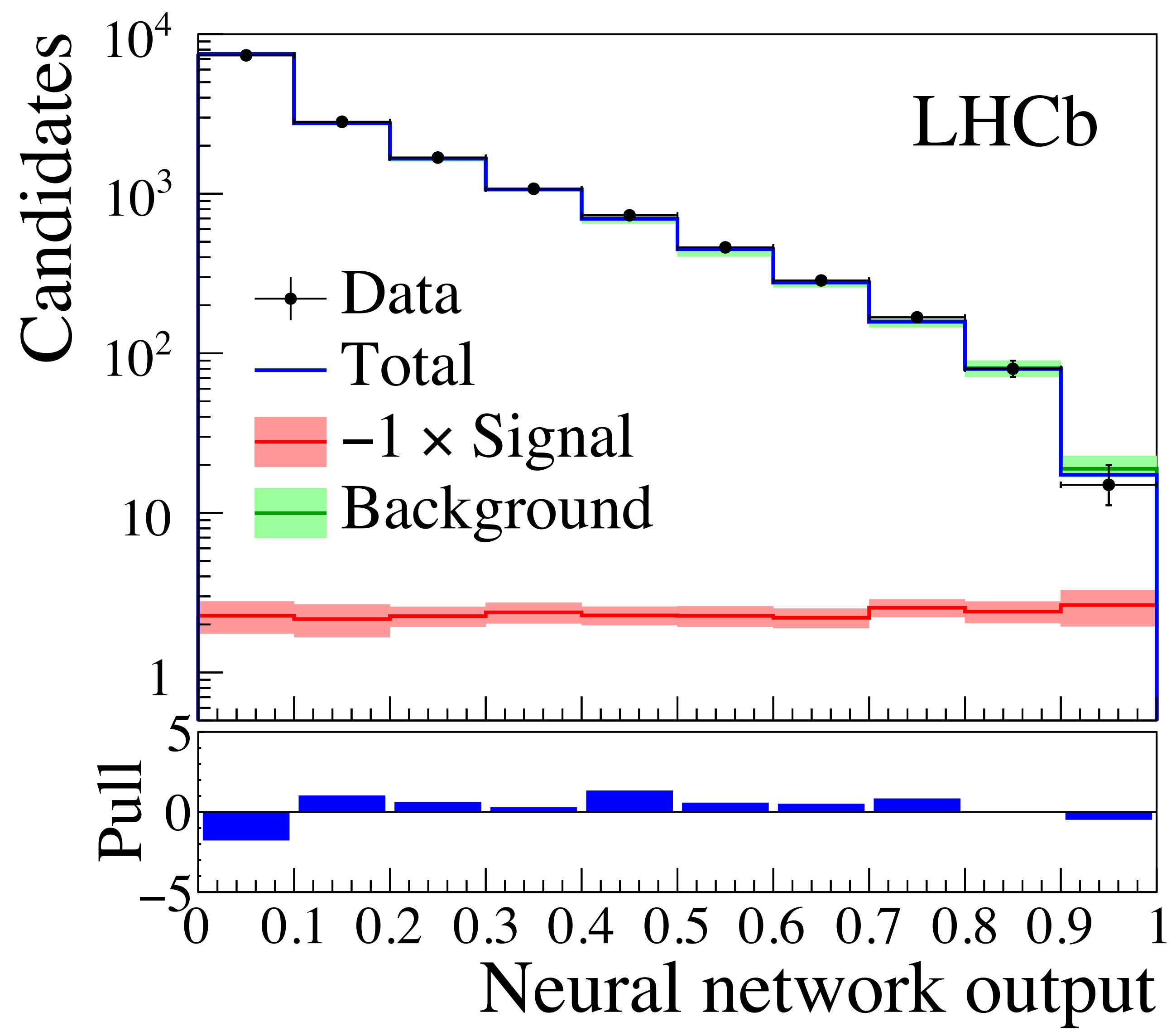
$b \to s\tau\tau$

See Hanae and Lakshan's talk on Wednesday

- 2 tau leptons in the final state
  - poor resolution due to missing neutrinos
  - backgrounds from B->DDX particularly dangerous
- Strategy exploits the Dalitz structure of the hadronic tau decay
- These analyses will improve with stats, but will remain challenging in Run 3 & beyond

	Run 1	Upgrade I (50/fb)	Upgrade II (300/fb)
$B_s^0 \to \tau^+\tau^-$	6.8 x 10^{-3}	~2 x 10^{-3}	~7 x 10^{-4}
$B^0 \to \tau^+\tau^-$	2.1 x 10^{-3}	~5 x 10^{-4}	~2 x 10^{-4}
$B^0 \to K^{*0}\tau^+\tau^-$			





[PRL 118 (2017) 251802]

Lepton flavour violation at LHCb U I/II

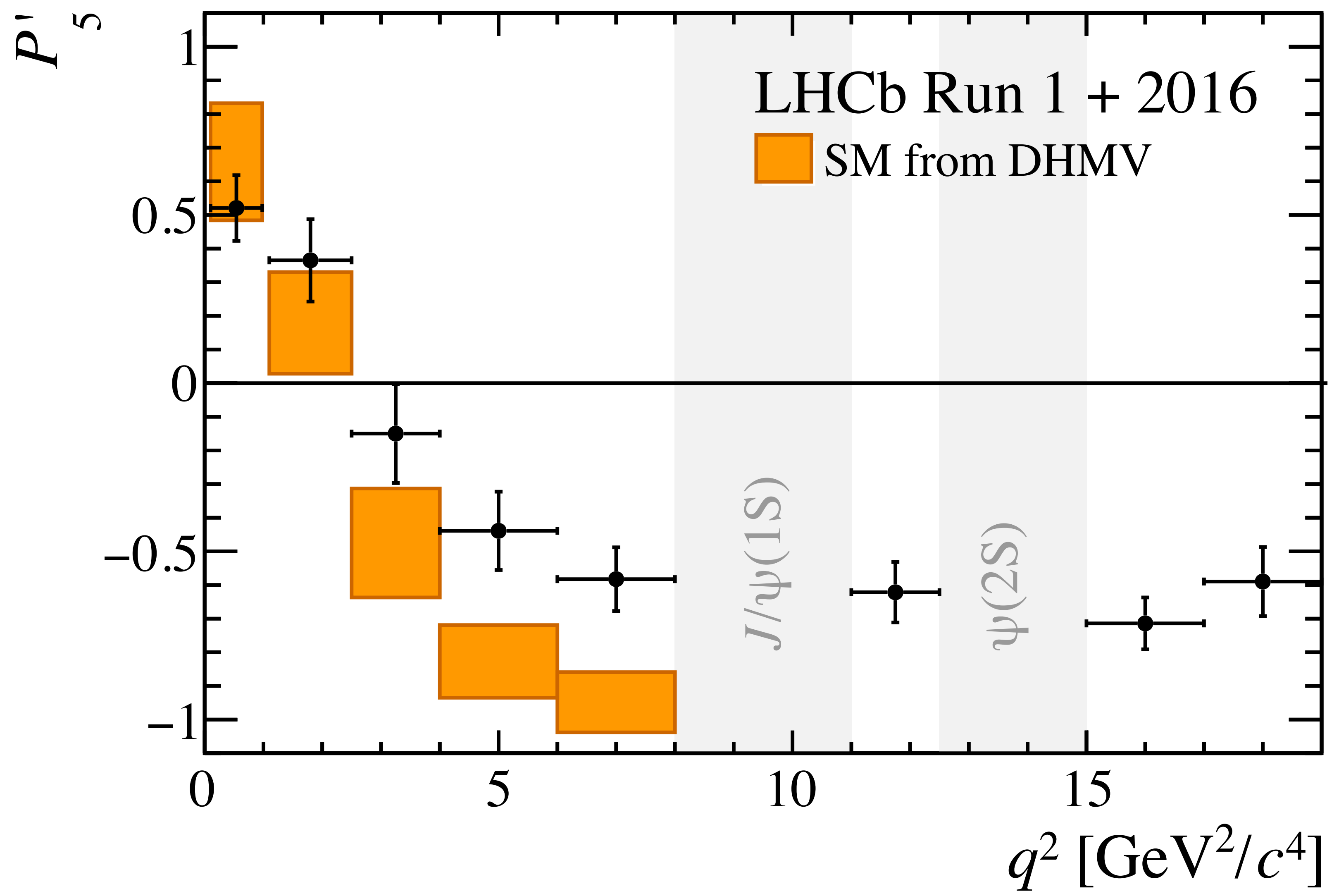
Decay	Limit @ 90% C.L.	Luminosity	Reference	Upgrade I	Upgrade II
$B^0 \to e\mu$	1.0 x 10^{-9}	3 fb^{-1} (Run1)	*JHEP 03 (2018) 078*	~2 x 10^{-10}	~9 x 10^{-11}
$B_s \to e\mu$	5.4 x 10^{-9}			~8 x 10^{-10}	~3 x 10^{-10}
$B^+ \to K^+ e^+ \mu^-$	7.0 x 10^{-9}	3 fb^{-1} (Run1)	*Phys. Rev. Lett. 123 (2019) 241802*	~4 x 10^{-10}	~7 x 10^{-11}
$B^+ \to K^+ e^- \mu^+$	6.4 x 10^{-9}			~4 x 10^{-10}	~6 x 10^{-11}
$B^0 \to K^{*0} \mu^{\pm} e$	9.9 x 10^{-9}	9 fb^{-1} (Run1+2)	*LHCb-PAPER-2022-008 (preliminary)*	~4 x 10^{-9}	~2 x 10^{-9}
$B^0 \to K^{*0} \mu^- e^+$	6.7 x 10^{-9}			~3 x 10^{-9}	~1 x 10^{-9}
$B^0 \to K^{*0} \mu^+ e^-$	5.7 x 10^{-9}			~4 x 10^{-9}	~1 x 10^{-9}
$B_s \to \phi \mu^{\pm} e$	1.6 x 10^{-8}			~4 x 10^{-9}	~4 x 10^{-9}
$B^0 \to \tau\mu$	1.2 x 10^{-5}	3 fb^{-1} (Run1)	*Phys. Rev. Lett. 123 (2019) 211801*	~3 x 10^{-6}	~1 x 10^{-6}
$B_s \to \tau\mu$	3.4 x 10^{-5}			~8 x 10^{-6}	~3 x 10^{-6}
$B^+ \to K^+ \tau\mu$	3.9 x 10^{-5}	9 fb^{-1} (Run1+2)	*JHEP 06 (2020) 129*	~1 x 10^{-5}	~5 x 10^{-6}
Also: *BR*($\tau \to \mu\mu\mu$) < *4.6 x 10^{-8} at 90% C.L.* *with* 3 fb^{-1} (Run1) *[JHEP 02 (2015) 121]*				~3 x 10^{-9}	~1 x 10^{-9}

$b \to s \ell^+ \ell^-$ angular analyses

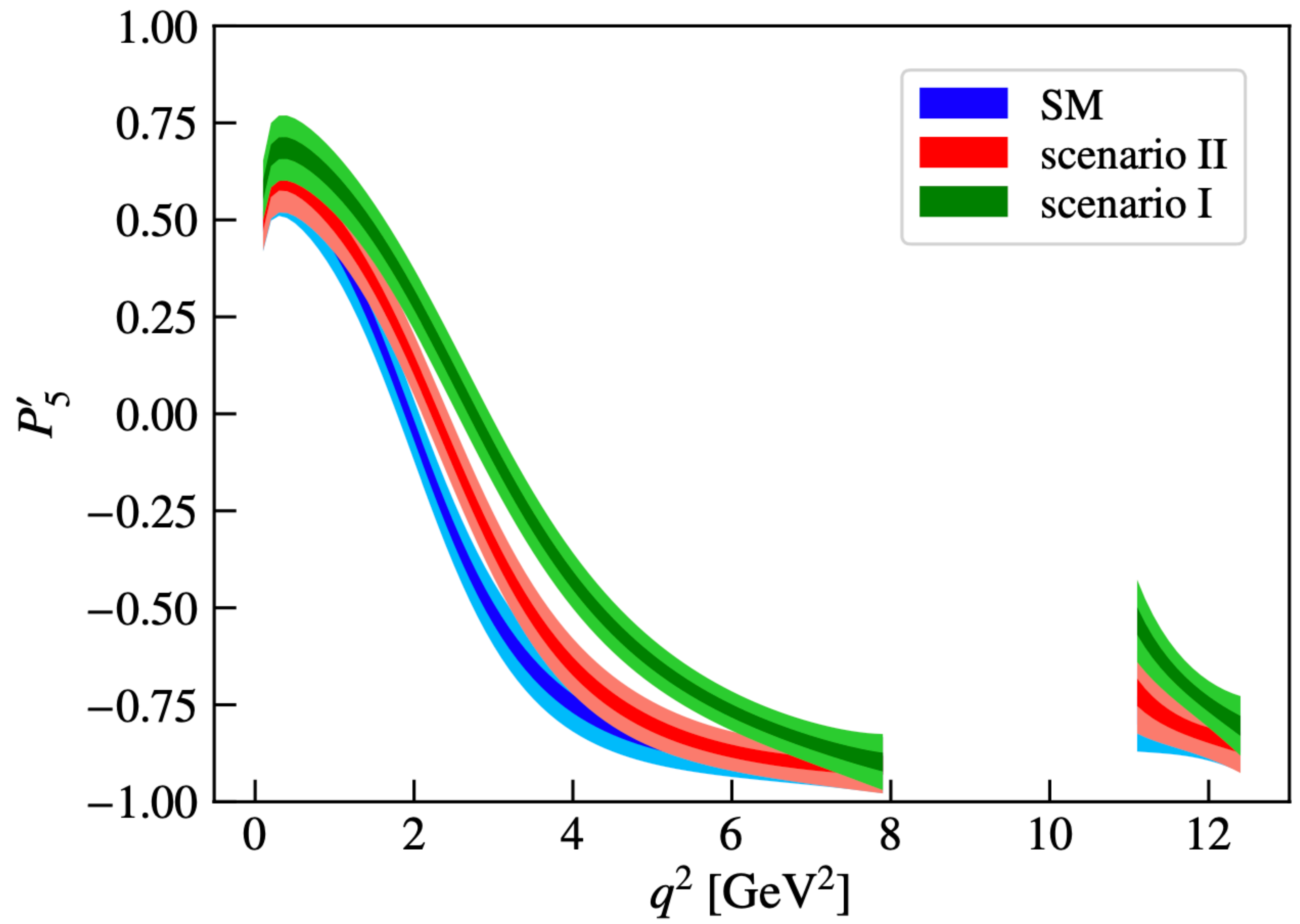
See Rafael and Tom's talk on Wednesday

- Many new information will become available already with the full Run2 dataset
  - Updates of binned observables
  - Several flavours of unbinned analyses
  - New hadronic systems

- Run 3 brings predominantly more stats
  - Get more information about the q2 shape with narrower bind in a model independent way
  - better modelling of the backgrounds



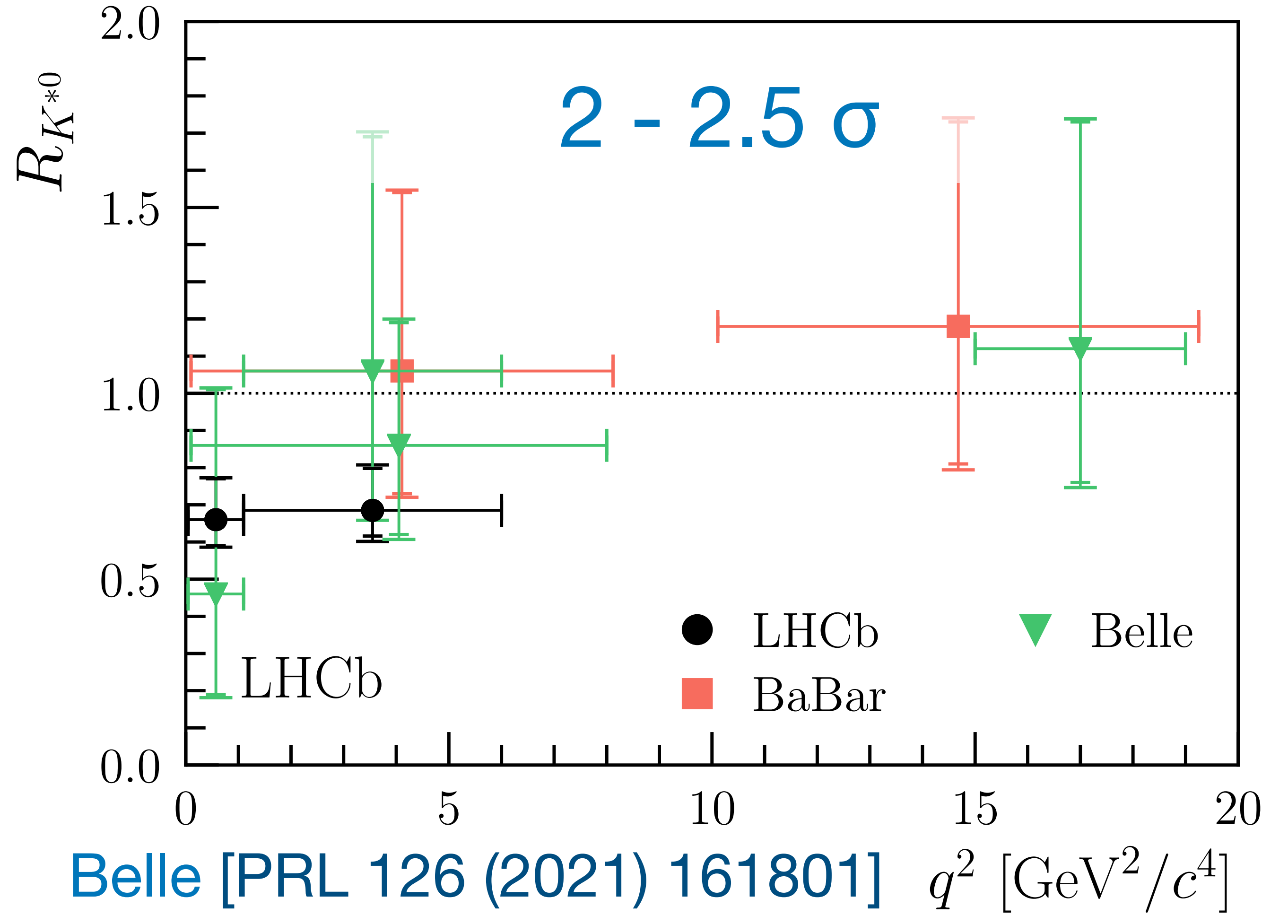
[PRL 125 (2020) 011802]



[LHCb, arXiv:1808.08865]

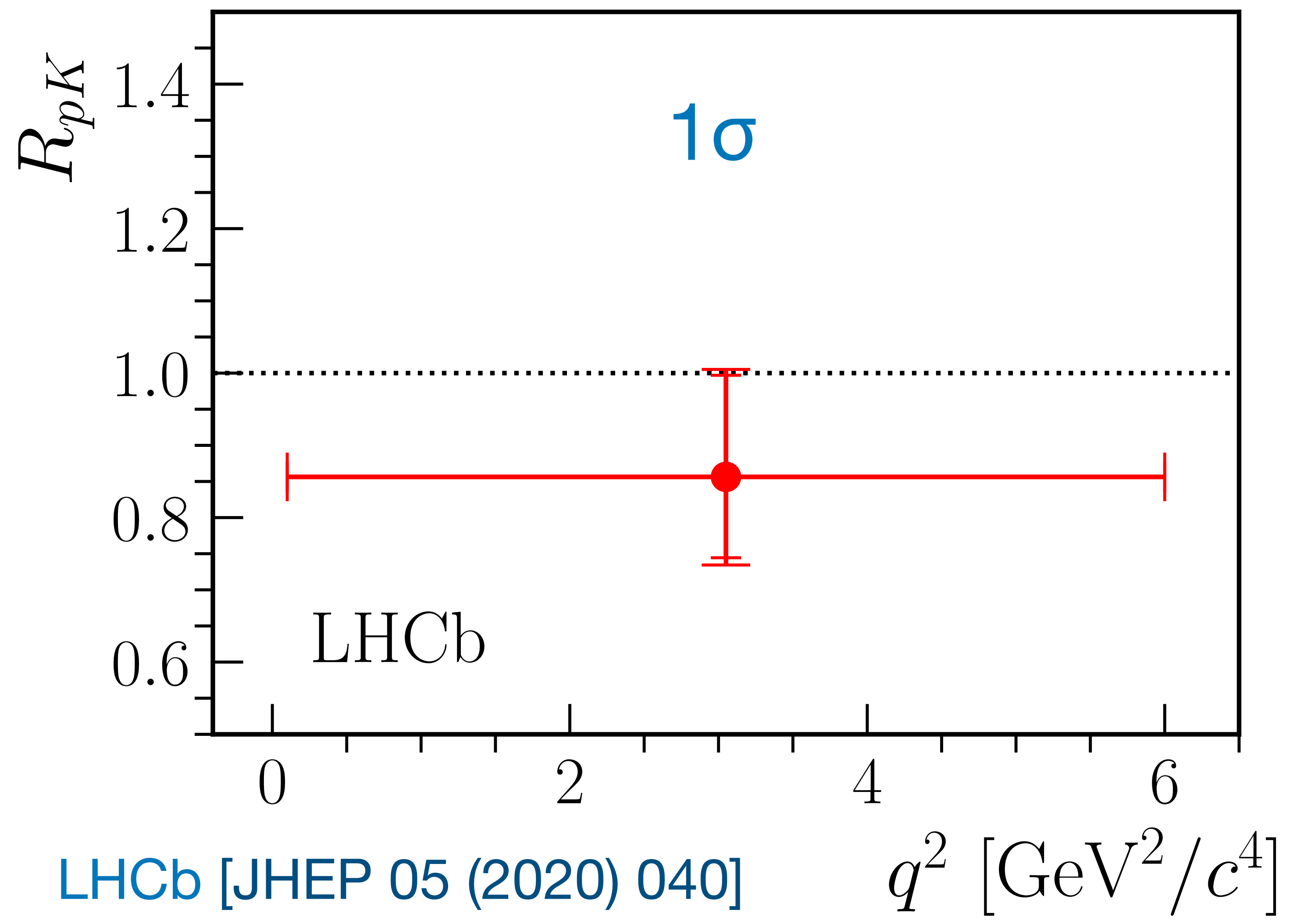
LFU tests at LHCb

$B^0 \to K^{*0}\ell^+\ell^-$



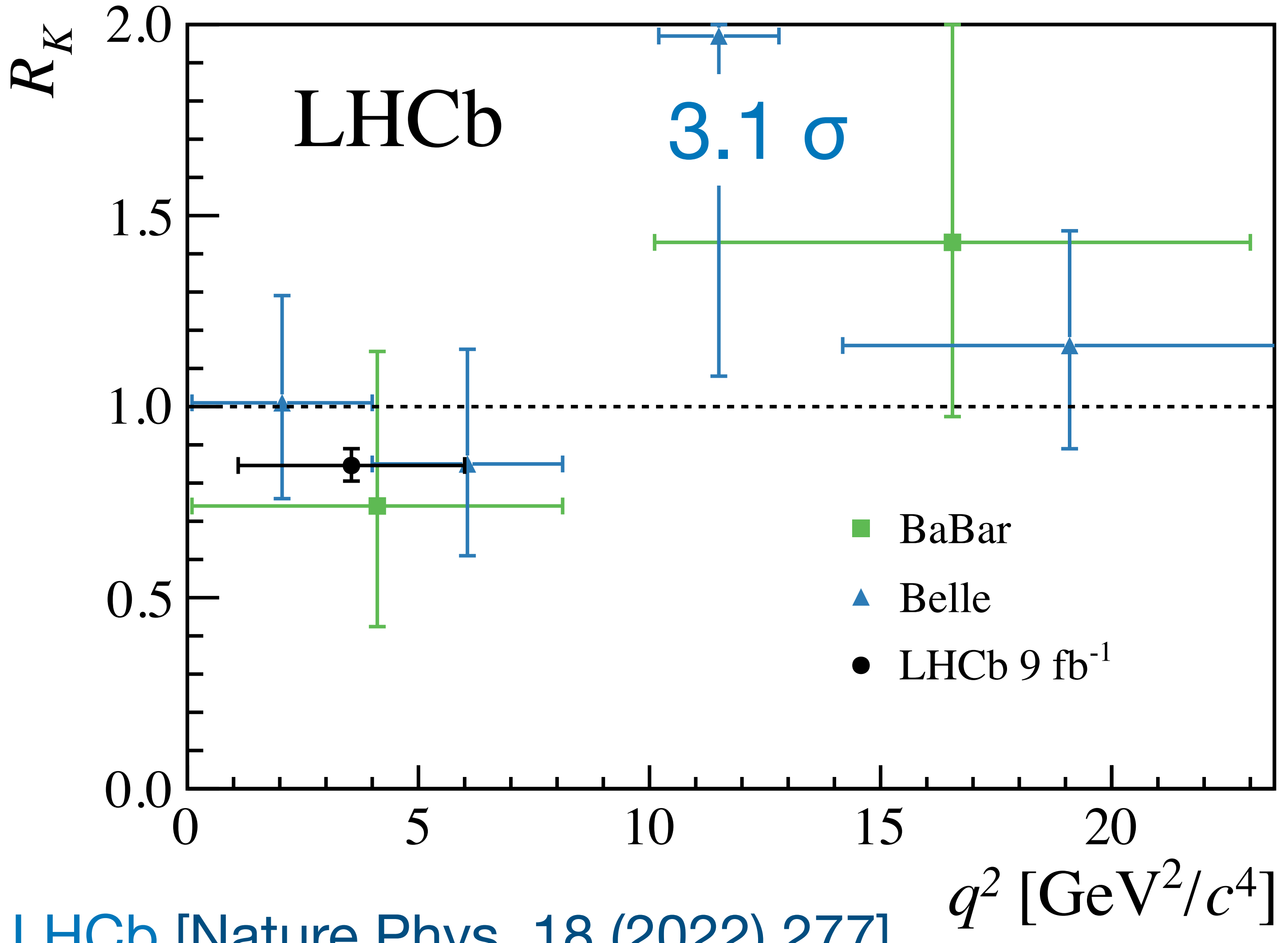
Belle [PRL 126 (2021) 161801]
BaBar [PRD 86 (2012) 032012]
LHCb [JHEP 08 (2017) 055]

$\Lambda_b \to pK^-\ell^+\ell^-$



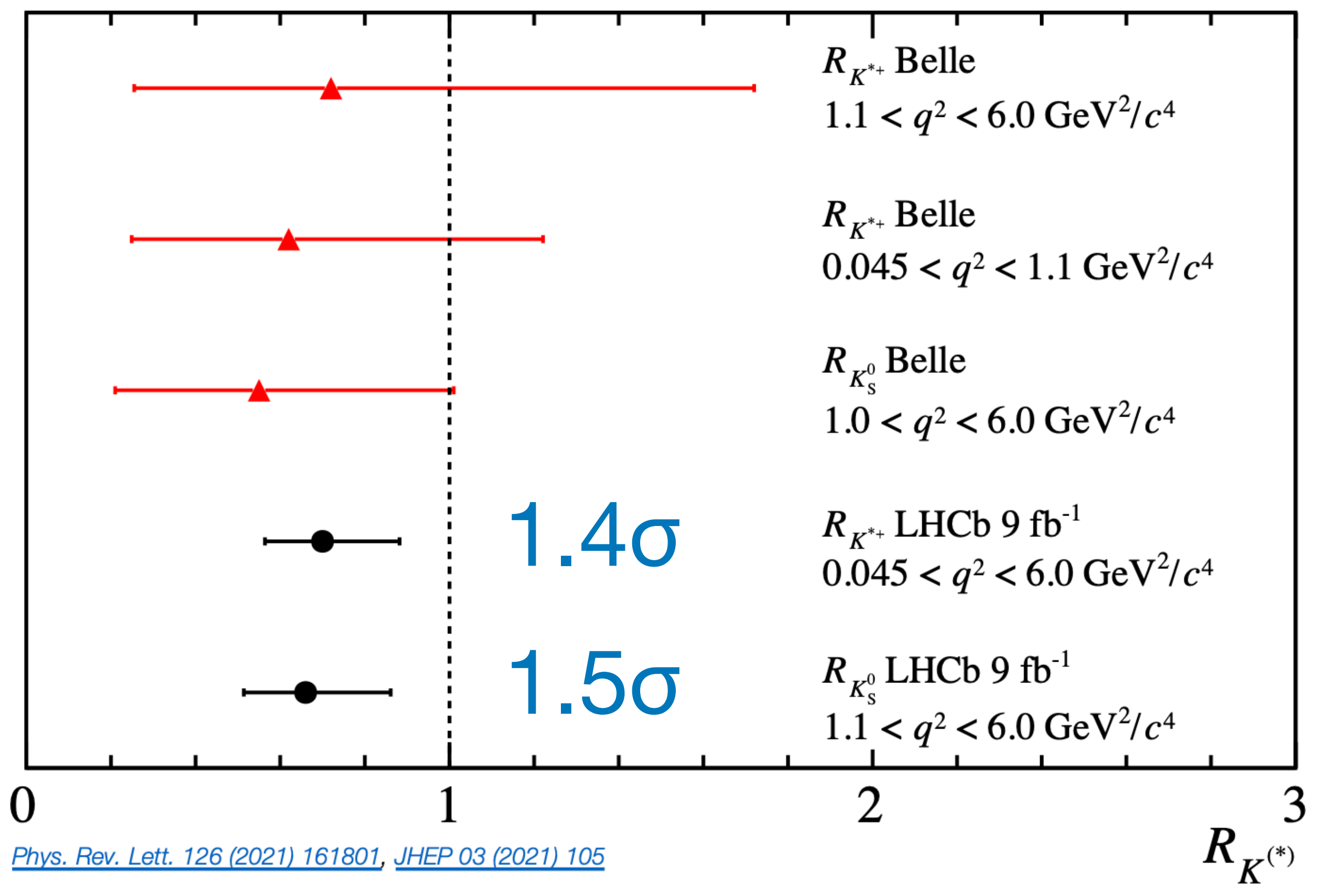
LHCb [JHEP 05 (2020) 040]

$B^+ \to K^+\ell^+\ell^-$



LHCb [Nature Phys. 18 (2022) 277]
BaBar [PRD 86 (2012) 03]
Belle [JHEP 03 (2021) 105]

$B^+ \to K^{*-}\ell^+\ell^-$
$B^0 \to K_S\,\ell^+\ell^-$



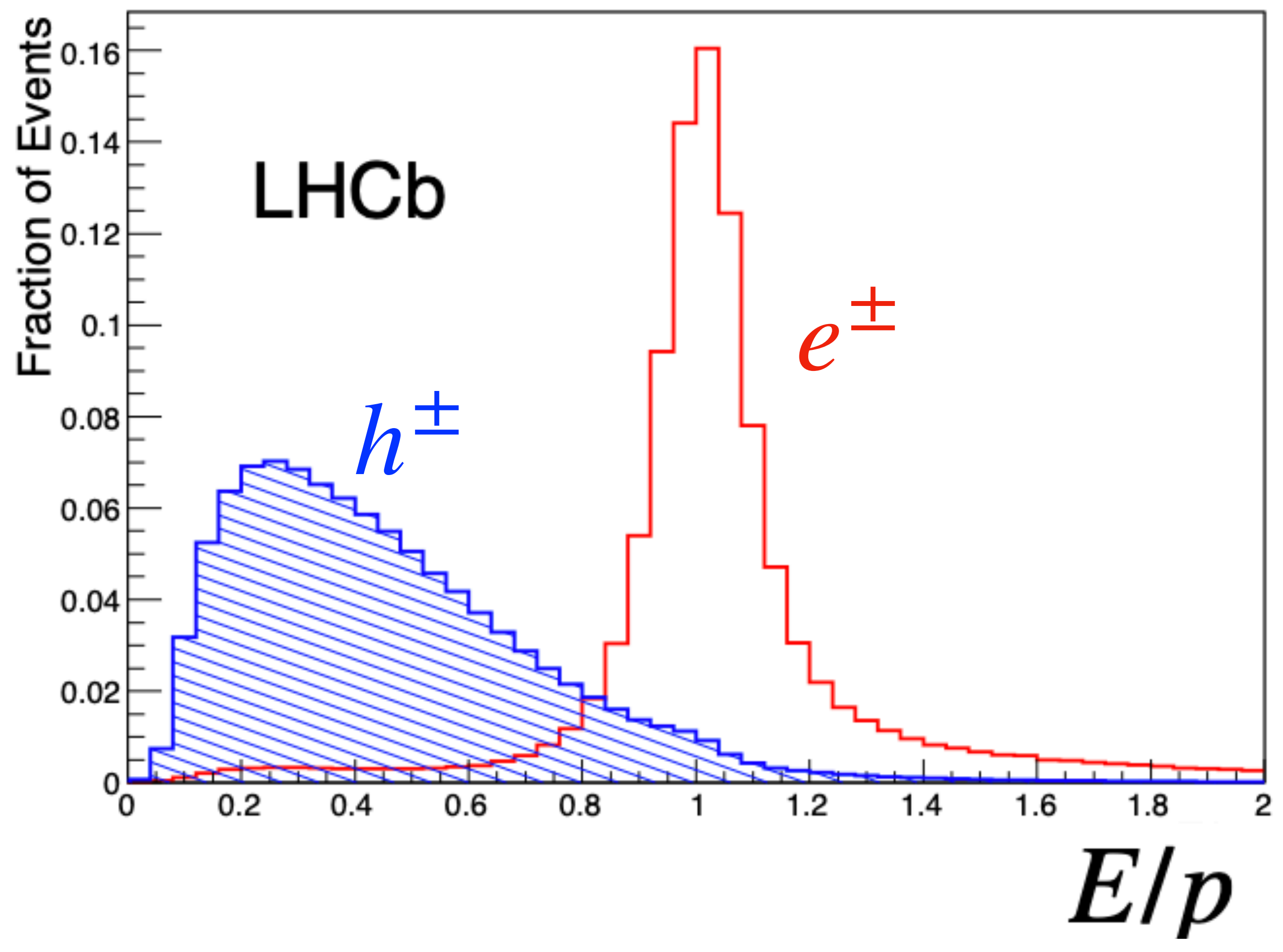
LHCb [arXiv:2110.09501]

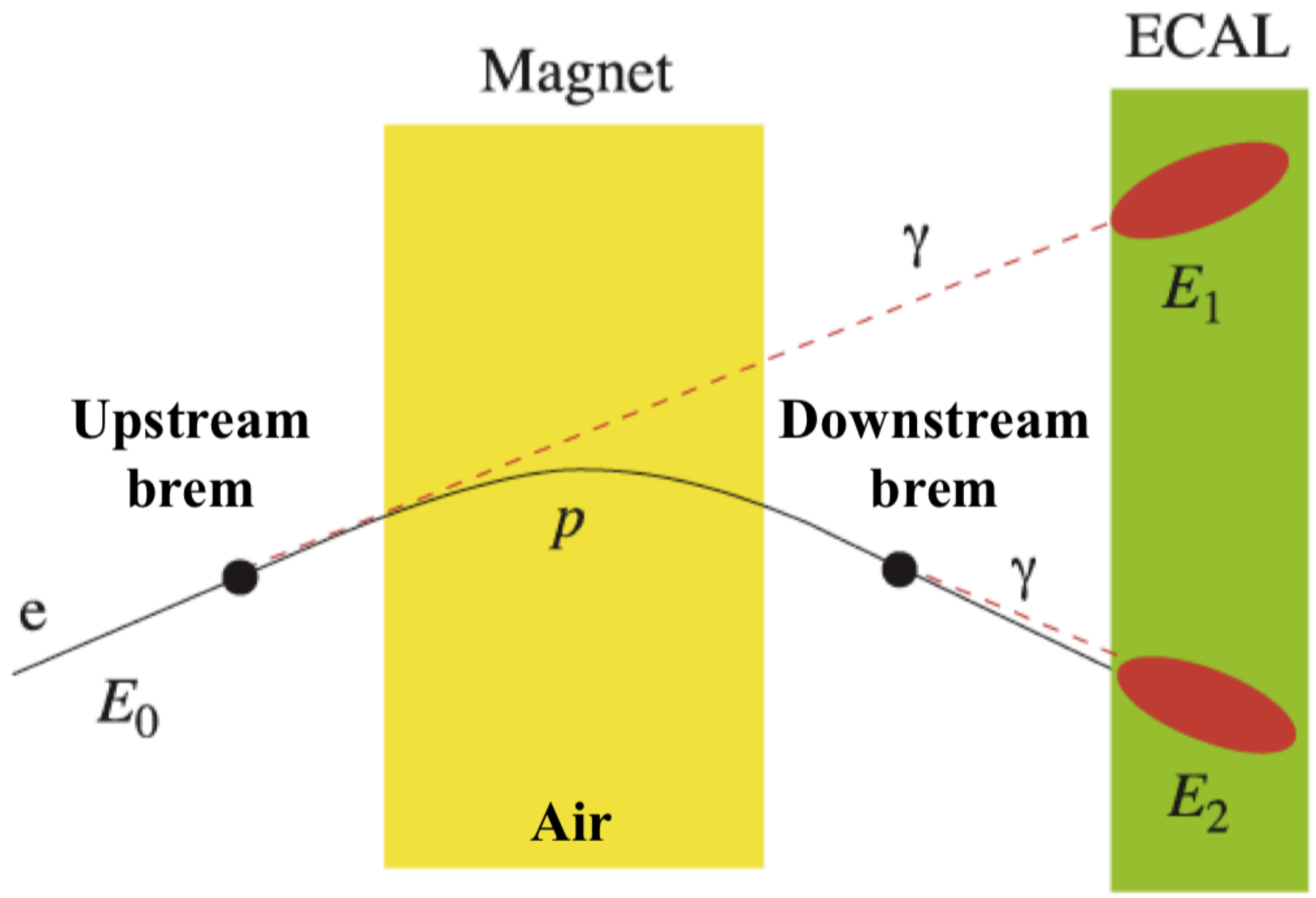
See Marie-Helene and
and Yasmine and Gianluca's talks on Wednesday

Electrons vs Muons at LHCb

- Lower trigger efficiency due hardware trigger
  - Need to cut harder in pT wrt muons
- Worse momentum & mass resolution
  - Electrons lose energy through bremsstrahlung
  - Recover brem. photons compatible with electron direction before magnet (E_T > 75 MeV)
- Particle Identification for electrons based on ECAL and track info (E/p) for the electrons

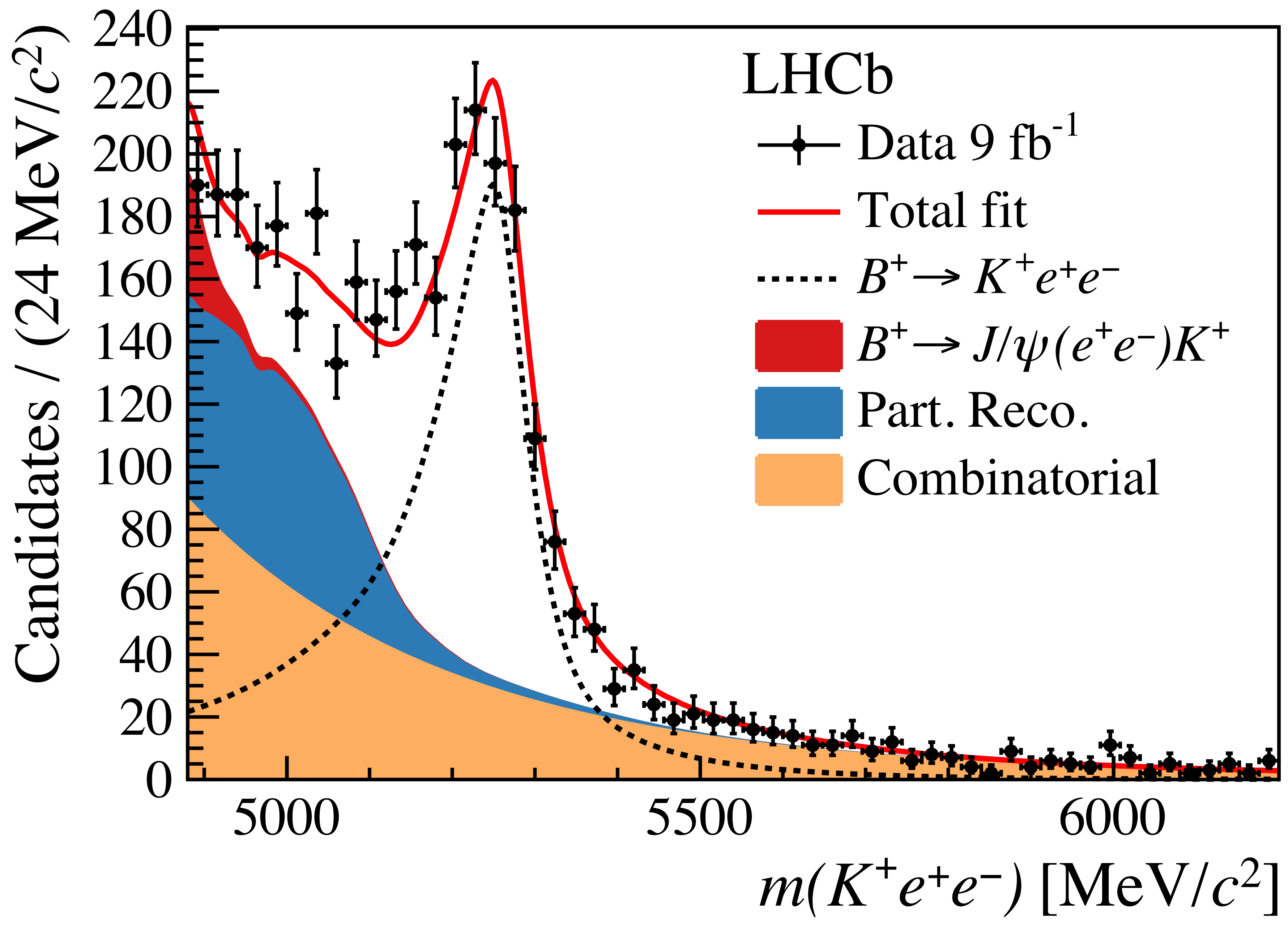
ECal electron ID

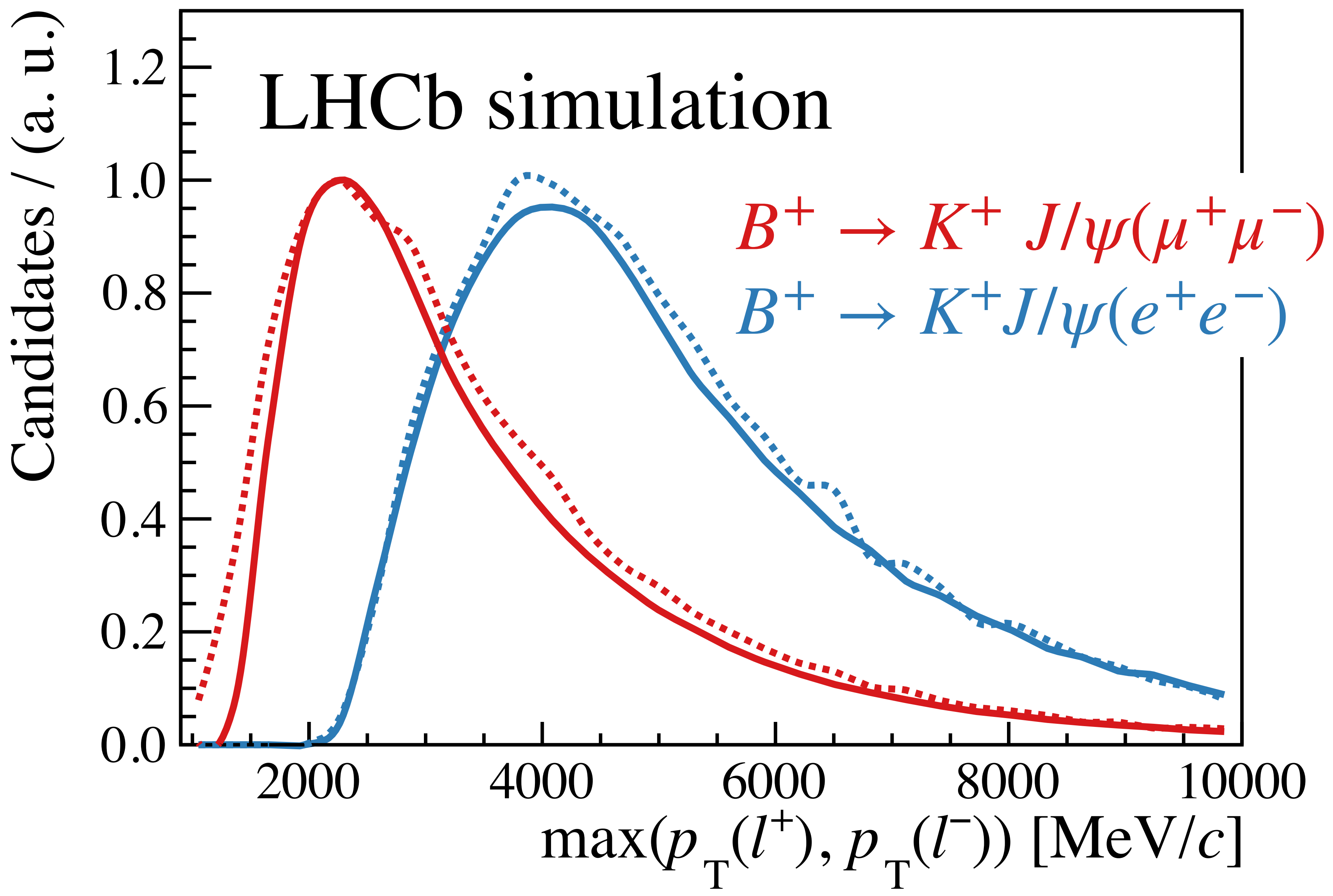




Electrons in Run3

- LHCb will be running at higher lumi ⇒ more pile-up
  - New tracking & vertexing to deal with ~5x more tracks
  - ECAL remains unchanged (new electronics) and removal of Pre-Shower and SPD detectors
- Momentum and mass resolution affected by more background in Brem. recovery and larger Brem loss because of more material
- Electron ID is more challenging in this environment, but a lot of work on ongoing to keep the performance at the same level as Run1/2
- With the removal of the hardware trigger, we can use higher level information to select electrons more efficiently
  - recover efficiency lost in the L0 and the L0 related systematic errors disappear (better kinematic overlap between μ and e)





LFU with LHCb Upgrade I

Significant increase in data opens the door to a very significant jump in precision and access to 'rarer' processes (b->dll)

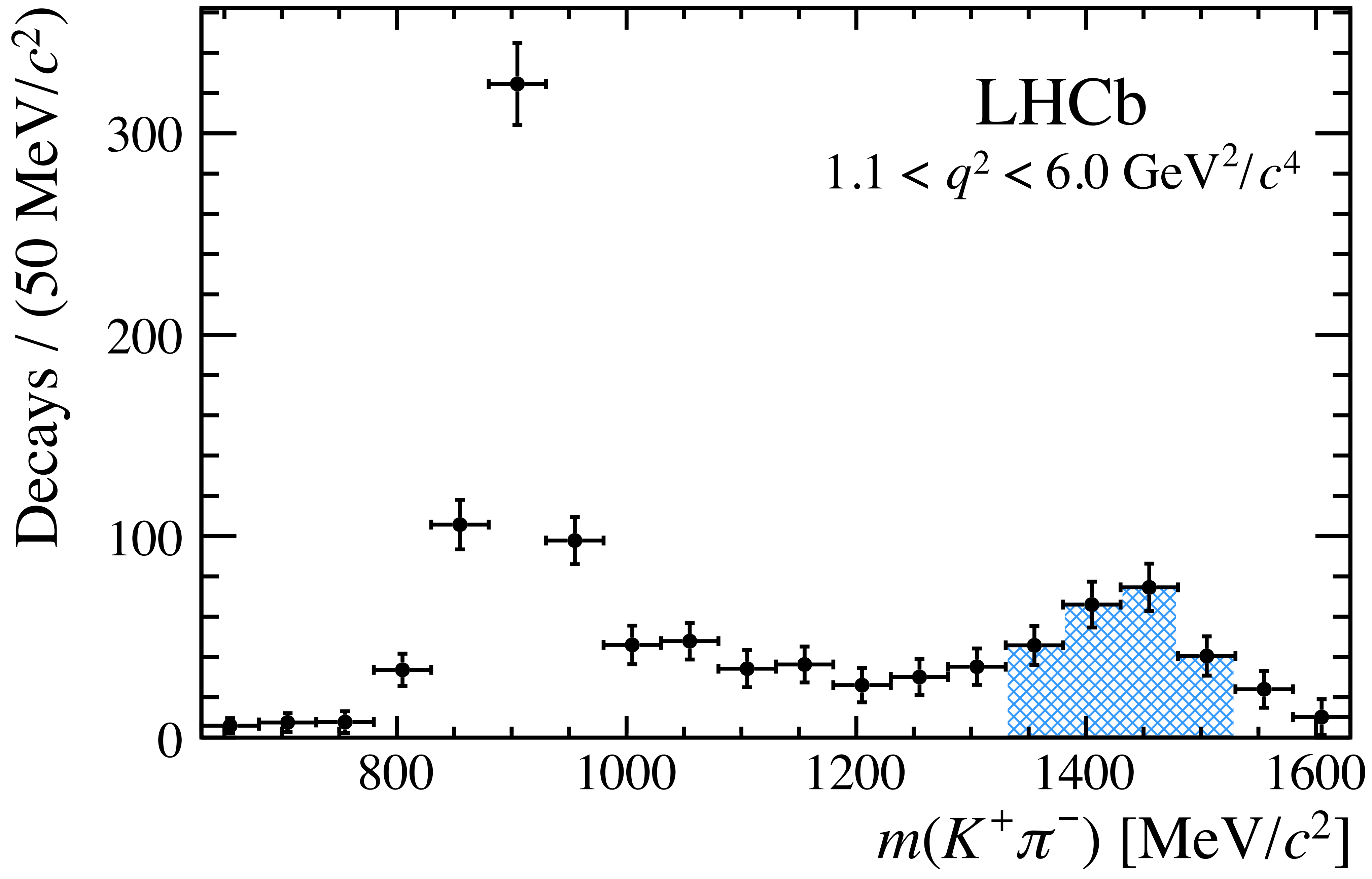
Systematics?

- Partially reconstructed backgrounds
  - Shape of partially reconstructed backgrounds can be studied in the data (Hb→Hs**e+e– BR's and amplitude structure)
- Corrections to simulation
  - Easier calibration in absence of hardware trigger
  - Larger control samples

[LHCb, arXiv:1808.08865]

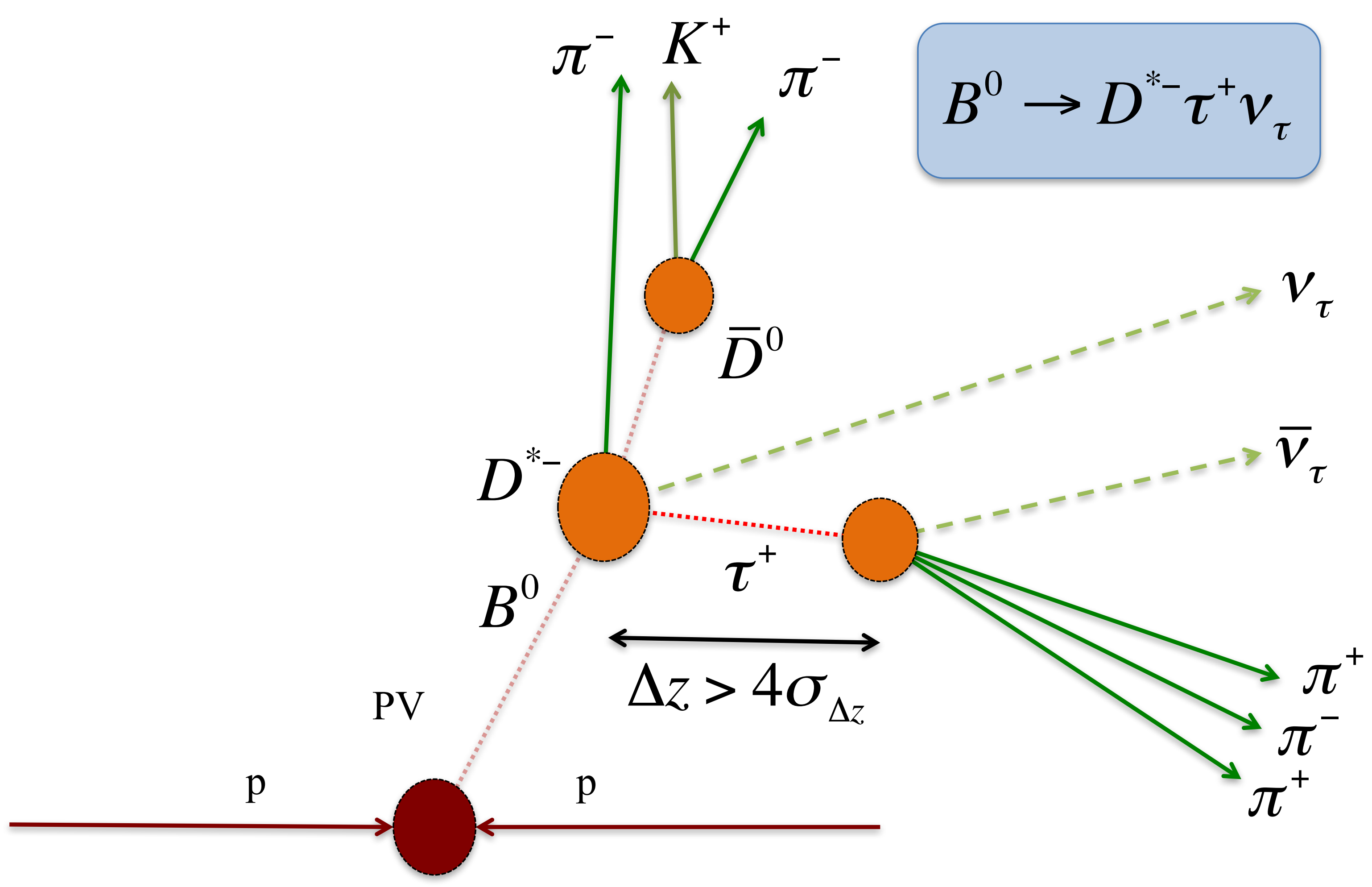
R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017
$R_{K^{*0}}$	0.052	0.031	0.020
R_ϕ	0.130	0.076	0.050
R_{pK}	0.105	0.061	0.041
R_π	0.302	0.176	0.117

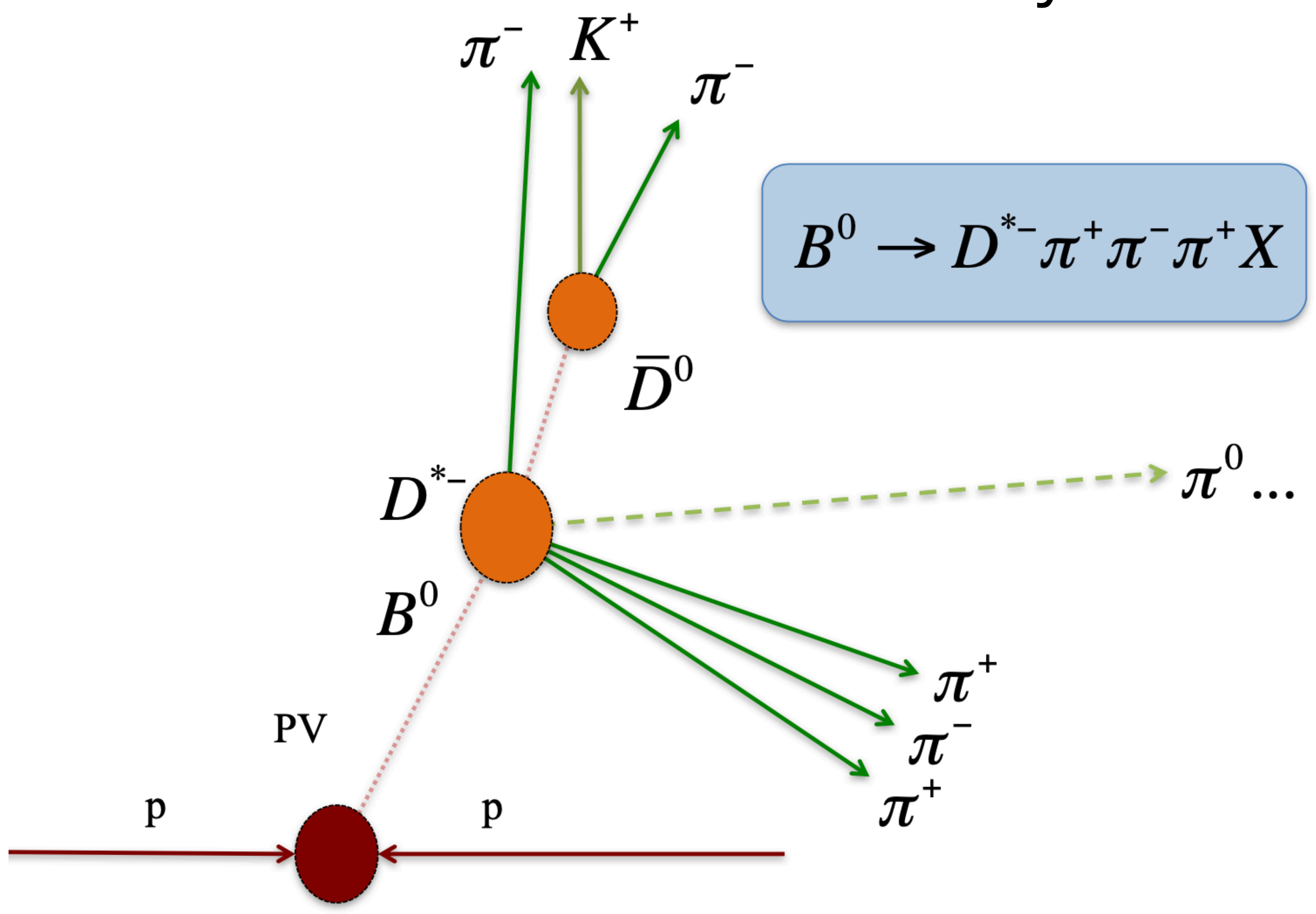
[LHCb, JHEP 12 (2016) 065]

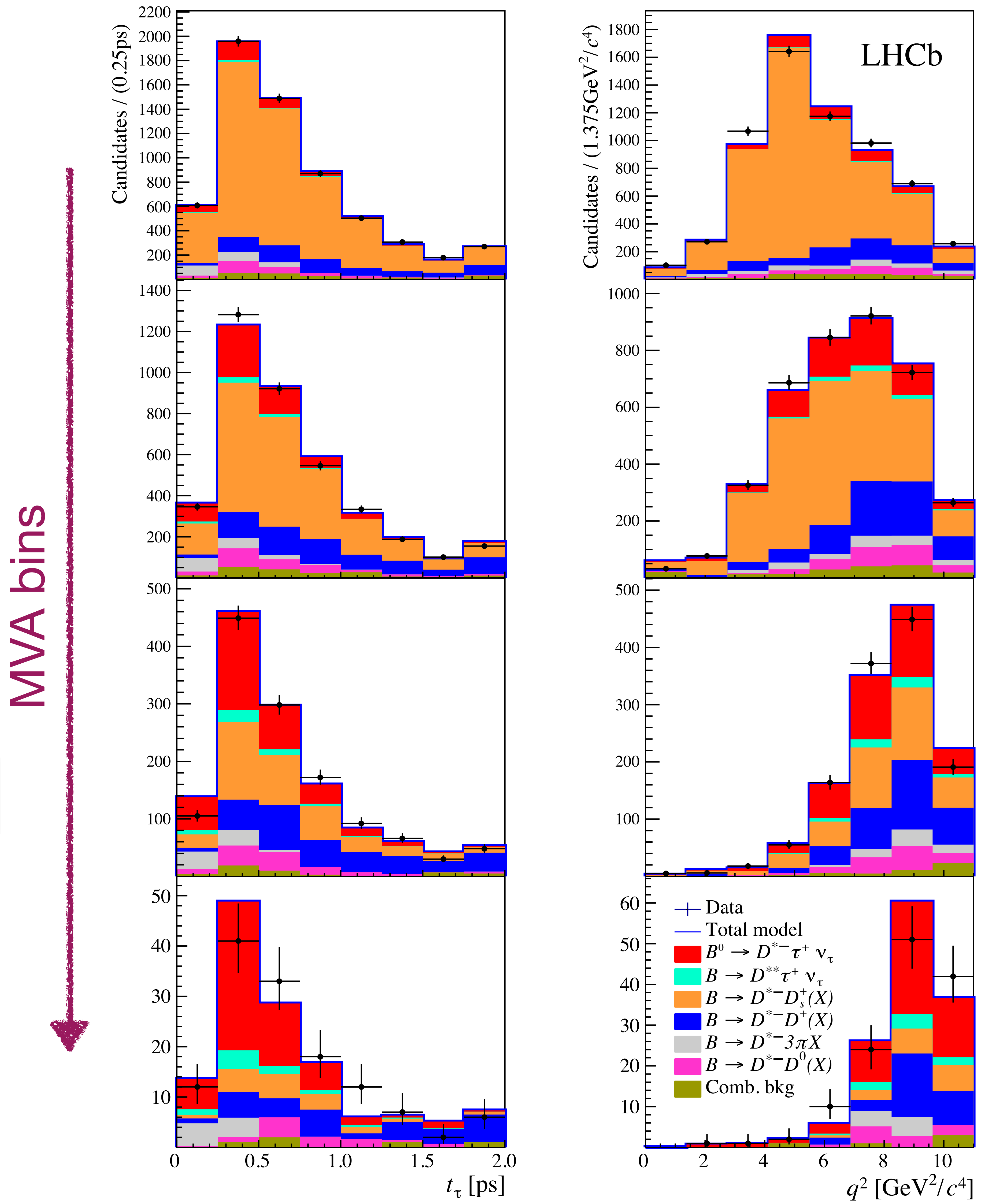


LFU in $b \to c \ell \nu$ transitions

- Experimentally challenging for LHCb due to the presence of multiple neutrinos
  - Use both $\tau \to \mu\nu\nu$, $\tau \to \pi\pi\pi\nu$
- Many backgrounds make it difficult to isolate the signal
  - Isolation, information about the physics of the different processes
- Very large datasets, need to control detector effects very well





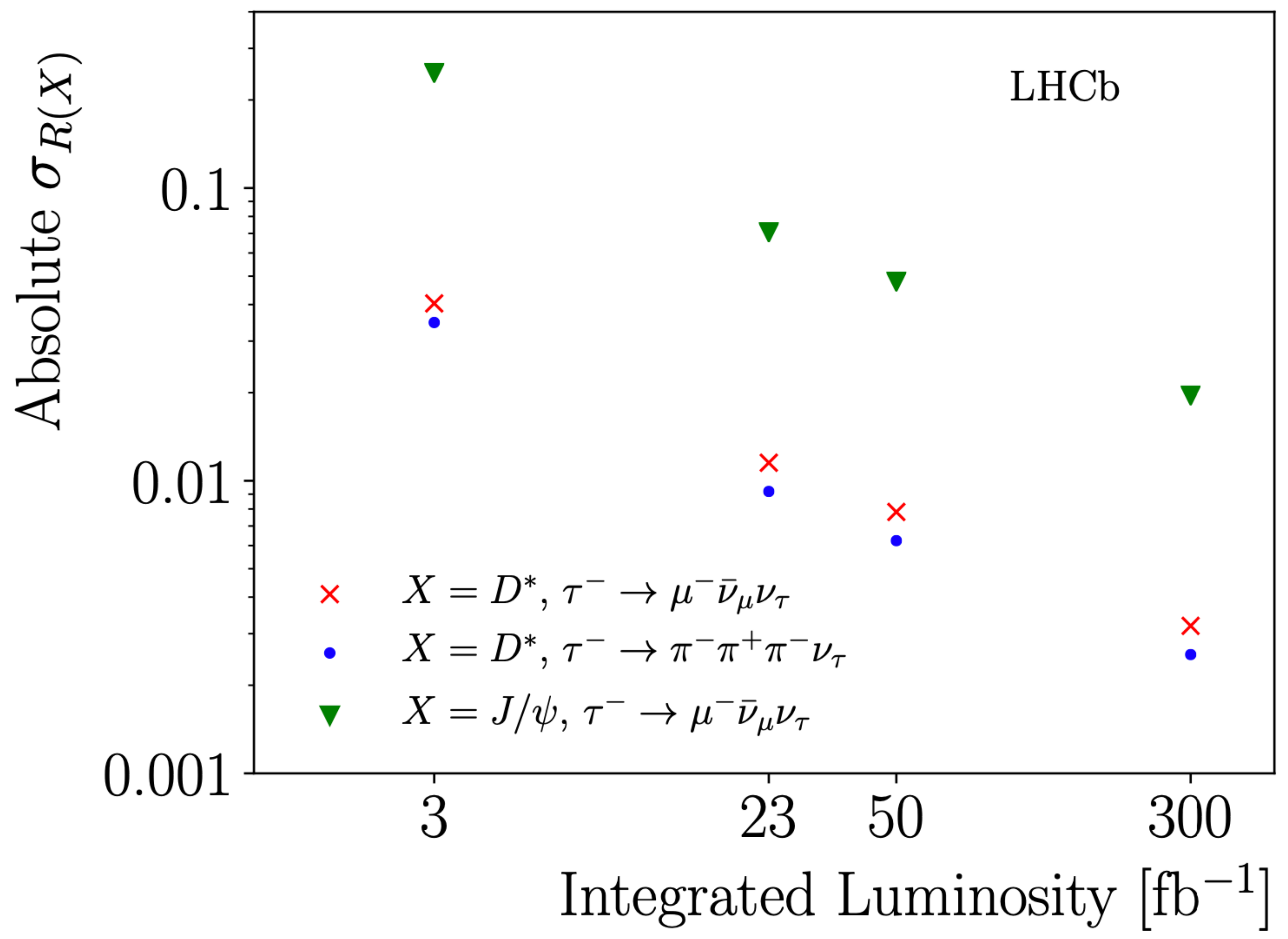


[LHCb, PRL 120 (2018) 171802]

$b \to c \ell \nu$ in Run3

See Abhijit and Mark's
and Martin and Julian's talks on Wednesday

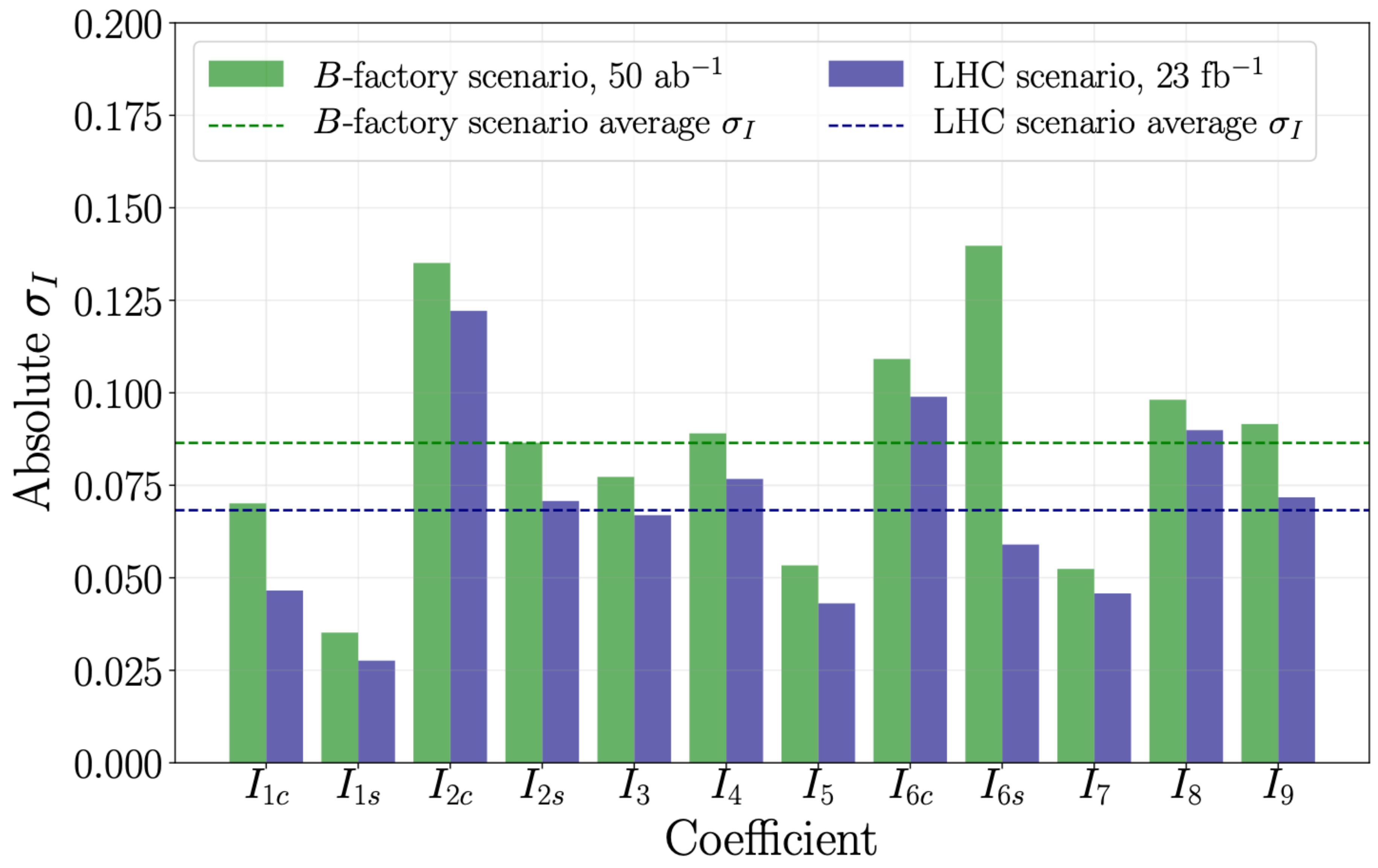
- Key to control the systematics
  - Understand the backgrounds using the data
  - Fast simulation to be able to increase the sample sizes according to the increase in data



[LHCb, arXiv:1808.08865]

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(B \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(B \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**

$\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$ - [PRL 115, 111803 (2015)]



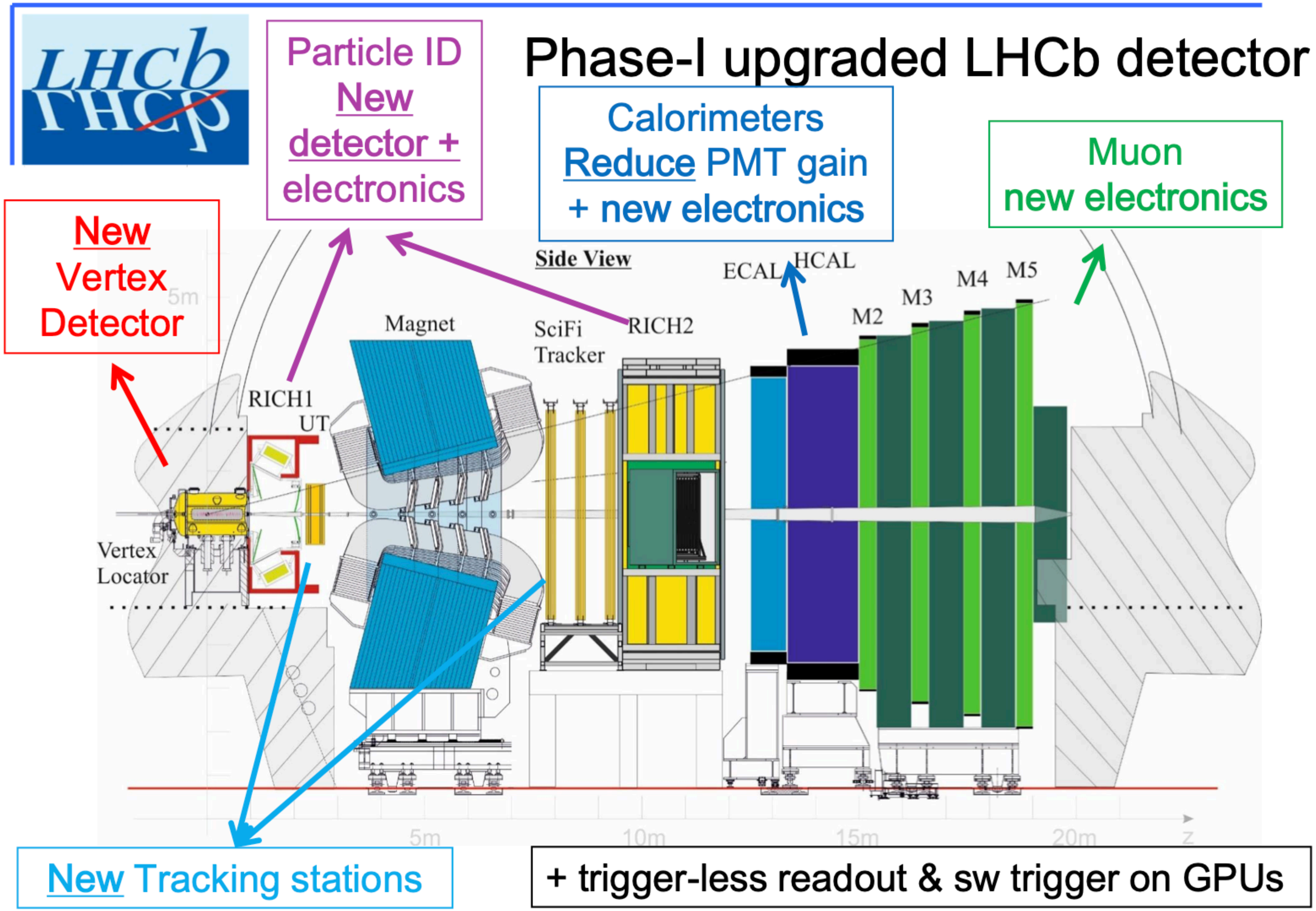
[D Hill et al, JHEP11(2019)133]

Summary

- Interesting times ahead
  - Yes, some challenges await in Run3, but experience from Run1 and 2 will help us in understanding the new detector performance
  - In the past we extended the reach of the experiment far beyond the design specs, can do the same with this new detector!

Backup

Run 3


Phase-I upgraded LHCb detector
LHCb
Particle ID
New detector + electronics
Calorimeters
Reduce PMT gain + new electronics
Muon
new electronics
New Vertex Detector
Side View
ECAL
HCAL
M2
M3
M4
M5
Magnet
SciFi Tracker
RICH2
RICH1
UT
Vertex Locator
5m
10m
15m
20m
z
New Tracking stations
+ trigger-less readout & sw trigger on GPUs

Fully software trigger

Decay	Run 1	Upgrade 10 kHz	TOPO 25 kHz	Output Rate 50 kHz
$b \to s$ penguins				
$B^0 \to K^*[K^+\pi^-]\mu^+\mu^-$	89%	85%	94%	94%
$B^0 \to K^*[K^+\pi^-]e^+e^-$	43%	38%	79%	85%
$B_s^0 \to \phi[K^+K^-]\phi[K^+K^-]$	20%	49%	79%	83%
semi-leptonic decays				
$B^0 \to D^{*-}[\pi^-\bar{D}^0[K^+\pi^-]]\mu^+\nu_\mu$	63%	58%	81%	90%
$B^0 \to D^-[K^+\pi^-\pi^-]\mu^+\nu_\mu$	40%	27%	61%	74%
$B^+ \to \bar{D}^0[K^+\pi^-]\mu^+\nu_\mu$	58%	48%	74%	81%
$B^+ \to \bar{D}^*[\bar{D}^0[K^+K^-\pi^0]\pi^0]\mu^+\nu_\mu$	39%	25%	64%	72%
$B^+ \to \bar{D}^0[K_S^0[\pi^+\pi^-]\pi^+\pi^-]\mu^+\nu_\mu$	32%	17%	58%	69%
$B_s^0 \to K^-\mu^+\nu_\mu$	59%	52%	67%	71%
$B_s^0 \to D_s^-[K^+K^-\pi^-]\mu^+\nu_\mu$	47%	29%	71%	79%
$\Lambda_b^0 \to p^+\mu^-\bar{\nu}_\mu$	54%	44%	59%	60%