LHCb Upgrade II

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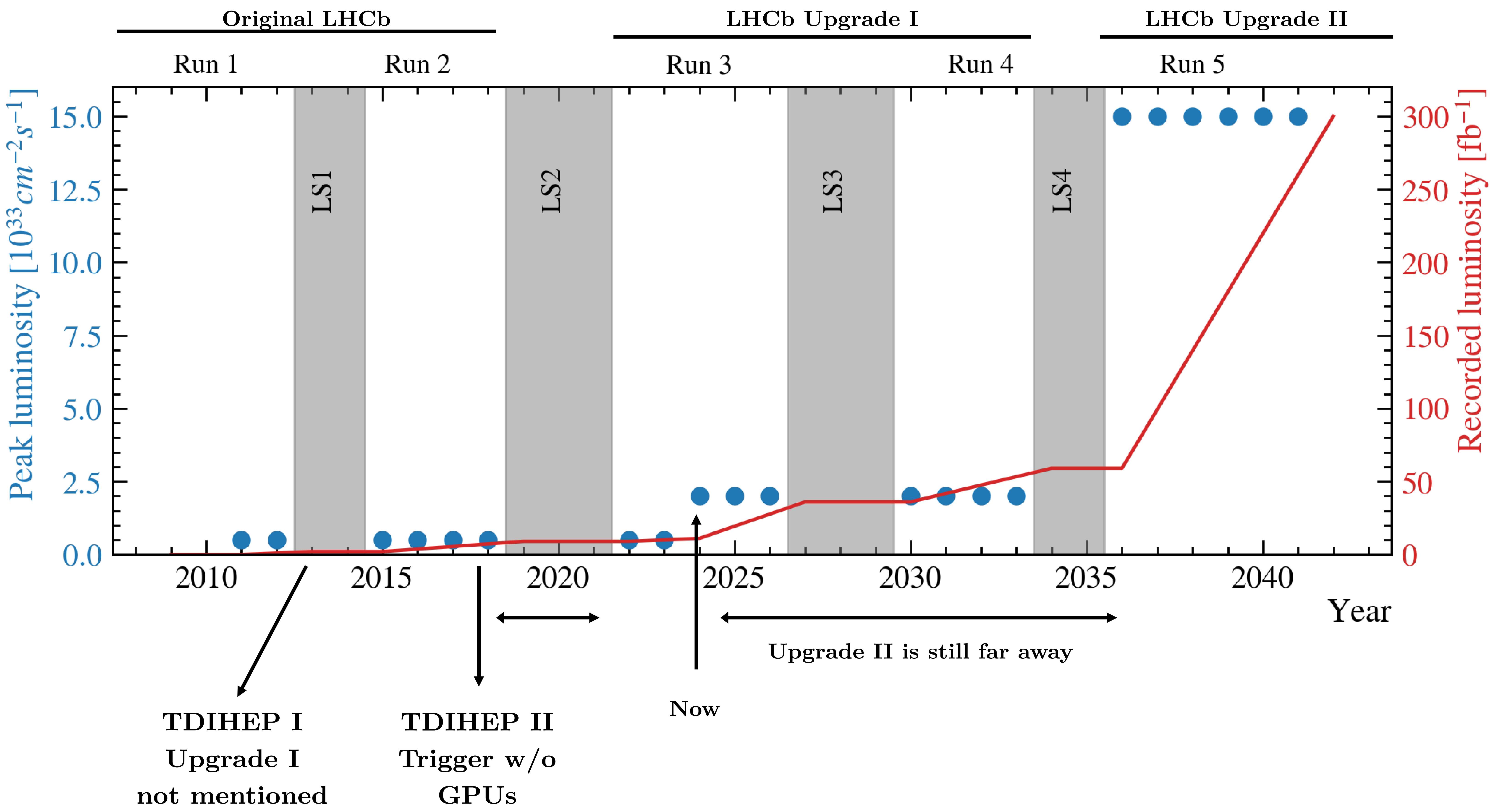
On behalf of the LHCb Collaboration

Triggering Discoveries in High Energy Physics III

9-13 Dec 2024

Timeline



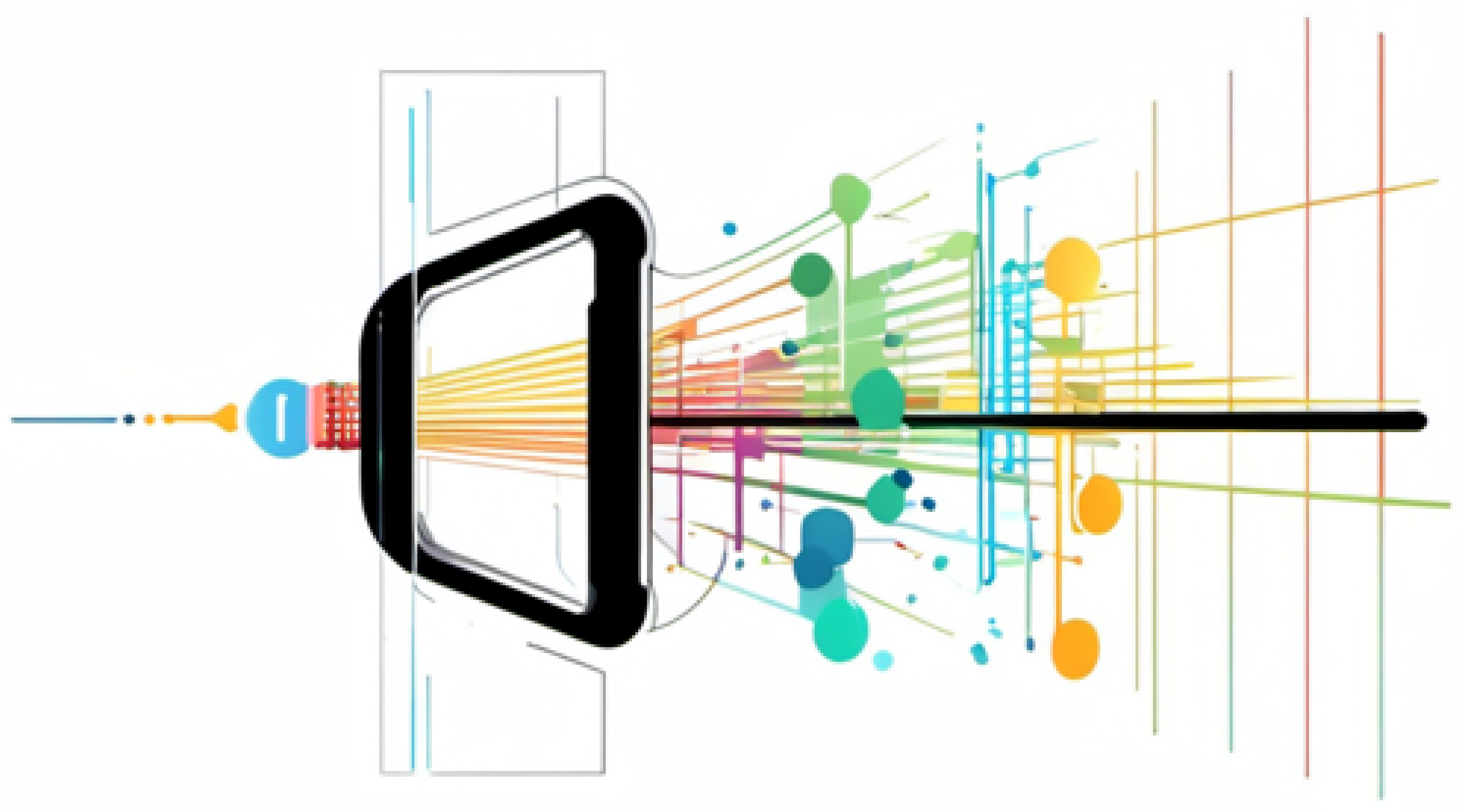
Original LHCb
LHCb Upgrade I
LHCb Upgrade II
Run 1
Run 2
Run 3
Run 4
Run 5
LS1
LS2
LS3
LS4
Peak luminosity [$10^{33} cm^{-2} s^{-1}$]
Recorded luminosity [fb^{-1}]
15.0
12.5
10.0
7.5
5.0
2.5
0.0
300
250
200
150
100
50
0
2010
2015
2020
2025
2030
2035
2040
Year
Upgrade II is still far away
Now
TDIHEP I
Upgrade I
not mentioned
TDIHEP II
Trigger w/o
GPUs

Overview

I. Physics motivation

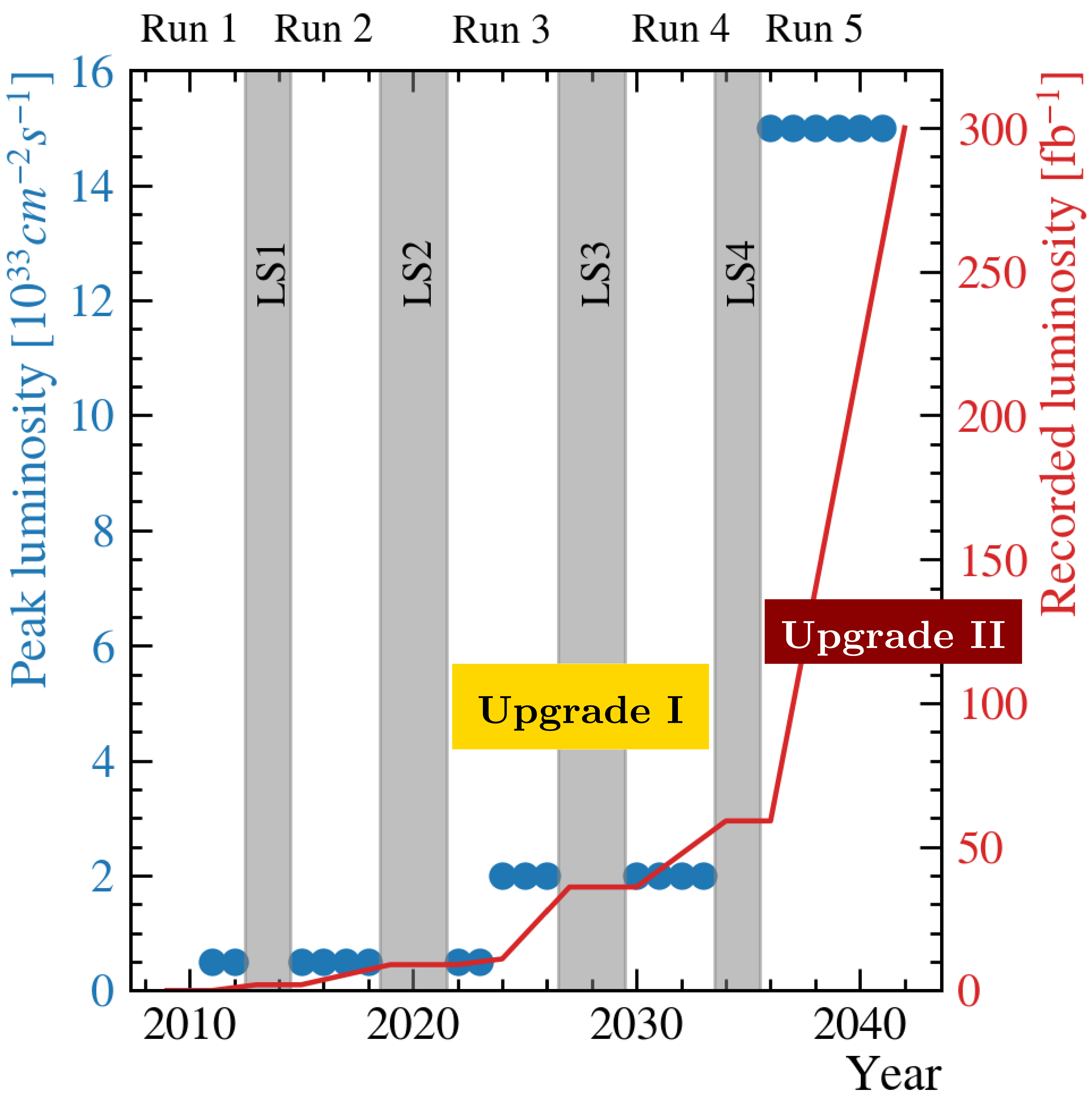
II. The LHCb Upgrade II detector

III. The trigger



LHCb physics motivation

- Possibly the only general purpose flavour physics facility
- European Strategy Update 2020: "*The full potential of the LHC and the HL-LHC, including the study of **flavour physics**, should be exploited*"
- Searches for new Physics:
  - ATLAS & CMS direct discovery with HL-LHC
  - Indirect discoveries with precision measurements → **LHCb**
    - Searches effects of virtual particles limited only by precision

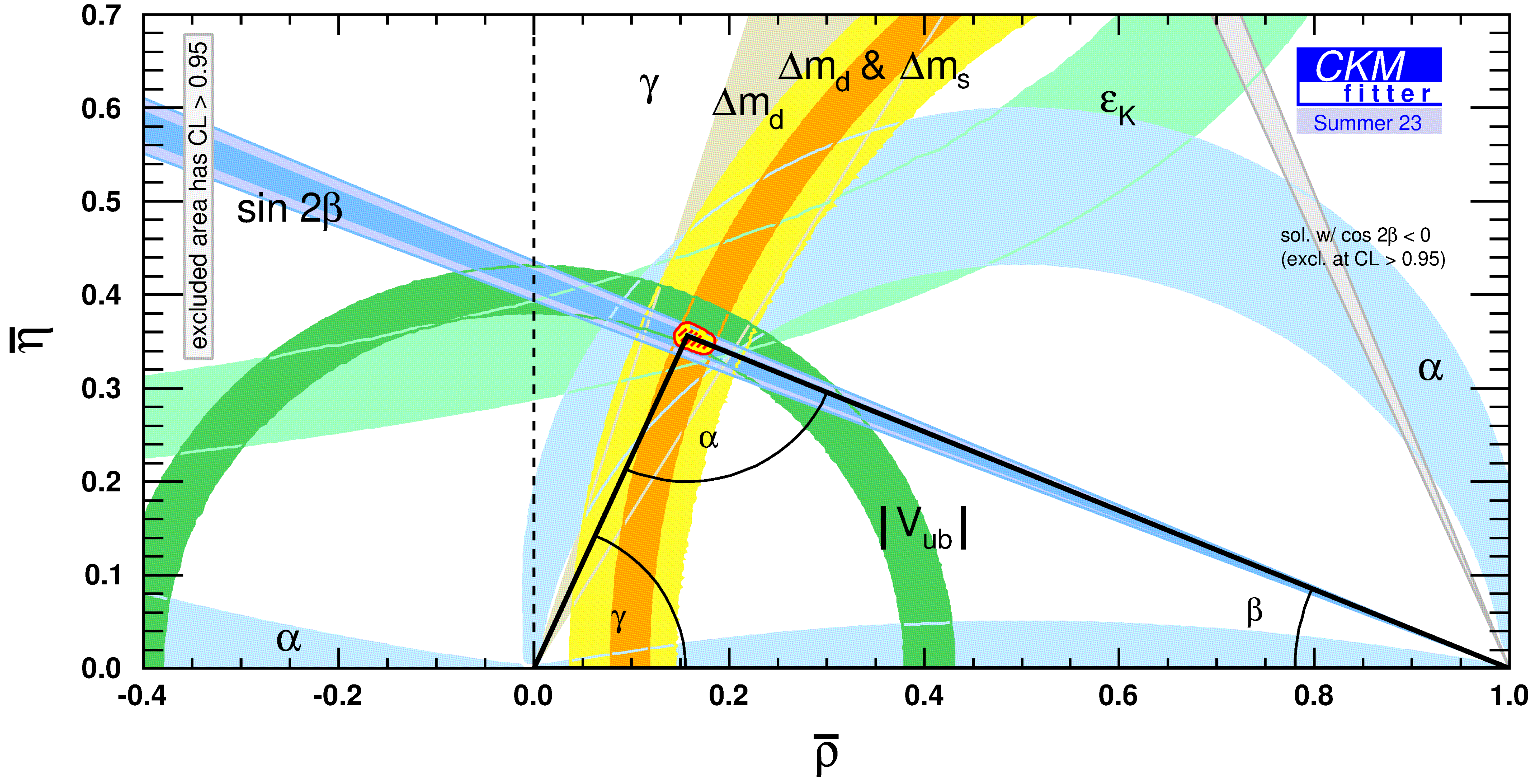


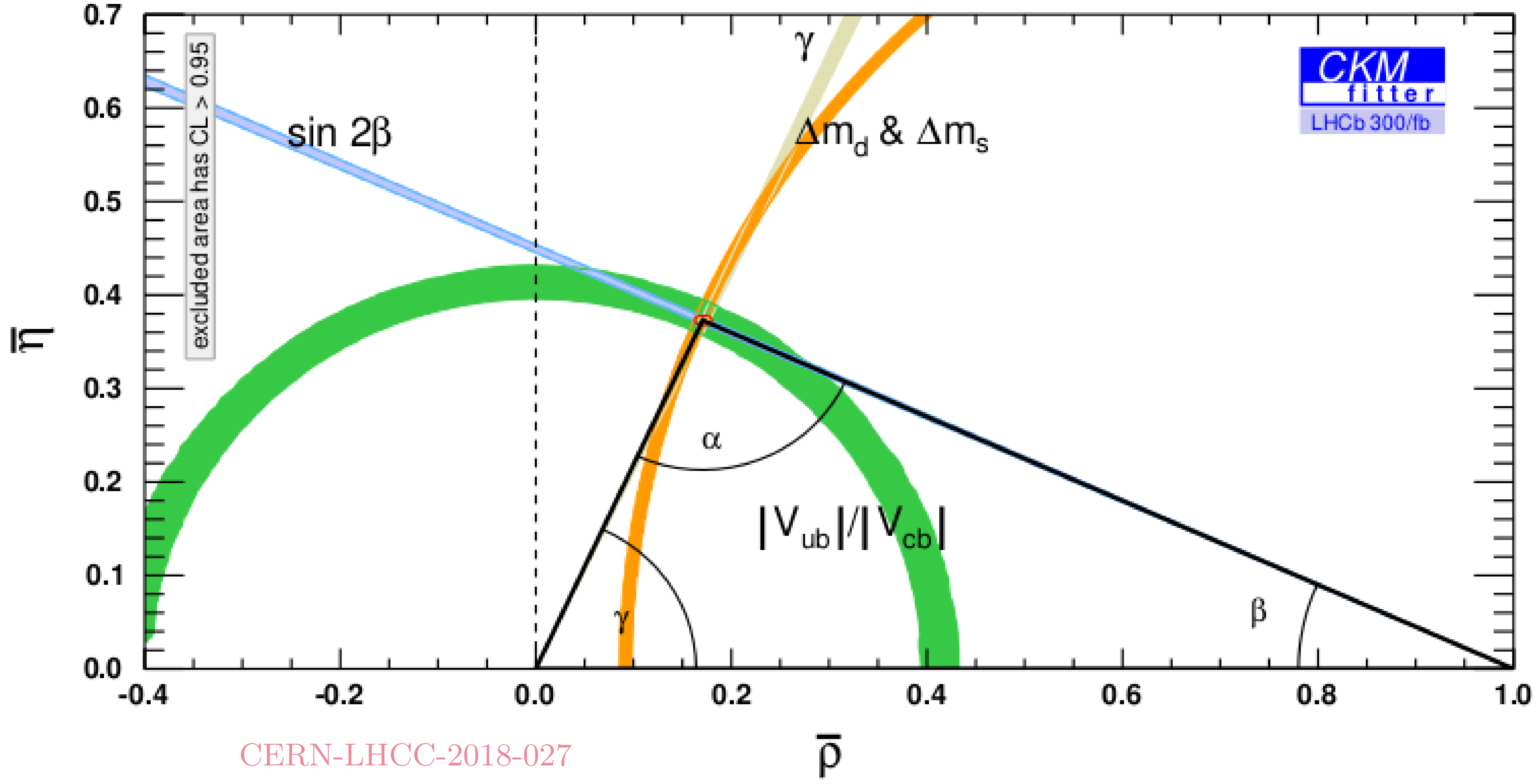
Physics case for an LHCb Upgrade II LHCC-2018-027

LHCb physics program

- CKM
- Charm
- Rare decays
- CP-violation
- Electro-weak
- Hadron-spectroscopy

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr





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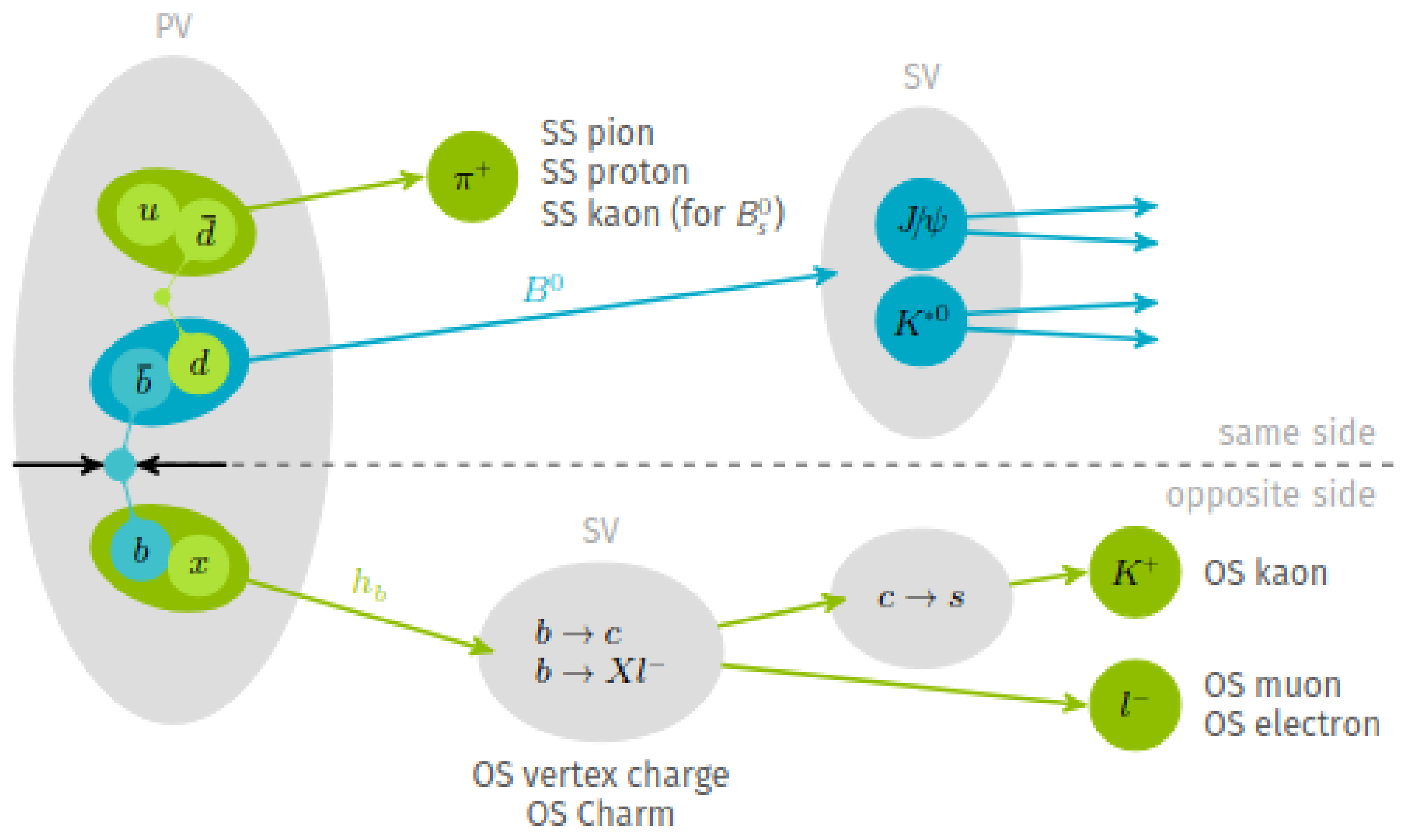
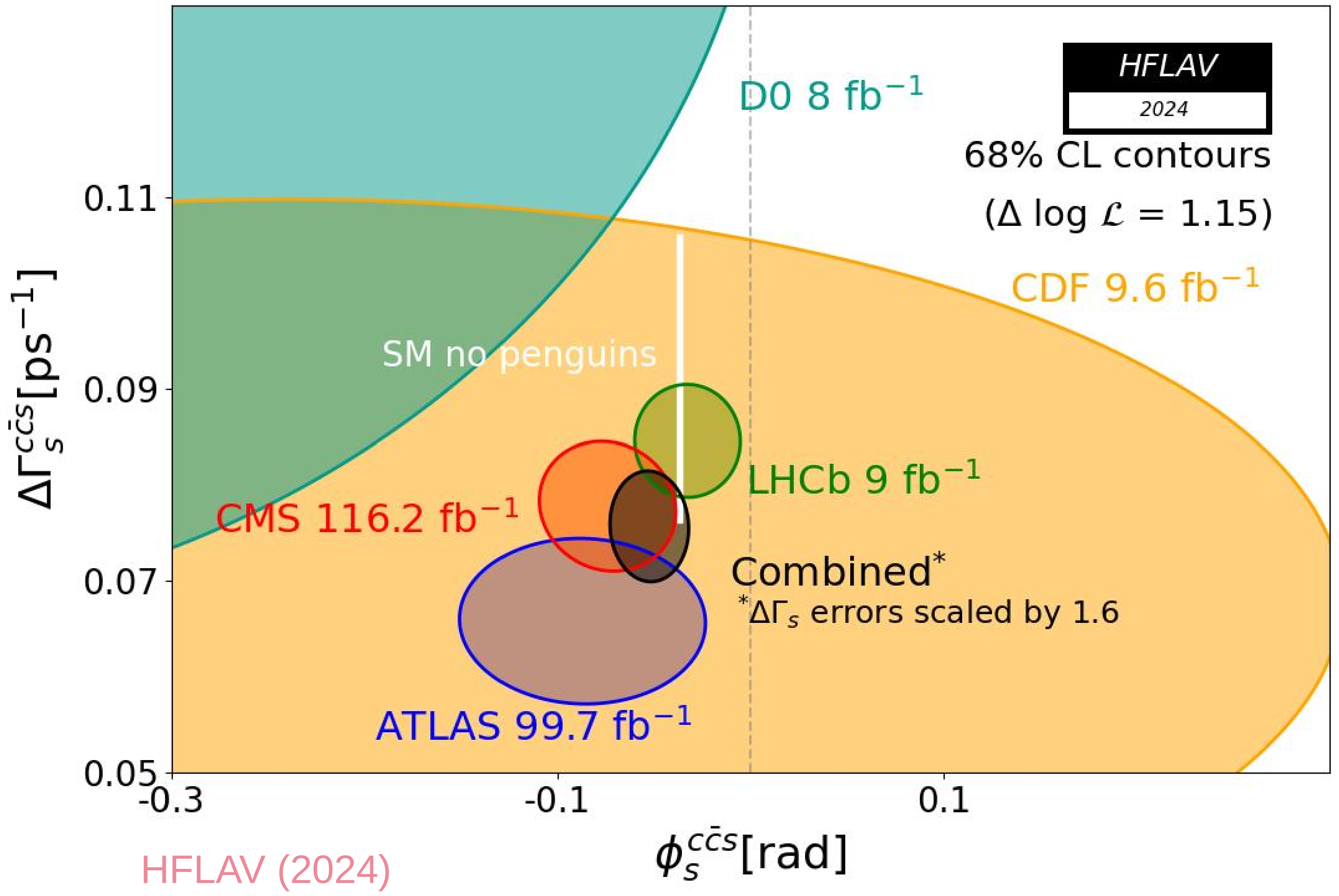
$\Delta\Gamma_{d(s)}$

Time-dependent CP-violation with b

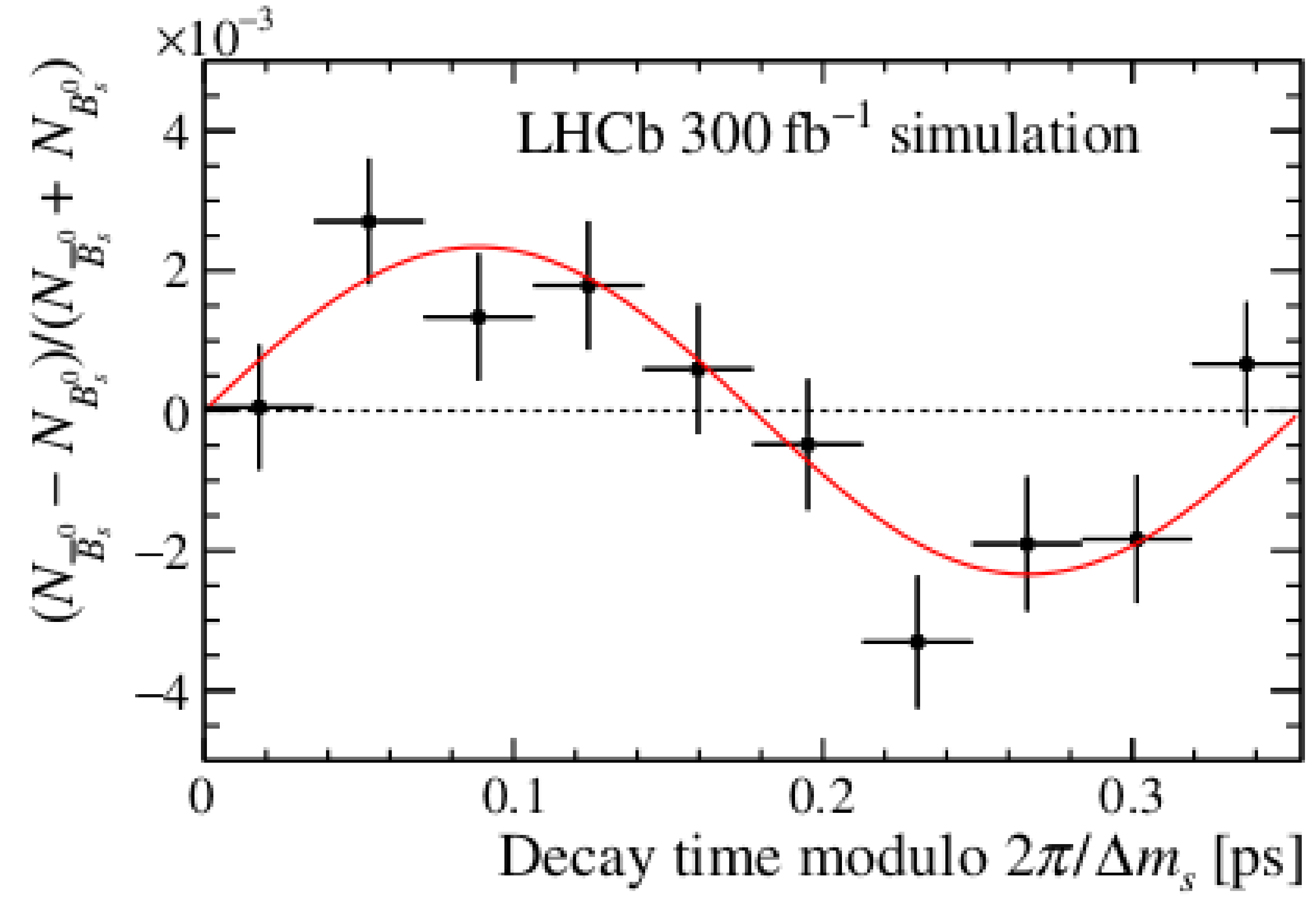
- $B^0_{(s)} - \bar{B}^0_{(s)}$ transitions are loop processes
  - Precision measurements of $\Delta m_{d(s)}$ $\Delta\Gamma_{d(s)}$
- $B^0_s \to J/\psi\phi$ CP-violating phase $\phi_s^{c\bar{c}s}$ and $\Delta\Gamma_s$
- Flavour tagging at high pile-up

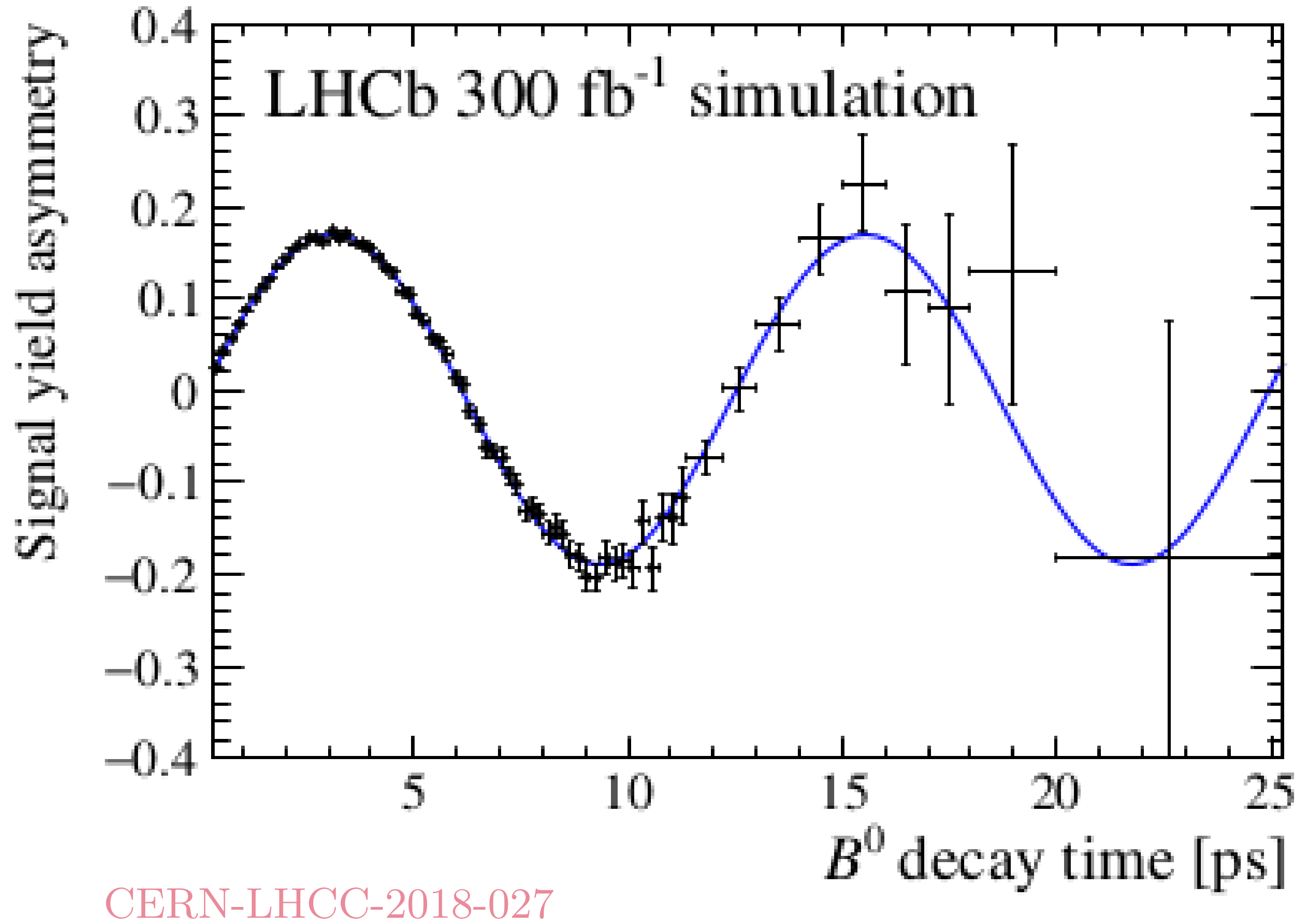


PoS(LHCP2018)230



HFLAV (2024)





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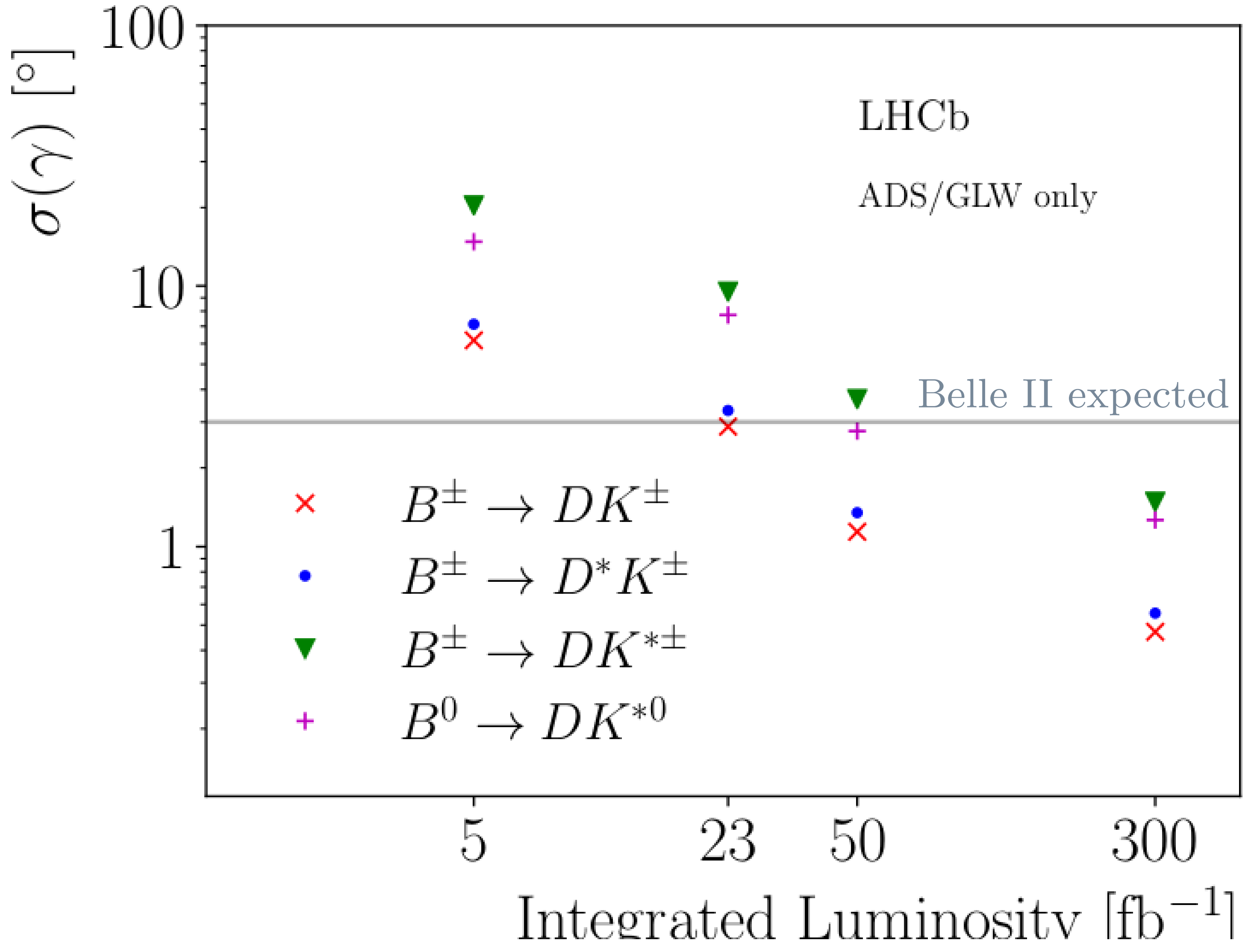
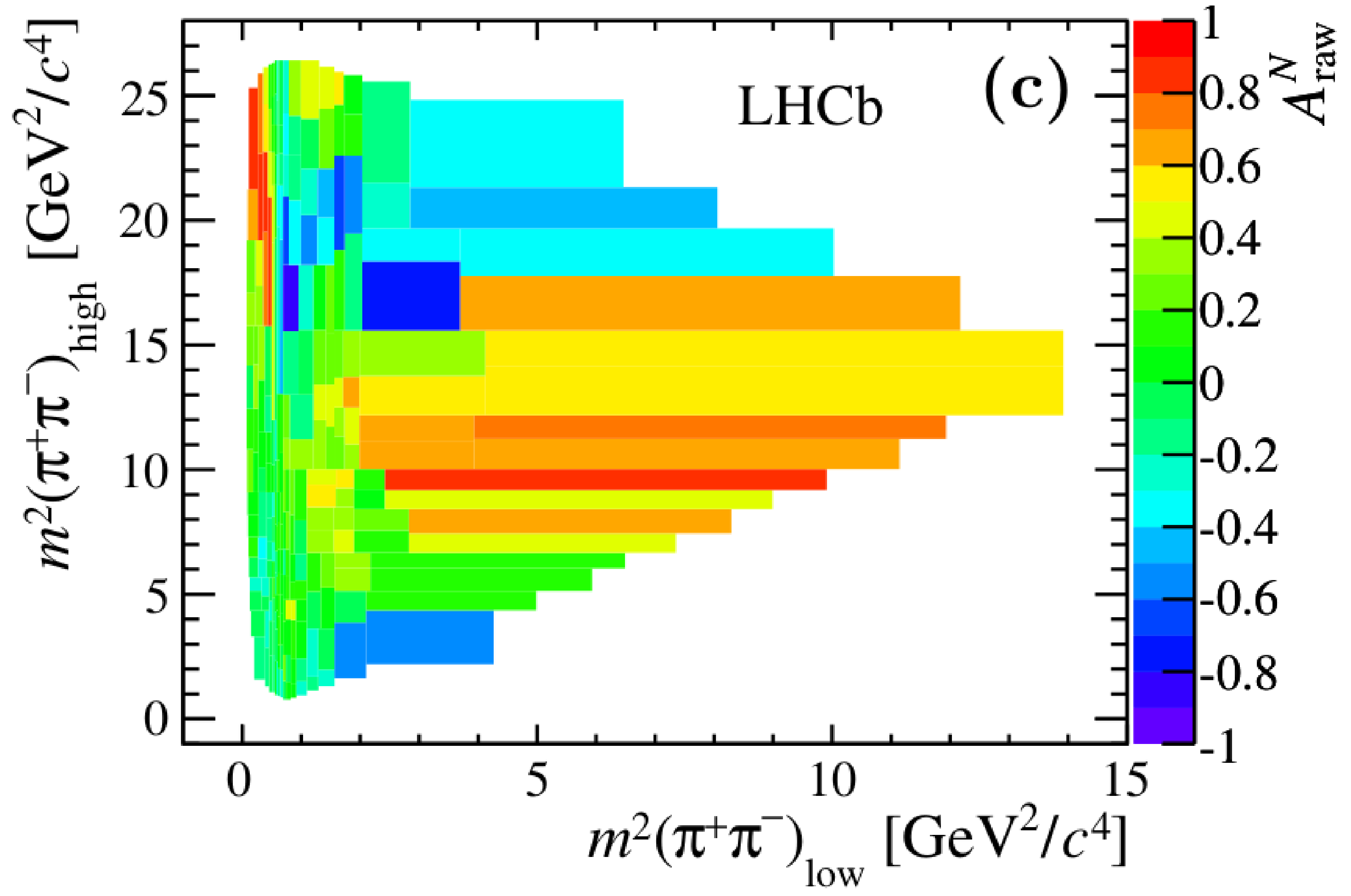
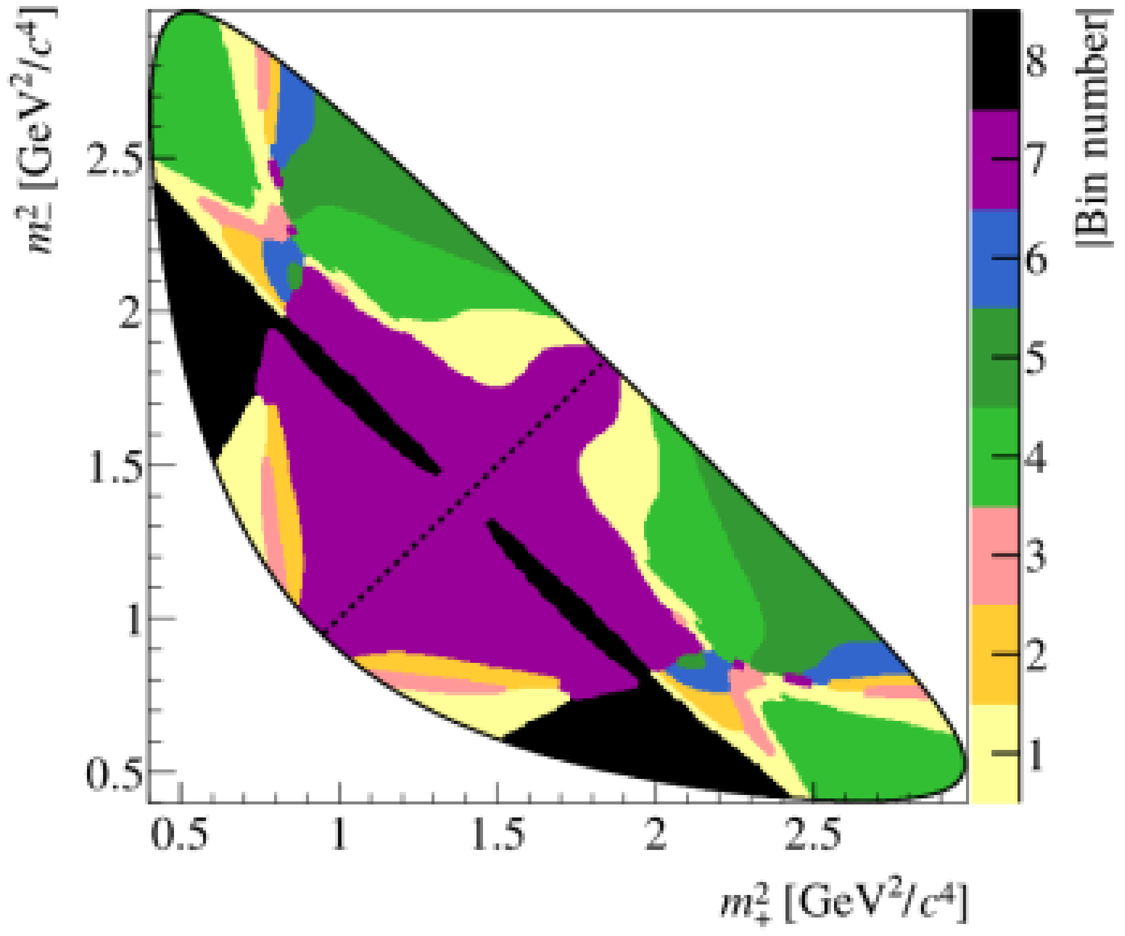
Time-integrated CP-violation measurements

- $\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ SM prediction free of top-quark coupling
  - $B \to DK$, many channels with complementary systematics
- Three body, self conjugate $B^{\pm} \to D^0(\to K_s^0 h^+ h^-)K^{\pm}$
- Amplitude analysis $B^+ \to h^+ h^+ h^-$
- Baryon decays





Phys. Rev. D 90, 112004



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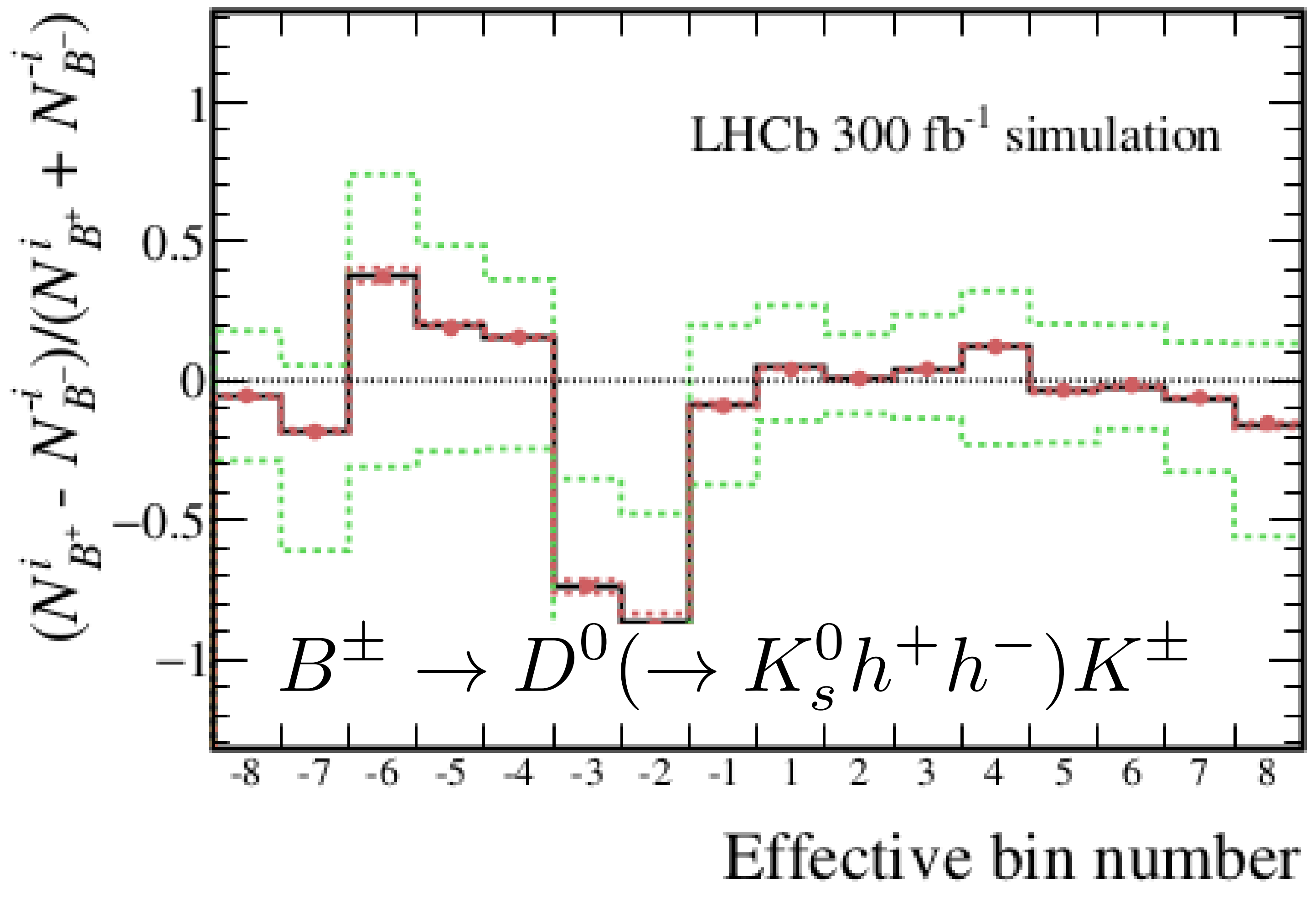

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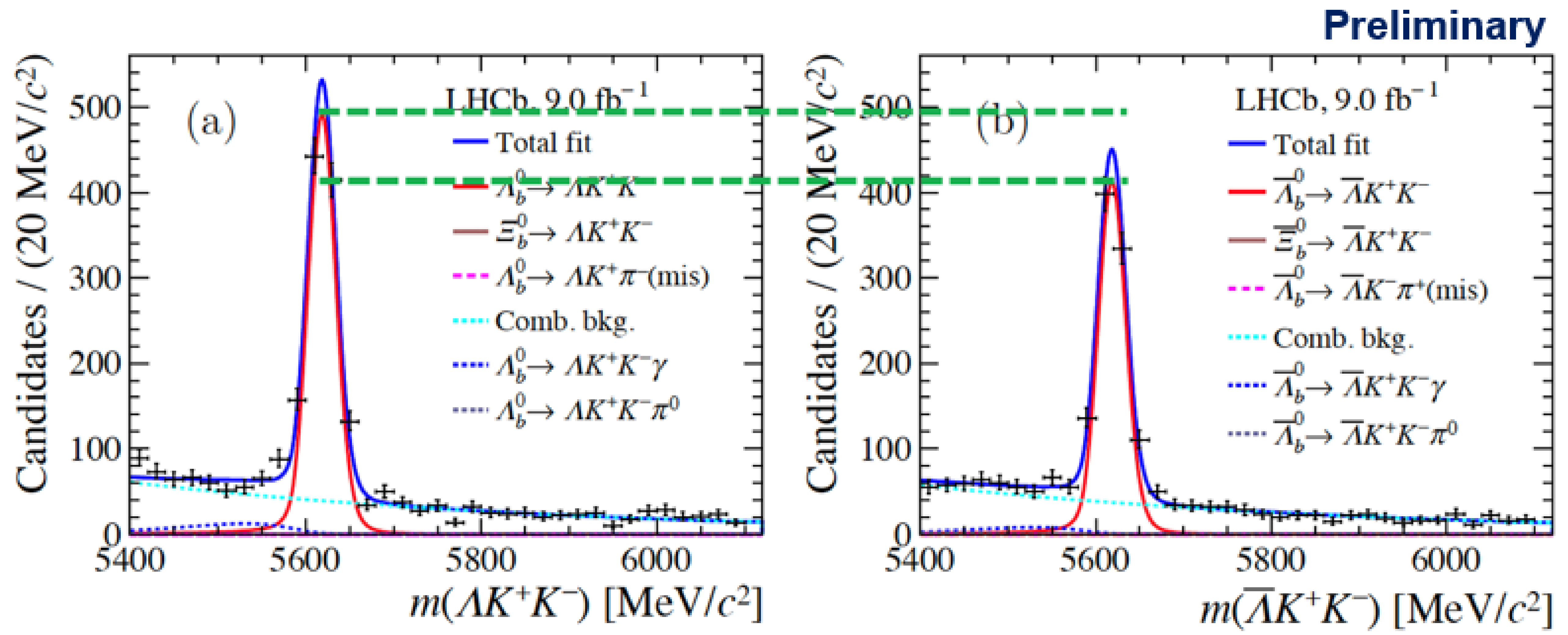
- **Baryon decays**



$\Lambda_b^0 \to \Lambda K^+ K^-$

$\Delta A_{CP} = 0.083 \pm 0.023 \pm 0.016$

First evidence of CP violation, 3.1σ

LHCb-PAPER-2024-043 (in preparation)
Figure from LHCb outreach page (08.11.24)
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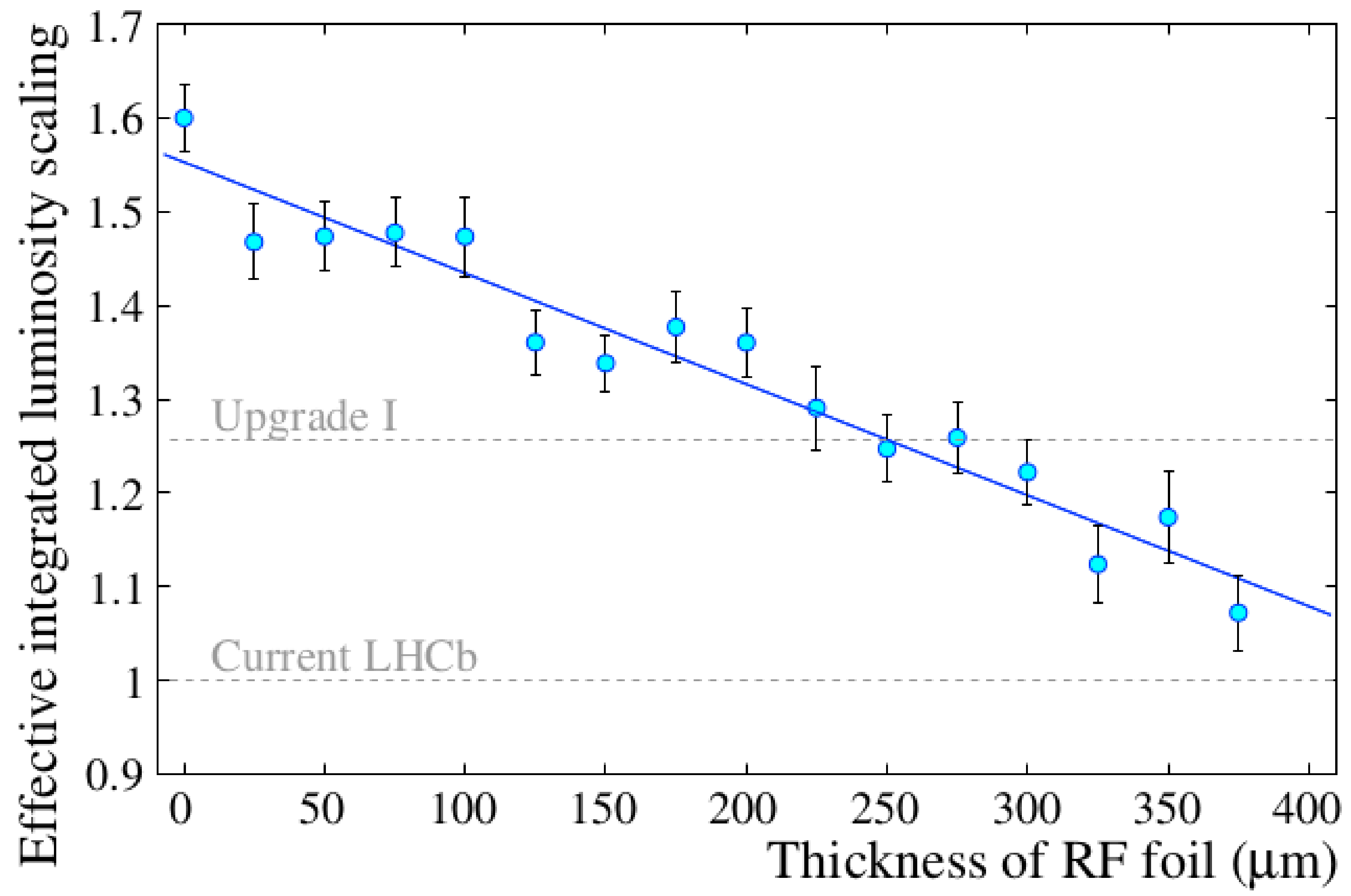
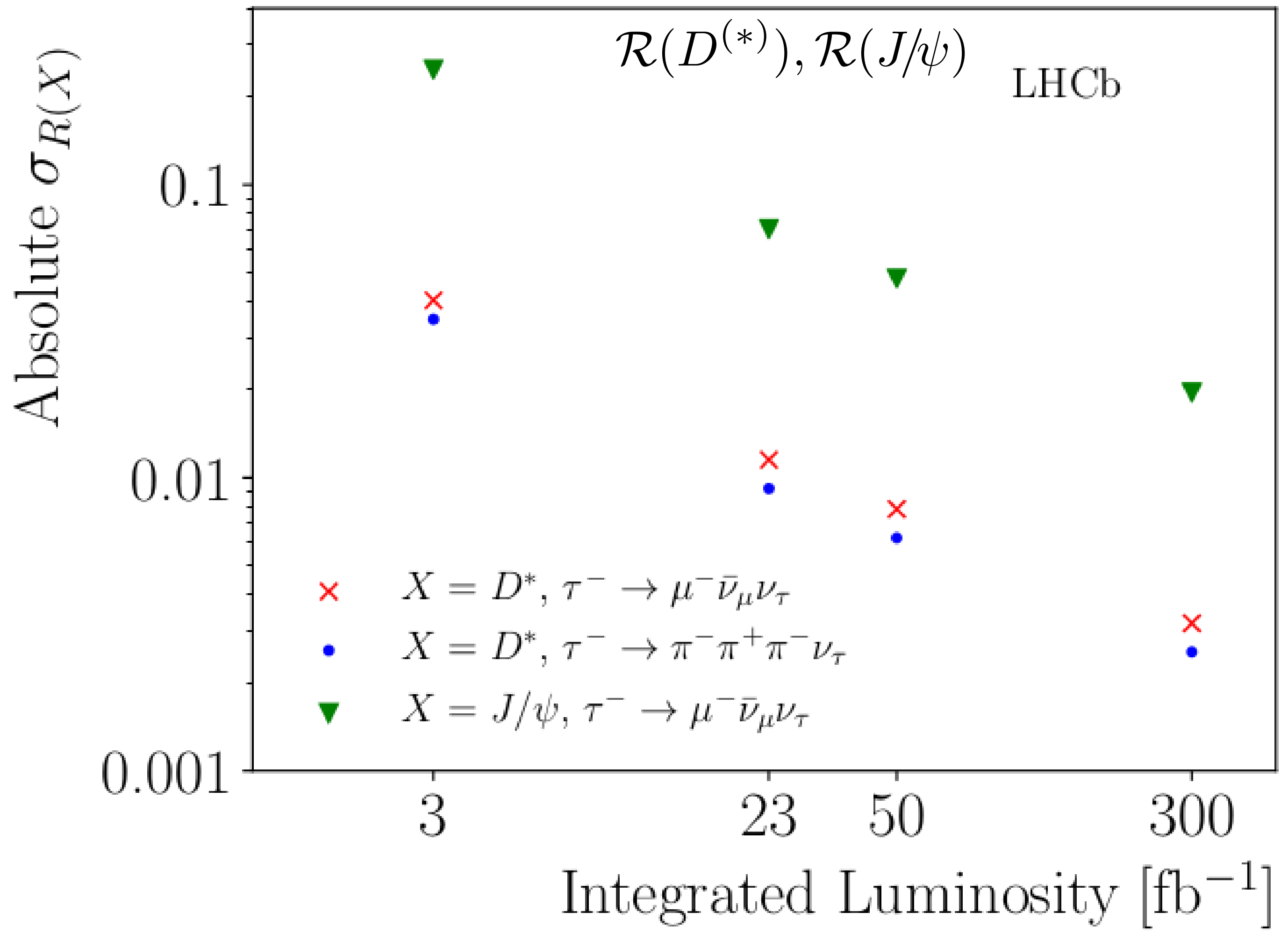
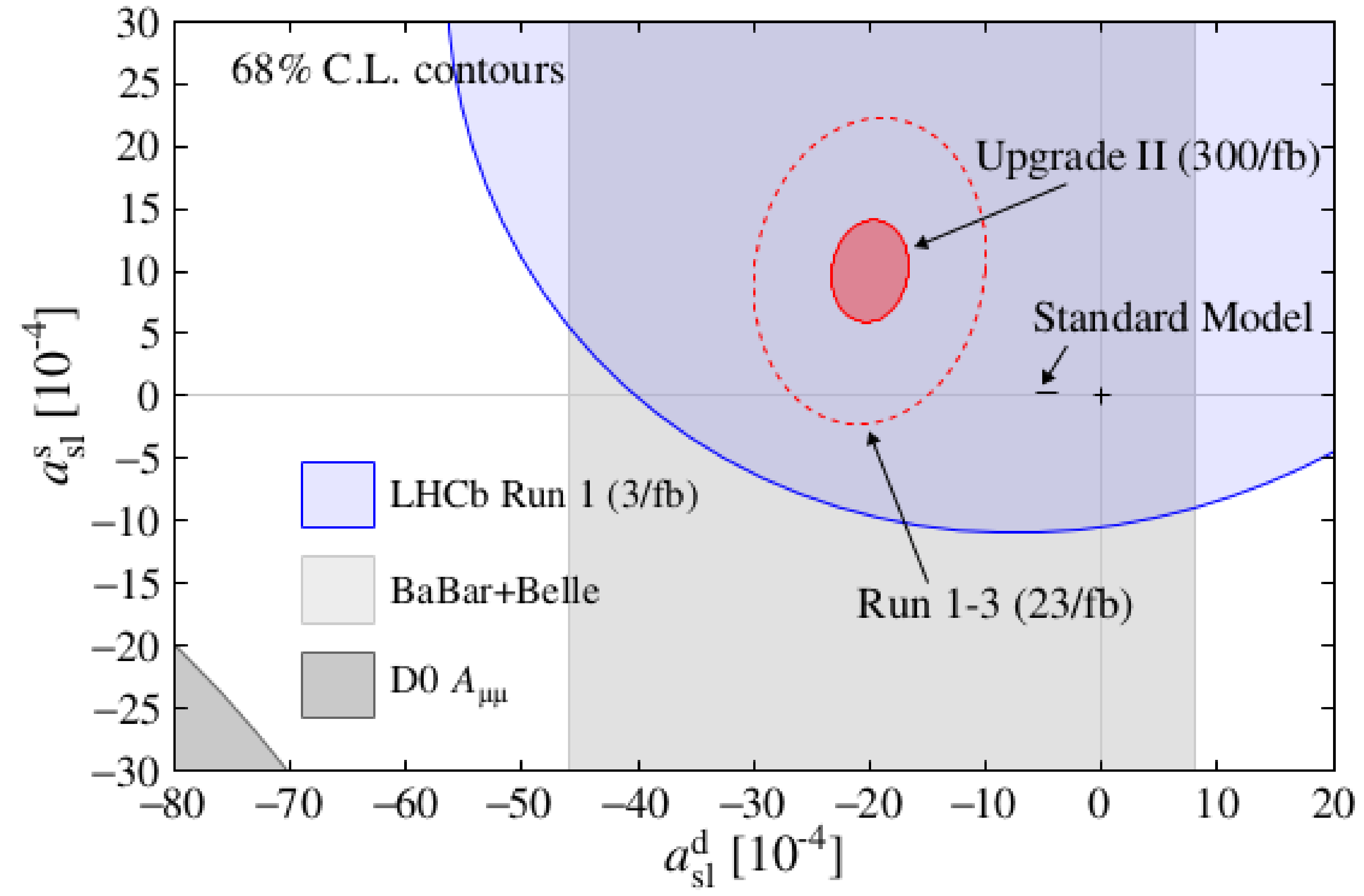
Unitarity triangle and semileptonic decays

- Tree-level charged-current semileptonic decays $b \to c\ell\nu,\ b \to u\ell\nu$
  - $B_s^0 \to K^-\mu^+\nu_\mu,\ B_s^0 \to D_s^-\mu^+\nu_\mu,\ \Lambda_b^0 \to p\mu^-\bar{\nu}_\mu,\ \Lambda_c^+ \to p\mu^-\bar{\nu}_\mu$
- Theoretically clean for $|V_{cb}|, |V_{ub}|$
- CP-violation in mixing $a_{sl}^q = \frac{\Gamma(\bar{B}_q^0 \to f) - \Gamma(B_q^0 \to \bar{f})}{\Gamma(\bar{B}_q^0 \to f) + \Gamma(B_q^0 \to \bar{f})} \approx \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_{12}^q$
- Lepton universality also in cleaner decays $\mathcal{R}(D_s^+), \mathcal{R}(D_s^{*(*)+})$
- Reliance on partial reconstructed and corrected masses







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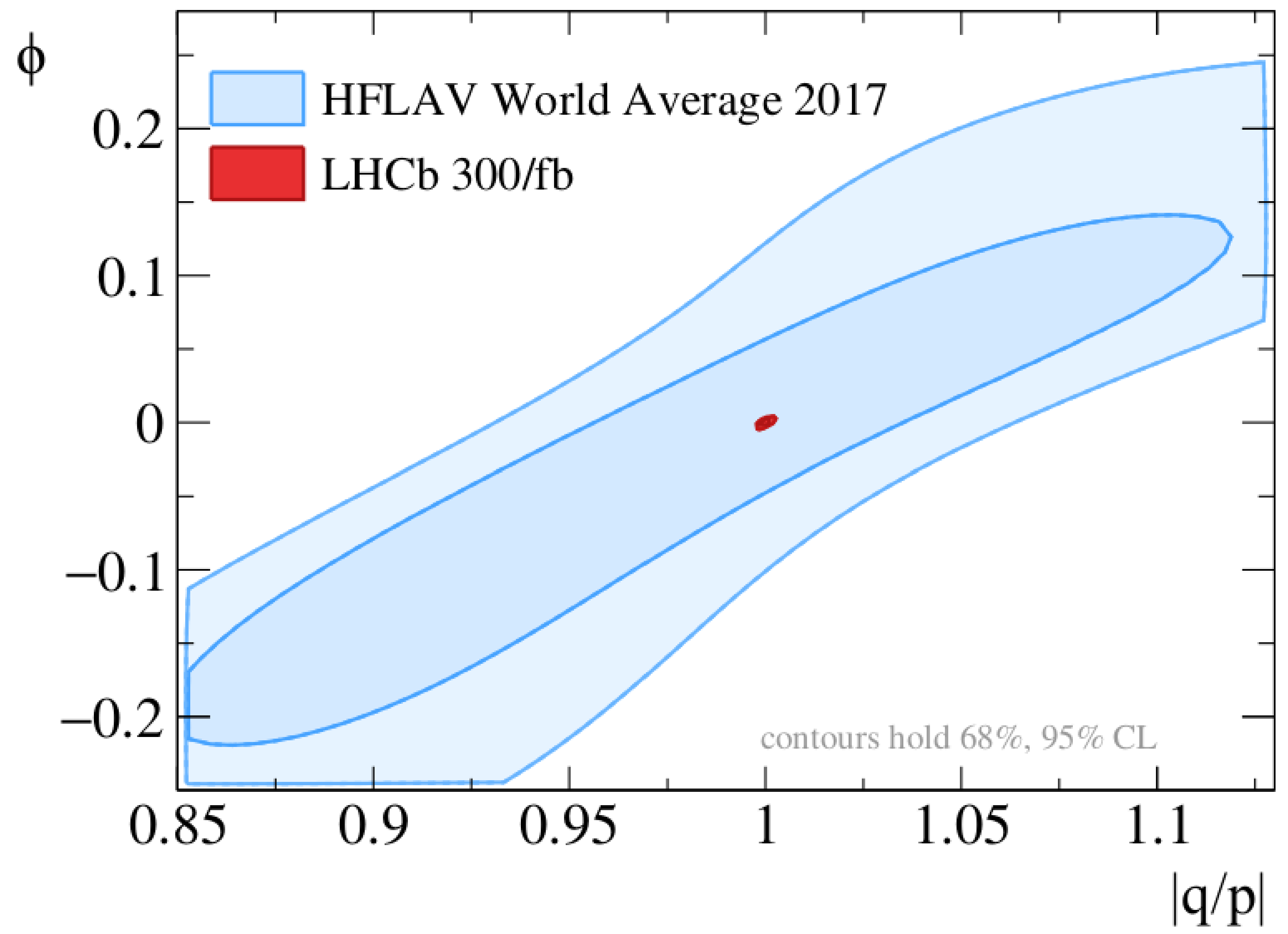
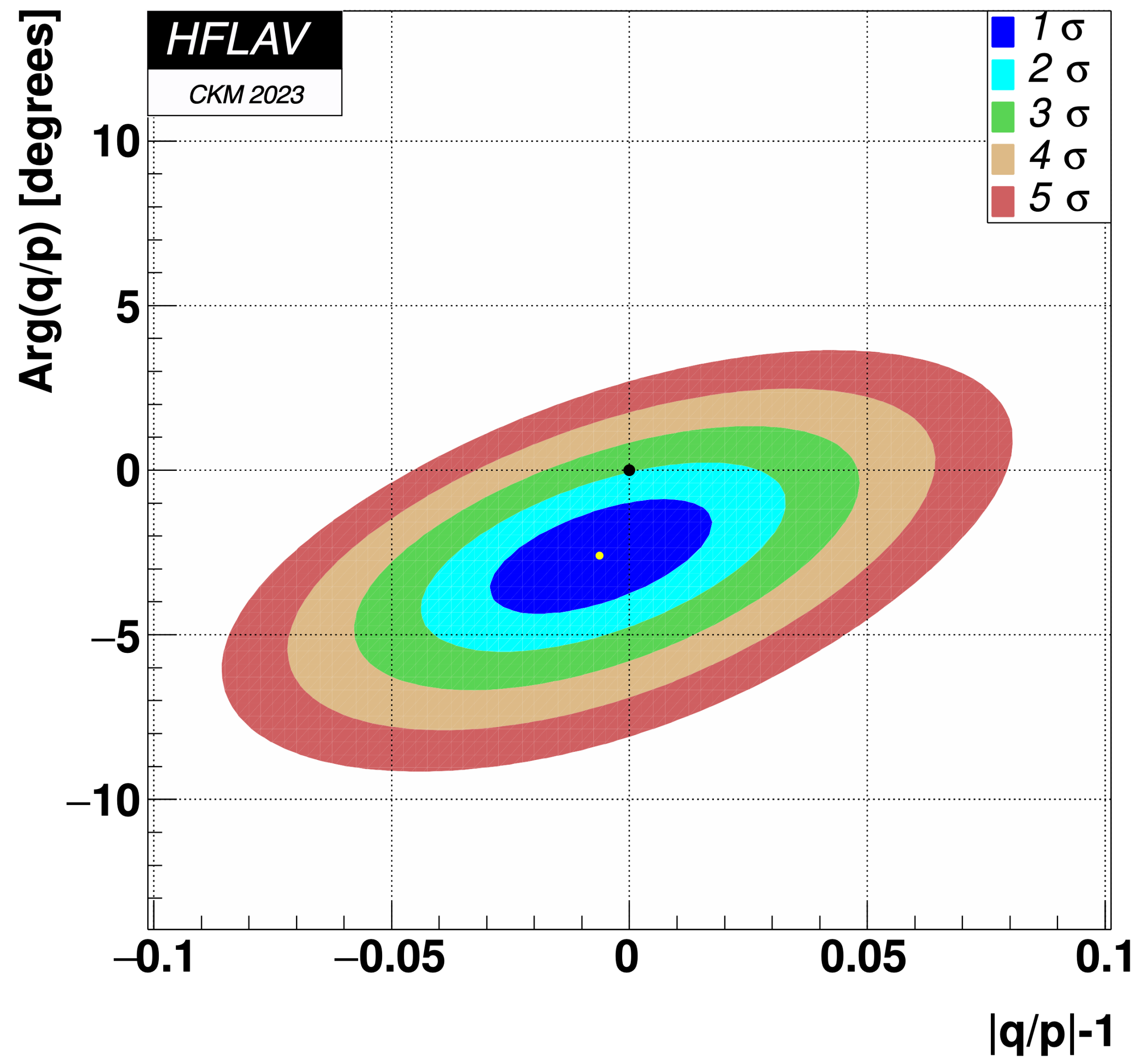
The charm sector

- Huge sample size, profit from magnet stations
- Direct CP-violation $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$
- Time-dependent CP-violation $A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$

- Mixing and indirect CP-violation:
  - Favoured decay 250x more abundant
  - $D^0 \to K^-\pi^+$ $D^0 \to K^-\pi^+\pi^-\pi^+$



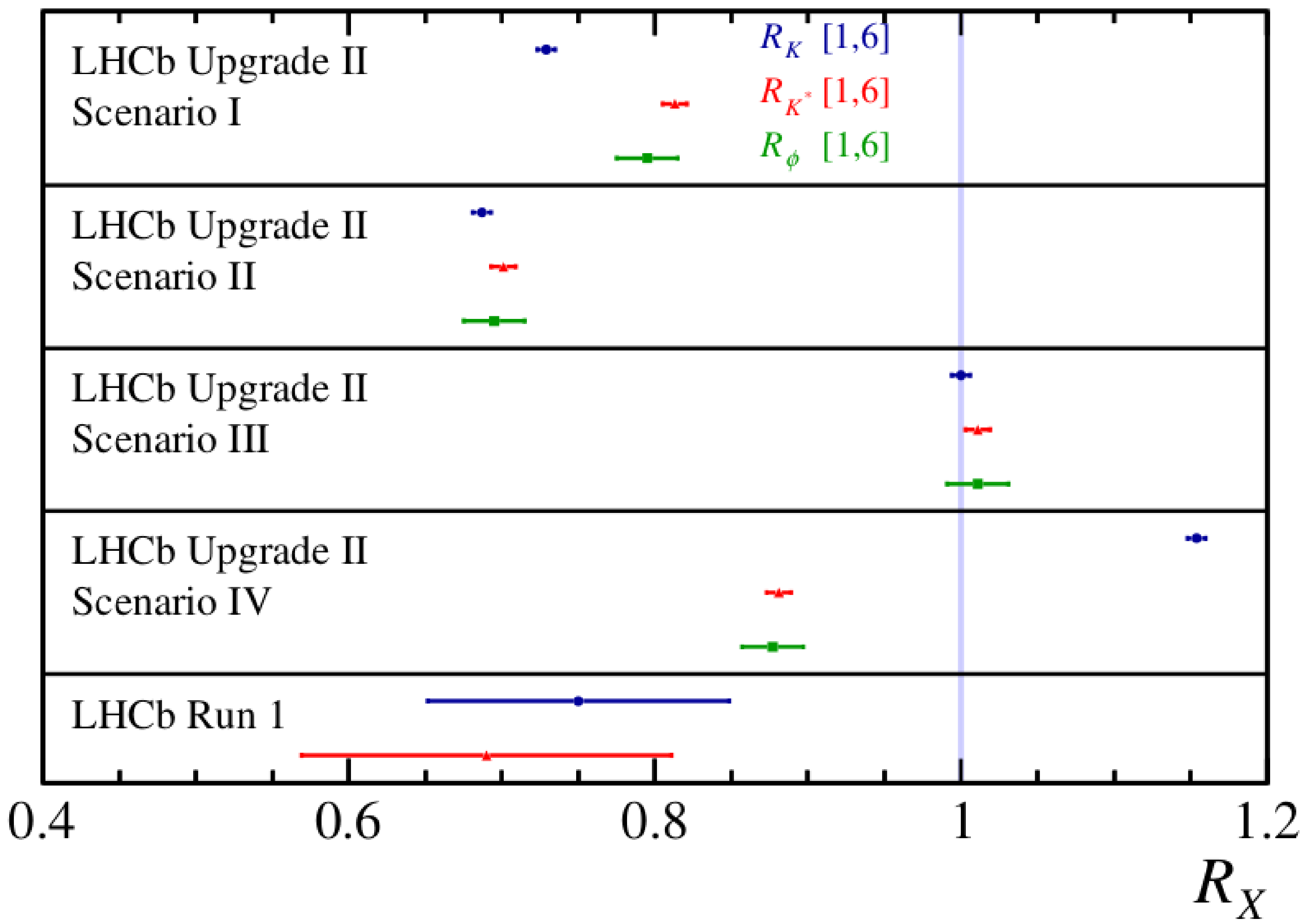


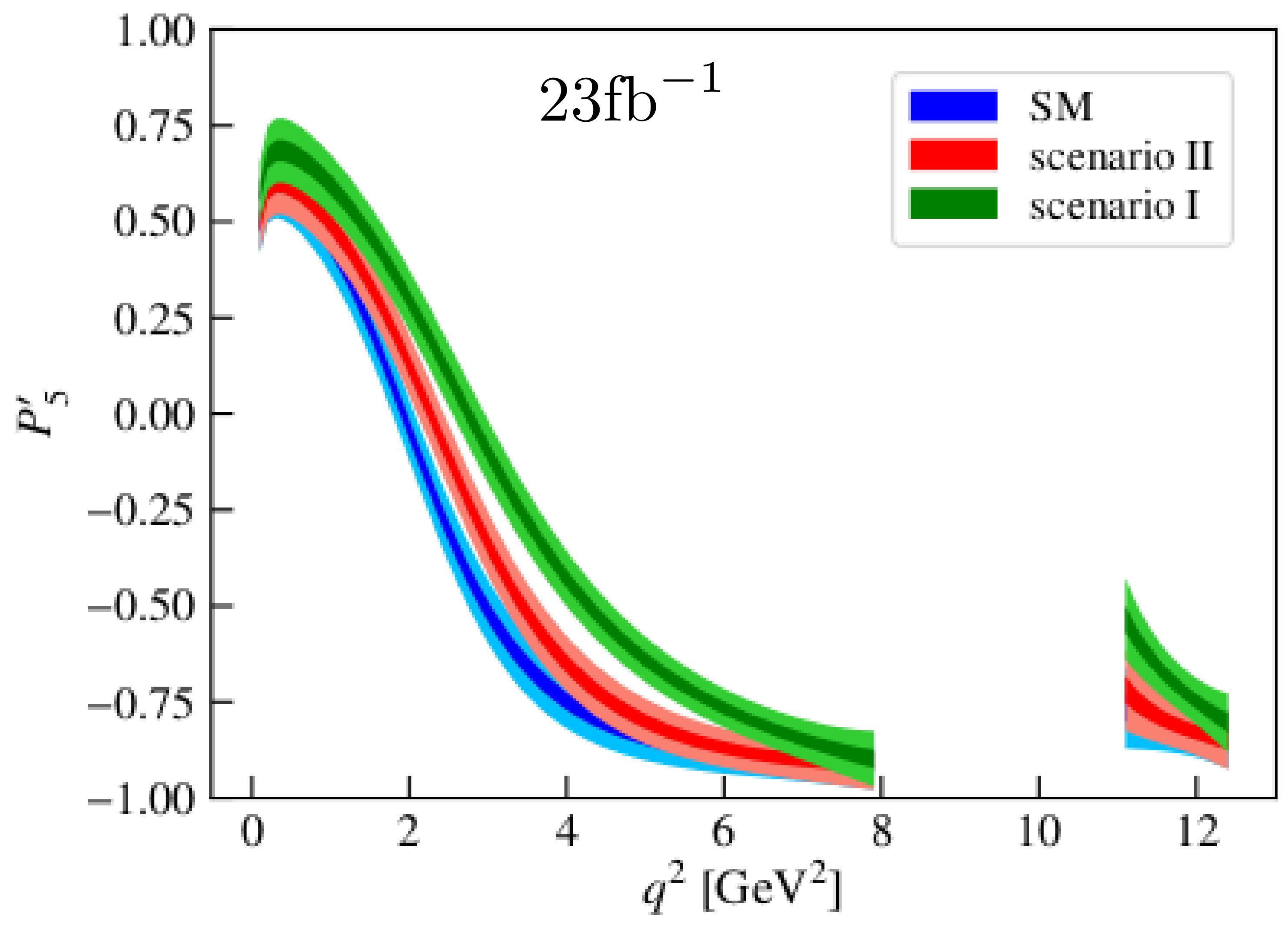
HFLAV (2023)

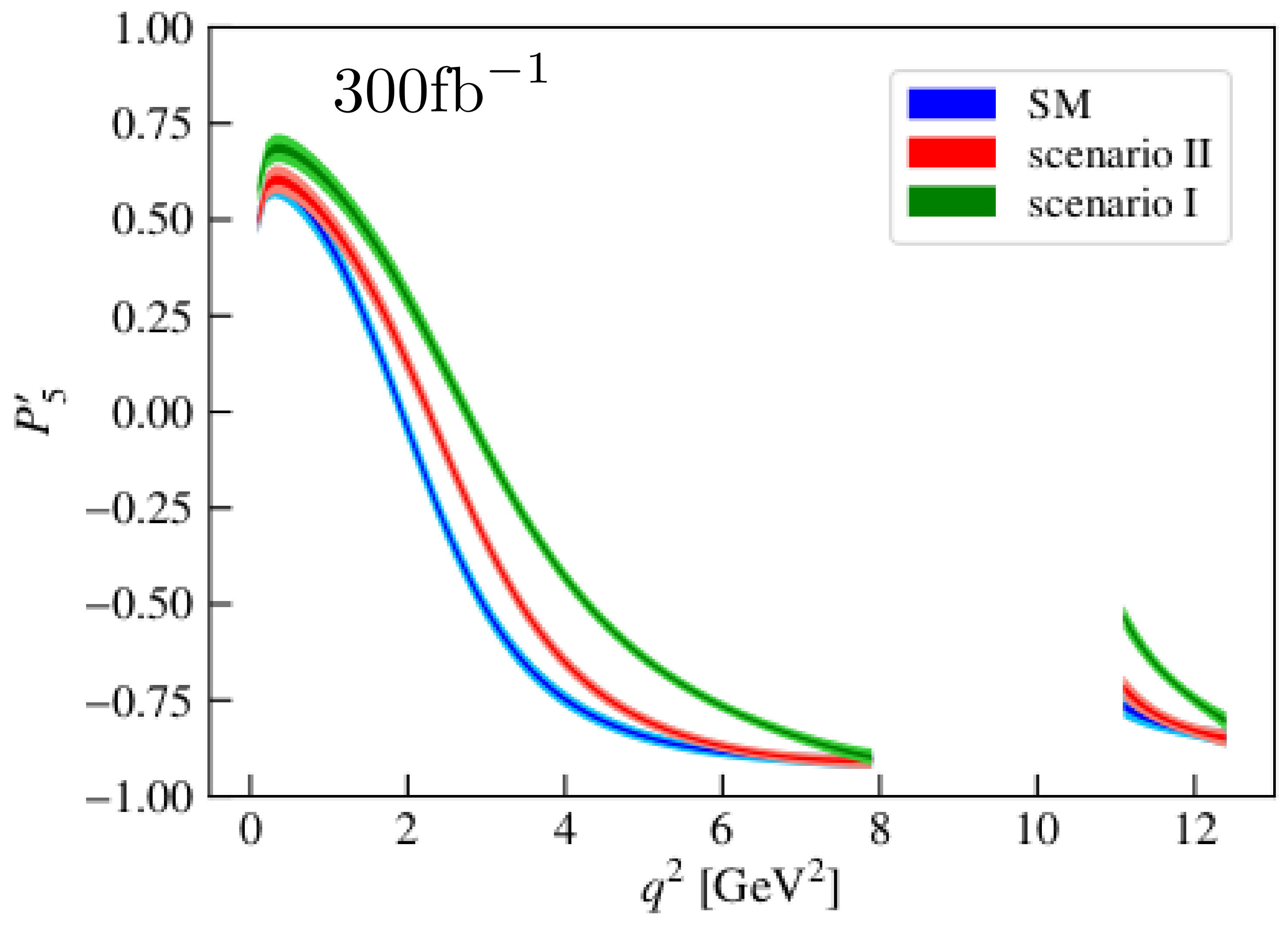
Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\|q/p\|)$	$\sigma(\phi)$
Run 1–2 ($9\,\text{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 ($23\,\text{fb}^{-1}$)	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 ($50\,\text{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 ($300\,\text{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

Rare decays

- Helicity suppressed $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with 10% relative uncertainty
- Tau decays $B_s^0 \to \tau^+\tau^-$
- Lepton-flavour violation $\mathcal{B}(B_{(s)}^0 \to e^\pm\mu^\mp)$down to $3 \times 10^{-10}(9 \times 10^{-11})$
- Null-searches for LNV and BNV $B^+ \to \pi^-\mu^+\mu^+, \Lambda_c^+ \to \mu^+\mu^-\mu^+, \Xi_b^0 \longleftrightarrow \bar{\Xi}_b$
- FCNC probes $B^0 \to K^{*0}\mu^+\mu^- \ldots$
- Lepton-flavour universality







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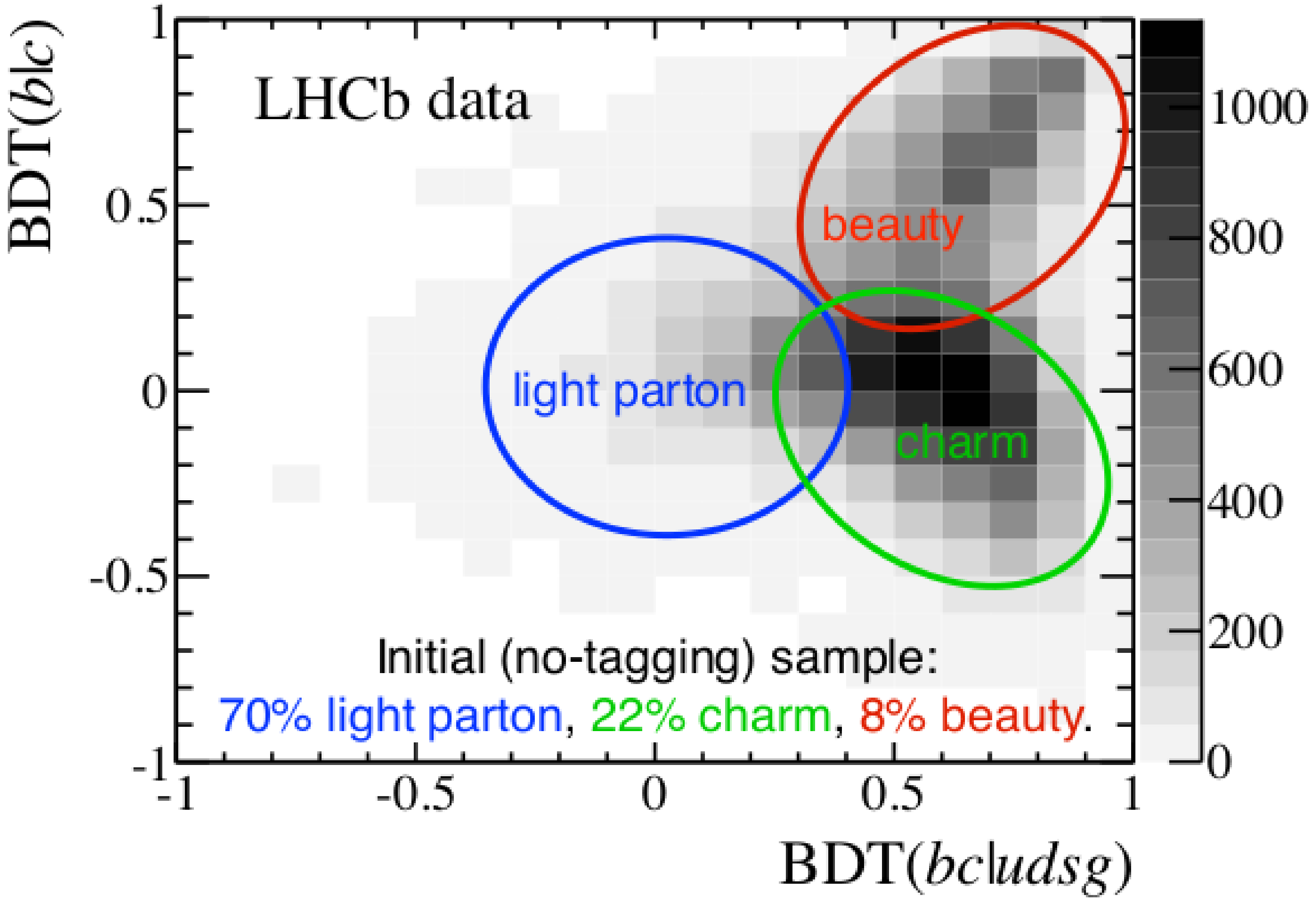
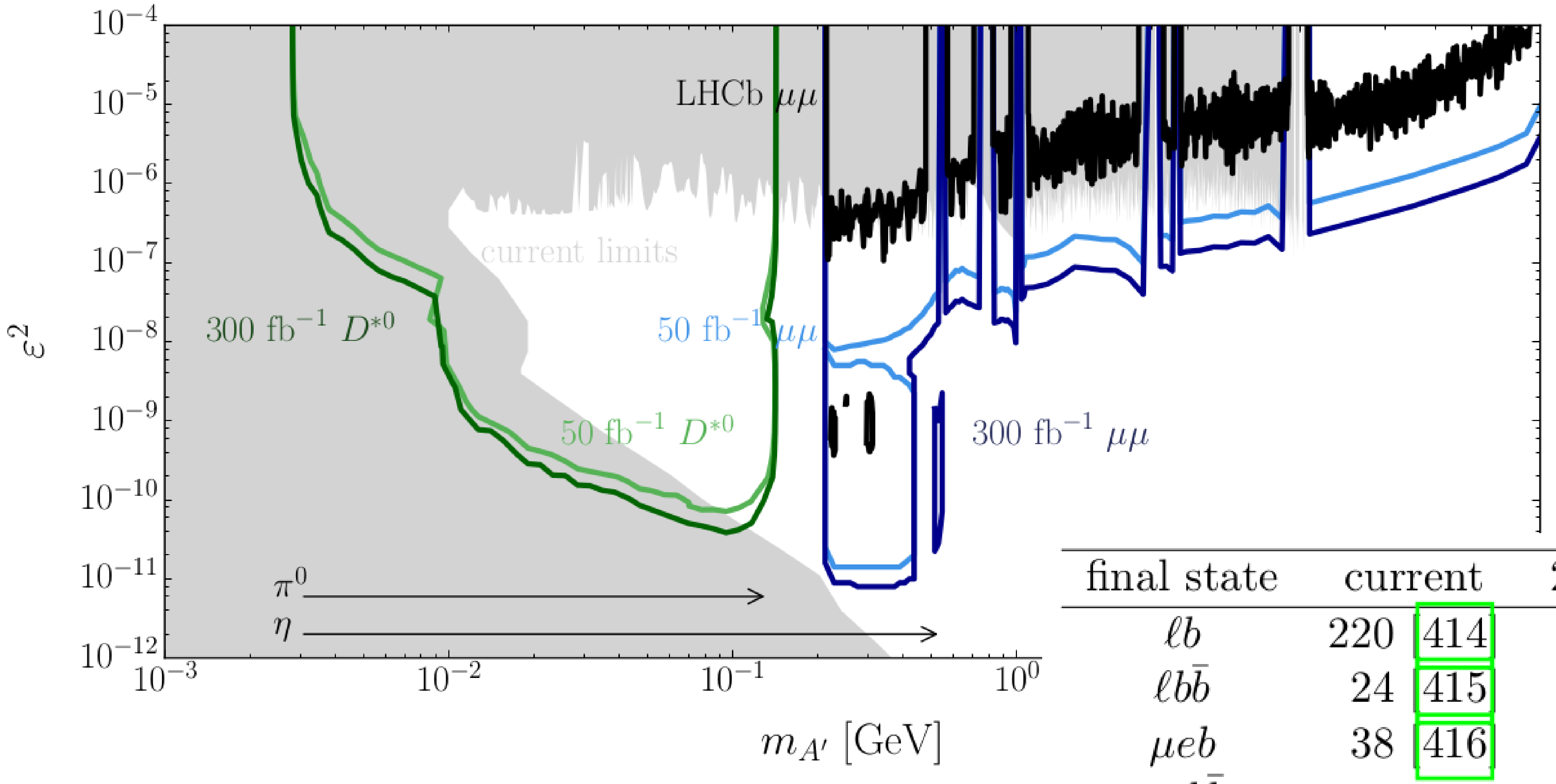
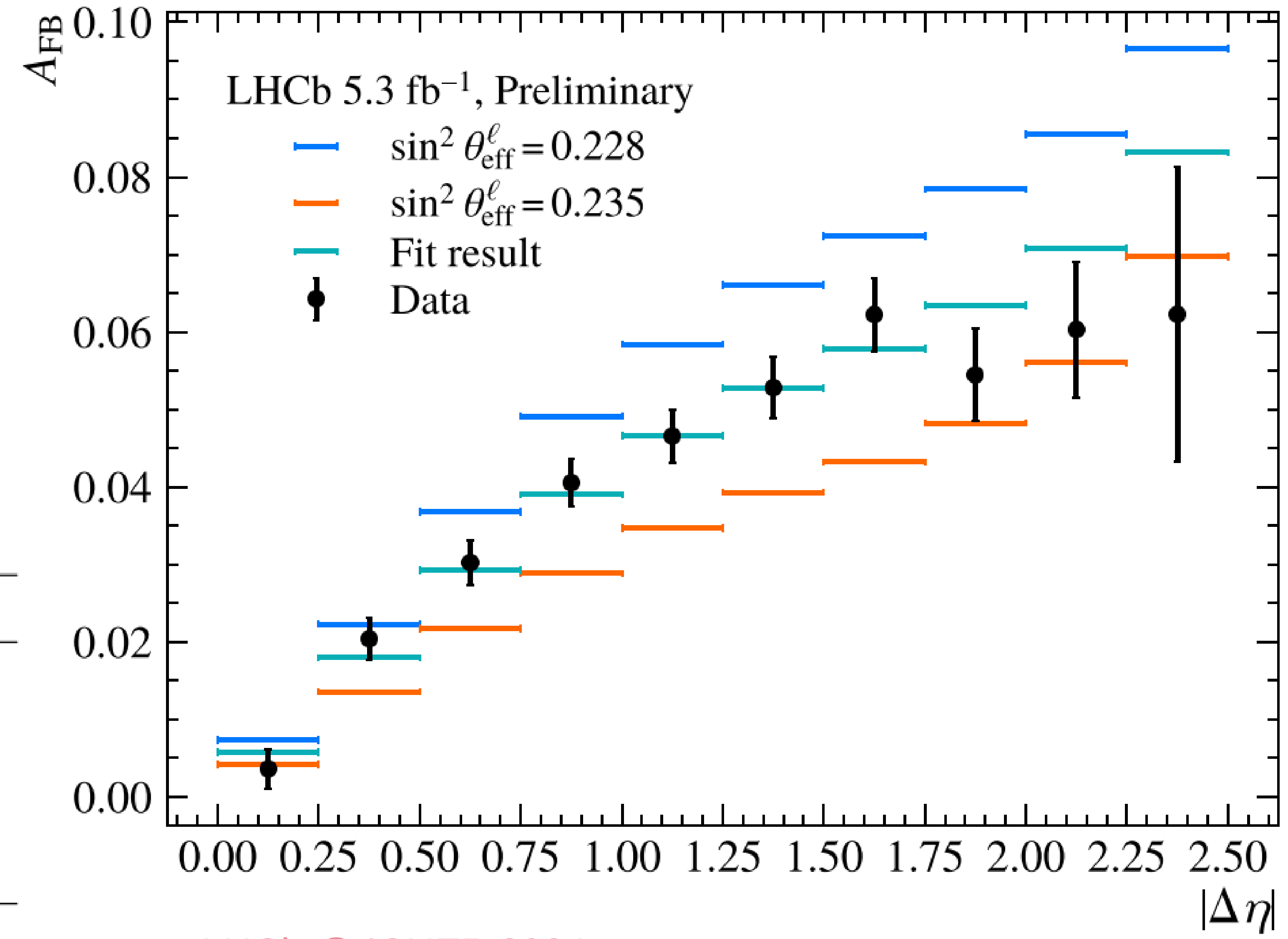
Forward and high-p_T

- Top quark production at large Bjorken-x
- Precision electroweak test $m_W, \sin^2\theta_W^{\mathrm{eff}}$
- Higgs to $c\bar{c}$, potential for best y^c at HL-LHC
- Dark photon searches, prompt + displaced





final state	current	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}	$< x >$
ℓb	220 [414]	54k	117k	830k	0.295
$\ell b\bar{b}$	24 [415]	8k	17k	130k	0.368
$\mu e b$	38 [416]	1k	2k	12k	0.348
$\mu e b\bar{b}$	-	120	260	1.5k	0.415



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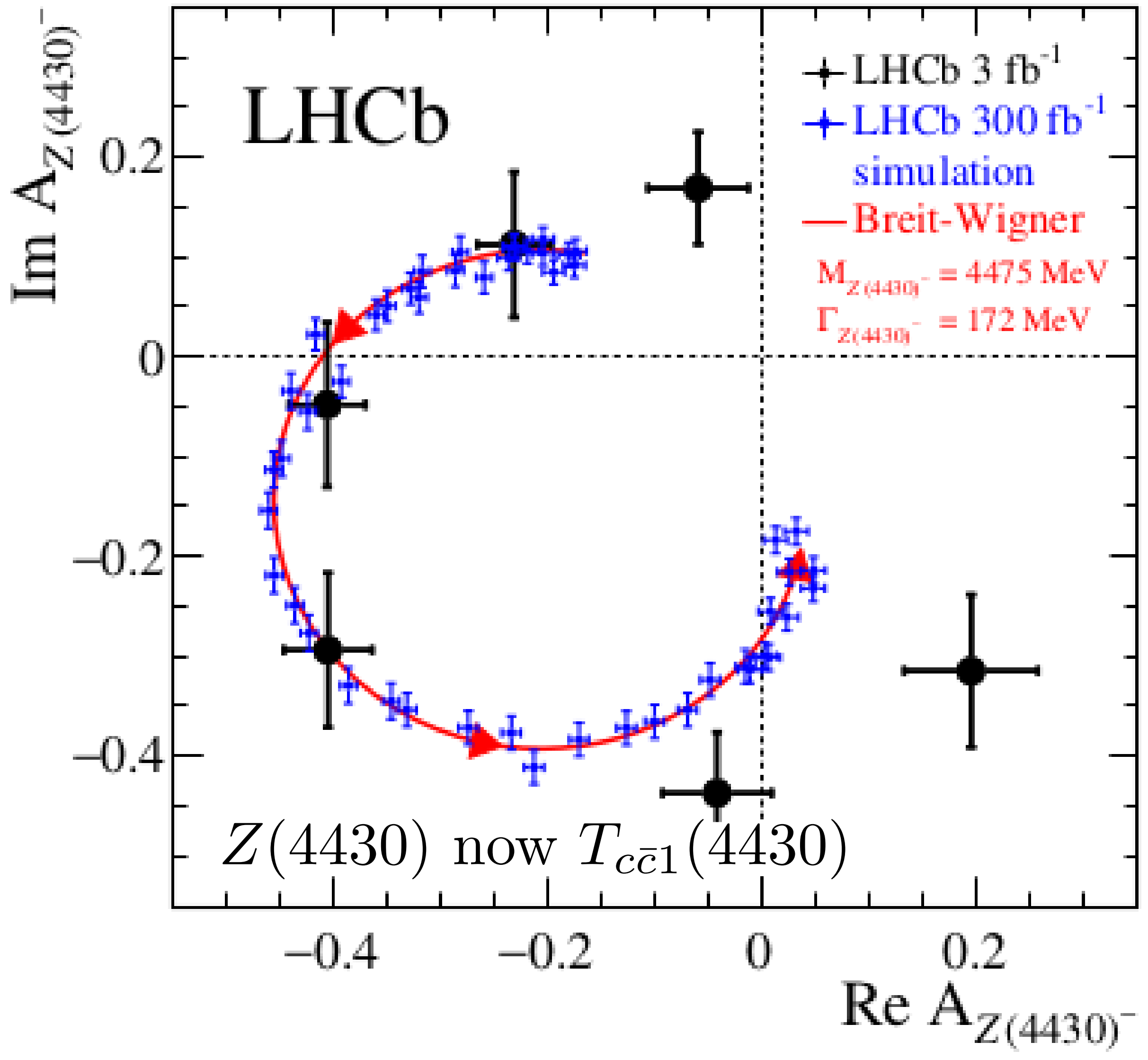
LHCb @ ICHEP 2024

Hadron spectroscopy / heavy-Ion and fixed target

- Tetra- and Pentaquark states $T_{c\bar{c}}, P_{c\bar{c}}$
- Molecular / hadron rescattering interpretation
- Probing QGP with b-hadrons
- Fixed target, potentially polarised (LHCspin)



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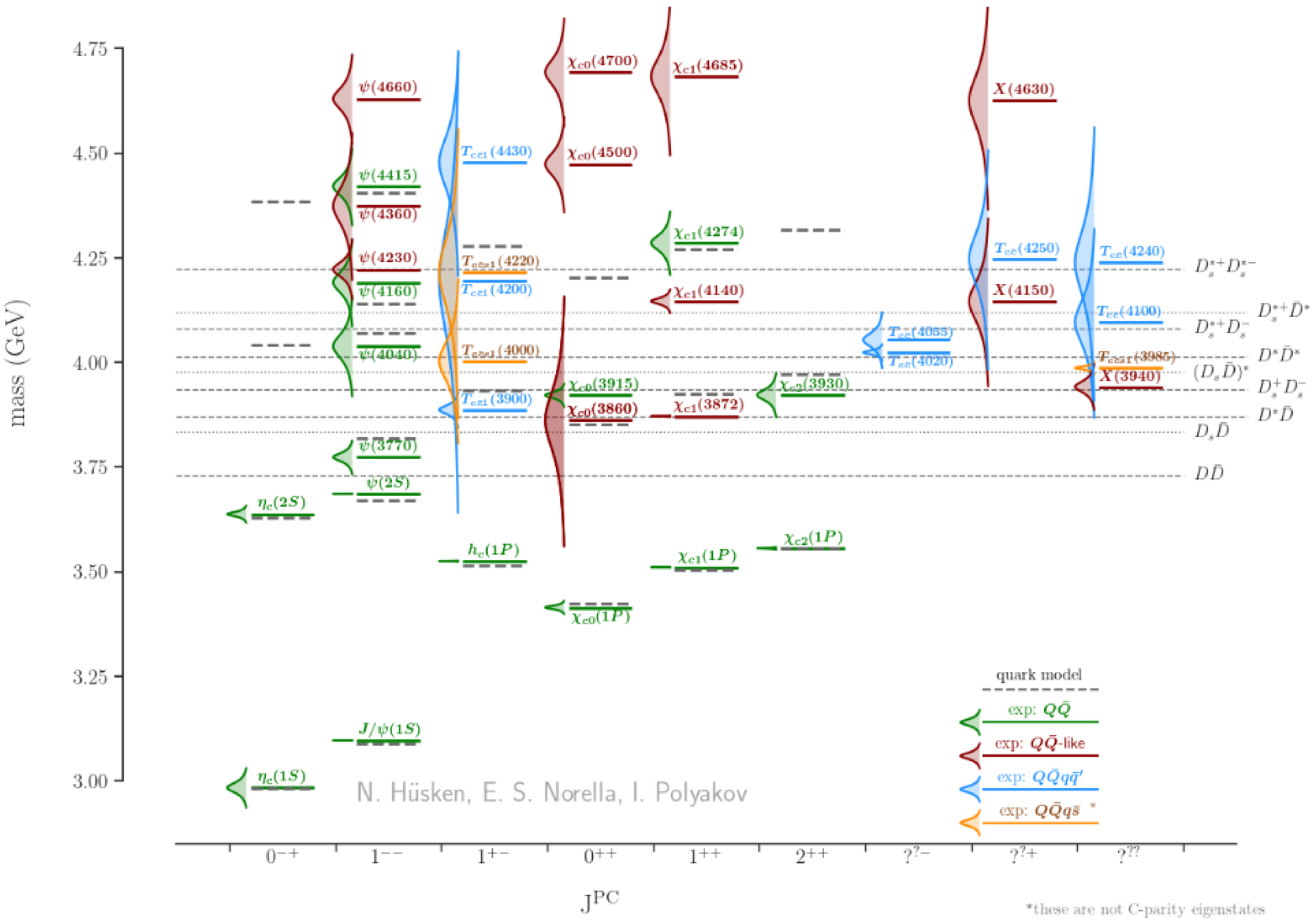
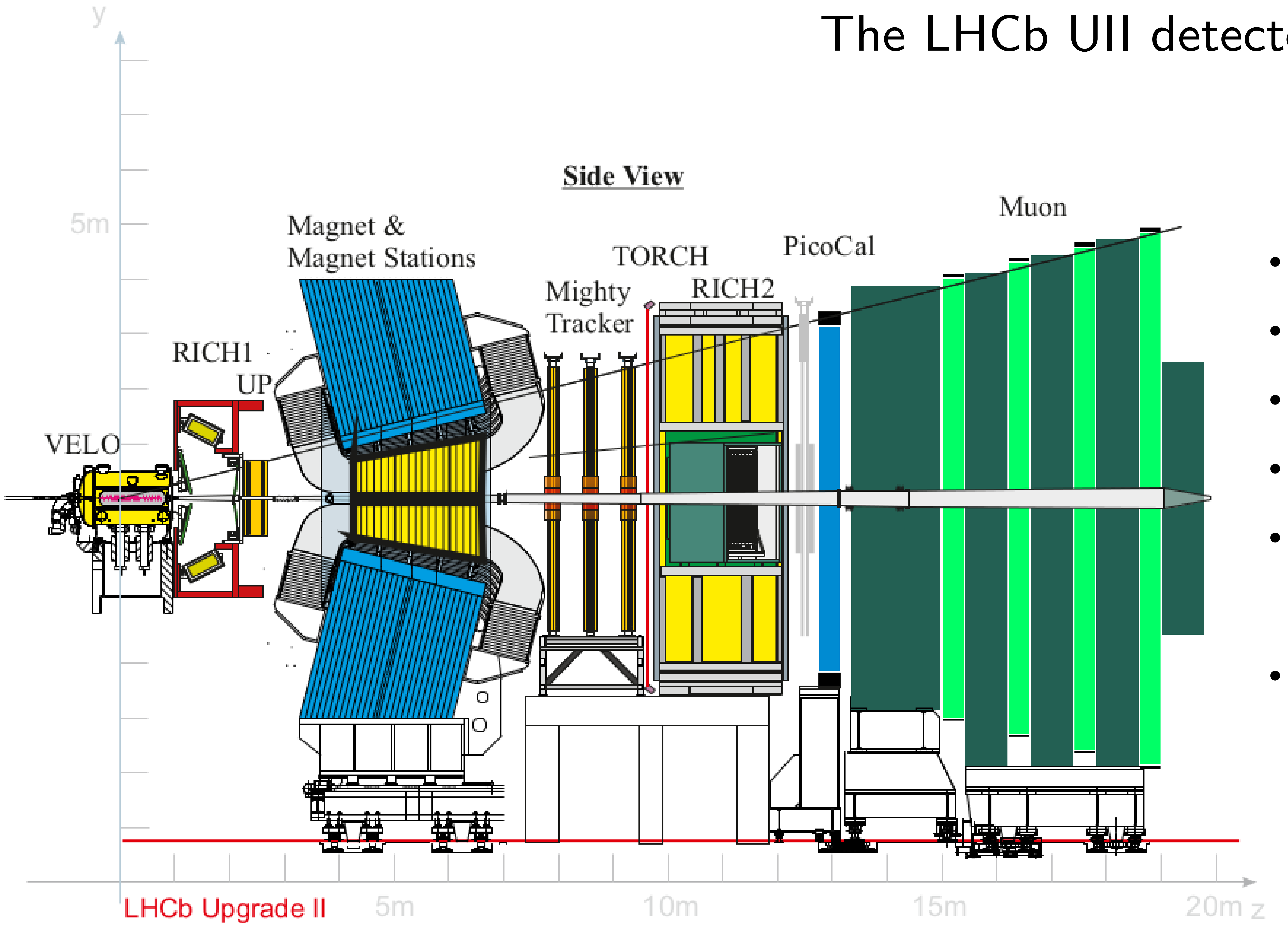


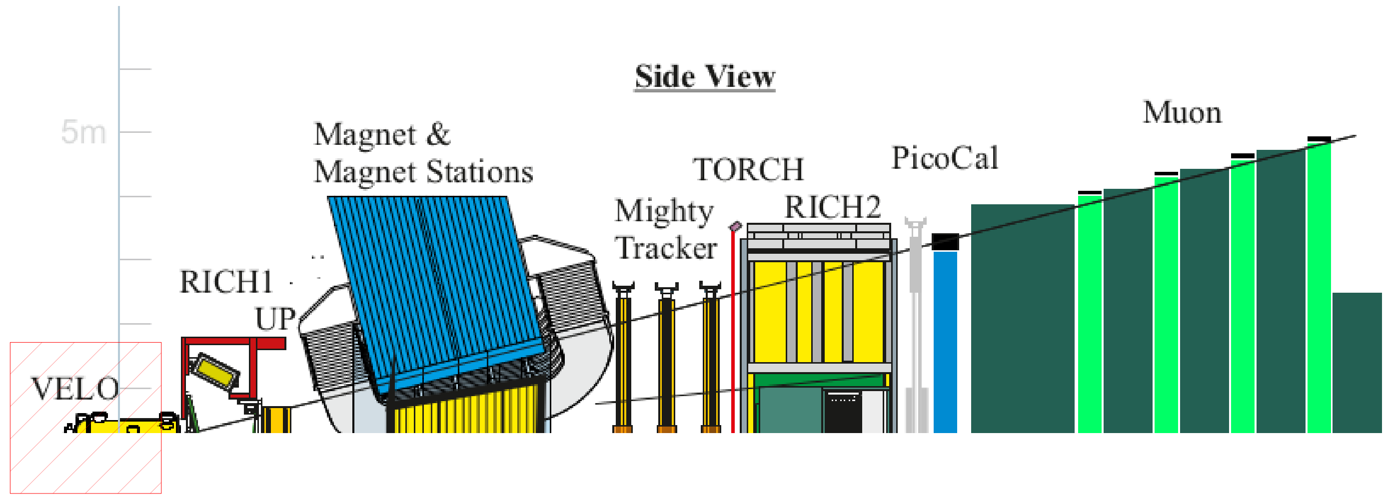
A Brief Guide To Exotic Hadrons arXiv:2410.06923

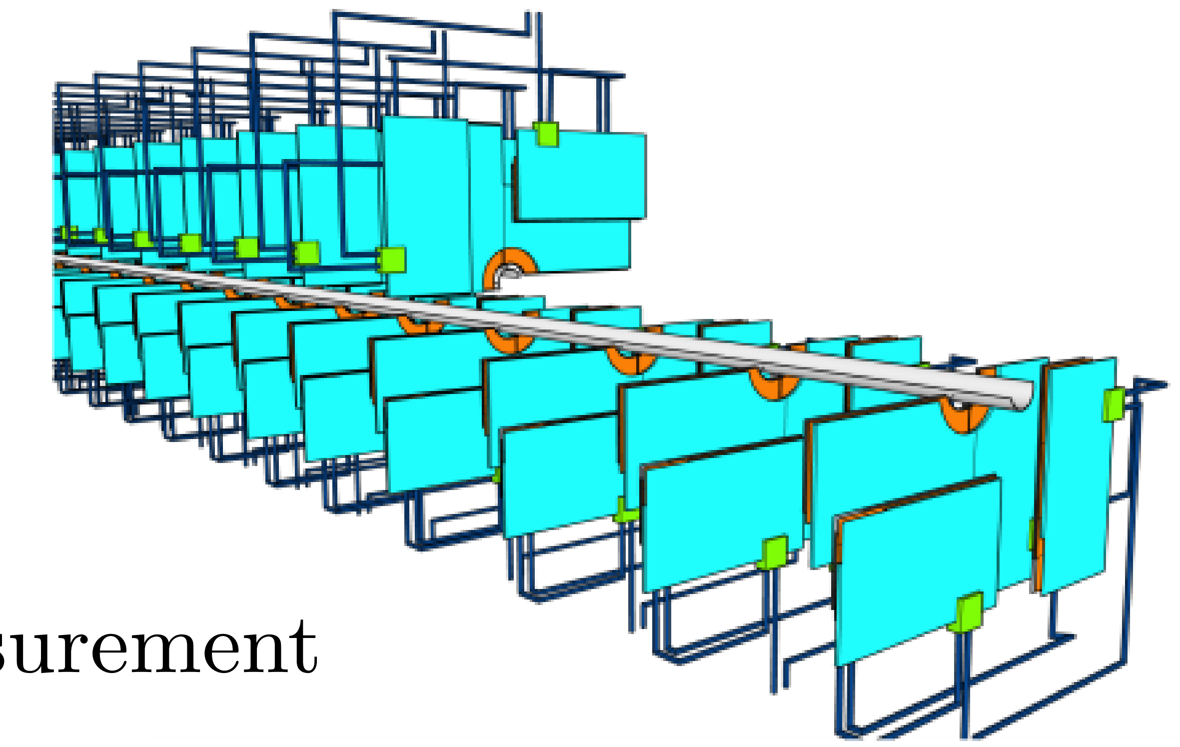
The LHCb UII detector

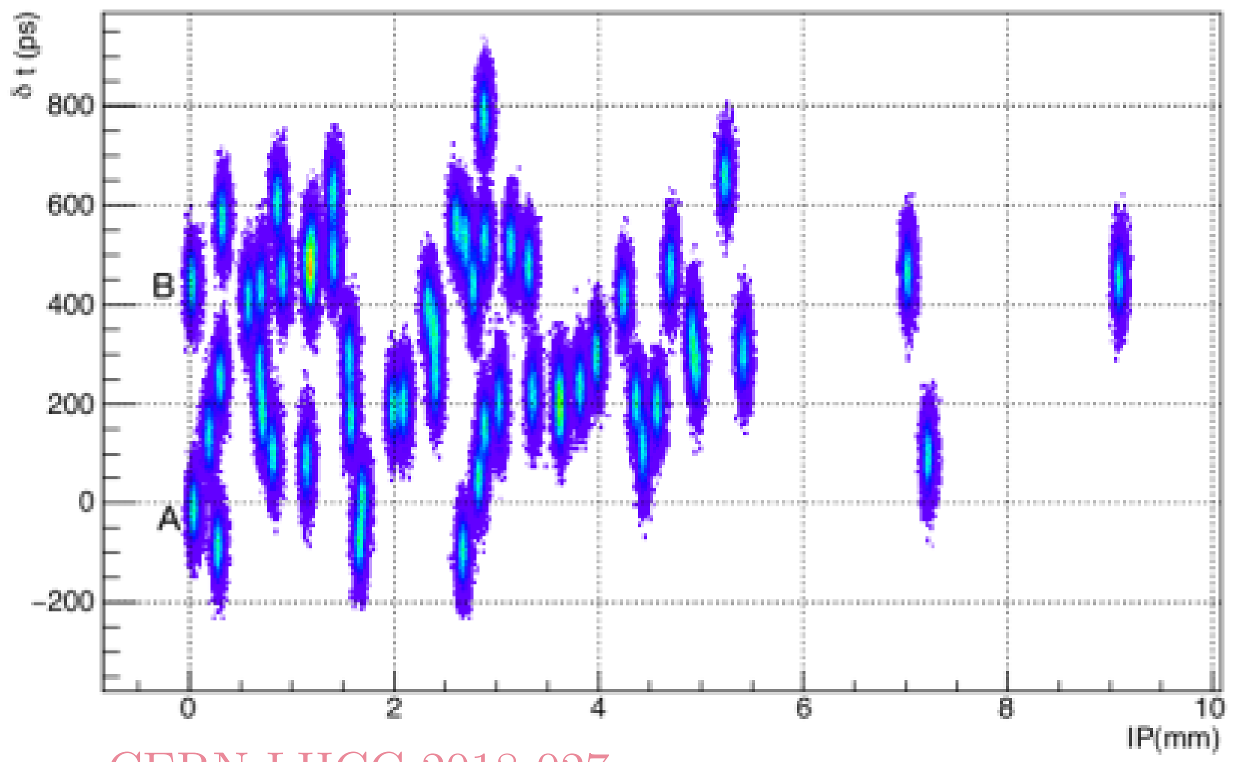


- Up to 300 fb^{-1} integrated luminosity
- ~ 40 interaction per BX
- ~ 2000 charged tracks per event
- Similar coverage as LHCb UI, $\eta = 2.0 \ldots 5.0$
- High granularity, high radiation resistance
- *Subject to changes*

Vertex Locator - VELO







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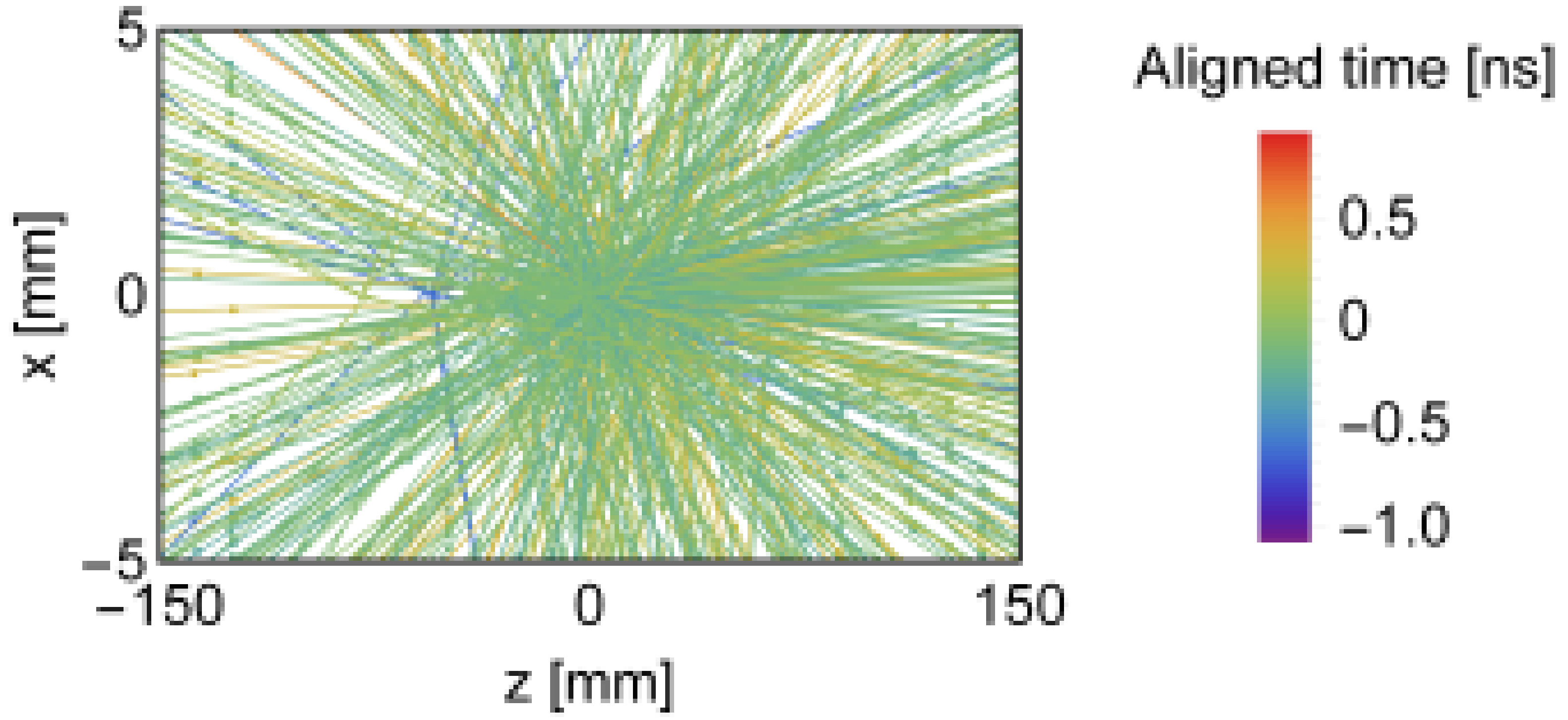
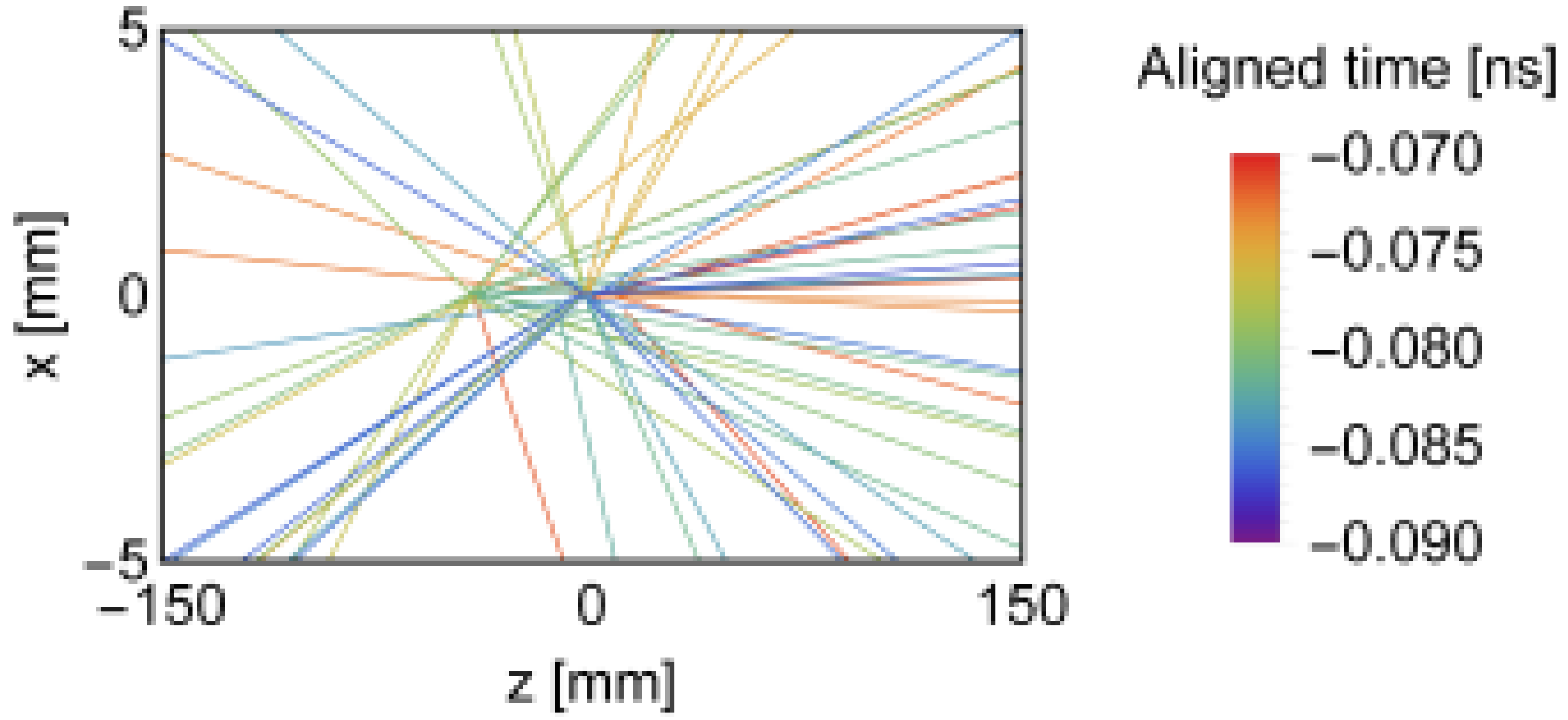
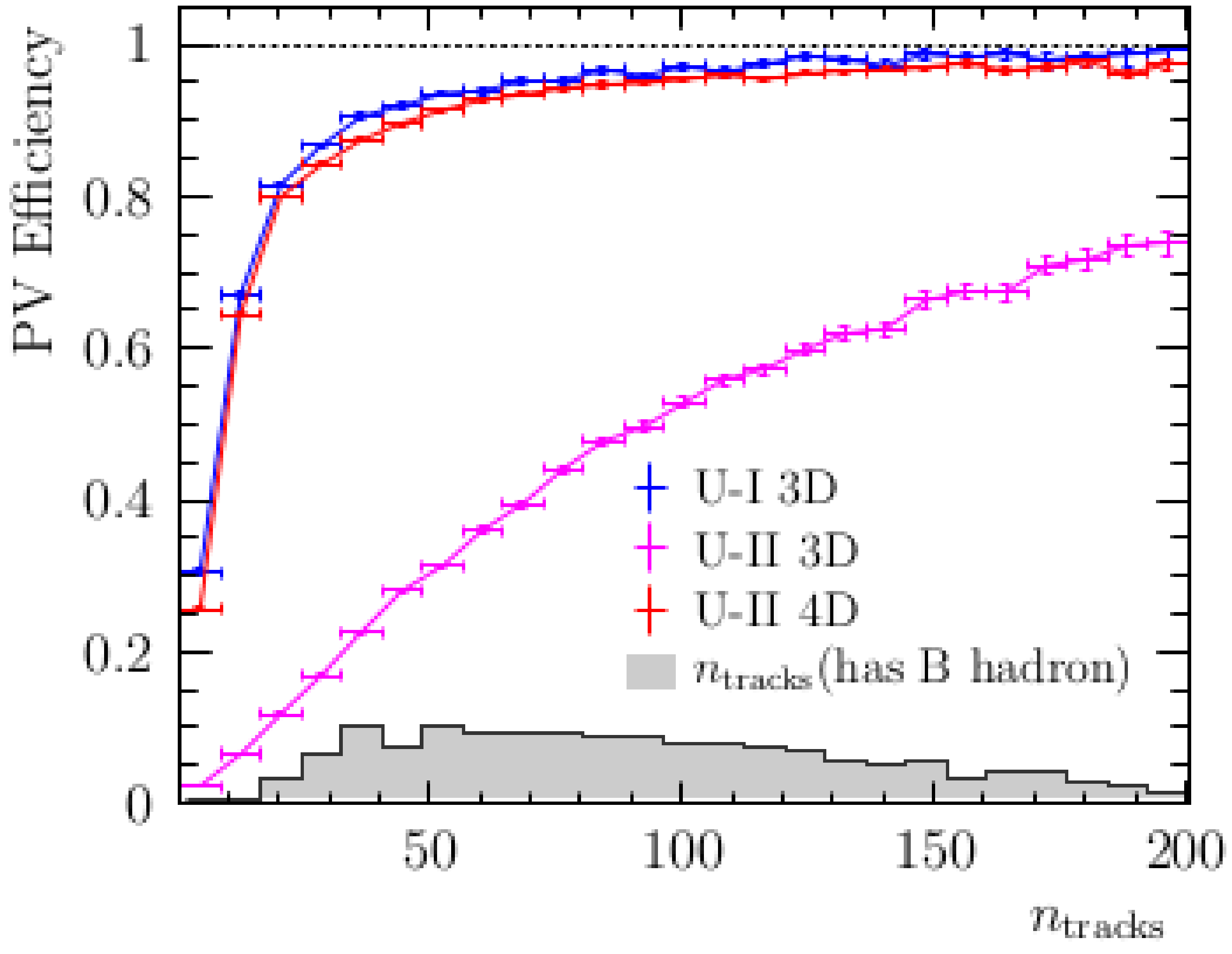
- Vital for primary vertex association
- Fast and radiation-hard 3D silicon sensors
- Thin RF-foil → reduce scattering before first measurement
- ps-timing for 4D tracking

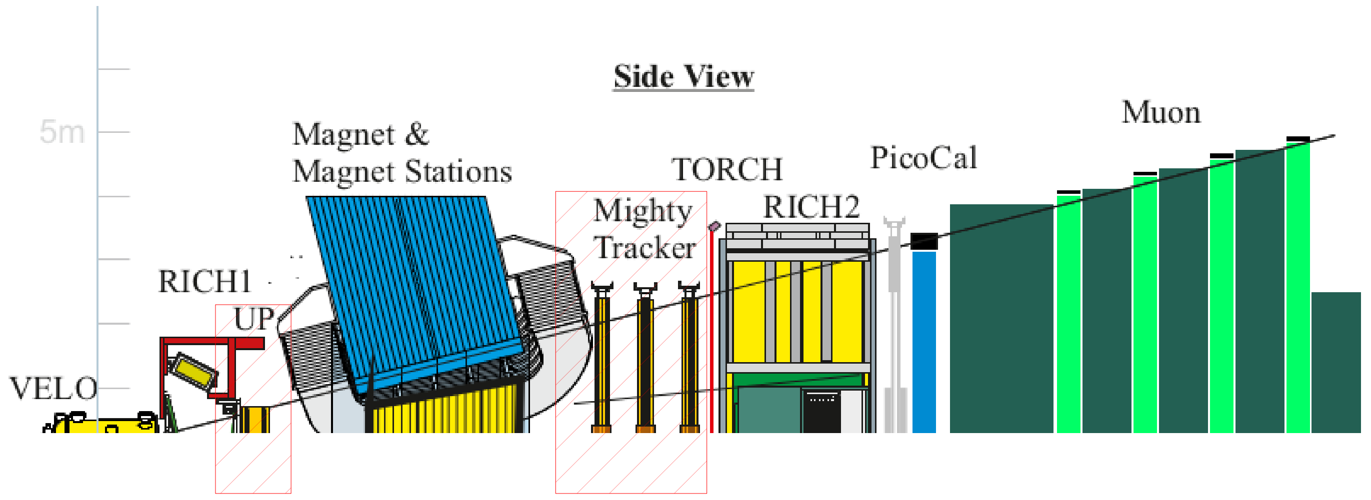






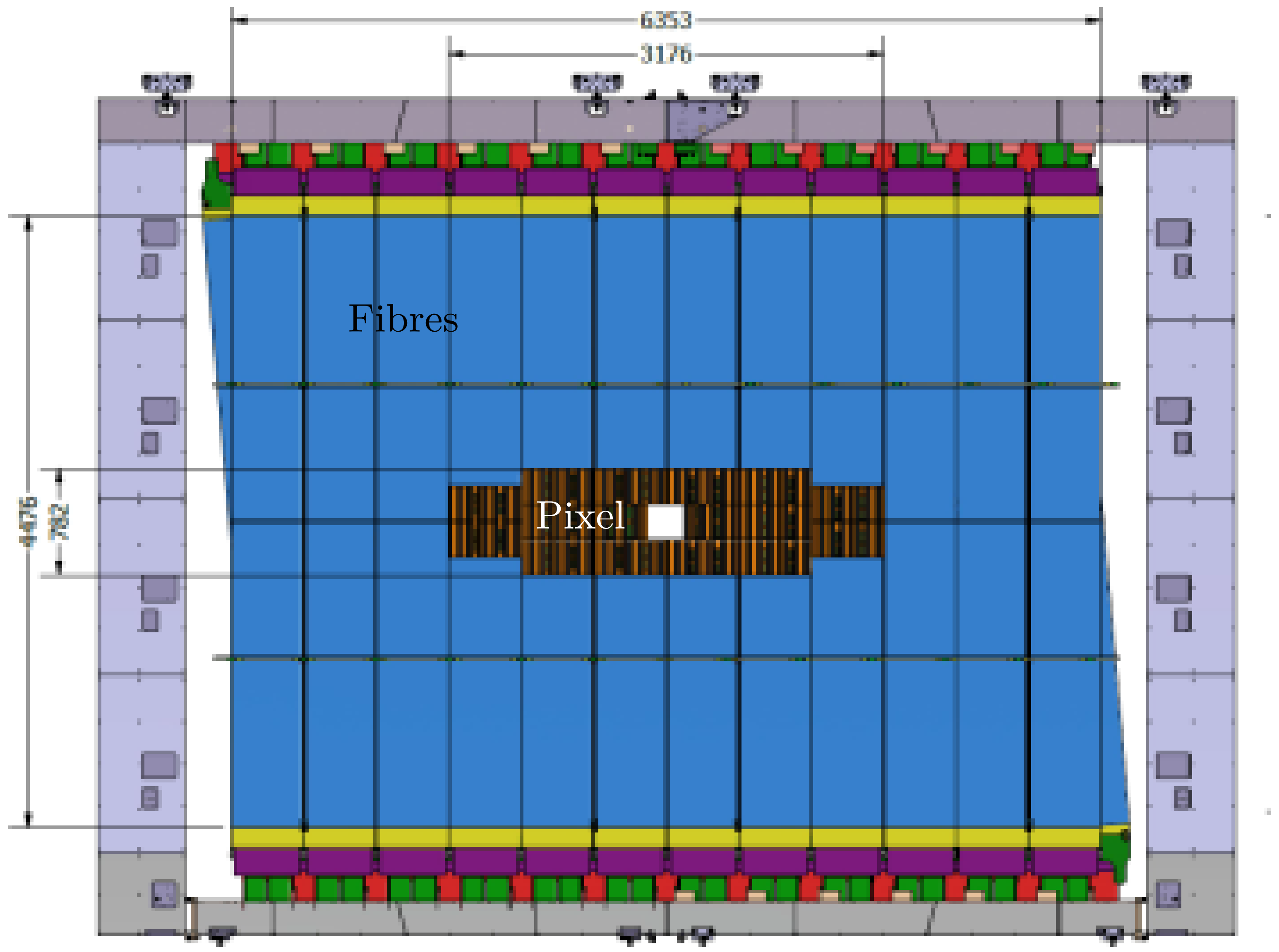
CERN-LHCC-2021-012

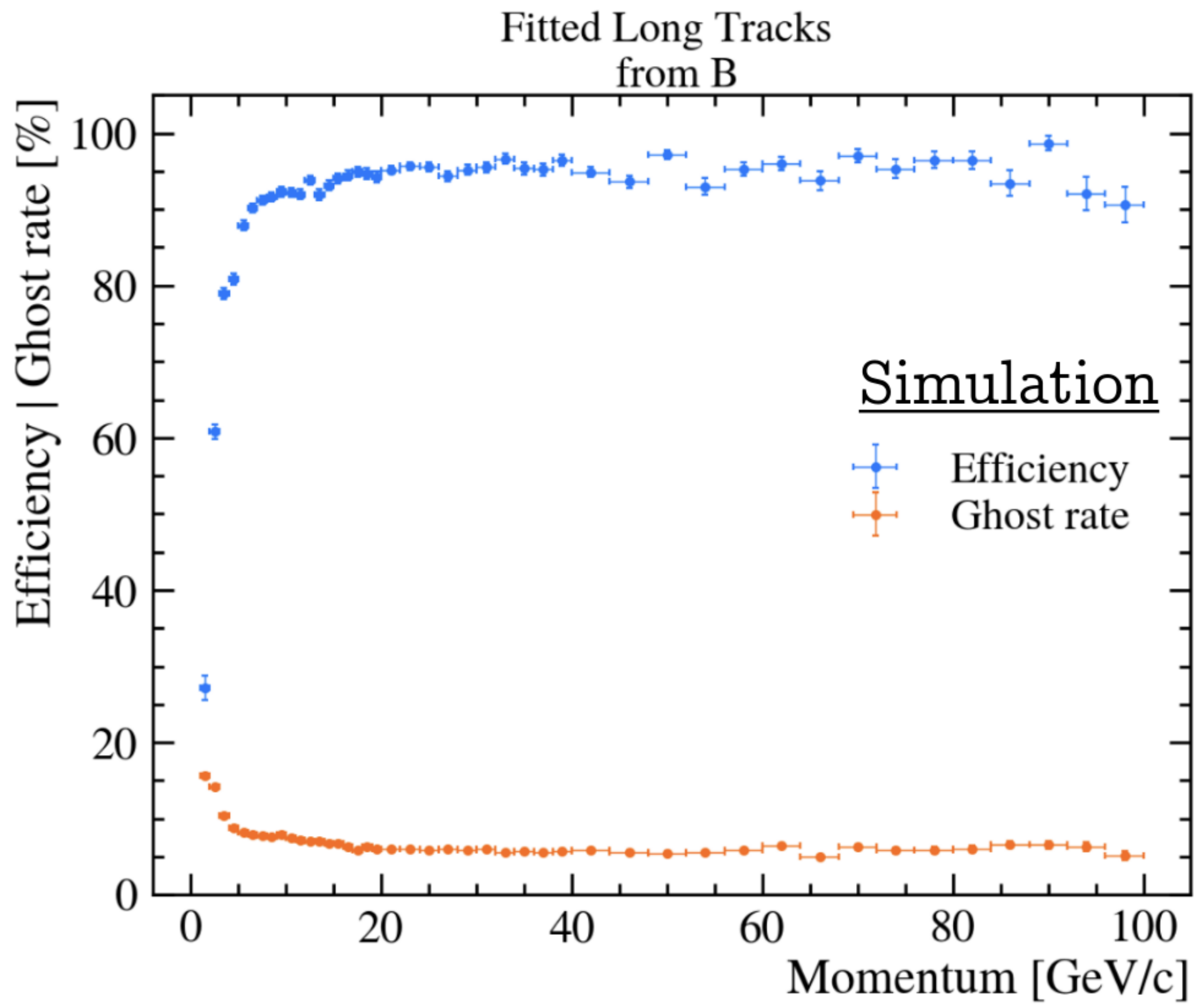
Upstream and Downstream tracking stations – UP, MT

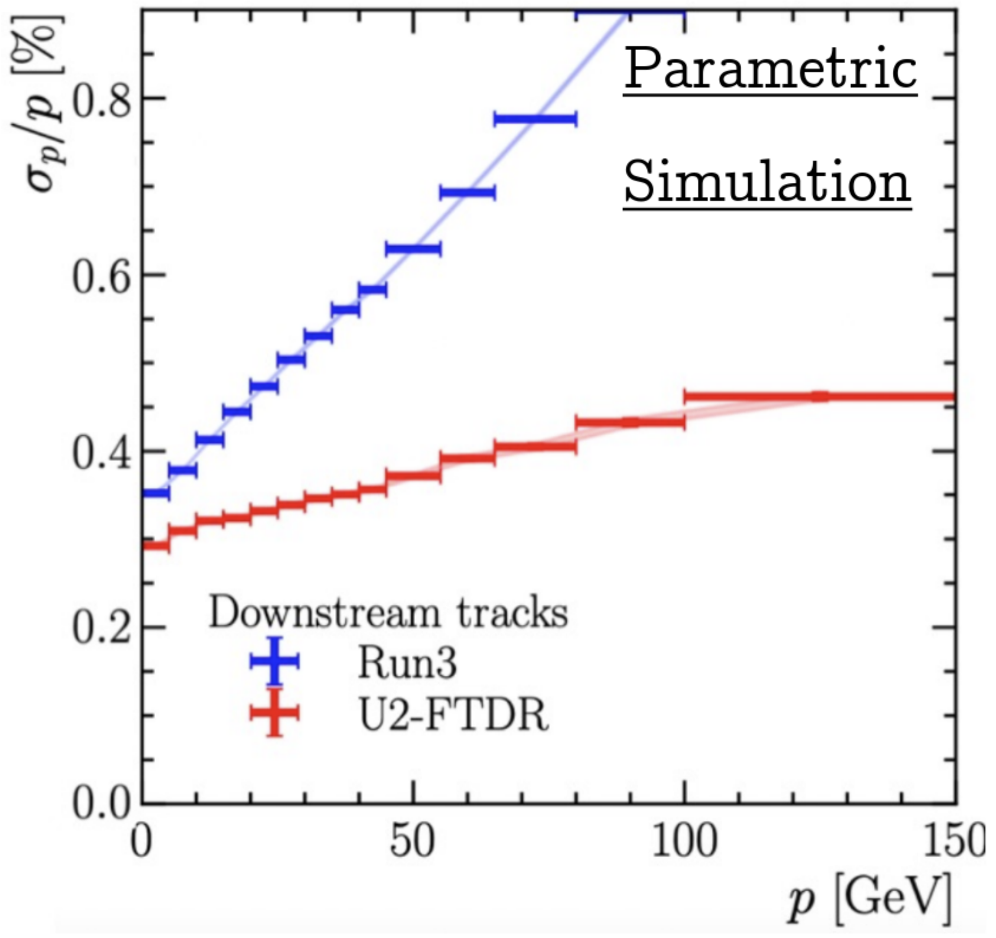


- UP: Tracker in front of magnet, 4 layer of pixel sensors, full acceptance
- MT: Scintillating fibre tracker (low hit density), 6 layers vertical, 6 stereo
  Pixel tracker in the inner region (high hit density) 6 layers
- Shared pixel technology, Monolithic Active Pixel Sensors (MAPS) ns-timing

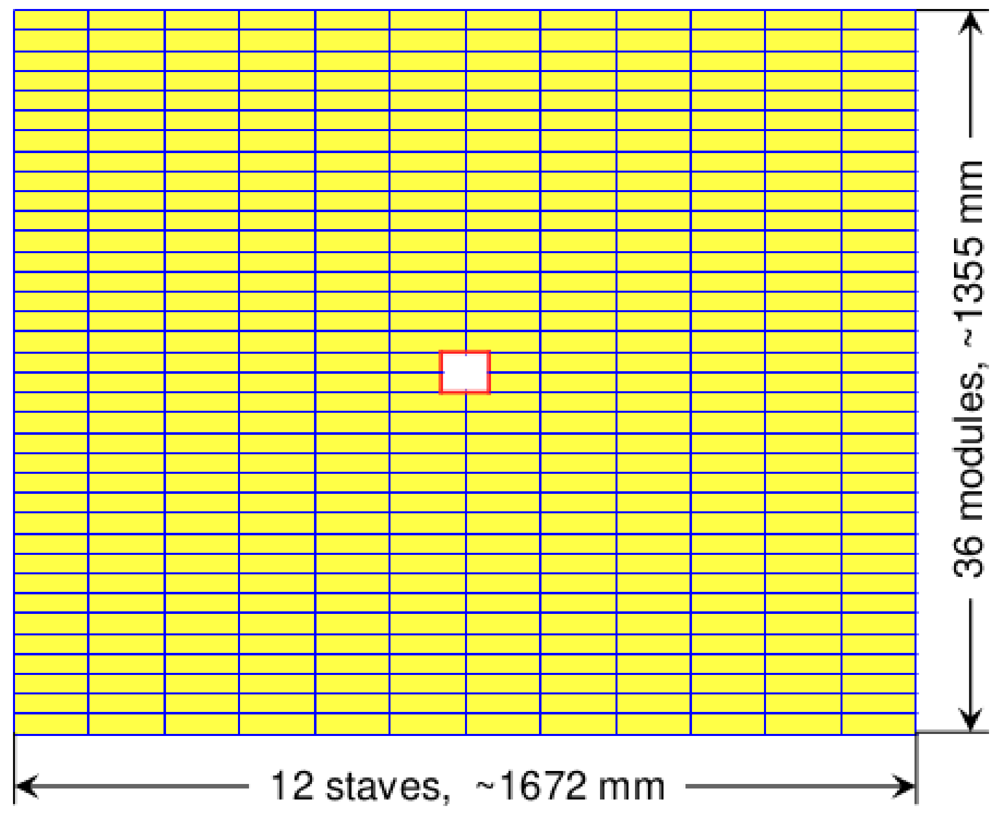
Might Tracker







Upstream Tracker



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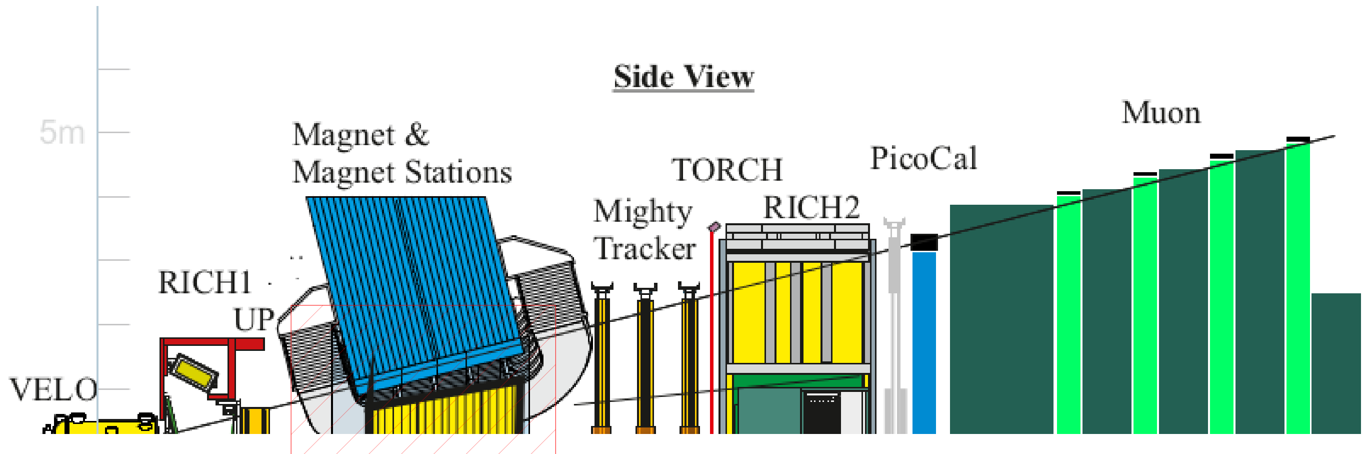
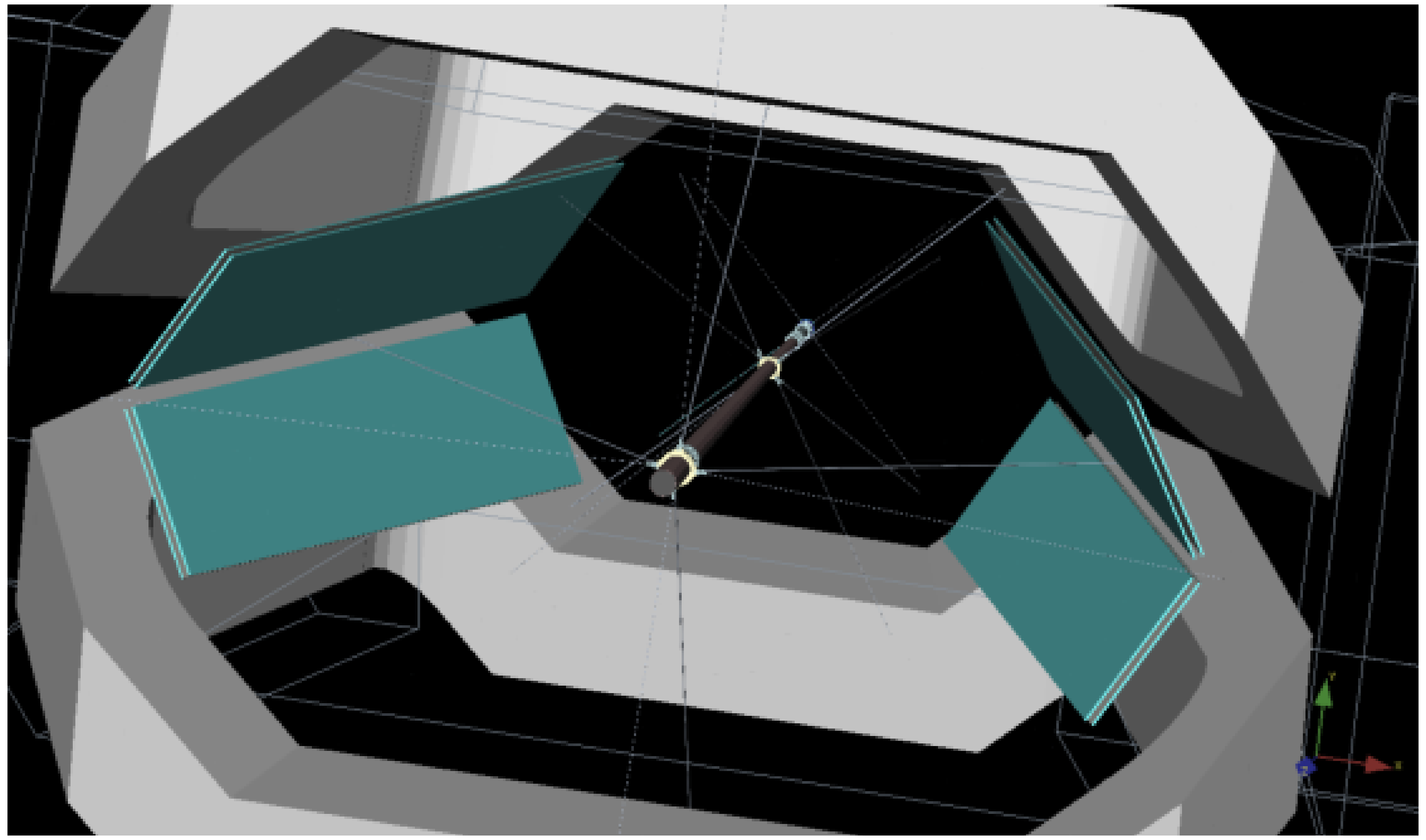
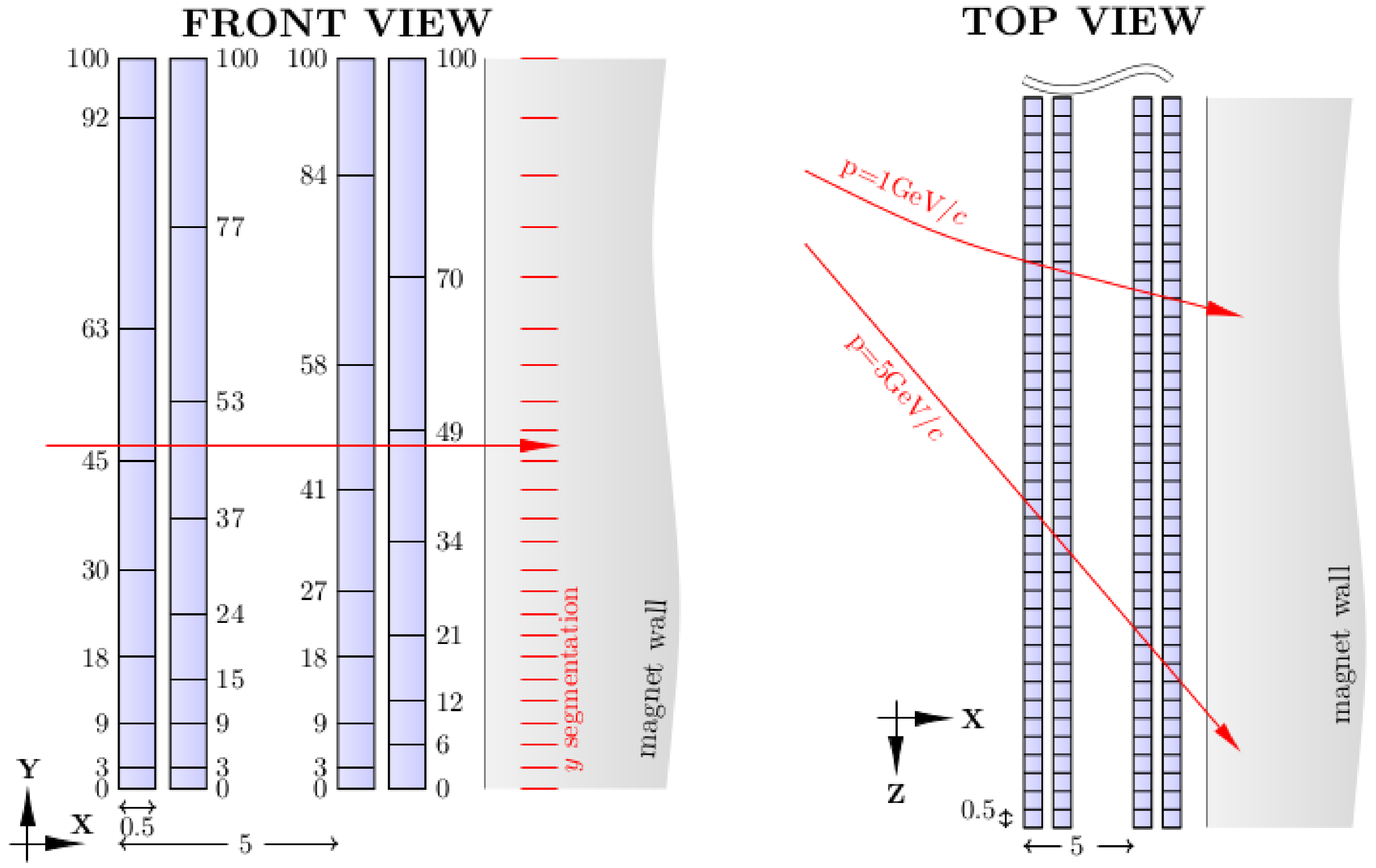
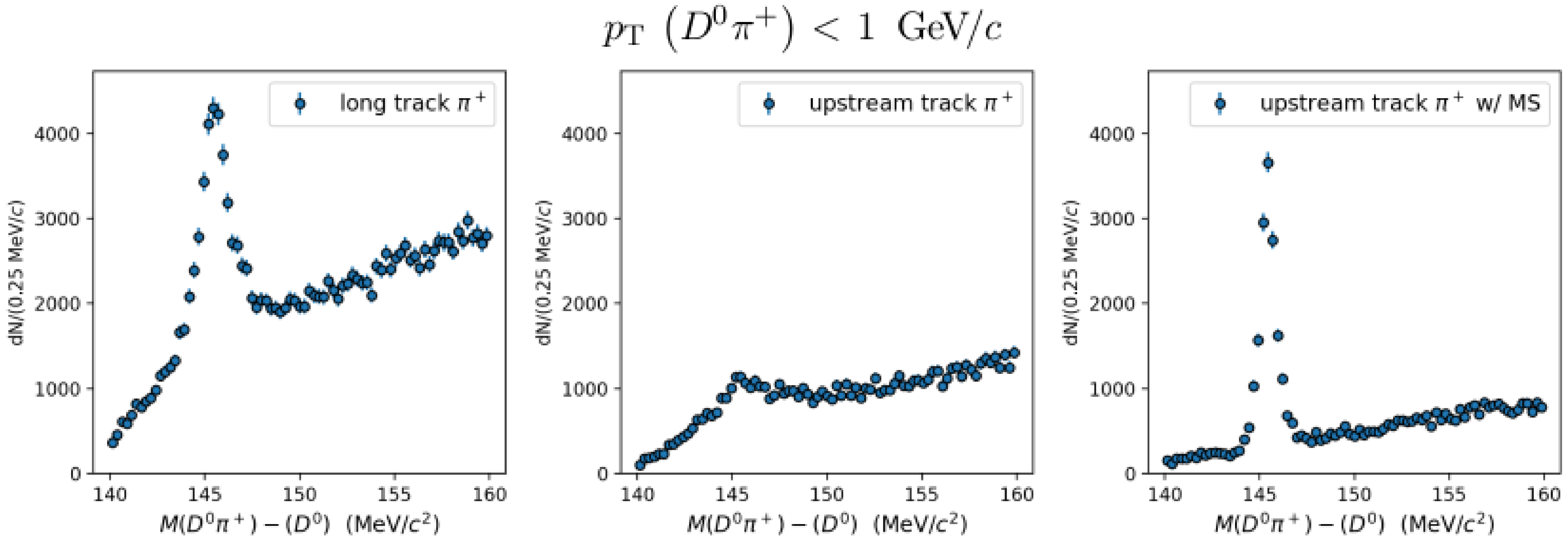
Magnet stations – MS (new)





- Scintillating slabs on the side walls of magnet
- Soft charged particles (charm tags $D^{*+} \to D^0\pi_s^+$)
- Low occupancy





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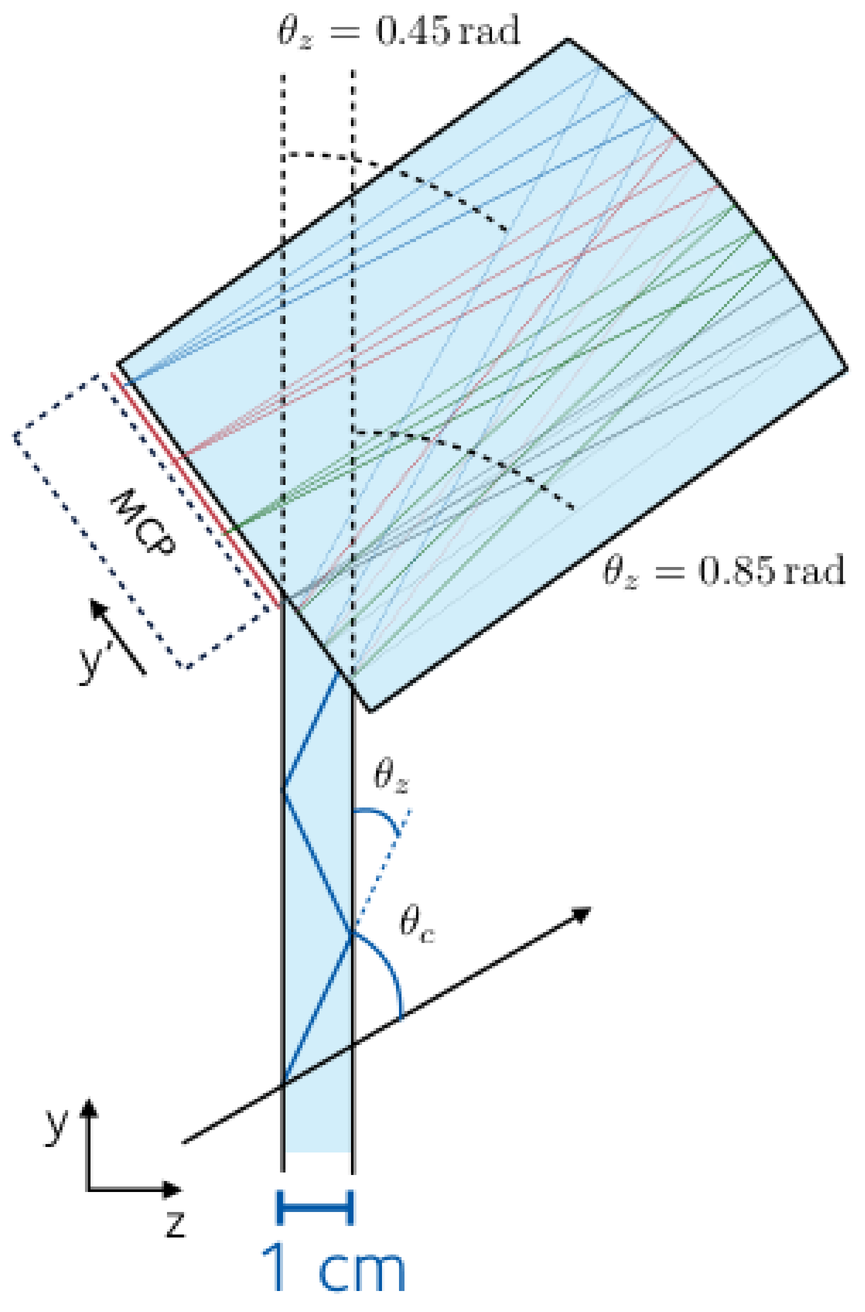
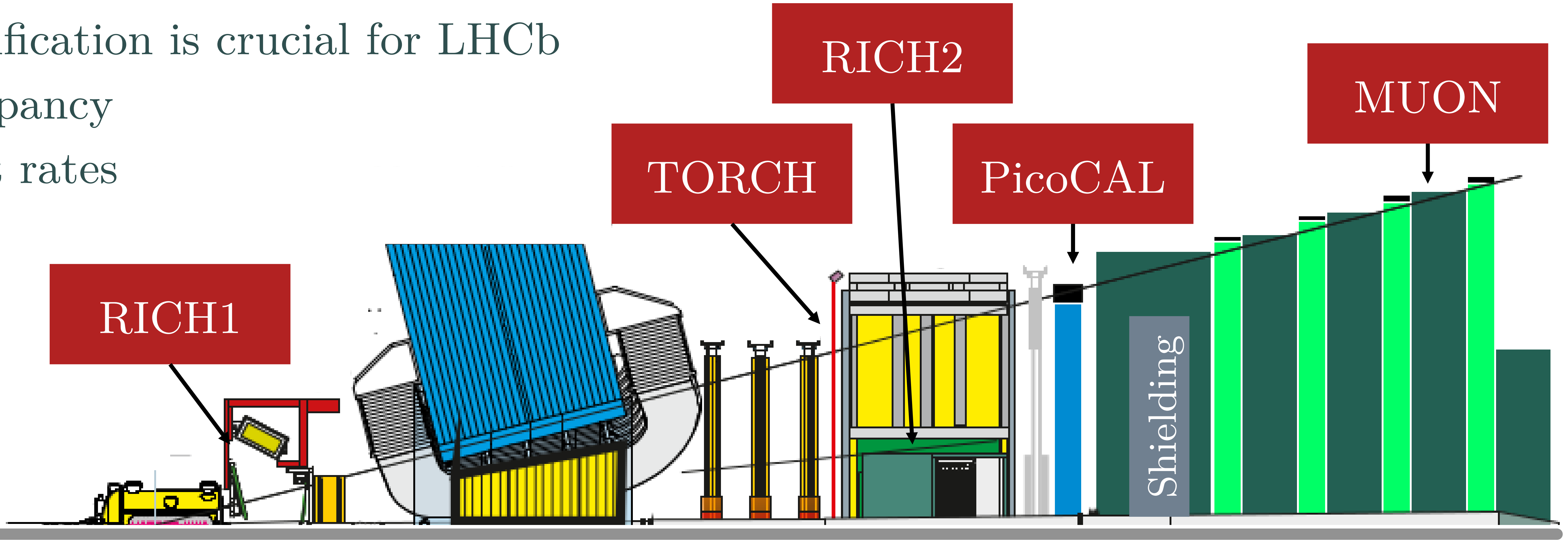
Particle ID

- RICH1 and RICH2: improved granularity, optics and per photon timing
- TORCH (new): detection of internally reflected Cherenkov light (DIRC) + downstream timing
- PicoCAL: Upgraded ECAL, better time, energy, spatial resolution
  - HCAL: replaced by shielding for MUON
- MUON: μRWELL in inner region, MWPC outer region



TORCH

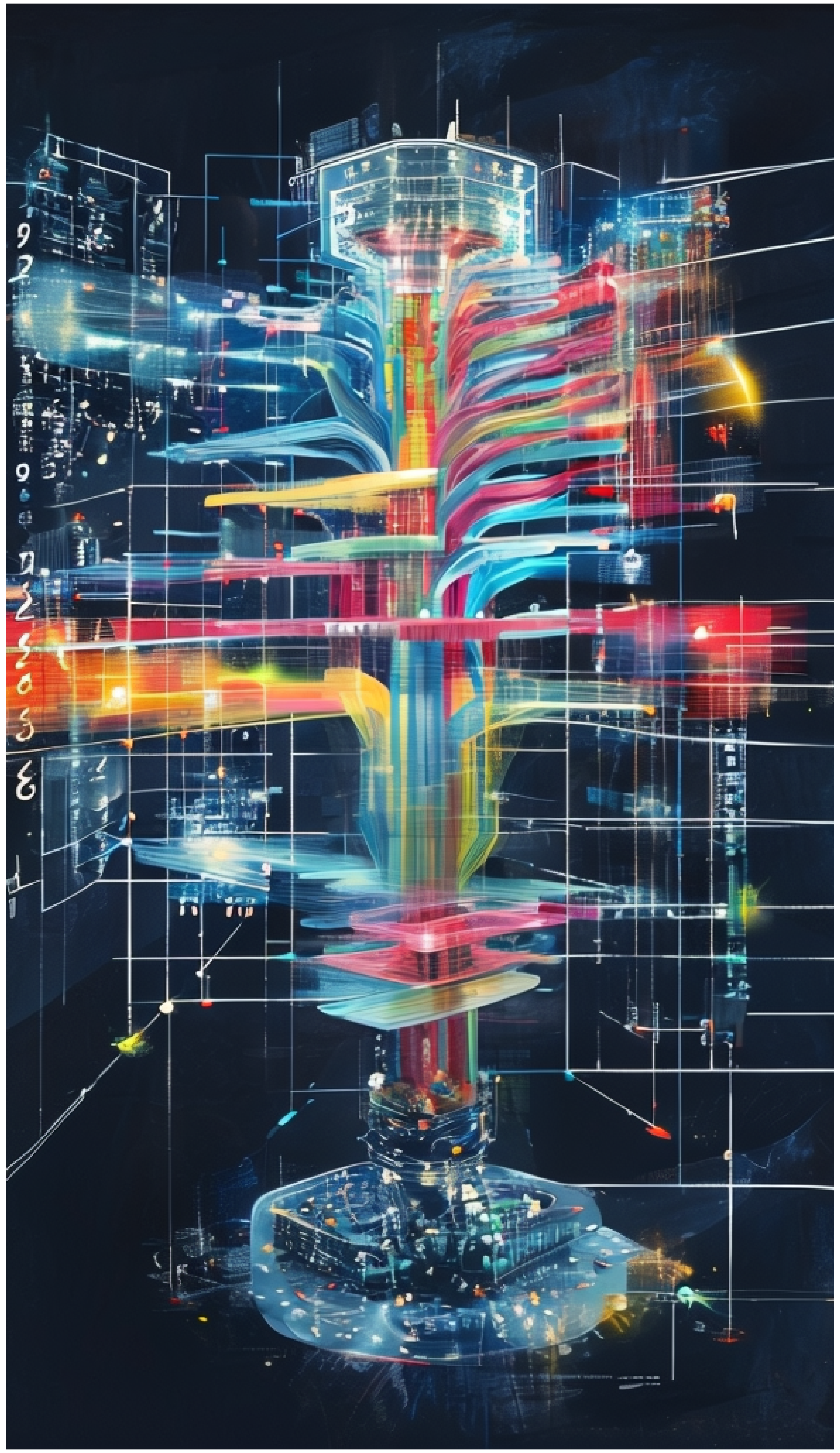
Photon, electron, muon and hadron identification is crucial for LHCb
PicoCAL and RICH need timing for occupancy
Downstream time stamp is good for ghost rates



CERN-LHCC-2021-012

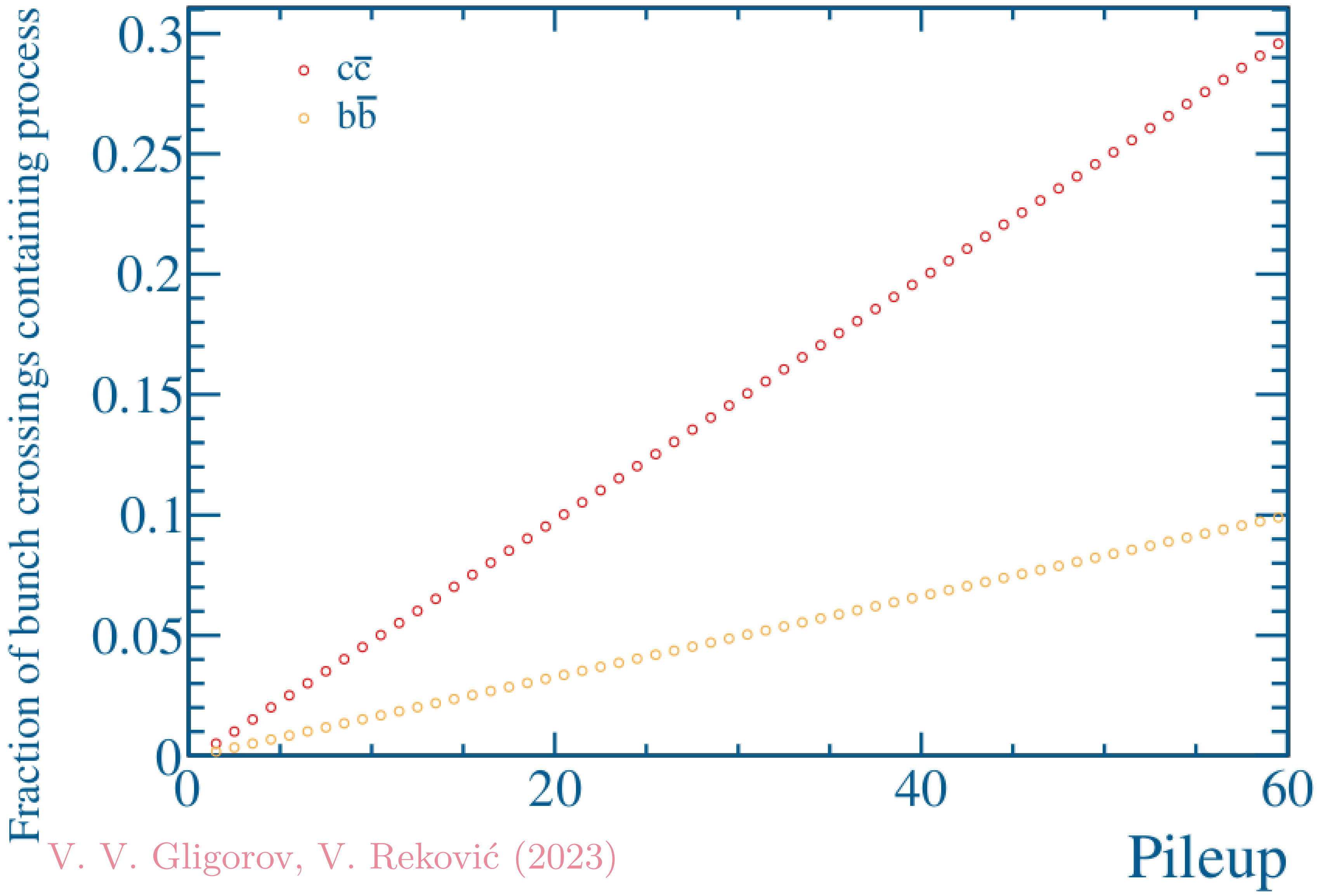
Trigger considerations

- Aim for similar trigger efficiency as Run 3
  - At 5 - 7.5 time higher pile-up
- Bandwidth exceeding ATLAS HL-LHC and CMS HL-LHC
  - LHCb Upgrade I: 4 TB/s | Run 3
  - ATLAS: 5 TB/s
  - CMS: 7.5 TB/s | Run 4
  - LHCb Upgrade II: 25 TB/s | Run 5
  - Europe largest internet exchange : 2TB/s



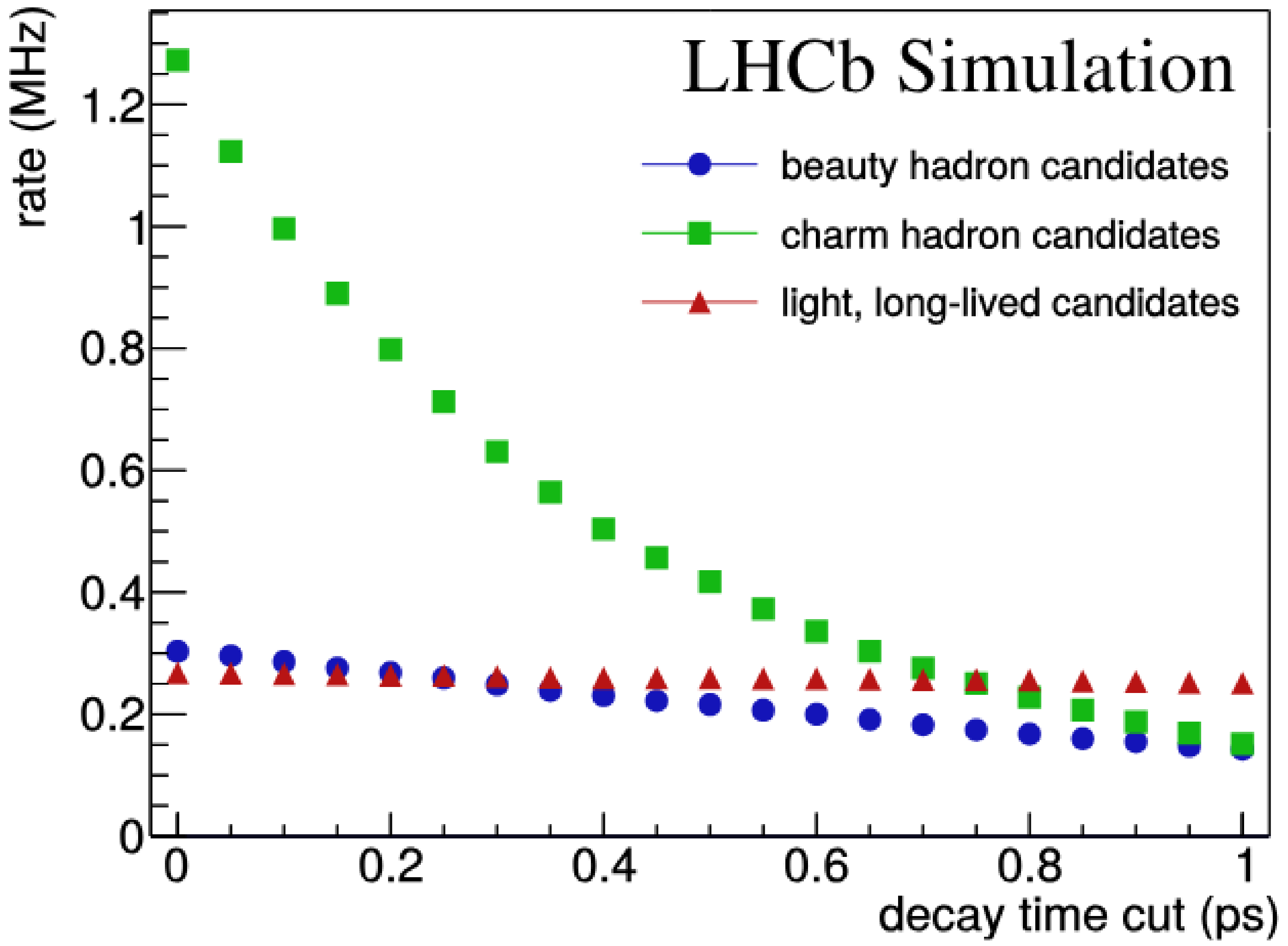
What to trigger?

- Most events are interesting to our physics program
- 5% of bunch crossings contain a reconstructible $b\bar{b}$ event
- 20% a $c\bar{c}$ event
- Aim for 50 GB/s data to analysts



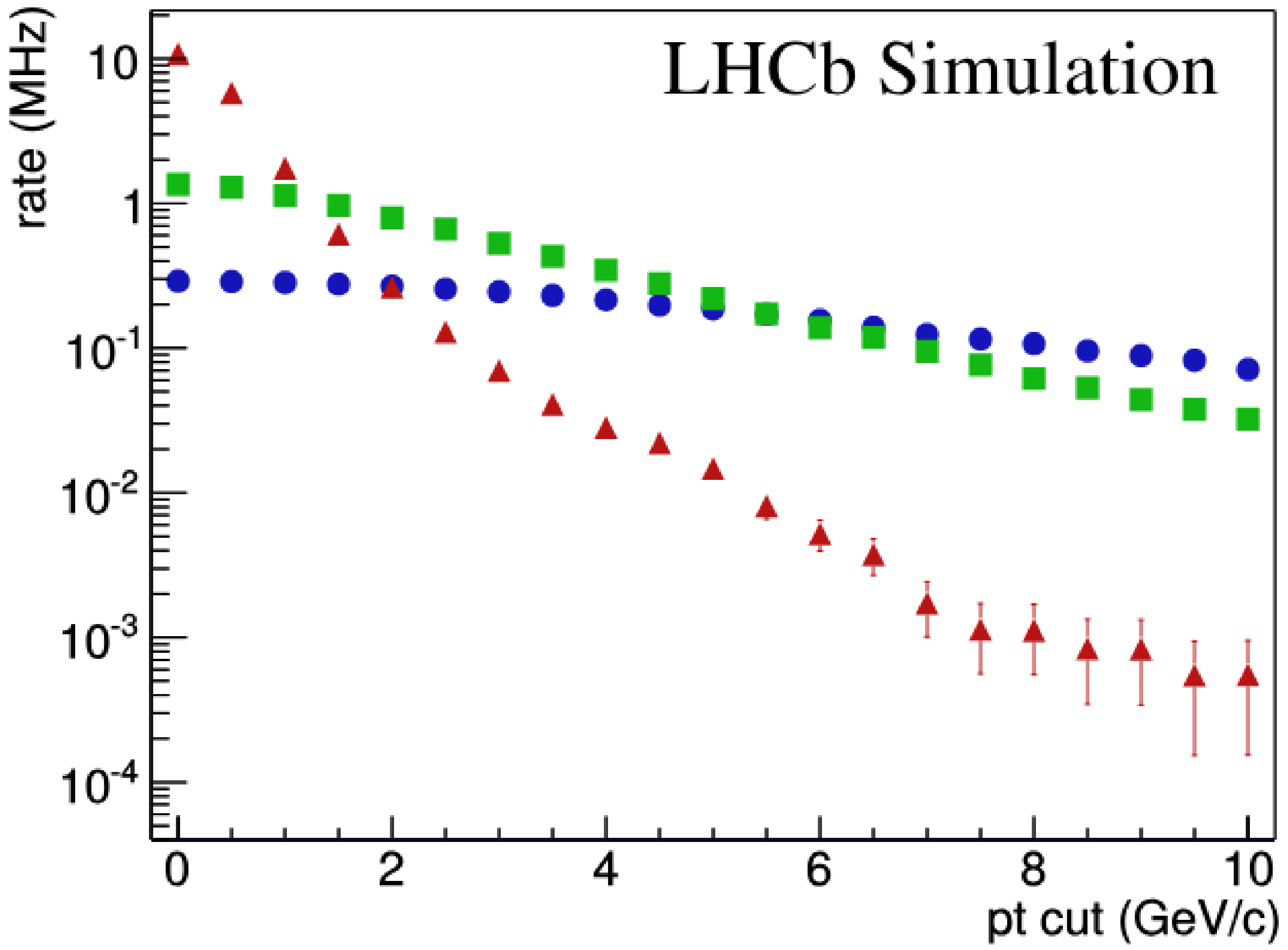
V. V. Gligorov, V. Reković (2023)

Rates as a function of decay time cut for part. reco. candidates

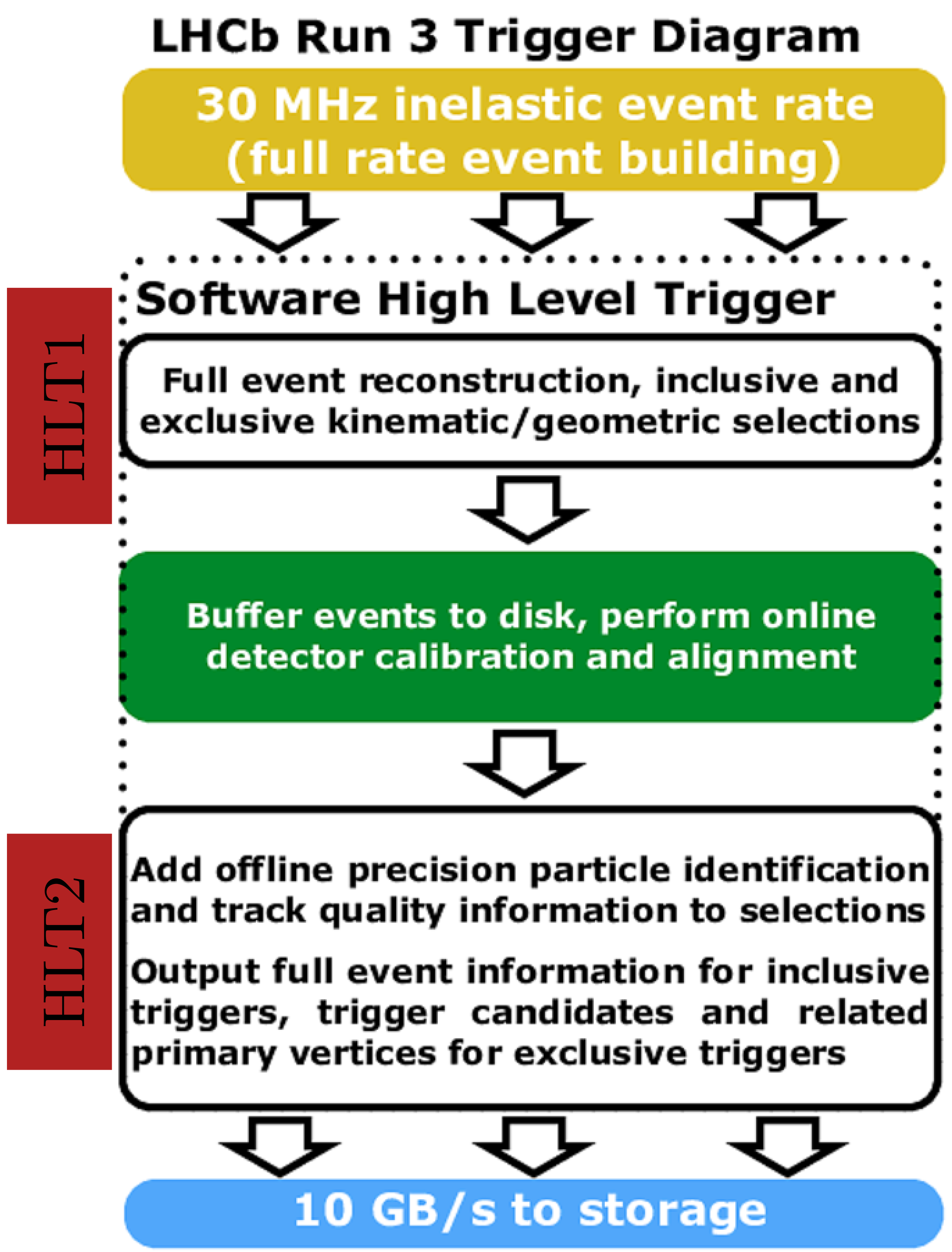


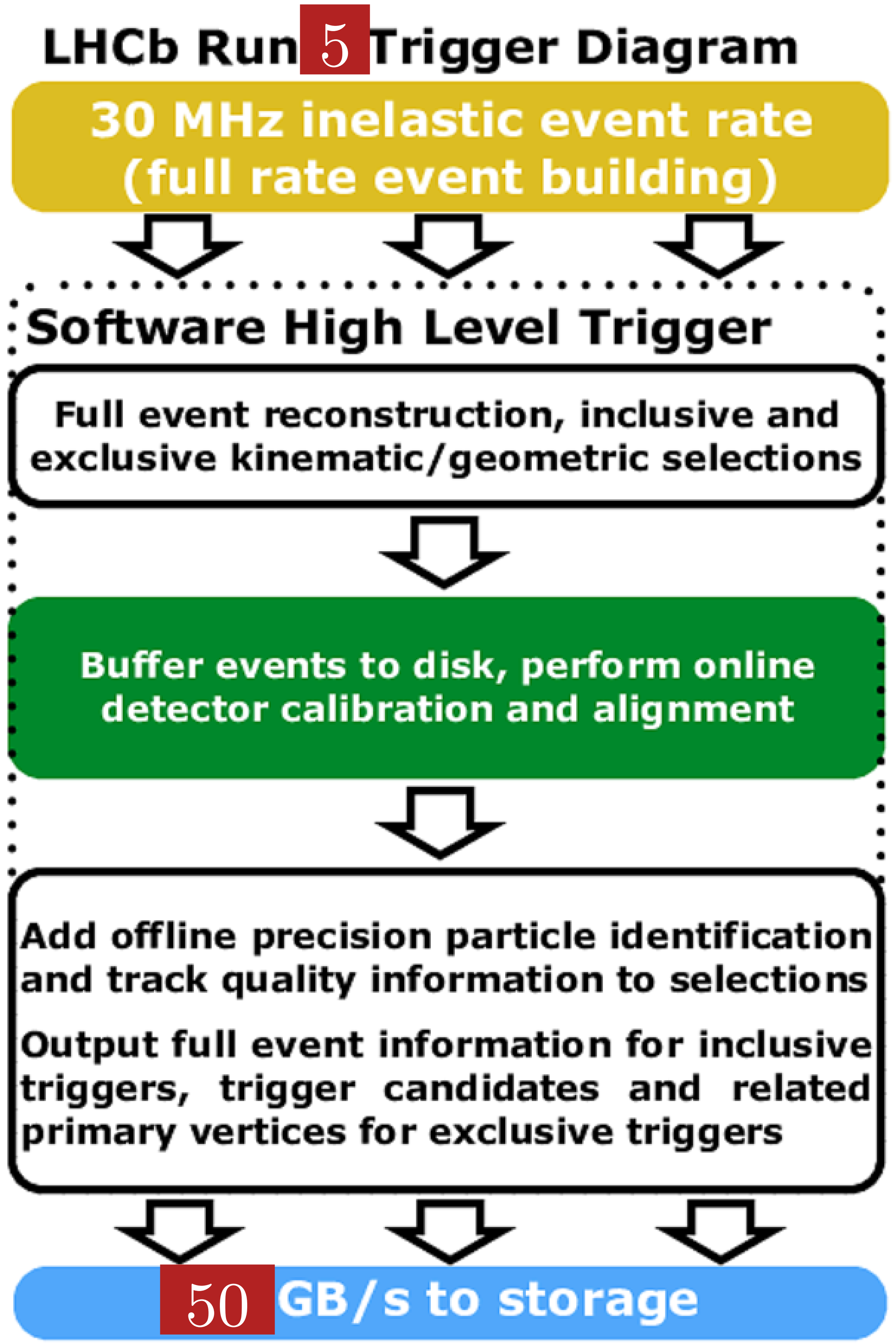
LHCb-PUB-2014-027

Rates as a function of pT cut for part. reco. candidates



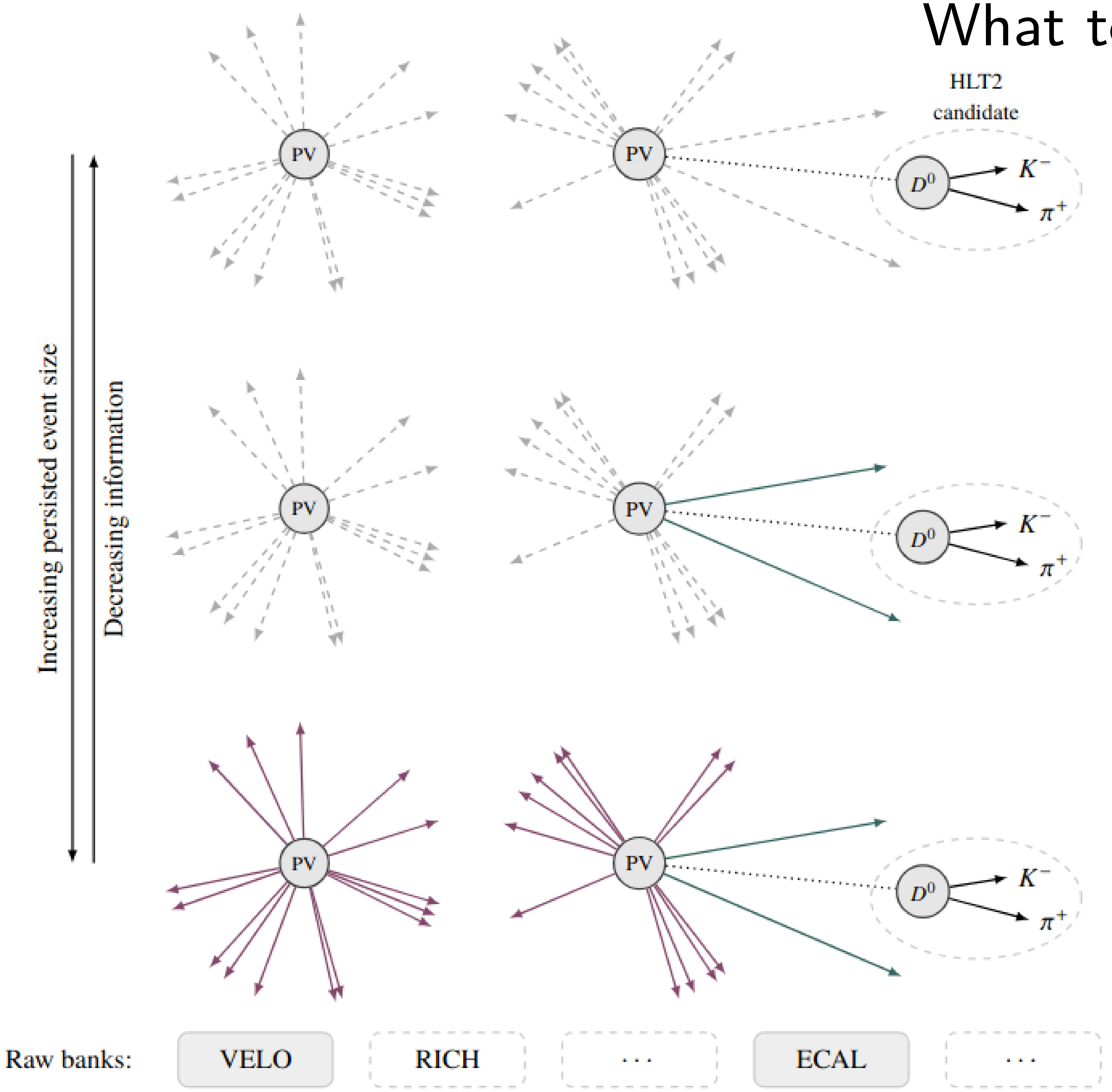
Meet the new trigger – same as the ~~old~~ current trigger





- Two stage trigger:
- HLT1 reconstructs every event
  - Inclusive and exclusive selections
- Saved to large buffer (days to weeks)
  - Online calibration and alignment
- HLT2 full offline-quality reconstruction
  - Selection on O(1000) trigger lines
- Distributed and redundant storage
  - Centralised reanalysis and tupling

What to write to disk?



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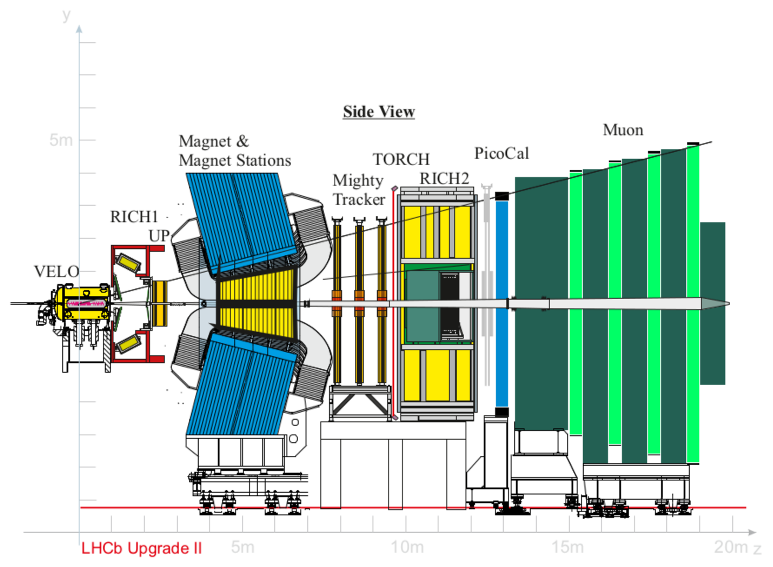
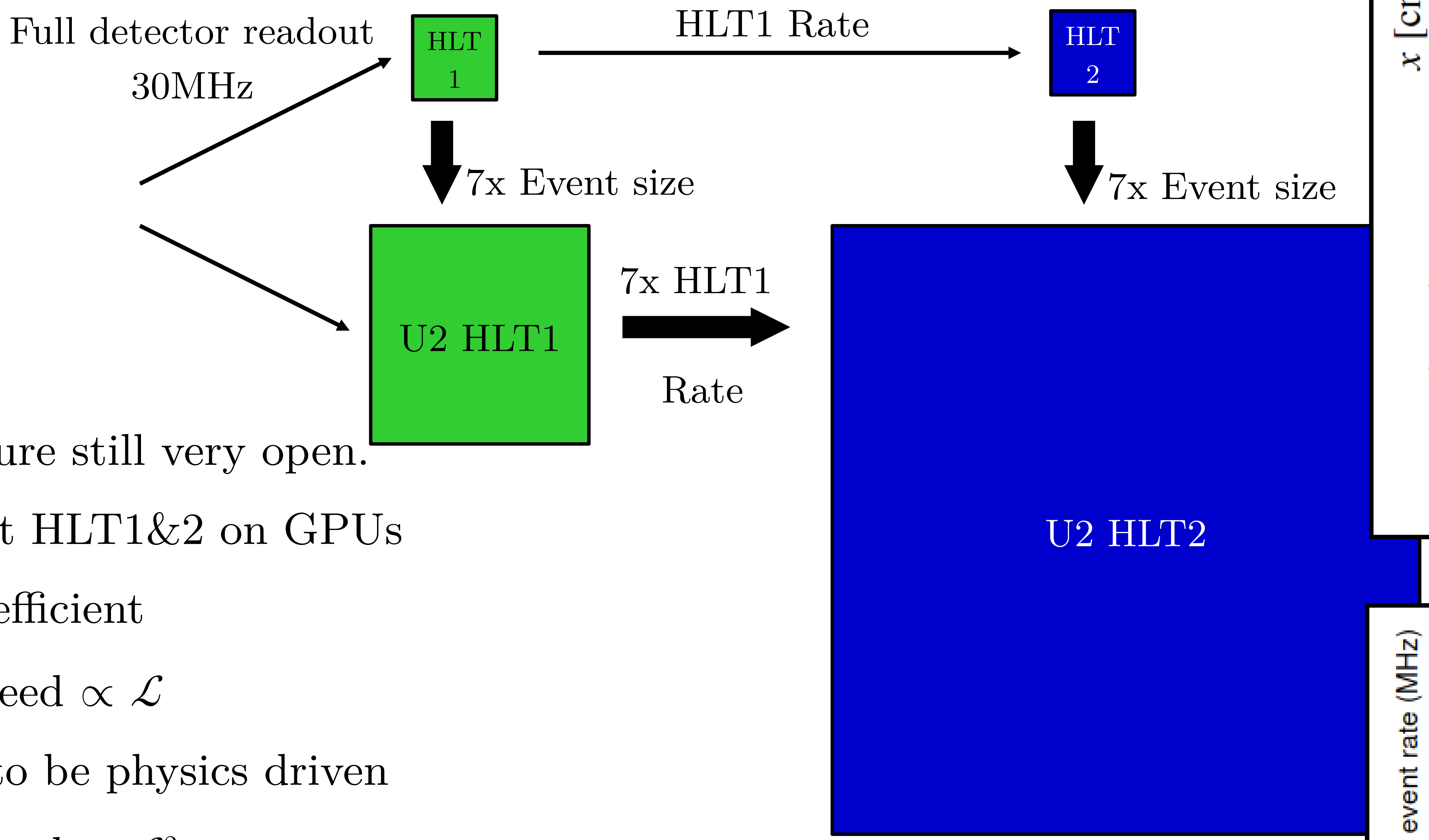
- ~40 PVs, each PV ~ 50 tracks
- Raw detector readout of 1 event ~ 900kB
- Saving the signal tracks ~ 10kB
- More information needed for:
  - Tagging, isolation, jets, ...

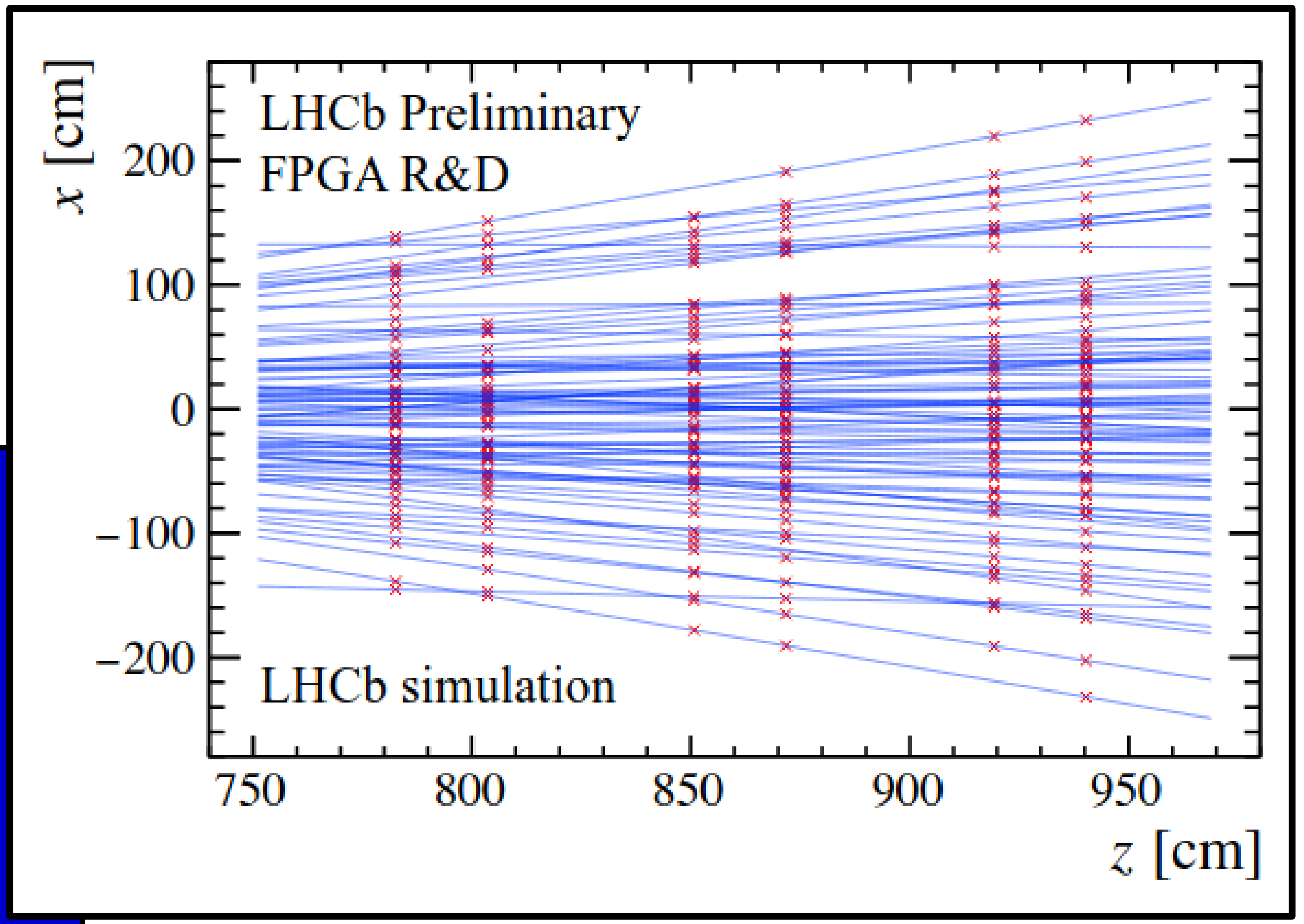
- Smart use of pre-scales
- Discarding detector information
- Effective pile-up suppression
  - Also good for analysis consistency
- Need a large calibration sample

Computing needs

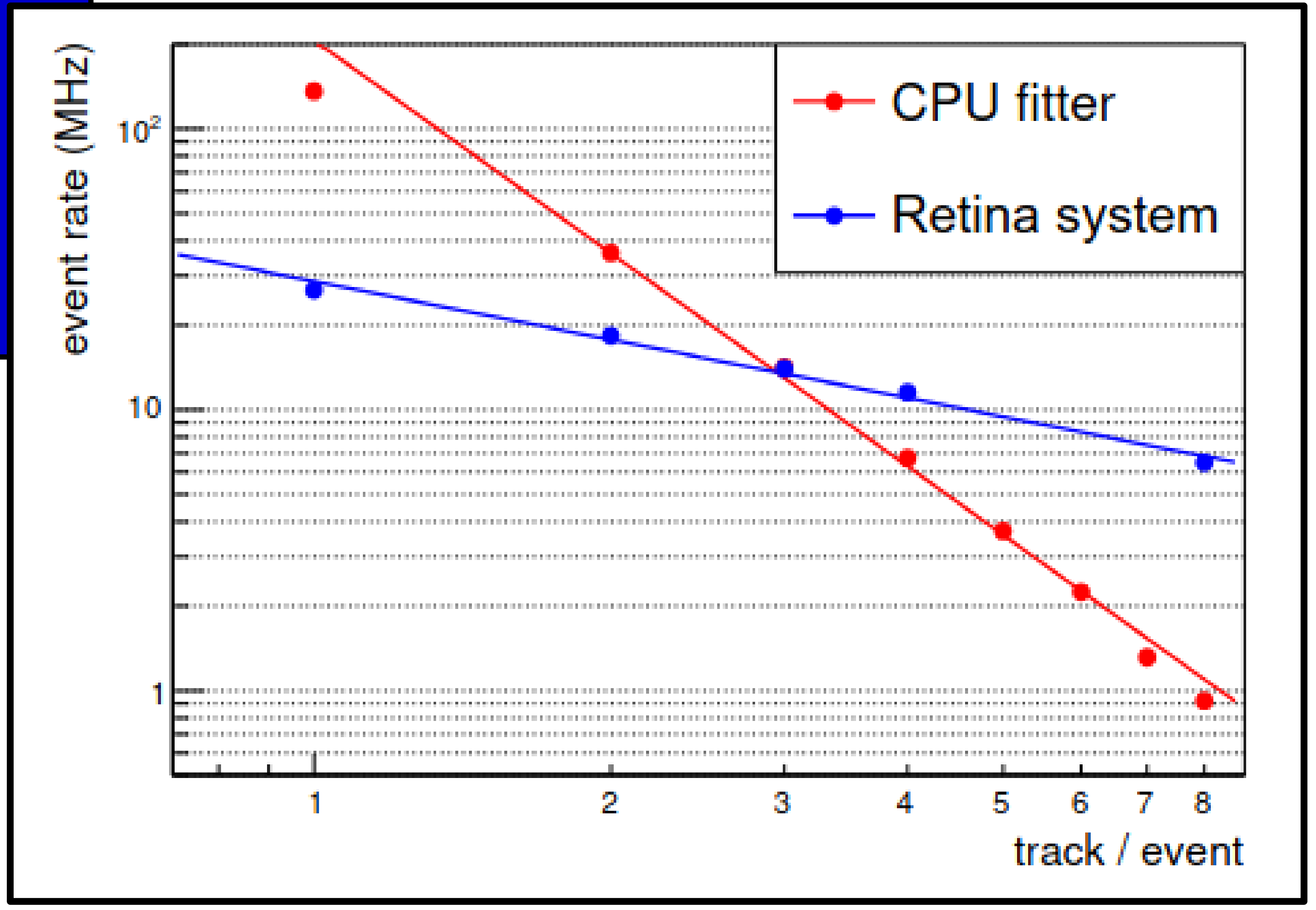




- Choice of architecture still very open.
  - Personally expect HLT1&2 on GPUs
  - Must be energy-efficient
- HLT1 computing need $\propto \mathcal{L}$
  - rate is assumed to be physics driven
- HLT2 computing need $\propto \mathcal{L}^2$
  - This assumes all reconstruction scales linearly $\rightarrow$ not really true
- Already working on more heterogeneous computing projects
  - Retina project: Clustering and tracking on FPGAs Run3&4



LHCb-FIGURE-2023-027



LHCB-TDR-25

Conclusion

LHCb Upgrade 2 will be The flavour factory. Enhancing sensitivities by factor 3-4 on top of LHCb Upgrade I. Unrivalled in many measurements.

LHCb Upgrade 2 is an ambitious project on both detector and real-time analysis part.

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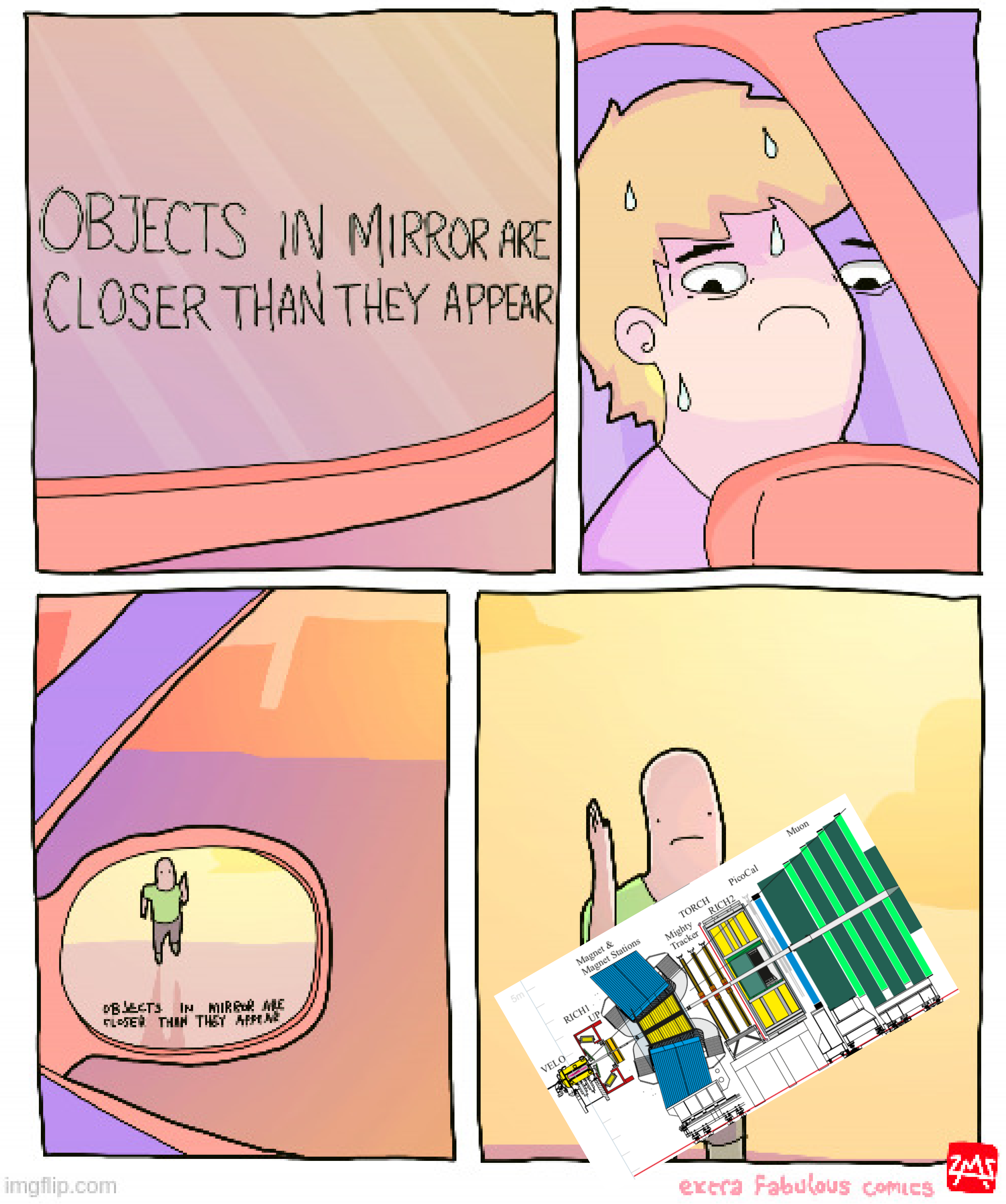
LHCb Upgrade 2 will be The flavour factory. Enhancing sensitivities by factor 3-4 on top of LHCb Upgrade I. Unrivalled in many measurements.

LHCb Upgrade 2 is an ambitious project on both detector and real-time analysis part, but rewarding.

2036 seems far away, but it's never too early start.



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