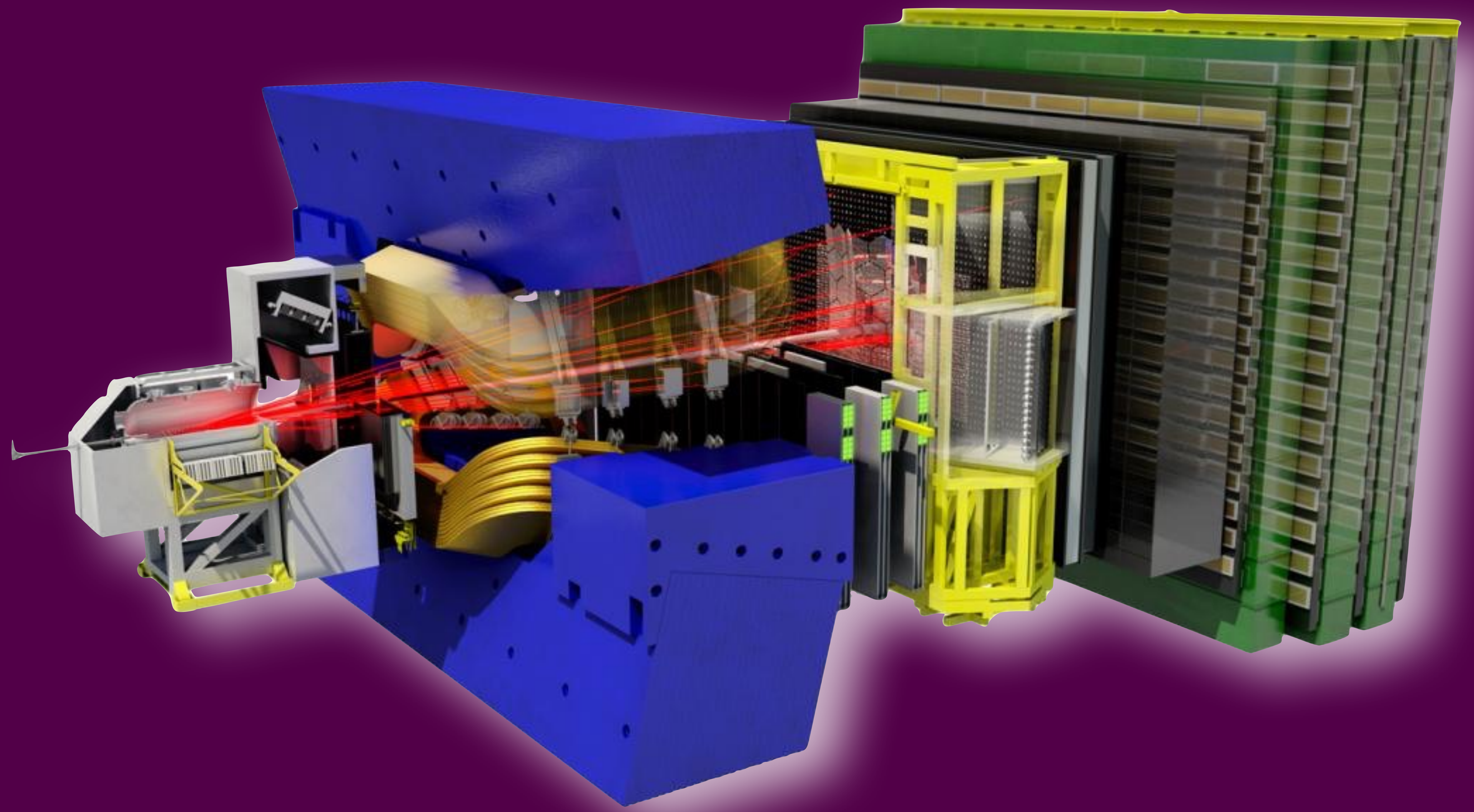
Closed captioning

A new frontier of precision physics: LHCb Upgrade II



Manuel Franco Sevilla

on behalf of the LHCb Collaboration

University of Maryland

22nd March 2023

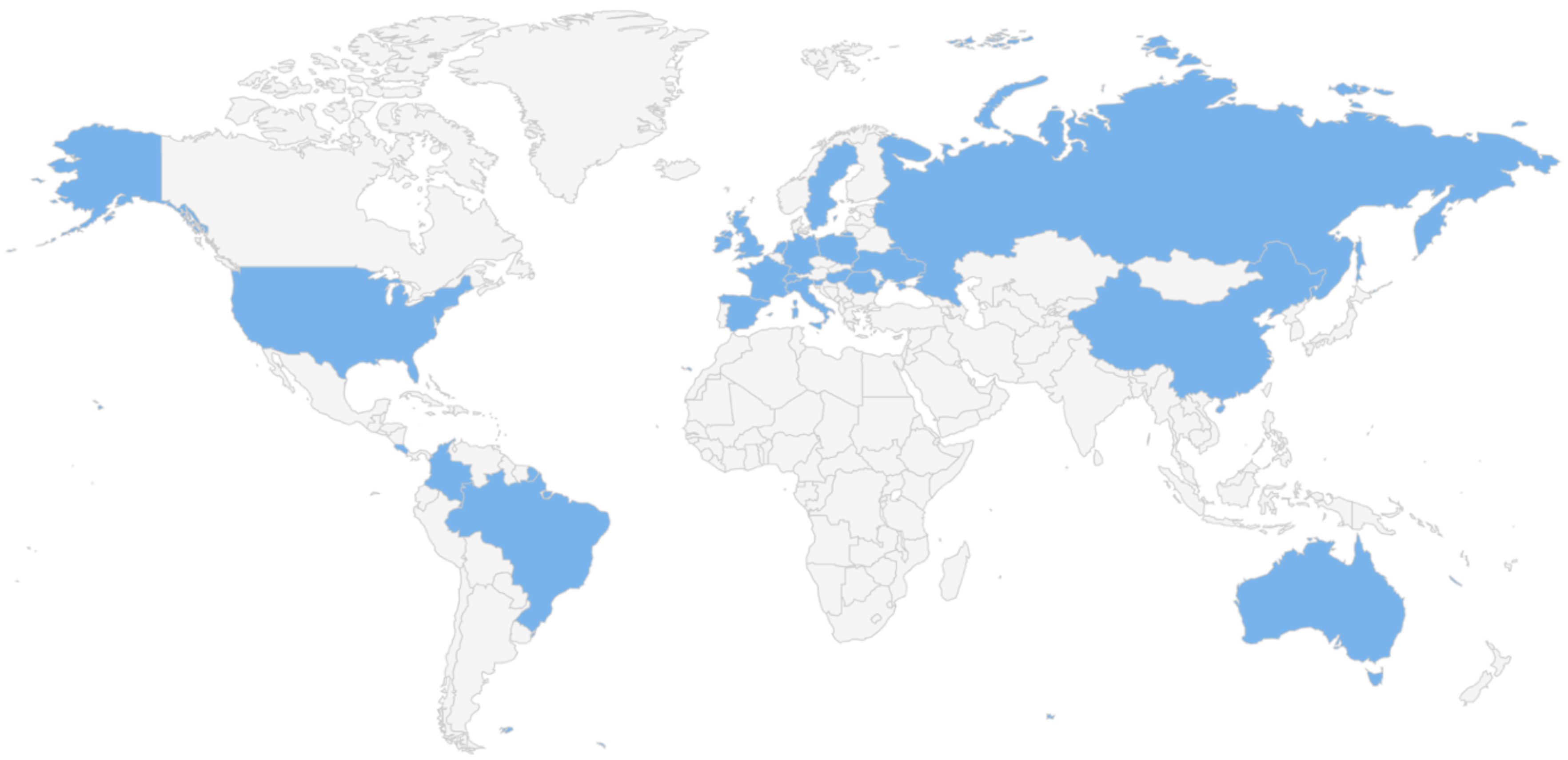
P5 Town Hall at Fermilab and Argonne

FNAL, Batavia, IL

The LHCb experiment

~ A **large collaboration**

- 21 countries, 96 institutes, 1572 members



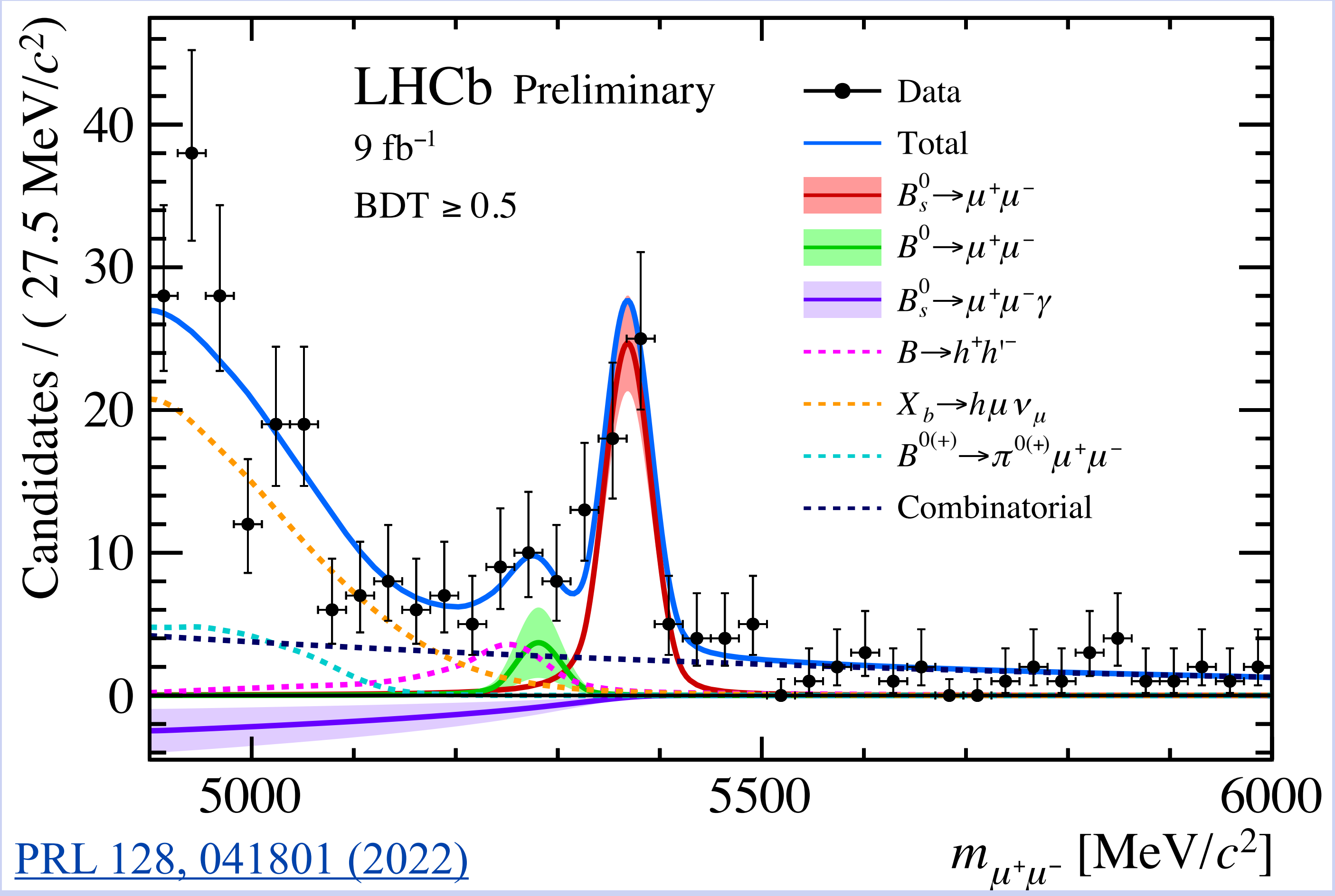
~ **US** participation

- Currently 6 institutes, 71 members
  - **NSF**: Cincinnati, Maryland, MIT, Syracuse
  - **DOE/NSF nuclear**: Los Alamos, Michigan

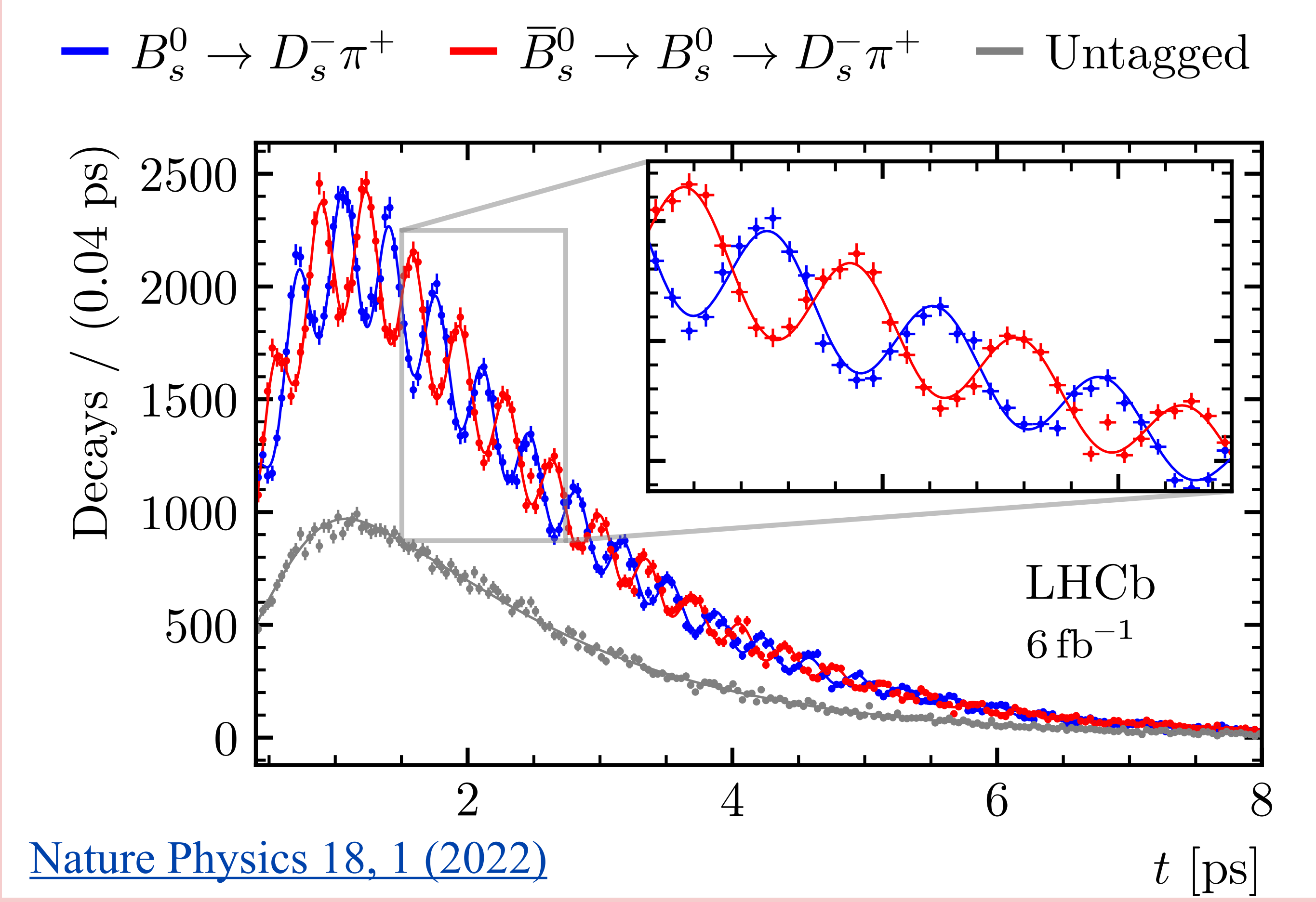
Hugely successful track record

- Access to **high mass scales** through **flavor physics** was **key through development of SM**
  - No $K_L \to \mu\mu \Rightarrow$ c quark
  - $\Delta m_K \Rightarrow m_c \sim 1.5$ GeV
  - $\epsilon_K \Rightarrow$ t, b quarks
  - $\Delta m_B \Rightarrow m_t \geq 100$ GeV
- LHCb has demonstrated emphatically that the **LHC is an ideal laboratory for flavor physics**

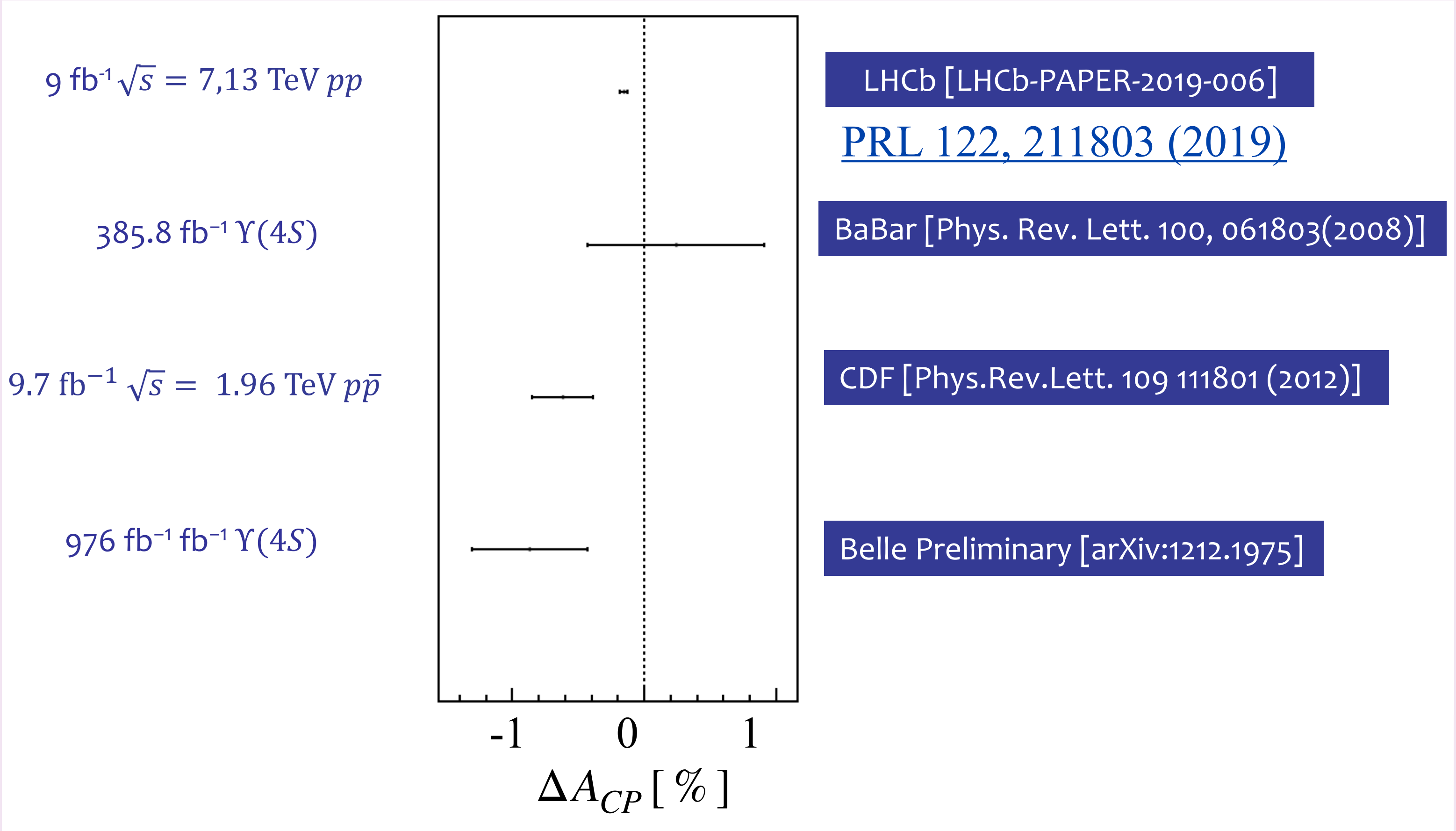
$B_{(s)} \to \mu\mu$



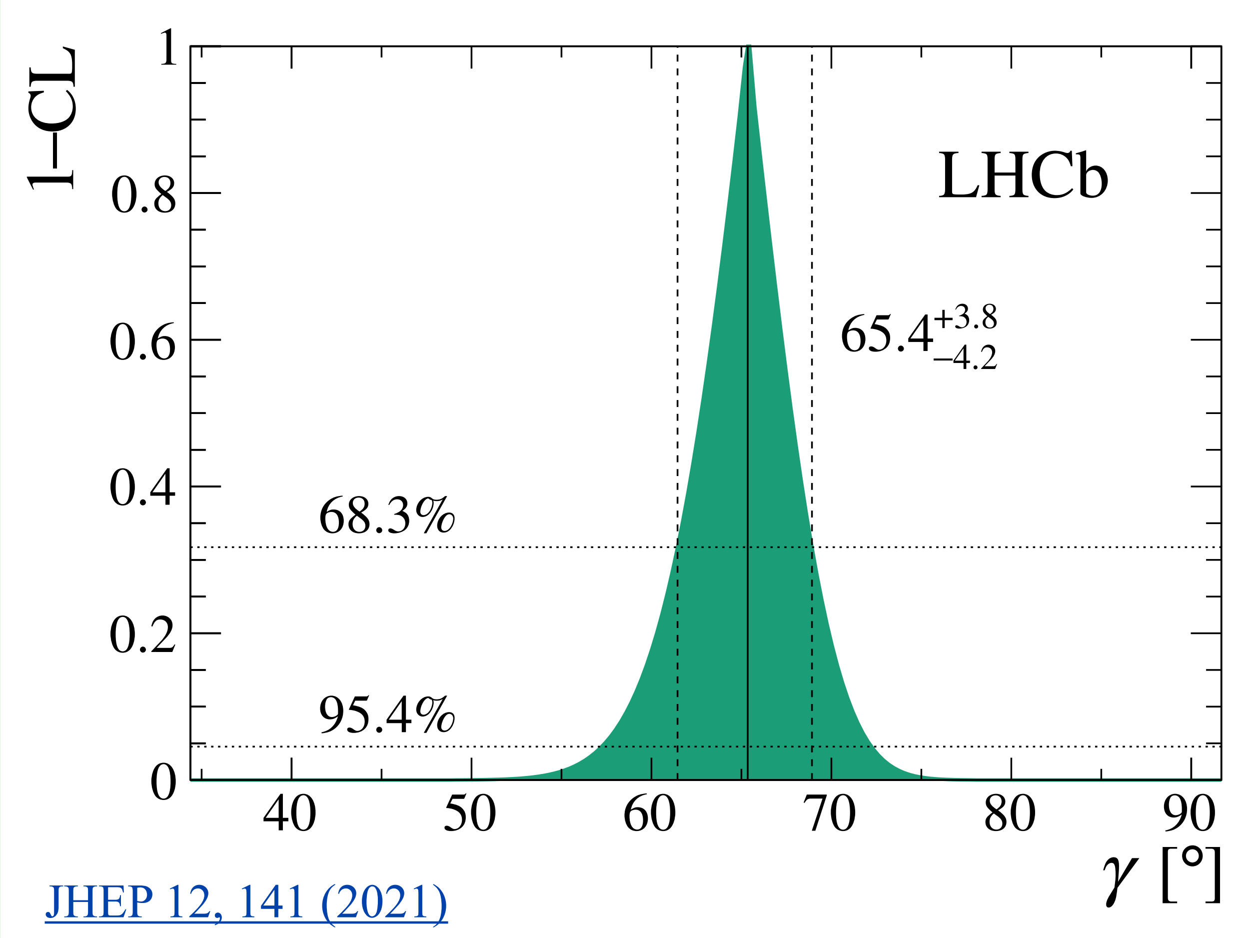
B_s oscillation $\to \Delta m_s$



First CP violation in charm



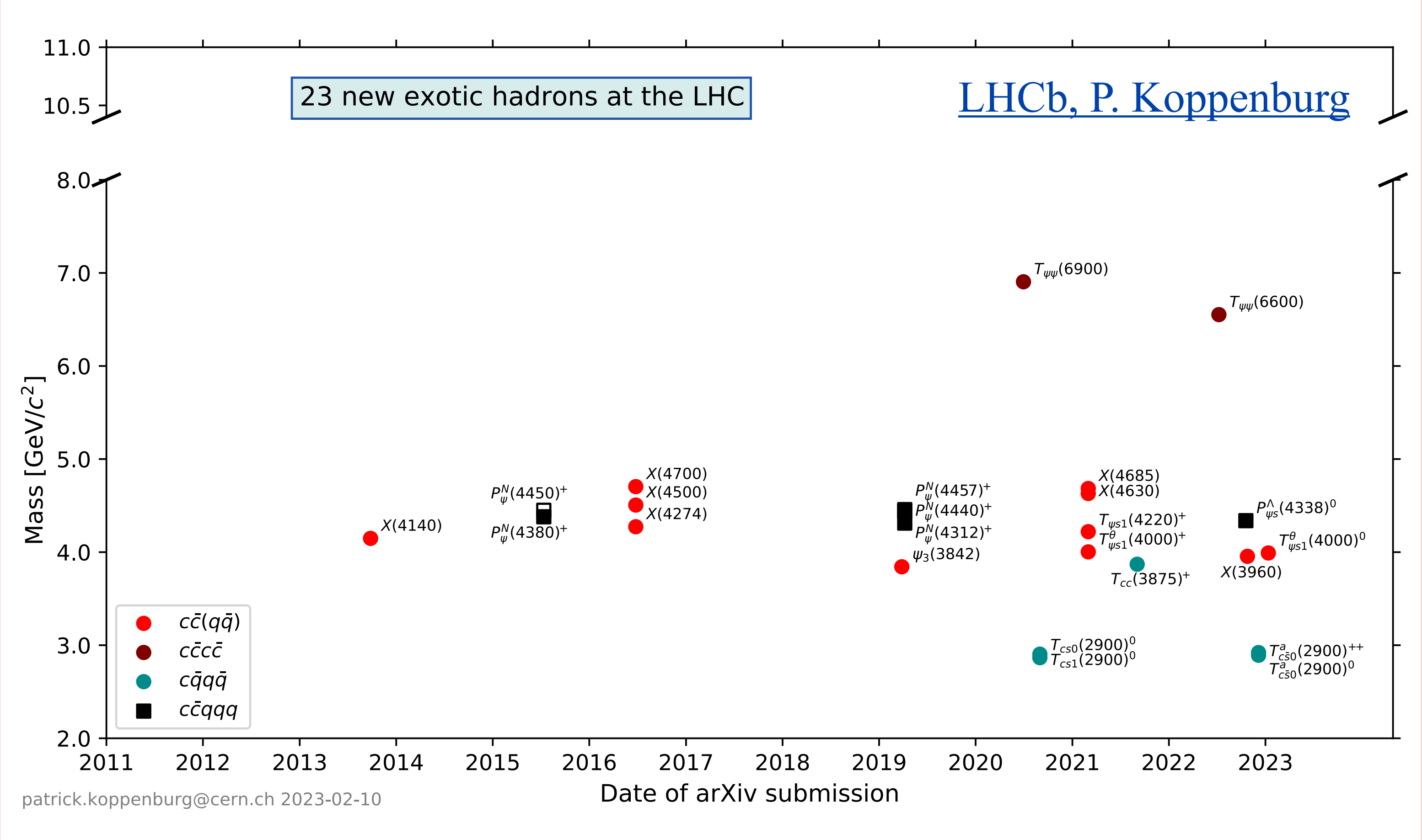
CKM angle γ



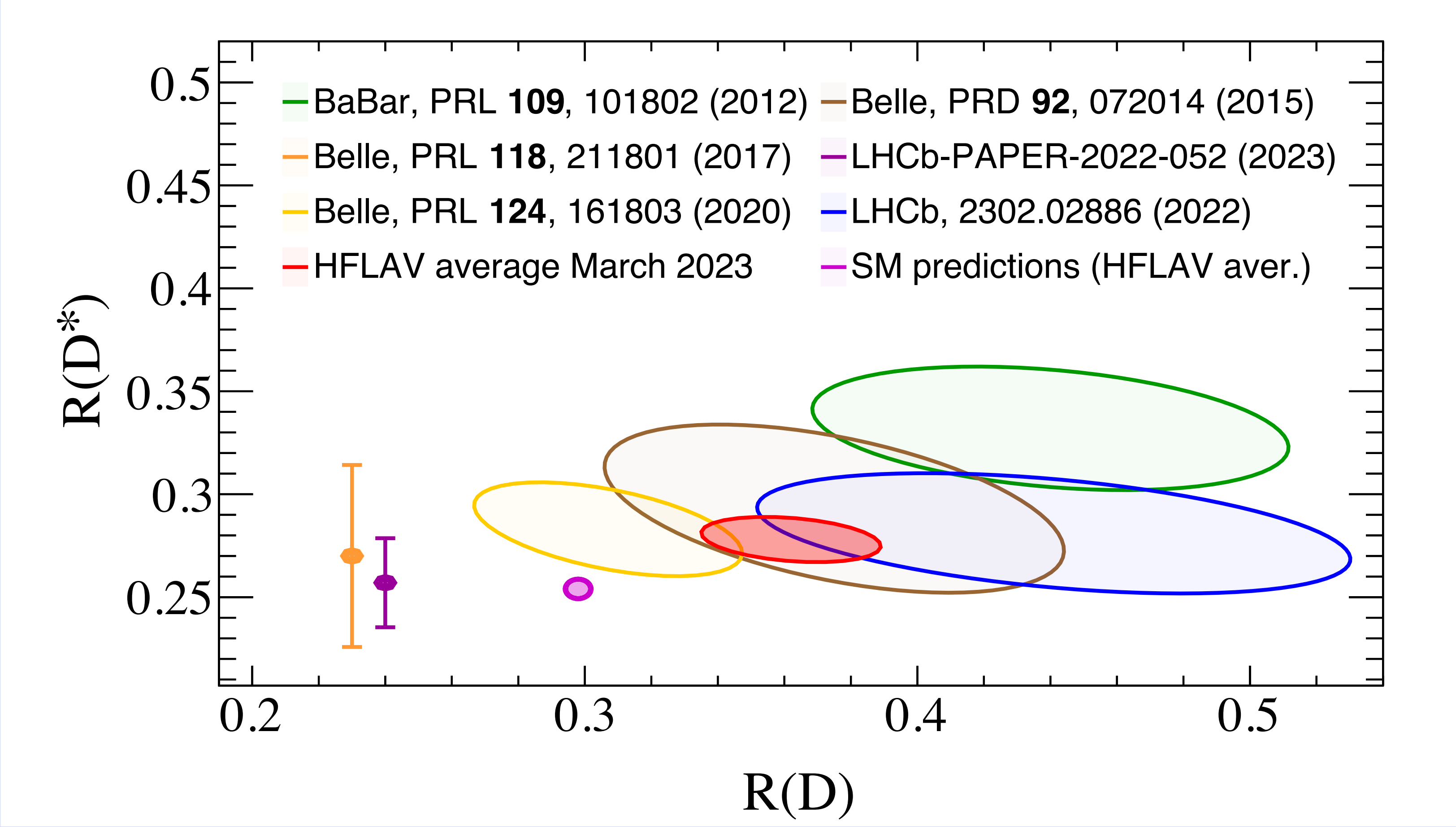
Flexible and broad program

- Leading and critical contributions **beyond core program**

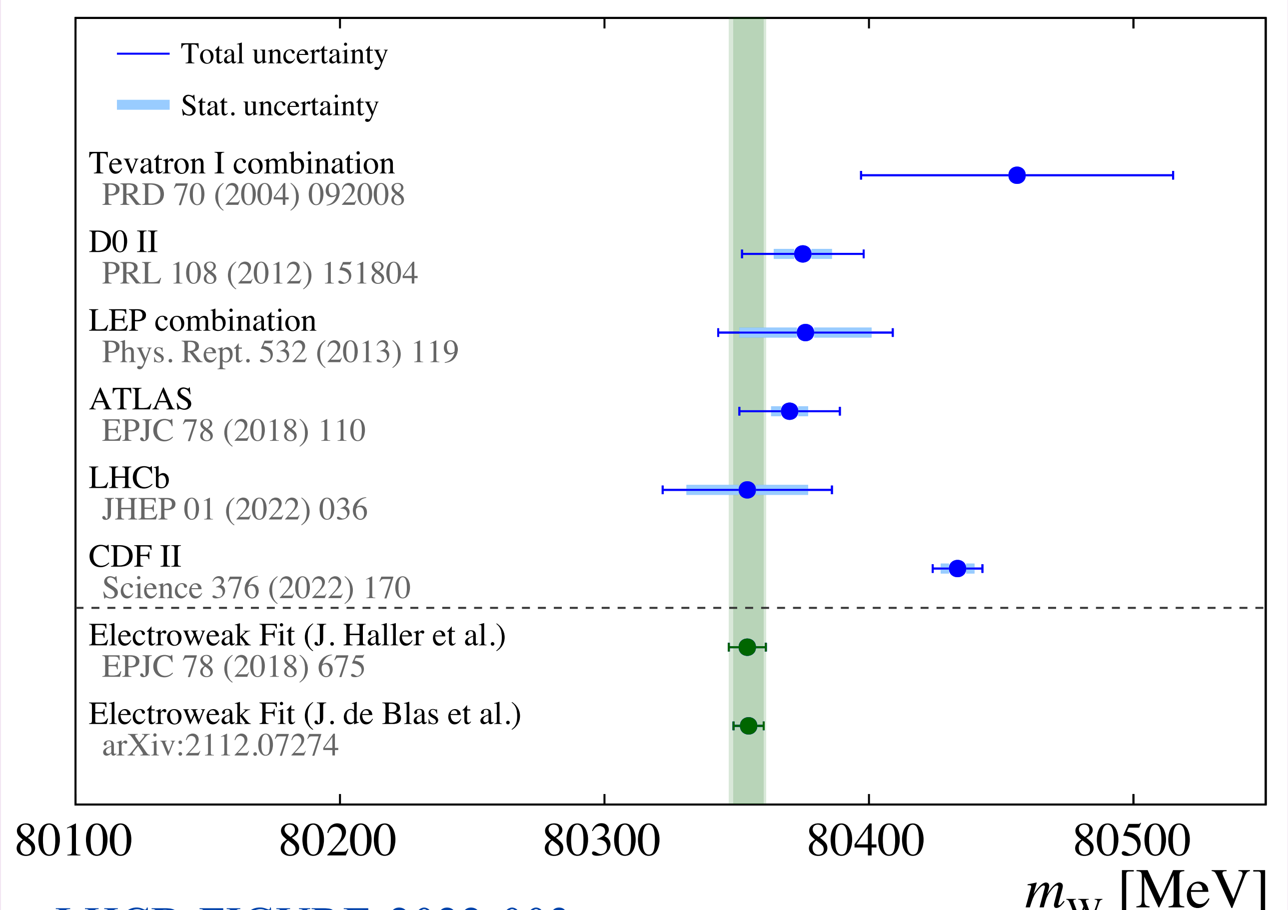
Tetraquarks, pentaquarks



Anomalies in $b \to c\tau\nu$

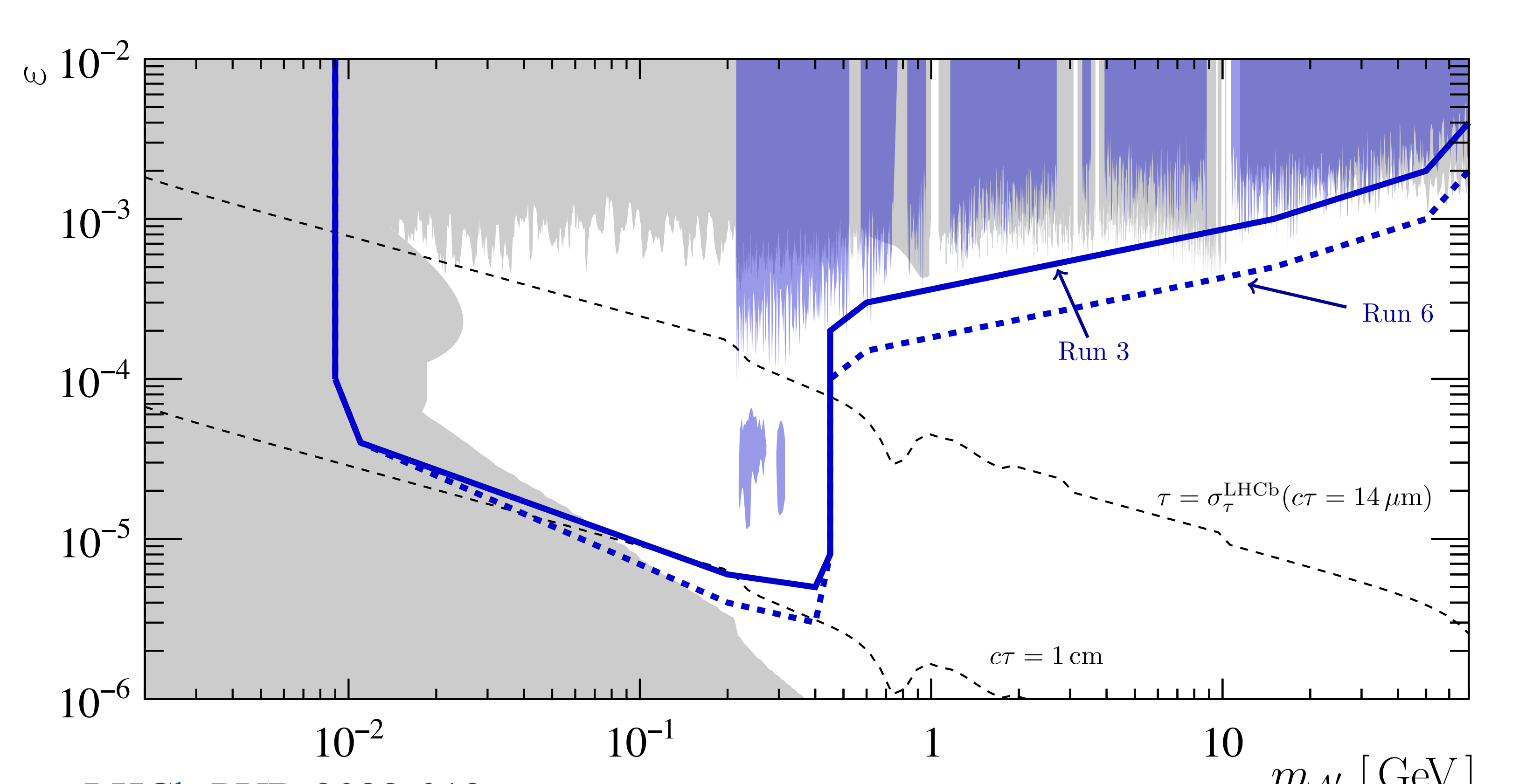


W mass



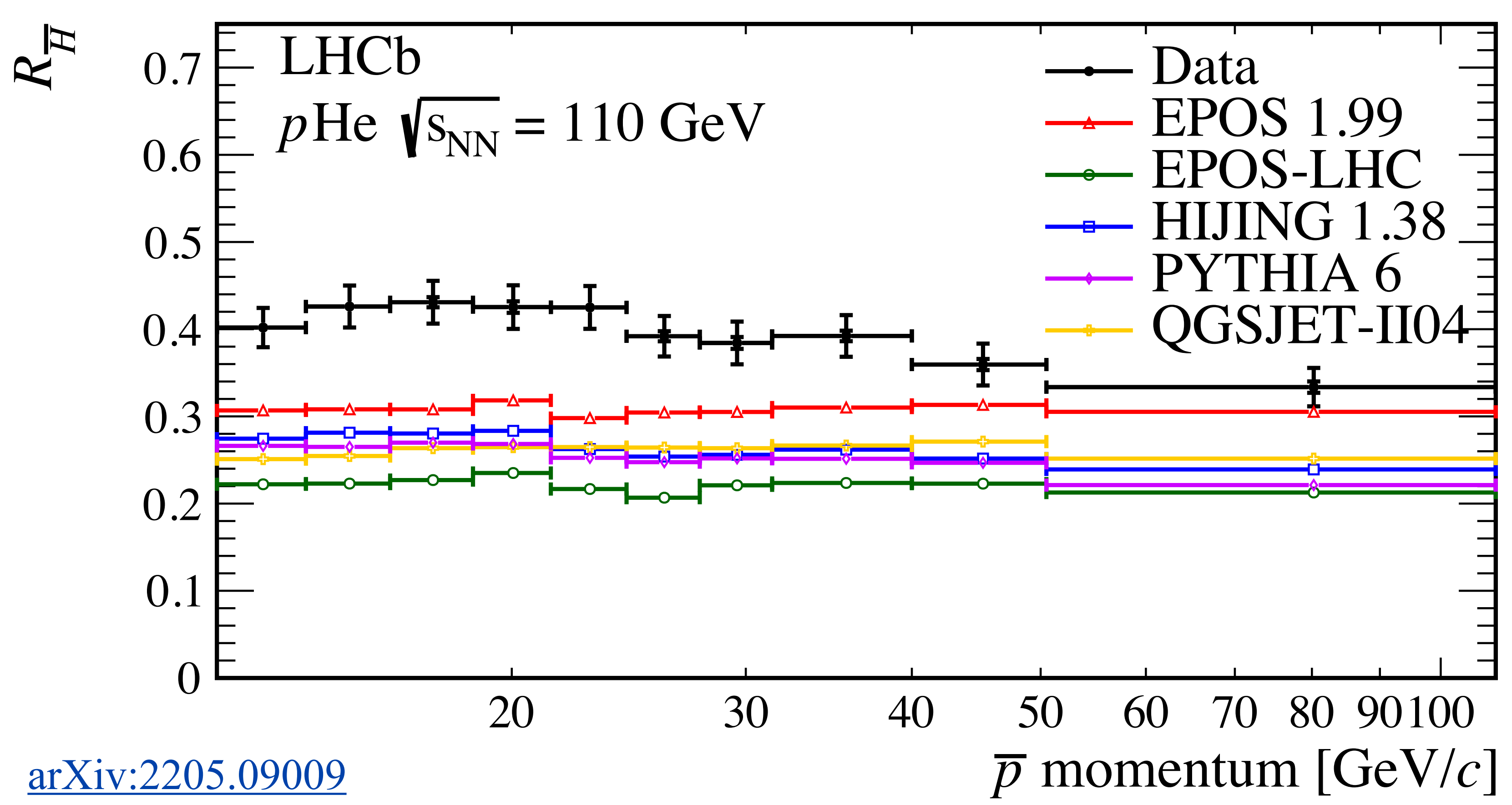
LHCB-FIGURE-2022-003

Dark sectors



LHCb-PUB-2022-012

$p\,He \to \bar{p}X$ with highest fixed-target $\sqrt{s}$



arXiv:2205.09009

Upgrade I

9 fb^{-1} — Upgrade I — Goal: 50 fb^{-1}

Run 1			LS1		Run 2				LS2				Run 3			LS3			Run 4			
2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032

Runs 1 and 2

40 MHz pp collisions → **L0** Hardware → 1 MHz Detector readout → **HLT** Software → 12.5 kHz (0.6 GB/s) Events on disk

Upgrade I

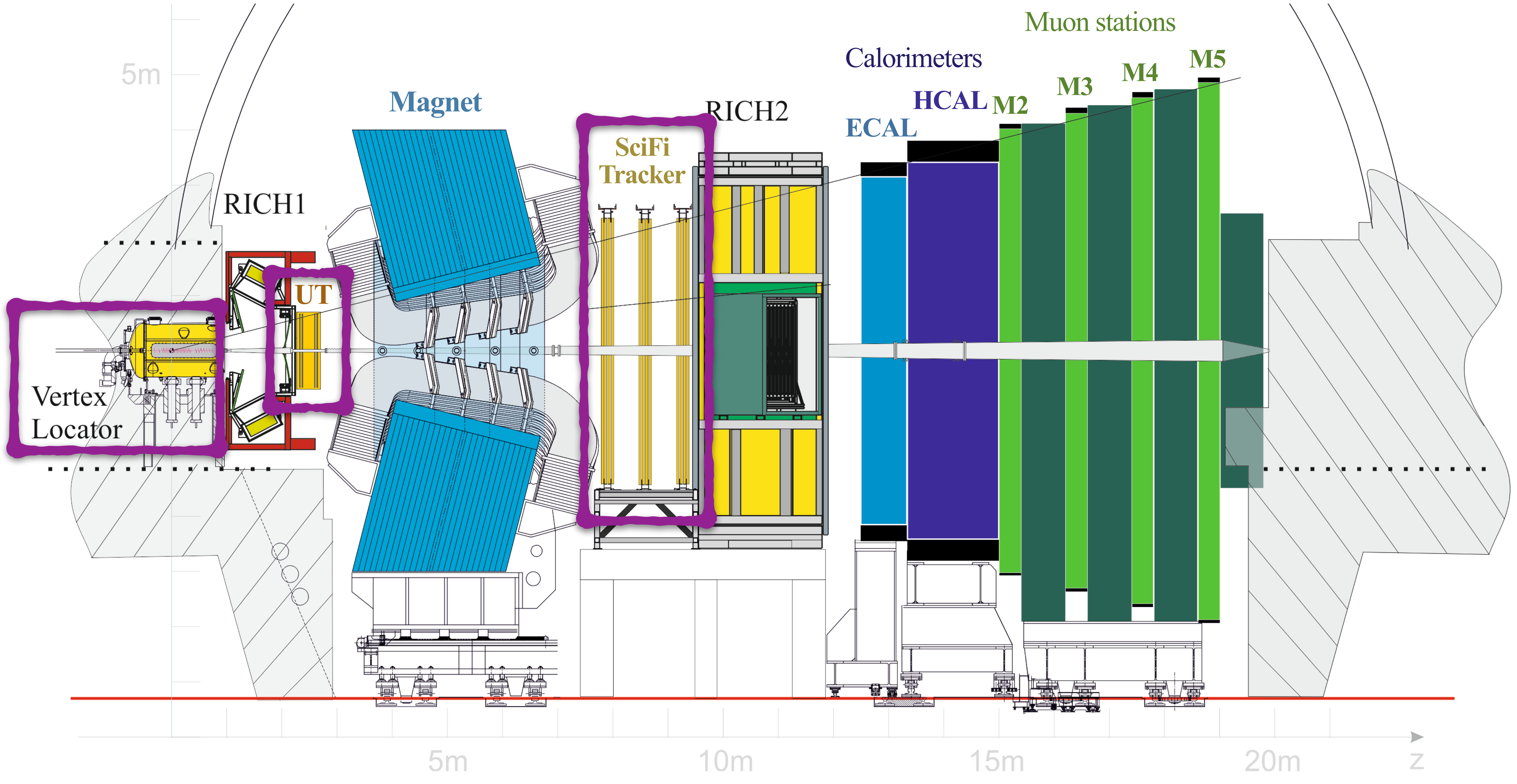
40 MHz pp collisions → Detector readout → **HLT** Software → $\mathcal{O}$(100 kHz) [$\mathcal{O}$(10 Gb/s)] Events on disk

All electronics upgraded to send every hit to **flexible software trigger (GPUs + CPUs)**

Real Time Analysis (RTA) of data with US leadership

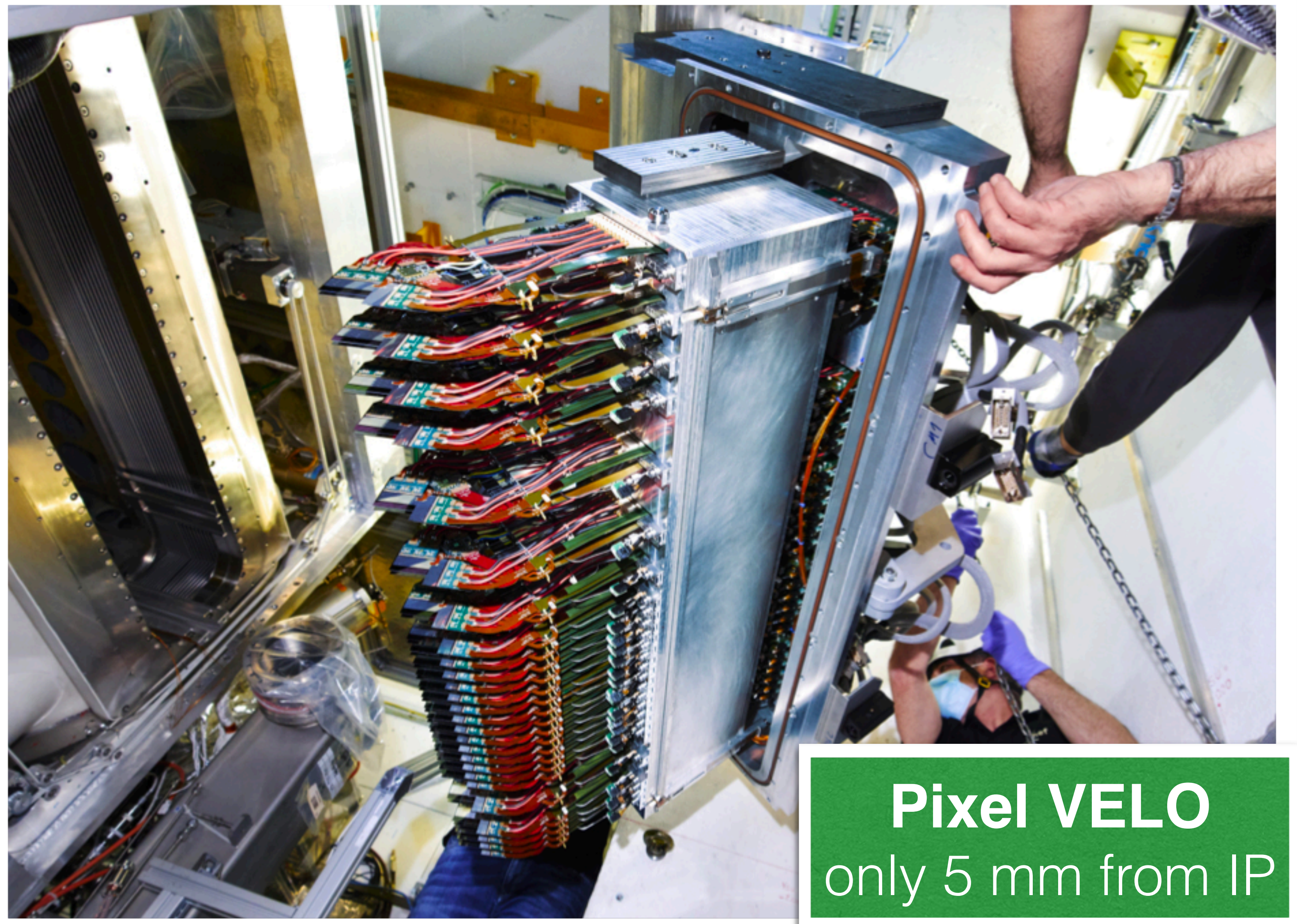
3 new trackers: Pixel VELO, UT, SciFi

Upstream Tracker (UT) with US leadership



CERN-LHCC-2012-007

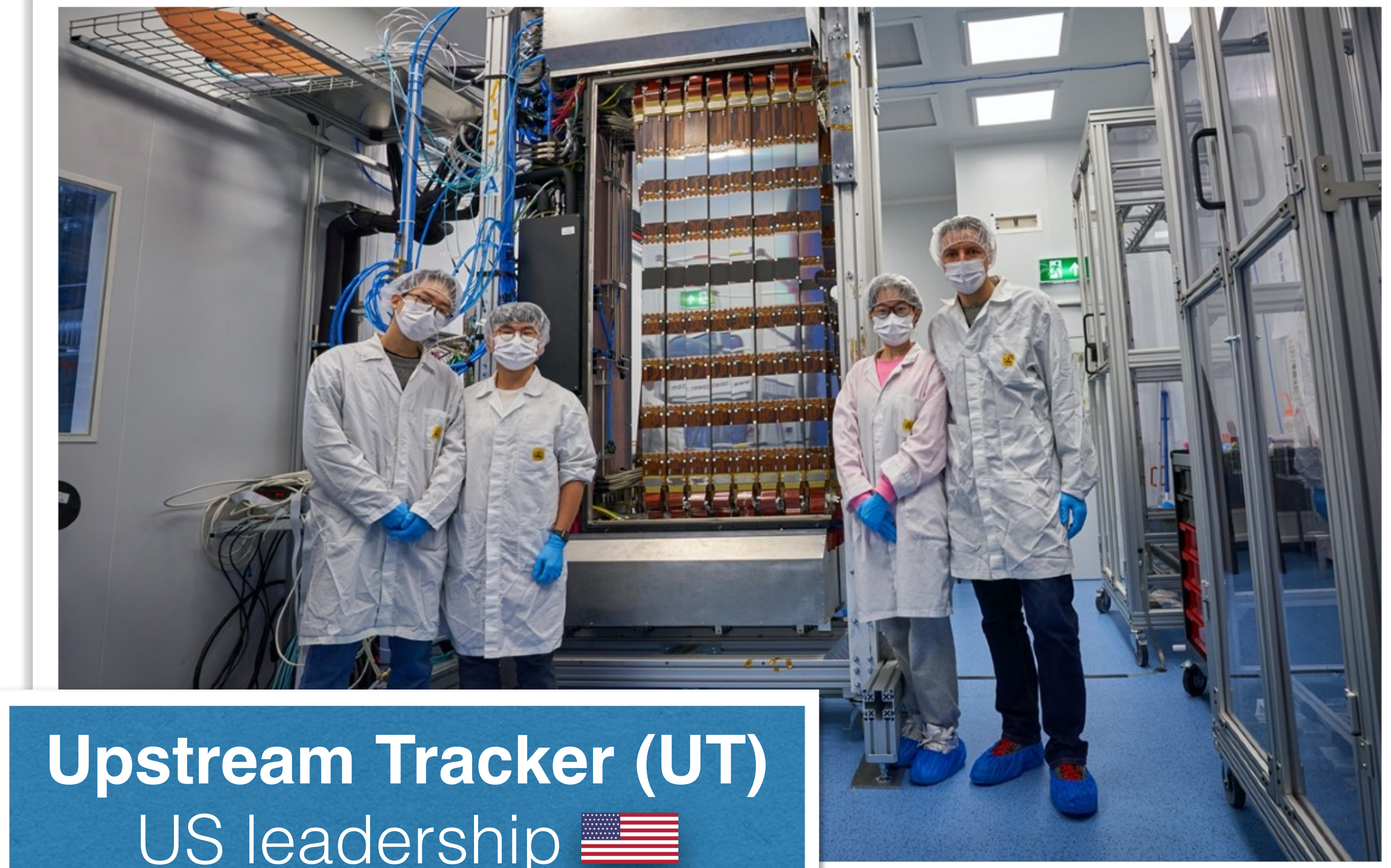
Upgrade I: installed



Pixel VELO
only 5 mm from IP

SciFi
11,000 km of scintillating fibers

PCIe40 cards with **FPGAs & GPUs** running HLT1



Upstream Tracker (UT)
US leadership 🇺🇸

Upstream Tracker (UT)
US leadership 🇺🇸

Major project installed successfully and **on budget**

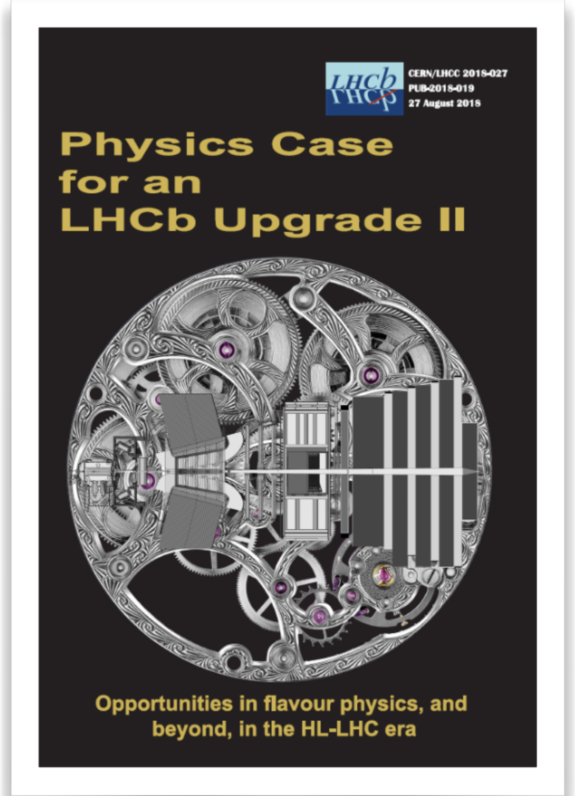
Exciting physics until 2032

Proposed Upgrade II

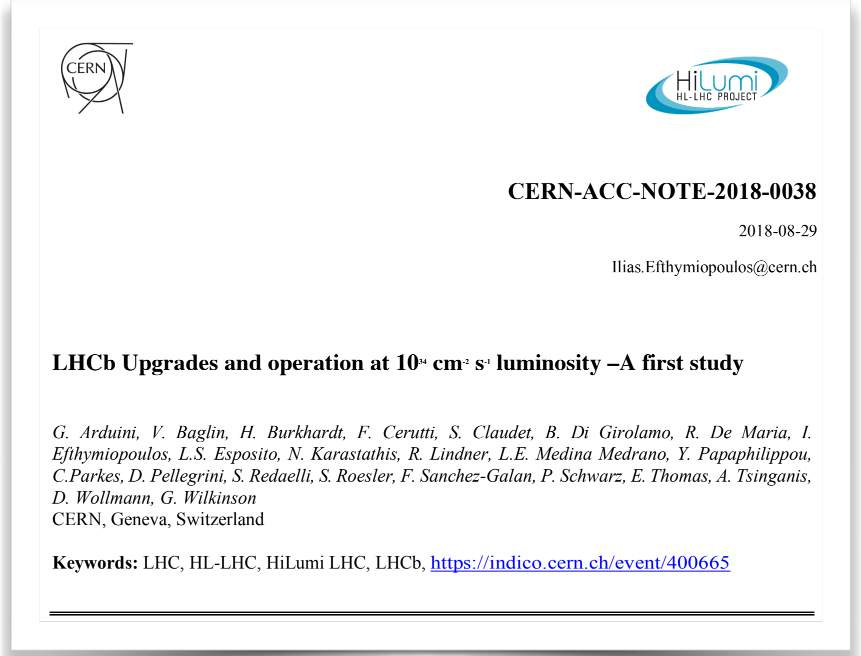
- **HL-LHC** program **until 2043**
- LHCb program limited by detector
  → **clear case for further upgrade**

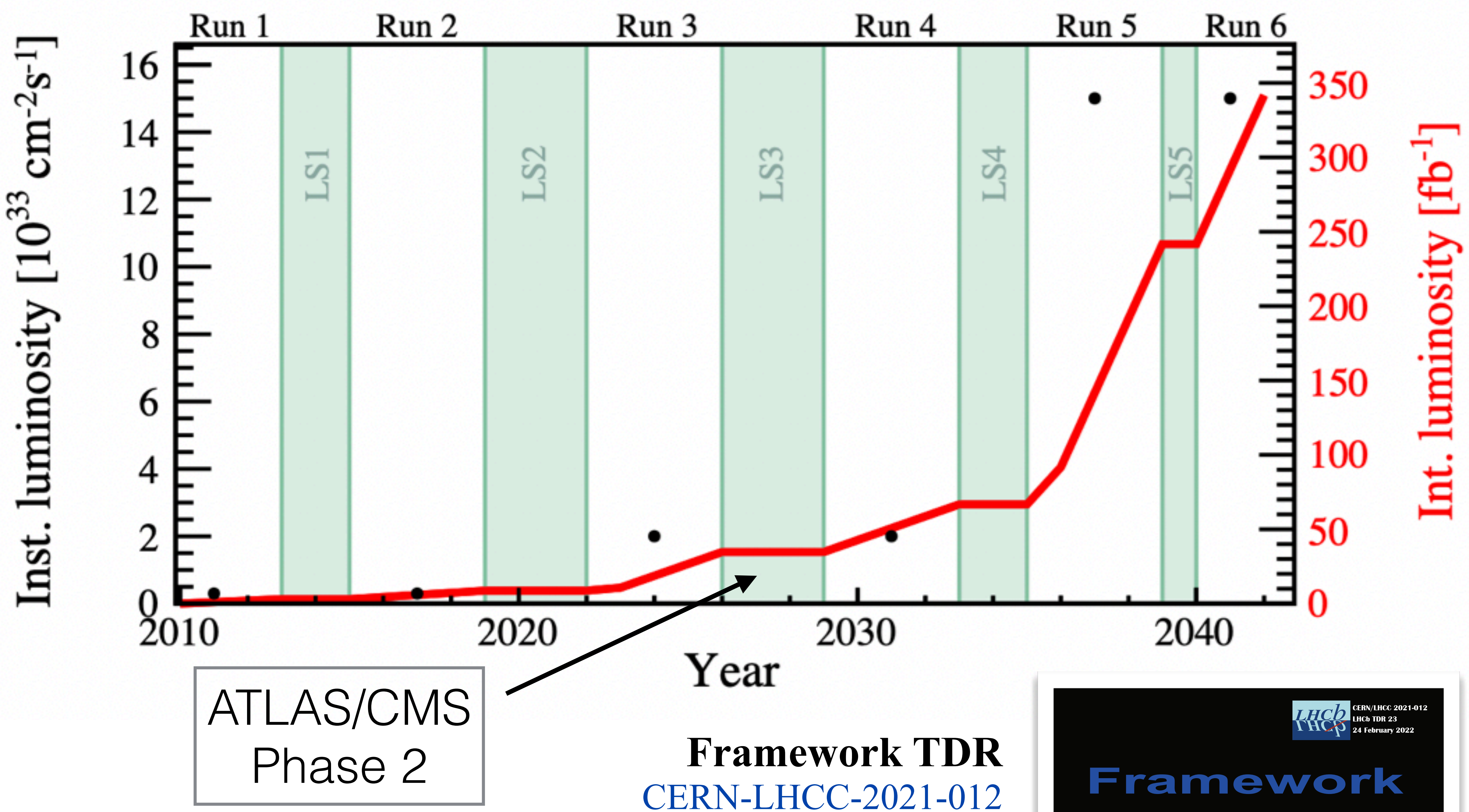
Expression of Interest
CERN-LHCC-2017-003

Physics case
CERN-LHCC-2018-027



Accelerator study
CERN-ACC-NOTE-2018-0038





Framework TDR
CERN-LHCC-2021-012
scoping document to be prepared, followed by sub-system TDRs

CERN Research Board 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."

European Strategy Update 2020

"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"

Upgrade II: very large b-hadron samples

Updated from Bernlochner, MFS, Robinson, Wormser, RMP, 94, 015003 (2022)

Experiment	*BABAR*	Belle	Belle II	LHCb Run 1	LHCb Run 2	LHCb Runs 3–4	LHCb Runs 5–6
Completion date	2008	2010	2035	2012	2018	2032	2043
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4)\times10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	424	711/121	$(50/4)\times10^3$	3	6	40	300
B^0 mesons [10^9]	0.47	0.77	50	100	350	2,500	19,000
B^+ mesons [10^9]	0.47	0.77	50	100	350	2,500	19,000
B_s mesons [10^9]	-	0.01	0.5	24	84	610	4,600
Λ_b baryons [10^9]	-	-	-	51	180	1,300	9,800
B_c mesons [10^9]	-	-	-	0.8	4.4	19	150

b-hadrons in acceptance

Upgrade I **Upgrade II**

Upgrade II would open an **era of unprecedented precision**

Complementing ATLAS/CMS in the search for a paradigm shifting **discovery at the HL-LHC**

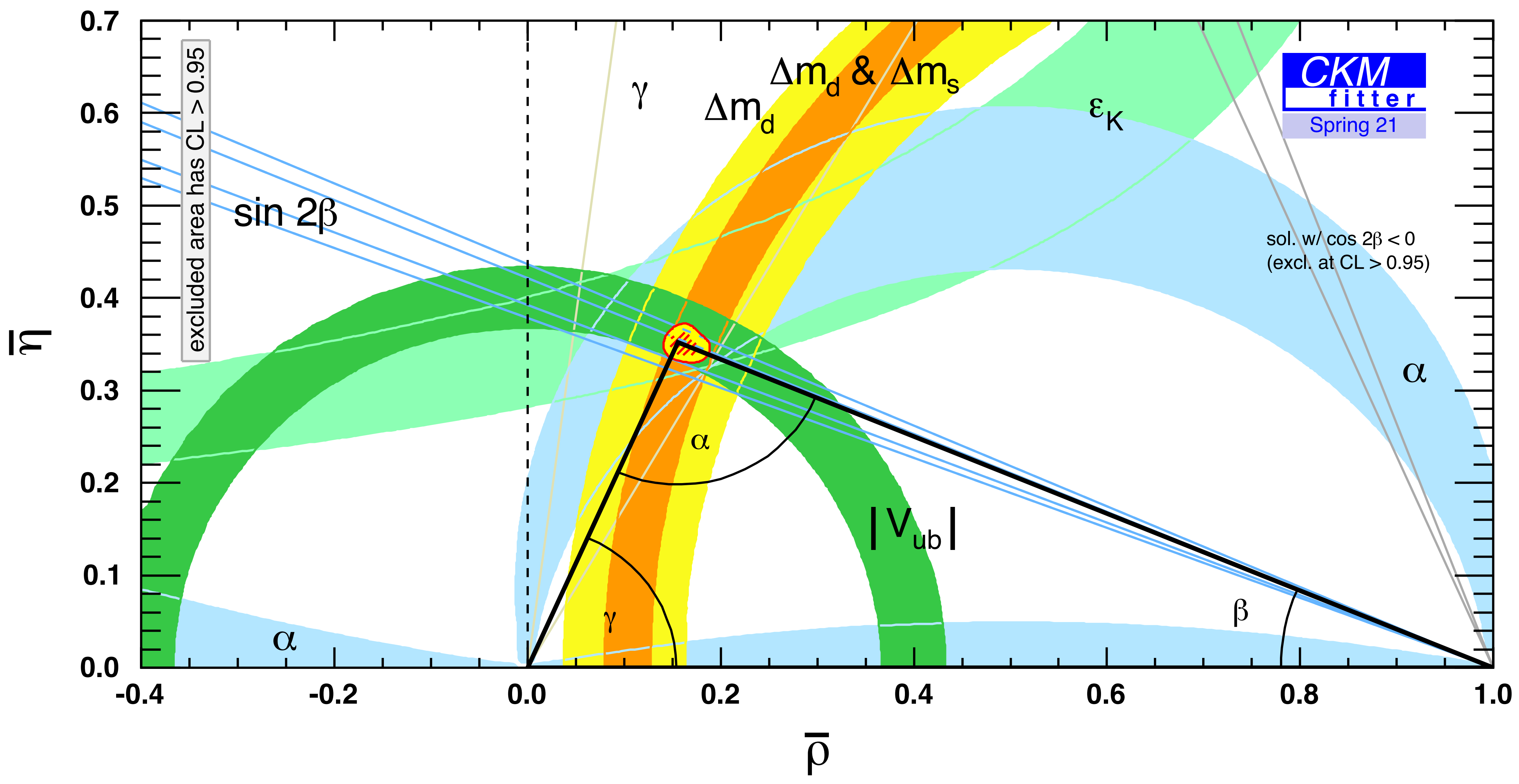
Unitarity Triangle

- LHCb Upgrade II will **test the CKM paradigm** with **unprecedented accuracy**
  - ➡ Key improvements also needed from theory, lattice

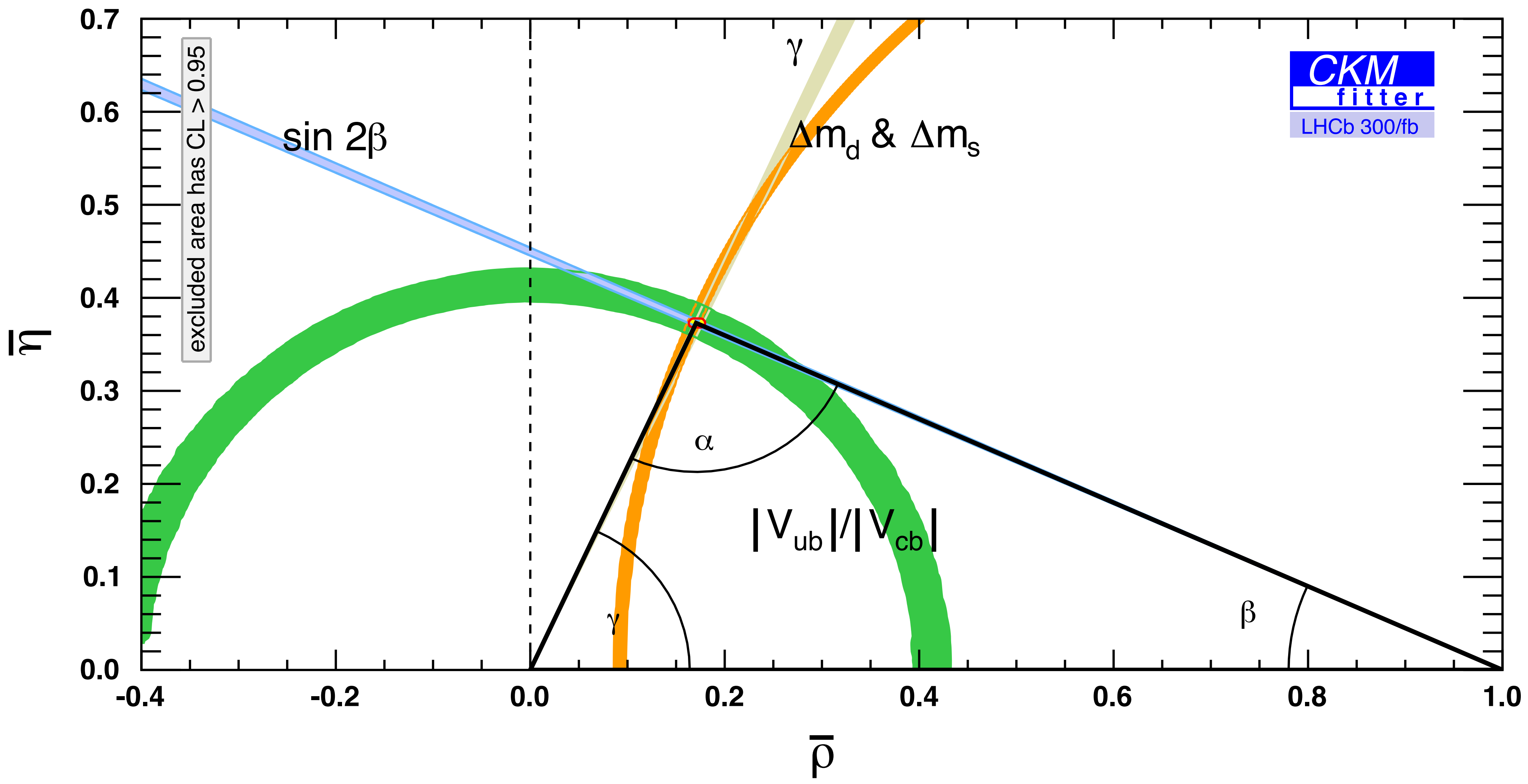
Observable	LHCb 2025	Belle II	Upgrade II
γ, with $B_s^0 \to D_s^+ K^-$	4°	–	1°
γ, all modes	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	39 mrad	–	11 mrad
$a_{\rm sl}^s$	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	3%	1%	1%

CERN-LHCC-2018-027

World average 2021



LHCb-only after Upgrade II

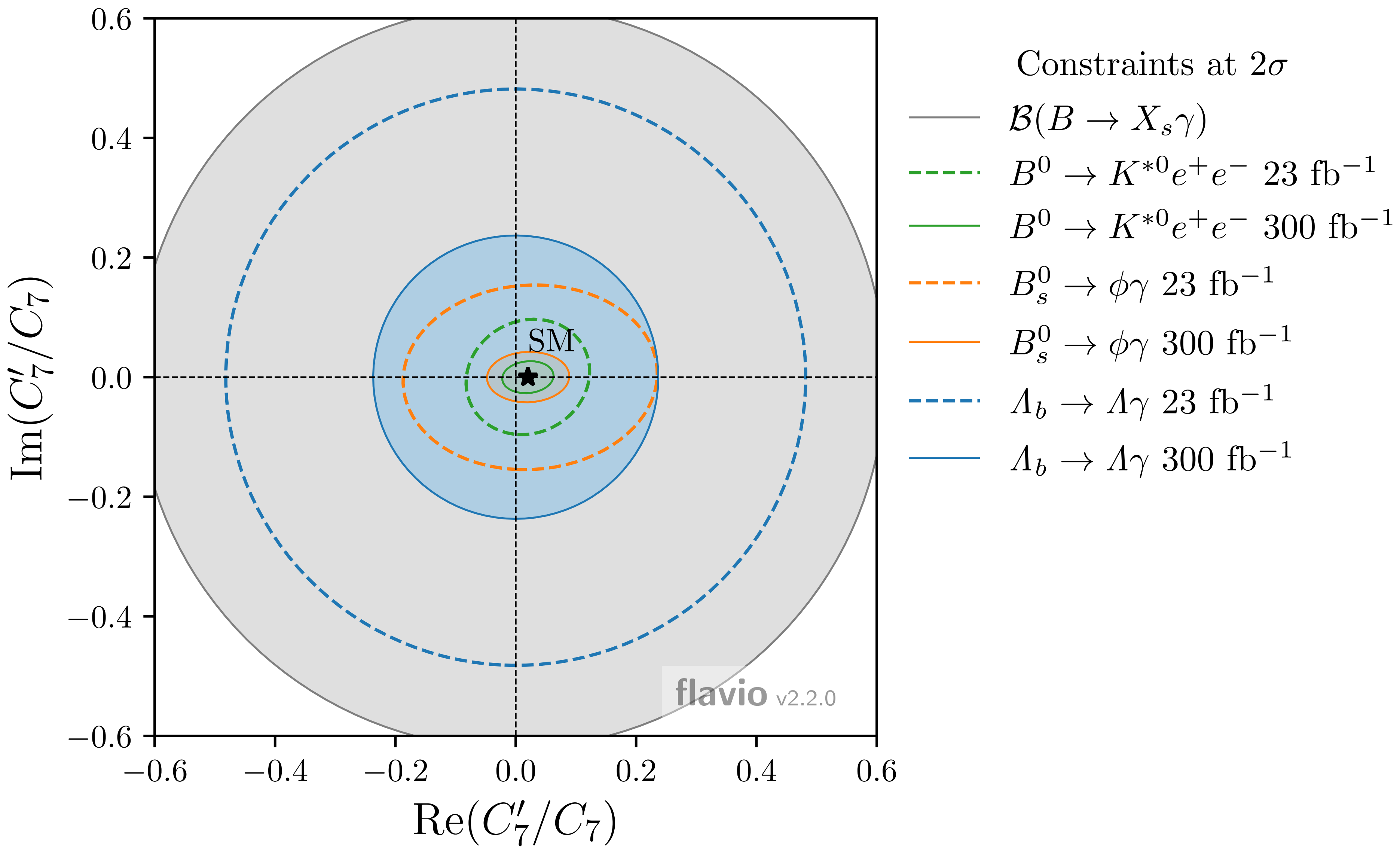


Access to extremely rare processes

- **Access to $C_7^{(')}$**

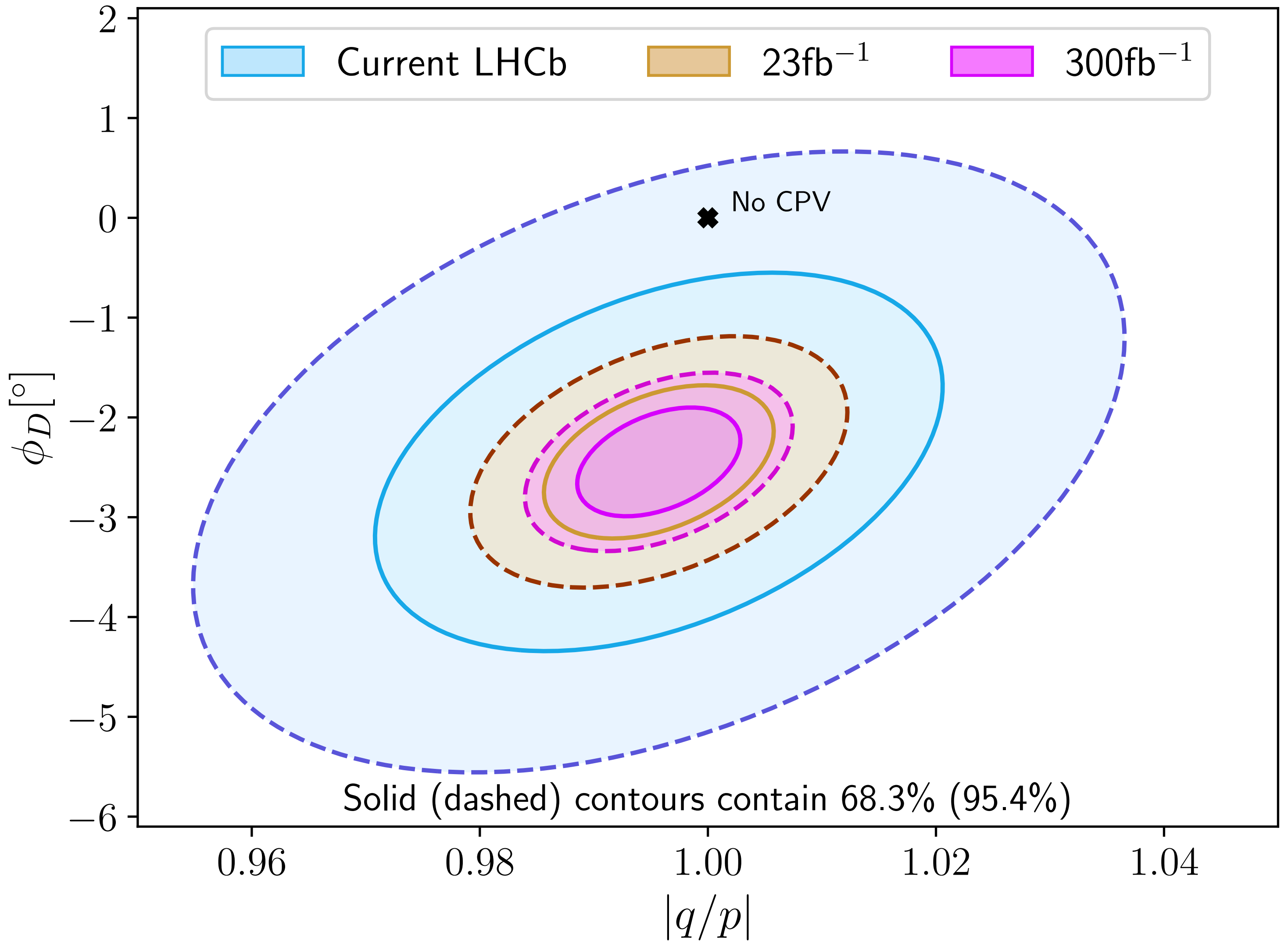
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu} \qquad \mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$$

  - ➡ Very sensitive to new physics
  - ➡ NP could cause non-zero value of C_7'



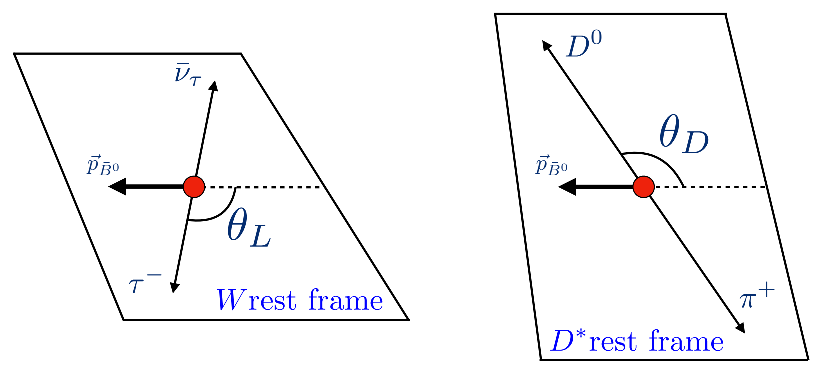
Achievable sensitivity will depend strongly on the **performance of the LHCb Upgrade II ECAL** in γ/e reco

- **CP violation** in **charm mixing**
  - ➡ LHCb Upgrade II is **only planned facility with realistic possibility** to observe SM CPV in $D^0 - \bar{D}^0$ mixing

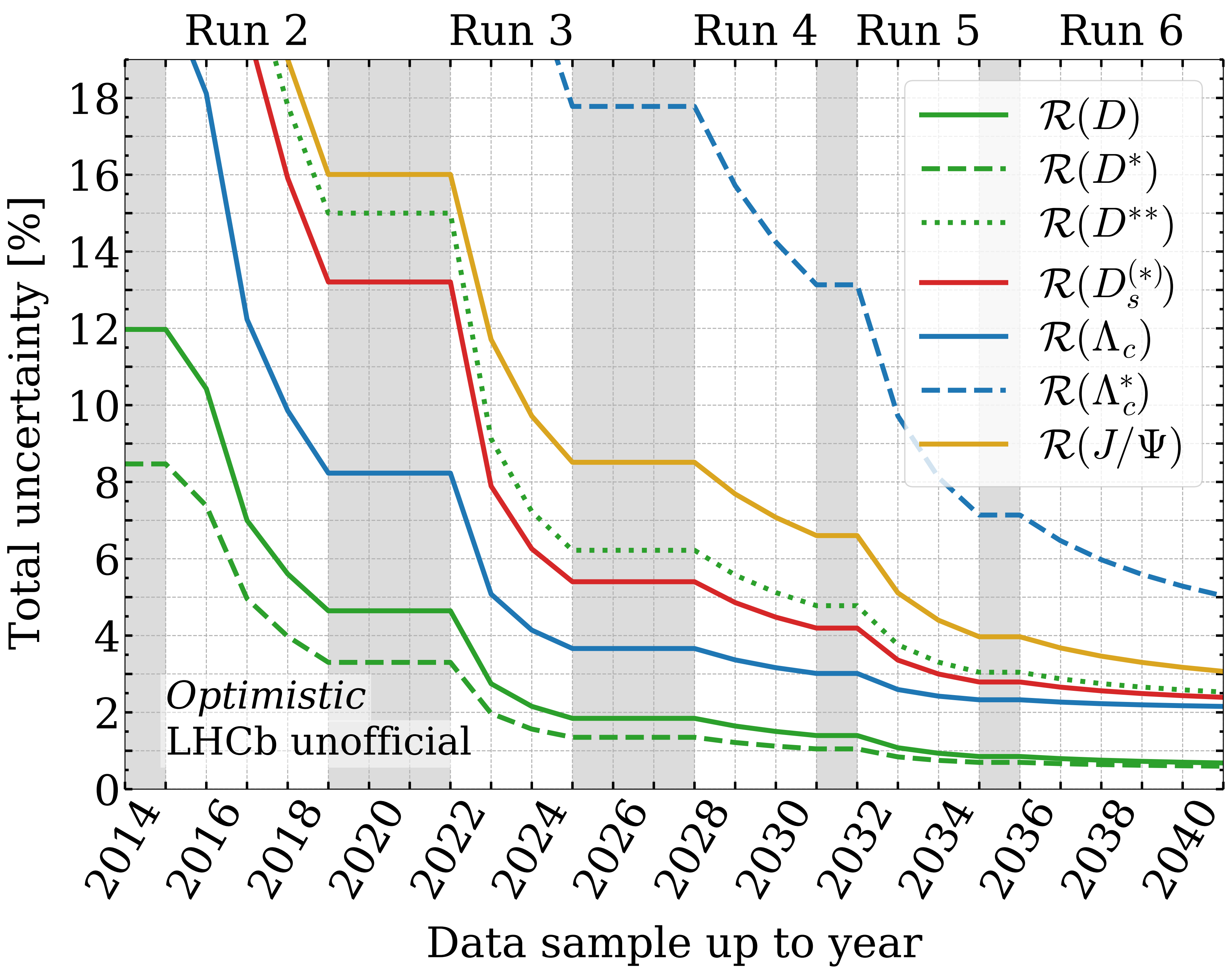


Characterizing unexpected effects

- Ability to **characterize present/future hints** of **New Physics**
  - ➡ Thanks to powerful general purpose detector and flexible data taking



- Eg, **if $b \to c\tau\nu$ anomalies were to be confirmed**
  - ➡ Upgrade II will allow **precision measurements beyond $\mathcal{R}(D^{(*)})$**

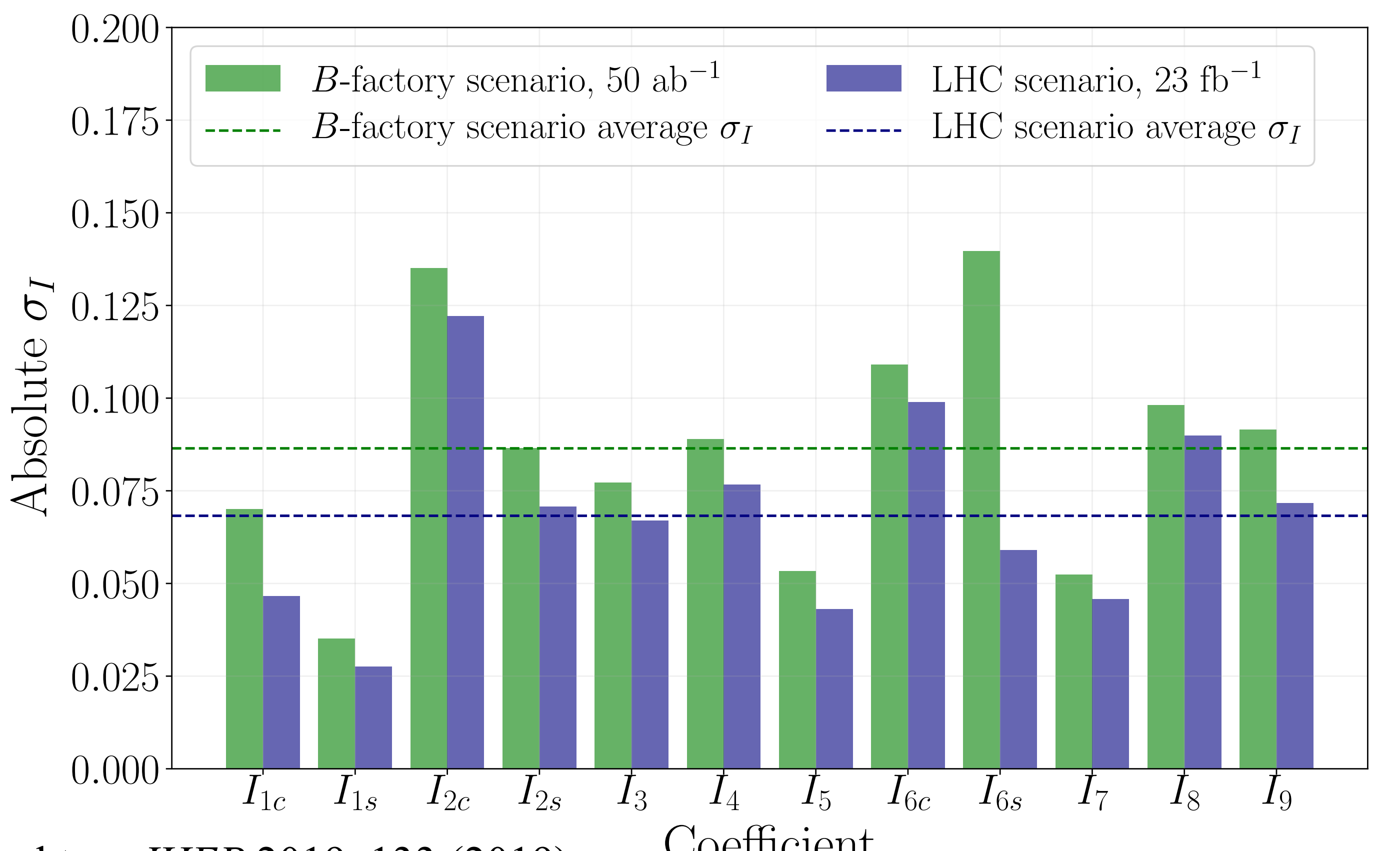


Bernlochner, MFS, Robinson, Wormser, RMP, 94, 015003 (2022)

$$\mathcal{R}(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell \nu_\ell)}$$

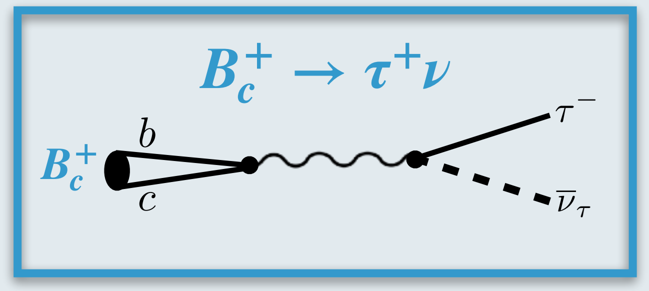
$\mathcal{R}(J/\Psi)$, $\mathcal{R}(D_s^{(*)})$, and $\mathcal{R}(\Lambda_c^{(*)})$ independent checks

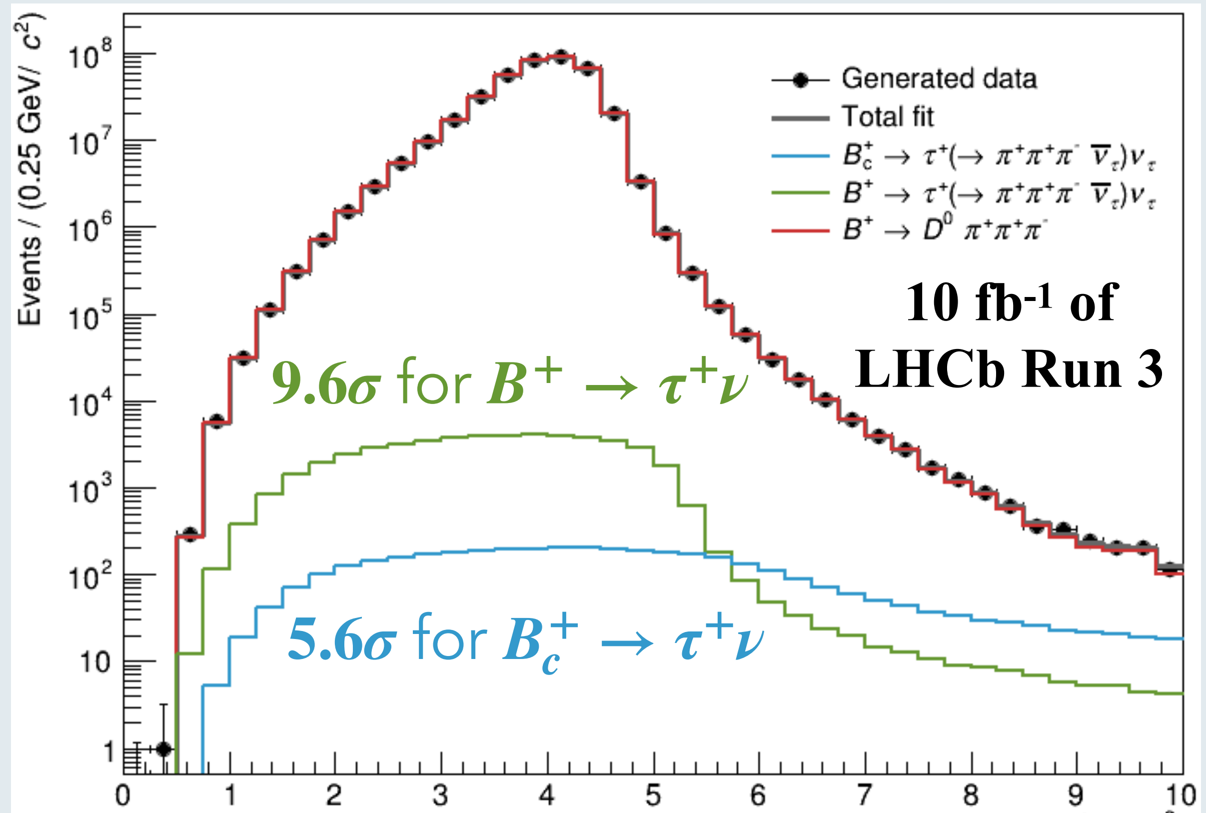
Access to all angular coefficients



Hill, John, Ke, Poluektov, *JHEP* 2019, 133 (2019)

Perhaps even $B_c^+ \to \tau^+\nu$, theoretically very clean



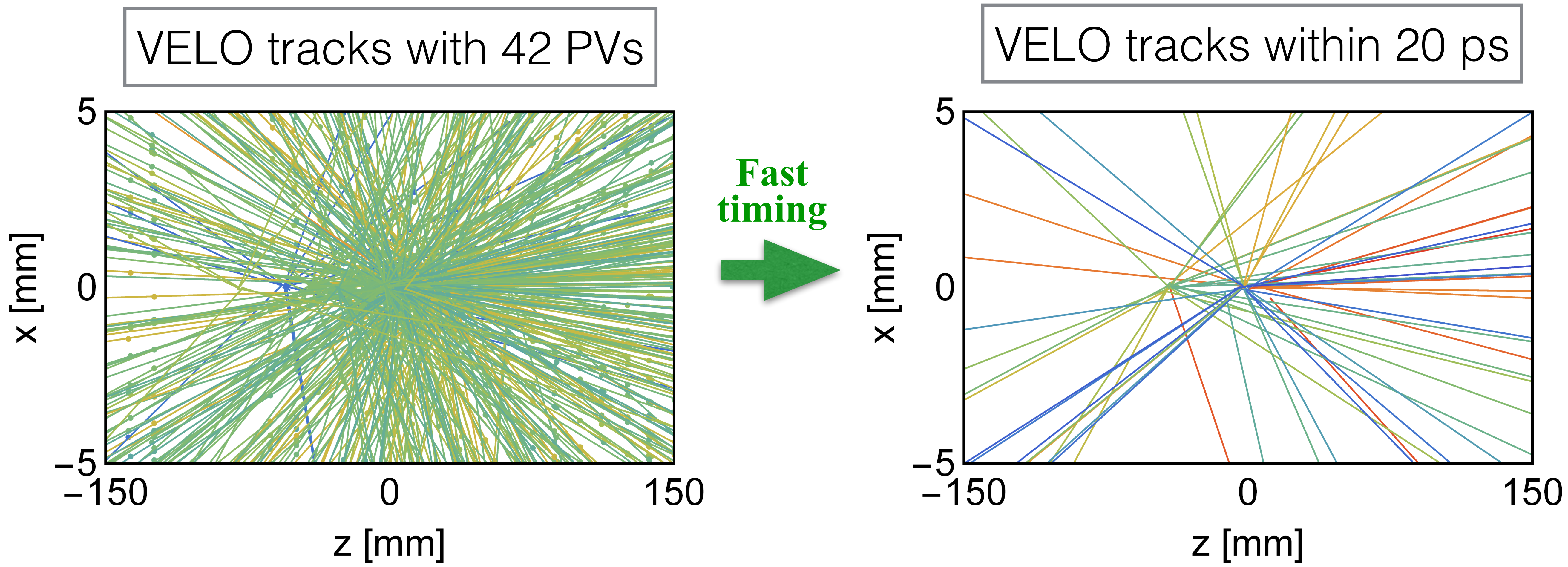


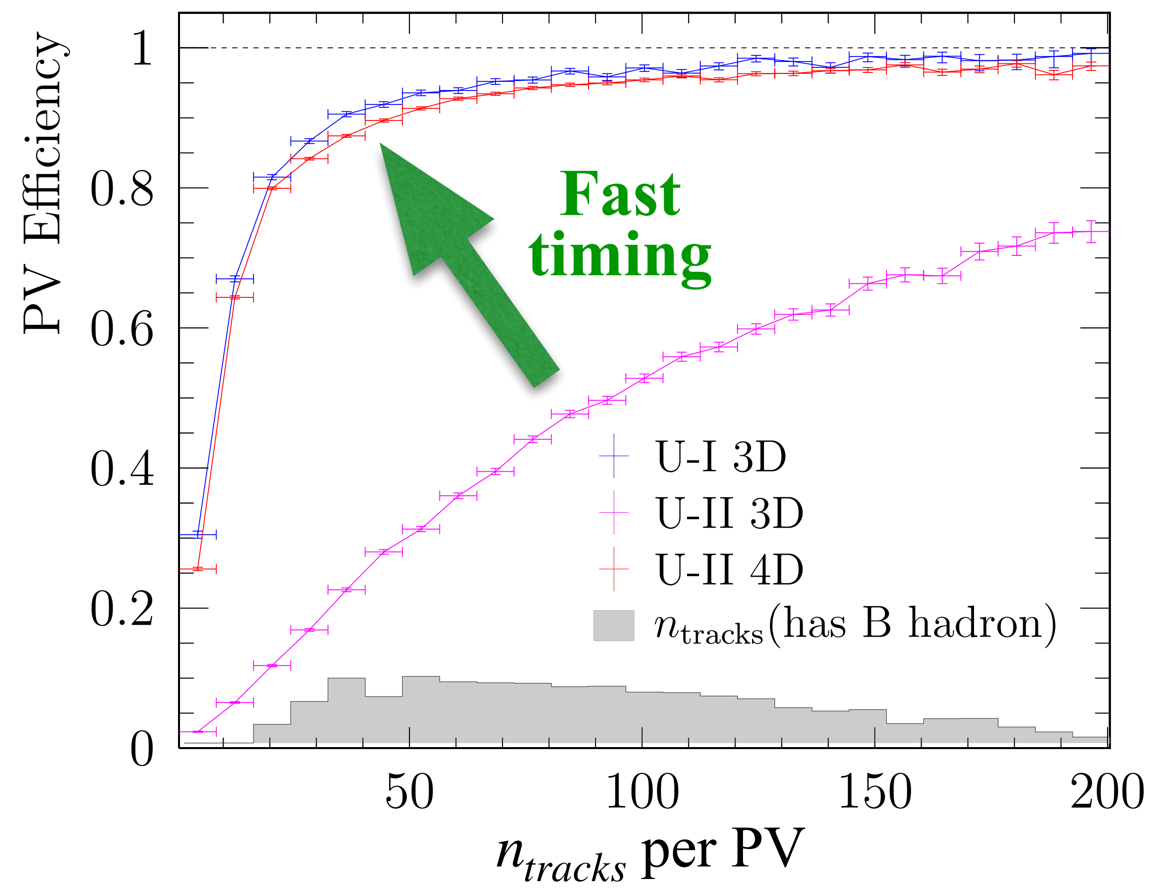
J. de Jong, Master thesis University of Groningen (2022)

Detector challenge and 4D tracking

Goal
Same detector performance as in Run 3

Challenge
Pile-up increases from 6 PVs to **42 PVs**!



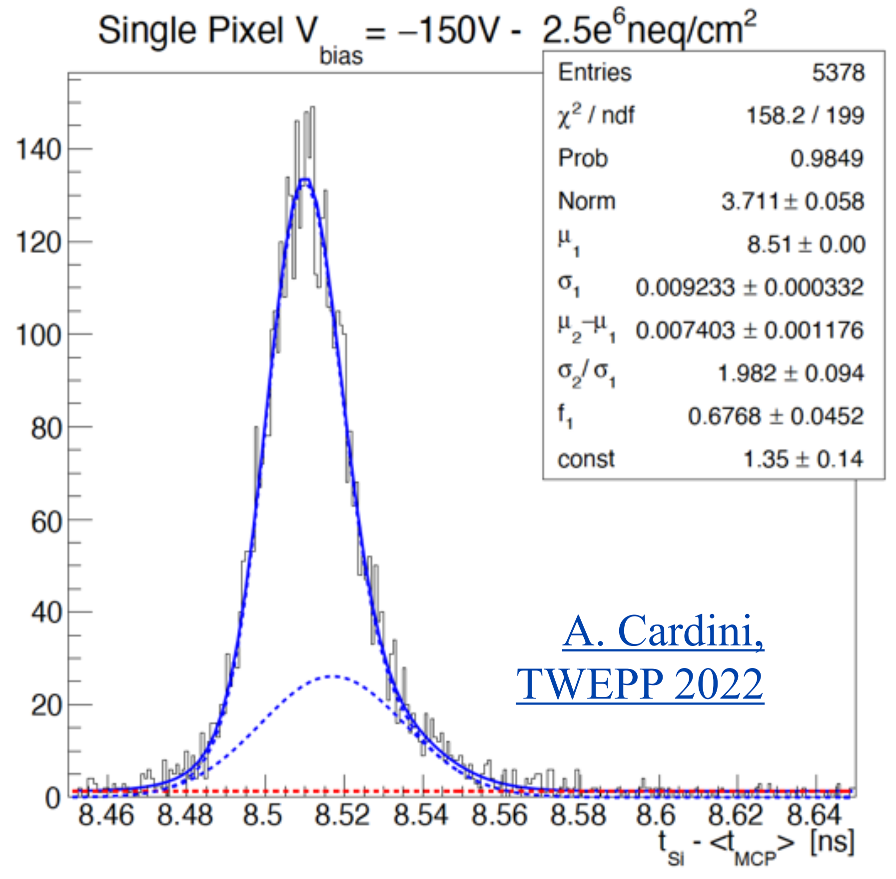


CERN-LHCC-2021-012

- Will employ **innovative technologies** with **key ingredients**
  - ➡ **Granularity**
  - ➡ **Fast timing** (few tens of ps)
  - ➡ **Radiation hardness**

VELO: ~**55 μm pitch**, ~**50 ps** per **hit**, fluence of **6×10^{16} n_{eq}/cm^2**

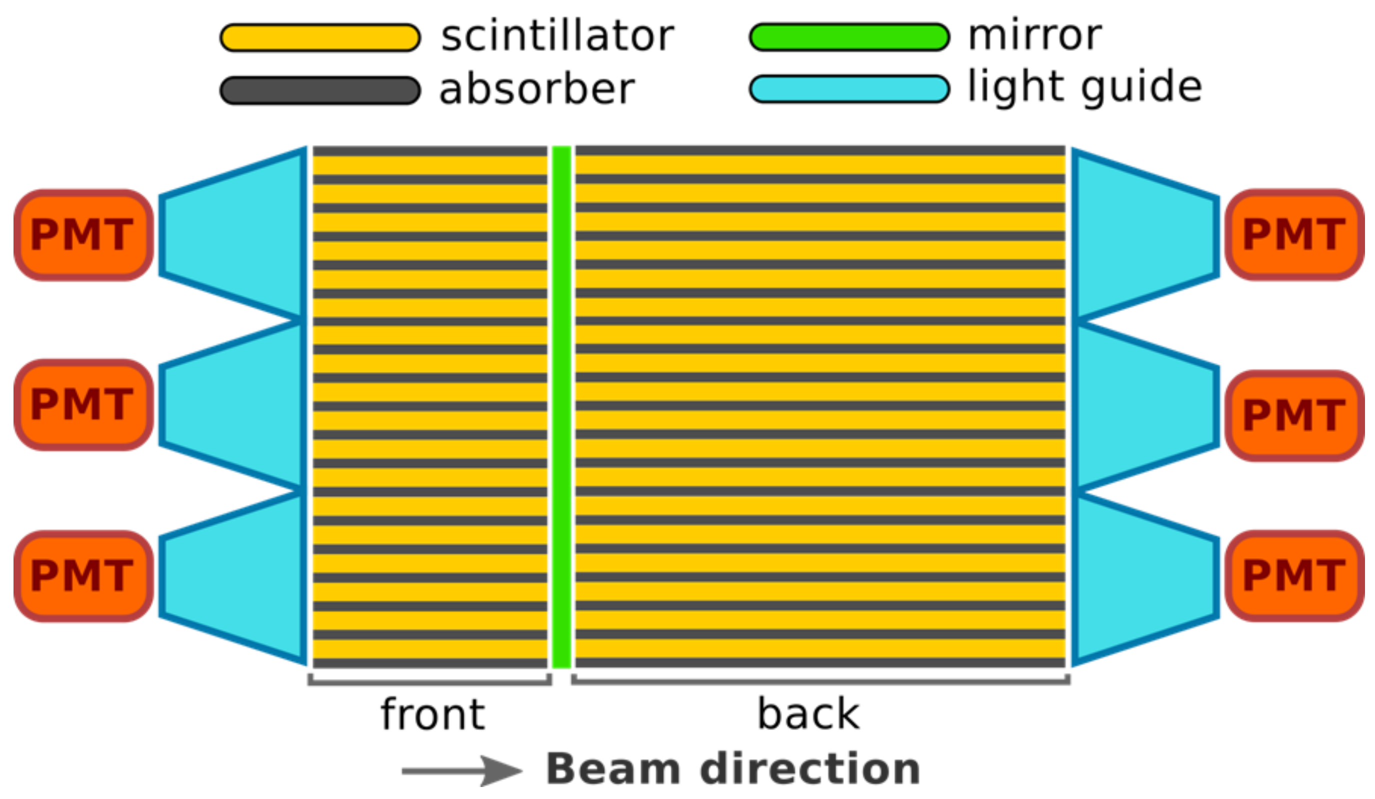
TimeSPOT, 3D silicon trench pixels achieve **σ_{eff} = 10.3 ps** after **2.5×10^{16} n_{eq}/cm^2**



A. Cardini, TWEPP 2022

5D calorimetry (x, y, z, E, t)

- Maintain $\frac{\sigma(E)}{E} \sim \frac{10\,\%}{\sqrt{E}} \oplus 1\,\%$
- **Radiation** up to **1 MGy**
- Increase central **granularity**
  - ➡ 4×4 cm² → 1.5×1.5 cm²
- Mitigate pile-up with **~20 ps timing**

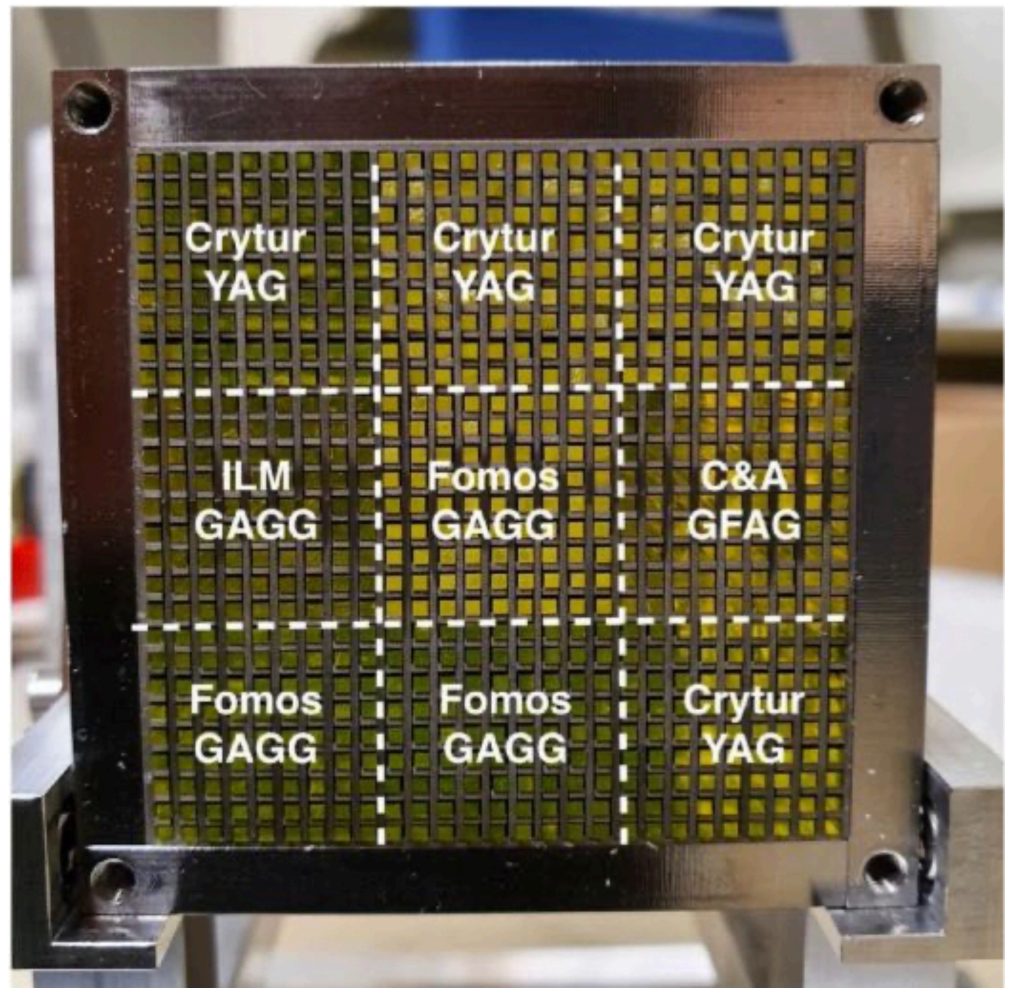


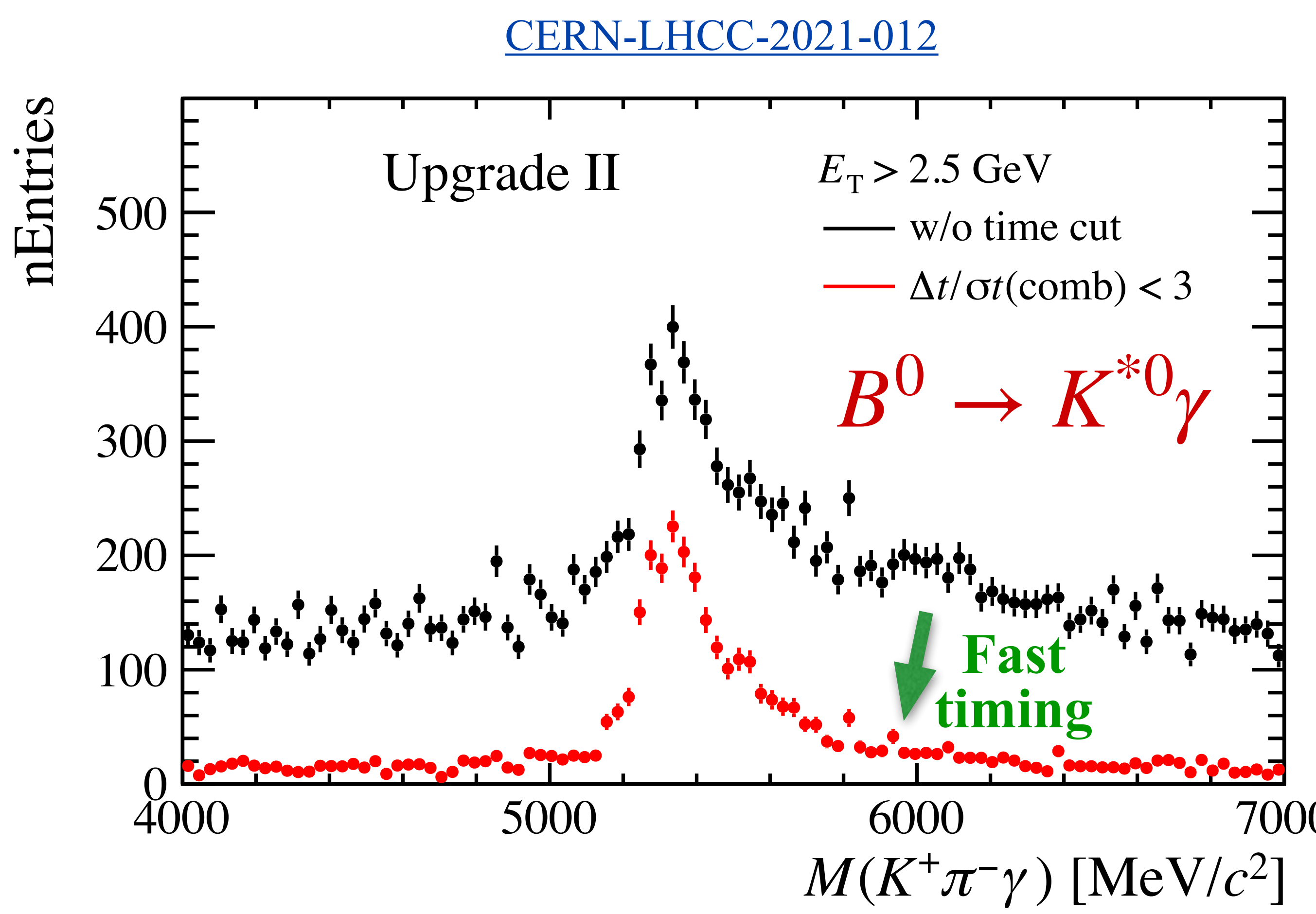
Extensive R&D remaining
Radiation hardness, PMT characterization, timing/imaging layer, optimization

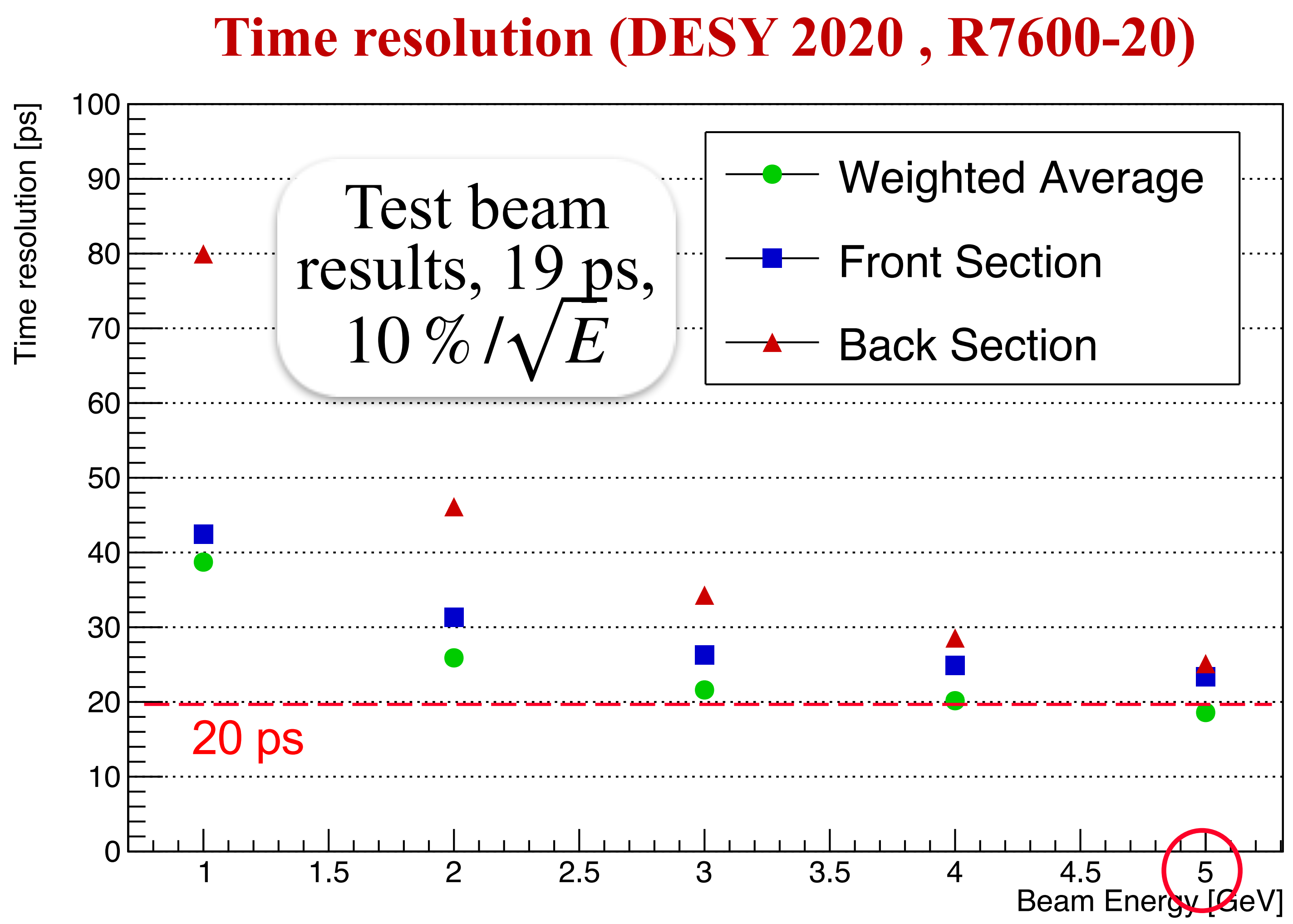
US involvement

Considering **W/Pb + GAGG crystal fibers** (central) and **current Shashlik** (outer)

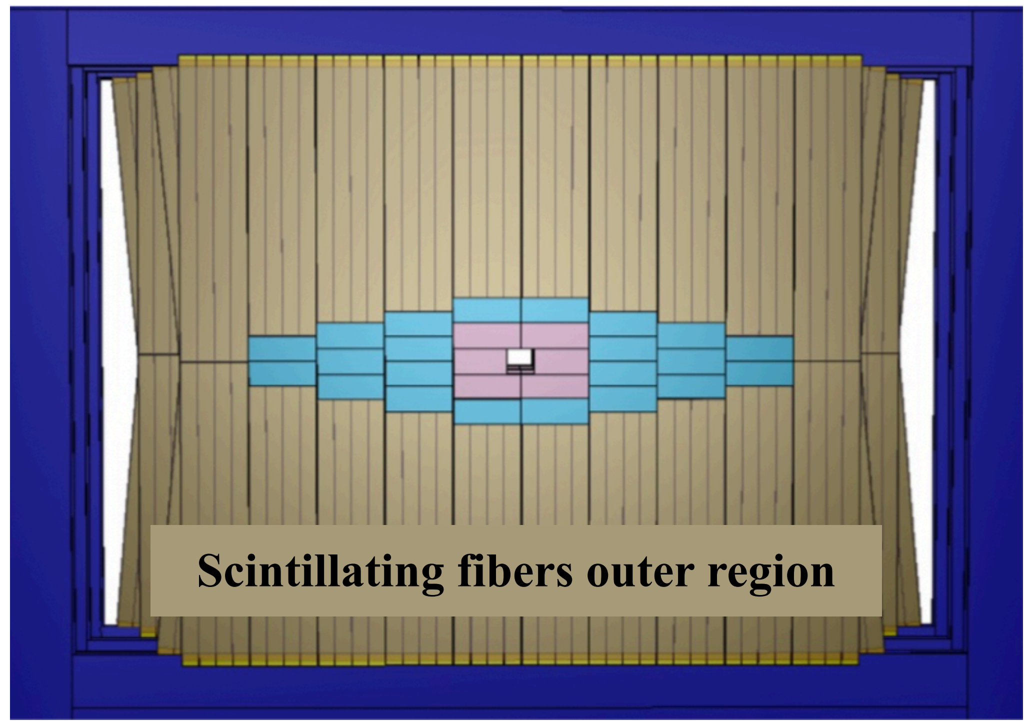
Timing/imaging layer could help deal with **frequent overlaps**





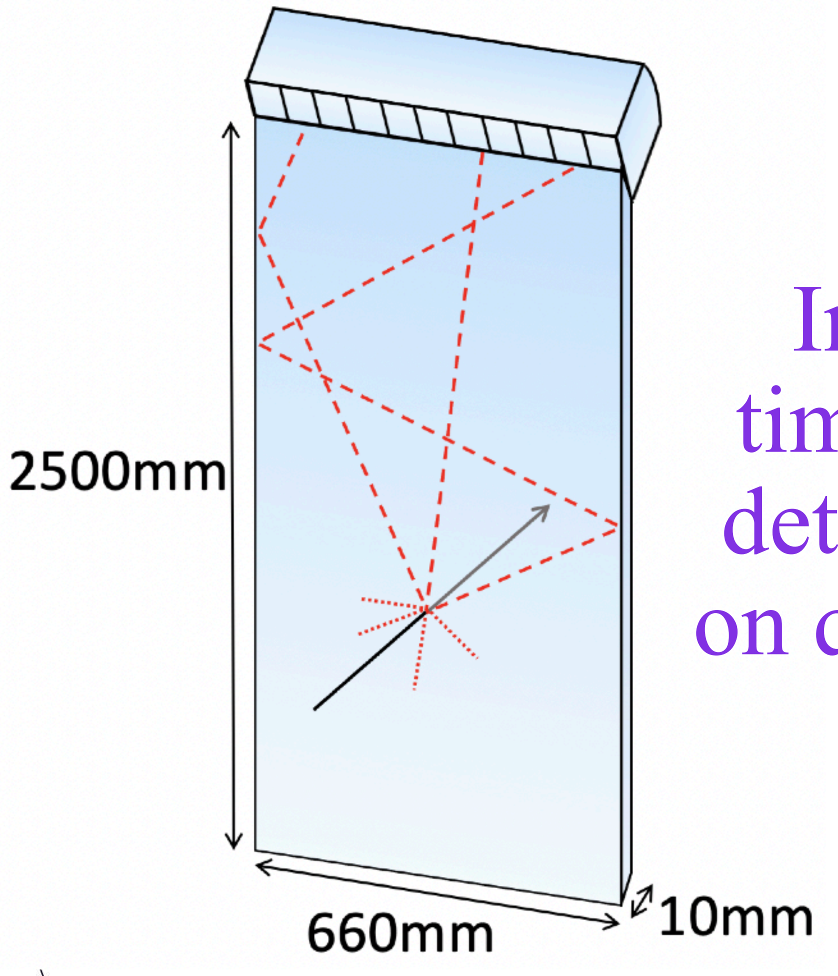


Other technologies



Rad-hard DMAPs

Monolithic Active Pixel sensors for UT/ Mighty Tracker, first time at LHC
Low-cost commercial process, low material budget



Innovative time-of-flight detector based on quartz plates

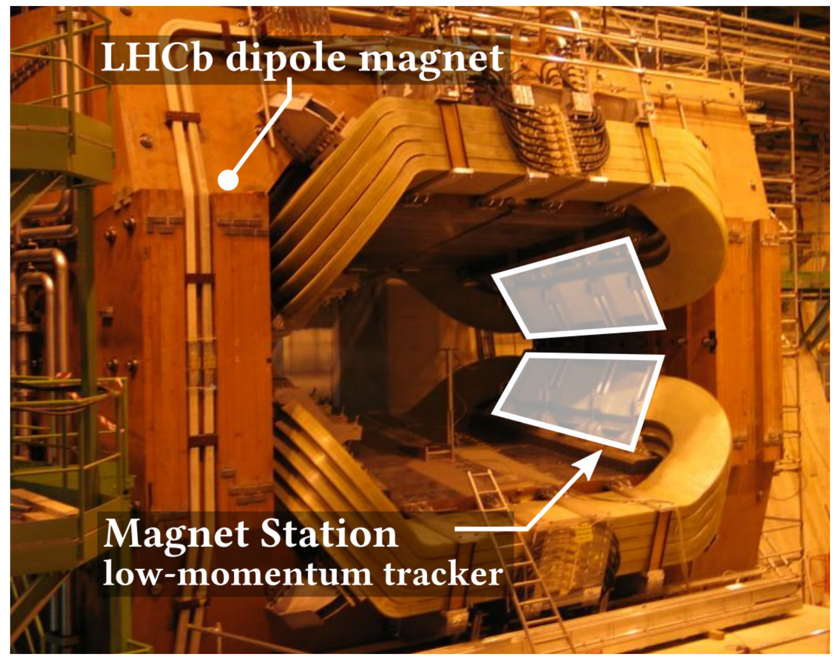
TORCH

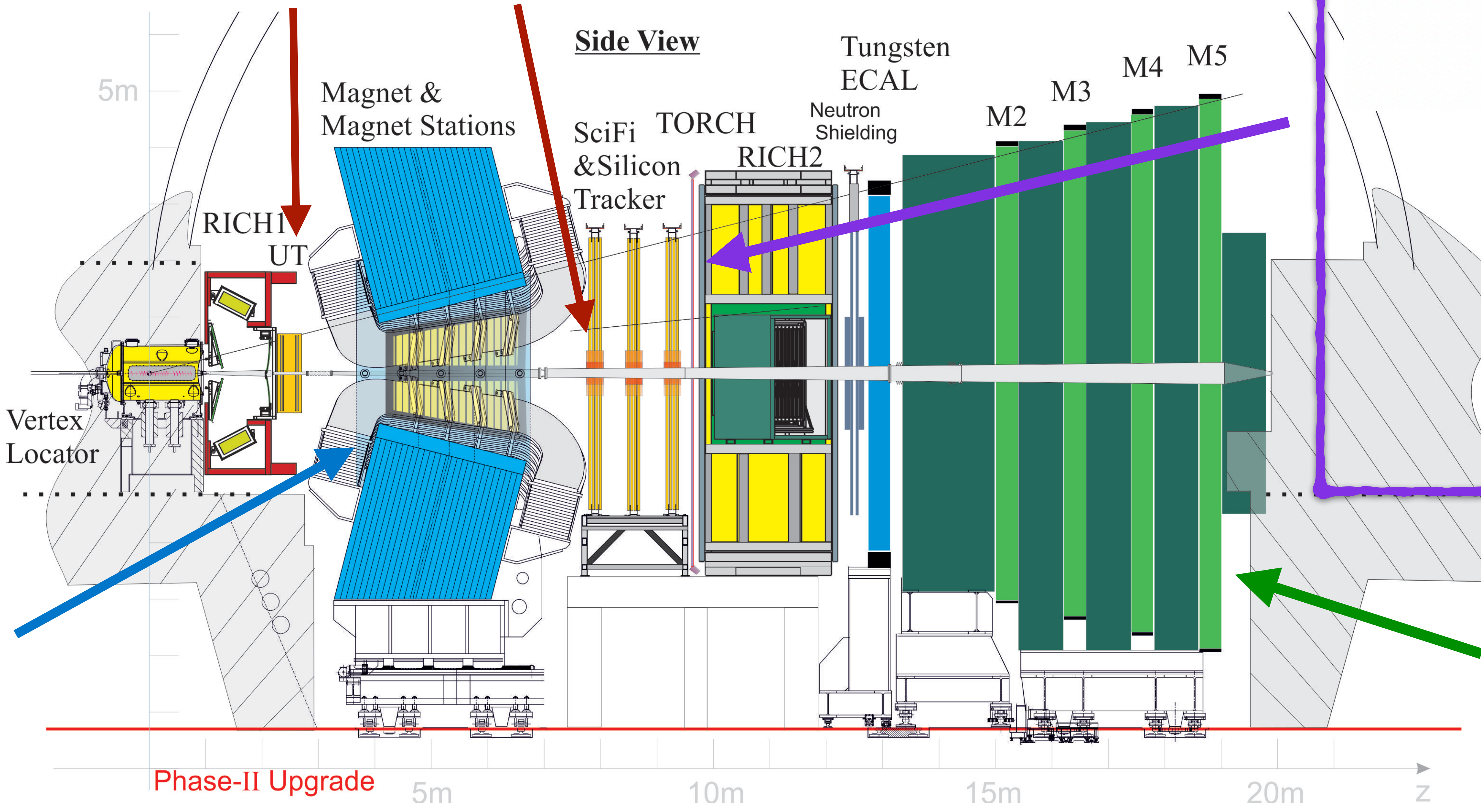
PID for **p < 10-20 GeV** with **15 ps timing** (70 ps per photon for ~30 photons)

MAGNET STATIONS (LS3)

New **scintillating fiber stations** on the **inside of dipole magnet**
Improved low-p_T tracking

US involvement

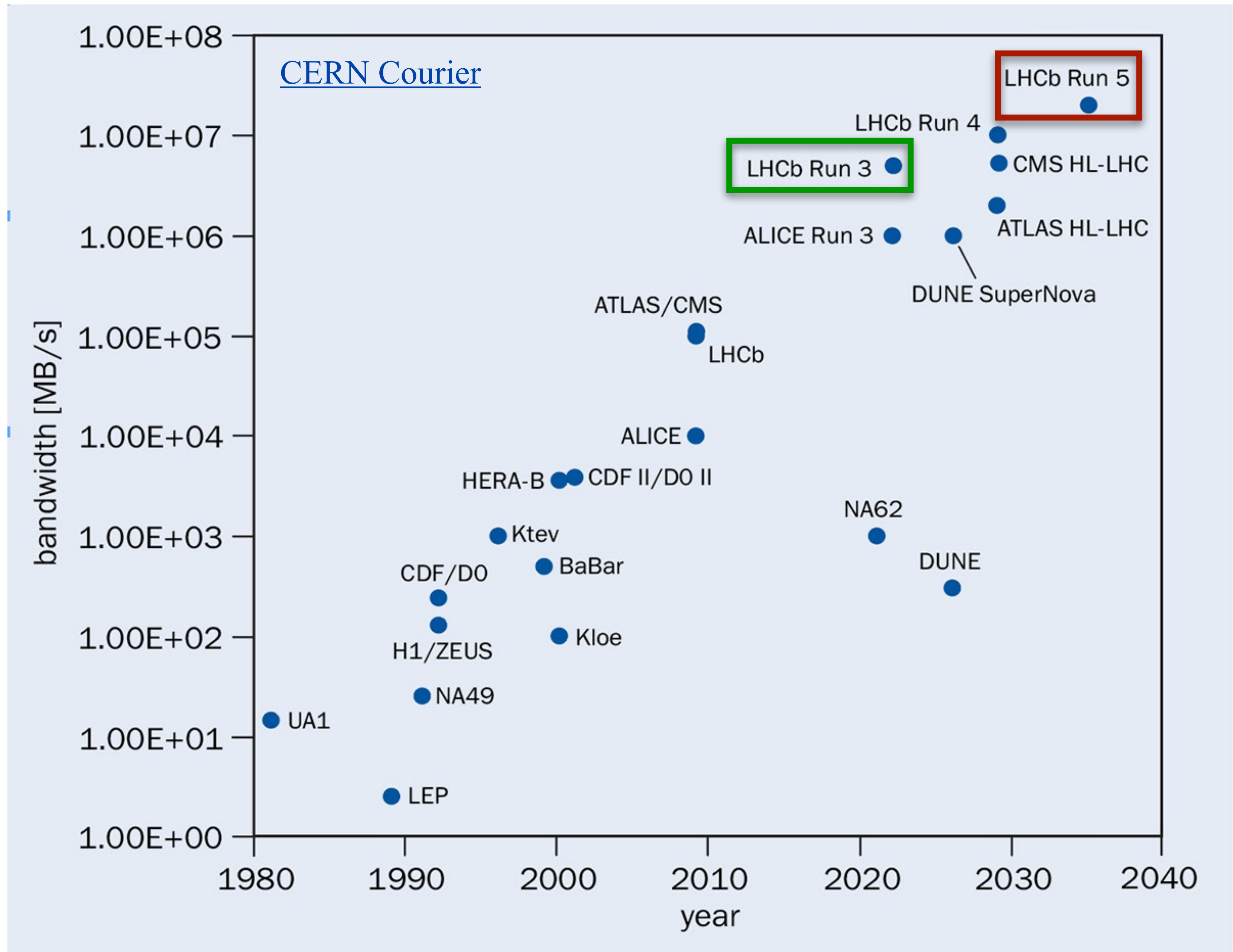




MUON

μ-RWELL to handle high central rates, MWPCs outside

Trigger & Offline computing



Model assumptions		
	Upgrade I	Upgrade II
Peak L ($cm^{-2}s^{-1}$)	2×10^{33}	1.5×10^{34}
Yearly integrated luminosity (fb^{-1})	10	50
Logical bandwidth to tape (GB/s)	10	50
Logical bandwidth to disk (GB/s)	3.5	17.5
Running time (s)	5×10^6	
Trigger rate fraction (%)	26 / 68 / 6 Full / Turbo / TurCal	
Ratio Turbo/Full event size	16.7%	
Ratio full/fast/param. MC	40:40:20	
CPU work per event full/fast/param. MC (HS06.s)	1200 / 400 / 20	
Number of simulated events	4.8×10^9 / fb^{-1}/year	
Data replicas on tape	2 (1 for derived data)	
Data replicas on disk	2 (Turbo); 3 (Full, TurCal)	
MC replicas on tape	1 (MDST)	
MC replicas on disk	0.3 (MDST, 30% of the total dataset)	

- **Novel trigger** system for **Upgrade I**
  - **Fully software** trigger (RTA)
  - **HLT1** based on **GPUs**
- Similar for **Upgrade II**… but at **200Tb/s**!
  - HLT2 not feasible on CPUs
    - Will require GPUs or FPGAs

US involvement

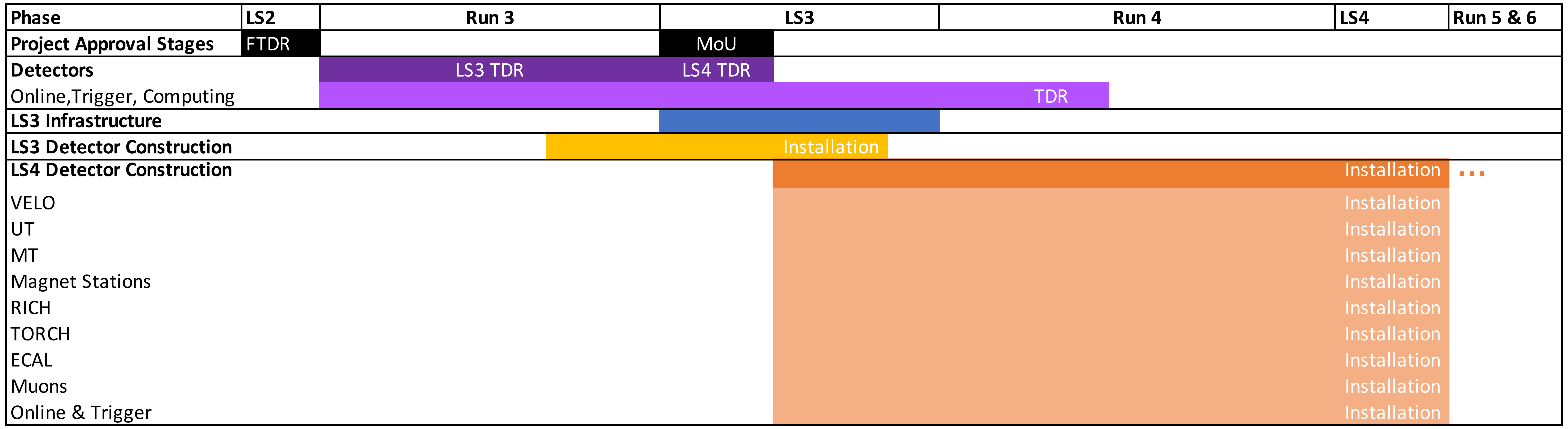
- Challenging **offline computing requirements**
  - **Upgrade I model not sustainable**
  - Issues similar to ATLAS & CMS Phase II (Run 4)
  - **Coordination** with **WLCG** and **HEP Software Foundation** on mitigation

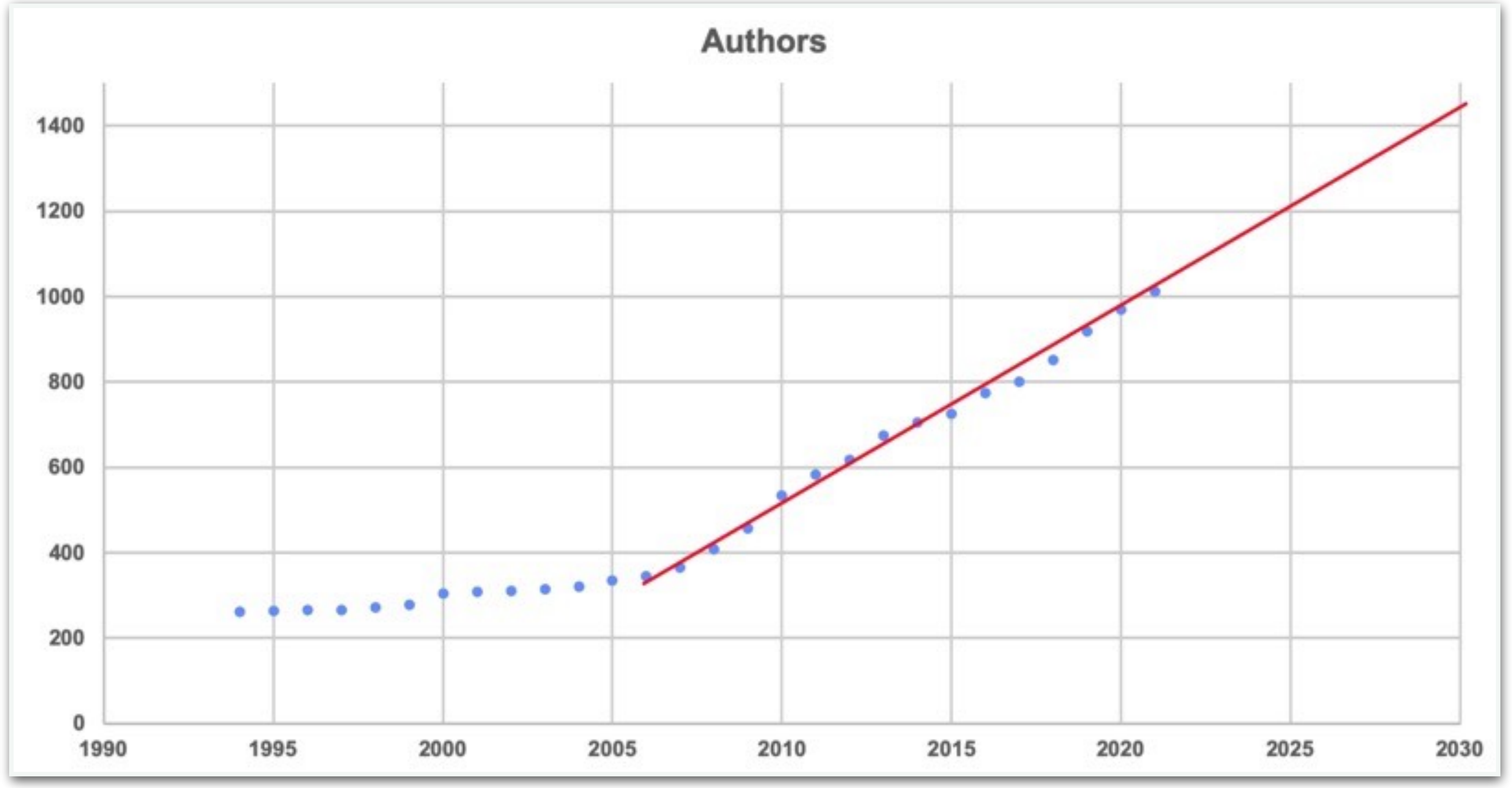
Status and timeline

- **Support** from **full** LHCb **collaboration**
- **Process** from FTDR to installation **defined with LHCC**
  - ➡ **R&D underway** leading to subdetector TDRs
  - ➡ In CERN's baseline schedule, LS4 1→2 years
- **Funding agency discussions underway**
  - ➡ **UK already committed** to funding their Upgrade II fair share

Detector	Countries involved
VELO	BR, CERN, ES, FR, IT, NL, PL, RU, SE, UK
UT	CN, FR
Magnet Stations	PL, US
Mighty Tracker (SciFi + MAPS)	BR, CH, DE, ES, SE, UK
RICH	CERN, IT, PL, RO, SI, UK
TORCH	CERN, UK, SI
ECAL	AU, CERN, CN, ES, FR, HU, IT, RU, US
Muon	IT, RU
RTA	BR, CERN, CN, DE, ES, FR, IT, NL, PL, RU, UK, US
Online	CERN, FR

Collaboration expanding, and new members are welcome





Costs and US contribution

Detector	Baseline (kCHF)
VELO	14800
UT	8900
Magnet Stations	2300
MT-SciFi	22400
MT-CMOS	19500
RICH	15600
TORCH	9900
ECAL	34800
Muon	7100
RTA	17400
Online	8900
Infrastructure	13500
Total	175100

Preliminary estimates in FTDR (European accounting), primarily based on Upgrade I

- **US interest** in **ECAL** and **RTA** in Upgrade II
  - Also Magnet stations for LS3
- Expected US contribution currently ~**5% of project cost**
- **Interest** from **Brookhaven National Lab** and **other institutions** to join Upgrade II effort
  - Currently DOE/OHEP does not support LHCb
  - Additional contributions proportional to increase of US membership
- **National lab infrastructure** could be **extremely beneficial** for LHCb Upgrade II construction
  - **Installation** in **2033-34**, **following** completion of final **ATLAS/CMS upgrade** in **2026-28**

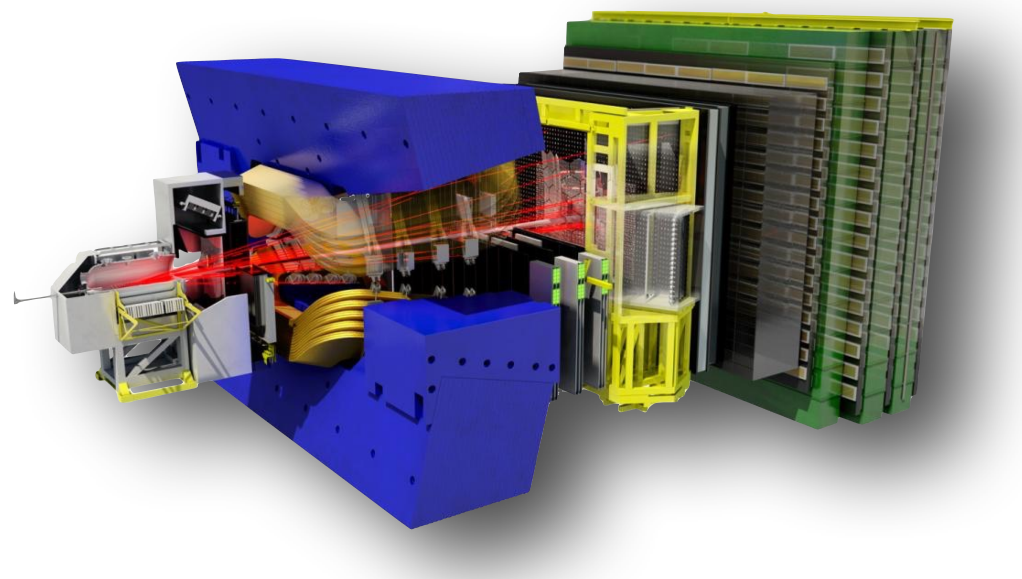
Summary

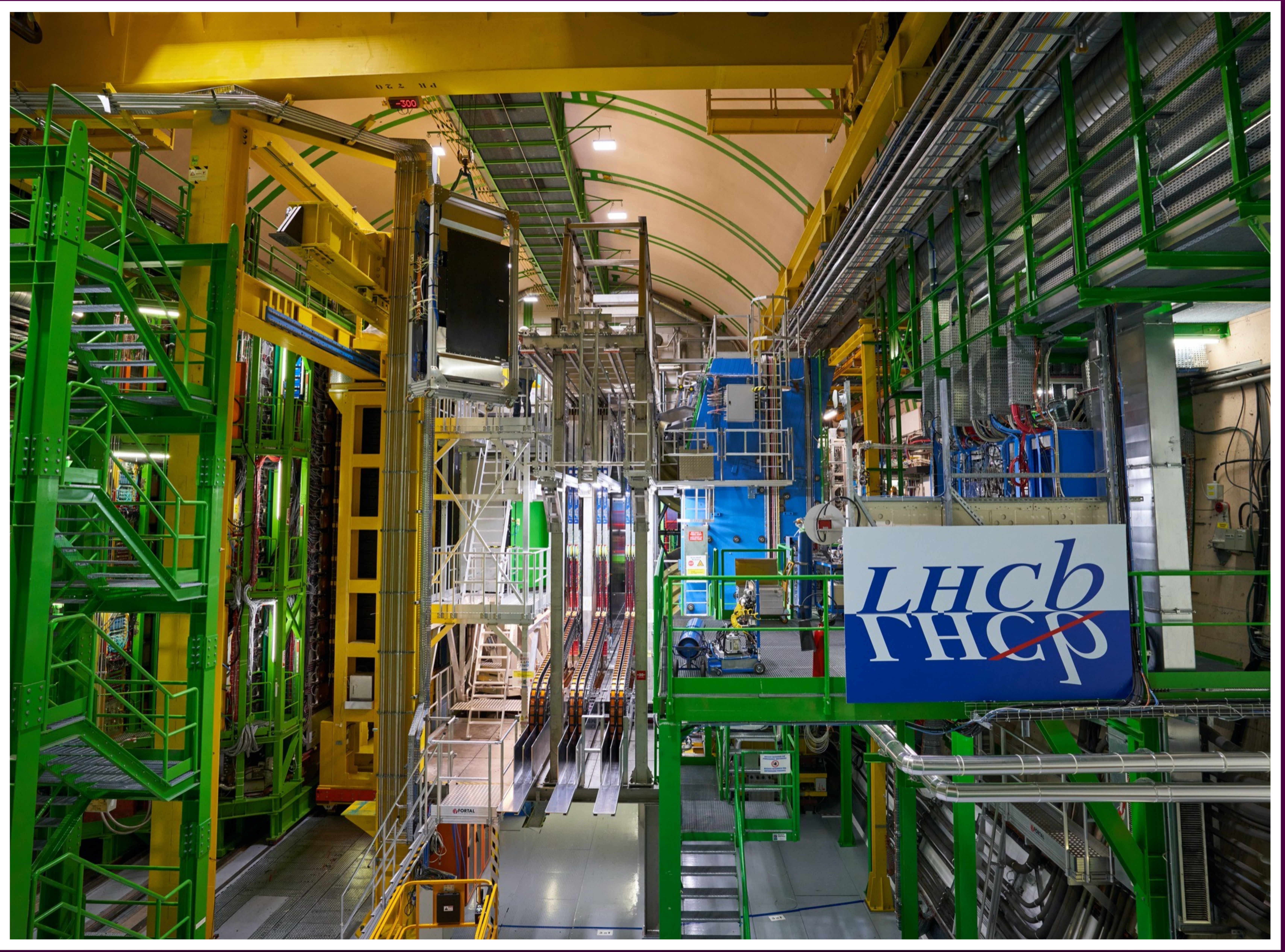
← $9\ fb^{-1}$ → Goal: $50\ fb^{-1}$ → ← Goal: $300\ fb^{-1}$ →

Upgrade I | Upgrade Ib | Upgrade II

Run 1	LS1	Run 2	LS2		Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022	2023 2024 2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2039	2040	2041 2042

- LHCb had **enormously successful Runs 1 and 2**
  - ➡ Key US contributions
- **Upgrade I** installed → **major project on budget**
  - ➡ Key US leadership
- Clear case for **Upgrade II** to **fully exploit HL-LHC**
  - ➡ **Complementing ATLAS/CMS** in the search for discoveries
- **Broad support** and **growing interest**
  - ➡ **Additional support from DOE/OHEP** would be **very beneficial**





Backup

Prospects for selected flavor observables

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

LHCb Upgrade II will significantly **exceed the precision of Belle II for the majority of observables of interest**, not only for B decays to charged final states involving hadrons and dimuons, and charm physics, but also for decays involving electrons, single neutrals, and semi-leptonic modes

Physics case
CERN-LHCC-2018-027

LHCb sweet spot for many flavor measurements

B-factories

$\mathcal{O}\left(10^{9}\right)$ $B^{0/+}$ **mesons**

Low uncertainty on absolute rates, 100% ε(trigger), PID, **low e-brem, knowledge of collision momentum**

Belle II

Aiming to collect $\mathcal{O}\left(10^{10}\right)$ $B^{0/+}$ mesons

LHC

$\mathcal{O}\left(10^{11}\right)$ $B^{0/+}_{(s)}$ **mesons**

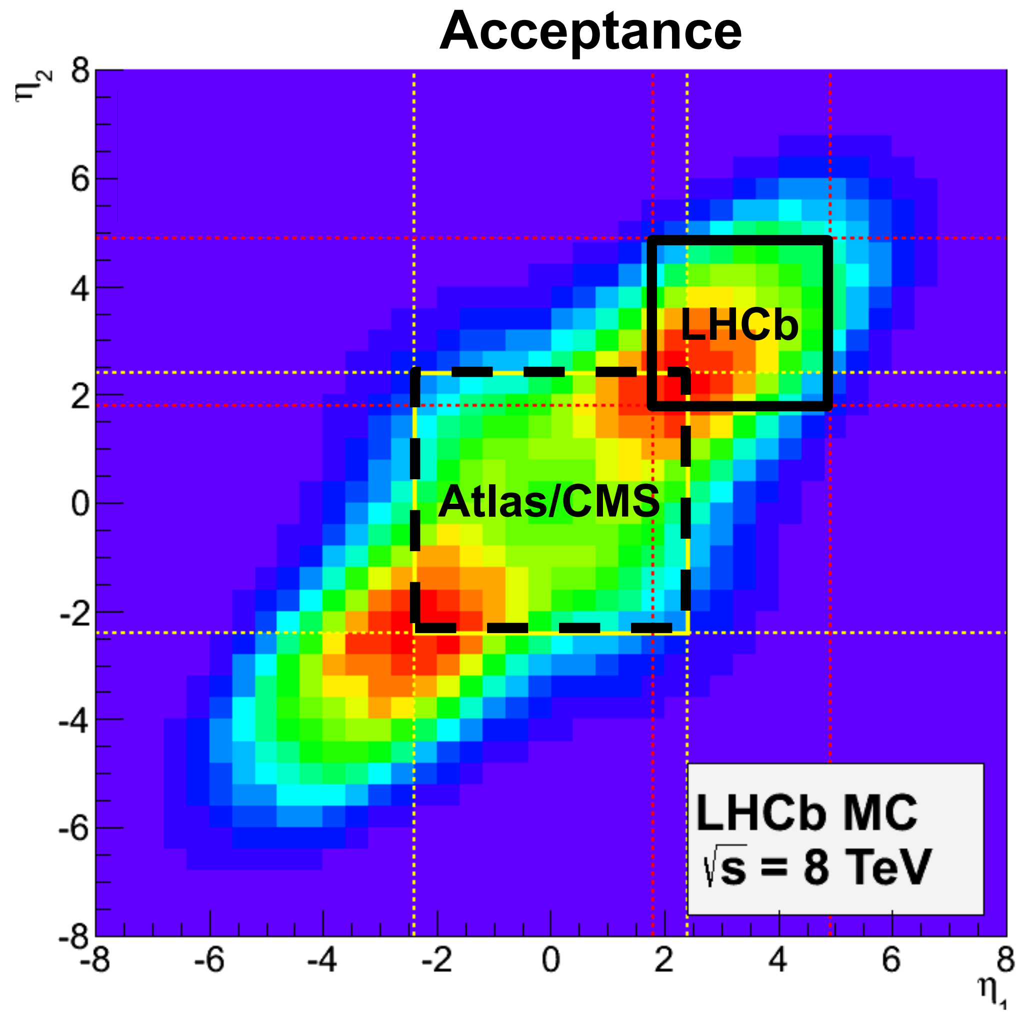
Triggers primarily for flavor, PID, VELO, **all b-hadron species**

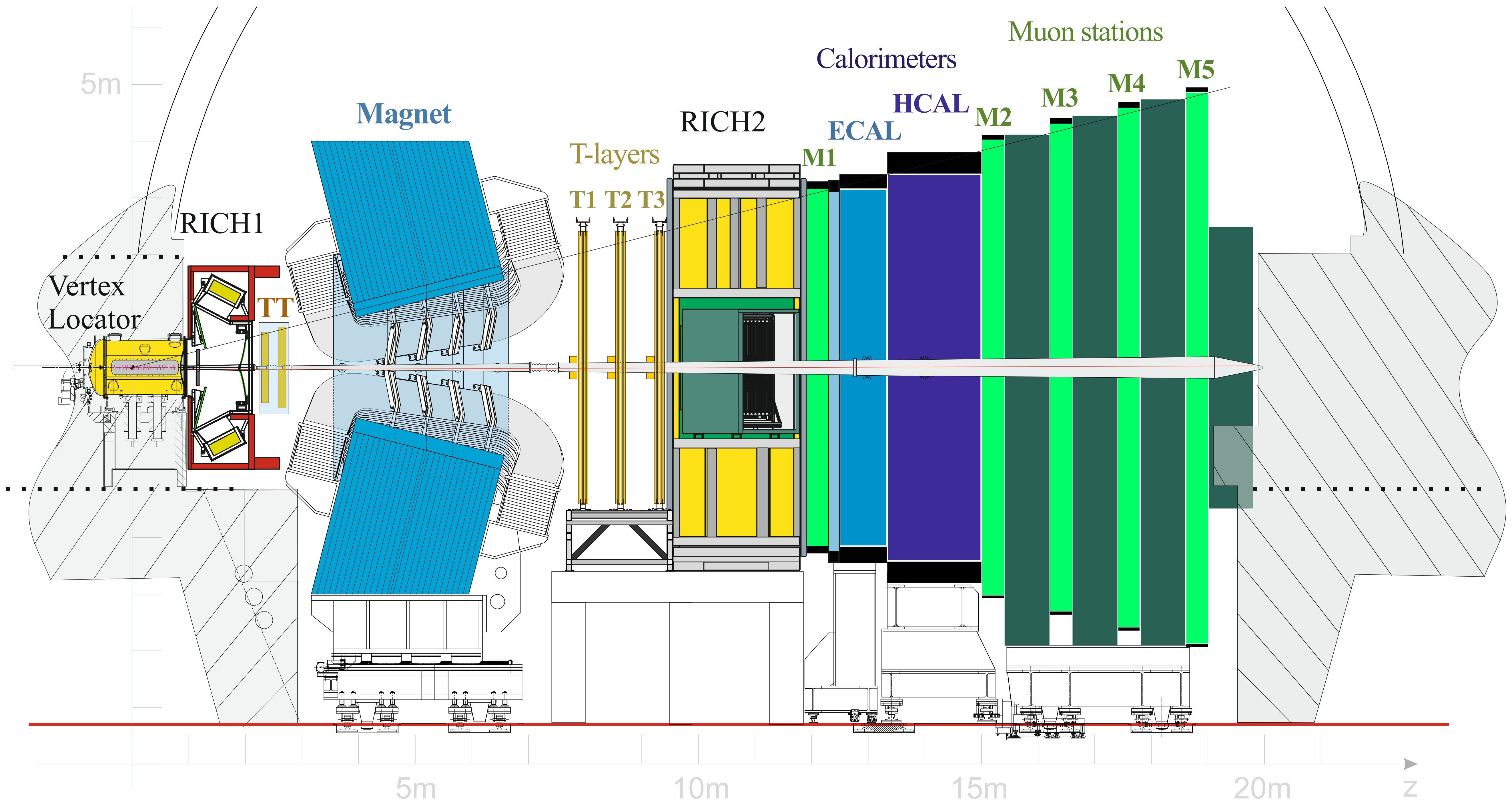
$\mathcal{O}\left(10^{12}\right)$ $B^{0/+}_{(s)}$ **mesons**

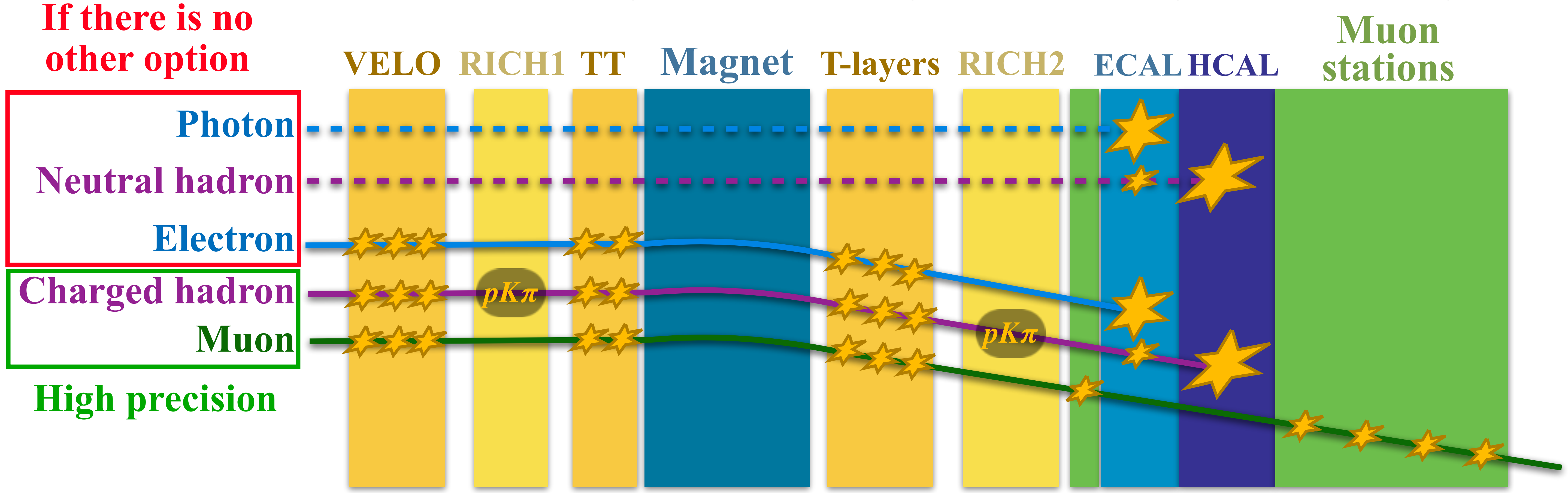
All b-hadron species

The LHCb experiment

- GPD with focus on **flavor physics**
  - 25% of $b\bar{b}$ production with 4% of solid angle (2 ≤ η ≤ 5)
  - 100k b-hadrons produced every second







- Excellent **secondary vertex reconstruction**
- **PID**: π, K, p, μ

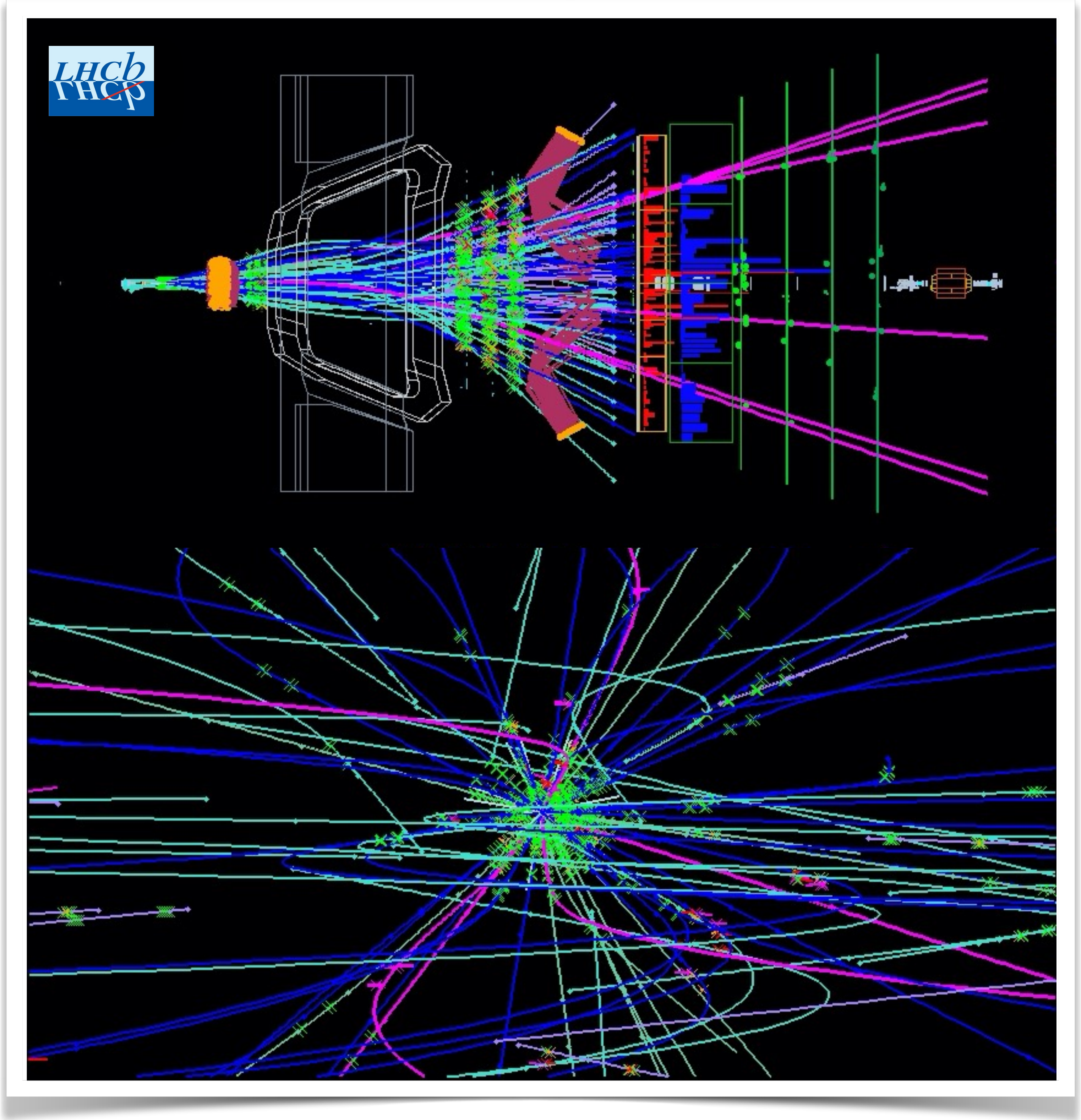
LHCb environment busier than B-factories

$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+\mu^-$

$e^+e^- \to B^+_{\mathbf{tag}} B^-_{\mathbf{sig}}$

$B^- \to \rho^0 \mu^- \nu_\mu$

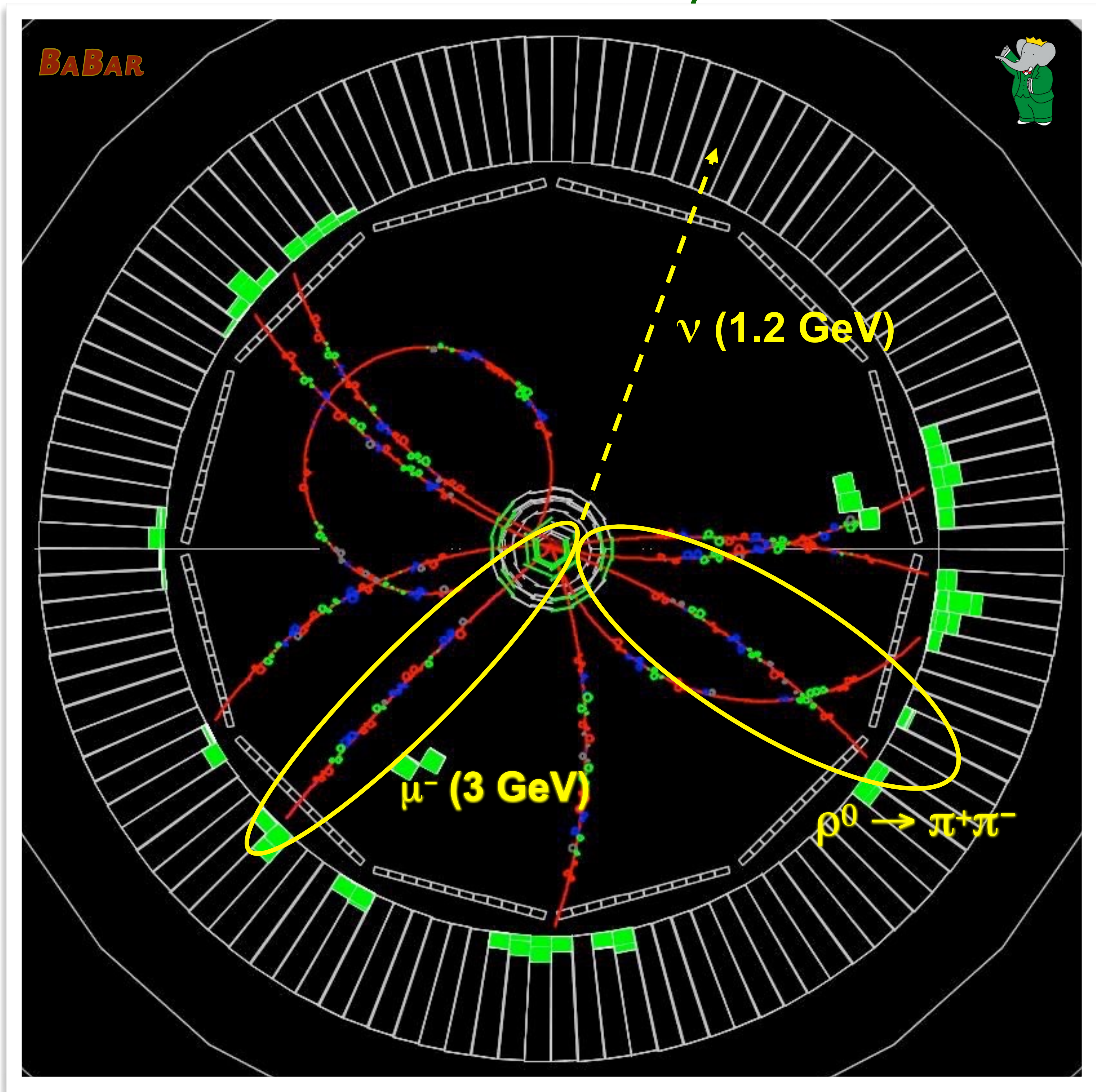


LHC

pp collisions have background from $b\bar{b}$ hadronization, underlying event, and pileup

B-factories

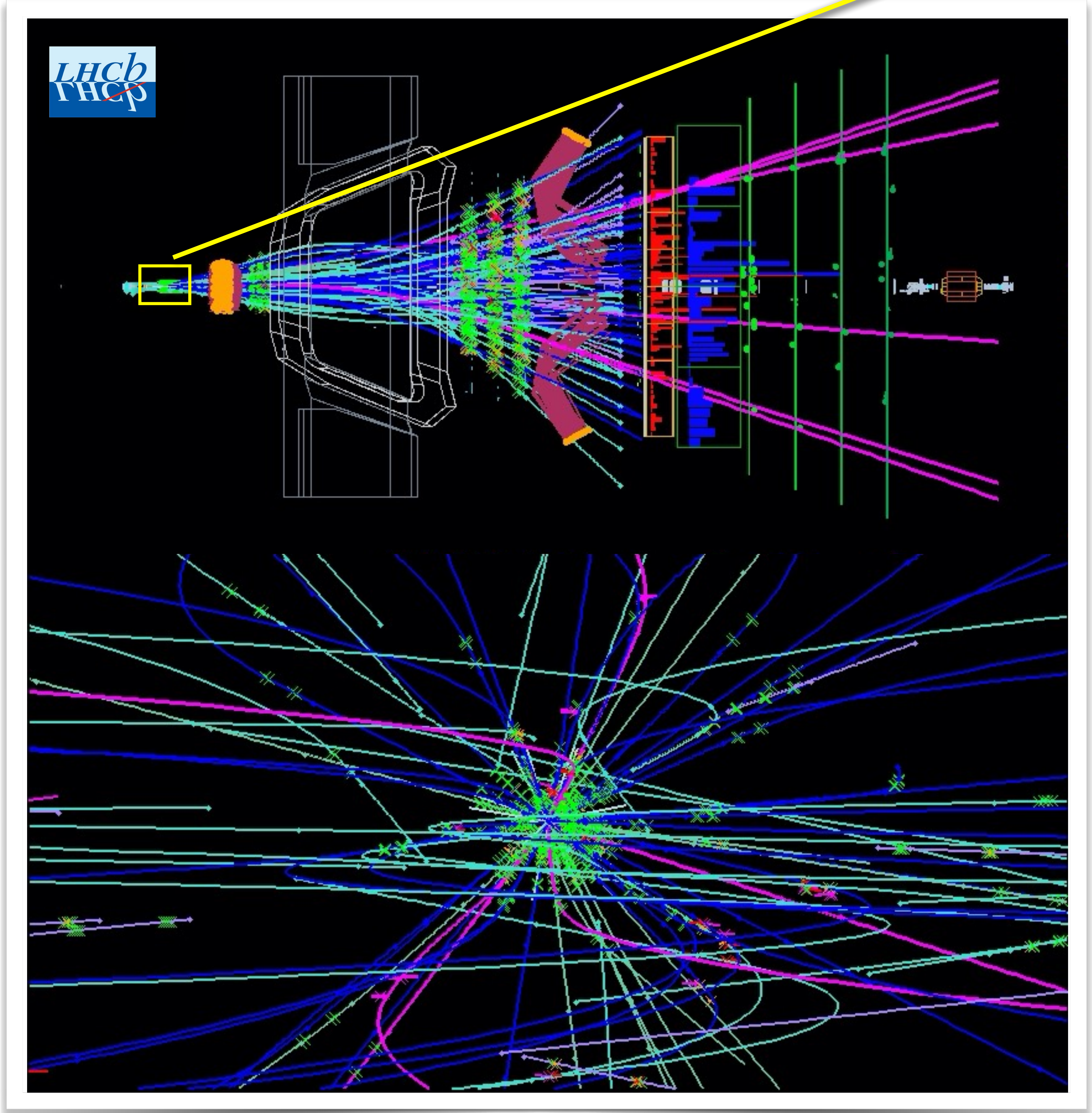
Clean e^+e^- collisions only produce two B mesons (for the most part)

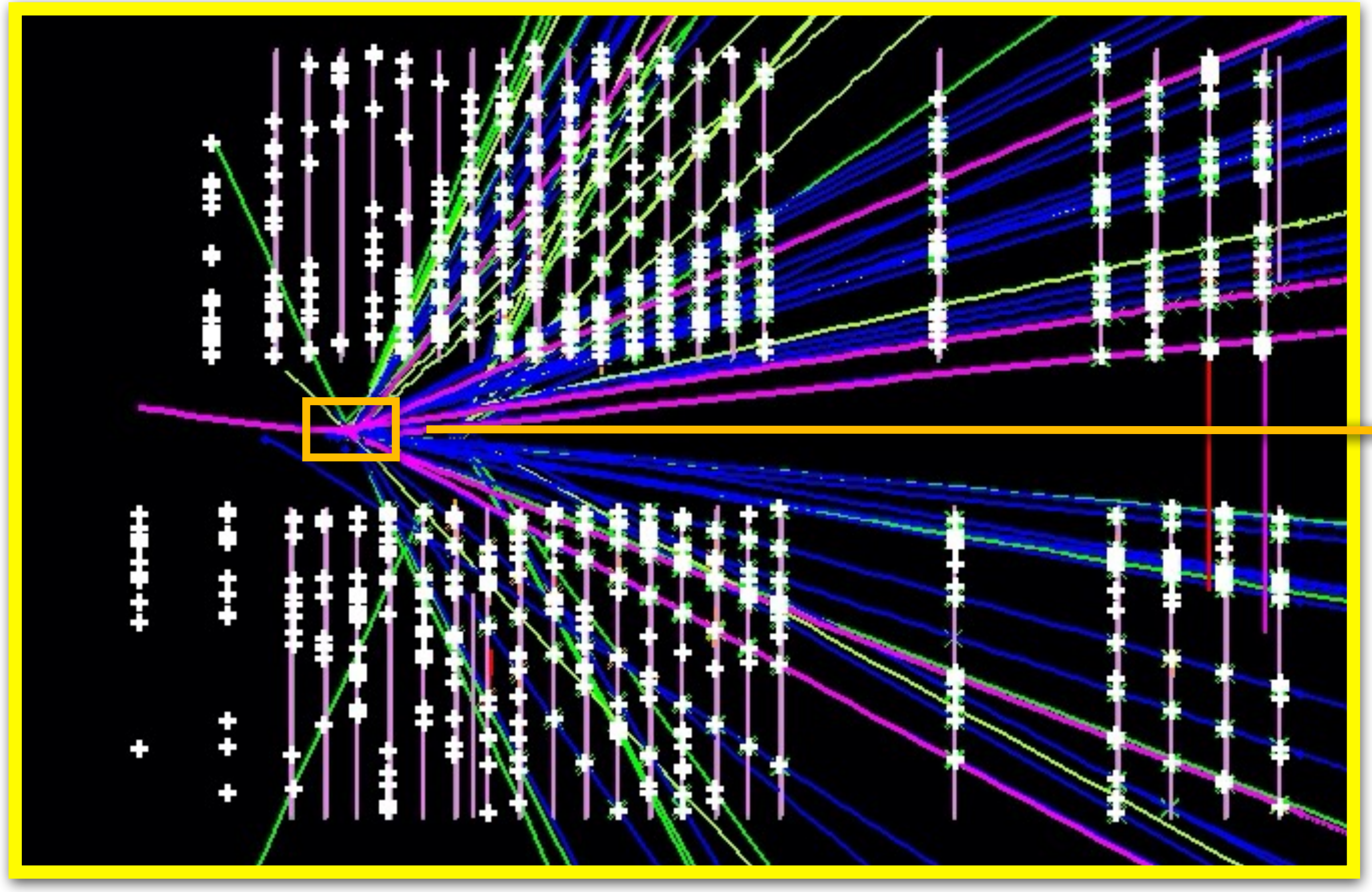


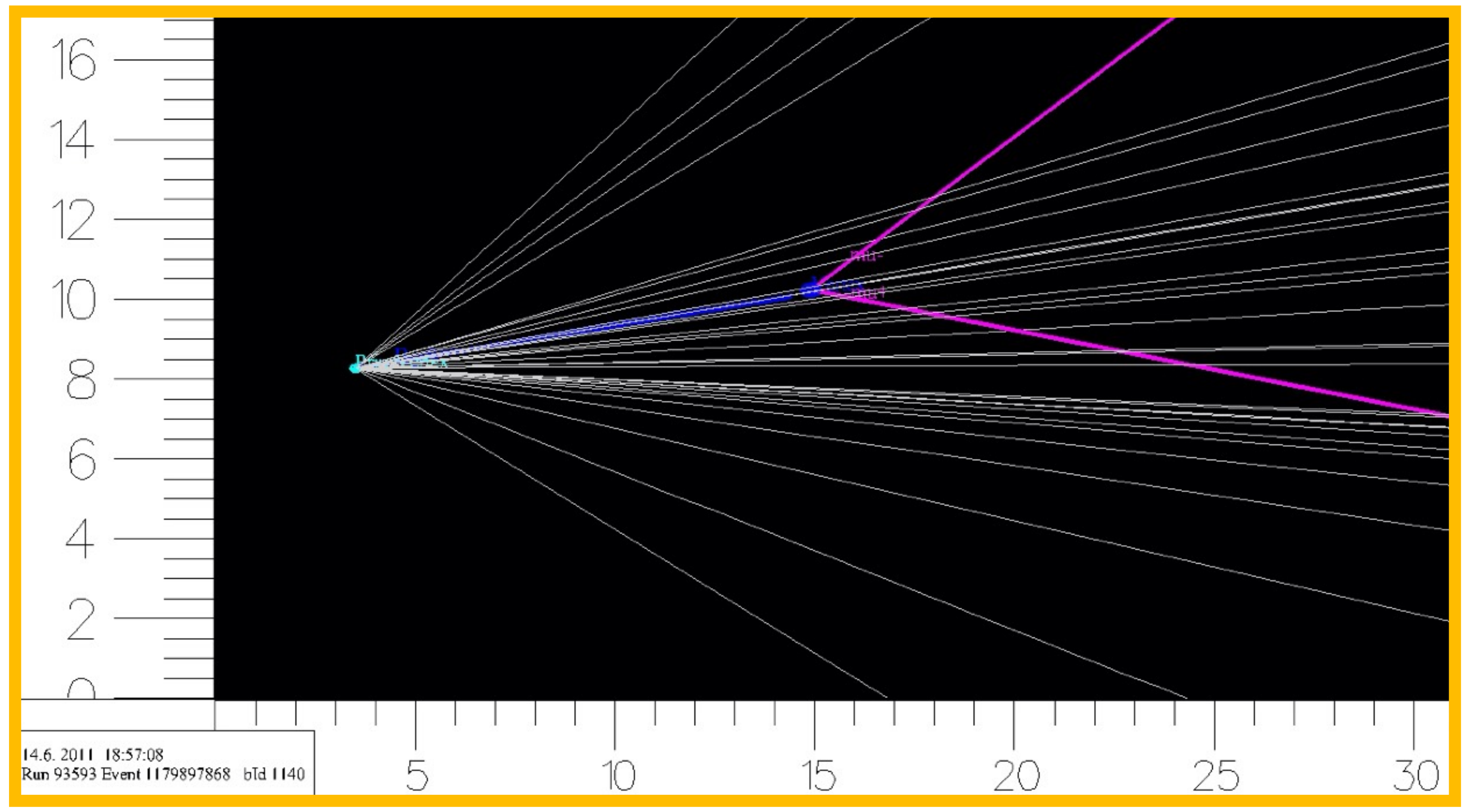
Vertexing and isolation key to LHCb

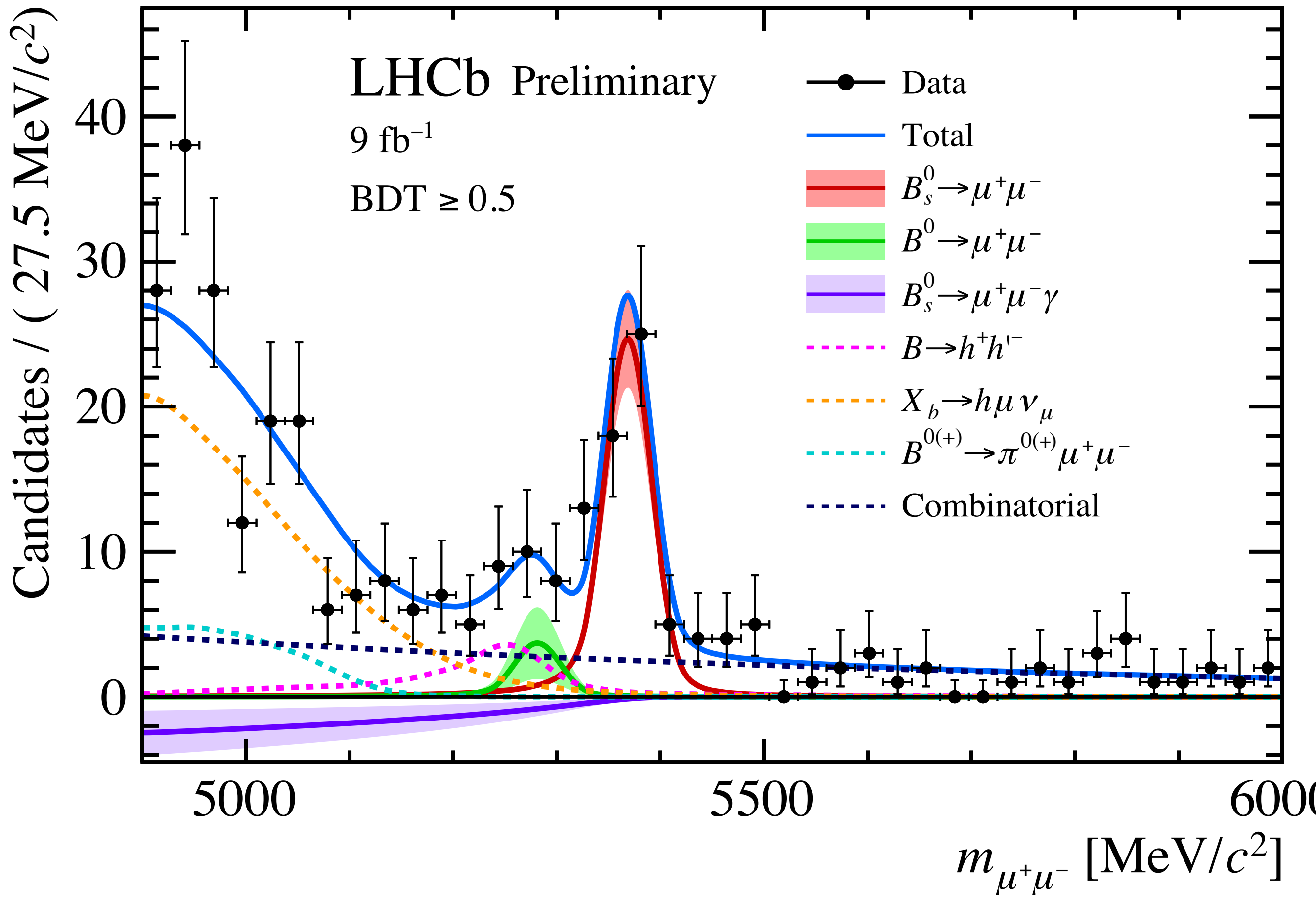
$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+ \mu^-$







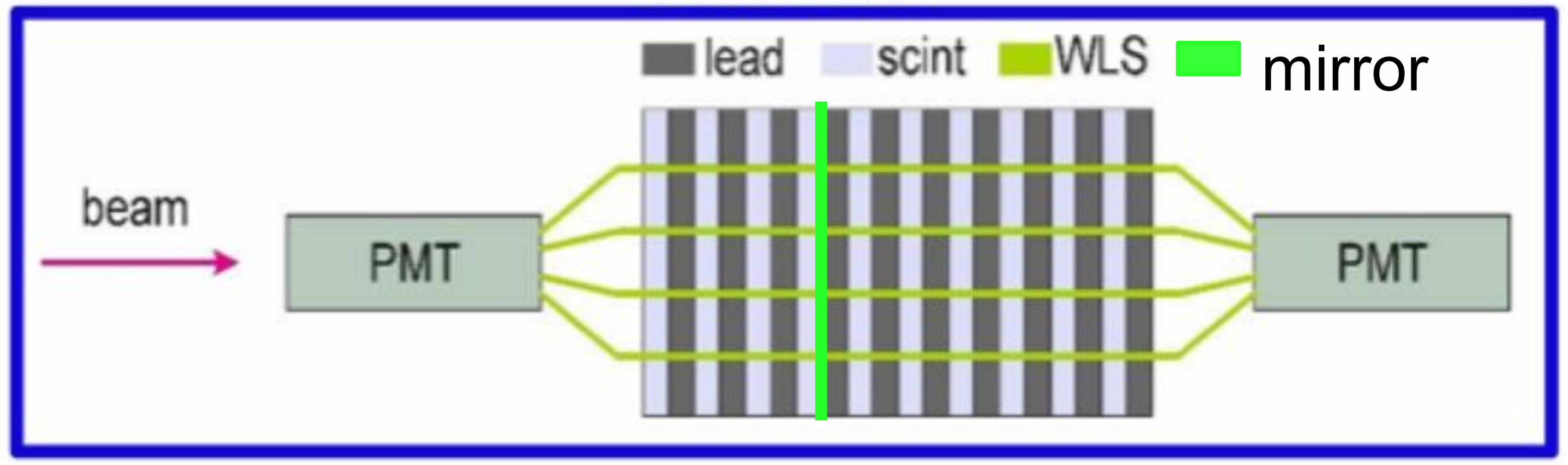


- **B mesons can fly ~cm** thanks to large boost
- **Superb vertexing** by VELO
  - Only 8.2 mm **from IP, reduced to 5.1 mm in upgrade**
- Multivariate algorithms ensure **tracks isolated**
  - Based on track impact parameter, other variables

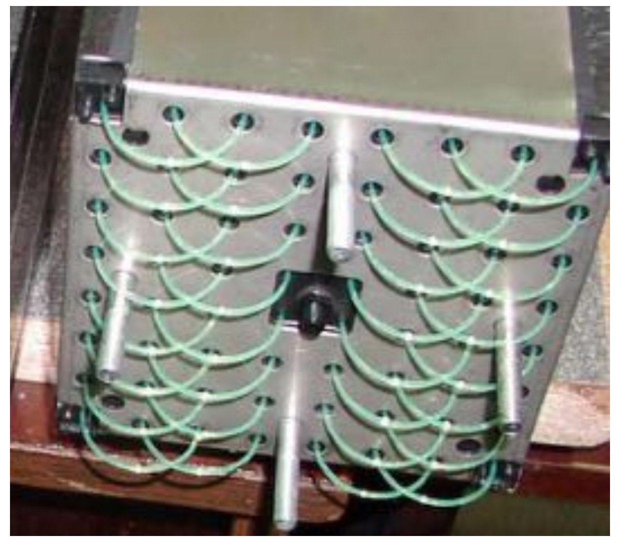
Baseline ECAL

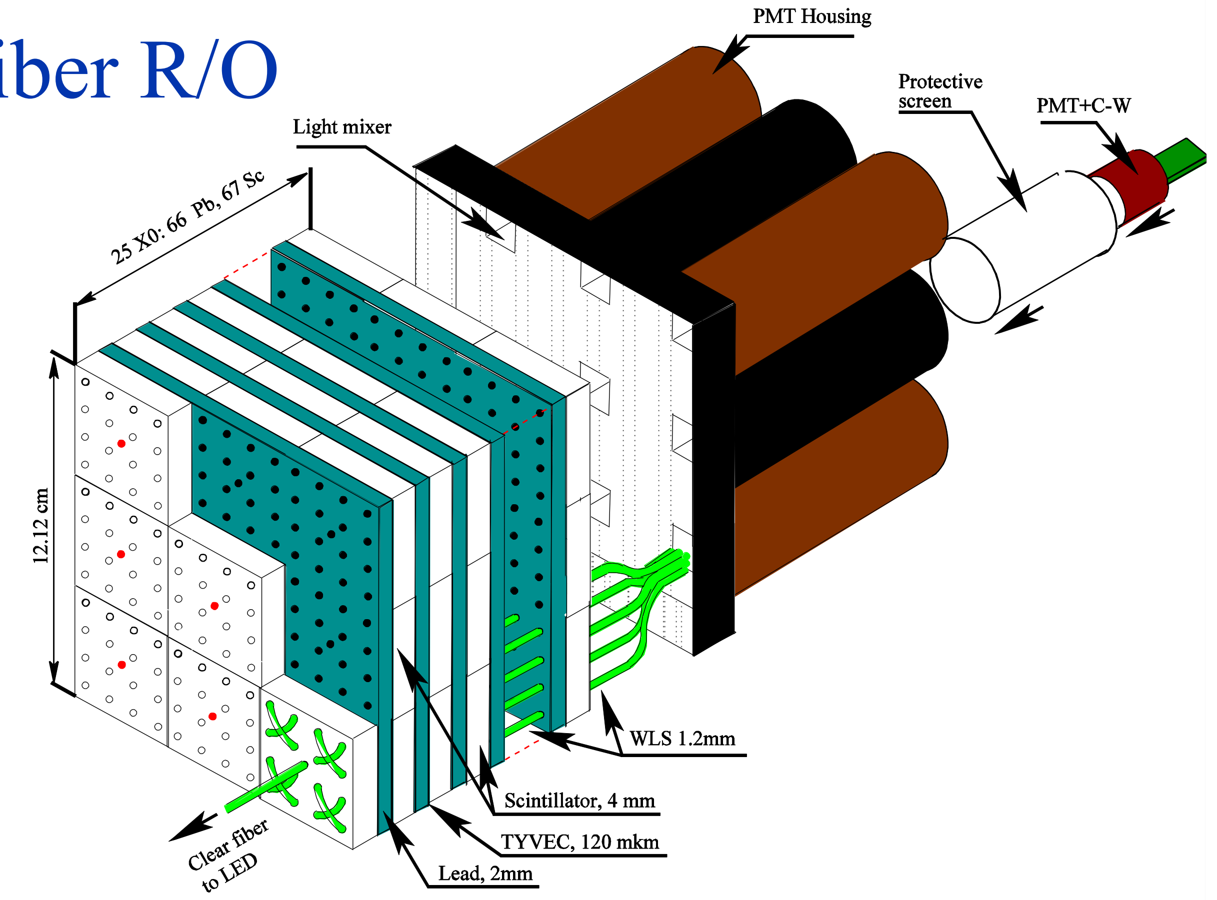
➢ <u>Two technologies for different radiation requirements</u>: **Shashlik** and **SPACAL**

Shashlik



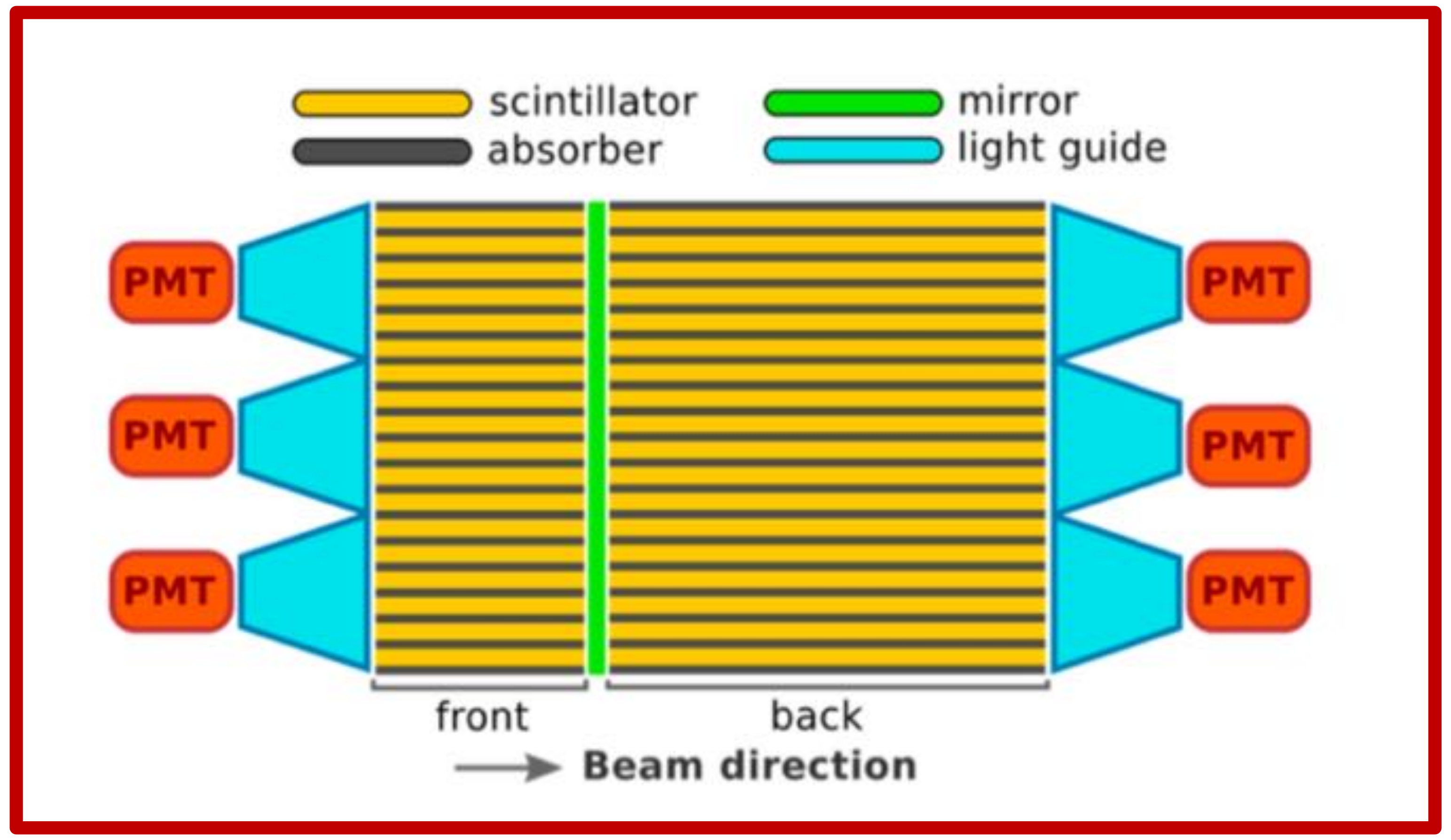
➢ Scintillator-Pb sandwich with WLS fiber R/O
➢ WLS fiber bundle readout by PMT
➢ Single or double sided R/O possible





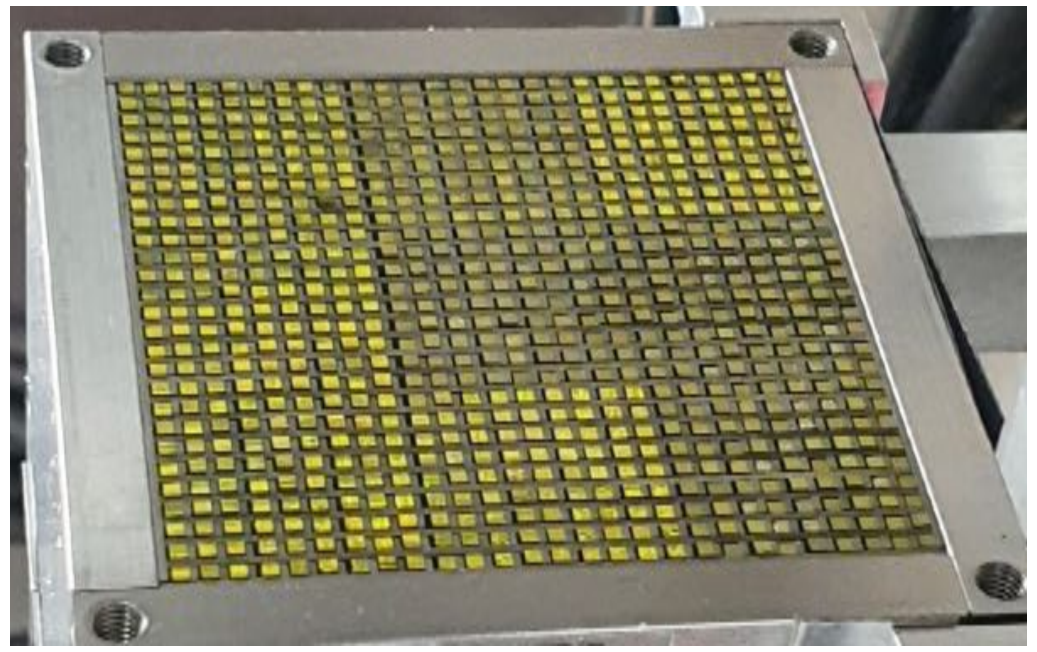
➢ Radiation tolerant up to 40-50 kGy

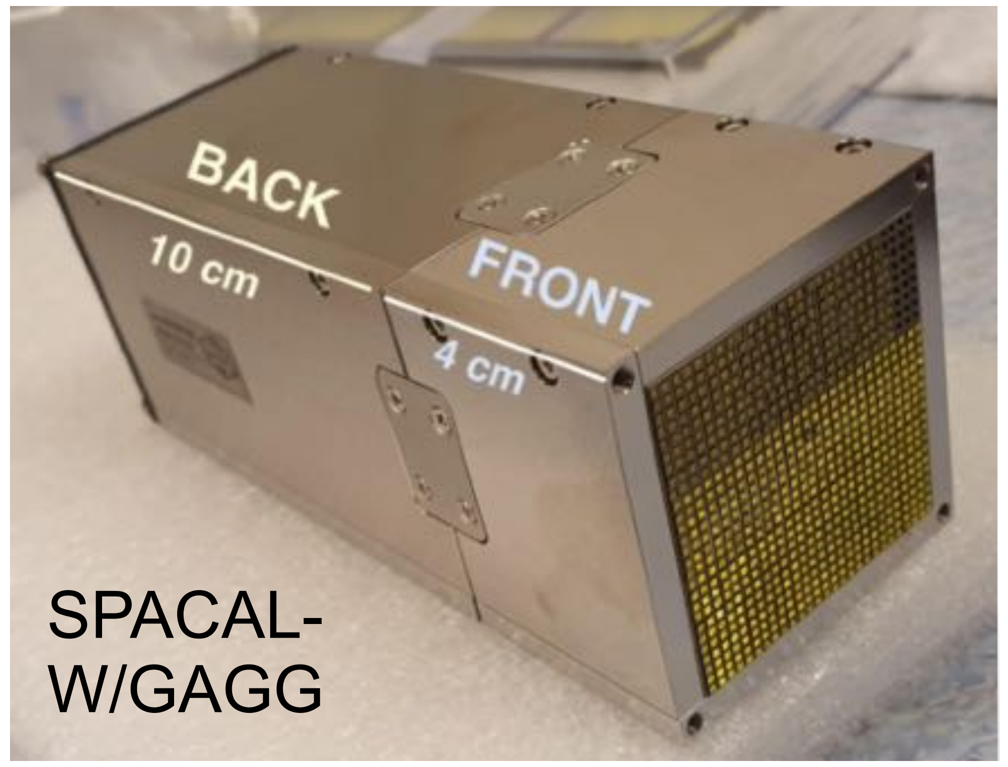
SPACAL (SPAghetti CALorimeter)



➢ Scintillating fibers hosted in an absorber
➢ Light collected via lightguide, readout by PMT
➢ Single or double sided R/O possible

✓ <u>Fibers</u>:
  ➢ crystal
  ➢ organic
✓ <u>Absorber</u>:
  ➢ tungsten
  ➢ lead



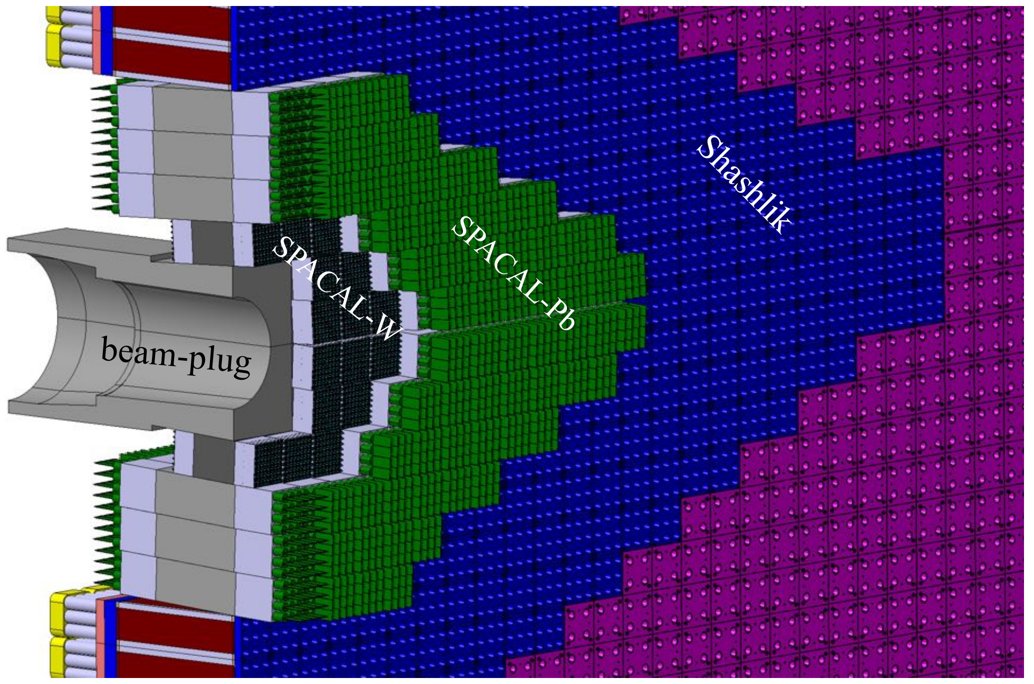


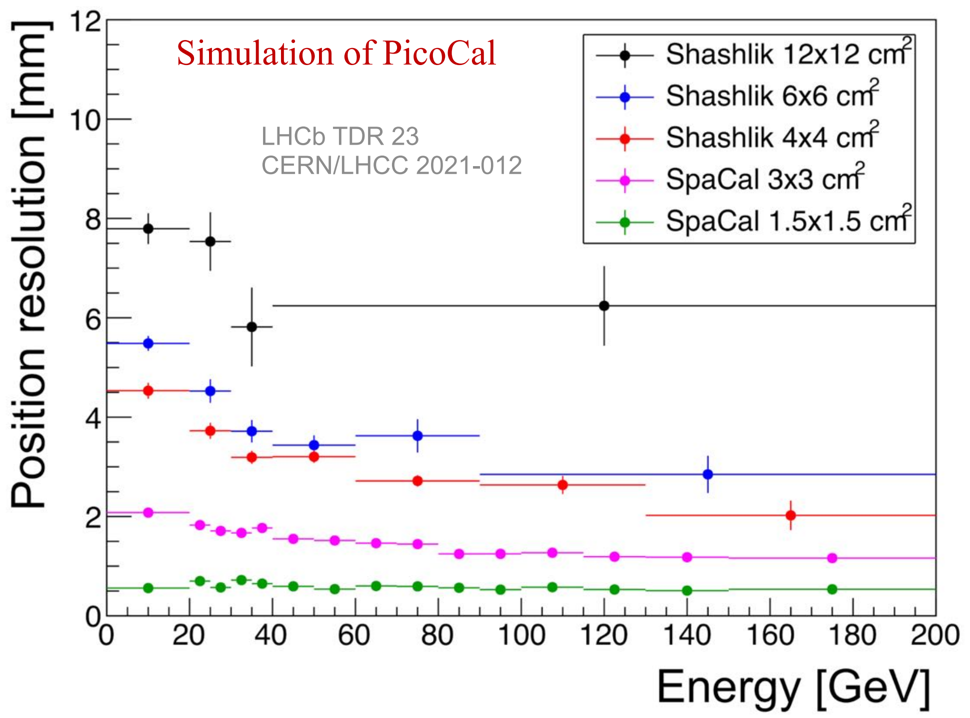
➢ Radiation hard up to 1MGy

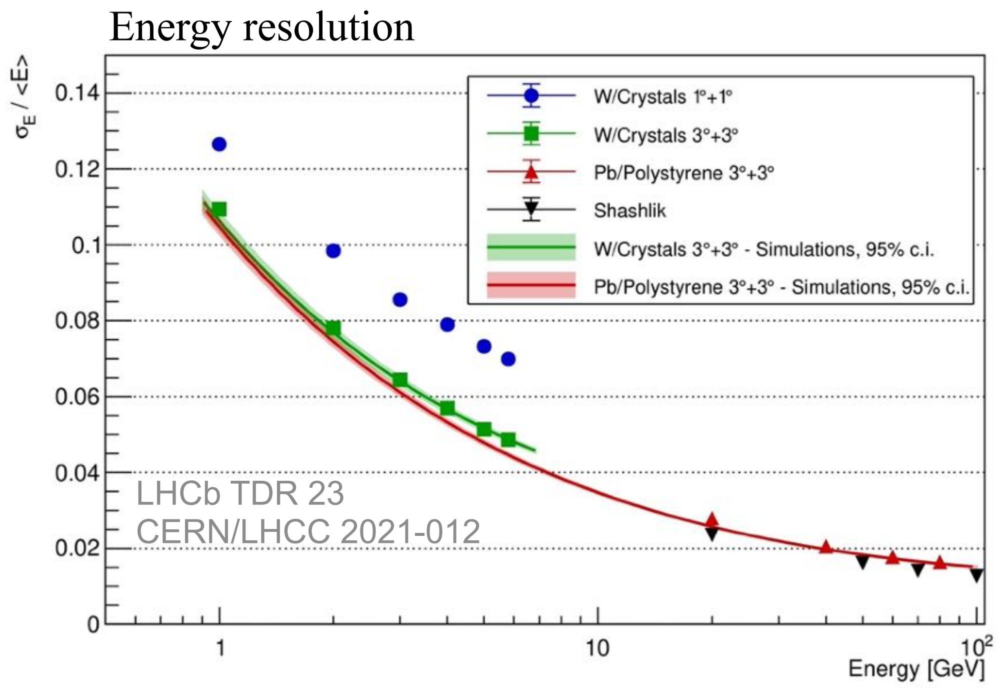
US LHCb UII Workshop 17 March 2023 Andreas Schopper 3

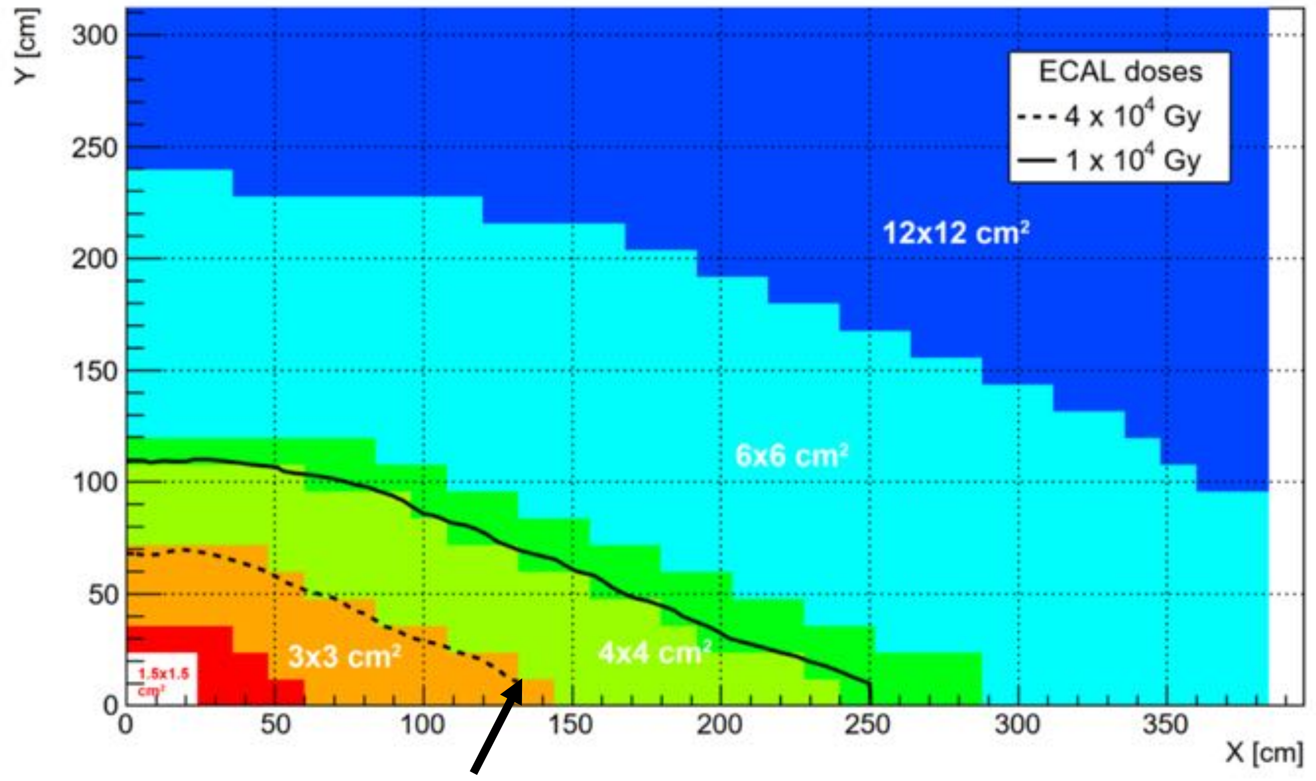
EP R&D

Baseline ECAL granularity









Radiation limit of current Shashlik technology (40 kGy)

Keep current Shashlik technology for region <40 kGy:

- Take advantage of timing properties with improved new WLS fibers
- Long. segmentation (double-sided readout) for timing and reconstruction

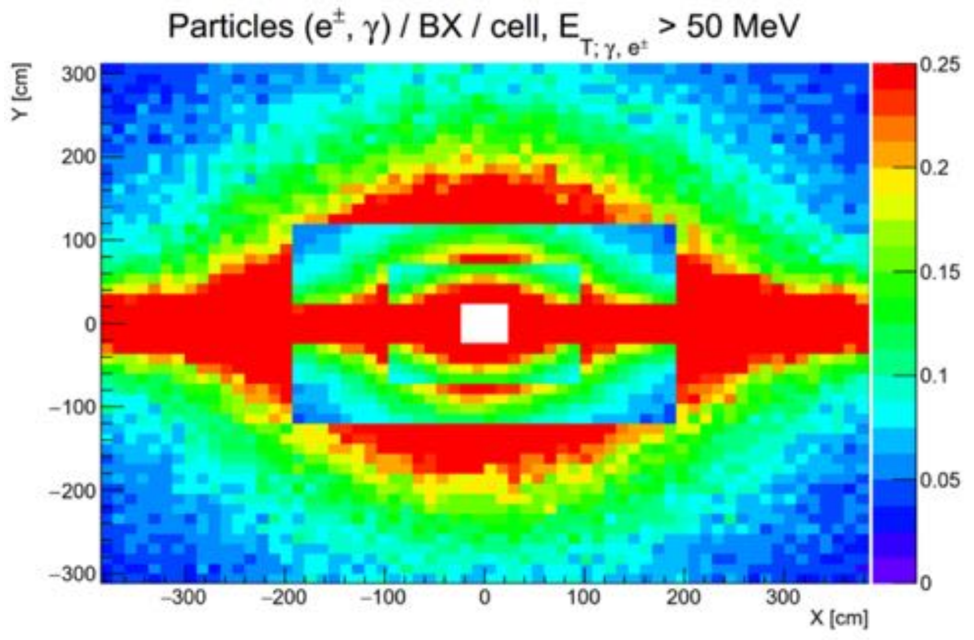
Introduce new SPACAL technology for region >40 kGy:

- 1 MGy region with scintillating **crystal-fibres & W-absorber**: SPACAL-W
  - ✓ Development of radiation-hard scintillating crystals
  - ✓ W-absorber for **1.5x1.5 cm²** cell size
- 40-200 kGy region with scintillating **plastic-fibres & Pb-absorber**: SPACAL-Pb
  - ✓ R&D on radiation-tolerant organic scintillators
  - ✓ Pb-absorber for **3x3 cm²** cell size

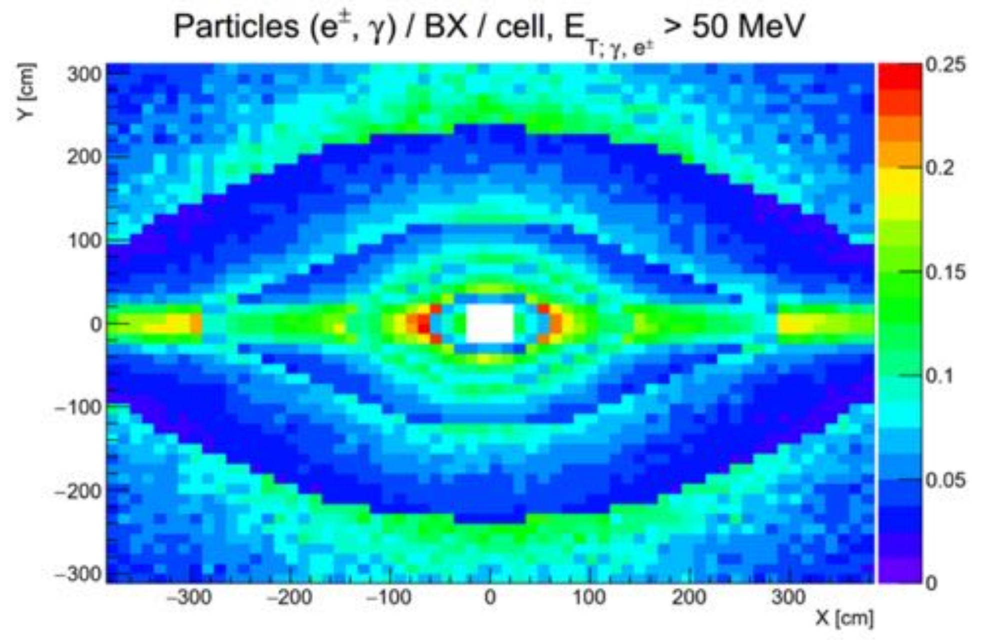
Comparison of current and **Upgrade II** calorimeter layouts at L = 1.5 x 10^{34} $cm^{-2}s^{-1}$

- occupancies manageable due to increased granularity and rhombic shape
- few 10th of ps-timing allows for pile-up mitigation

Current ECAL



Upgrade II configuration



Note: For consolidation during **Long Shutdown 3 (LS3)**

- scintillating **plastic-fibres & W-absorber**
- **2x2 cm²** cell size

US LHCb UII Workshop 17 March 2023 Andreas Schopper 5

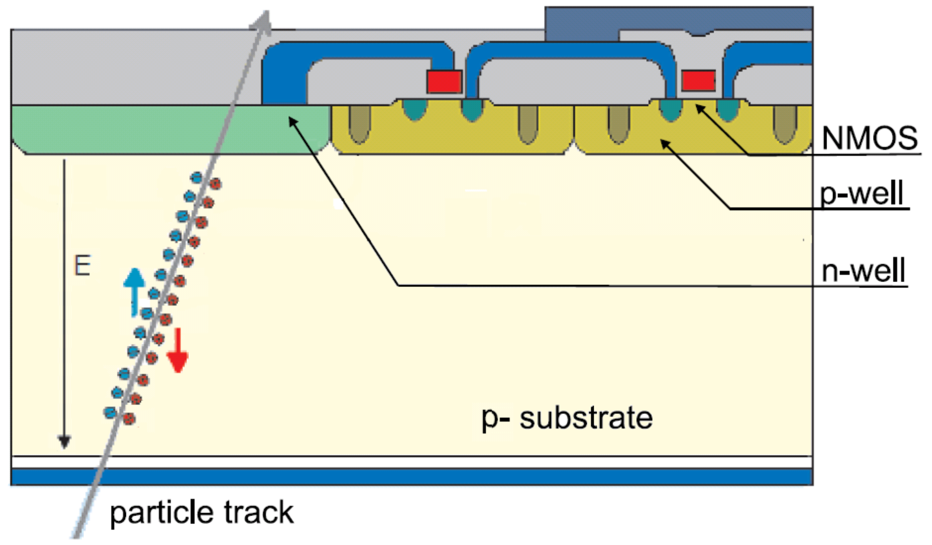
EP R&D

DMAPs

UNIVERSITY OF LIVERPOOL

Monolithic pixel detectors – Depleted MAPS

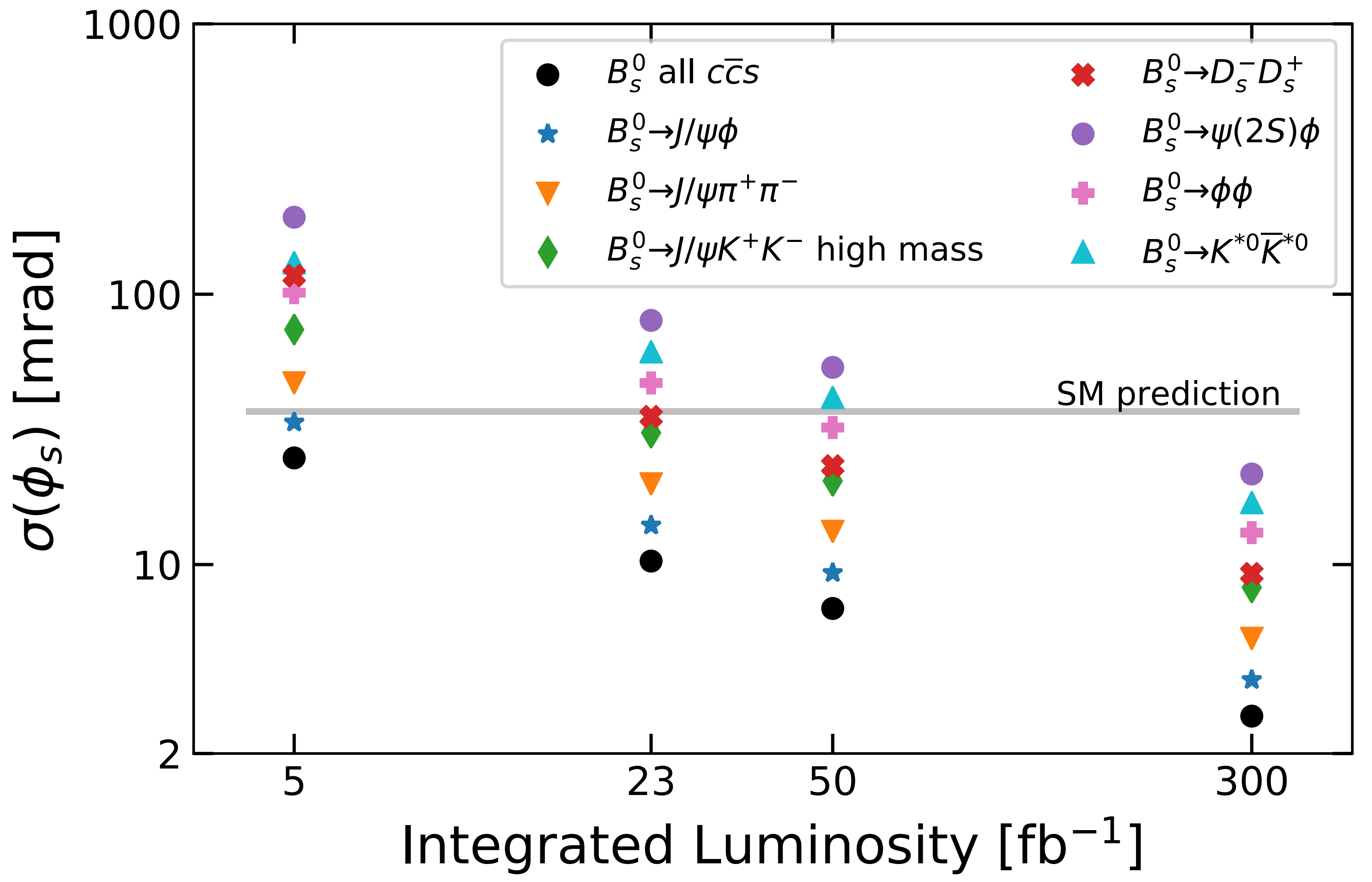
- Sensor and readout electronics on single wafer in standard High Resistivity/High Voltage-CMOS (HR/HV-CMOS)
  - Reduced material thickness (50 µm)
  - Small pixel size (50 µm x 50 µm)
  - In-pixel amplification
  - More cost effective (~£100k/m^2)
  - Larger bias voltage (V_{bias})
    - Fast charge collection by drift (15 ns time resolution)
    - Good radiation tolerance (10^{15} 1MeV n_{eq}/cm^2)
  - One limitation: The chip size is in principle limited to 2 cm x 2 cm, although stitching options are being investigated
- **Next generation**



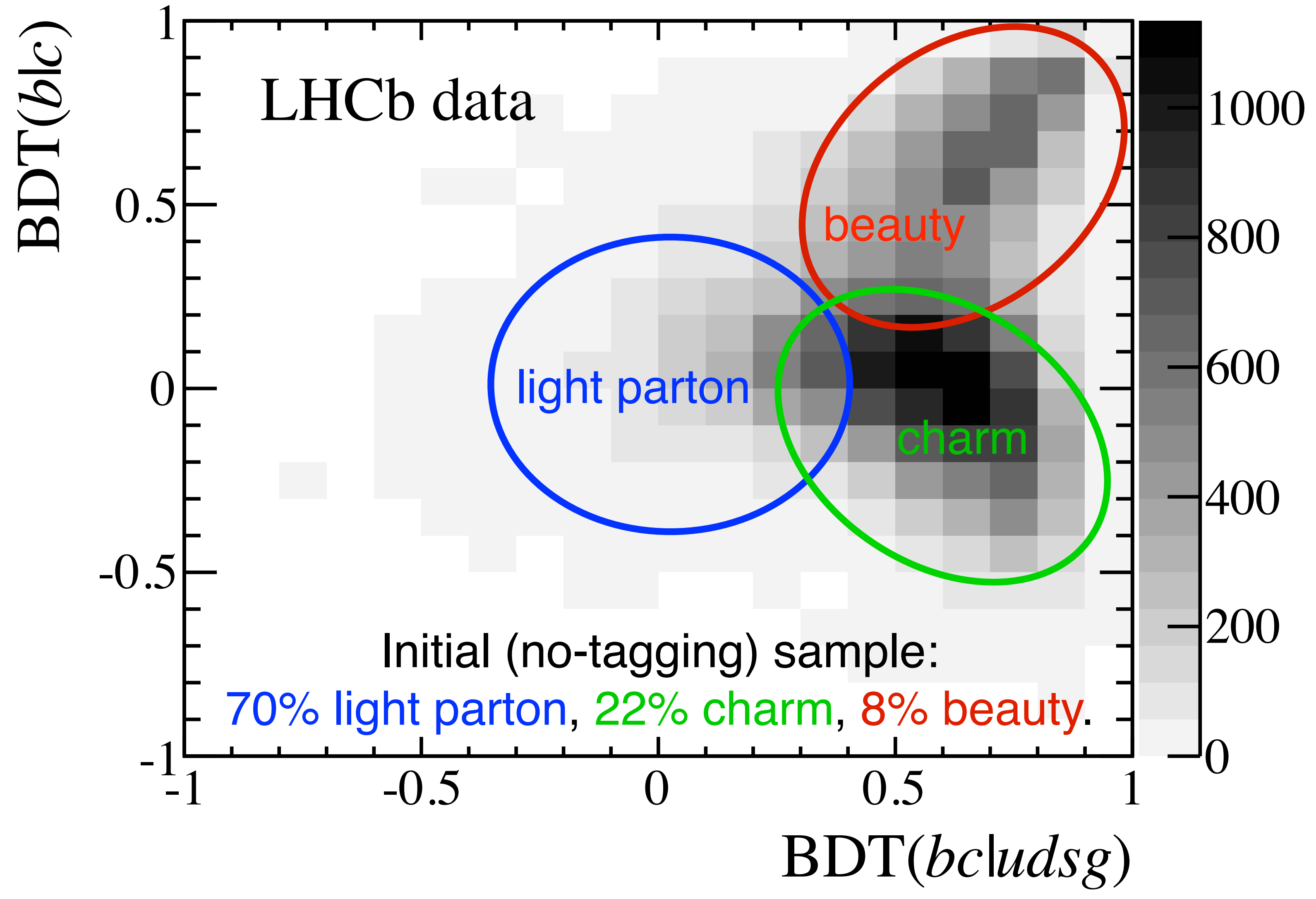
- **DMAPS in HR/HV-CMOS processes have huge potential for future particle physics experiments**
  - Reduced material thickness (50 µm)
  - Small pixel size (50 µm x 50 µm)
  - More cost effective (~£100k/m^2)
  - Fast charge collection by drift (15 ns time resolution)
  - Good radiation tolerance (10^{15} 1MeV n_{eq}/cm^2)
- **Quite a few experiments are interested in DMAPS**
  - Mu3e (first application of DMAPS)
  - ATLAS ITk upgrade (cancelled)
  - LHCb Mighty Tracker upgrade
  - CLIC
  - CERN-RD50 (detector R&D)
- **Several prototypes and "pre-production" detectors developed for these experiments**
- **Detector R&D to further develop its performance done within CERN-RD50**

ϕ_s, $H \to c\bar{c}$

- **CP violating phase ϕ_s**
  - Sensitive to new physics
    - Small and well predicted in SM
  - Upgrade II sensitivity below SM prediction in multiple channels

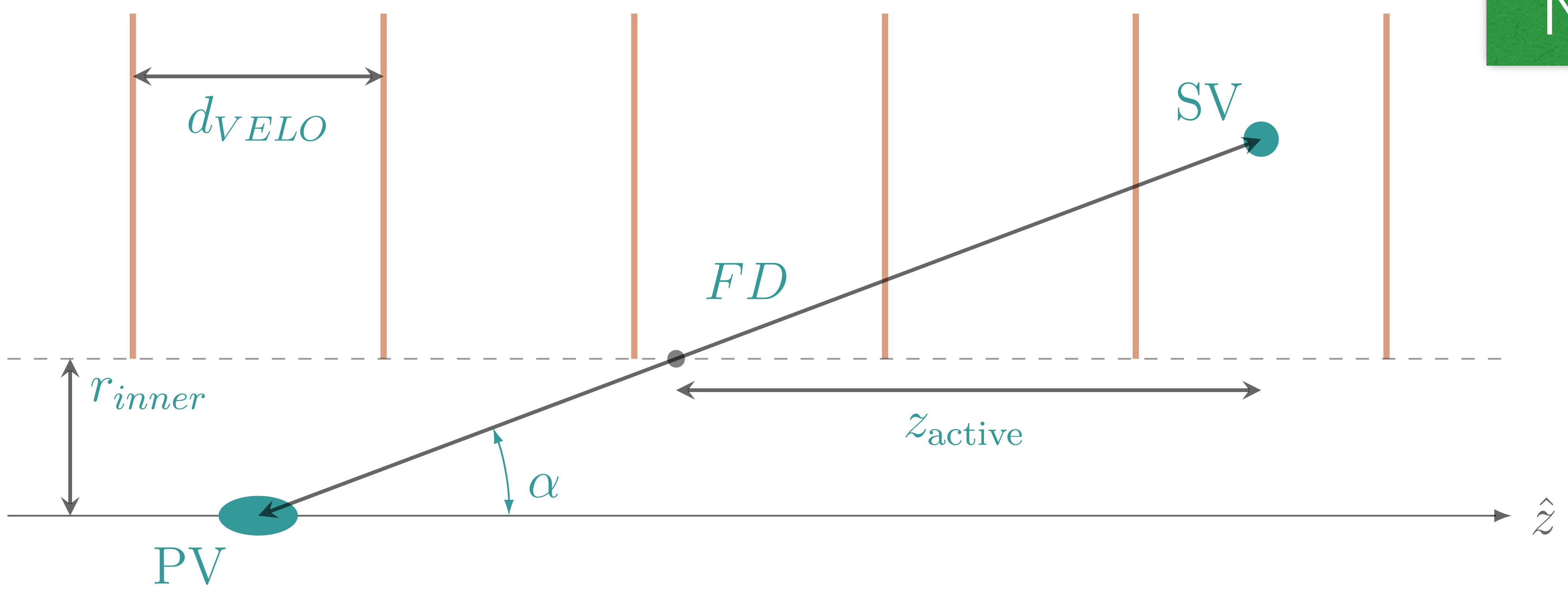


- Leverage world-leading VELO to set **most stringent constraint on Higgs to charm**
  - Currently set limit at $80 y^c_{SM}$ at 8 TeV
  - With 300 fb^{-1} at 14 TeV → $7 y^c_{SM}$
    - Improved VELO, electron performance, ML could push it to $2 y^c_{SM}$

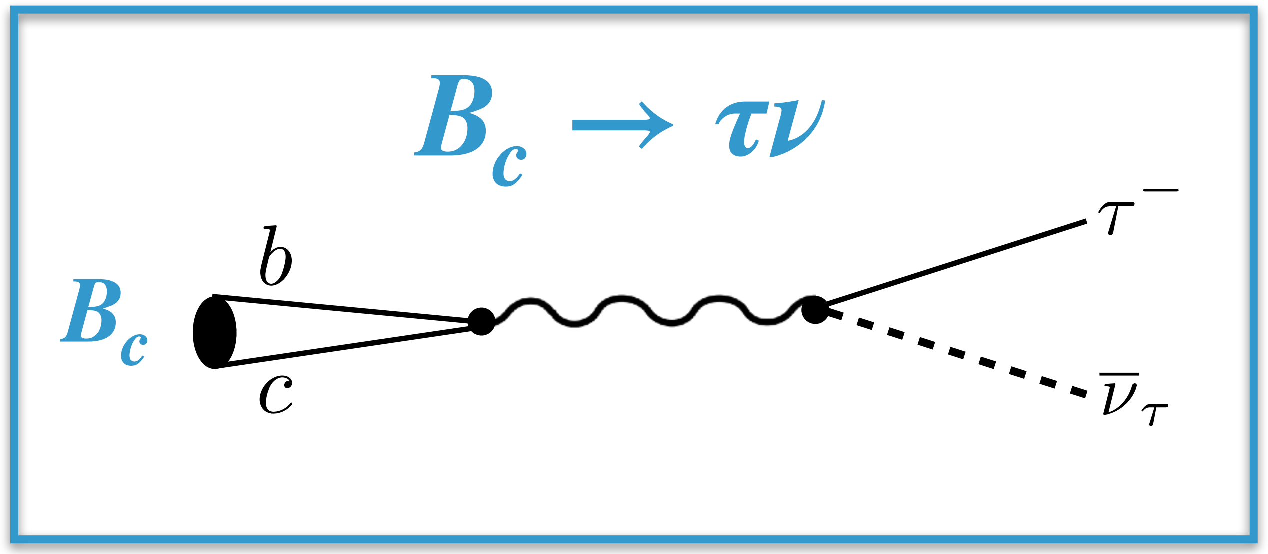


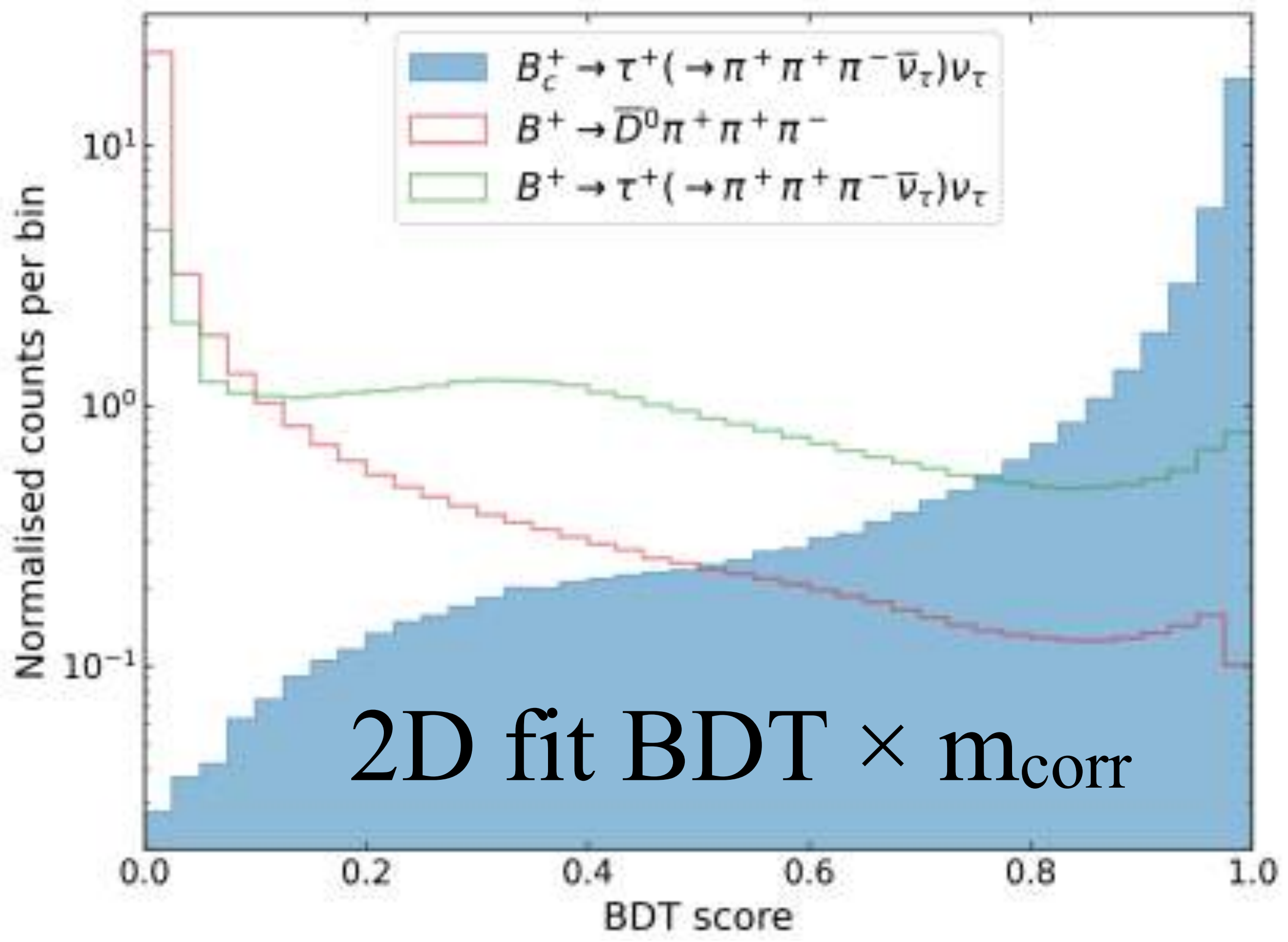
$B_c \rightarrow \tau\nu$

Relies on VELO hits left by the $B^+_{(c)}$ meson



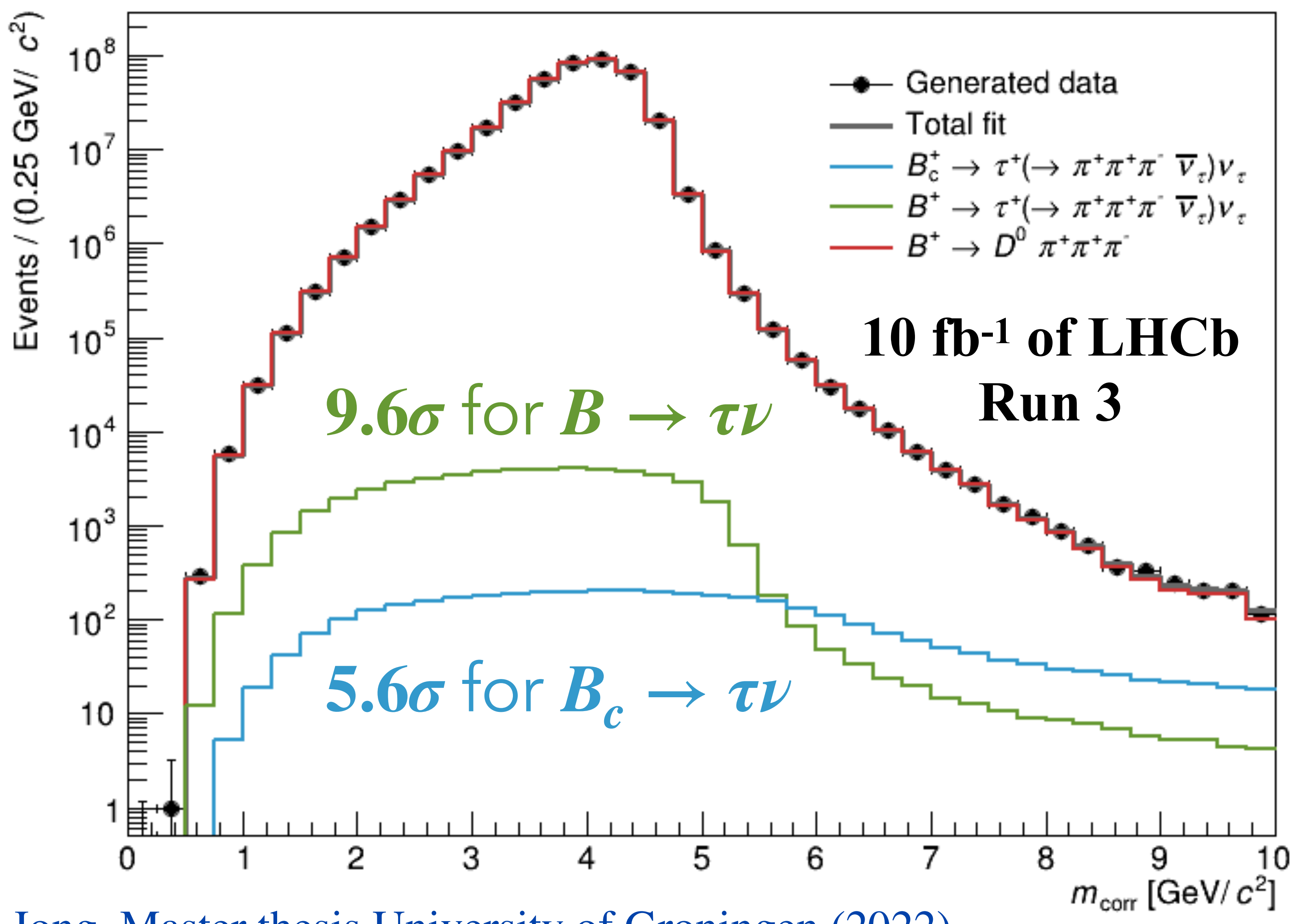
Very clean way to study possible NP hinted in $b \rightarrow c\tau\nu$ anomalies





Feasibility study fitting $m_{corr} \times BDT_1$, assuming $\mathscr{BF}\left(B^+ \rightarrow D^0\pi\pi\pi\right)$, worst-case scenario, ε_{rec} = 88%

ϵ_{rec}	$f_{B_c^+} \pm \sigma_{B_c^+}$	$f_{B^+} \pm \sigma_{B^+}$	$f_{B_c^+}/\sigma_{B_c^+}$	f_{B^+}/σ_{B^+}
84 %	$(4.72 \pm 1.40) \cdot 10^{-6}$	$(9.32 \pm 1.10) \cdot 10^{-5}$	3.3	8.4
88 %	$(9.38 \pm 1.66) \cdot 10^{-6}$	$(1.25 \pm 0.128) \cdot 10^{-4}$	5.6	9.6
92 %	$(1.20 \pm 0.207) \cdot 10^{-5}$	$(1.73 \pm 0.158) \cdot 10^{-4}$	5.7	10.8
96 %	$(2.11 \pm 0.307) \cdot 10^{-5}$	$(3.91 \pm 0.228) \cdot 10^{-4}$	6.8	17.0
98 %	$(4.59 \pm 0.474) \cdot 10^{-5}$	$(7.20 \pm 0.328) \cdot 10^{-4}$	9.8	21.8
99 %	$(9.68 \pm 0.760) \cdot 10^{-5}$	$(1.46 \pm 0.0476) \cdot 10^{-3}$	12.7	30.4
99.5 %	$(2.23 \pm 0.128) \cdot 10^{-4}$	$(2.89 \pm 0.0715) \cdot 10^{-3}$	17.1	40.7



J. de Jong, Master thesis University of Groningen (2022)