The future of LHCb

Federico Leo Redi on behalf of the LHCb collaboration

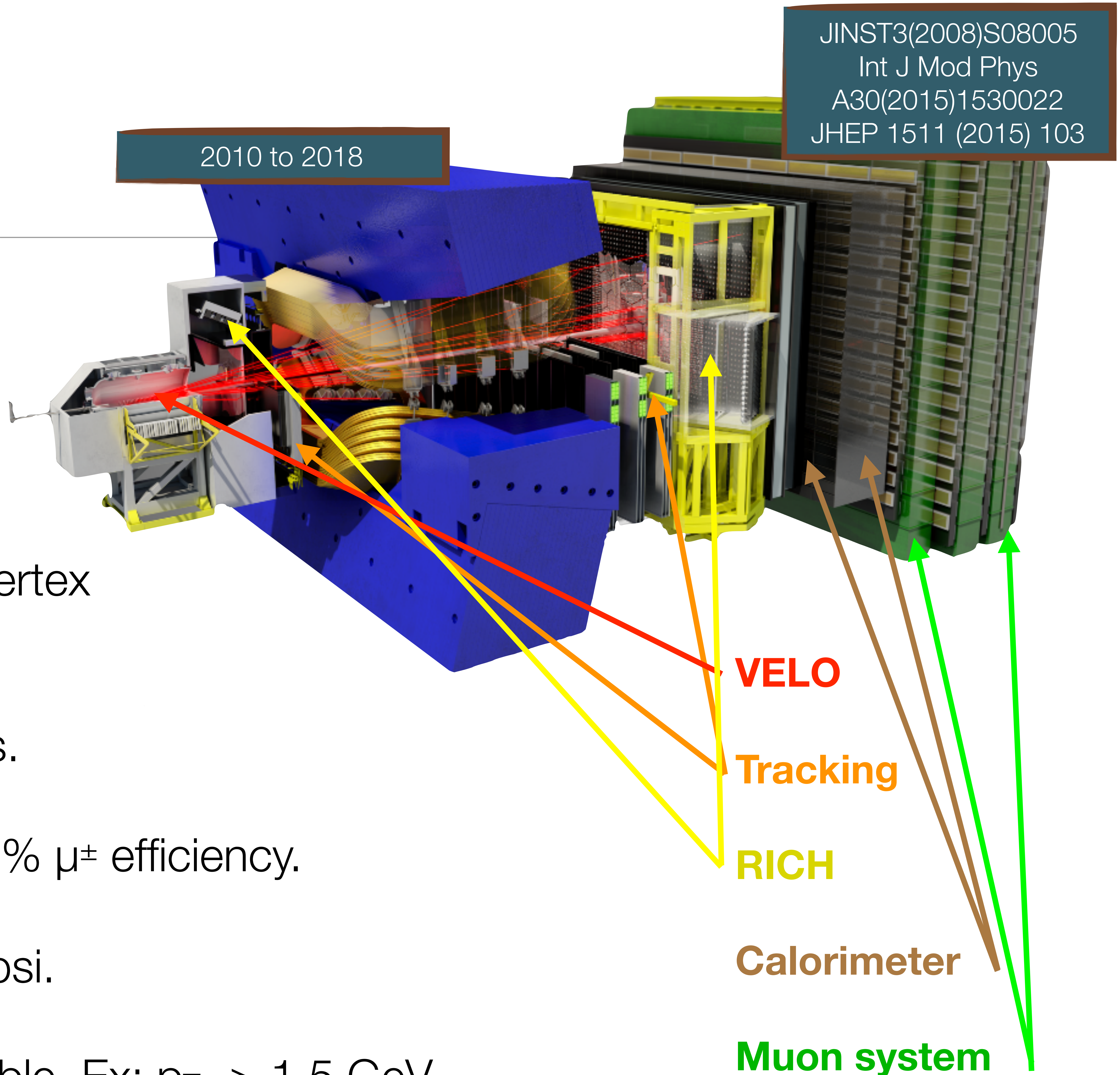
STEALTH physics at LHCb - Santiago, Spain
February of 2020

Landscape today / 1

- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **the future of LHCb**
- **Landscape**: LHC results in brief:
  - Direct searches for **NP** by **ATLAS** and **CMS** have not been successful so far
    - Parameter space for popular **BSM** models is **decreasing rapidly**, but only < 5% of the complete HL-LHC data set has been delivered so far
    - NP discovery **still may happen**!
  - **LHCb** reported intriguing hints for the violation of lepton flavour universality
    - In $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to s e^+ e^-$ / $b \to s \mu^+ \mu^-$ decays
  - Possible evidence of **BSM** physics **if substantiated** with further studies (e.g. **BELLE II**)

LHCb detector / 1

- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC ($1.9 < \eta < 4.9$) (~1°-15°)
- **Precise vertex reconstruction** < 10 μm vertex resolution in transverse plane.
- Lifetime resolution of ~ 0.2 ps for $\tau = 100$ ps.
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency.
- Great **mass resolution**: e.g. 15 MeV for J/psi.
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu} > 1.5$ GeV.



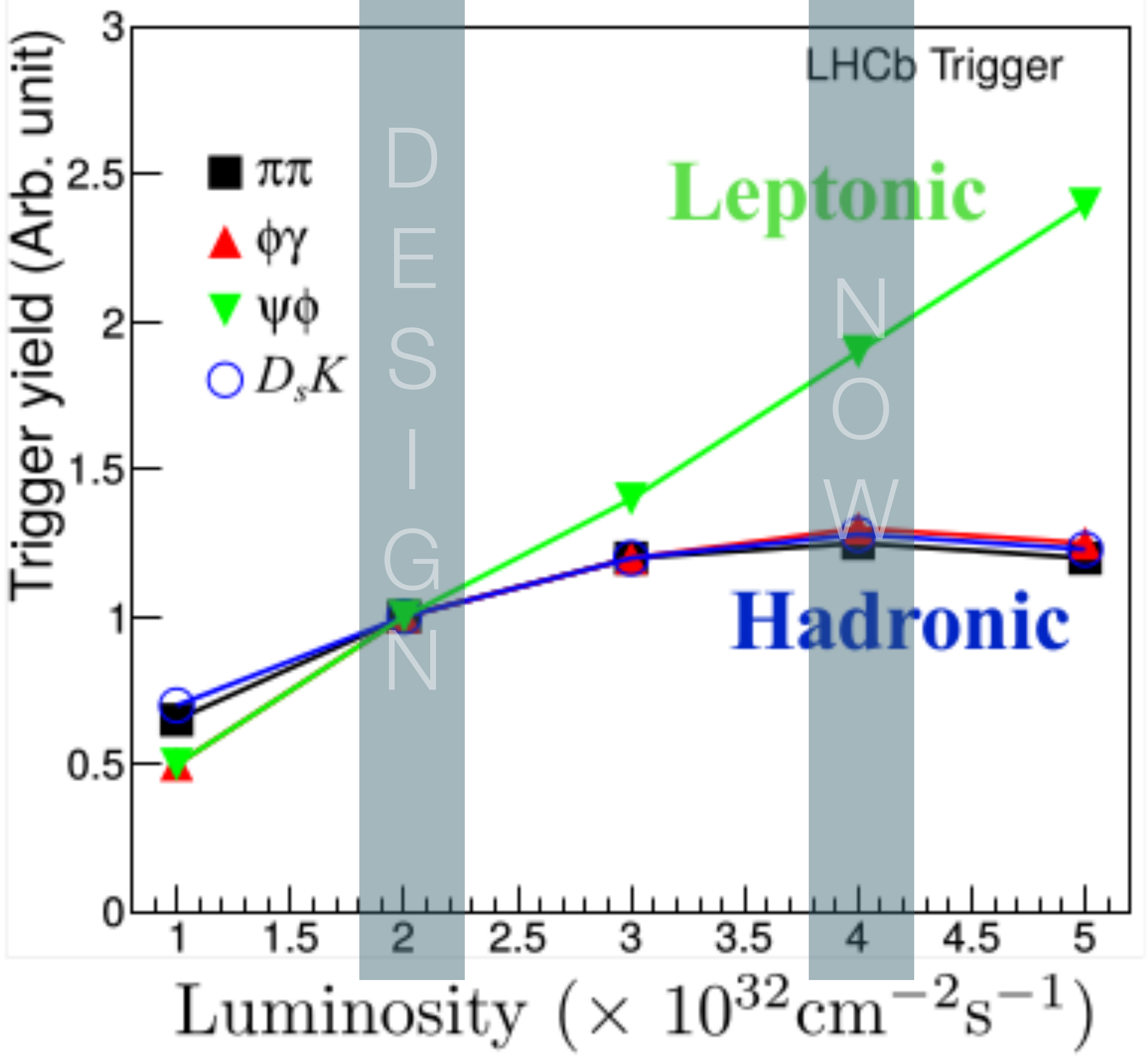
LHCb Timeline / 1

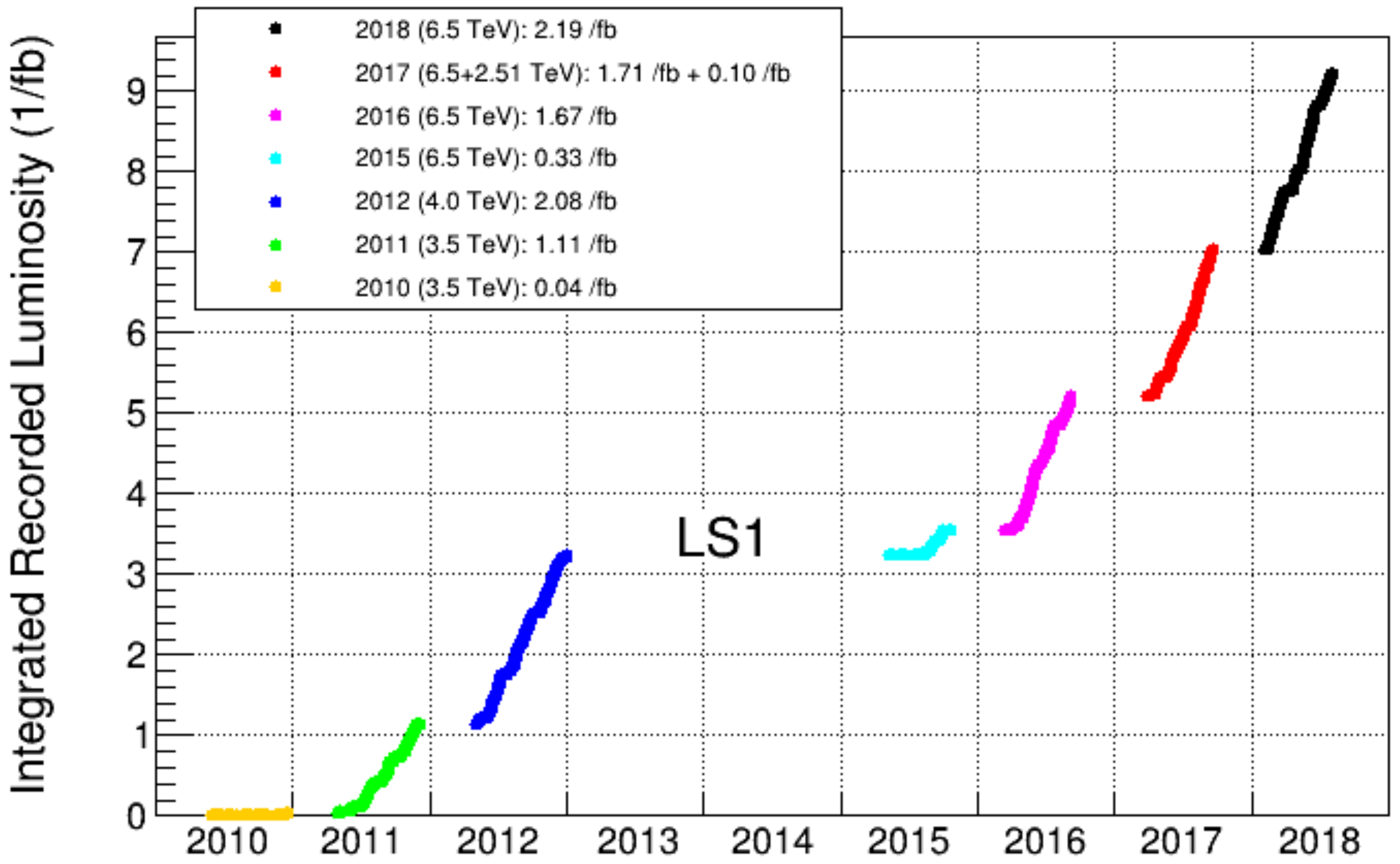
- The amount of data and the physics yield from data recorded by the current LHCb experiment is **limited by its detector**:
- But **LHC** will **increase its performance**:
  - **Energy / beam** (3.5 to 4 to 6.5 to 7 TeV)
  - **Luminosity** (peak $8x10^{33}$ to $2x10^{34}$ $cm^{-2}s^{-1}$ to HL-LHC)
- Timeline of the Upgrades is in line with LHC timeline but **asynchronous w.r.t. CMS and ATLAS**
  - Where Phase II will happen in LS2

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
LS2		RUN 3			LS3			RUN 4			LS4		RUN 5	
LHCb 40 MHz Upgrade Ia		$L = 2x10^{33}$			LHCb Upgrade Ib			$L = 2x10^{33}$; **50 fb^{-1}**			LHCb Upgrade II (proposed)		$L = 2x10^{34}$; **300 fb^{-1}** (proposed)	

LHCb Phase-Ia upgrade / 2

- First-level (L0) **hardware trigger is limited** at higher luminosities for hadronic channels:
  - Almost a factor 2 between di-muon events and fully hadronic decays
  - Due to trigger criteria based on p_T and E_T to reduce trigger rate to the bandwidth limited to 1.1 MHz
- Any **higher luminosity = harsher** cuts on p_T and E_T
  - Waste luminosity while not retaining amount of data
  - **Increases complexity** of track reconstruction = higher computational times in processing farm
- Ageing and fast degradation of sub-detectors designed to operate 5 yr at $2\text{x}10^{32}$ $cm^{-2}s^{-1}$ currently reaching 7 yr at $>3\text{x}10^{32}$ $cm^{-2}s^{-1}$





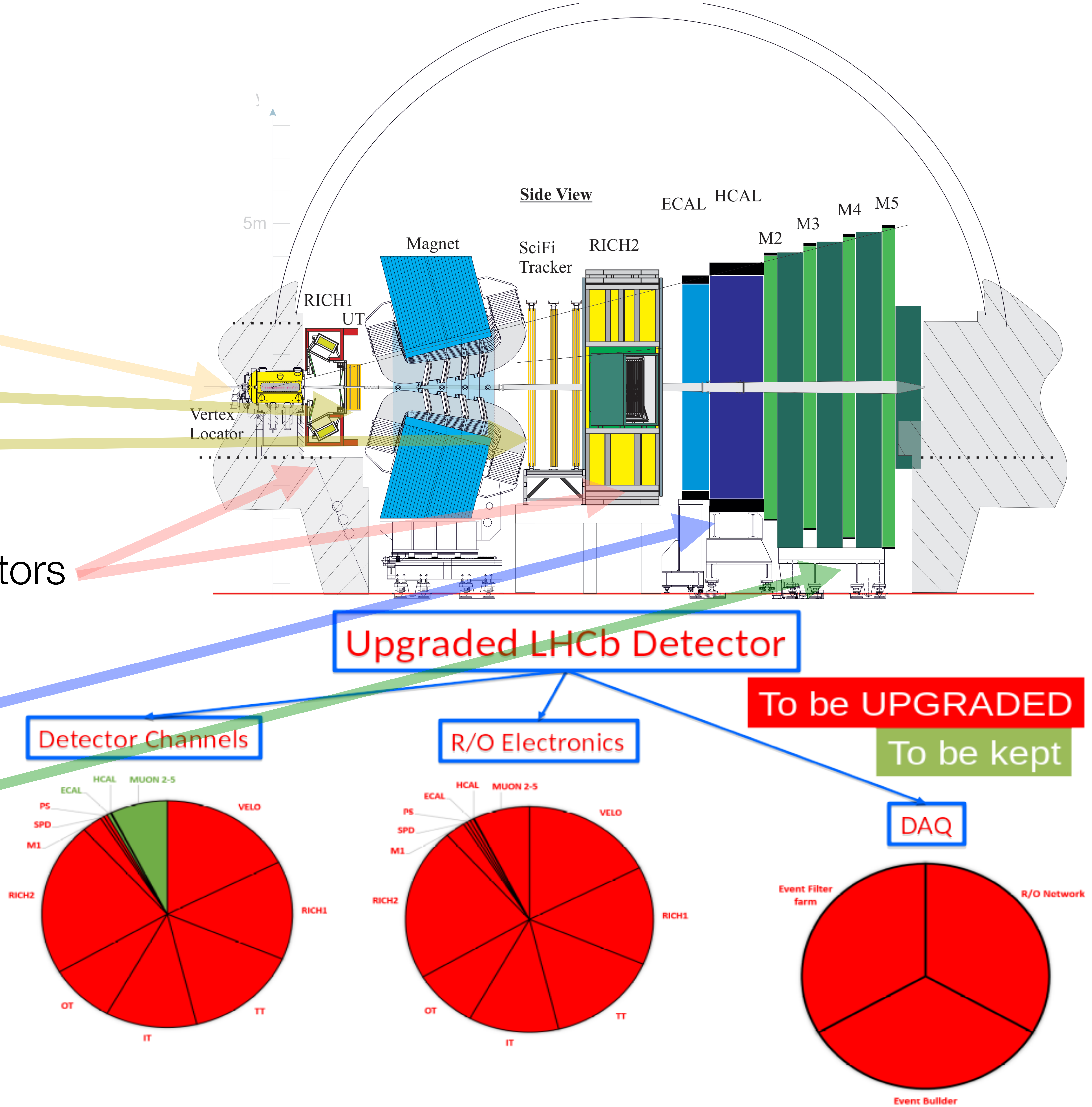
Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

Observable	Current LHCb
EW Penguins	
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]
	–
CKM tests	
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]
$a_{\rm sl}^s$	33×10^{-4} [211]
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]
$B_s^0, B^0 \to \mu^+\mu^-$	
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]
$S_{\mu\mu}$	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies	
$R(D^*)$	0.026 [215, 217]
$R(J/\psi)$	0.24 [220]
Charm	
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]
A_Γ ($\approx x \sin\phi$)	2.8×10^{-4} [240]
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]

σ(stat)/σ(sys)	Largest source of systematic
2.5	Mass shape & trigger eff
2.2	MC correction & residual bkgd
3	Δm_s, time res, tagging, det asymmetry
-	
8	Decay time: bias and efficiency
8	Angular efficiency
8	Decay time resolution
5	Acceptance (angular and time)
1.3	Track reco asymmetry
0.5	External BR(Λ_c)
6	f_d/f_s
9	Decay time acceptance
1	MC sample size
1	F($B_c \to J/\psi$) form factor
2.7	Mass model
2.8	Contribution from sec $b \to D^*X$ decays
2	Contribution from sec $b \to D^*X$ decays

LHCb Phase-Ia upgrade / 3

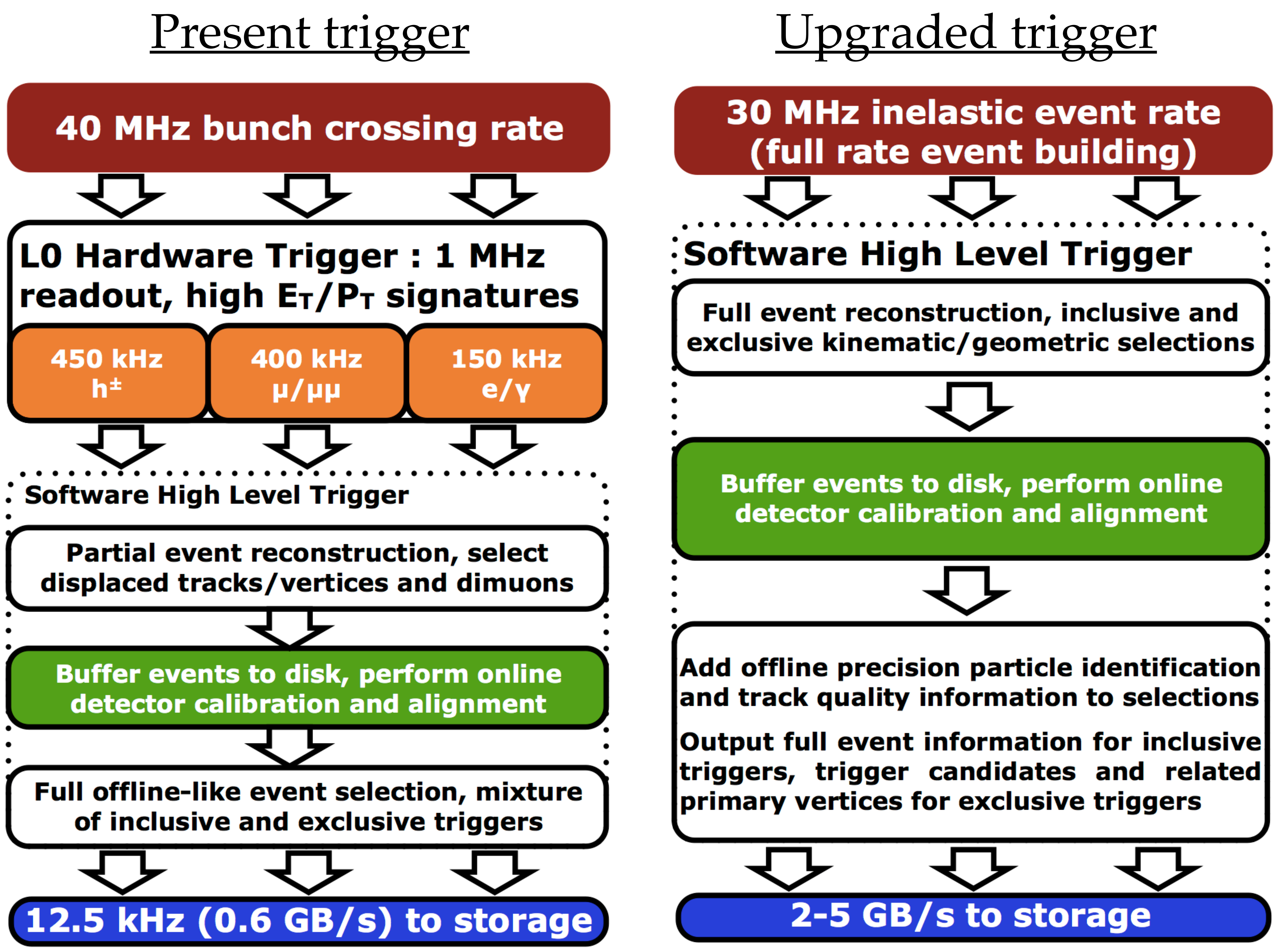
- **New Vertex Locator**
- New silicon strip detector
- New scintillating fibre detector
- Particle ID: new optics, new photon detectors
- Calorimeters: reduce PMT gain and new electronics
- Muon: new electronics and increased granularity
- **No hardware trigger**



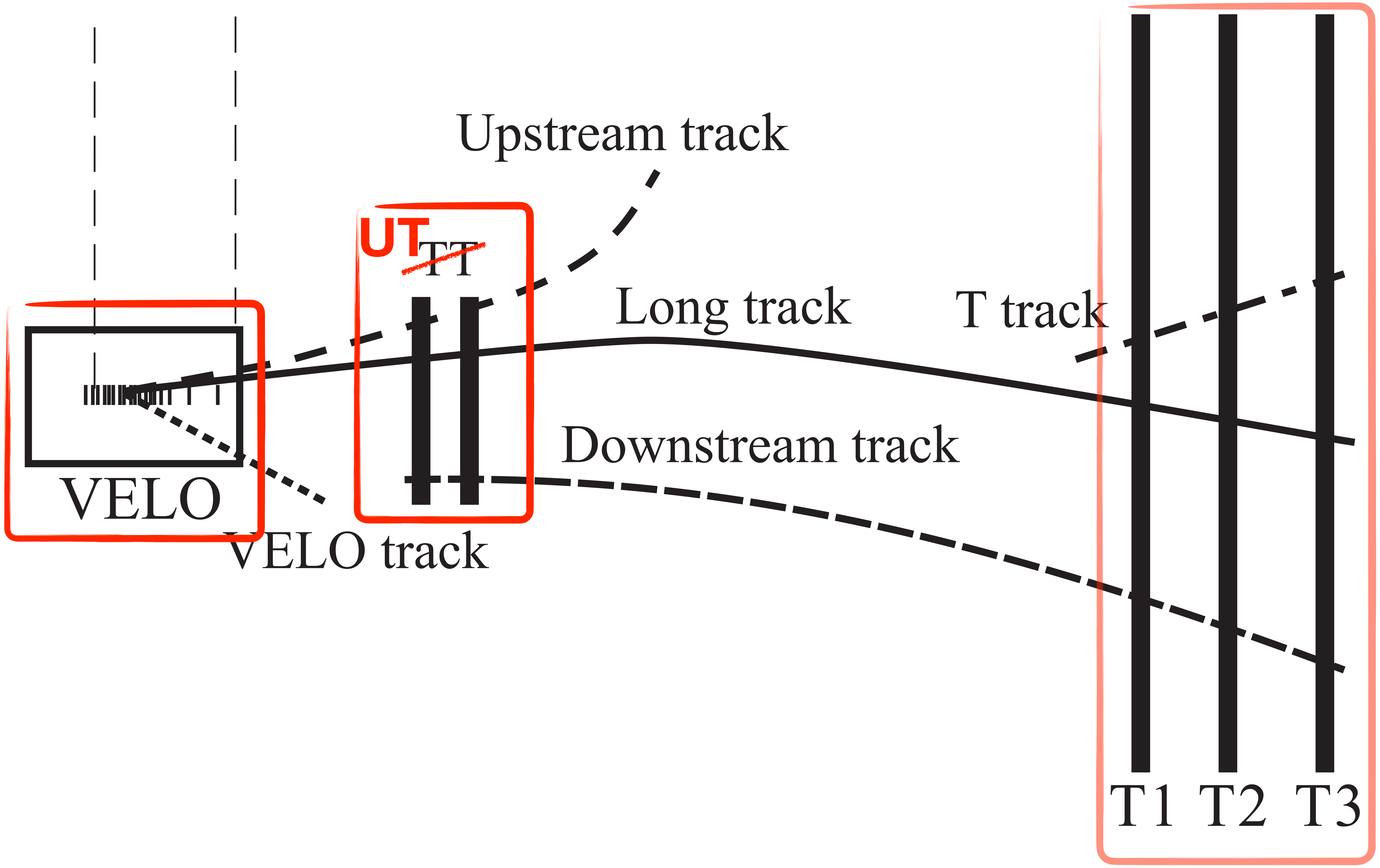
Trigger / 1

- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- Hardware **L0 trigger** to be removed
- **Full real-time** reconstruction for all particles available to select events (since 2015)
  - **Real-time reconstruction** for all charged particles with $p_T > 0.5$ GeV
  - We go from 1 TB/s (post zero suppression to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a **hardware-less readout system** for LHC Run 3 (2021-2023) and process 5 TB/s in real time on the CPU farm.

(More details in yesterday's talk by Miguel)

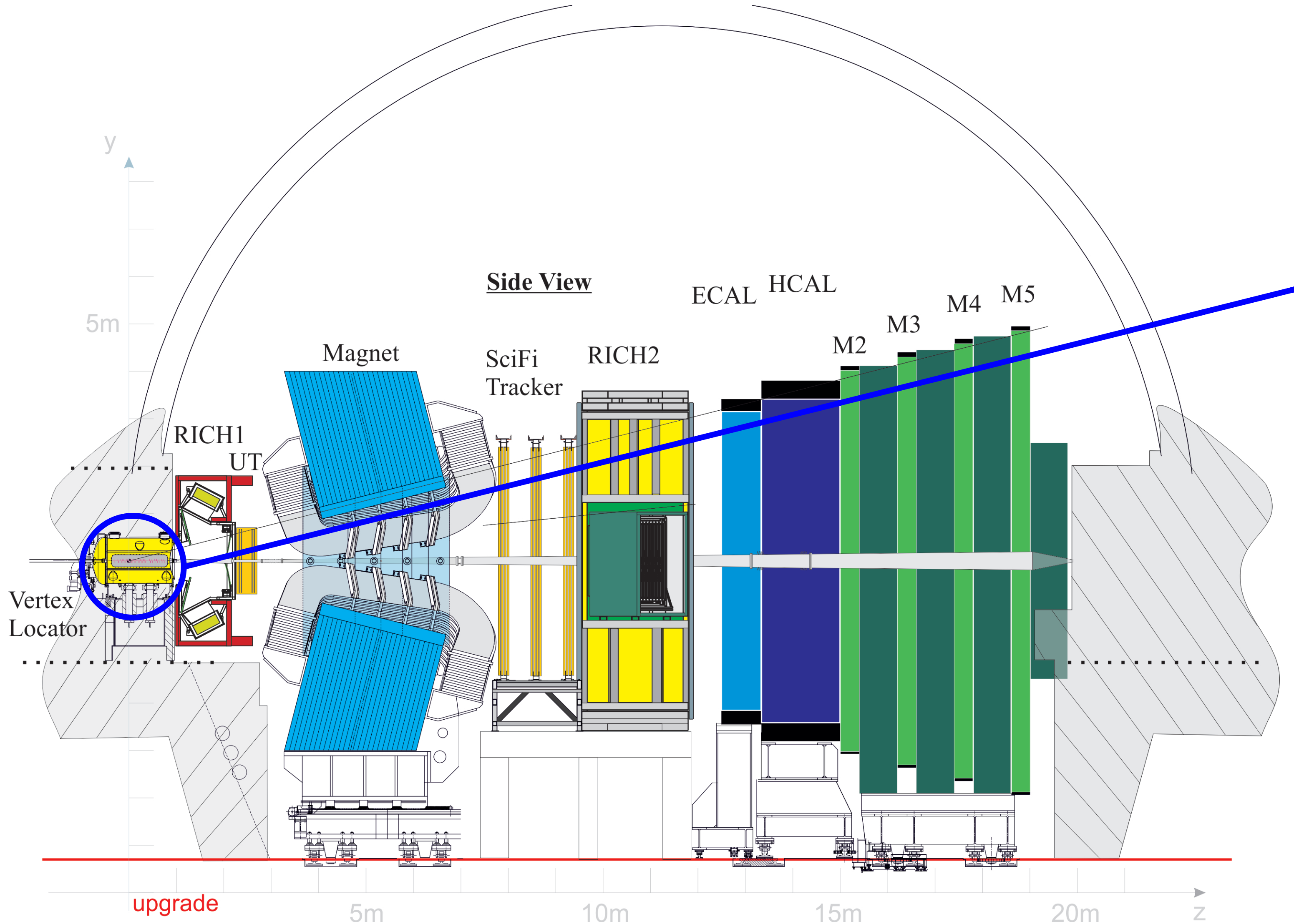


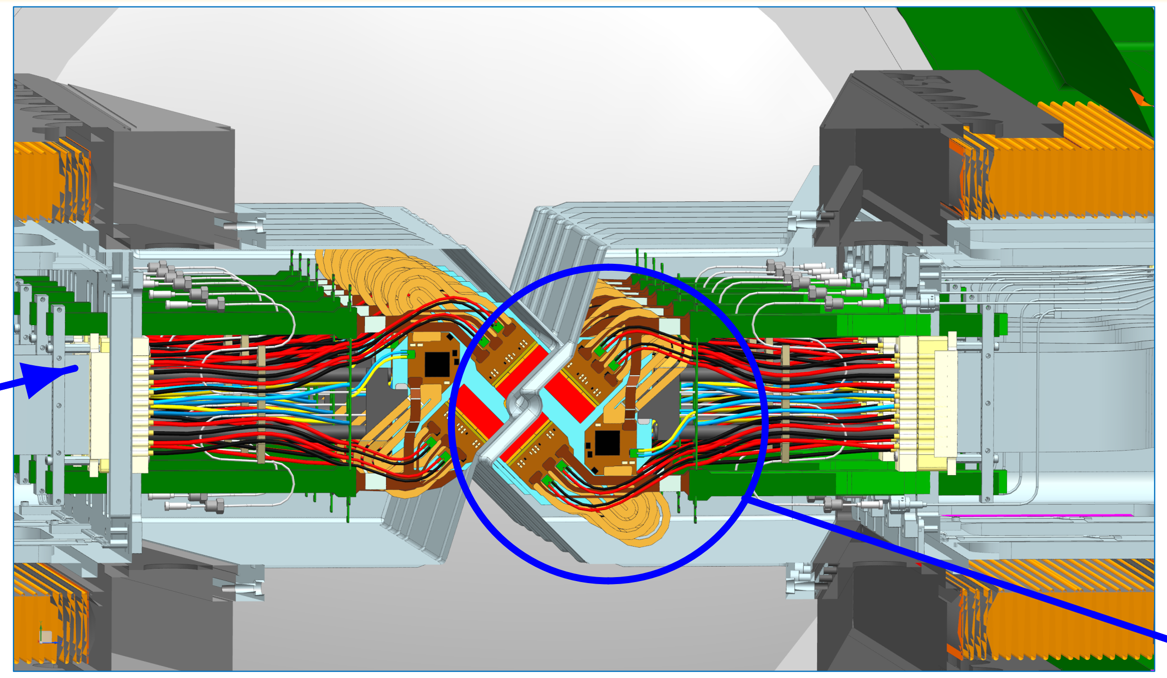
LHCb track types / 1

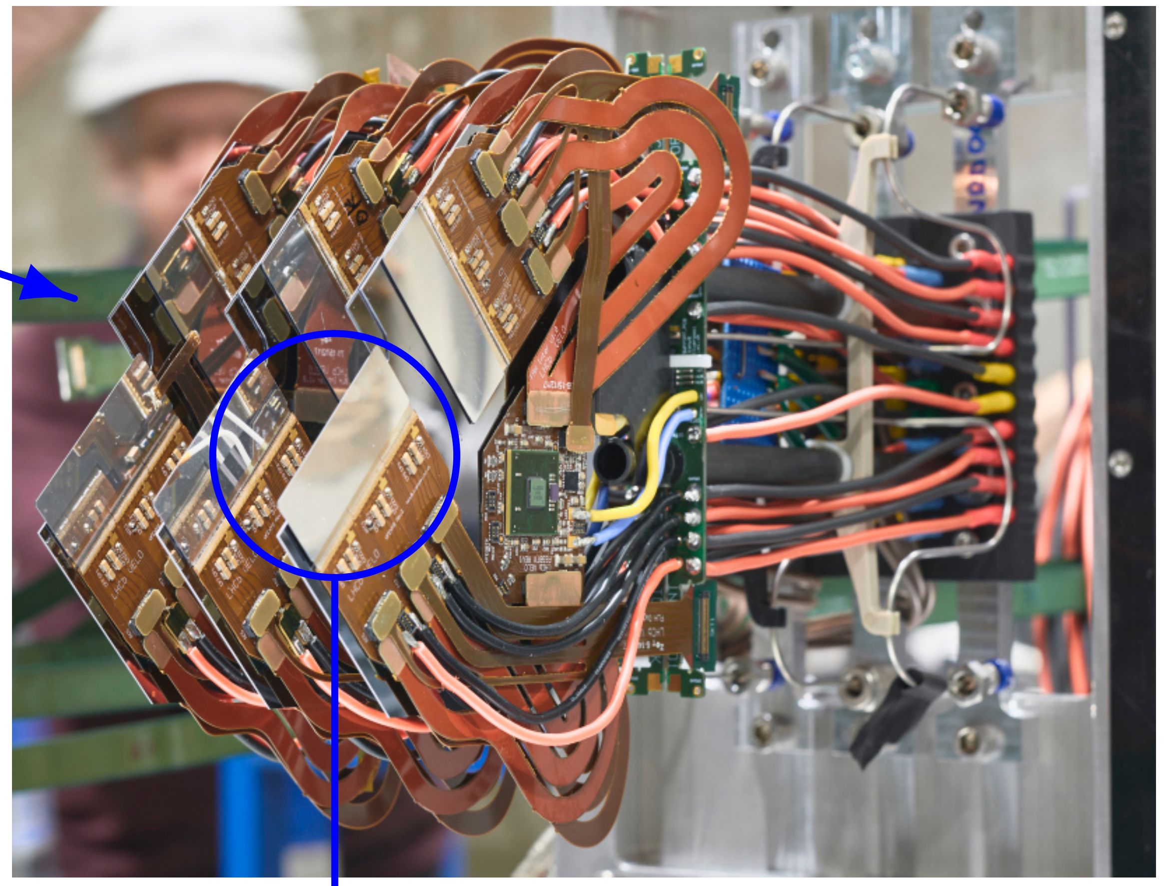


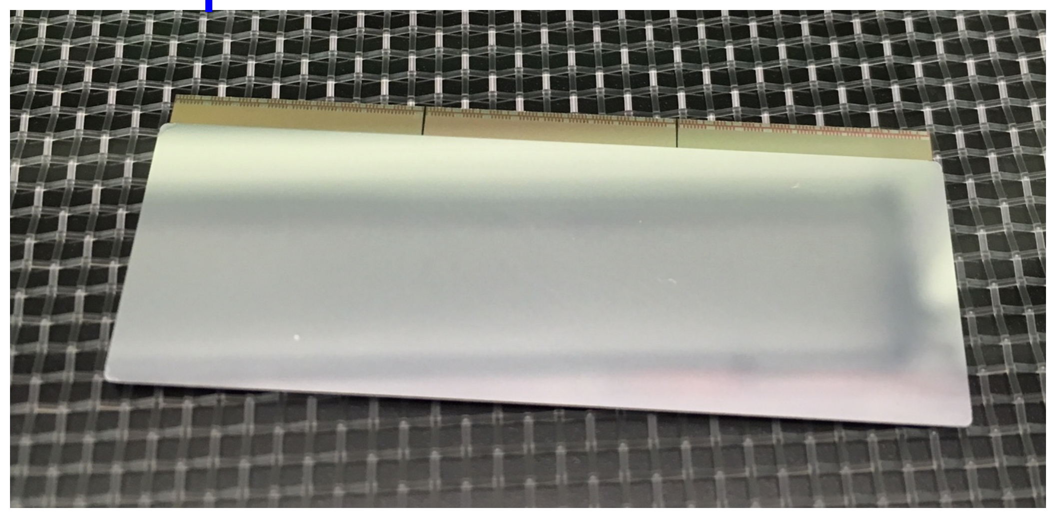
CERN-LHCC-2013-021 and LHCB-TDR-013

VELO / 1







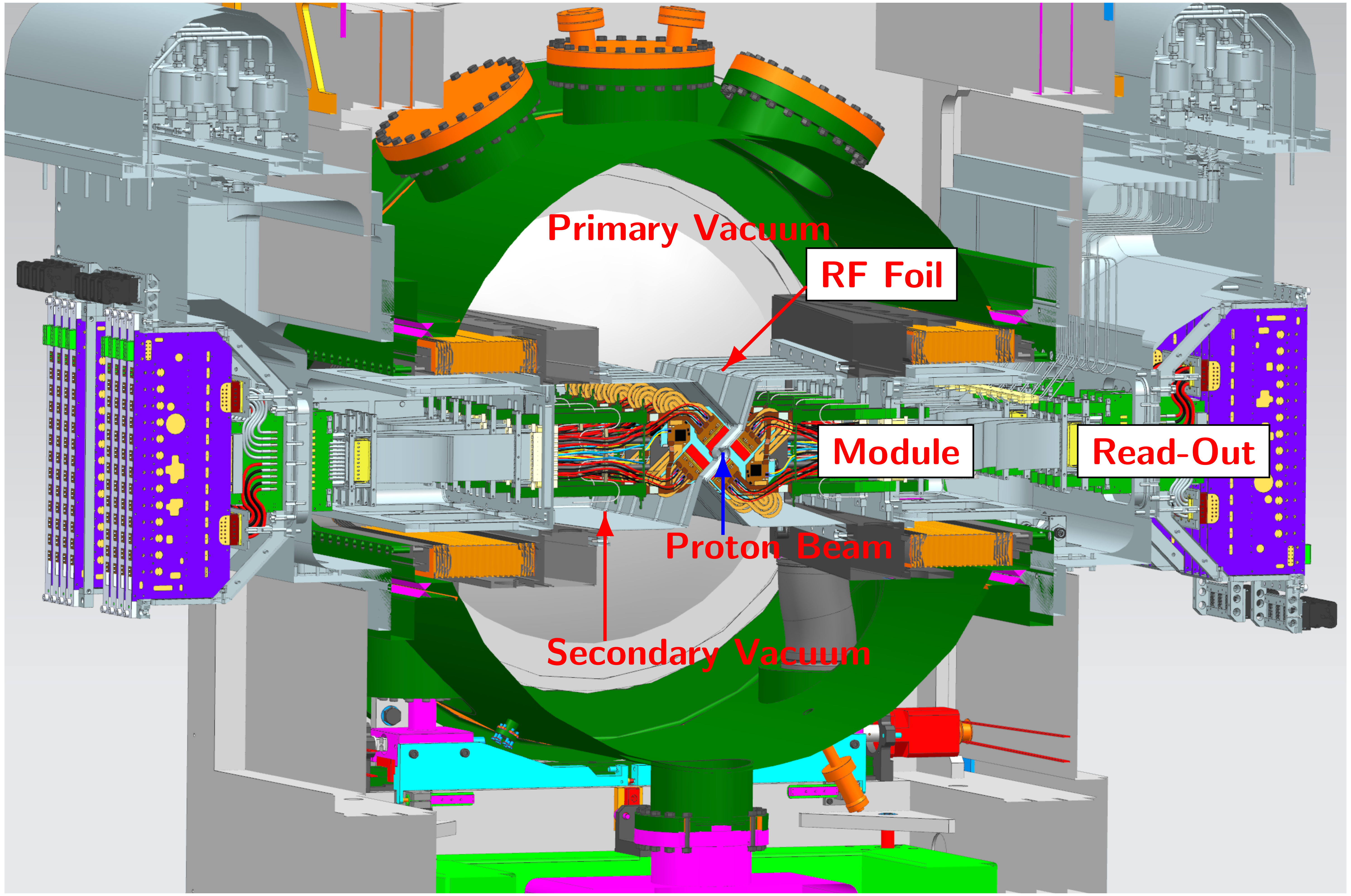


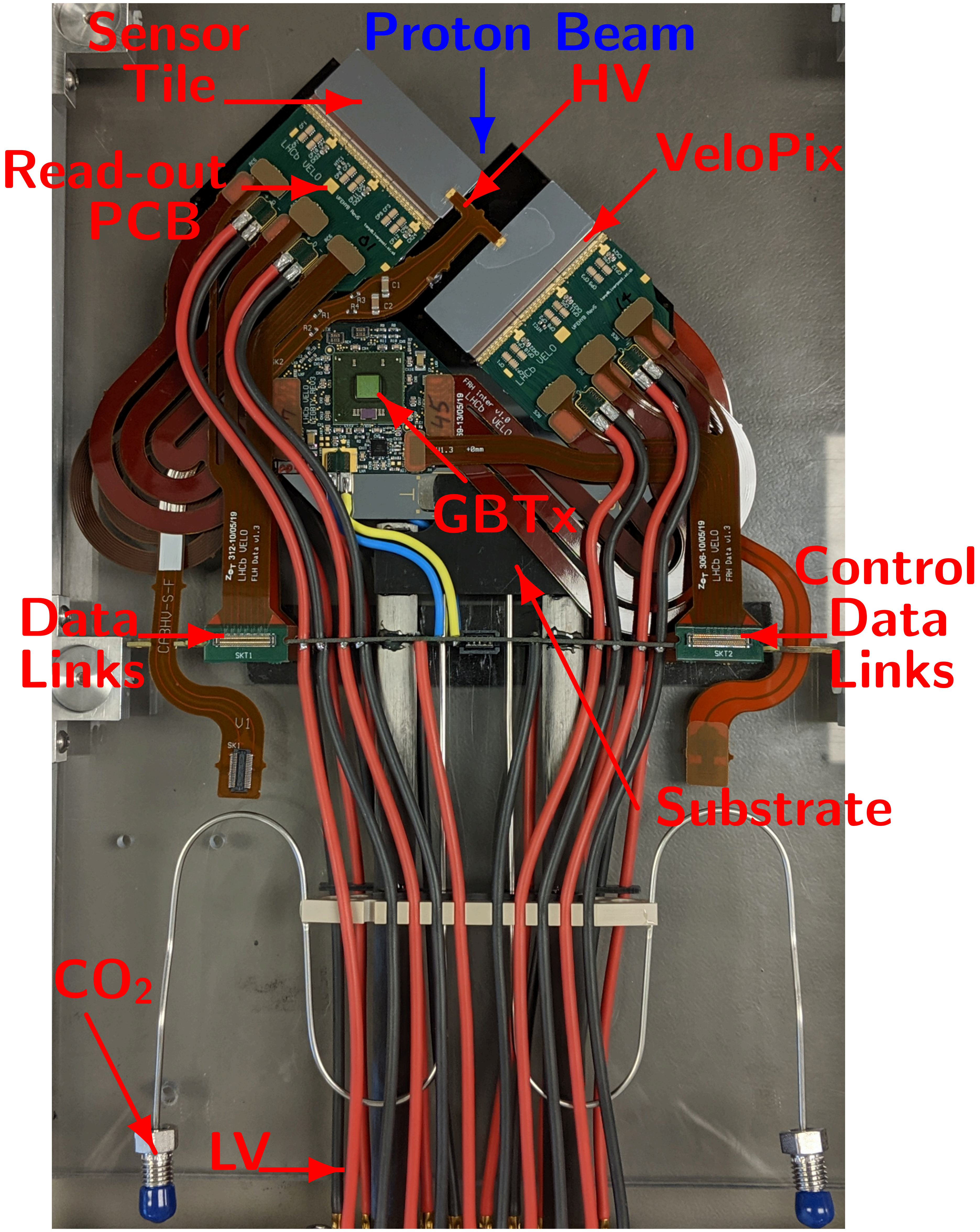
- Increased data rate
- Improve performance
  - → Reduce material budget
  - → Reduce inner radius of active silicon to 5.1mm

⇒ Requires increased radiation hardness

- Completely new silicon pixel detector
  - Based on MediPix/TimePix technology

VELO / 2

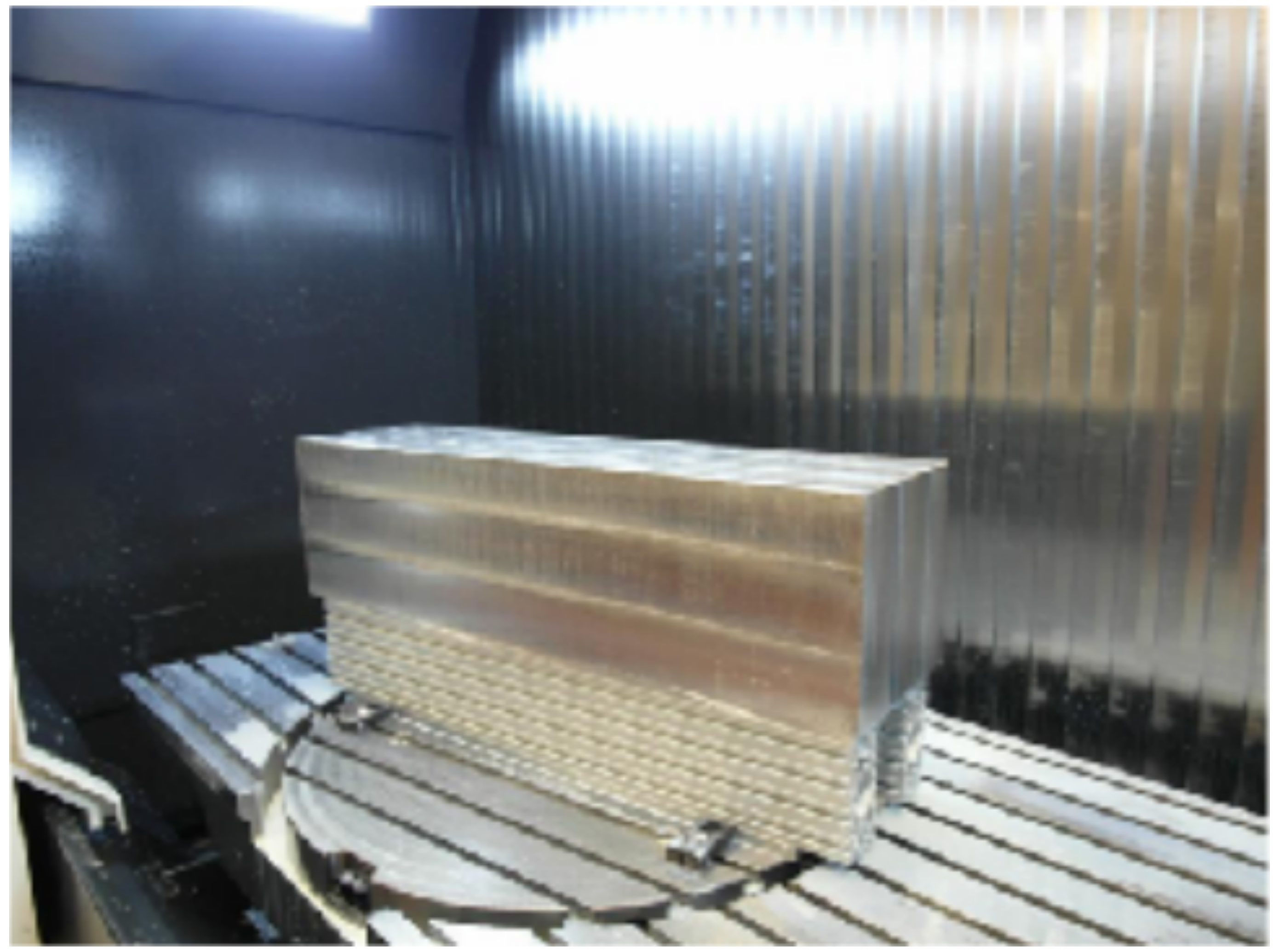

Primary Vacuum
RF Foil
Module
Read-Out
Proton Beam
Secondary Vacuum


Sensor Tile
Proton Beam
HV
VeloPix
Read-out PCB
GBTx
Control Data Links
Data Links
Substrate
CO2
LV

CERN-LHCC-2013-021 and LHCB-TDR-013

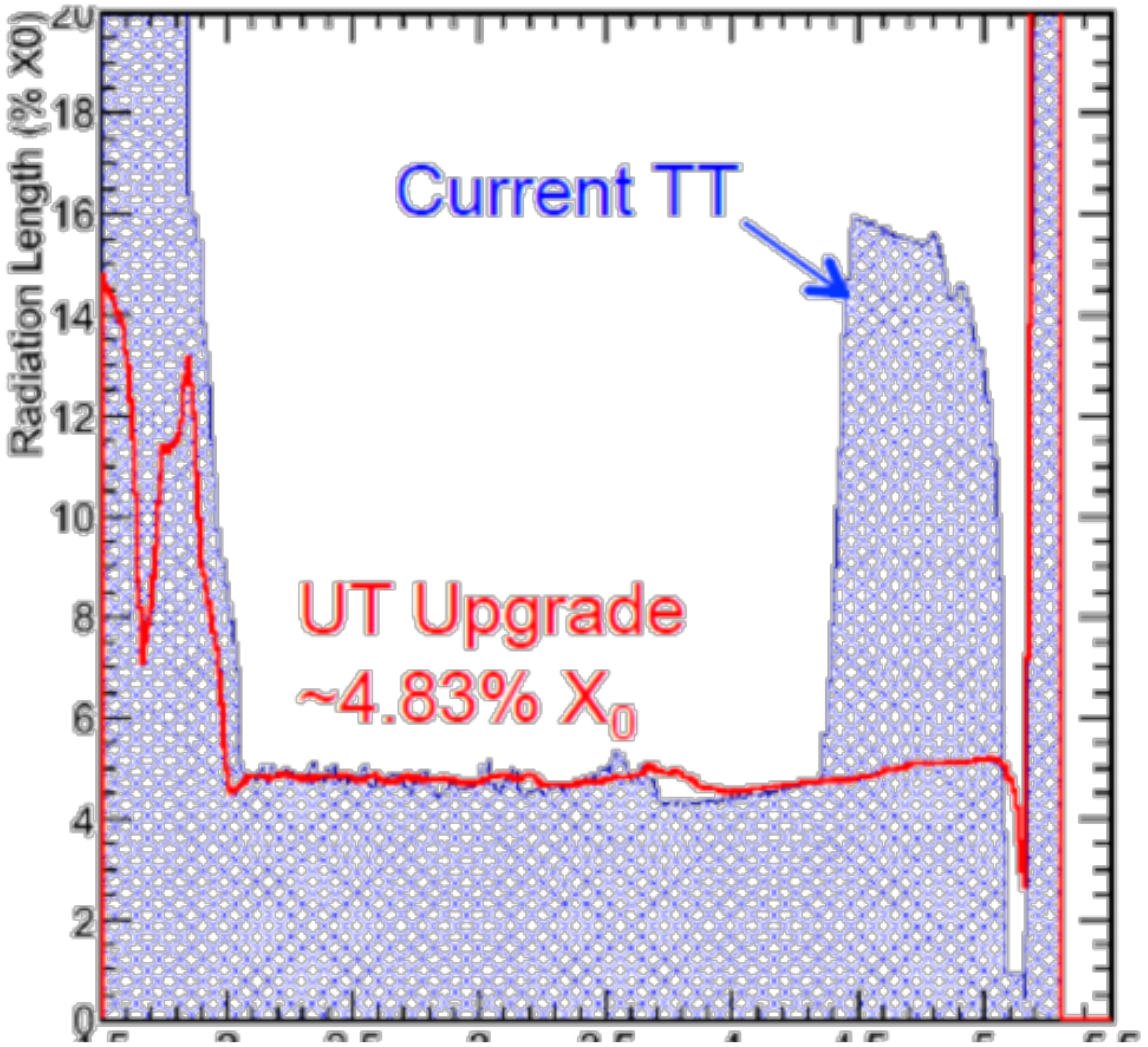
VELO / 3

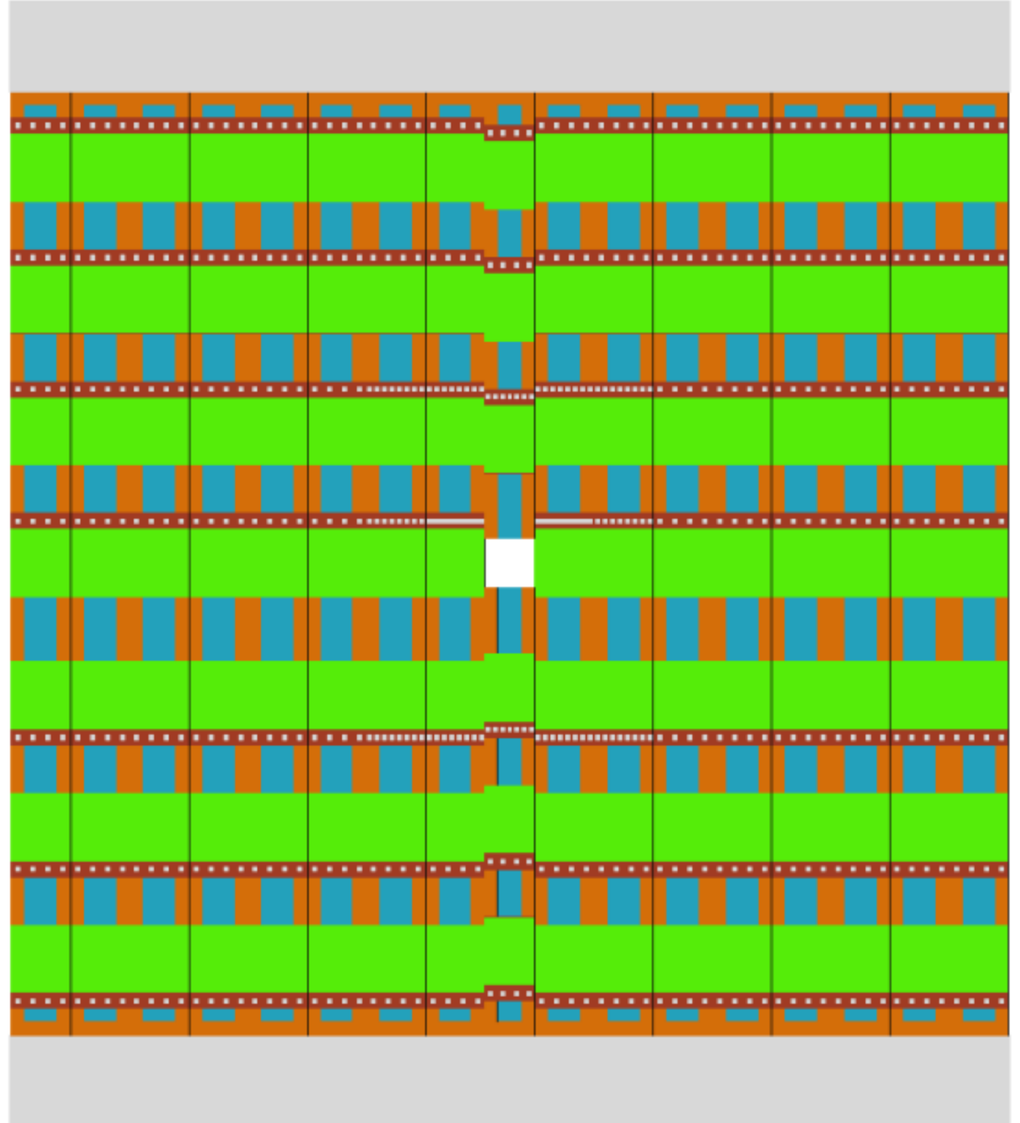
- **Example**: the RF foil separates primary to secondary vacuum
- **Guide** beam-induced **current**
- RF **shielding** for electronics
- It uses **as little** material as possible
- Withstand 10 mbar pressure difference
- Dimensions: **1m × 0.2m × 0.4m**
- Start from a single, forged **AlMg3** alloy block
- **98%** of material is milled away (6 months)
- Final thickness at tips of modules: on average **250 μm**

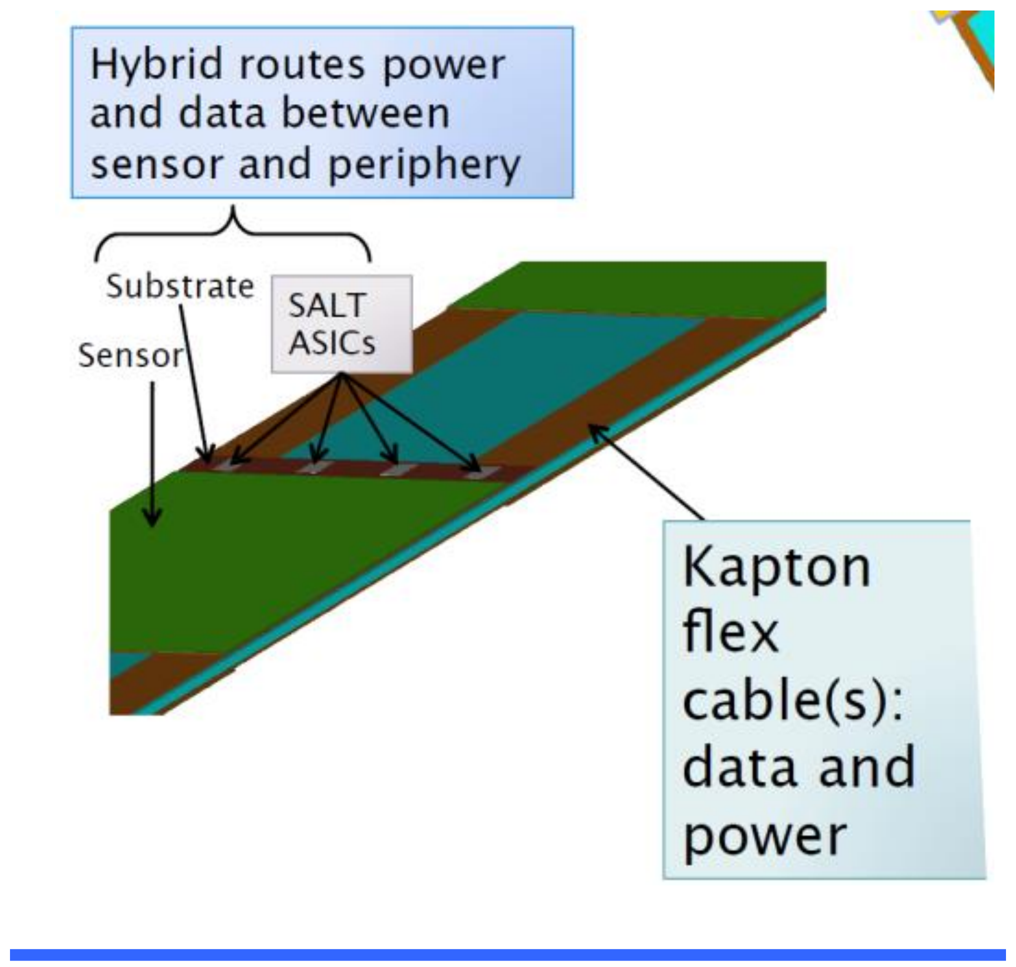


Upstream Tracker / 1

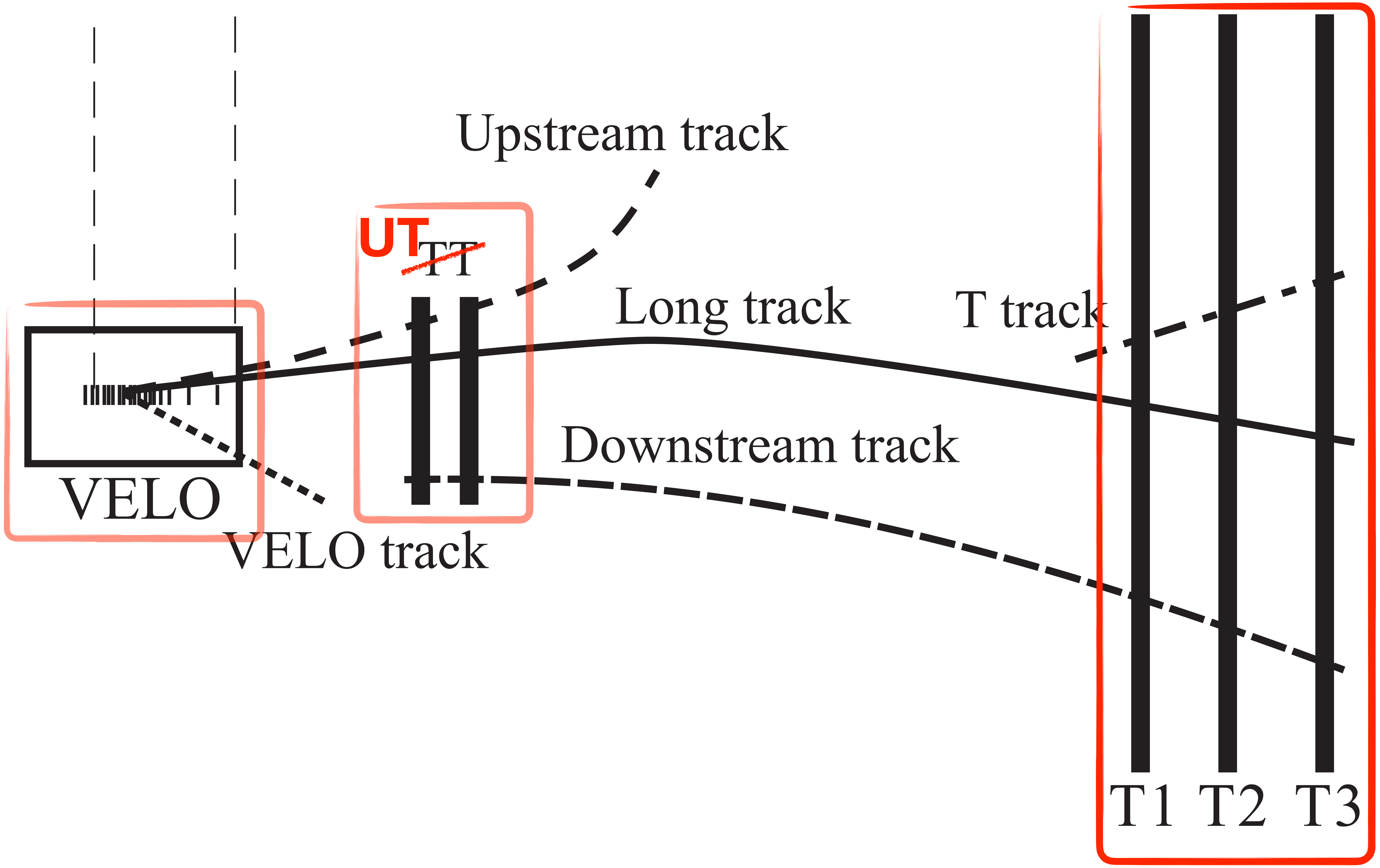
- **4 stations** with silicon microstrip detectors: **XV-UX**
- Finer segmentation:
  - Better coverage, no gaps
    - Innermost cut-out at **34 mm**
  - Increased radiation hardness
  - Mounted onto light-weight staves
  - New read-out based on Silicon readout ASIC (extracts and digitises analogue signals from the sensor, performs digital processing and transmits a serial output data)
  - **Small material budget** (< 5% X_0)







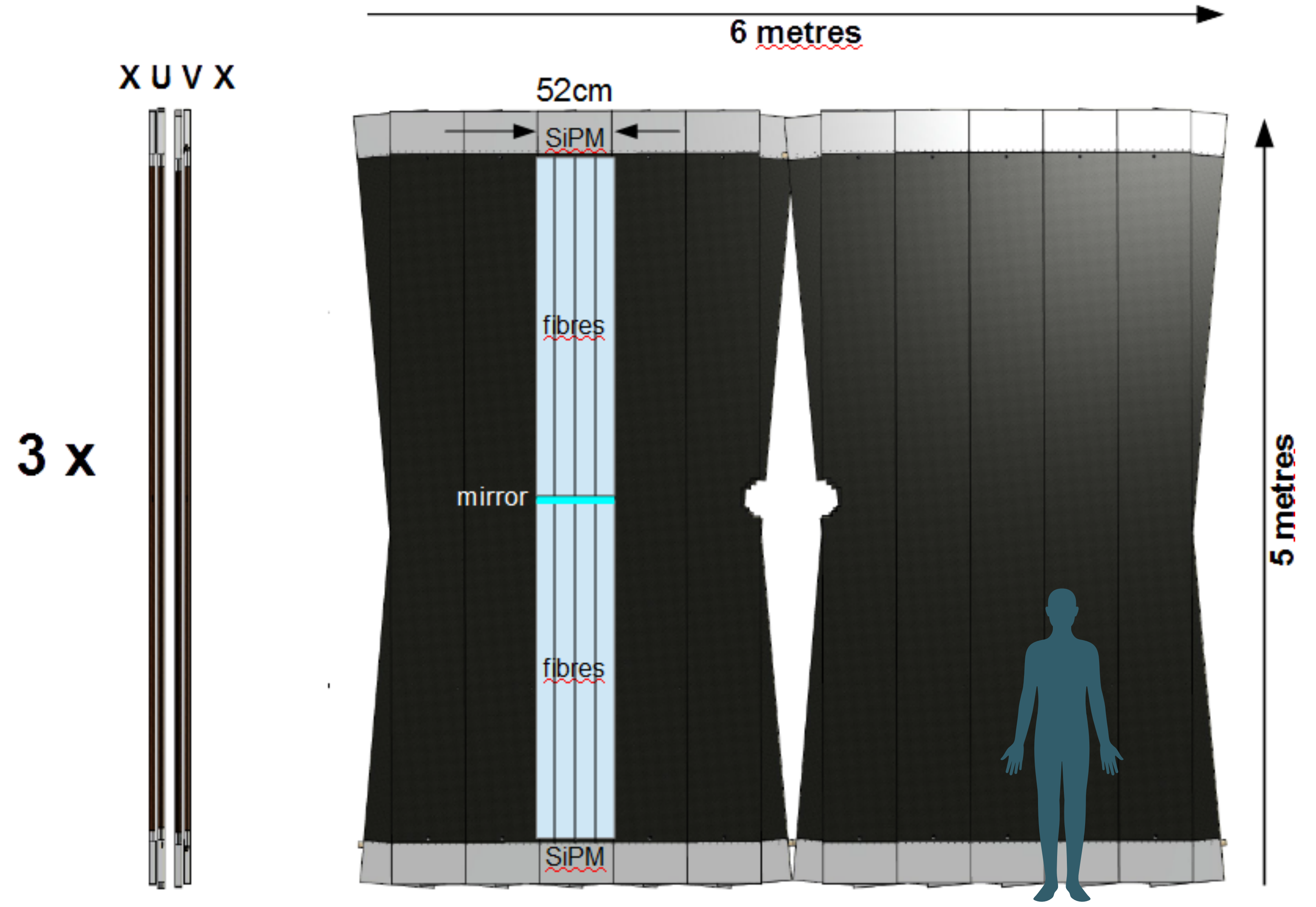
LHCb track types / 1

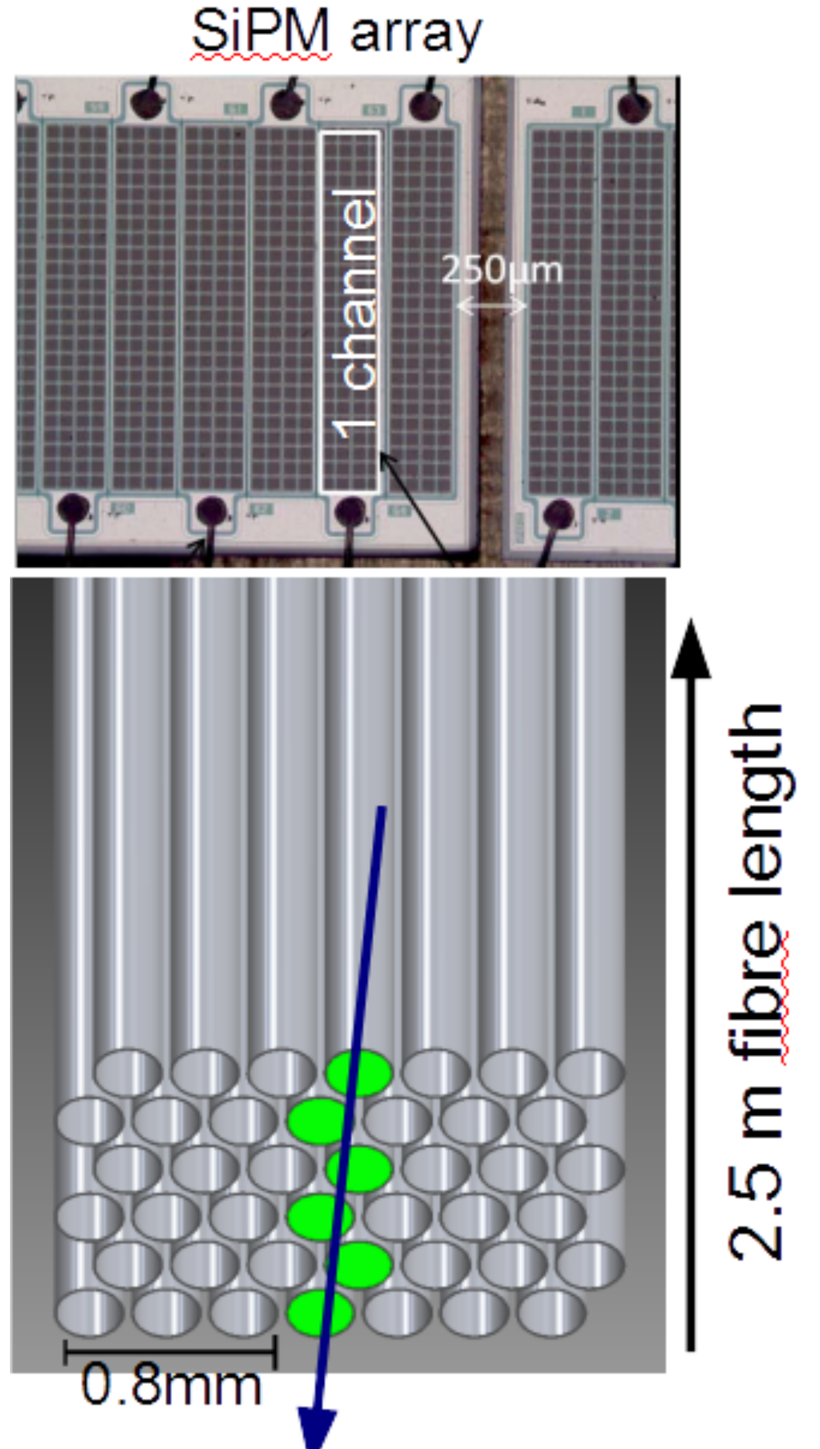


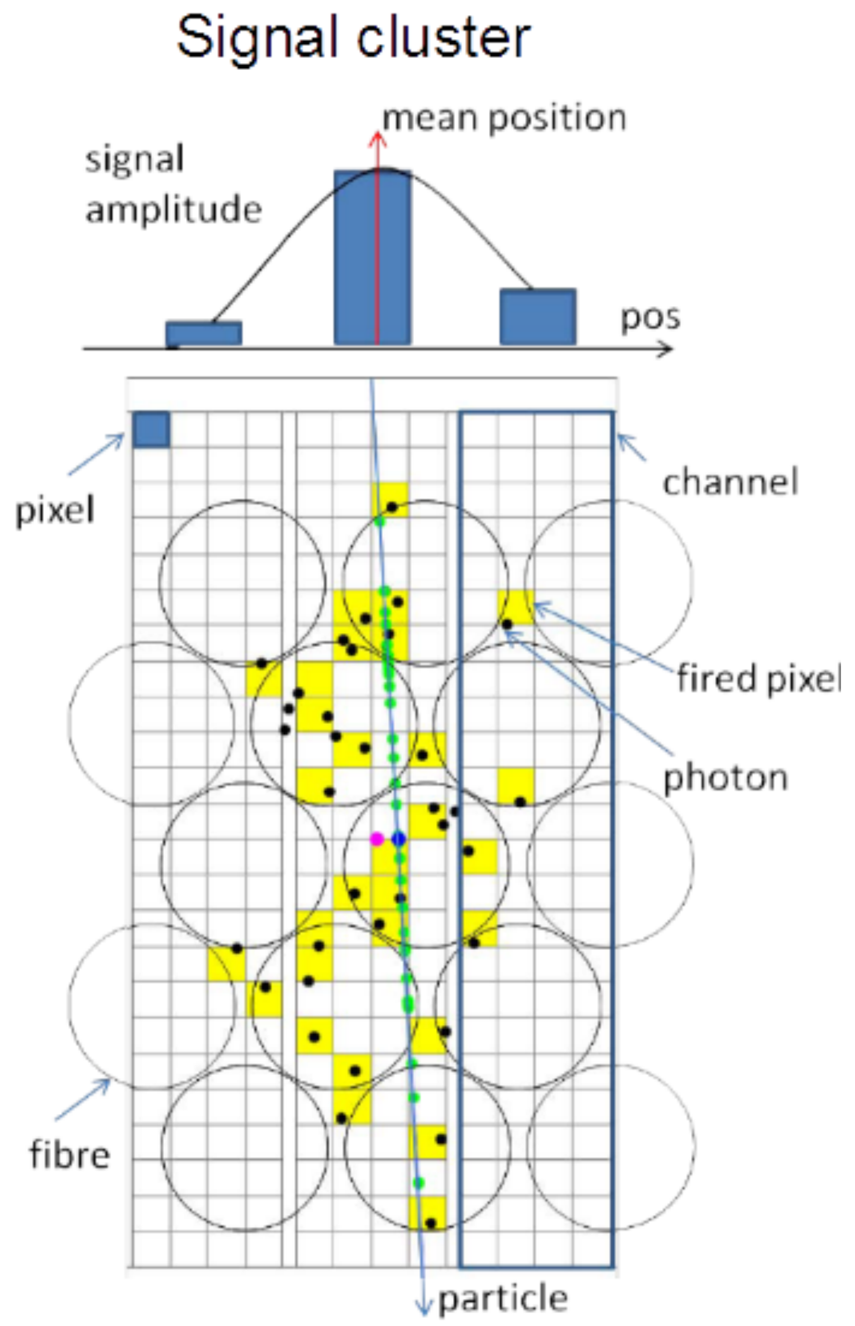
CERN-LHCC 2014-001 LHCb-TDR-013

TT / 1

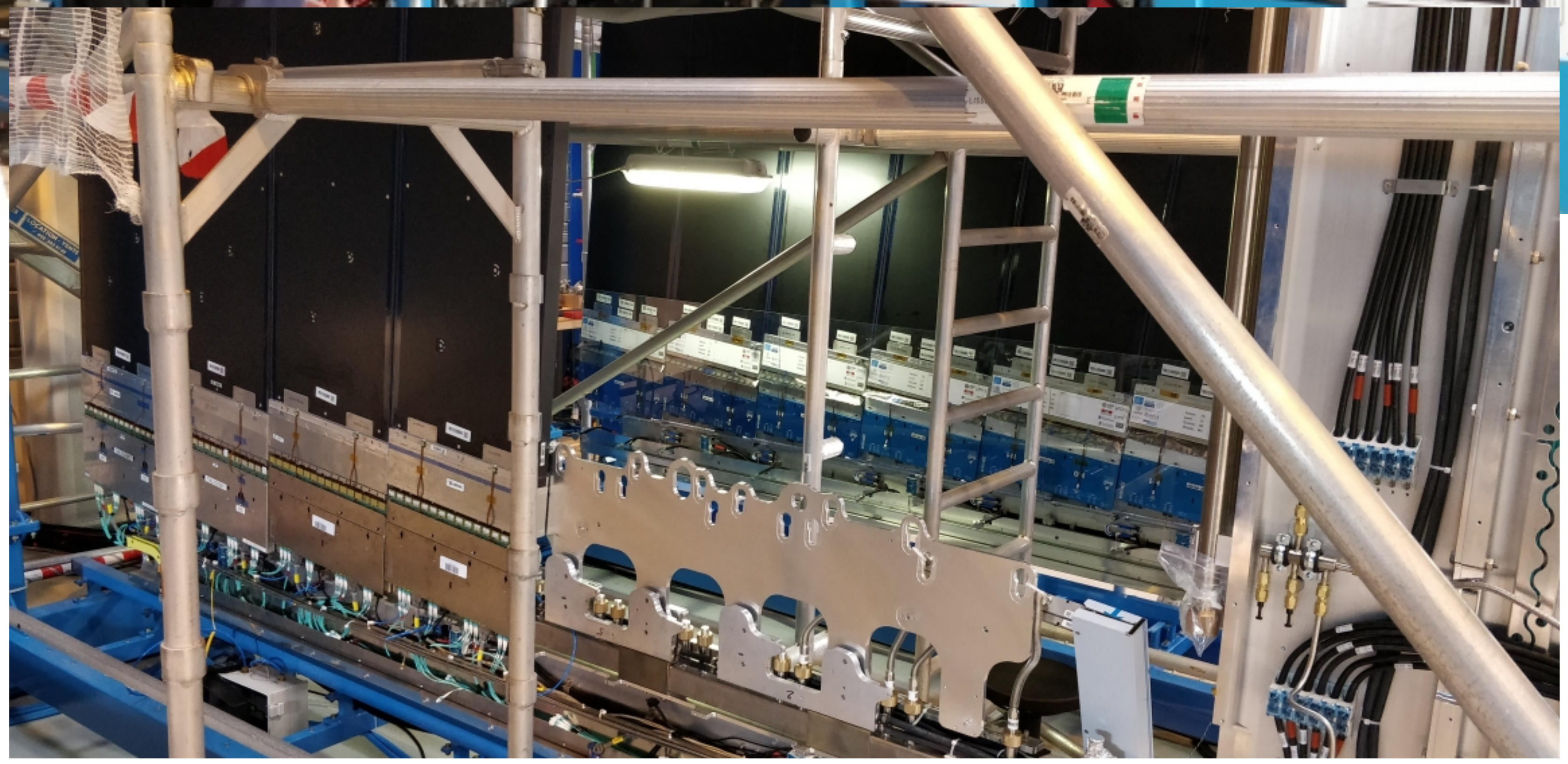
- SciFi tracker covers an area of 340 m^2
- Using more than 10 000 km of scintillating fibre
- 250 µm diameter, enabling a spatial resolution of better than 100 µm for charged particles
- 12 layers of modules in different layout (**XU-VX**)
- Silicon Photomultipliers cooled to –40° C are placed at the fibre ends
- Custom-designed front-end electronics (trigger-less)







LHCb track types / 1



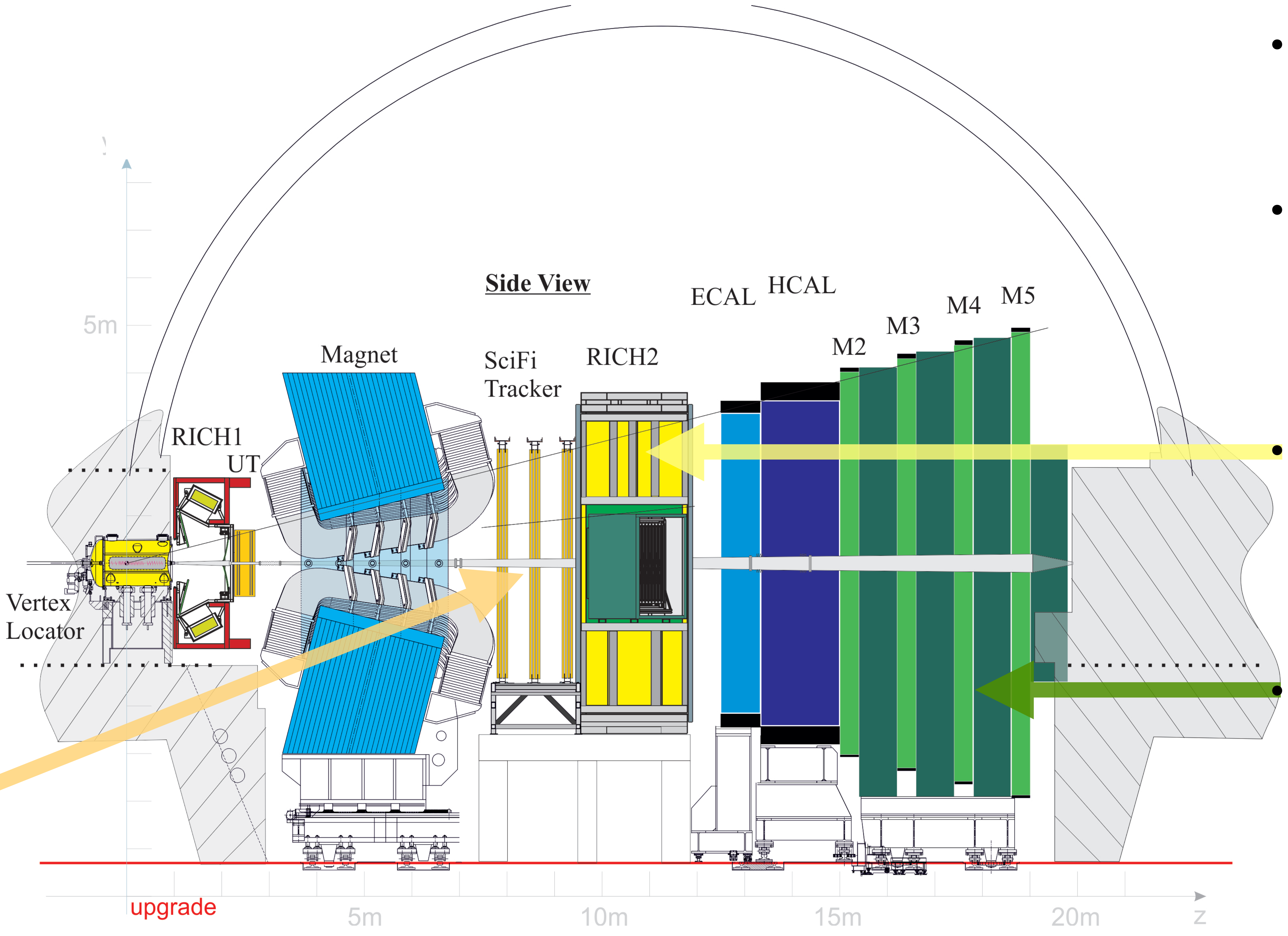
LHCb Phase-II upgrade / 1

- LHCb Phase-II upgrade can run at an instantaneous luminosity of **1.5 x 10^{34} cm^{-2} s^{-1}** and **28-55** interactions per bunch crossing which is x50-x100 more than today and x10 more than Phase-I upgrade
- Withstanding **up to 350/fb** during Run 5 and 6
- Be ready for **LHC Run 5** and to **fully exploit HL-LHC** improving even more the Phase-Ia LHCb precision
- LHCC meeting minutes: "The LHCC commends the LHCb collaboration for successfully preparing the physics case report for running beyond LS4 and supports the activities of the LHCb collaboration in planning for HL-LHC running through the preparation of TDRs"

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
LS2		**RUN 3**			LS3			**RUN 4**			LS4		**RUN 5**	
LHCb 40 MHz Upgrade Ia		L = 2x10^{33}			LHCb Upgrade Ib			L = 2x10^{33}; **50 fb^{-1}**			LHCb Upgrade II (proposed)		L = 2x10^{34}; **300 fb^{-1}** (proposed)	

LHCb Phase-II upgrade / 2

- **VELO**
  Thinner & smaller σ_t<200 ps/hit
- **UT**
  Microstrip and <u>**RETINA**</u> tracking (no CPU)
- **Magnet**
  New SciFi stations inside the dipole for low p_T tracking
- **Mighty tracker**
  New silicon around beam line

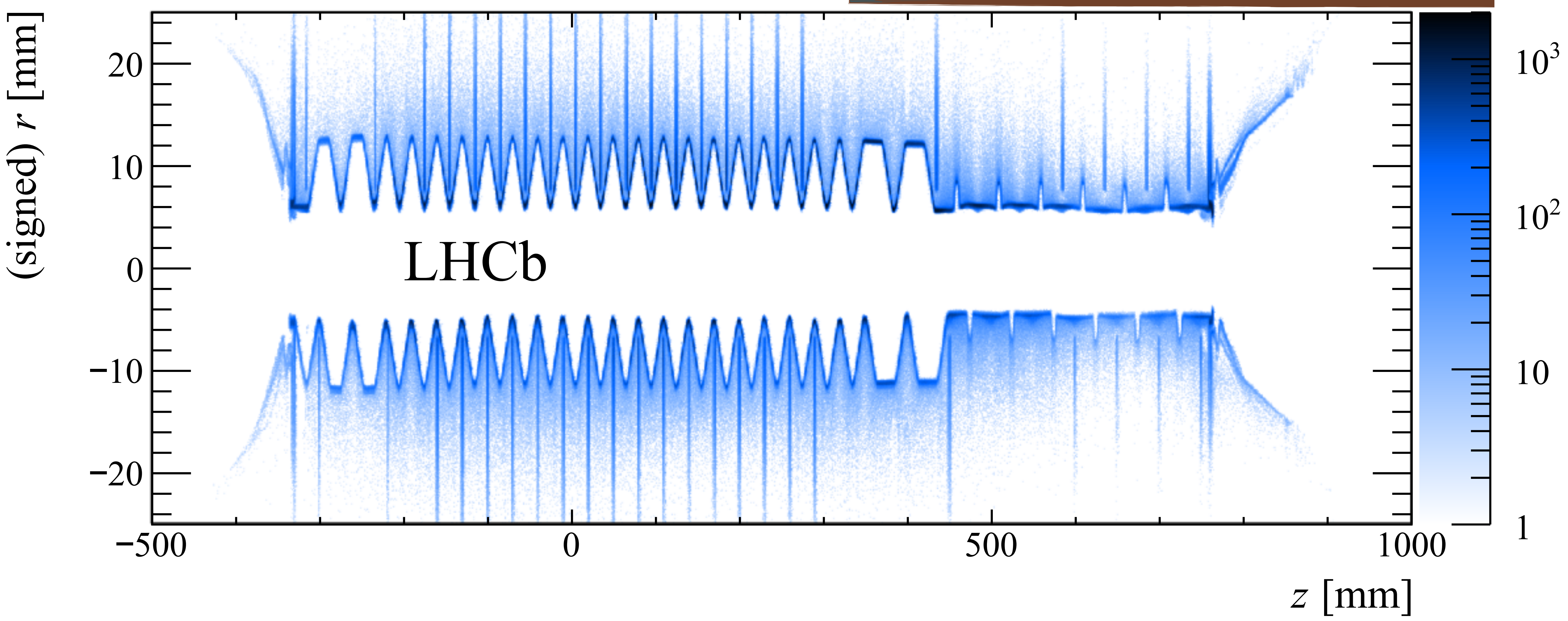


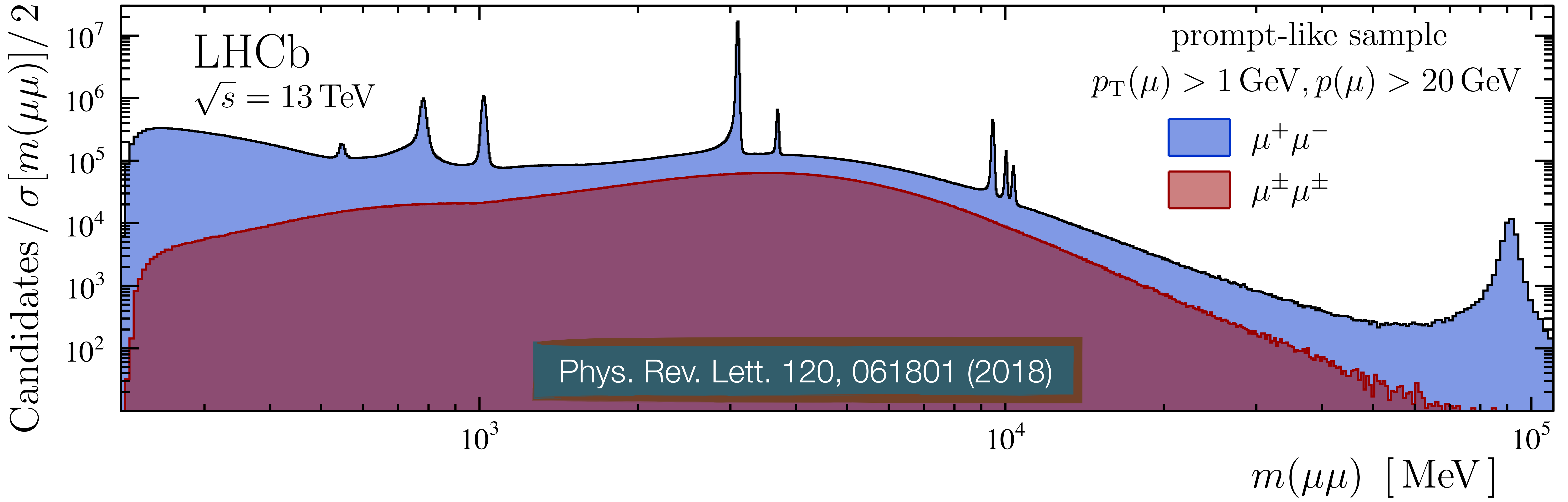
- **HCAL**
  Remove
- **ECAL**
  Improve granularity and σ_t ~50ps/hit
- **TORCH**
  PID for p<10 GeV and σ_t~15 ps
- **Muon stations**
  Improve shielding and replace Multi Wire Proportional Chambers

LHCb detector for Run1 / 1

- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an **alternative approach** is required to fully map the VELO material
- **Real-time calibration** in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT

JINST 13 (2018) no.06, P06008



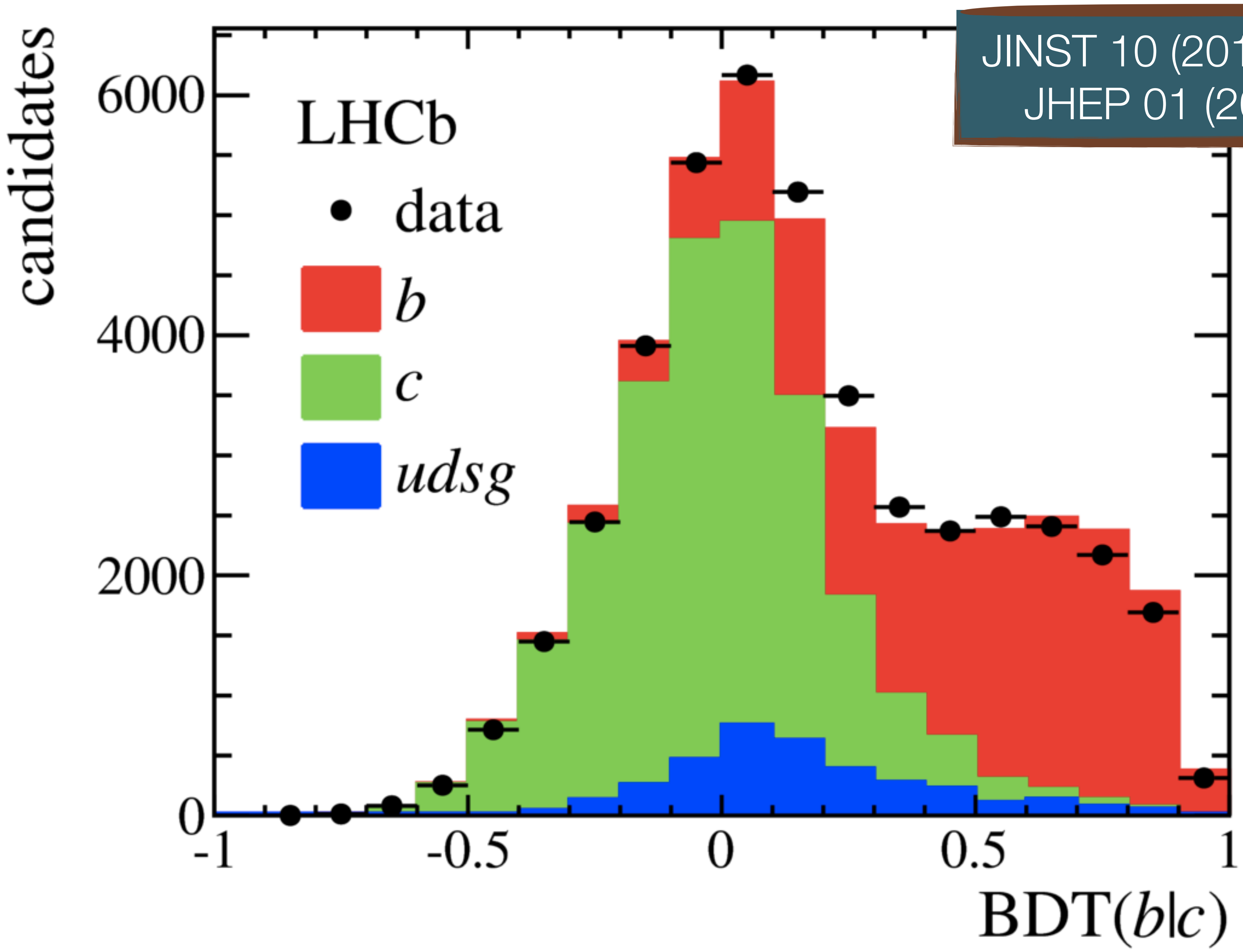


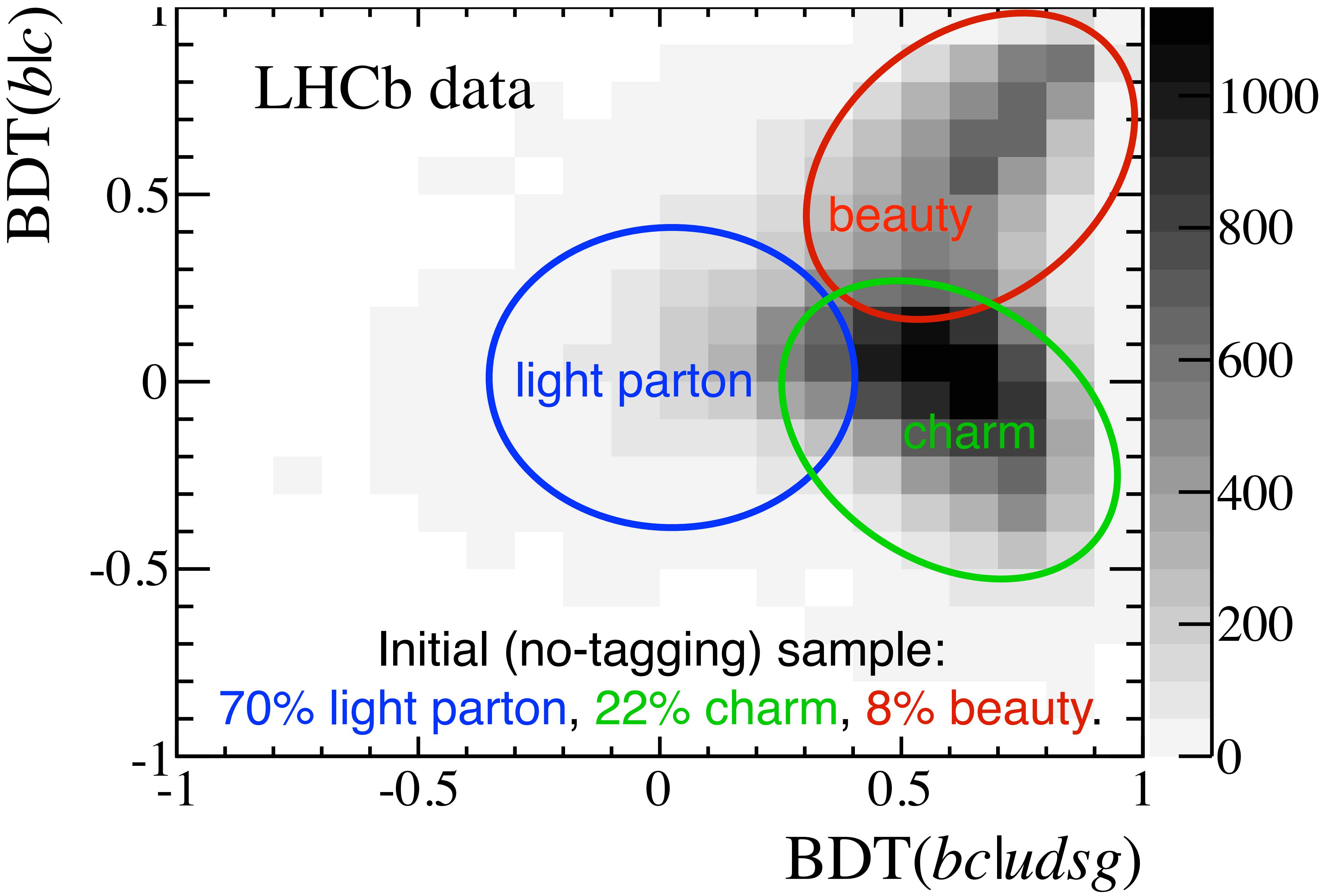
Phys. Rev. Lett. 120, 061801 (2018)

JINST 10 (2015) P06013
JHEP 01 (2014) 033

LHCb detector for Run1 / 2

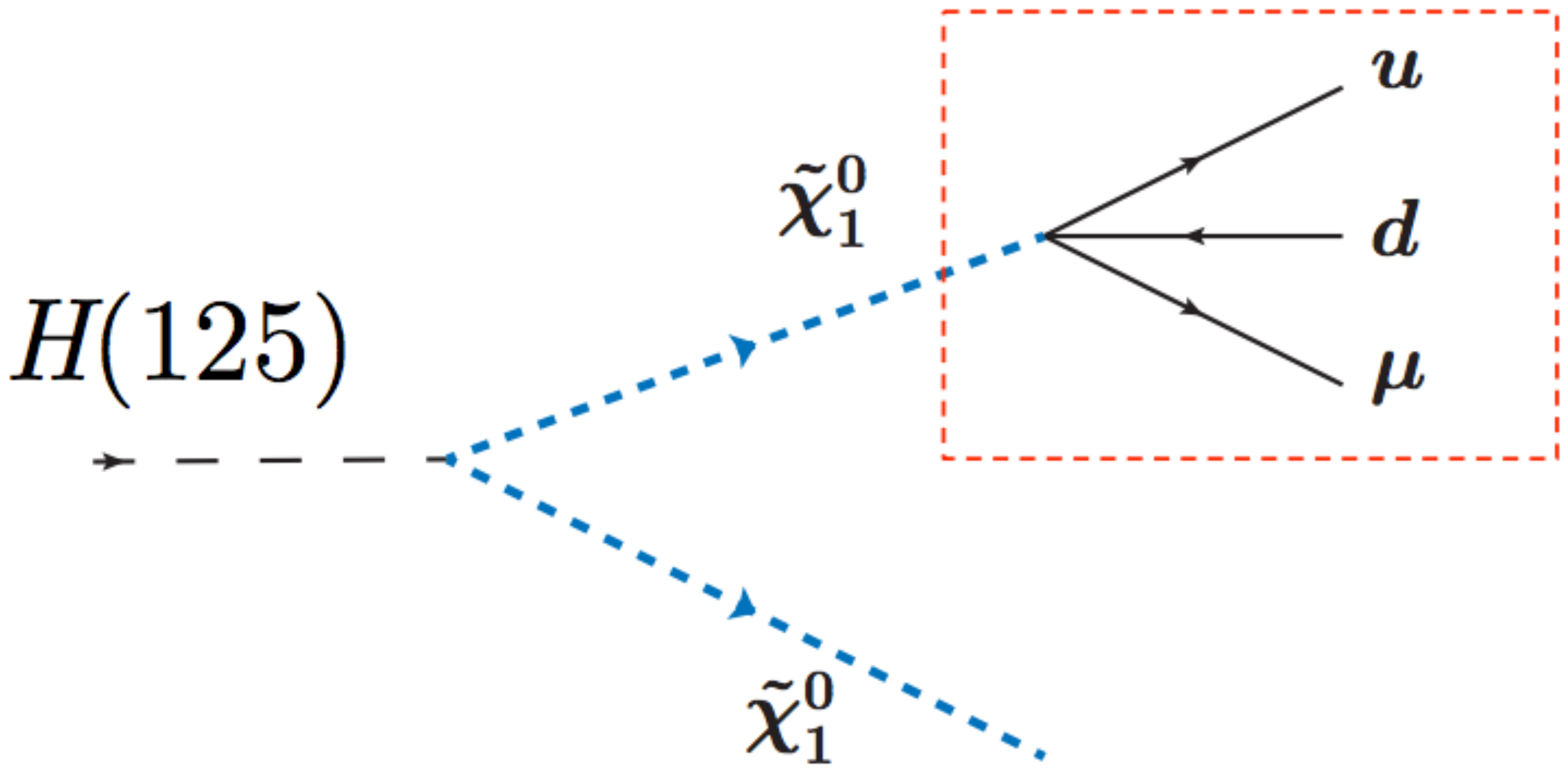
- Efficiency above 90% for jets with p_T above 20 GeV/c
- Jets reconstructed both online and offline!
- **b and c jet tagging**
- Require jets with a secondary vertex reconstructed
- **Light jet** mistag rate < 1%, $\varepsilon_b \sim 65\%$, $\varepsilon_c \sim 25\%$
- SV properties (**displacement**, **kinematics**, **multiplicity**, etc) and jet properties combined in **two** BDTs
  - $\mathbf{BDT_{bc|udsg}}$ optimised for heavy flavour versus light discrimination
  - $\mathbf{BDT_{b|c}}$ optimised for b versus c discrimination

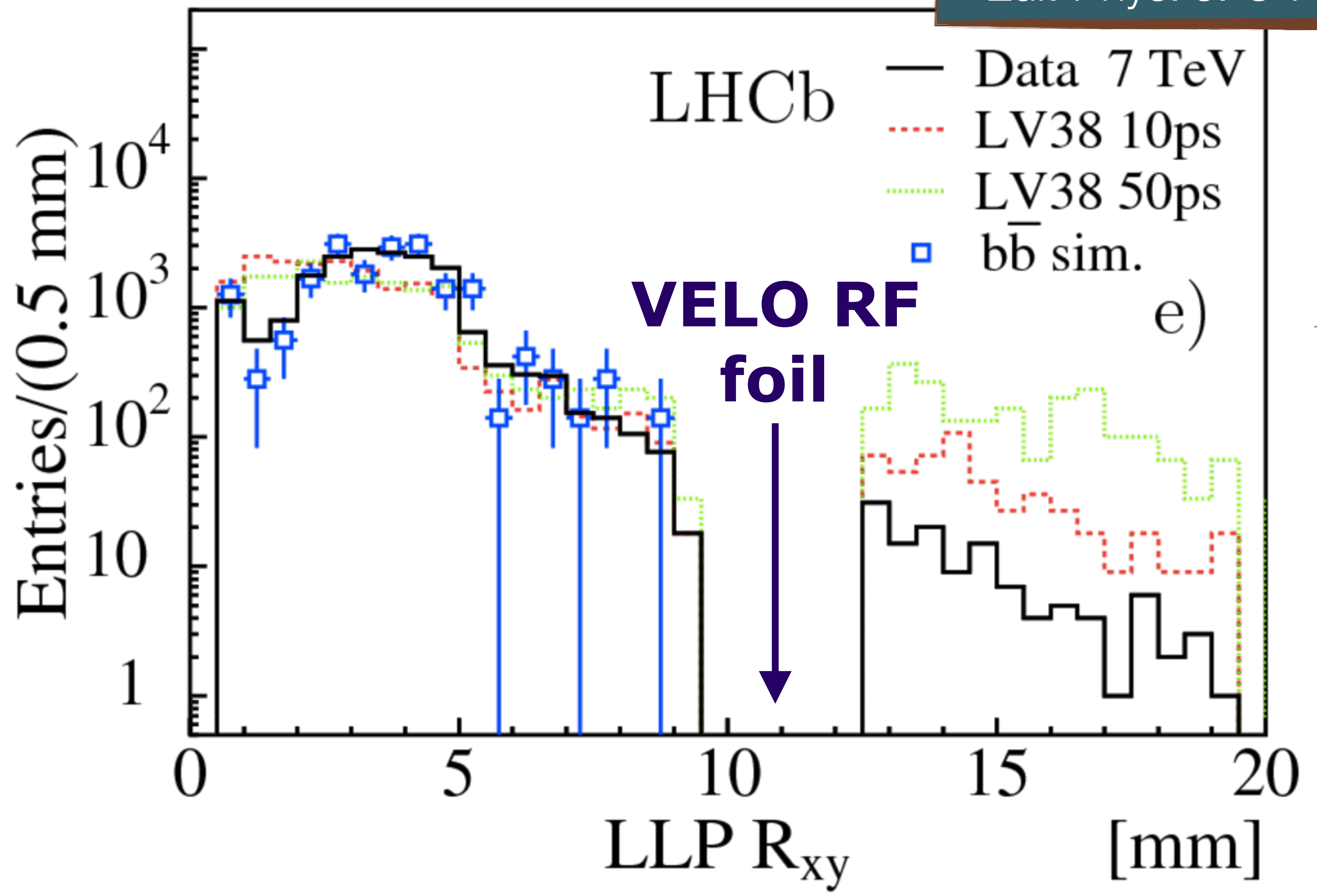


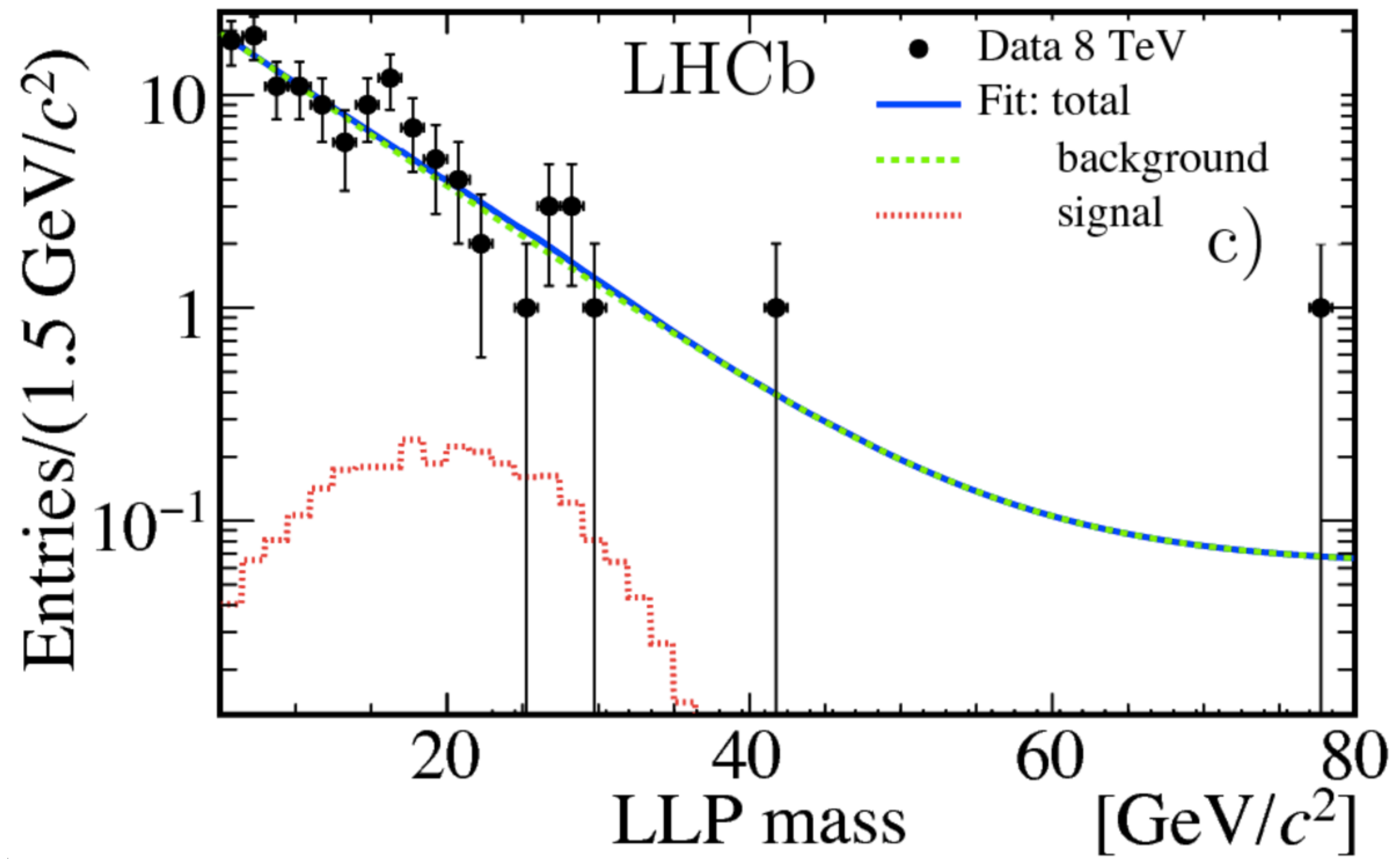


Higgs→LLP→μ+jets / 1

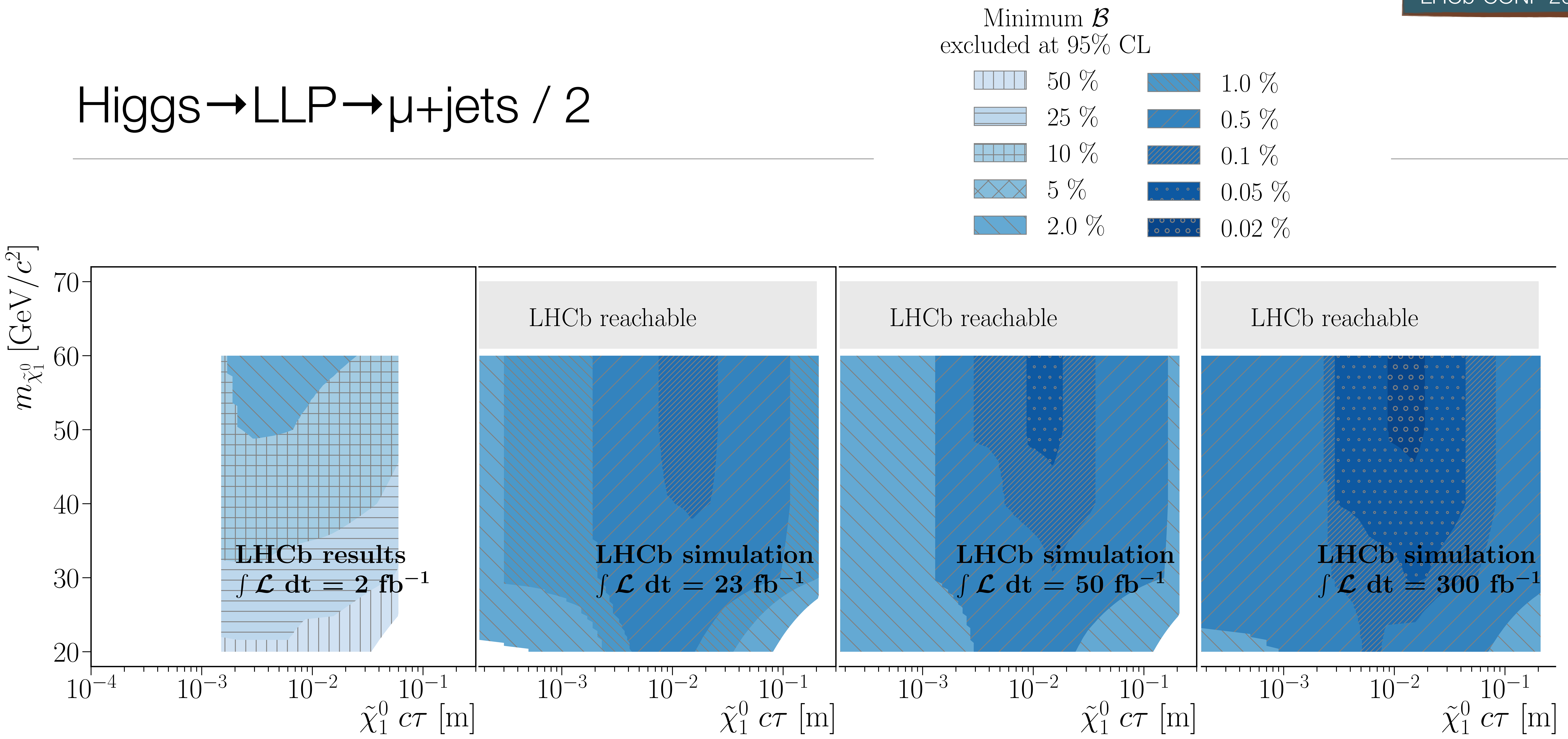
- Massive **LLP** decaying → **μ+jets**
- **Single displaced vertex** with several tracks and a high p_T muon; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs
- **m_{LLP}=[20; 80] GeV** and **τ_{LLP}=[5; 100] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models



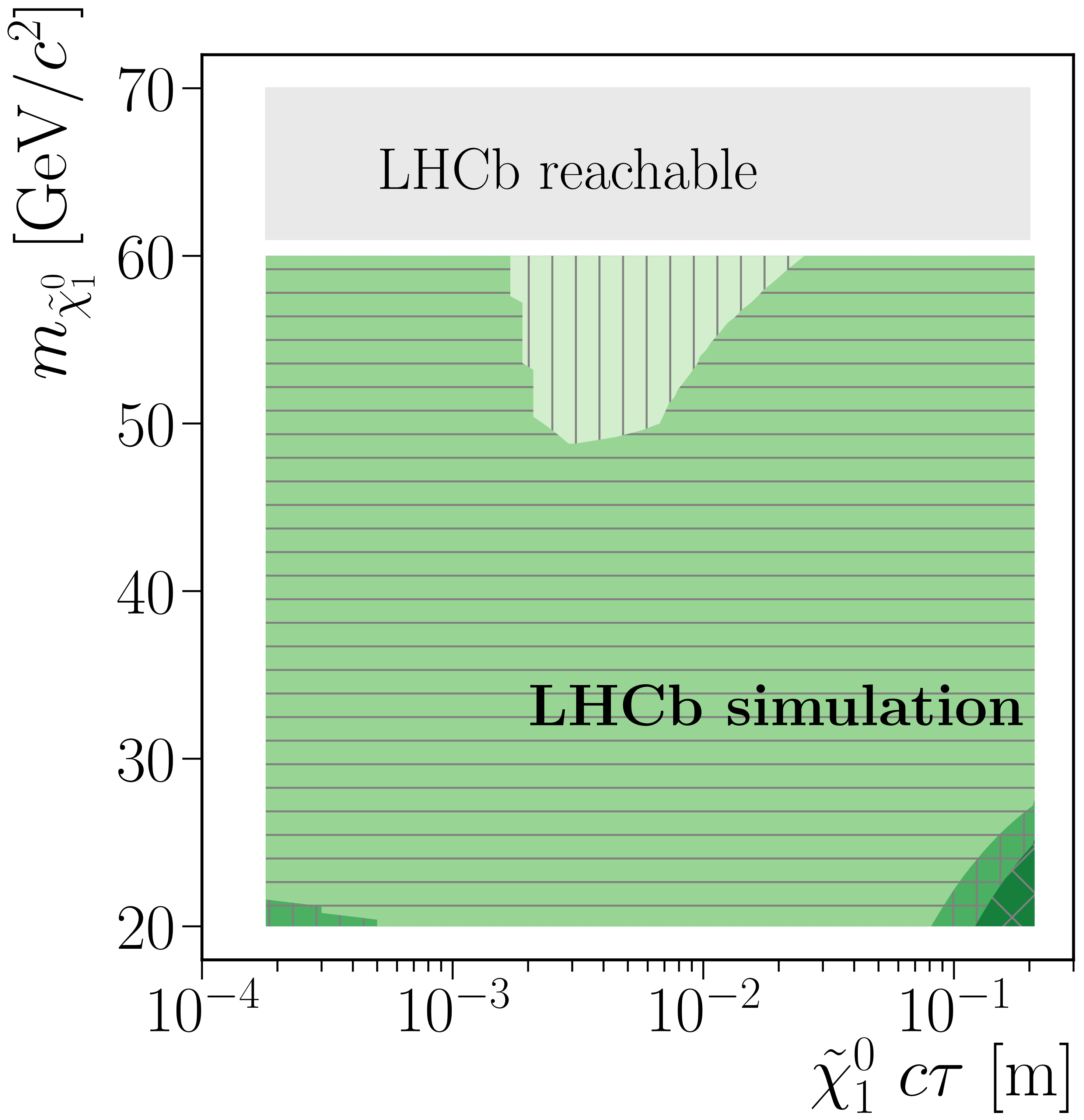




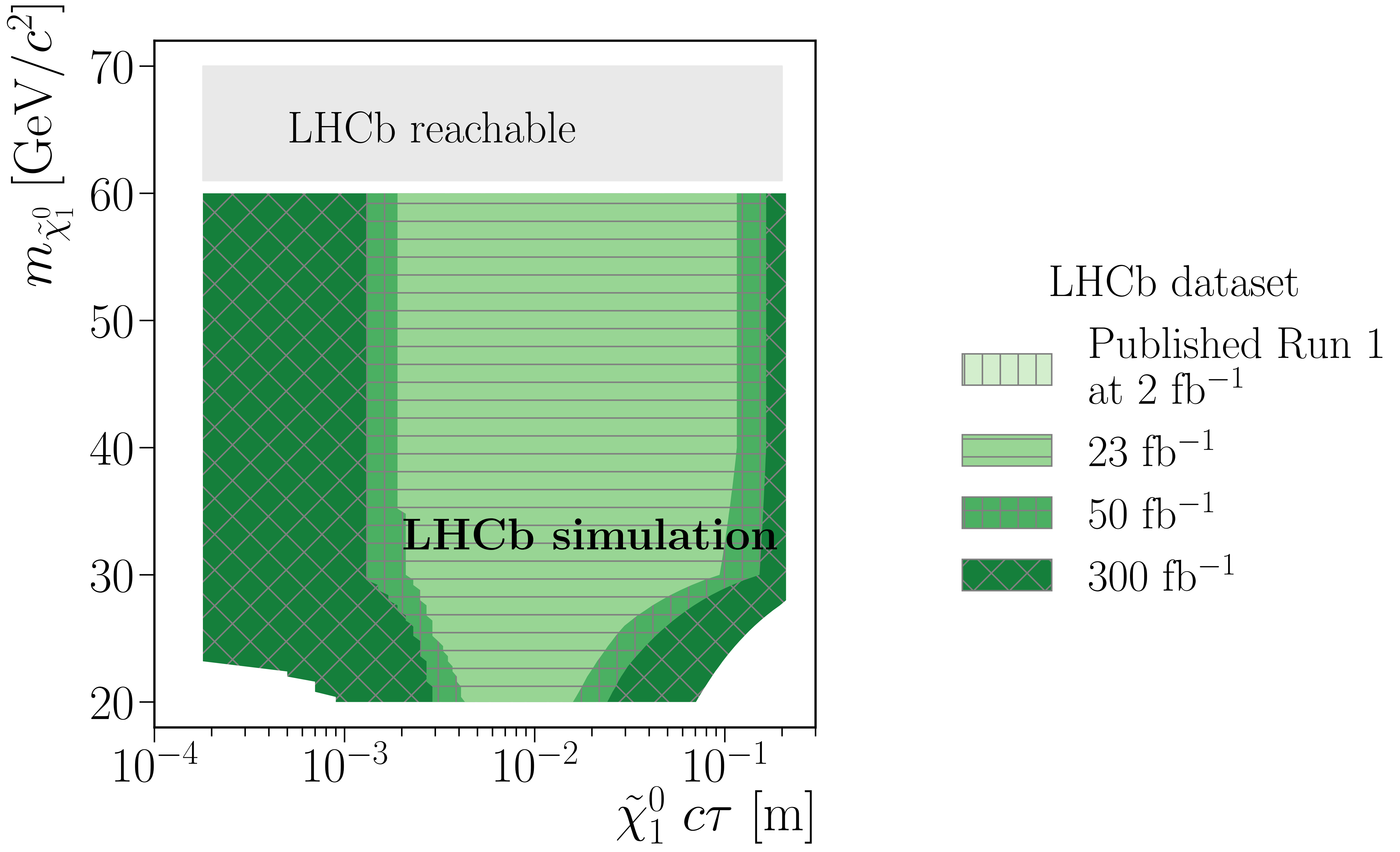
Higgs→LLP→μ+jets / 2



Higgs→LLP→μ+jets / 3



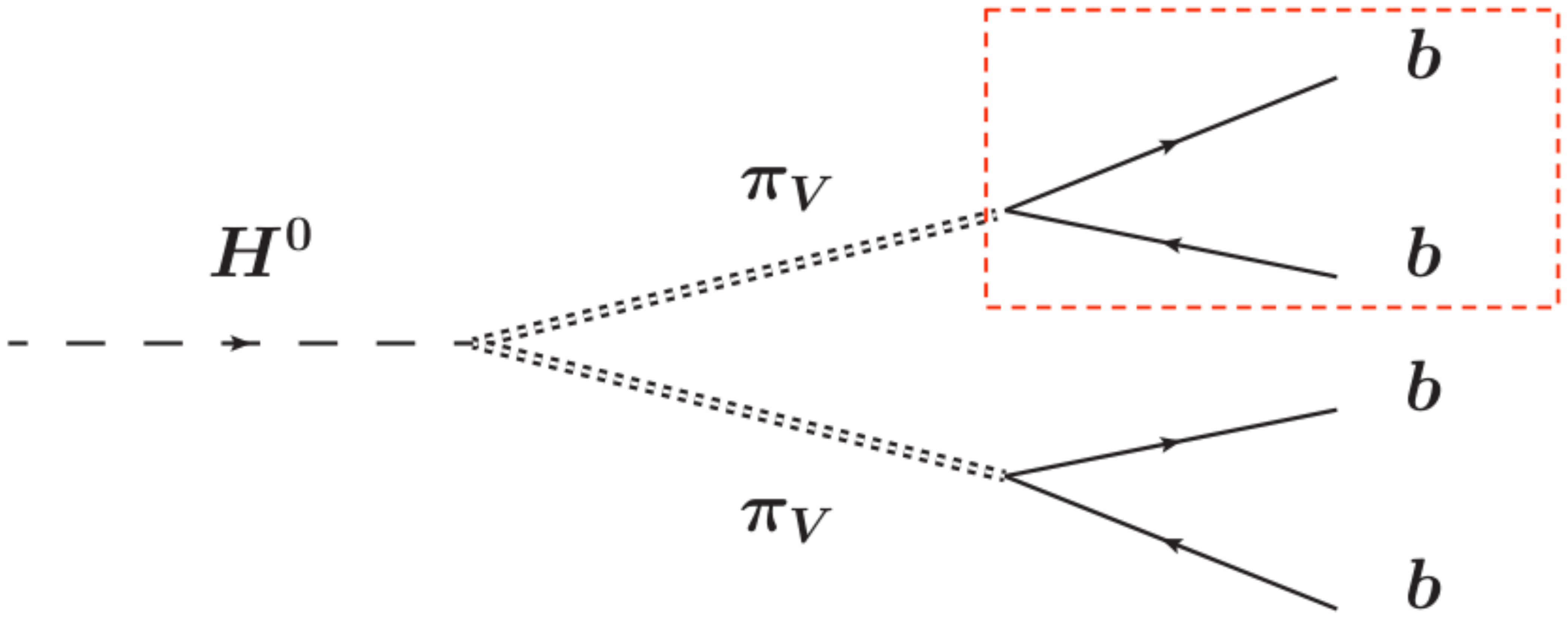
B(Higgs→LLP+LLP) < 2 %

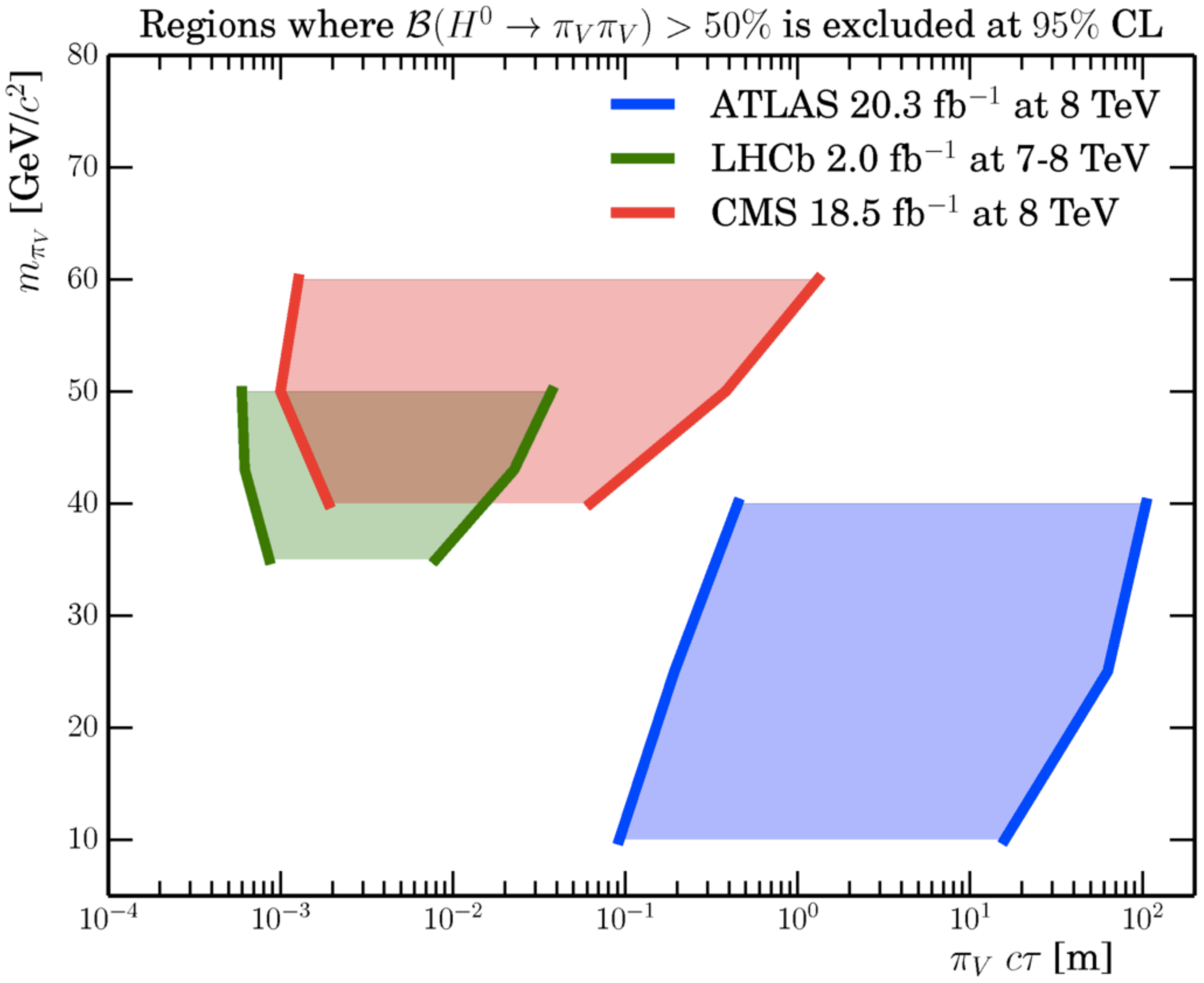


B(Higgs→LLP+LLP) < 0.5 %

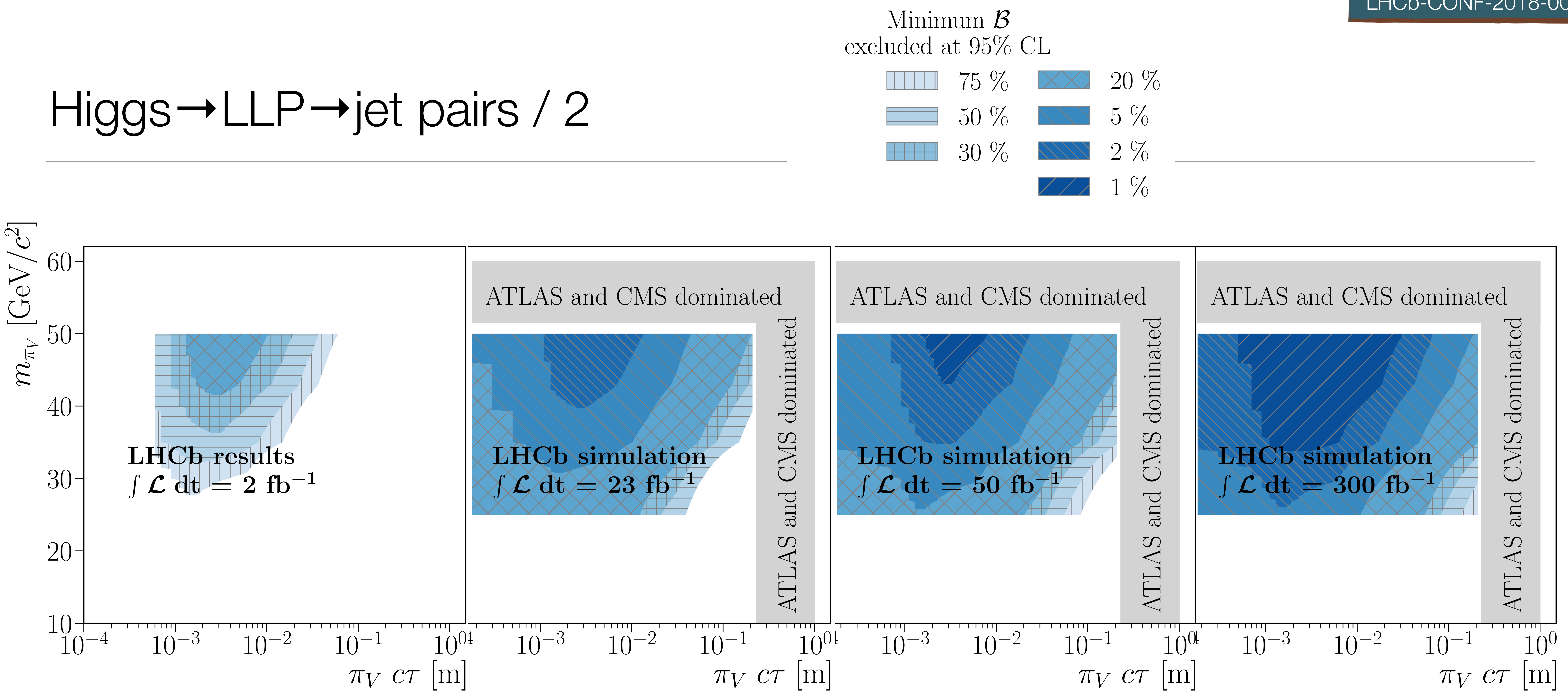
Higgs→LLP→jet pairs / 1

- Massive **LLP** decaying → **jets**
- **Single displaced vertex** with two associated tracks; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs (e.g. π_V)
- **$m_{\pi V}$=[25; 50] GeV** and **$\tau_{\pi V}$=[2; 500] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models

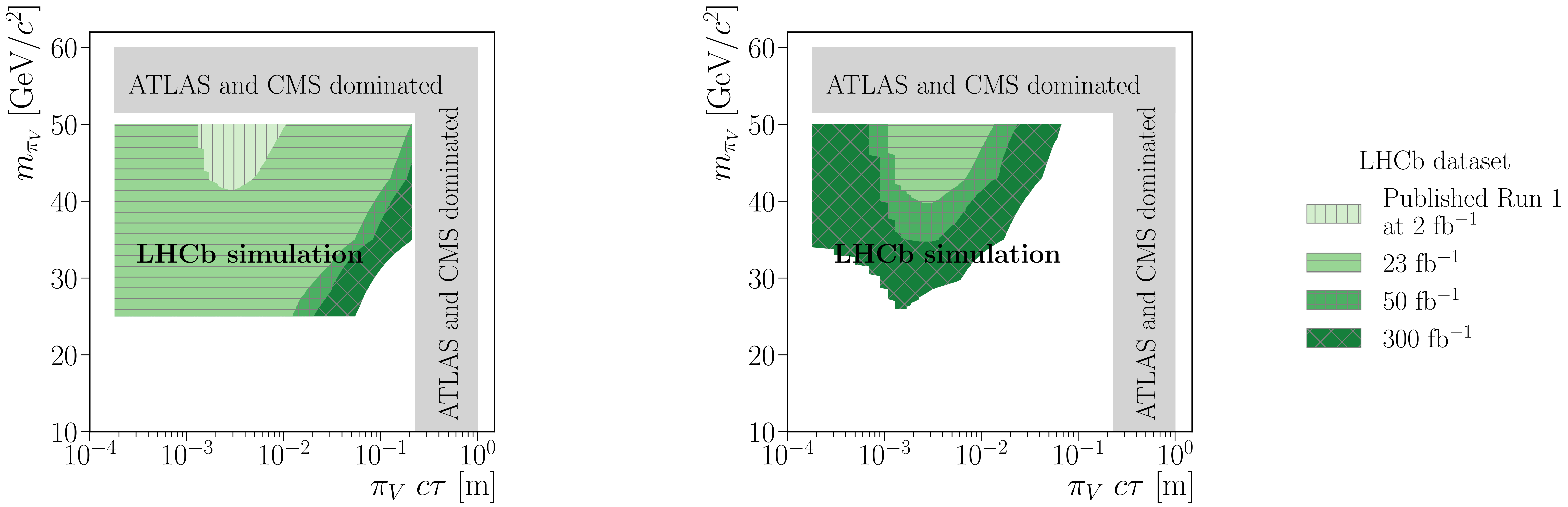




Higgs→LLP→jet pairs / 2



Higgs→LLP→jet pairs / 3



Bf(Higgs→πV+πV) < 20 %

Bf(Higgs→πV+πV) < 2 %

Conclusions

- LHCb has an **extensive program** of searches even beyond flavour physics
  - Searches for **on-shell** and **off-shell** new physics from heavy flavour decays
  - Searches for **long-lived** particles with low mass and short lifetime
  - Searches for **dimuon resonances** in very broad parameter space
- Bright future ahead:
  - 3 fb^{-1} in Run 1, 7 fb^{-1} in Run 2 (with larger cross-sections); LHCb Upgrade II: 300 fb^{-1}
  - A lot of potential in the upgraded trigger (also 5x luminosity)

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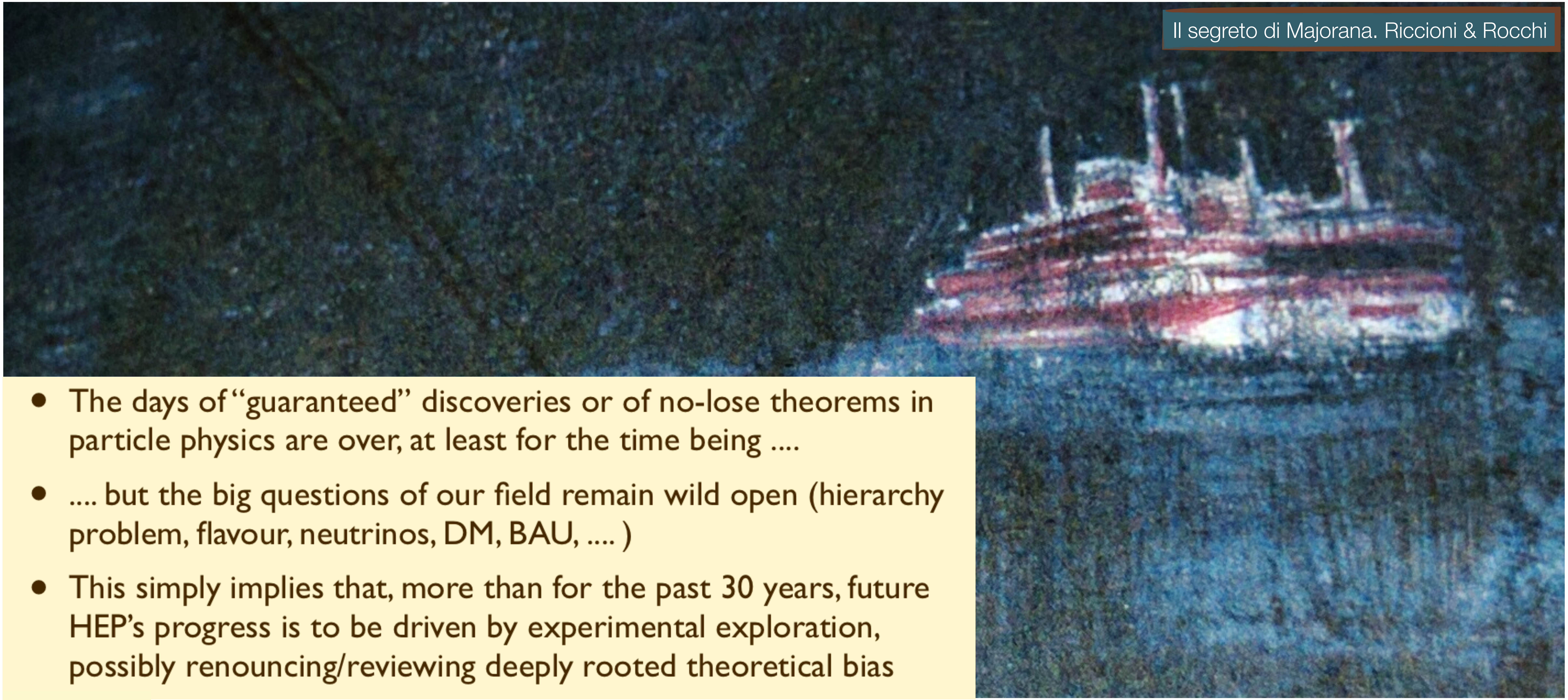


Il segreto di Majorana. Riccioni & Rocchi

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

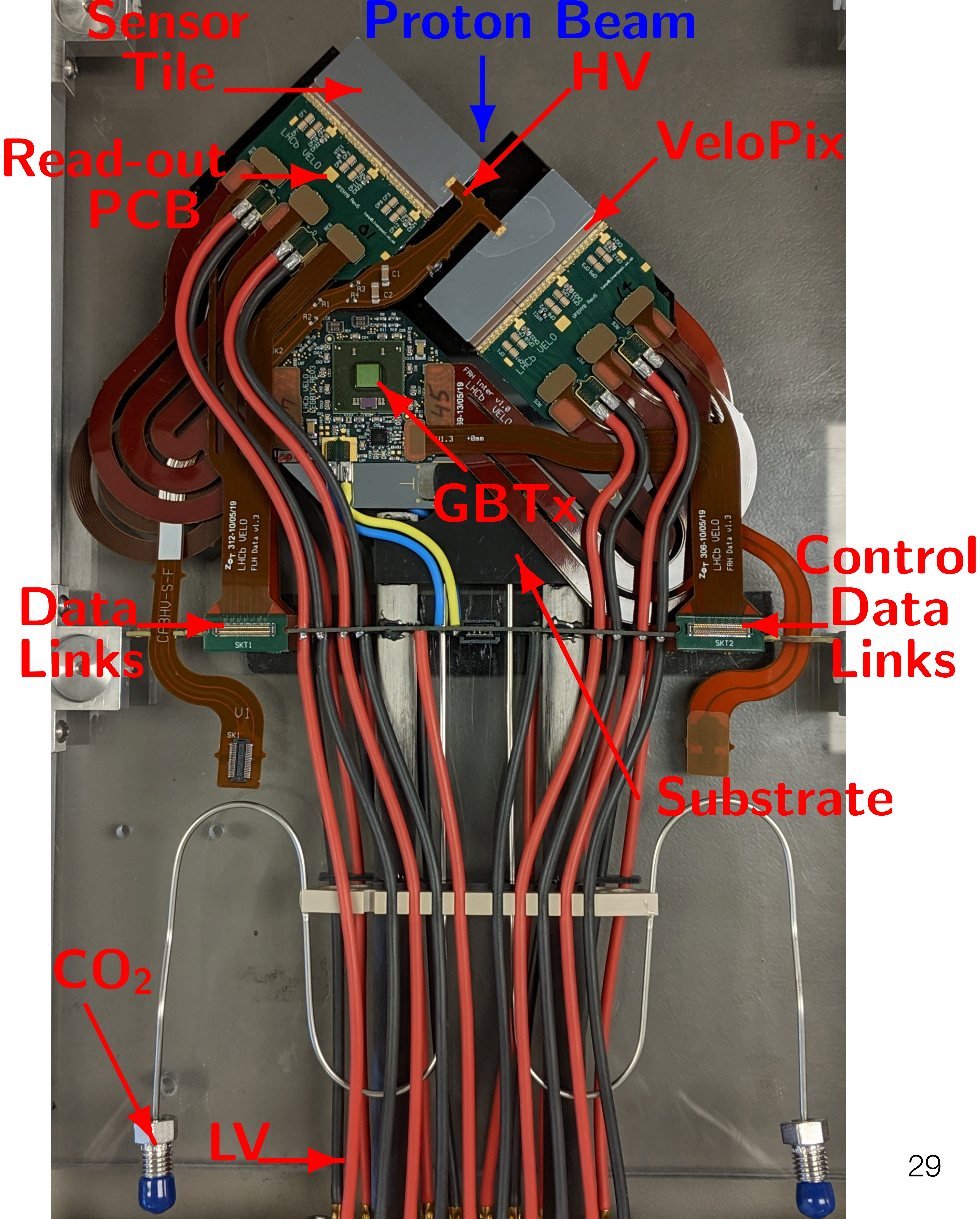
M. Mangano

Thanks

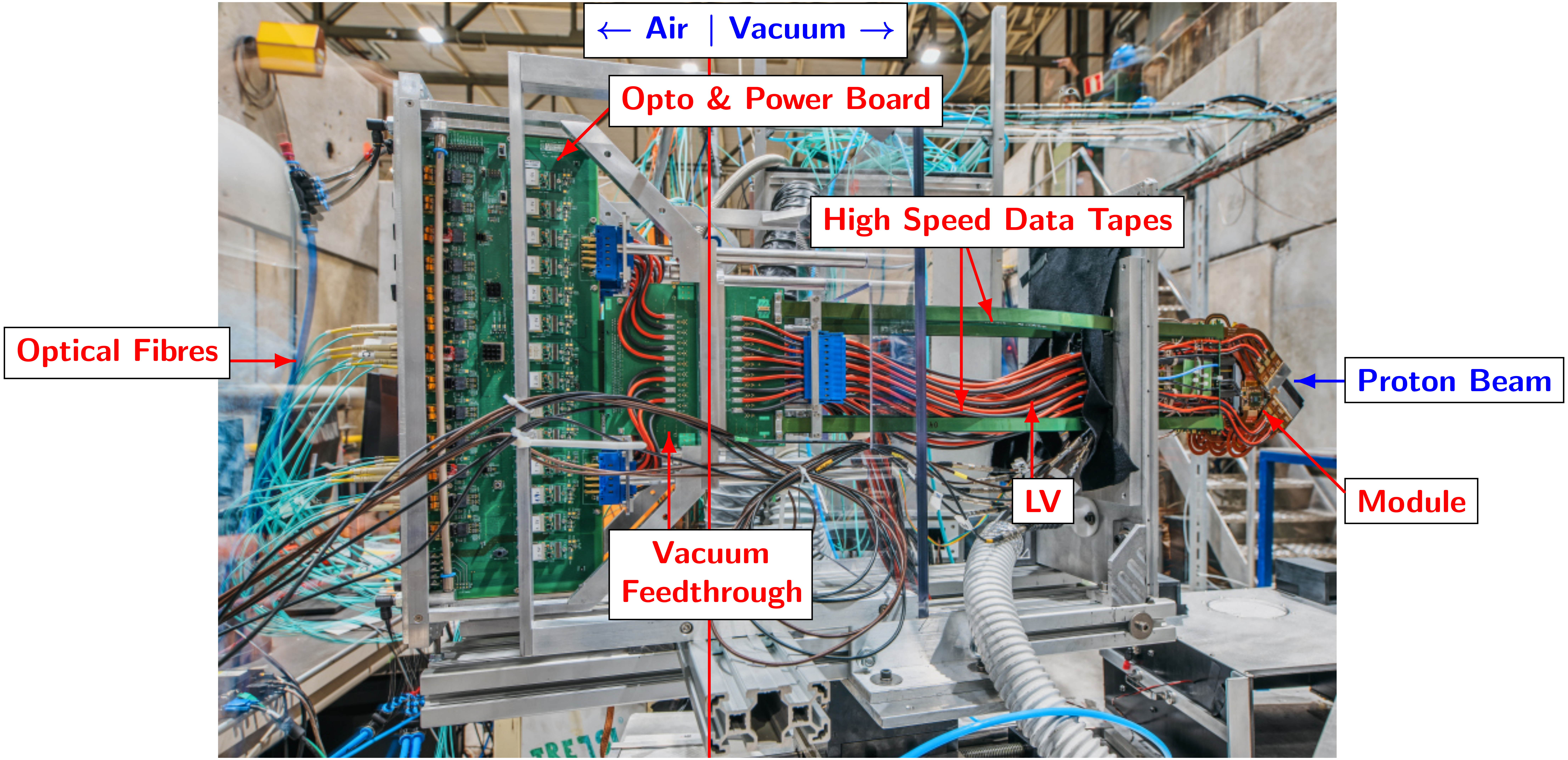
Federico Leo Redi

VELO / 4

- 4 n-on-p **silicon sensor tiles** (2 front + 2 back)
- 3 **VeloPix** read-out ASICs per tile (12/module)
  256×256 pixels with 55µm × 55µm pitch
- Silicon micro-channel substrate
- 2 GBTx ASICs for signal fan-out to VeloPix
- 2 bi-direction slow control links (4.8 Gbit/s)
  - Configuration, Monitoring, Timing, Control
- 20 unidirectional high speed data links (5.12 Gbit/s)
- **Complete VELO:**
  - 52 Modules, 26 per detector half
  - 624 VeloPix, or 40.9M pixels

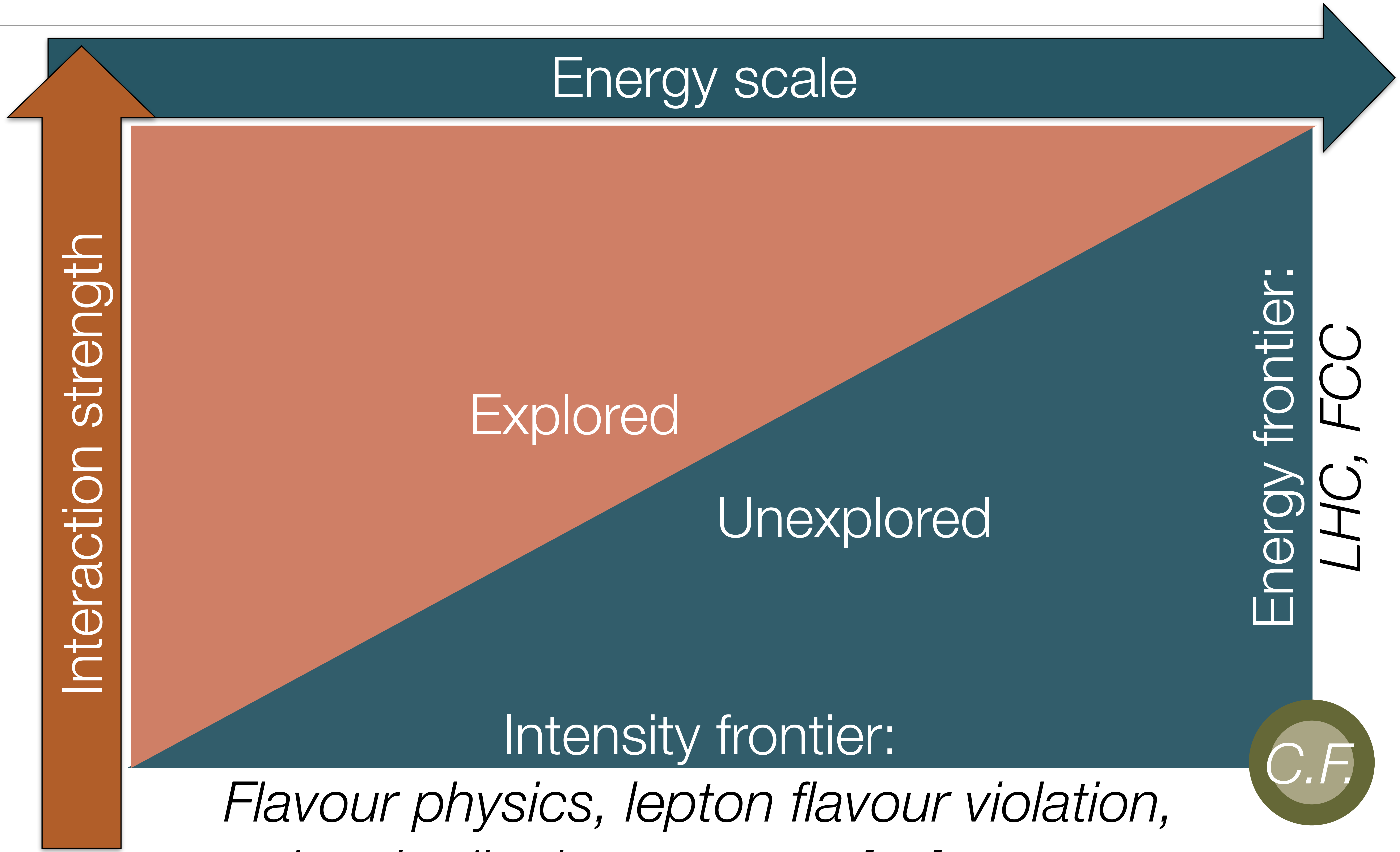


VELO / 5


← Air | Vacuum →
Opto & Power Board
High Speed Data Tapes
Optical Fibres
Proton Beam
LV
Module
Vacuum Feedthrough

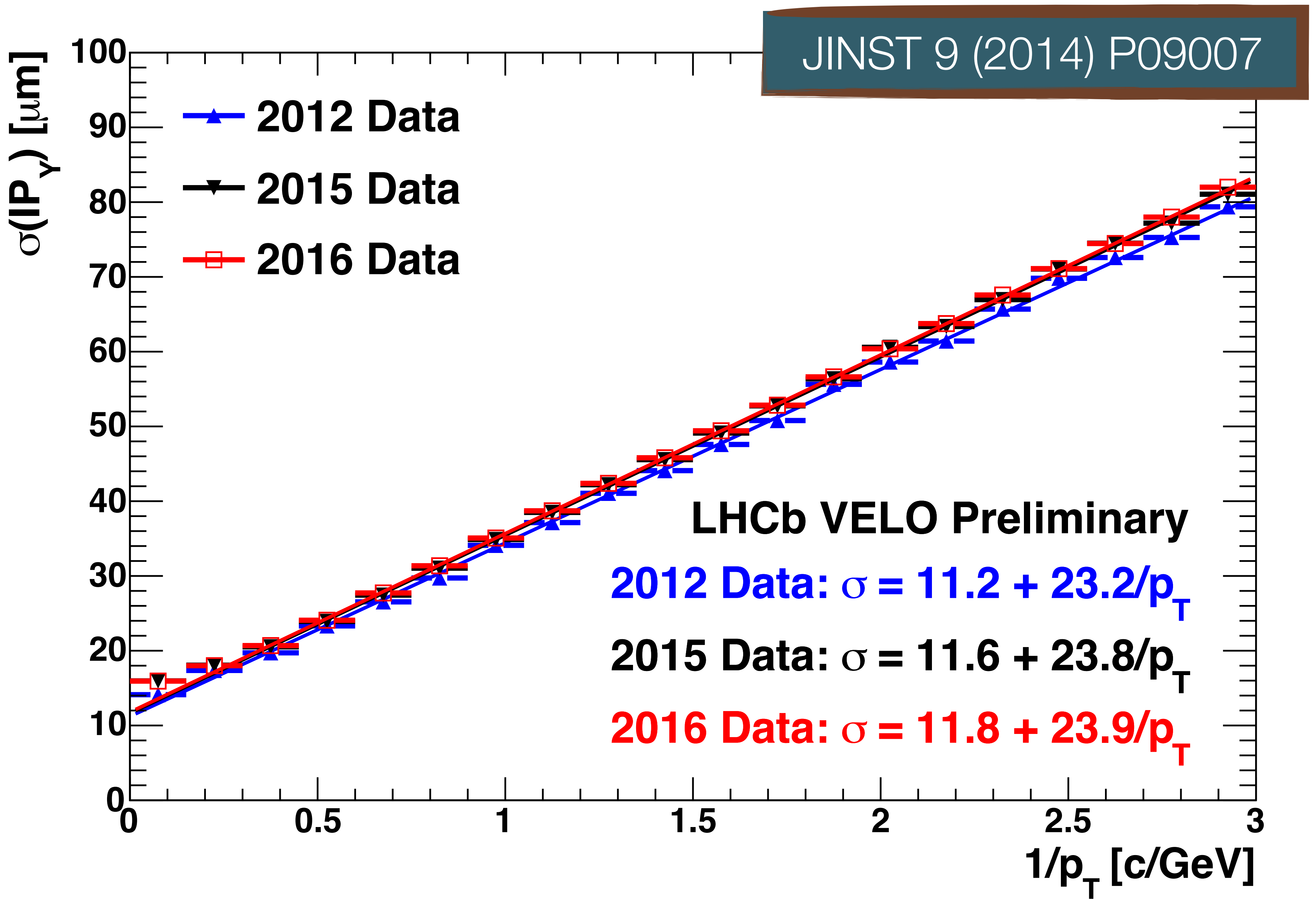
Introduction / 1

- Naturalness does not seem to be a **guiding principle** of Nature
- There are some **anomalies in flavour physics** which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that **we have a 2D problem** (Mass VS Coupling)
- Low coupling → Long Lived
- *Thanks to X. Cid, C. Vazquez, and L. Sestini*



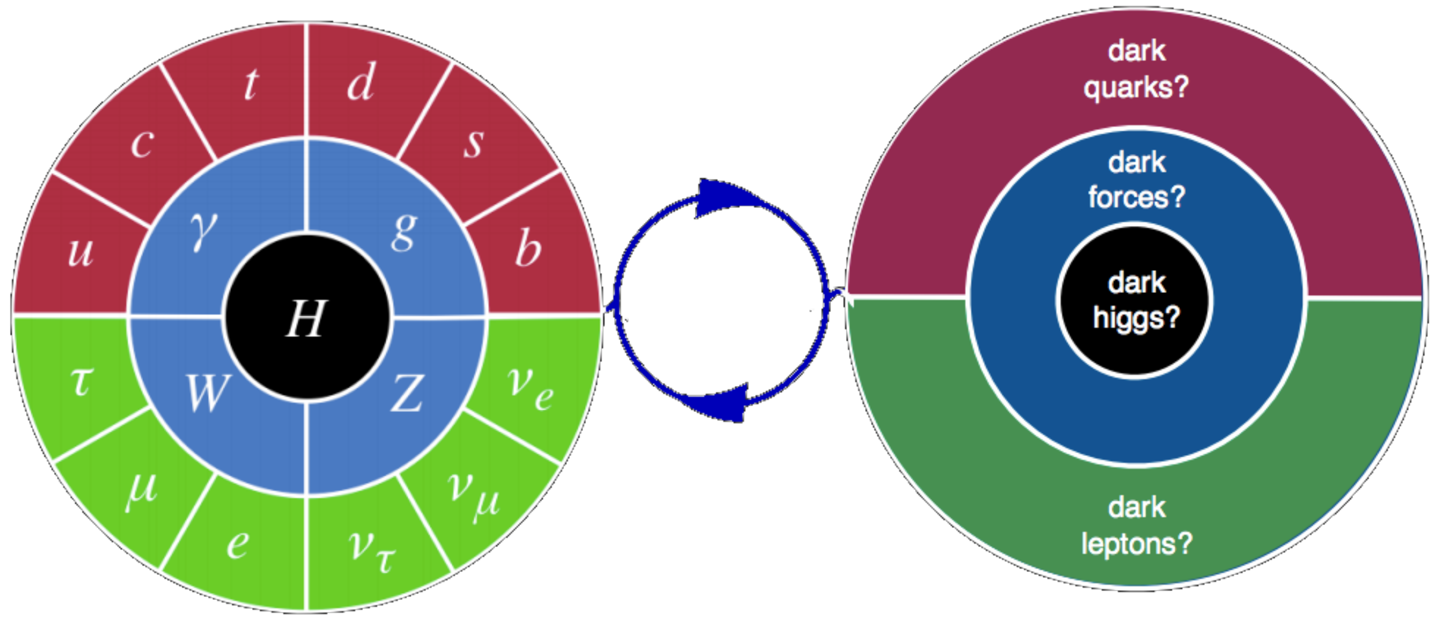
Flavour physics, lepton flavour violation, electric dipole moment, ***dark sector***

Landscape today / 2



- In the dark sector: $\boldsymbol{L = L_{SM} + L_{mediator} + L_{HS}}$
  - Hidden Sector decay rates into SM final states is suppressed
  - Branching ratios of $O(10^{-10})$
  - Long-lived objects
  - Interact very weakly with matter
- Experimental challenge is **background suppression**
- **Full reconstruction**, **low pT** triggering, and **PID** are essential to minimise model dependence
  - **Two** strategies of searching for mediators at accelerators:
  - **Not decaying in the detector**
    - Missing energy technique
    - Scattering technique: electron or nuclei scattered by DM…
  - **Decaying in the detector**
    - Reconstruction of decay vertex

M. Williams



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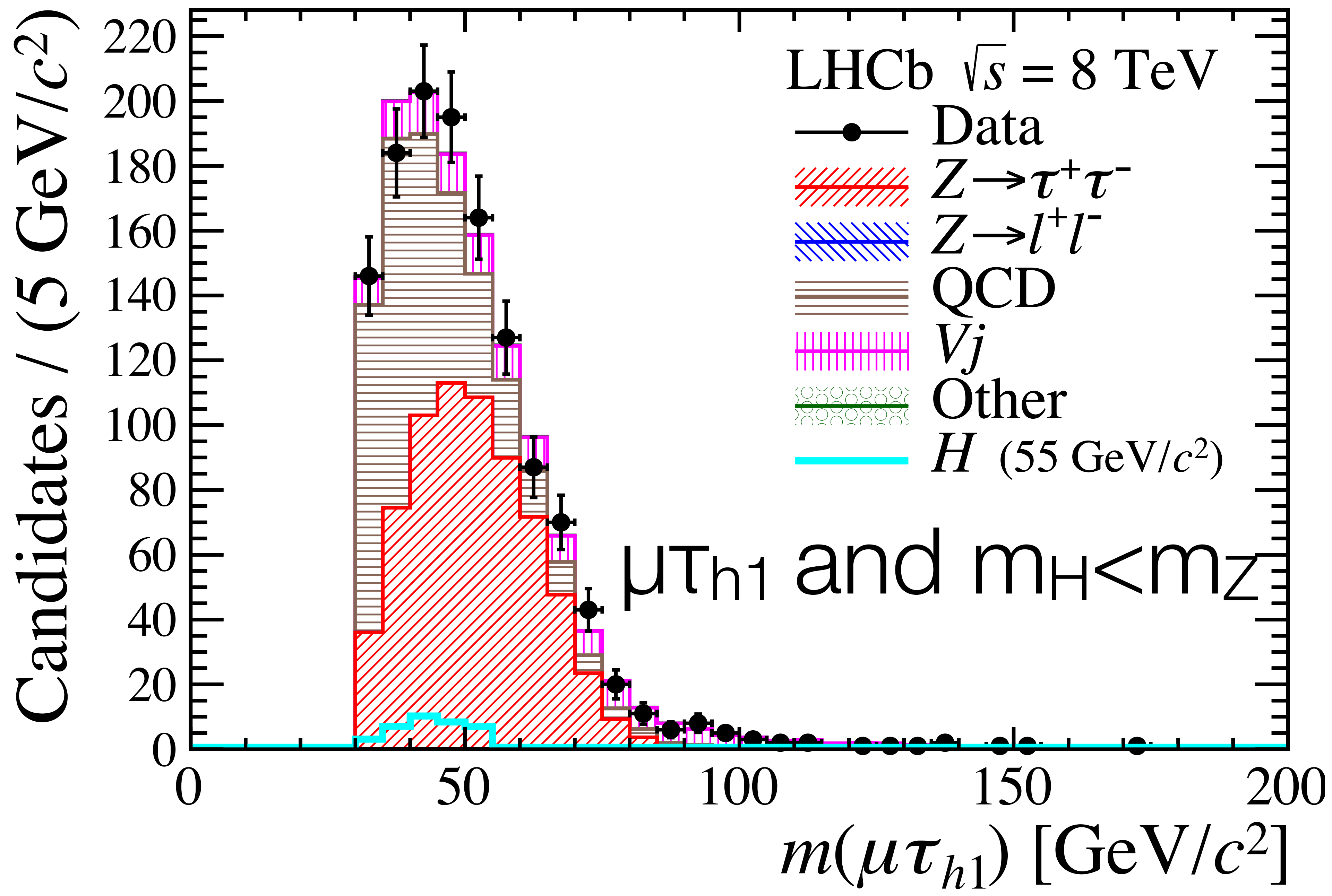
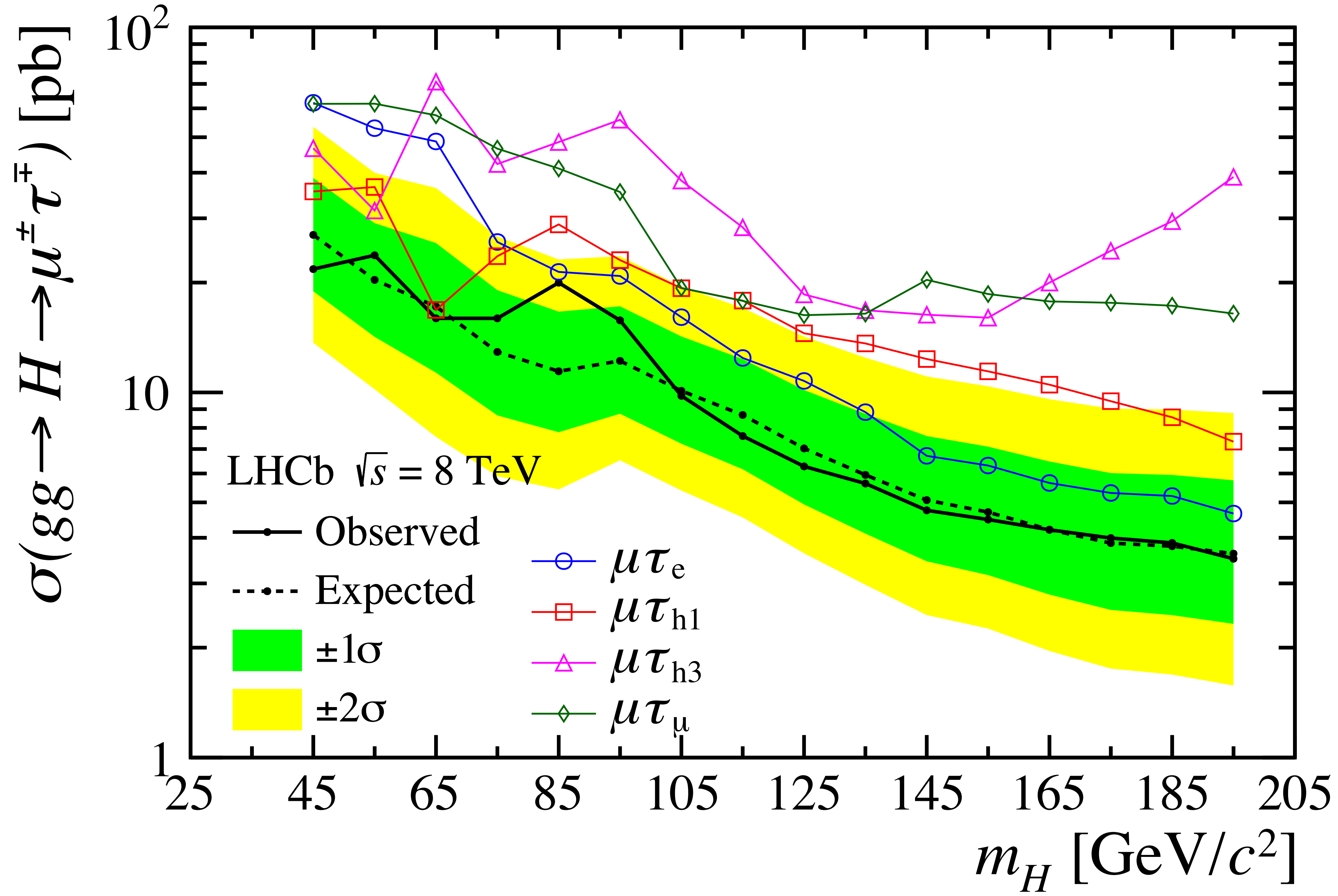
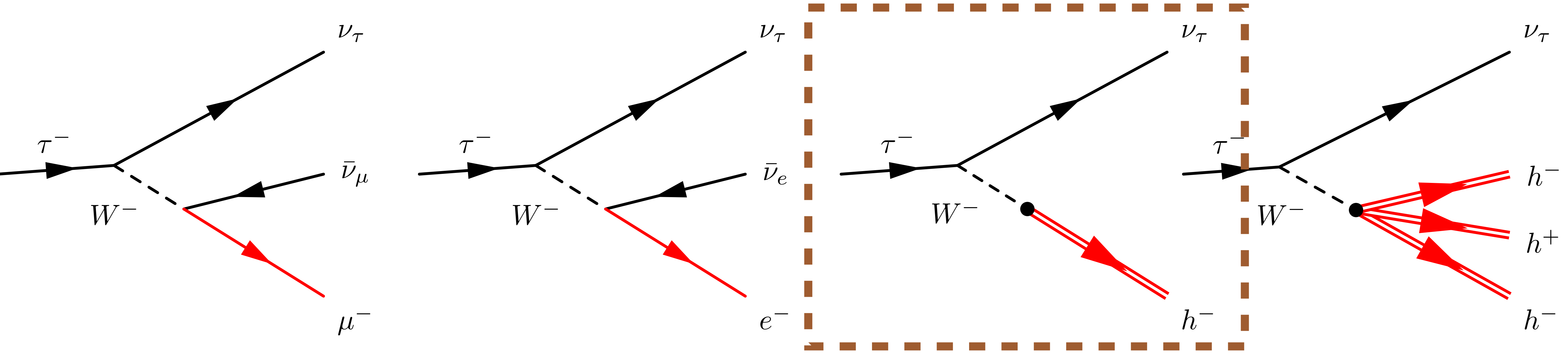
H→μτ decays / 1

- Higgs-like boson decaying → μτ charged-lepton flavour-violating (CLFV)
- Analysis is separated into **four channels**
- **m_H=[45; 195] GeV** and **minimal flight distance** (impact parameter) of the reconstructed candidate is imposed
- Three different selections based on **m_H** w.r.t. **m_Z**
- Background dominated by **QCD**, **Z→ττ**, **Vj**
- No excess found







Searching in the Υ mass region / 1

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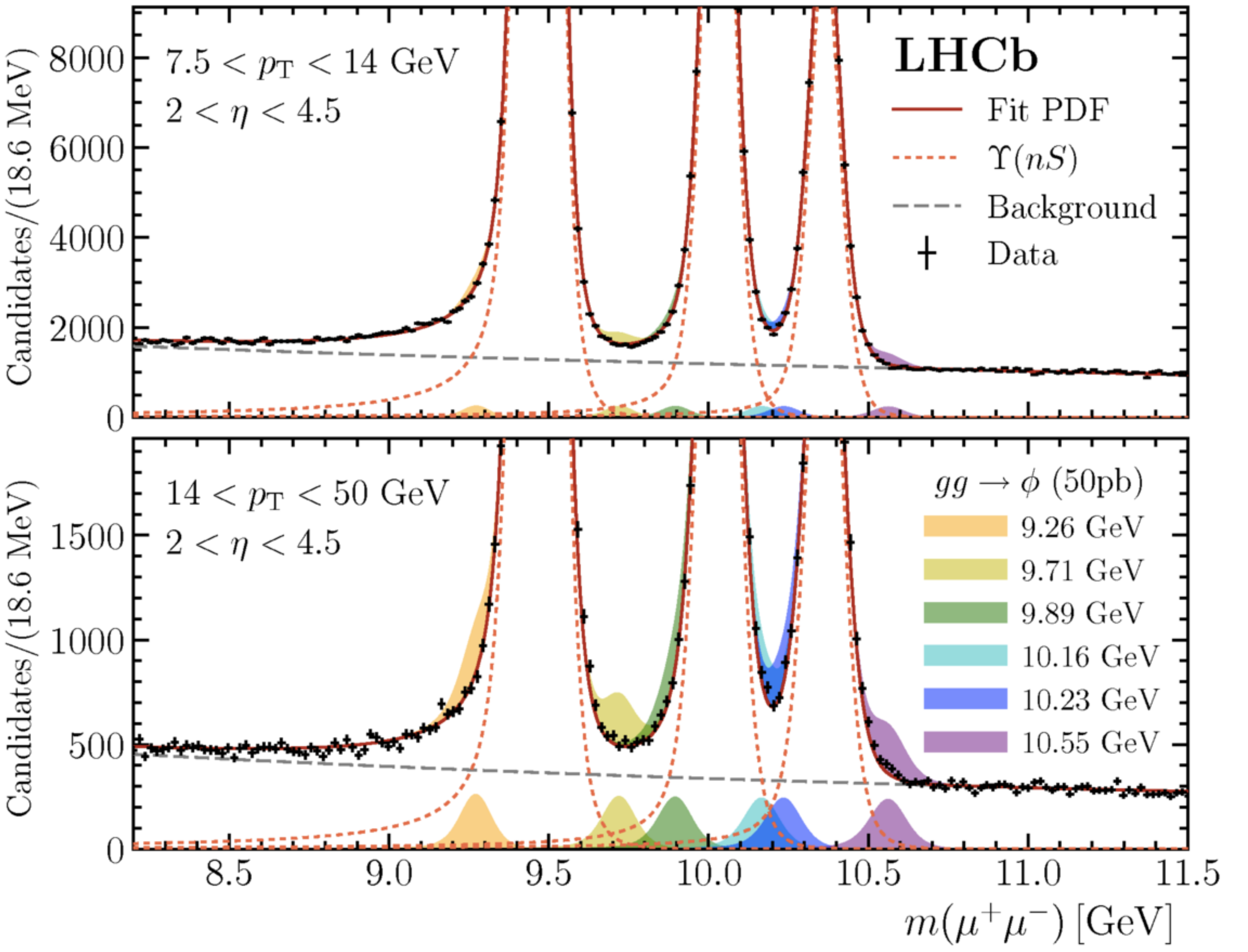
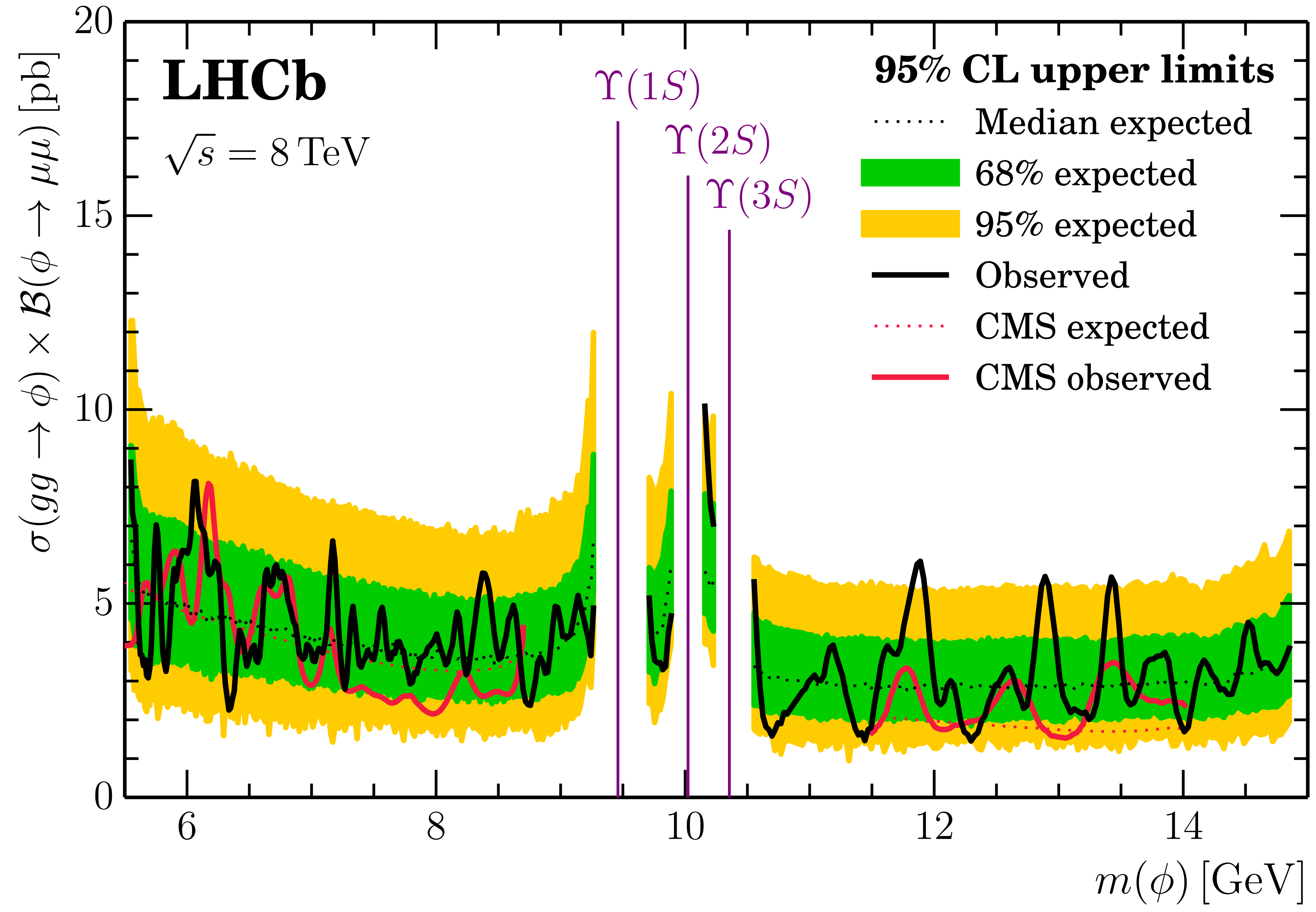
- Other light spin-0 particles in which LHCb can do well are light bosons from pp; **only Run 1**
- Spin-0 boson, ϕ, using Run 1 prompt $\phi \to \mu^+\mu^-$ decays, have been searched for
- Use **dimuon** final states:
    - Access to different mass window w.r.t γγ or ττ searches in 4π experiments
- Done in **bins of kinematics** ([p_T,η]) to maximise sensitivity
- Precise modelling of Υ(nS) tails to extend search range as much as possible
- **Mass independent** efficiency (uBDT)

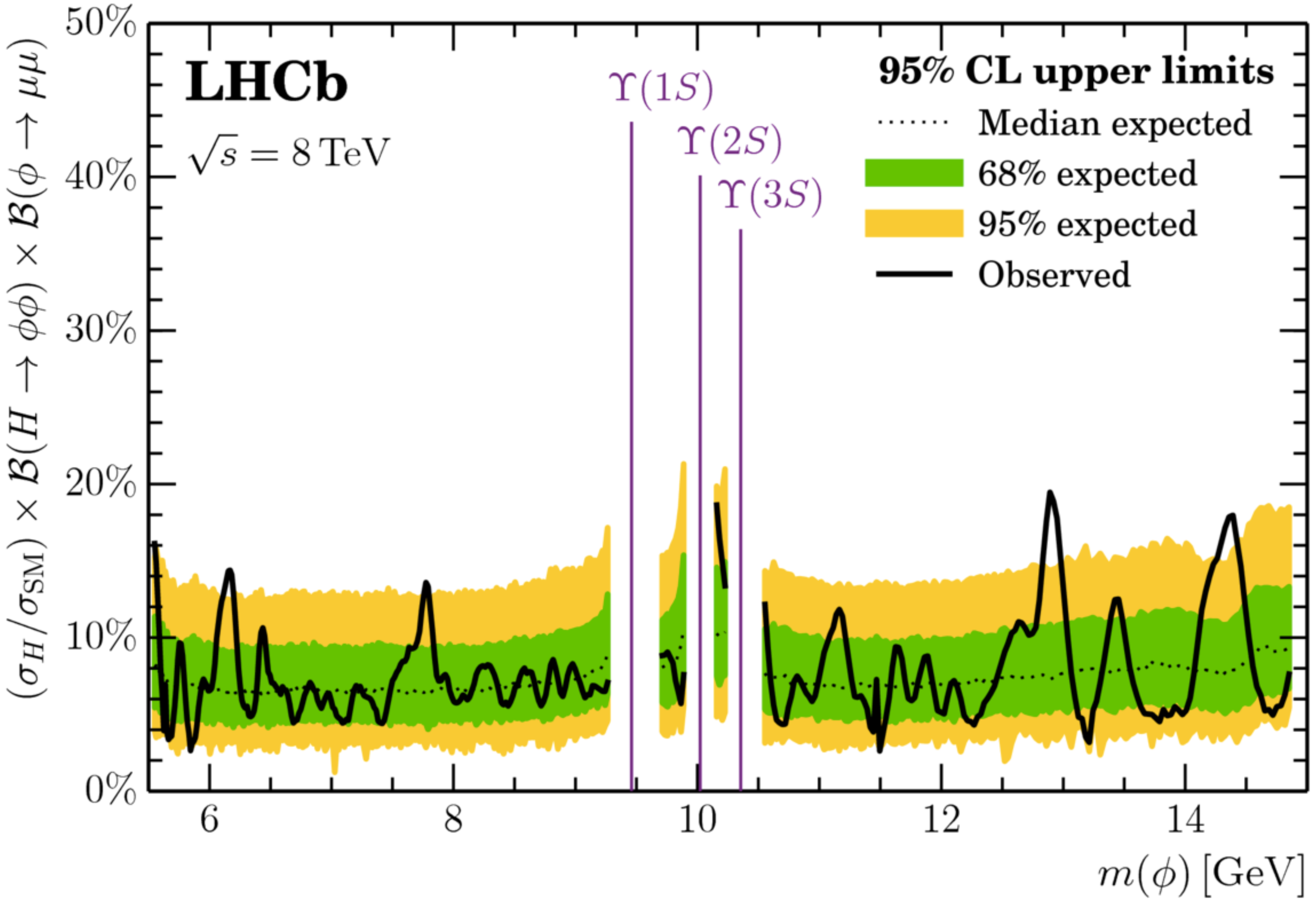


Searching in the Y mass region / 2

JHEP 1809 (2018) 147

- Search for dimuon resonance in **$m_{\mu\mu}$ from 5.5 to 15 GeV** (also between Y(nS) peaks)
- No signal: limits on σ•BR set on (pseudo)scalars as proposed by **Haisch** & **Kamenik** [1601.05110]
- First limits in 8.7-11.5 GeV region - elsewhere competitive with CMS
- Interpreted as a search for a scalar produced through the SM Higgs decay





Mass resolution

JHEP 1511 (2015) 103

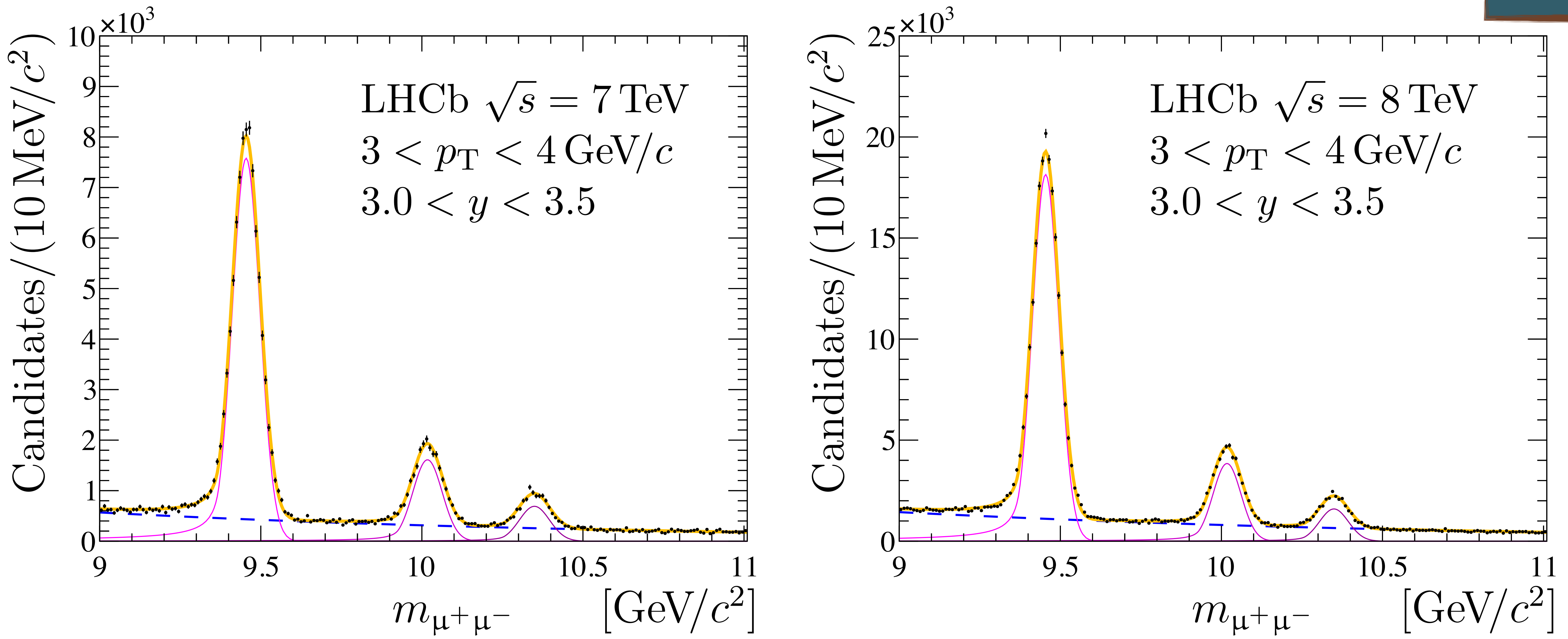


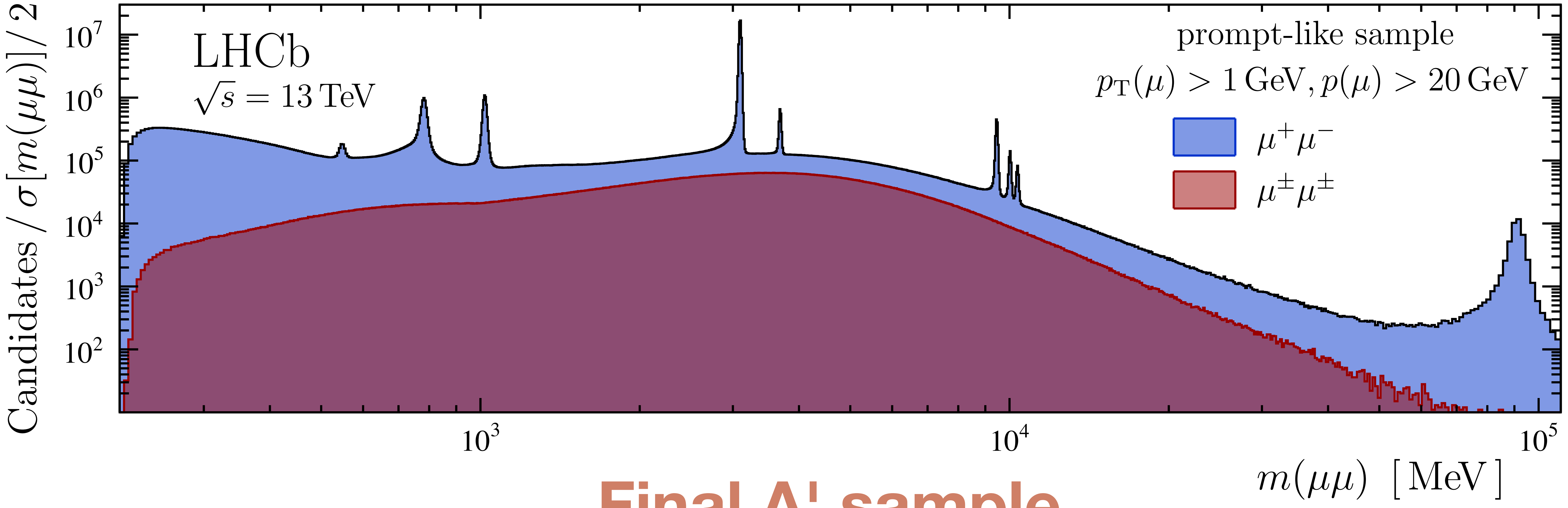
Figure 1: Efficiency-corrected dimuon mass distributions for (left) $\sqrt{s} = 7$ TeV and (right) $\sqrt{s} = 8$ TeV samples in the region $3 < p_T < 4$ GeV/c, $3.0 < y < 3.5$. The thick dark yellow solid curves show the result of the fits, as described in the text. The three peaks, shown with thin magenta solid lines, correspond to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ signals (left to right). The background component is indicated with a blue dashed line. To show the signal peaks clearly, the range of the dimuon mass shown is narrower than that used in the fit.

Searching for Dark Photons / 1

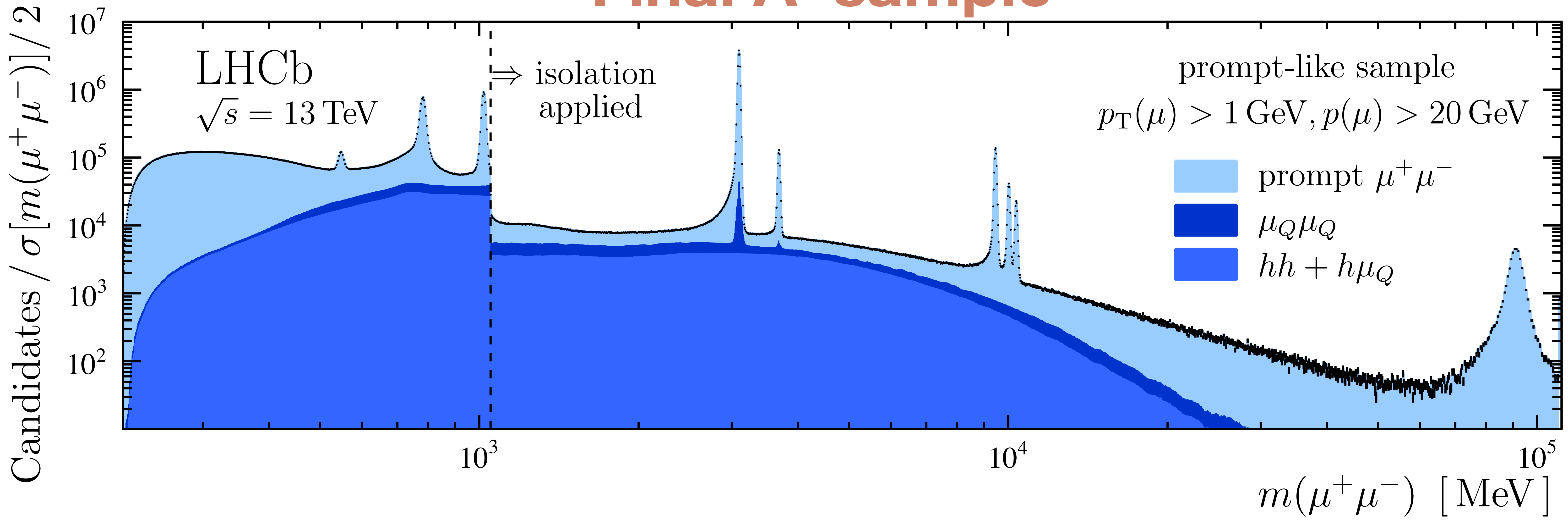
Phys. Rev. Lett. 120, 061801 (2018)

- Suppressing misidentified (non-muon) backgrounds and reducing the event size enough to record the **prompt-dimuon sample**
- Accomplished these by moving to **real-time calibration** in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT

Trigger output



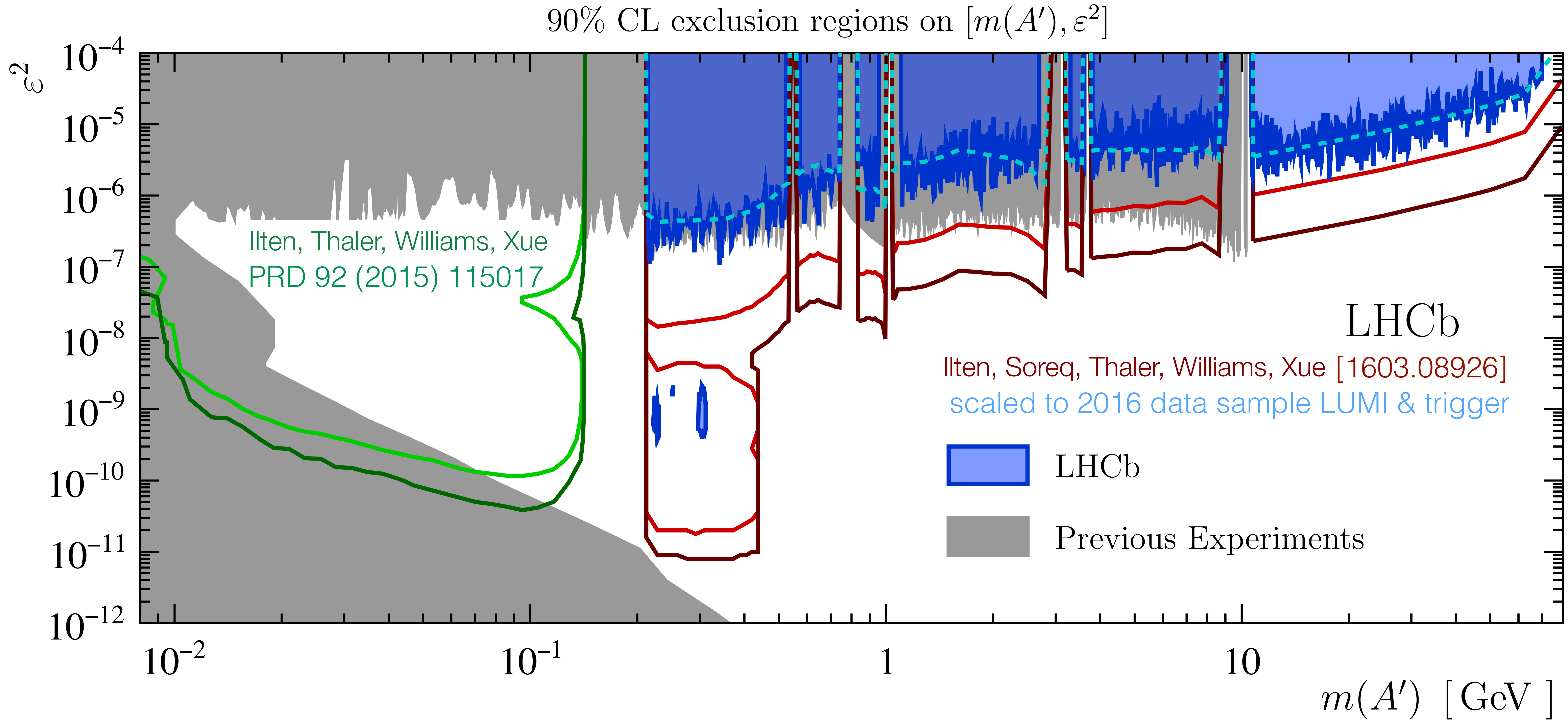
Final A' sample



Search for Dark Photons / Results

Phys. Rev. Lett. 120, 061801 (2018)

- The 2016 dimuon results are consistent with (better than) predictions for prompt (long-lived) dark photons as discussed in [1603.08926]. We implemented huge improvements in the 2017 triggers for low masses, so plan quick turn around on 2017 dimuon search - then onto electrons.



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H→μτ decays / 1bis

from top to bottom: $\mu\tau_e$, $\mu\tau_{h1}$, $\mu\tau_{h3}$, $\mu\tau_\mu$

from L to R: $\mu\tau_\mu$, $\mu\tau_e$, $\mu\tau_{h1}$, $\mu\tau_{h3}$,