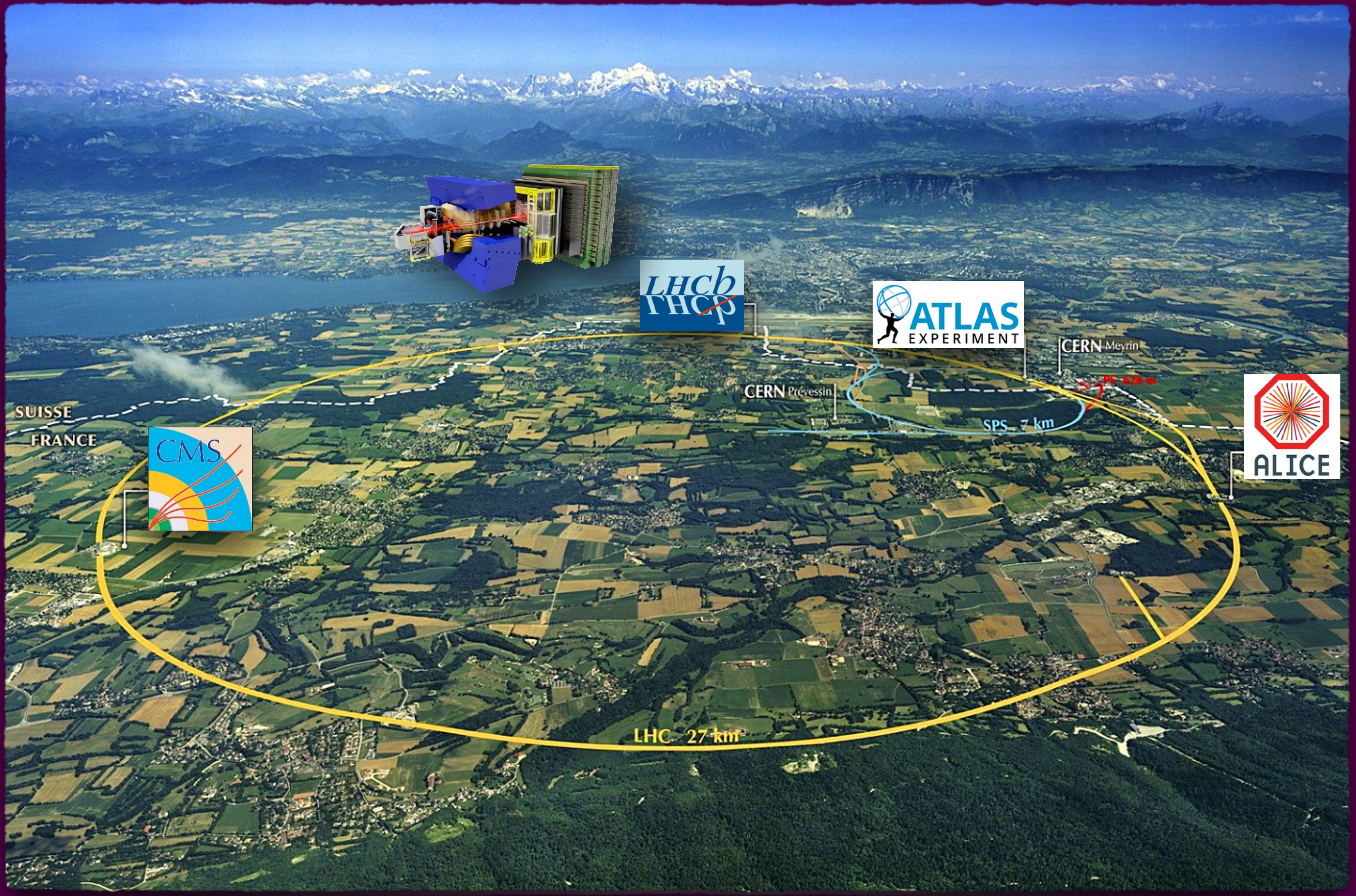
LHCb upgrades and prospects for charged Lepton Universality Violation



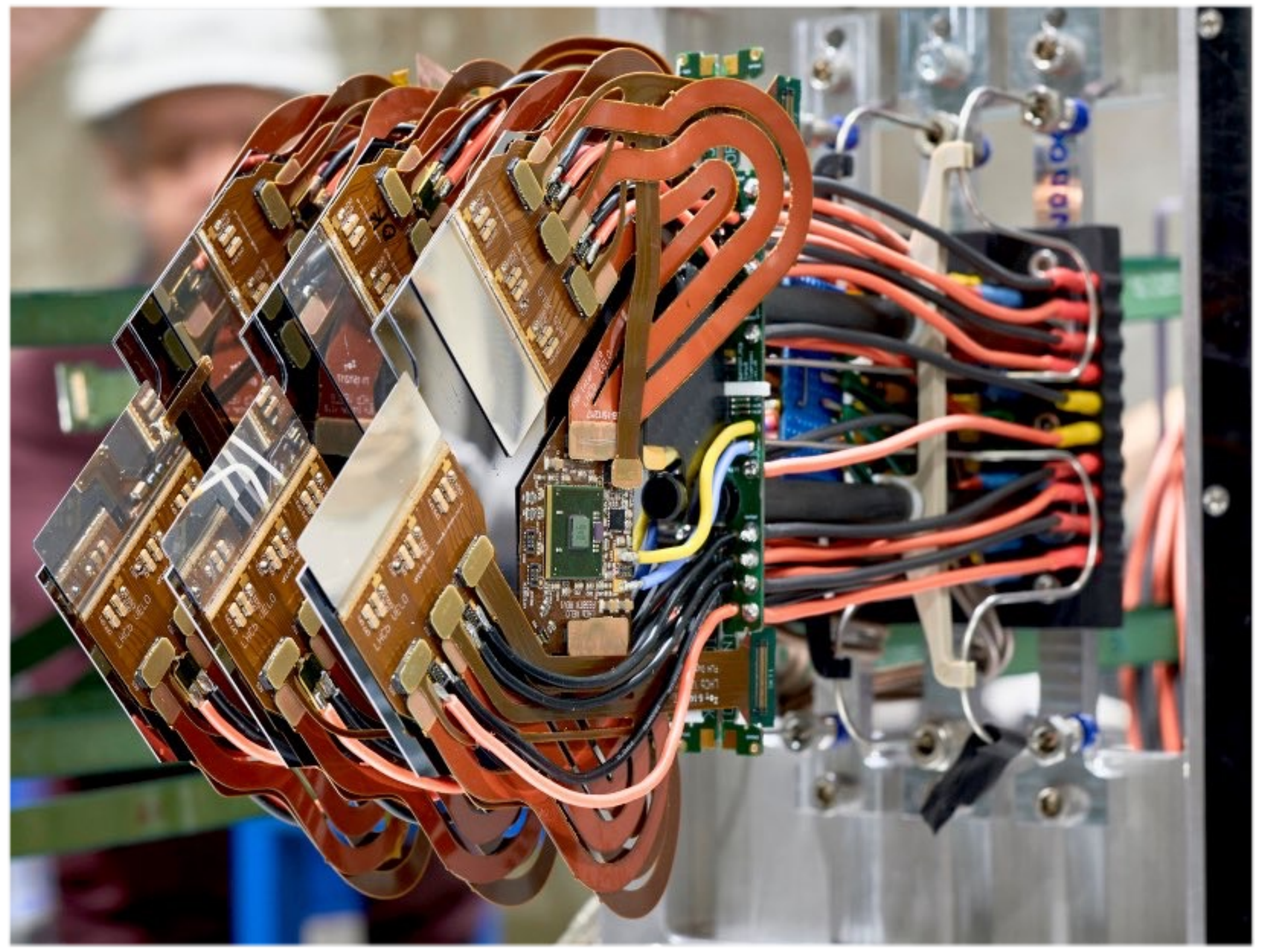
Manuel Franco Sevilla
University of Maryland

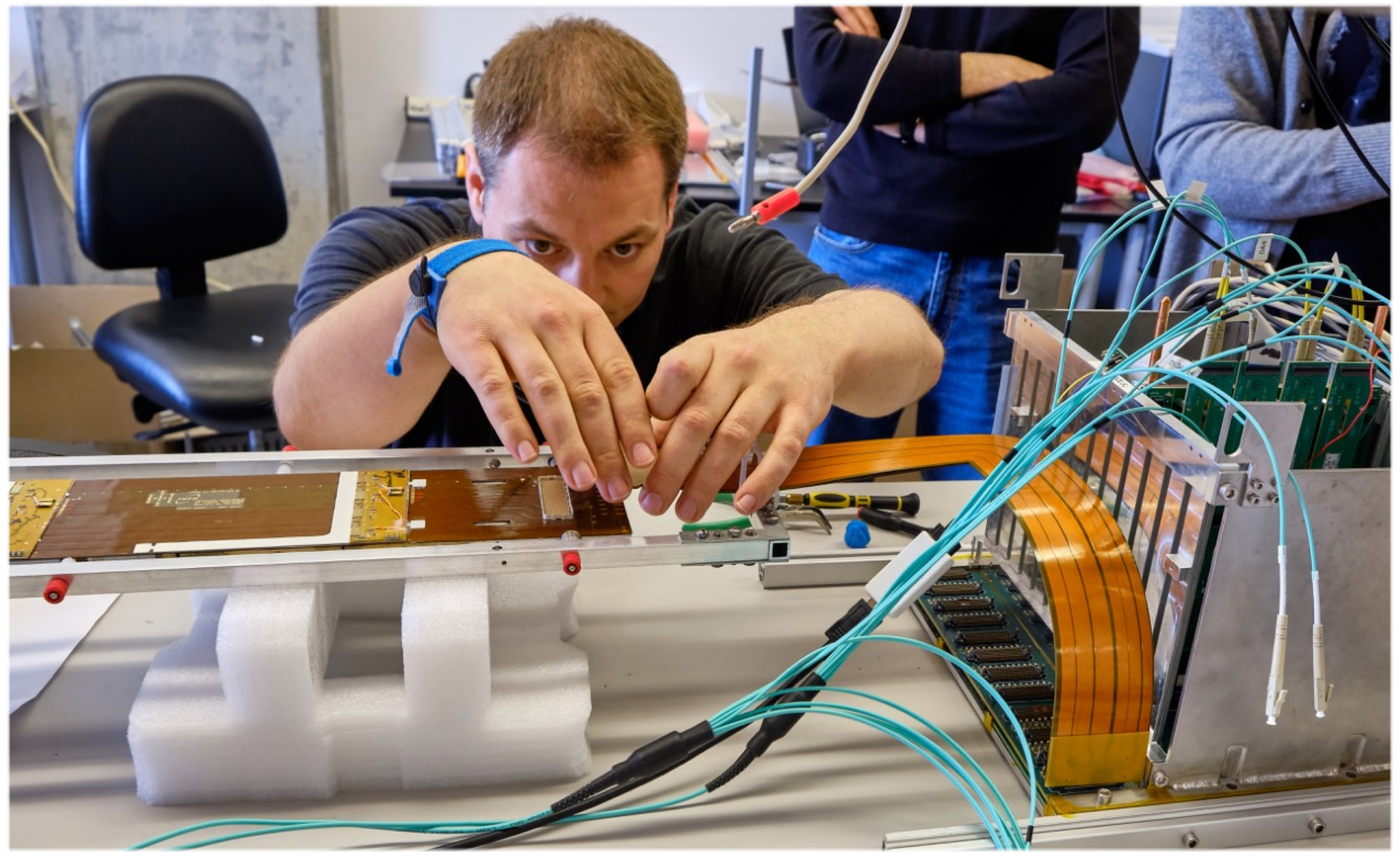
<u>14th October 2020</u>

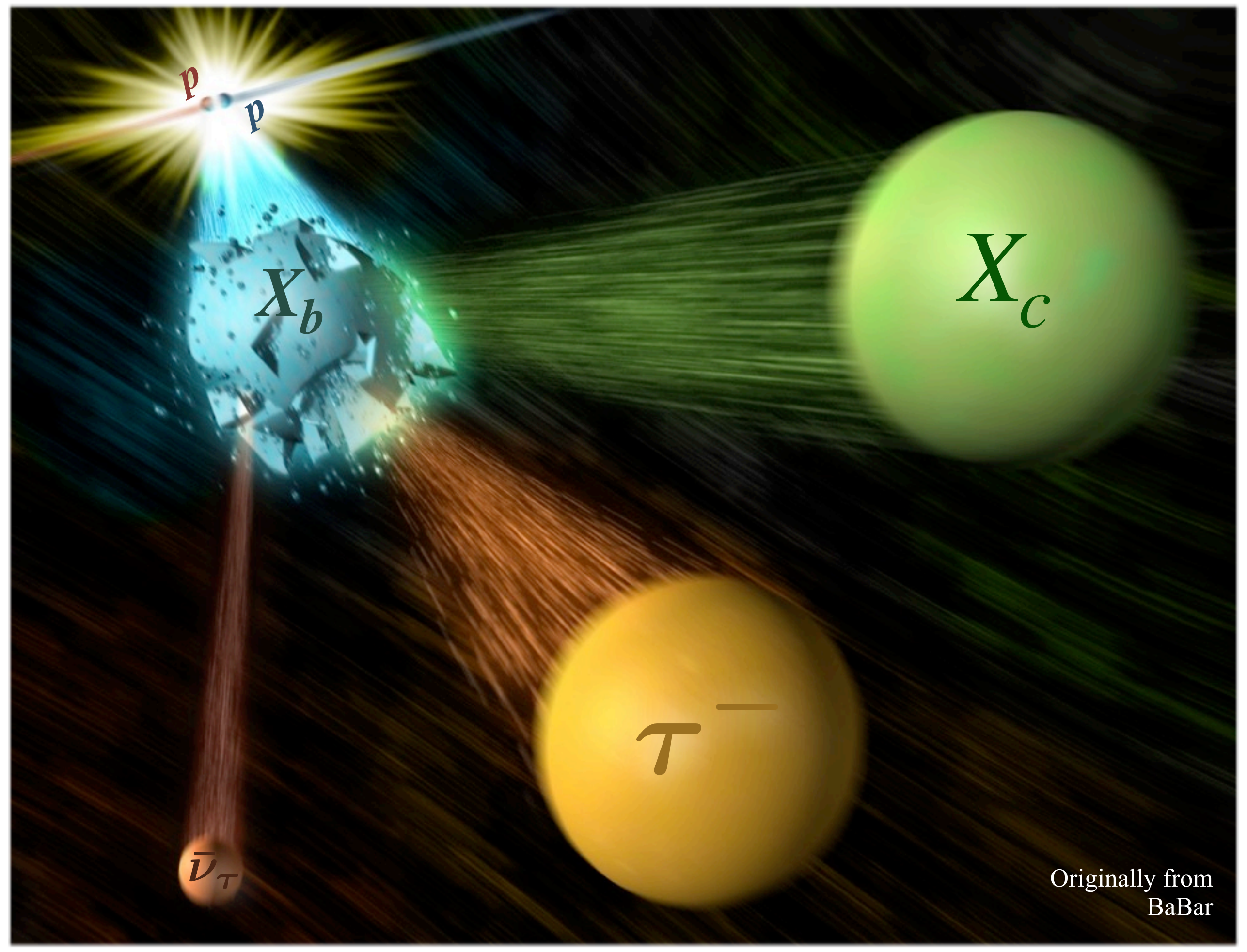
Virtual UMD High energy and astrophysics seminar

Outline

- LHCb upgrades
  - Upgrade I (2019-2021)
    - Pixel Vertex Locator
    - Upstream Tracker
  - Upgrade Ib (2025-27) and II (2031)



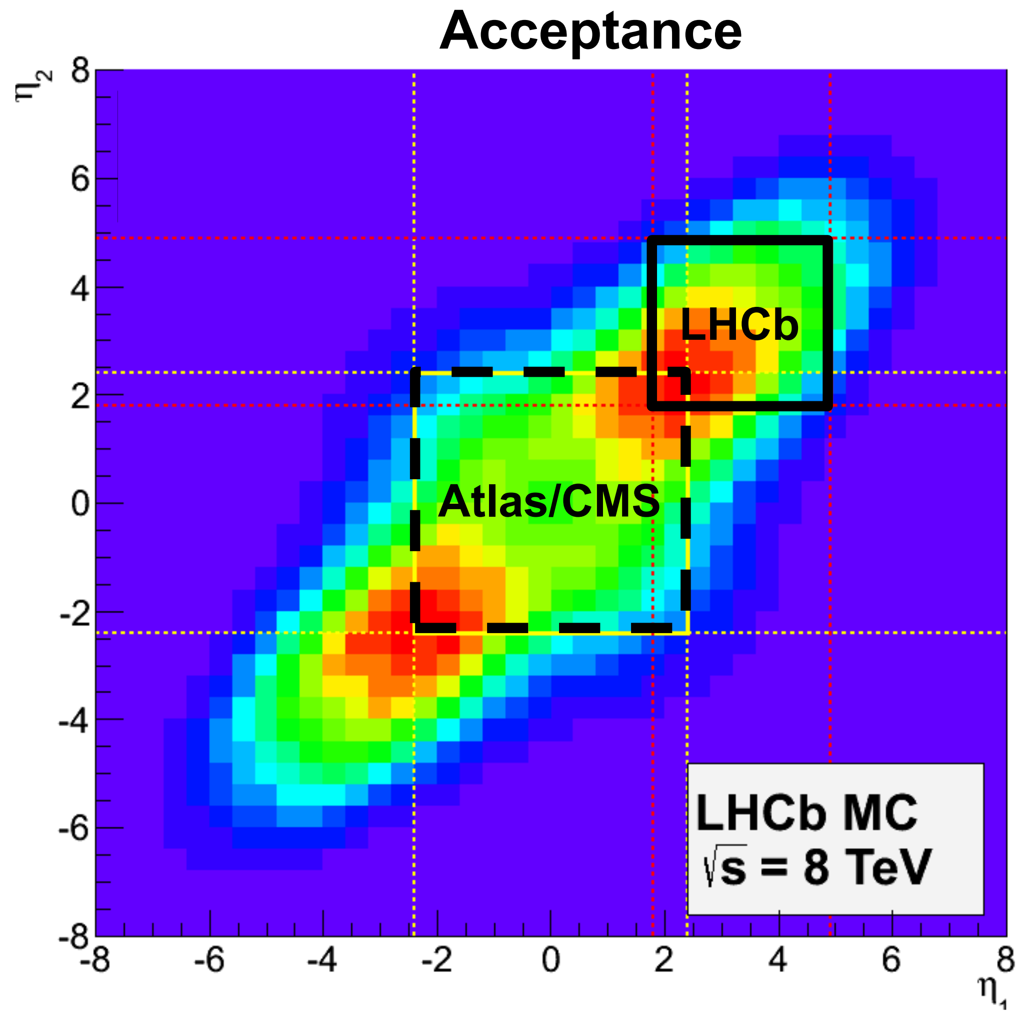




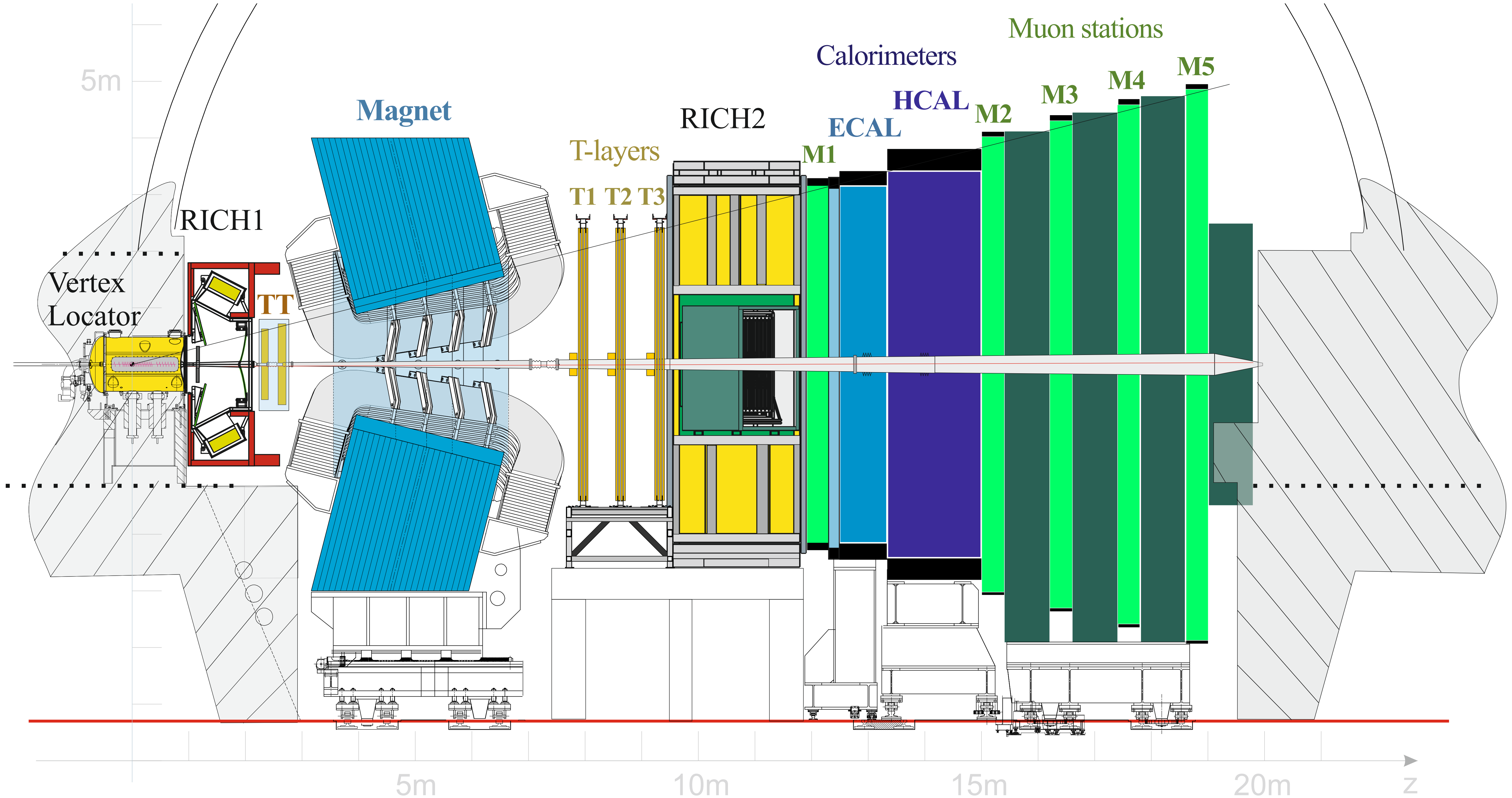
- **Prospects** for charged **Lepton Universality Violation (LUV)** at LHCb
  - **Features** of **current $b \to c\tau\nu$ measurements at LHCb**
  - Possible **precision** on $\mathscr{R}(X_c)$
  - Measuring **kinematic distributions**

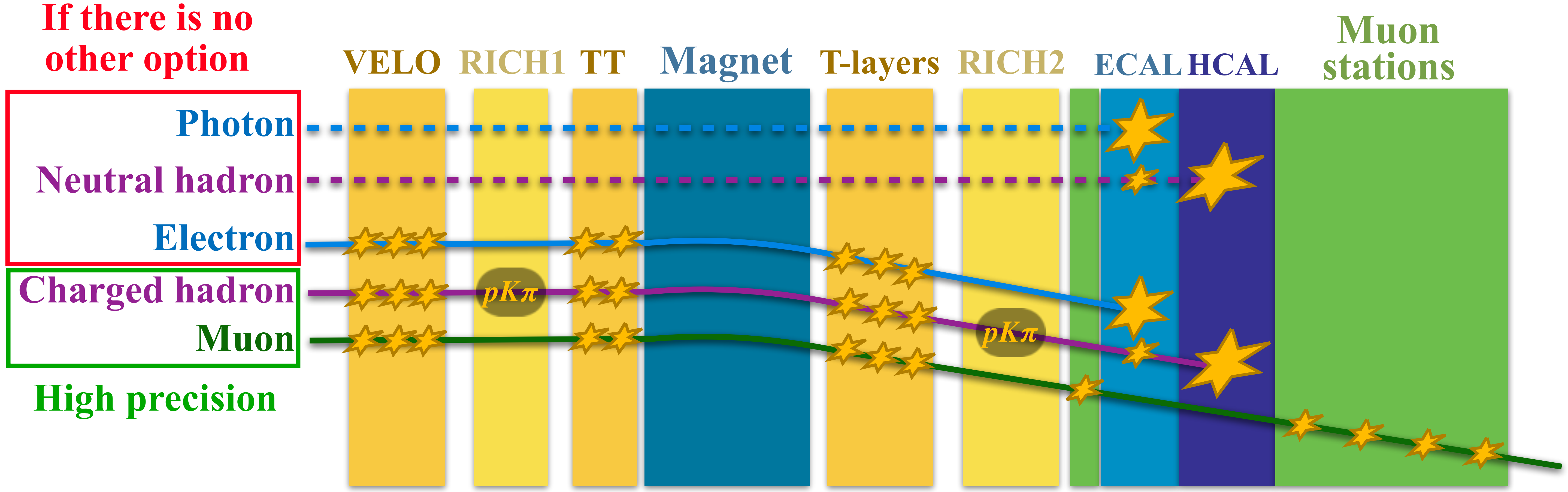
The LHCb experiment

- 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

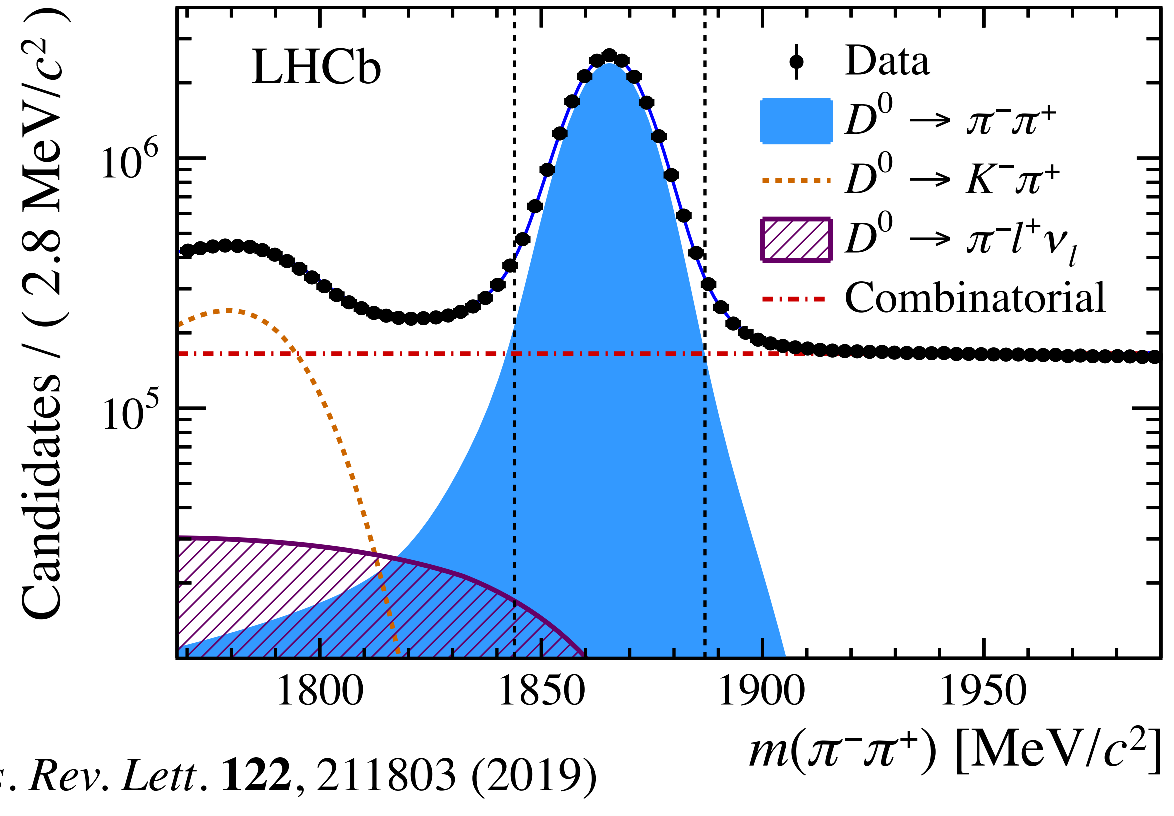




Hugely successful Runs 1 and 2

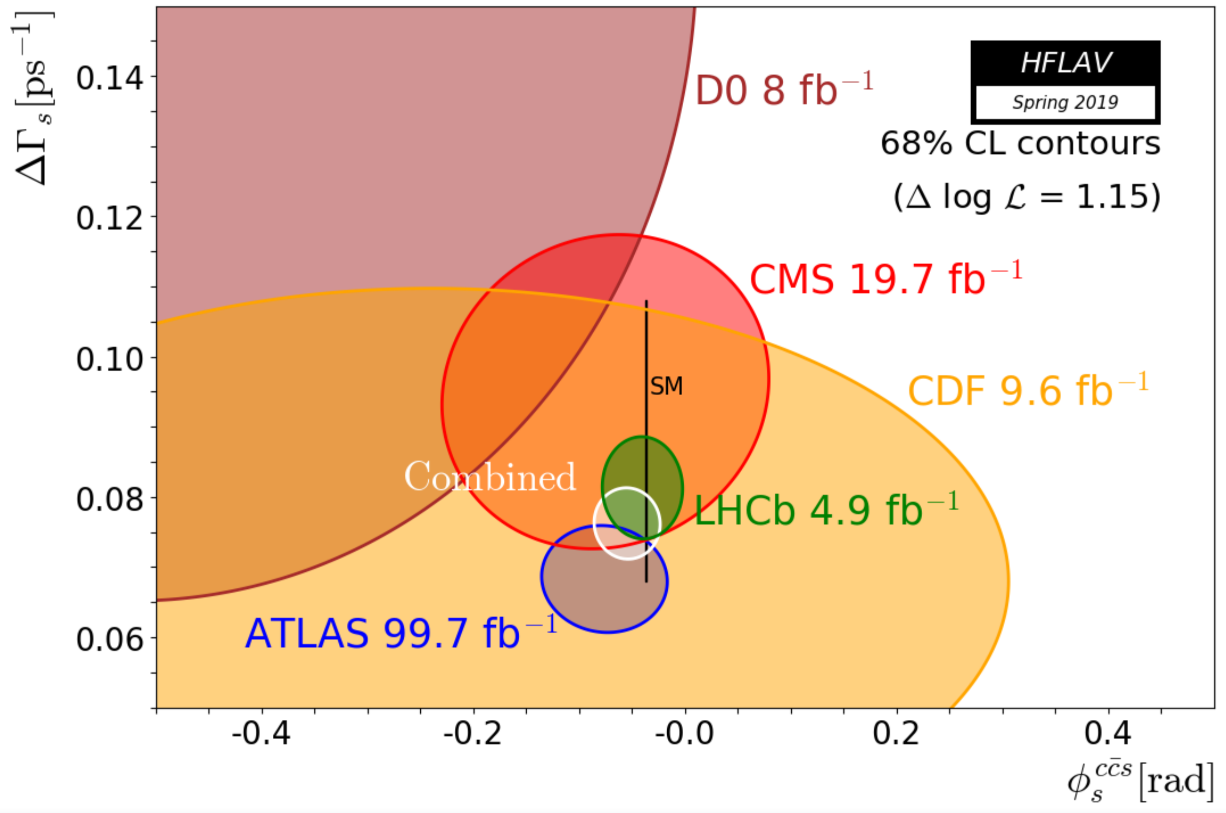
LHCb has **demonstrated** emphatically that the **LHC is an ideal laboratory for flavor physics**

First CPv in charm sector

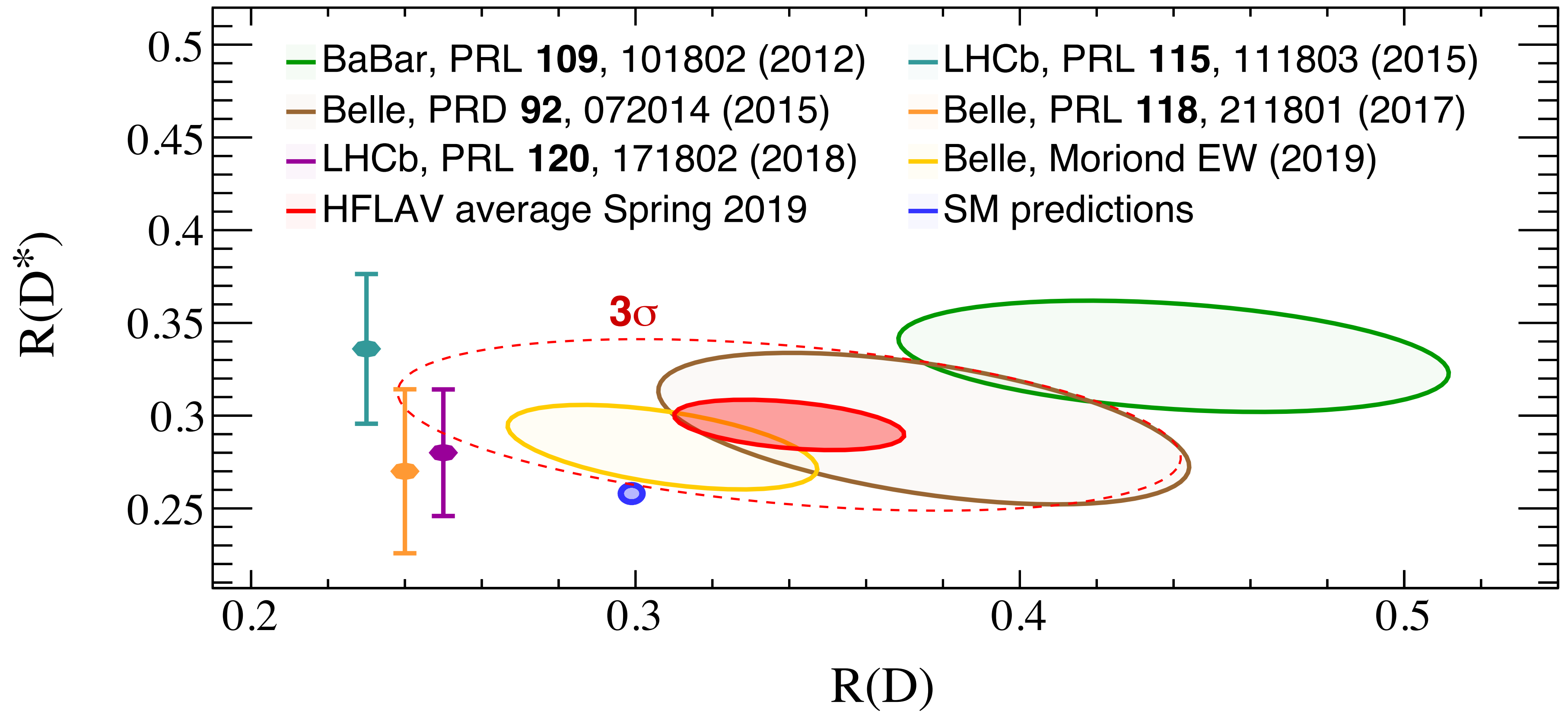


Phys. Rev. Lett. **122**, 211803 (2019)

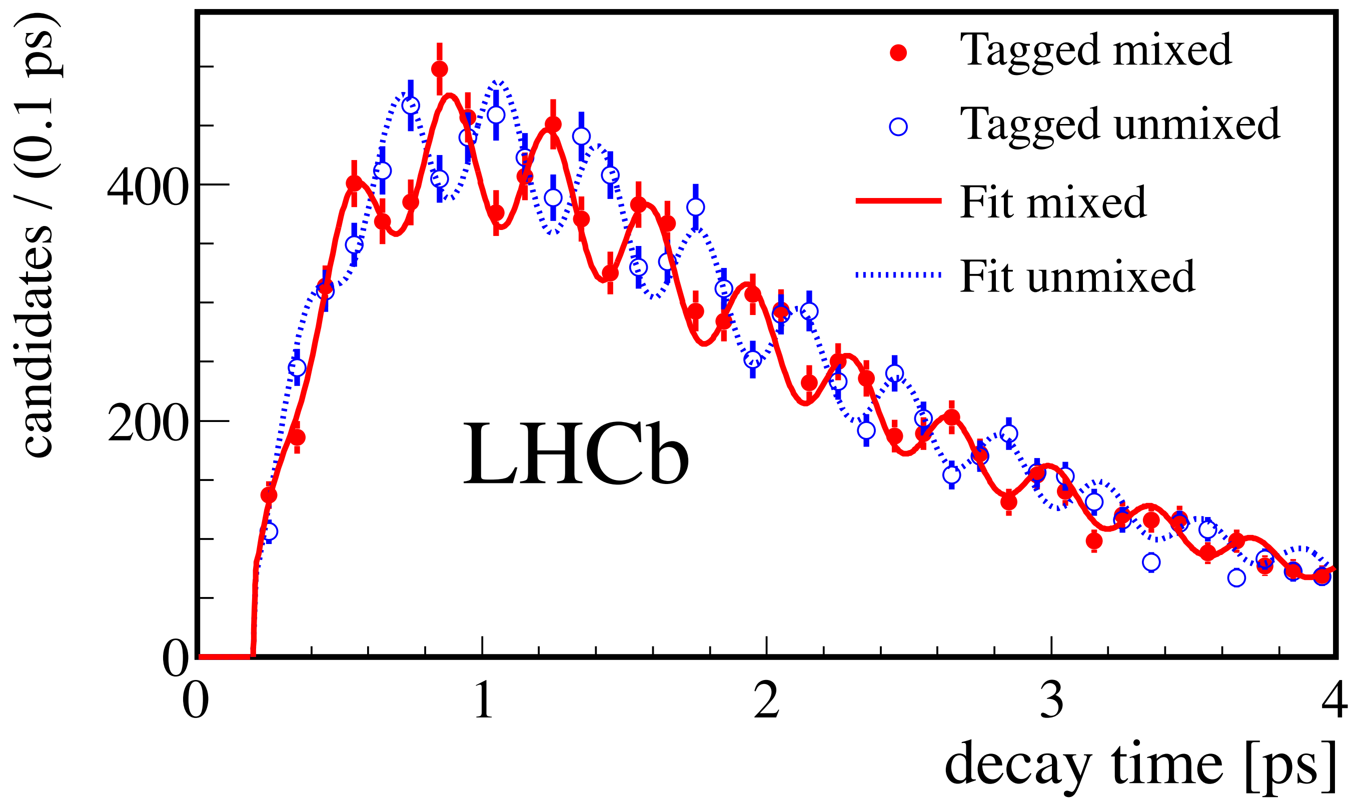
Most precise measurement of φ_s



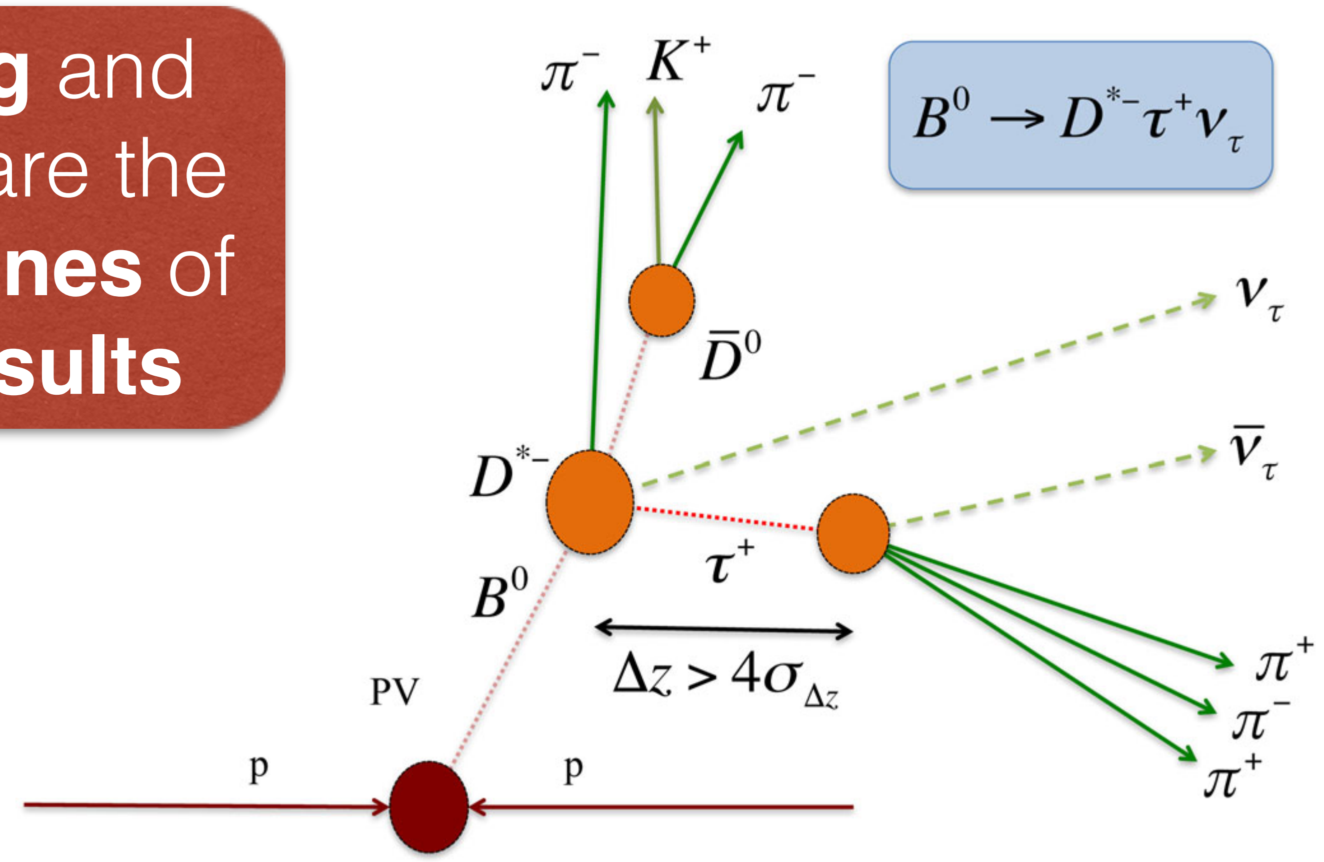
R(D*) from B → D*τν



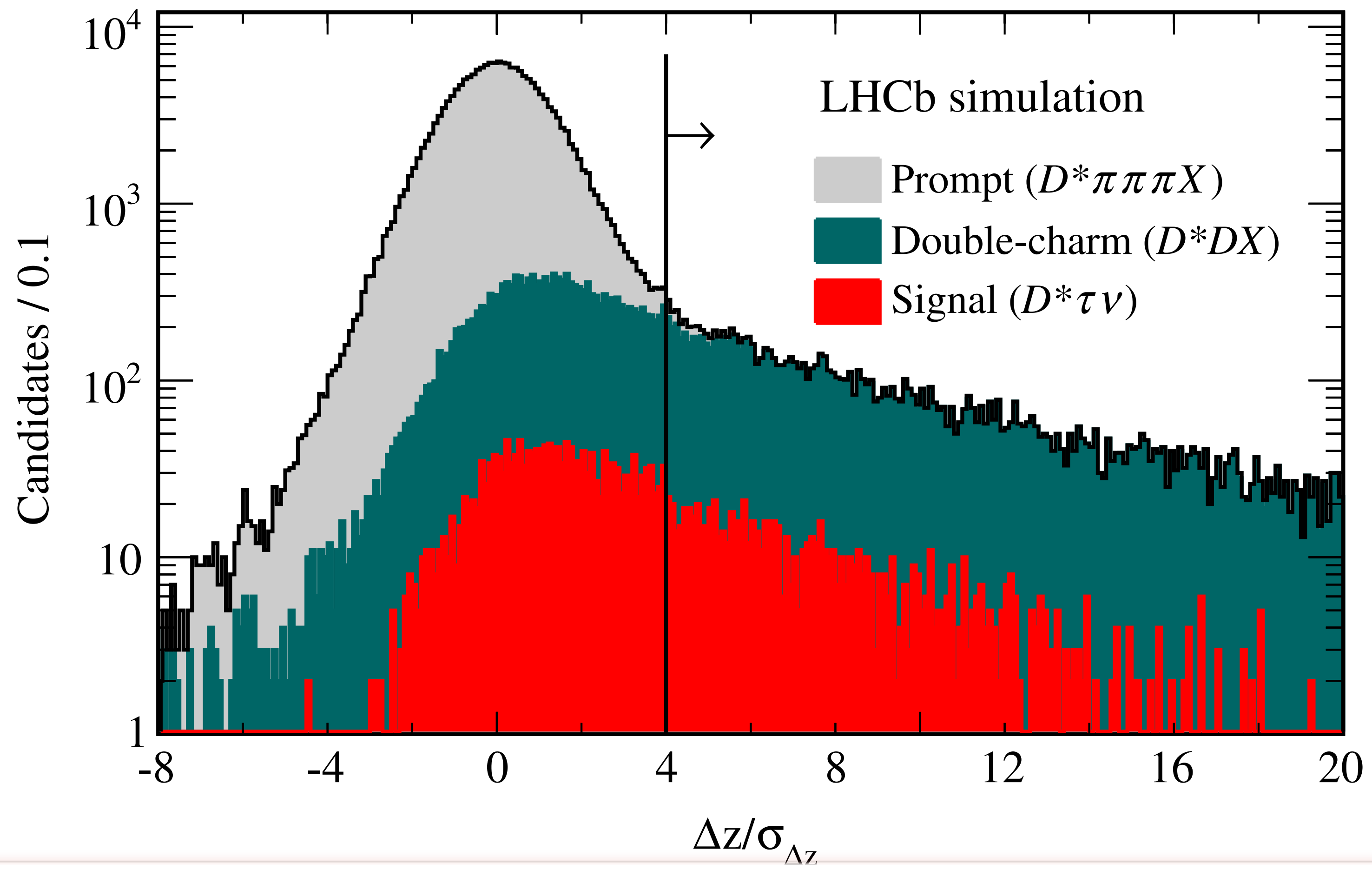
New J. Phys. **15**, 053021 (2013)

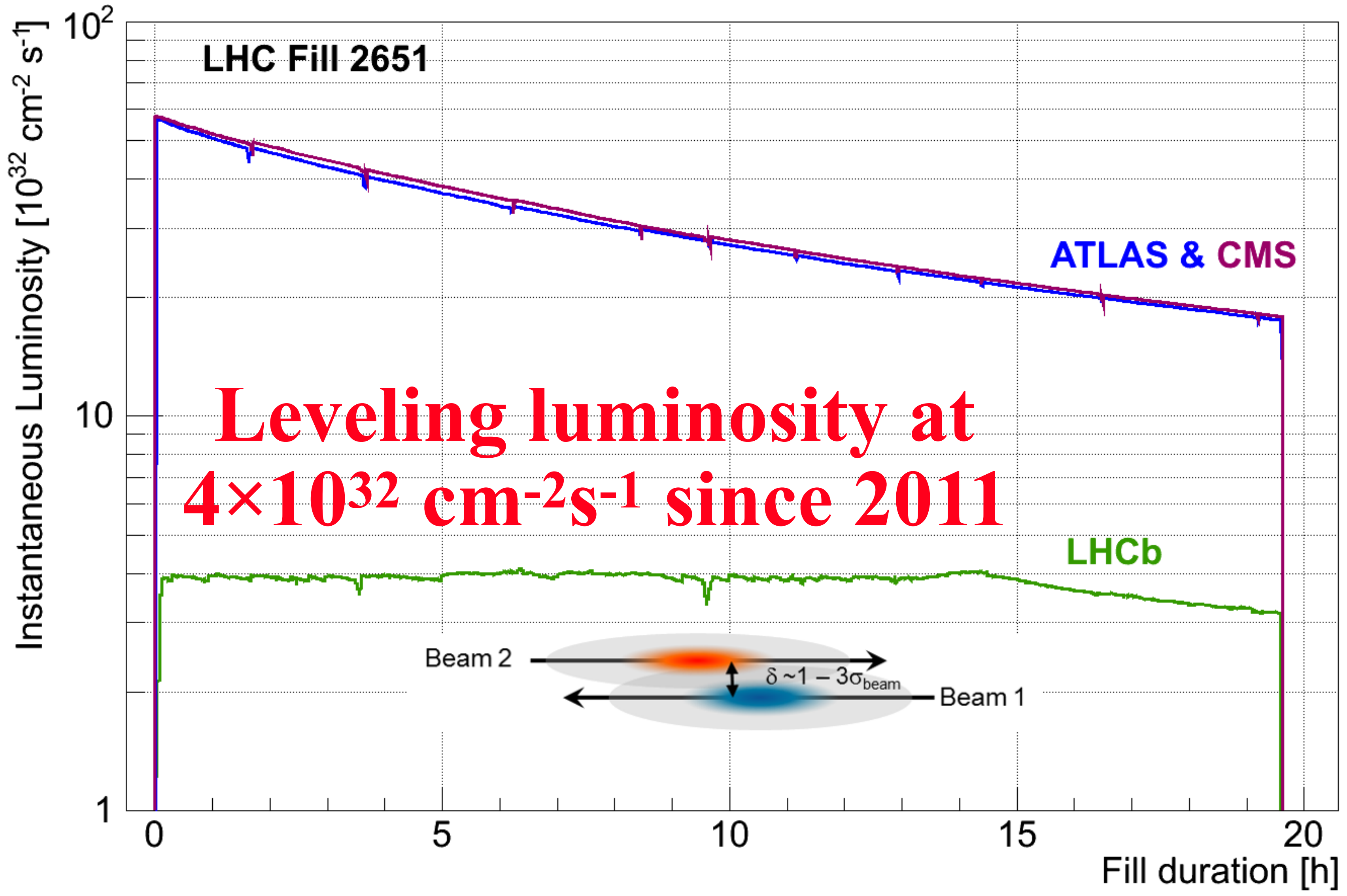


Vertexing and **tracking** are the **cornerstones** of **these results**

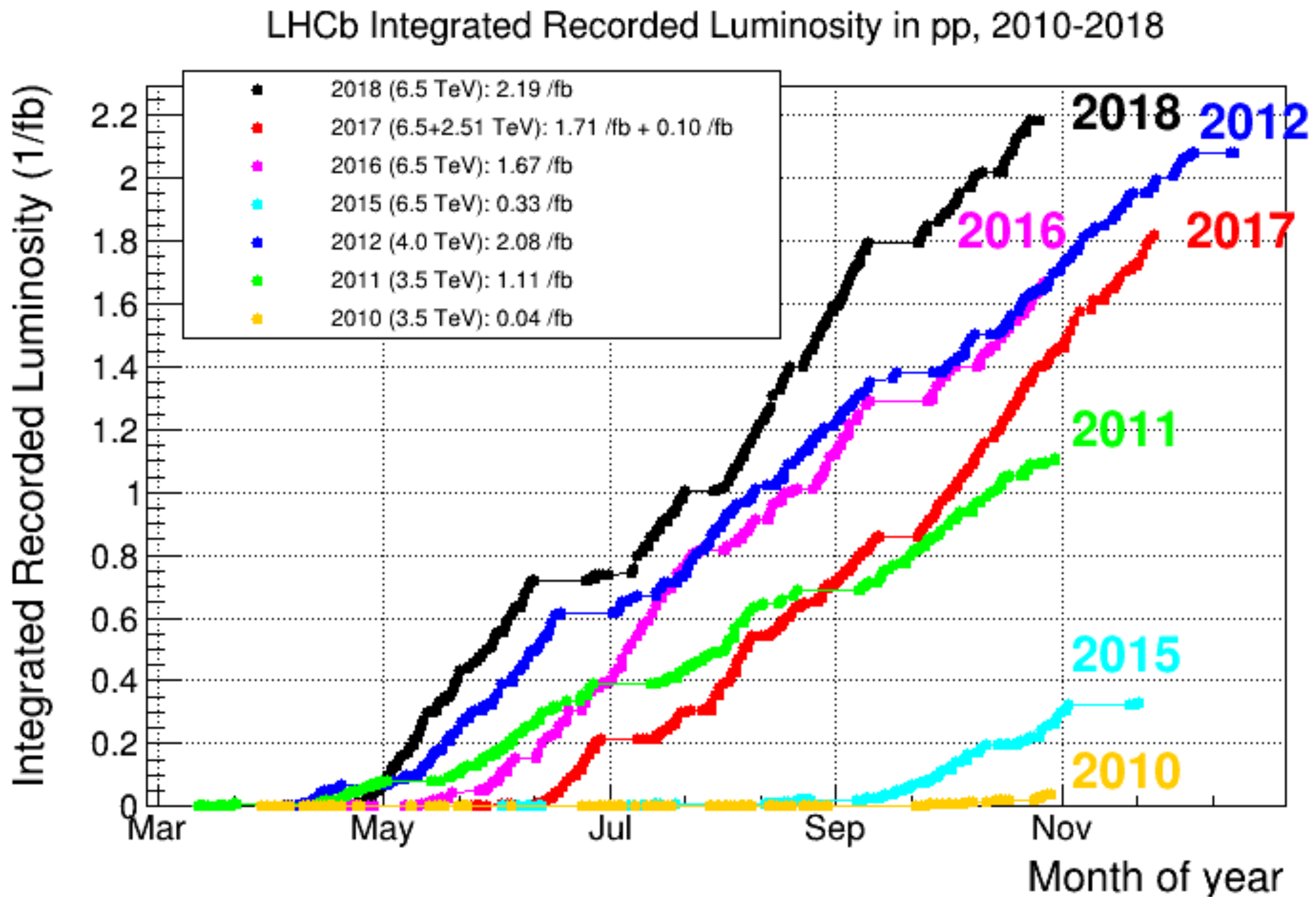


Phys. Rev. D **97**, 072013 (2018)

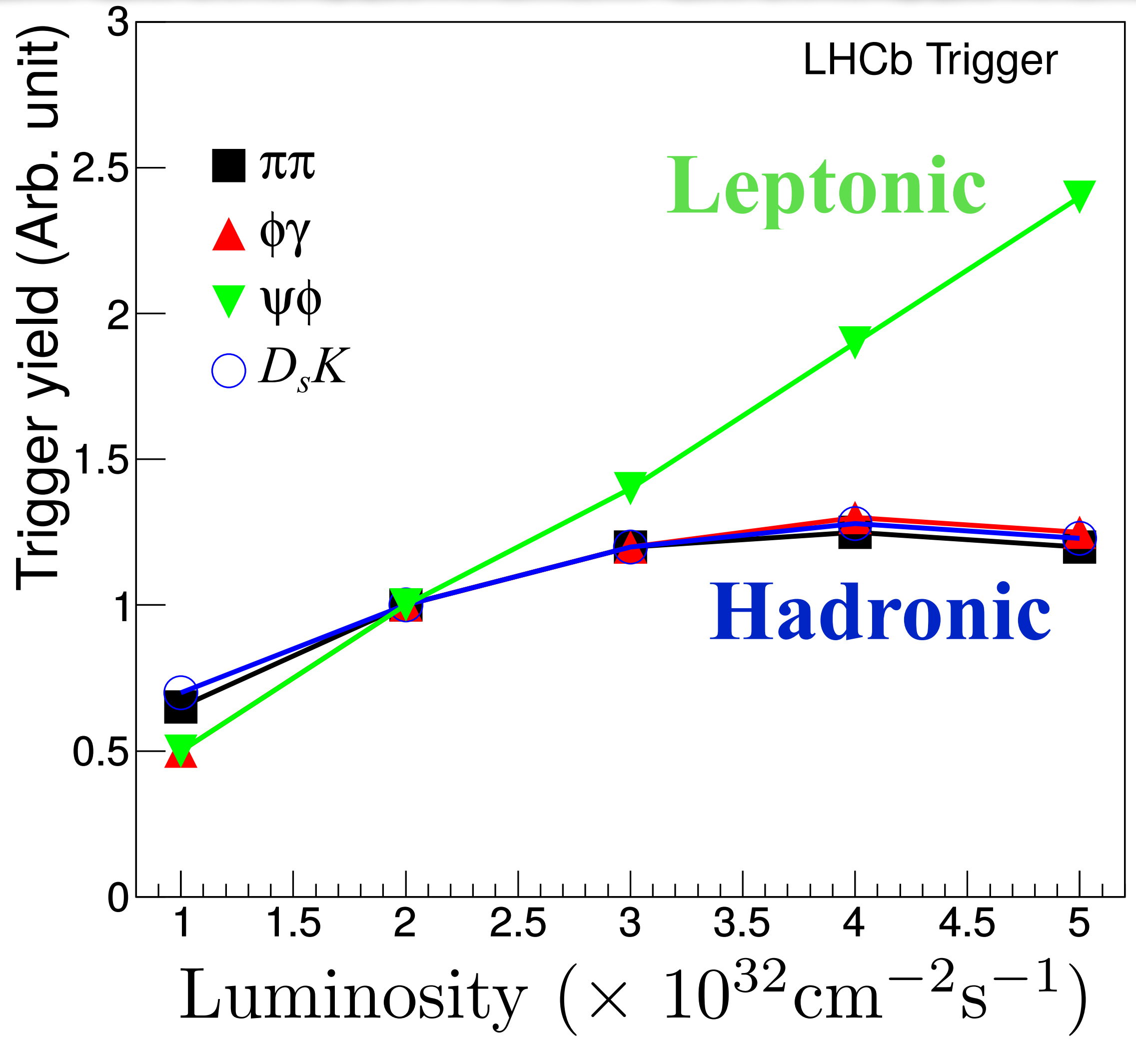


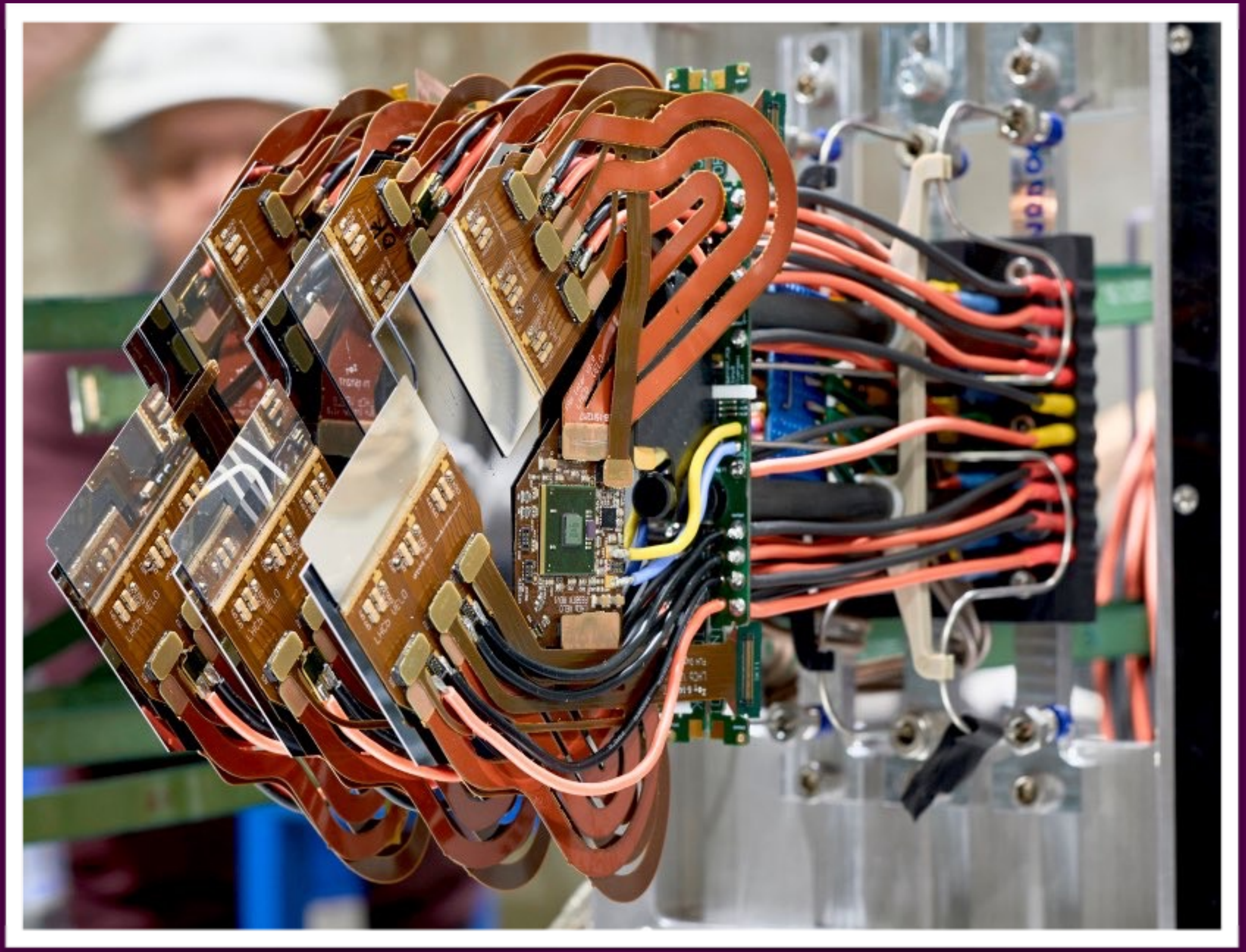


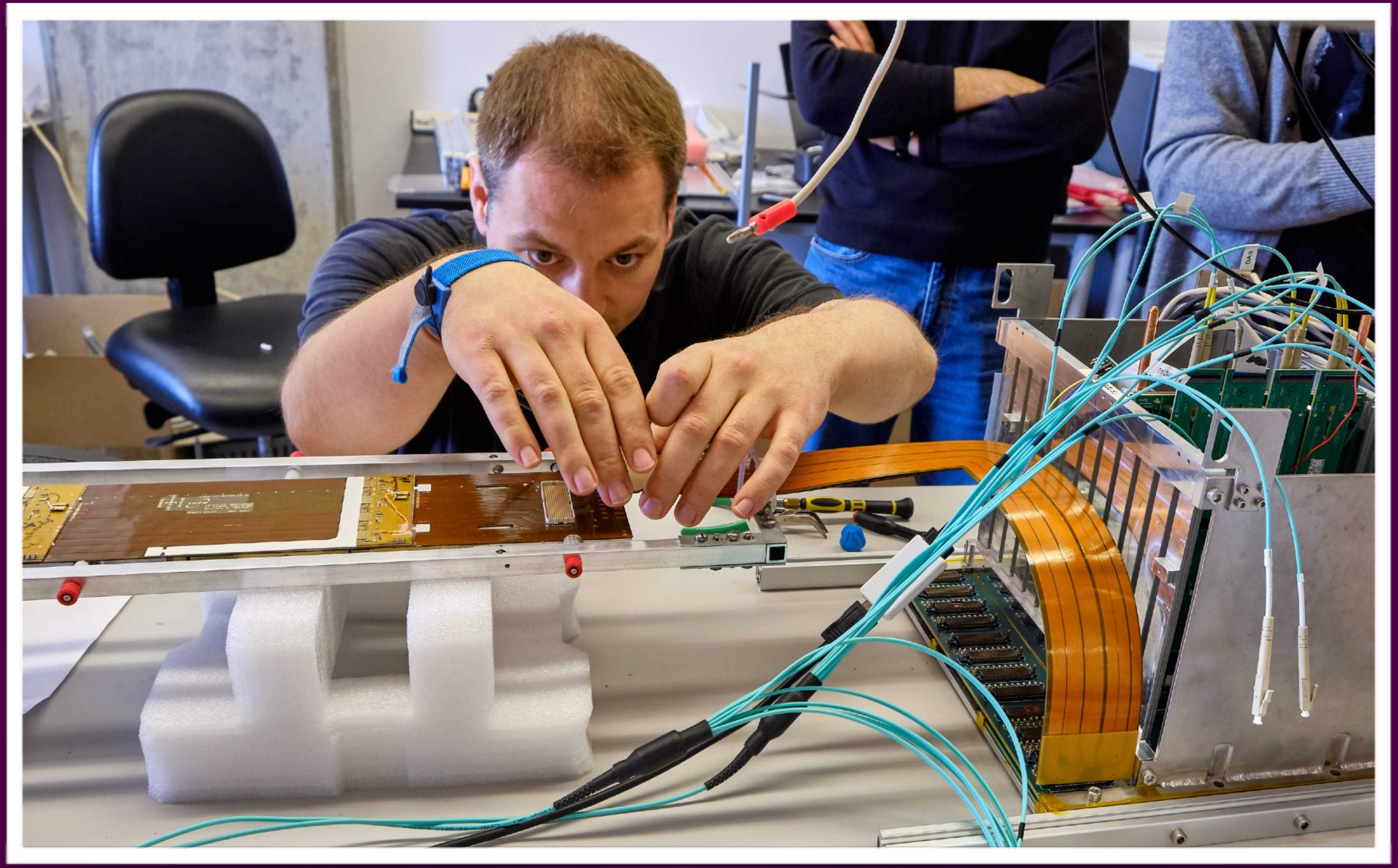
- **~** Have been **luminosity leveling since 2011**
  - ➡ Data sample limited to **1-2 fb^{-1}/year**

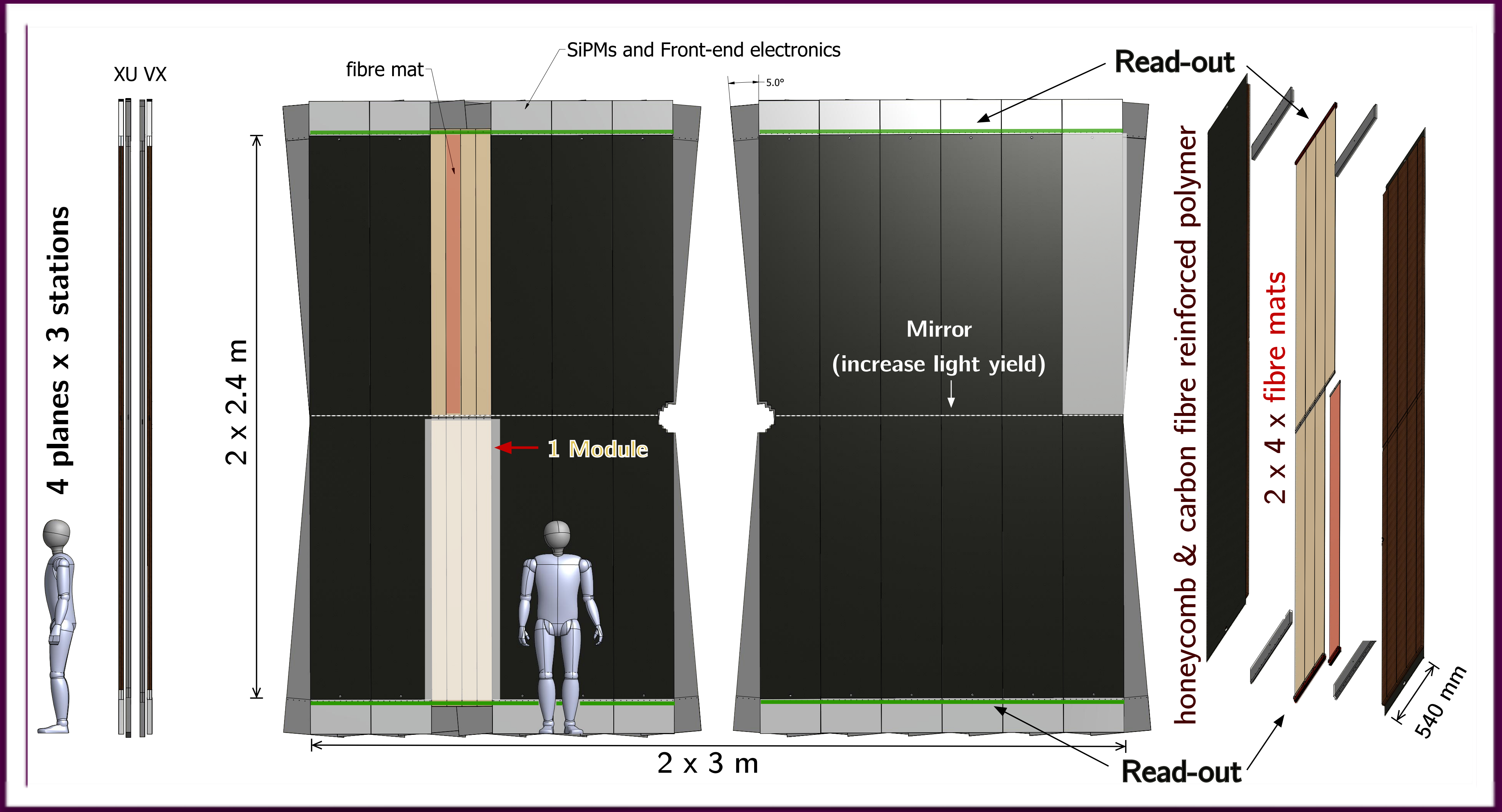


- **~** **Limitations** for higher luminosity of **2011-2018 detector**
  - ➡ **Low efficiency** for **hadronic** decays at higher lumi **due to hardware trigger**
  - ➡ **Overall performance degrades** quickly for **high occupancy**
  - ➡ **Radiation hardness** of **trackers**









XU VX
4 planes x 3 stations
fibre mat
SiPMs and Front-end electronics
2 x 2.4 m
1 Module
Mirror
(increase light yield)
Read-out
Read-out
2 x 3 m
honeycomb & carbon fibre reinforced polymer
2 x 4 x fibre mats
540 mm

Upgrade I

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

Runs 1 and 2

40 MHz pp collisions → **L0** Hardware → 1.1 MHz Detector readout → **HLT** Software → 12.5 kHz (0.6 GB/s) Events on disk

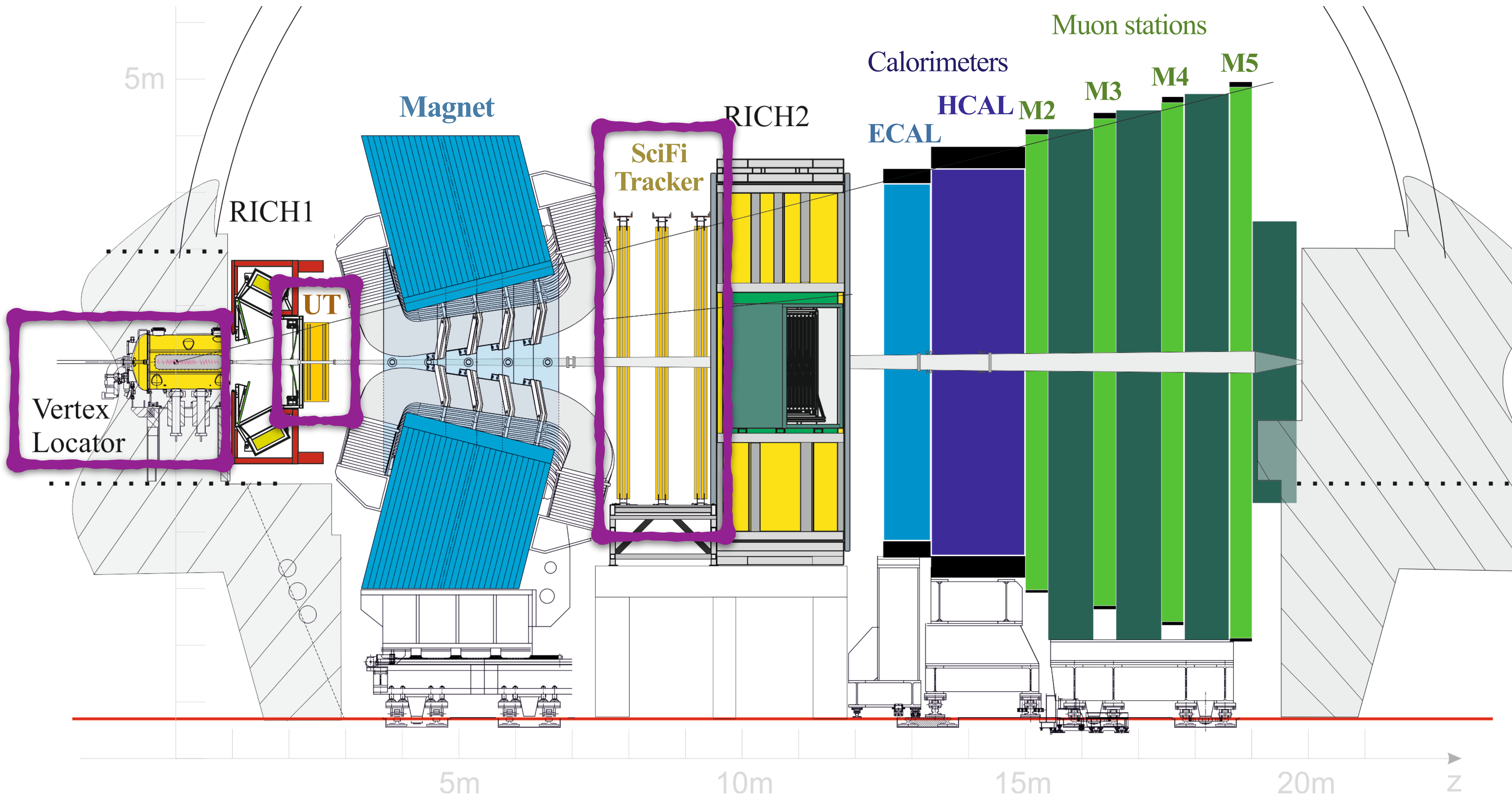
Upgrade I (being installed)

40 MHz pp collisions Detector readout → **HLT** Software → 100 kHz (2-5 GB/s) Events on disk

All electronics upgraded to send every hit to **flexible software trigger**

Increase granularity and longevity of **3 new trackers**

New RICH optics, lower PMT gain in CALO

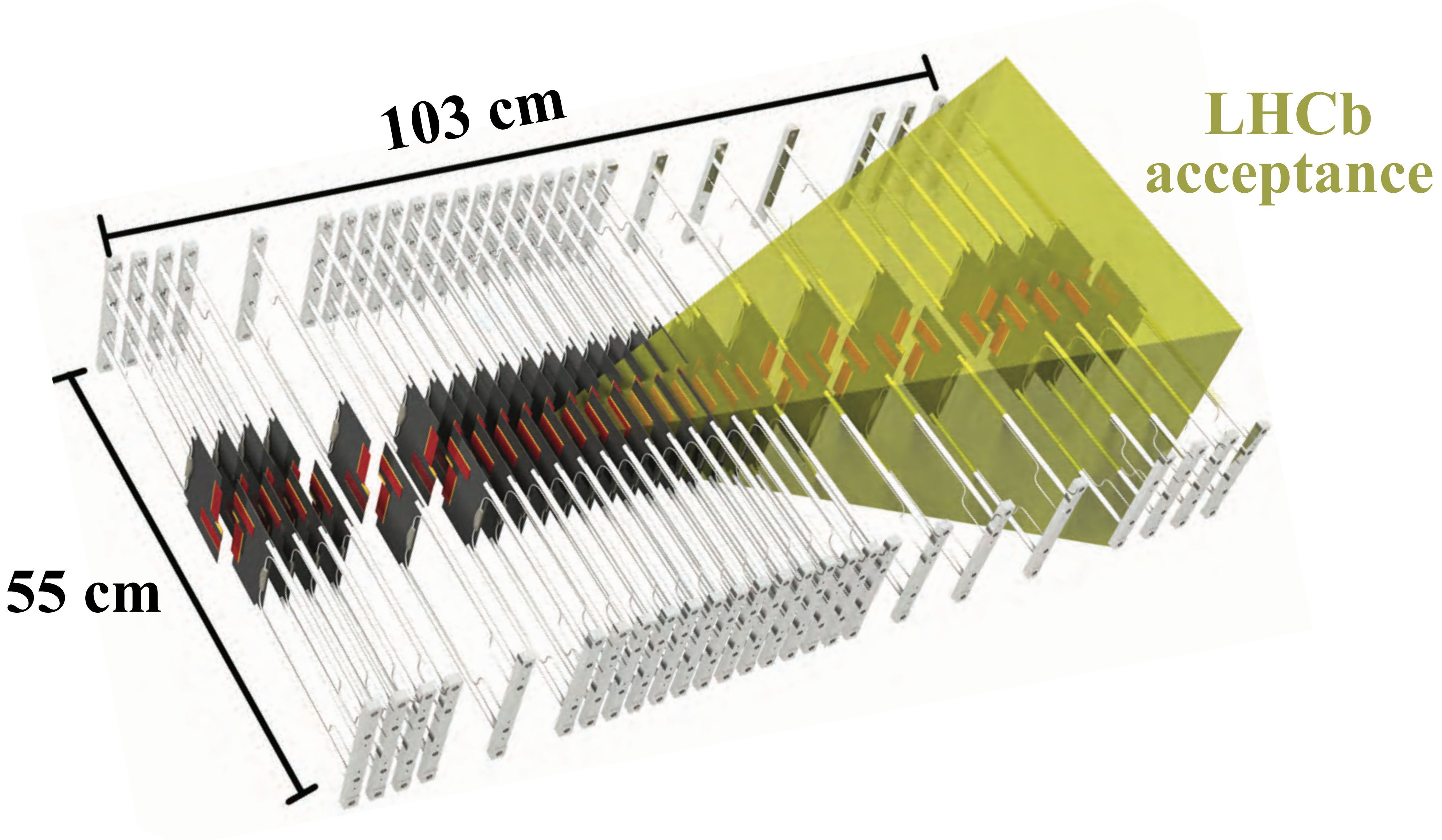


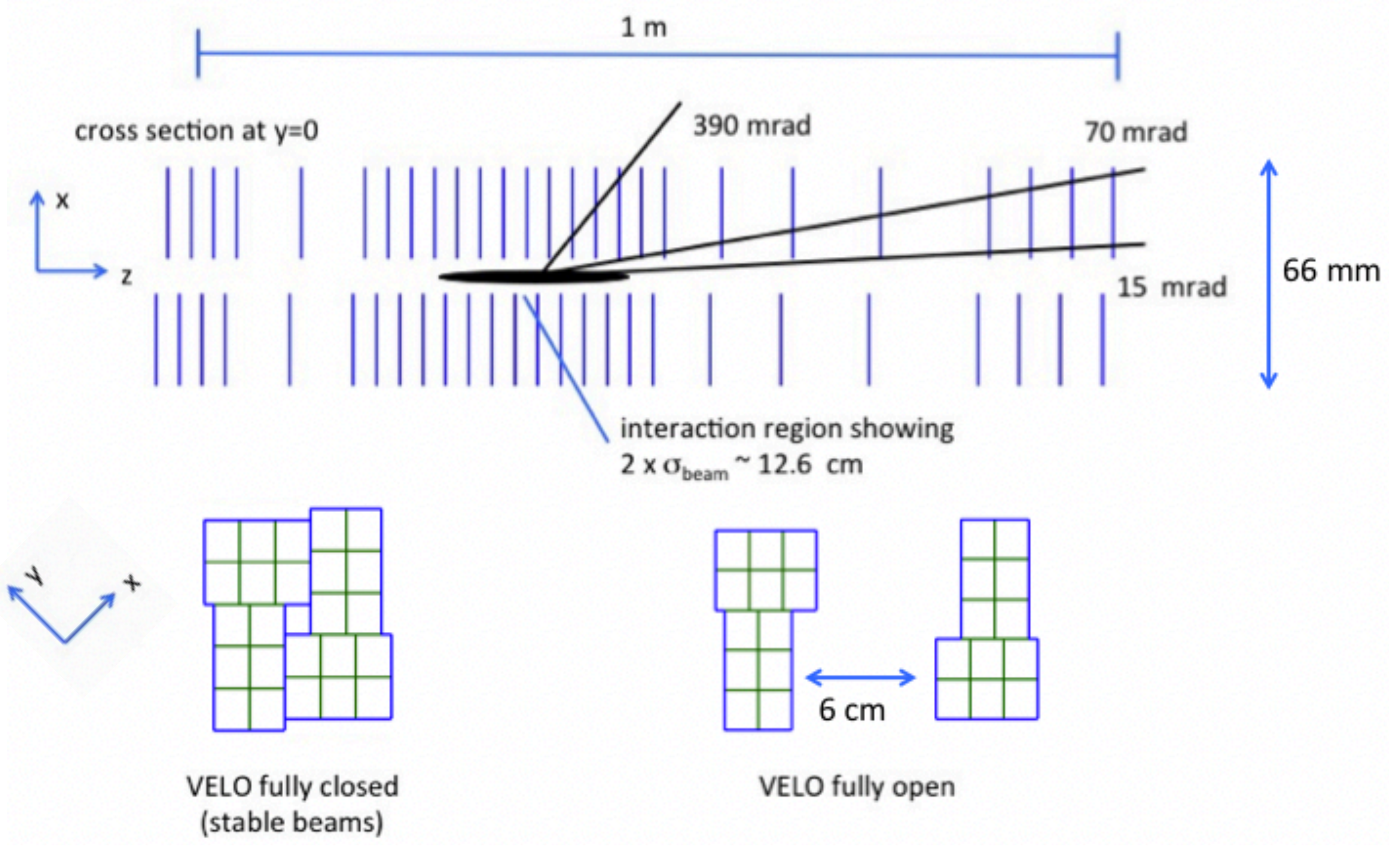
VELO Silicon strips → **Pixel VELO** Silicon pixels

TT Silicon strips → **UT** Silicon strips

IT + OT Silicon strips + straw tubes → **SciFi** Scintillating fibers

Pixel VELO overview





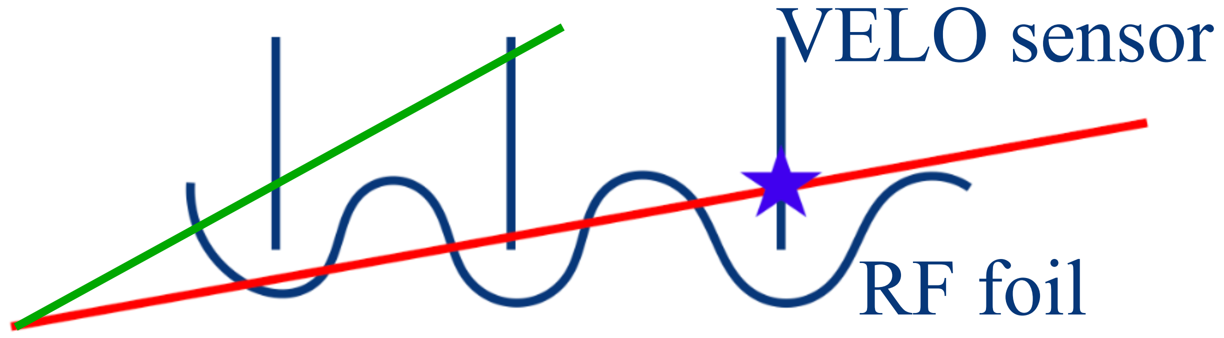
~ In vacuum as close to IP as possible

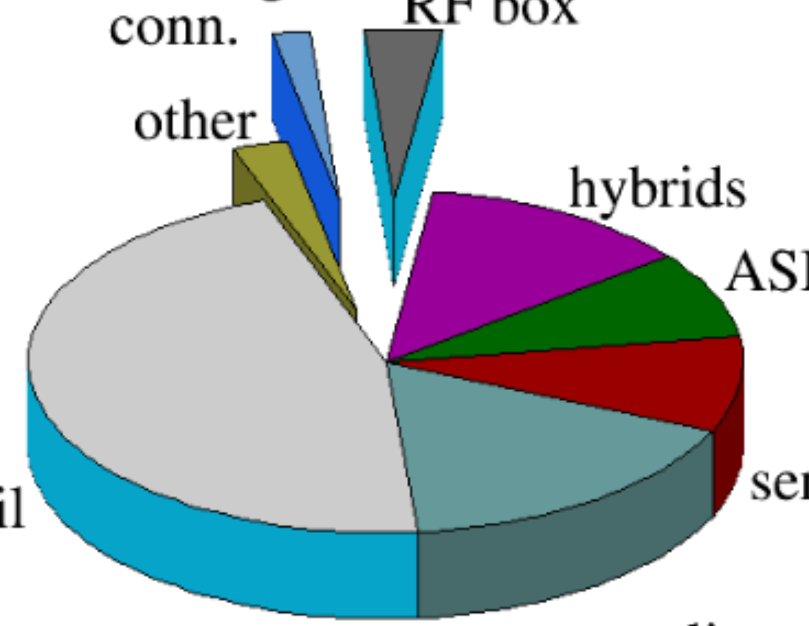
➡ **Crucial** for **vertexing** and **tracking**

	VELO	Pixel VELO
Years of operation	2010 – 2018	2022 – 2030
Sensors	**173k R-φ**	**41M pixels**
Number of layers	**23**	**26**
Distance from IP	**8.2 mm**	**5.1 mm**
$Fluence_{max}$ [1 MeV n_{eq} cm^{-2}]	4.3×10^{14}	8×10^{15}
HV Tolerance	500 V	1000 V
ASIC Readout	**1 MHz**	**Data driven**
Data Rate	~150 Gb/s	2.8 Tb/s
Power	~0.8 kW	~1.6 kW
Operating temp.	-8°C	-25°C

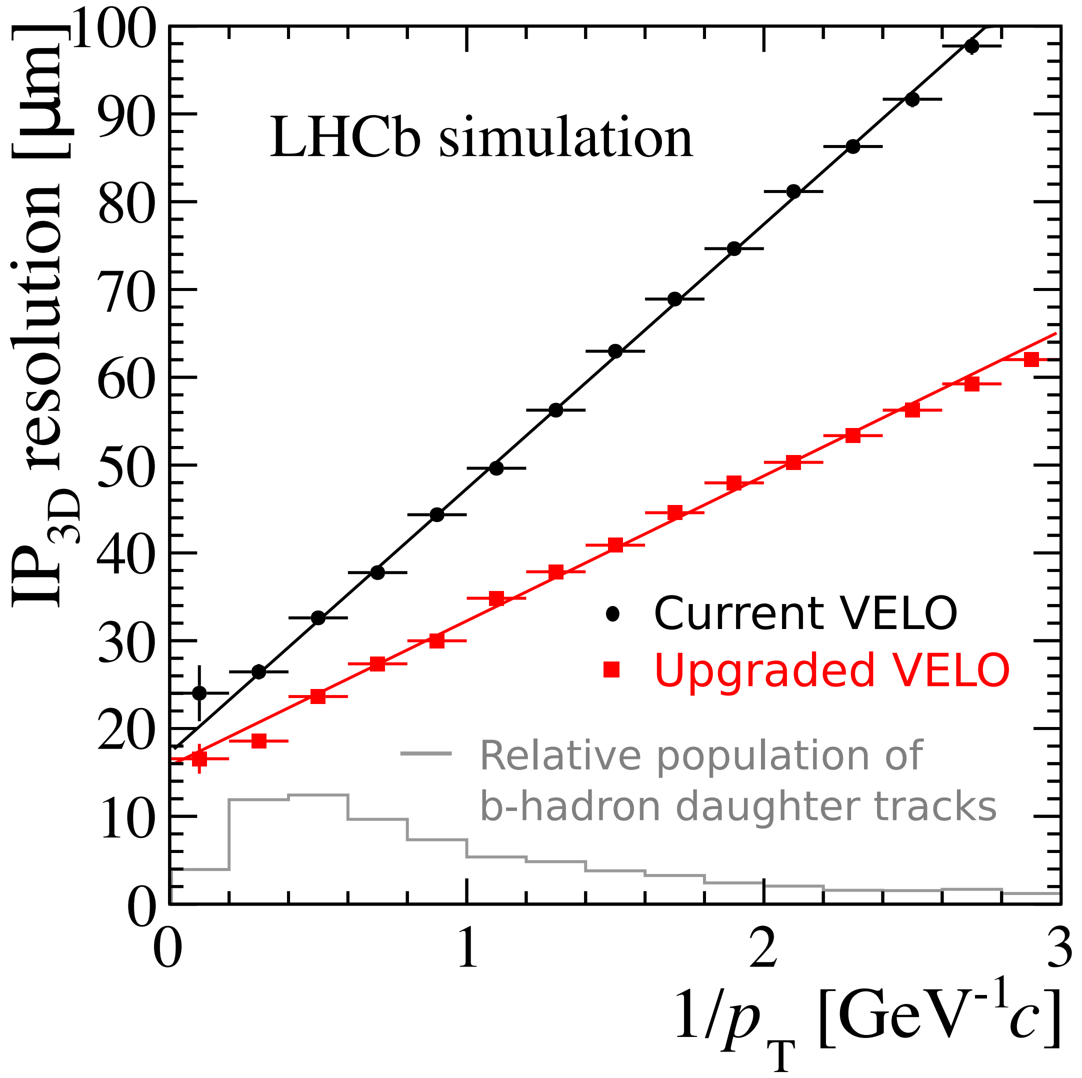
Pixel VELO overview

New RF foil



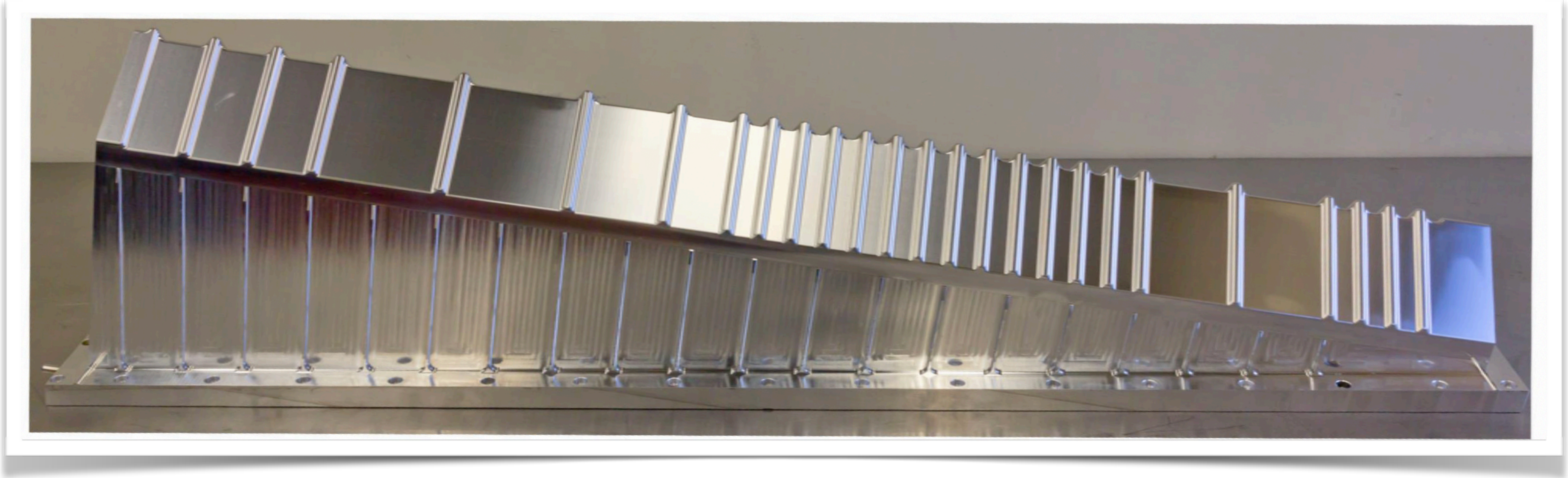


- **RF foil separates beam/VELO vacua** and **shields electronics**
- **Largest** contributor to **material budget**
- Initial proposal to **reduce thickness from 300 to 250 μm**
  - Decided last year to **chemically etch it to 150 μm!**
- **RF now milled and etched**
  - Extensive metrology campaign

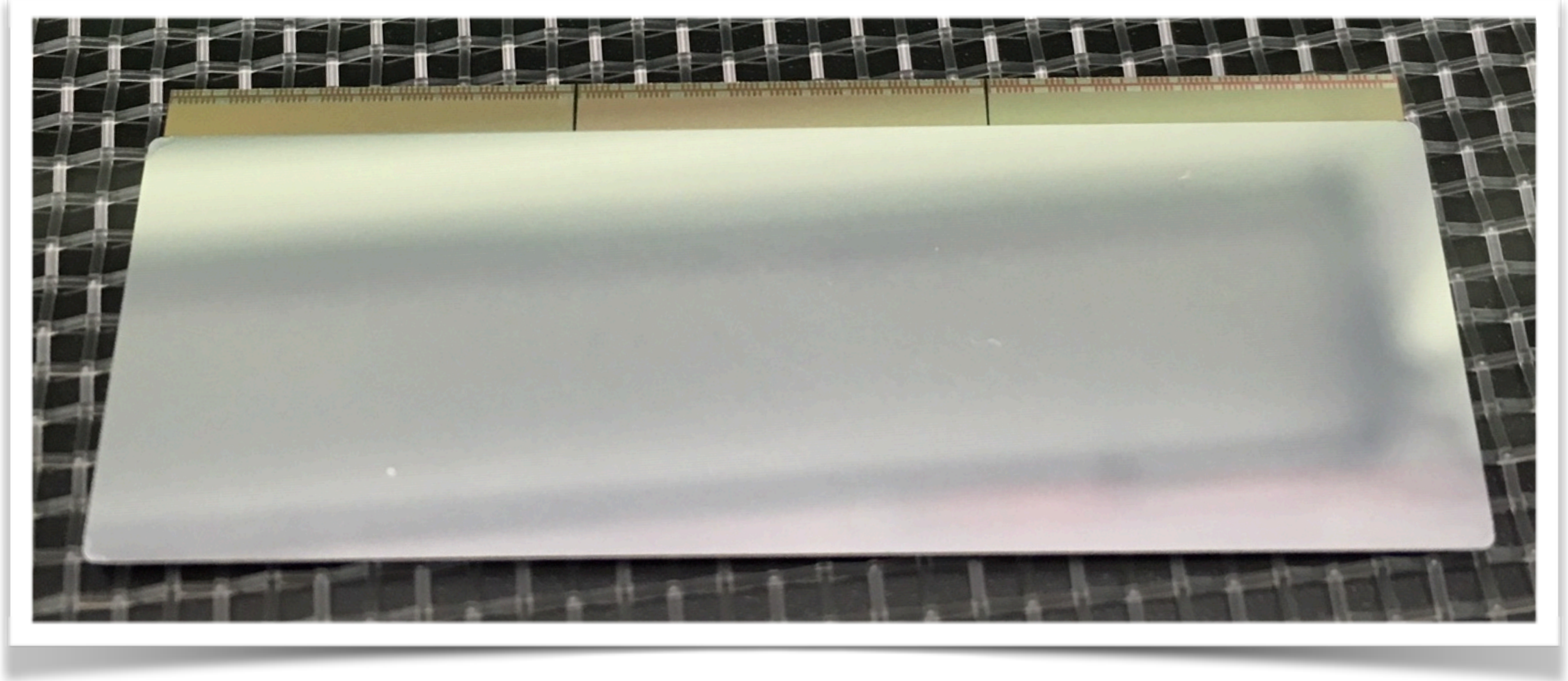


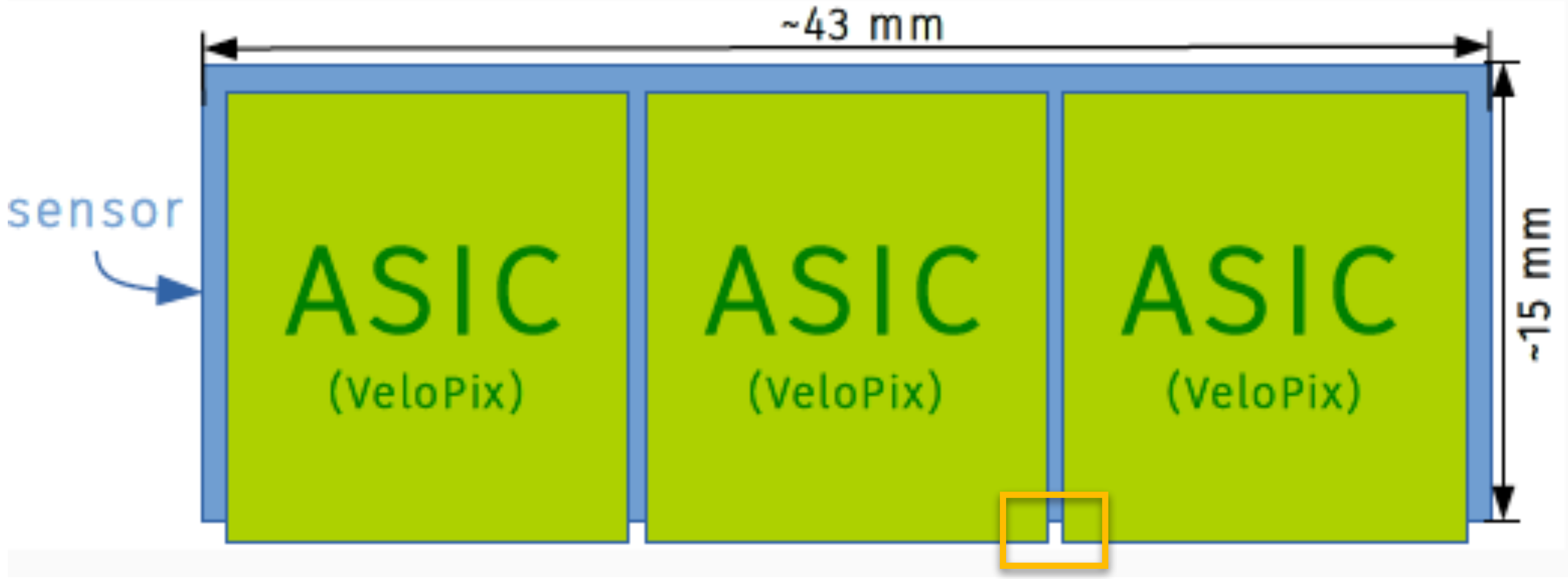
Chemical etching the innermost region with NaOH

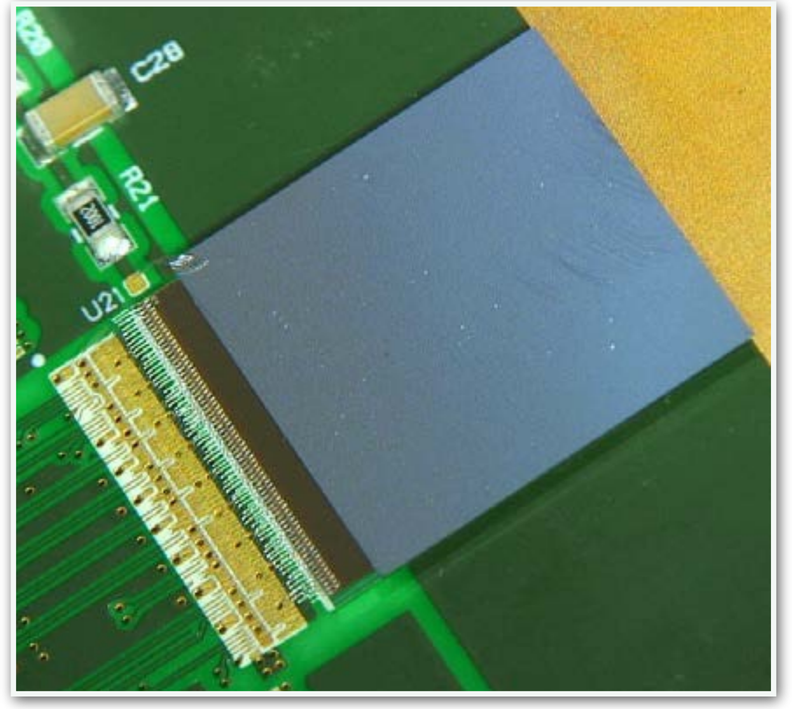
Milled from Aluminum block
Beautiful video



Sensors and ASICs

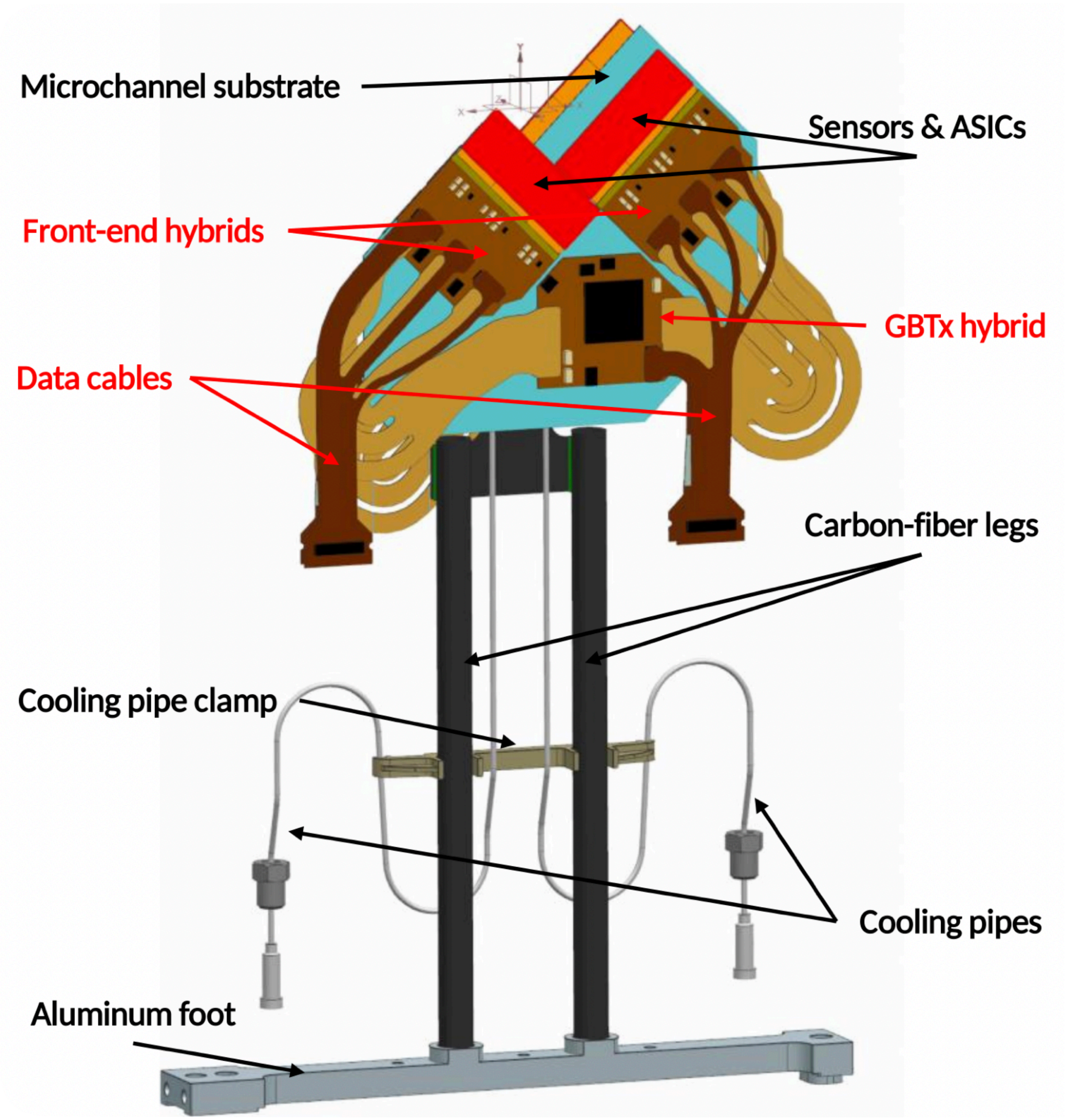






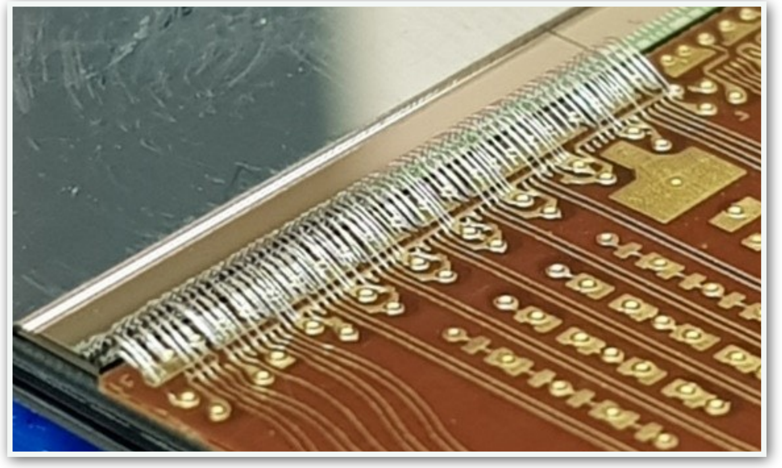
- **200 μm**-thick **silicon sensor**
  - **n-in-p** built by HPK
    - Lifetime fluence of **8×10^{15} 1 MeV n$_{eq}$/cm^2**, 400 Mrad
  - 768×256 pixels, each **55×55 μm^2**
- **Three VeloPix ASICs per** sensor (**tile**)
  - Thinned to 200 μm, 130 nm CMOS technology
  - Each **bump-bonded to 256×256 pixels**
  - **400 Mrad** and SEU tolerant
  - **Readout of every hit**
    - 800 Mhits/s → 50 khits/s/pixel
  - Up to **four output lines at 5.12 Gbps** each
  - Power consumption < 2 W

Readout electronics

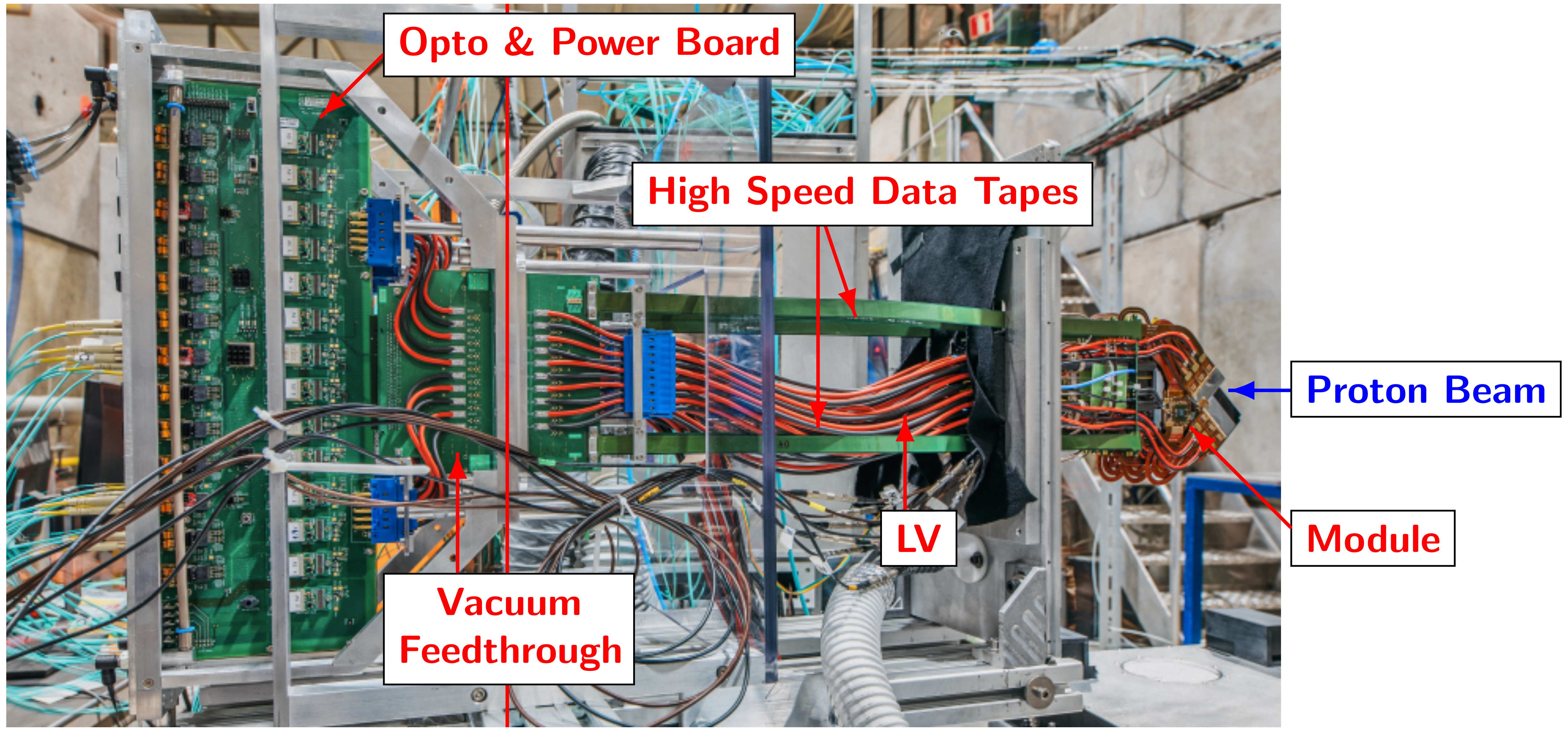


$T_{sensor} < -20° C$ for longevity

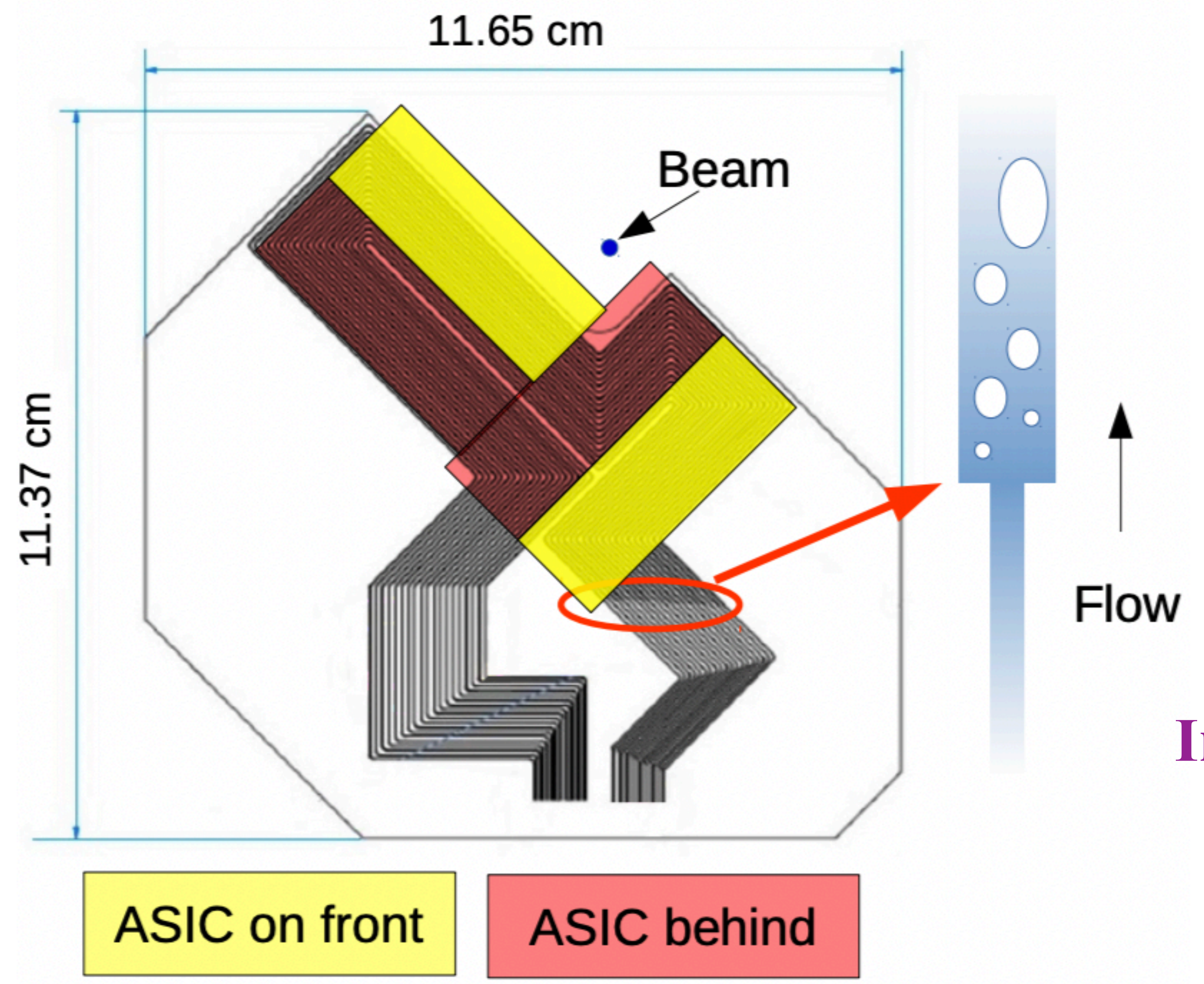
- **ASICs wirebonded** to **FE hybrids**
  - **20 data links** at **5.12 Gbps**
    - Up to 4 links/ASIC on innermost ASICs



- **GBTx hybrids** deserialize **control** signals
  - Issue with GBTx relocking at -20°C, but charge-pump current increase fixes it
- **OPB outside vacuum** and **high radiation zone**
  - FEASTMP DC/DC converters, 10 VTTx and 3 VTRx

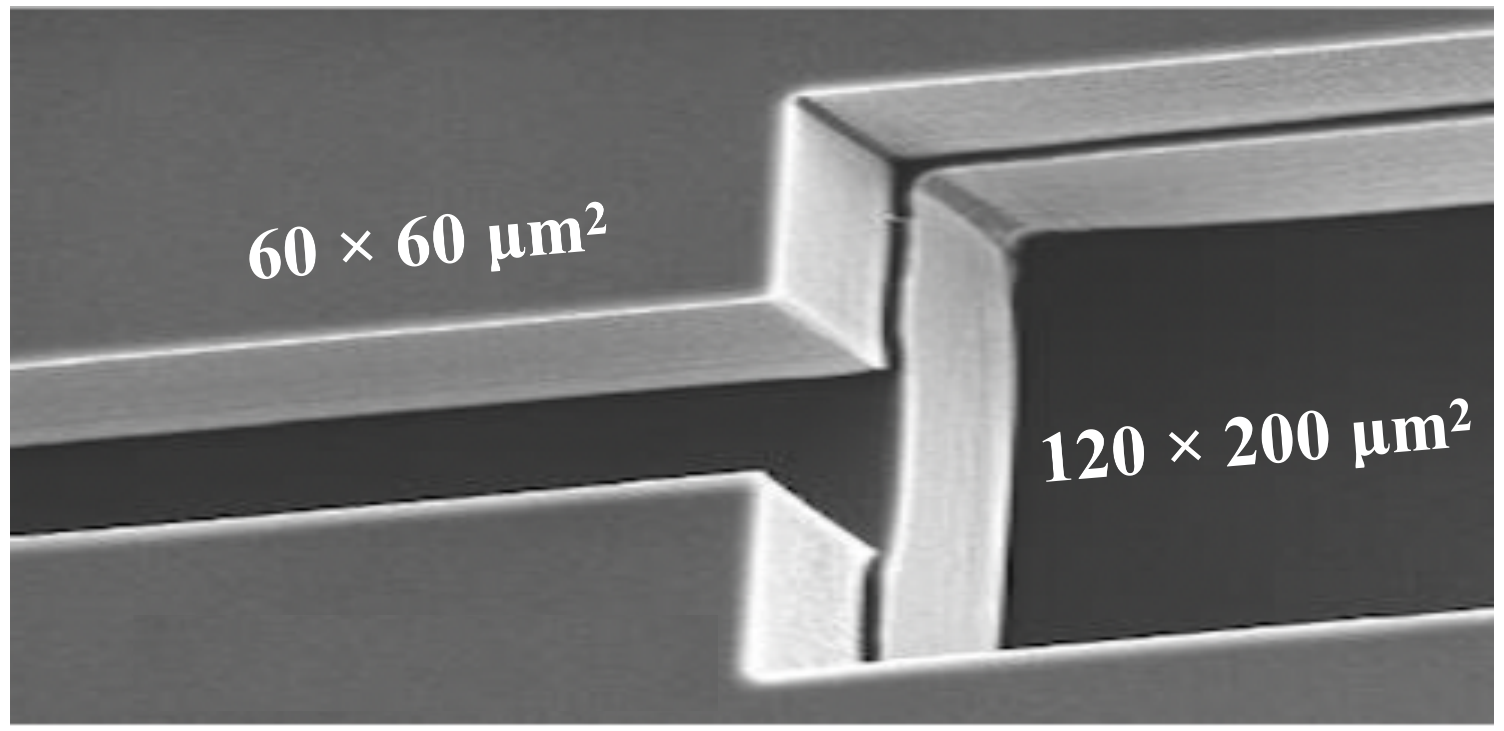


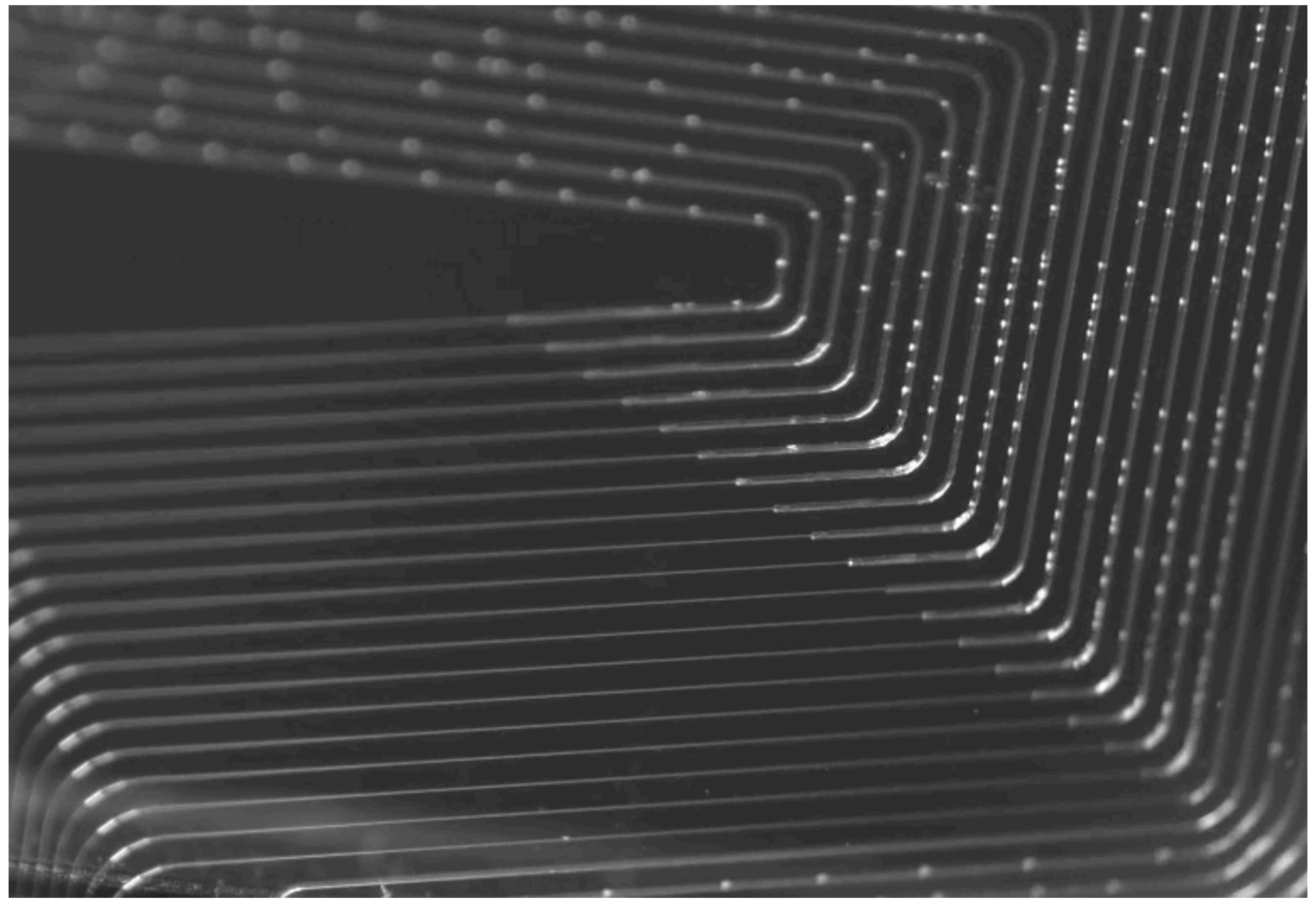
Micro-channel cooling



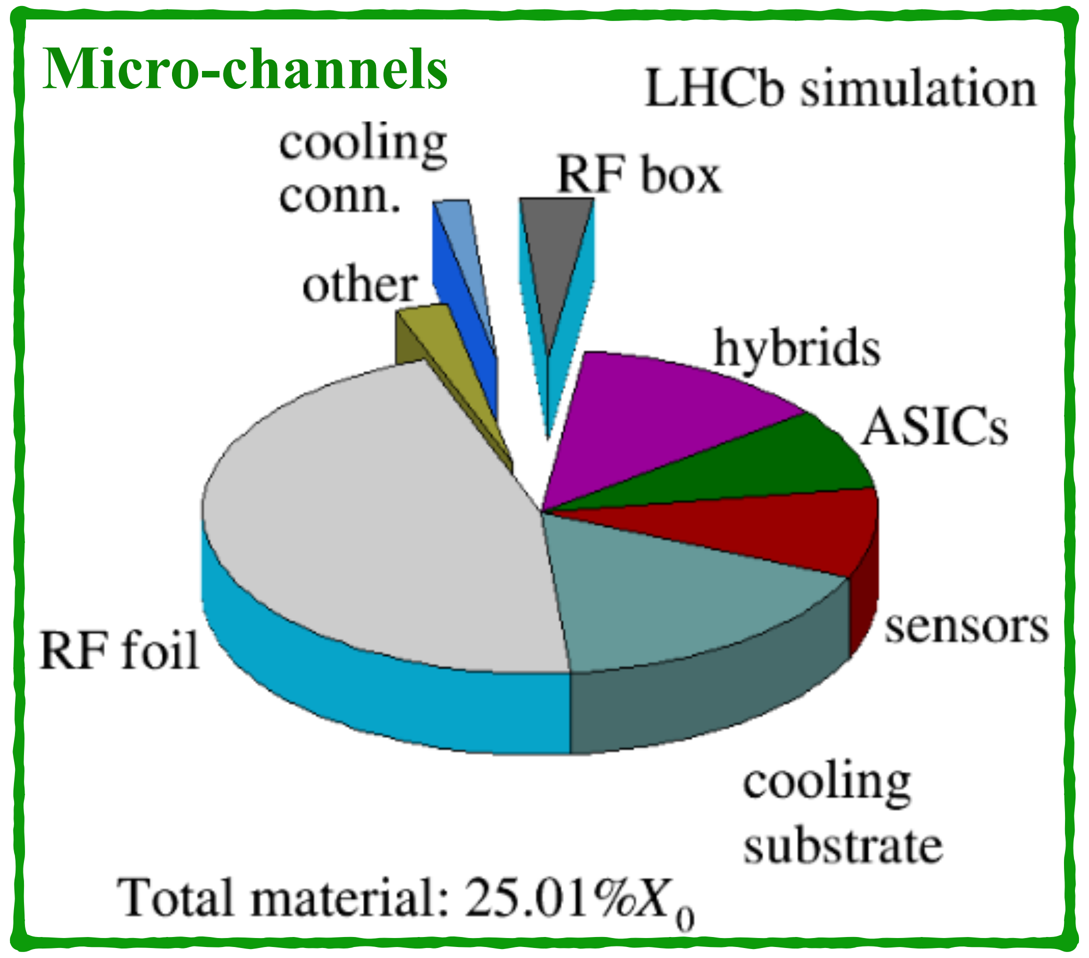
- 4 tiles (12 ASICs) on each module
- Cooled by **evaporative CO_2** in **micro-channels**
  - **Etched** in **500 µm-thick silicon**
  - Excellent thermal efficiency
  - **No thermal expansion mismatch** with silicon ASICs/sensors

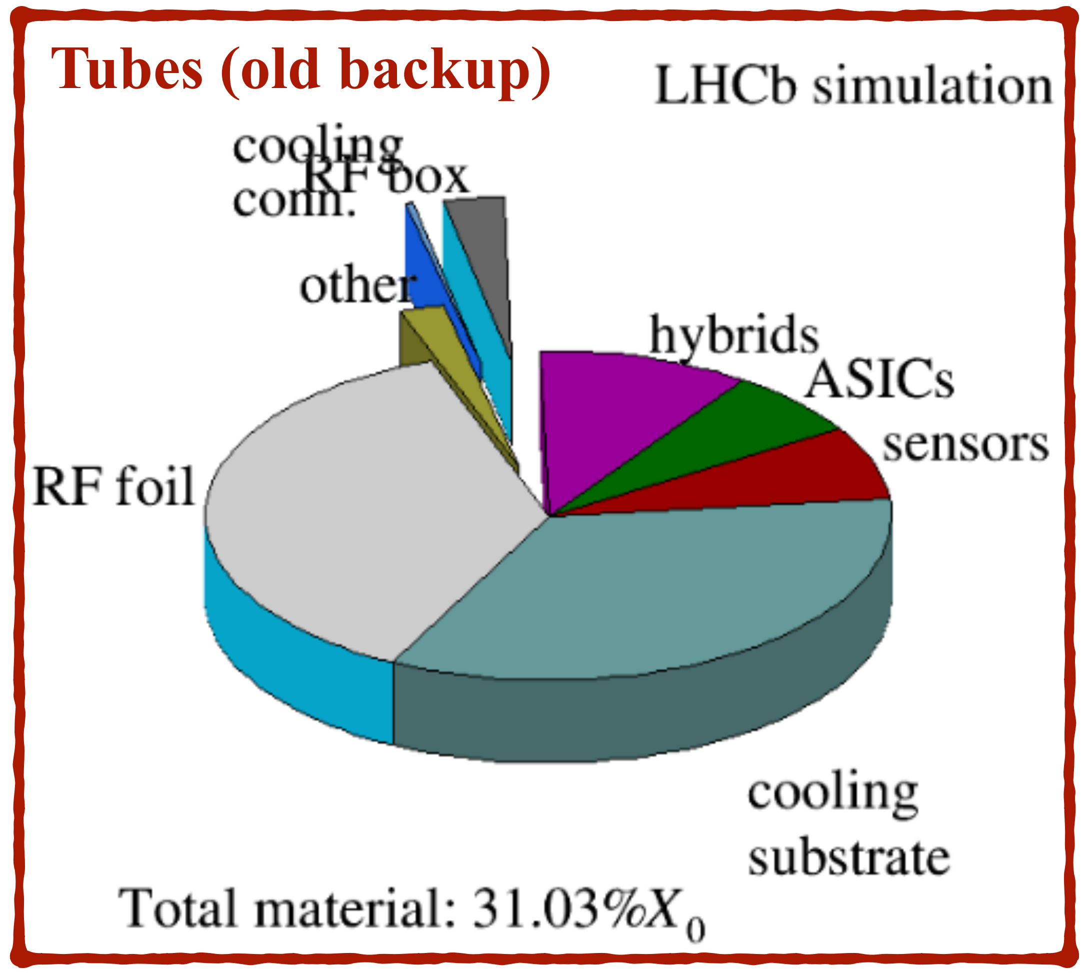
Increase in cross section between the restriction and the main channels **triggers the boiling**



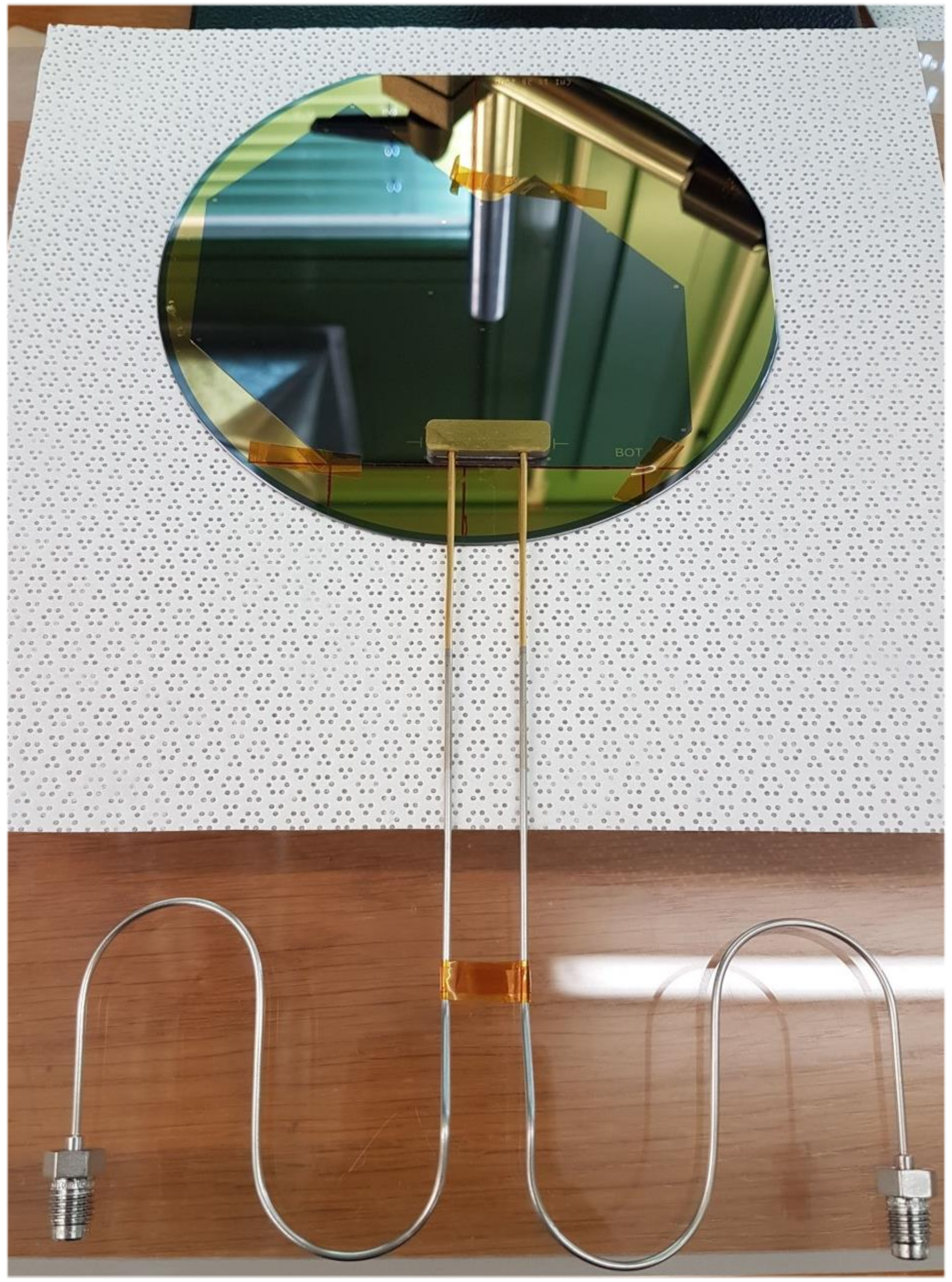


Minimal material budget!

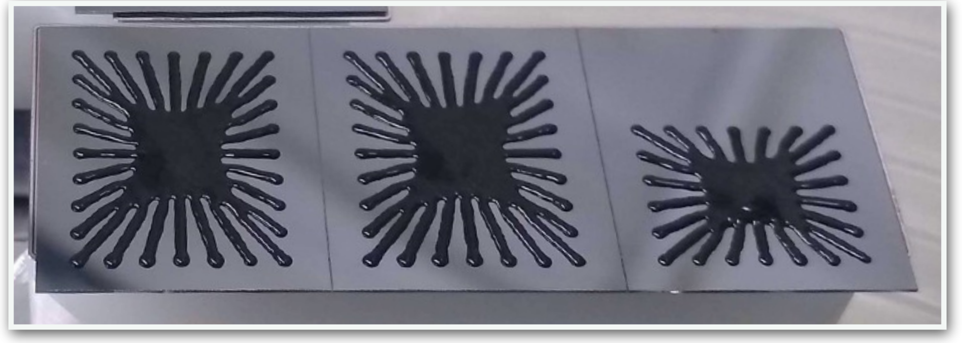


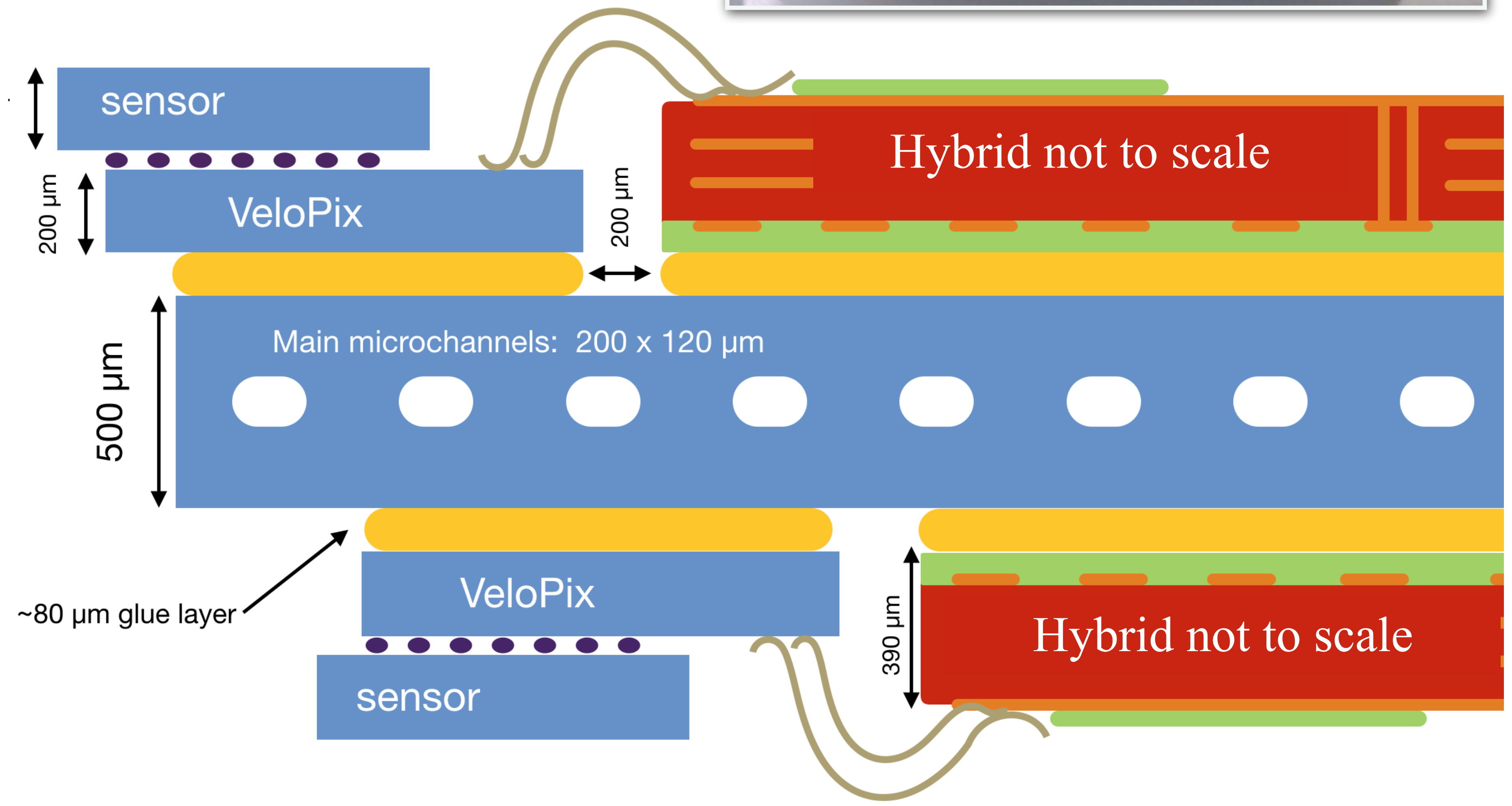


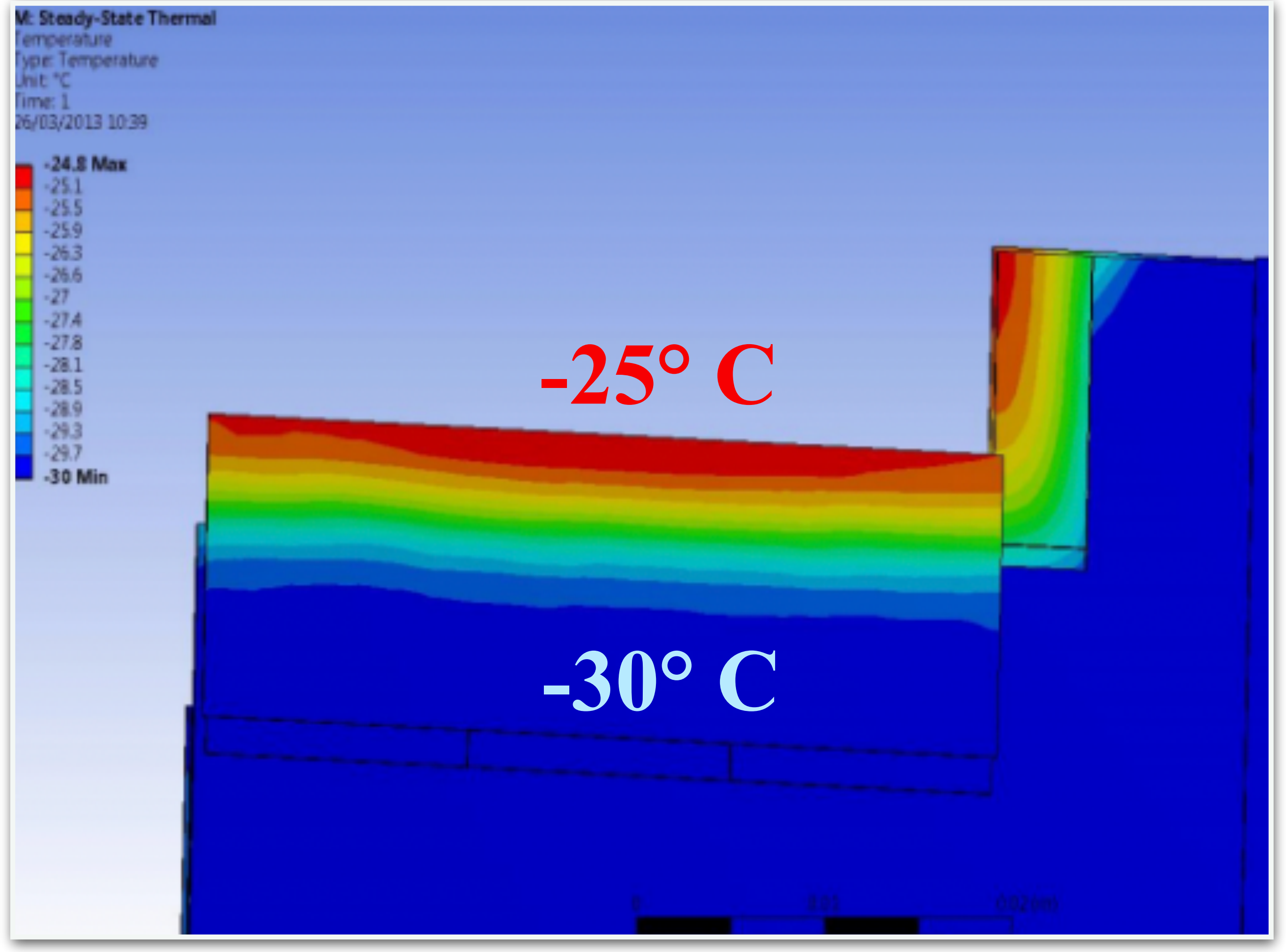
CO_2 pipes soldered to metallization on micro-channels
Leak tight, keep planarity, pressure up to 186 bar



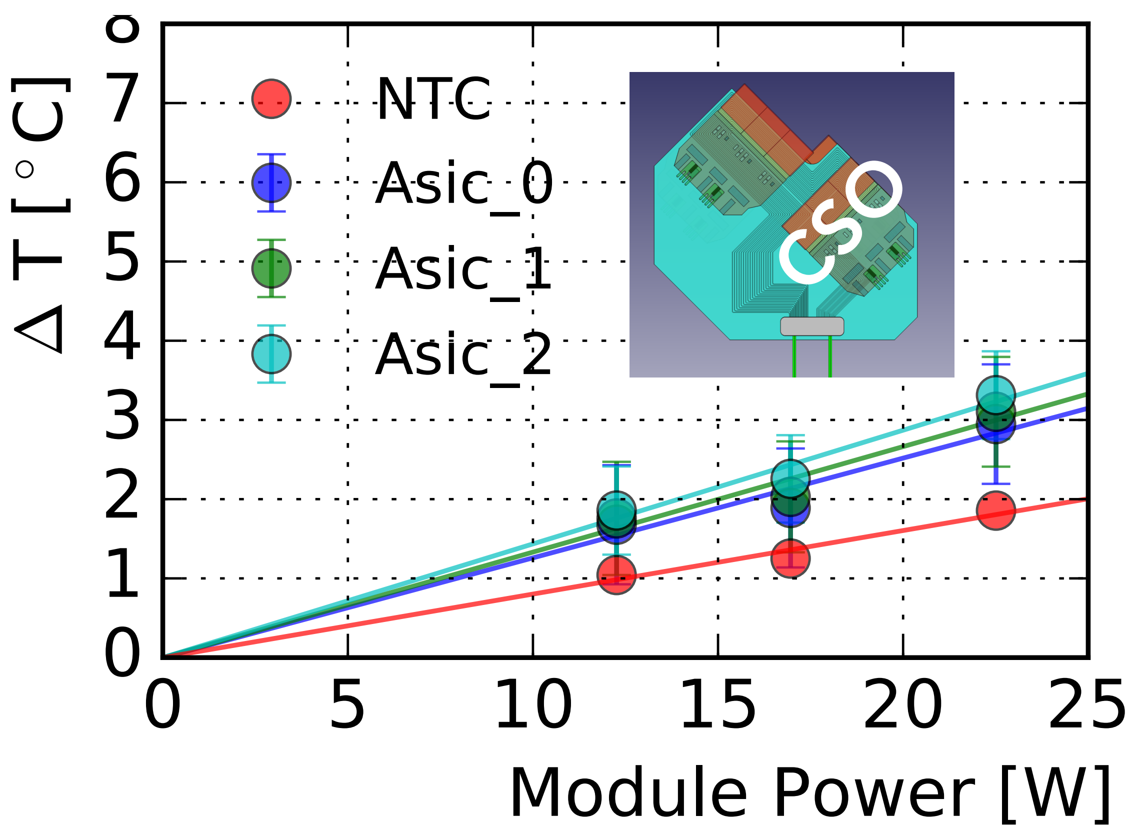
- **ASICs glued** to micro-channels
  - **Innermost sensors** have **5 mm overhang**
- Demonstrated power dissipation **up to 30 W** with **small ΔT** on the sensor
  - Even by end of life (27 W), T_{sensor} well below -20°C



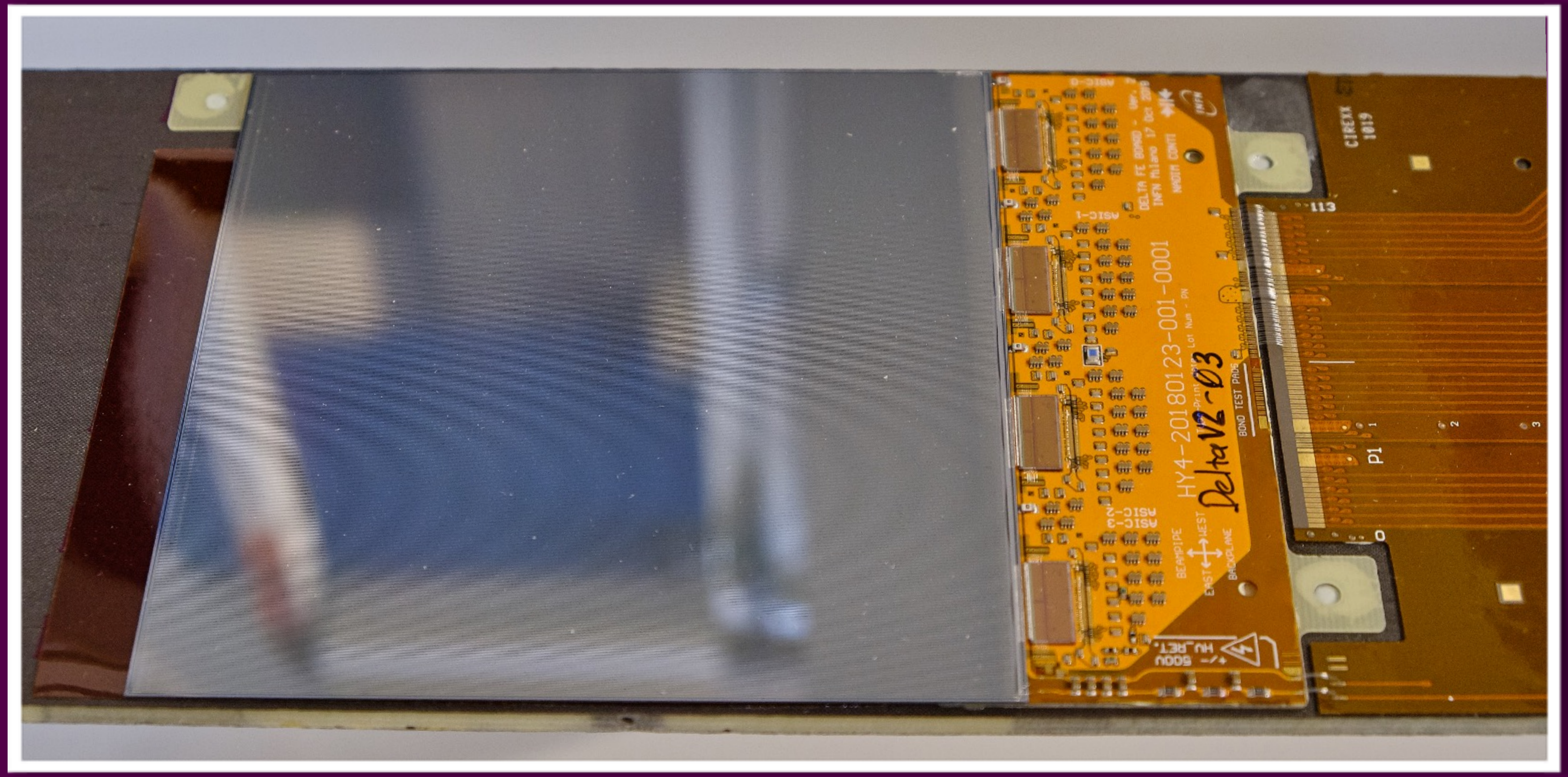




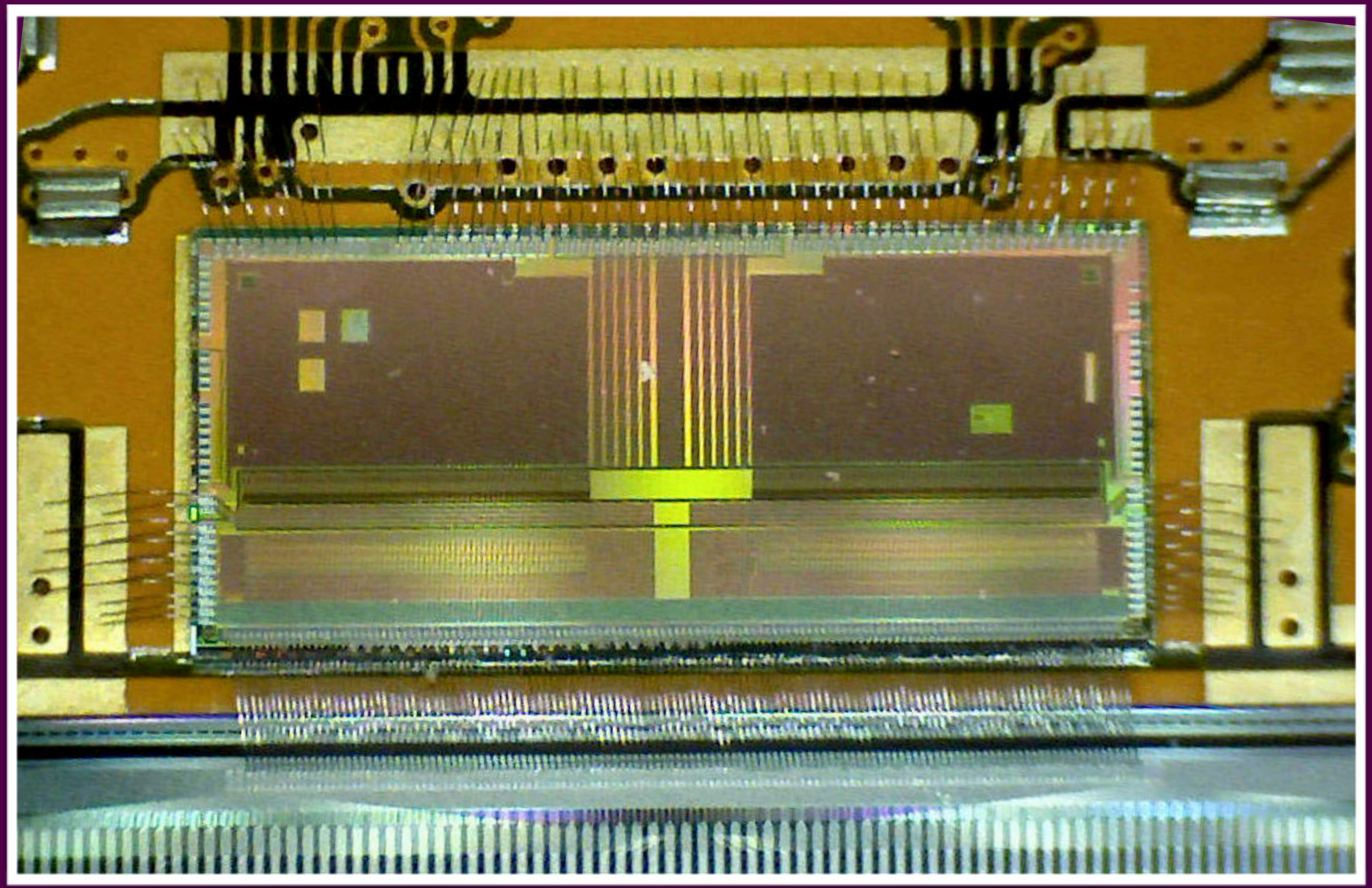
CO_2 at -32°C and 0.3 g/s flow

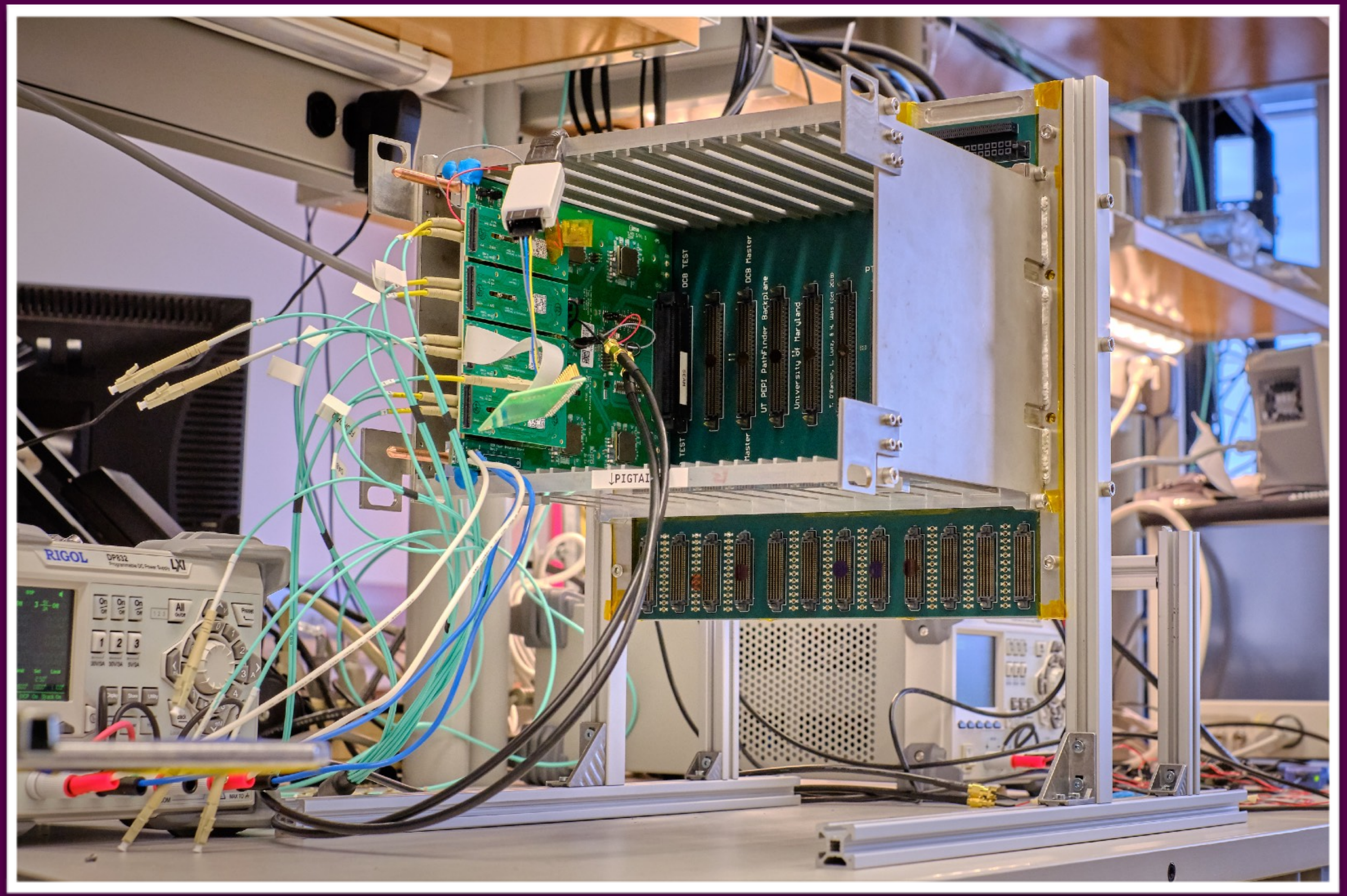


Long R&D campaign proved **great robustness**, **quality**, and **performance** of the substrate, **micro-channel production finalized**

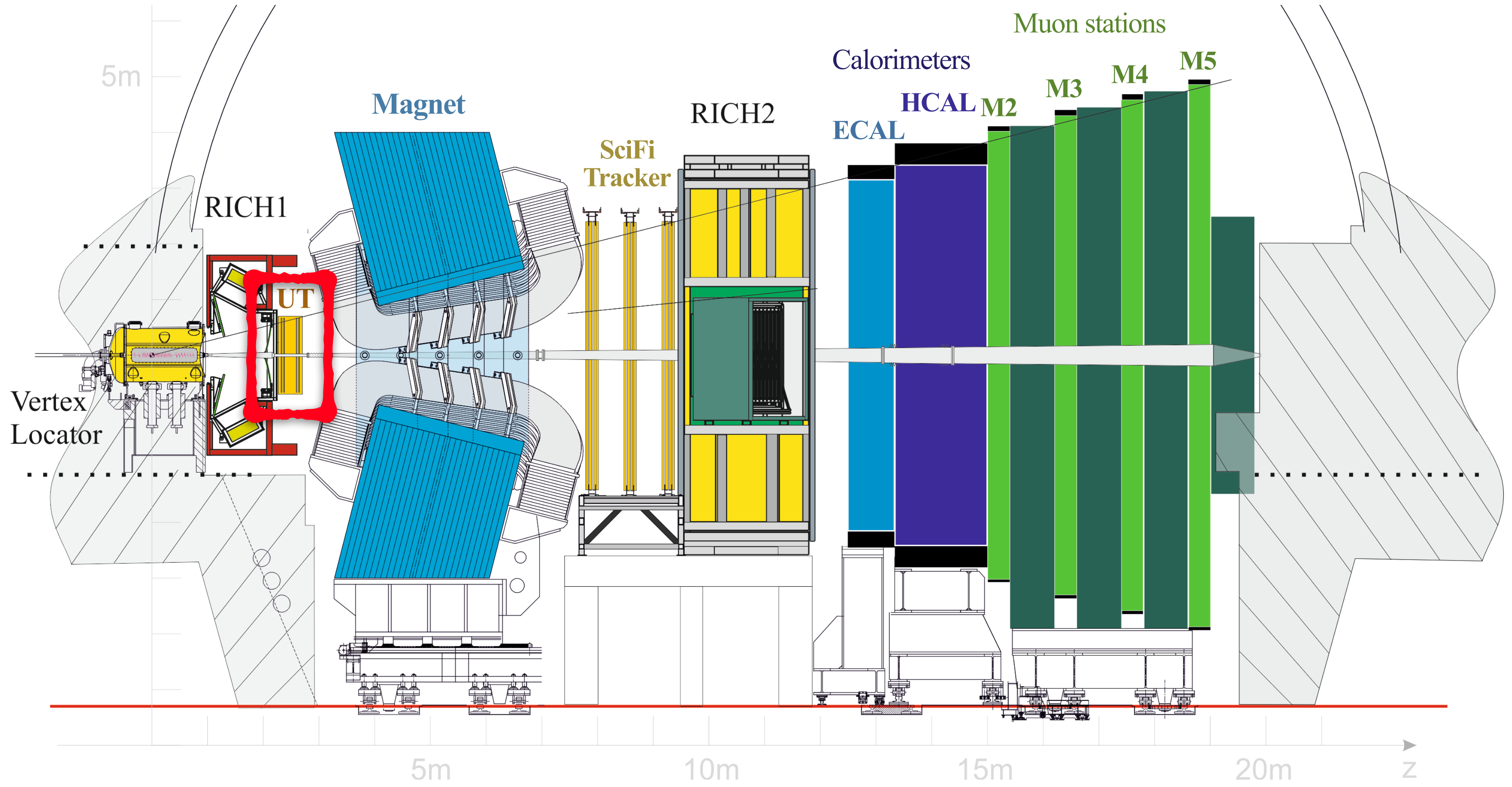


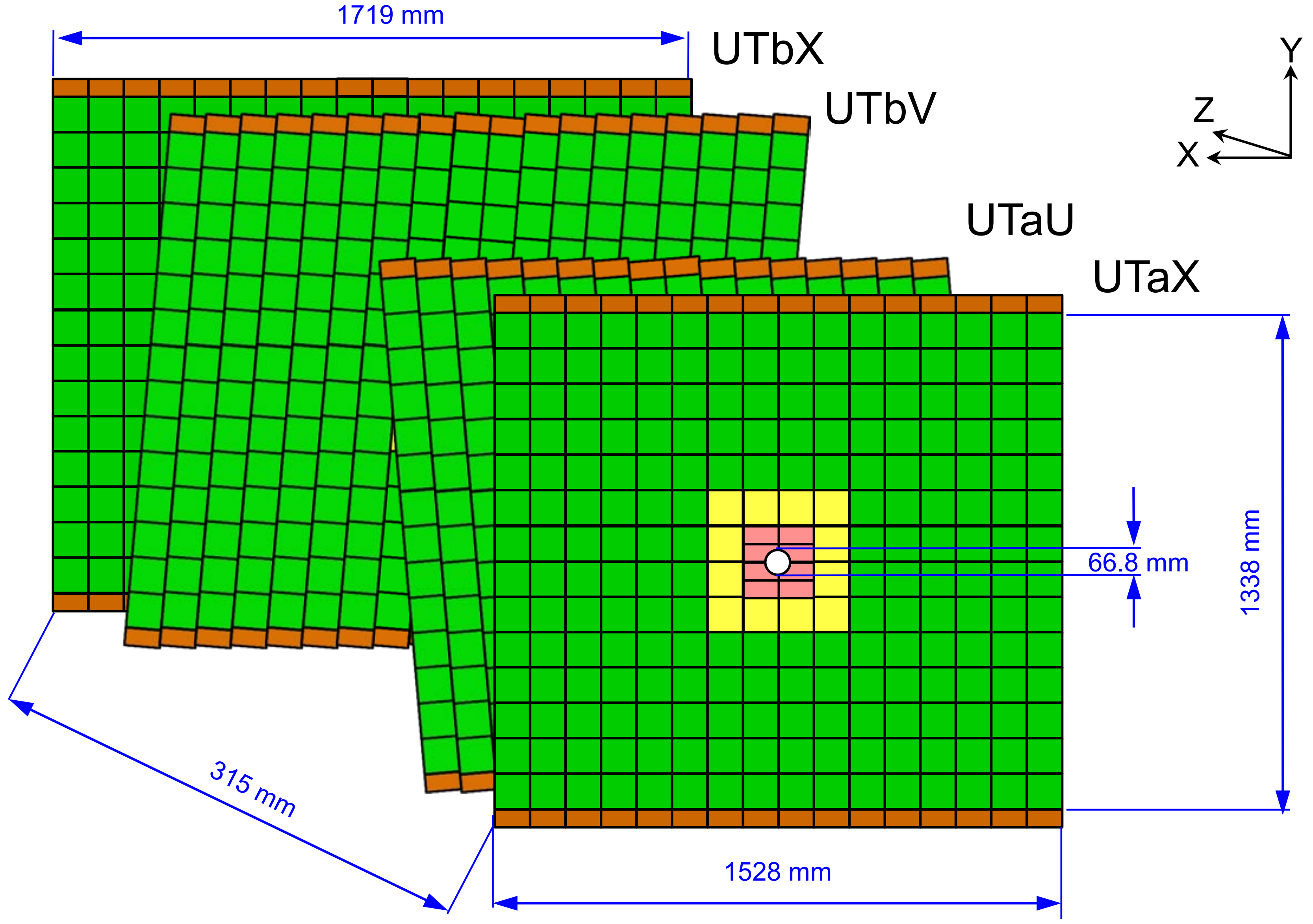
Upstream Tracker (UT)





UT overview



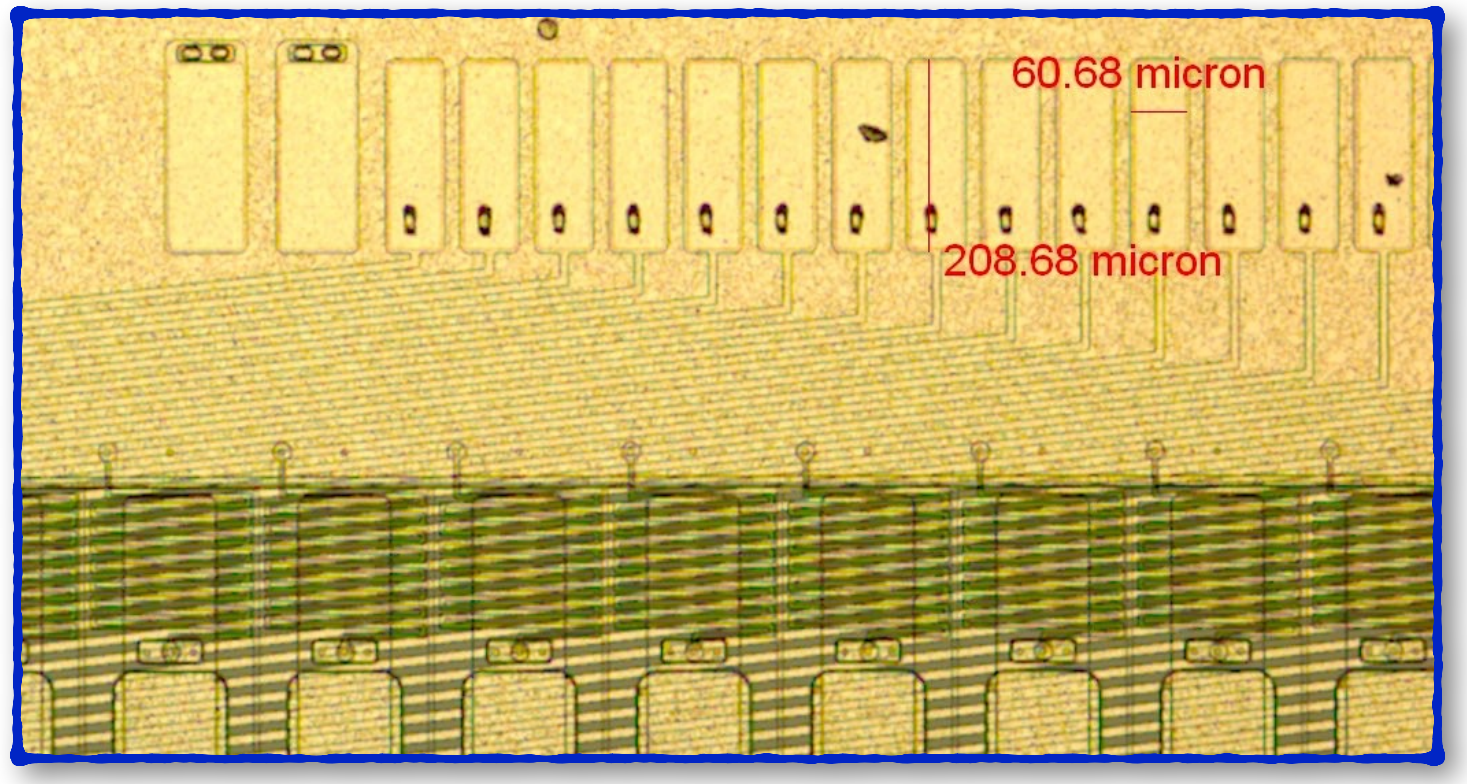


- Placed between VELO and dipole magnet
  - **Crucial** for **triggering** and **long-lived particle** reconstruction
- **4 layers** of **silicon strips** with same arrangement as TT
  - **Vertical/stereo layers** provide x-y position
- Improved performance
  - **40 MHz readout**
  - **Finer granularity**
    - Close to the beam 187.5 μm pitch → 93.5 μm
  - **Larger coverage** (closer to beampipe)
  - Reduced material budget

Silicon sensors

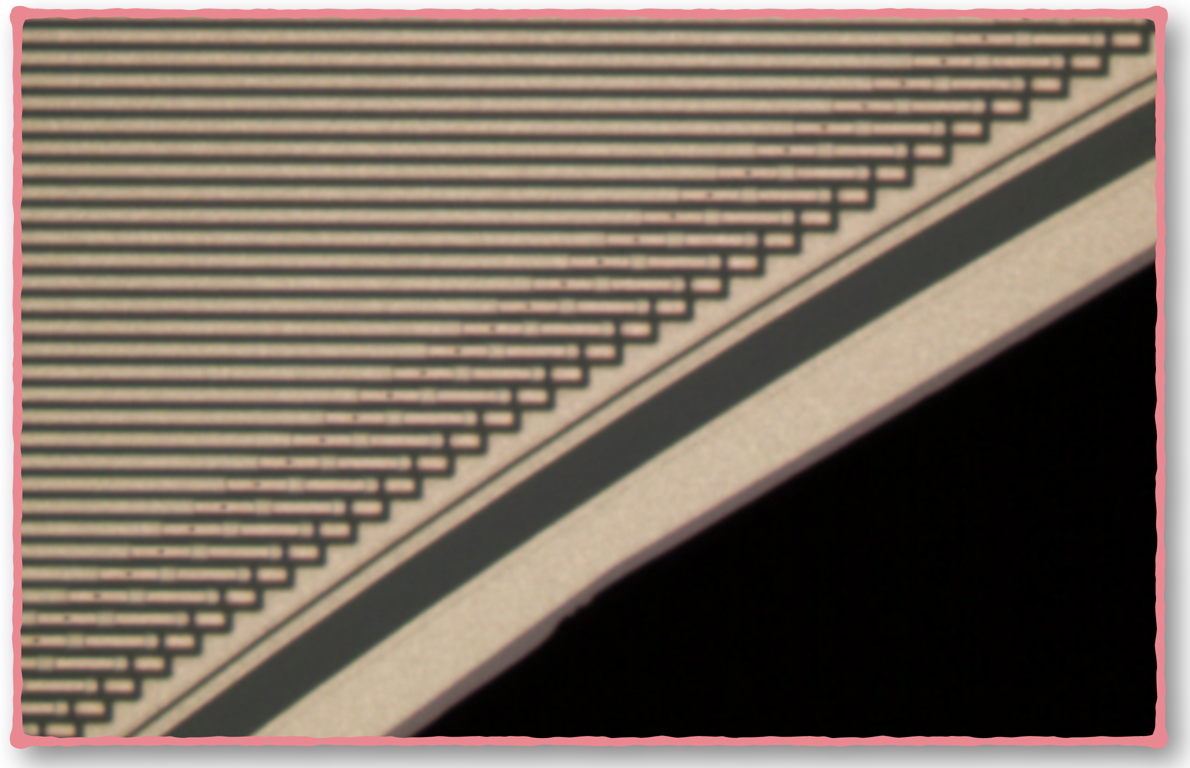
Sensor	Type	Pitch	Length	Strips	# sensors
A	p-in-n	187.5 μm	99.5 mm	512	888
B	n-in-p	93.5 μm	99.5 mm	1024	48
C	n-in-p	93.5 μm	50 mm	1024	16
D	n-in-p	93.5 μm	50 mm	1024	16

- Optimization with 4 designs
  - **Outer region** with **p-in-n**, **187.5 μm pitch**
    - Cost effective

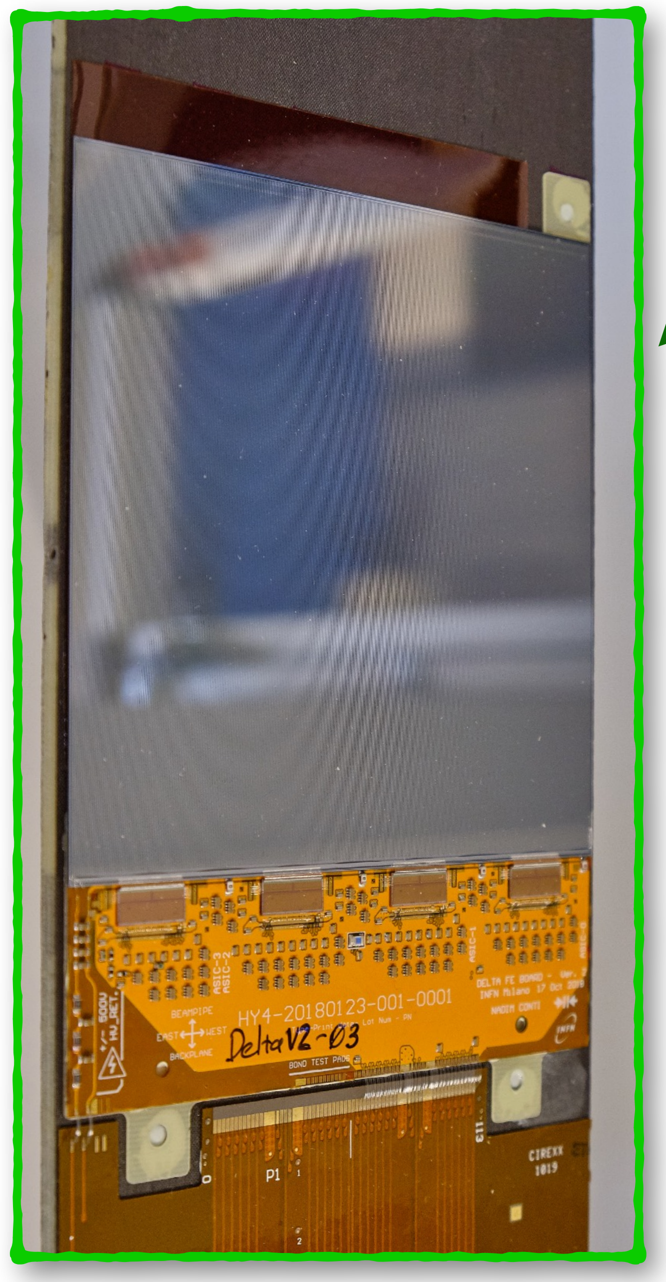


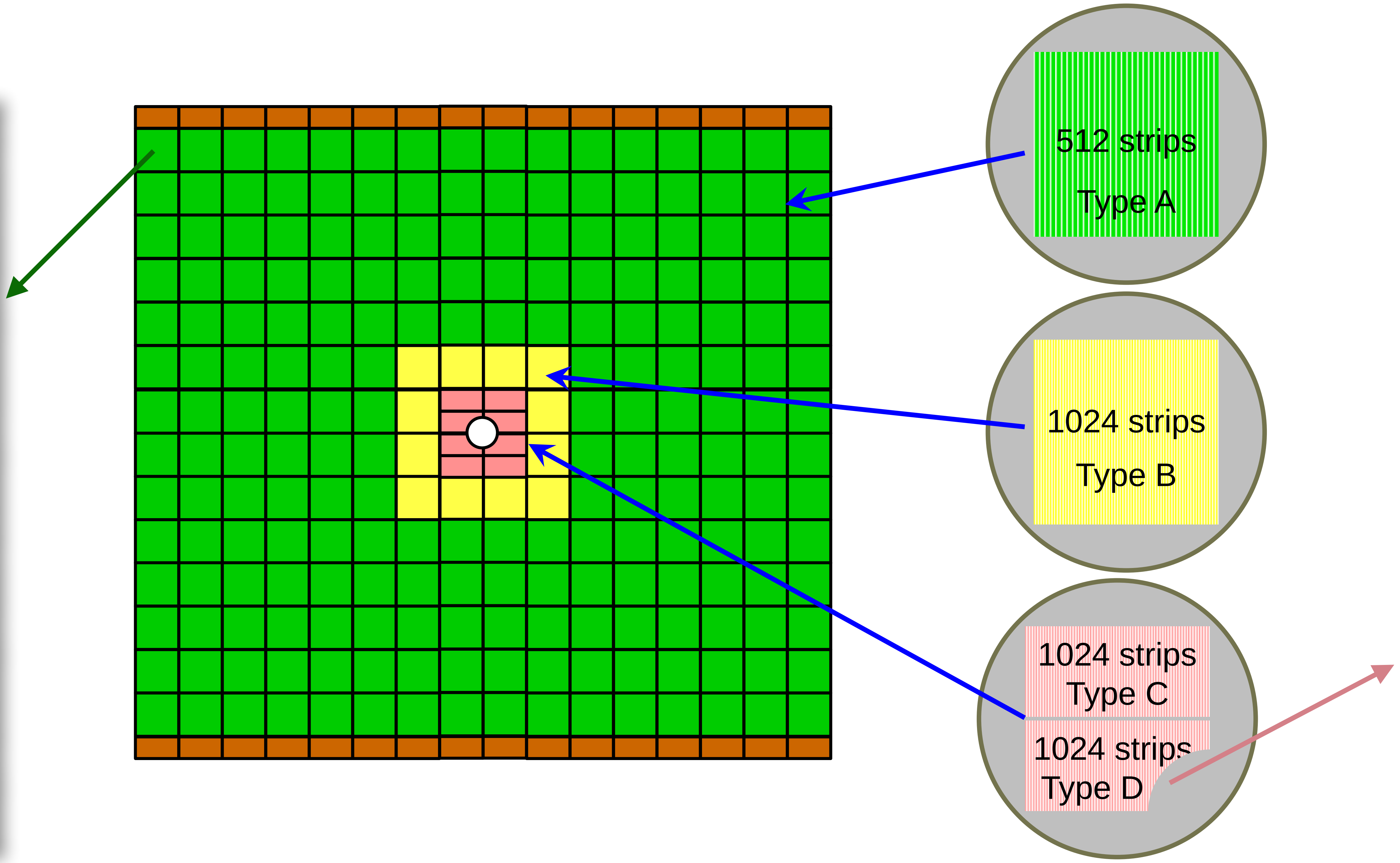
Embedded pitch adapters

  - **Inner region** with **n-in-p**, **93.5 μm pitch**
    - Radiation-hard and good granularity



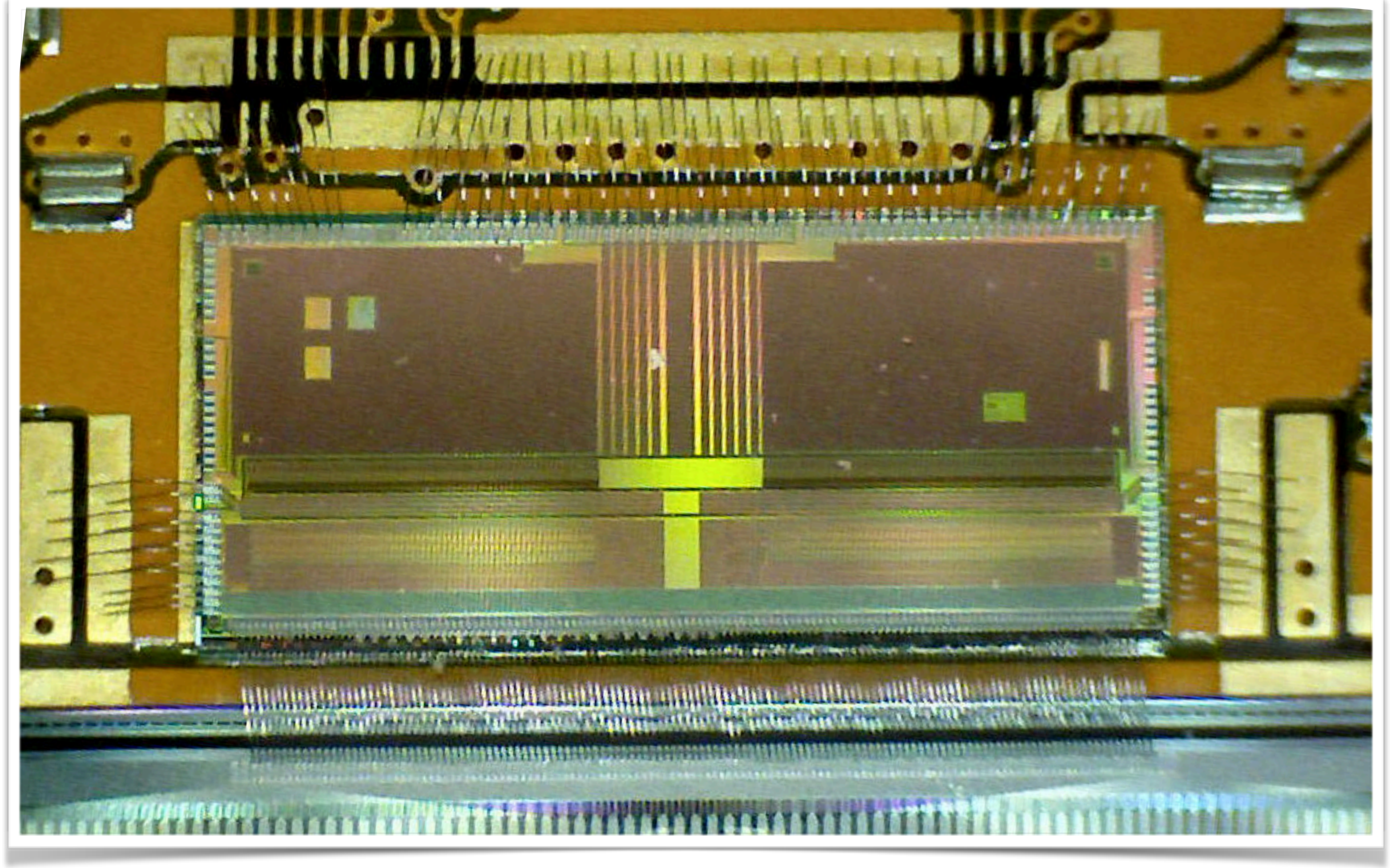
Circular cutout near the beamline

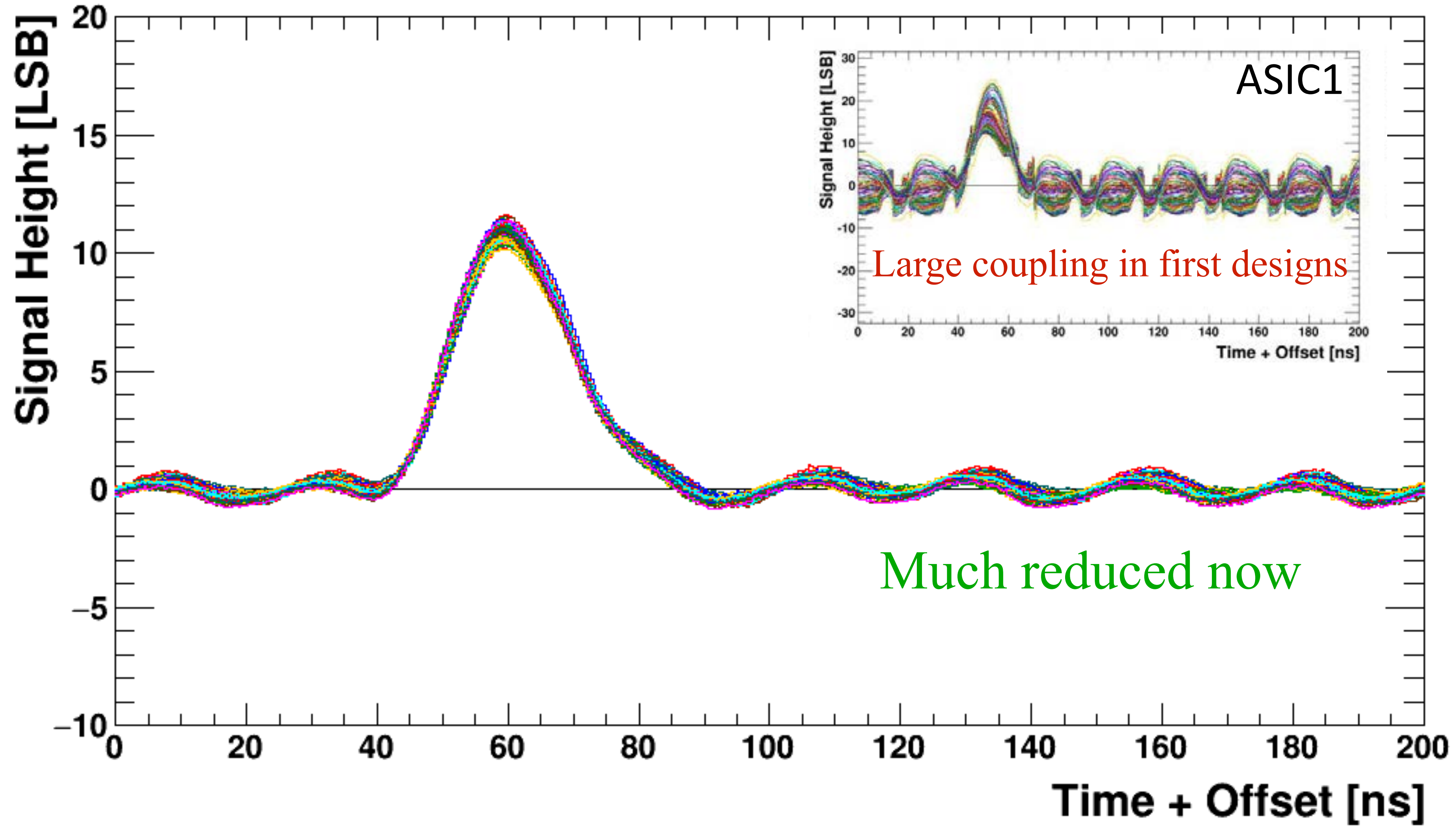


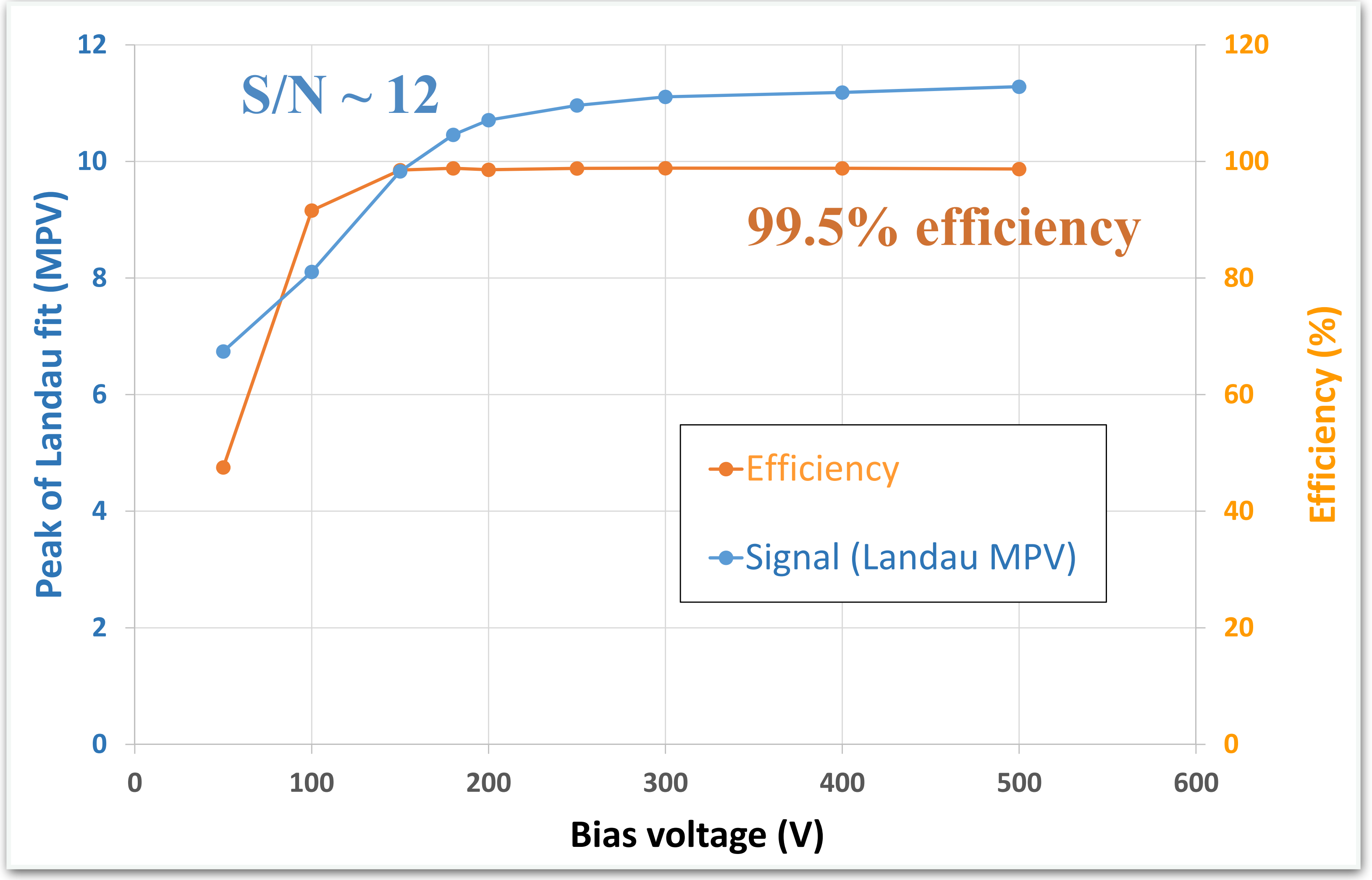


SALT: Silicon ASIC for LHCb Tracking

- 4192 ASICs with **128 channels** each
  - 130 nm-TSMC with **30 MRad** radiation tolerance
- **Wire-bonded** to sensors
  - Input pitch 80μm
- Allow for **40 MHz readout of UT**
  - Up to 5 SLVS **e-links @ 320 Mbps**



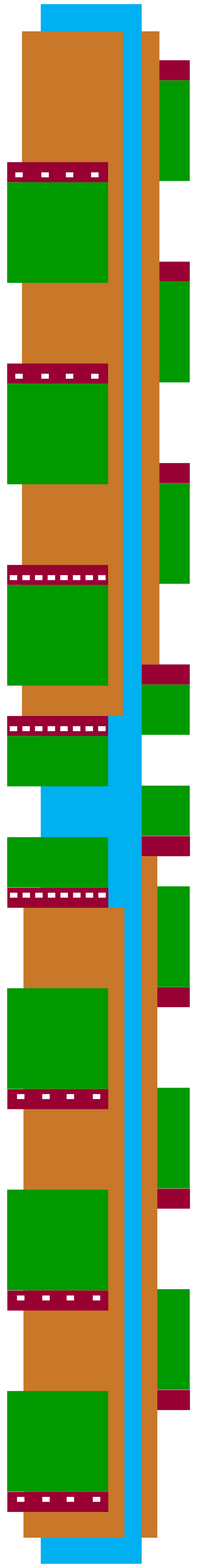


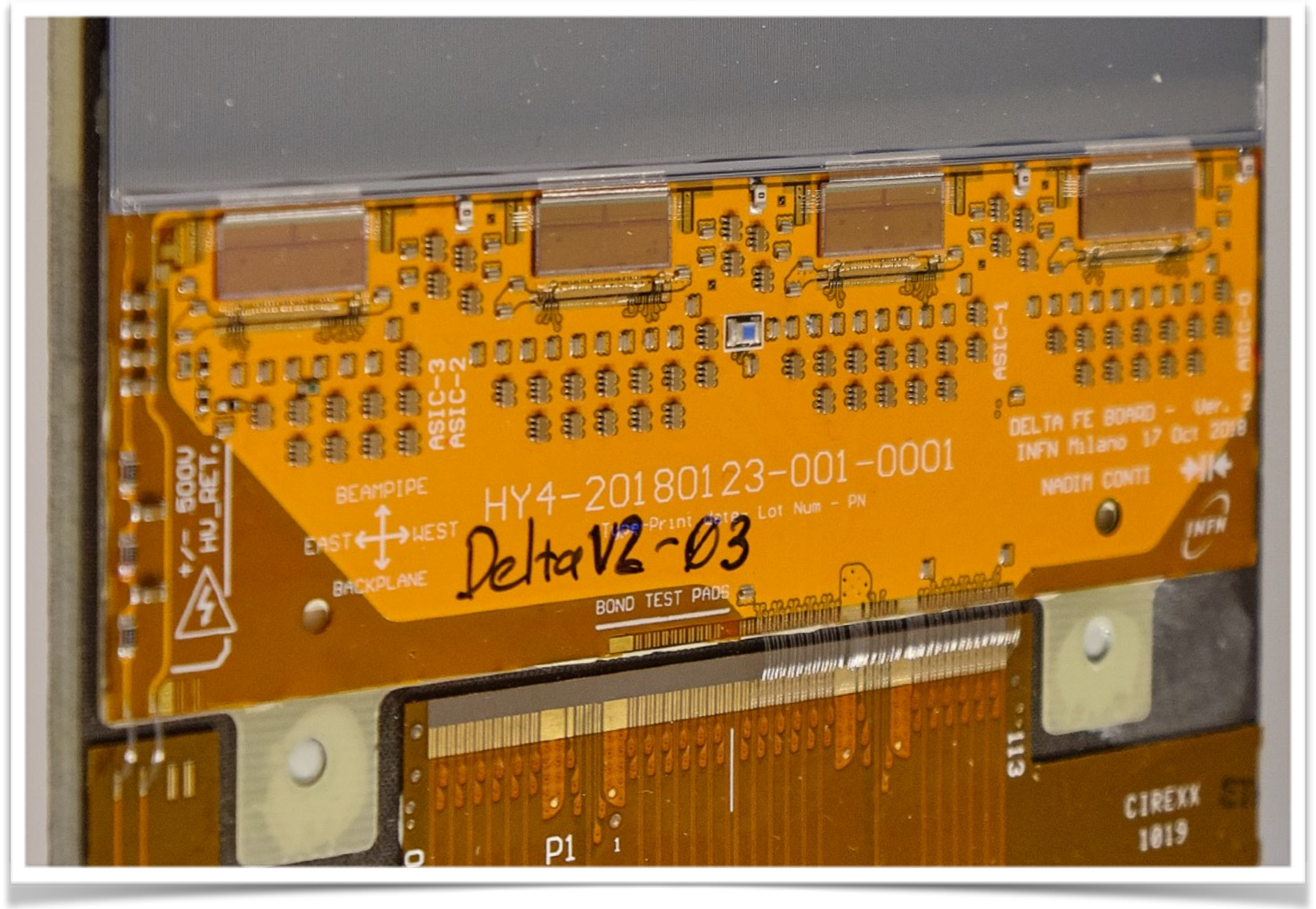


After a bumpy road and a few iterations, performance is now more than satisfactory!

Integration into stave

- **Modules** (hybrids + wirebonded ASICs + sensors) and **flex cables** are mounted onto a **stave**
  - Low-mass support of 1.6 m x 10 cm
  - **Overlap** between **sensors** on the front and **back**
  - Integrated **titanium pipe** for **CO_2 cooling**

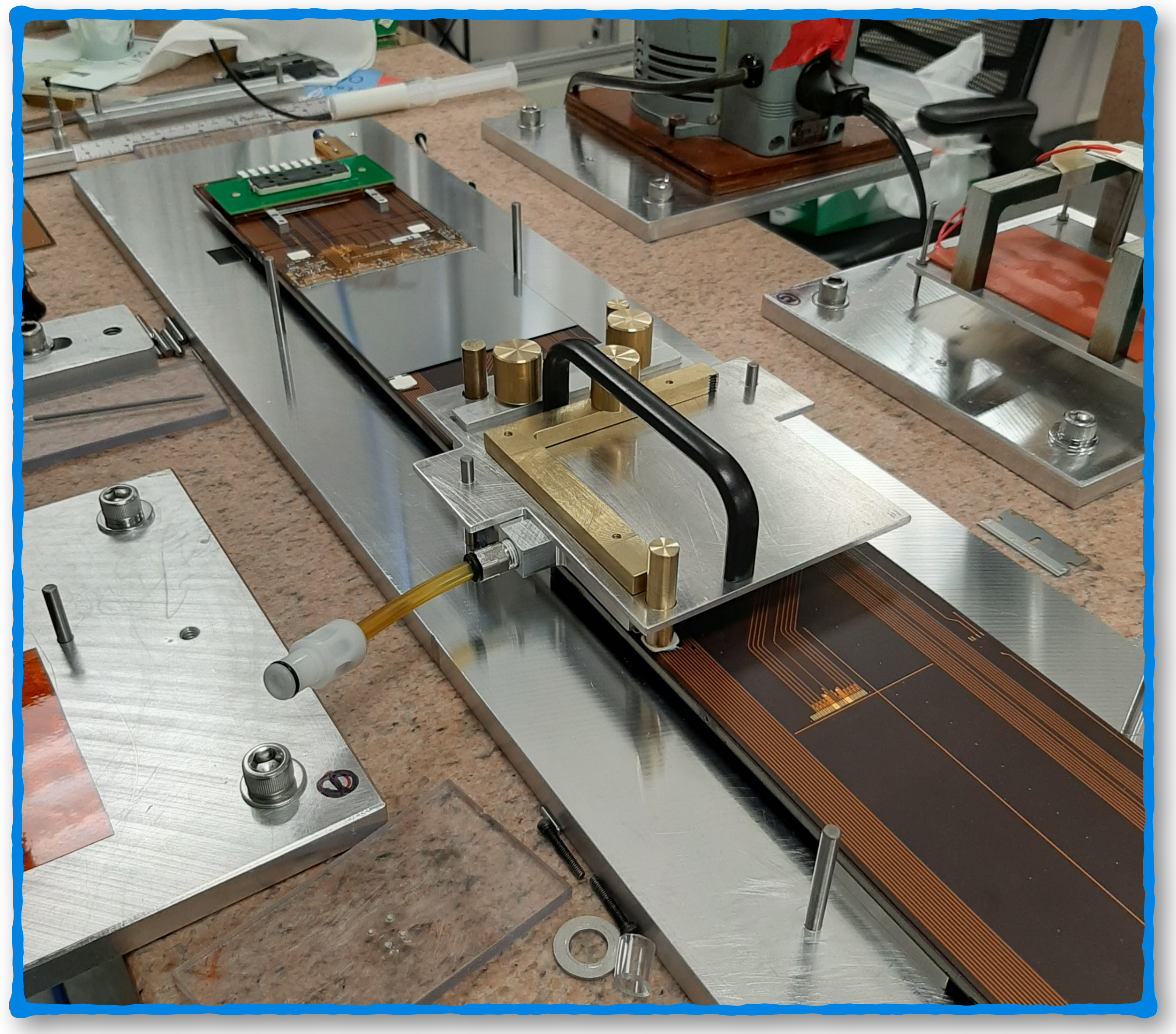




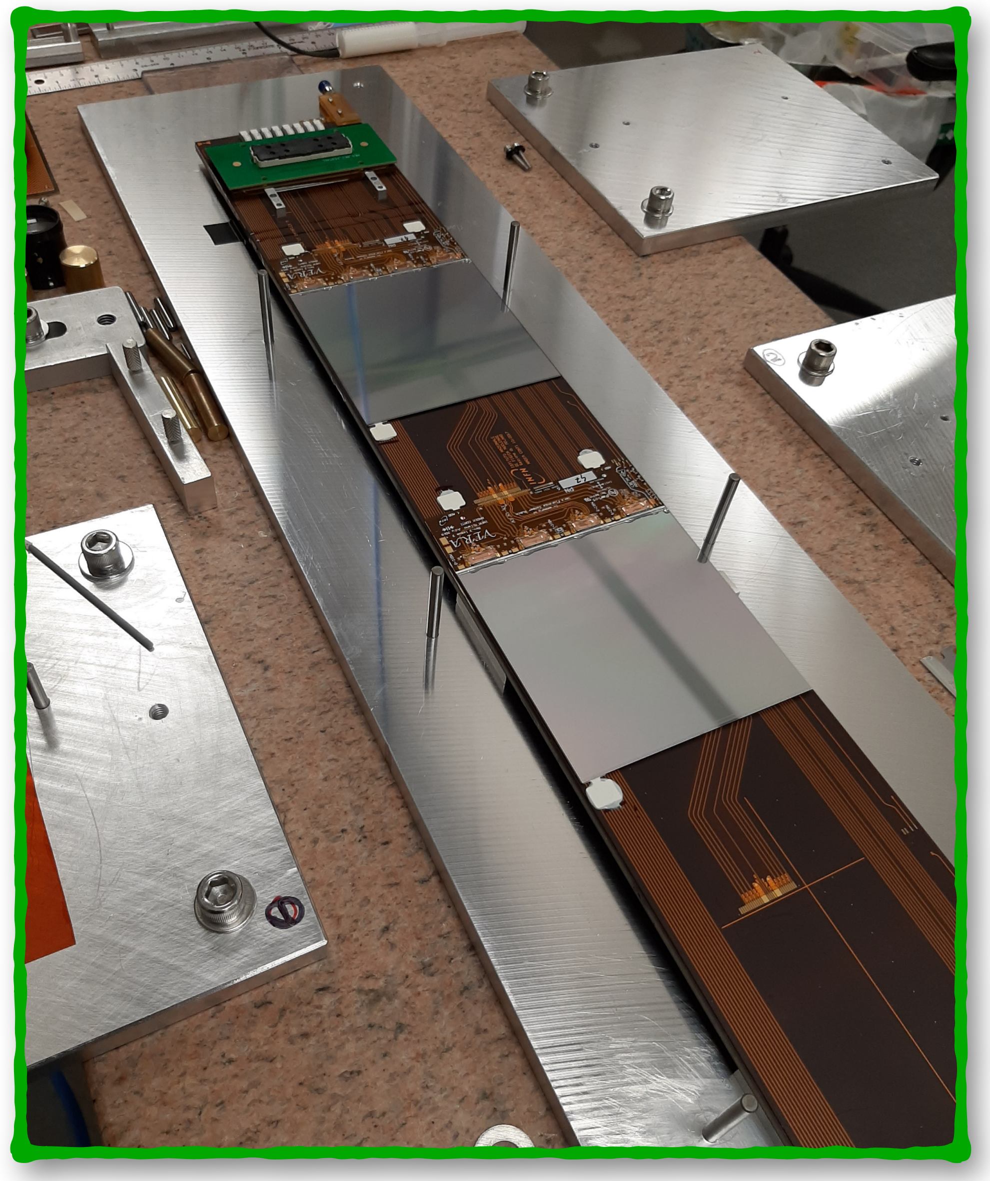
Stave
Flex cable
Hybrid + ASICs
Sensor

Stencil application of TIM, epoxy, silicone pedestal

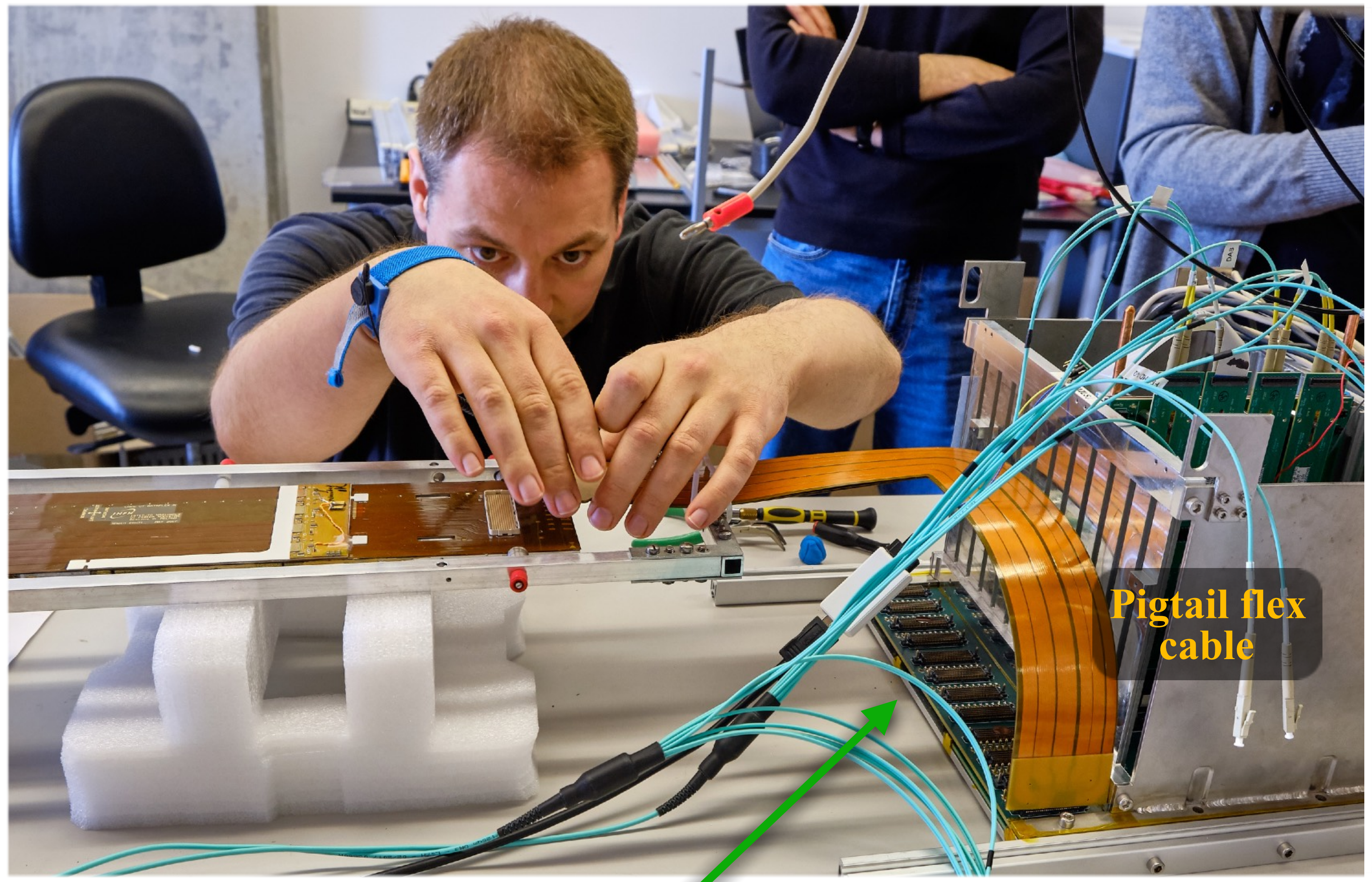
Heat TIM, place module, overnight curing



Another module on the stave!

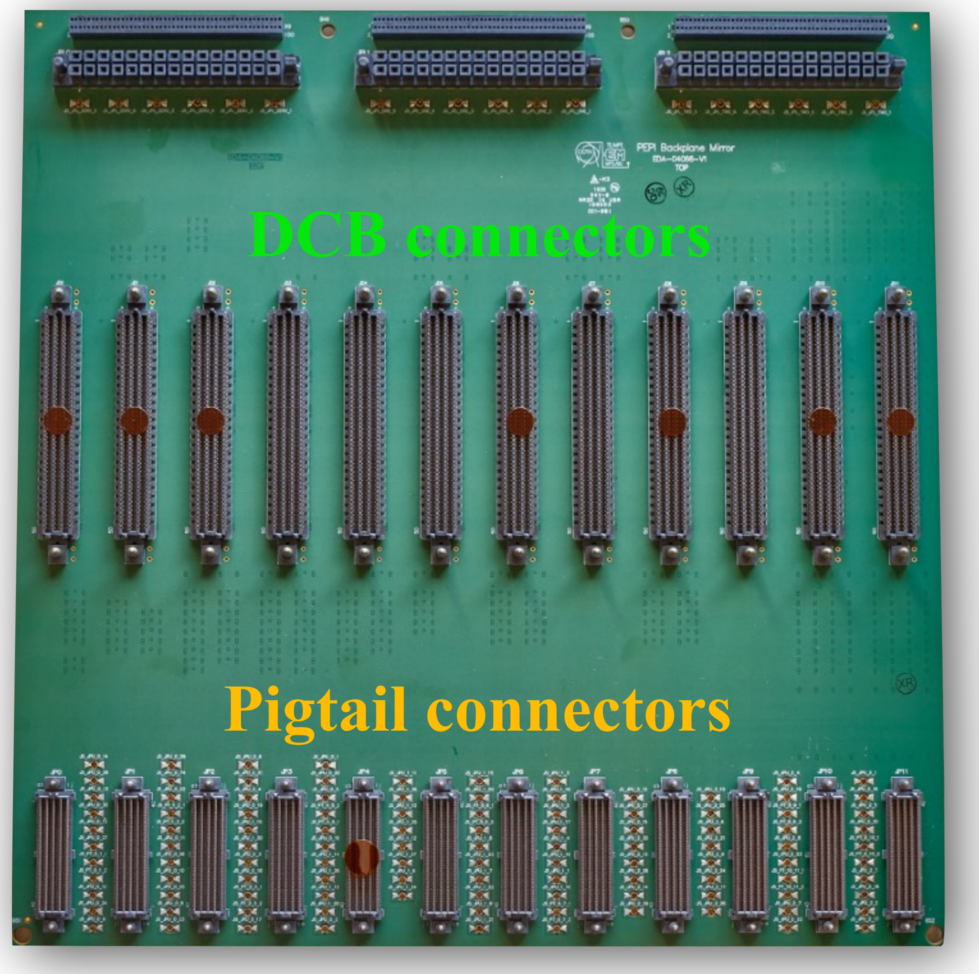


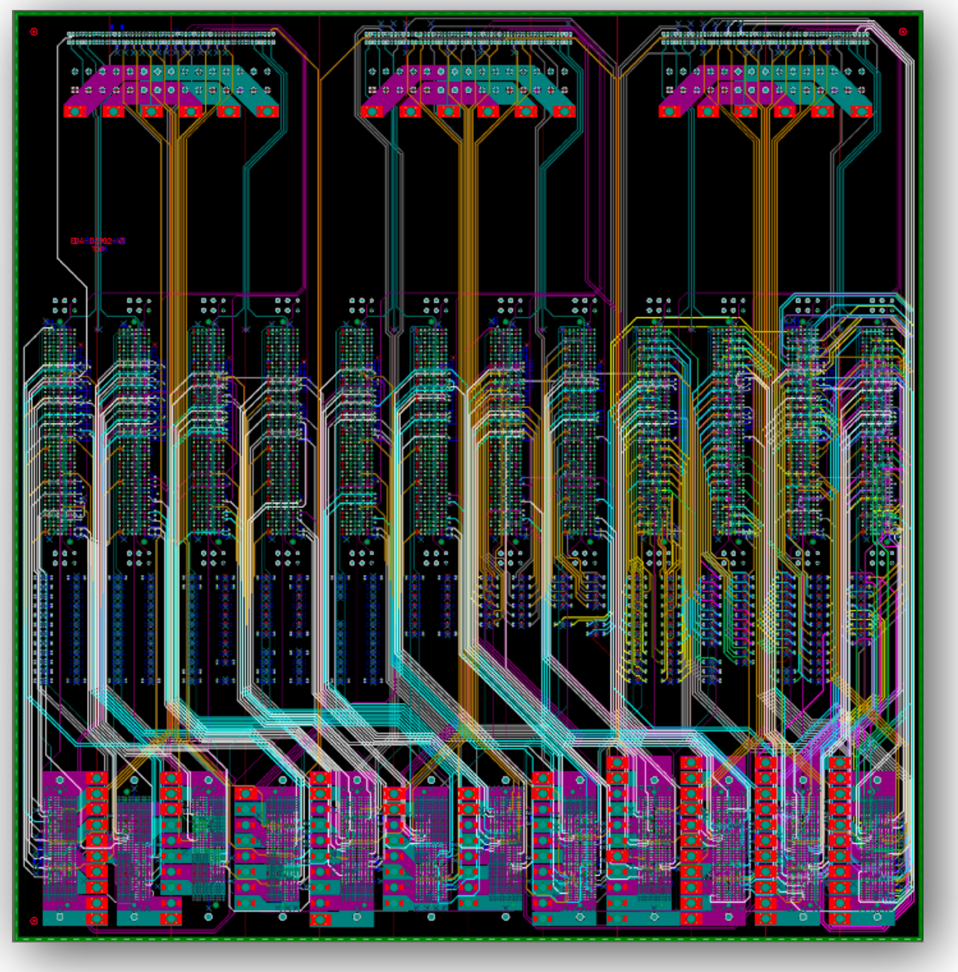
Peripheral electronics (PEPI)

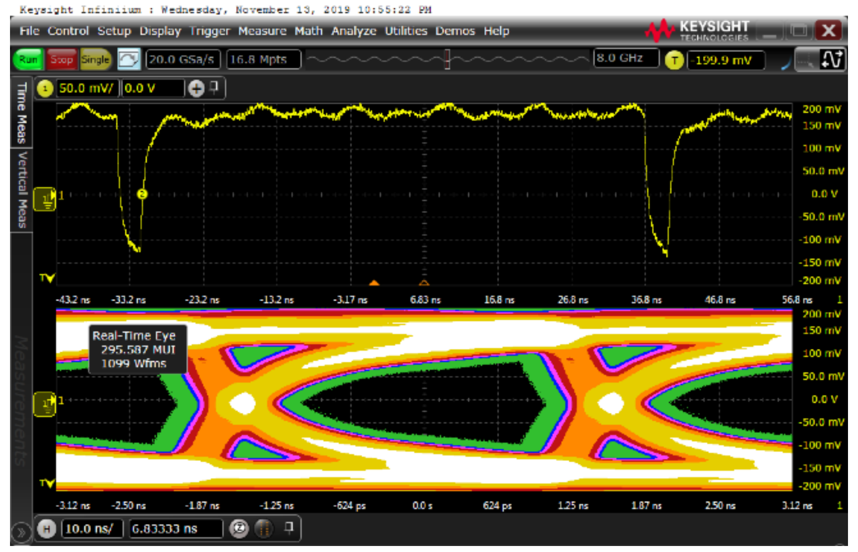


- A **flexible pigtail cable** connects the **stave to PEPI**
- **Backplane** distributes **balanced load** to DCBs
- **DCBs optically** send **data** to **LHCb DAQ**
  - ➡ **Bandwidth:** 248 DCBs × 3 VTTx/DCB × 2 links/VTTx × 4.8 Gb/s = **7.1 Tb/s**
  - ➡ Also **control system** via **VTRx**

Each **DCB** (Data Control Board) has **7 GBTx** (rad-hard serdes ASIC), **3 VTTx** (twin optical transmitter), and **1 VTRx** (optical TX/RX)







Due to space constraints, **backplane** ended up being an **ultra-dense** board with **28 layers at the limit of manufacturability**

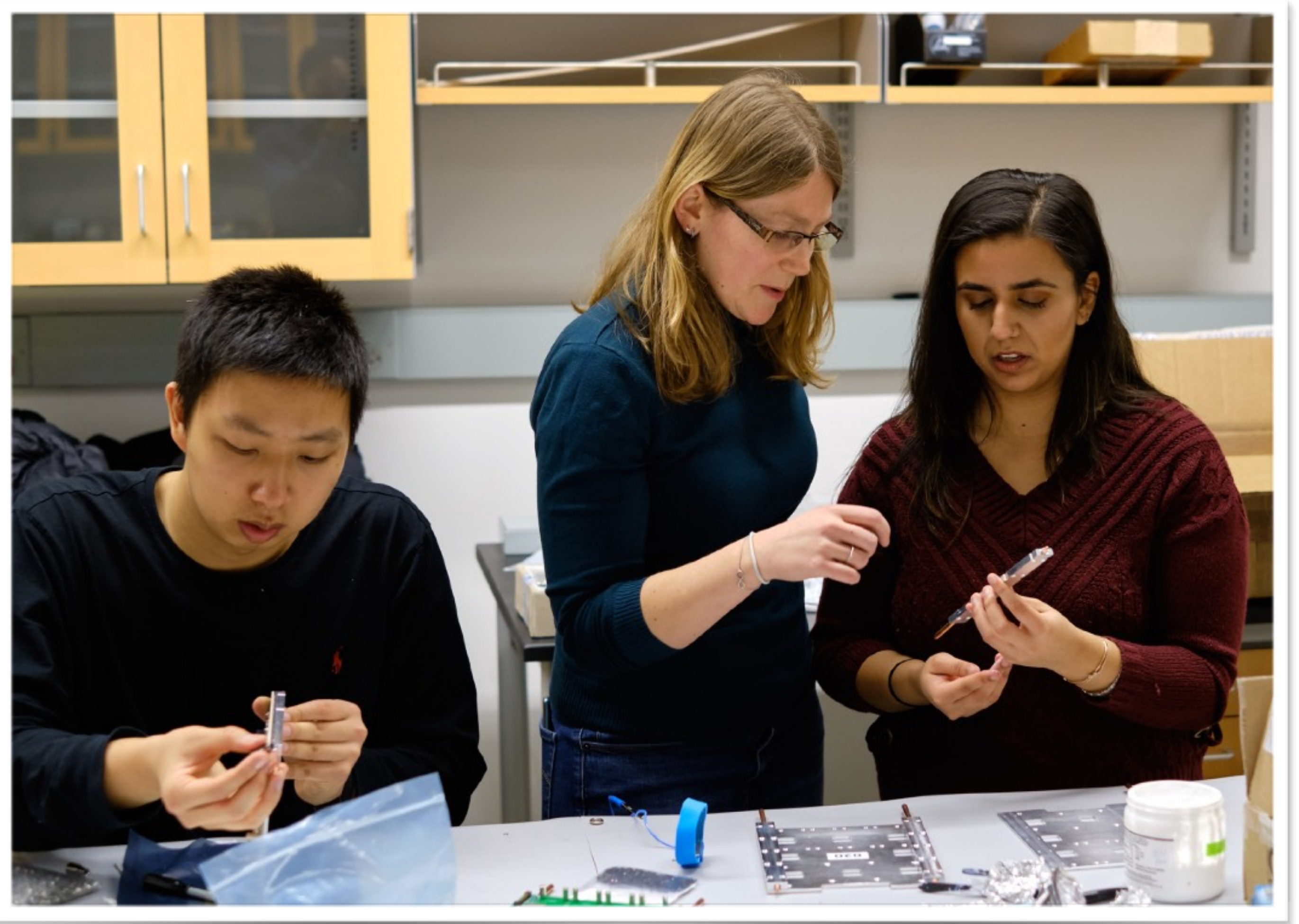
UT integration

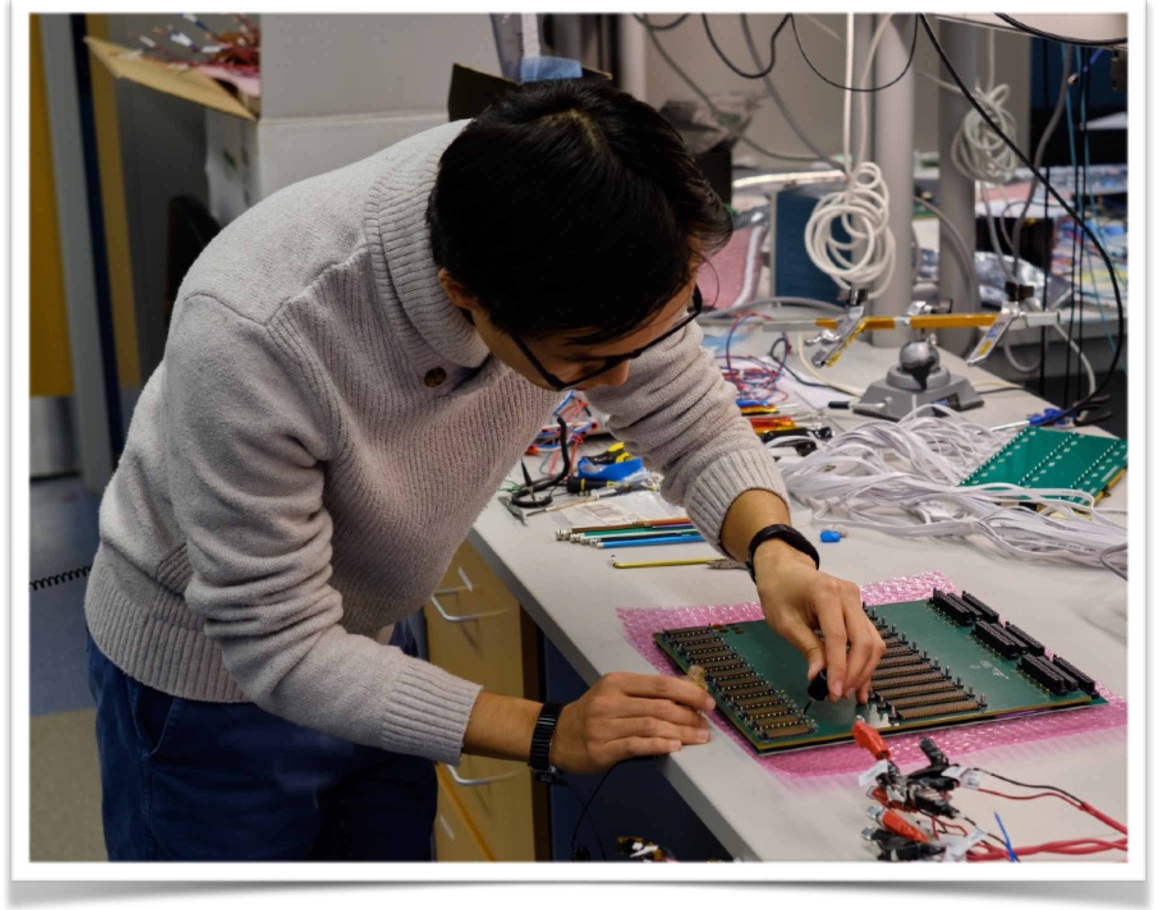
Staves cooled by **CO_2**, tested between -30° and 20°

PEPI cooled by **water**, boxes sit directly on top and below staves

LV and **HV** regulation at the service bays

A piece of the Free state in LHCb





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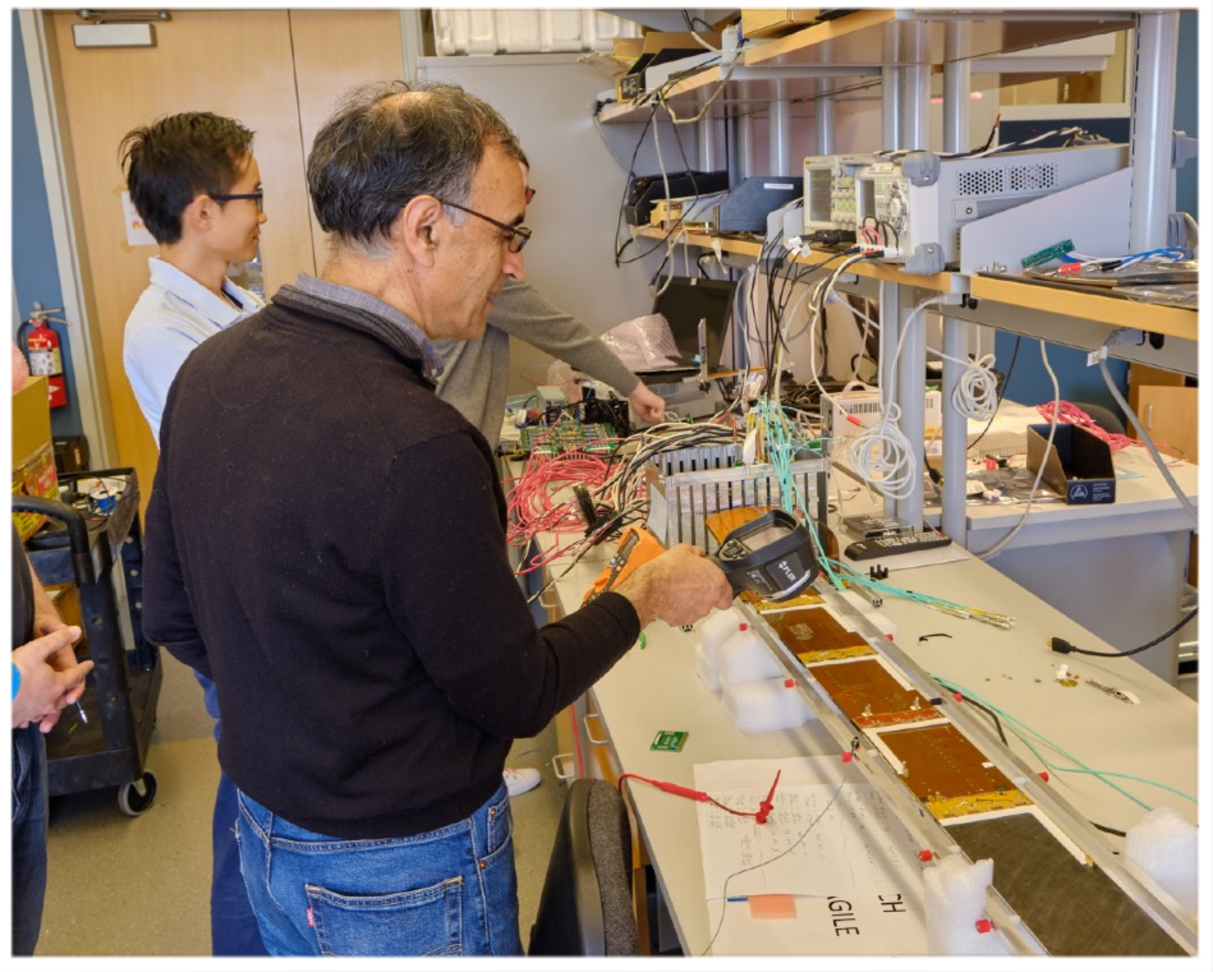
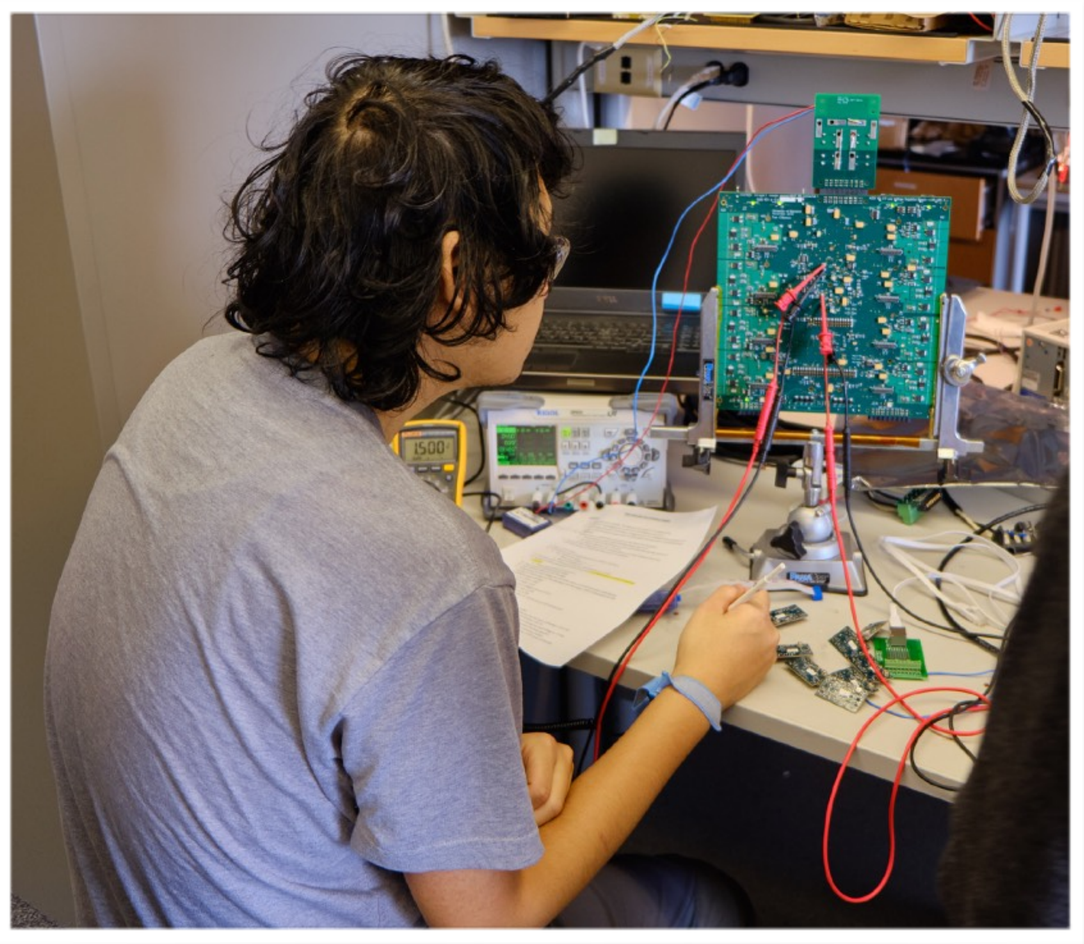
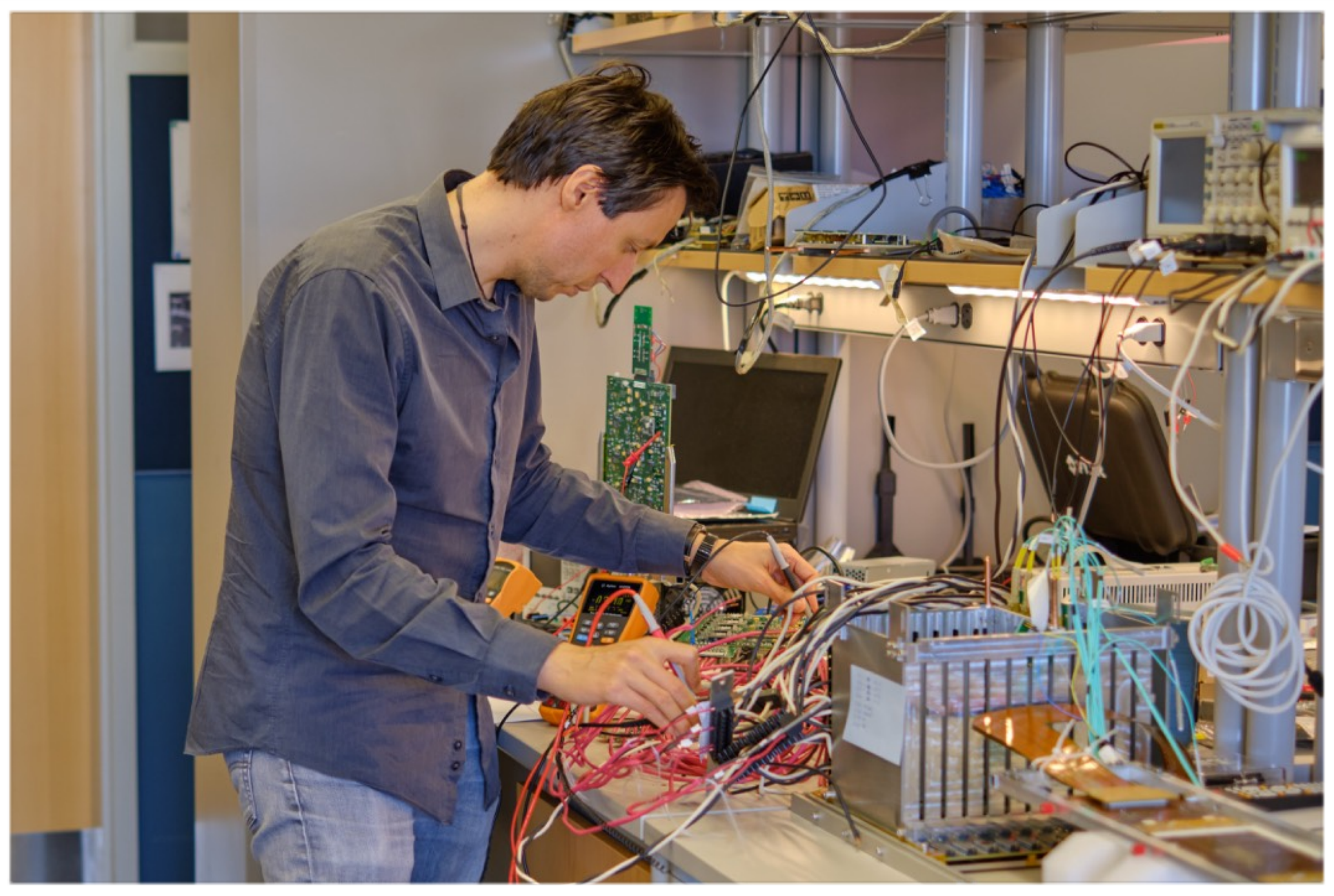
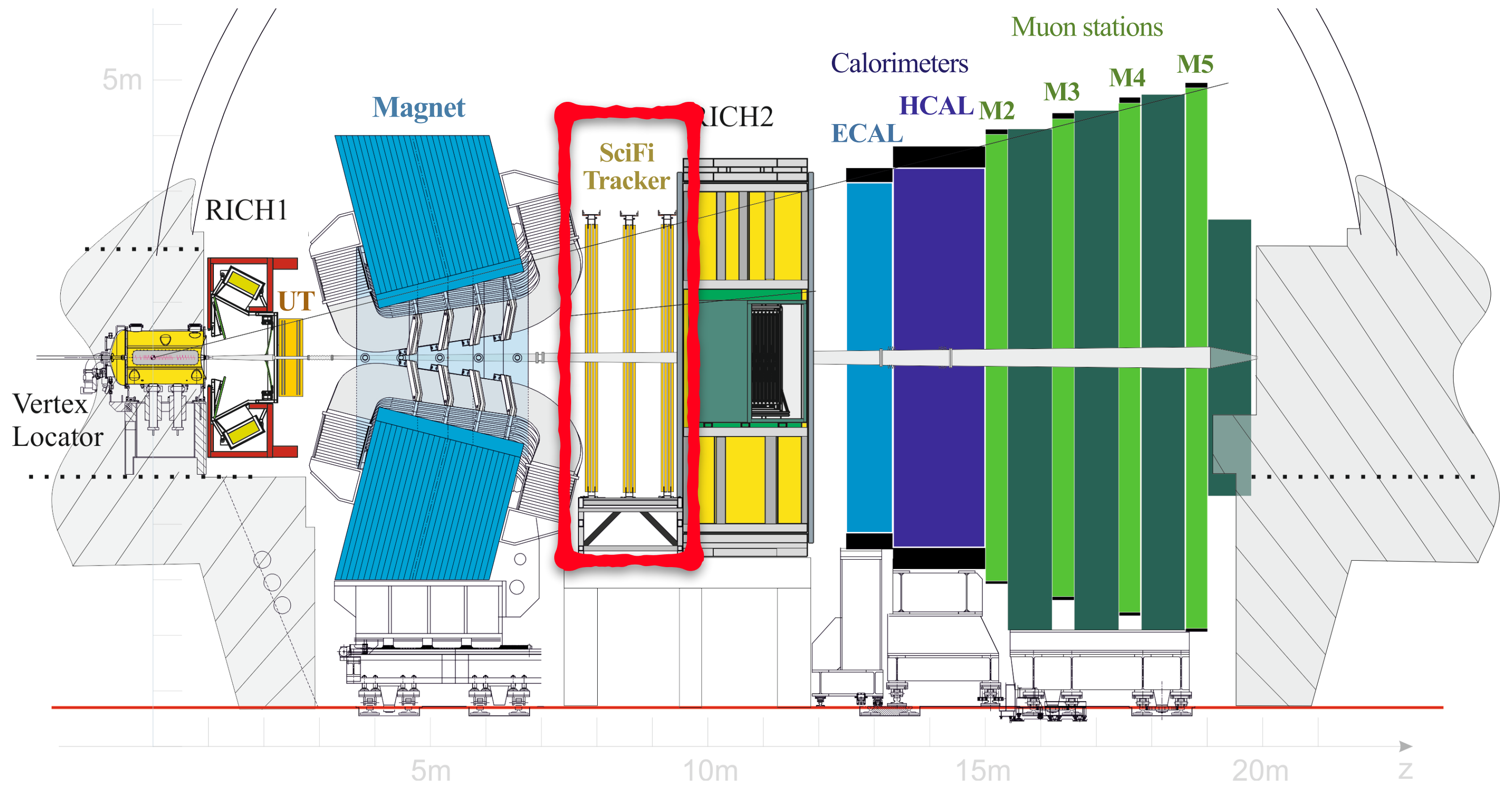


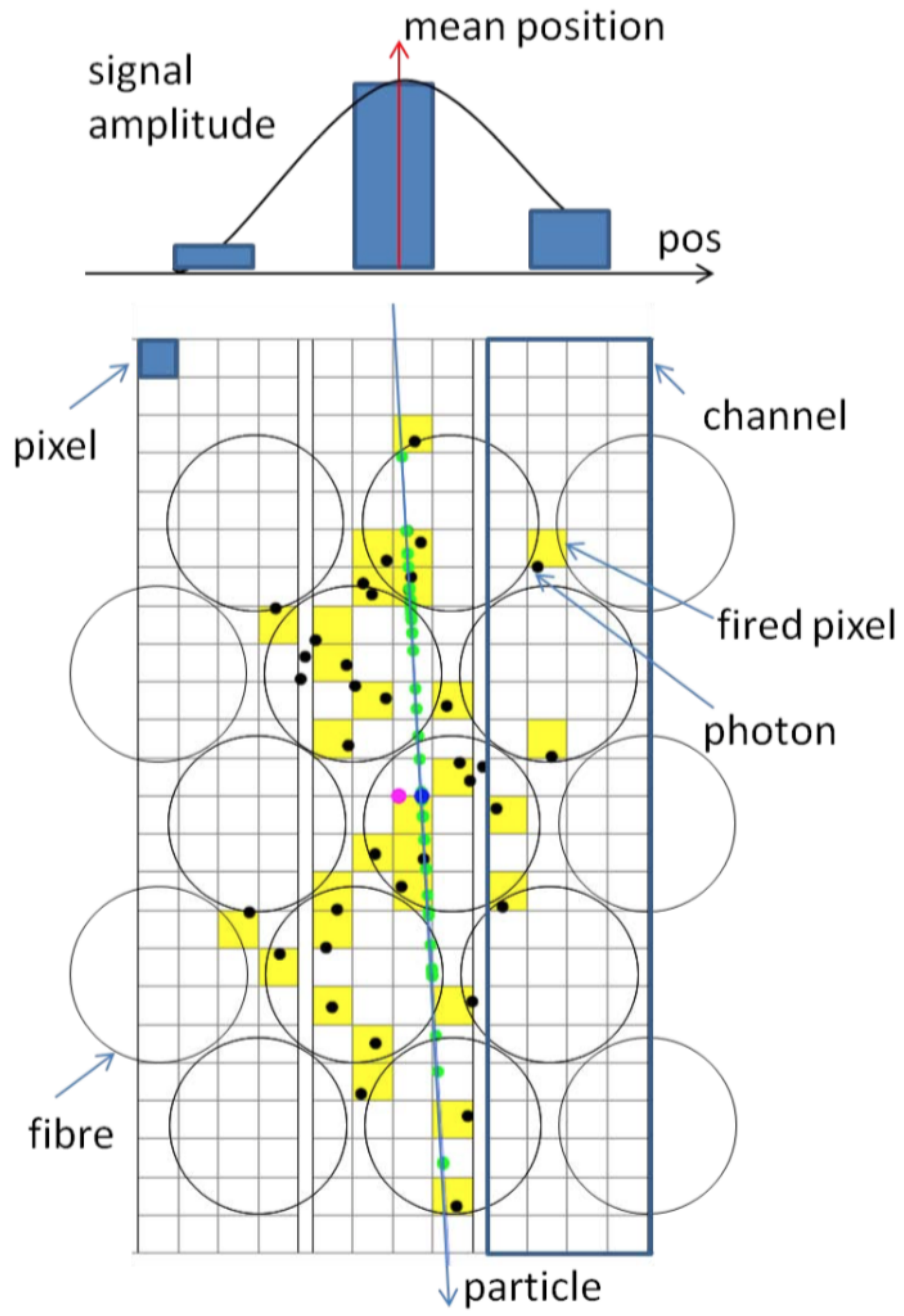


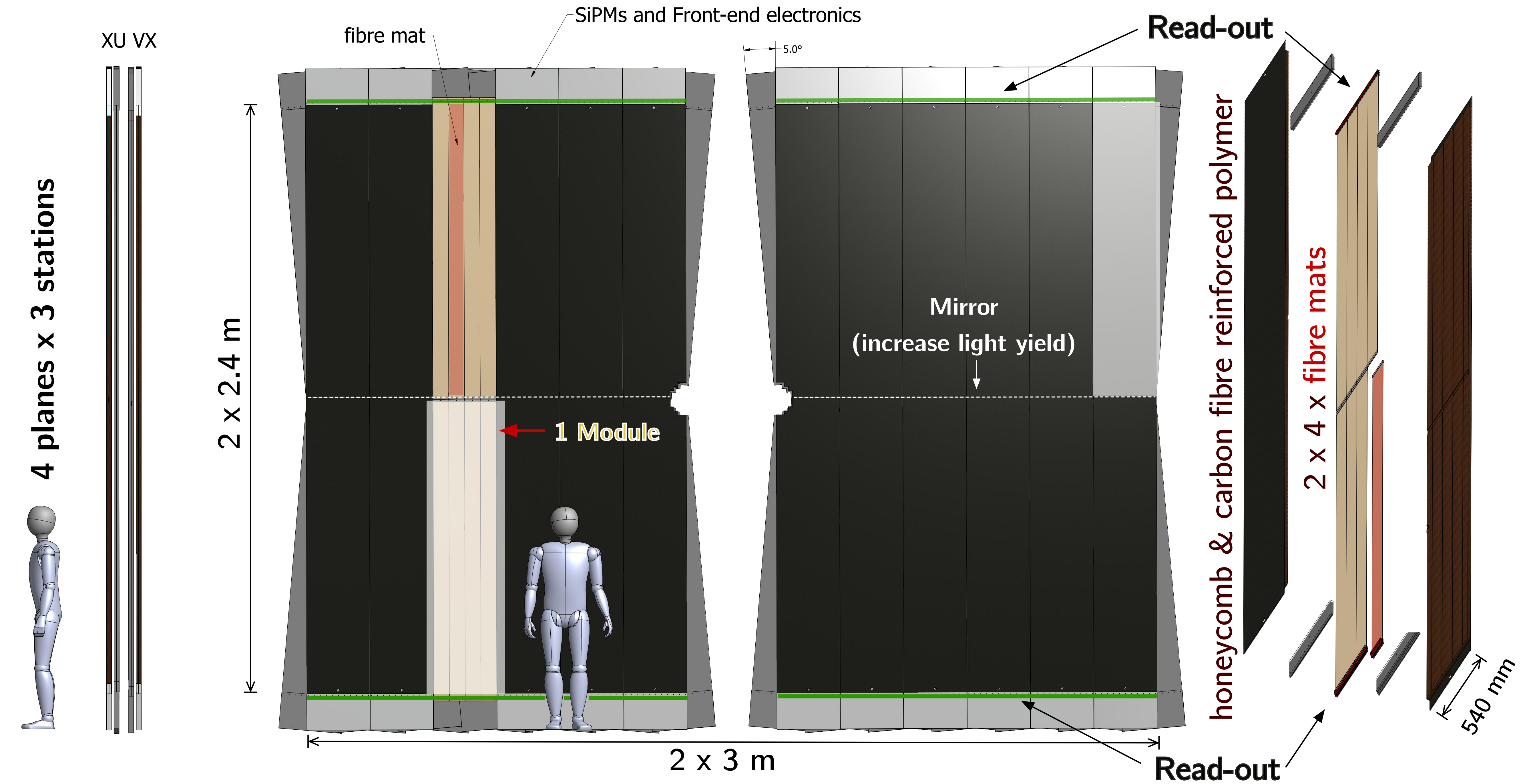


Scintillating Fibers (SciFi)



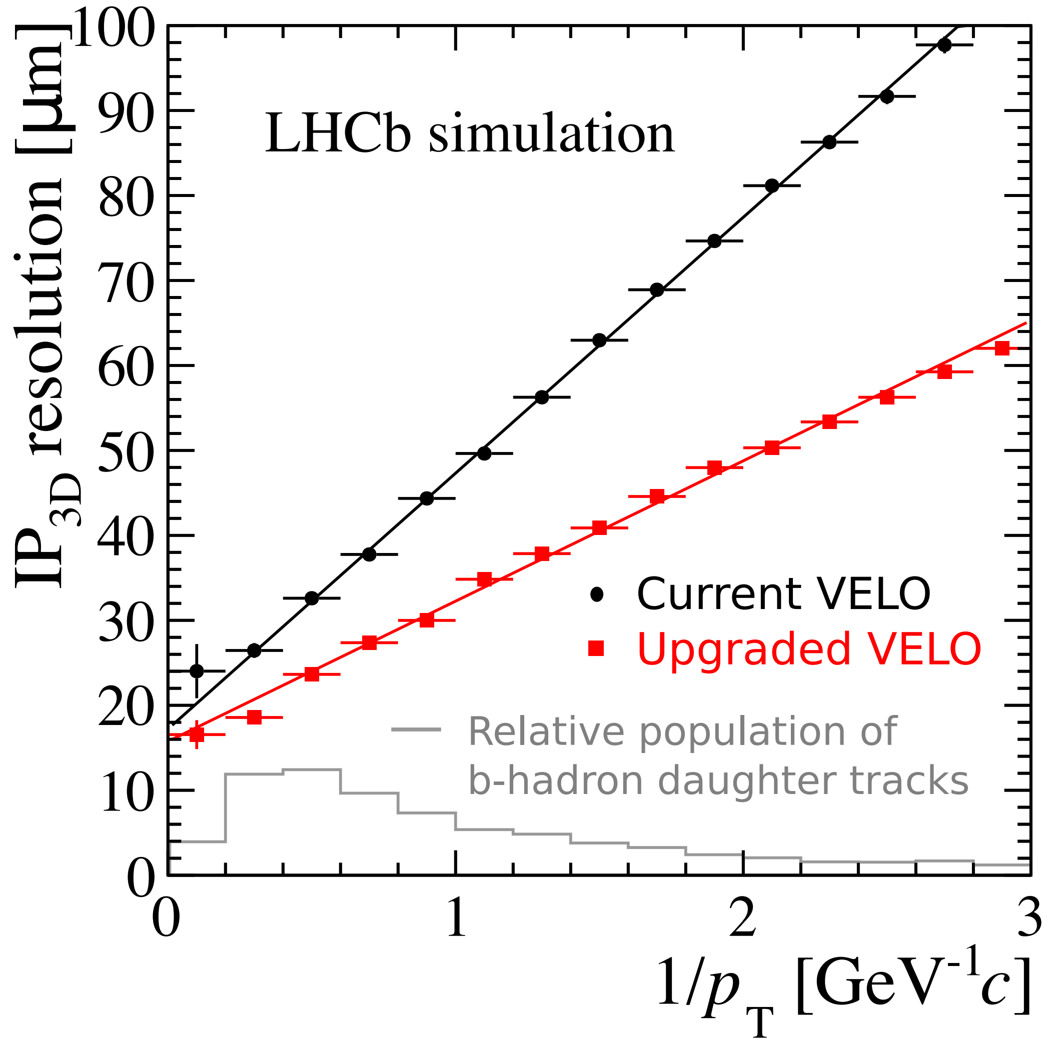
- Replace straw tubes and silicon Outer Tracker
  - ➡ Slow drift time of tubes limit occupancy
- **12 layers of scintillating fibers**
  - ➡ Readout with SiPMs
  - ➡ Fibers 250 μm, **80 μm resolution** with CoM fit



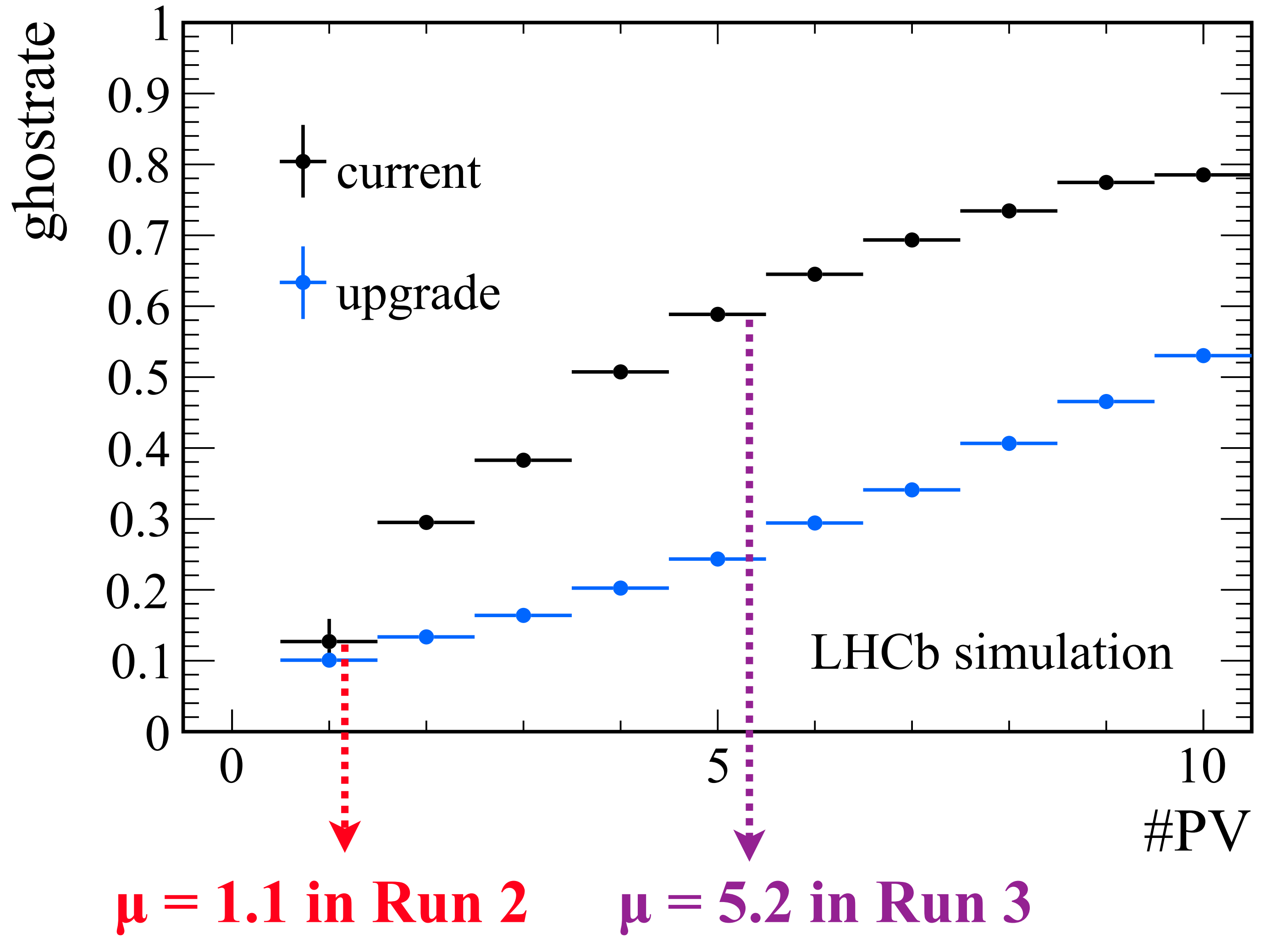


The best LHCb yet

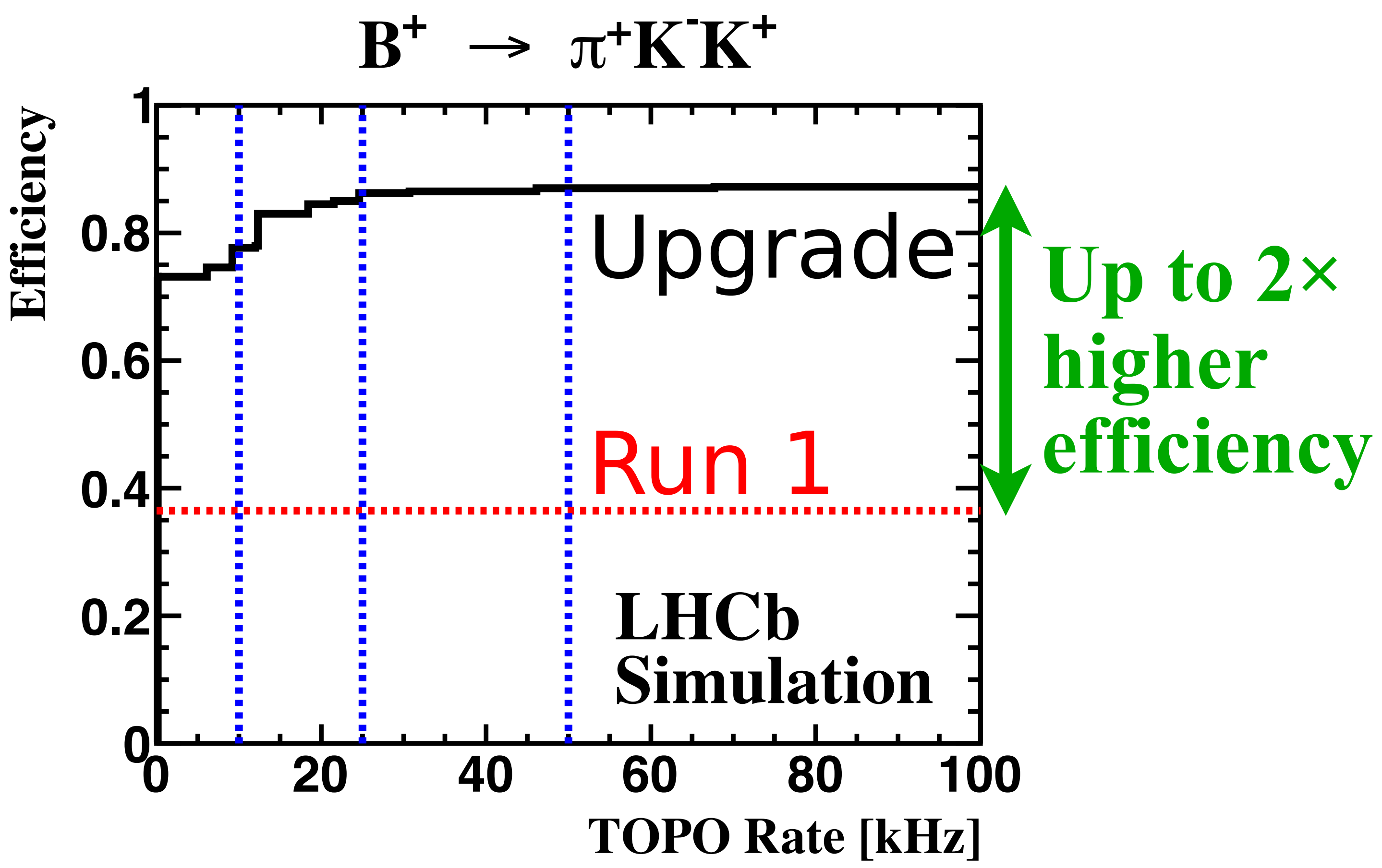
- Not only able to **withstand 50 fb^{-1}** and **40 MHz readout**, but also
  - **Better 3D impact parameter resolution**
    - Translates to improvements of 10-15% in the B decay time resolution
  - **Better p_T resolution**
  - Dramatic **reduction** of **ghost rate**

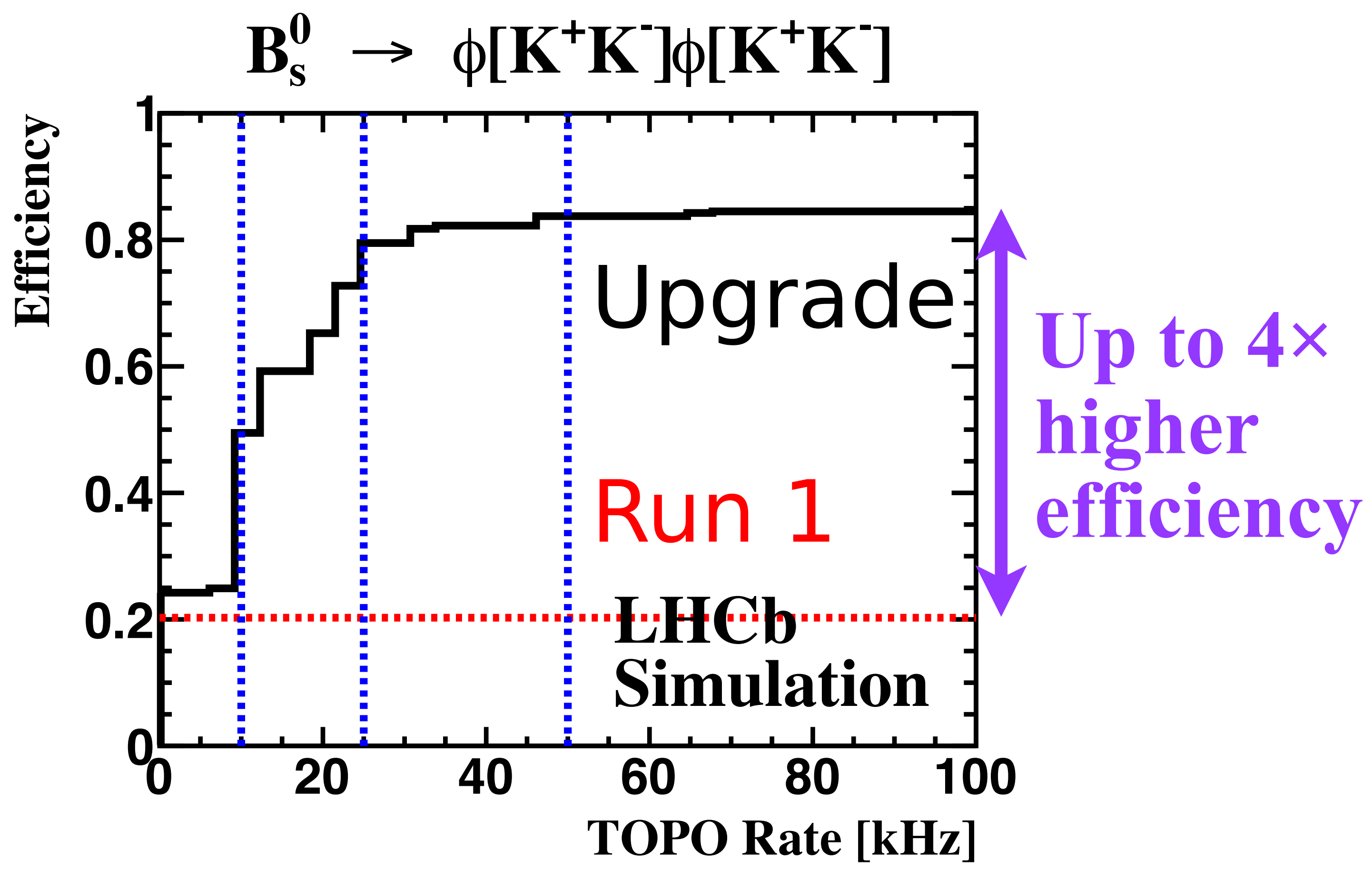


Speed-up makes SW trigger possible



- **SW trigger very flexible** → if you can reconstruct it offline, you can trigger on it!
  - Will **open up possibilities not yet thought of**





Proposed Upgrades Ib and II

Upgrades

9 fb^{-1} (2011–2018) · Goal: 50 fb^{-1} (2022–2030) · Goal: 250 fb^{-1} (2032–2037)

Upgrade I (LS2) · Upgrade Ib (LS3) · Upgrade II (LS4)

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

Runs 1 and 2

pp collisions → 40 MHz → **L0** Hardware → 1.1 MHz Detector readout → **HLT** Software → 12.5 kHz (0.6 GB/s) Events on disk

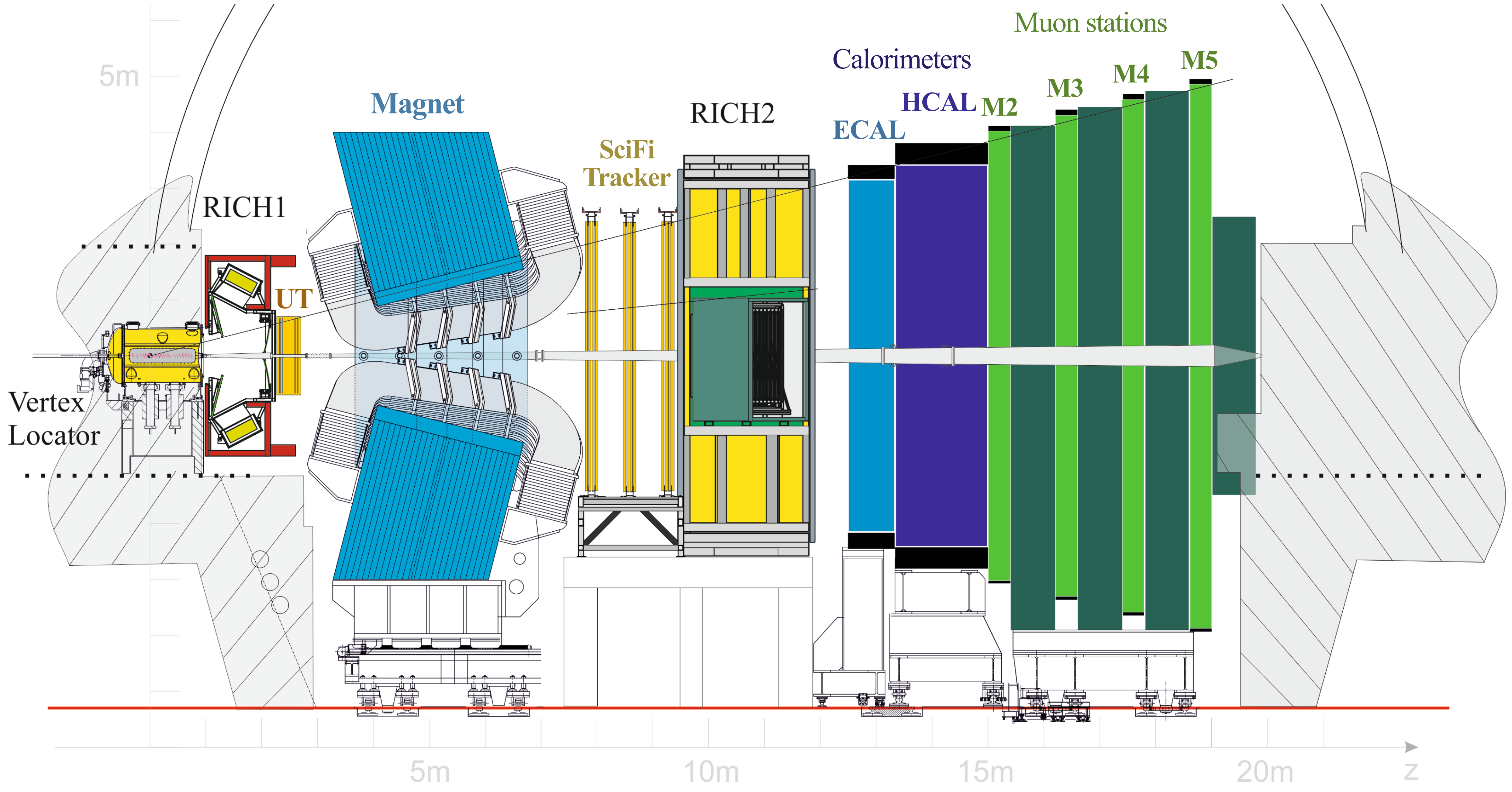
Upgrade I (being installed)

pp collisions → 40 MHz Detector readout → **HLT** Software → 100 kHz (2-5 GB/s) Events on disk

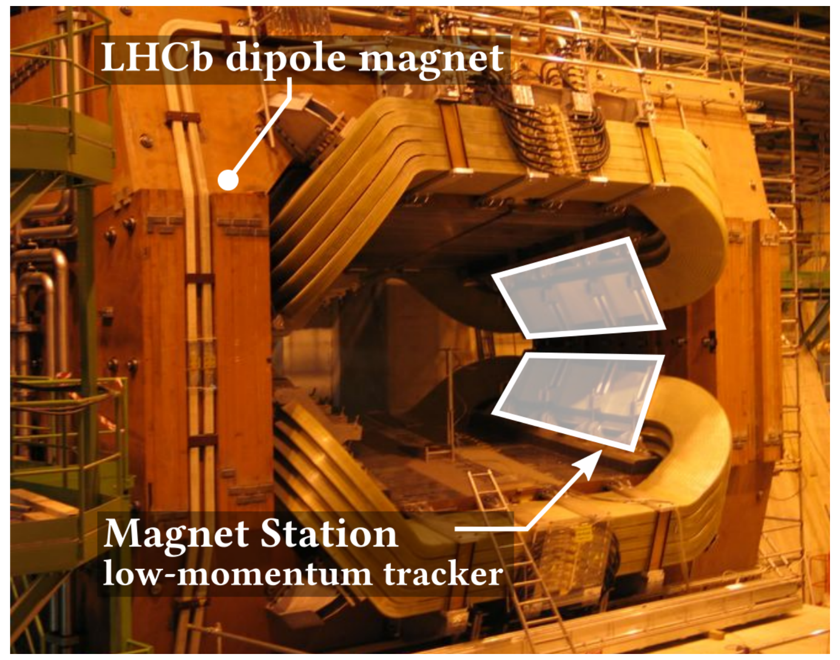
Flexible software trigger and 3 new/better trackers

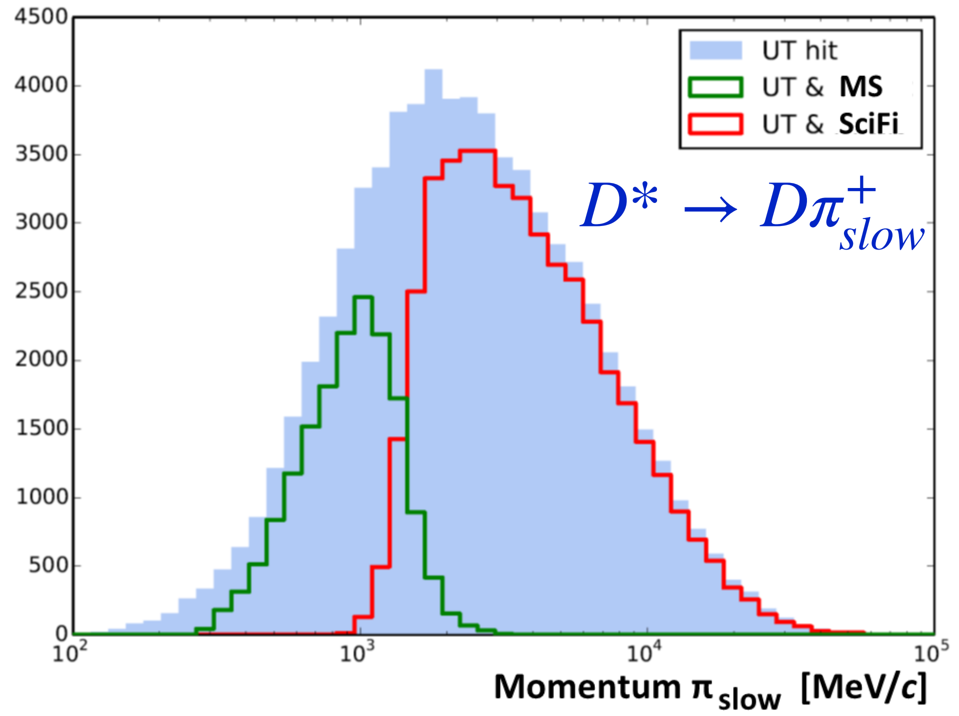
Upgrades Ib and II (proposed)

Even better granularity, improved calorimeter, and fast timing



Upgrade Ib possibilities



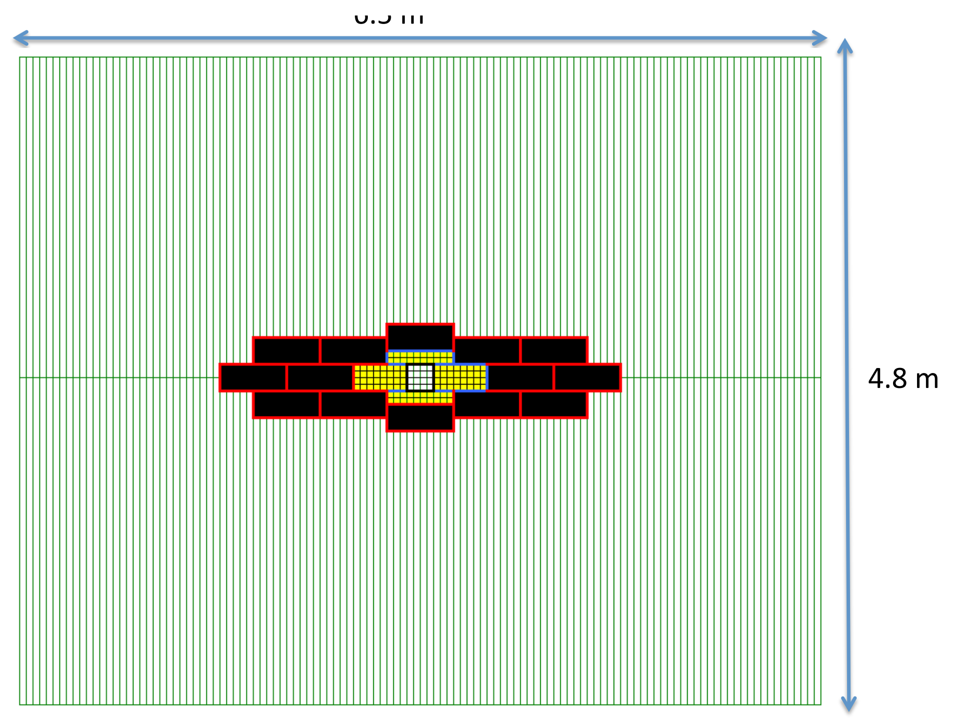


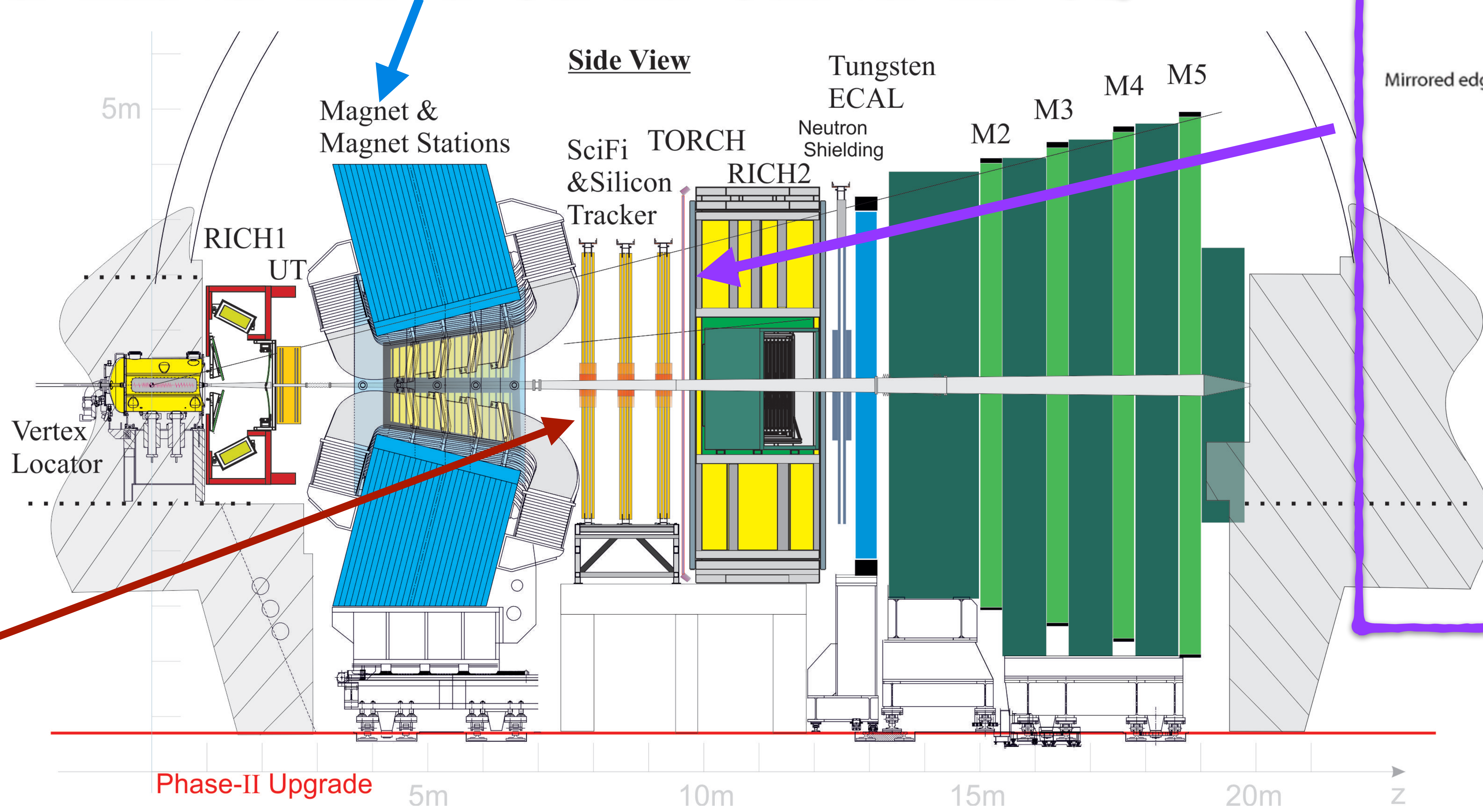
MAGNET STATIONS

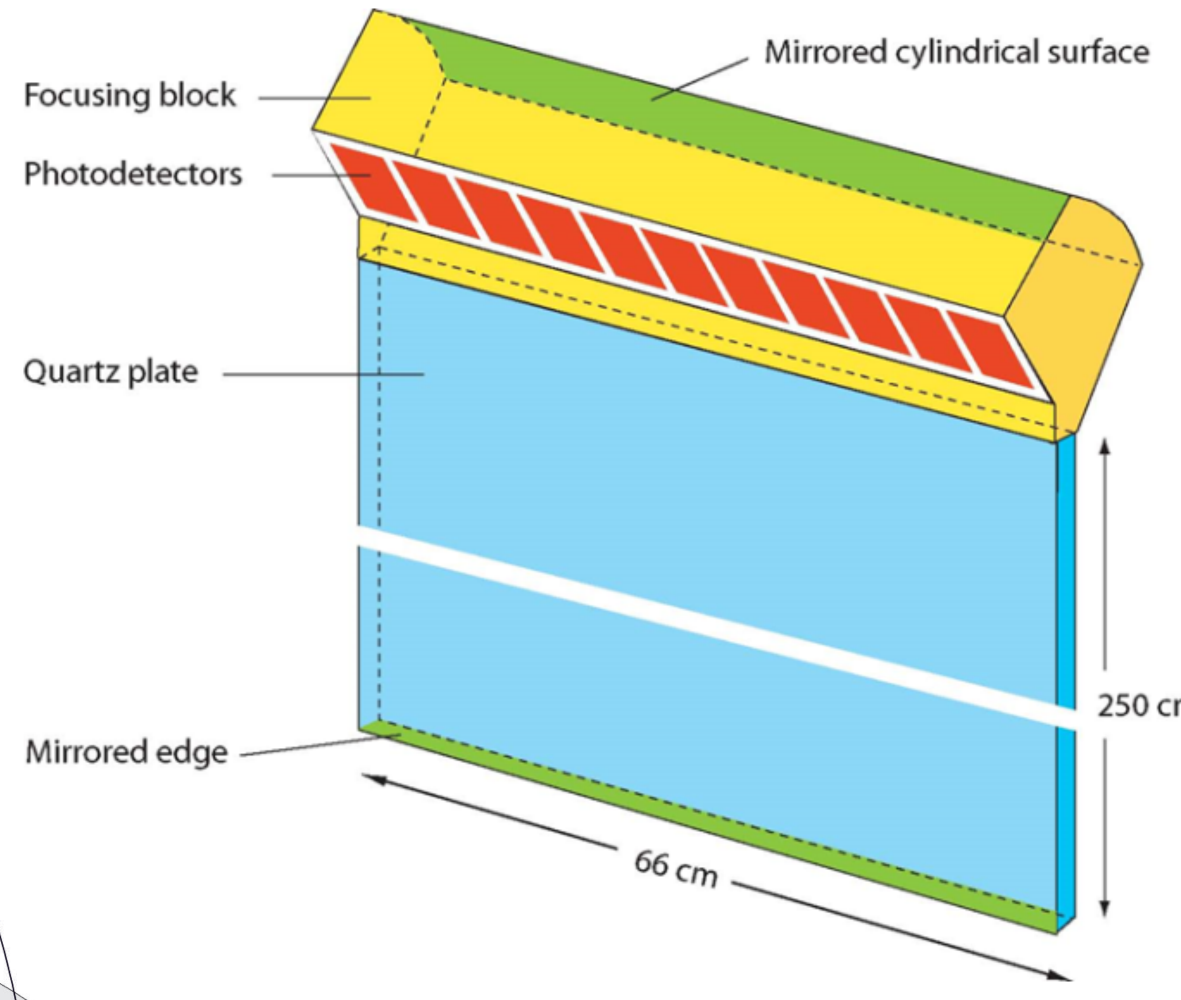
New **scintillating fiber stations** on the **inside of dipole magnet**
Improved low-p_T tracking

MIGHTY TRACKER

New **silicon stations around beamline** for **radiation hardness** and **granularity**







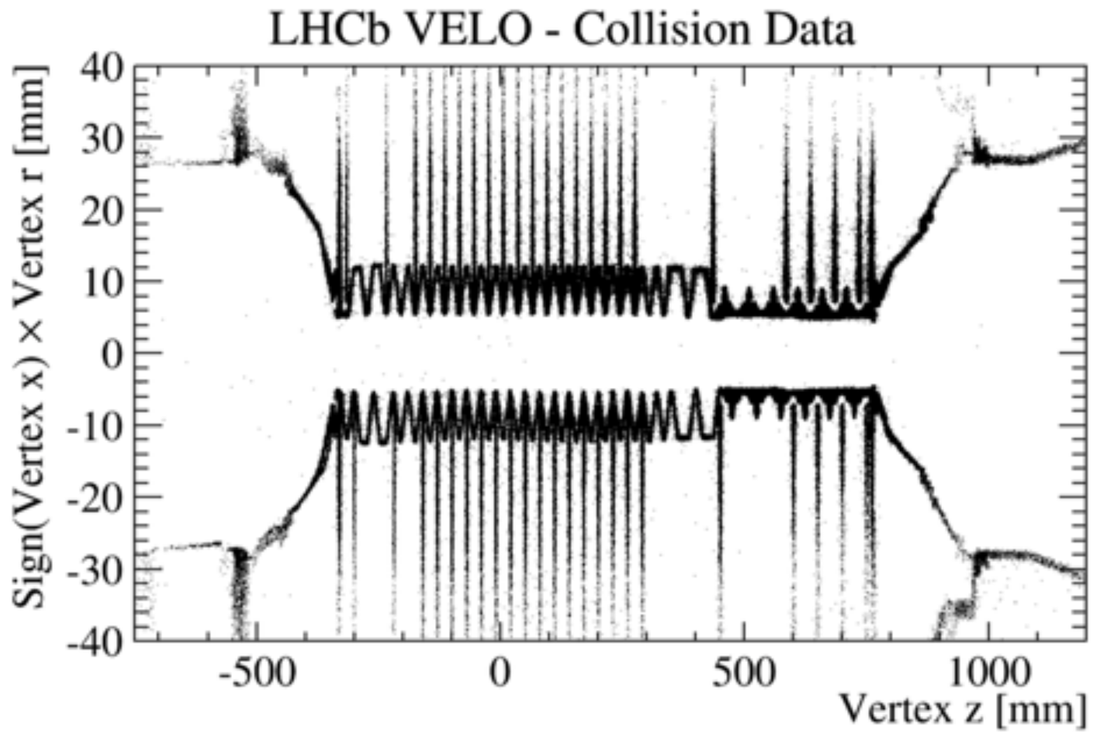
TORCH

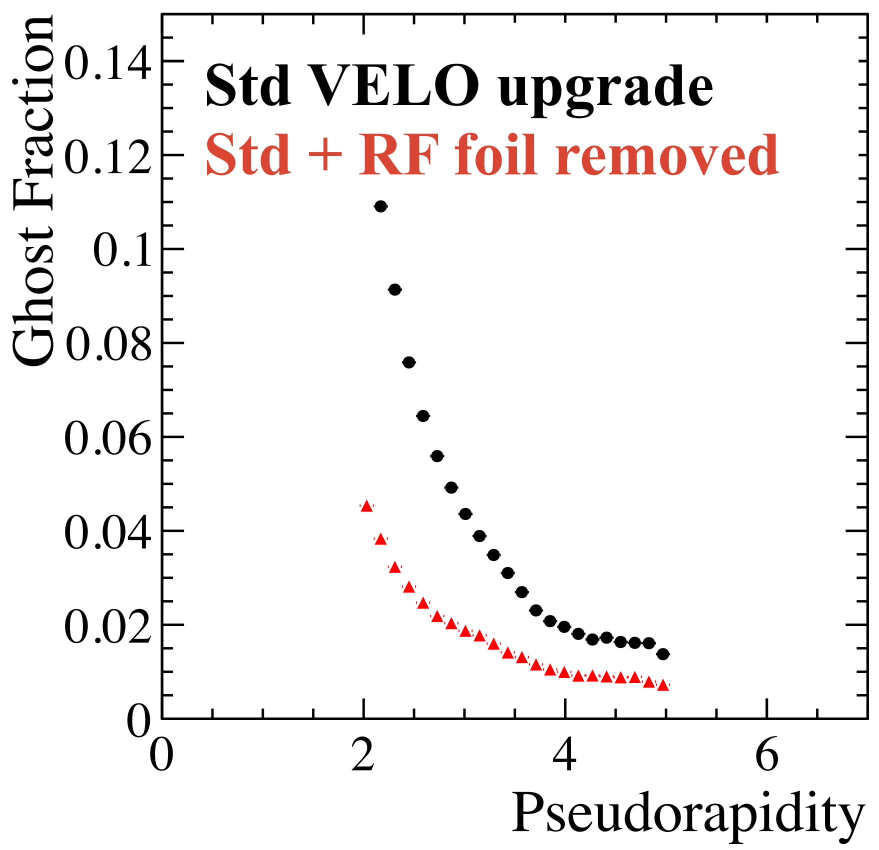
PID for **p_T < 10 GeV** with **15 ps timing** (70 ps per photon for ~30 photons)

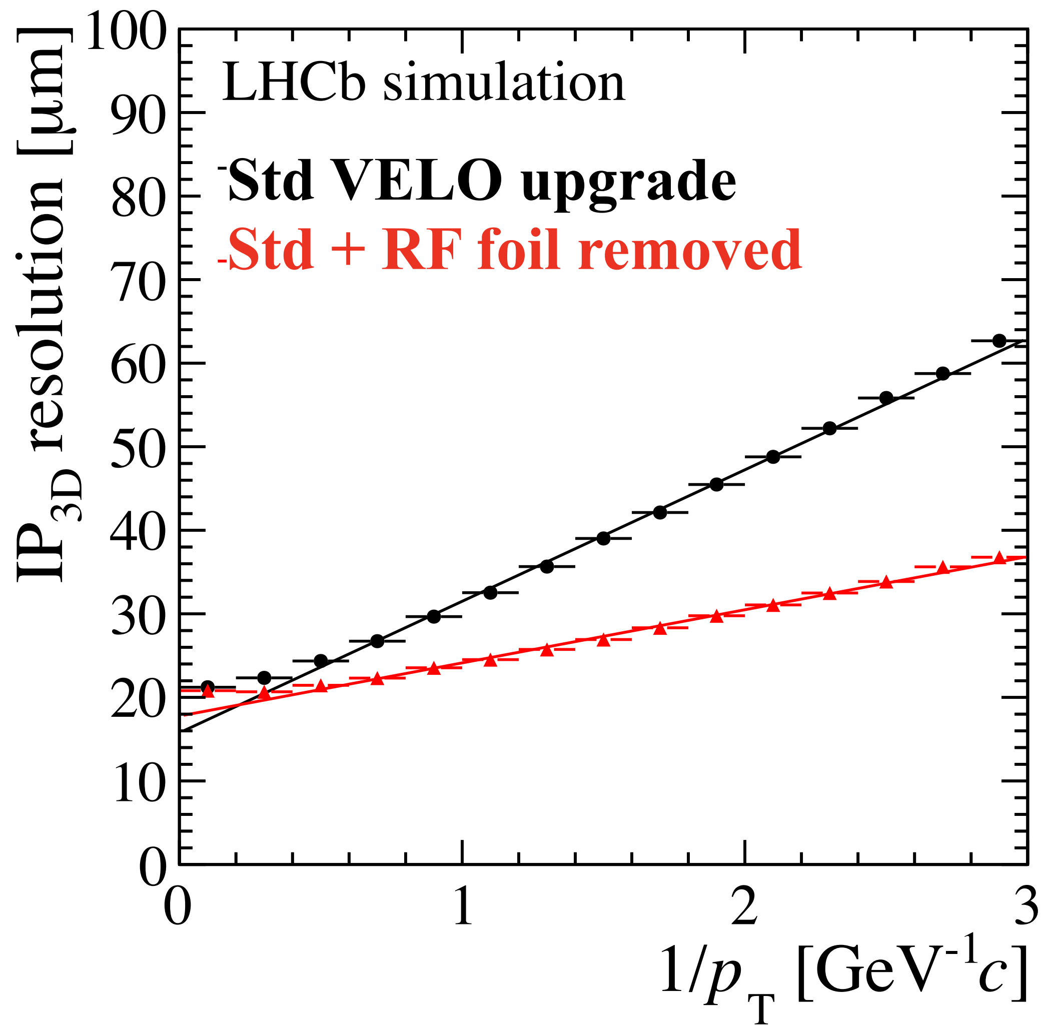
VELO, ECAL upgrades

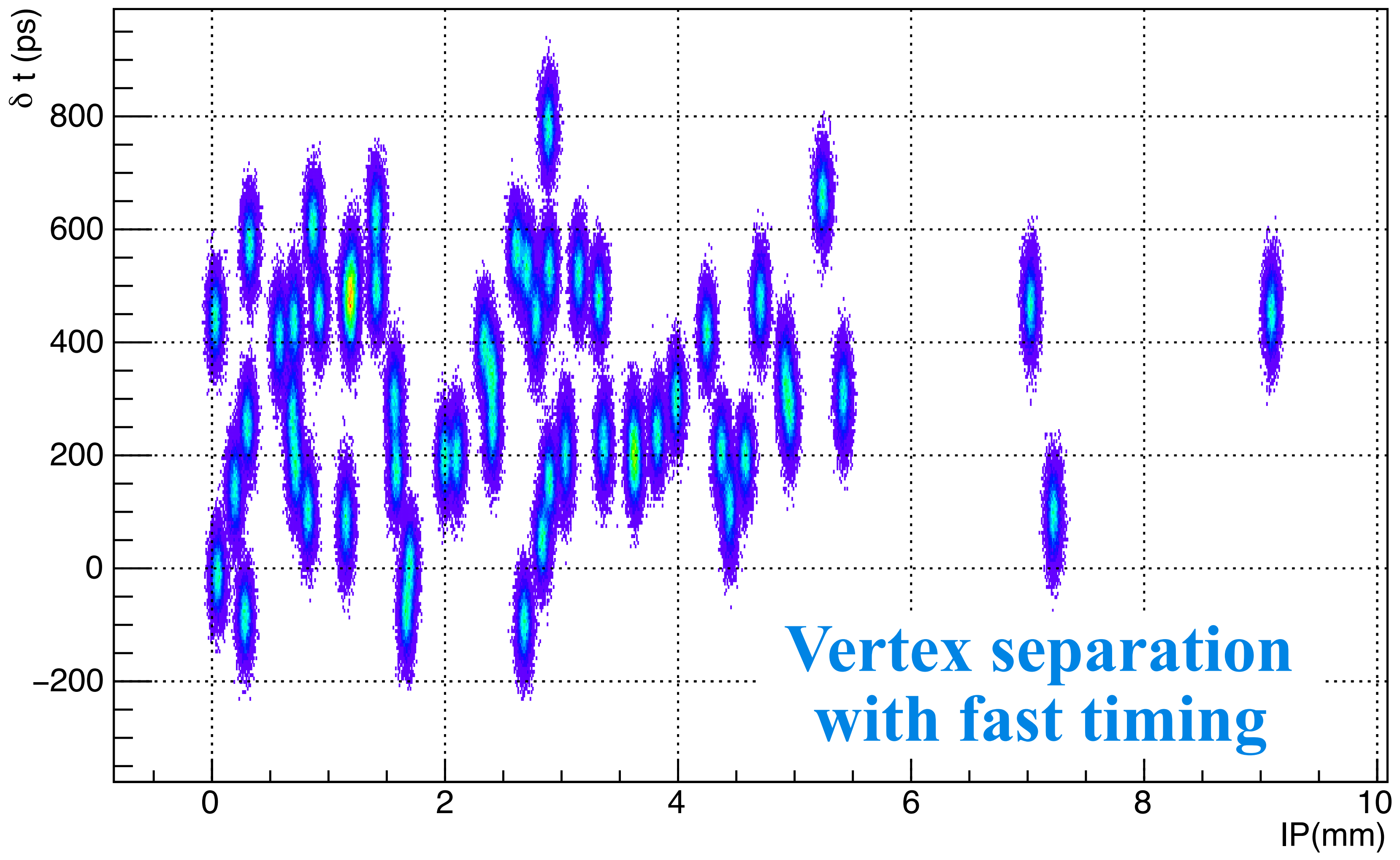
VELO

Improved **granularity**, **thinner RF foil**, **timing** better than 200 ps



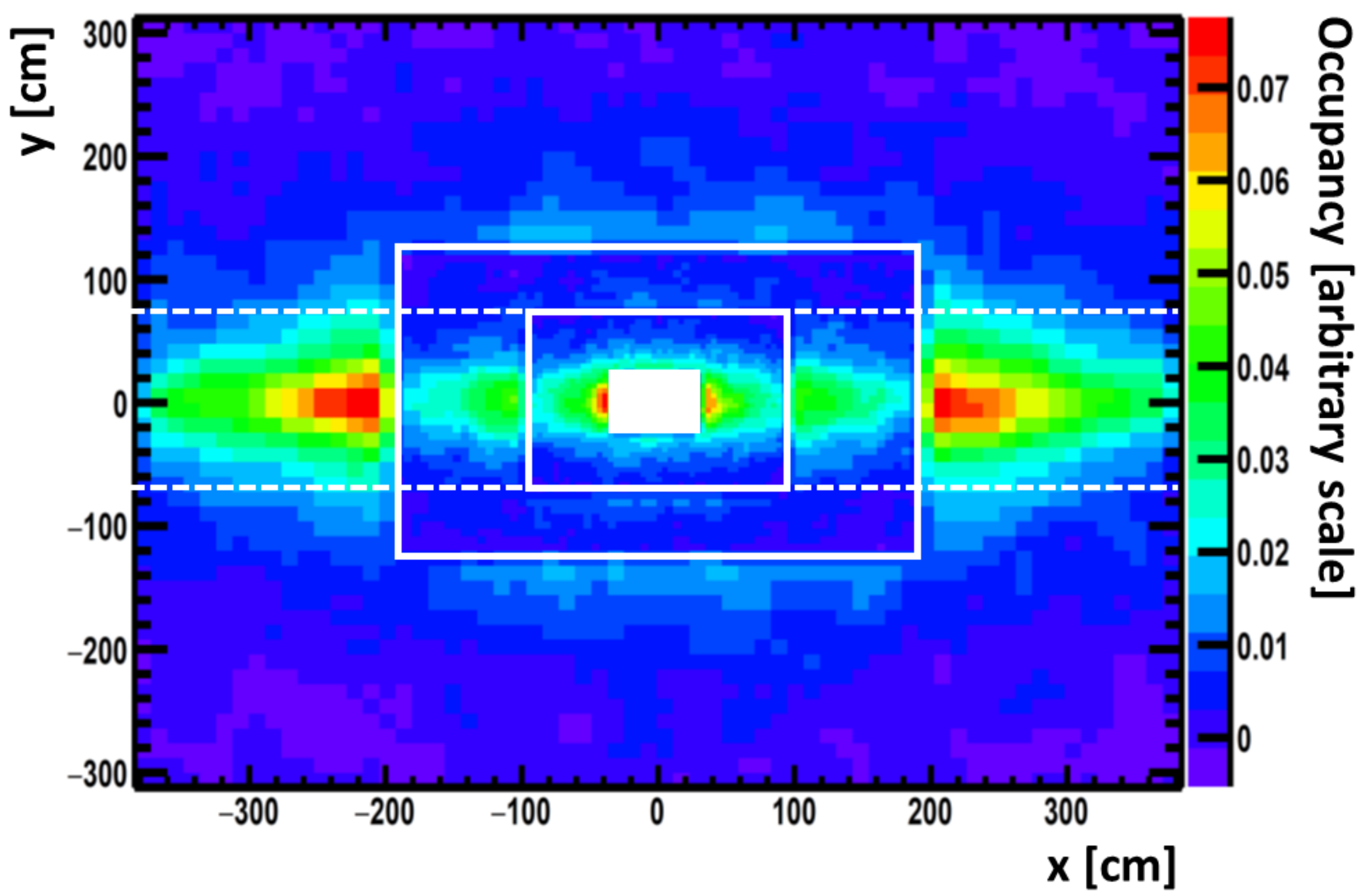


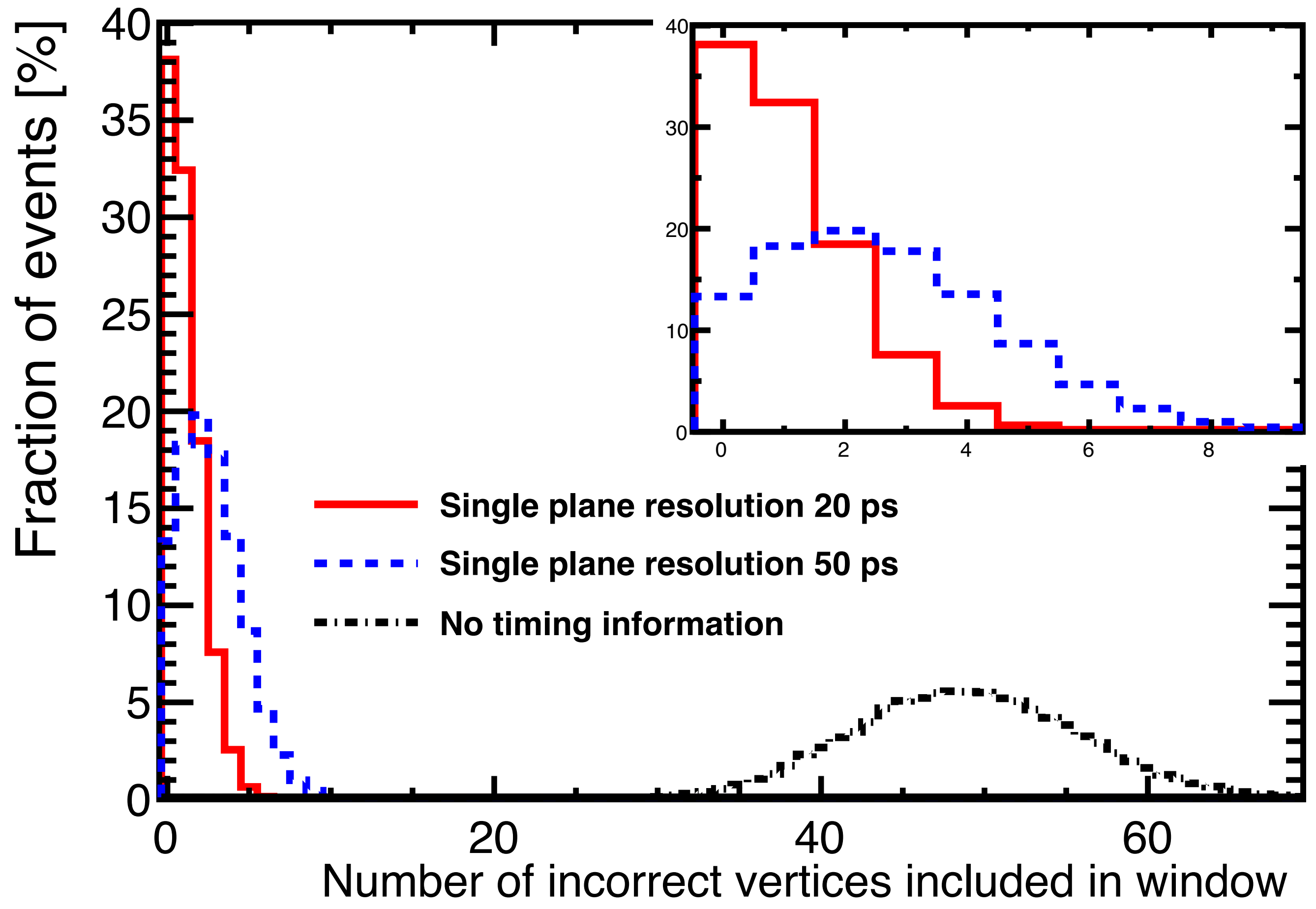




ECAL

Improved **granularity**, **timing** of ~50 ps, possible in upgrade Ib

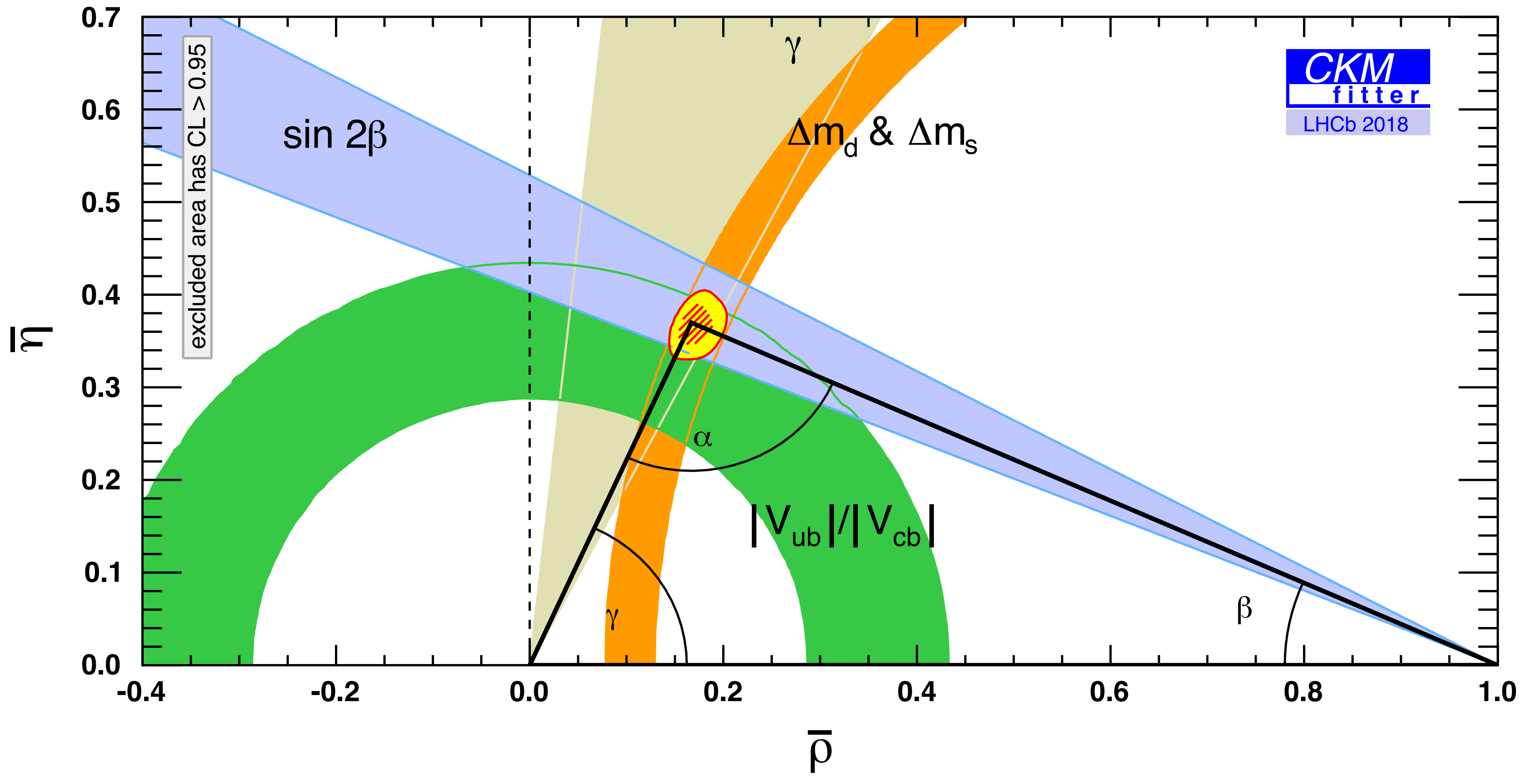


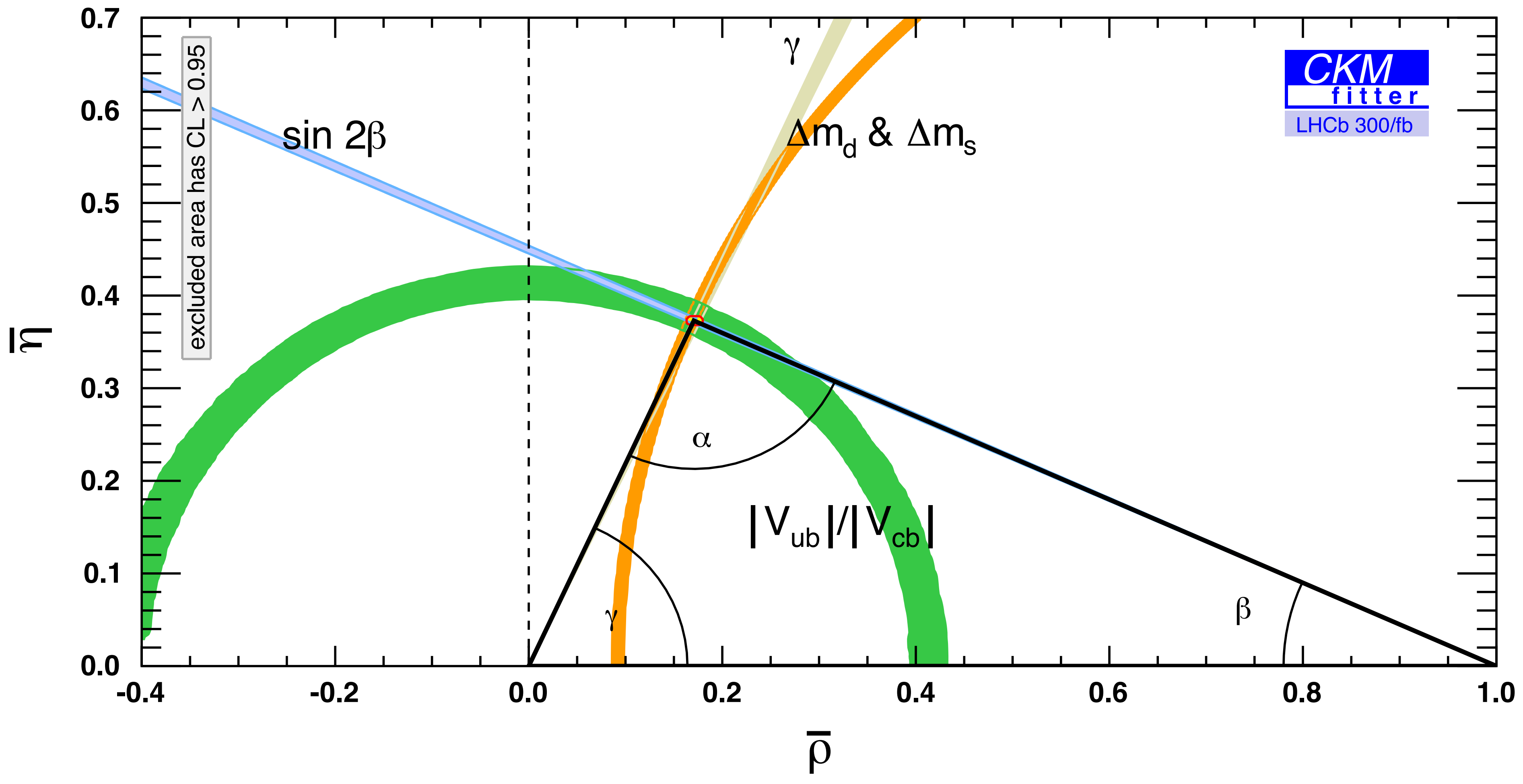


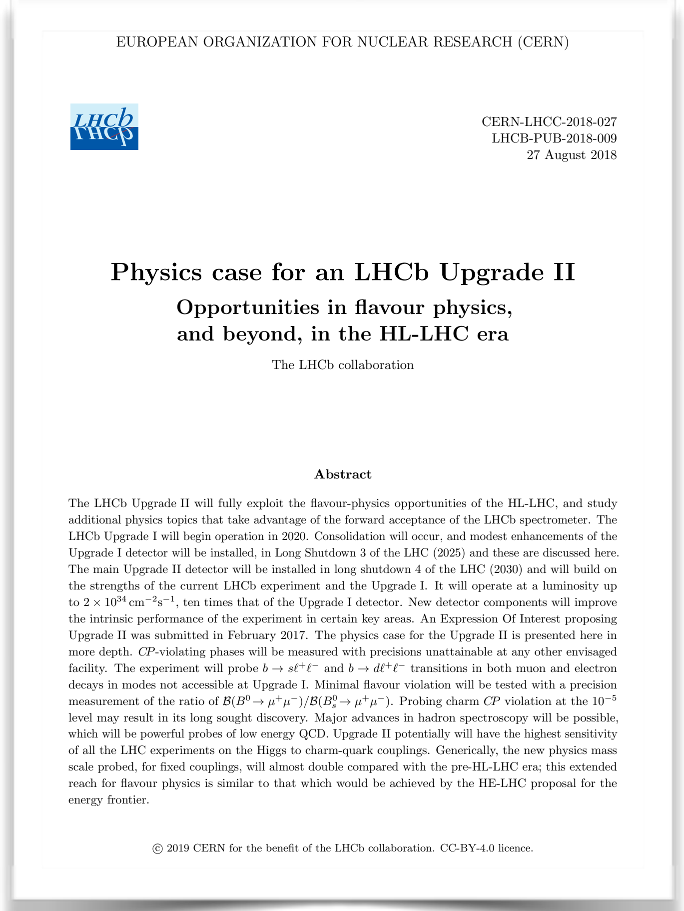
Physics reach of Upgrade II

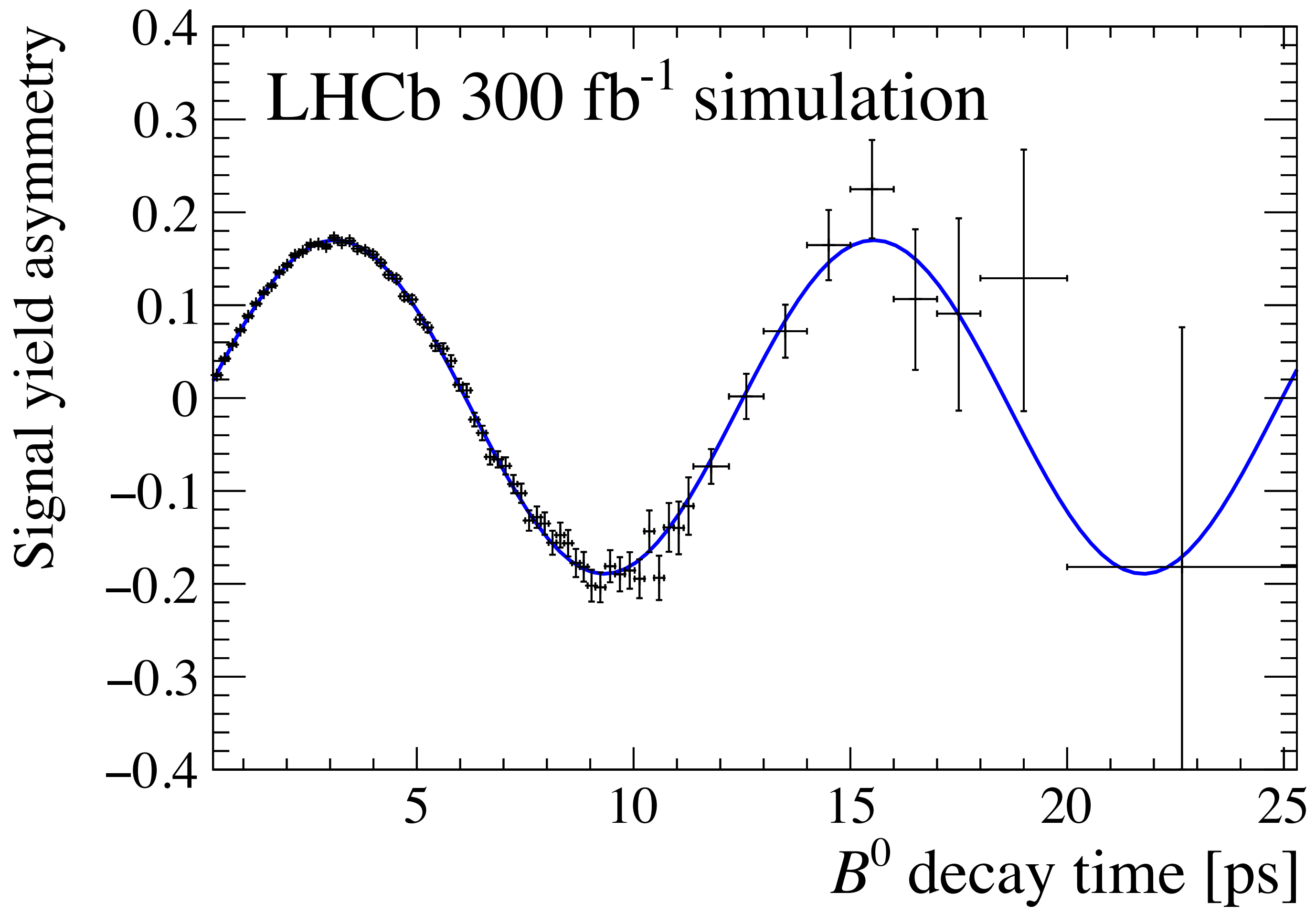
And many more!
CERN-LHCC-2018-027

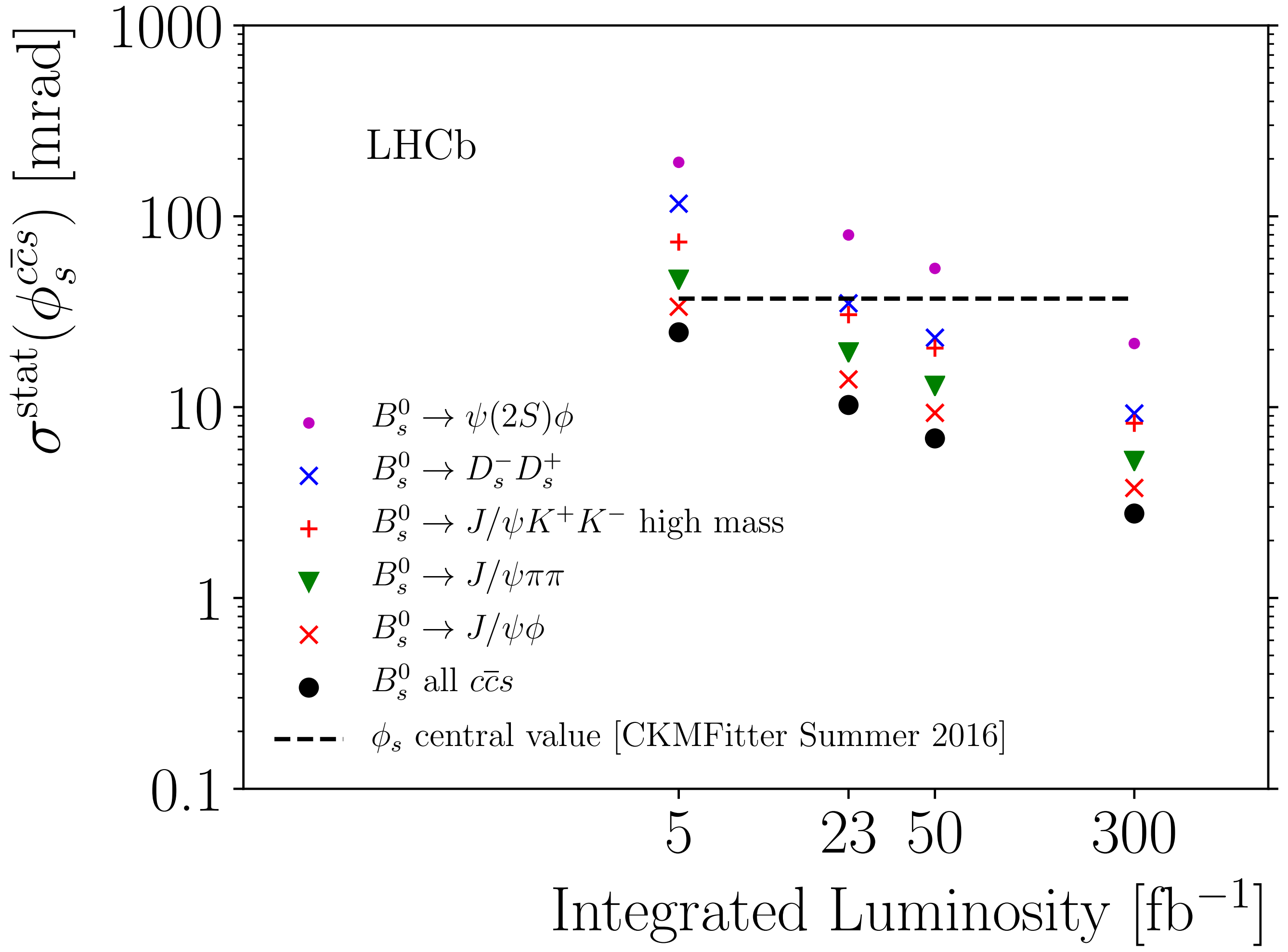
- **Exquisite precision** in all kinds of landmark flavor measurements

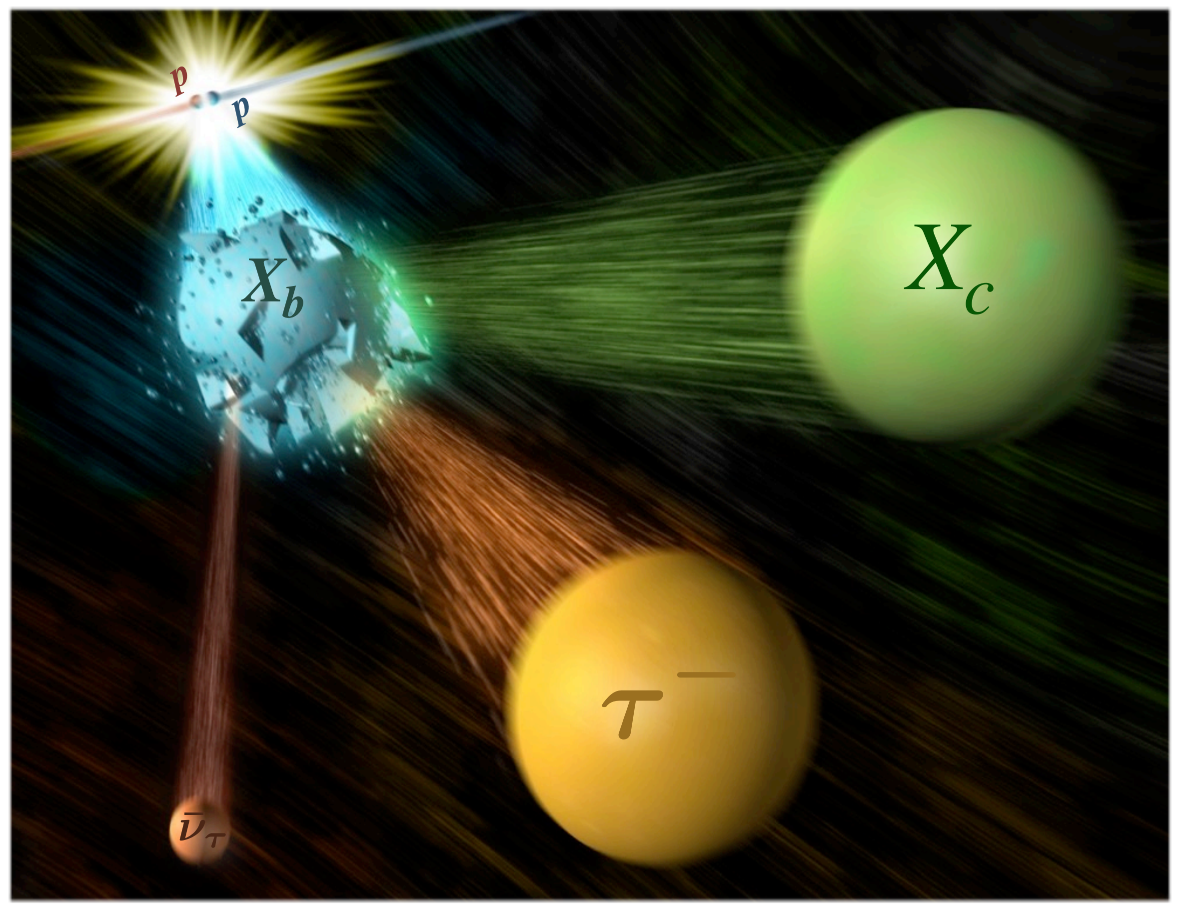


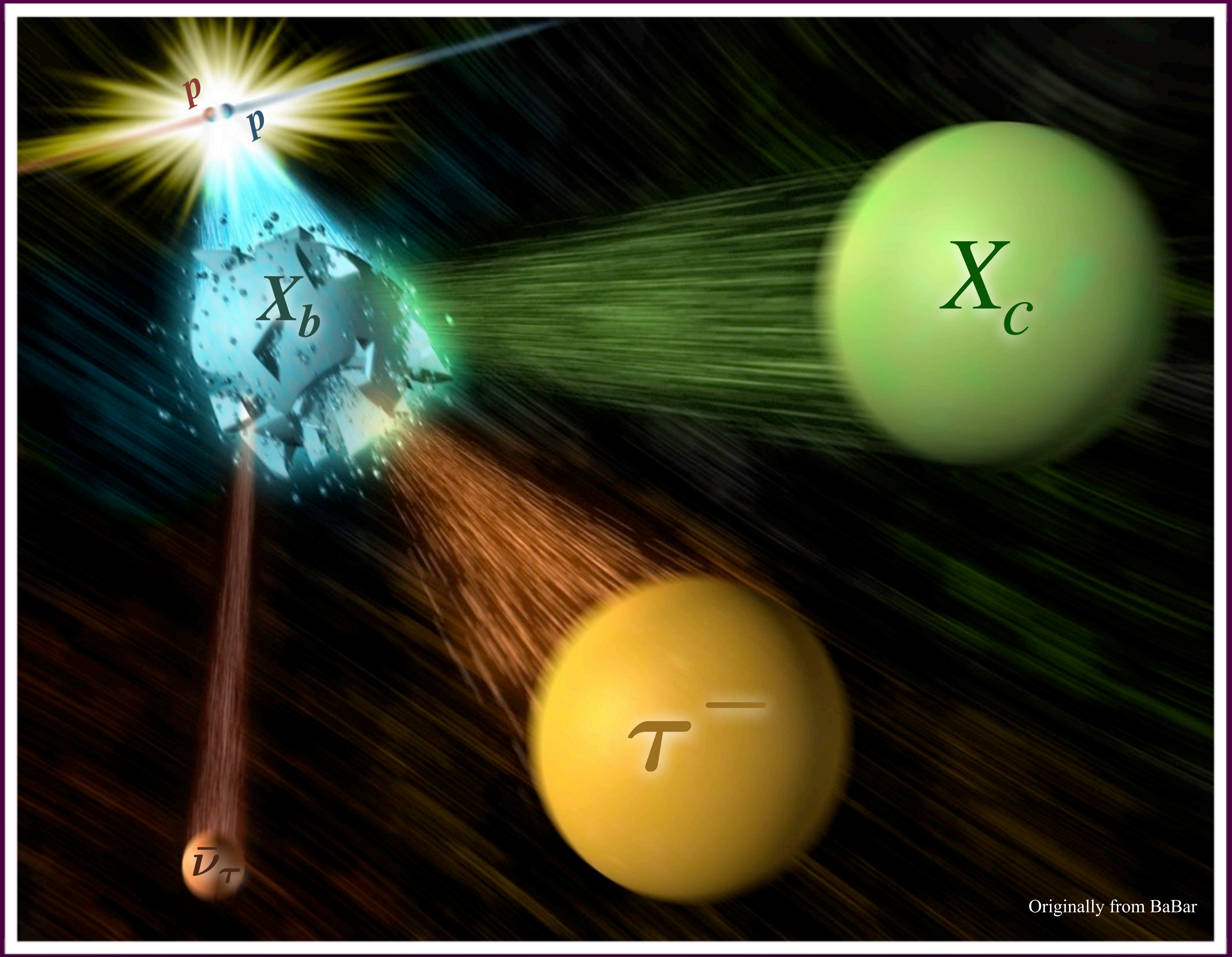










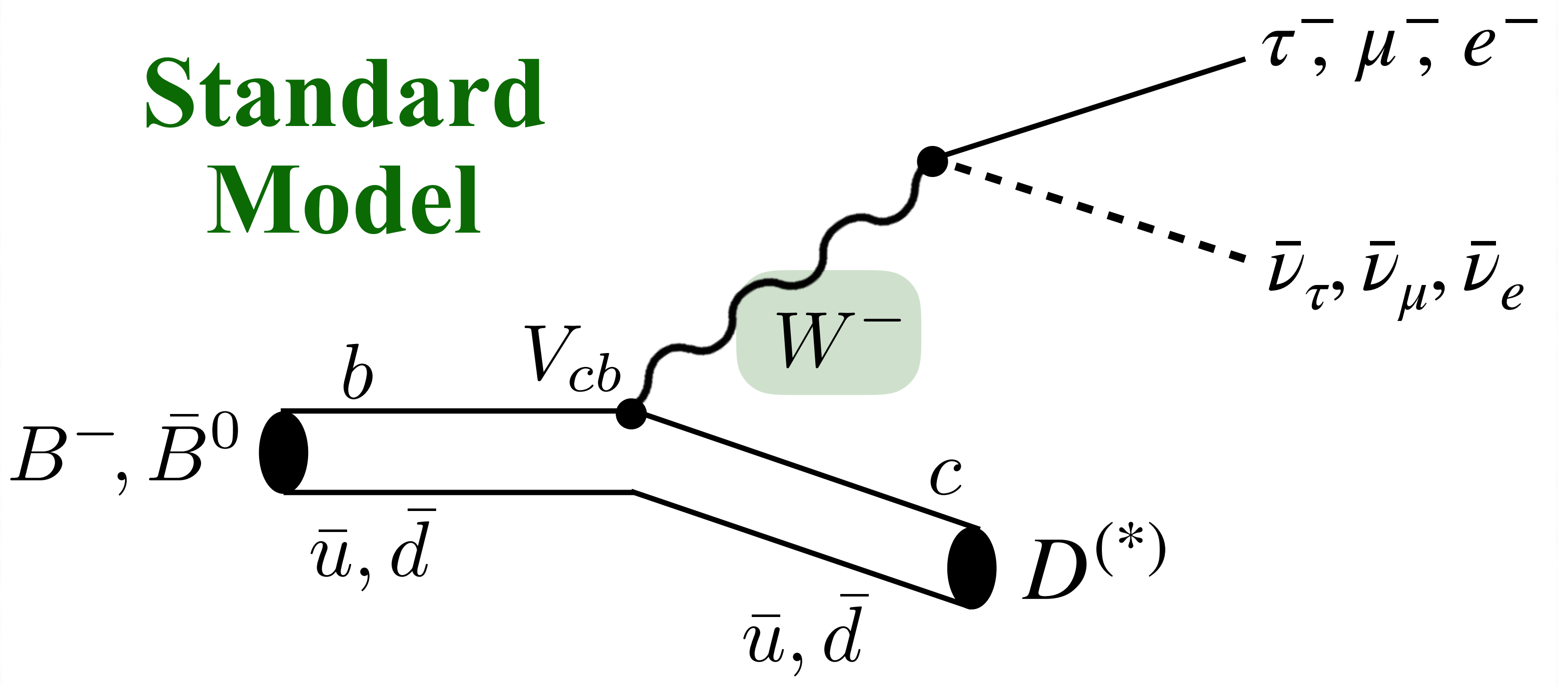


Prospects for charged LUV at LHCb

Lepton universality

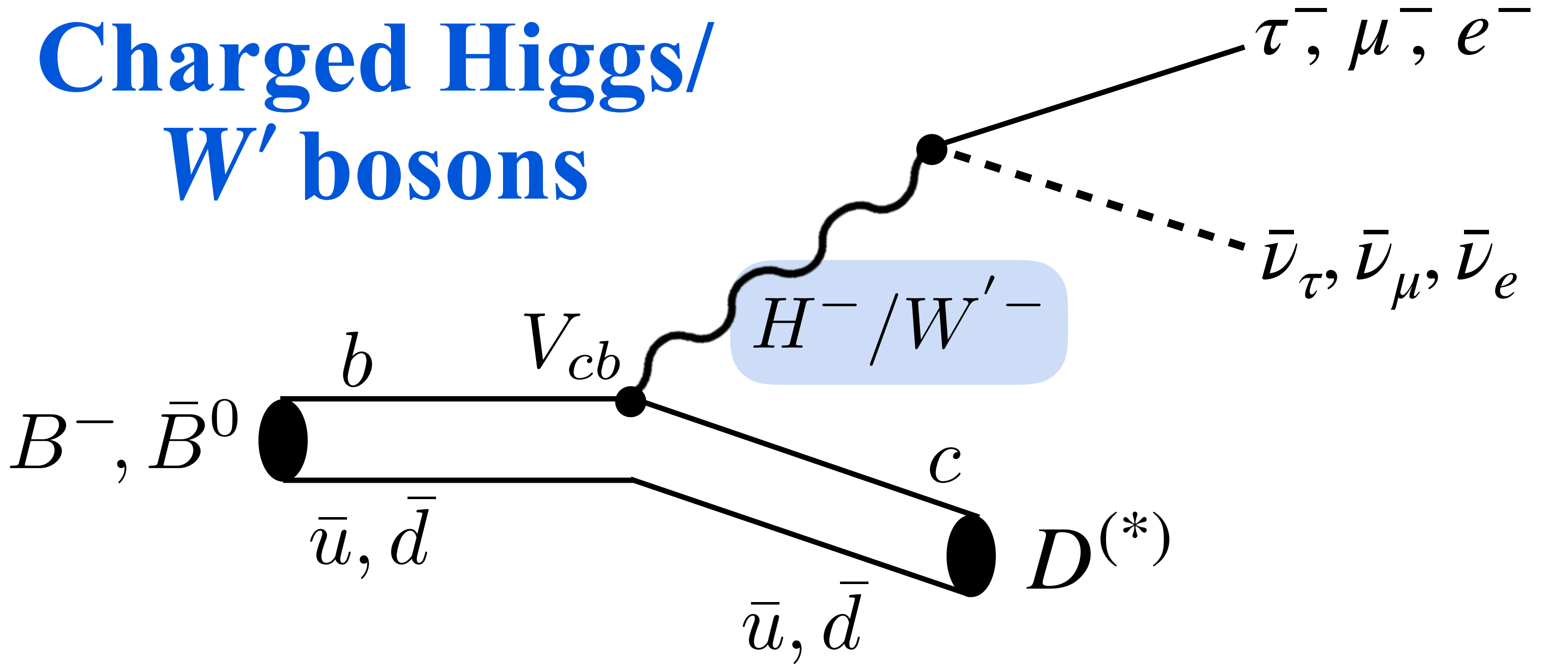
Fundamental assumption within the SM:
The interactions of ***all charged leptons*** *(electrons, muons, and taus)* ***differ only*** *because of their* ***different masses***

Standard Model

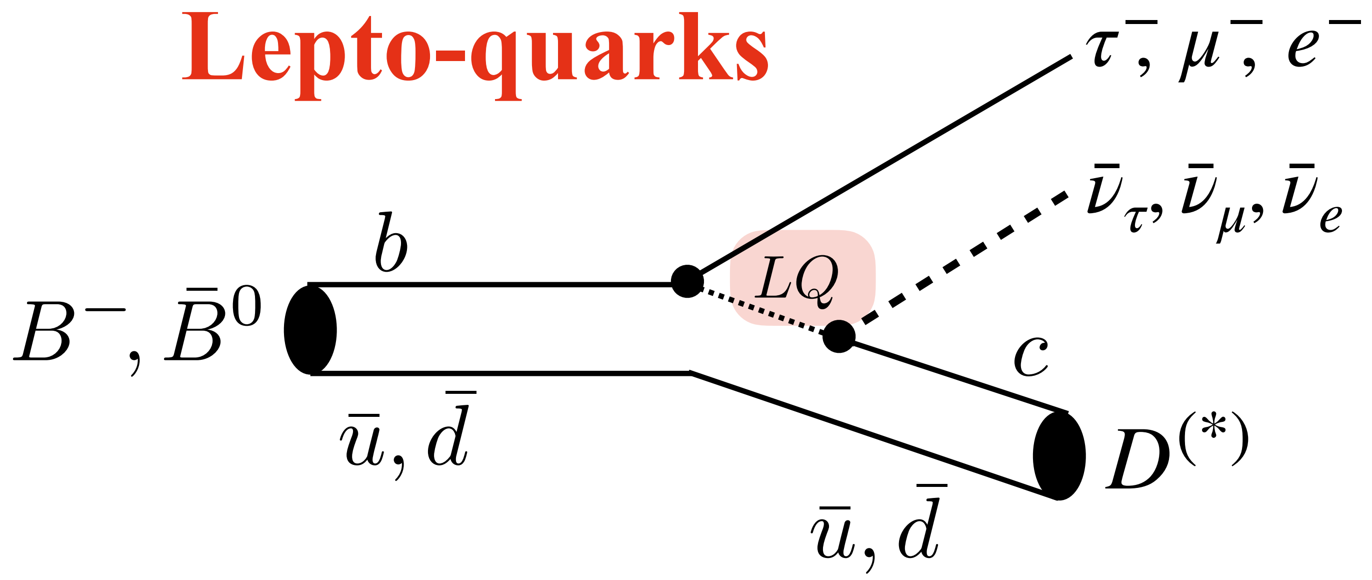


New physics could **affect** these decays **differently for e, μ, and τ**

Charged Higgs/ W' bosons



Lepto-quarks



- By **measuring ratios**, theoretical/experimental uncertainties greatly cancel

Charged LUV with $b \to c\tau\nu$

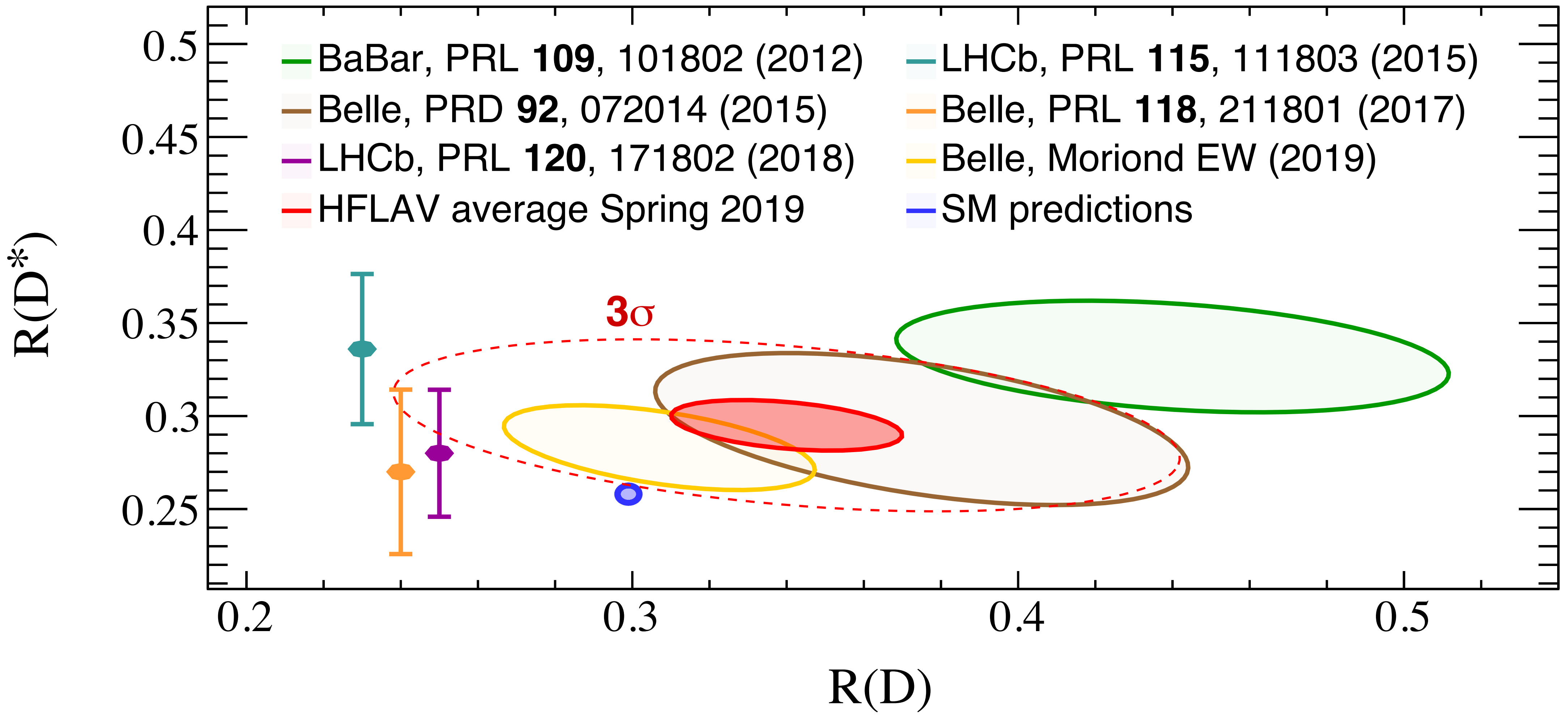
$$\mathscr{R}\left(D^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to D^{(*)}\tau\nu_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^{(*)}\mu\nu_\mu\right)}$$

$$\mathscr{R}\left(K^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to K^{(*)}\mu^+\mu^-\right)}{\mathscr{B}\left(\bar{B} \to K^{(*)}e^+e^-\right)}$$

Neutral LUV with $b \to s\ell\ell$

$\mathcal{R}(D^{(*)})$ measurements

Experiment	τ decay	Tag	$\mathcal{R}(D)$	σ_{stat} [%]	σ_{syst} [%]	$\mathcal{R}(D^*)$	σ_{stat} [%]	σ_{syst} [%]	$\rho_{\text{stat}}/\rho_{\text{syst}}/\rho_{\text{tot}}$
BABAR[a]	$\mu\nu\nu$	Had.	$0.440 \pm 0.058 \pm 0.042$	13.1	9.6	$0.332 \pm 0.024 \pm 0.018$	7.1	5.6	$-0.45/-0.07/-0.31$
Belle[b]	$\mu\nu\nu$	Semil.	$0.307 \pm 0.037 \pm 0.016$	12.1	5.2	$0.283 \pm 0.018 \pm 0.014$	6.4	4.9	$-0.53/-0.51/-0.51$
Belle[c]	$\mu\nu\nu$	Had.	$0.375 \pm 0.064 \pm 0.026$	17.1	7.1	$0.293 \pm 0.038 \pm 0.015$	13.0	5.2	$-0.56/-0.11/-0.50$
Belle[d]	$\pi\nu$	Had.	–	–	–	$0.270 \pm 0.035^{+0.028}_{-0.025}$	13.0	$^{+10.3}_{-9.3}$	–
LHCb[e]	$\pi\pi\pi\nu$	–	–	–	–	$0.280 \pm 0.018 \pm 0.029$	6.4	10.4	–
LHCb[f]	$\mu\nu\nu$	–	–	–	–	$0.336 \pm 0.027 \pm 0.030$	8.0	8.9	–
Average[g]	–	–	$\mathbf{0.340 \pm 0.027 \pm 0.013}$	**7.9**	**3.8**	$\mathbf{0.295 \pm 0.011 \pm 0.008}$	**3.7**	**2.7**	$\mathbf{-0.39/-0.34/-0.38}$



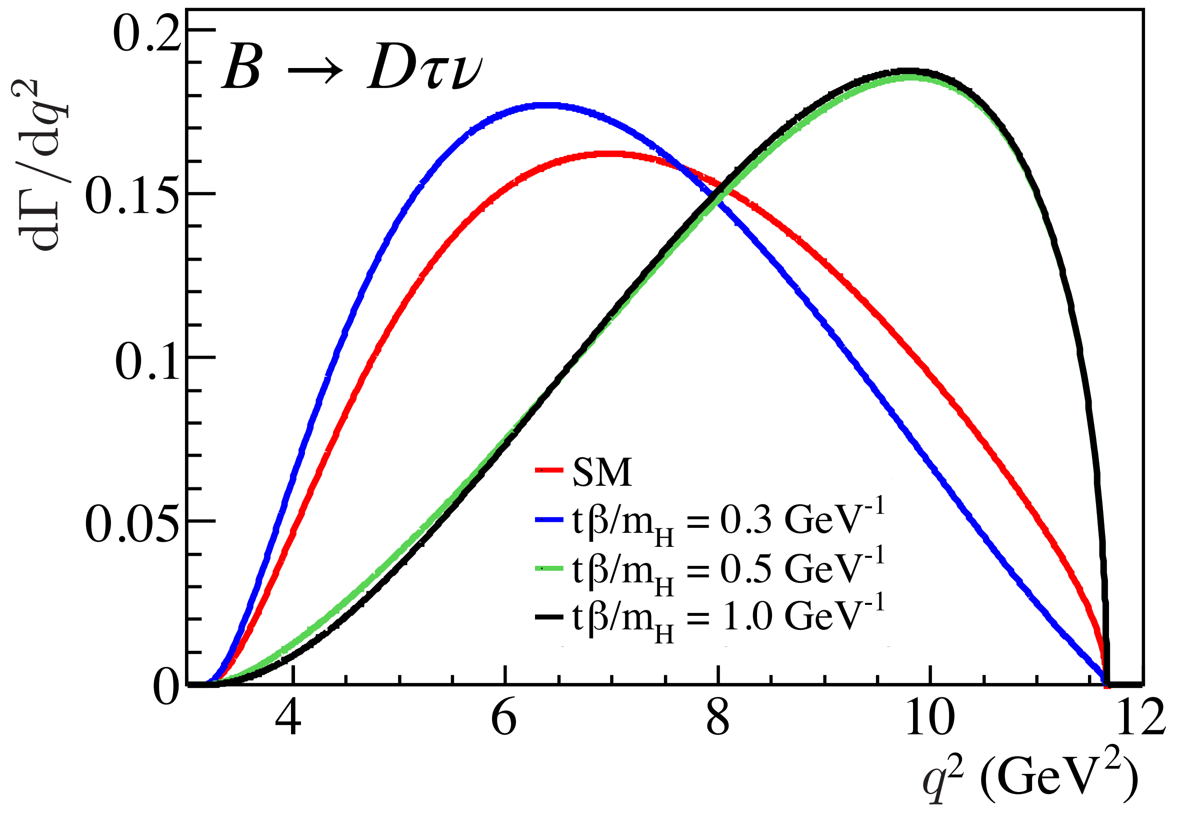
- **Significant deviation** in $\mathcal{R}(D^{(*)})$ from SM
  - ➡ Measurements from BaBar, Belle, and LHCb
- Is **LHCb systematics limited** already?
  - ➡ **No!** Let's see how

Characterizing an anomaly

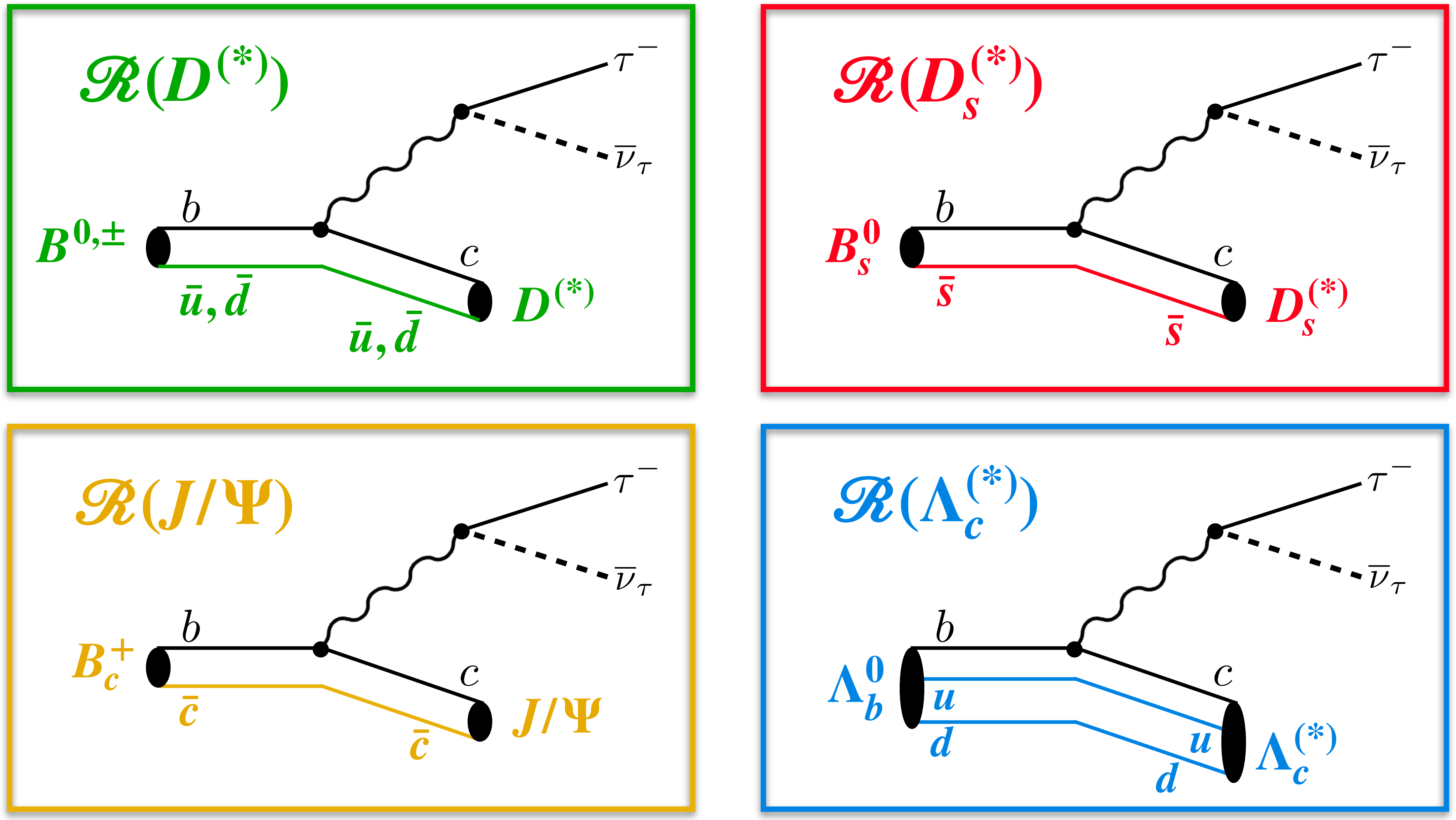
- Even a **5σ** on $\mathscr{R}(D^{(*)})$ **would not be sufficient** to **convince** ourselves of **NP**
  - **Indirect measurement** with **broad signal distributions** due to multiple ν in final state
- It will be important to have
  - Confirmation of **decay rate anomalies** by **independent experiments**
  - Confirmation of **decay rate anomalies** in **different decays**
  - Characterization of anomalies in **kinematic distributions**

q^2 is the invariant mass of the τν system

MFS "Evidence for an excess of $B \to D^{*+}\tau\nu$ decays" Dissertation, Stanford University (2012)



LHCb has a unique ability to study $b \to c\tau\nu$ transitions because $b\bar{b}$ production at the LHC hadronizes into all species of b-hadrons

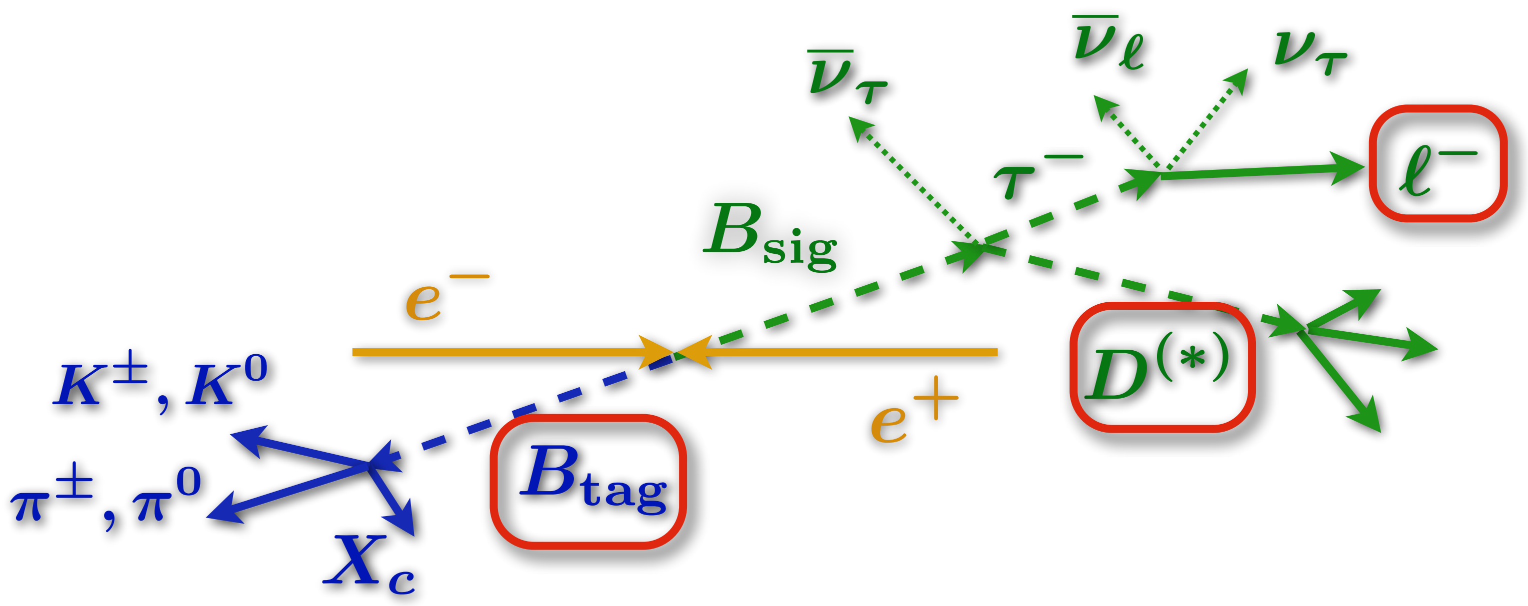


LHCb already published first non-$\mathscr{R}(D^{(*)})$ measurement

$$\mathscr{R}(J/\Psi) = 0.71 \pm 0.17 \pm 0.18$$

Measuring $\mathscr{R}(D^{(*)})$ in B-factories

- Reconstruct full event with B-tagging



Reconstructed particles

Same visible final state for signal/normalization when $\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell$ used

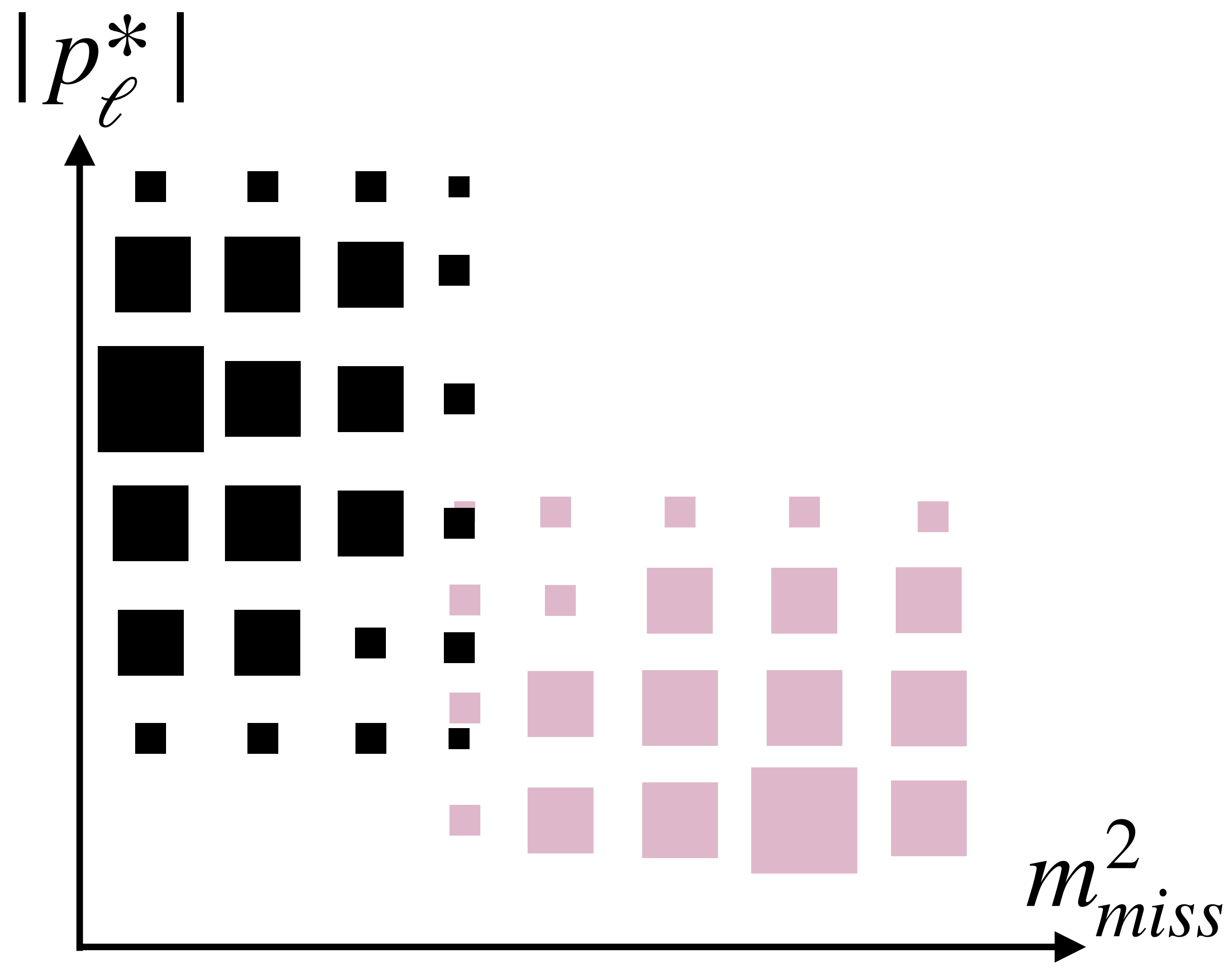
$$m^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}} - p_\ell\right)^2$$

Normalization (1 neutrino)

$$B \to D^{(*)} \ell \nu$$

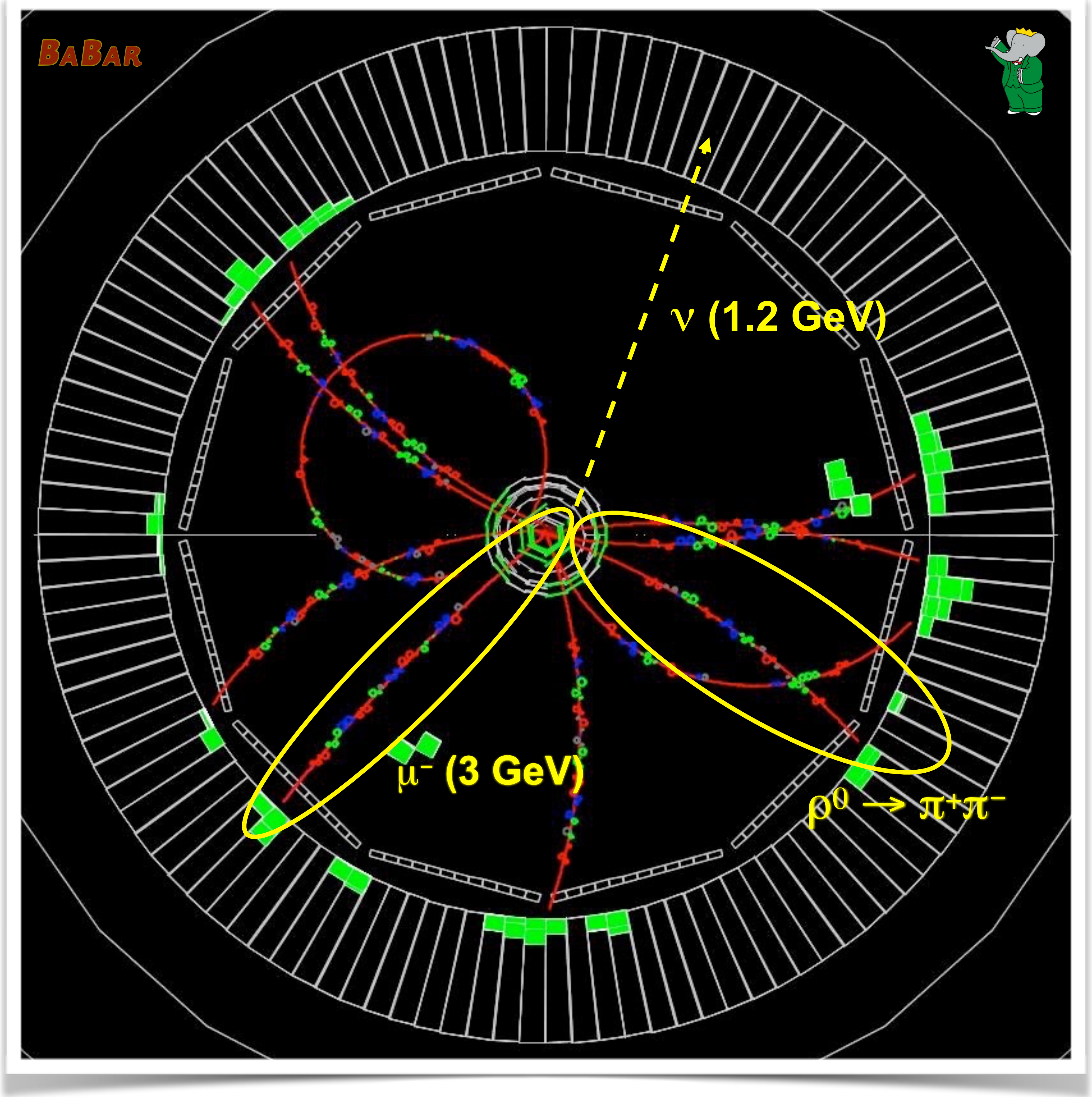
Signal (3 neutrinos)

$$B \to D^{(*)} \tau \left(\to \ell \nu \bar{\nu} \right) \bar{\nu}$$



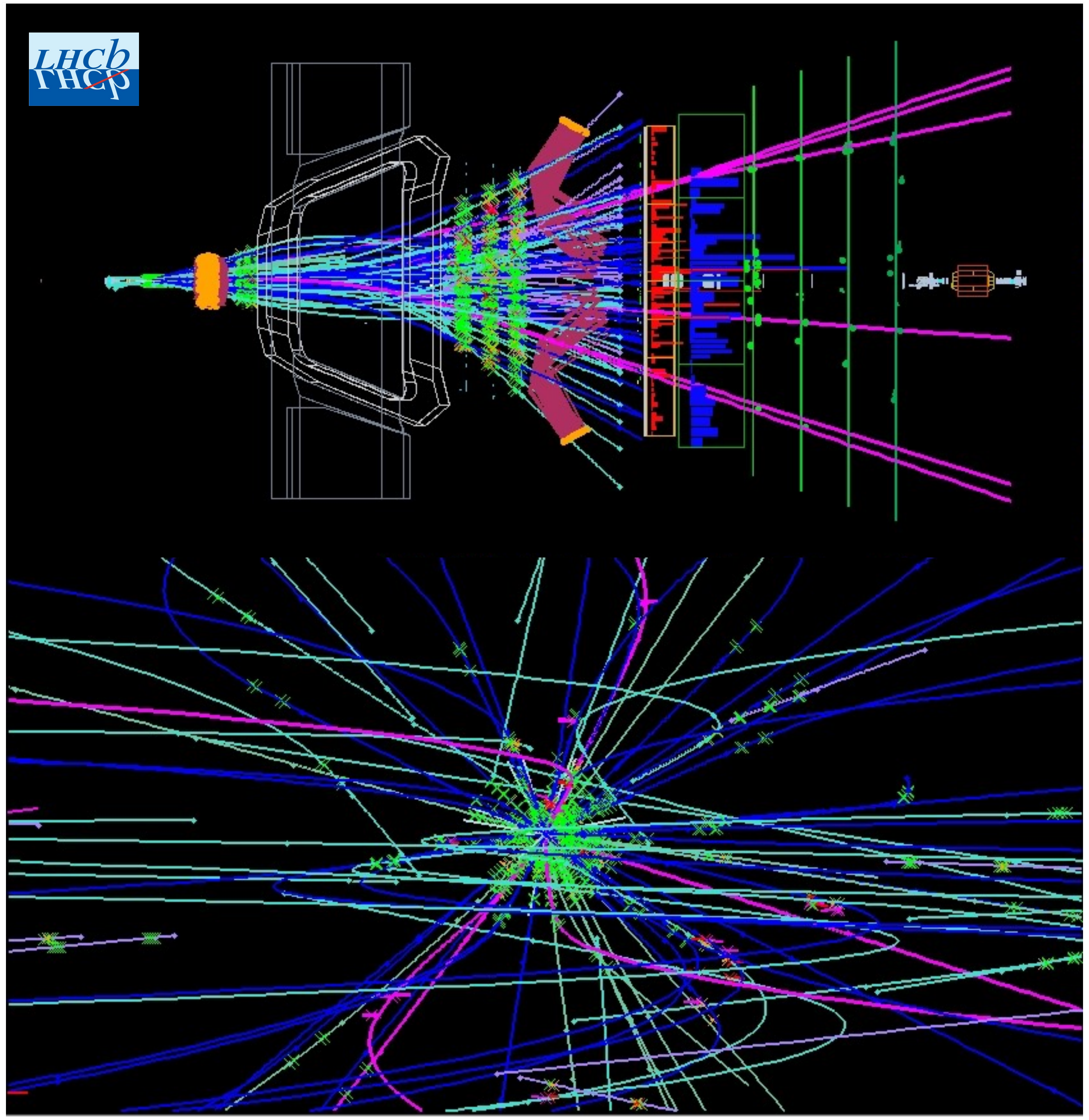
$e^+e^- \to B^+_{tag} B^-_{sig}$

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

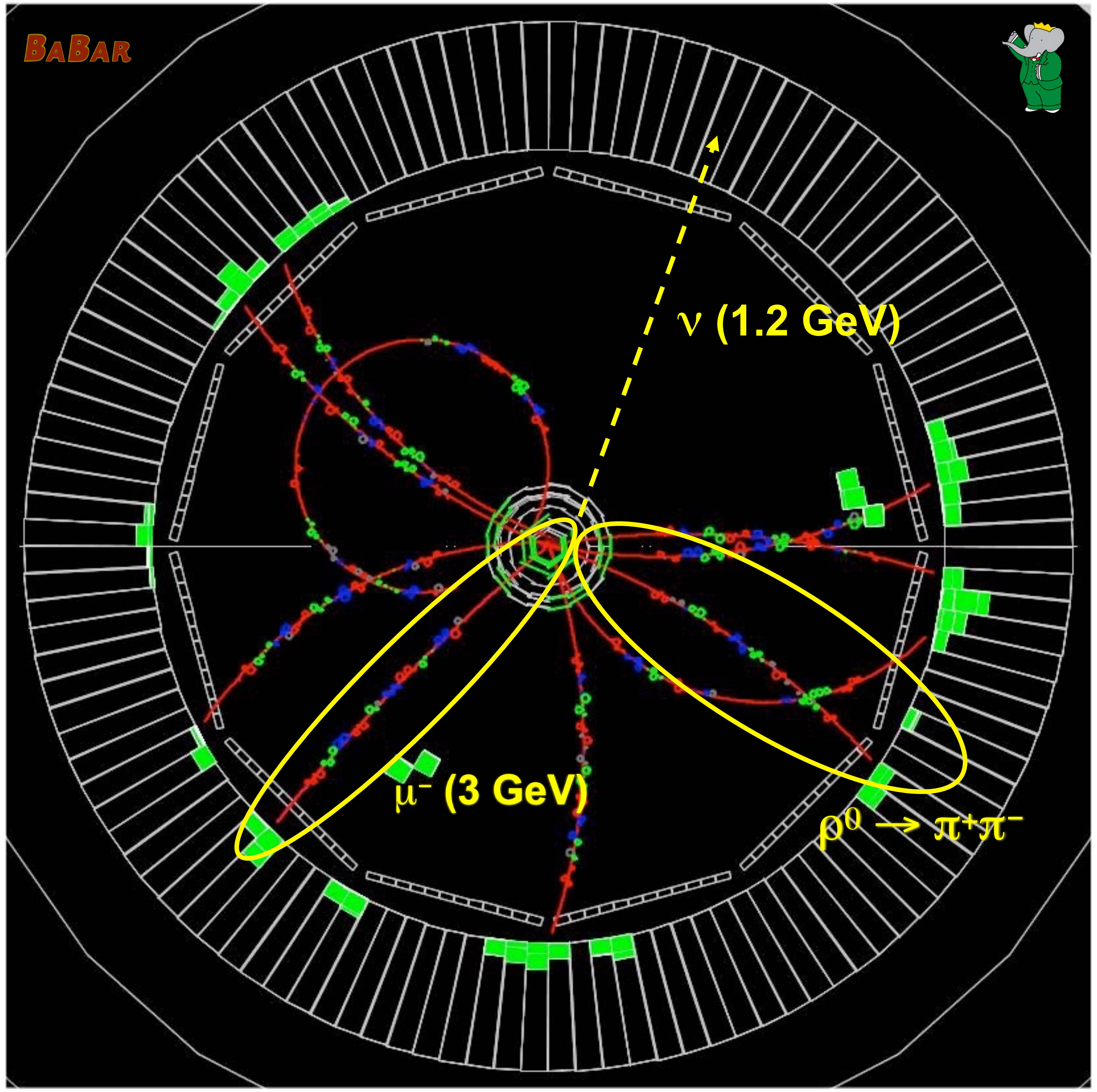


LHCb environment is slightly busier

$$pp \to X_b B_s^0 X$$
$$B_s^0 \to \mu^+\mu^-$$



$$e^+e^- \to B^+_{\mathrm{tag}} B^-_{\mathrm{sig}}$$
$$B^- \to \rho^0 \mu^- \nu_\mu$$



B-factory advantages

Lower backgrounds

Collision momentum known

Neutrals and electron reco

LHCb advantages

Higher statistics

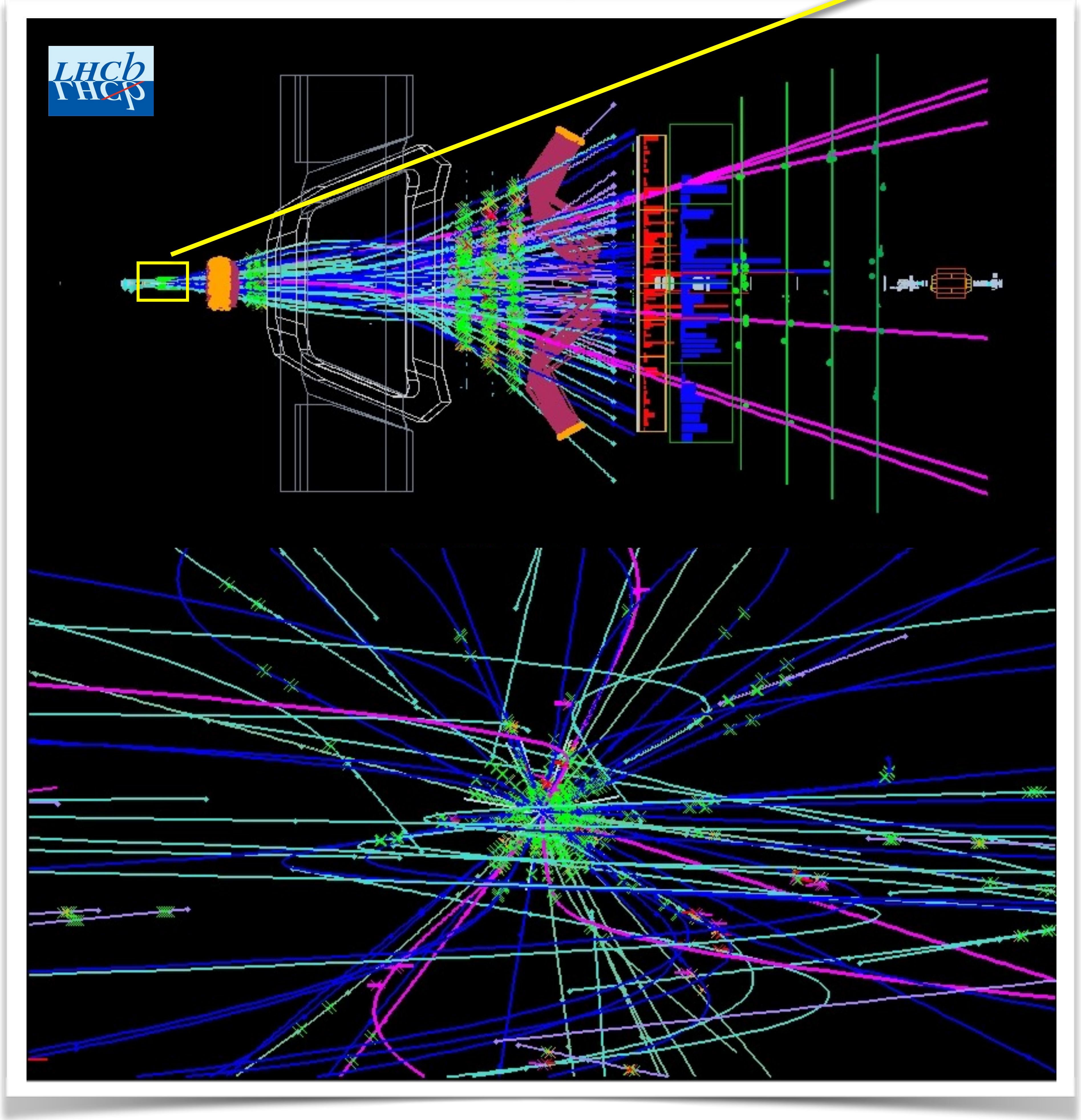
All b-hadron species

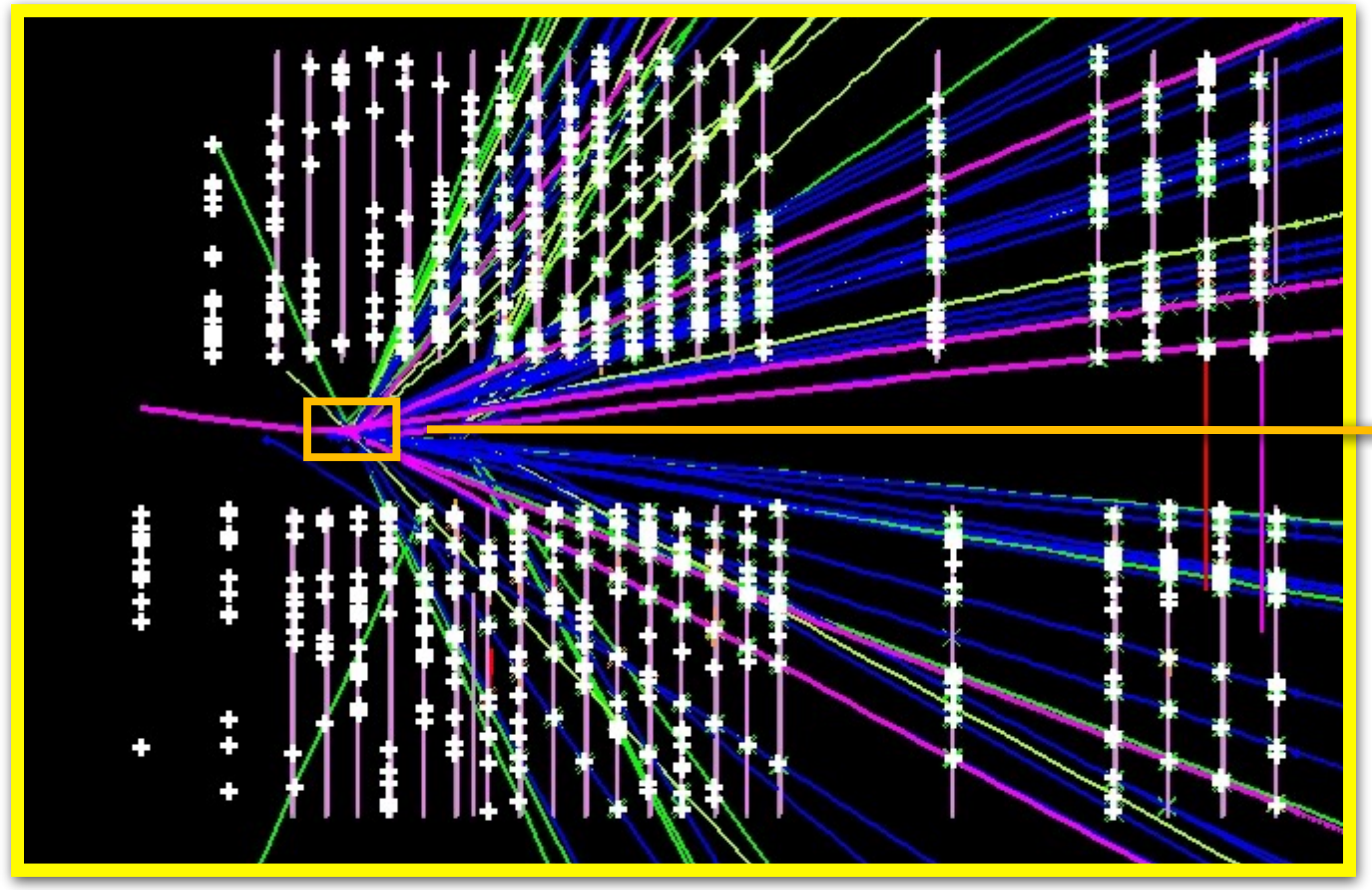
Larger boost

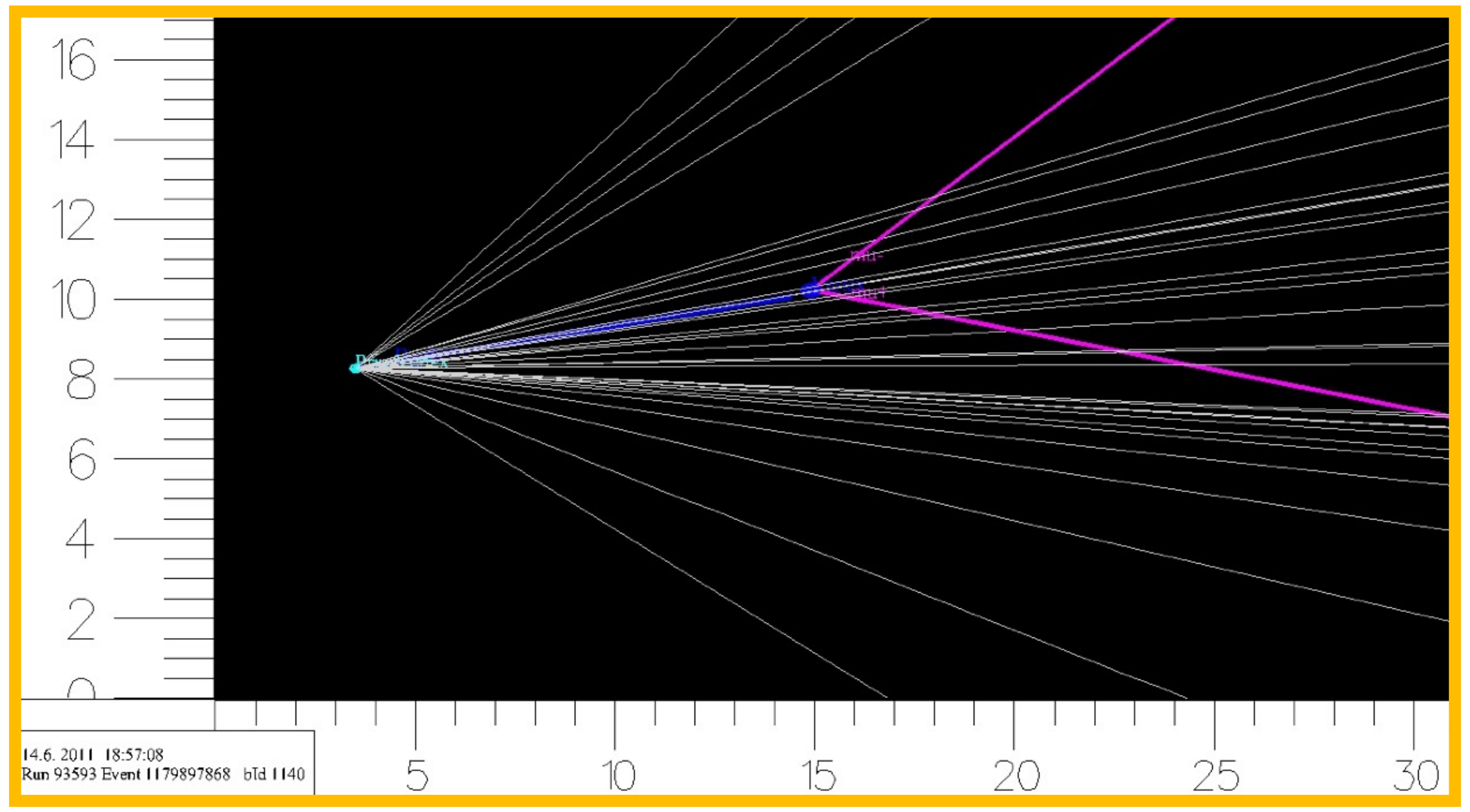
Vertexing and isolation

$pp \to X_b B_s^0 X$

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







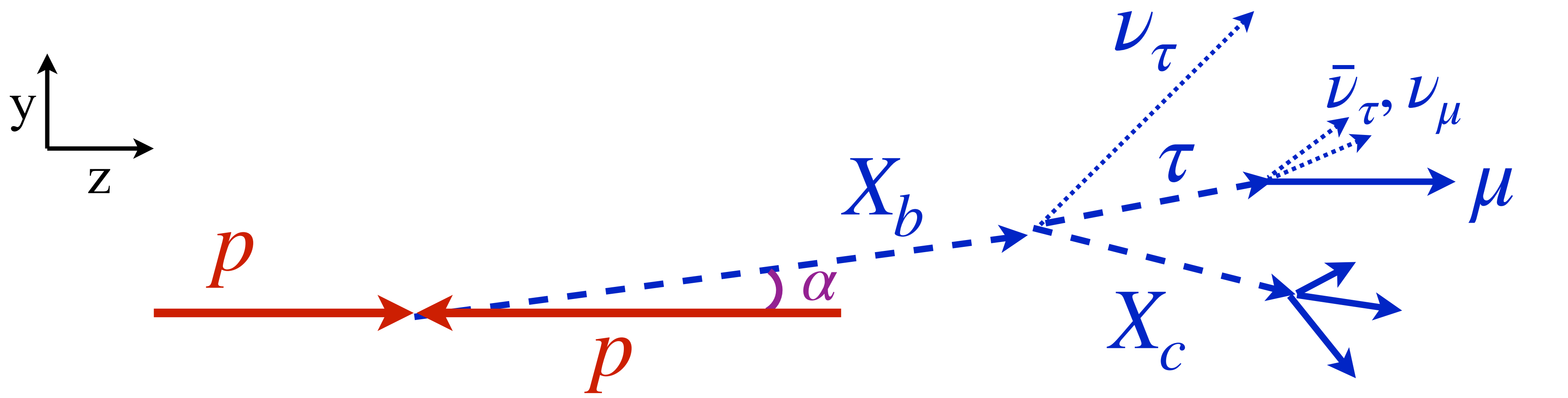
- Superb vertexing by VELO (in vacuum)
  - Only 8.2 mm from IP, 300 μm of material
  - Reduced to 5.1 mm from IP, 150 μm of material in upgrade
- **B mesons fly several cm** thanks to large boost
- Developed **isolation BDT for** $\mathscr{R}(D^*)$ measurement
  - Assign probability of track coming from B vertex
  - IPX^2_{PV}, IPX^2_{B}, p_T, track angle, refitted B vertex with track

Rest Frame Approximation (RFA) for muonic τ

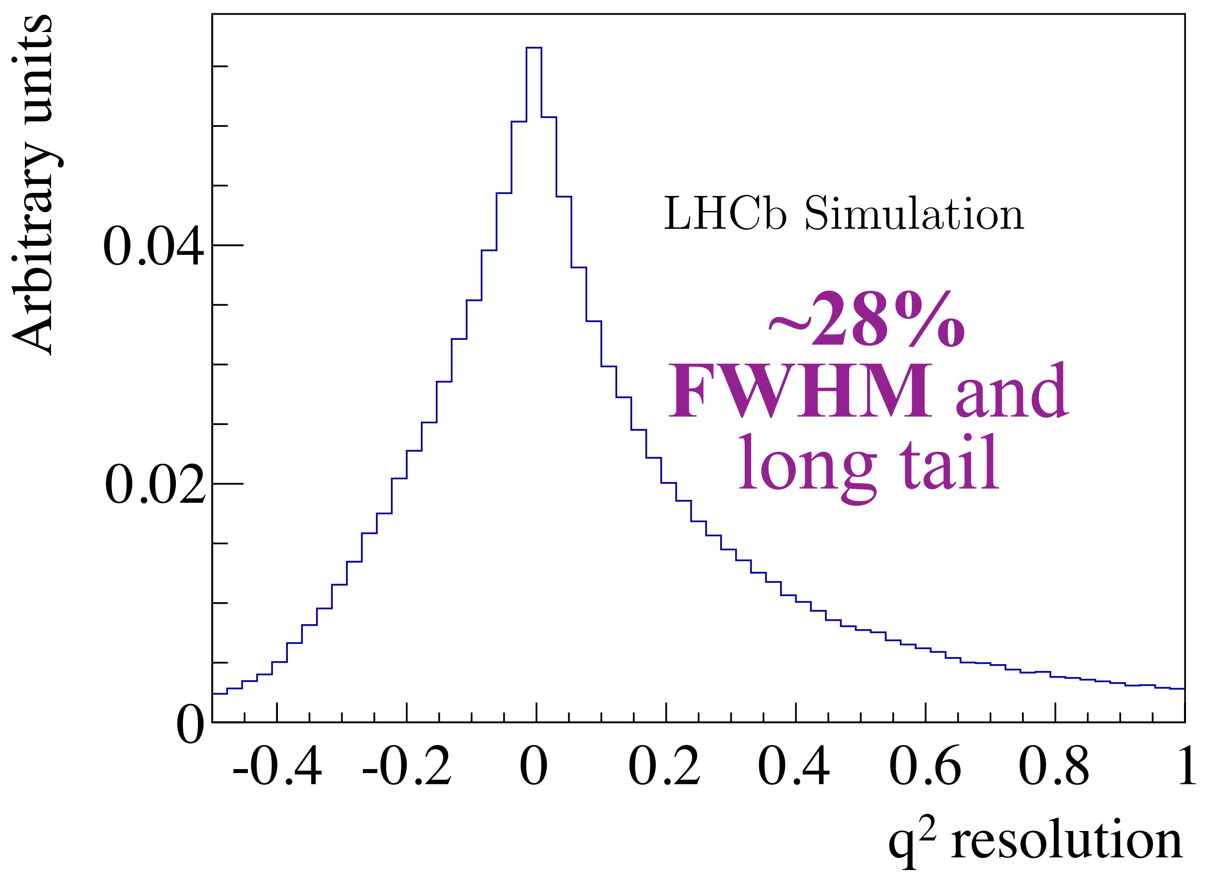
- **B-factories** effectively reconstruct $p_{B_{sig}}$ with **B-tagging**
  - $p_{B_{sig}} = p_{e^+e^-} - p_{B_{tag}}$ allows you calculate $p_{miss} = p_{B_{sig}} - p_{D^{(*)}} - p_\ell$

- **LHCb** estimates p_{X_b} with **RFA**
  - Good approximation thanks to large X_b boost

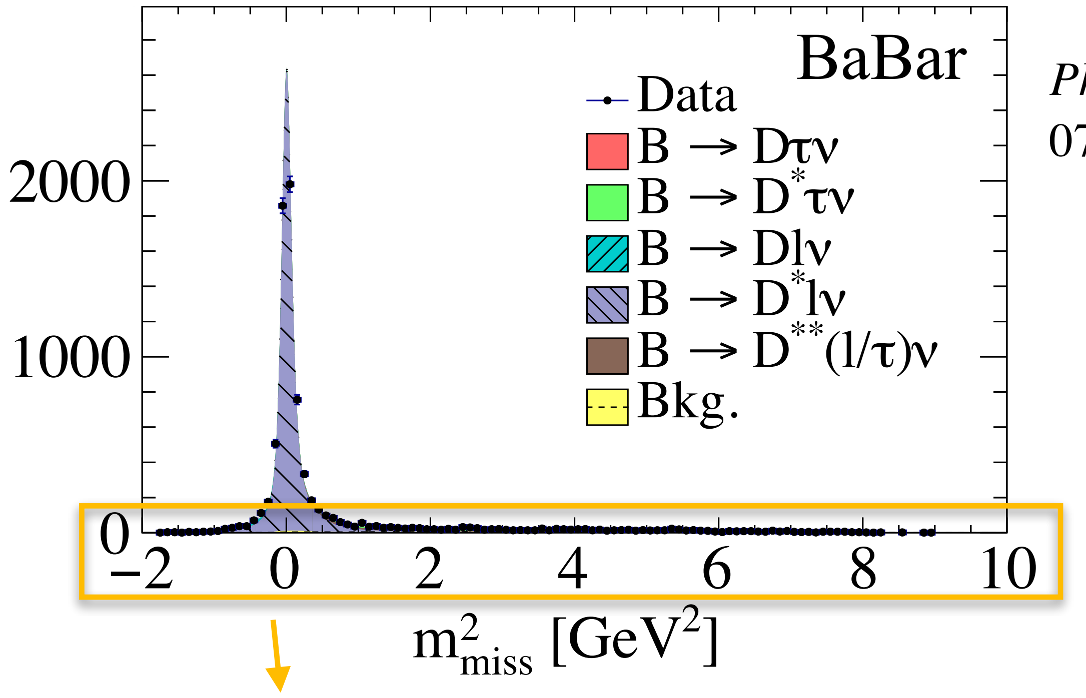
$$|p_{B_{sig}}| = \frac{m_B}{m_{\mu X_c}} \left(p_{\mu X_c}\right)_z \sqrt{1 + \tan^2 \alpha}$$

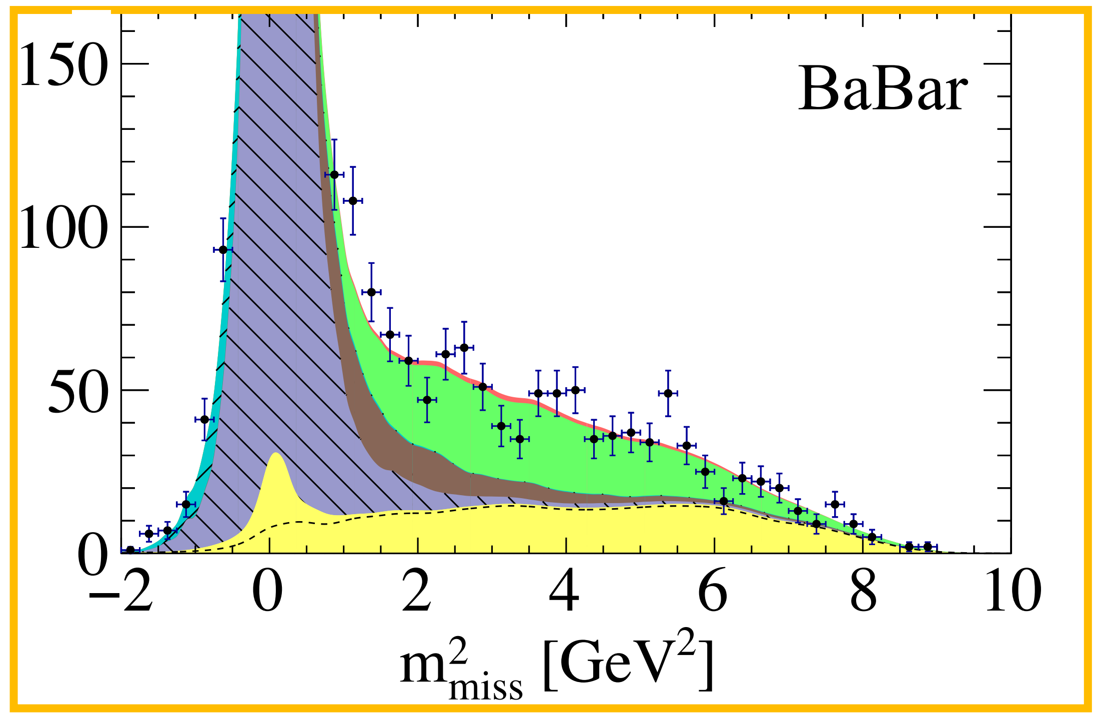


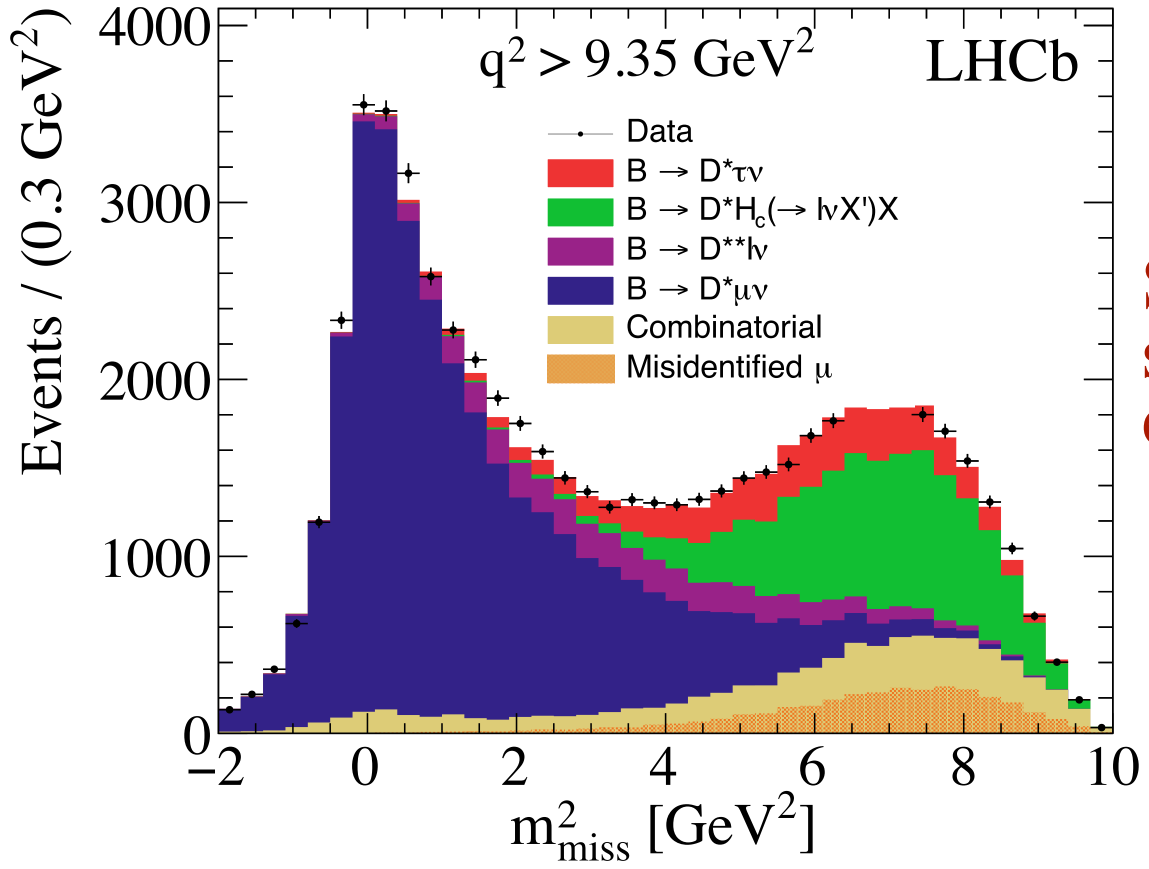
Phys. Rev. Lett. **115**, 111803 (2015)



Phys. Rev. D **88**, 072012 (2013)



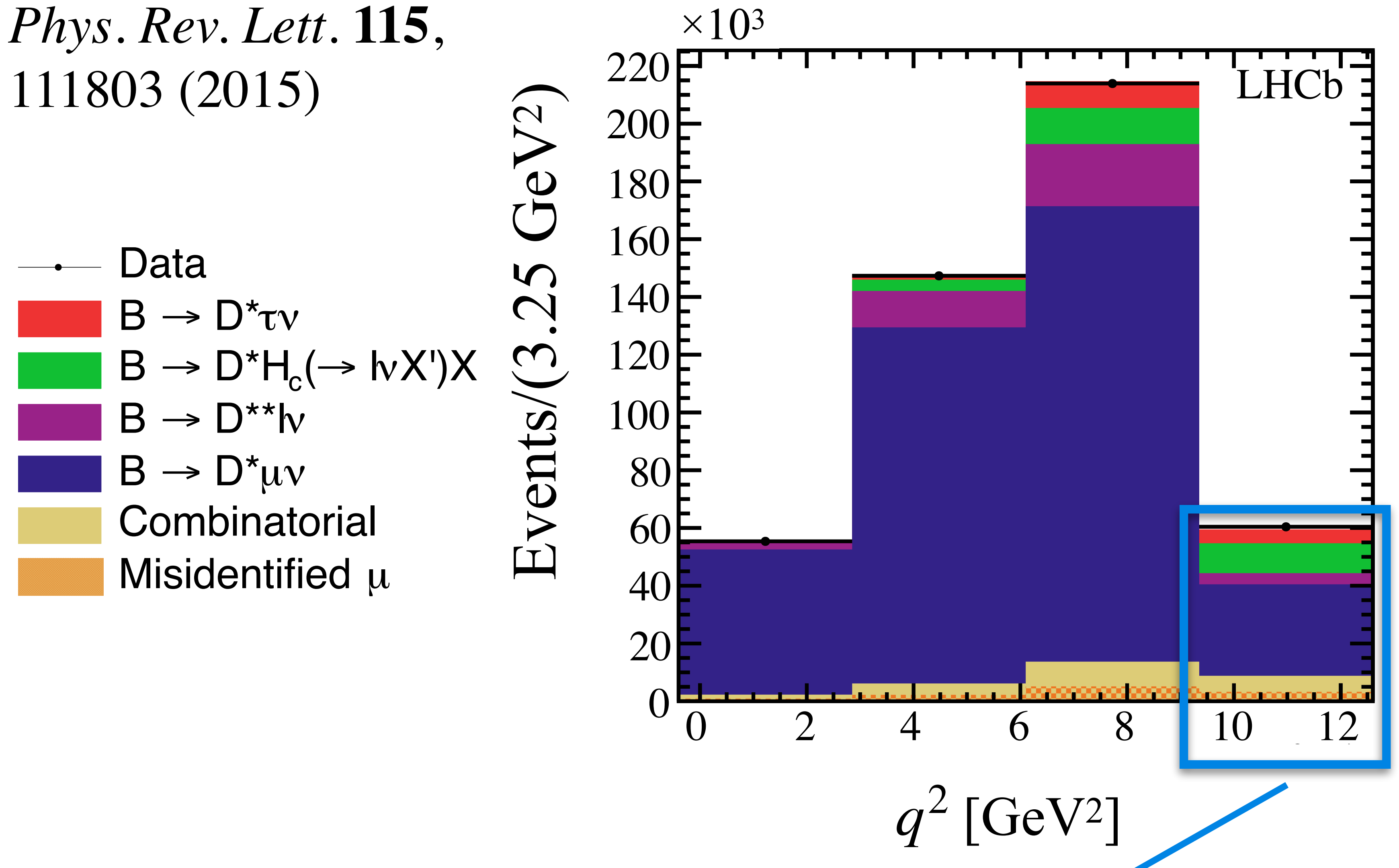




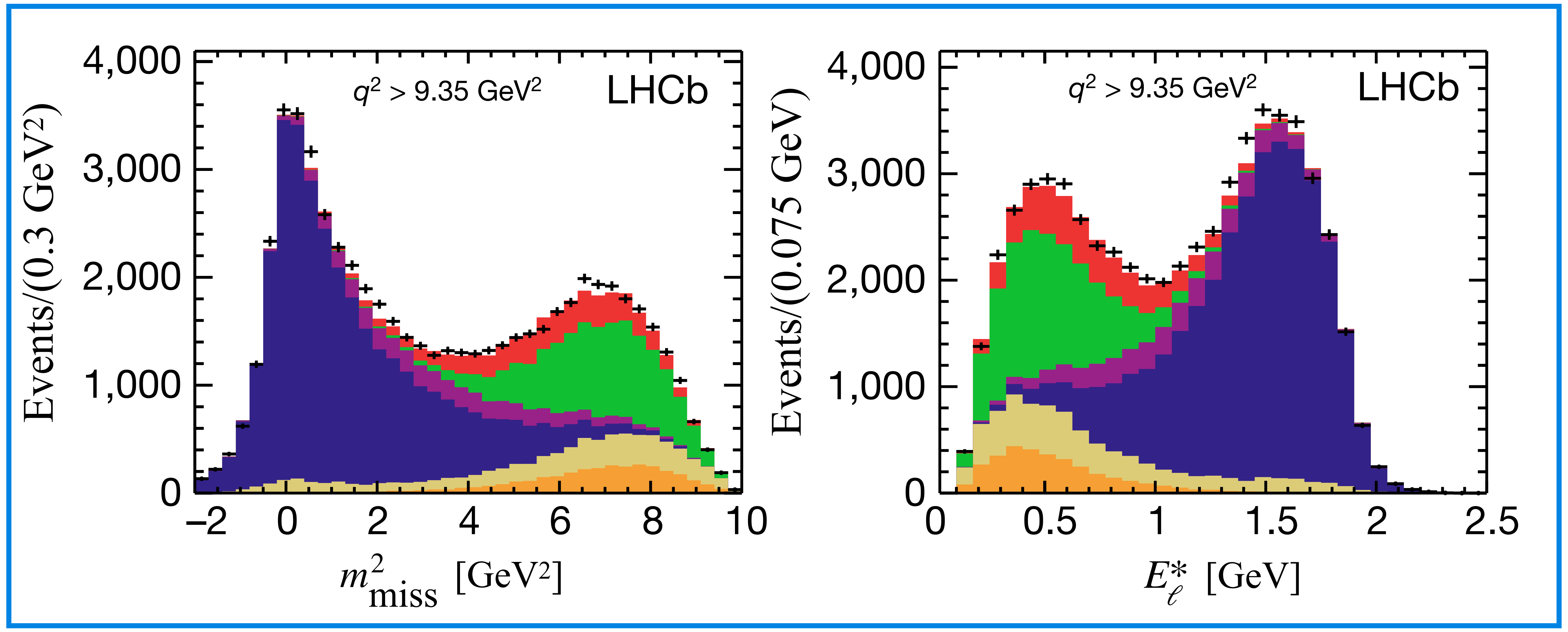
Sufficient separation if enough stats

Muonic $\mathcal{R}(D^{*+})$

Phys. Rev. Lett. **115**, 111803 (2015)



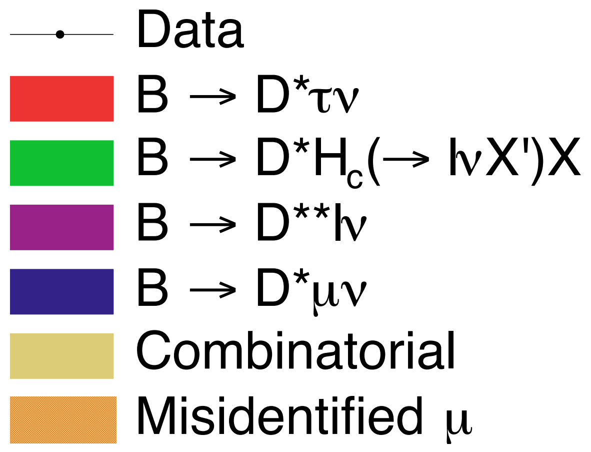
- Proof of concept measurement in 2015
  - ➡ Not clear if possible beforehand!
- 3D simultaneous fit to q^2, m^2_{miss}, and E^*_μ

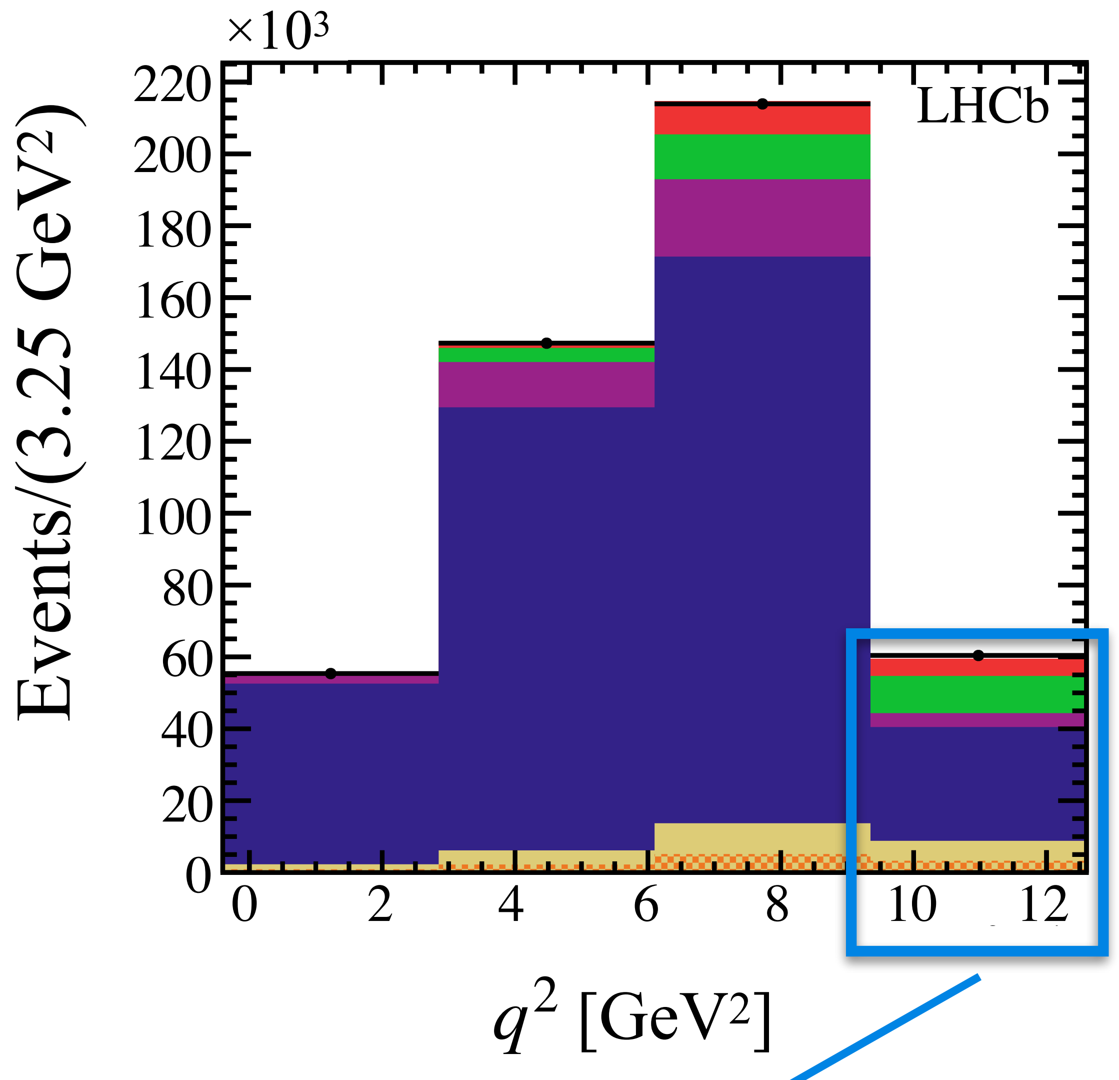


$$\mathcal{R}(D^*) = \frac{\mathcal{B}\left(\bar{B} \to D^*\tau\nu_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^*\mu\nu_\mu\right)}$$

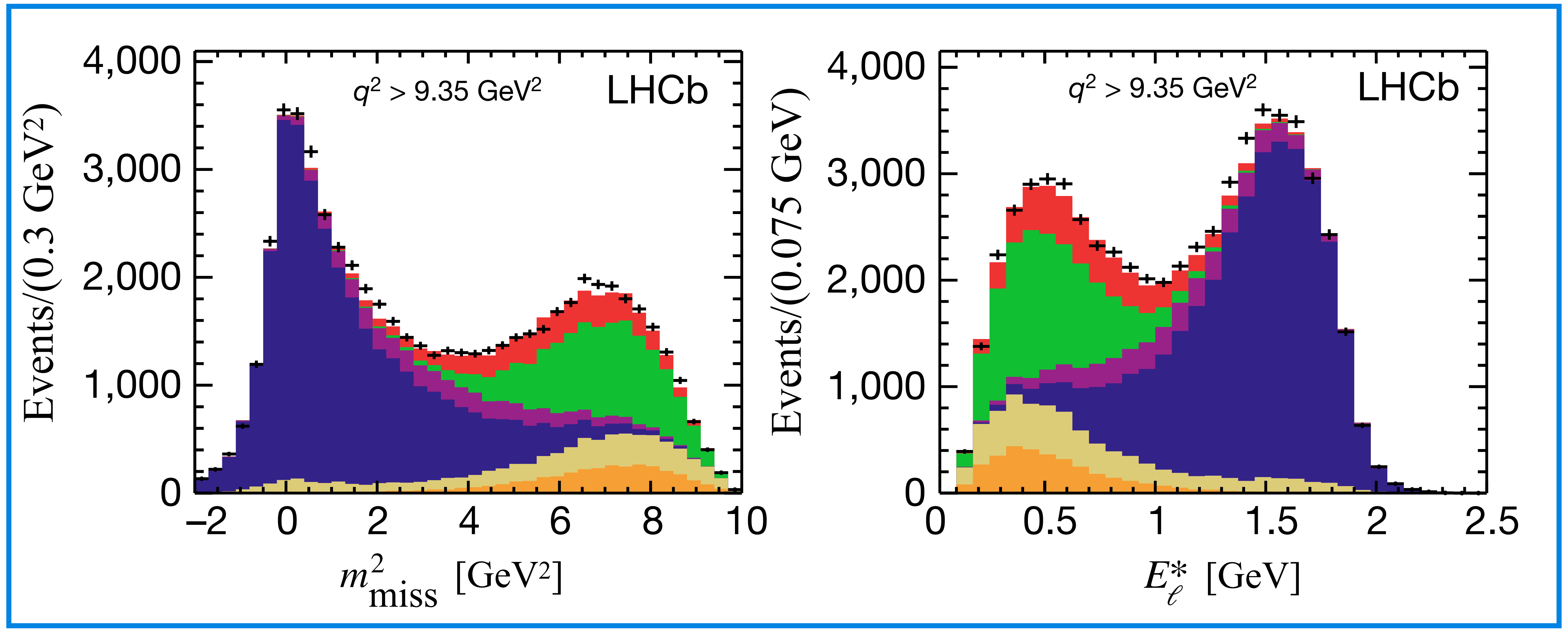
Muonic $\mathscr{R}(D^{*+})$ control samples

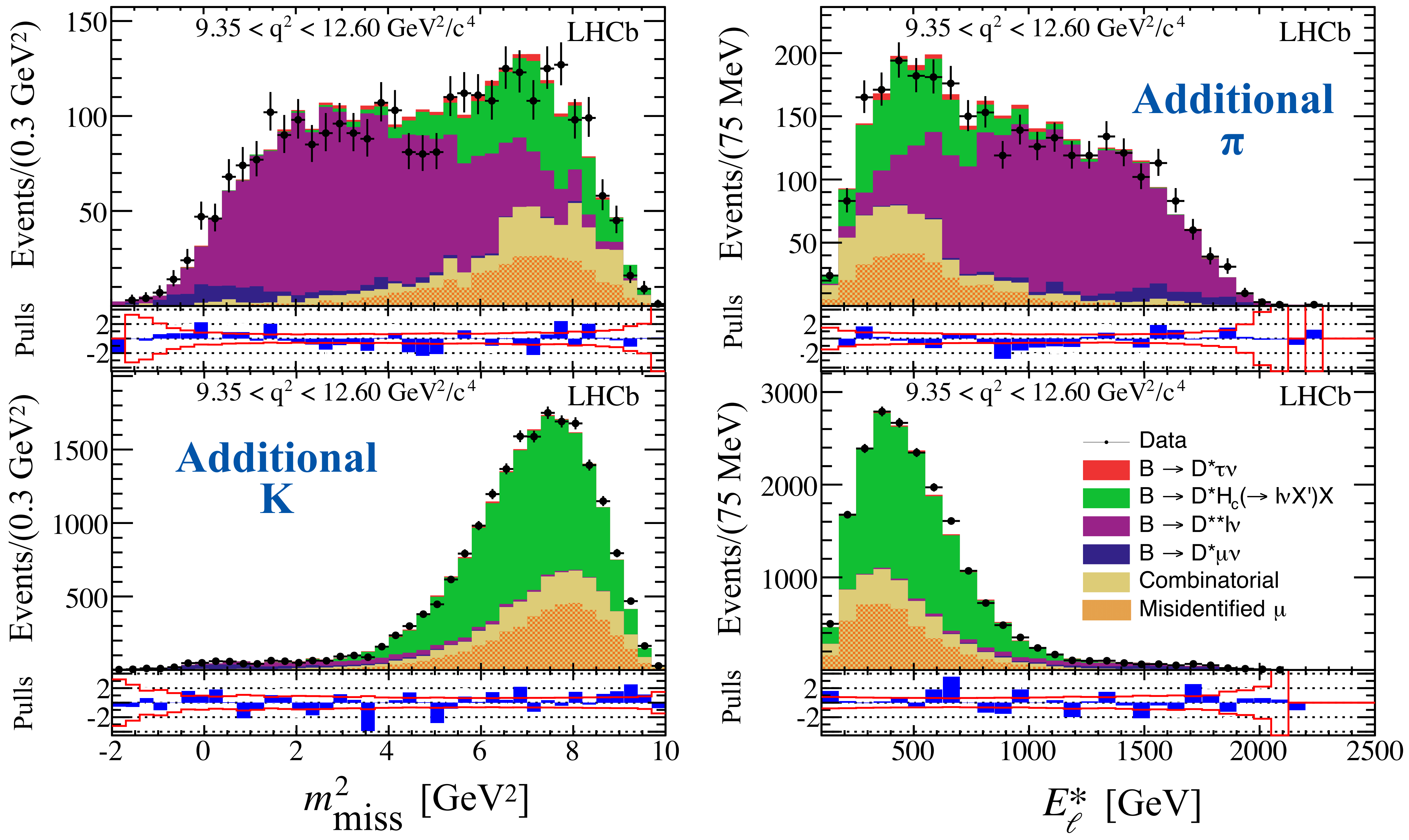
Phys. Rev. Lett. **115**, 111803 (2015)





- **Control samples instrumental** to determine bkgs.
  - Additional K: $B \to D^* H_c X$
  - Additional π: $B \to D^{**}(\to D^*\pi)\ell\nu$
  - Additional ππ: $B \to D^{**}(\to D^*\pi\pi)\ell\nu$





Muonic $\mathscr{R}(D^{*+})$ systematics

Contribution	Uncert. [%]
Simulated sample size	6.2
Misidentified μ bkg.	4.8
$\overline{B} \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ bkg.	2.1
Signal/norm. FFs	1.9
Hardware trigger	1.8
DD bkg.	1.5
MC/data correction	1.2
Combinatorial bkg.	0.9
PID	0.9
Total systematic	**8.9**
Total statistical	**8.0**
Total	**12.0**

FastSim gives a **factor of 10×**, which **only covers Run 2**
Hopefully will scale with data, but it will require **faster FastSim**, **faster hardware progress, or more restrictive generator cuts**

Data driven procedure developed for $\mathscr{R}(J/\Psi)$ **will** reduce it to **less than 2%** in updated measurement

Primarily data driven

Disappears in Run 3

Primarily data driven

Primarily data driven

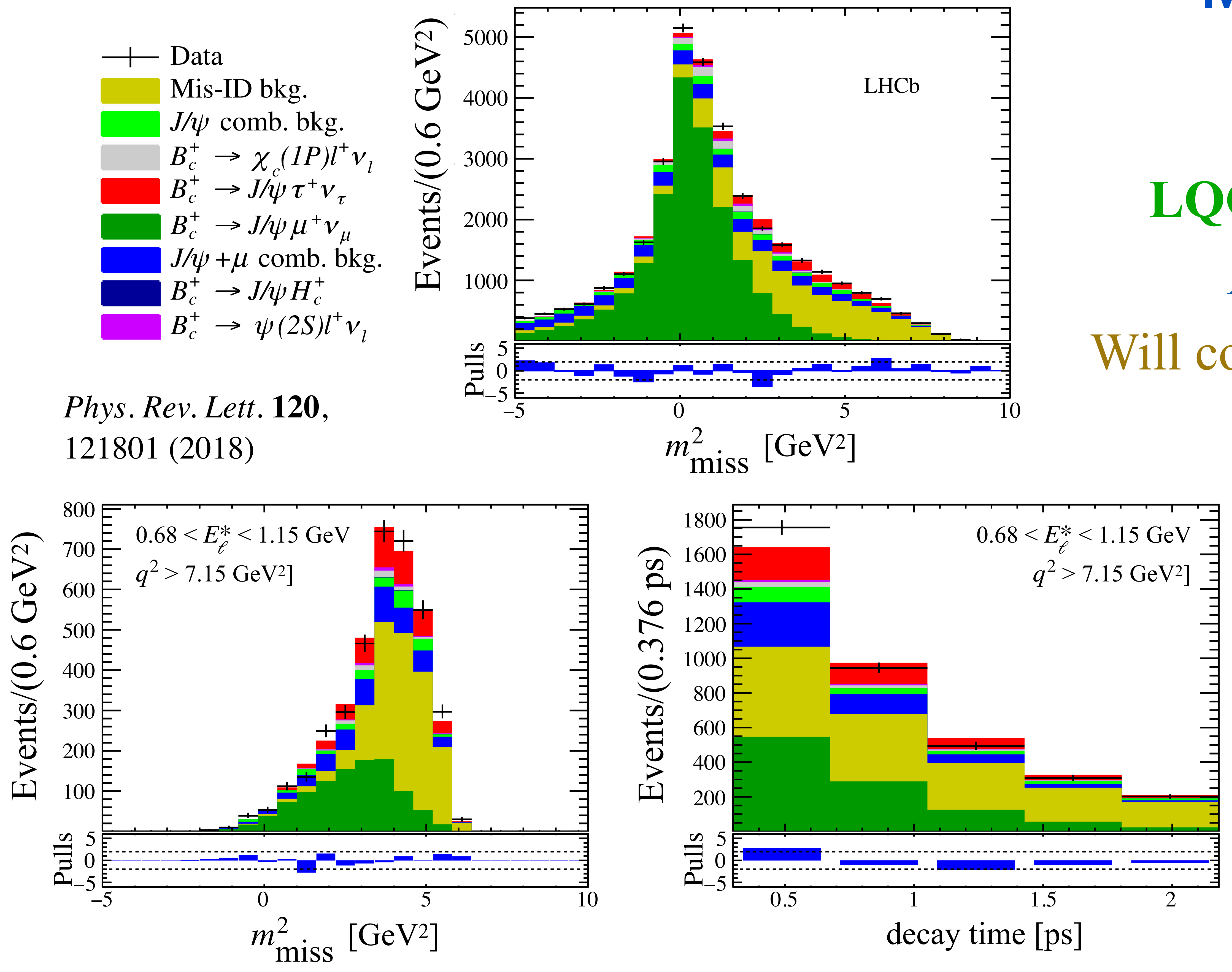
Note that only 30% of the systematic uncertainty is multiplicative, so the majority does not scale with central value

Generally, **systematic uncertainties** will **come down with data**, but there will probably be a **0.5-3% systematics floor** from the extrapolations to signal region and certain assumptions

Muonic $\mathscr{R}(J/\Psi)$

$$\mathscr{R}\left(J/\Psi\right) = \frac{\mathscr{B}\left(\bar{B}_c \to J/\Psi\tau\nu_\tau\right)}{\mathscr{B}\left(\bar{B}_c \to J/\Psi\mu\nu_\mu\right)}$$

- Very similar strategy to muonic $\mathscr{R}(D^{*+})$
  - ➡ Add **decay time** to **separate B_c from $B_{u,d}$**
  - ➡ **Main background** is **muon misID**



Phys. Rev. Lett. **120**, 121801 (2018)

Contribution	Uncert. [%]
Signal/norm. FFs	17.0
Simulated sample size	11.3
Fit model	11.2
Misidentified μ bkg.	7.9
Partial B_c bkg.	6.9
Combinatorial bkg.	6.5
$\epsilon_{\text{sig}}/\epsilon_{\text{norm}}$	0.9
Total systematic	**25.4**
Total statistical	**23.9**
Total	**34.9**

LQCD calculation already helps (Signal/norm. FFs)

Hopefully will scale with data (Simulated sample size)

Will come down with more robust fit (Fit model)

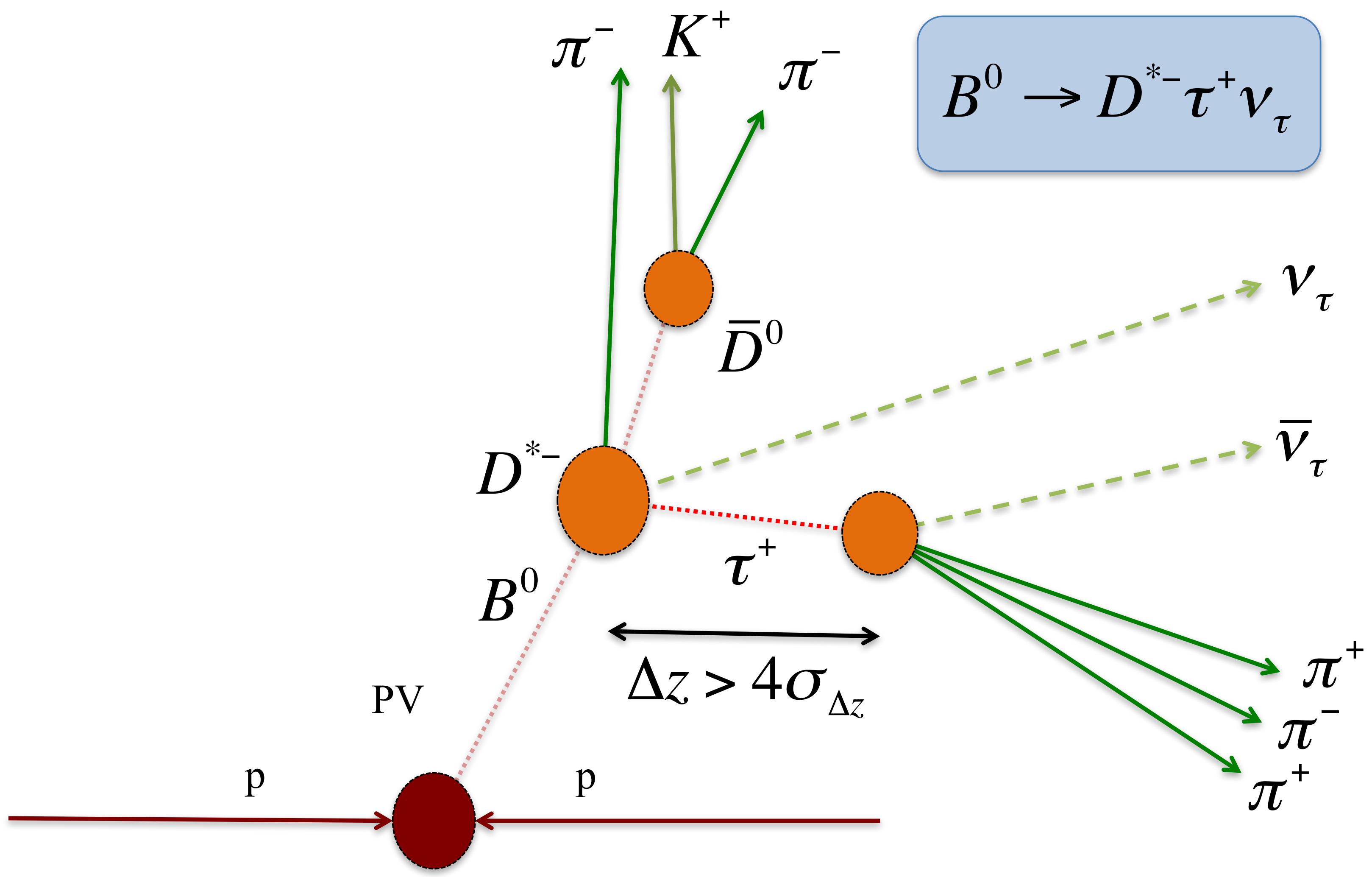
Primarily data driven (Misidentified μ bkg., Partial B_c bkg., Combinatorial bkg.)

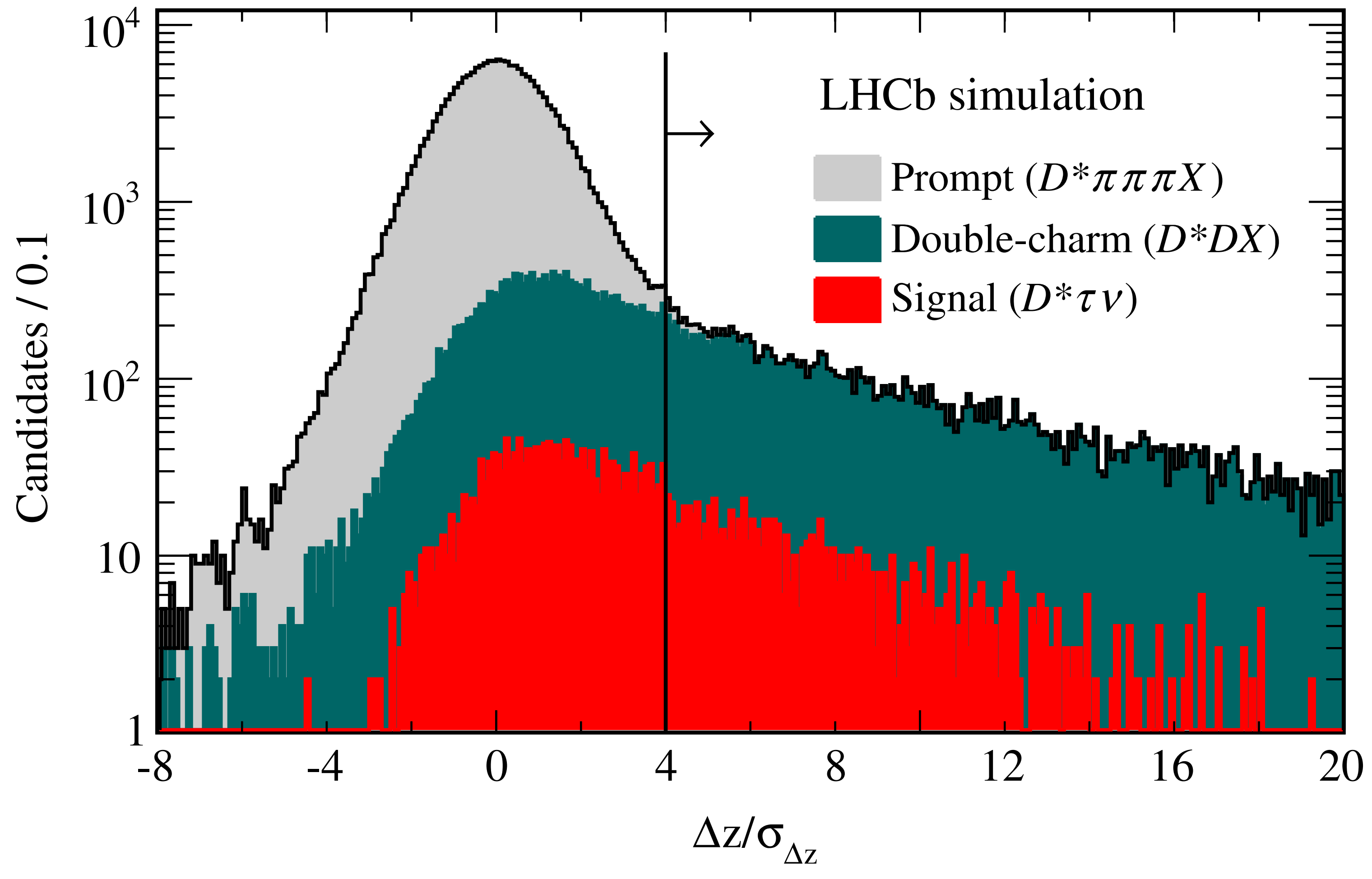
Expect a larger **1-5% floor** from difficulty of measuring FFs

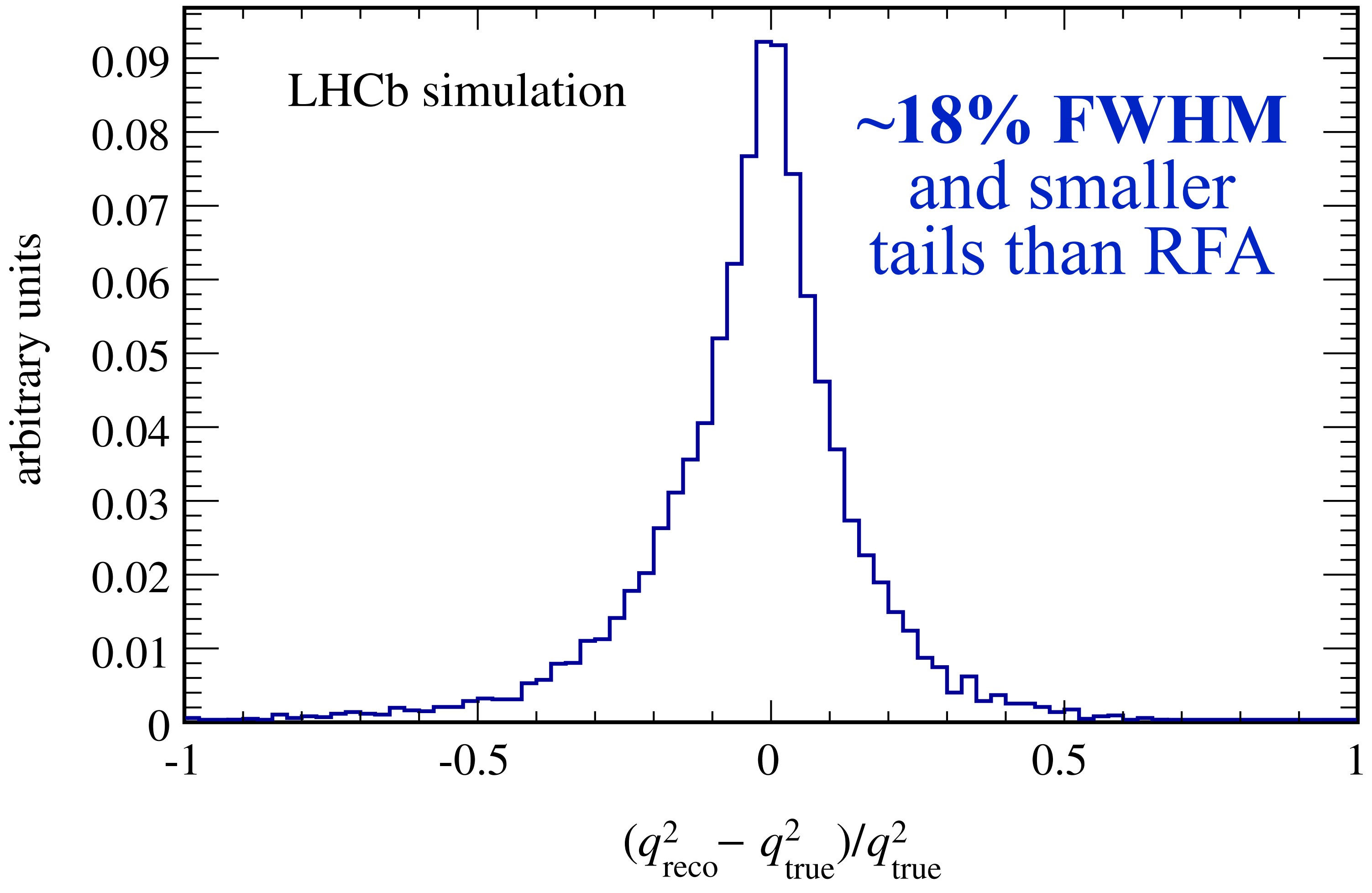
Hadronic* $\mathscr{R}(D^{*+})$

- Leverages **additional vertex** when $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ is used
  - **Main background** prompt $B \to D^*\pi\pi\pi X$ **reduced by 10⁴** with **τ flight distance**
  - **Better q^2** and **m^2_{miss} resolution** thanks to more precise determination of B momentum

Phys. Rev. D **97**, 072013 (2018)







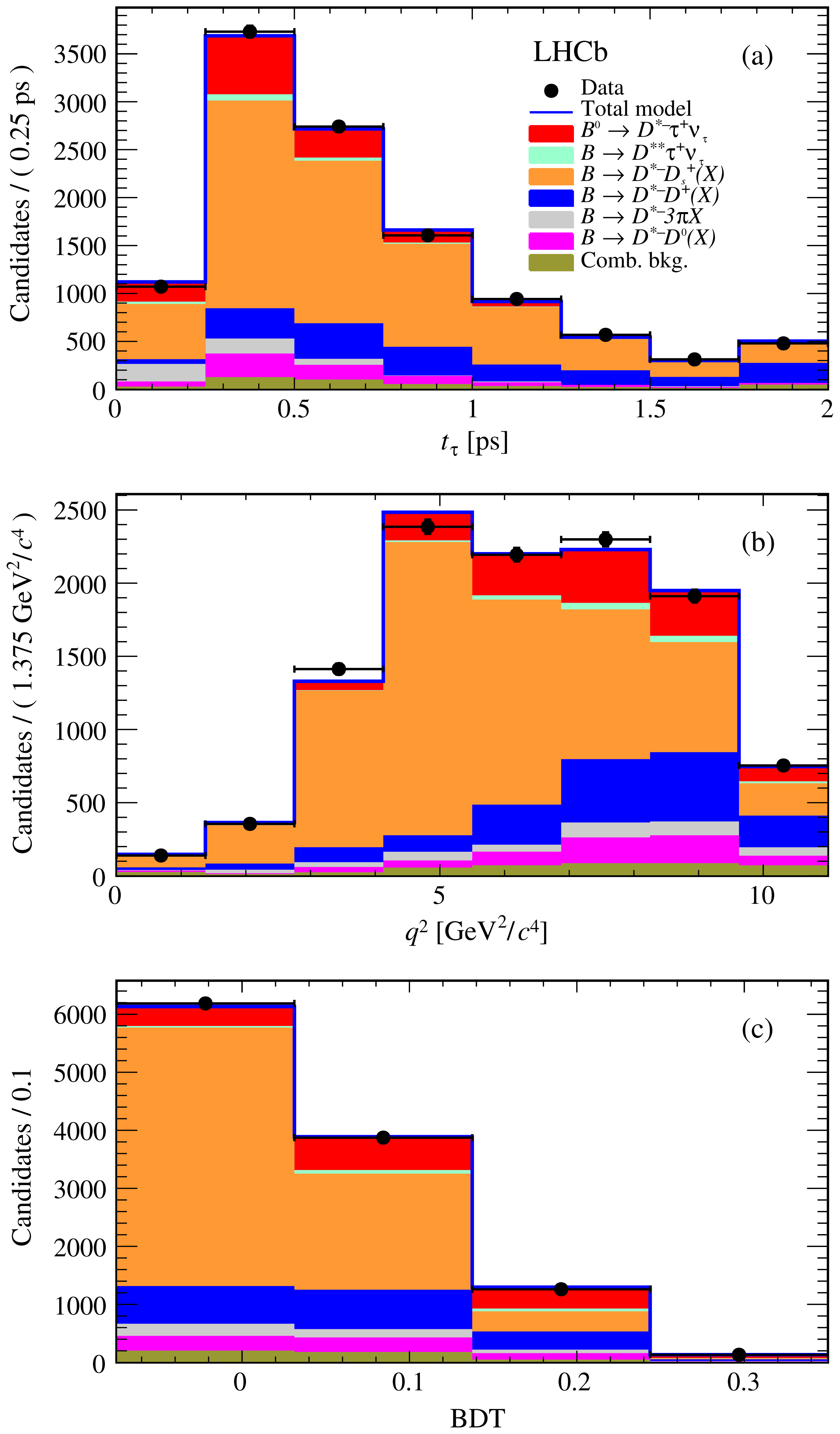
$$\mathscr{R}(D^*) = \frac{\mathscr{B}(\bar{B} \to D^*\tau\nu_\tau)}{\mathscr{B}(\bar{B} \to D^*\pi\pi\pi)} \times \frac{\mathscr{B}(\bar{B} \to D^*\pi\pi\pi)}{\mathscr{B}(\bar{B} \to D^*\mu\nu_\mu)}$$

Measure this ratio

$\mathscr{R}(D^{*+})$ depends on external branching fractions

*Actually, the $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ decay is semileptonic

Hadronic* $\mathcal{R}(D^{*+})$ systematics



- Similarly to previous measurements, **many systematic uncertainties** are expected to **scale down with data**
- However, **a floor of ~3-4% is more likely** due to dependence from **external branching fraction measurements**

Phys. Rev. D **97**, 072013 (2018)

Contribution	Uncert. [%]
DD bkg.	5.4
Simulated sample size	4.9
MC/data correction	3.7
$\overline{B} \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ bkg.	2.7
Trigger	1.6
PID	1.3
Signal/norm. FFs	1.2
Combinatorial bkg.	0.7
τ decay	0.4
Total systematic	**9.0**
$\mathcal{B}(B \to D^*\pi\pi\pi)$	3.9
$\mathcal{B}(B \to D^*\mu\nu)$	2.0
$\mathcal{B}(\tau^+ \to 3\pi\nu)/\mathcal{B}(\tau^+ \to 3\pi\pi^0\nu)$	0.7
Total external	**4.4**
Total statistical	**6.5**
Total	**12.0**

*Actually, the $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ decay is semileptonic

Muonic vs Hadronic τ decay

- Run 1 measurements show key features of future LHCb LUV possibilities
  - ➡ Dominated by systematics, but will scale with data for the most part

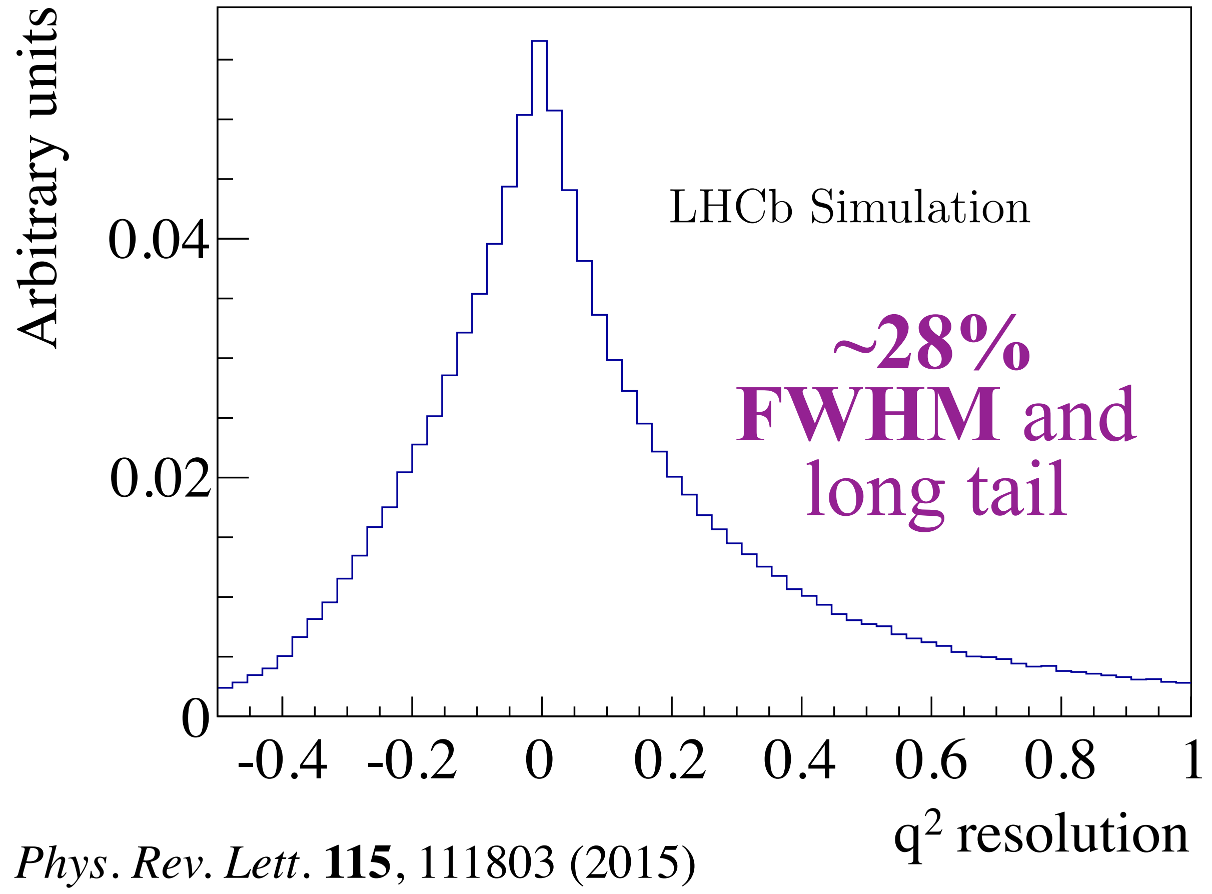
Note that the majority of the uncertainty does not scale with central value

Muonic $\mathcal{R}(D^{*+})$	Uncert. [%]
Total systematic	**8.9**
Total statistical	**8.0**
Total	**12.0**

Systematics floor probably 0.5-3%

Muonic $\mathcal{R}(J/\Psi)$	Uncert. [%]
Total systematic	**25.4**
Total statistical	**23.9**
Total	**34.9**

Systematics floor 1-5% due to FFs



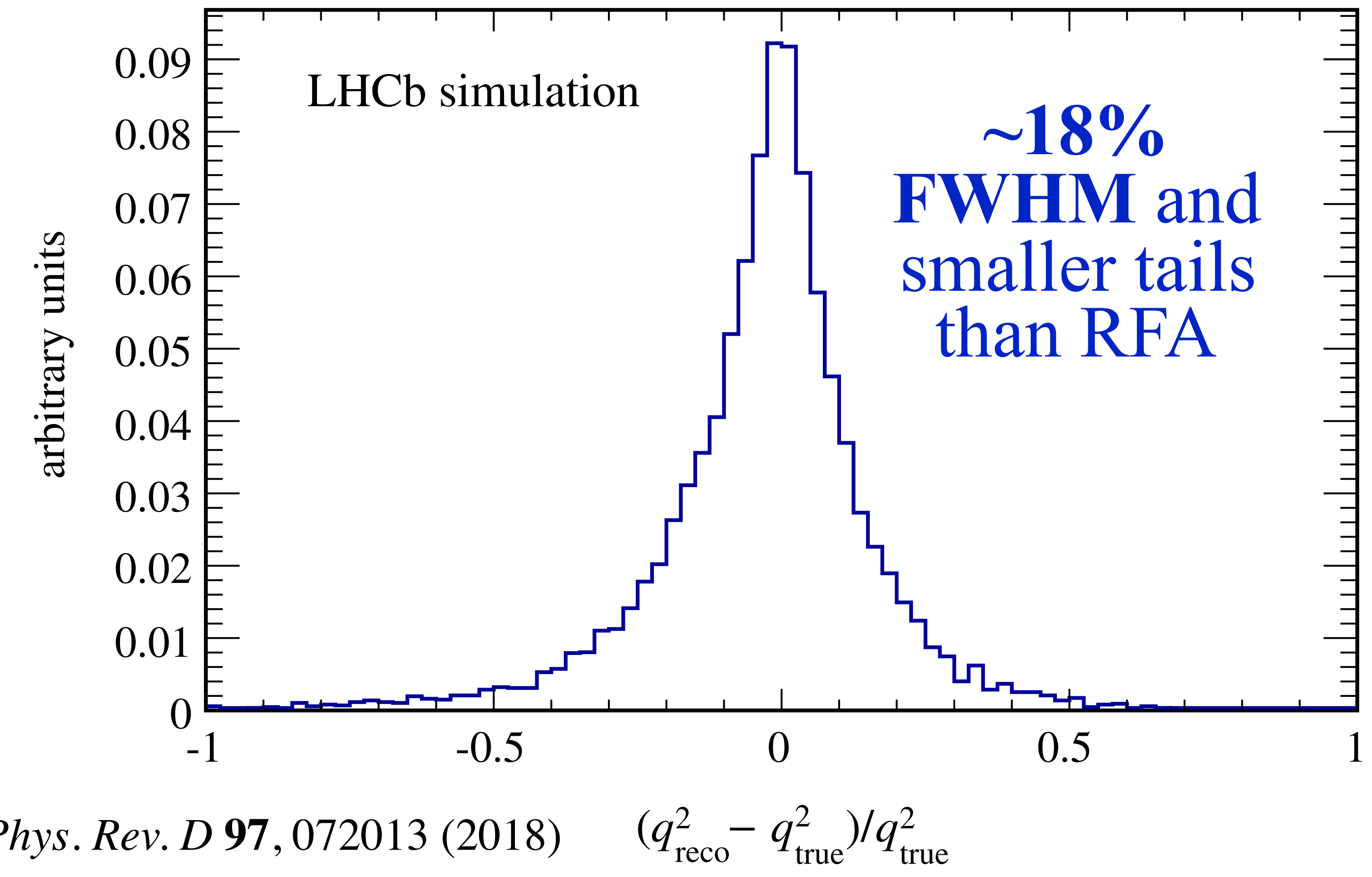
Phys. Rev. Lett. **115**, 111803 (2015)

Muonic decays of τ allow for **precise determinations** of $\mathscr{R}(X_c)$ at higher stats

Hadronic $\mathcal{R}(D^{*+})$	Uncert. [%]
Total systematic	**9.0**
Total external	**4.4**
Total statistical	**6.5**
Total	**12.0**

Systematics floor 3-4% due to BF_{ext}

$\mathscr{R}(X_c)$ precision with **hadronic** decays of τ may be limited by external measurements



Phys. Rev. D **97**, 072013 (2018)

But may allow for **better measurements** of **kinematic distributions**

Upcoming Run 1-2 measurements

- Analyses at an advanced stage
  - Run 1 muonic $\mathcal{R}(D^0) - \mathcal{R}(D^*)$
  - Hadronic $\mathcal{R}(D^{**})$

B^0, B^+

B_s^0

B_c^+

Λ_b^0

- Analyses in early to very early stages primarily using Run 2
  - Run 2 muonic $\mathcal{R}(D^0) - \mathcal{R}(D^*)$, muonic $\mathcal{R}(D^+) - \mathcal{R}(D^{*+})$
  - Run 2 hadronic $\mathcal{R}(D^{*+})$, hadronic $\mathcal{R}(D^0) - \mathcal{R}(D^*)$, hadronic $\mathcal{R}(D^+) - \mathcal{R}(D^{*+})$
  - Muonic $\mathcal{R}(p\bar{p})$
  - Hadronic $B \to D^{*+}\tau\nu$ polarization of D* and τ
  - Muonic $B \to D^{*+}\tau\nu$ angular distributions
  - $\mathcal{R}(D^{*+})_{light}$
  - Muonic $\mathcal{R}(D_s) - \mathcal{R}(D_s^*)$, hadronic $\mathcal{R}(D_s) - \mathcal{R}(D_s^*)$
  - Run 2 muonic $\mathcal{R}(J/\Psi)$, hadronic $\mathcal{R}(J/\Psi)$
  - Muonic $\mathcal{R}(\Lambda_c)$, hadronic $\mathcal{R}(\Lambda_c)$

Some of these may take several years, but **aim to cover as many observables as possible**

Assumptions on evolution of $\mathscr{R}(X_c)$

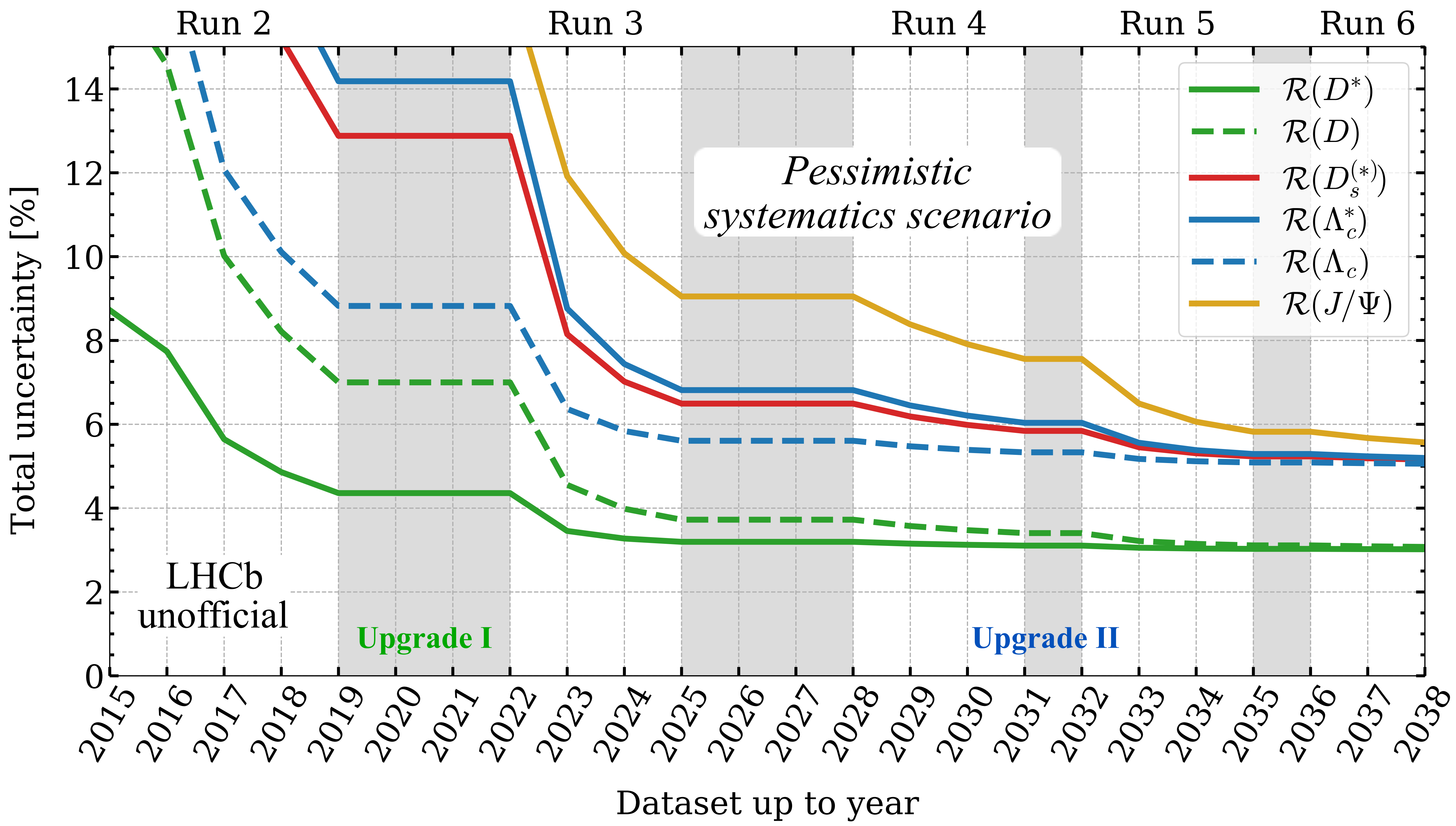
Run 1		LS1		Run 2				LS2			Run 3			LS3			Run 4			LS4	Run 5			LS5	Run 6		
2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
1.1	2.0	-	-	0.3	1.7	1.7	2.2	-	-	-	8.3	8.3	8.3	-	-	-	8.3	8.3	8.3	-	50	50	50	-	50	50	fb^{-1}

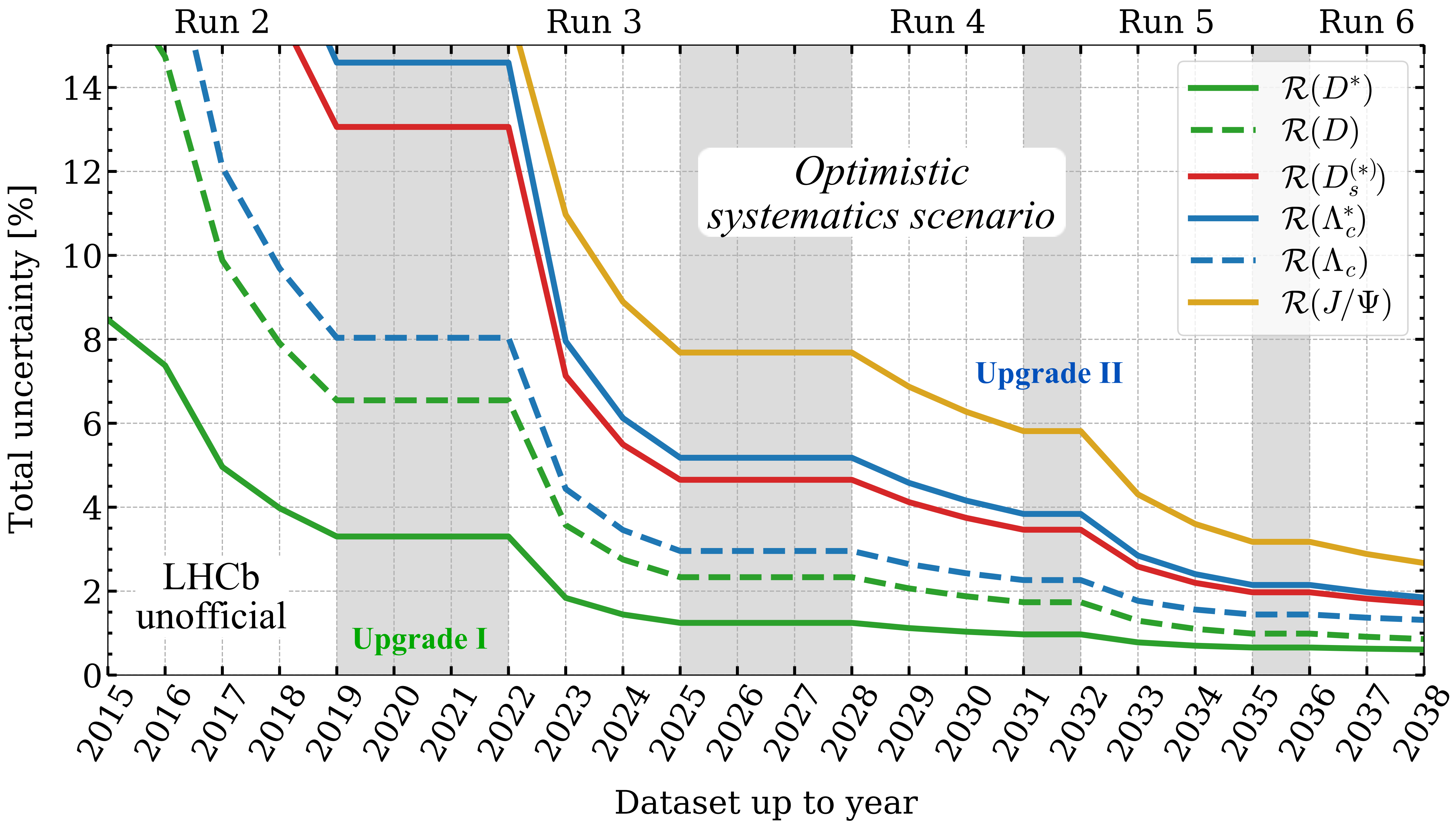
- **Extrapolate $\mathscr{R}(D^*)$** based on Run 1 muonic $\mathscr{R}(D^{*+})$ **assuming**
  - **2×** more stats starting in **Run 1** from **adding $\mathscr{R}(D^{*0})$**
  - **3×** more stats starting in **Run 2** from **better HLT** (1.5×) and **cross section** (2×)
  - **2×** more stats starting in **Run 3** from **no hardware trigger**
  - **Systematics scale with data** but **floor** of **0.5%** (optimistic) **and 3%** (pessimistic)
- **Extrapolate $\mathscr{R}(J/\Psi)$** based on Run 1 muonic $\mathscr{R}(J/\Psi)$
  - **Systematics scale with data** but **floor** of **1%** (optimistic) **and 5%** (pessimistic)
- Estimate the other species based on $\mathscr{R}(D^*)$ extrapolation and
  - **1/4×** stats for $\mathscr{R}(D)$ from smaller BF and no feed-down
  - **1/16×** stats for $\mathscr{R}(D_s^{(*)})$ from $f_s/(f_u+f_d)$ and extra track (1/2×)
  - **1/6×** stats for $\mathscr{R}(\Lambda_c)$ from $f_{\Lambda_b}/(f_u+f_d)$ ~ 1/4, extra track (1/2×), and larger Λ_c BF
  - **1/20×** stats for $\mathscr{R}(\Lambda_c^*)$ from $f_{\Lambda_b}/(f_u+f_d)$ ~ 1/4, two slow pions and lower BF
  - **Systematics scale with data** but **floor** of **1%** (optimistic) **and 5%** (pessimistic) but for $\mathscr{R}(D)$ same as $\mathscr{R}(D^*)$

Rough assumptions based on BFs and fragmentation fractions and building on work from Patrick Owen

Prospects for $\mathscr{R}(X_c)$

- **Enormous improvement from Upgrade I** (Runs 3+4)
  - ➡ 50 fb^{-1} plus factor of two from no hardware trigger
- **After Upgrade II** (Runs 5+6) it **depends** on **systematics scenario**
  - ➡ **Significant gains** for $\mathscr{R}(J/\Psi)$, $\mathscr{R}(D_s^{(*)})$, and $\mathscr{R}(\Lambda_c^*)$ if we can control FF systematics



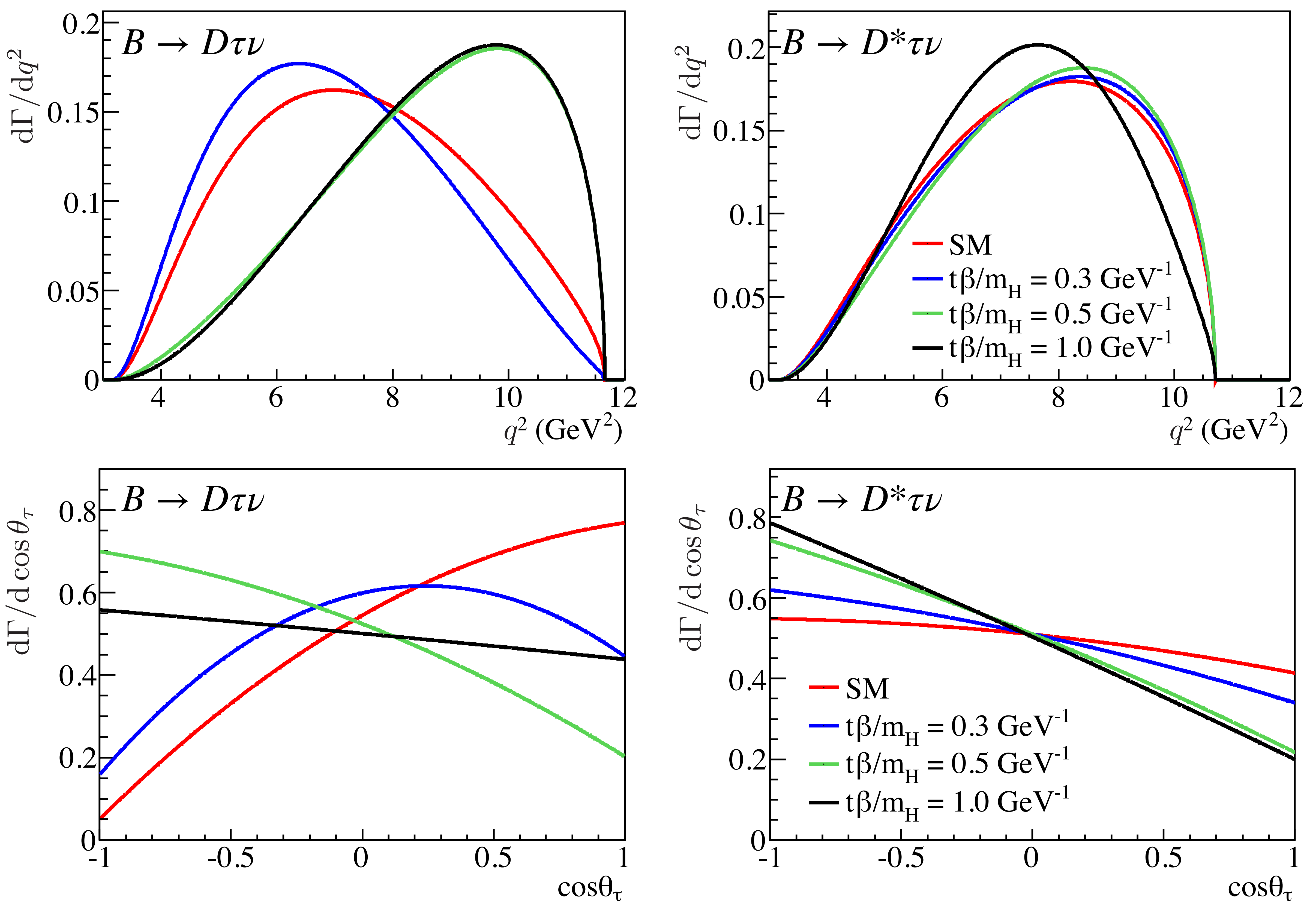


Measuring distributions

- Upgrades give **access kinematic distributions sensitive to NP**
  - Instrumental in characterizing any anomaly
  - Unique sensitivity to $B_s \to D_s^{(*)}\tau\nu$, $B_c \to J/\Psi\tau\nu$, and $\Lambda_b \to \Lambda_c\tau\nu$ (see following talk by A. Datta)

Impact of 2HDM on q^2 and $\theta_\tau = \pi - \theta_L$

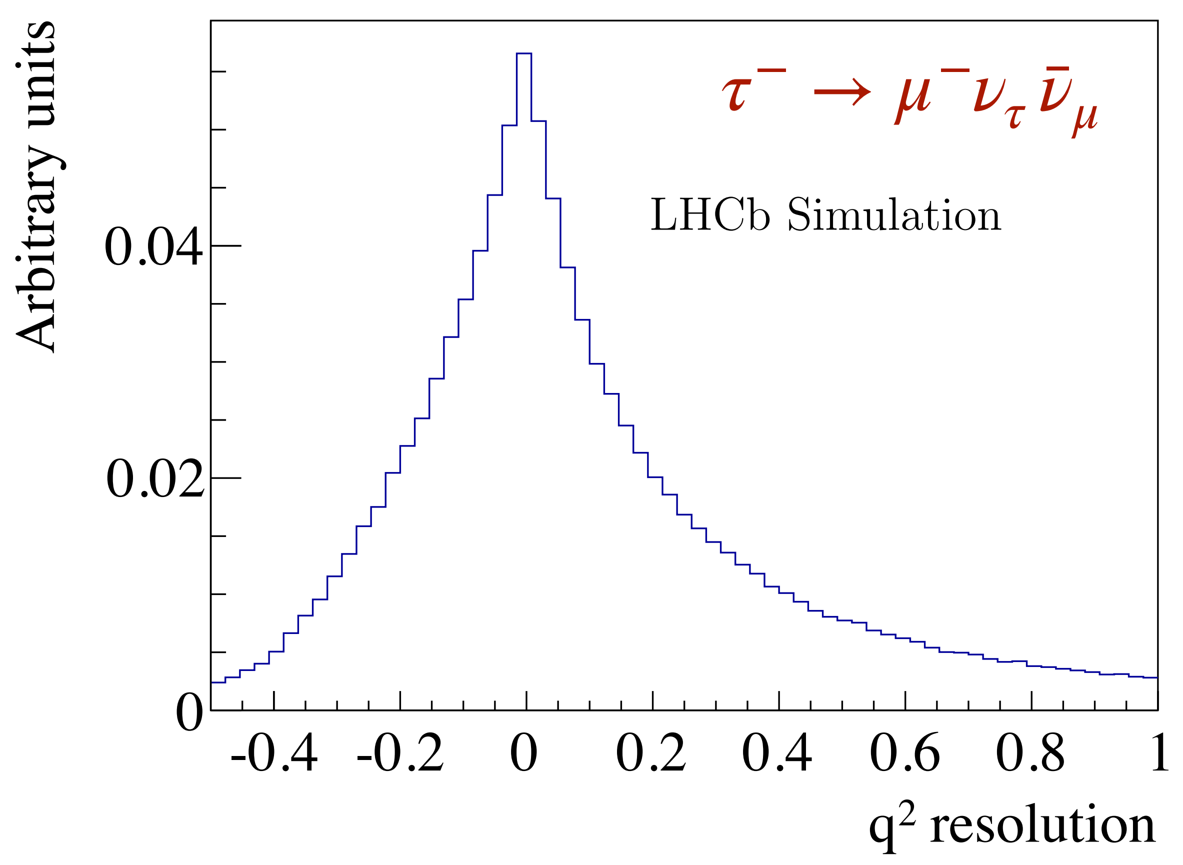
MFS "Evidence for an excess of $B \to D^{*+}\tau\nu$ decays" Dissertation, *Stanford University* (2012)

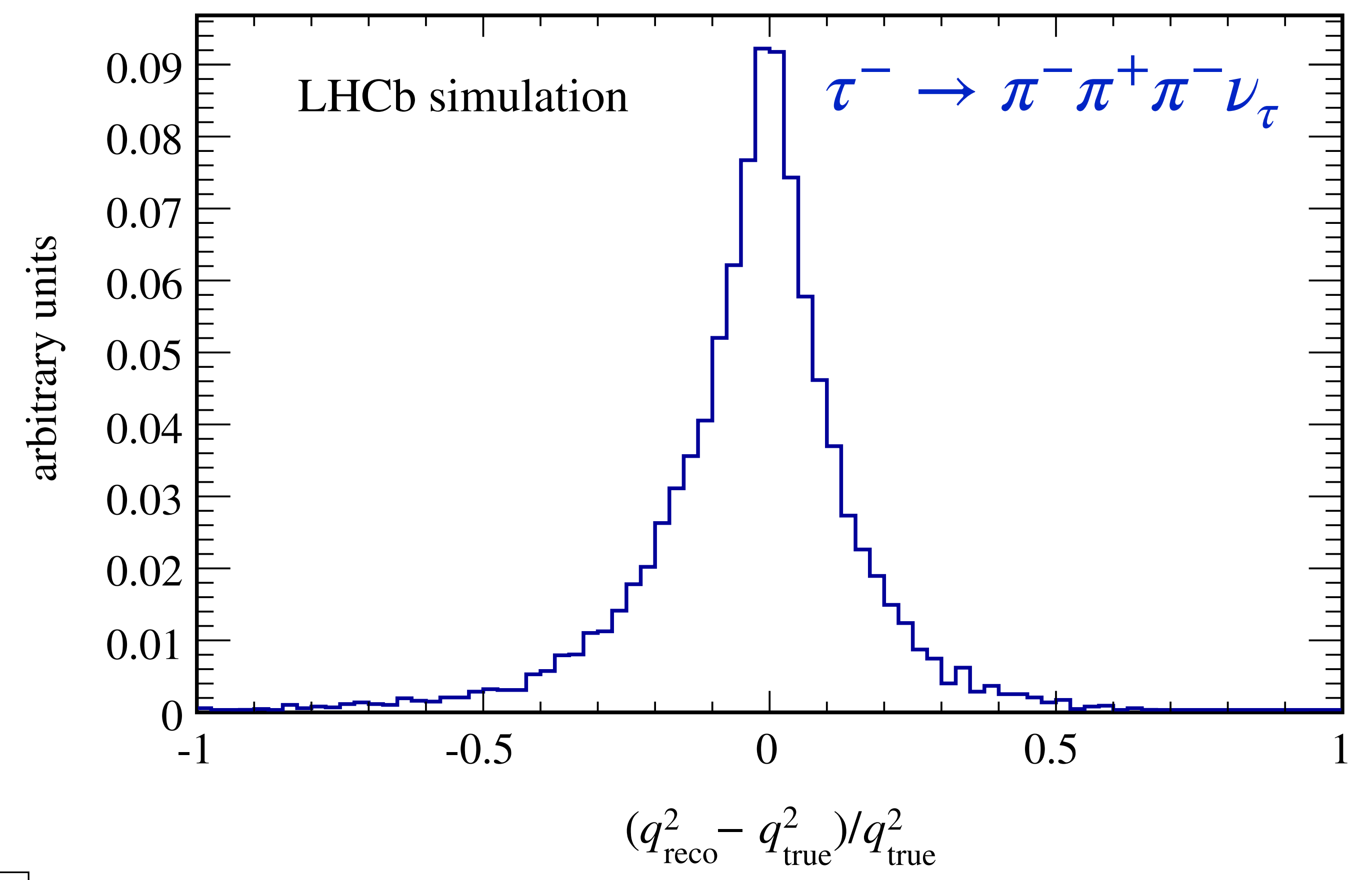


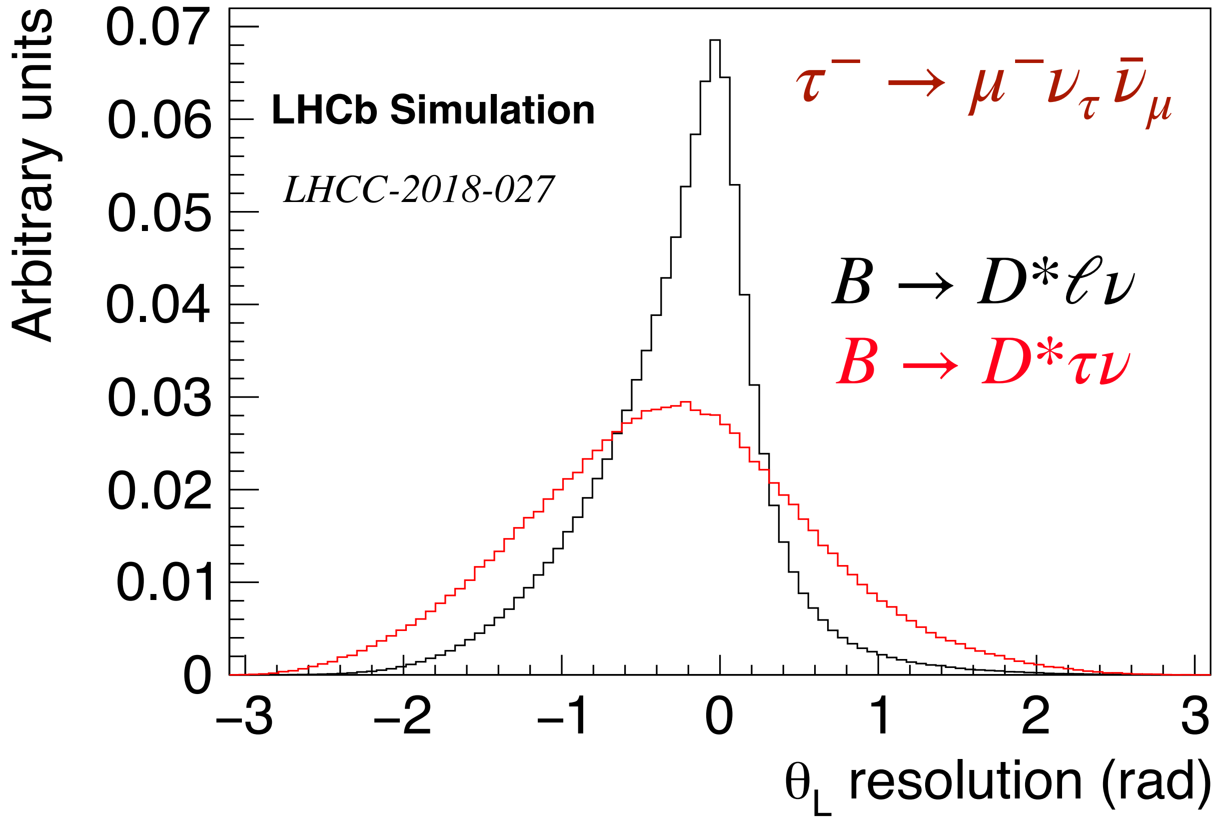
LHCb resolution on q^2 and θ_L

Phys. Rev. Lett. **115**, 111803 (2015)

Phys. Rev. D **97**, 072013 (2018)







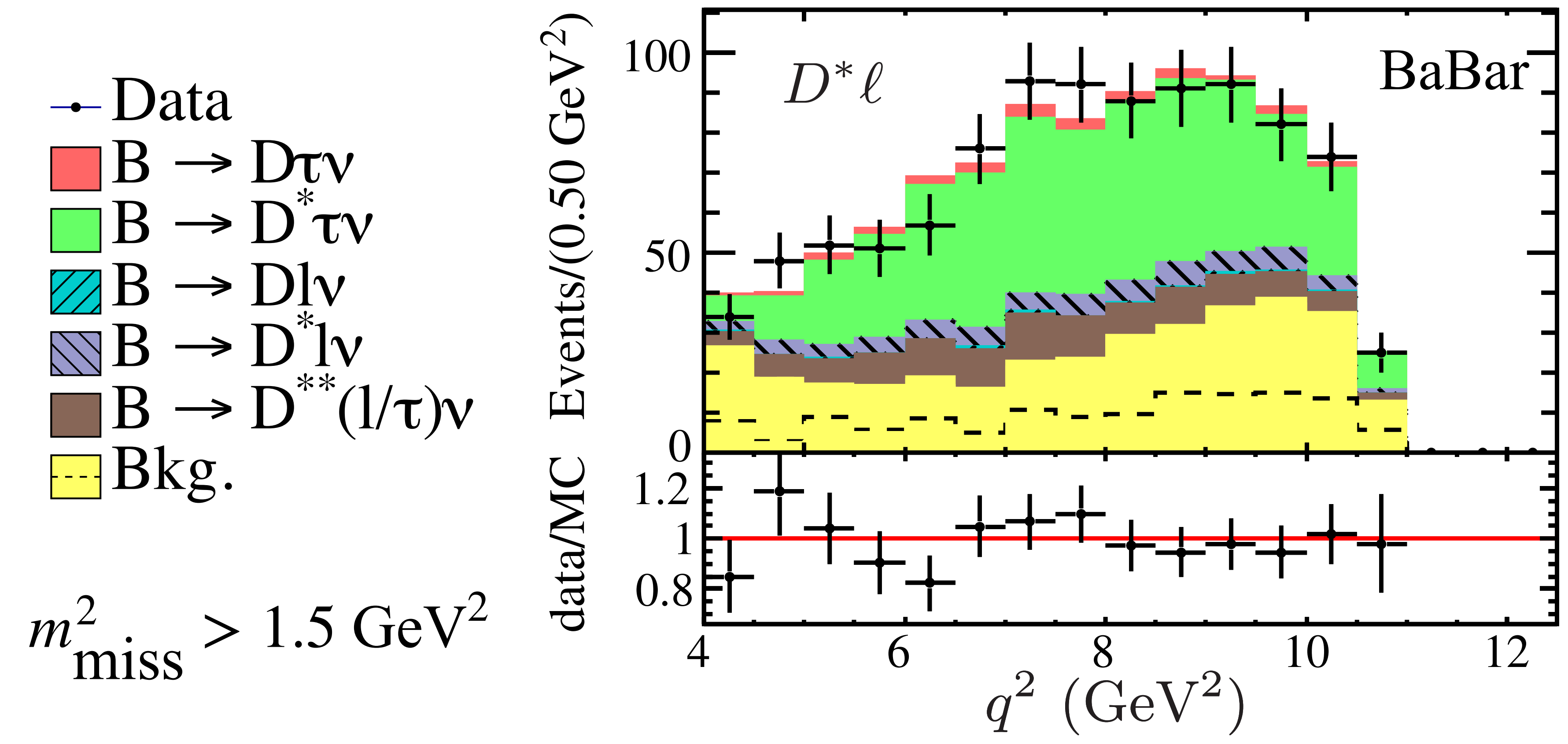
The **hadronic reconstruction** of the **τ** provides **higher sensitivity**, but the **muonic** reconstruction can **also contribute**

Challenges of measuring distributions at LHCb

- Larger backgrounds and lack of full event reconstruction make distributions **challenging**
  - ➡ Upgrade 2 samples may allow for techniques such as $B^*_{s2} \to B^+K^-$ tagging

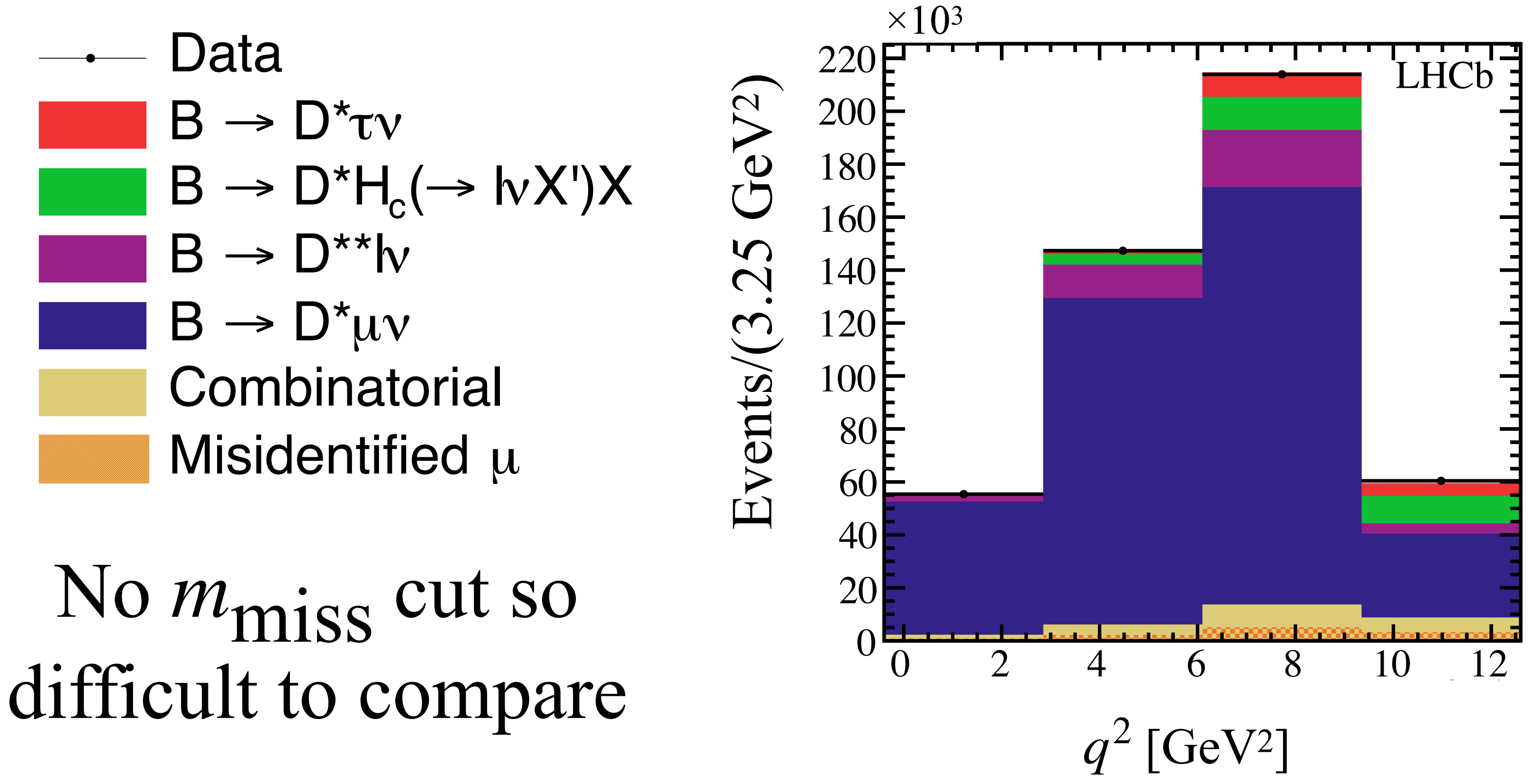
Phys. Rev. D **88**, 072012 (2013)

$\sigma_{\text{stat}}\left(\mathscr{R}(D^*)\right) = 7.1\,\%$



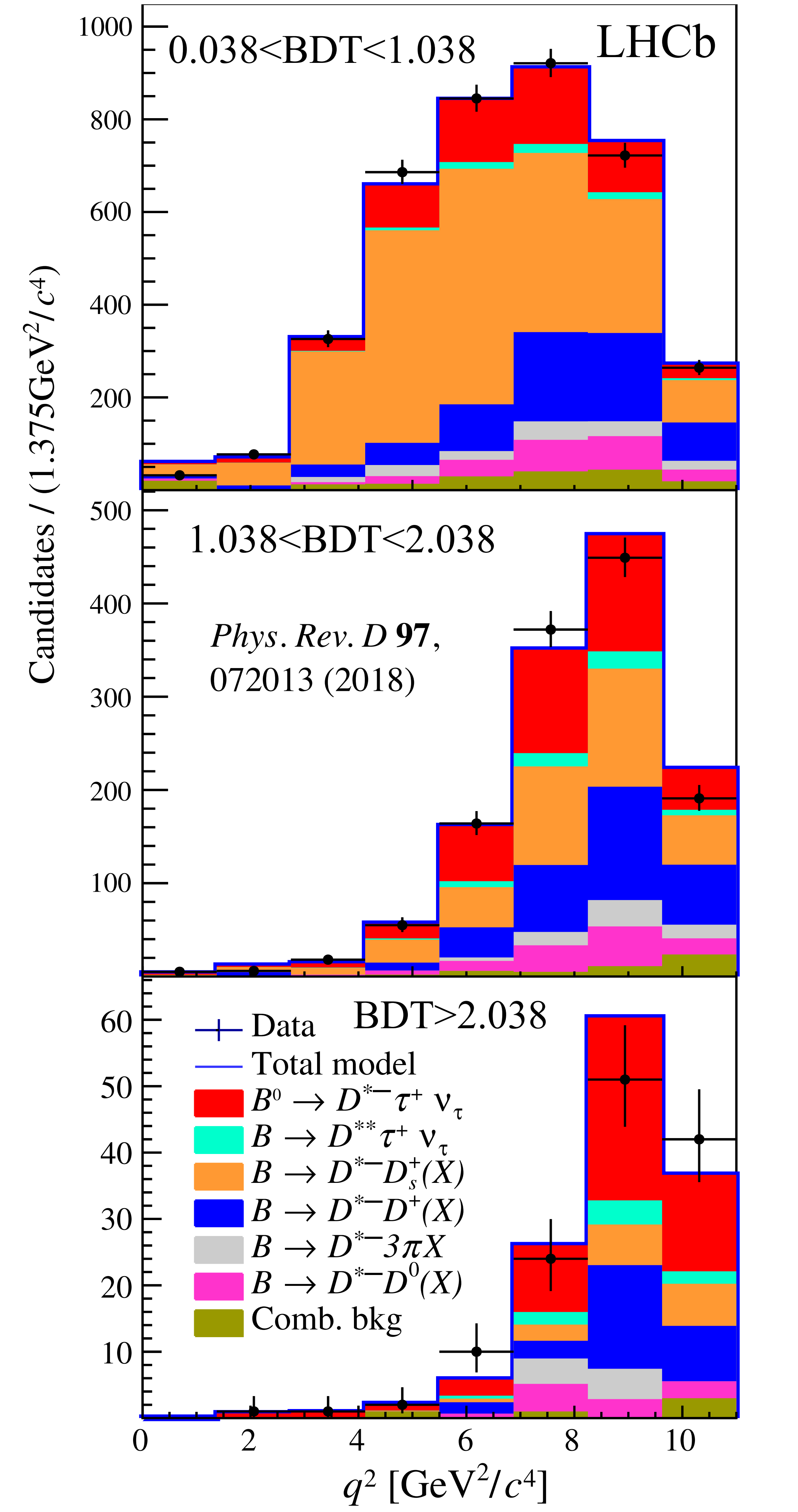
Phys. Rev. Lett. **115**, 111803 (2015)

$\sigma_{\text{stat}}\left(\mathscr{R}(D^*)\right) = 8.0\,\%$



No m_{miss} cut so difficult to compare

$\sigma_{\text{stat}}\left(\mathscr{R}(D^*)\right) = 6.4\,\%$

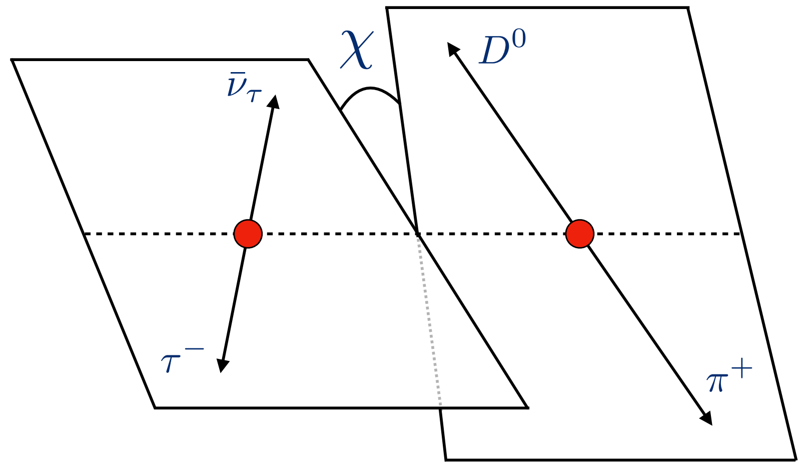


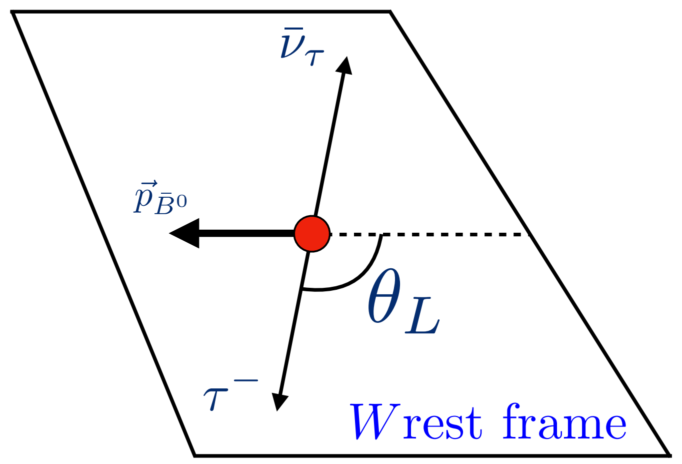
- **Run 1 hadronic measurement** already shows some **sensitivity to q² distribution**

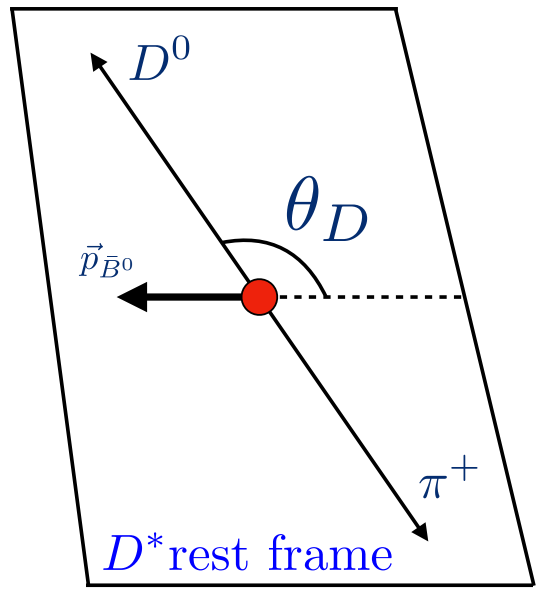
Possible sensitivity to angular distributions

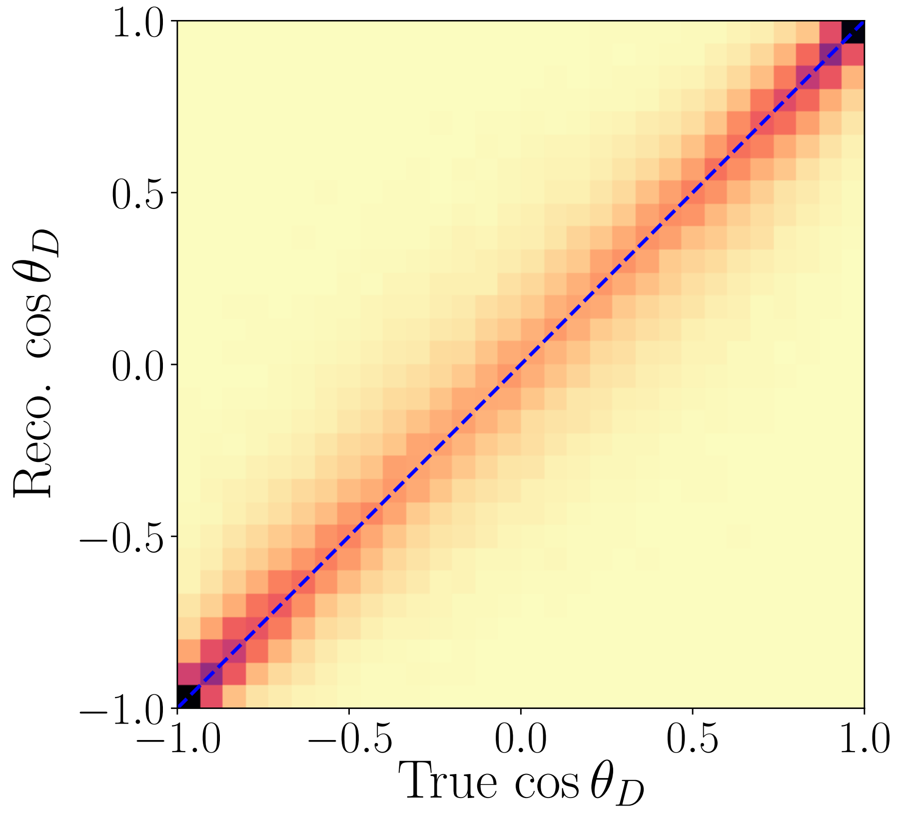
- Hadronic analyses expected to have good angular sensitivity
  - ➡ Hill, John, Ke, Poluektov, *JHEP* **2019**, 133 (2019) 1908.04643

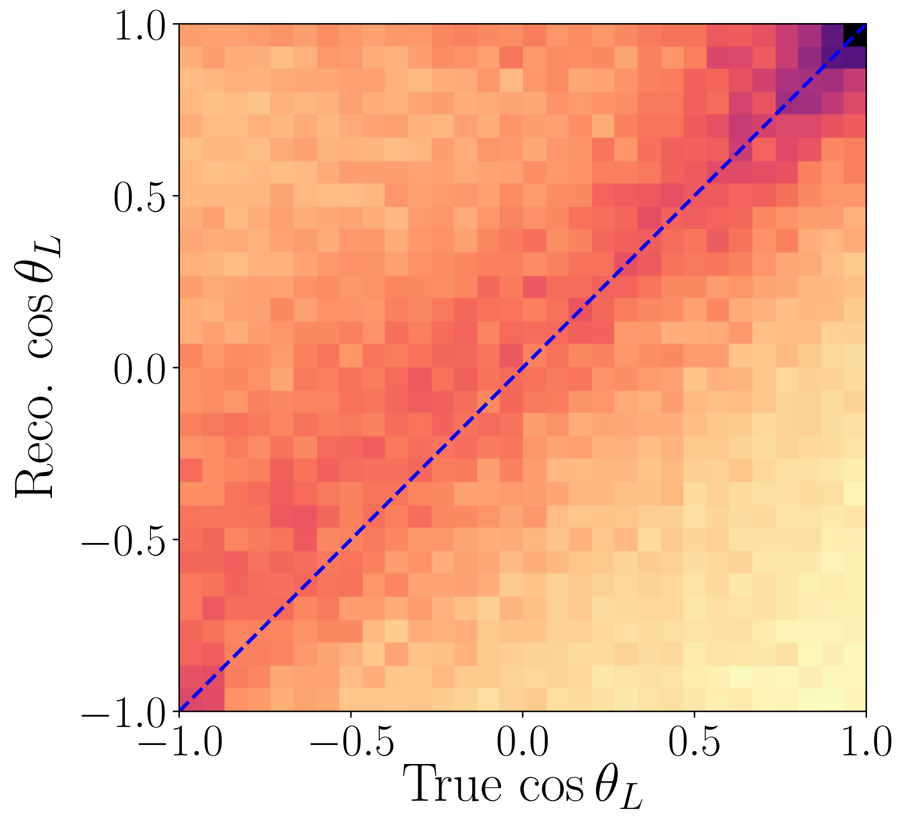
$$
\begin{aligned}
\frac{d^4\Gamma}{dq^2\, d(\cos\theta_D)\, d(\cos\theta_L)\, d\chi} \propto\; & I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D \\
& + [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L \\
& + [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L \\
& + [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D \\
& + [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D \\
& + [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\,,
\end{aligned}
$$

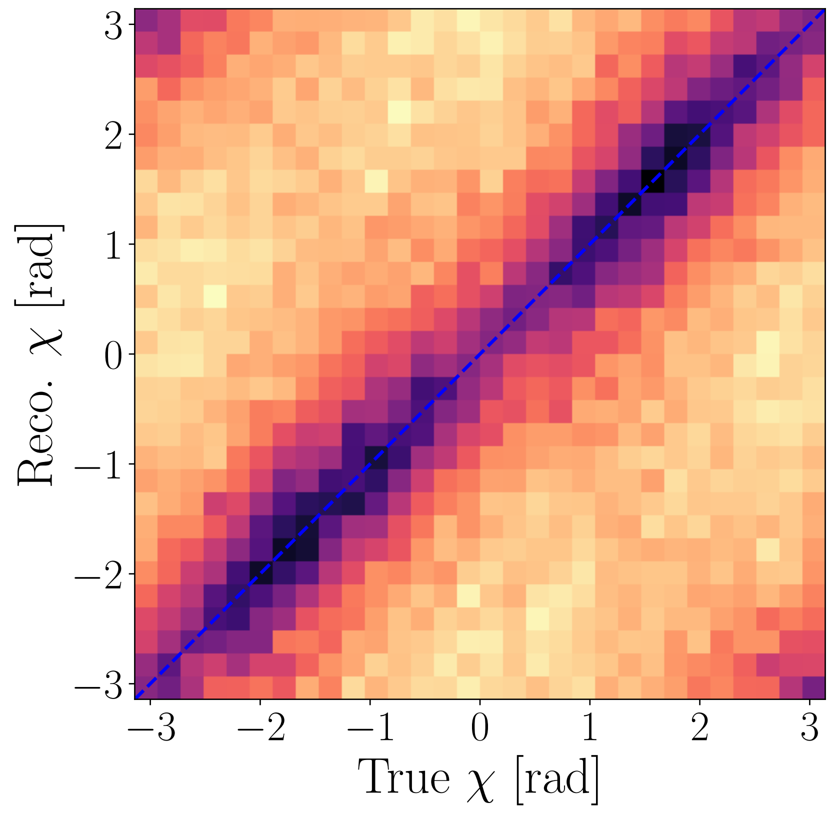


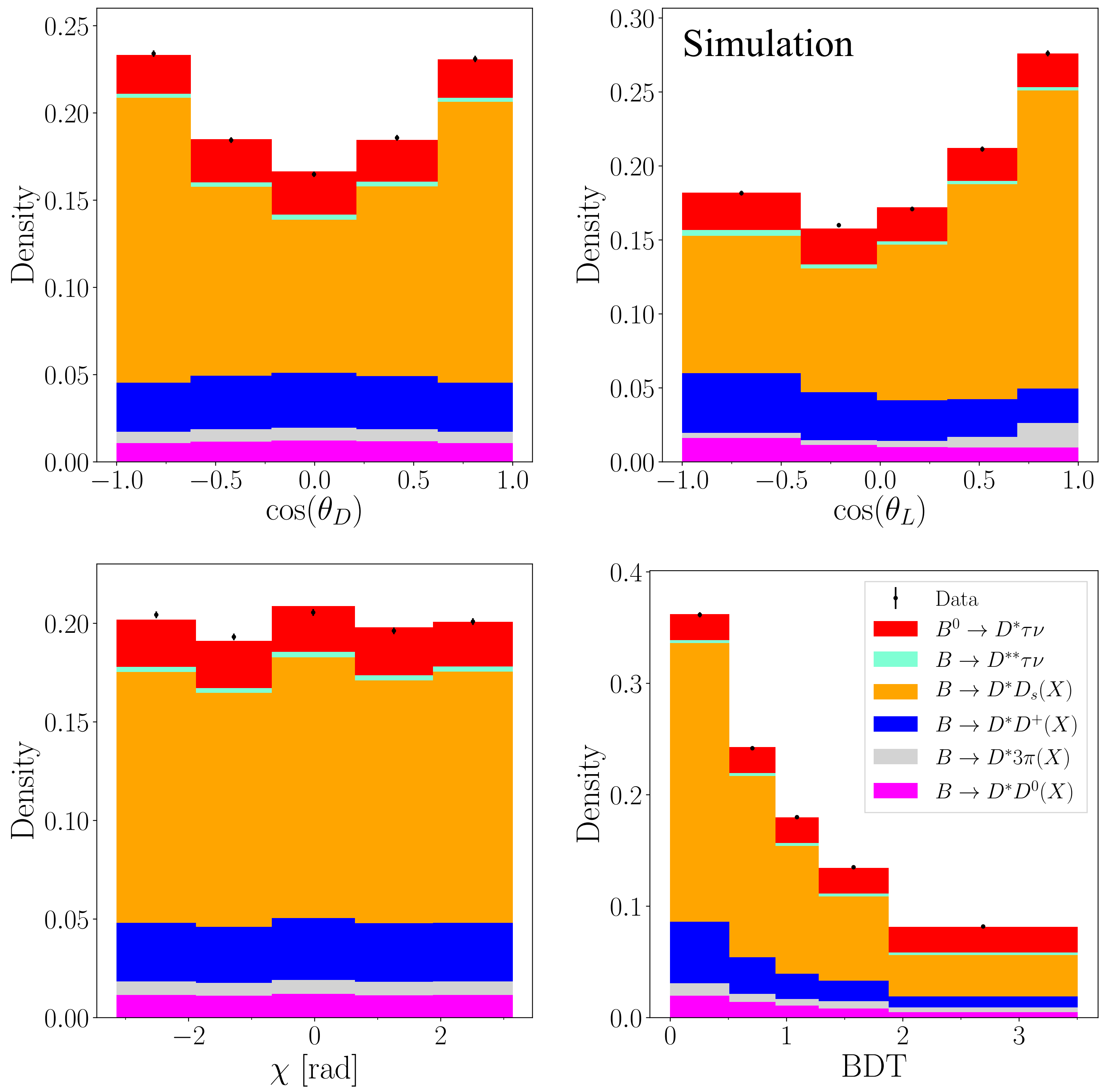


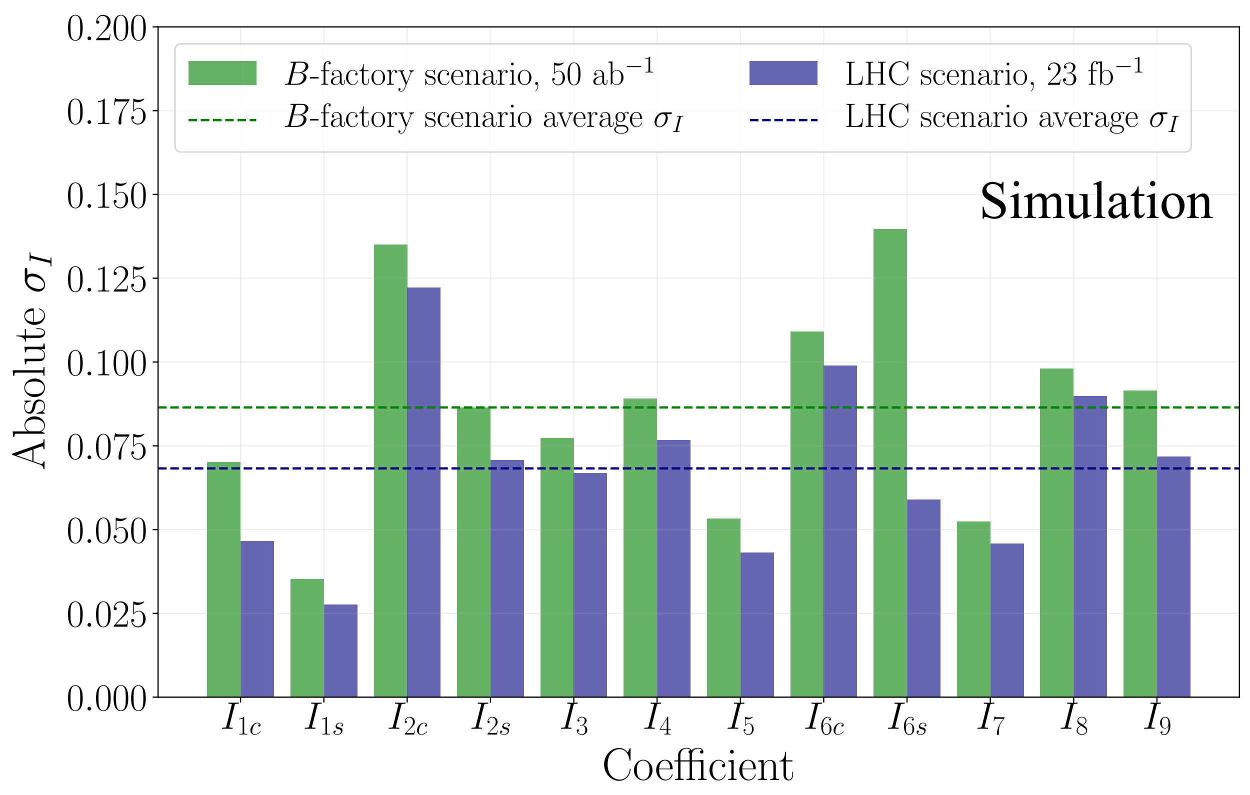












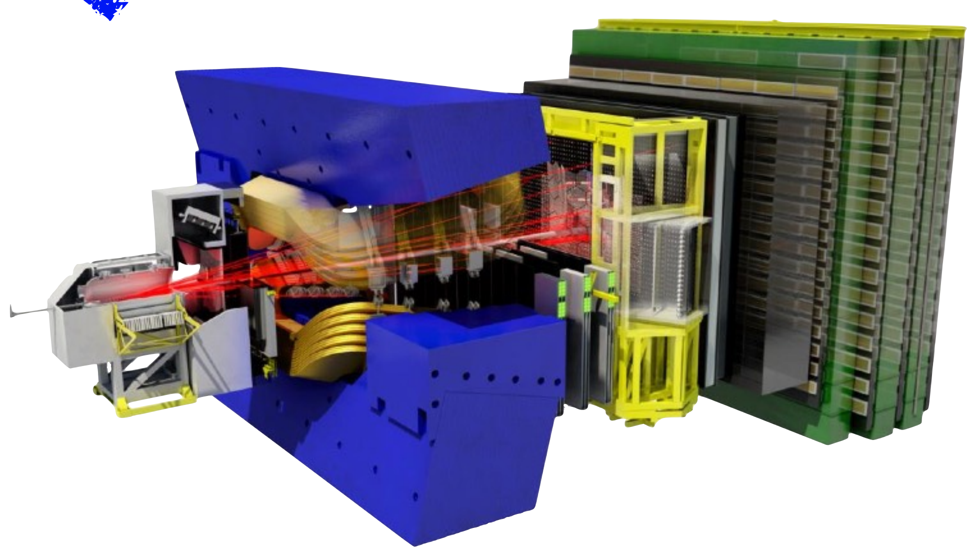
Summary

9 fb^{-1} — Goal: 50 fb^{-1} — Goal: 250 fb^{-1}

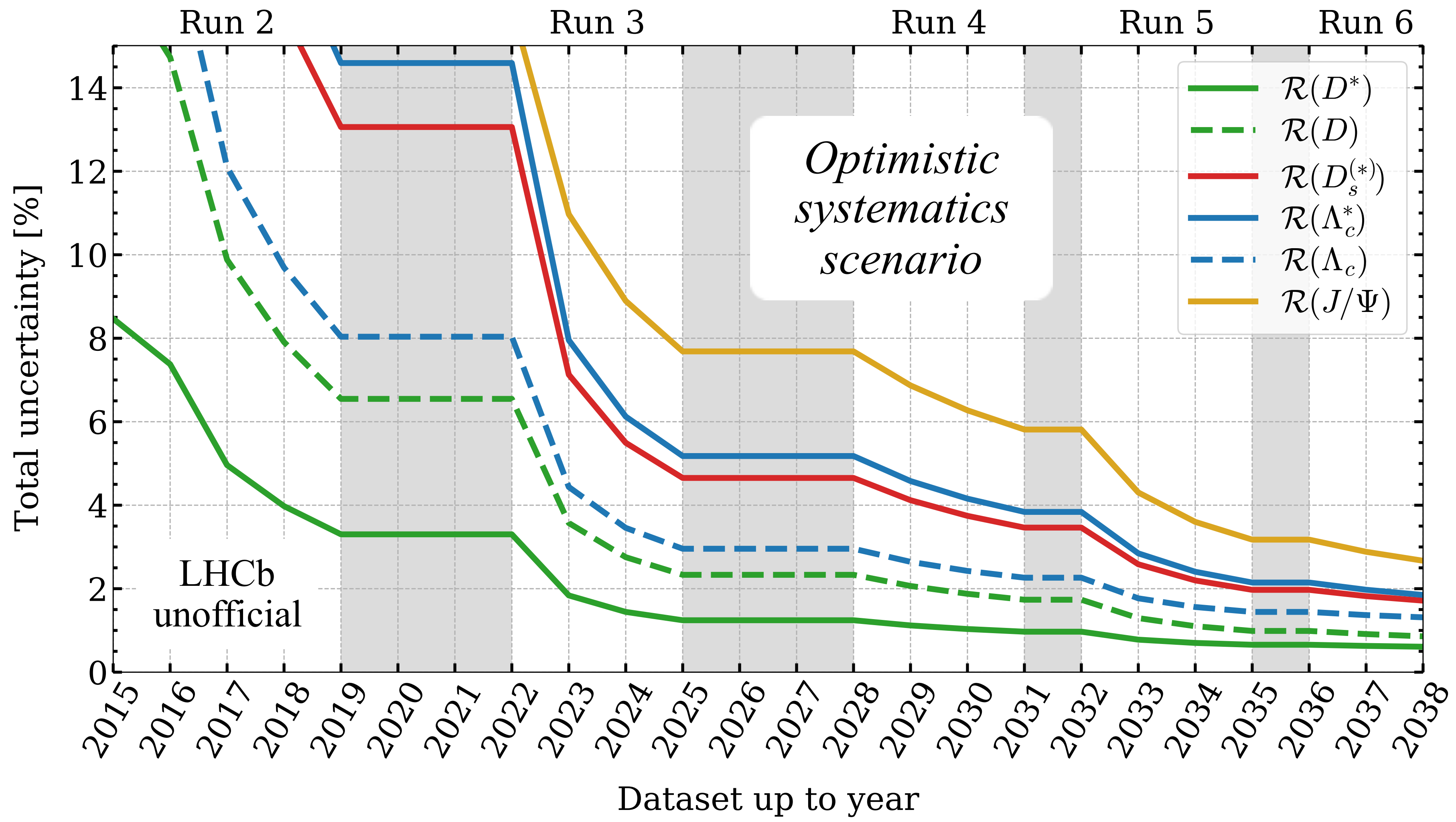
Upgrade I (LS2) — Upgrade II (LS4)

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

Belle II (2019–2031)

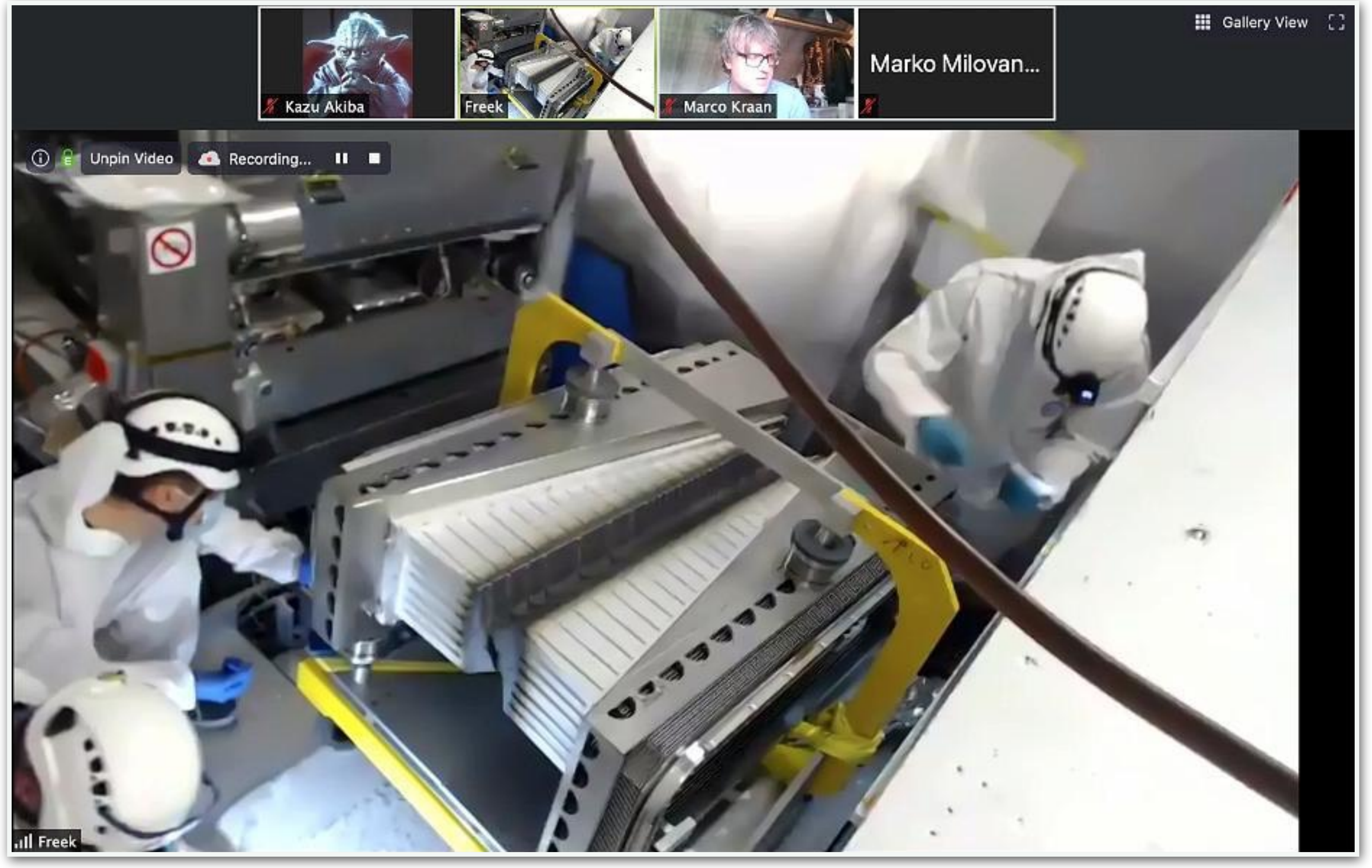


- A **program of updates** is being carried out to fully exploit the LHC potential for flavor physics
  - **Remove hardware trigger**, improve detector **longevity** and **performance**
  - **Major challenges** have been **overcome** for U1, but schedule challenging
- LHCb has a **unique ability** to **study $b \to c\tau\nu$ transitions**
  - $\mathcal{R}(D^{(*)})$, $\mathcal{R}(D^{**})$, $\mathcal{R}(D_s^{(*)})$, $\mathcal{R}(J/\Psi)$, $\mathcal{R}(\Lambda_c^{(*)})$ with muonic analyses
  - **Important kinematic distributions** with hadronic analyses
  - Upgrades will allow us to reach 0.5-3% uncertainties
  - **Challenges** ahead
    - Will need an **order of magnitude more MC** than what FastSim can do today
    - Important to **calculate** and **measure all FF** and **control other systematics**

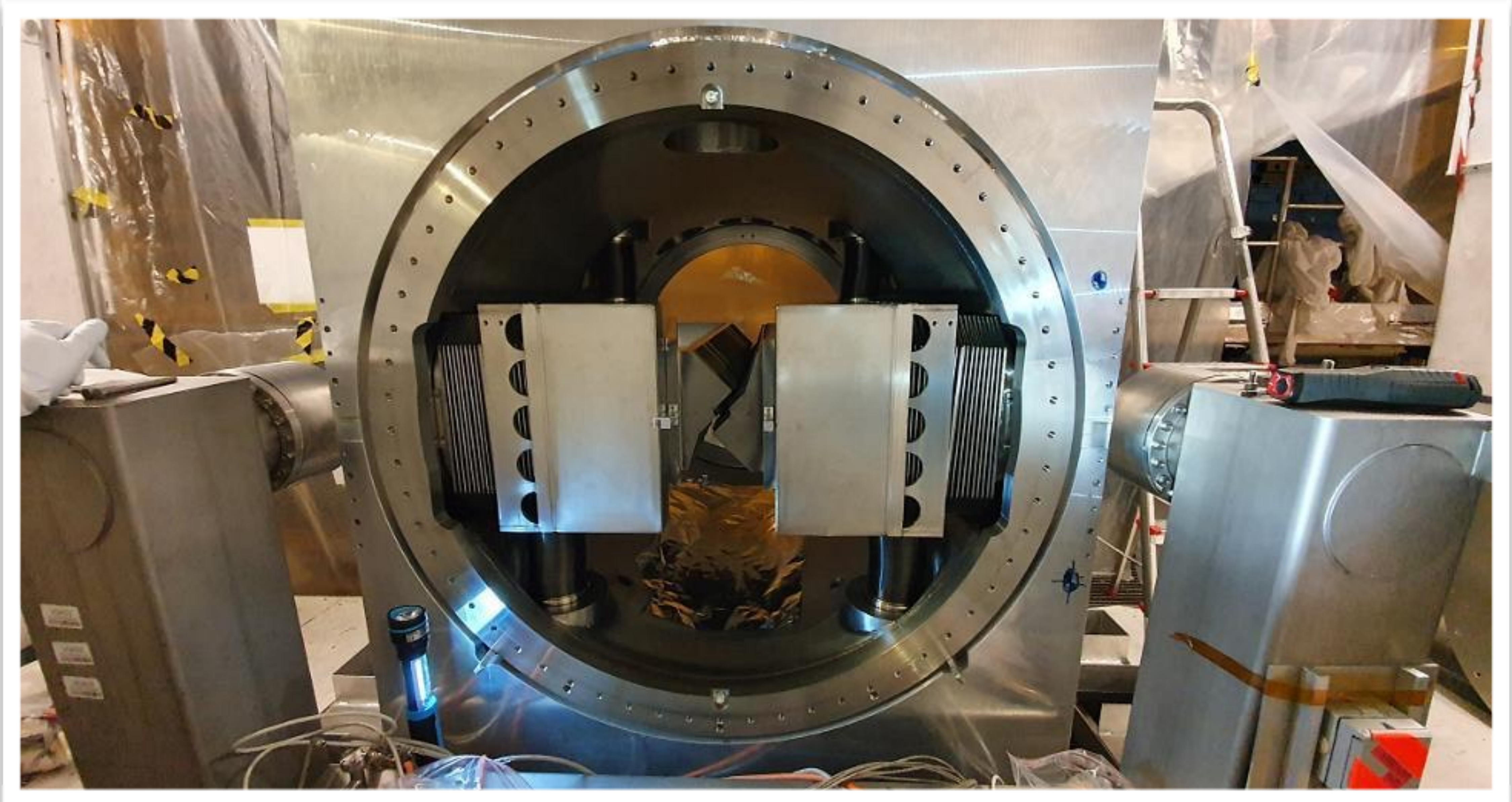


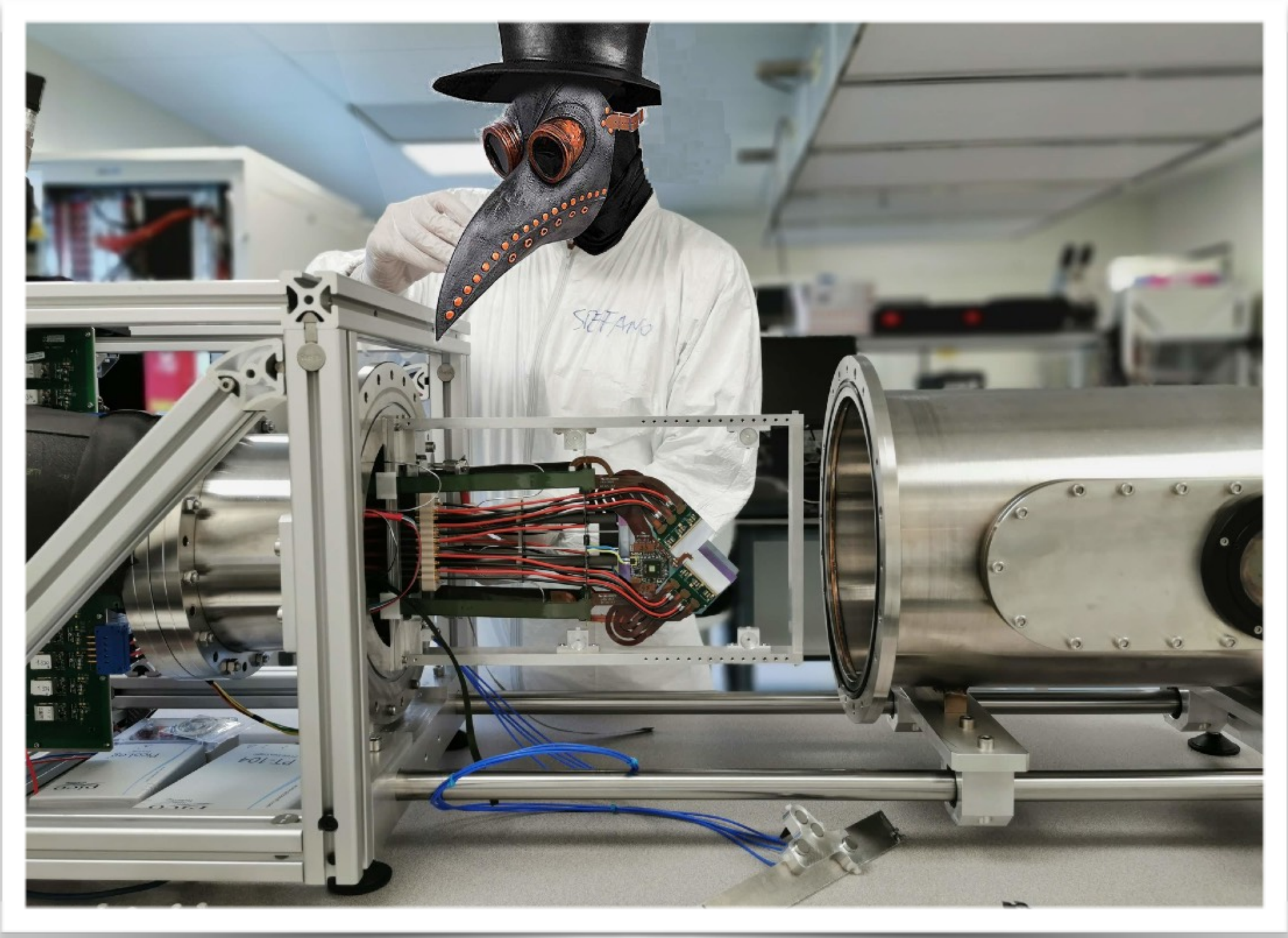
Backup

COVID-19 impact



- **COVID-19 shut down most activities** in March
  - ➡ Work on documentation, database, procedure optimization
- **RF foil installation** one of CERN's pilot projects
  - ➡ Zoom-supervised and **completed in May!**
- **Module production resumed** over Summer
  - ➡ Pandemic slows down everything
  - ➡ On track to meet updated LS2 schedule



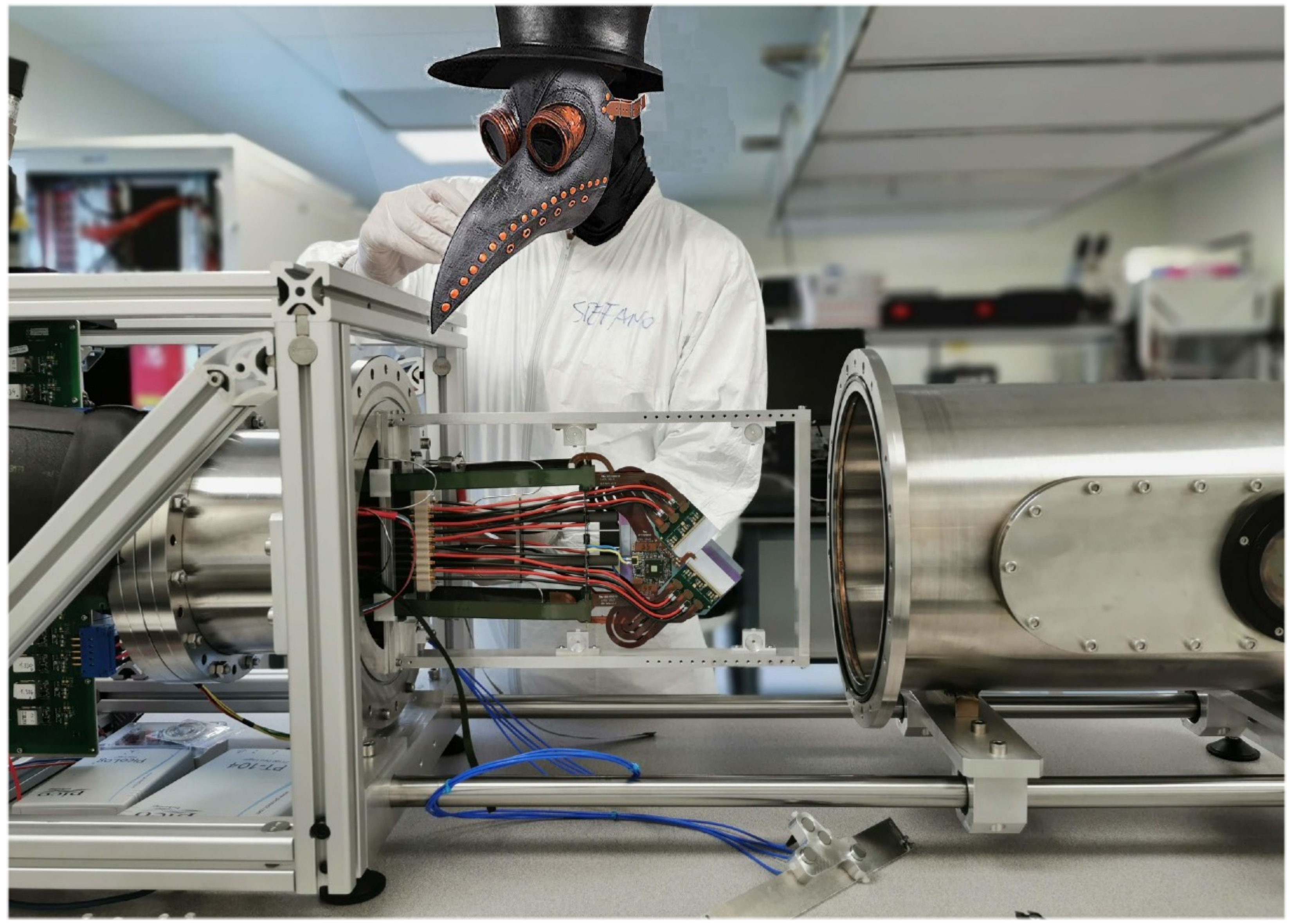


No PPE shortage will stop the VELO production

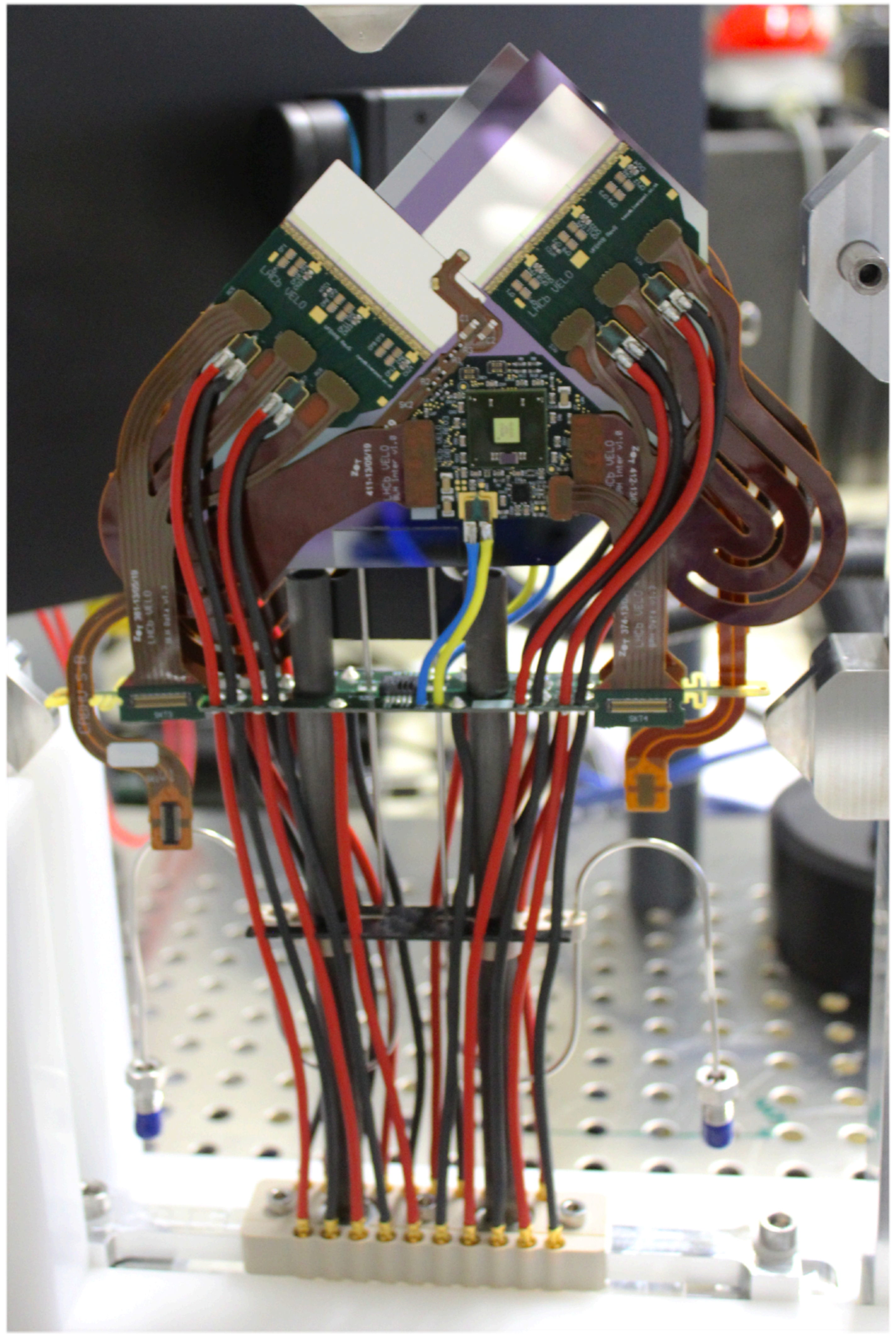
First post-COVID-19 modules

- **Module production resumed** over the summer
  - ➡ Improved procedures
- **On track** to meet updated LS2 schedule

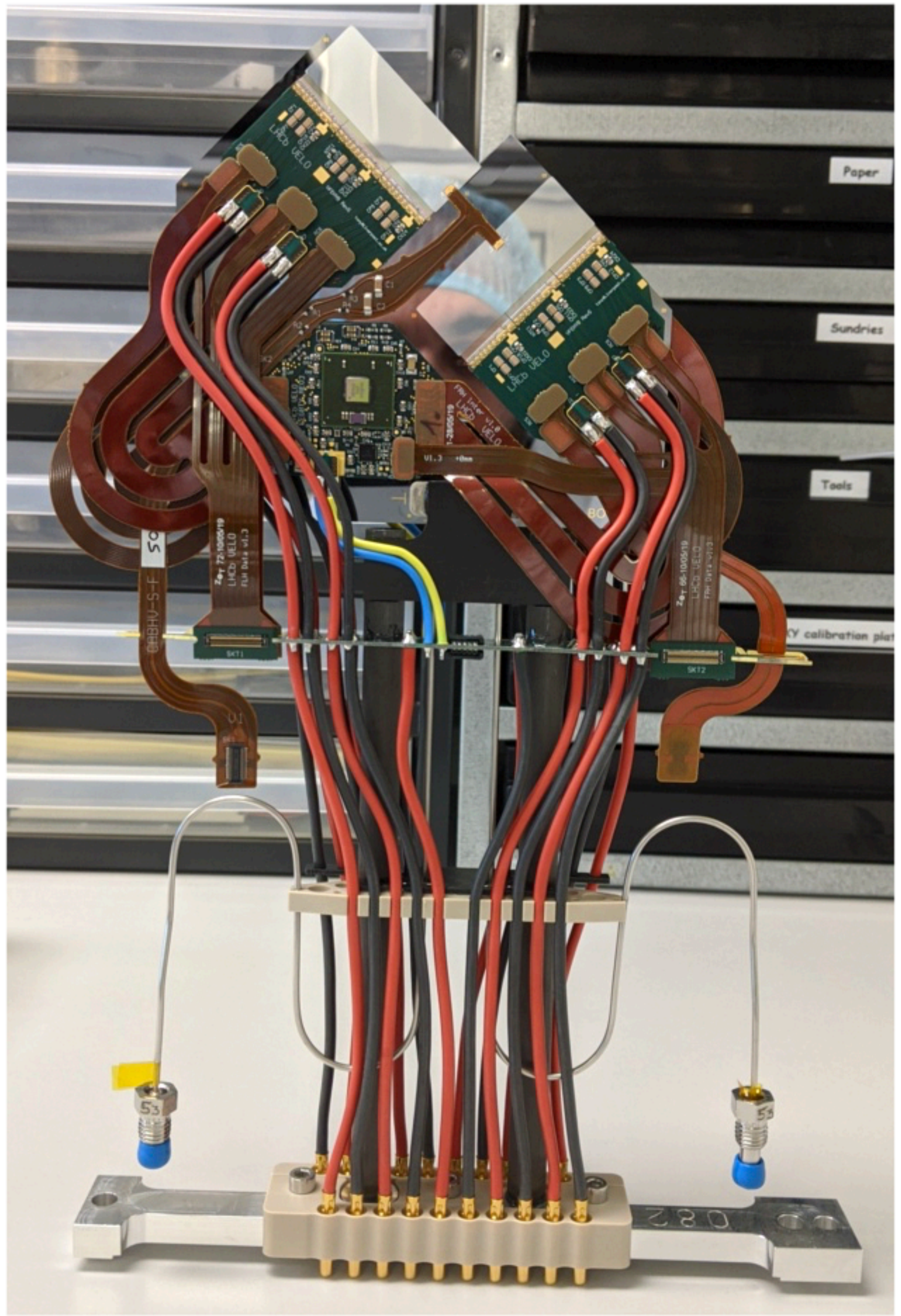
No PPE shortage will stop the VELO production



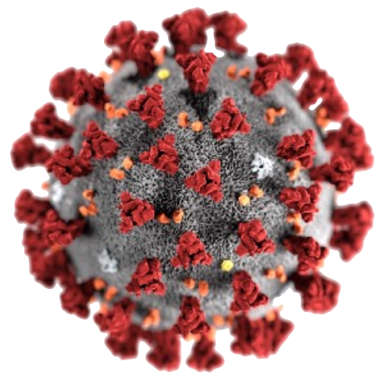
-free module from Nikhef

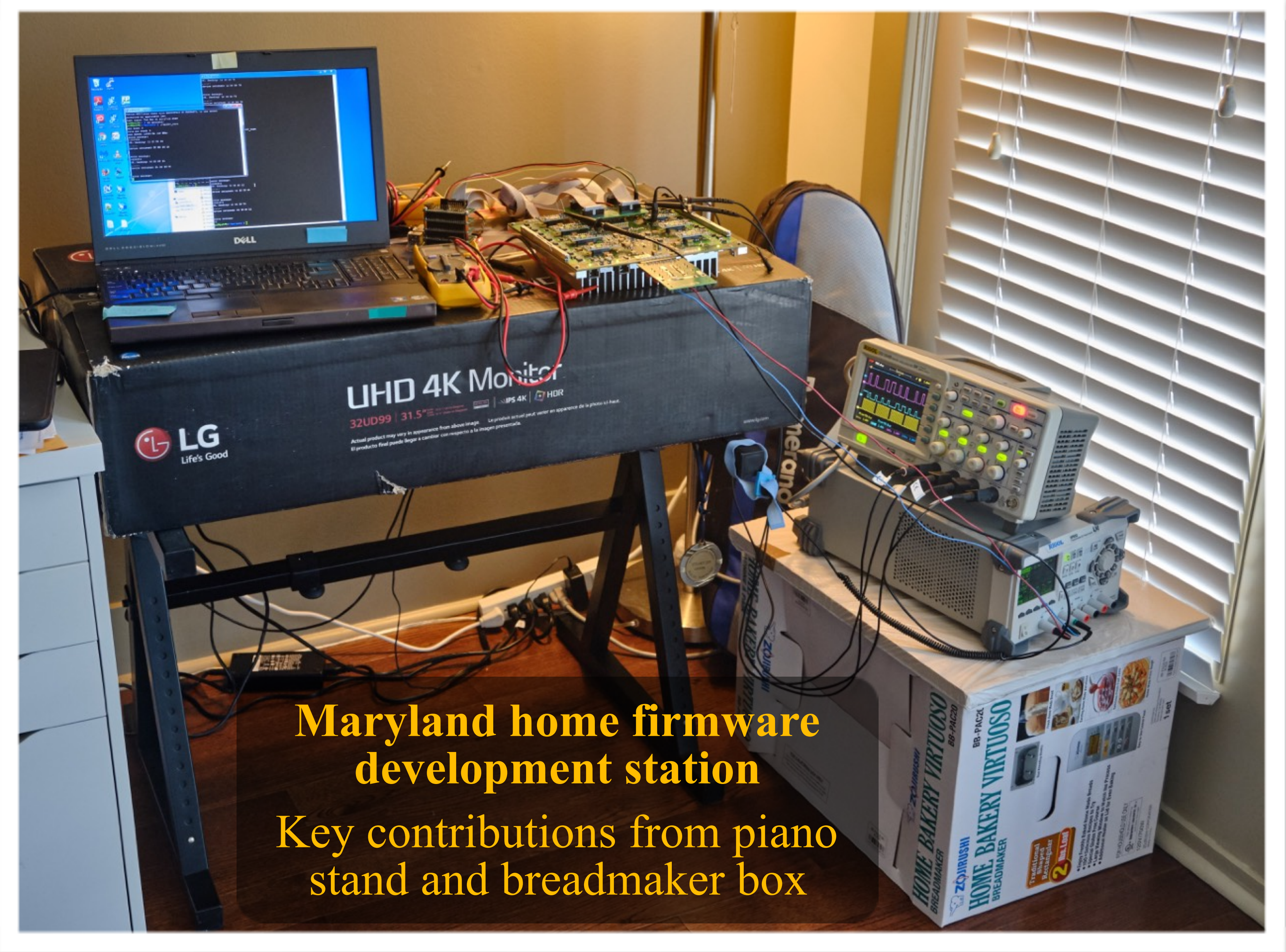


-free module from Manchester



COVID-19 impact and project status

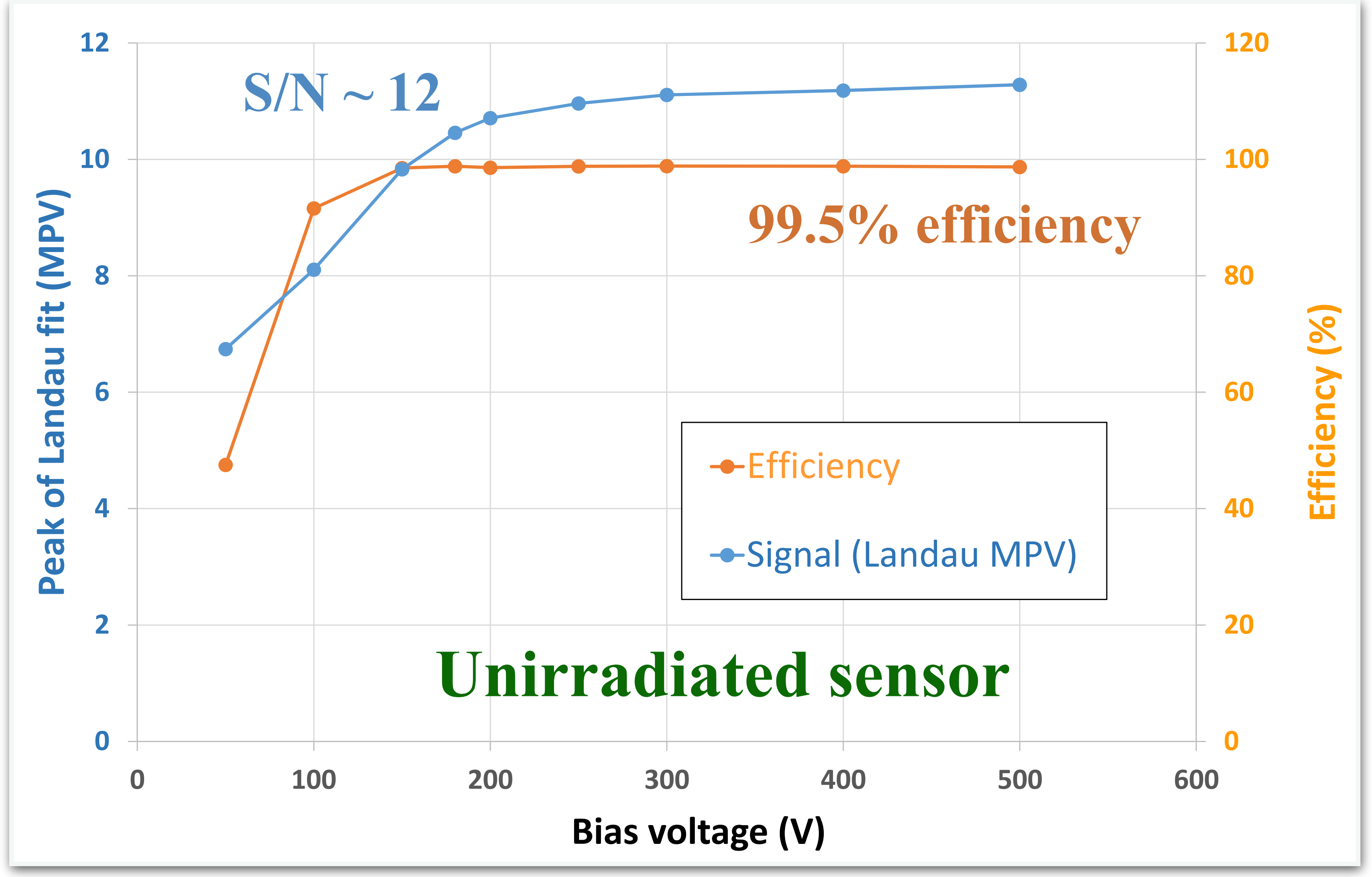


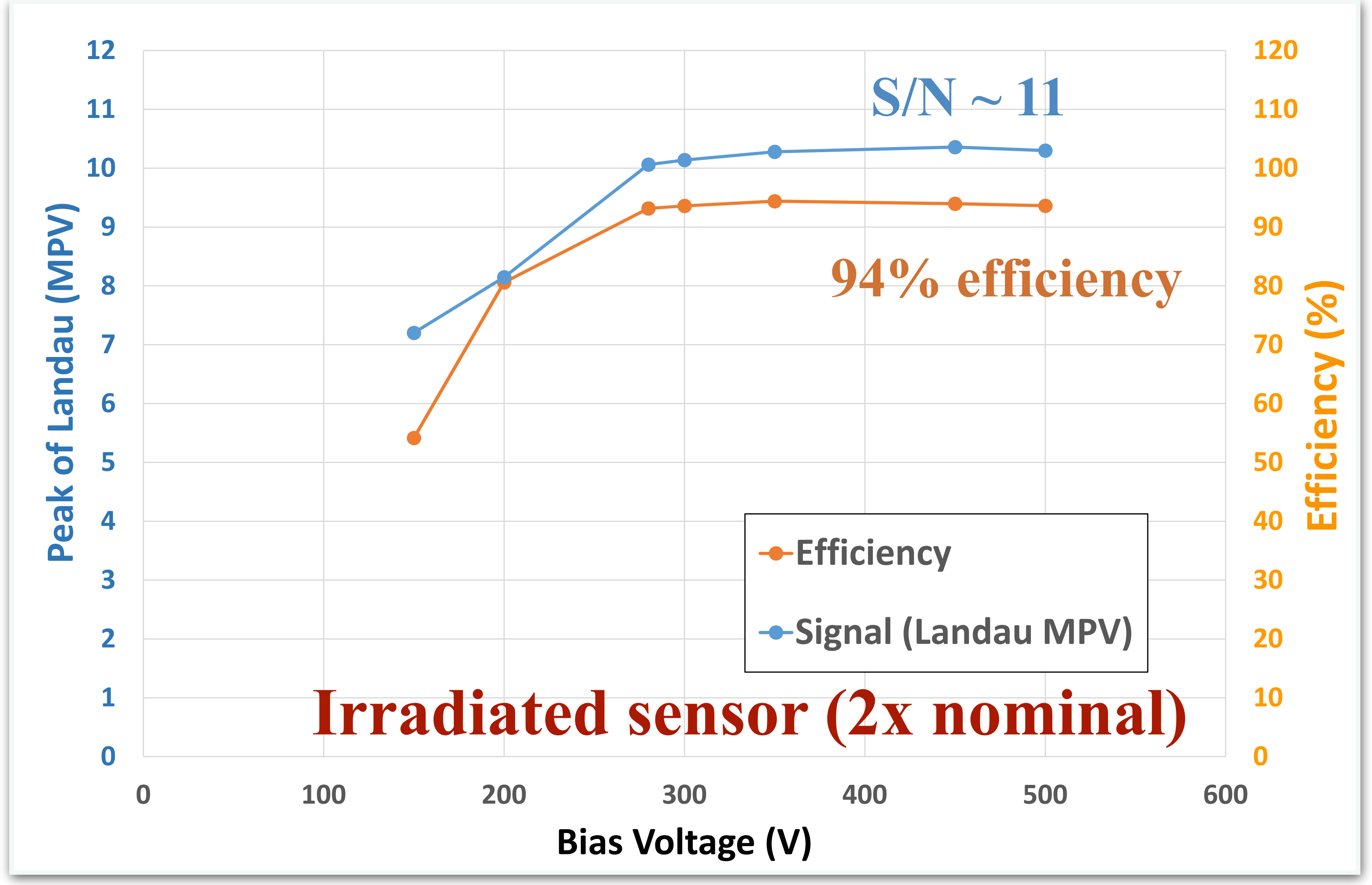


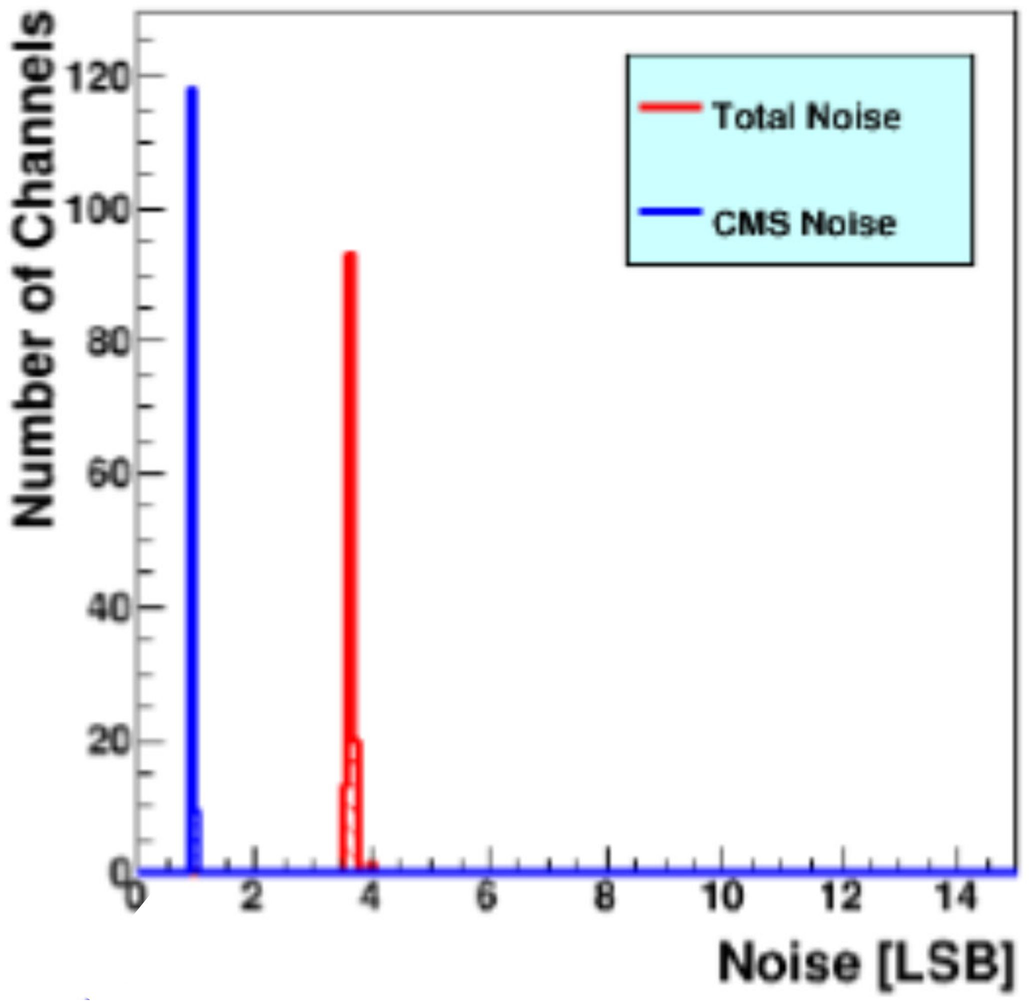
- Operations severely impacted by lockdowns set up to stop the spread of COVID-19
  - Some activities such as design or fw/sw development continued
- **Most components delivered**
- **Ongoing activities**
  - Hybrid and readout electronics qualification
  - Module production and stave assembly
  - Cabling, soldering, and mechanics assembly/procurement
- **Key challenges**
  - **Inner ASIC** and **8-ASIC hybrid designs** to be validated
  - **Manpower at CERN** for installation and commissioning
- **On track to meet updated LS2 schedule**, but no contingency!

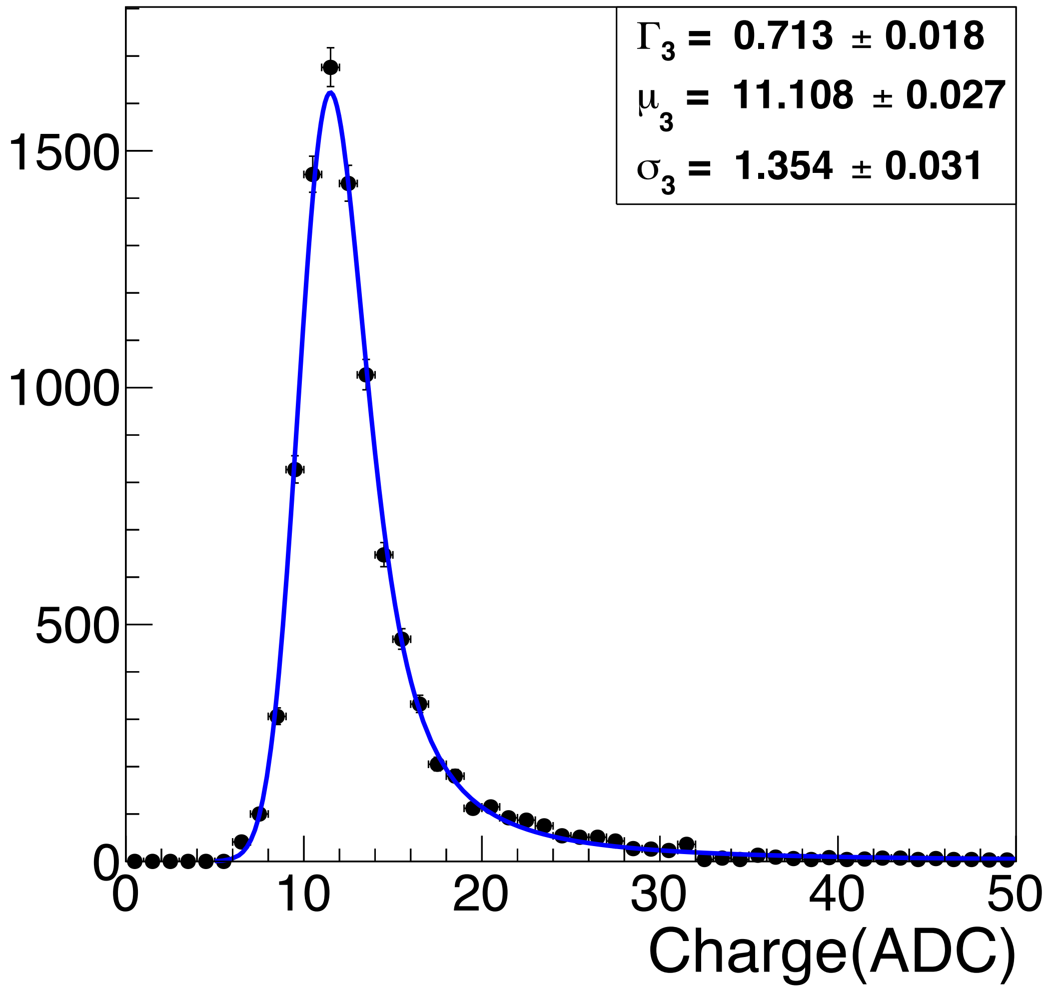
Sensor+ASIC characterization

- **Beam test** at Fermilab (March 2019)
- Type A **unirradiated sensor**
  - ➡ **99.5% efficiency** and **SN ~ 12**
- Type B sensor **irradiated** to **2x maximum dose**
  - ➡ **94% efficiency** and **SN ~ 11**
    - ✦ Partly due to readout limitation, **most efficiency will be recovered with LHCb readout**









Final system expected to have single-hit **high efficiency** (> 99%) and **good signal-to-noise ratio** throughout experiment lifetime

M. Artuso et al, "First Beam Test of UT Sensors with the SALT 3.0 Readout ASIC" (2019) DOI:10.2172/1568842