ADVANCING PRECISION: CMS PHASE-2 OUTER TRACKER UPGRADE AND INNOVATIONS IN ONLINE MUON RECONSTRUCTION

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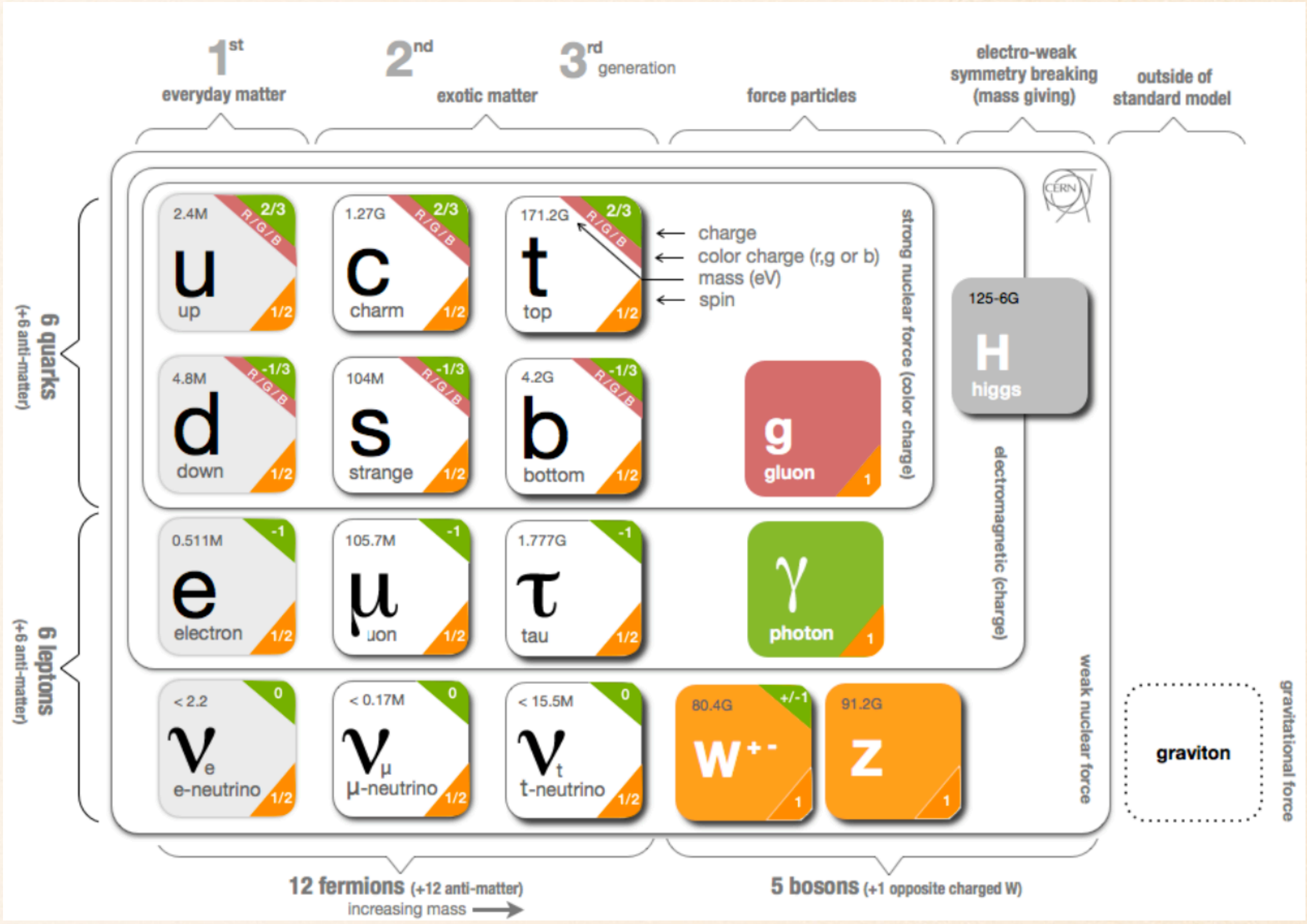
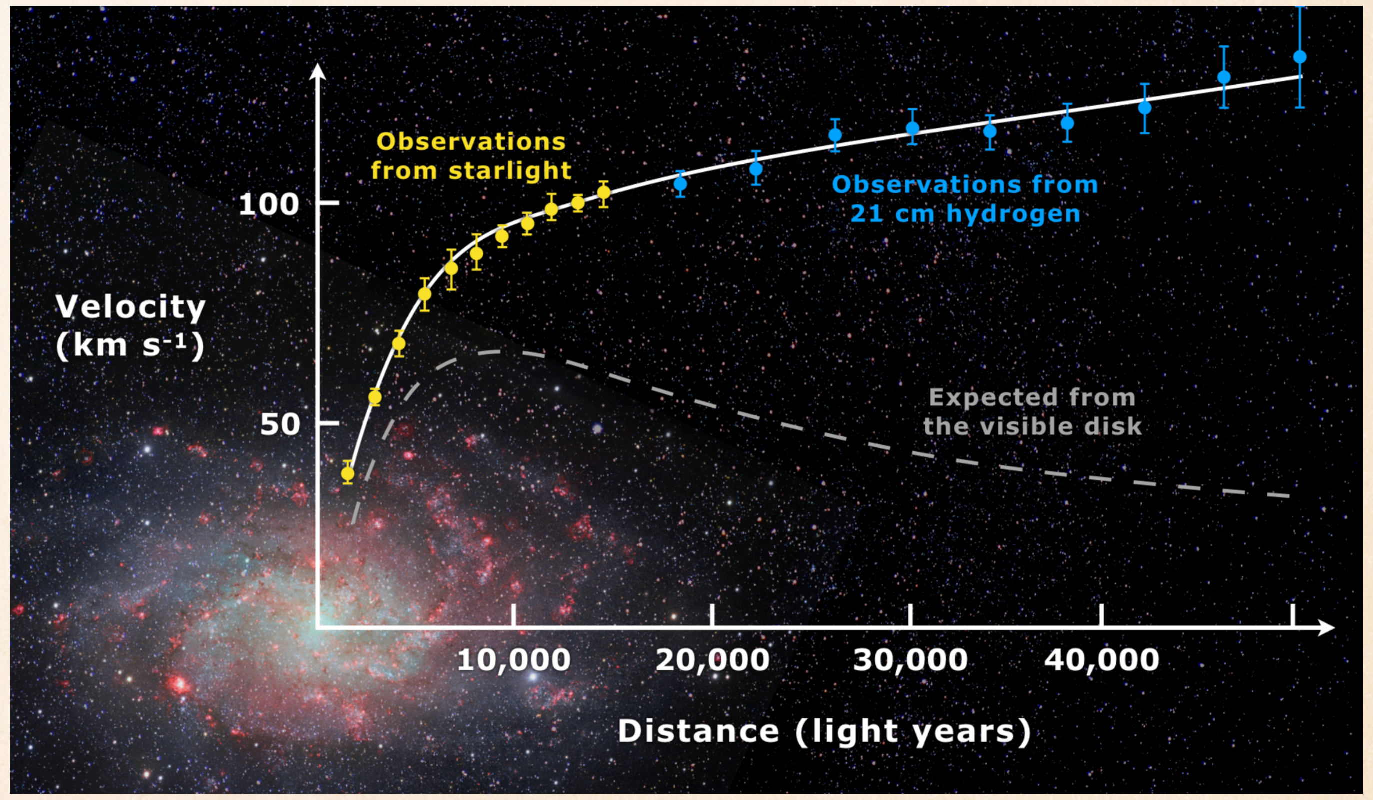
OUTLINE

- Introduction
- CMS Outer Tracker Upgrade
- Muon Reconstruction @ HLT
- Projection of Higgs to muon coupling with Phase-2 detector

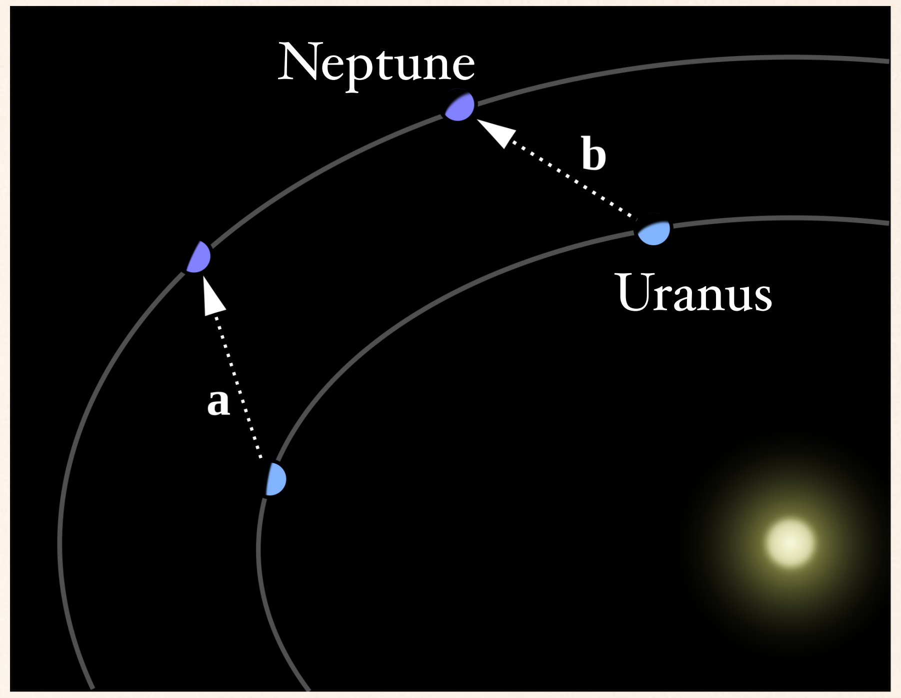
WE ARE LIVING IN THE DARK

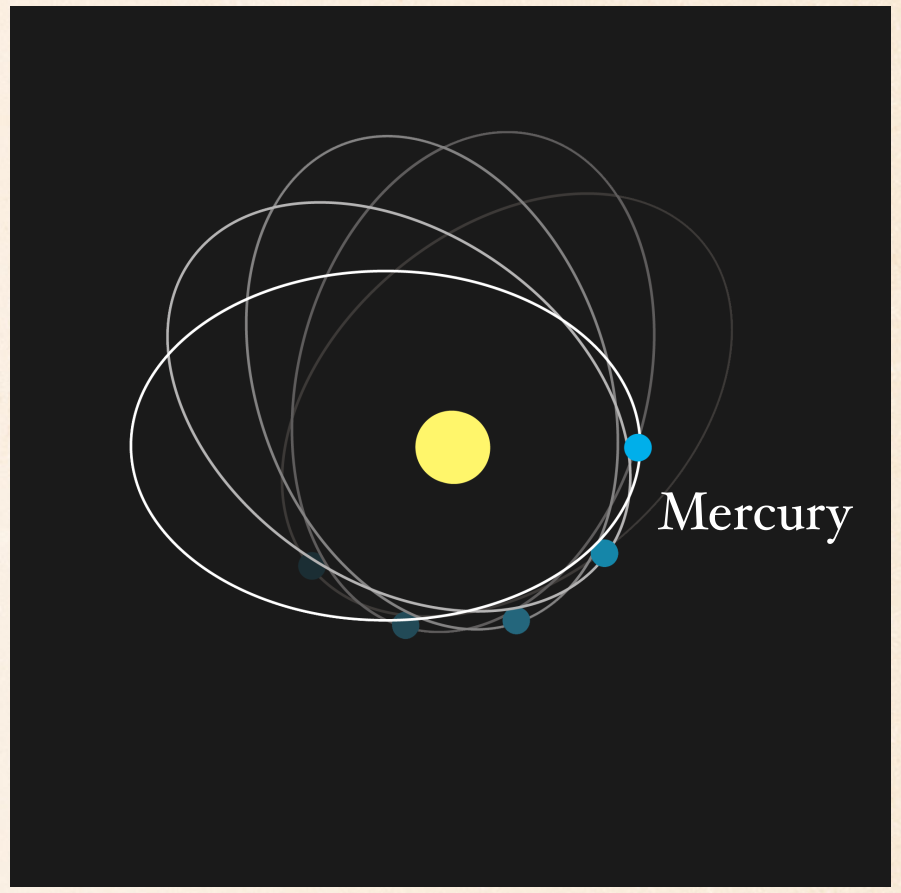
- Why are there **three particle generations?**
- What causes **the particles to posses their specific masses?**
- Why there is **only one Higgs bosons? Are there more?**
- Through what **mechanism neutrinos acquire mass?**
- What is the **source of CP violation? Where are all the antimatter?**
- **Does dark matter truly permeate the Universe?**
- **Is dark energy a component of the cosmic landscape?**





PRECISION AS A DISCOVERY TOOL

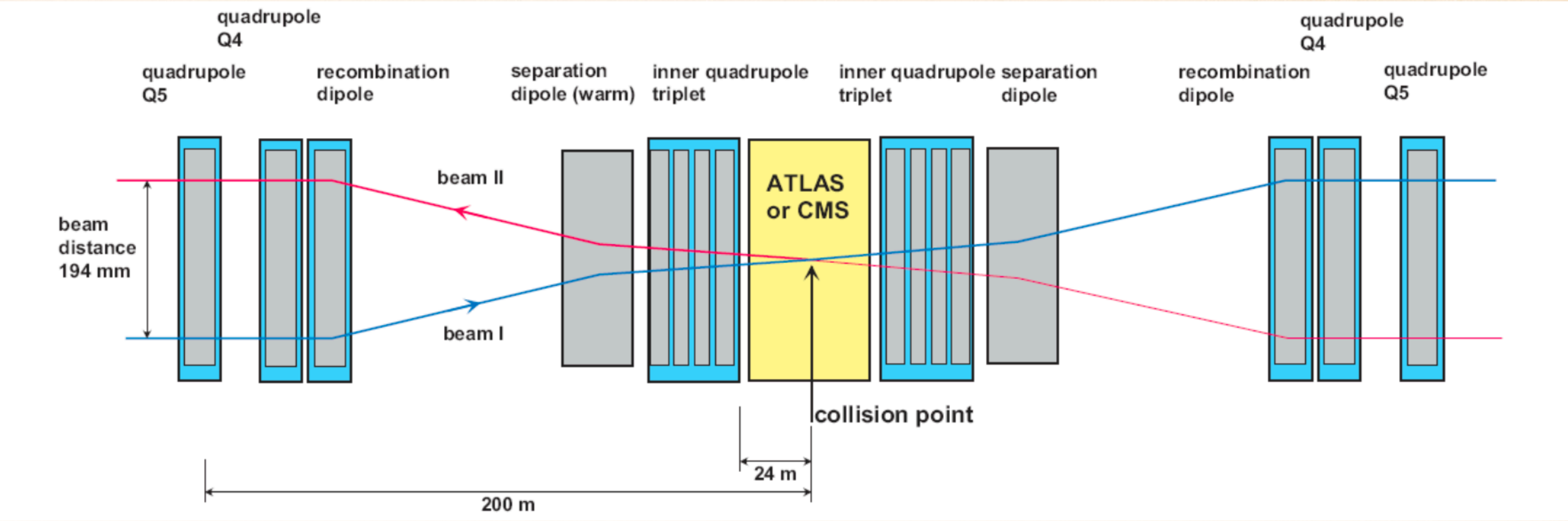


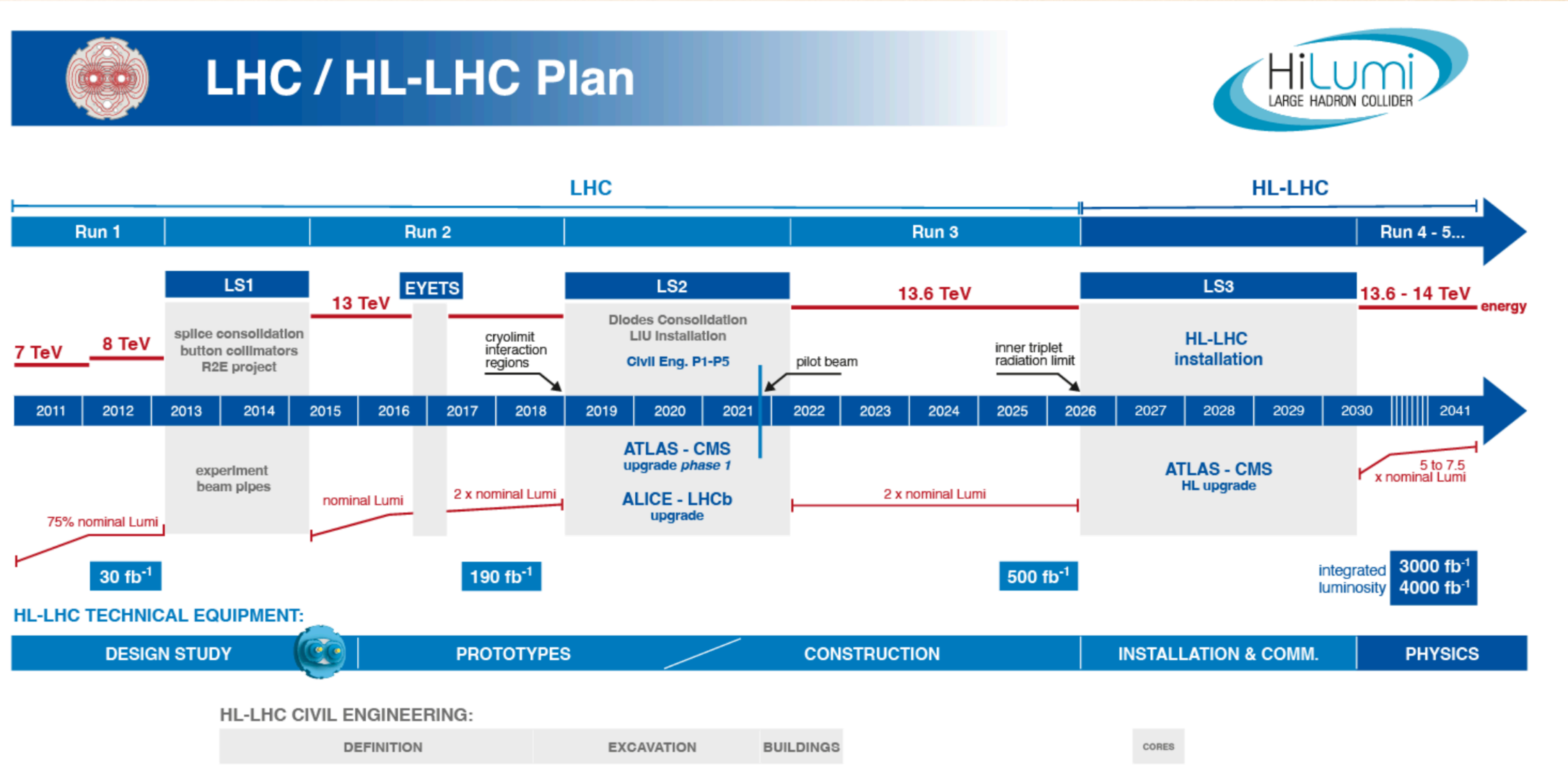


- **From the past experiences:**
  - Uranus anomalous trajectory → Neptune
  - Mercury perihelion → General Relativity
  - Z/W interactions to quark and leptons → Higgs boson.
- At times when we have no precise theoretical guidance, we need powerful experimental tools to make progress.

LARGE HADRON COLLIDER (HIGH LUMI)

- A Torch !!!
- Instantaneous luminosity, $\mathcal{L} = \frac{N^2 n f_{rev}}{4\pi\epsilon\beta^*}$
  - Increase number of protons in each bunch (N)
  - Increase number of bunches (n)
  - Reduce emittance (ϵ) and β^*
- Instantaneous Luminosity **5-7 times higher** than nominal LHC.
- **High luminosity LHC will enable us to get a lot more out of LHC than we have been able to get so far.**
- **Look at very rare processes of nature.**





OPPORTUNITIES

- **Standard Model:Higgs Physics:**
  - Precise measurements and Constraints within the Standard Model.
- **Higgs Physics:**
  - Detailed analysis of the Higgs properties
  - Search for new phenomenon in the Higgs sector.
- **BSM Searches:**
  - Search for Long Lived particles
  - Supersymmetry
  - Dark matter
  - Heavy resonances
- **Flavor:**
  - CKM metrology and QCD spectroscopy.
  - Rare decays -> Flavor anomaly
- **Heavy Ion:**
  - Precision study of material properties of QCD media.
  - Study of HI-like behaviour in the small systems (pp or pA)

3 Billion top/exp

Higgs Factory:
150 Million Higgs and 120k HH

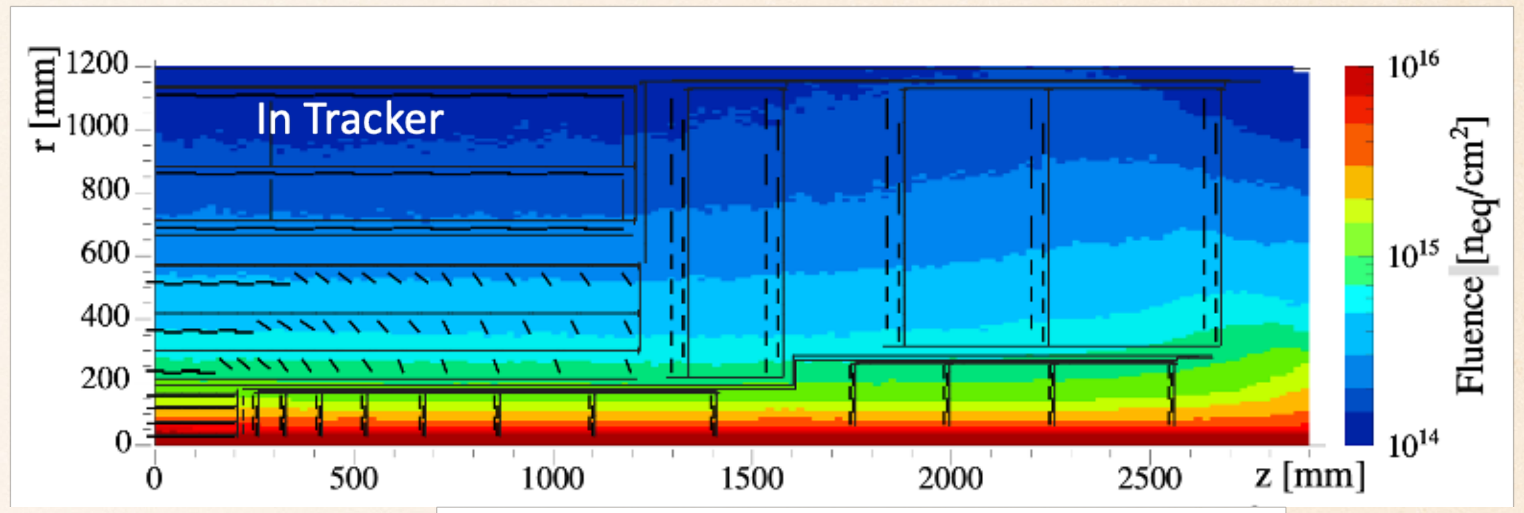
Novel approaches, better detectors: stringent tests of BSM scenarios

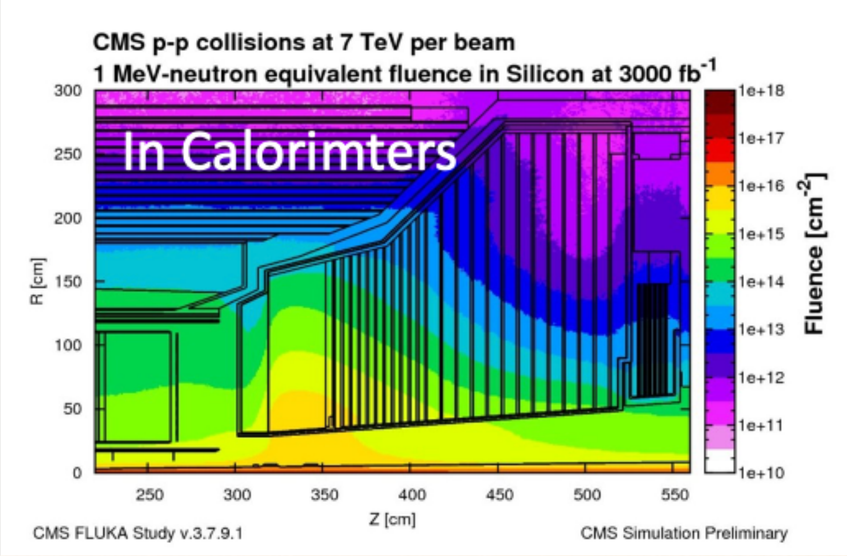
Low-P_T/high-P_T complementarity

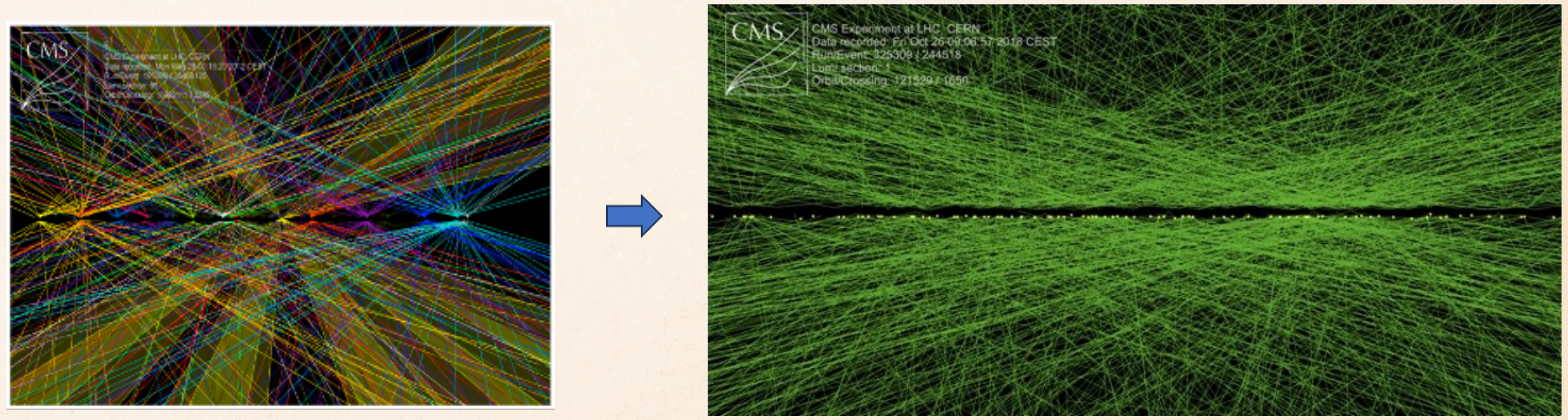
Precise differential measurements

MAIN CHALLENGES

- **Expect unprecedented amount of radiation**
  - Ionising Doses of up to 1 Grad (surface damage)
  - Fluences up to 2 × 10^{16} n_{eq}/cm^2 (displacement damage)
  - Rate up to 3 GHz/cm^2
- **Large number of overlapping collisions: Pile-up**
  - Luminosity levelling with up to 200 pp interactions per bunch crossing every 25 ns (40 MHz) 3-4 times current LHC Runs.
  - Vertex and track reconstruction algorithms less discriminating.
  - Existing trigger and readout bandwidth constraints imply tighter selection requirements to increase purity at the cost of signal acceptance.







COMPACT MUON SOLENOID (UPGRADE)

Upgraded Trigger and Data Acquisition system:

- Tracking in L1 at 40 MHz. Output rate 750 kHz.
- Latency 12.5 μs, longer pipelines.
- High Level Trigger output 7.5 kHz

Trigger requirements are driving most of the electronics upgrades

750 kHz

L1 Trigger Rate

100 kHz

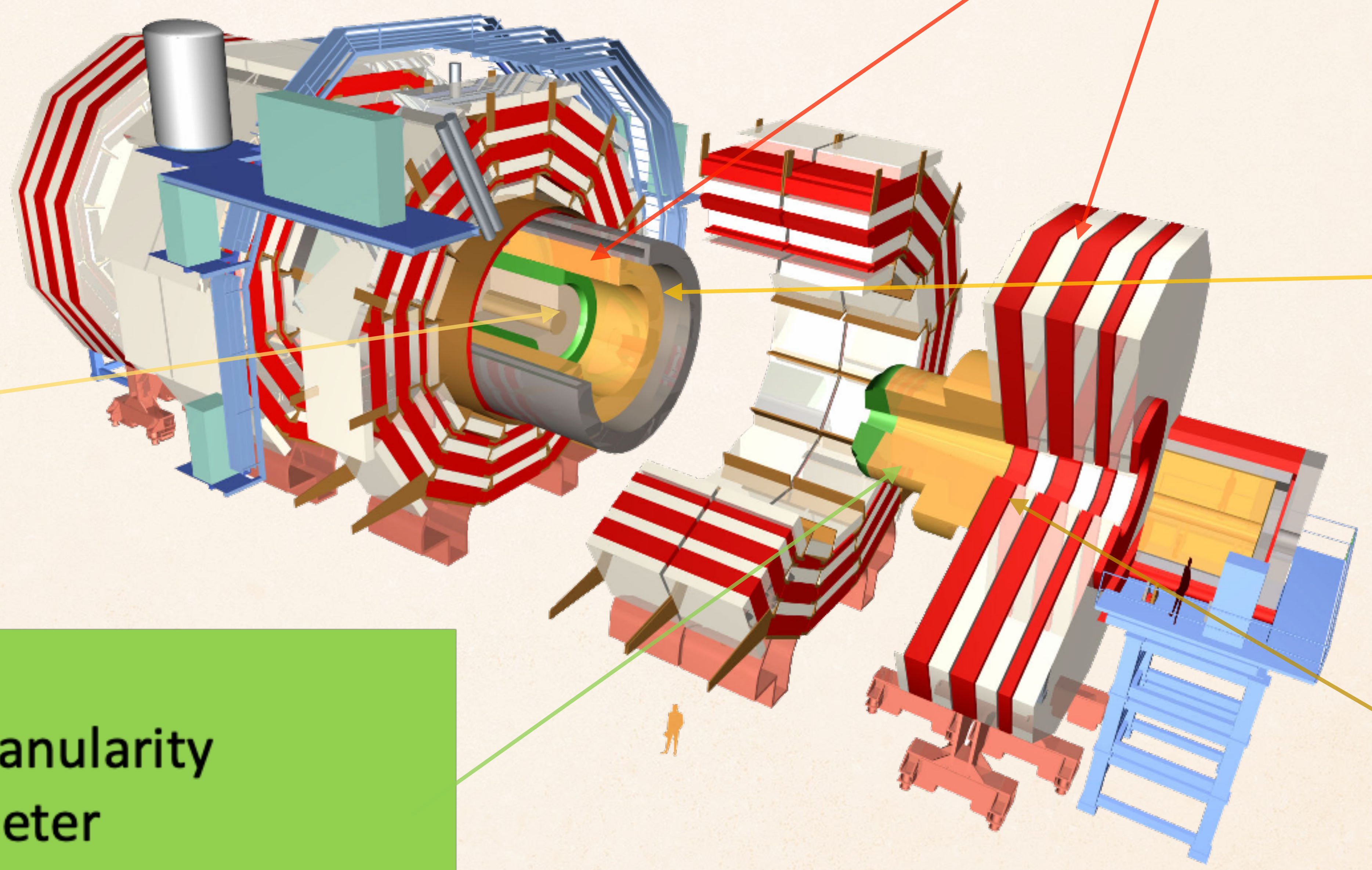
7.5 kHz

High Level Trigger Rate

1 kHz

Electronics upgrade: Barrel Calorimeter and muon system

NEW
MIP Timing detector precision timing for pileup mitigation

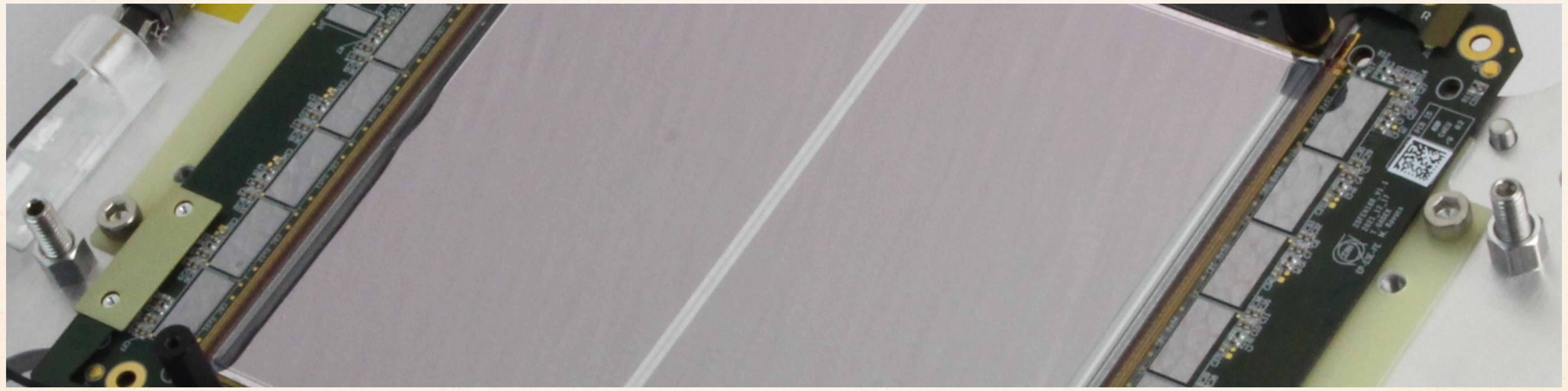


NEW
Inner Tracker, coverage up to |η|= 3.8, reduced material

NEW
High-granularity calorimeter endcap

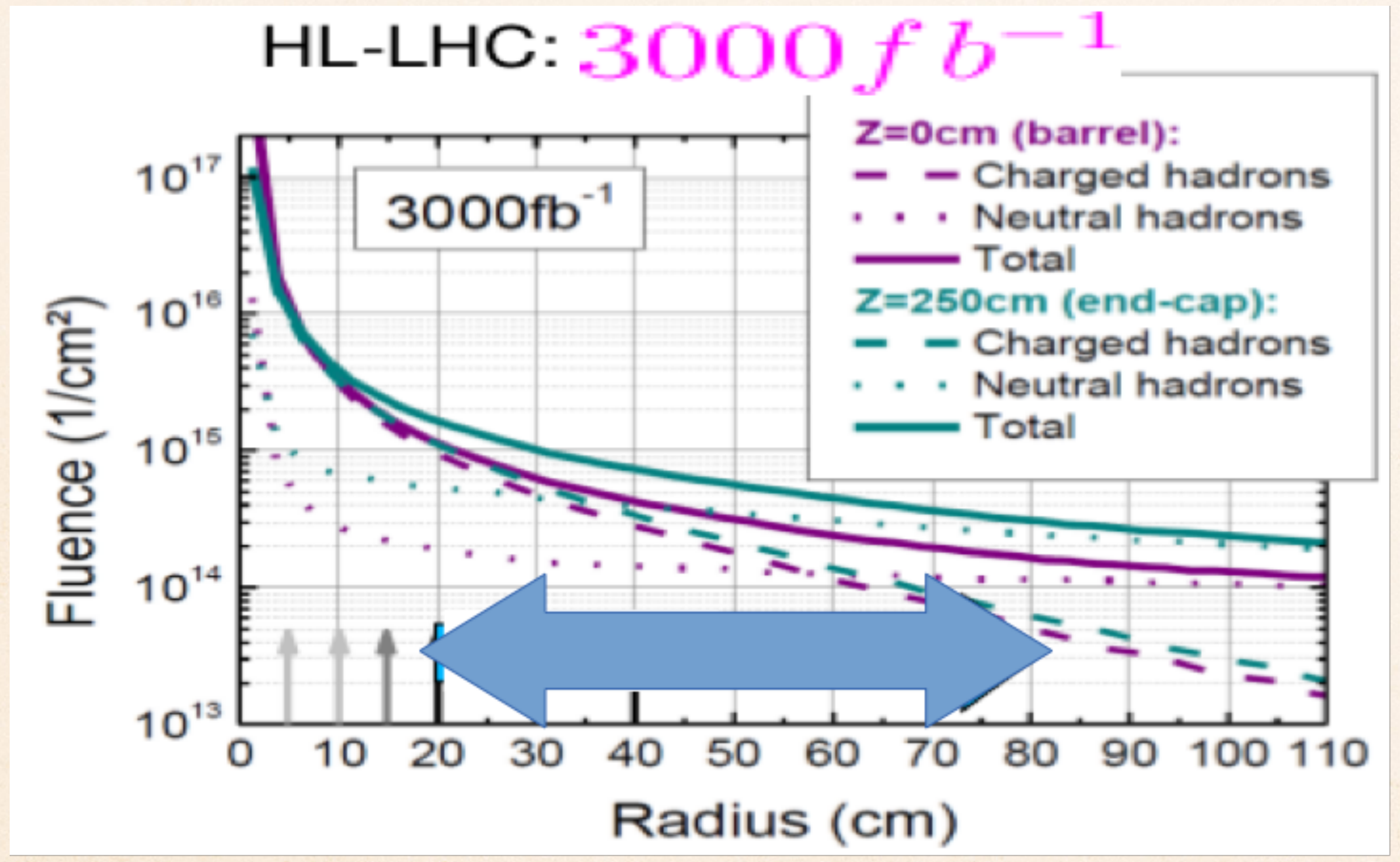
NEW
Muon detector
GEM/RPC 1.6<η<2.4

THE CMS OUTER TRACKER UPGRADE FOR THE HIGH LUMINOSITY LHC

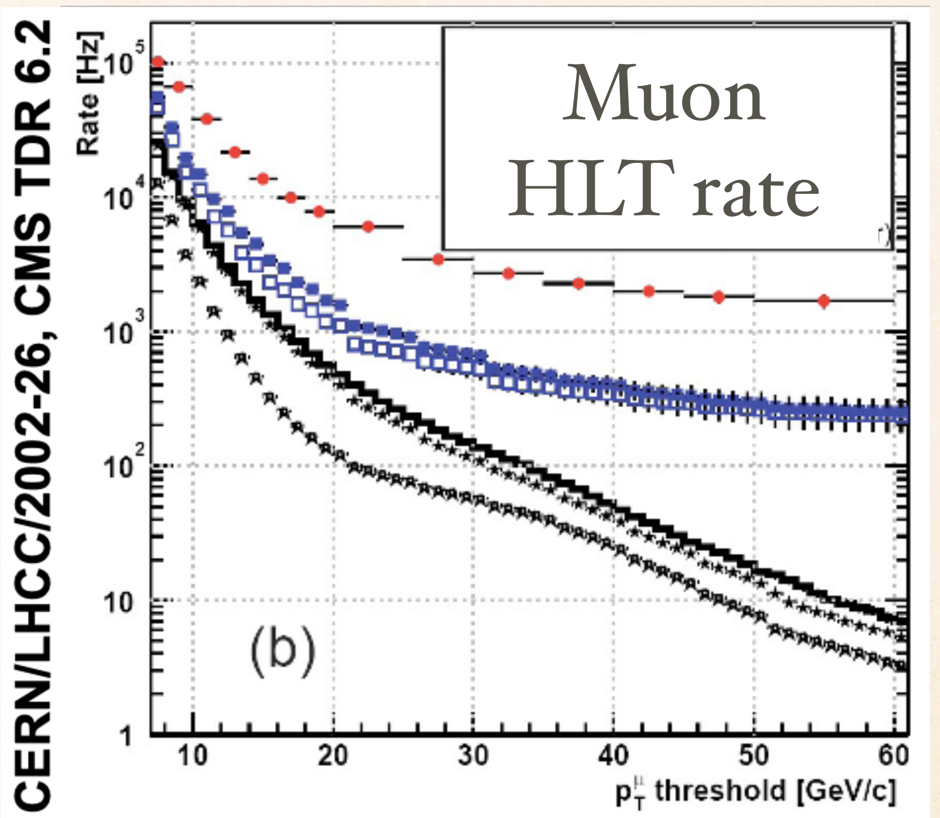


REQUIREMENTS AND SOLUTIONS

- **Main Requirements:**
  - Capable to deal with hit, track and data rates expected for 7.5 x 10^{34} $cm^{-2}s^{-1}$
  - Radiation-tolerance up to 2 x 10^{16} n_{eq}/cm^2
  - Sharper L1 trigger thresholds
  - Improve track measurement



- **Potential Solutions:**
  - Higher granularity (Shorter Strips)
  - Radiation hard sensors and low temperature operation.
  - Tracker Contribute to the L1 trigger
  - Reduce material (better low p_T track reconstruction)
  - Reduce average pitch (better high p_T track reconstruction)

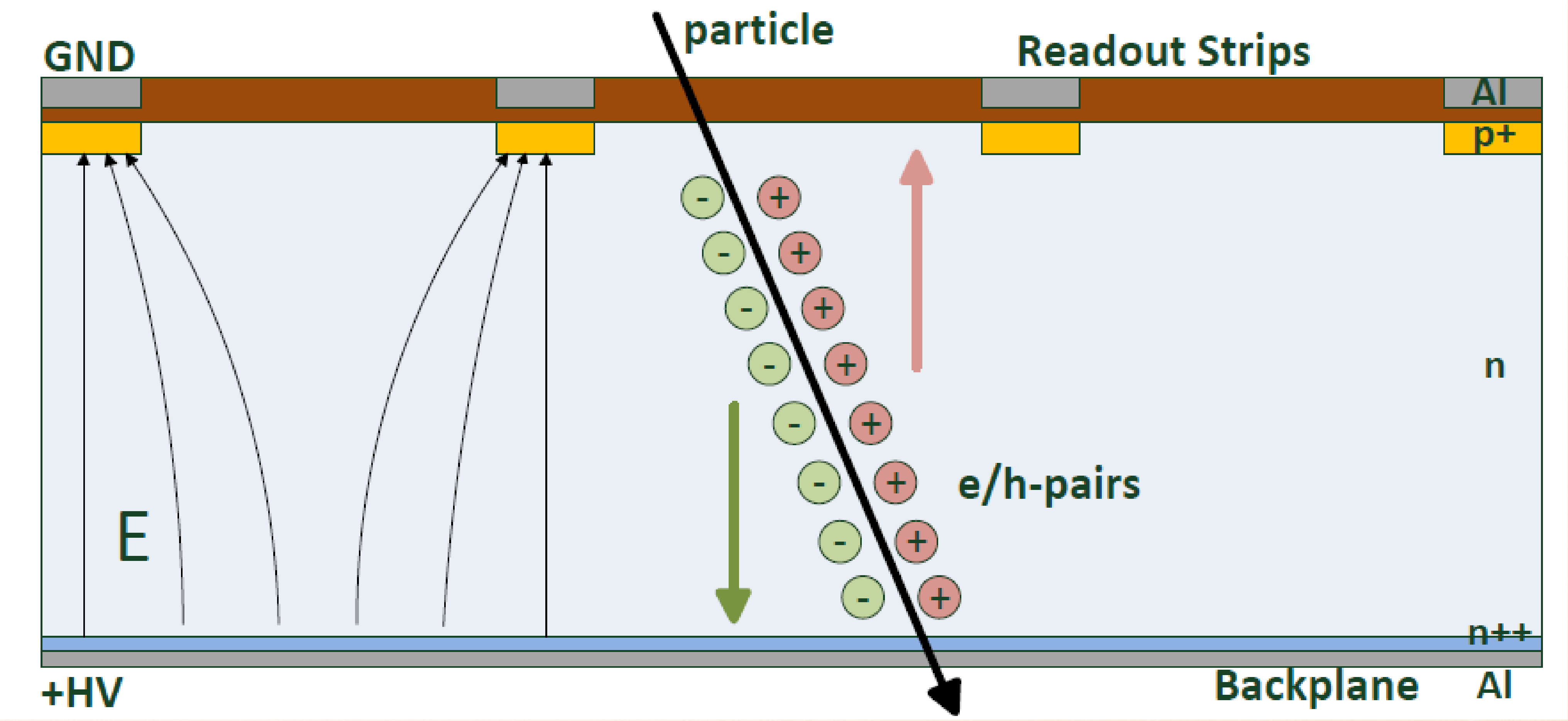


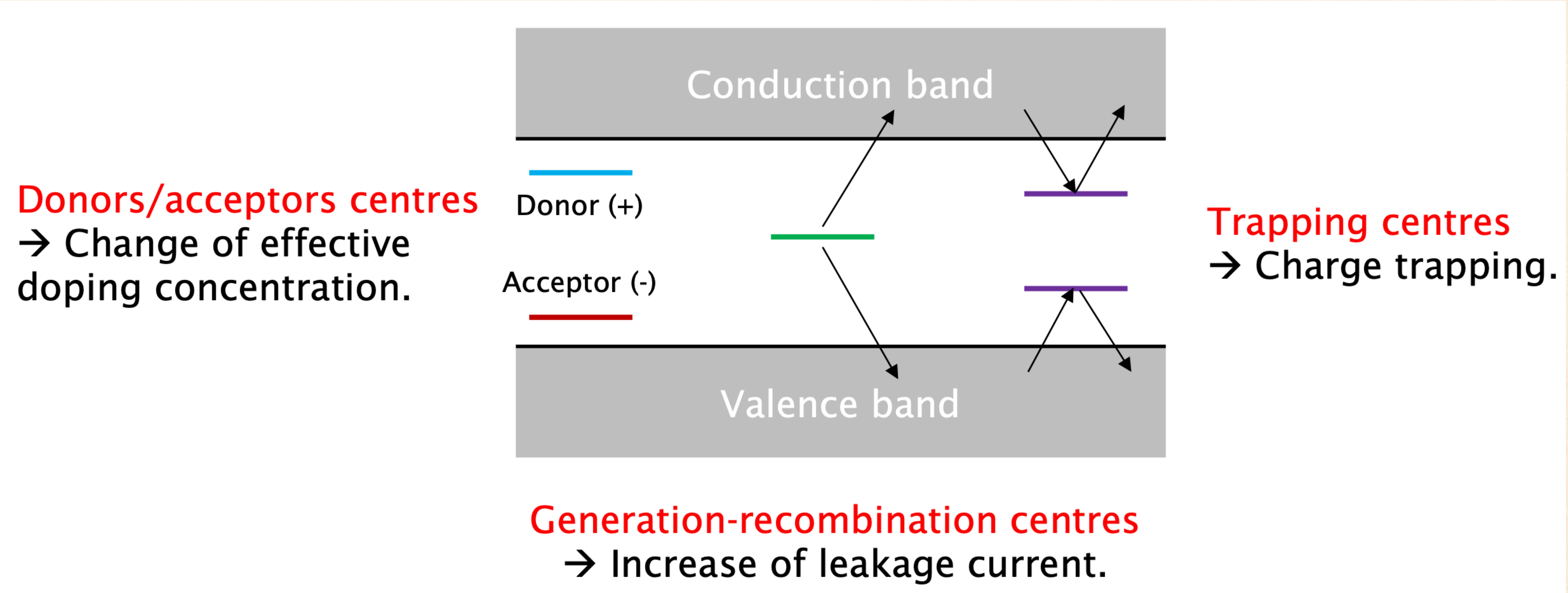
Without Tracker

Using Tracker

SILICON MODULES

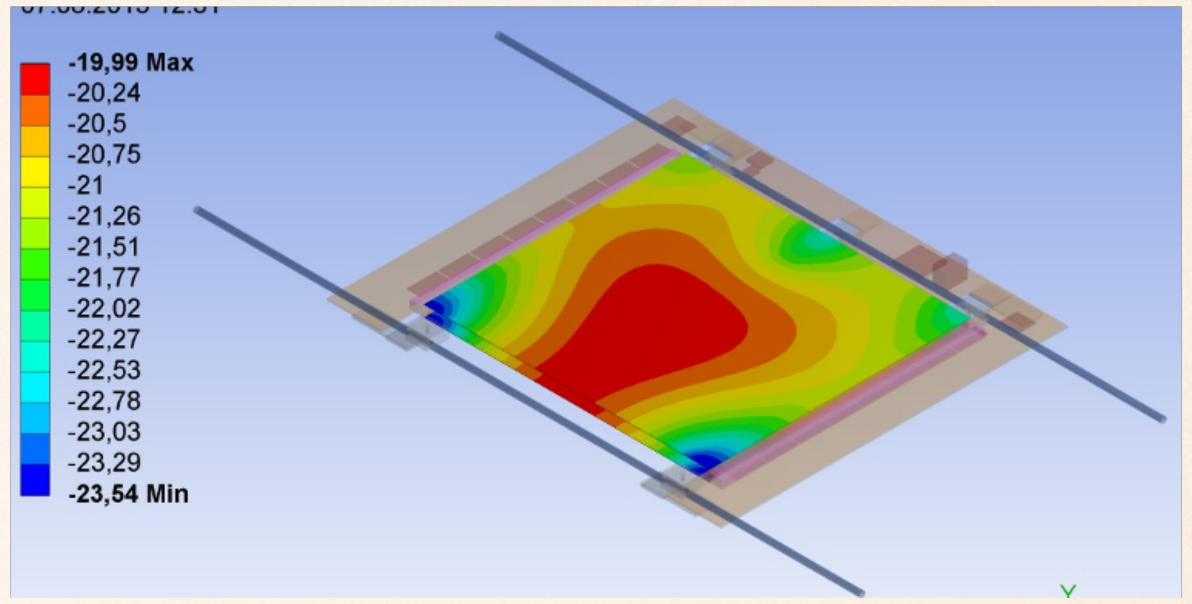
- **Why Silicon?**
  - Moderate Band Gap: $E_g = 1.12$ eV
    Comparatively lower than for **gas detectors 30 eV** or for **scintillator 100 eV**.
  - **High Carrier Yield:** Provides better energy resolution and stronger signals.
  - **Fast charge collection** (<10 ns)
  - **High Radiation Hardness:** Intrinsically resilient to radiation, extending detector longevity.
  - **Microelectronics Compatibility:** Leverages proven industrial techniques for cost-effective, precise manufacturing.
- **Electron-hole-pairs generated by ionizing particles traversing the silicon are separated by E-field and 'drift' to the electrodes**
- **Most probable MIP signal is ≈22,500 e/h pairs for 300 µm silicon.**

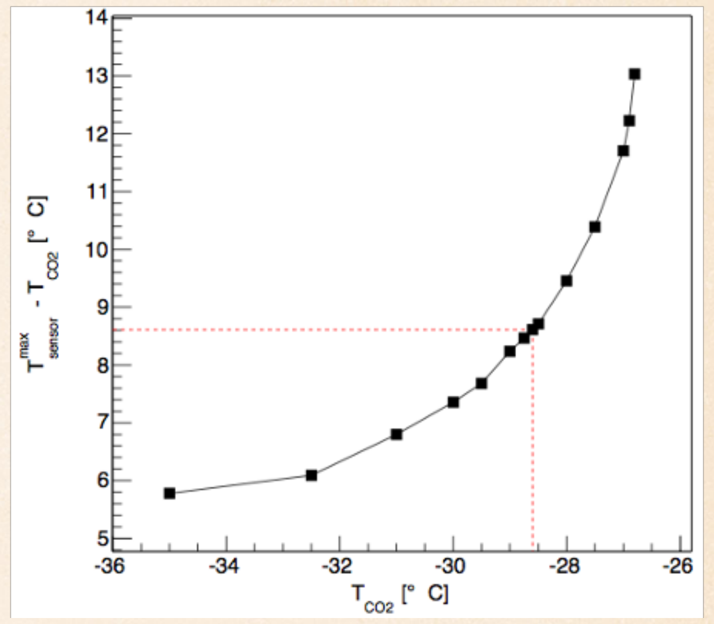




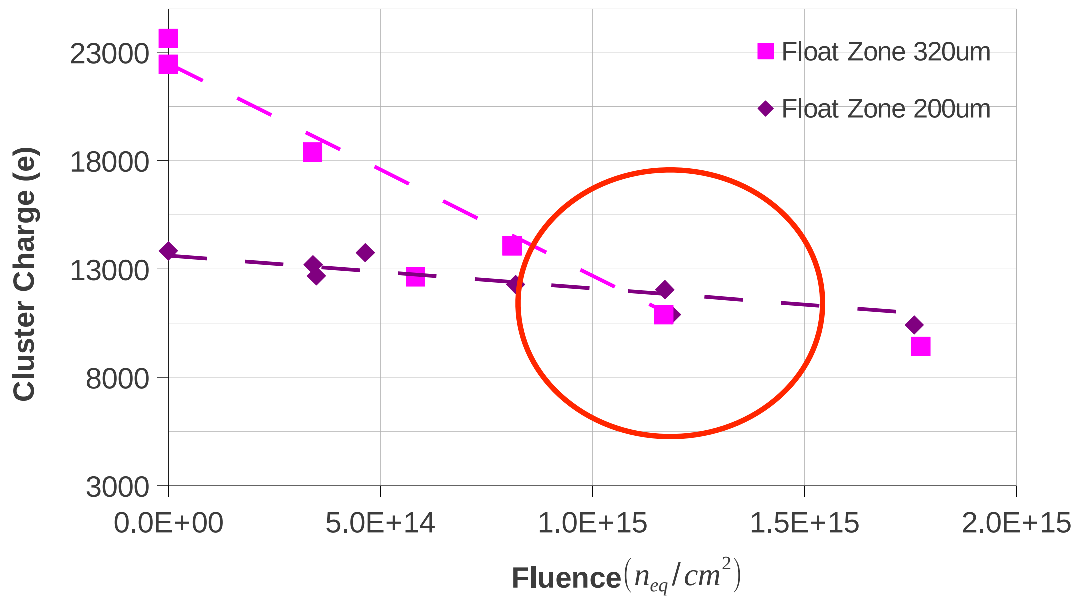
DESIGN CHOICES

- **Complex interplay between design choices**
  - Passive material
  - Sensor thickness
  - Detector longevity
  - ASIC power consumption
  - Channel density
  - Module geometry
- **All affecting detector performance**

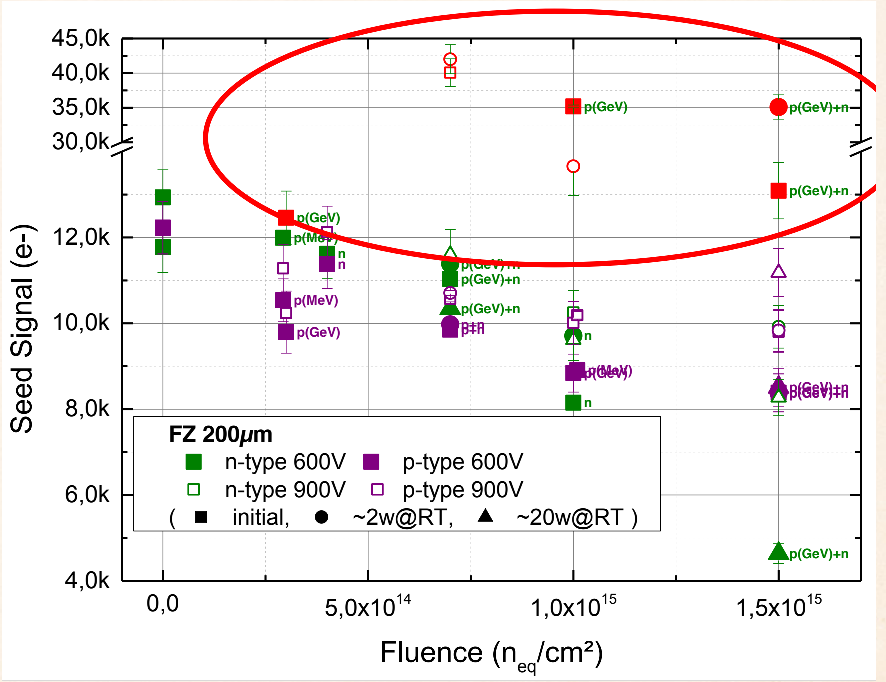




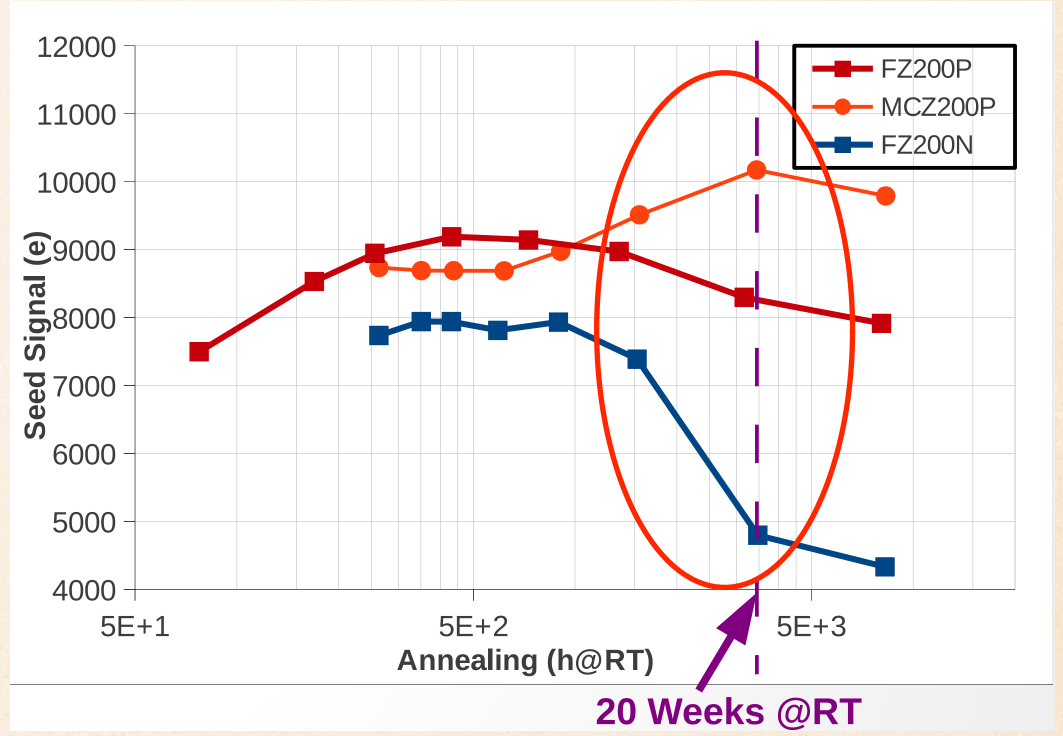
Thermal runaway if T_{CO_2} > -27° C



Thick sensors stop to deliver more signal than thin sensors at about Φ = 10^{15} n_{eq}/cm^2



With large fluence n-type deliver less signal than p-type or they are noisy

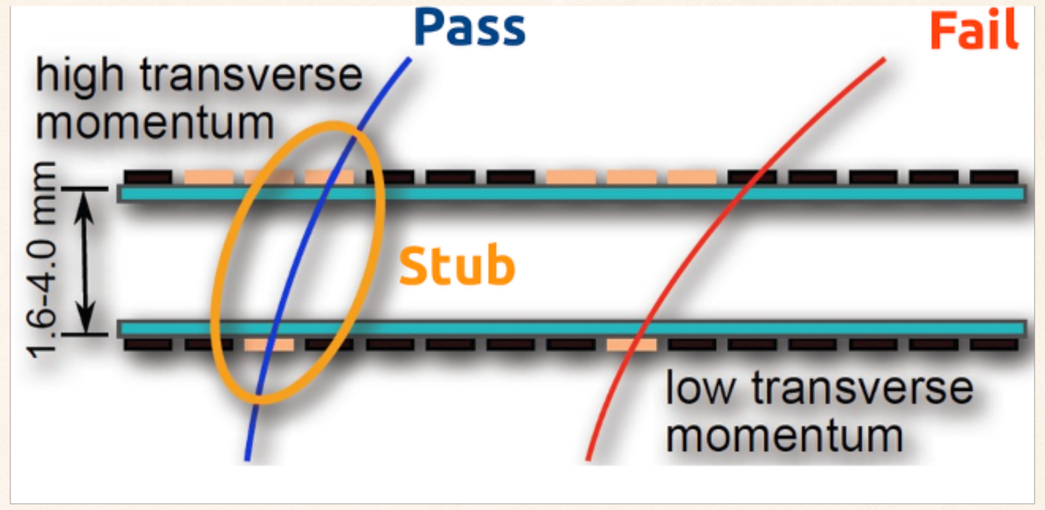


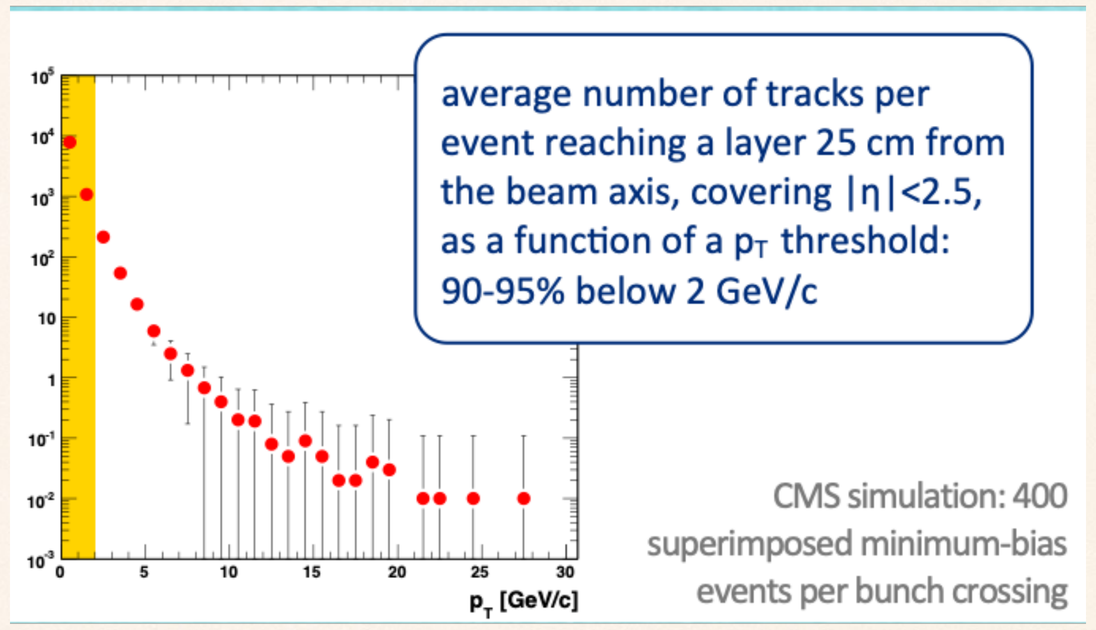
p-type sensors continue to deliver good signal (>8000 e-) even after 2 weeks at RT annealing

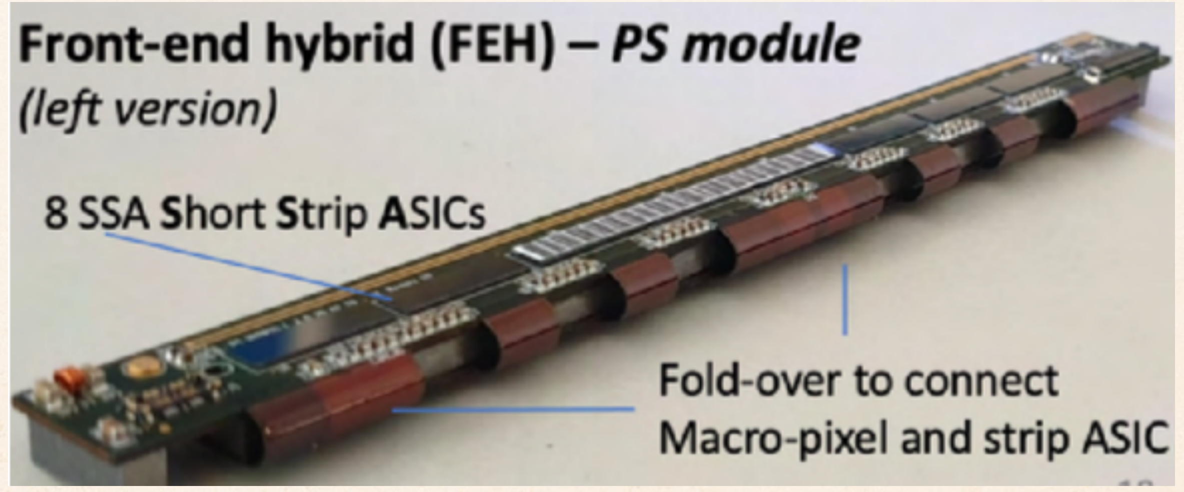
Very useful to decrease leakage current during shutdowns

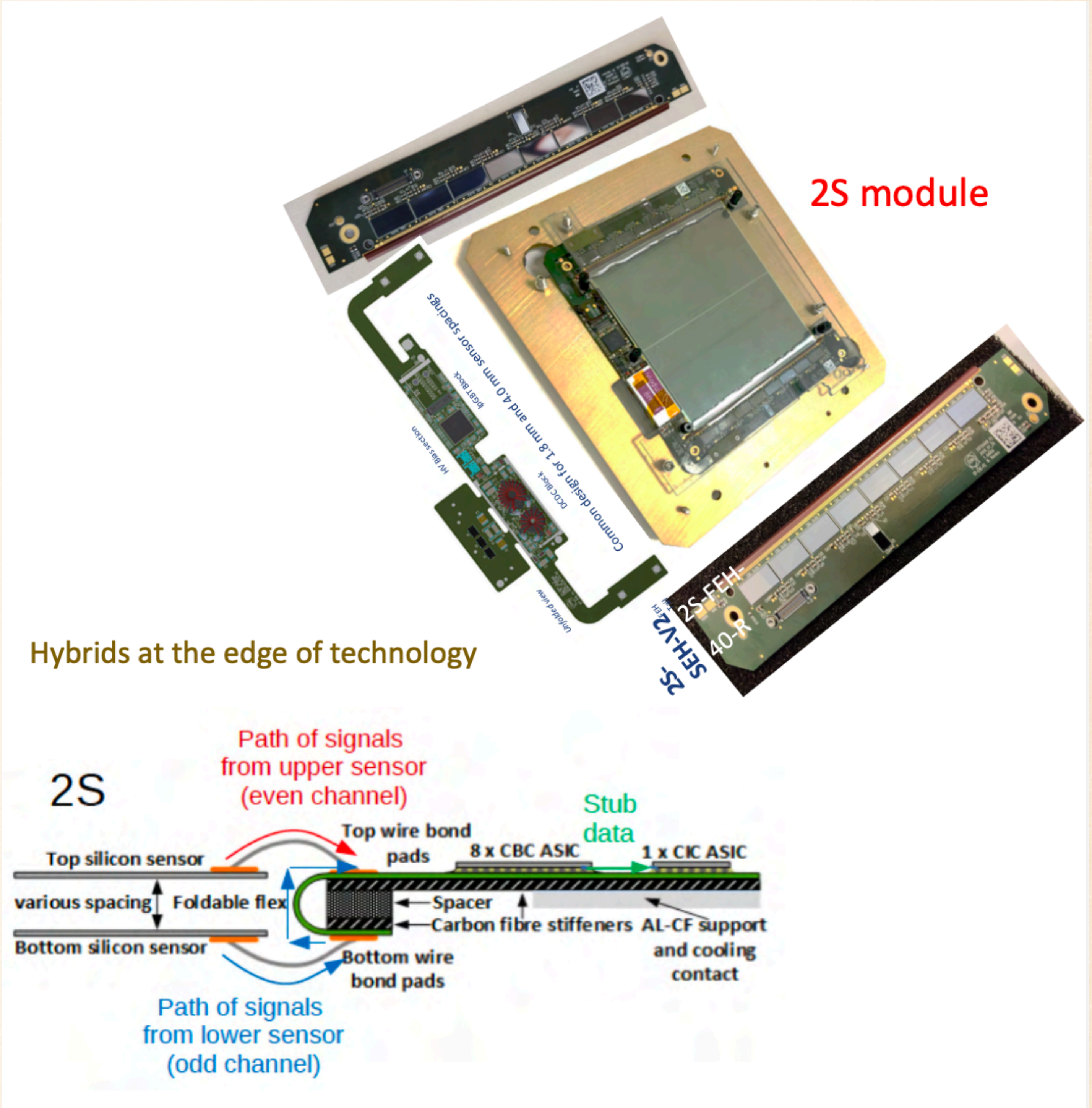
TRIGGER MODULE CONCEPT

- **Modules provide p_T discrimination in front-end electronics**
  - **New concept:**
    - Tag high p_T segments locally on the same module
    - Contains ALL electronics = full system
    - Effective way to have 2 space points in single mechanics - light weight
    - Frontend electronics gives Level-1 track finder 'vectors' instead of points
  - **Hybrids with fold-over:**
    - Allow to wire-bond both sensors to the same hybrid
    - Provide adequate stiffness for wire bonding
    - Minimize material
    - Complicated fabrication and delicate part!



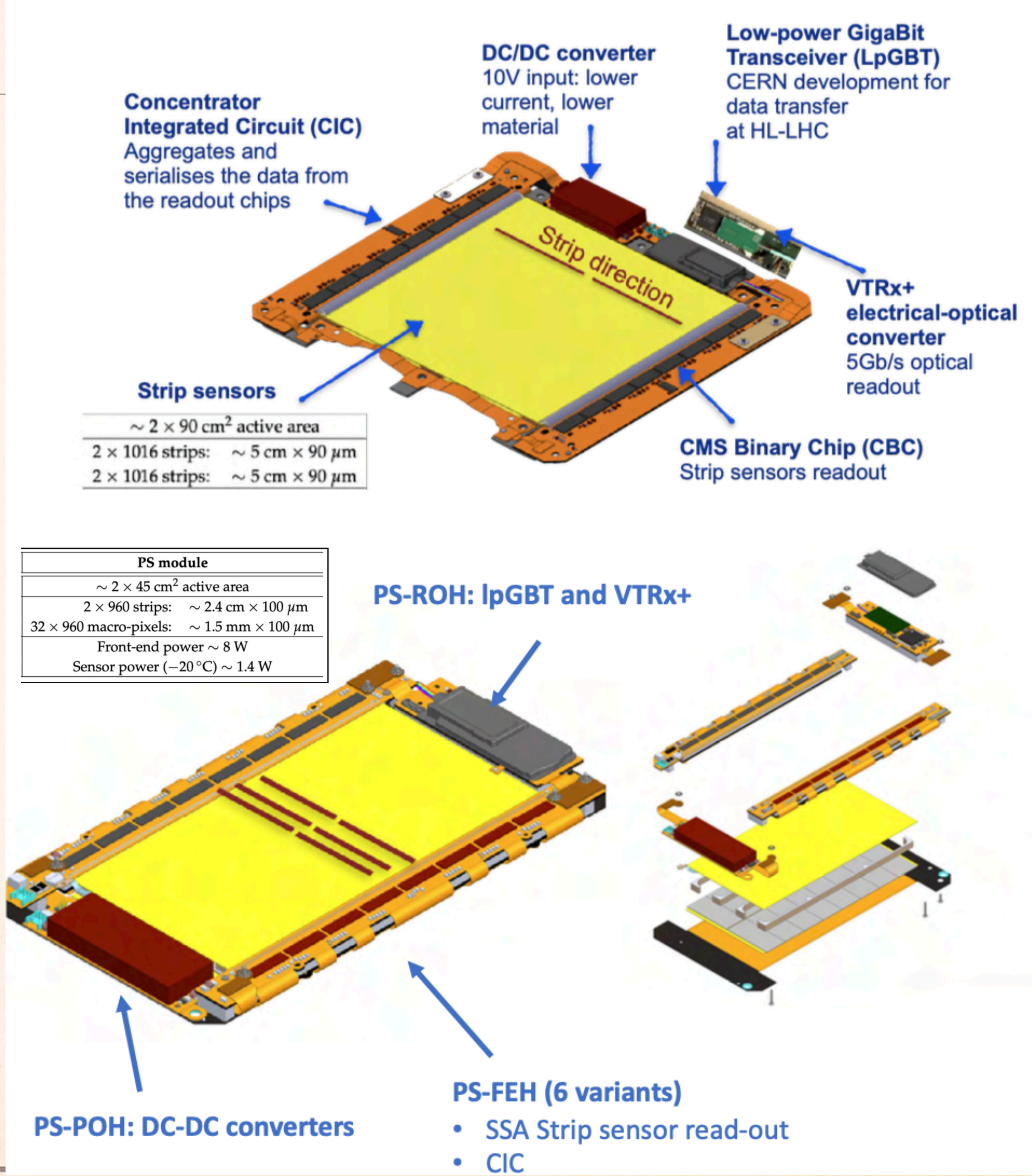






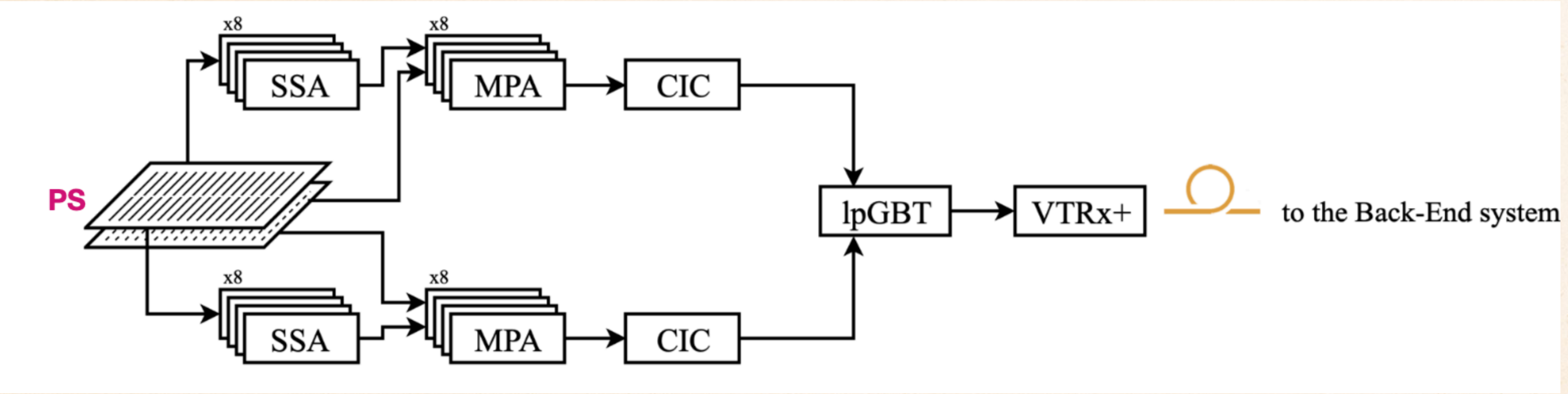
PS AND 2S MODULES

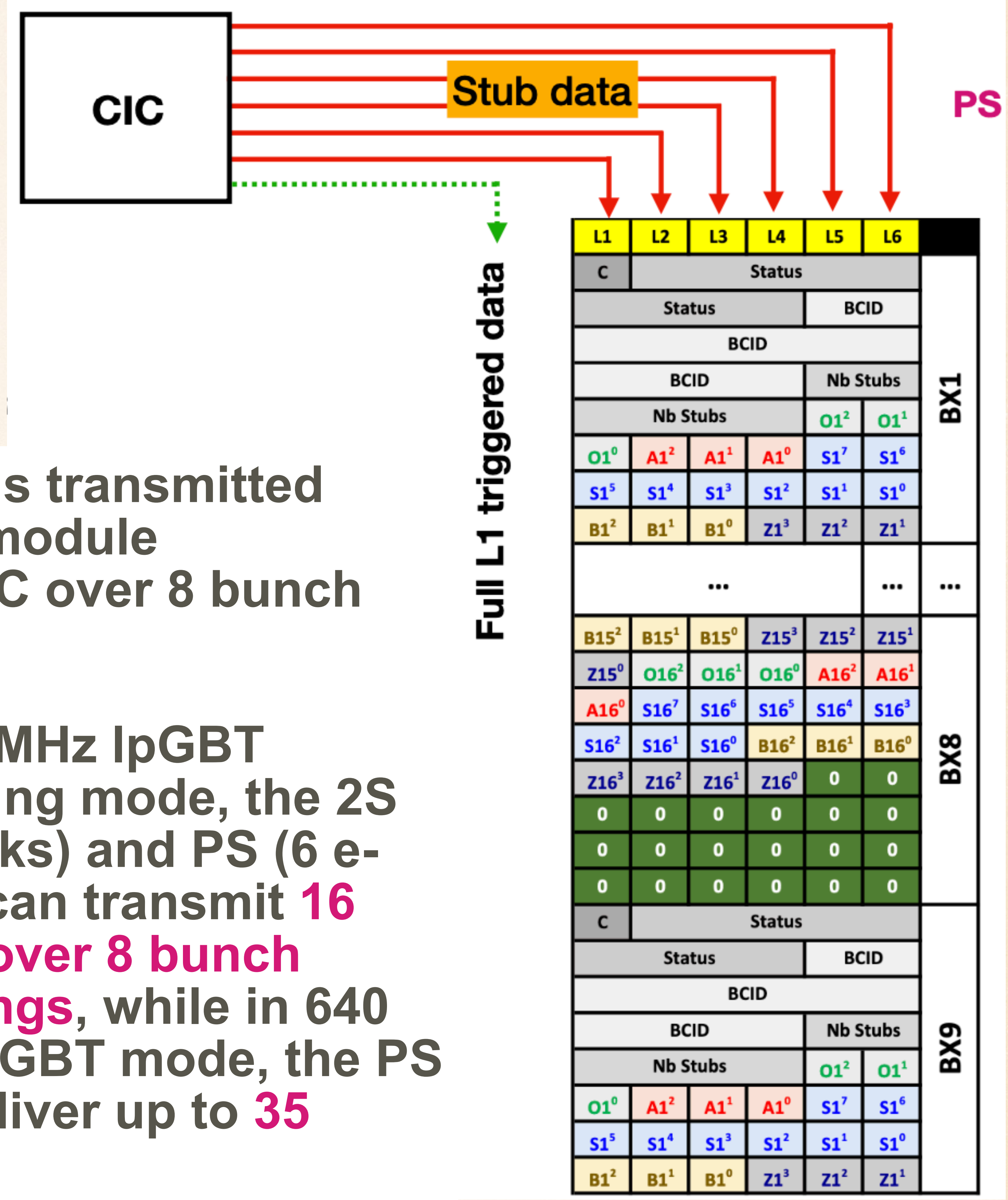
- **Strip-strip (2S) module**
  - **2 AC-coupled strip sensors**
    - 10cm x 10cm (5cm long strips, 90μm pitch)
  - 2 sensor spacings: 1.8mm and 4.0mm
  - R>60cm
- **Pixel-strip (PS) module**
  - AC-coupled strip sensor
    - 5cm x 10cm (2.5cm long strips, 100μm pitch)
  - Macro-Pixel Subassembly (MaPSA)
    - DC-coupled pixel sensor (1.4mm long macro-pixels, 100μm pitch) bump bonded to 16 MPA chips
  - 3 sensor spacings: 1.6mm, 2.6mm* and 4.0mm
  - R<60cm



MODULE READOUT

- **Front-end (FE) ASIC**
  - **2S module:**
    - Strips from both the top and bottom sensor are readout by the same ASIC, **CMS Binary Chips (CBC)** (65 nm CMOS technology)
    - 4064 channels to readout
  - **PS module:**
    - Macro-Pixel ASICs (MPA), Strip Sensor Array (SSA) ASIC *(both in 65 nm CMOS technology)*
    - 30720 (pixels) + 1920 (strips) to read out

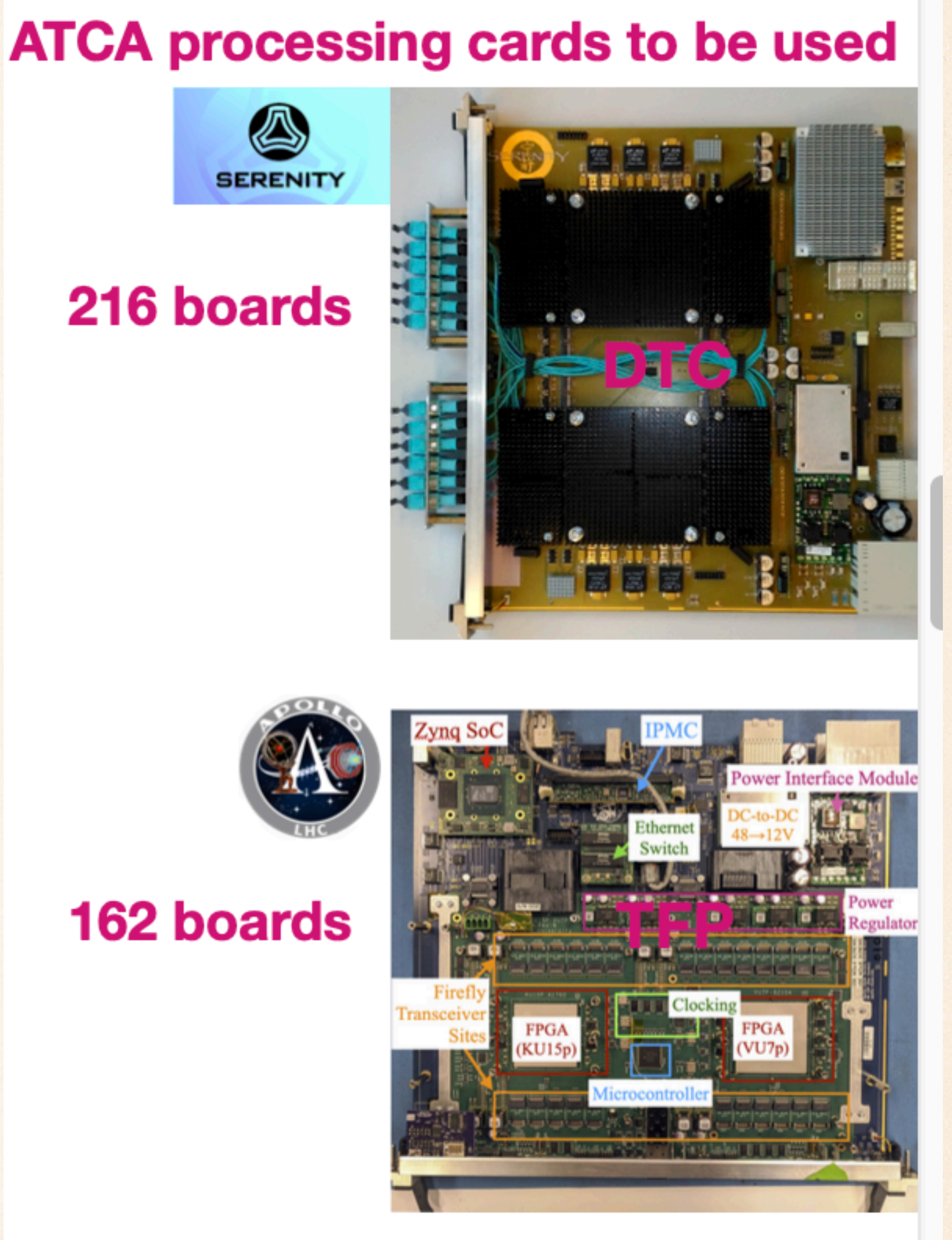


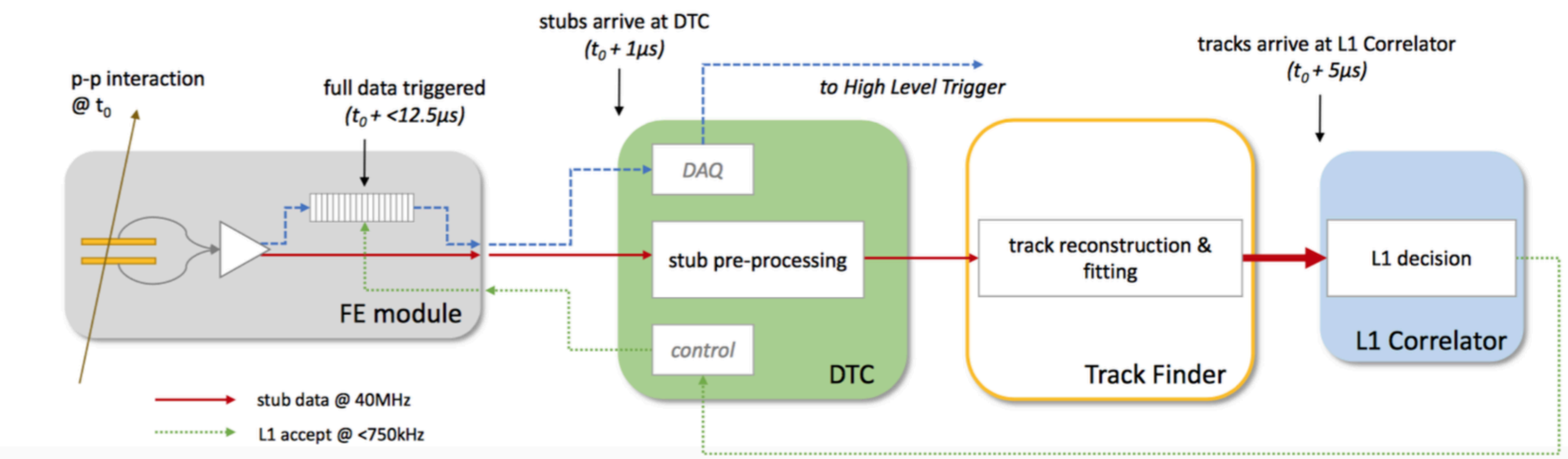


- **A boxcar is transmitted from the module to the DTC over 8 bunch crossing**
  - **In 320 MHz lpGBT operating mode, the 2S (5 e-links) and PS (6 e-links) can transmit 16 stubs over 8 bunch crossings, while in 640 MHz lpGBT mode, the PS can deliver up to 35 stubs.**

MODULE READOUT

- **The tracker Back-End (BE) system includes two stages:**
  - **Data, Trigger and Control (DTC):**
  - **Track Finder Processor (TFP)**
- The **DTC** supports both the **trigger** and **DAQ** systems in CMS.
- For the **DAQ**, it collects and packets data from Level 1 (L1)-accepted events.
- DTC facilitates the transfer of L1-accepted events to the **High-Level Trigger (HLT)**.
- Upon receiving an **L1A signal**, DTC forwards it to all connected modules, which then send hit data from the relevant bunch crossing via a dedicated L1A path.
- Each DTC card handle **72** front-end modules.

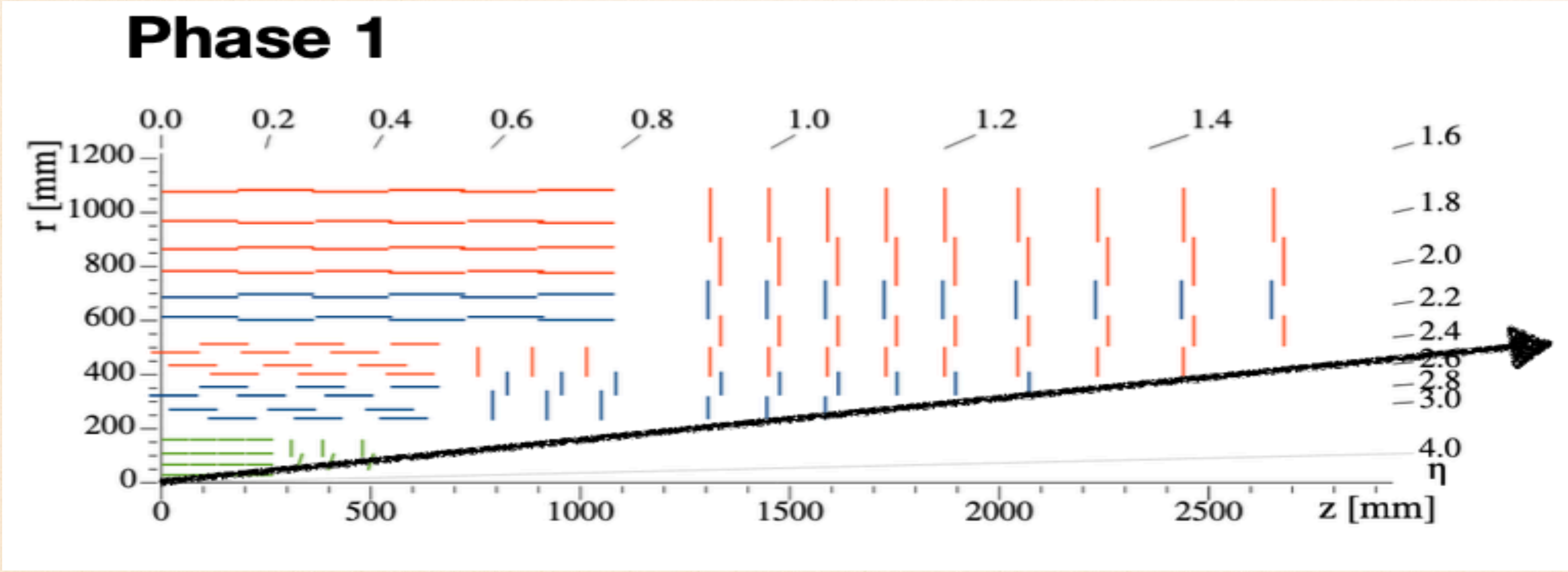


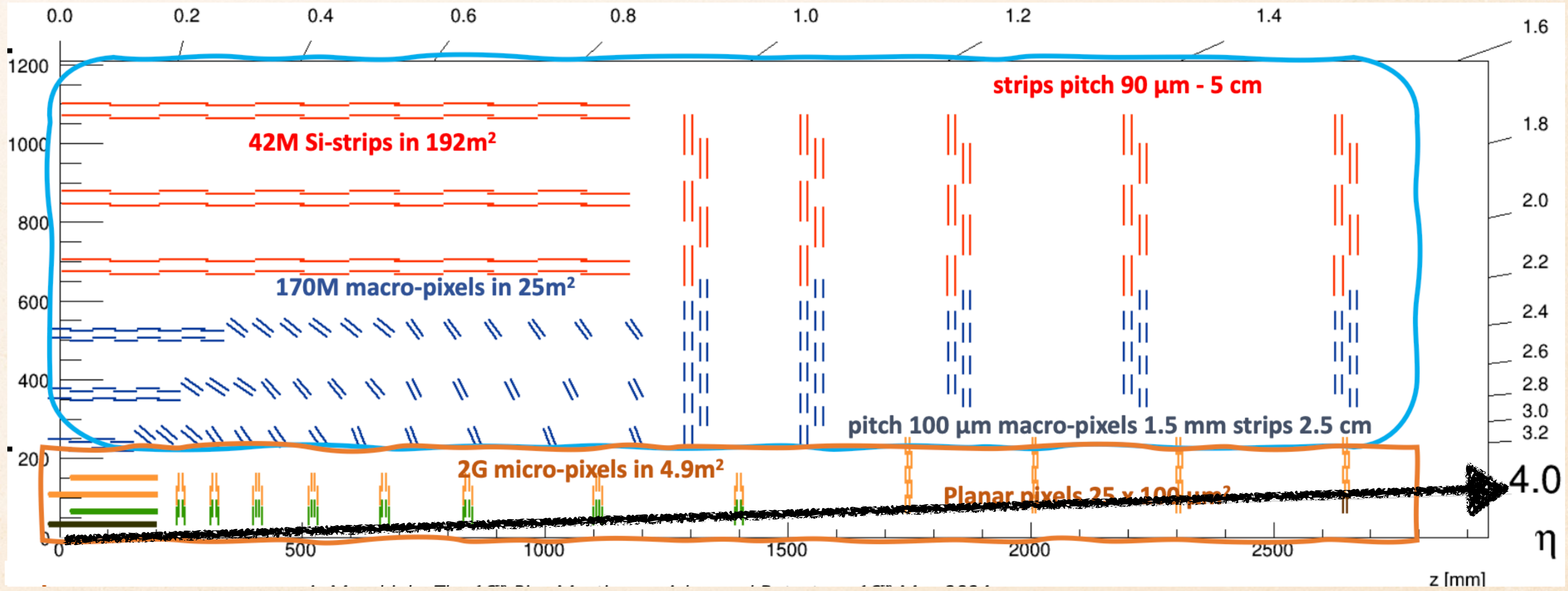


TRACKER UPGRADE OVERVIEW

- **The present Tracker (Phase 1)**
  - **Strip tracker:**
    - ≃ 9.3×10^{6} strip channels (198 m^2), Mono-phase cooling.
  - **Pixel System:**
    - ≃ 125×10^{6} pixels (~1.9 m^2), Bi-phase CO_2 cooling.
    - Innermost layer at 2.9 cm from beam pipe (occupancy 2 x 10^{-3})

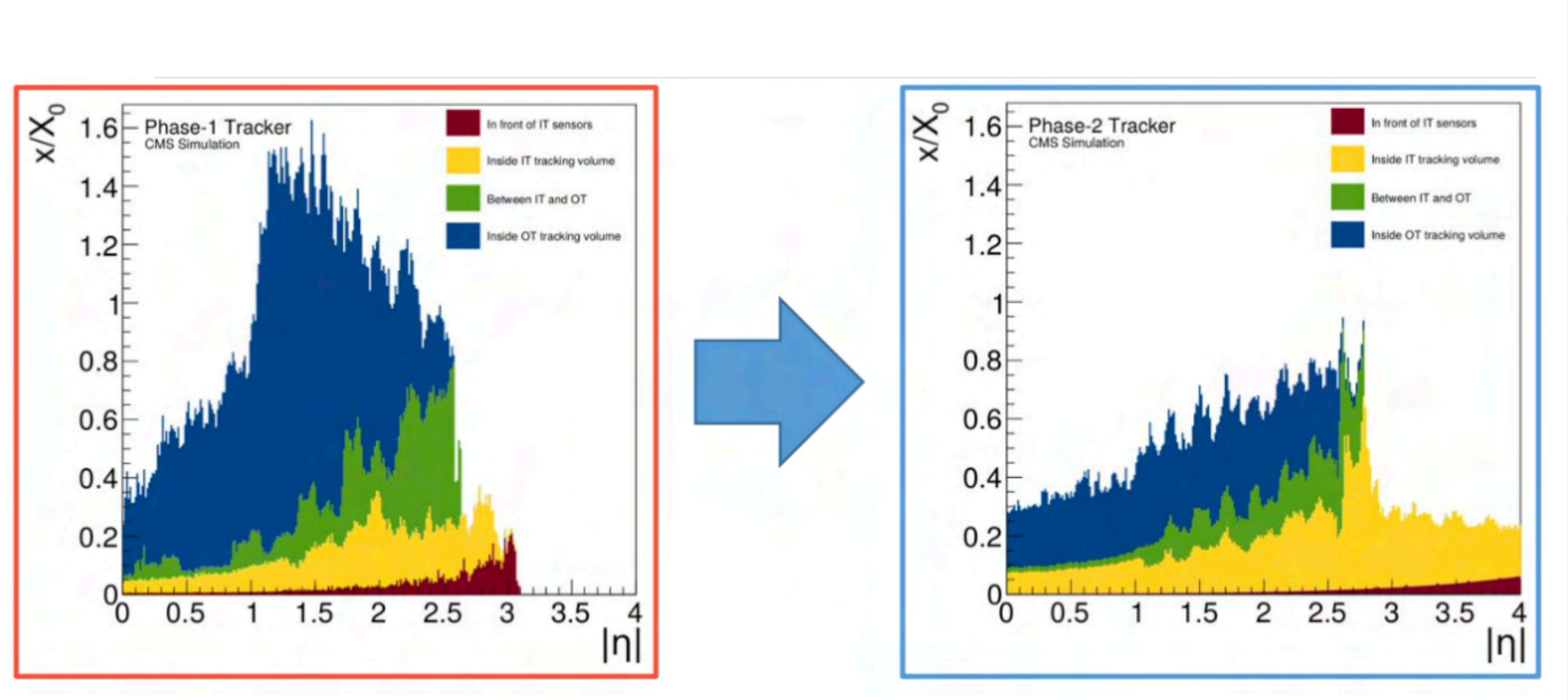
- **Phase 2 Tracker**
  - **Outer tracker:**
    - ≃ 200×10^{6} strip channels (200 m^2), Mono-phase cooling.
    - Tilted geometry.
  - **Pixel Inner Tracker:**
    - ≃ 2×10^{9} pixels (~4.9 m^2), Bi-phase CO_2 cooling.
    - Innermost layer at 2.8 cm from beam pipe (occupancy 2 x 10^{-3})





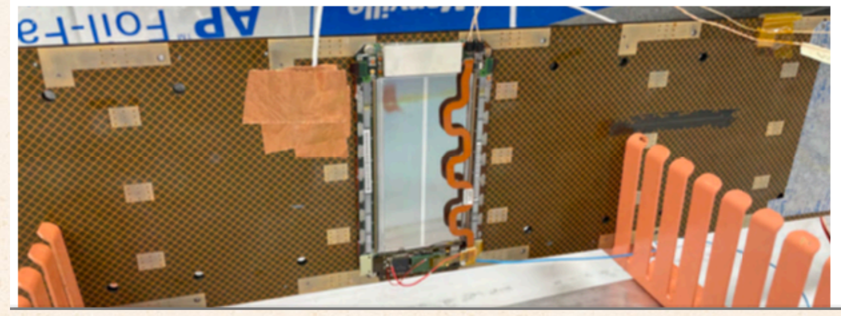
MATERIAL BUDGET AND MECHANICS

- DC-DC converters – fewer cables
- Fewer layers
- Lighter materials
- Optimized service routing – 3D modelling
- CO_2 bi-phase cooling – thin pipes
- Inclined geometry

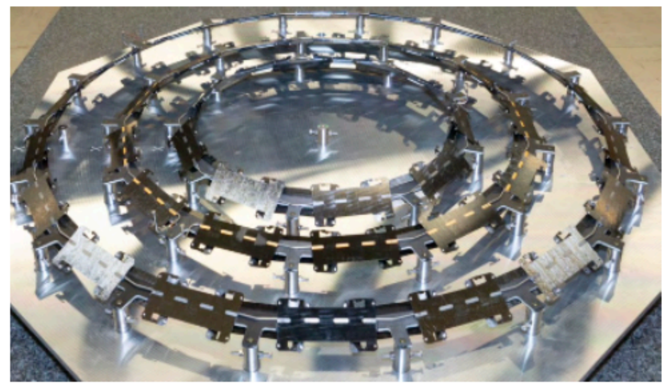


2S ladder

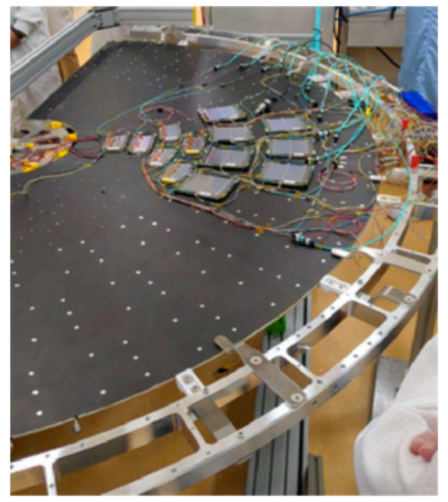
PS module on TBPS plank



OT tilted rings



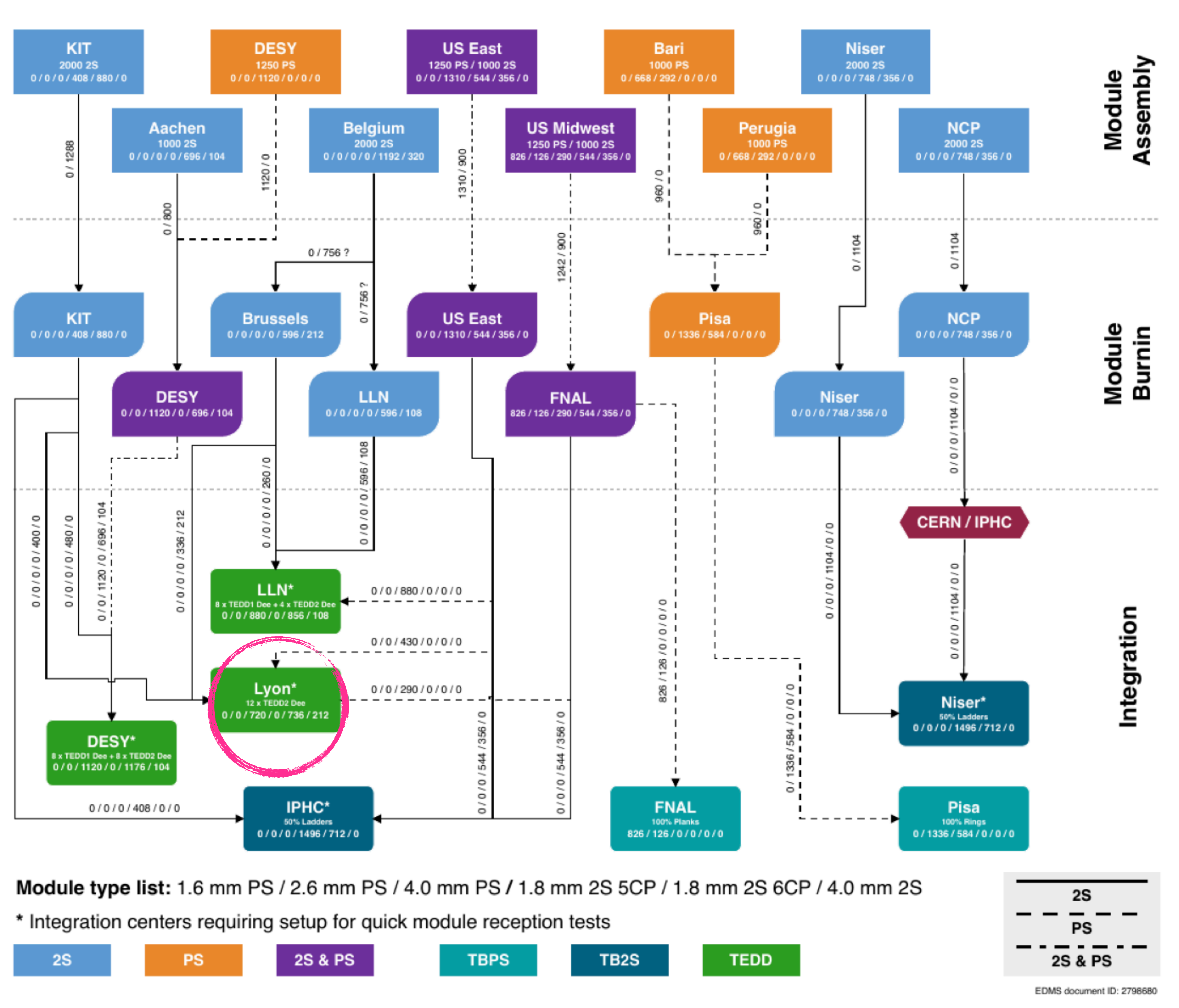
OT endcap dee

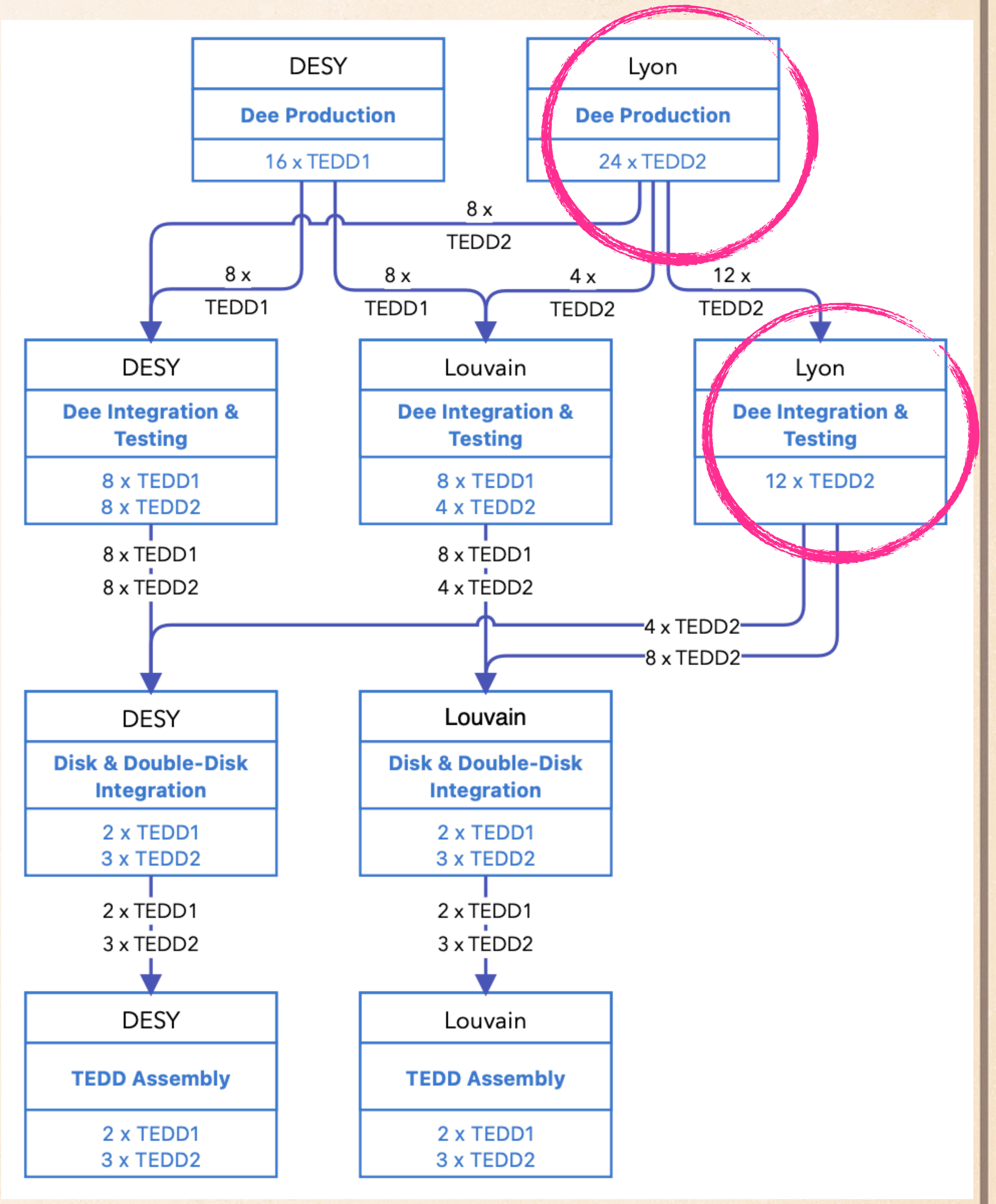


Carbon foam layer 3 end ring pieces

WORK AT IP2I

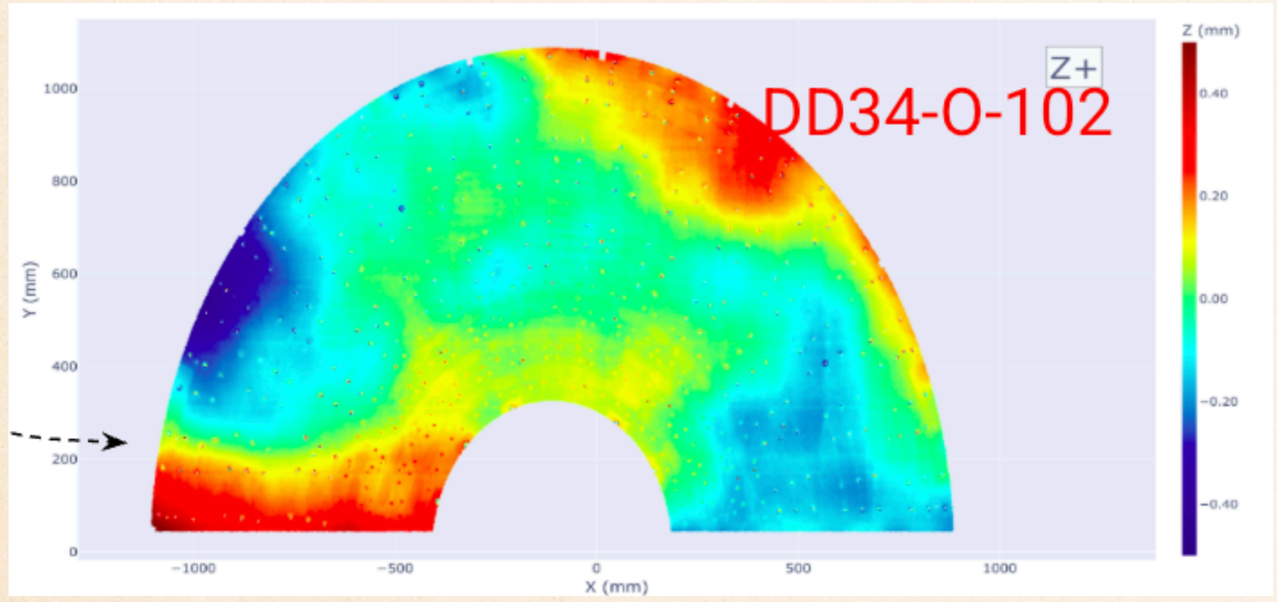
- At IP2I Lyon, we are in charge of **Producing and qualifying 24 Dees**.
- We shall **integrate and test 12 Dees**.

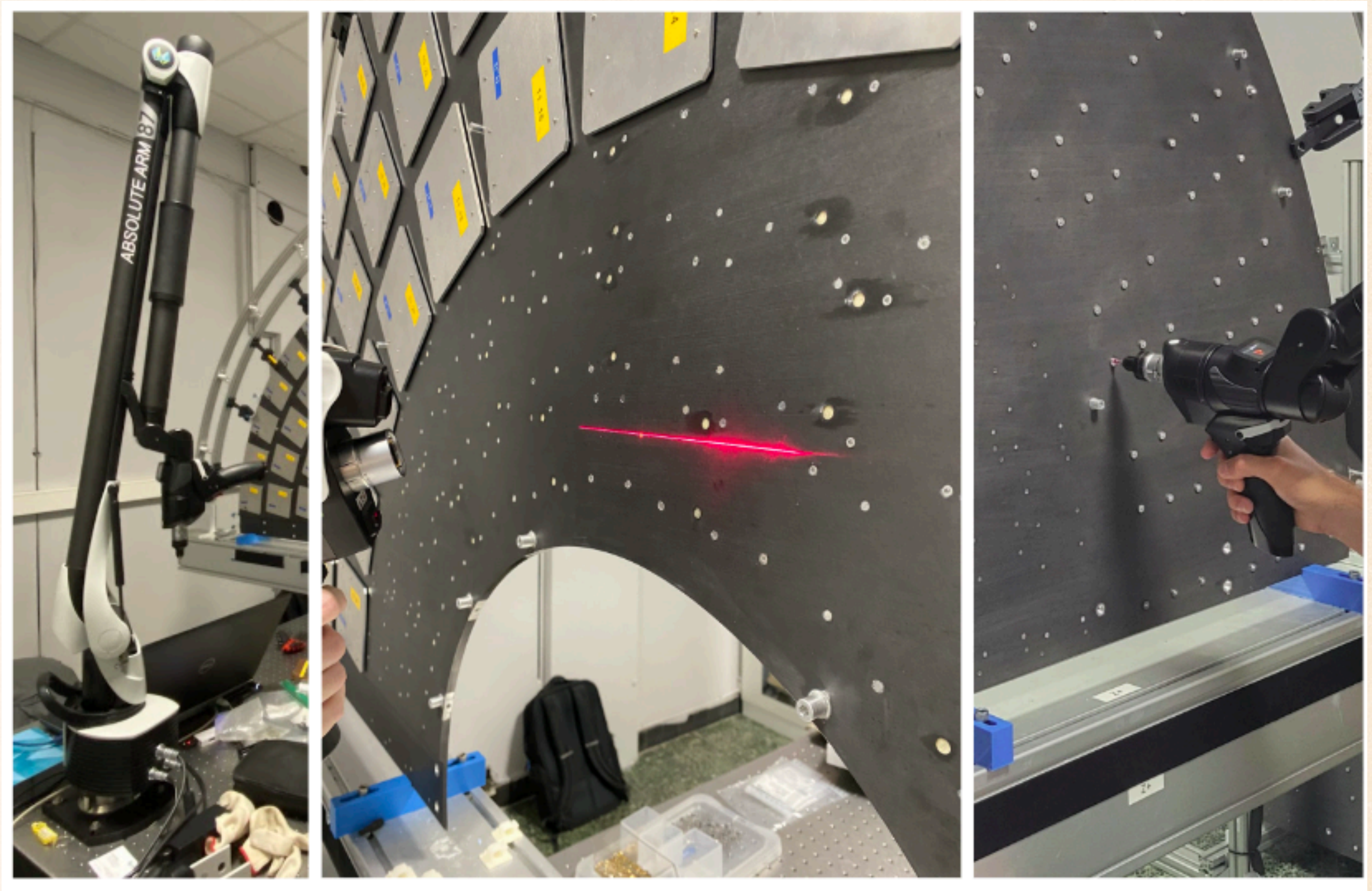


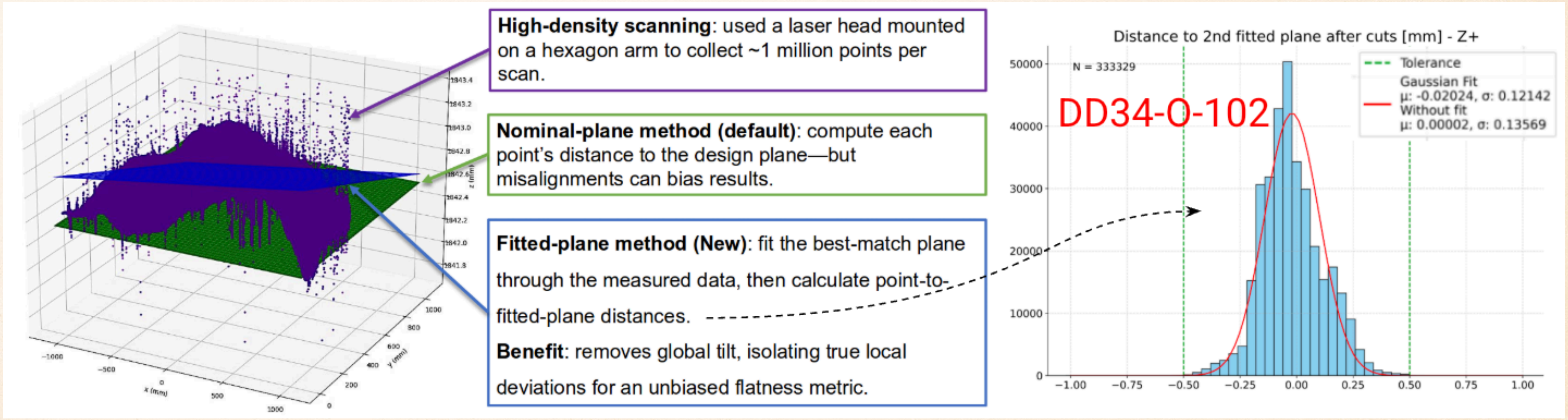


QUALIFYING DEES (FLATNESS)

- **Metrology measurement:**
  - Scanning DEE surface with a laser for flatness. Take about 10^6 points/surface.

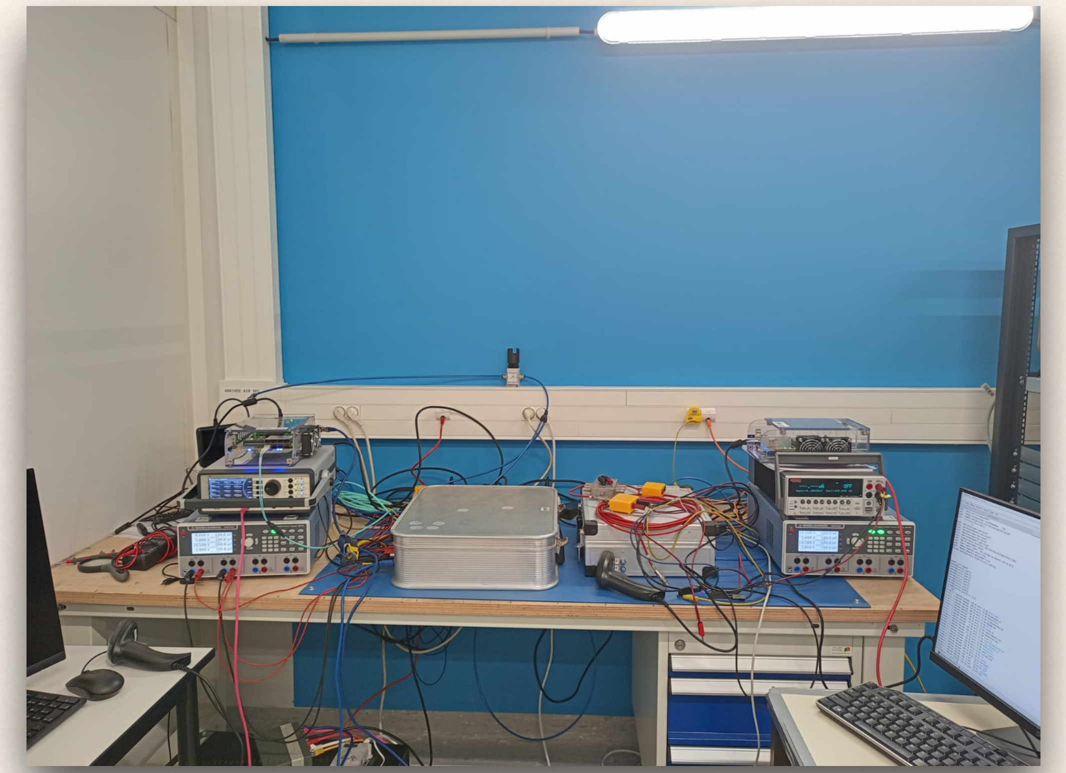




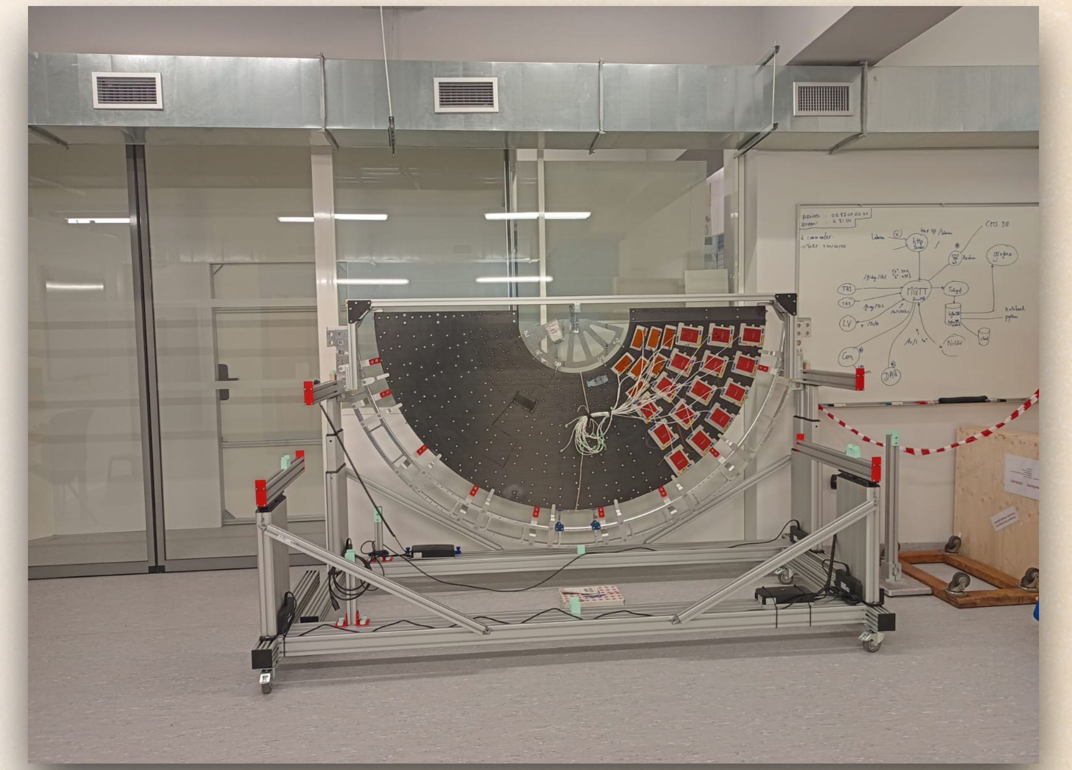


MODULE INTEGRATION & TESTS

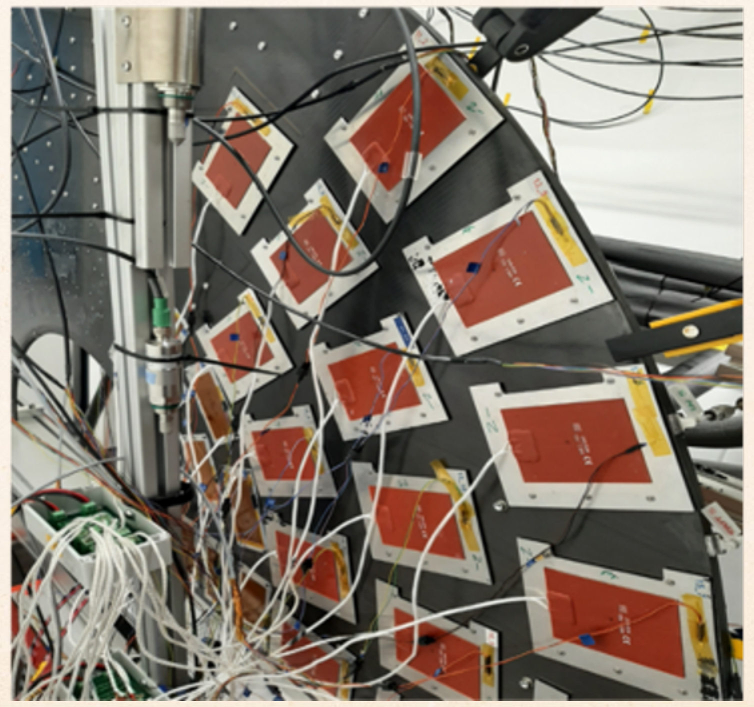
- According to the plan, **each module** will undergo some **functionality tests upon reception**.
  - The reception tests will be done for each module using **module test benches**.
- Once all modules have been integrated on a given dee, the dee will be subjected to a series of tests in order to verify that the modules still perform as expected.
  - **Module tests at Room Temperature.**
  - **Dees to be actively cooled (-18^{O}C). Measurement of module quality (Noise) in realistic cold environment.**



Stage 1: Module test upon Reception



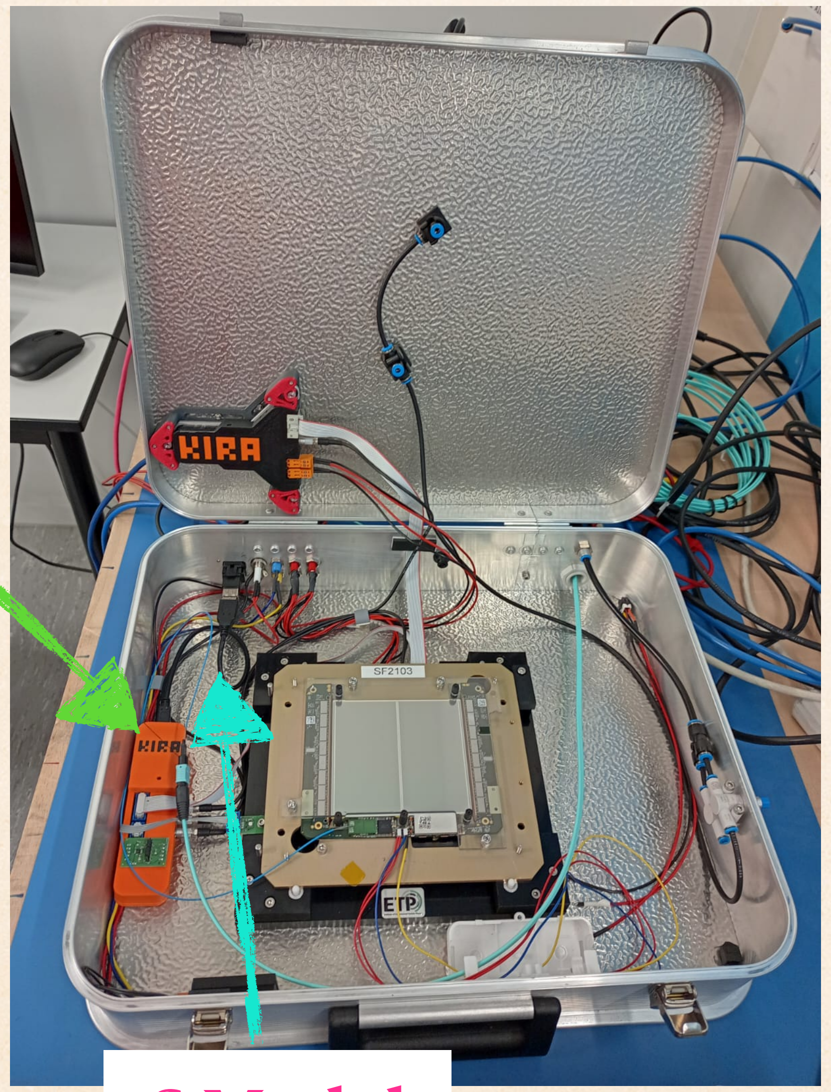
Stage 2: Module test after Integration at Room temperature

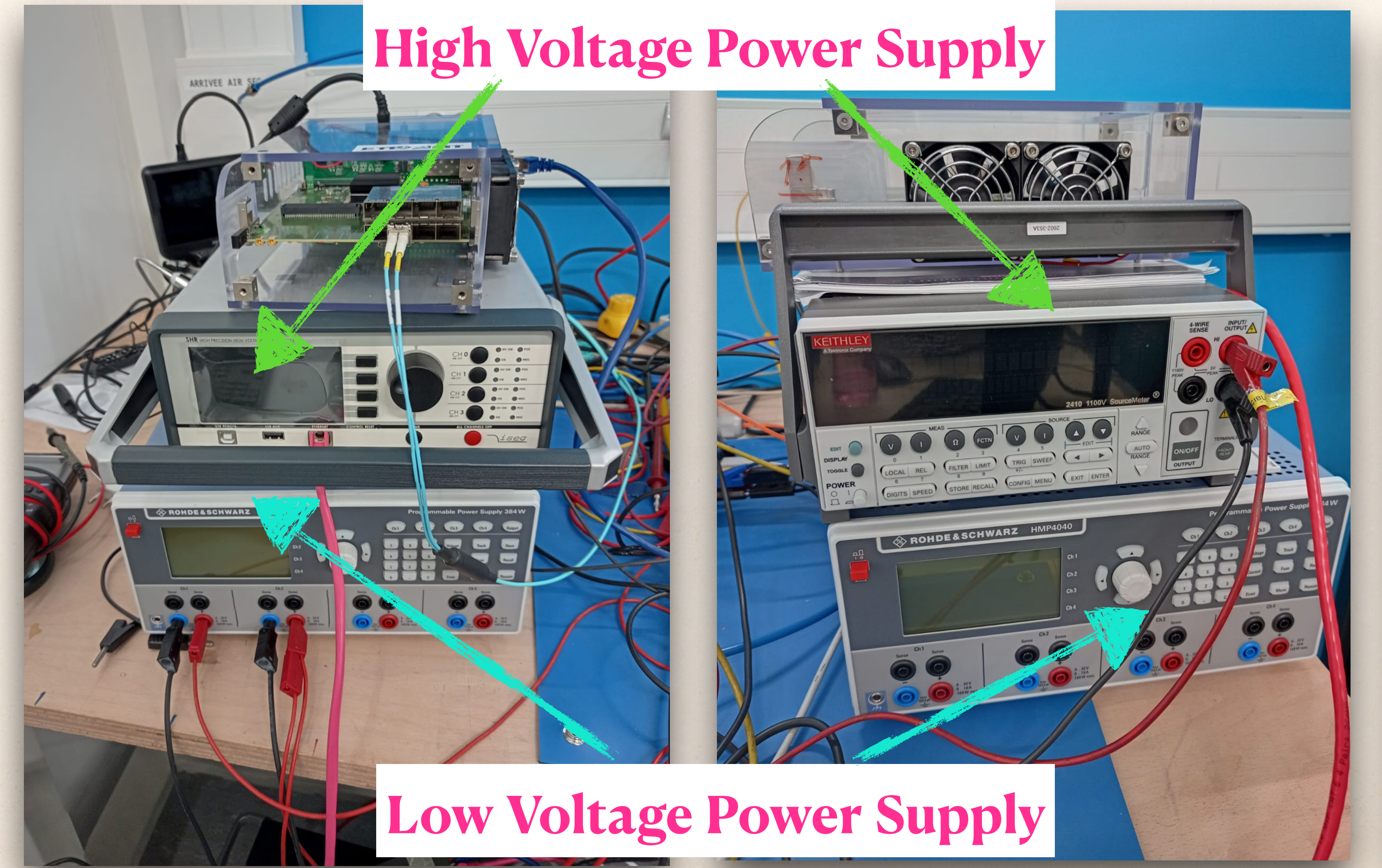


Stage 3: Multi Module test Inside cold chamber

MODULE RECEPTION TEST

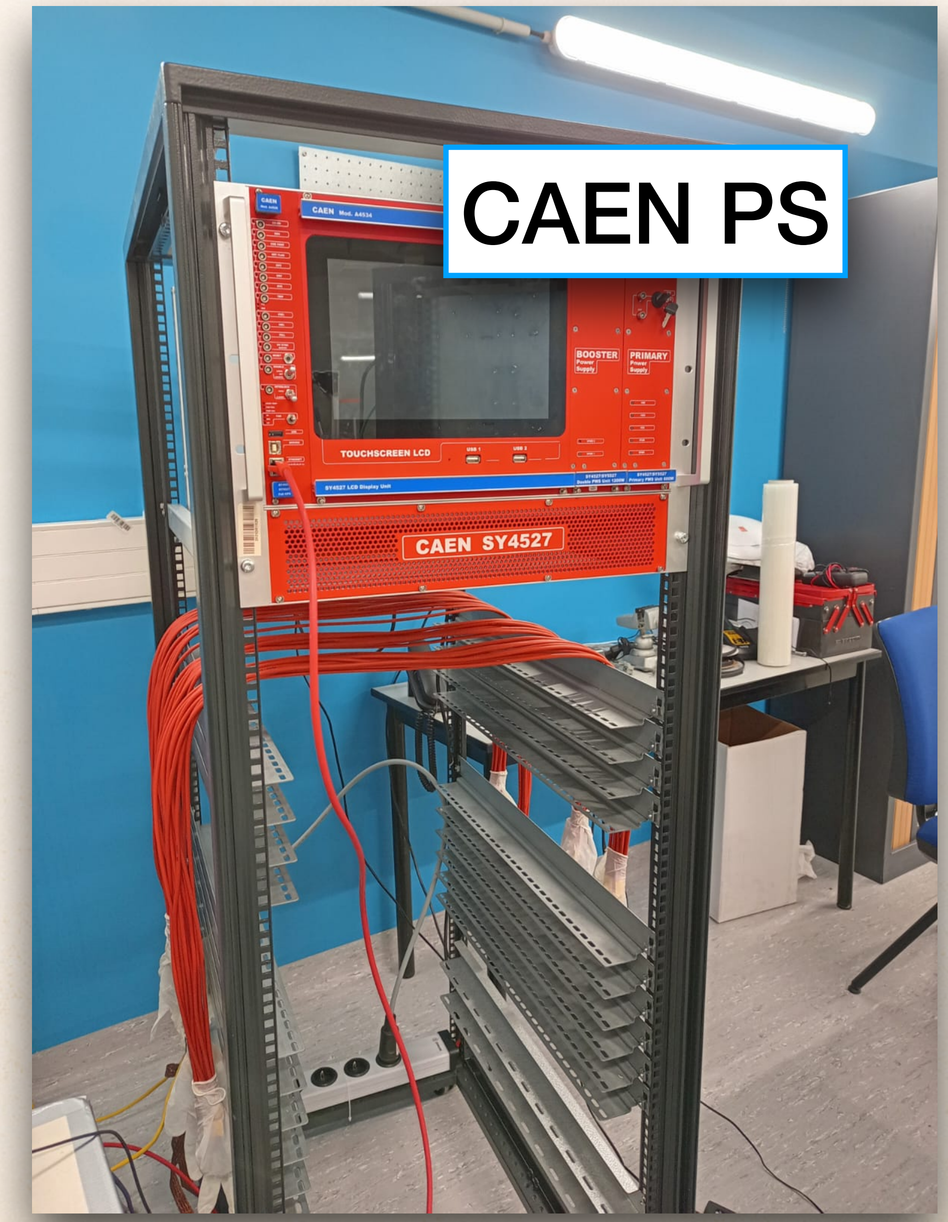
- Modules will be distributed all over the world. To ensure equal testing condition a dedicated test station is used.
- The OT module test box is an aluminium-covered box which houses one OT module.
- To read out an OT module in the test bench it is necessary to connect low and high voltage power supplies as well as one FC7.
- We can inject external signals using Karlsruhe InfraRed Array (KIRA) system.
- An Arduino is used to monitor temperature and humidity in the box. It also controls KIRA.

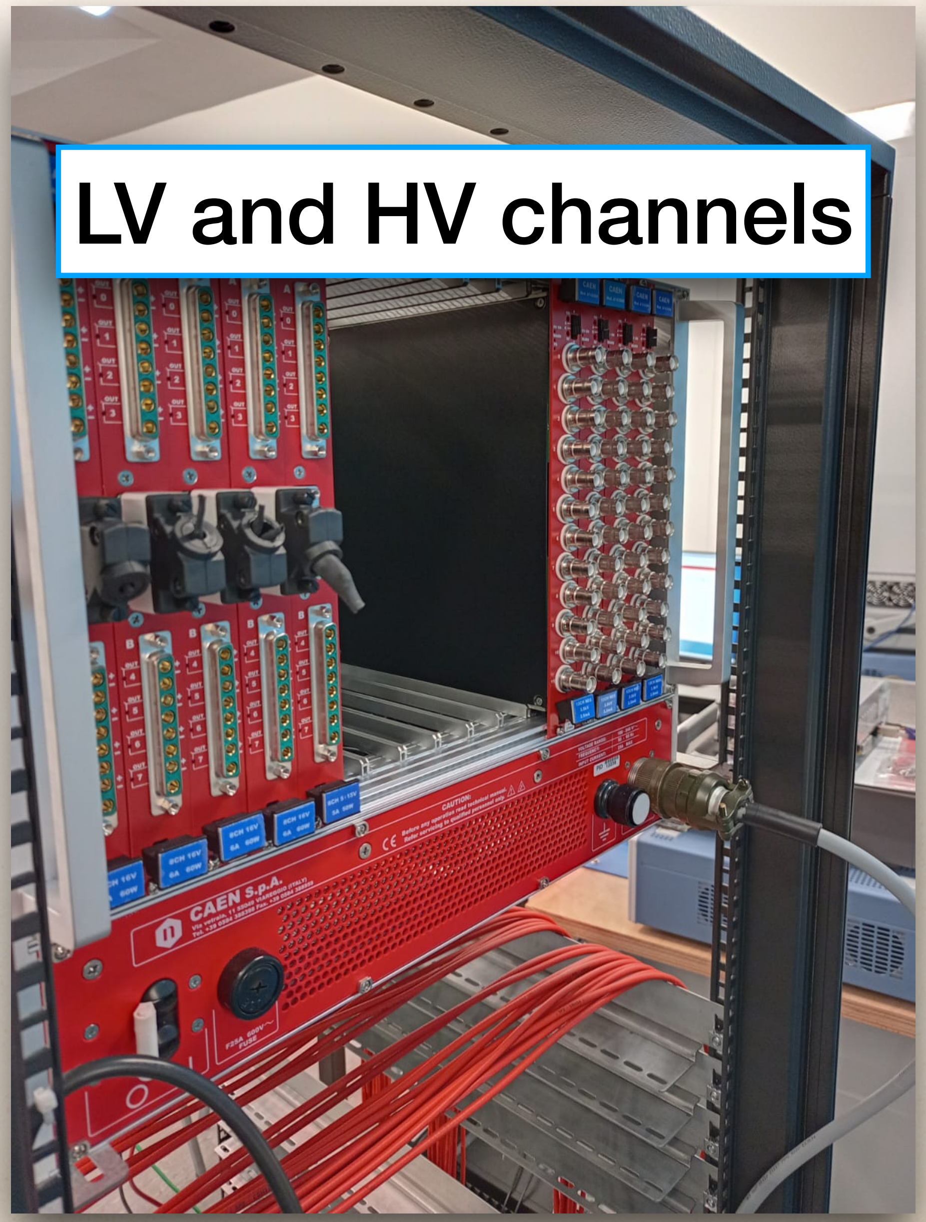


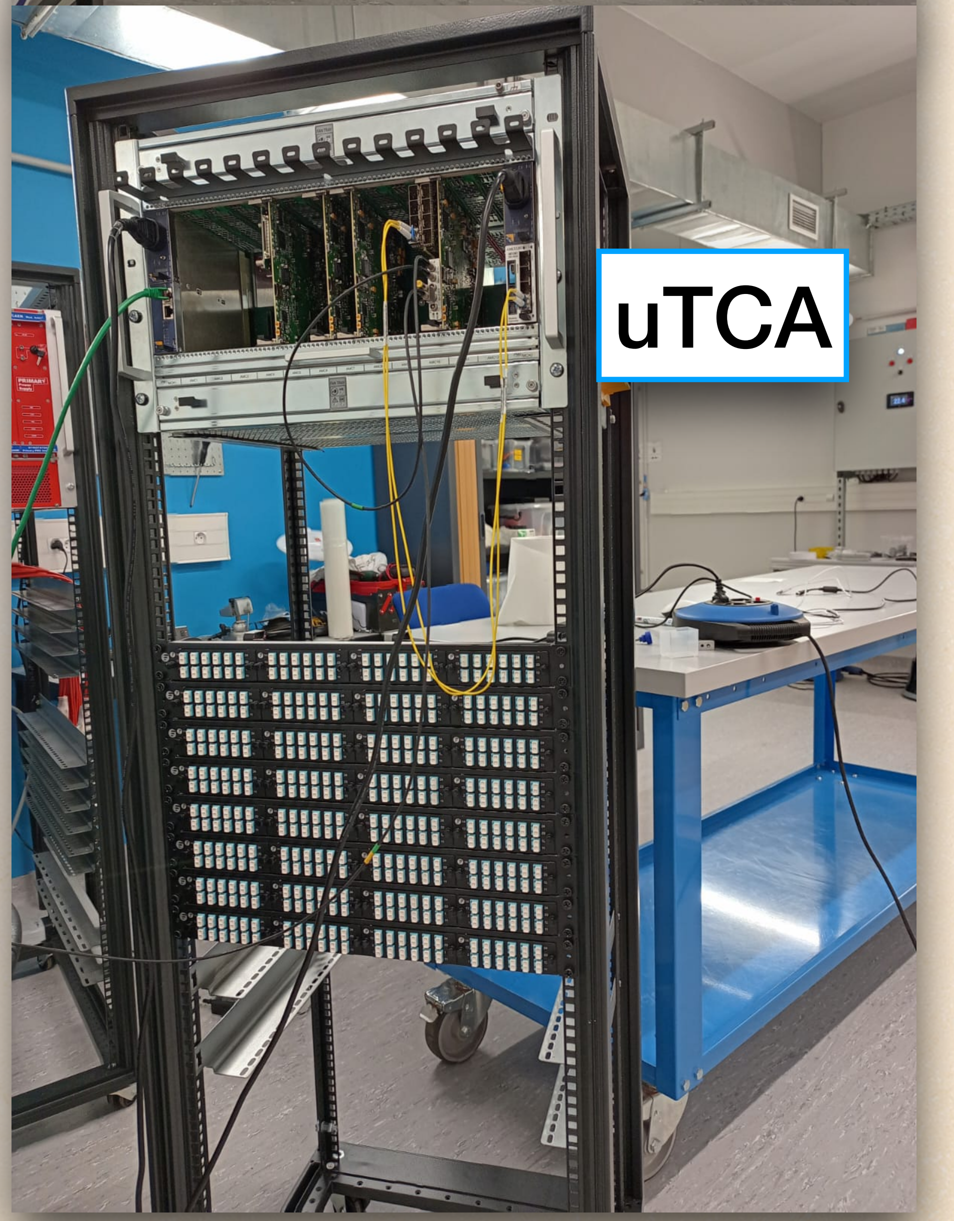


DEE INTEGRATION

- To verify that the modules perform as expected, and validate the thermal contact between the modules and the dee surface is very important.
- The above tests require the DEEs to be actively cooled.
- We have a custom cold chamber
- Temperature and humidity sensors readout with Labview.

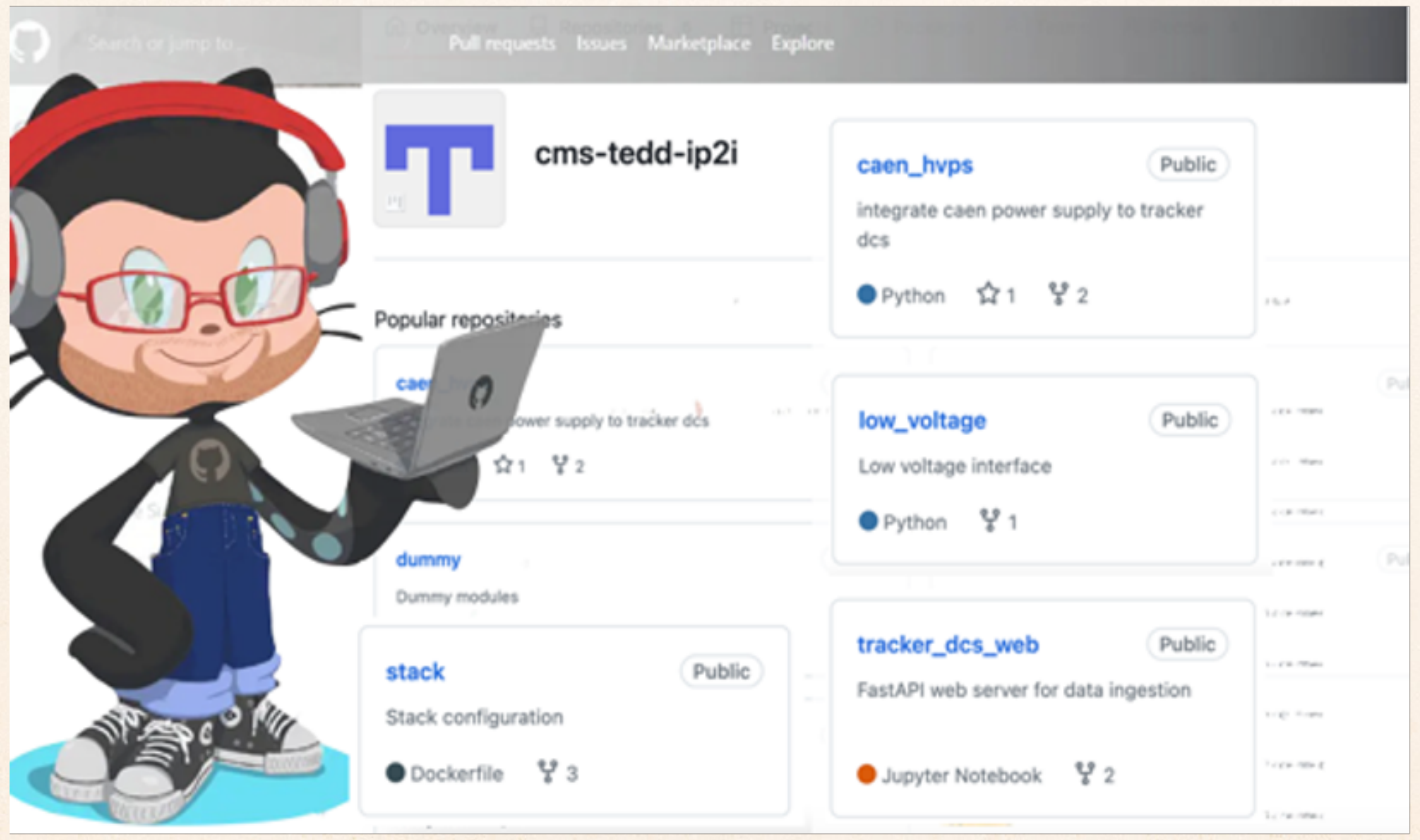


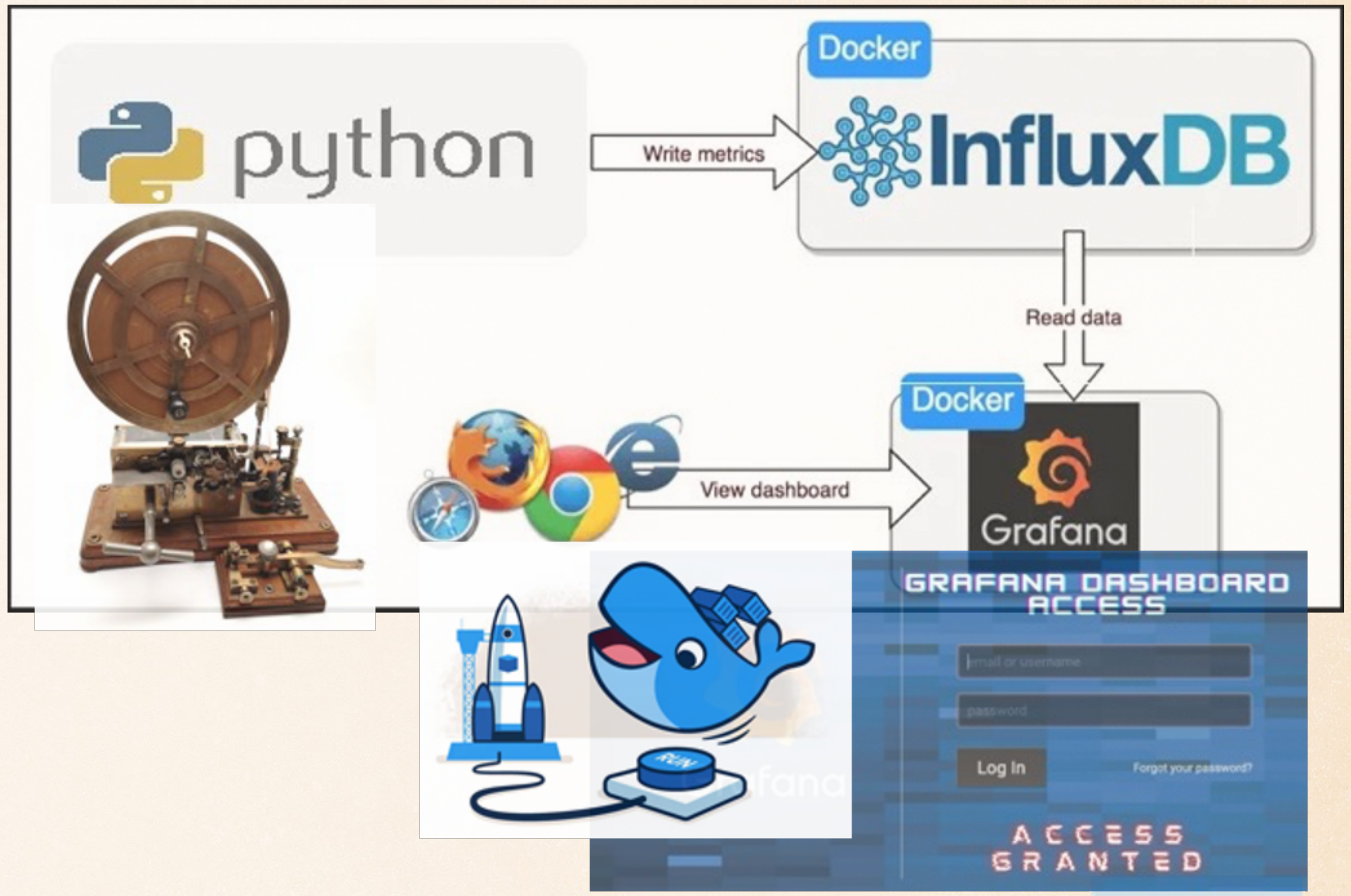


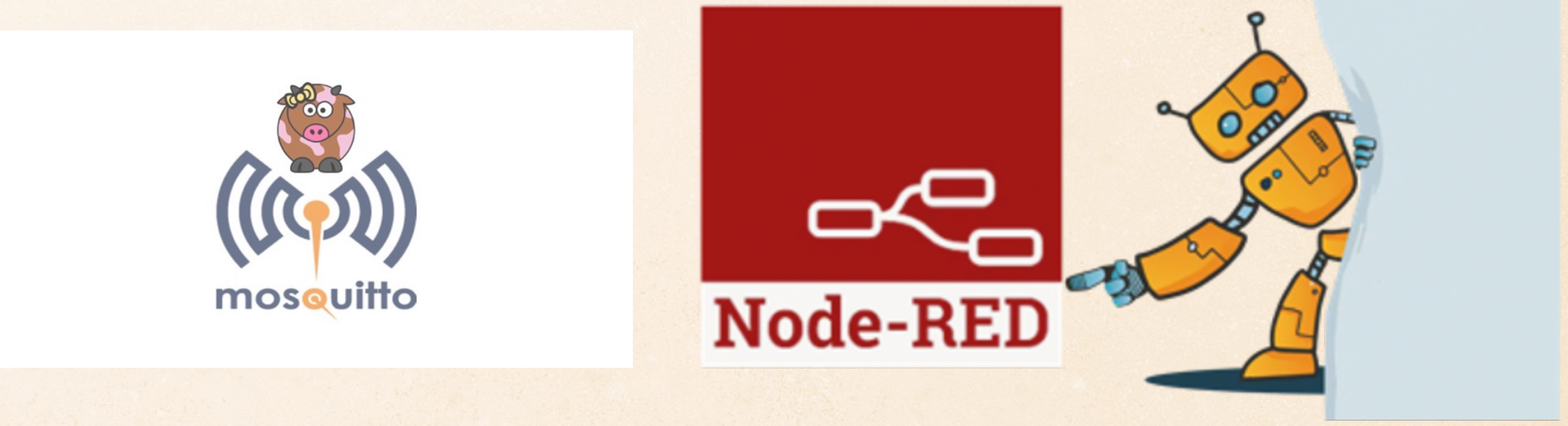


DETECTOR CONTROL SYSTEM

- We need a DCS system to monitor conditions for Dee cold test, and store the results, connect to CMS database.
- A **local DCS system** has been designed and developed using **IoT** (Internet Of Things) data pipe line with modern **open-source** tools.





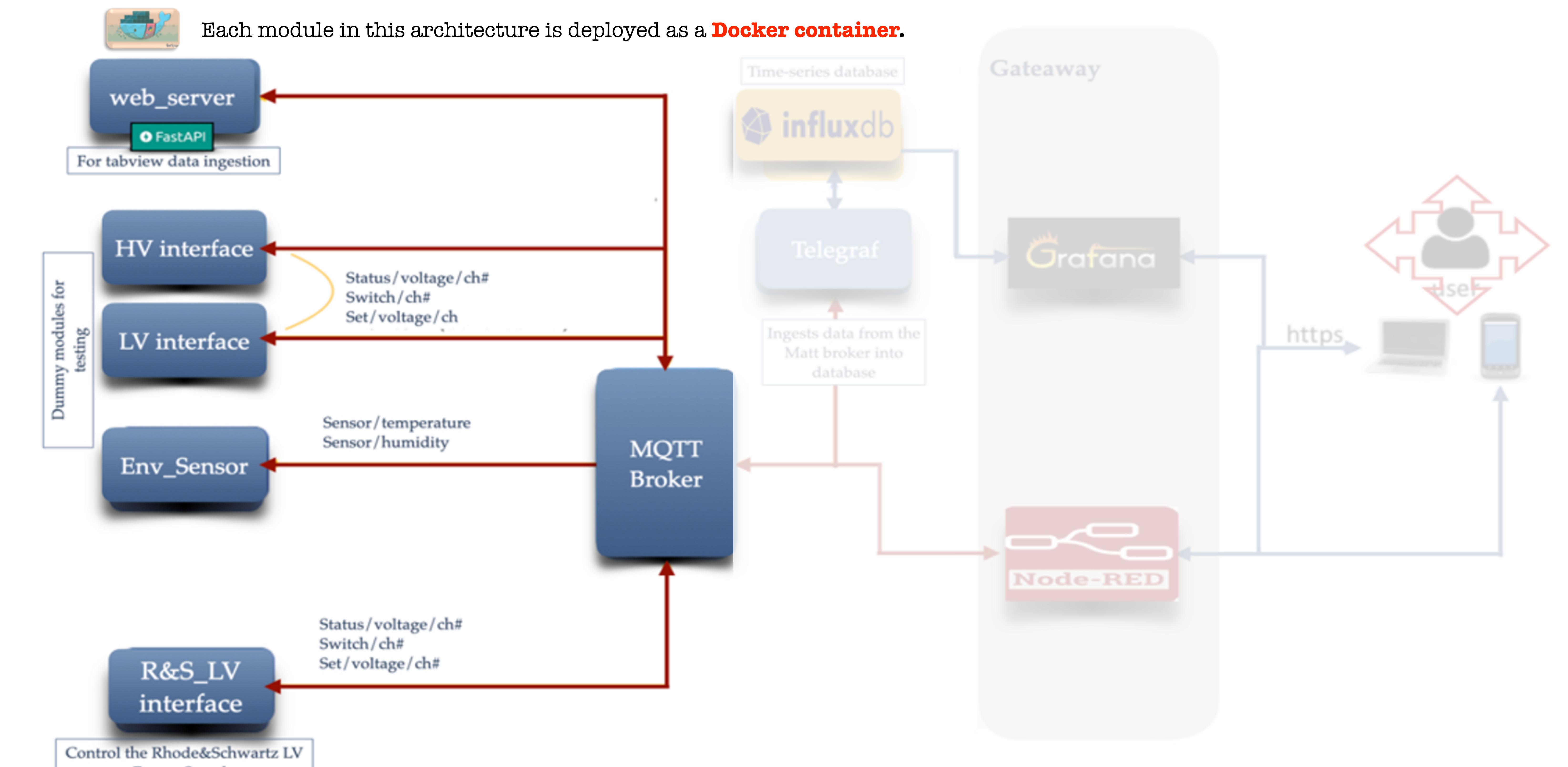


DETECTOR CONTROL SYSTEM

A data pipeline consists of 3 stages

Stage 1. Time series Data is collected from the interfaces.

These services emit to the topics:
/hv/status
/lv/status
/sensor/measure1 - (temp/humidty)
with a JSON list as payload with one dictionary element per channel.



Docker-Stack-configuration

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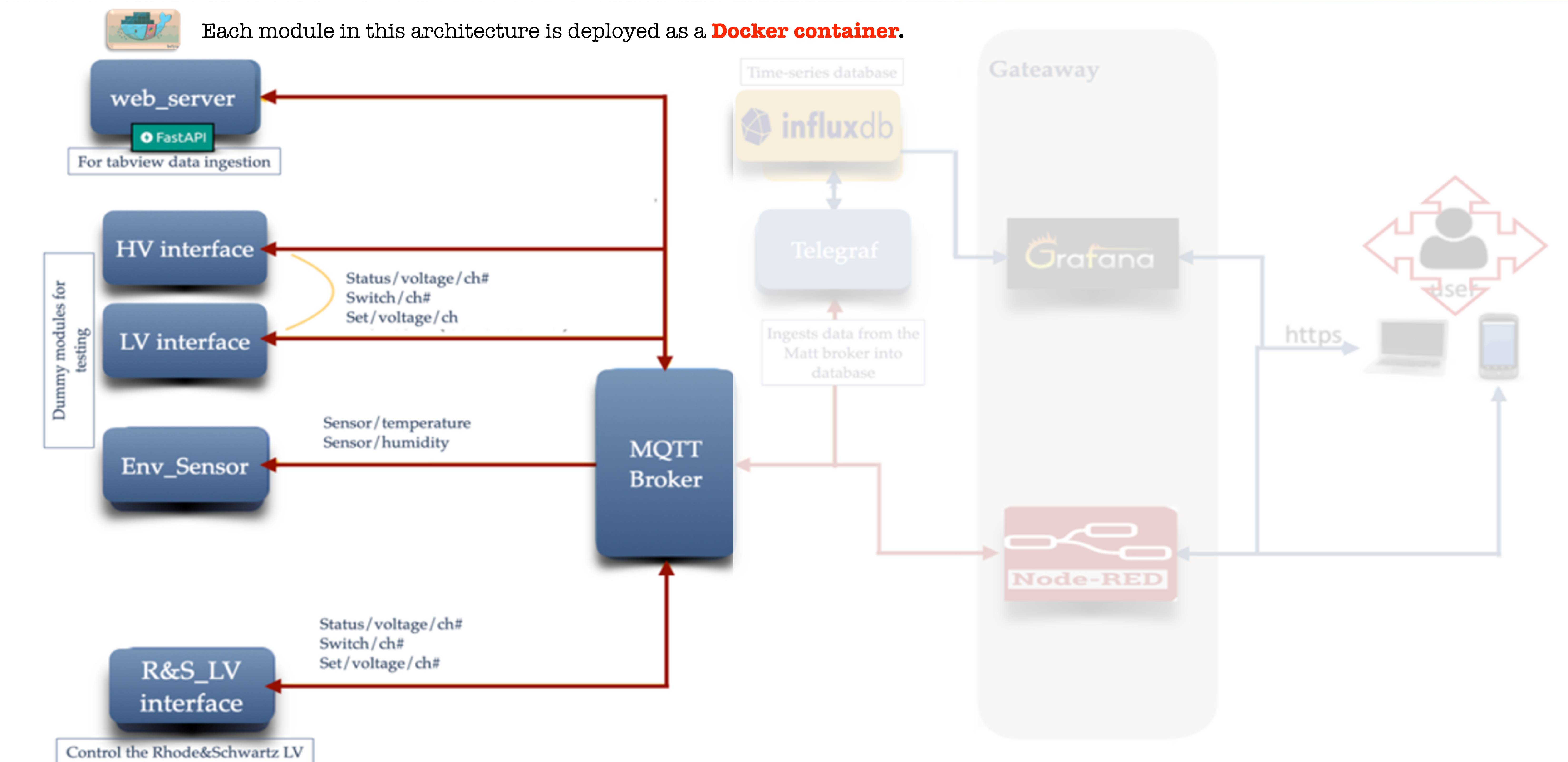


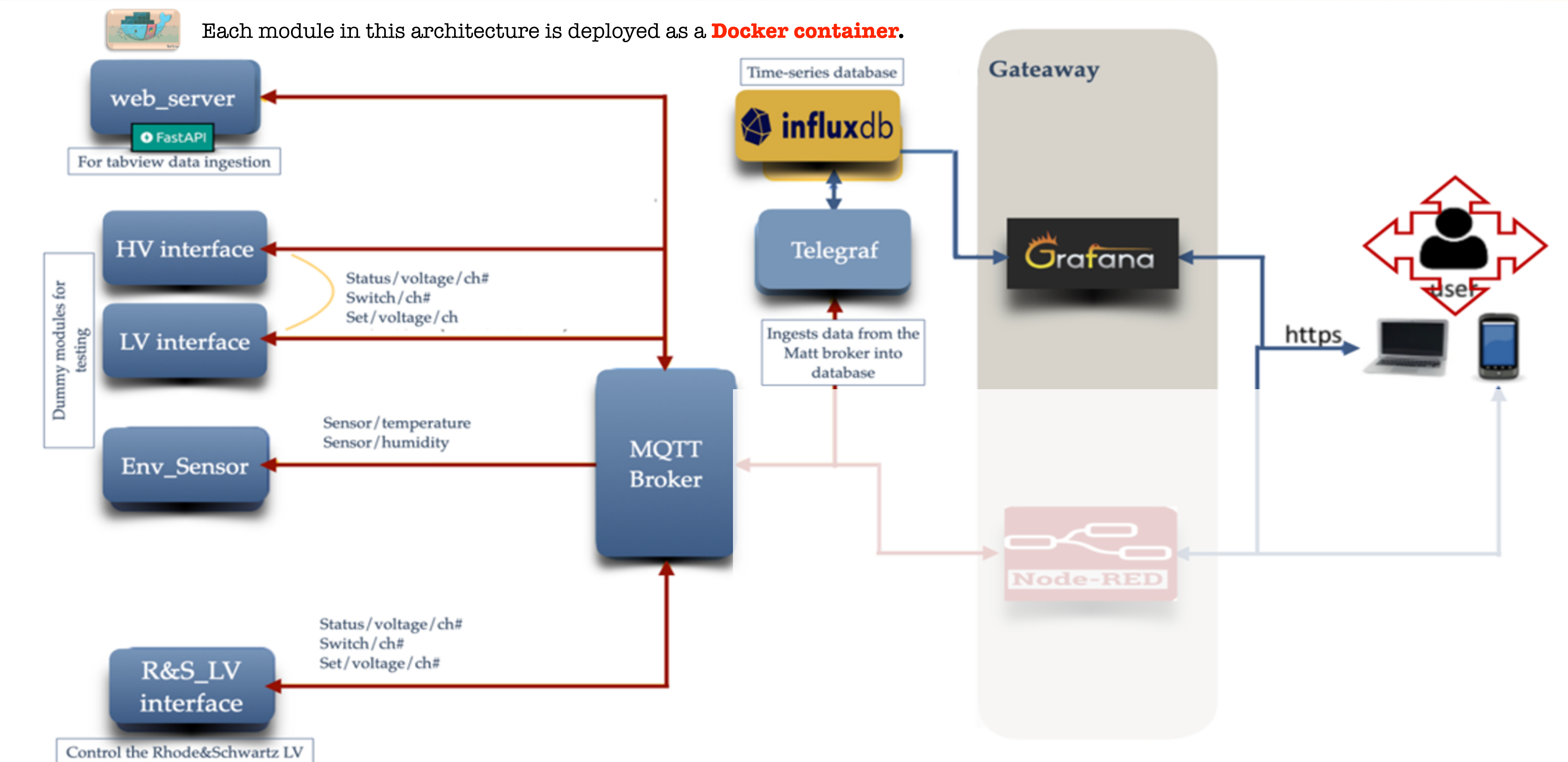
Docker-Stack-configuration

DETECTOR CONTROL SYSTEM

A data pipeline consists of 3 stages

Stage 3. A Dashboard accesses the database to Visualise the data

Garafana webserver: Monitoring dashboard



Docker-Stack-configuration

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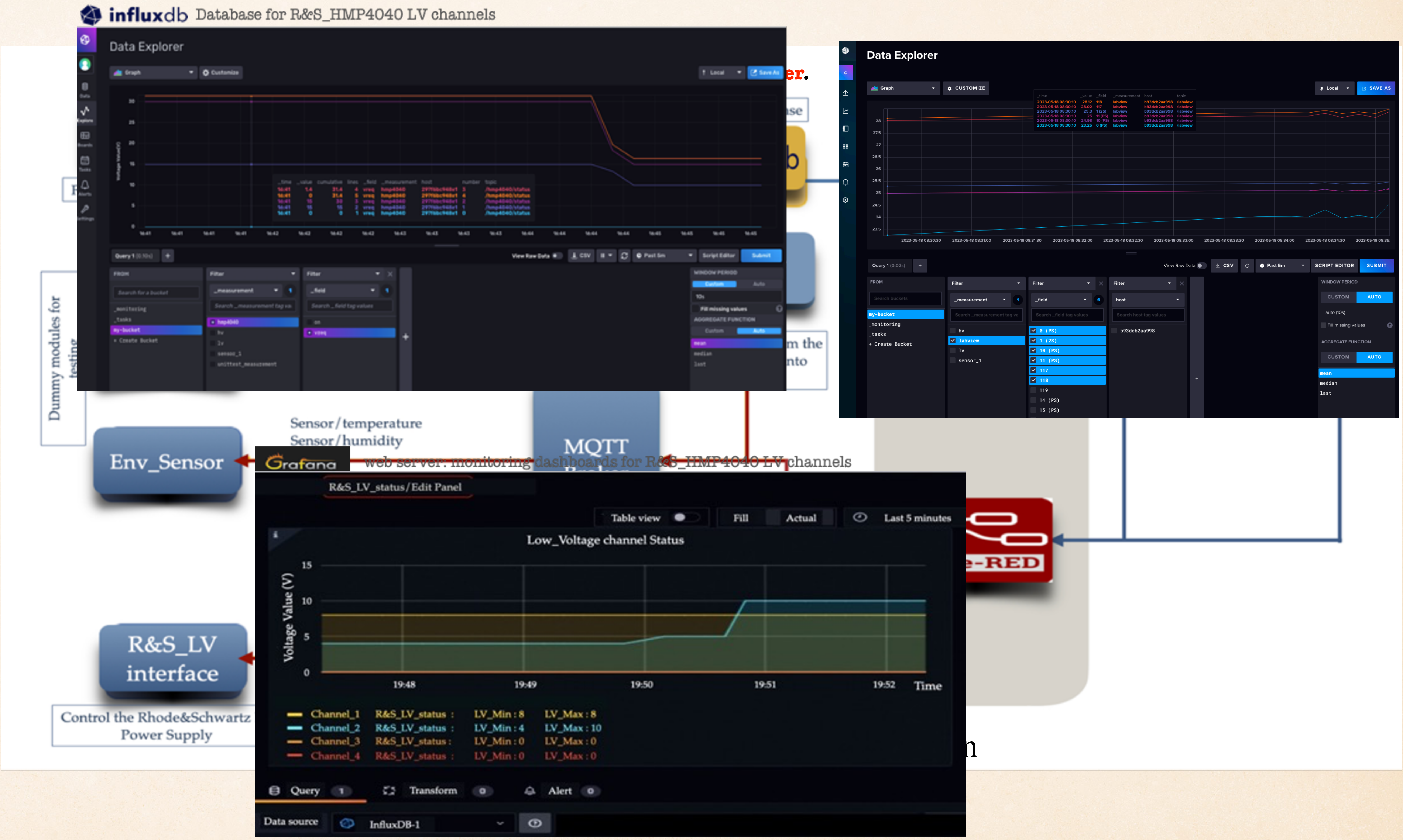

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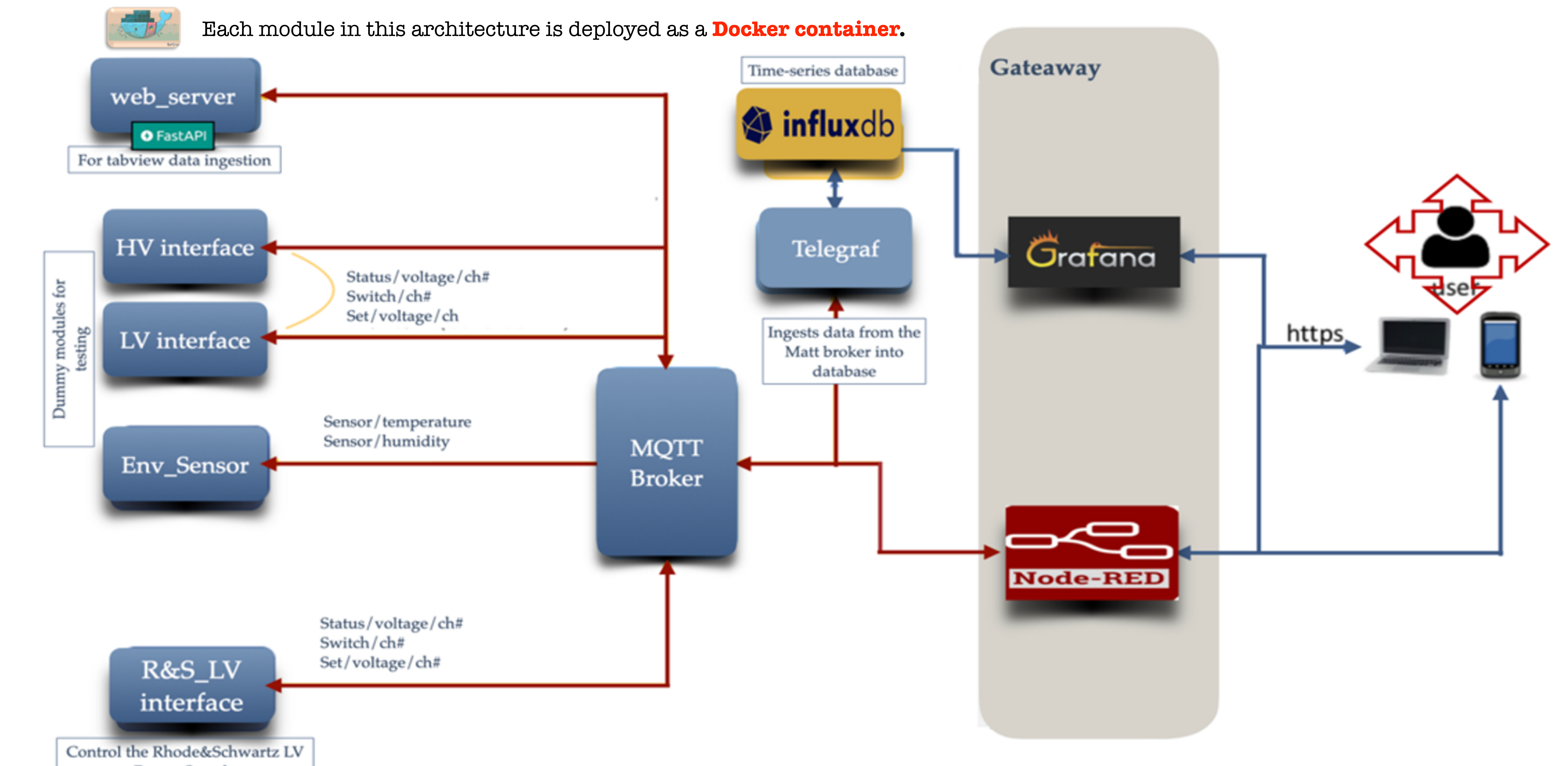
➡ Users interact with the architecture through a Gateway

➡ The Connections to these modules is secured with TLS (Transport Layer Security)



Docker-Stack-configuration

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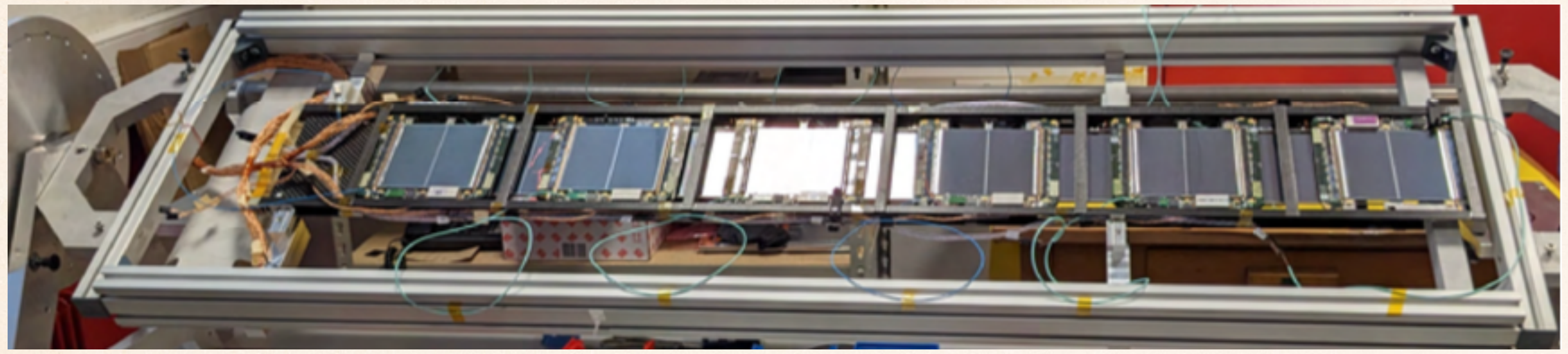
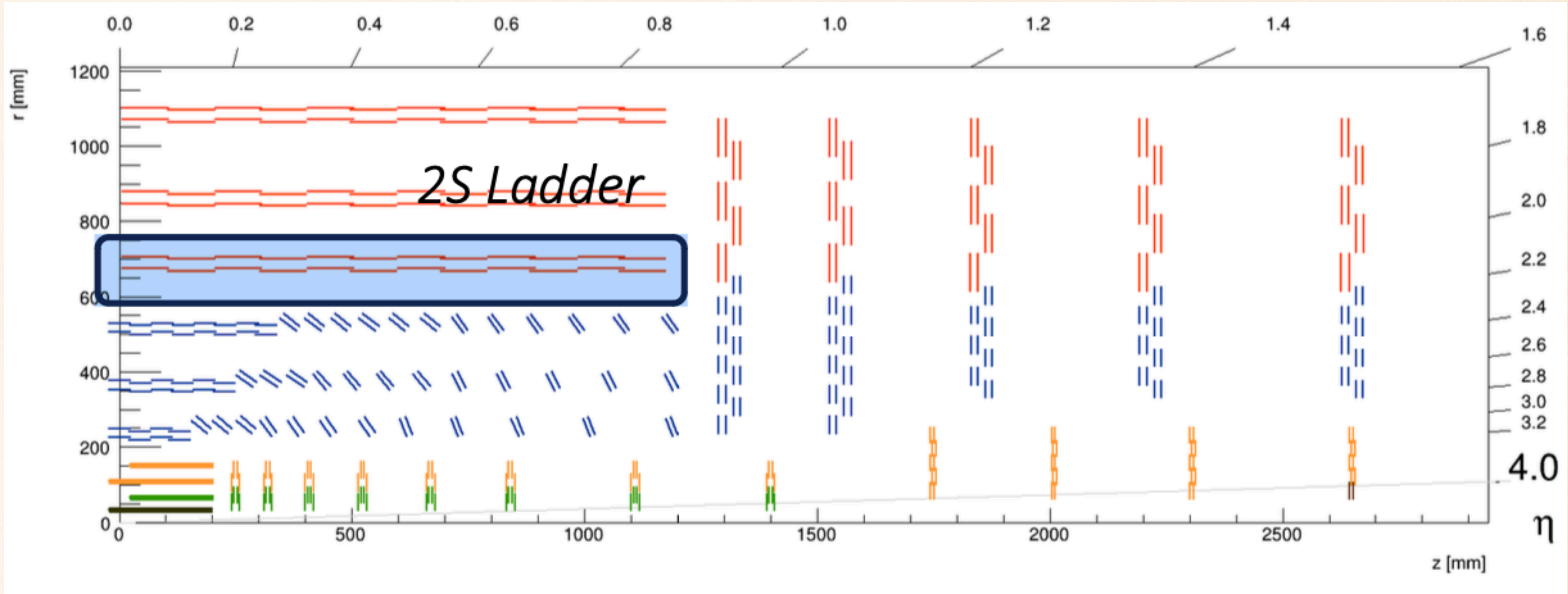
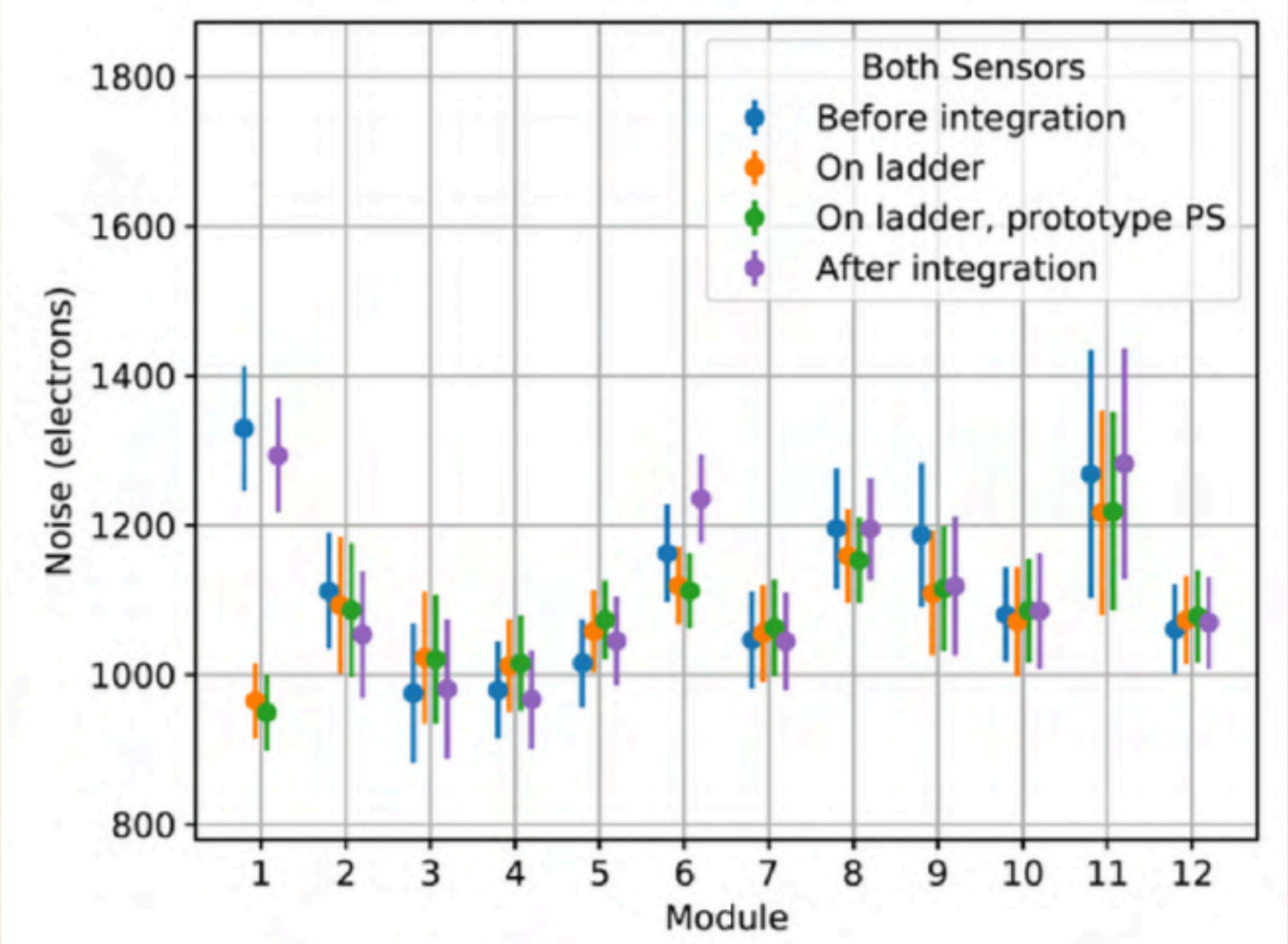
OT SYSTEM TEST RESULTS LADDERS



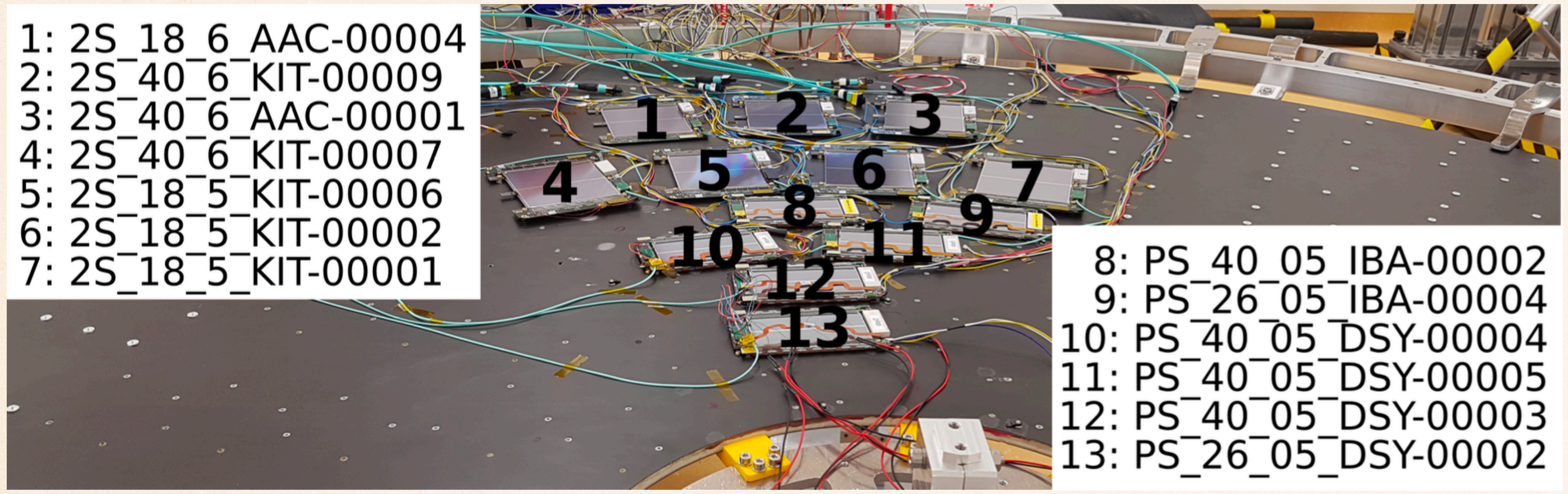


- **In a recent exercise at IPHC, 12 2S modules on a ladder with prototypes of electrical and optical services:**
  - Prototype power supply for the Phase-2 Tracker with 60 m long cable
  - Module noise shows no significant increase on the ladder compared to the measurement before integration
  - No noise degradation throughout integration test

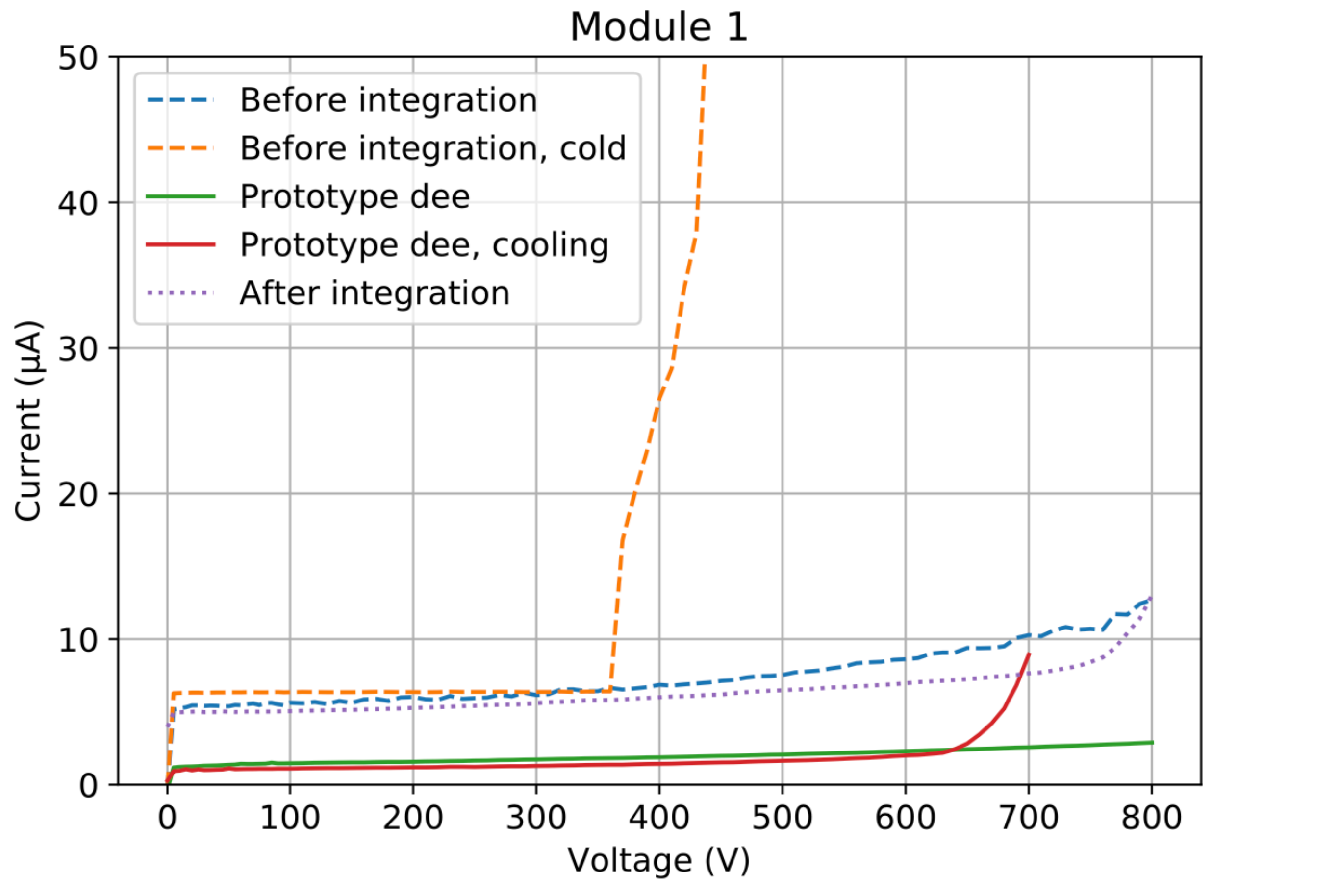
Lea Stockmeier, TIPP Conference, 2023

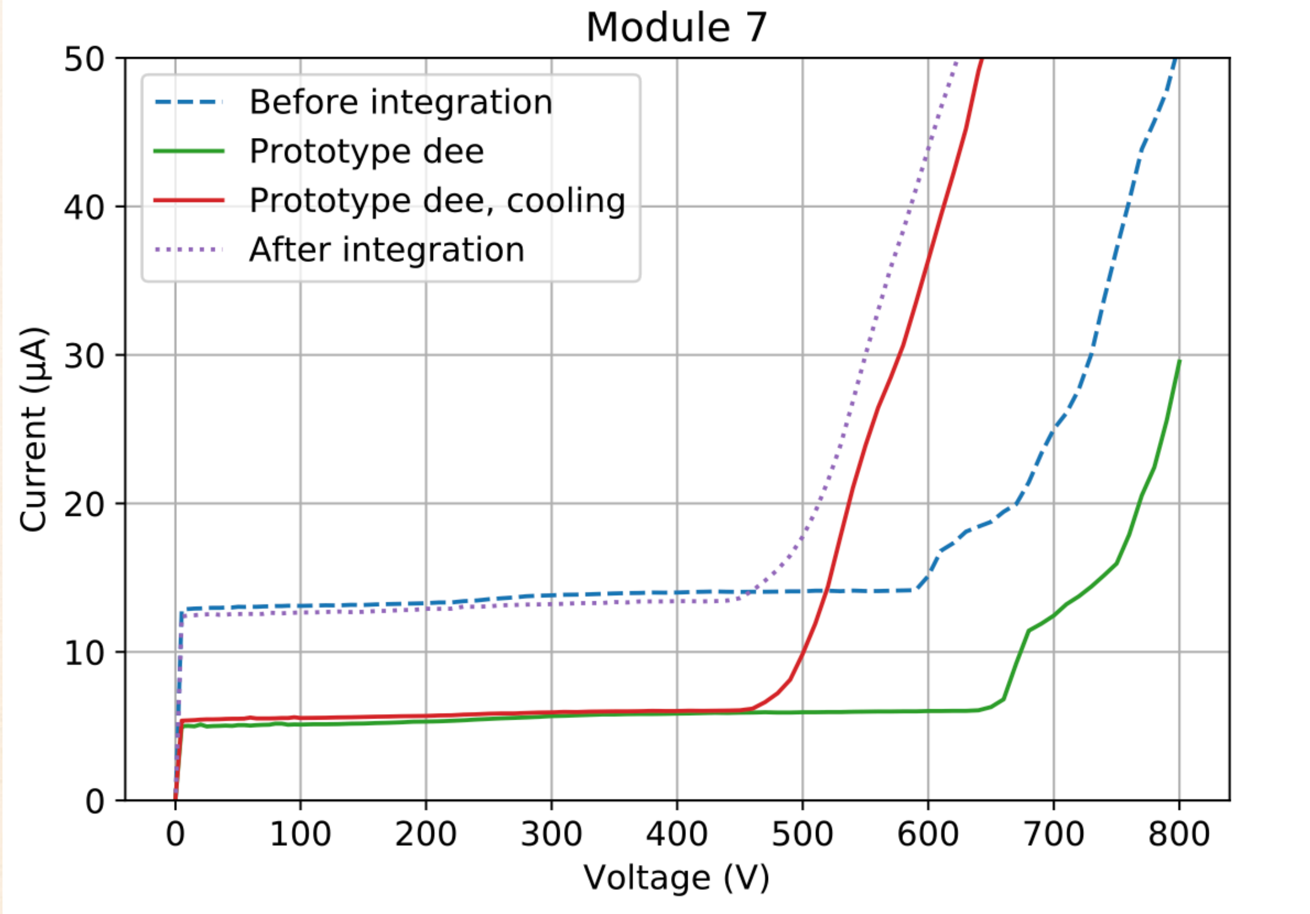


OT SYSTEM TEST RESULTS TEDD



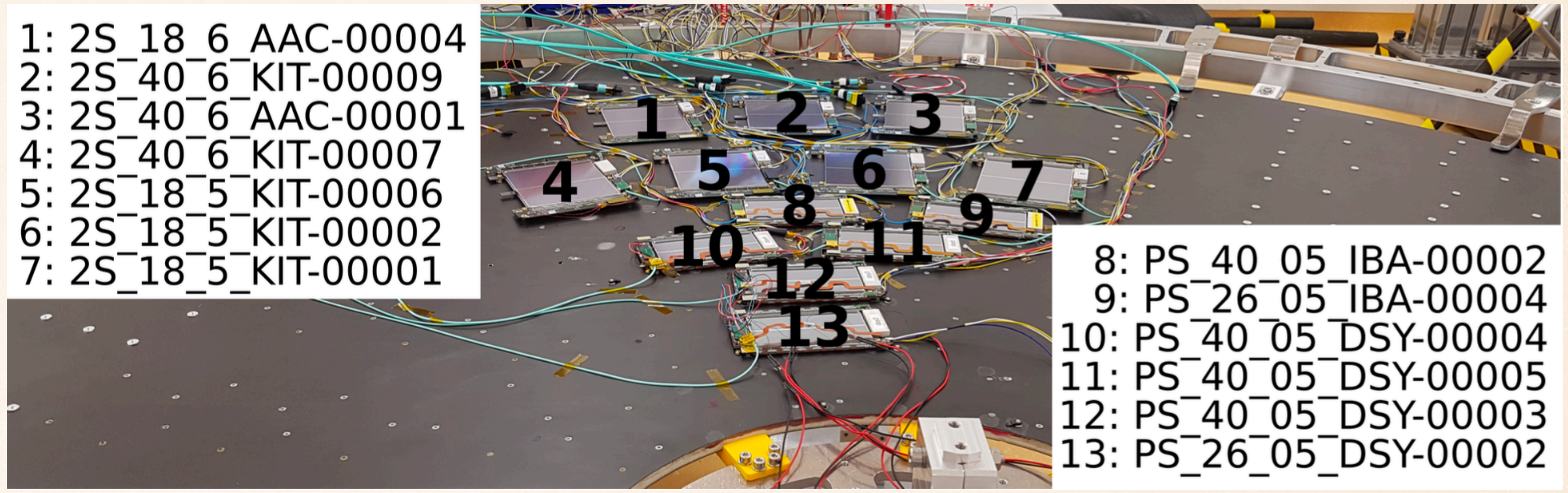
- **In a recent exercise at DESY, 13 pre-production modules (7 2S and 6 PS) were tested.**
  - Reception test of all modules (IV and noise)
  - Measurements after dee integration (IV and noise)



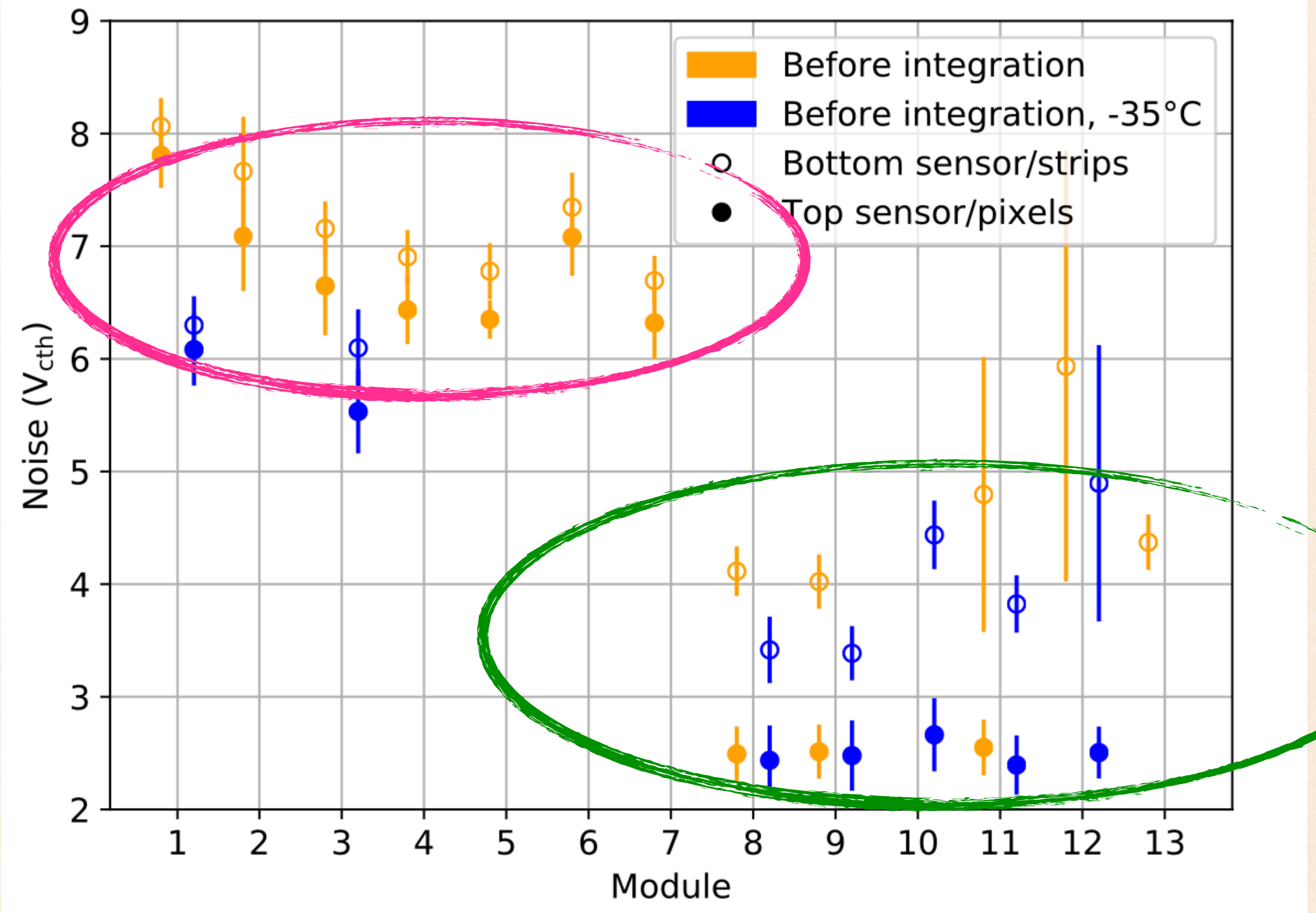


OT SYSTEM TEST RESULTS TEDD

- **In a recent exercise, 13 pre-production modules (7 2S and 6 PS) were tested.**
  - Reception test of all modules (IV and noise)
  - Measurements after dee integration (IV and noise)
- 1 $V_{threshold}$ for 2S module front end chip = 150 electrons
  - Total noise about 7*150 = 1050 electrons where signal is about 12000 electrons.
- 1 $V_{threshold}$ for PS module front end chips = 250/94 electrons
  - Noise about 2.5*250 / 4*94 = 625/376 electrons where signal is about 8000 electrons.



2S modules



PS modules

MUON TRACK RECONSTRUCTION AT HLT

TRACK RECONSTRUCTION

- **Iterative tracking philosophy**

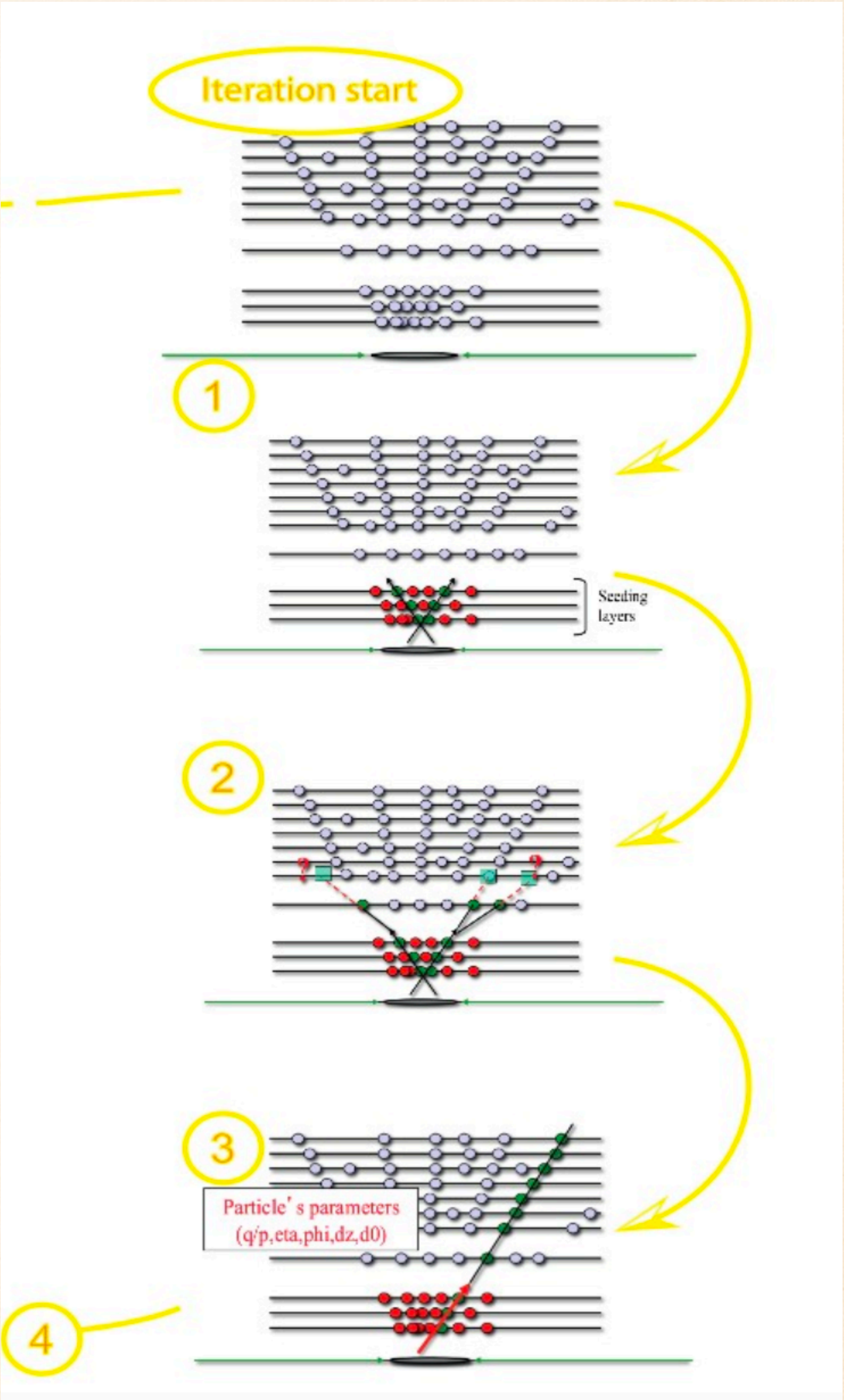
- **Tracks reconstructed in several iterations of the Combinatorial Track Finder → (search of easiest tracks + hits removing)**

1. **Seed Generation:**
   Provide initial track candidates and trajectory parameters.

2. **Track Finding:**
   Extrapolate current trajectory parameters to the next layer and find compatible hits and update with Kalman filter.
   Continue until there are no more layers or there is more than 1 missing hit.

3. **Track Fitting:**
   Perform a final Kalman or Gaussian sum smoother to obtain the trajectory parameters at the interaction point.

4. **Track Selection:**
   Final selection and classification of tracks according to quality criteria

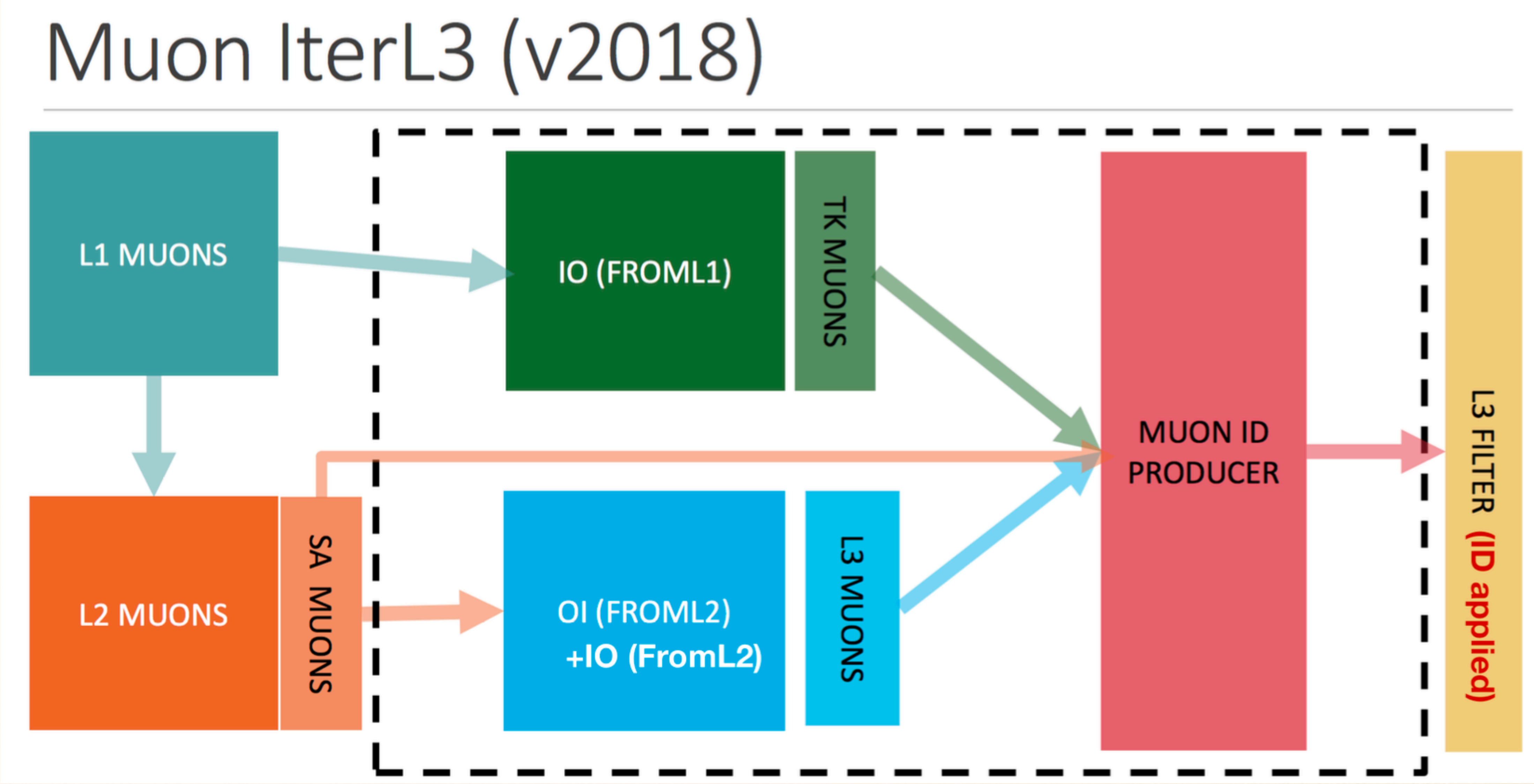


MUON RECONSTRUCTION

- The hardware trigger (**L1 trigger**) uses only the signals from muon system (DTs, CSCs, RPCs, as well as GEMs since Run 3).

- **L2 reconstruction:** building trajectories seeded by filtered L1 muons and using only information from the muon system. A Kalman filter approach similar to the track reconstruction in the silicon tracker is used.

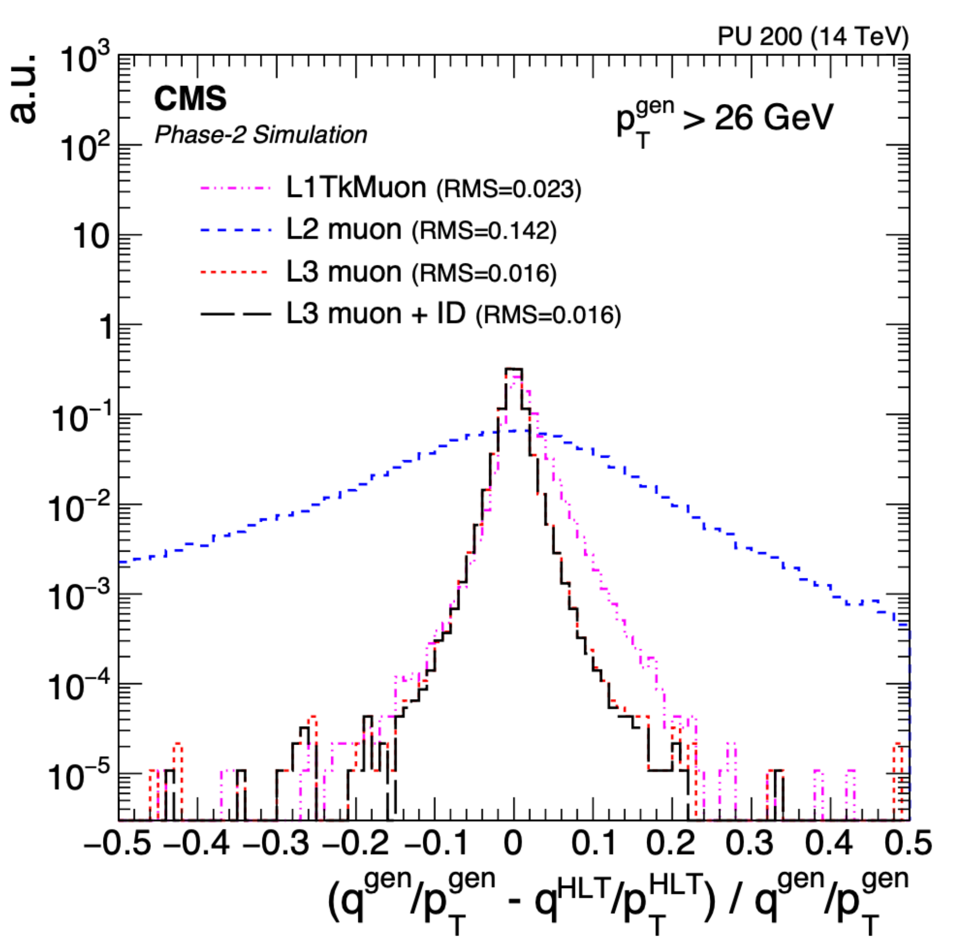
- **L3 reconstruction:** combine information from muon system and tracker. The trajectory building in the tracker is seeded by either L2 or L1 muons, and the recon- struction is performed using the Kalman filter.
  Inside-out (IO) from L1 and L2, and outside-in (OI) from L2.

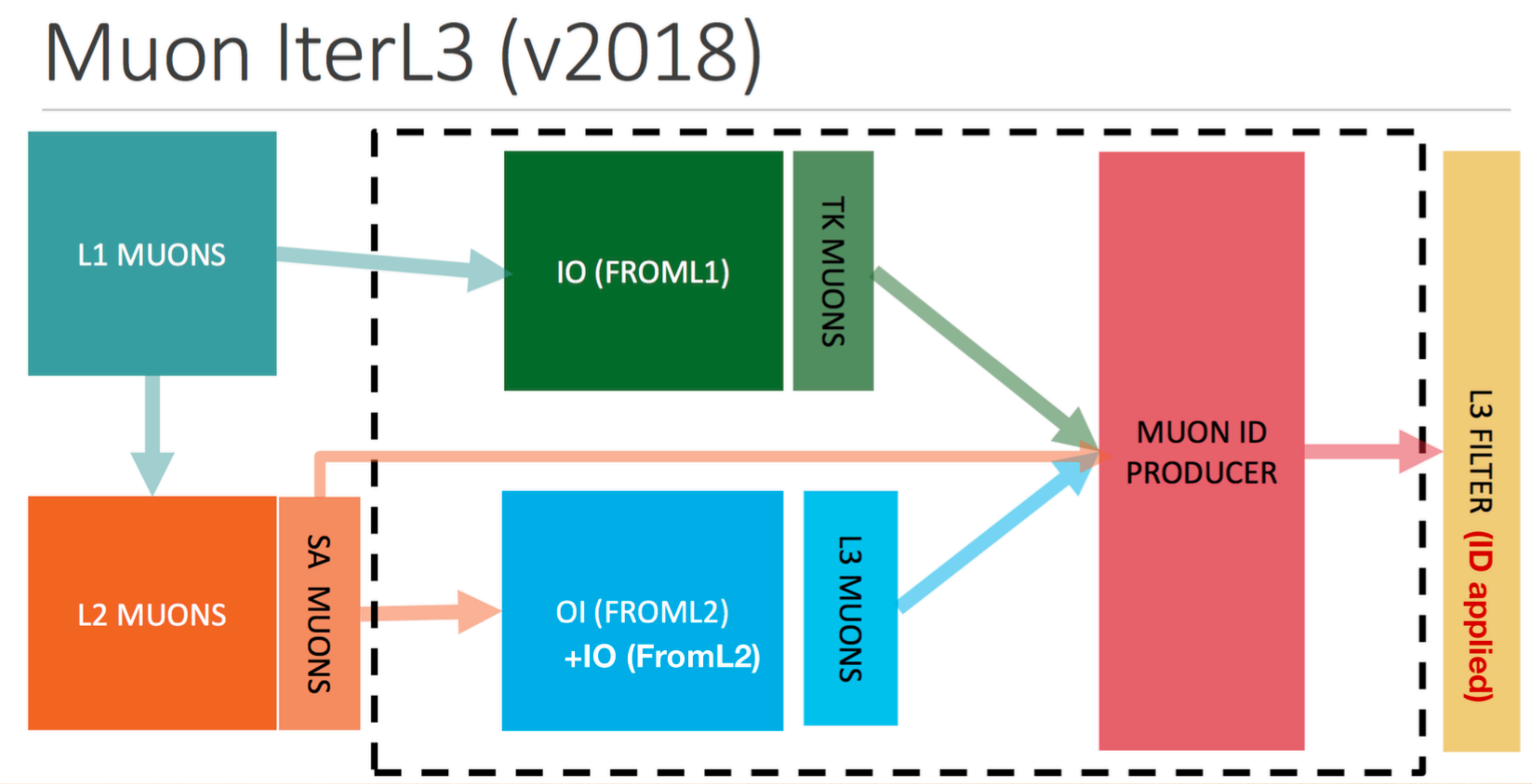


MUON RECONSTRUCTION

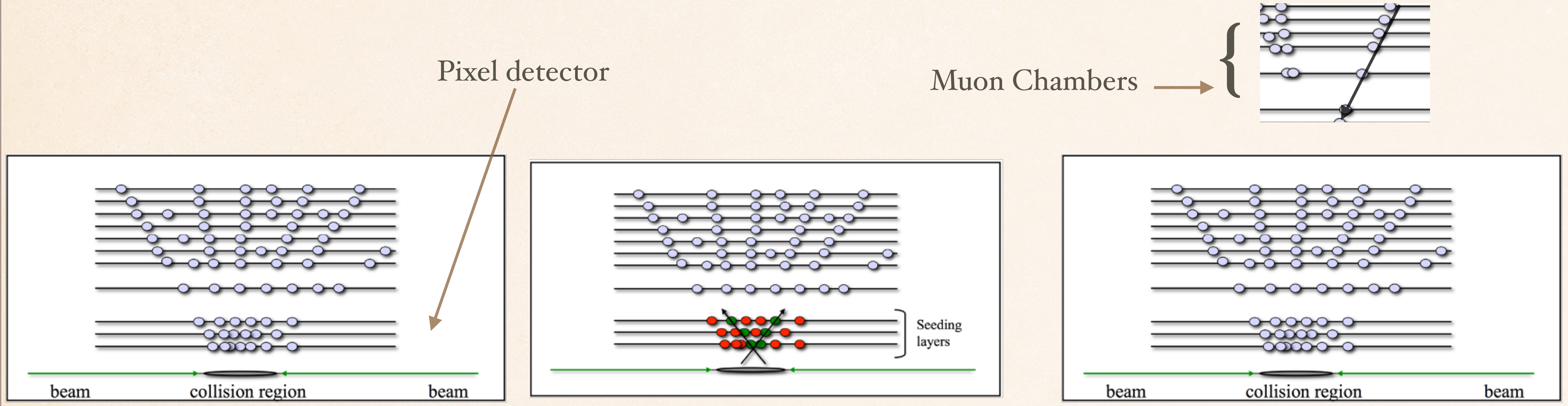
- In the upgraded L1 trigger, muon system information can be combined with tracks from the L1 track trigger to improve the momentum and position resolution of the muons. These objects are referred to as *L1TkMuons*

- As the use of tracker information in the L1 tracker muon implies a requirement on the muons to originate at the interaction point, their use limits the acceptance for displaced muons. Therefore, both types of L1 muons will be used in Phase-2.

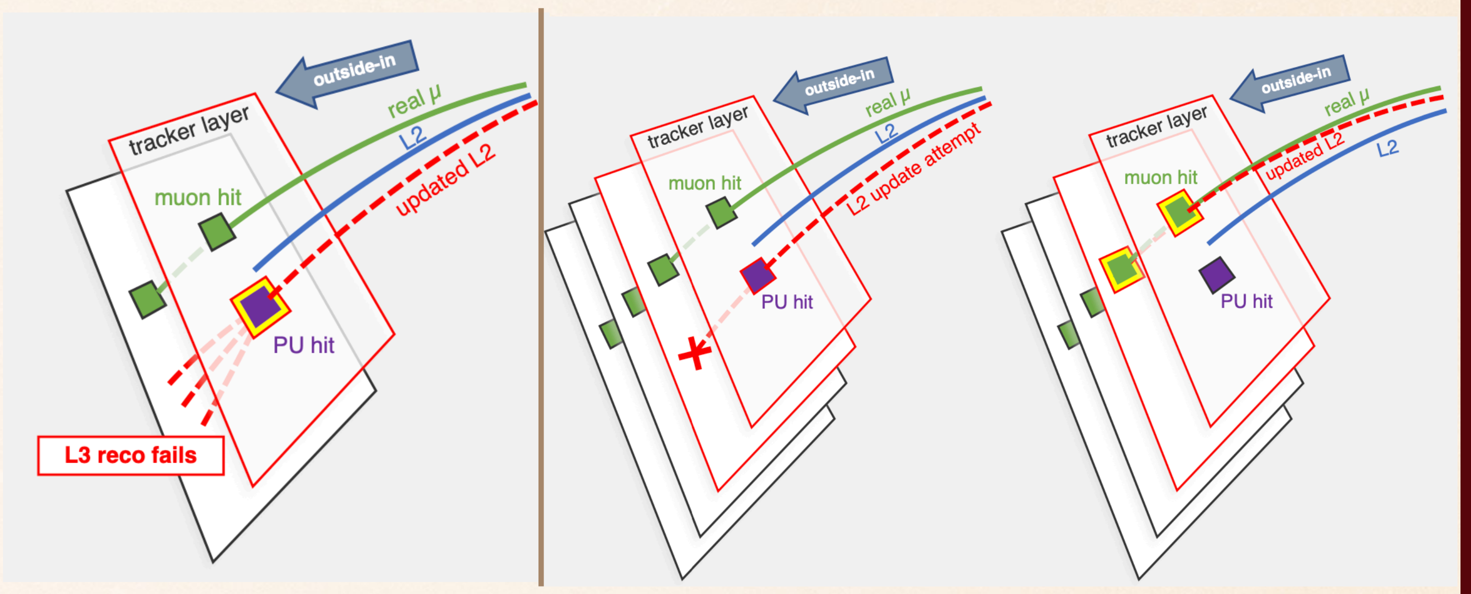


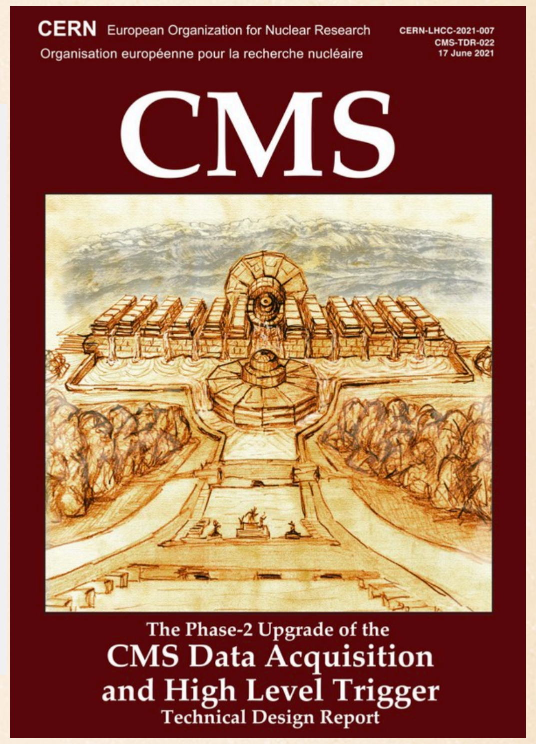


IMPROVEMENT IN MUON TRIGGER

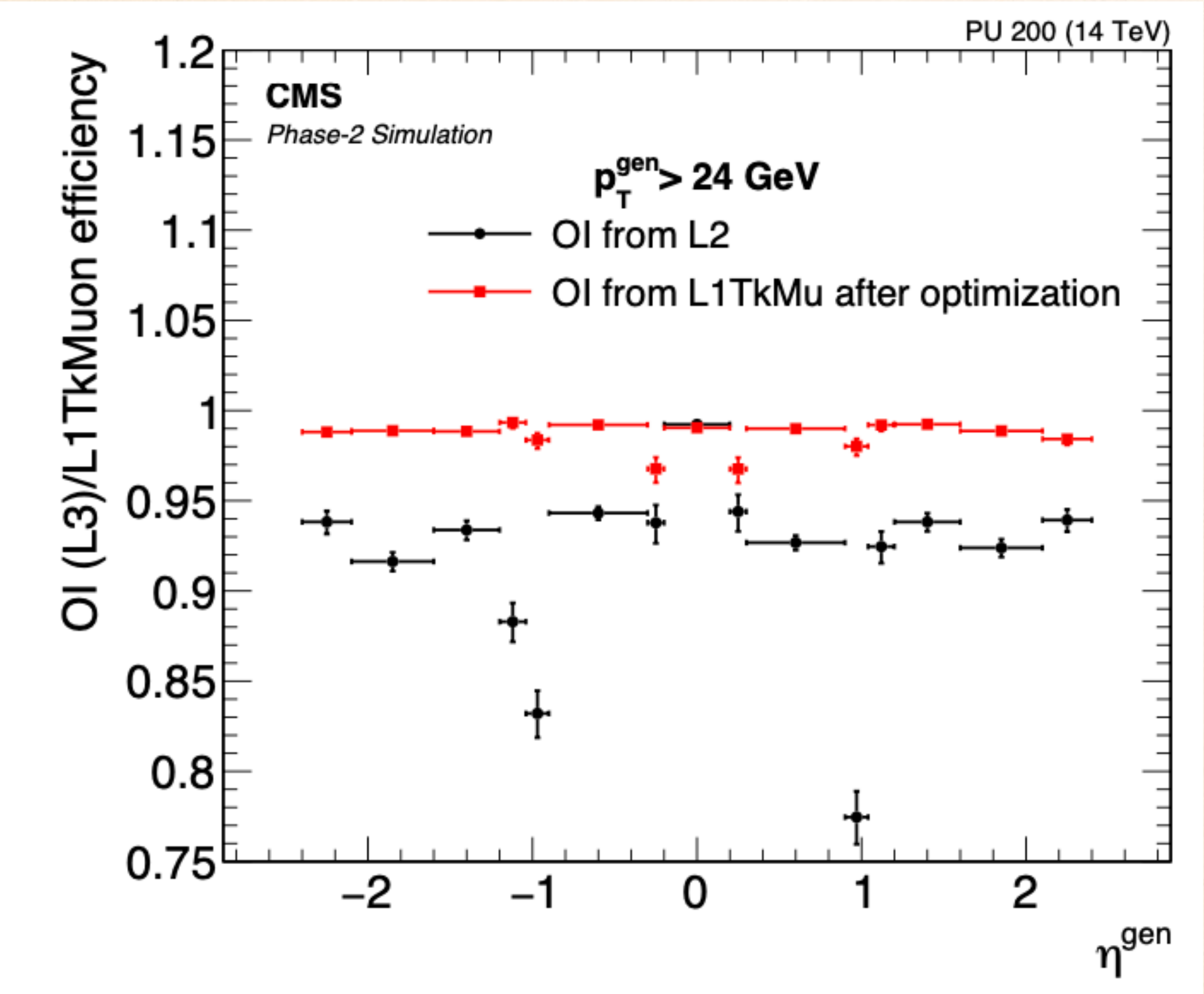


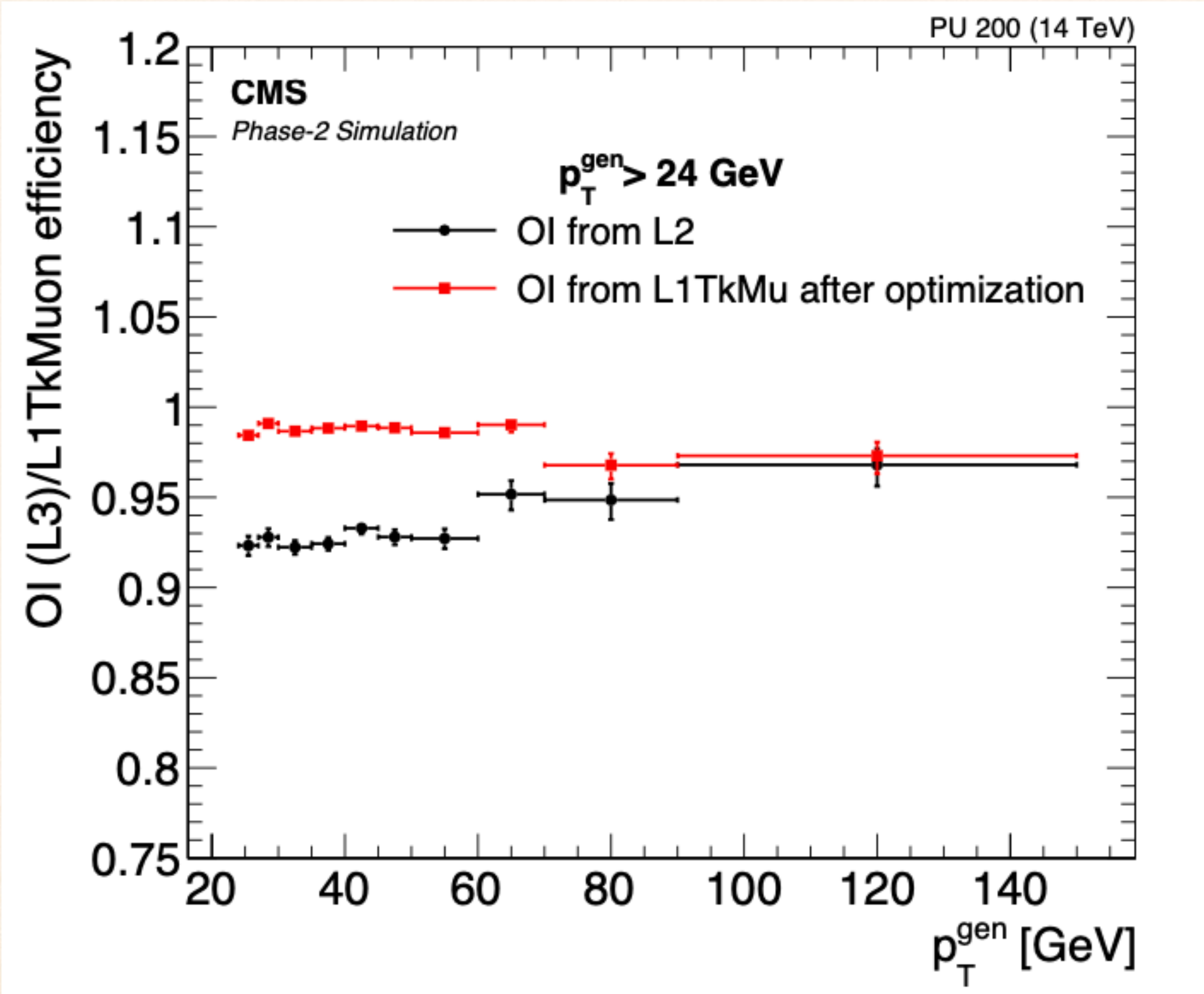
Muon track fitting





Technical design report





3 layers
128
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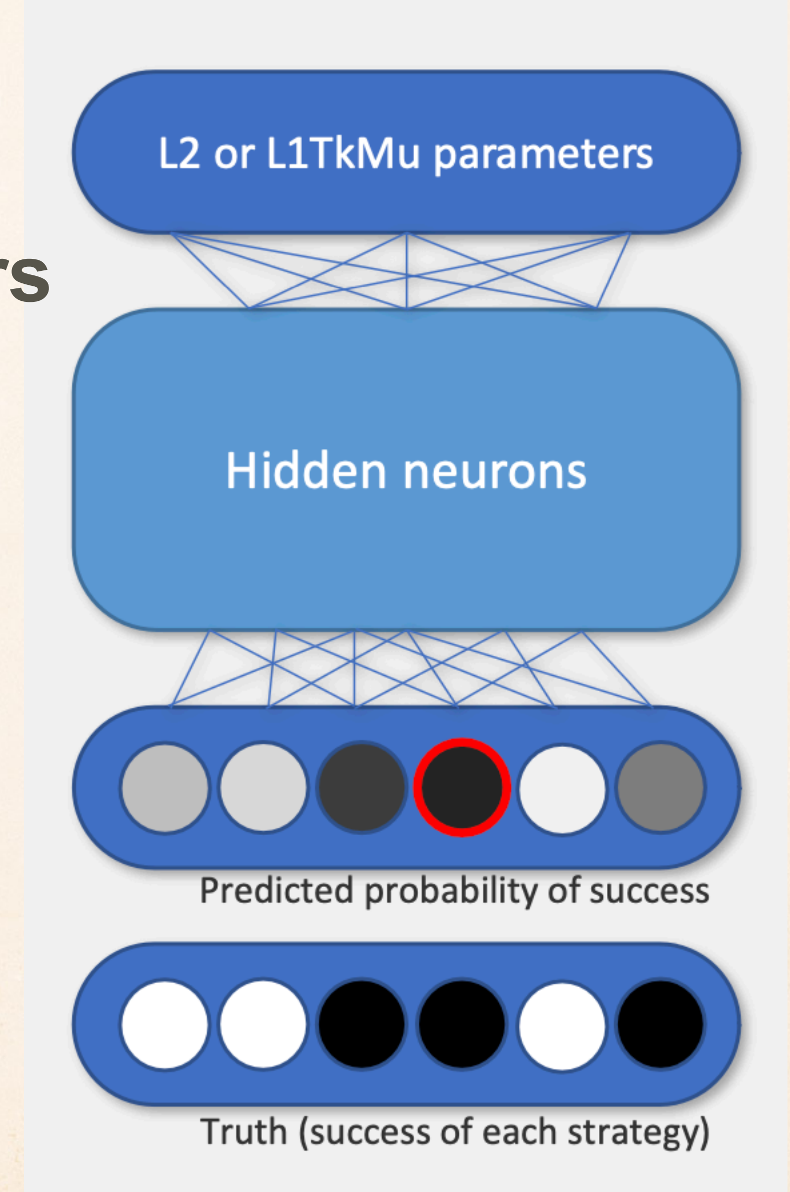
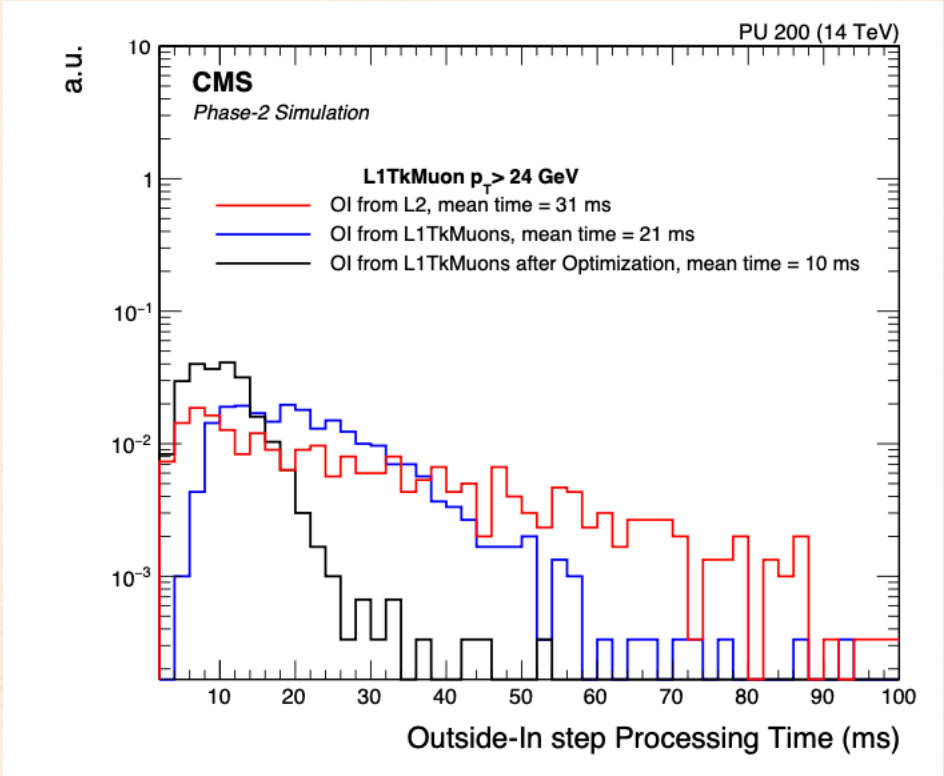




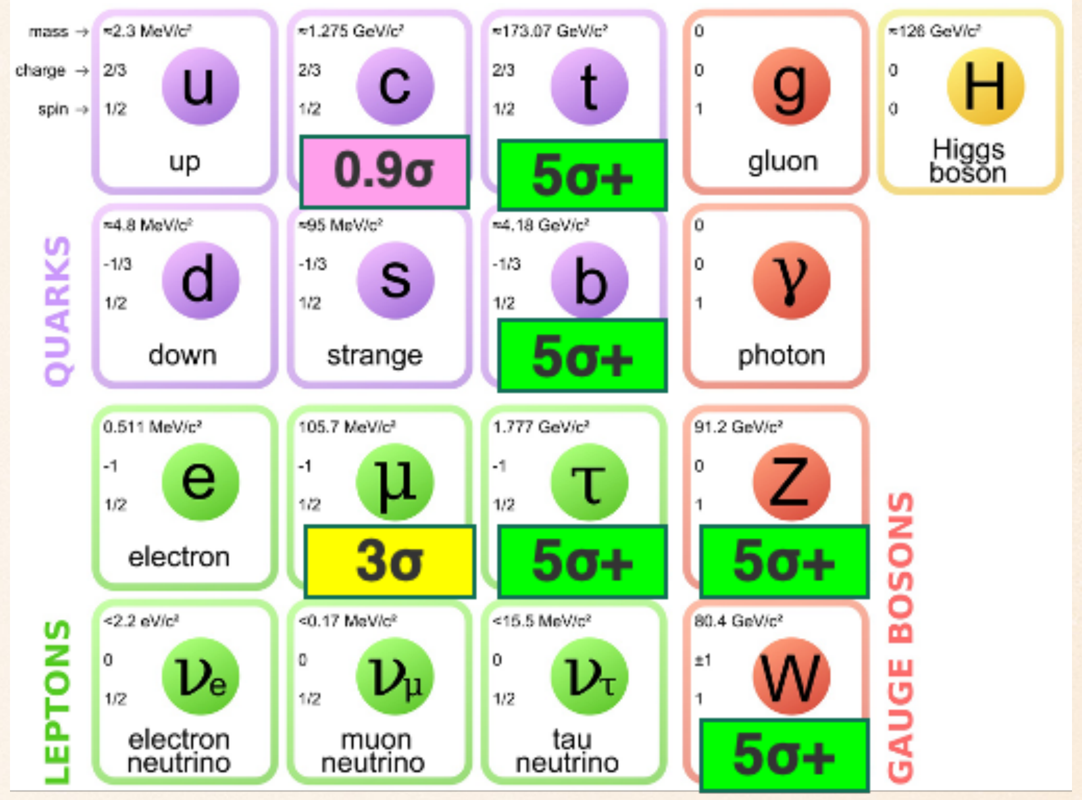
THE PRECISE MEASUREMENT OF THE HIGGS BOSON COUPLING TO MUONS

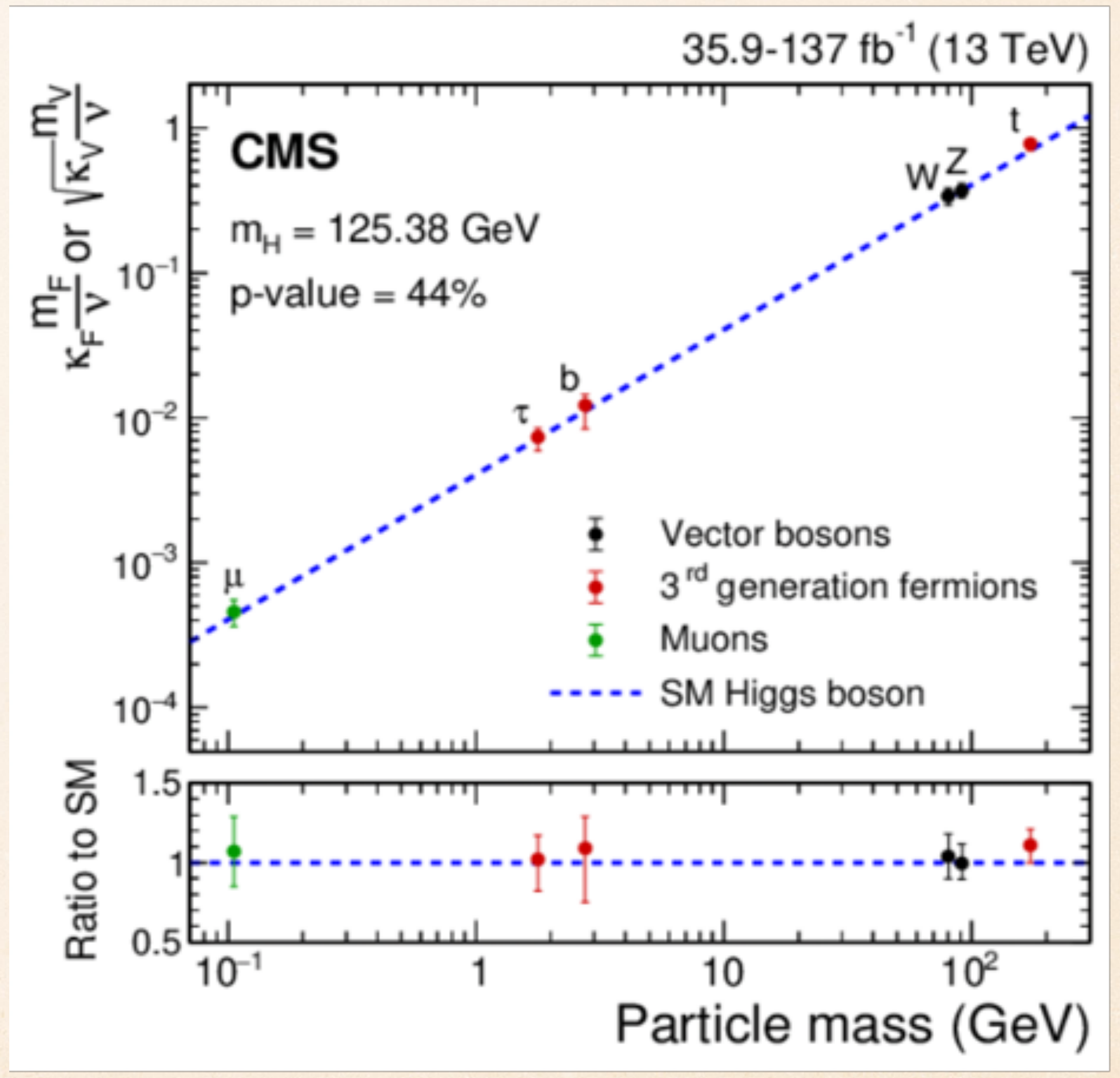
HIGGS BOSON PHYSICS

- In the last decade, **LHC** has established couplings of **Higgs** boson to **gauge** bosons (Z/W) and **3rd generation** fermions (t, b and τ) through observation of corresponding decay or production modes with a significance of 5σ or larger.

- Thanks to the **advent of new machine learning algorithms and larger computing resources** which have helped the analyzers to extract the signal from the heap of background and observe the Higgs boson signal in channels which were never anticipated with only Run 2 data.

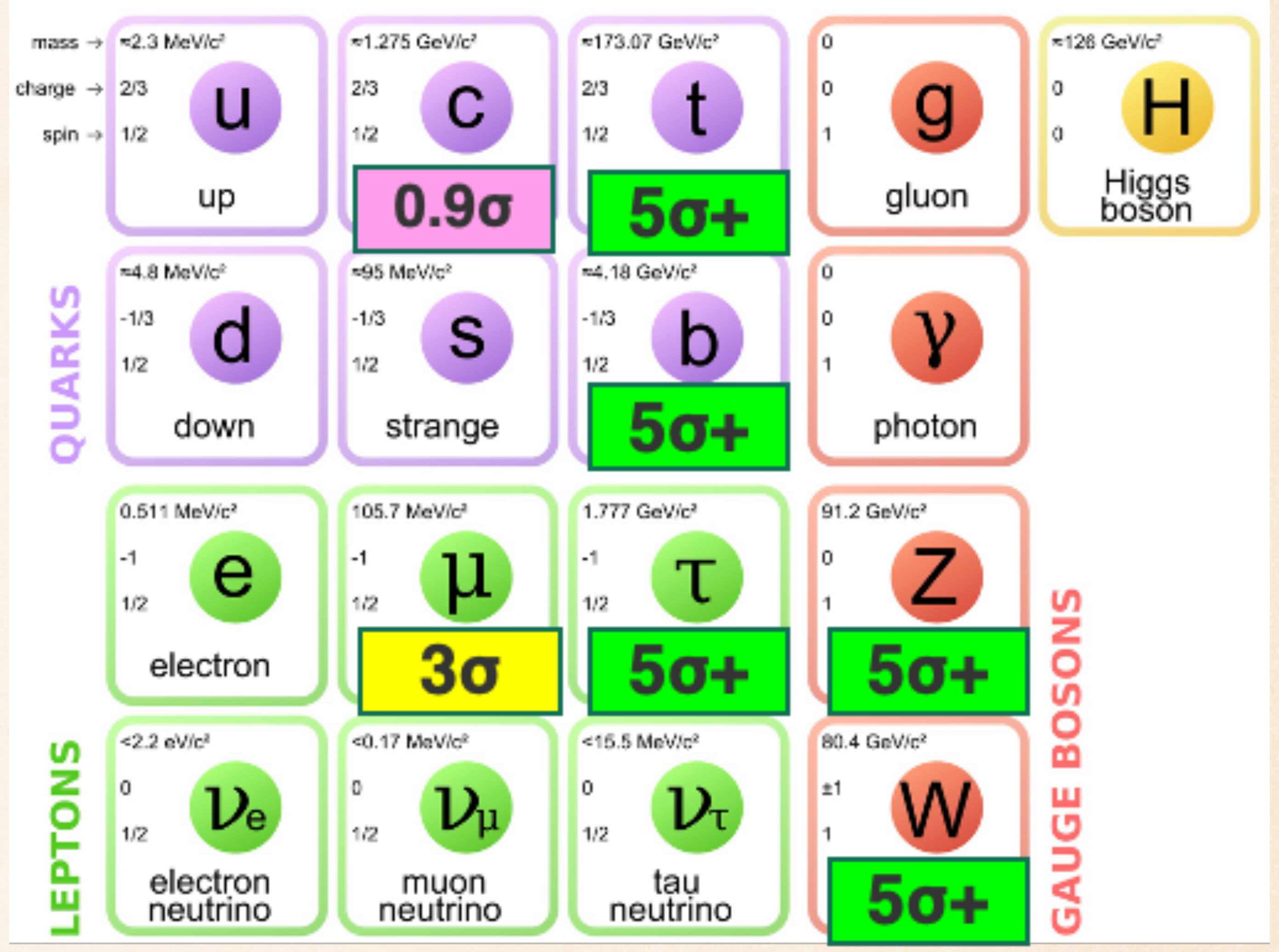
- All measured properties are **compatible with the SM predictions** within their uncertainties but there is still room for BSM theories.

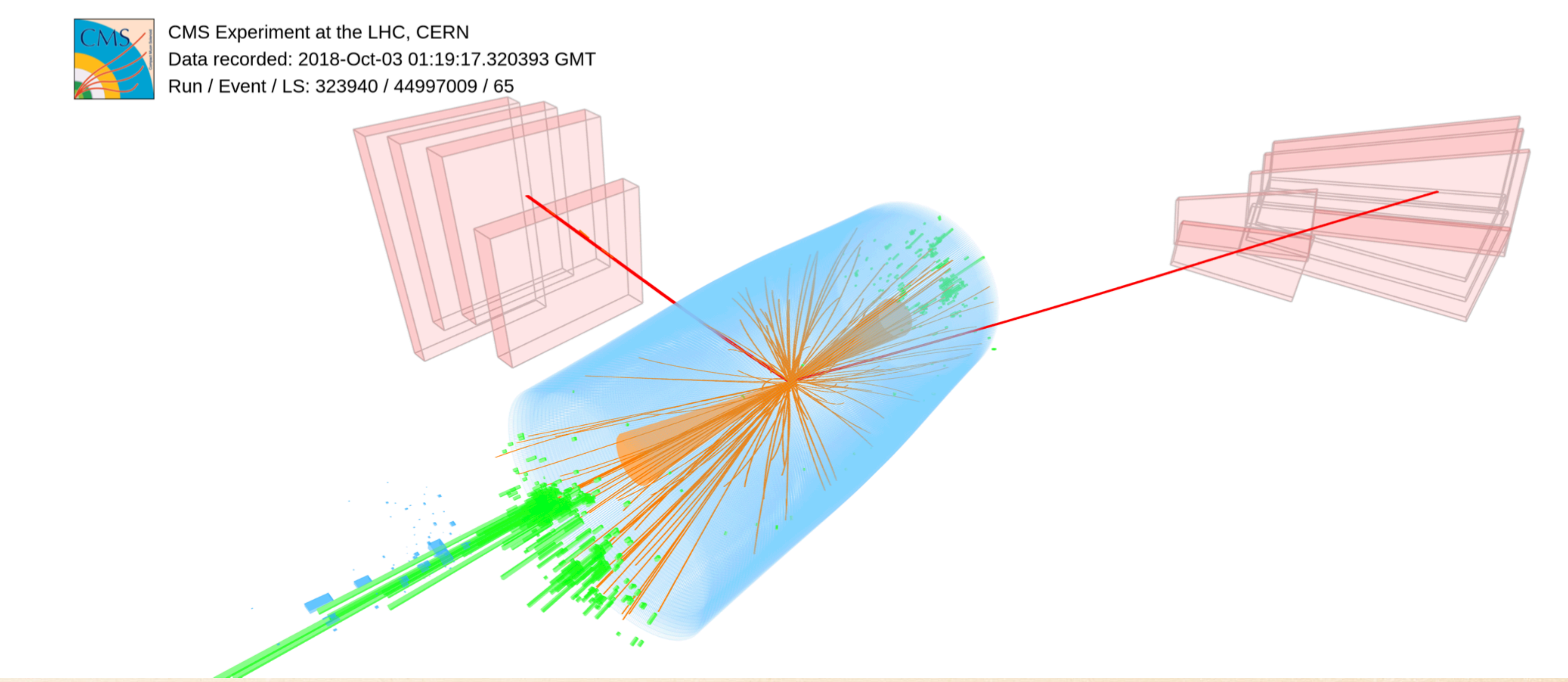




MOTIVATION FOR H $\rightarrow \mu\, \mu$

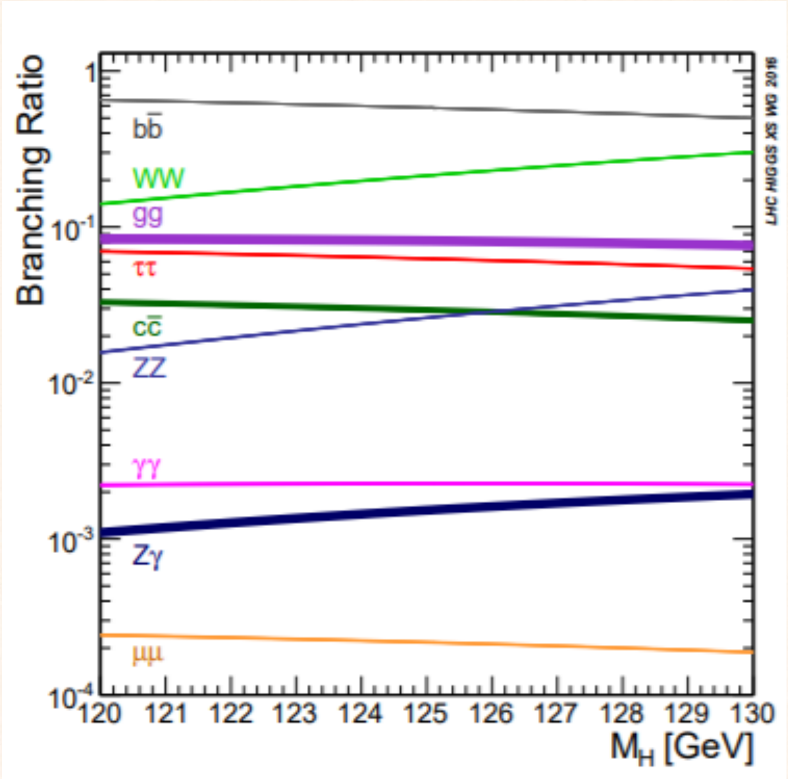
- The HL-LHC will greatly expand the physics potential of the LHC, in particular for statistically limited processes.
- The enormous dataset from the HL-LHC and the upgraded CMS detector will allow us to achieve **percent level precision for many Higgs couplings**, including the coupling to muons, which has a branching fraction of only 0.02%.
- H $\rightarrow \mu\, \mu$ channel provides the first insight into Higgs couplings to 2nd generation fermions.
    - Data collection in Run 3 and at the HL-LHC will be crucial to achieve **observation-level significance**.

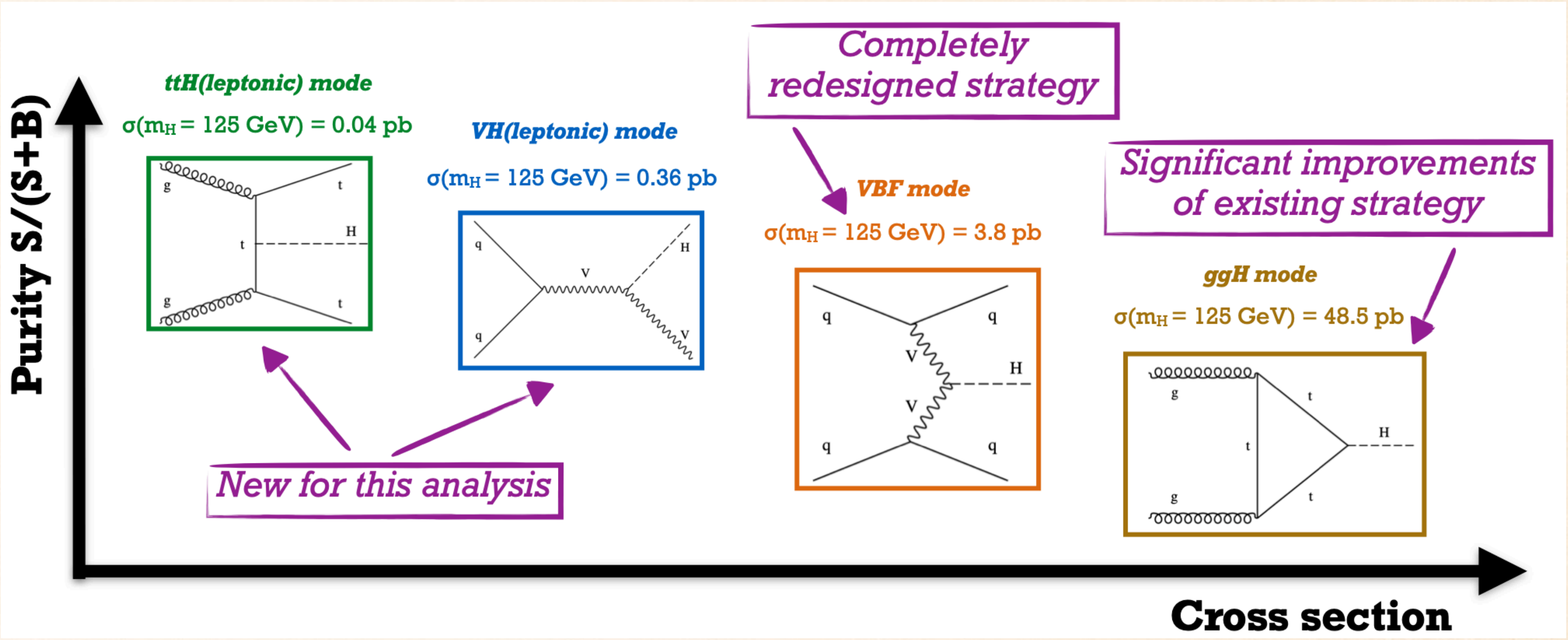


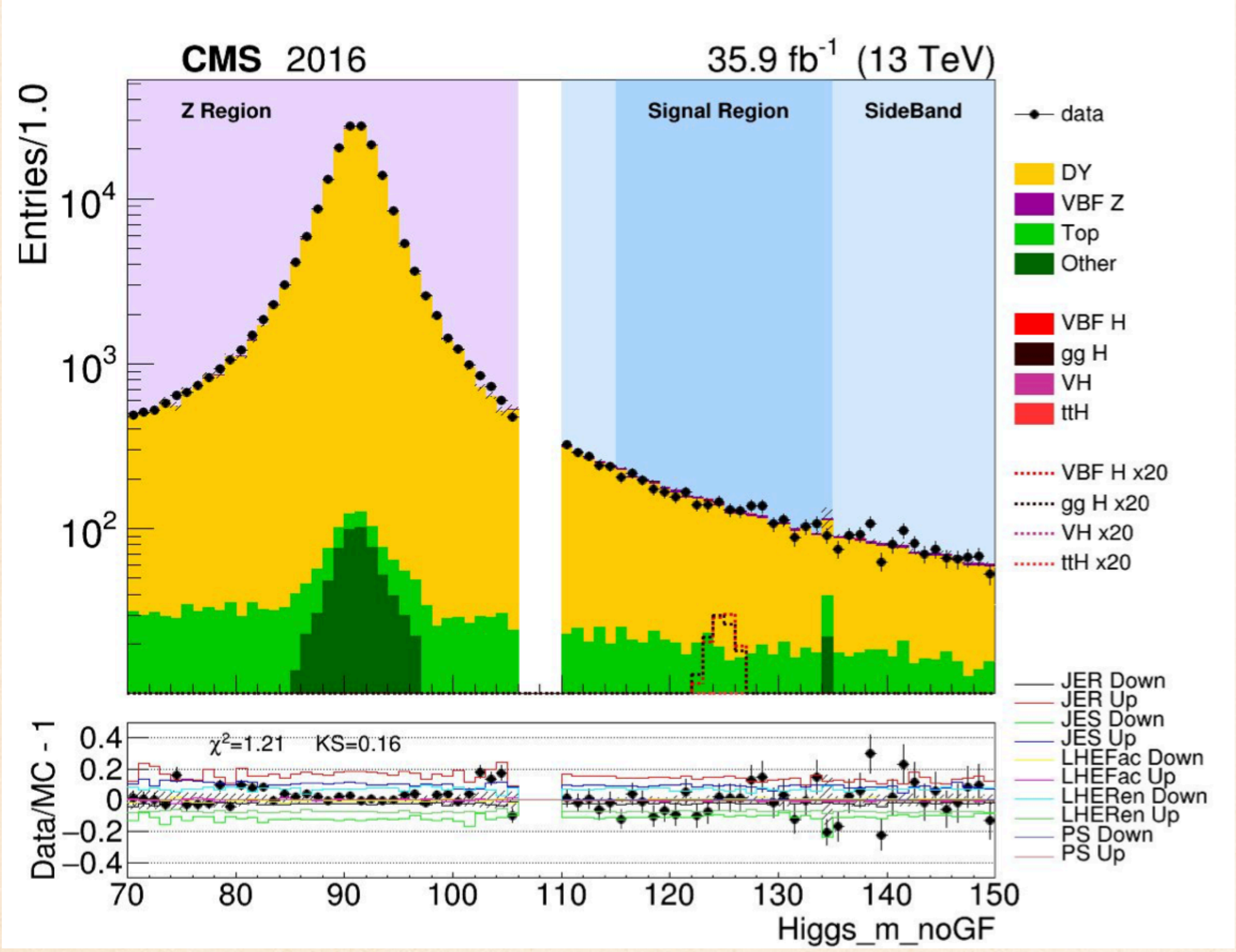


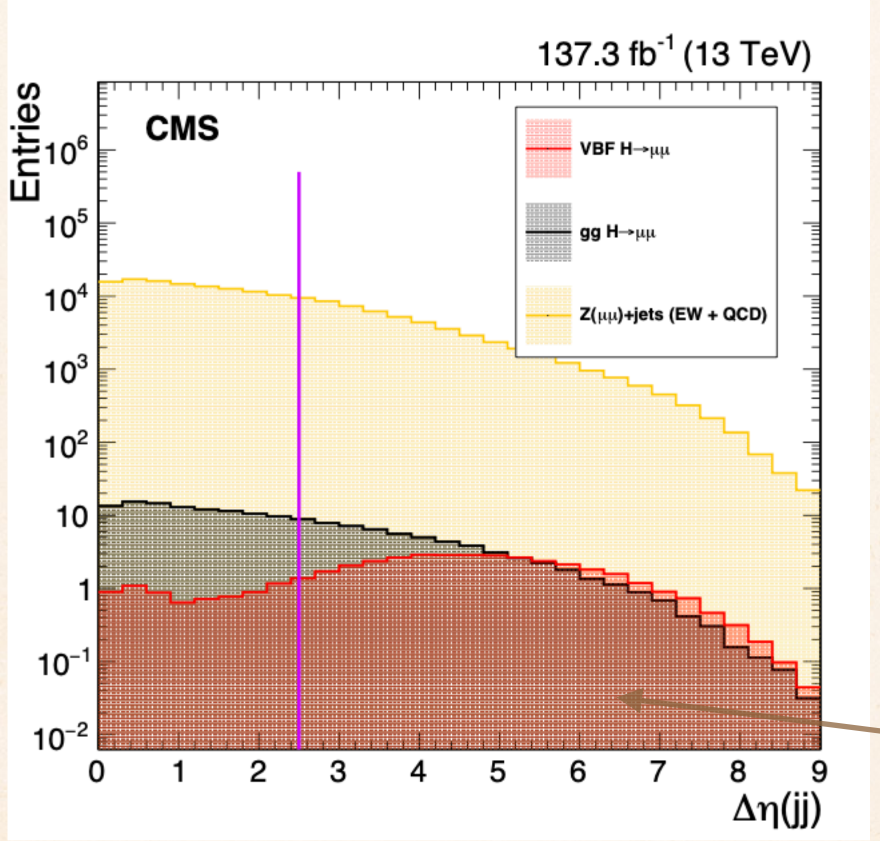
ANALYSIS STRATEGY

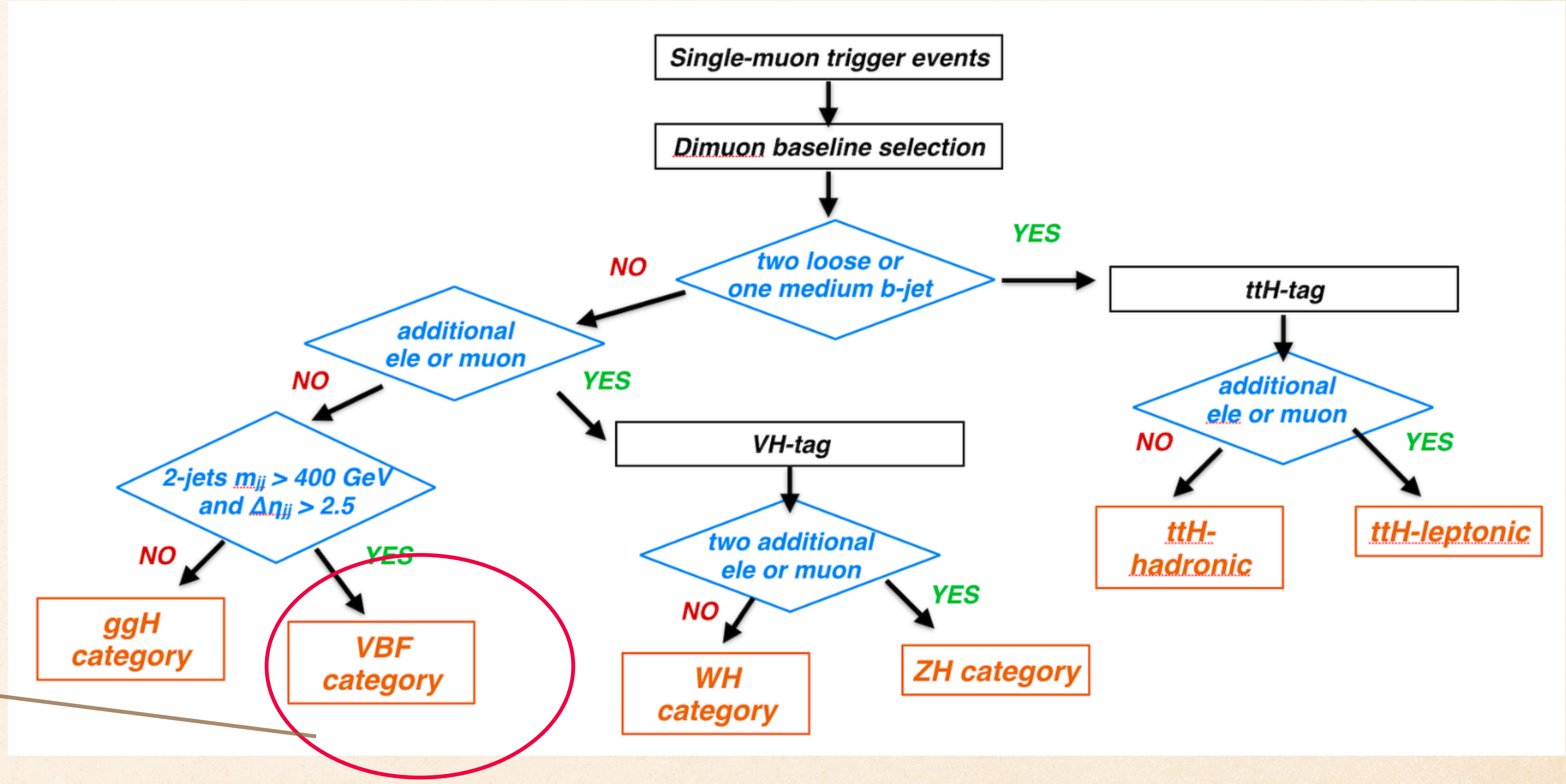
- **Experimentally challenging search:**
    - Branching fraction: **0.02%**, another order of magnitude smaller than the diphoton channel.
    - Very large **Drell-Yan background**.





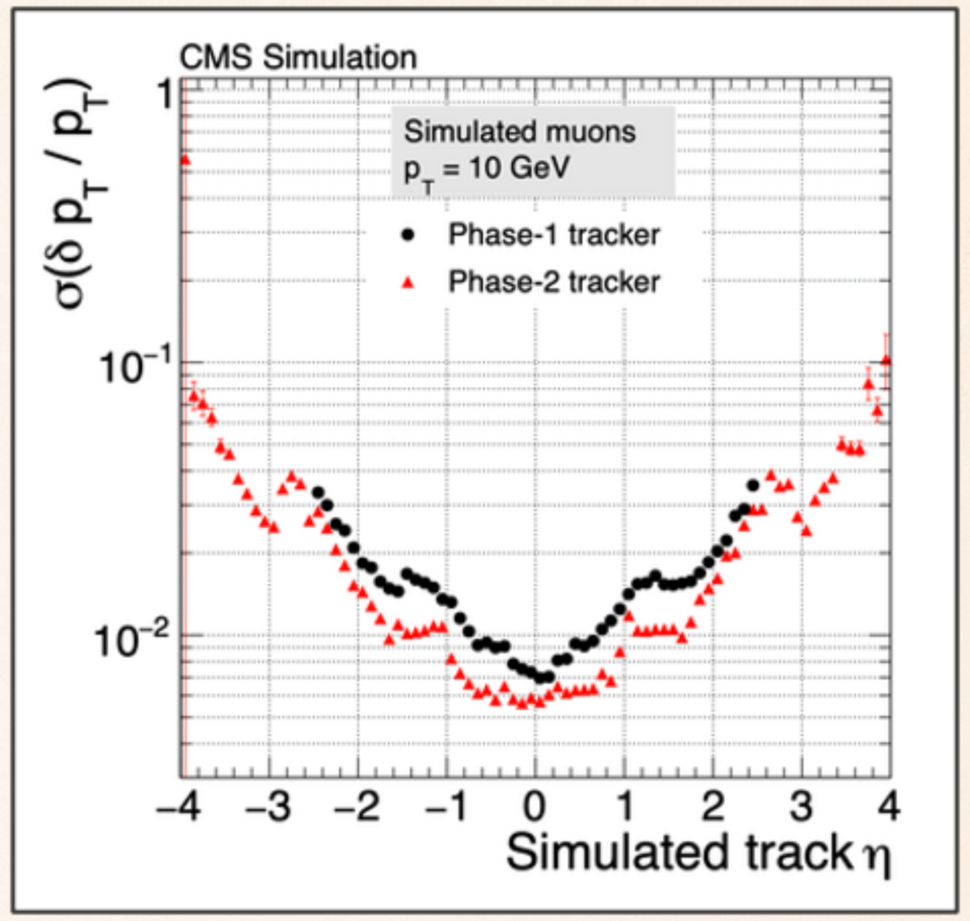


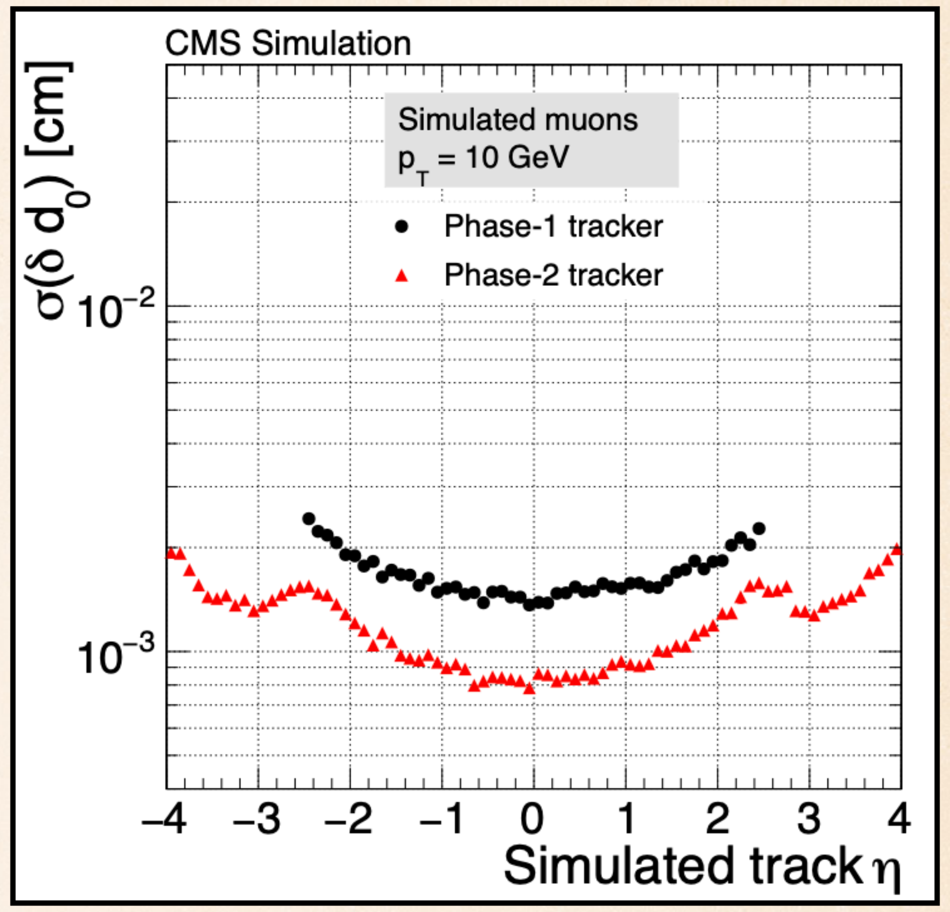


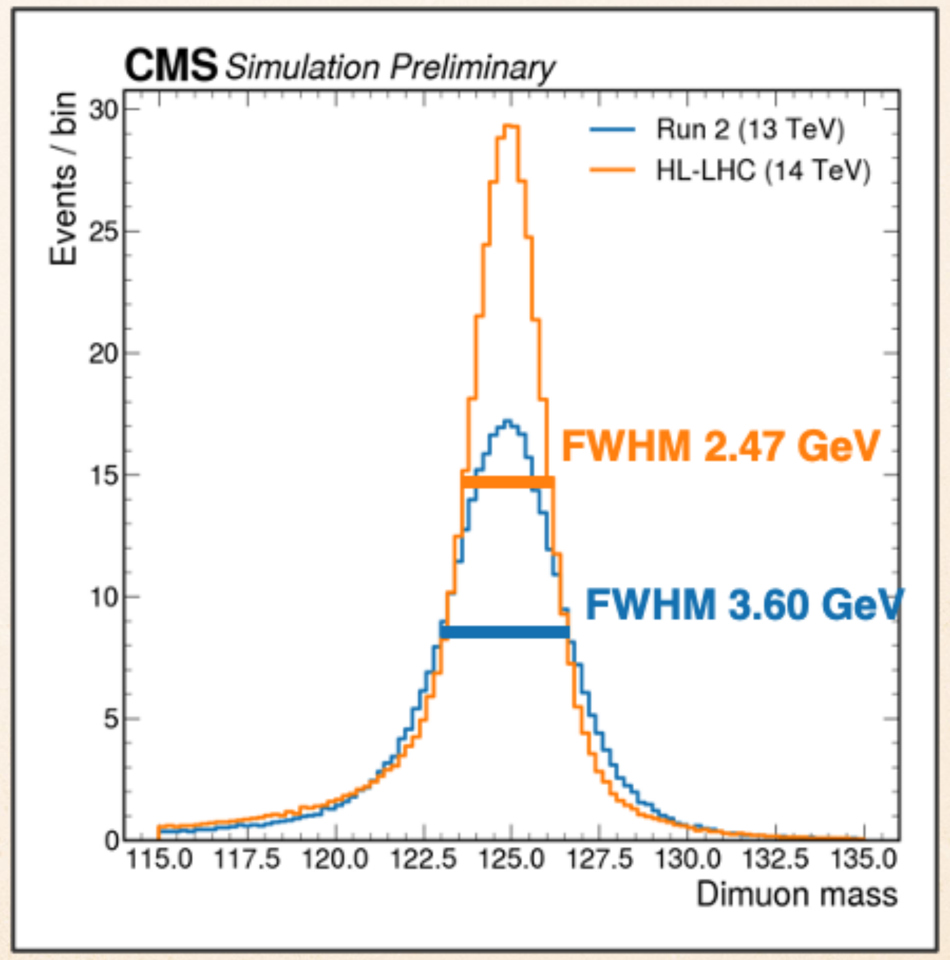


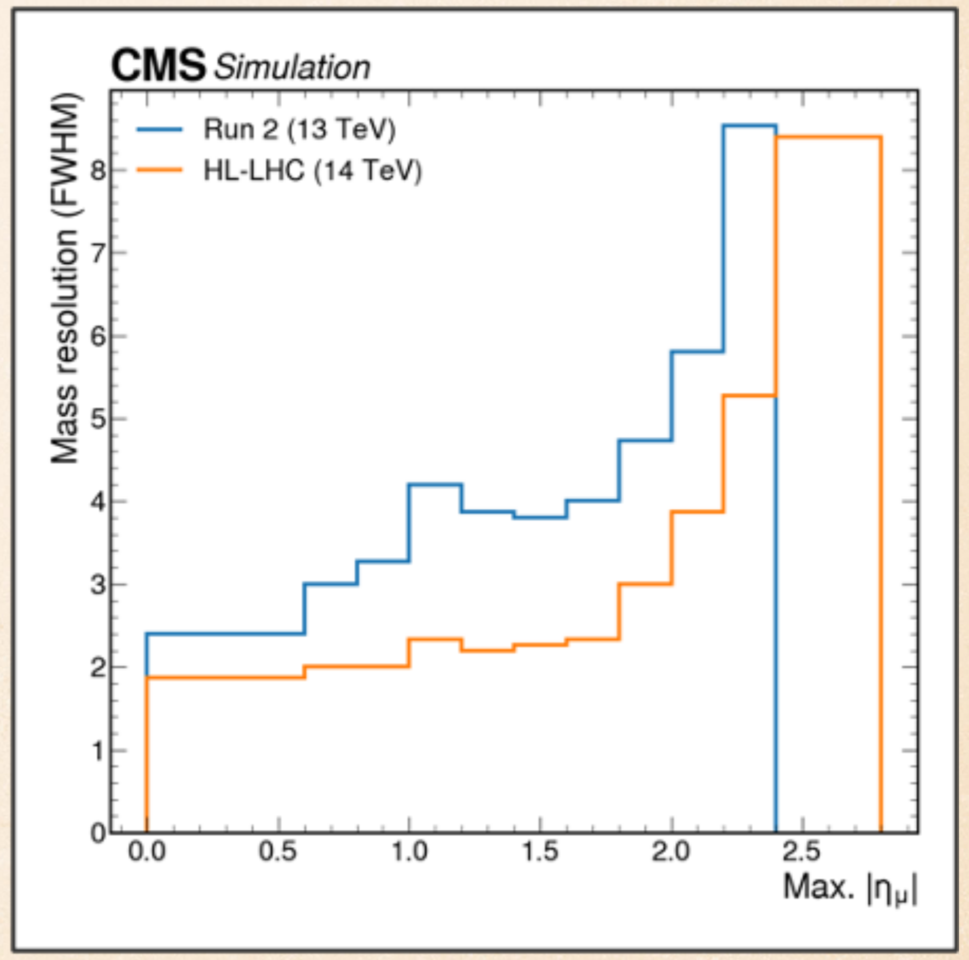
IMPACT ON MASS RESOLUTION

- We estimate the improvement by evaluating full width at half maximum (FWHM) for ggH H→μμ invariant mass distribution.
  - Inclusively, FWHM of Higgs peak for HL-LHC is **68.5%** of that in Run 2.



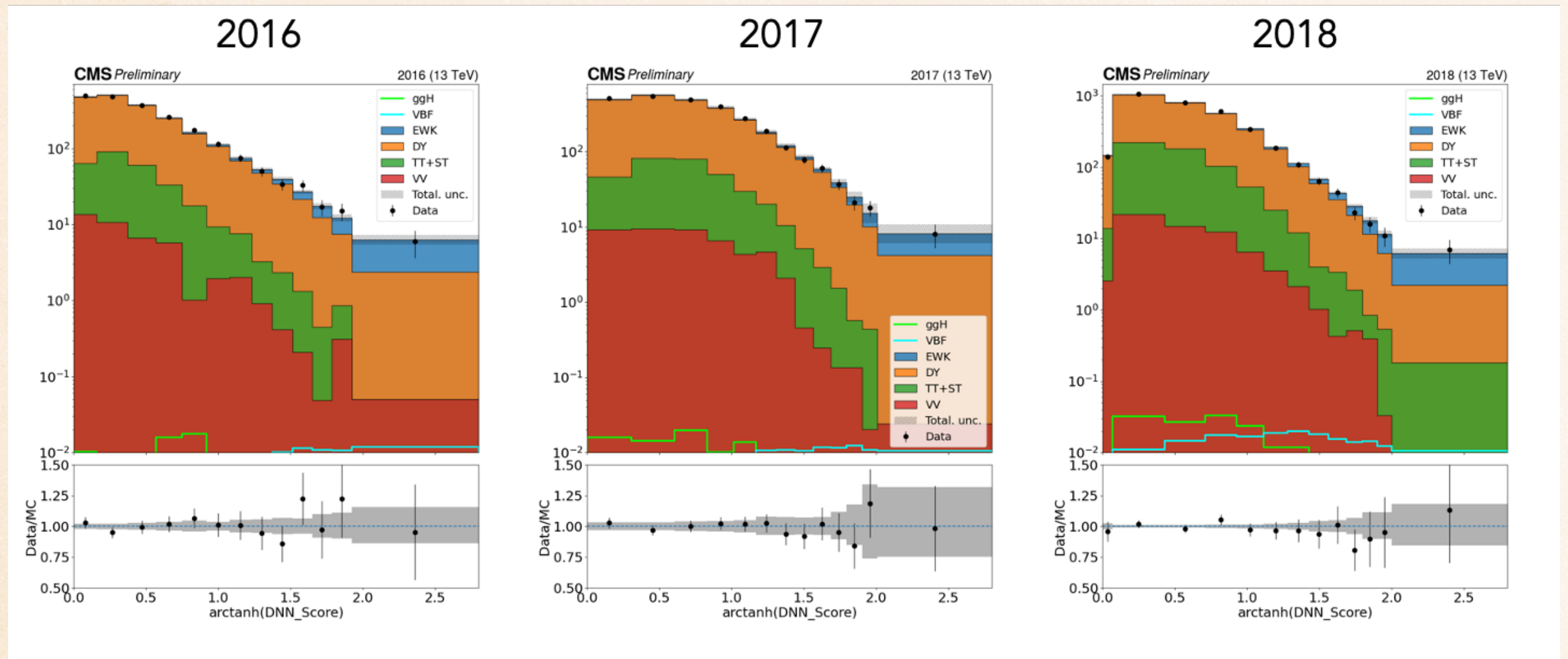




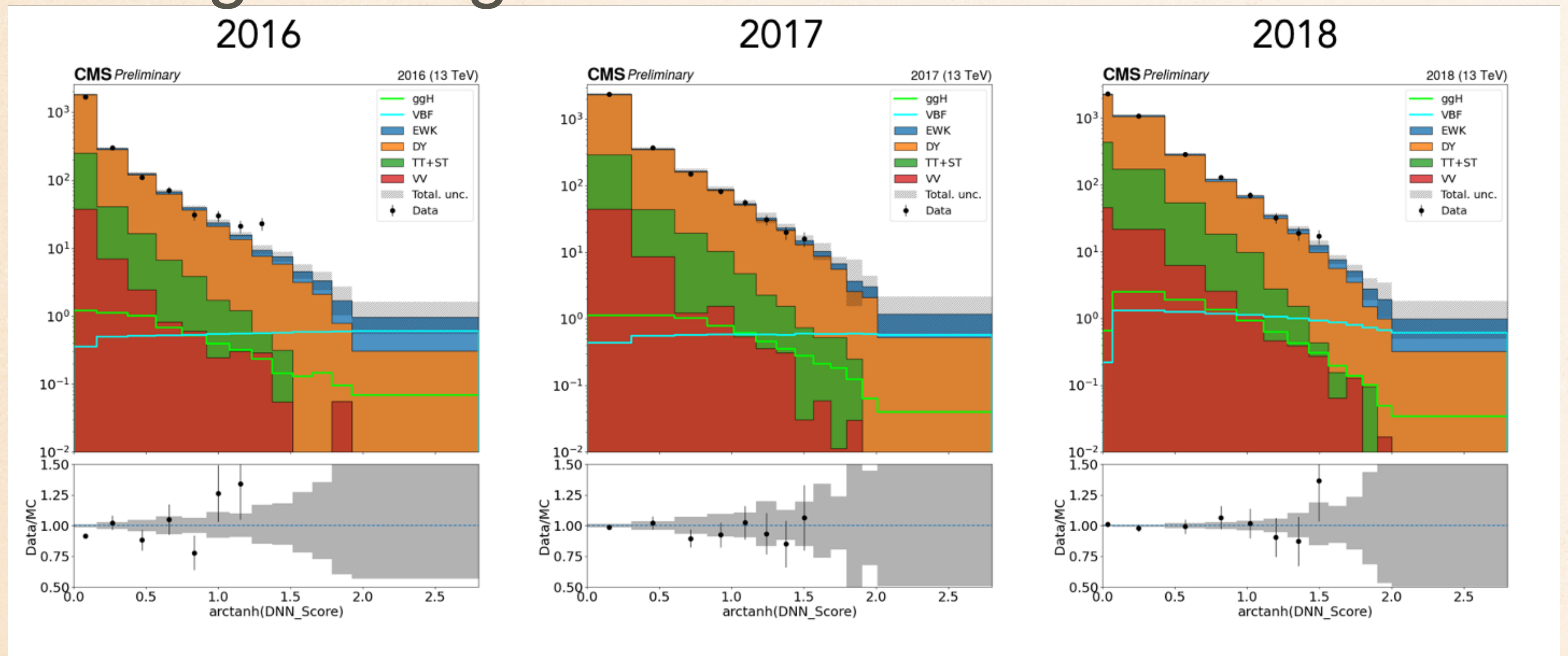


IMPROVE SENSITIVITY USING DEEP NEURAL NETWORK

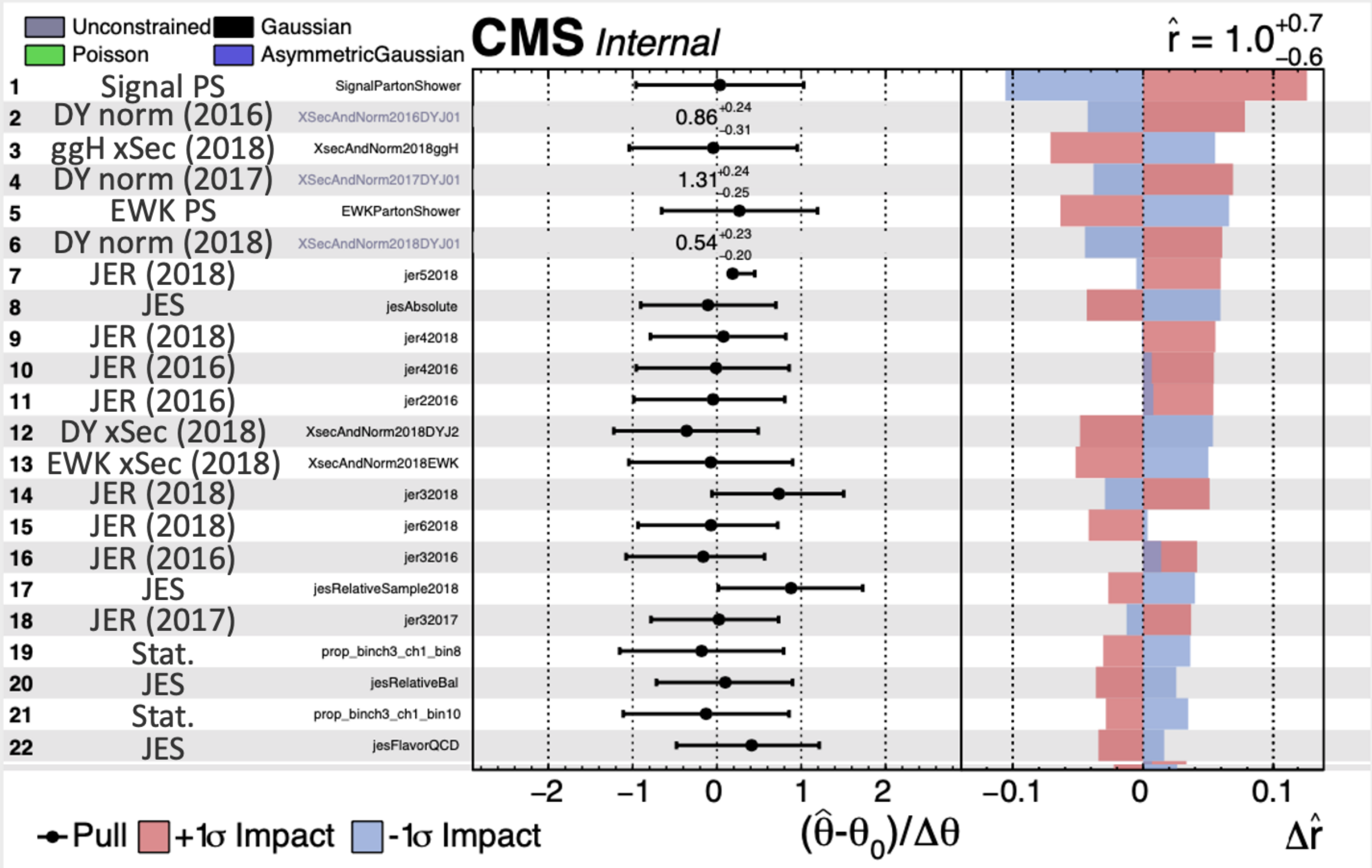
Mass Sideband 110 GeV to 150 GeV

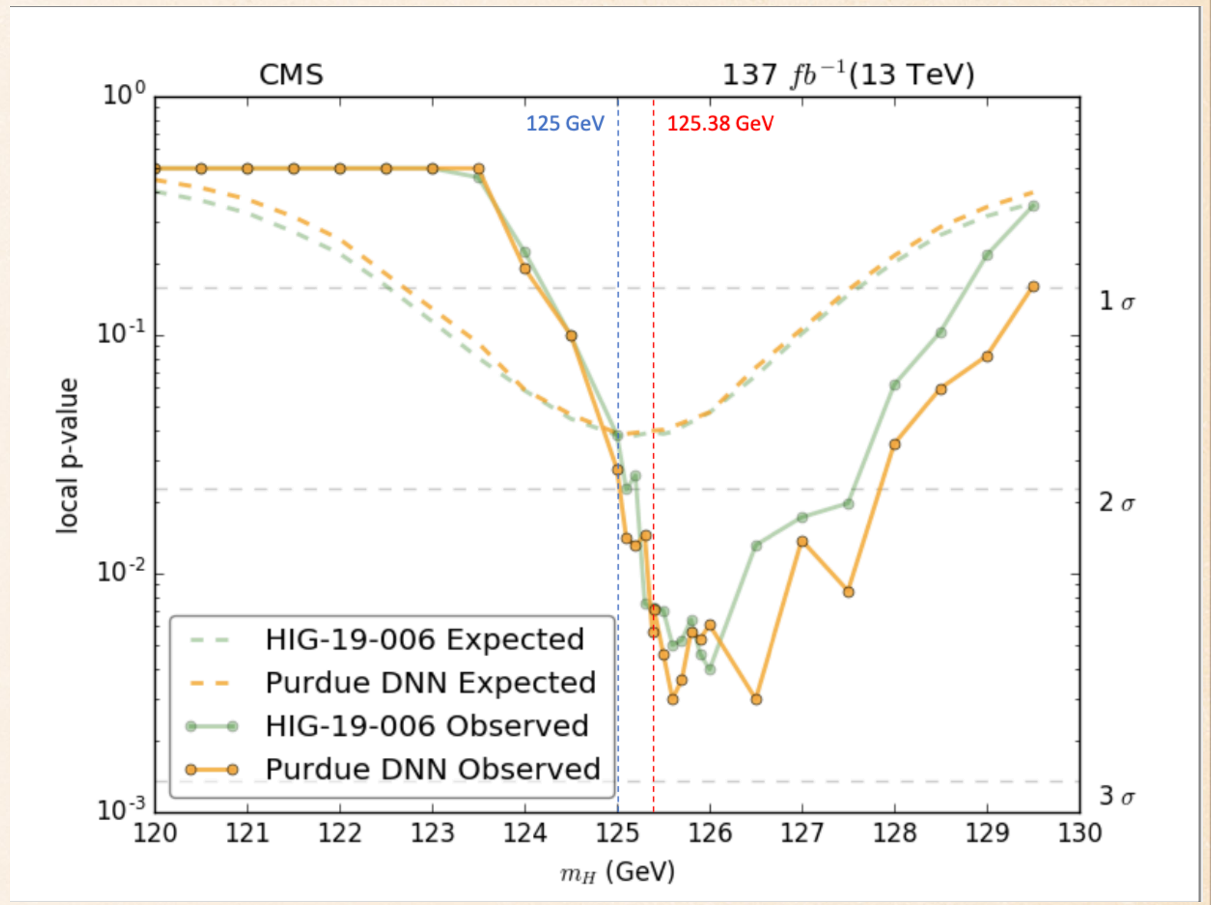


Signal Region 115 GeV to 135 GeV



A **Simultaneous fit** of DNN in Signal Region and SideBand for signal strength extraction

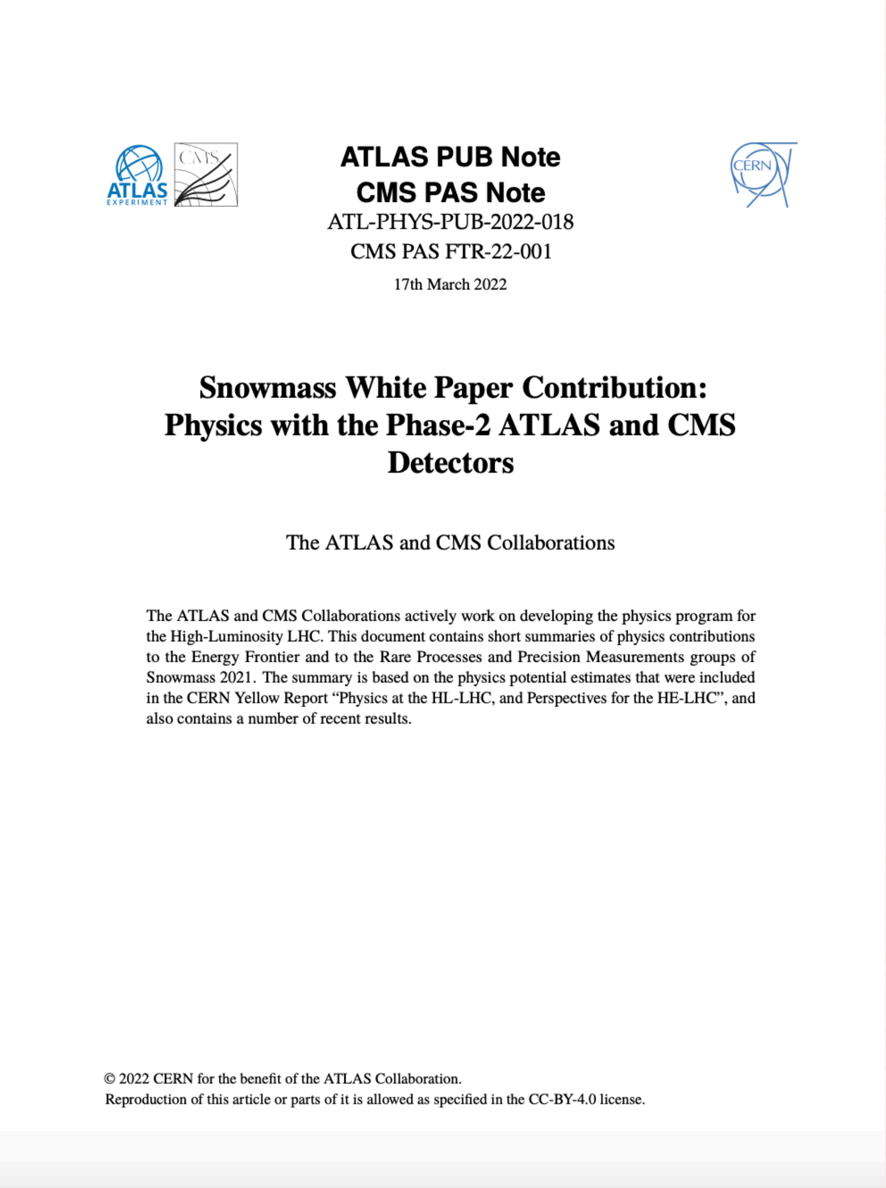




	Old analysis	New strategy
Expected significance at m_H = 125 GeV	1.81σ	1.77σ
Observed significance at m_H = 125 GeV	**1.72σ**	**1.92σ**
Expected significance at m_H = 125.38 GeV	1.77σ	1.76σ
Observed significance at m_H = 125.38 GeV	**2.40σ**	**2.50σ**

SNOWMASS 2021

- **The previous results were used to extrapolate for the integrated luminosity up to L=3000 fb^{-1}.**
- **Using 2018 datasets** (for Run 2, using latest detector conditions) and DELPHES datasets (for HL-LHC) to estimate various extrapolation effects.
- **Effects taken into account:**
  - Scaling center of mass energy from 13 TeV to 14 TeV.
  - Update the cross-sections of signal and major background channels.
  - Reimplement the event selections for 14 TeV kinematics.
- **Detector effects (Phase-II upgrade):**
  - Updated detector acceptance due to extended tracker coverage.
  - Improved $m_{\mu\mu}$ resolution due to upgraded tracker with less material budget than in Run 2.
  - Normalization scaling not evaluated separately for ggH and VBF categories, because jet kinematics used in categorization are not properly modeled in the DELPHES datasets.
- Rescale uncertainties based on the estimates of performance achievable in Phase-II detector and HL-LHC machine.

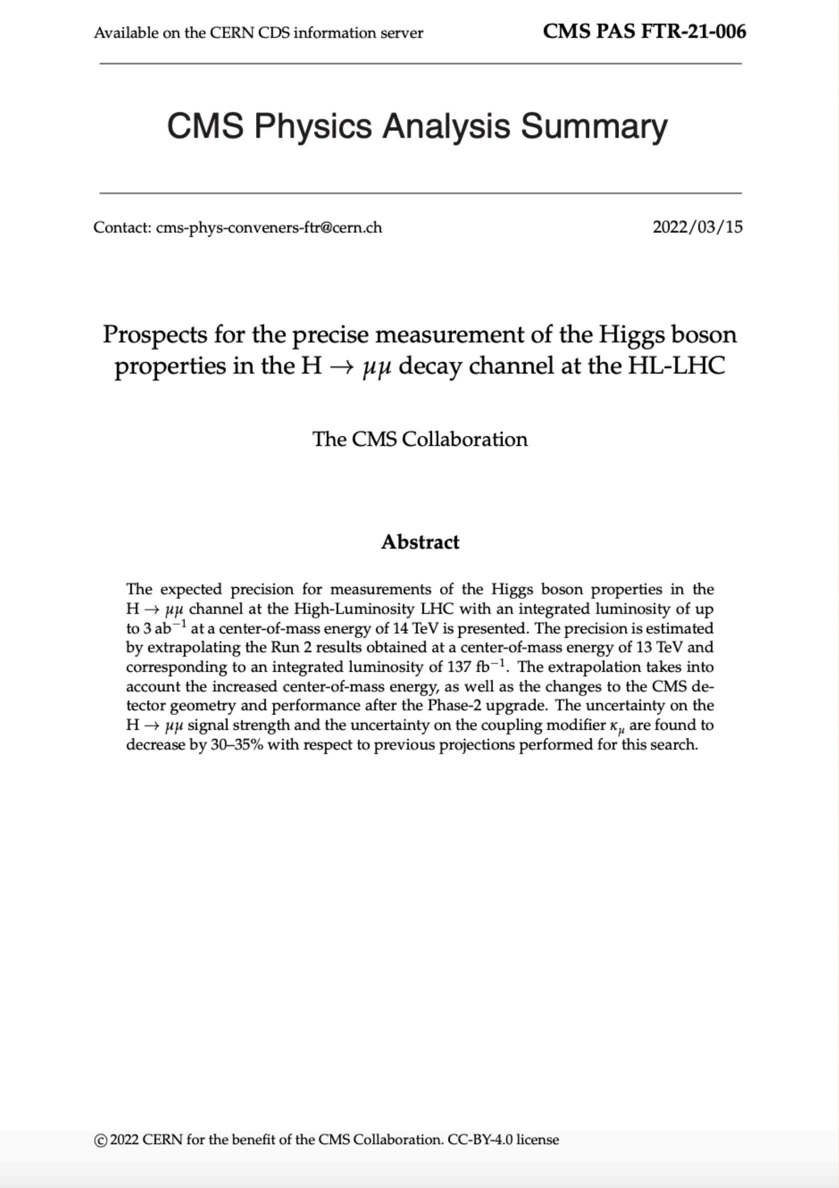


ATLAS PUB Note
CMS PAS Note
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
17th March 2022

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.



Available on the CERN CDS information server **CMS PAS FTR-21-006**

CMS Physics Analysis Summary

Contact: cms-phys-conveners-ftr@cern.ch 2022/03/15

Prospects for the precise measurement of the Higgs boson properties in the $H \to \mu\mu$ decay channel at the HL-LHC

The CMS Collaboration

Abstract

The expected precision for measurements of the Higgs boson properties in the $H \to \mu\mu$ channel at the High-Luminosity LHC with an integrated luminosity of up to 3 ab^{-1} at a center-of-mass energy of 14 TeV is presented. The precision is estimated by extrapolating the Run 2 results obtained at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 137 fb^{-1}. The extrapolation takes into account the increased center-of-mass energy, as well as the changes to the CMS detector geometry and performance after the Phase-2 upgrade. The uncertainty on the $H \to \mu\mu$ signal strength and the uncertainty on the coupling modifier κ_μ are found to decrease by 30–35% with respect to previous projections performed for this search.

RESULTS

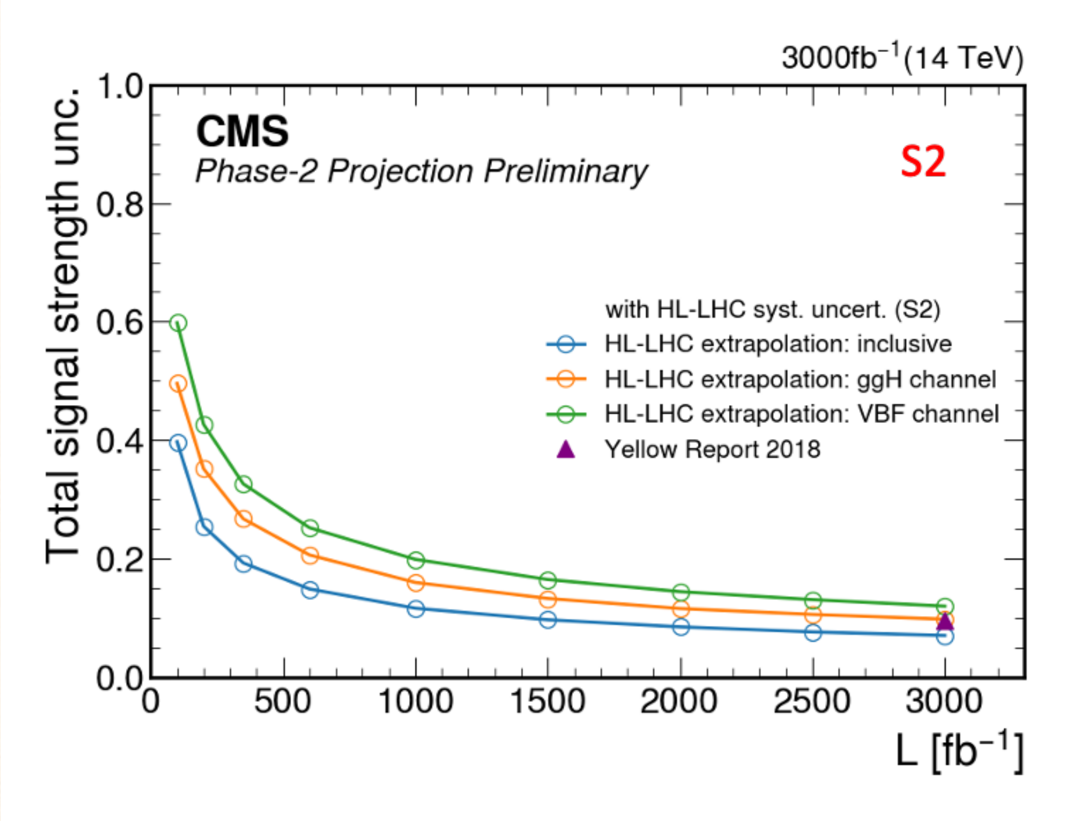
- **Uncertainty treatment:**
  - Statistical uncertainties scaled by $1/\sqrt{L}$
  - Two scenarios of Systematic uncertainties:
    - Run 2 syst. uncert. (**S1**): all systematic uncertainties are kept constant w.r.t. L
    - Yellow Report 2018 syst. uncert. (**S2**): theoretical uncertainties are scaled down by a 50%, while experimental systematic uncertainties are scaled down as 1/√L until they reach a defined lower limit.

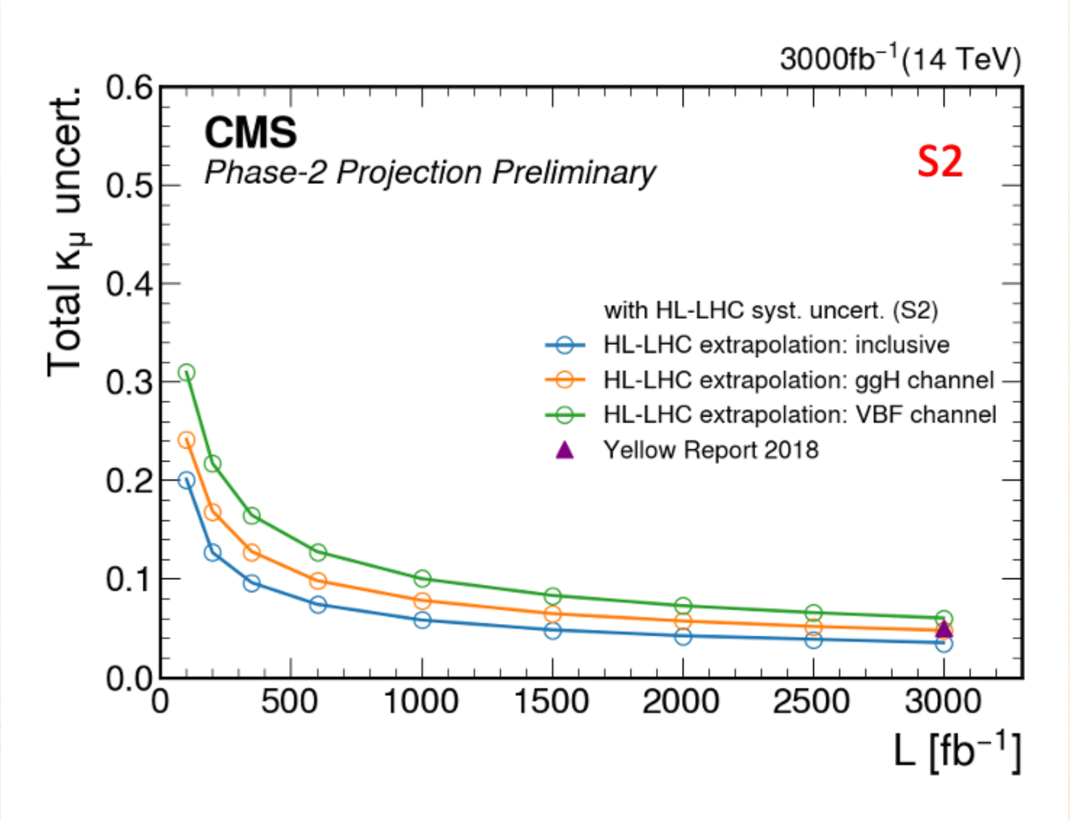
Table 3: Uncertainty on the signal strength modifier $\mu^{\mu\mu}$.

		Statistical	Experimental	Theoretical	Total
S1	YR 2018	9.1%	7.6%	4.8%	12.8%
	Snowmass	6.4%	3.7%	4.2%	8.5%
S2	YR 2018	9.1%	1.7%	2.7%	9.6%
	Snowmass	6.4%	2.0%	2.0%	7.0%

Table 4: Uncertainty on the coupling modifier κ_μ.

		Statistical	Experimental	Theoretical	Total
S1	YR 2018	4.7%	2.7%	3.9%	6.7%
	Snowmass	3.2%	1.9%	2.2%	4.3%
S2	YR 2018	4.7%	1.5%	1.1%	5.0%
	Snowmass	3.2%	1.1%	0.8%	3.5%





CONCLUSION

- **Design of the new CMS Tracker for Phase-2 driven by the inclusion of the Outer Tracker in the decision forming process for the L1 Trigger**

- Highlight of the Inner Tracker is increased granularity and extended acceptance in the forward region from |h|<3 to 4

- Most of the components for Inner and Outer Tracking are in production or preproduction phase

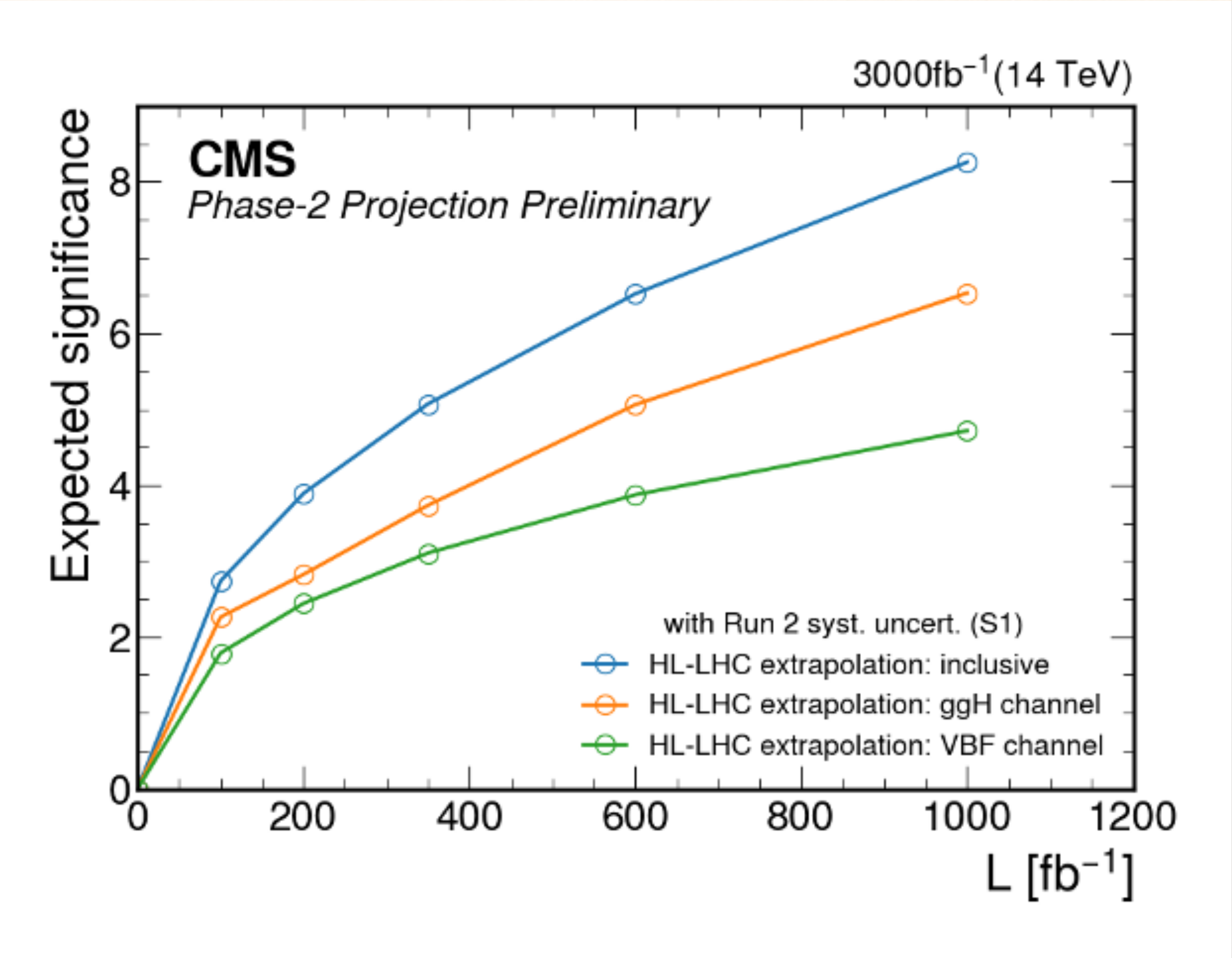
- System tests being conducted to validate all the components, powering, read-out and thermal performance of the sub-detectors

- New Muon reconstruction in Phase 2 will increase discovery potential.

- Improved analysis techniques used in $H\to\mu\mu$ search.

- Allowed to achieve substantial improvement in the extrapolated measurement precision of μ and κ_μ at the HL-LHC for Snowmass 2021.

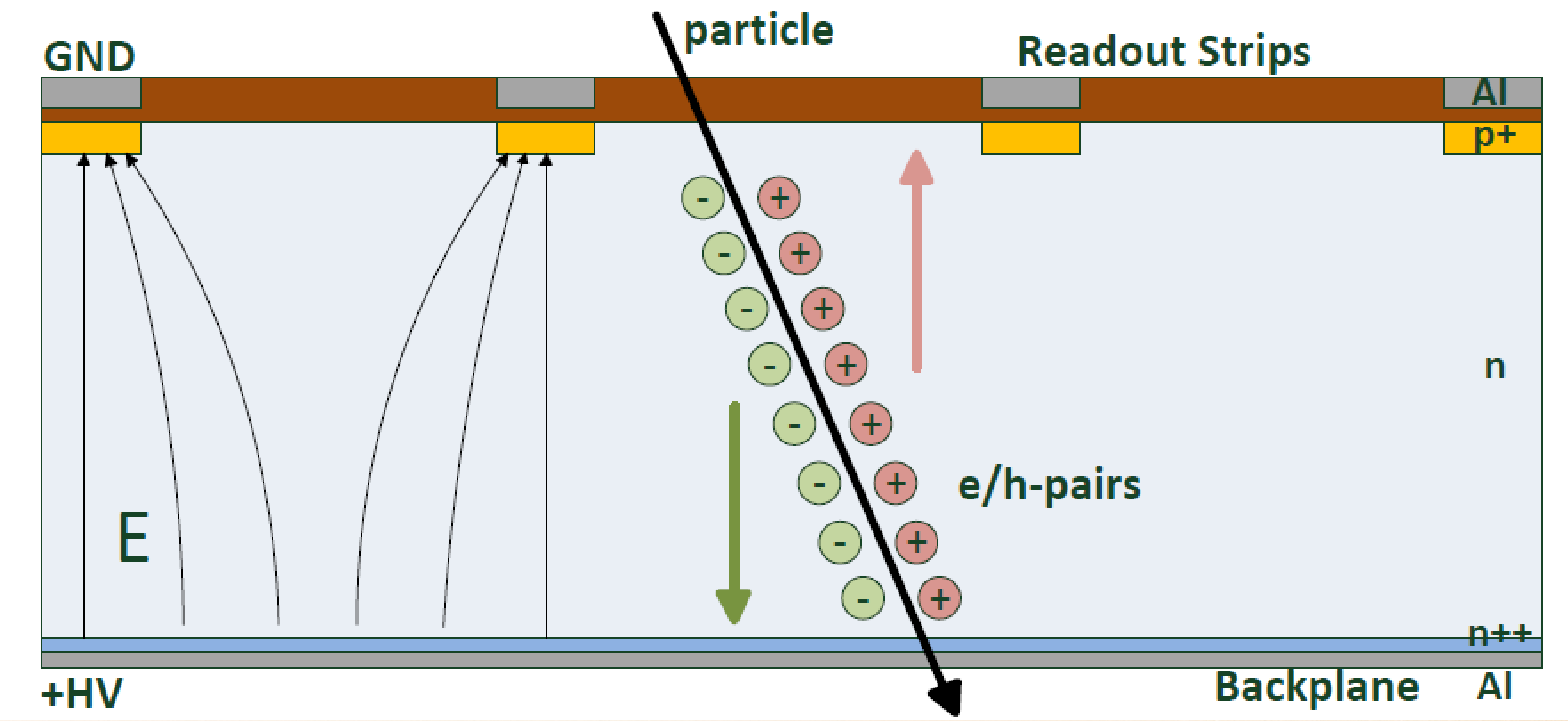
- Our results show, that we do not need to wait until the end of HL-LHC to get 5 sigma significance for $H\to\mu\mu$.



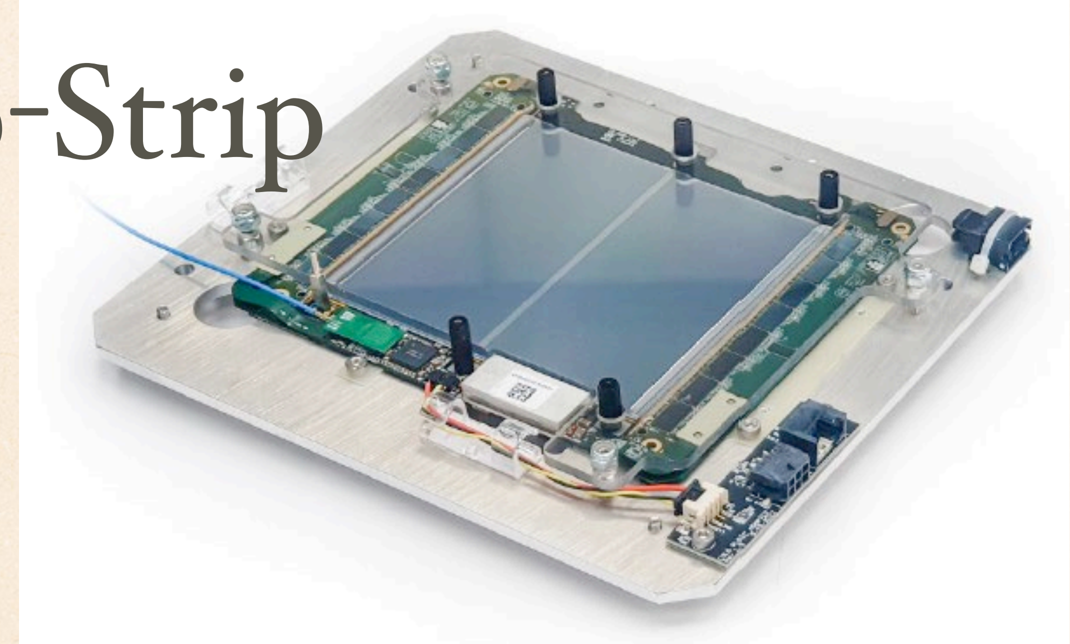
BACK UP

SILICON MODULES

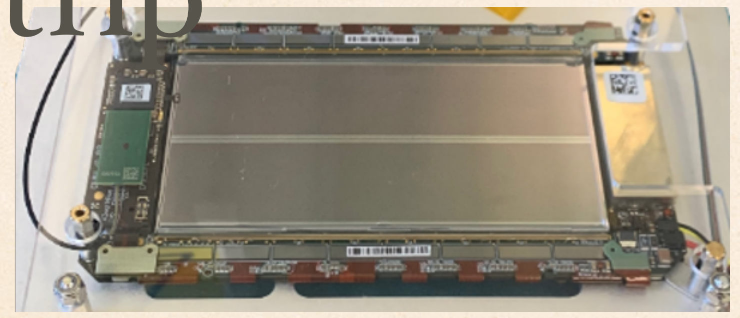
- Electron-hole-pairs generated by ionizing particles traversing the silicon are separated by E-field and 'drift' to the electrodes
- Most probable MIP signal is ≈22,500 e/h pairs for 300 μm silicon.

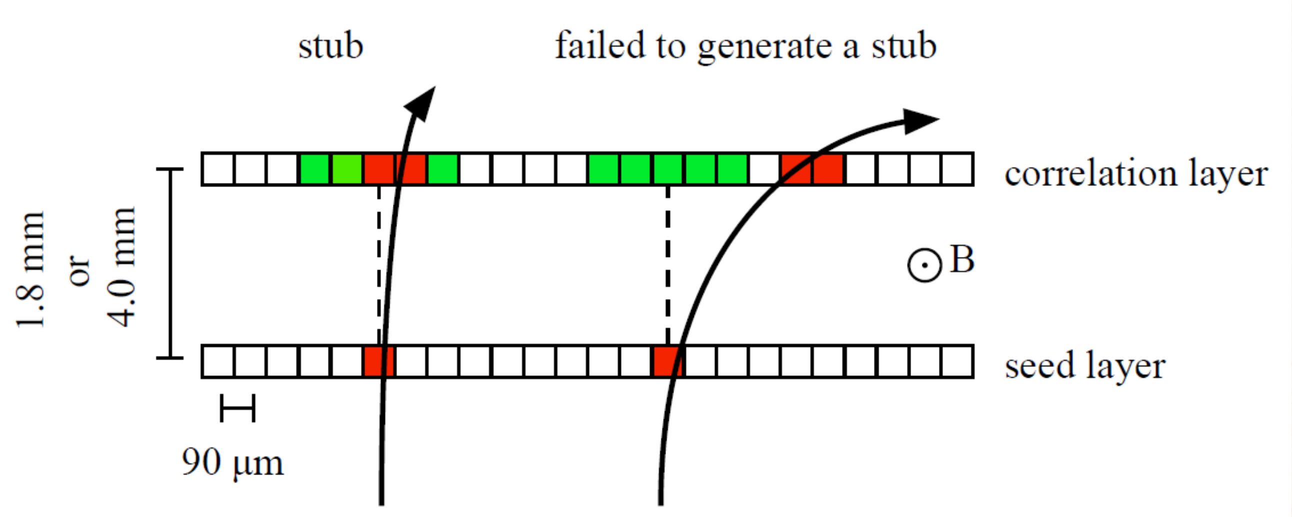


Strip-Strip

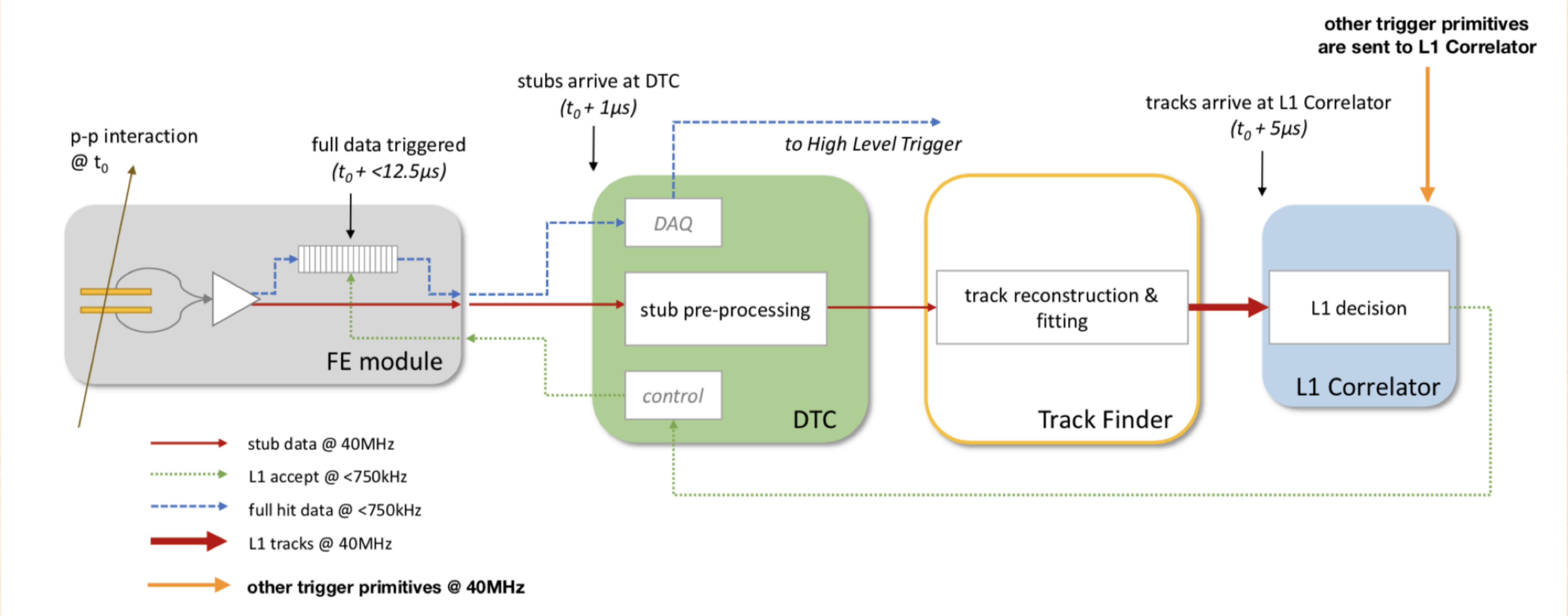


Pixel-Strip



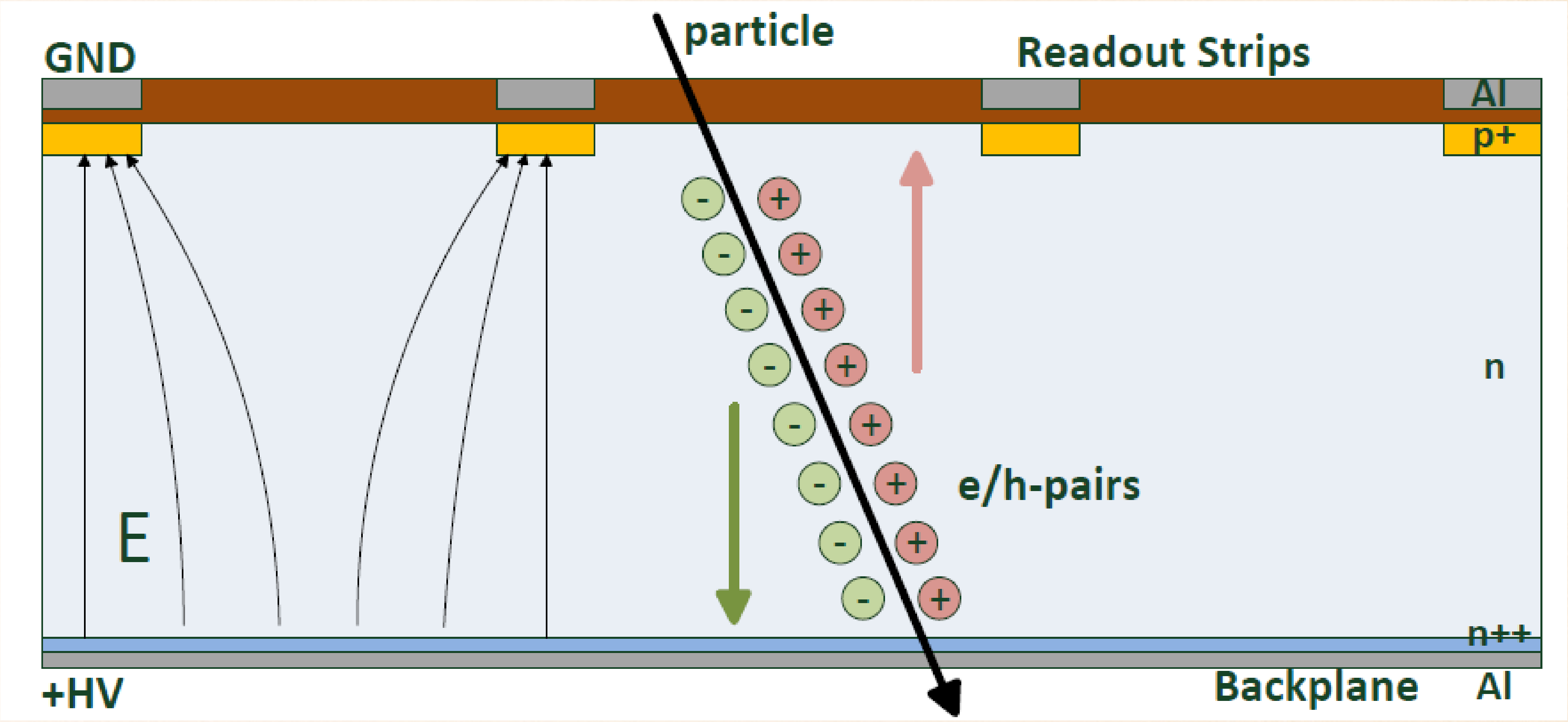


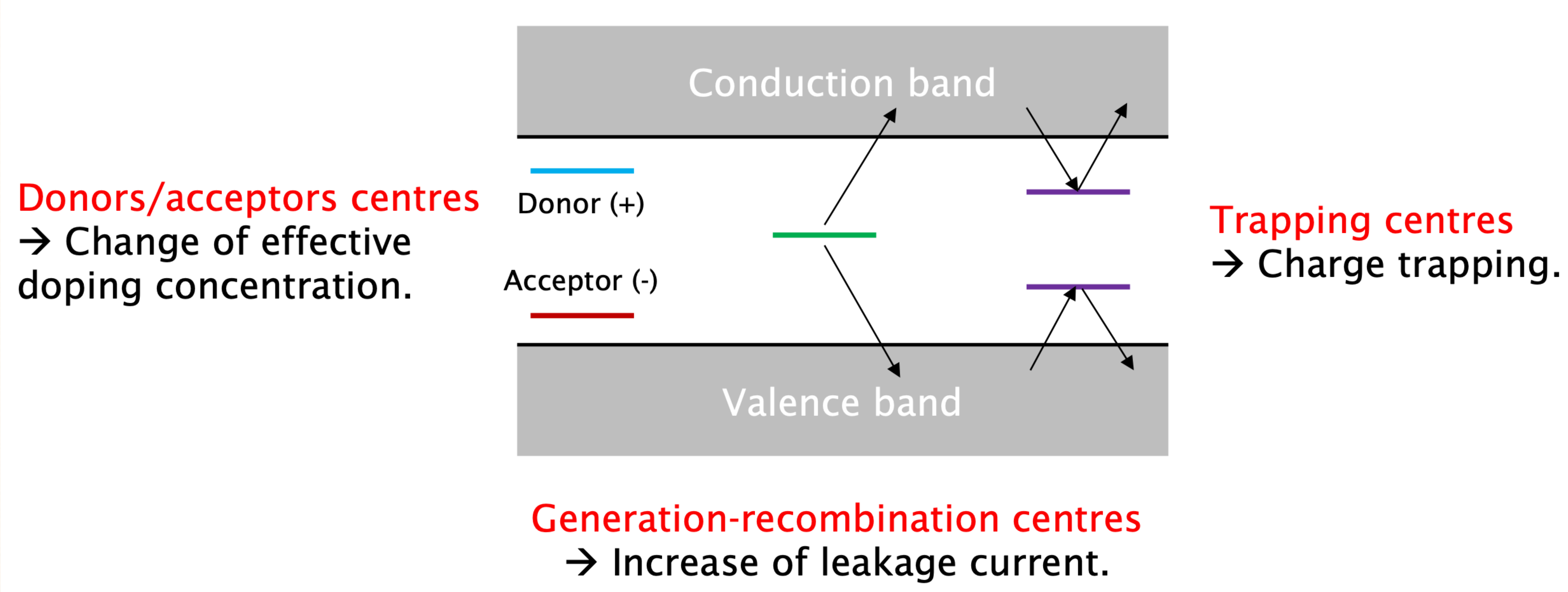
2 layers



RADIATION DAMAGE IN SEMICONDUCTOR

- In semiconductor devices, high-energy particles produce three main types of effects [Lint87]:
  - Displacements. These are dislocations of atoms from their normal sites in the lattice, producing less ordered structures, with long term effects on semiconductor properties.
  - Transient ionization. This effect produces electron-hole pairs; particle detection with semiconductors is based on this effect.
  - Long term ionization. In insulators, the material does not return to its initial state, if the electrons and holes produced are fixed, and charged regions are induced.





DNN INPUT VARIABLES

The simulated samples used in the training are:

- the background samples:
  - `DYJetsToLL_M-105To160*_13TeV-madgraphMLM-pythia8`
  - `DYJetsToLL_M-105To160_VBFFilter*_13TeV-madgraphMLM-pythia8`
  - `EWK_LLJJ_MLL_105-160*_13TeV-madgraph-herwig*`
  - `TT_*_13TeV-powheg-pythia8` (inclusive W decays)
- the signal sample:
  - `VBF_HToMuMu_M125*_13TeV_powheg_pythia8`

The variable used in the current setup of the DNN are:

- $m(\mu\mu)$, $\Delta m(\mu\mu)_{rel}$, $\Delta m(\mu\mu)$ - the dimuon mass and the relative and absolute mass resolutions
- $m(jj)$, $\log m(jj)$ - the dijet mass and its logarithm
- $R(p_T)$
- $z*$
- $\Delta\eta(jj)$ - the pseudorapidity difference between the 2 selected jets
- N_5^{soft} - # soft jet with $p_T > 5$ GeV
- $\min_j \Delta\eta(\mu\mu, j)$ - the minimum pseudorapidity difference between a jet and the dimuon system
- $p_T(\mu\mu)$, $\log p_T(\mu\mu)$, $\eta(\mu\mu)$ - dimuon 4-vector components
- $p_T(j_1)$, $p_T(j_2)$, $\eta(j_1)$, $\eta(j_2)$, $\phi(j_1)$, $\phi(j_2)$ - jets' 4-vectors components
- $qgl(j_1)$, $qgl(j_2)$ - the the quark-gluon likelihood discriminators for the selected jets.

The first three variables are the ones used by the network (4) as shown in figure 7.13, while the

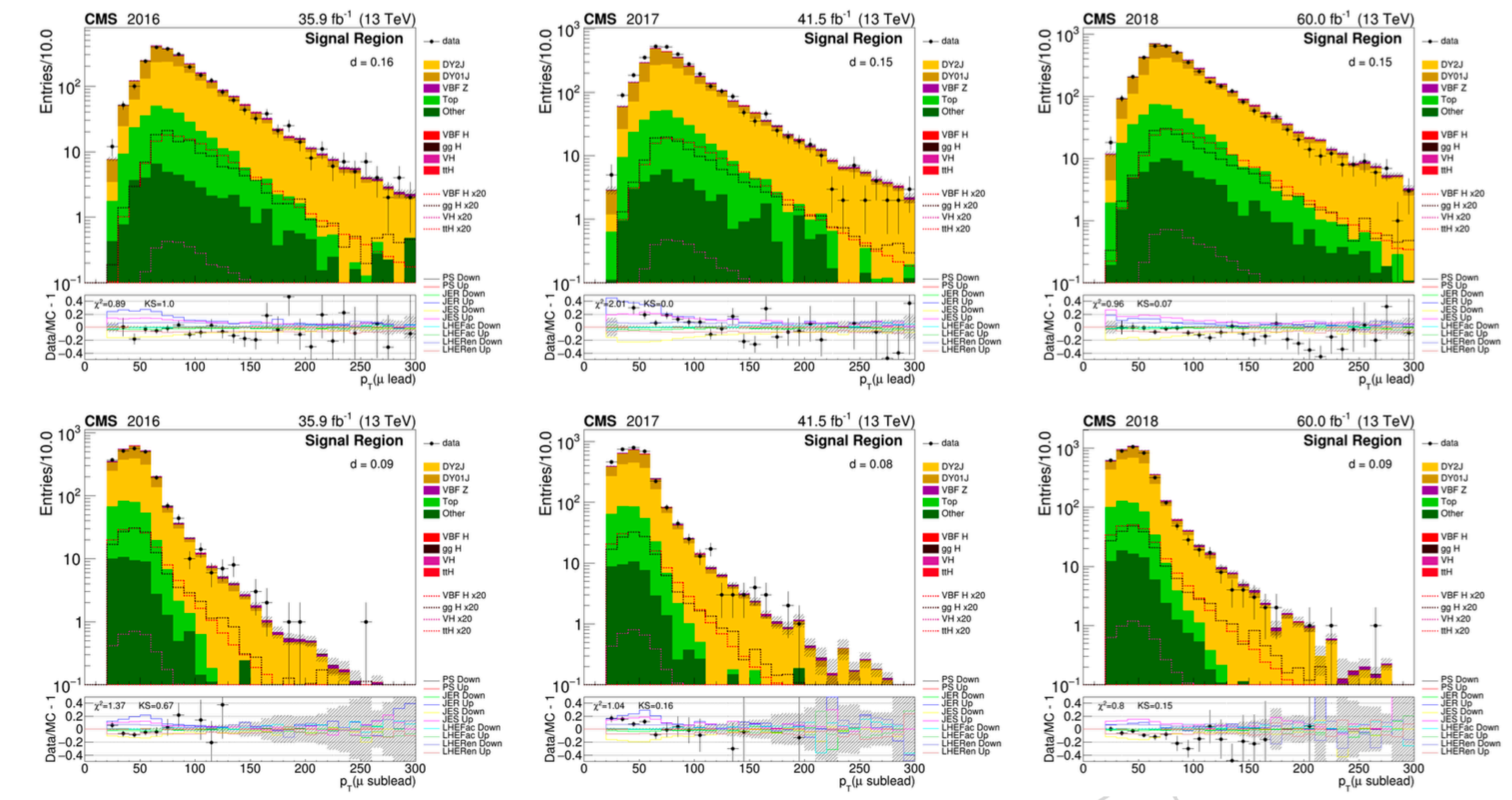


Figure 7.3: Leading (top) and subleading muon (bottom) transverse momentum distributions after the event selection in Signal Region for 2016 (left), 2017 (center) and 2018 (right).

DNN INPUT VARIABLES

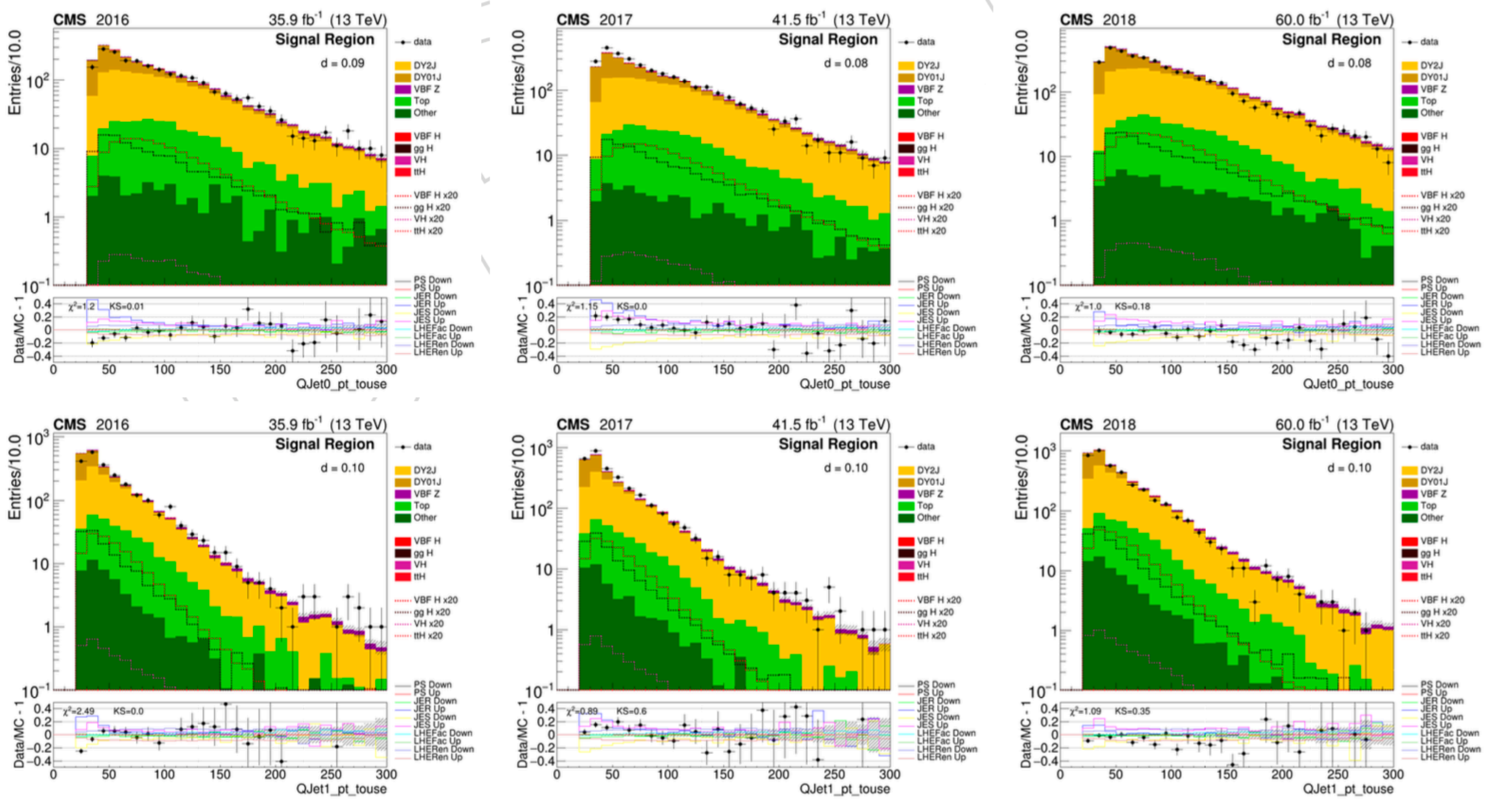


Figure 7.6: Leading and subleading jets transverse momentum distributions after the event selection in Signal Region for 2016 (left), 2017 (center) and 2018 (right).

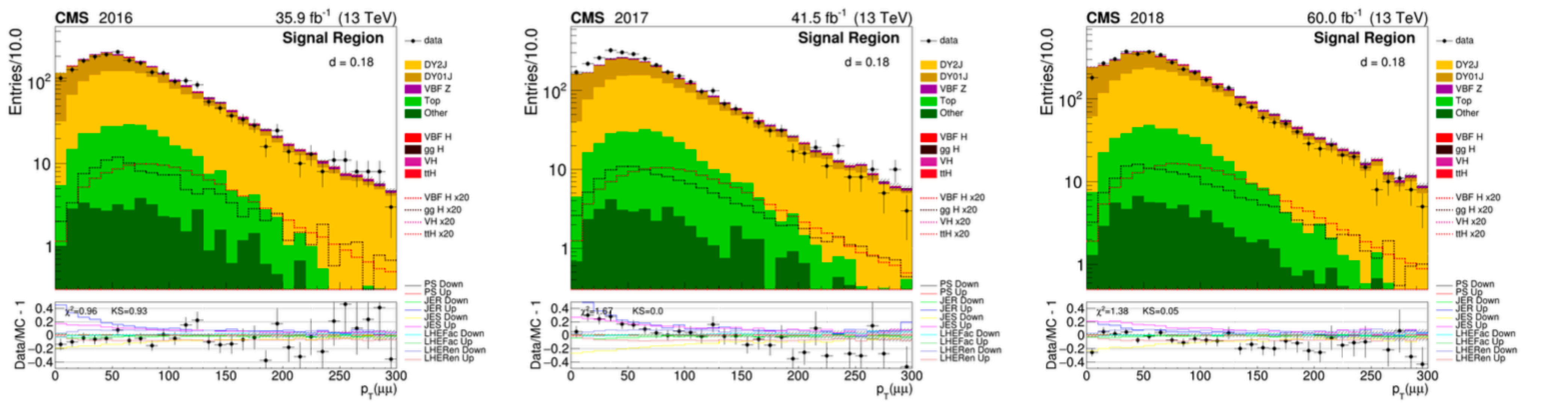
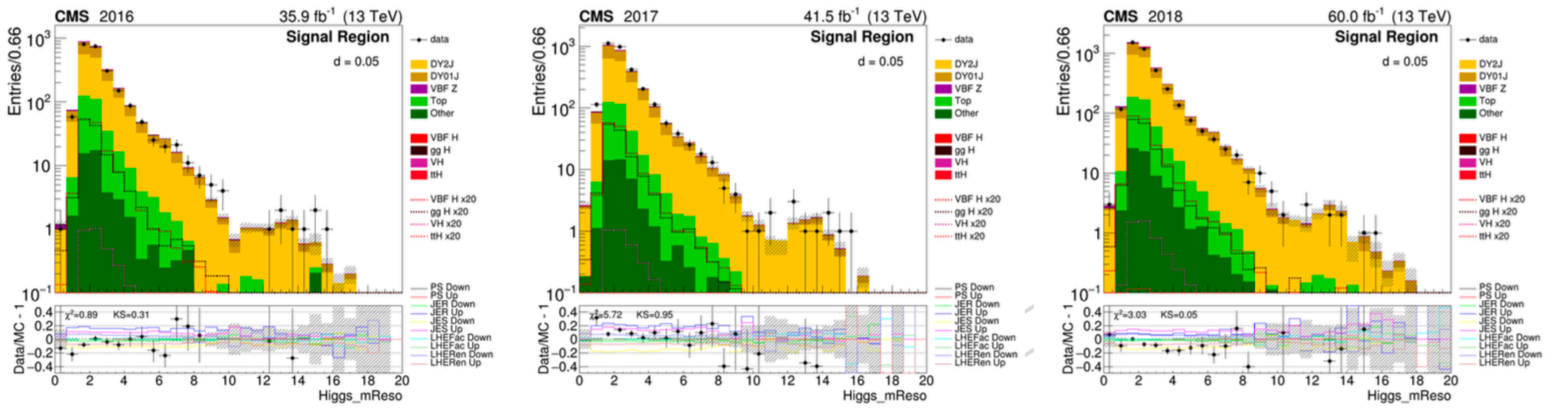


Figure 7.4: Transverse momentum distribution of the dimuon system after the event selection in in Signal Region for 2016 (left), 2017 (center) and 2018 (right).



DNN INPUT VARIABLES

7.2.3 Other relevant variables

The "Zeppenfeld" variables $y^\star(H)$ and $z^\star(H)$ are defined by

$$y^\star(H) = y_{\mathrm{H}} - \frac{y_1 + y_2}{2} \qquad z^\star(H) = \frac{y^\star(H)}{\mid y_1 - y_2 \mid}$$

where y_1 and y_2 are the rapidity of the two selected jets and y_{H} is the one of the dimuon system. The variables $z^\star(H)$ results in $\mid z^\star(H) \mid < 0.5$ for events where the H is located in the rapidity opening of the two jets.

Figure 7.9 shows $z^\star(H)$ after the event selection in Signal region for all the years.

The $\mu\mu jj$ transverse momentum balance $R(p_{\mathrm{T}})$ is defined by

$$R(p_{\mathrm{T}}) = \frac{|\vec{p_{\mathrm{T}}}(jj) + \vec{p_{\mathrm{T}}}(\mu\mu)|}{|\vec{p_{\mathrm{T}}}(j_1)| + |\vec{p_{\mathrm{T}}}(j_2)| + |\vec{p_{\mathrm{T}}}(\mu\mu)|}$$

Figure 7.10 shows $R(p_{\mathrm{T}})$ after the event selection in Signal region for all the years.

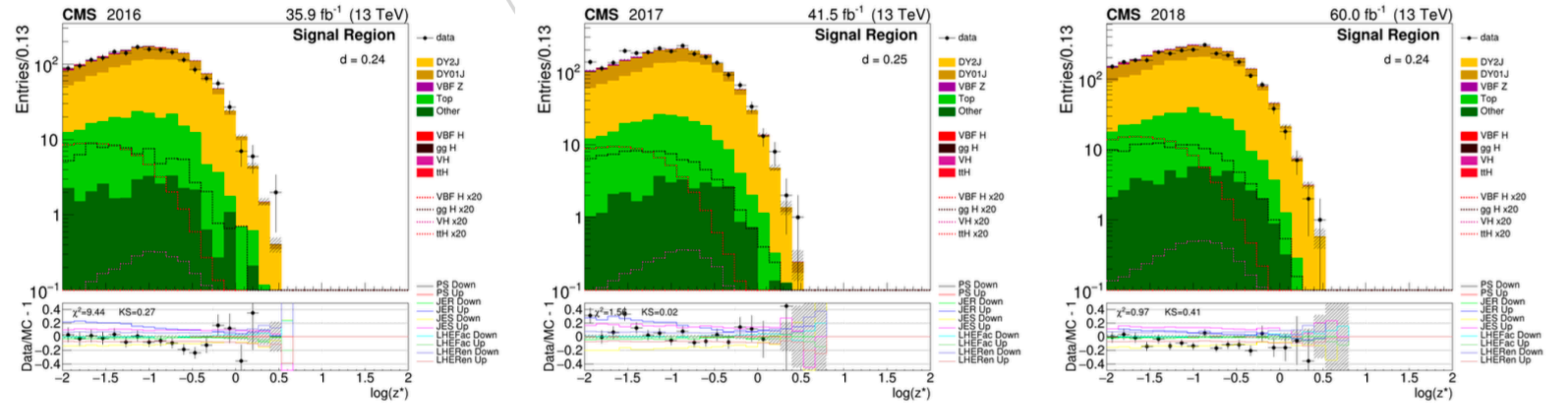


Figure 7.9: Distributions of the "Zeppenfeld" variable $z^\star(H)$ after the event selection in Signal Region for 2016 (left), 2017 (center) and 2018 (right).

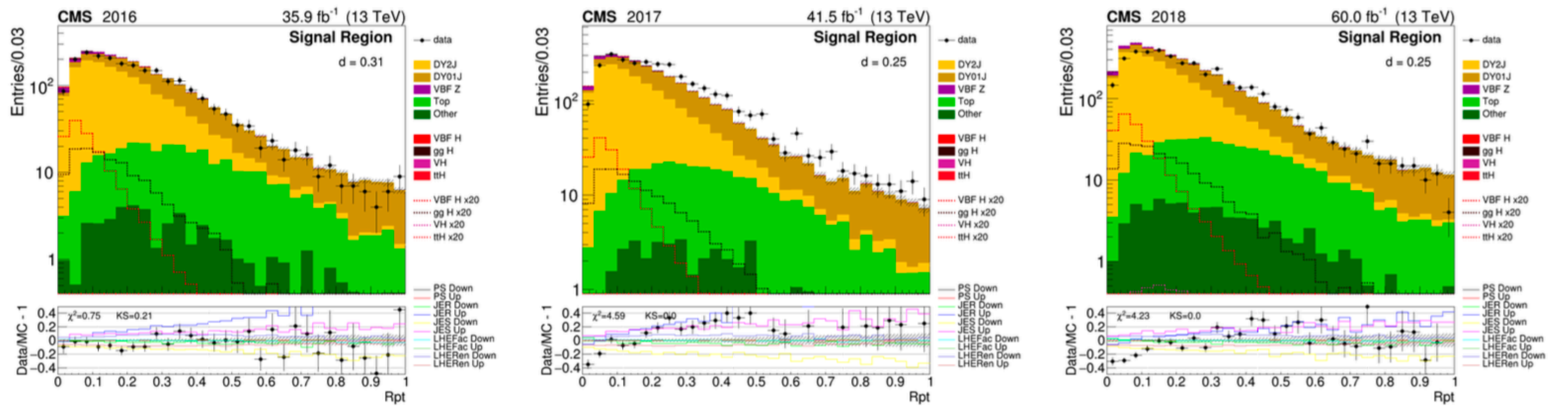


Figure 7.10: Distributions of the transverse momentum balance $R(p_{\mathrm{T}})$ after the event selection in Signal Region for 2016 (left), 2017 (center) and 2018 (right).

DNN INPUT VARIABLES

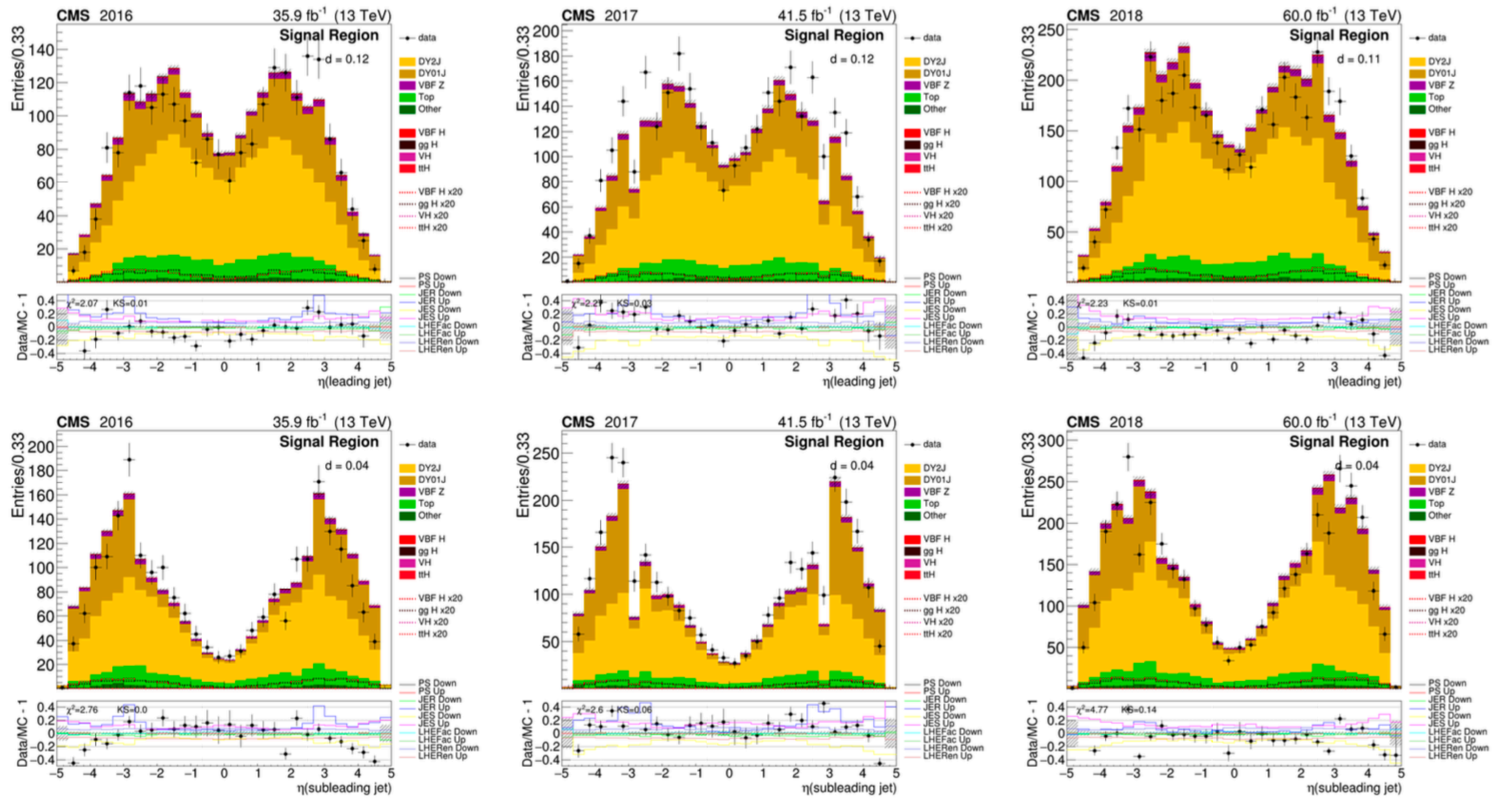
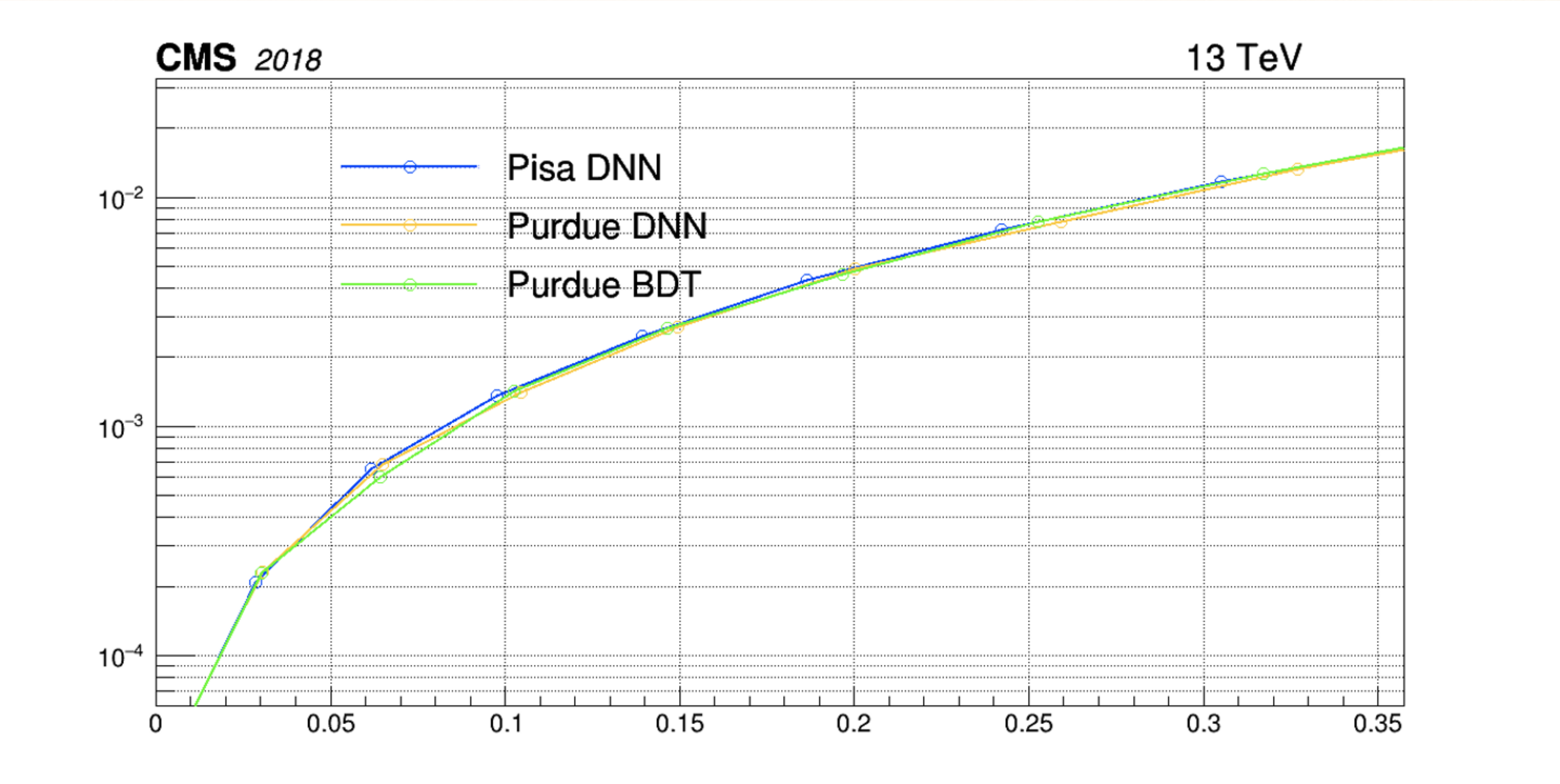


Figure 7.7: Leading and subleading jets pseudorapidity distribution after the event selection in Signal Region for 2016 (left), 2017 (center) and 2018 (right).

DNN RESULTS



CMS 2018
13 TeV
Pisa DNN
Purdue DNN
Purdue BDT
10^{-2}
10^{-3}
10^{-4}
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

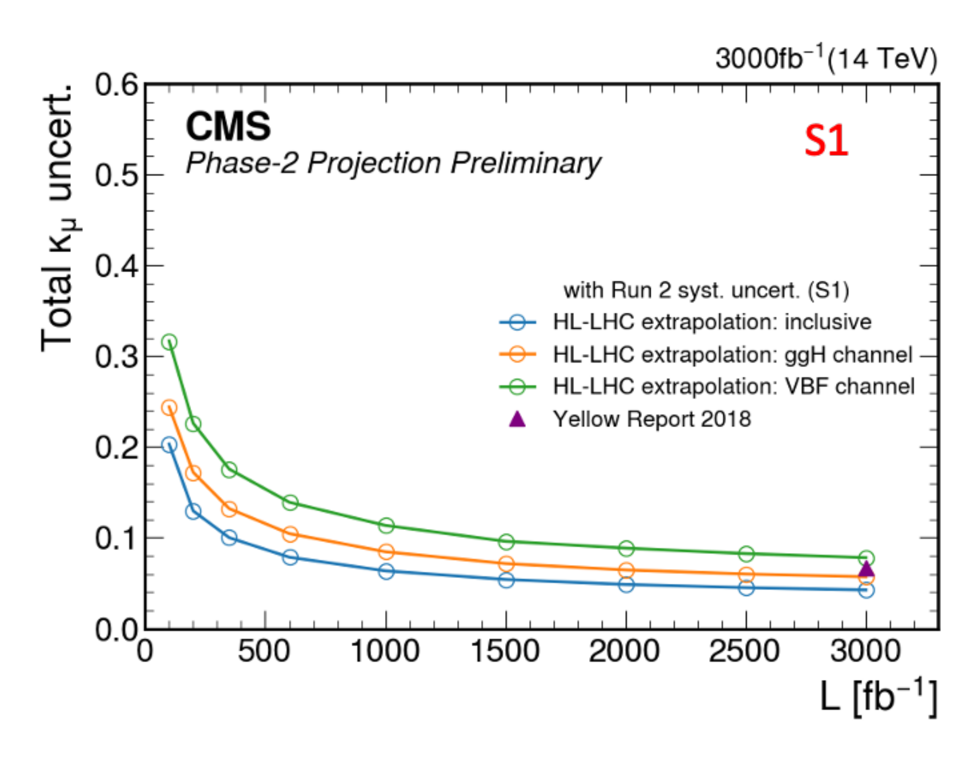
RESULTS

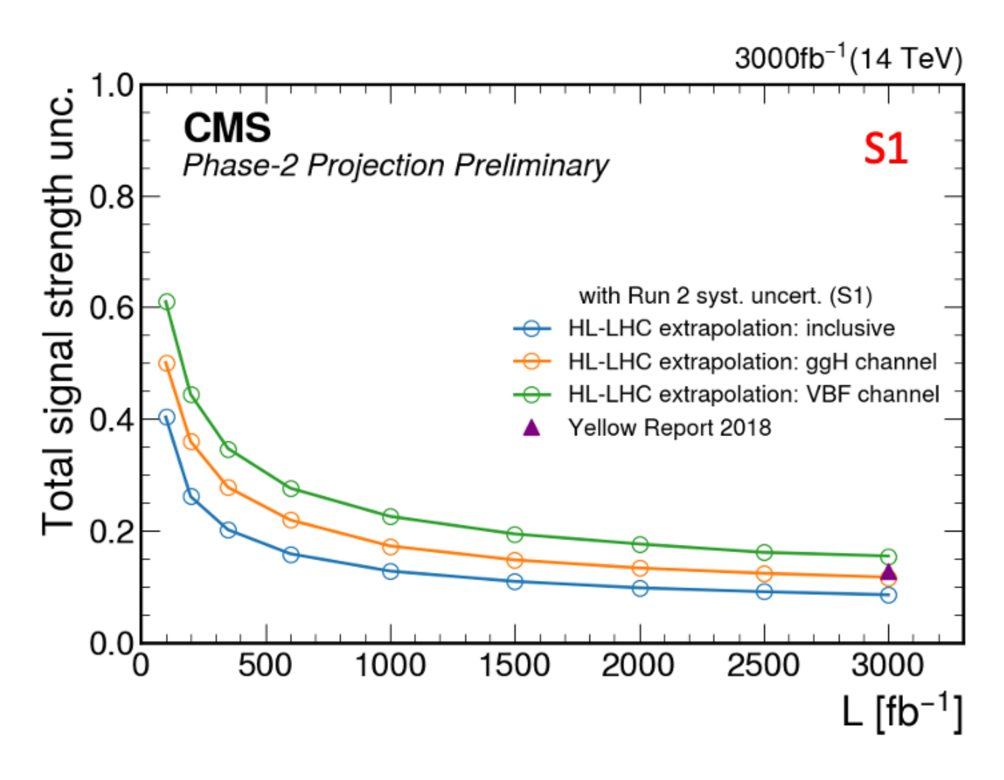
Process		Run 2 yield	HL-LHC yield	Change
Backgrounds	Drell-Yan (MG)	720623	900825	+25.0%
	TTJets Dilepton	62585	87592	+40.0%
	EWK $Z \to ll$	1439	1865	+29.6%
	Total background	784647	990282	+26.2%
$H \to \mu\mu$ signal	ggH	383	477	+24.5%
	VBF	30.7	37.8	+23.1%

- **Uncertainty treatment:**
  - Statistical uncertainties scaled by $1/\sqrt{L}$
  - Two scenarios of Systematic uncertainties:
    - Run 2 syst. uncert. (S1): all systematic uncertainties are kept constant w.r.t. L
    - Yellow Report 2018 syst. uncert. (S2): theoretical uncertainties are scaled down by a 50%, while experimental systematic uncertainties are scaled down as $1/\sqrt{L}$ until they reach a defined lower limit.

Source of uncertainty	Scenario 1 (Run 2 syst.)	Scenario 2 (YR18 syst.)
Jet energy scale	5-6%	1/5 - 1/2
Jet energy resolution	2-3%	3-5%
μ ID, isolation, trigger	0.1-7.0%	0.5%
electron ID, isolation, trigger	0.1-0.5%	0.5%
b-tagging efficiency	5%	1%
L1 prefiring correction	20%	4%
Theory	9.4%	1/2
Integrated Luminosity	2.5%	1%
Limited number of MC events	Barlow-Beeston method	-

Table 5.7: Comparison between different uncertainty scaling scenarios





EMITTANCE AND BETA*

- A •Coupling strength modifier (κ_μ) is defined as Γ^($\mu\mu$)/(Γ_SM^($\mu\mu$)).