Construction of a tracking detector for the future experimental exploration of particle interactions

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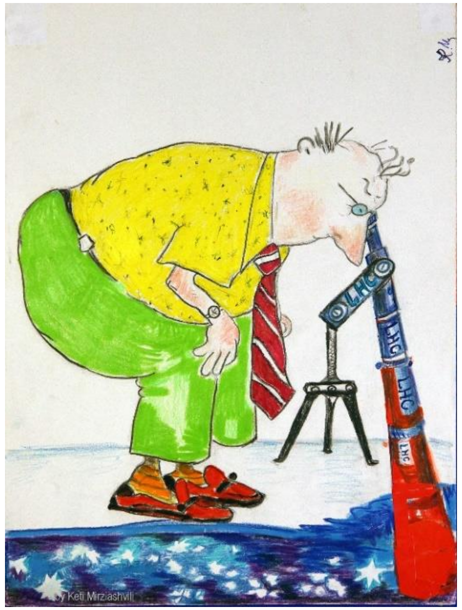
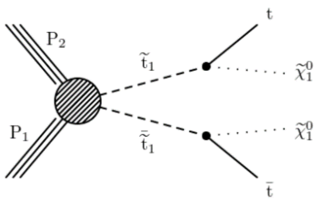
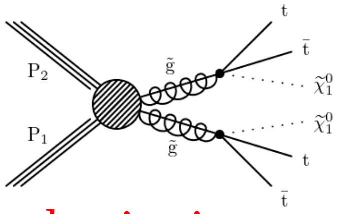
Standard Model and New Physics Research Group

Searching for the new physics

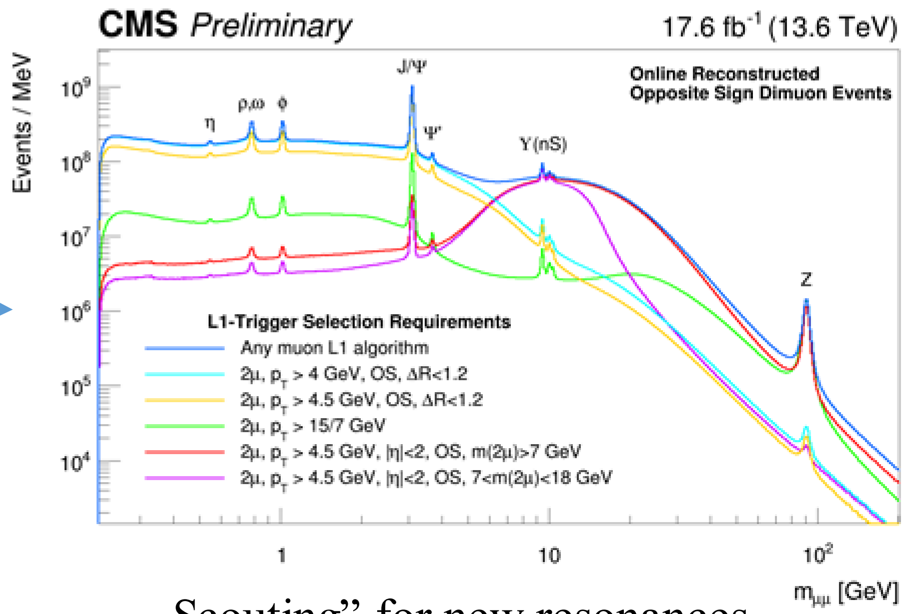


- **Extending our knowledge in particle interactions by**
  - advancing specialized fields: QCD, B-physics, and HI
  - direct search for the unknown
  - investigate known particles, deviation from theory (precision measurements)
- **Direct searches for new physics**
  - resonance searches, differences from expected distributions, e.g. di-muon invariant mass spectrum
  - model-guided searches
    - assuming very simple (natural) supersymmetry production process





But discovery of any **other** new physics is not ruled out!
(in similar final states)

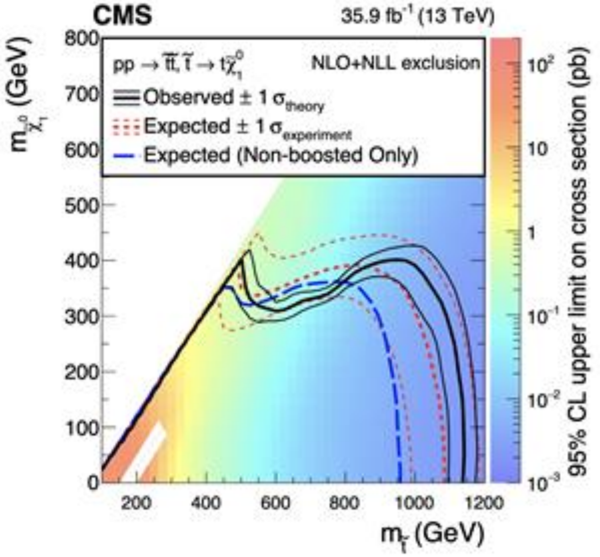


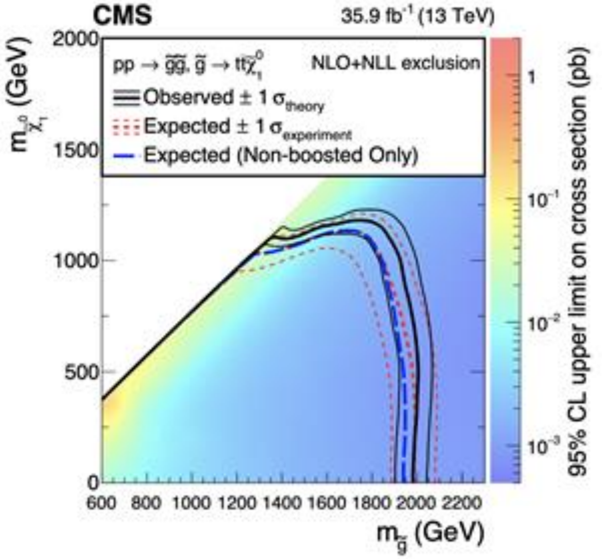
„Scouting" for new resonances

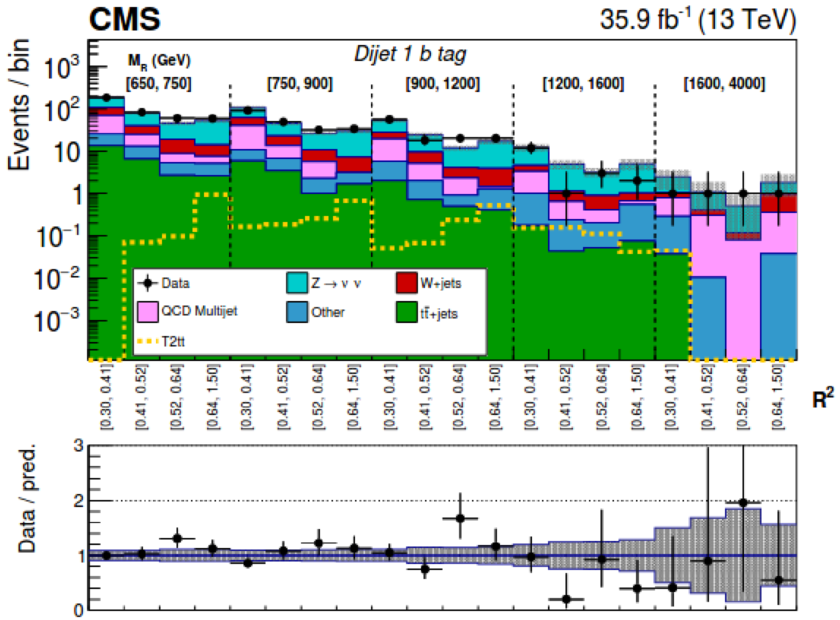
Boosted SUSY

- **Exclusion:** 5% chance that we falsely rule out the existence of these processes (e.g. in blue area: they have occurred in ~180 collisions but were considered measurement error of the background)
- **Search for SUSY published in 2019** (1 PhD in our group)
- **Extended search with ~4 times more data being prepared for publication in 2023** (+1 MSc so far)
- **Interesting next time in ~2026-27**

Inclusive search in 0ℓ & 1ℓ final states

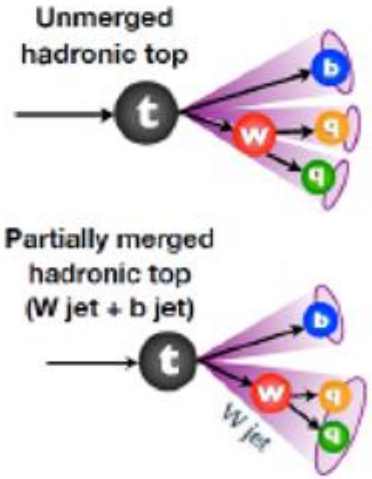






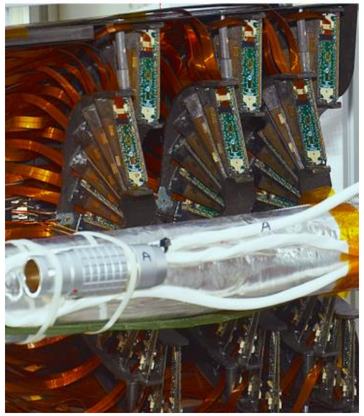
JHEP 03 (2019)031

Assumed appearance of SUSY processes in the pp collisions, leading to „boosted" ojects



Data flow

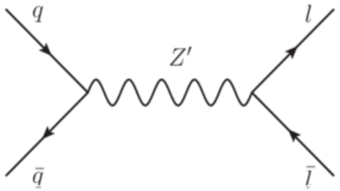
1 560 000 000 pp-coll/s



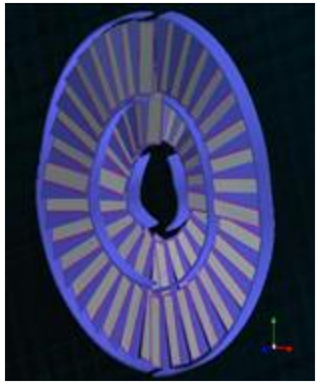
130 000 pp-coll/s

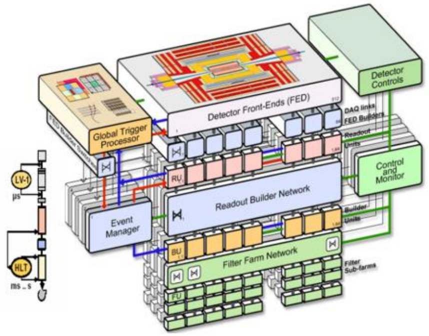
Real collision → Measurement → Online event selection (trigger)

Simulated collision → Detector simulated response → Trigger emulation efficiency



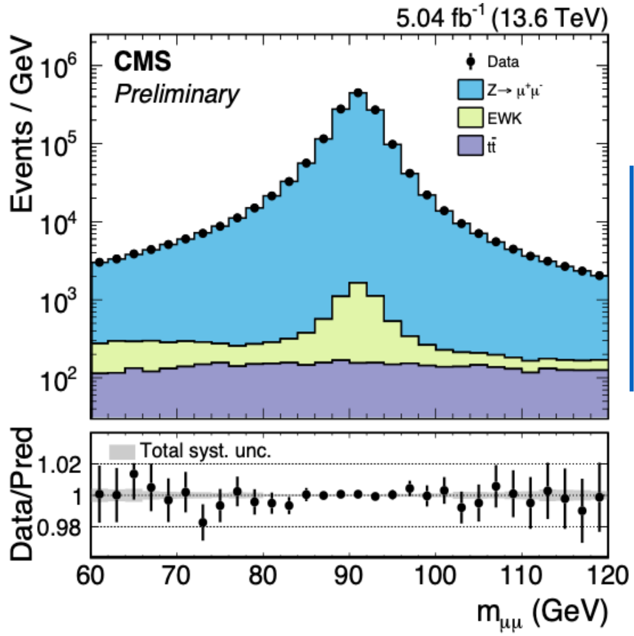
Theory calculations
Monte Carlo generators





doi:10.1088/1742-6596/219/3/032009

Event reconstruction, selection



SMP-22-017

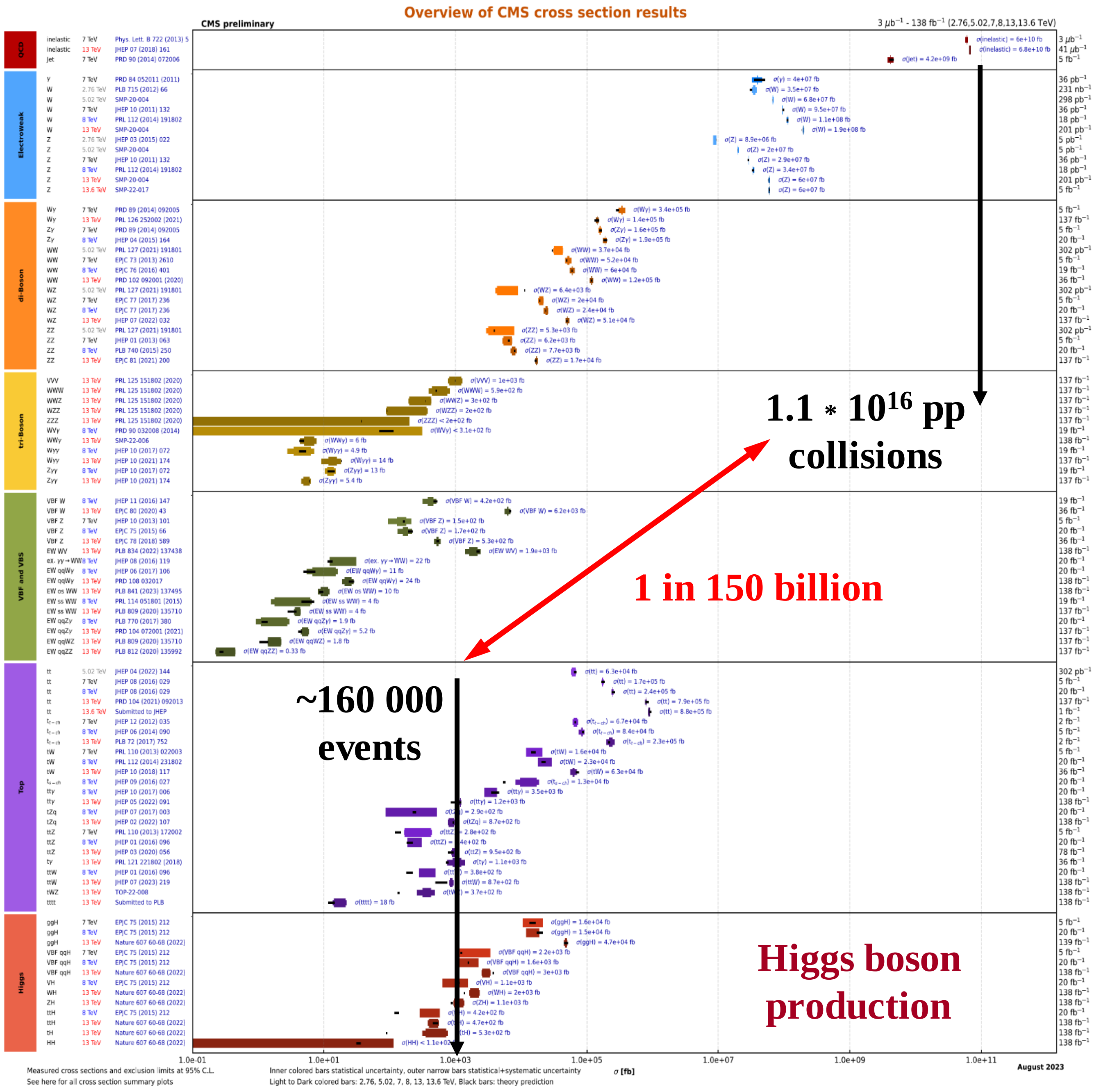
Event reconstruction, correction factors, event-weighting

Precision physics

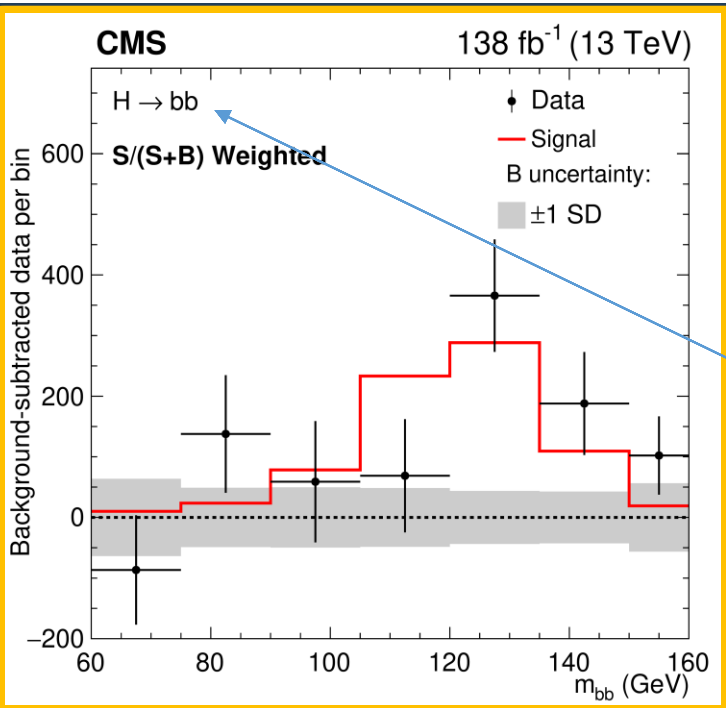
Standard model processes are thoroughly tested

- Motivates more precise theoretical calculations
- Signs of new physics: deviations from theoretically expected parameters or cross-sections
- Simulations also need to be improved for better background estimates
  - e.g. for measuring properties of the Higgs boson

→ Not even all Higgs couplings are observed, yet

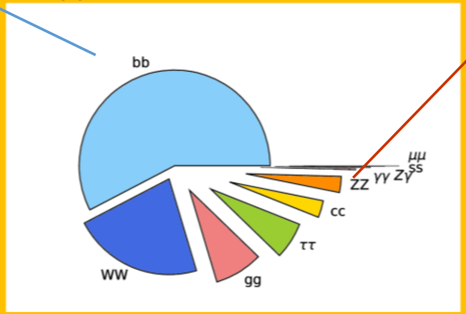


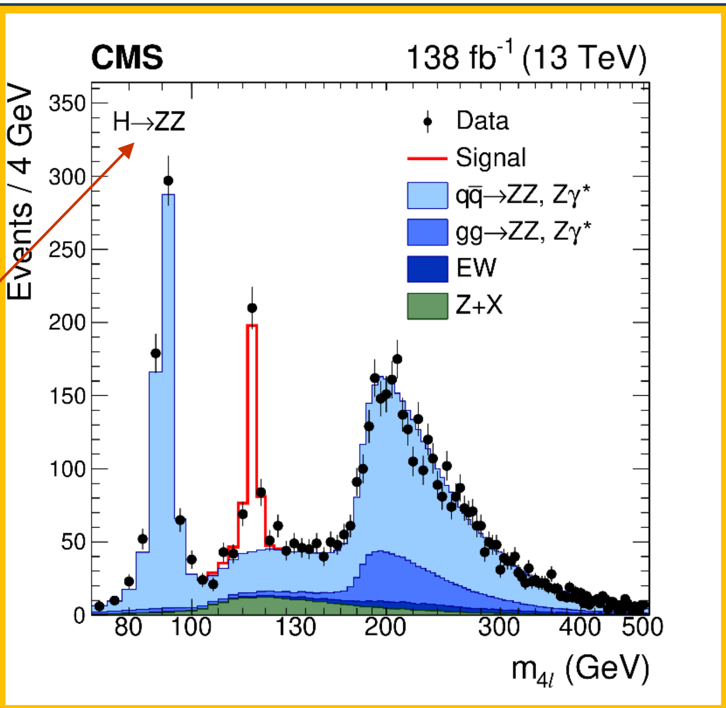
Various Higgs decays (couplings)

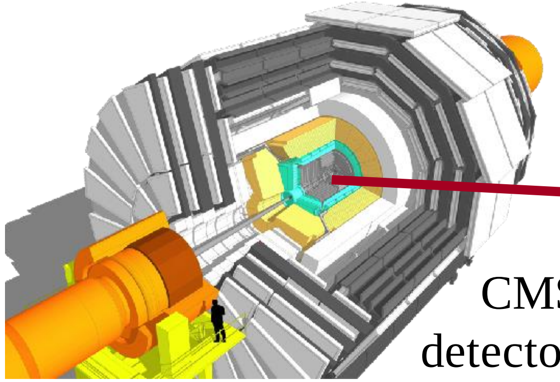


Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
$\tau\tau$	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
$\gamma\gamma$	0.227 ± 0.005
$Z\gamma$	0.157 ± 0.009
ss	0.025 ± 0.001
$\mu\mu$	0.0216 ± 0.0004

?
!

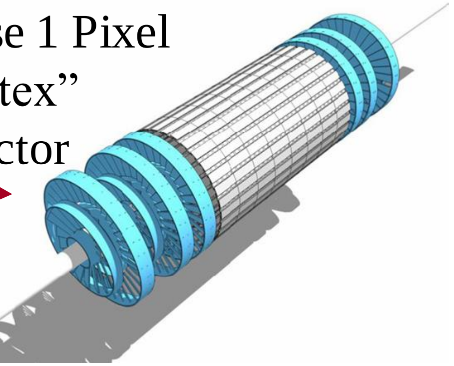






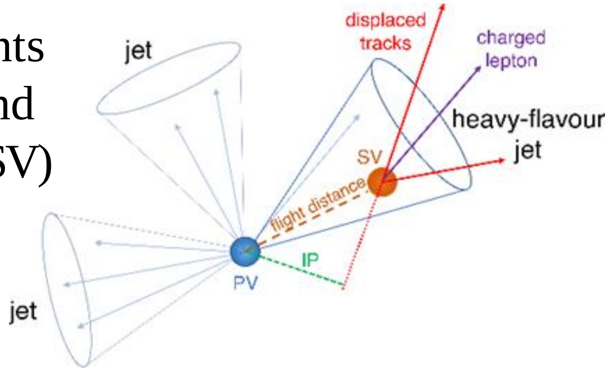
CMS detector

Phase 1 Pixel „vertex" detector



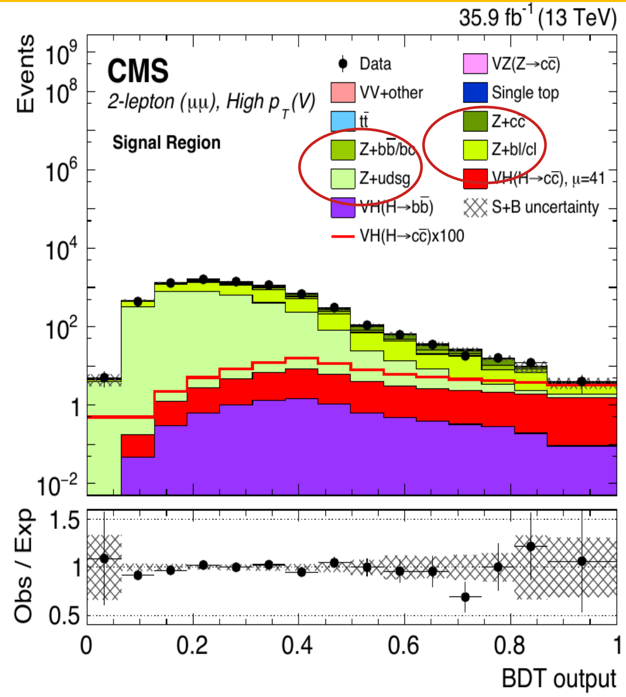
Detector to measure points of pp interaction (PV) and **b- or c-quark decays** (SV)

⟹



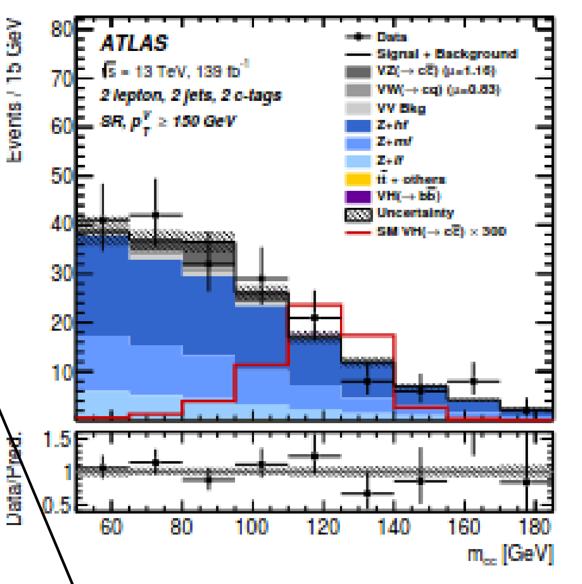
Higgs decays to charm and Z + cc

[Phys. Rev. Lett. 131, 041801](#)



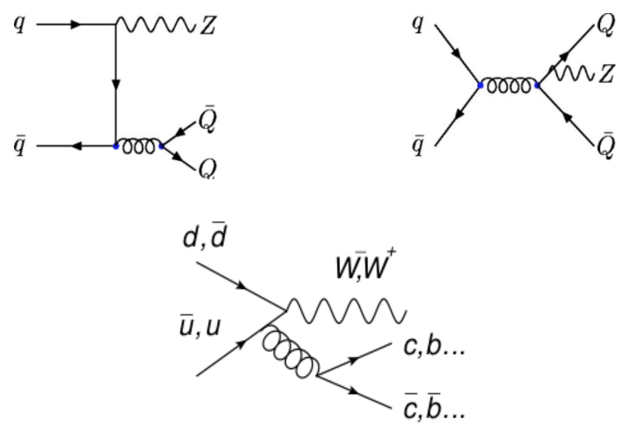
[Eur. Phys. J. C 82 (2022) 717](#)

$VH(\rightarrow b\bar{b})$	
$WH(\rightarrow b\bar{b})$ normalisation	27%
$ZH(\rightarrow b\bar{b})$ normalisation	25%
Diboson	
$WW/ZZ/WZ$ acceptance	10%/5%/12%
p_T^V acceptance	4%
N_{jet} acceptance	7%–11%
$Z+$jets	
$Z+hf$ normalisation	Floating
$Z+mf$ normalisation	Floating
$Z+lf$ normalisation	Floating
$Z+bb$ to $Z+cc$ ratio	20%
$Z+bl$ to $Z+cl$ ratio	18%
$Z+bc$ to $Z+cl$ ratio	6%
p_T^V acceptance	1%–8%
N_{jet} acceptance	10%–37%
High-ΔR CR to SR	12%–37%
0- to 2-lepton ratio	4%–5%
$W+$jets	
$W+hf$ normalisation	Floating
$W+mf$ normalisation	Floating
$W+lf$ normalisation	Floating
$W+bb$ to $W+cc$ ratio	4%–10%
$W+bl$ to $W+cl$ ratio	31%–32%
$W+bc$ to $W+cl$ ratio	31%–33%
$W\rightarrow\tau\nu(+c)$ to $W+cl$ ratio	11%
$W\rightarrow\tau\nu(+b)$ to $W+cl$ ratio	27%
$W\rightarrow\tau\nu(+l)$ to $W+l$ ratio	8%
N_{jet} acceptance	8%–14%
High-ΔR CR to SR	15%–29%
$W\rightarrow\tau\nu$ SR to high-ΔR CR ratio	5%–18%
0- to 1-lepton ratio	1%– 6%



20% error on Z + bb / Z + cc background

V + bb, V + cc production diagrams:



- Beyond this motivation, also poorly modelled

  → outstanding topic for the QCD calculations

- **No measurements exist for Z + cc cross-sections at the LHC at 13 TeV**
- **We are also working on the Z + cc / Z + bb cross-section ratio measurements in Run 2 data**

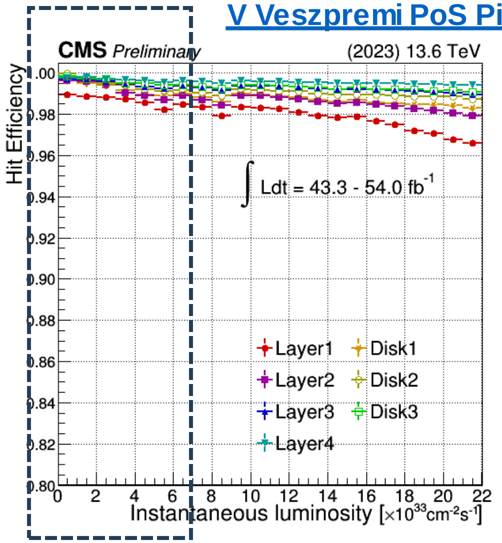
Limits in collision rates

How to make progress with these measurements → Need more statistics!

- in the LHC, only possible by increasing pp-collisions per beam-crossing
  - leads to larger data-rate (busy events)

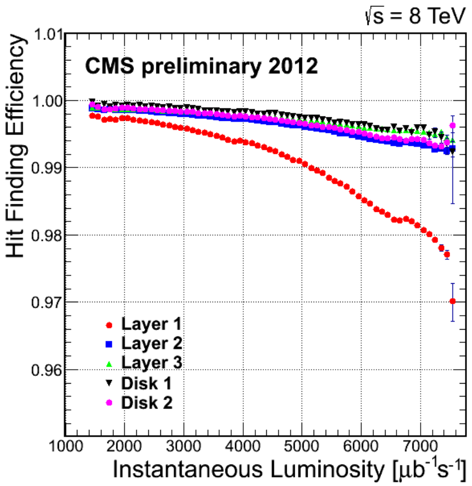
V Veszpremi JINST 12 (2017) C12010
JINST 14 (2019) P10017
JINST 16 (2021) P02027

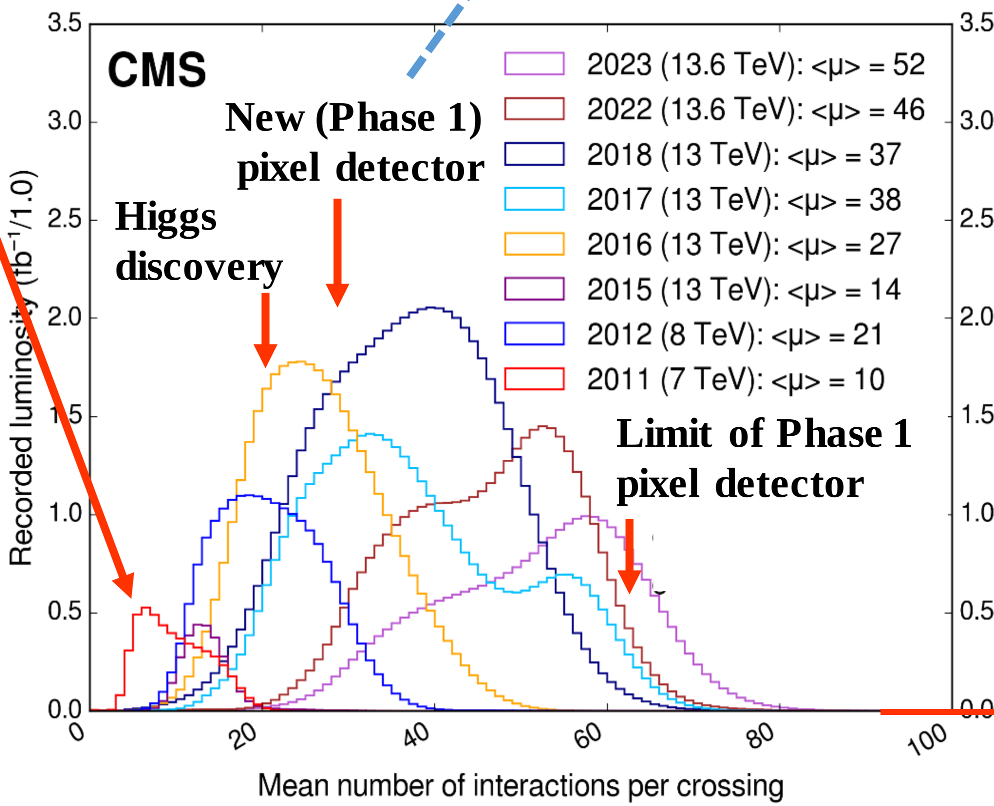
V Veszpremi PoS Pixel2022 (2023) 008



Phase 0 range

LHC start-up with Phase 0 Pixel detector





New (Phase 1) pixel detector

Higgs discovery

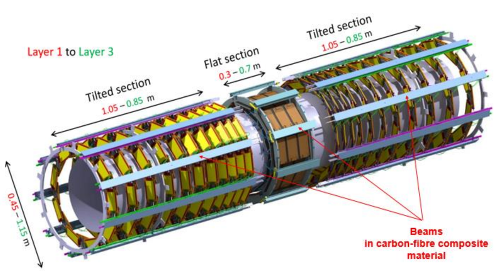
Limit of Phase 1 pixel detector

HL-LHC

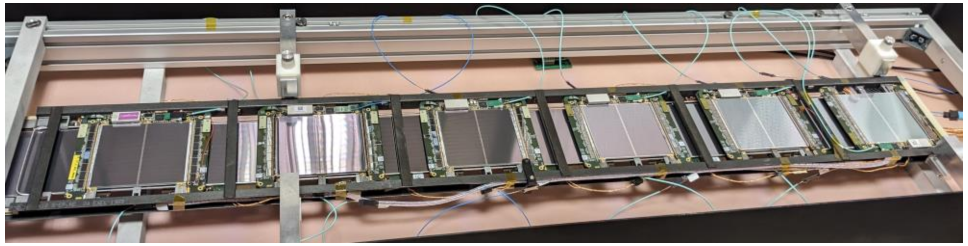
V Veszpremi JINST 9 (2014) C03005
M Bartók JINST 10 (2015) C05006
V Veszpremi JINST 10 (2015) C04039

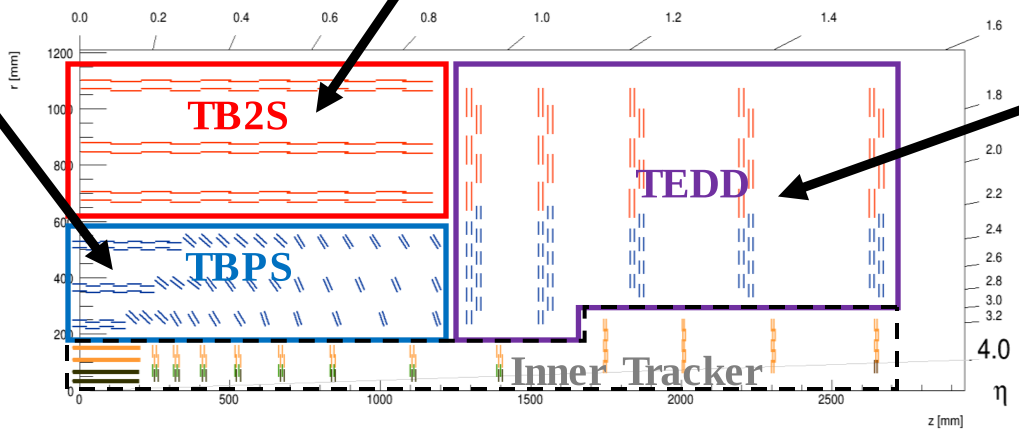
CMS Phase 2 Tracker

Tracker **B**arrel with **PS** modules

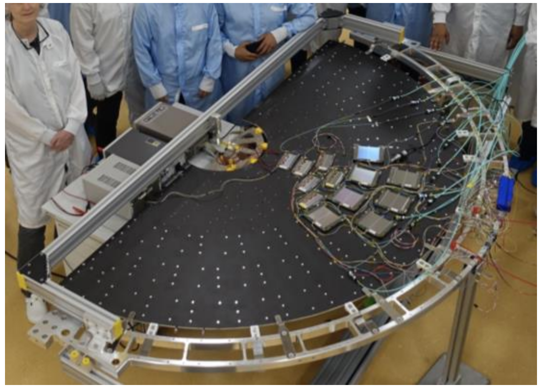


Tracker **B**arrel with **2S** modules





Tracker **E**ndcap **D**ouble-**D**iscs



Requirements for the OT:

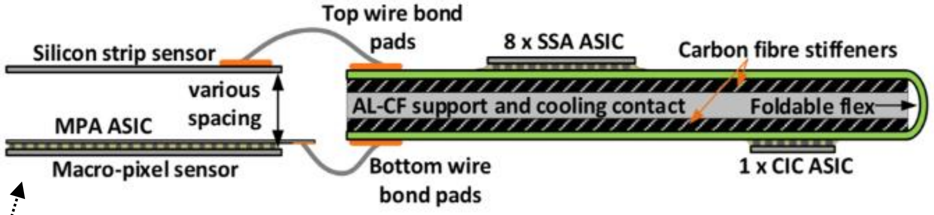
- increased radiation hardness
- extended pseudo-rapidity coverage
- higher granularity, better track separation
- compatible with higher data rates
- provide information to the L1 trigger

K Marton doi.org/10.5281/zenodo.8346835

- Two types of semiconductive silicon modules („p_T modules")
  - 7608 2S modules (at r > 60cm) + 5592 PS modules (at r < 60cm)
  - 190 m^2 total silicon area, 213 million readout channels

The p_T modules

Top: 2 columns of 960 strips
- cell size: 2.5 cm x 100 µm

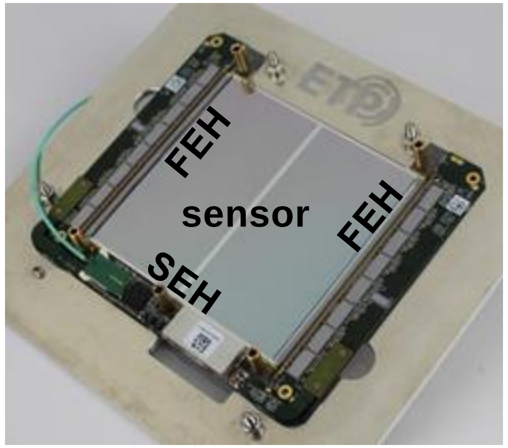


Bottom:32 x 960 pixels
- cell size: 1.5 cm x 100 µm

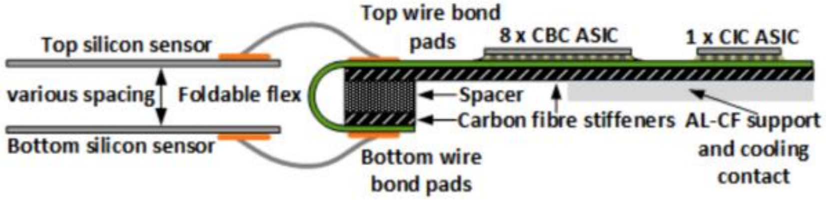
- Standalone units (power and readout)
- Two silicon sensors, separated by a few millimeters and read out by common front-end electronics
- **Provides tracking information to the L1 trigger at every bunch-crossing (40 MHz)**

2S module

- both sides **micro-strip sensors**
- front-end hybrid (**2S-FEH**) electronics wire-bonded to the strips
- one service hybrid (**SEH**) for powering, control, and data-transfer

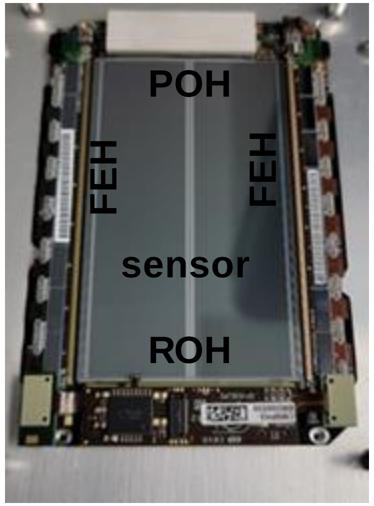


2 columns of 1016 strips
- cell size: 5 cm x 90 µm



PS module

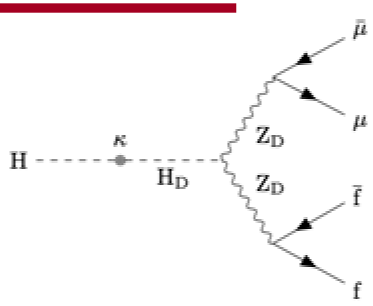
- top side **micro-strip sensor**
- bottom side **macro-pixel sensor**
- 16 chips bump-bonded to bottom
- front-end hybrids (PS-FEH) wire-bonded to the sensors
- powering (POH) and read-out (ROH)

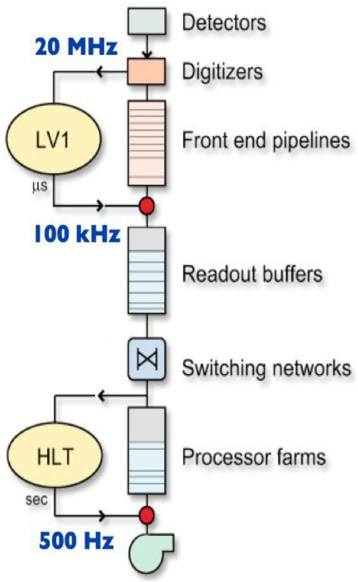


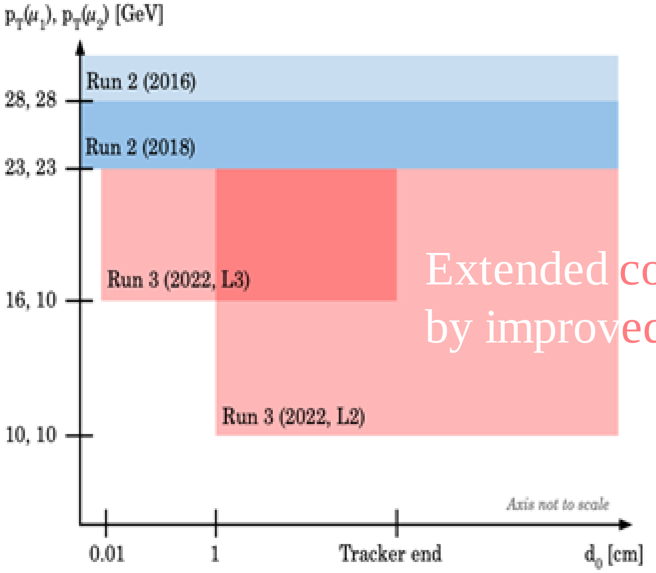
Trigger matters!

Recent inclusive search for long-lived exotic particles

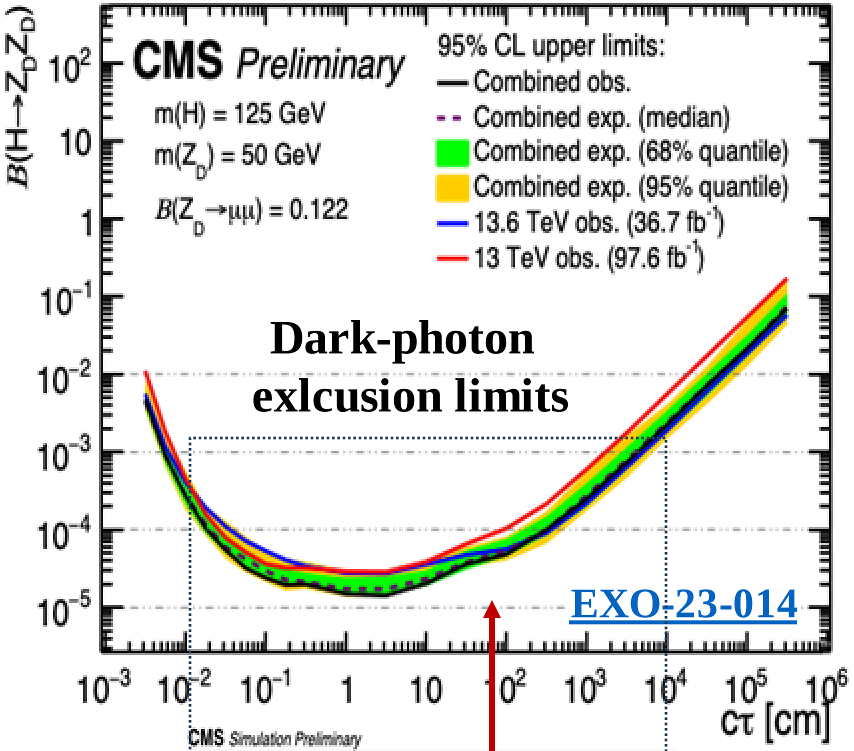
- Data taken in 2022: muons from common decay vertex ~100 μm to meters away from pp-interaction





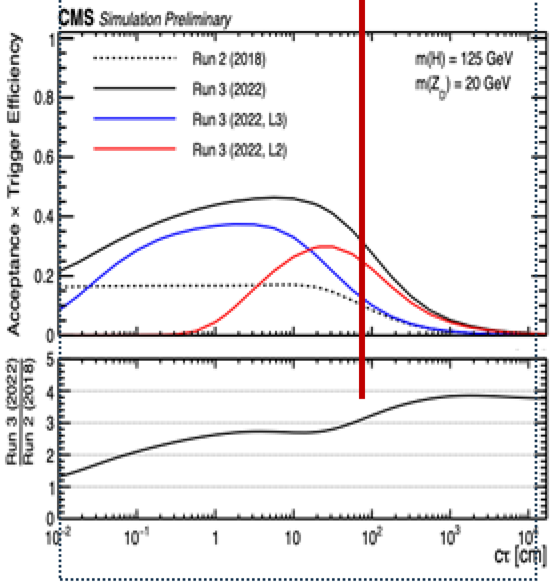


Extended coverage by improved trigger



Dark-photon exlcusion limits

[EXO-23-014]

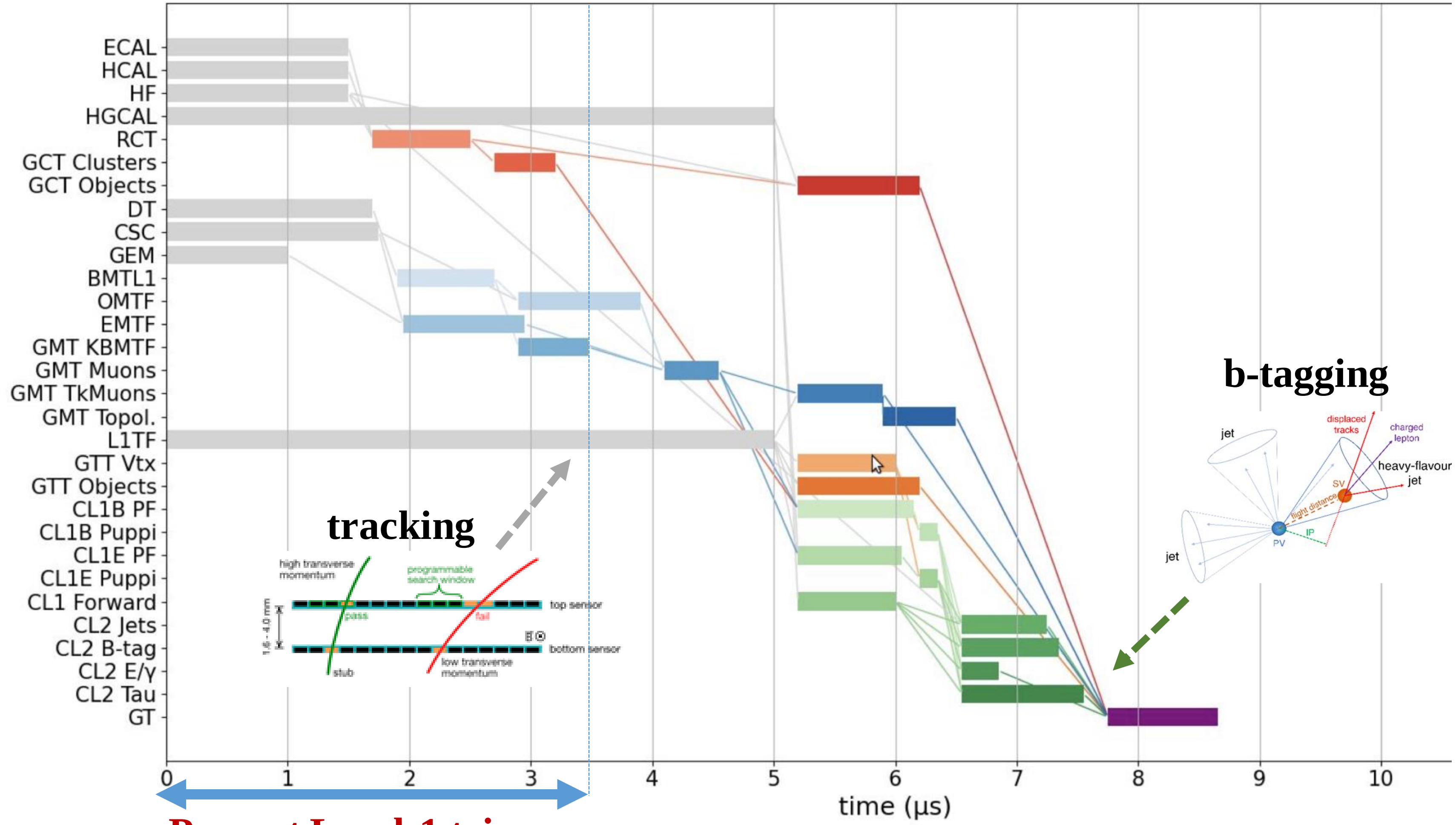


Present CMS trigger: Level-1 hardware
+ High-Level Trigger (HLT) in CPU farm

- Level-1 triggers muon-only → relaxed selections allowed HLT to partially use tracking information

The CMS Phase 2 trigger system

Phase 2 Level-1 trigger will perform full event-reconstruction on-the-fly!

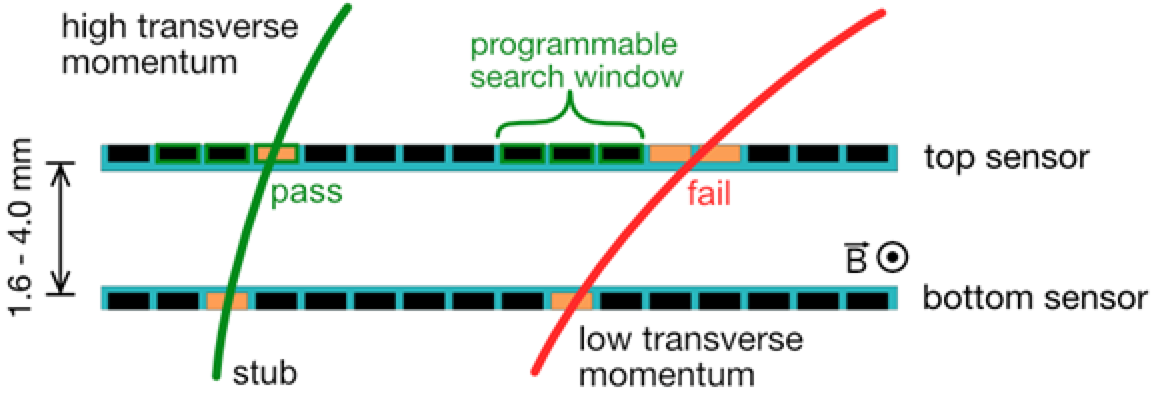


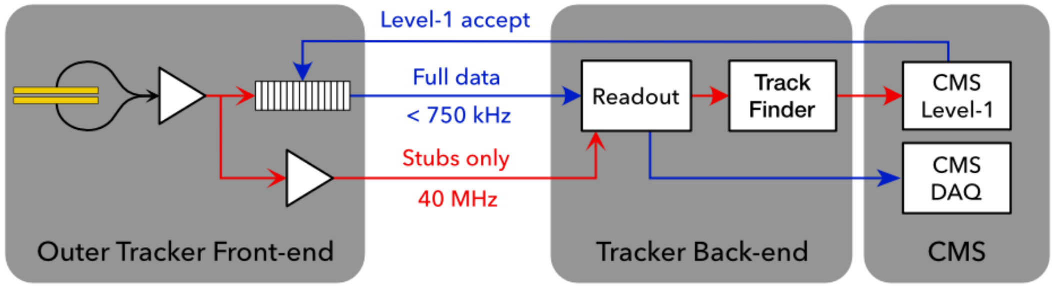
Present Level-1 trigger decision time

- New trigger decision time expanded to **12.5 us**
- Decision based on full particle flow reconstruction!
- Event reconstruction implemented in FPGA-s

Outer Tracker L1 trigger

- Curvature of particles tracks → transverse momentum measurement
- Hit-pairs from the bottom and top sensors are matched
  → form short track segment (stub) if compatible with pp interaction region





- Stub information sent to the track finder (FPGA) system at every bunch crossing
- Track finding in two steps: pattern recognition and track fitting
- **Full readout up to 750 kHz!**

High-rate test

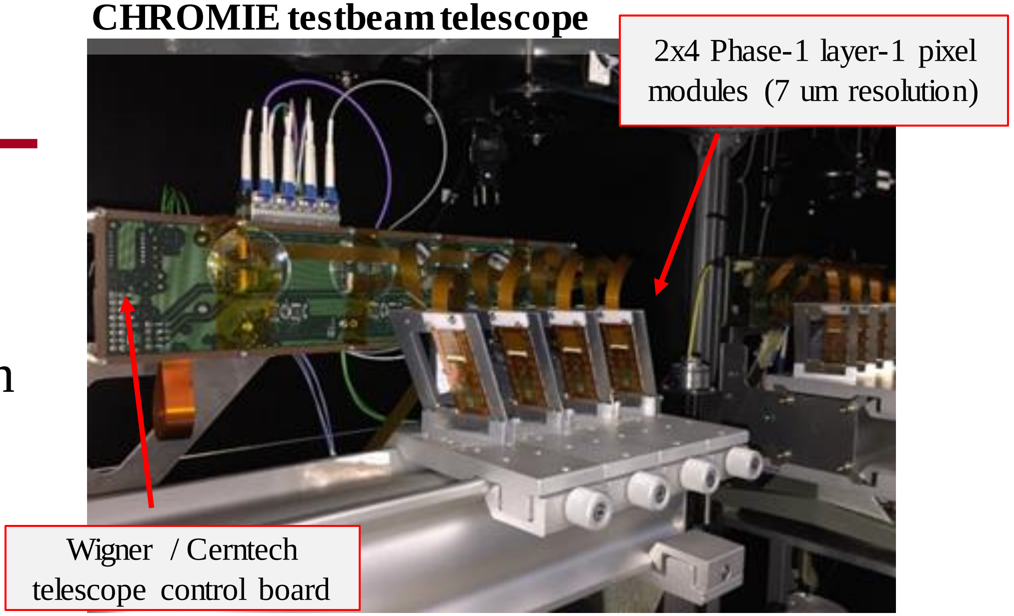
OT read-out to be tested in realistic conditions

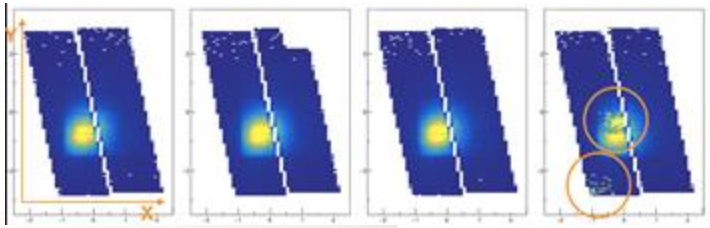
- **CHROMIE** test-beam telescope (see more here)
  - To perform extensive system-level testing before production (radiation tolerance, speed, resolution)
  - Electronics produced by Wigner joint with local company, reconstruction software by our group
- **„mini"-CRHOMIE**: smaller version sold to Strasbourg to be used in high-rate test at Cyrce

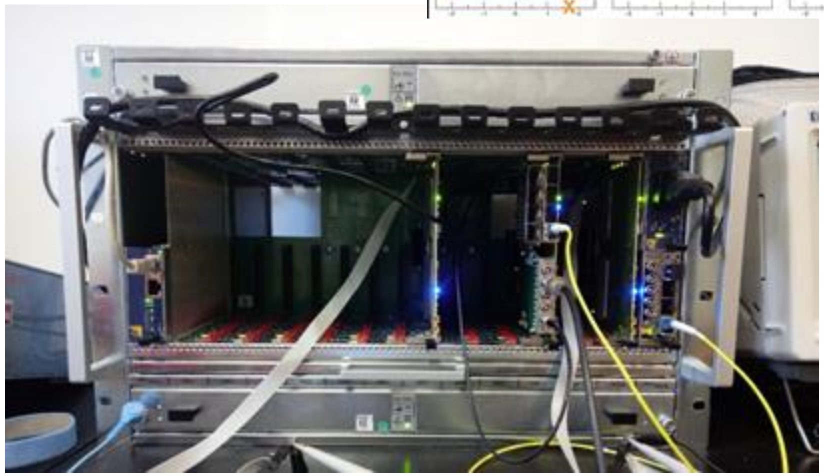
TTC-FC7: FPGA-based μTCA back-end electronics system and firmware development ongoing

- Emulate Phase 2 timing, trigger and control

CHROMIE testbeam telescope



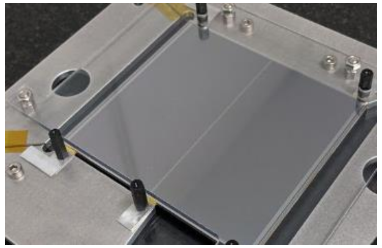




Test crate

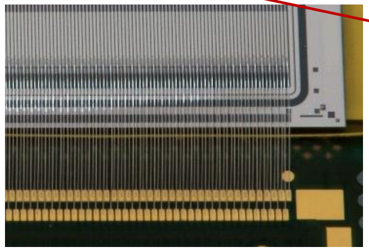
Module production

- Next 3 years: >13,000 modules to be built, largely manually at several assembly centers
- The OT operates in extreme environmental conditions, without possibility to repair
- **All sensors and hybrid electronics to be tested!**

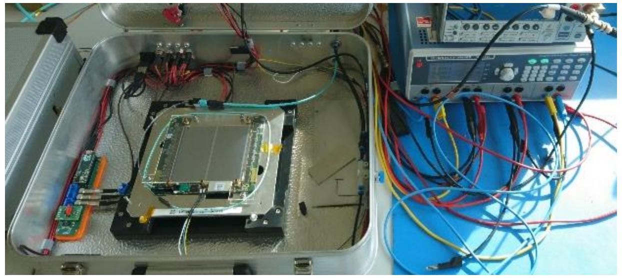


1. Sensor „sandwich" gluing and metrology

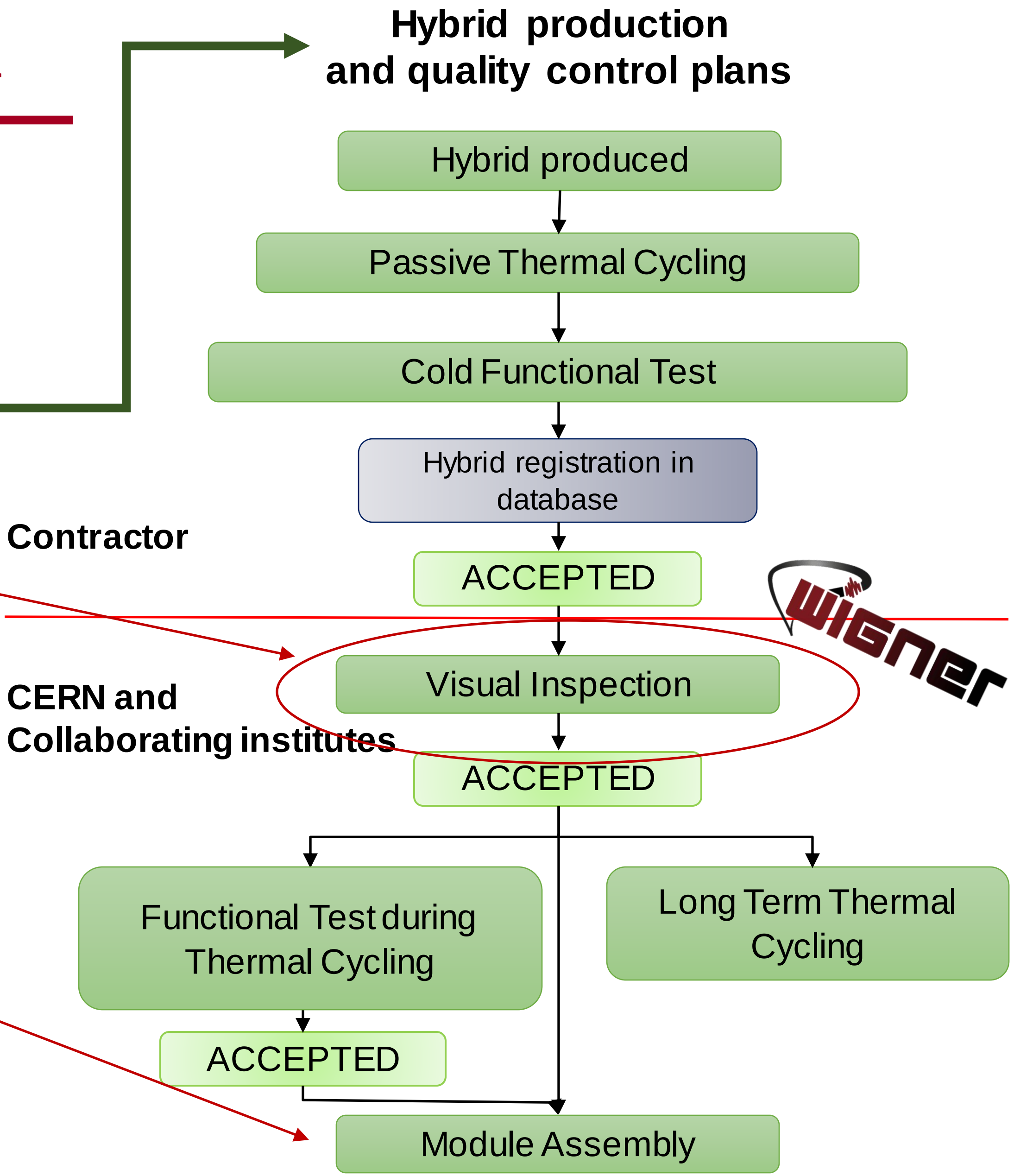
2. Hybrid gluing and optical inspection



3. Wire-bonding and encapsulation



4. Functional test of the assembled module



Visual Inspection of the hybrid circuits

Good quality hybrids are necessary for module assembly and for long-term reliability

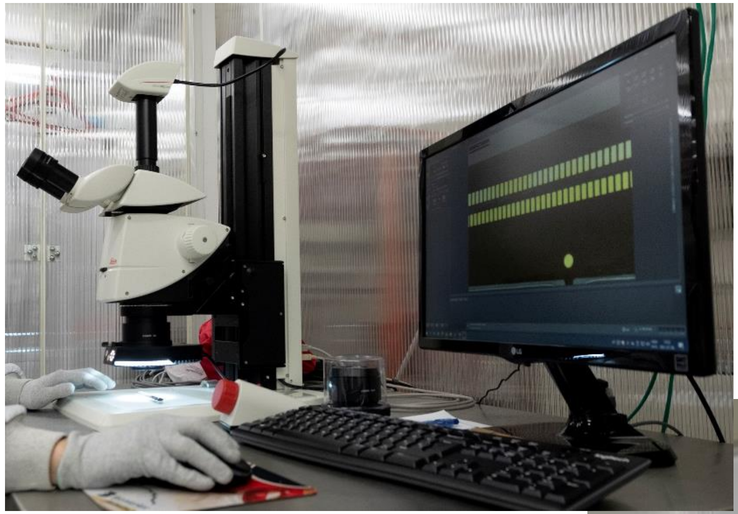
→ VI will be performed on nearly 50,000 hybrid electronics during production

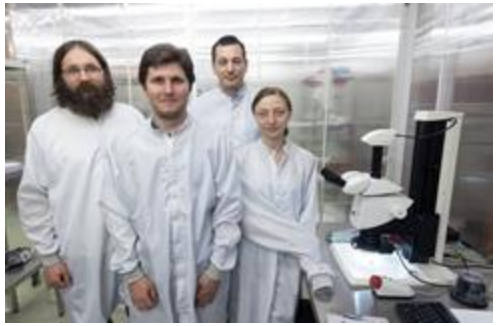
2/3 at CERN + 1/3 at Wigner RCP

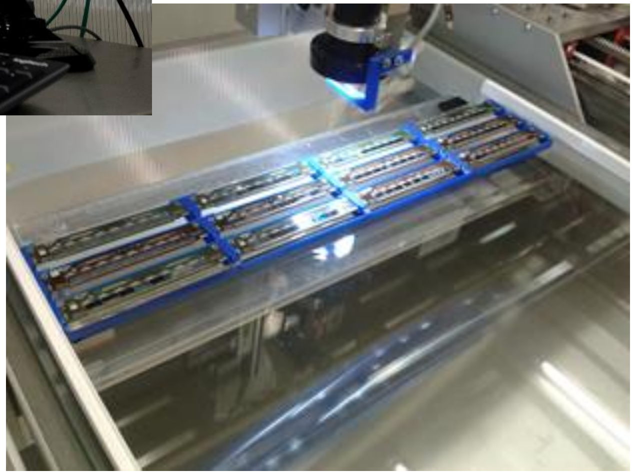
- **Stereo-microscopes** will be used to check
  - bond pads
  - soldering quality and component correctness
  - cleanliness of the circuit
  - alignment and adhesive aspect of the layers
  - local and global flatness, etc.
- **Manual measurements:** weight, flatness, etc.
- **Automated measurements** with a large area optical scanner and special image processing

K Marton poster@LHCC

Cleanroom







Summary

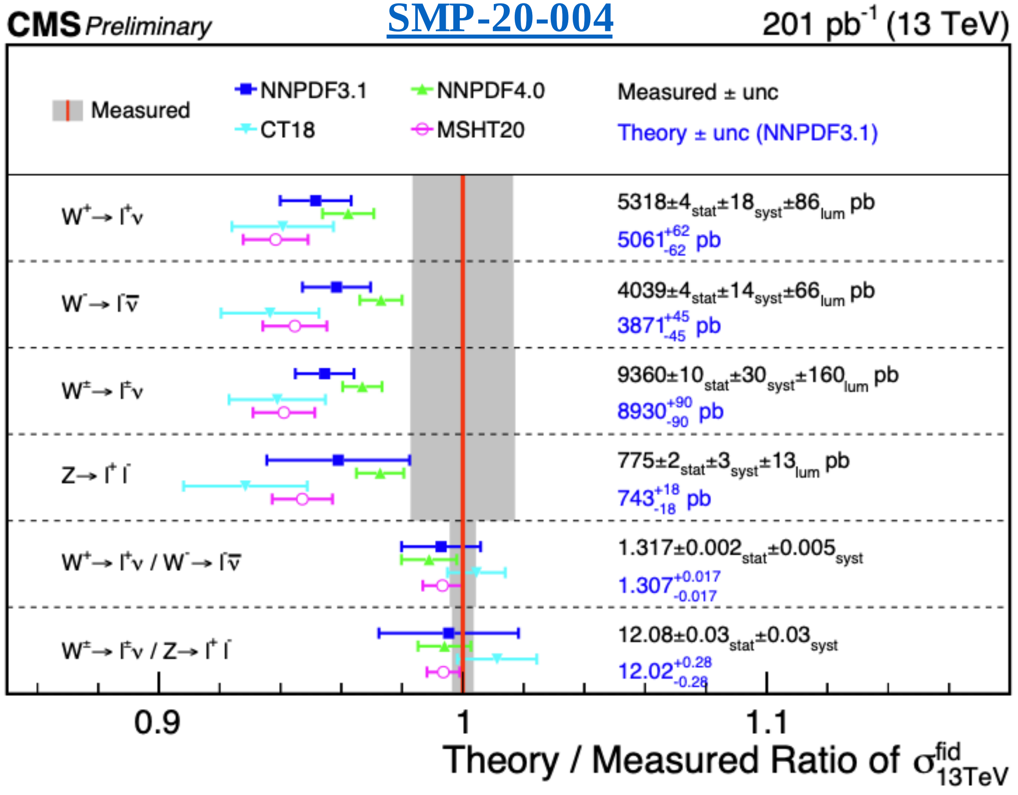
- Interesting direct searches for new physics are being pursued at CMS
- Enormous amount of work is done also in precision physics measurements
- The properties of the Higgs boson are still being tackled, however, some channels will need significantly more collision data
- The High-Luminosity LHC will need entirely new detectors to cope with higher pp-collision rates
- The production of the new CMS Phase 2 tracker is starting now with the participation of Wigner RCP

Backup

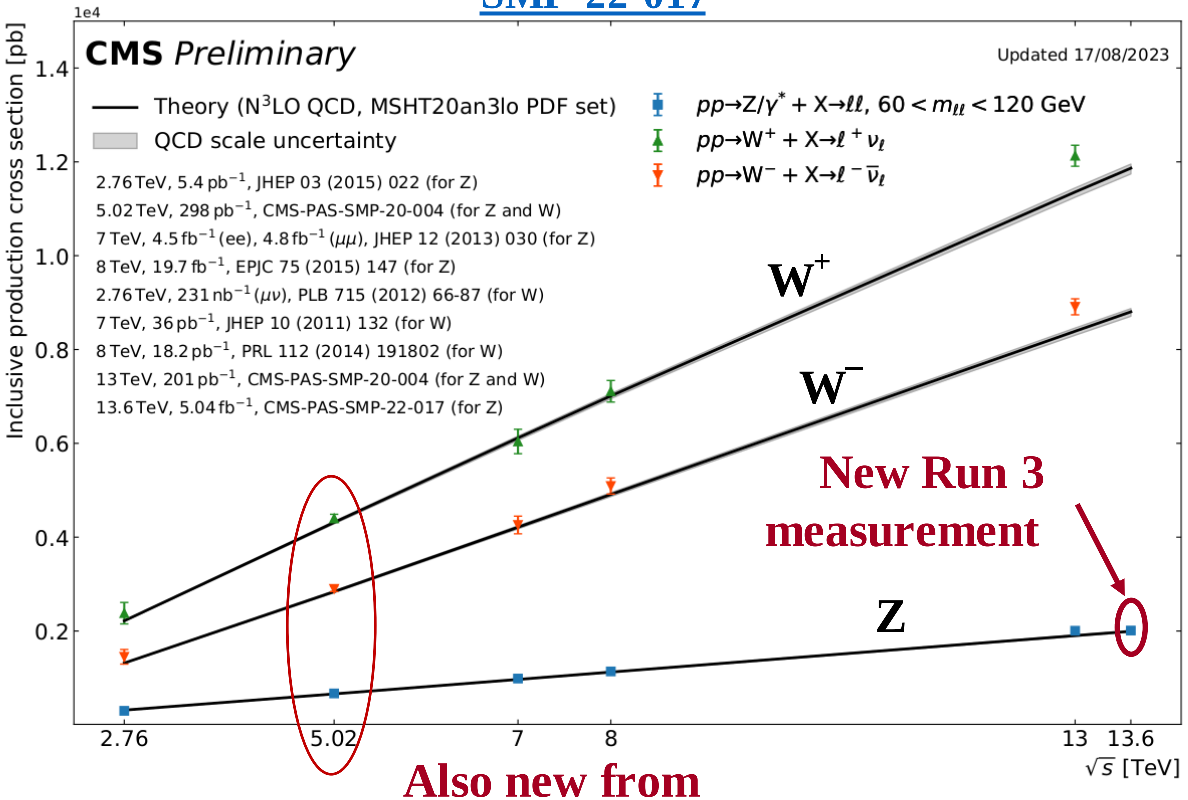
Feedback to theory

Measurement of the Z boson production cross section in pp collisions at 13.6 TeV

SMP-20-004



SMP-22-017

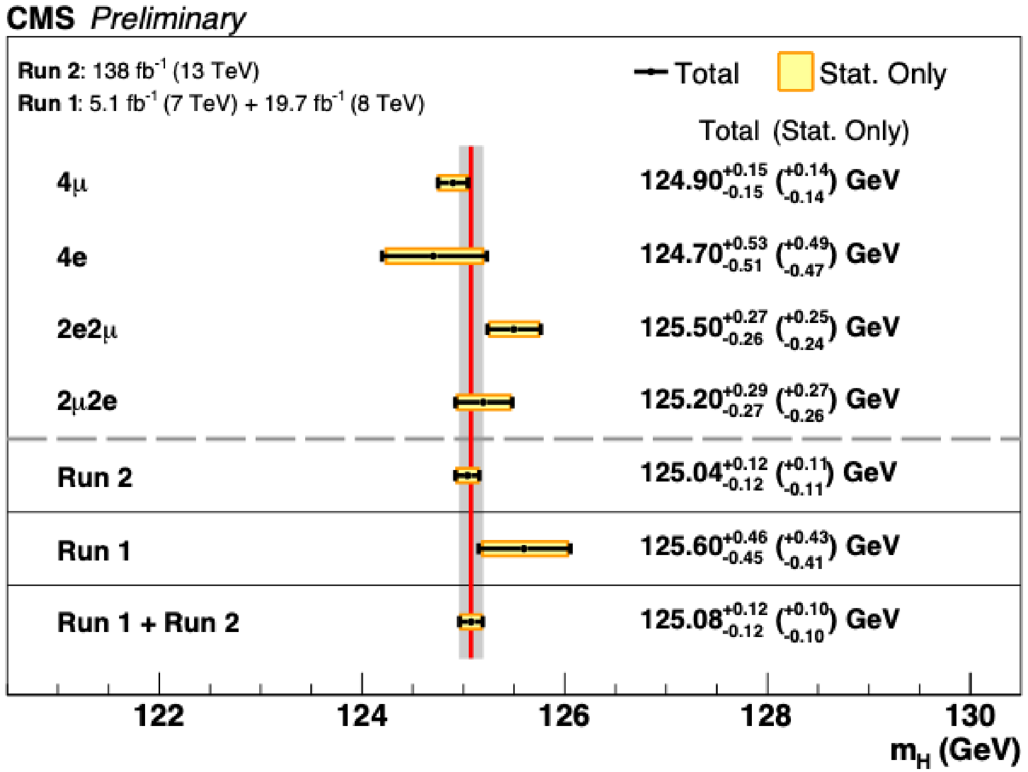


Also new from Summer 23 results

Higgs boson mass and width measurements

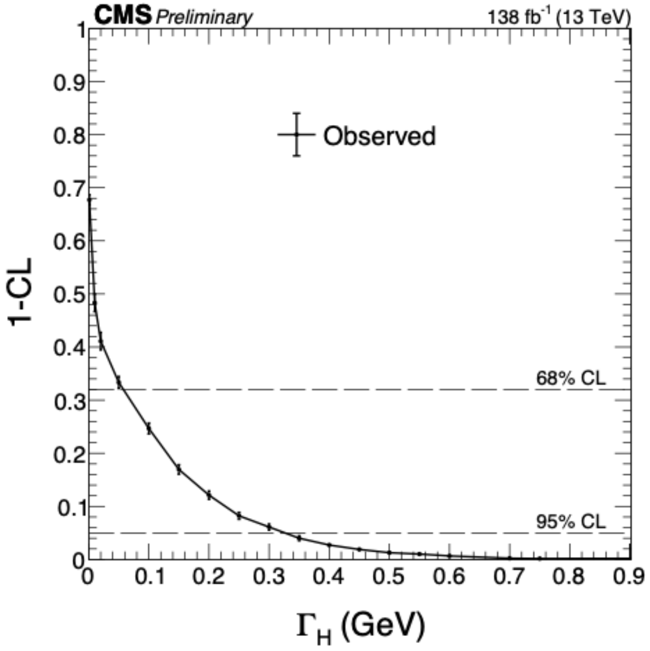
HIG-21-019

H → 4ℓ decay channel using the full Run2 LHC dataset



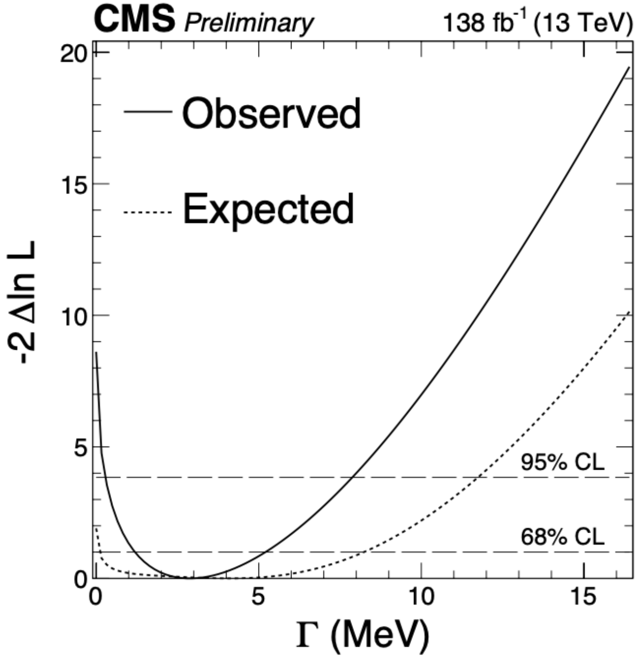
m_H = 125.08 ± 0.10 (stat) ± 0.05 (syst) GeV

Most precise single channel measurement to date!



On-shell Higgs width

95% CL upper limit:
0.33 GeV obs. (0.75 exp.)

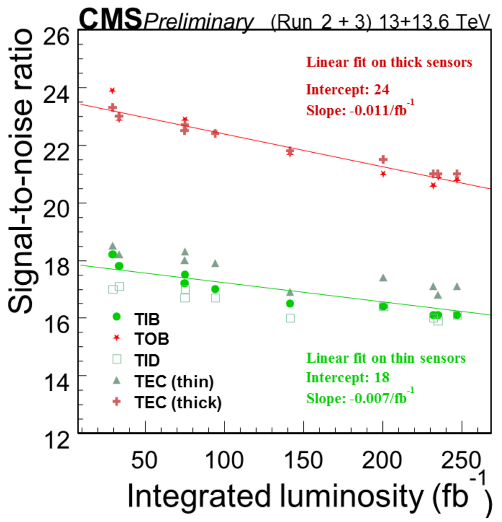


Off-shell Higgs width

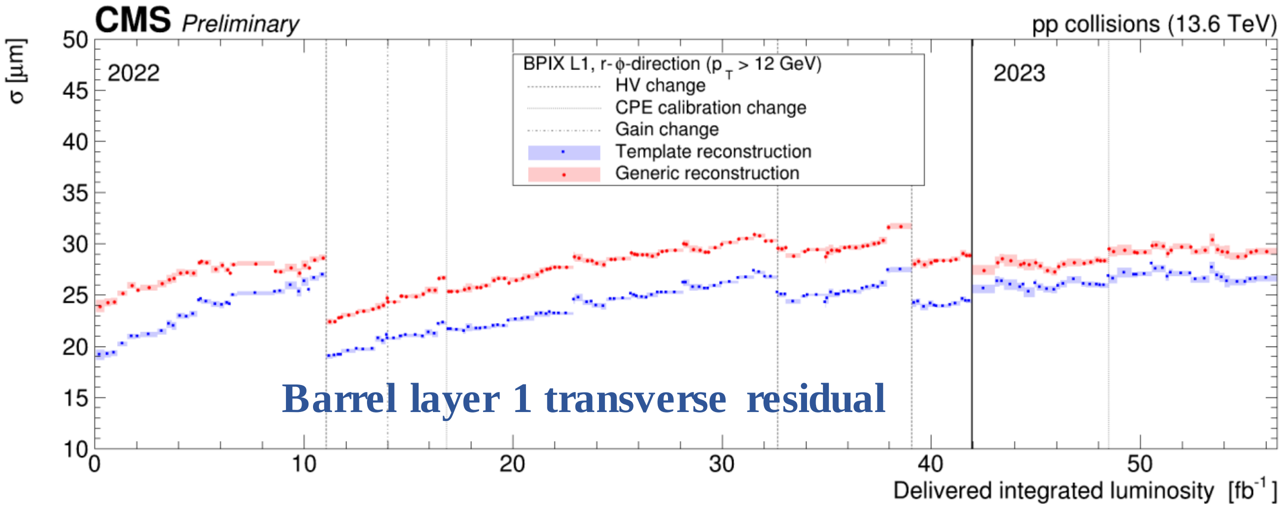
Extracted width:
$\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV
Consistent with SM and confirms previous results

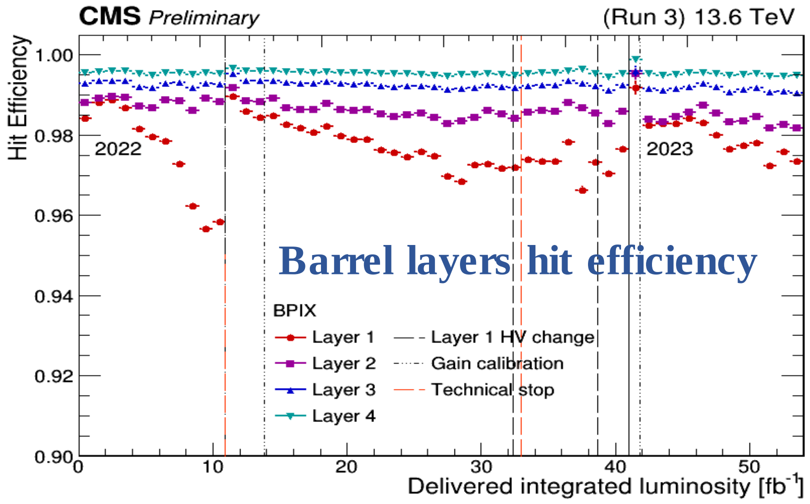
Wigner Tracker

Strip detector signal to noise ratio

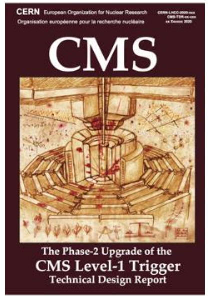


- **Strip detector**
  - Active fraction of Strip detector is stable
  - Performance keeps evolving along expected trend
- **Pixel detector:**
  - Lost 4-hit coverage in about 3% of the barrel area due to a hardware failure in the master layers
  - Change in performance due to radiation damage in layer 1 slowed down as expected, uni ıt 2023
  - Despite the larger average pileup in recent fills, the efficiency remained high
- **Smooth restart coming back from powered-down state over August**





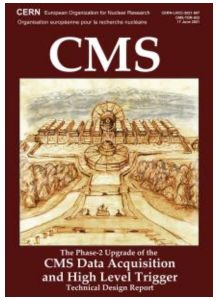
The CMS Phase 2 Upgrade



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

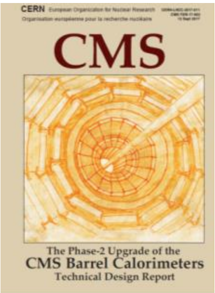
https://cds.cern.ch/record/2759072

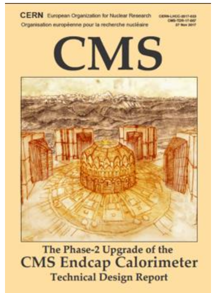
- Full optical readout
- Heterogeneous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

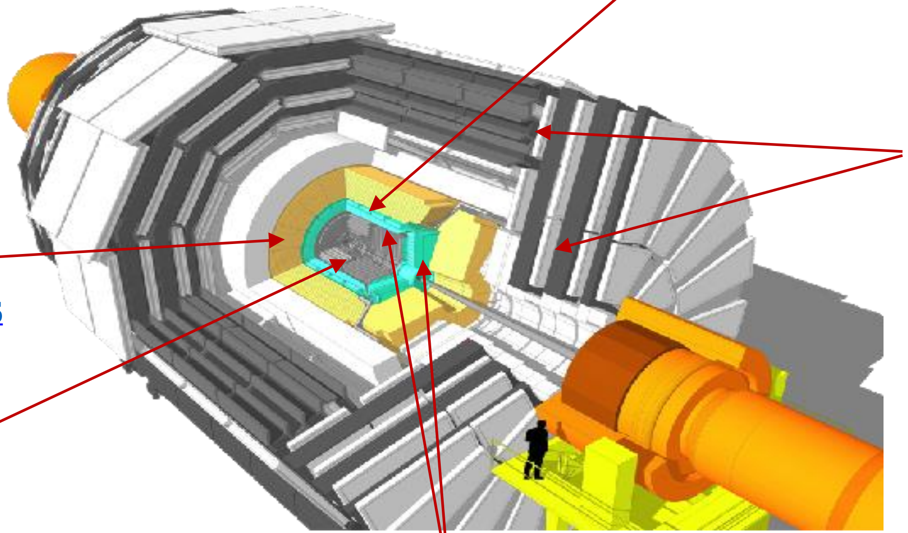
Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards







Calorimeter Endcap

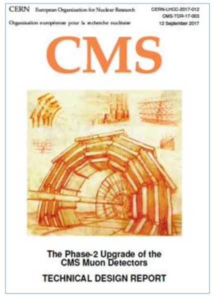
https://cds.cern.ch/record/2293646

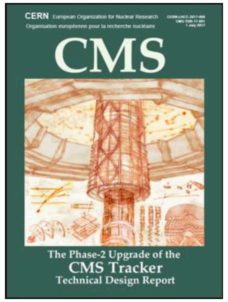
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

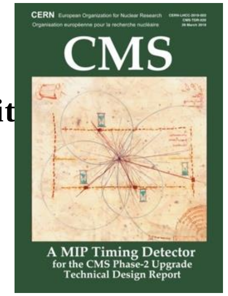




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularit
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector

https://cds.cern.ch/record/2667167

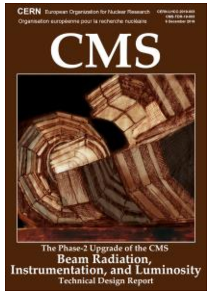
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors

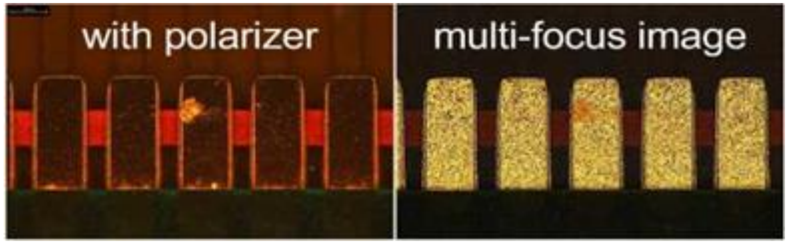


Optical tests of Phase-2 Outer Tracker FE hybrid electronics

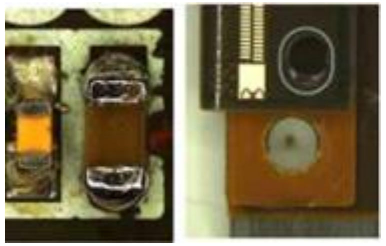
Assembly of more than 13.2 k OT modules in ~3 years

- Thorough component testing before module assembly to check production quality, component alignment, etc.
- ~55k hybrid circuits to be inspected from Feb 2023 at Wigner RCP (~20k) and CERN
  - 2 technicians to be hired from mid-2024
  - Collaboration with CERNTech (engineering) and FFT Kft (maintenance of clean room)

100μm wide pads for wire-bonding (to inspect: cleanliness, color, damages)



Soldering & alignment to be checked



Infrastructure and equipment

- 15 m^2 ESD-safe laminar clean room with 3 air filtering stages (cleanliness > ISO7) with active ventilation, humidity and temperature monitoring and control

- Leica M205C stereo-microscope with motorized vertical stage
- 2 x Nikon SMZ800N stereo-microscopes
- Large area optical scanner (60 cm x 90 cm) with ~5 μm resolution