25th May 2022

30ps precision timing calorimetry with the CMS High Granularity Calorimeter

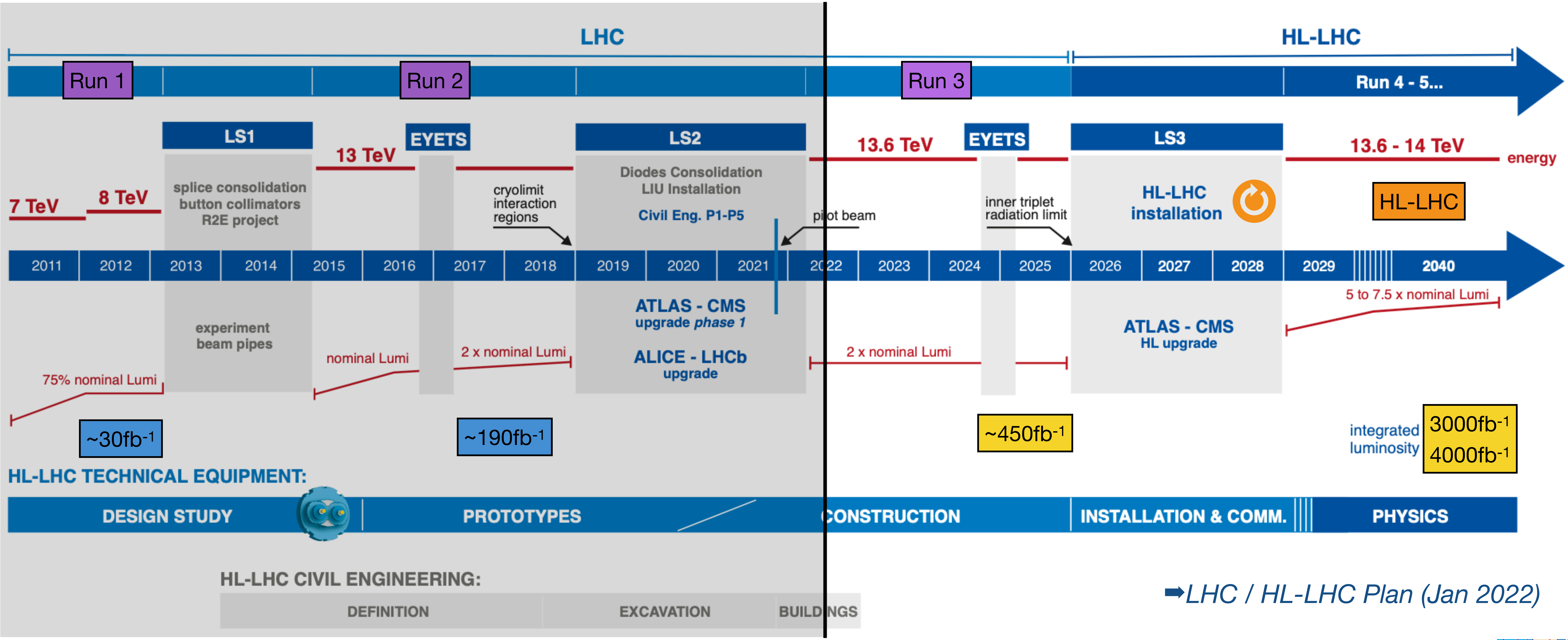
on behalf of the CMS collaboration

Thorben Quast (CERN)

The medium-term future at CERN: High Luminosity LHC

Experimental testing of the Standard Model of Particle Physics via high-energy particle collisions:
Large Hadron Collider (LHC) @ CERN.

LHC upgrade to >5x design luminosity = HL-LHC



➡*LHC / HL-LHC Plan (Jan 2022)*

HL-LHC necessitates upgrades to the CMS detector

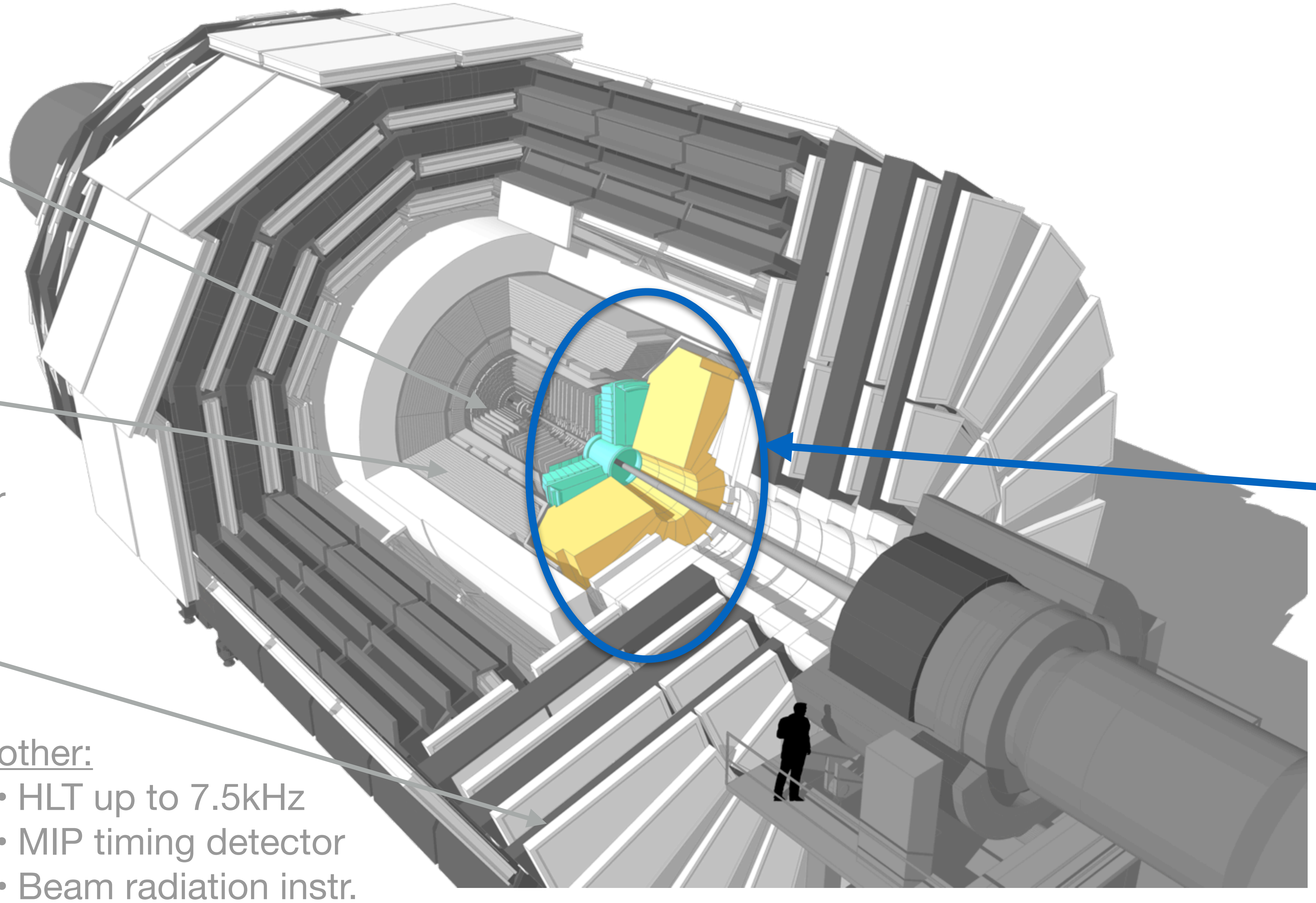
Experimental challenges	**LHC**		**HL-LHC**	**General mitigation strategy**
• inst. luminosity	$2 \times 10^{34}\ s^{-1}\ cm^{-2}$	→	up to $7.5 \times 10^{34}\ s^{-1}\ cm^{-2}$	‣ improved trigger & computing
• detector irradiation	$O(10^{14}\ neq/cm^2)$		$>O(10^{15}\ neq/cm^2)$	‣ radiation-tolerant sensors & electronics
• pile-up interactions	O(40)		140-200	‣ timing and increased granularity

Compact **M**uon **S**olenoid (CMS)
HL-LHC Upgrades

Tracker:
Radiation tolerant,
high granularity,
less materials, tracks in hardware trigger (L1),
coverage up to $|\eta| = 3.8$

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

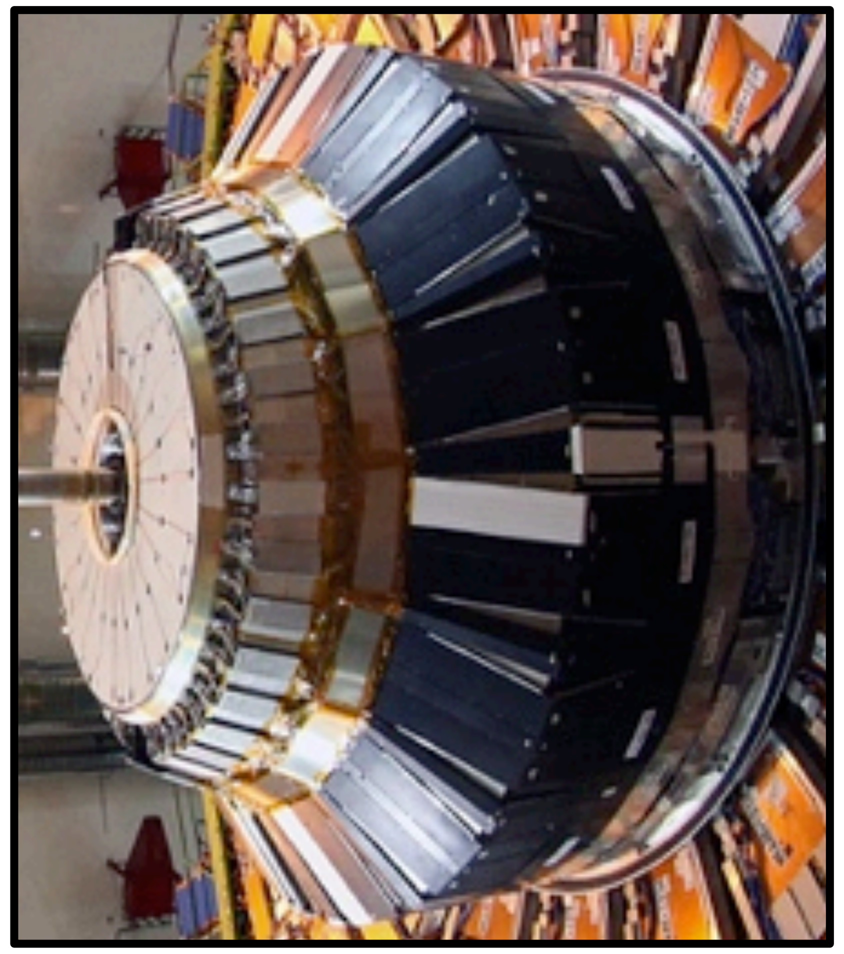
Muon system:
New electronics
GEM/RPC coverage in $1.5 < |\eta| < 2.8$,
investigate muon tagging at higher η



other:
• HLT up to 7.5kHz
• MIP timing detector
• Beam radiation instr. and luminosity

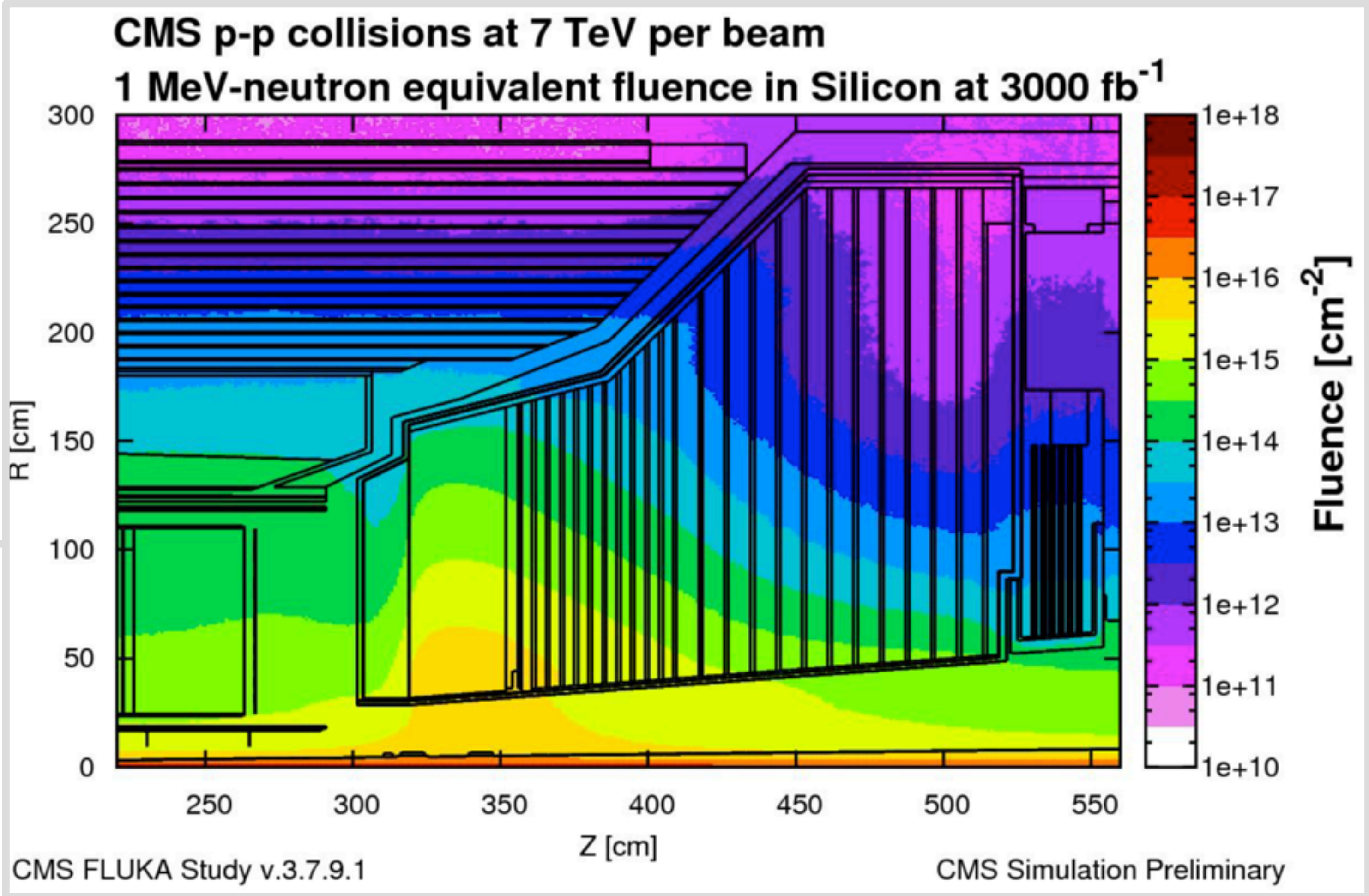
To be replaced for HL-LHC

Endcap Calorimeters:
$1.5 < |\eta| < 3.0$



New calorimeter endcap: High-Granularity Calorimeter (HGCAL)

➡*CMS-TDR-019*



HGCAL = Sampling calorimeter

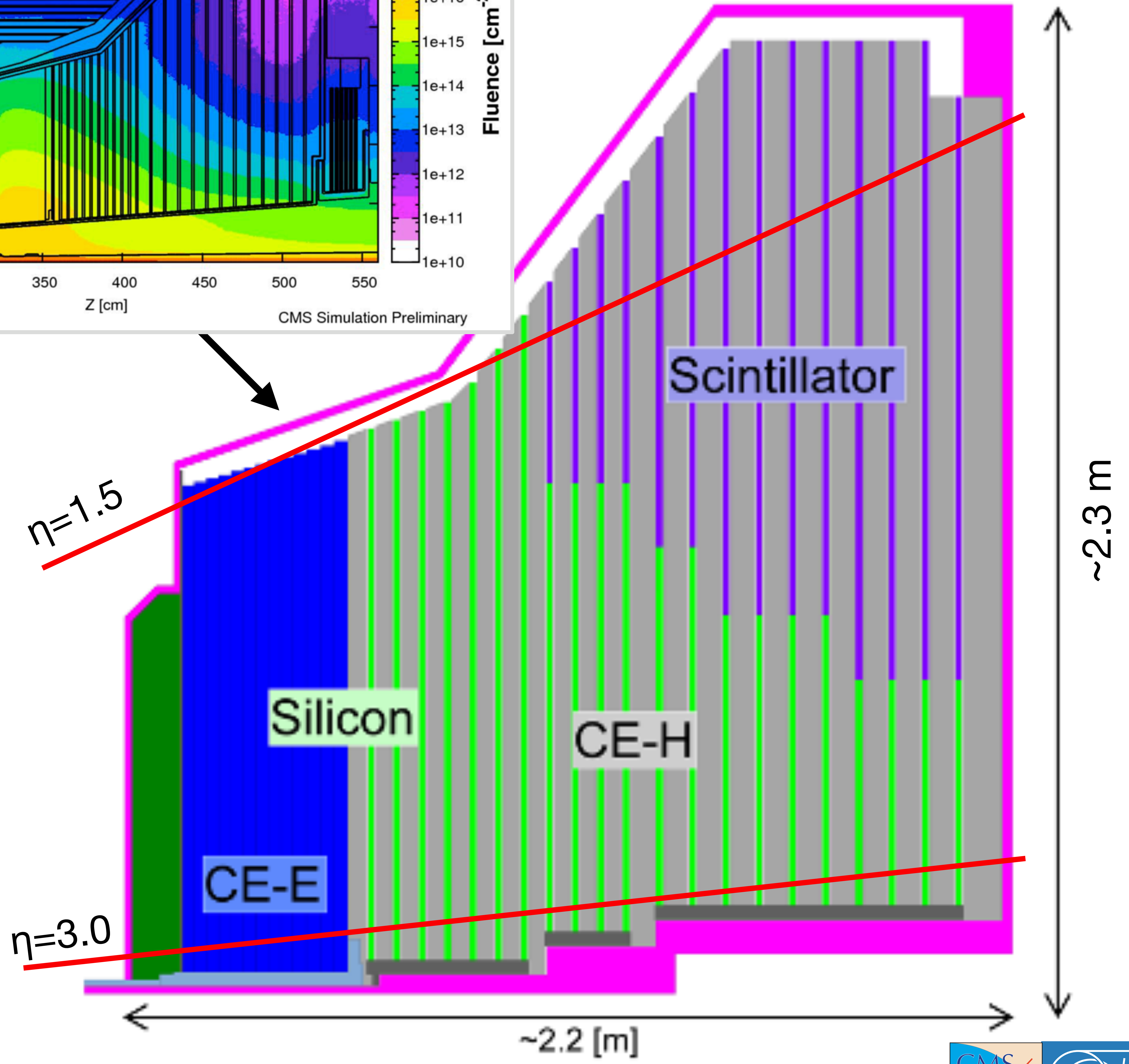
- Hexagonal **silicon sensor** based modules in CE-E and high radiation regions of CE-H.

Active material

Both endcaps	Silicon	Scintillators
Area	**~620m²**	~370m²
#Modules	**~26000**	~3700
Channel size	**0.5 - 1.2 cm²**	4-30 cm²
#Channels	**~6 M**	~240k
Op. temp.	-30 ° C	-30 ° C

Passive material

Per endcap	CE-E	CE-H (Si)	CE-H
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	8.5 λ	
Layers	26	7	14
Weight	~215 t / endcap		



Idea: HGCAL will be a 3D imaging calorimeter

Simulated VBF H (γγ) signatures in the granular endcap calorimeter

LHC —> HL-LHC: Much more pile-up in the CMS detector

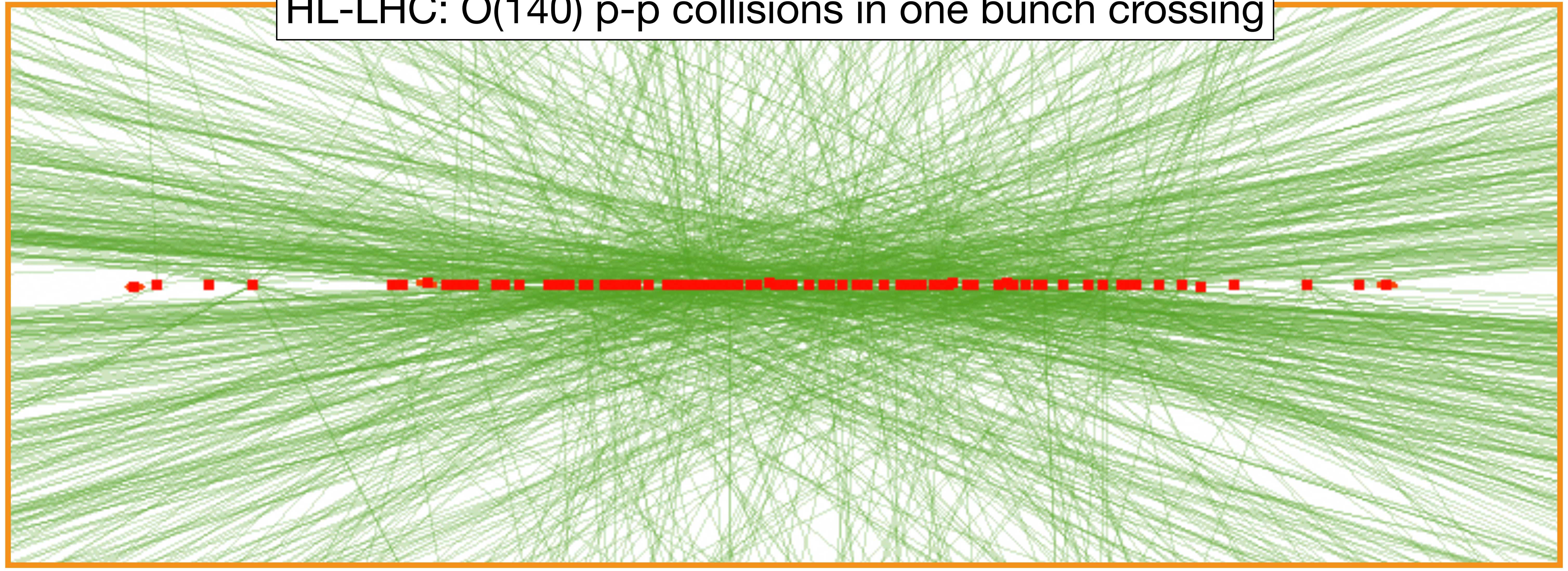
Nominal 5E34 $cm^{-2}s^{-1}$ luminosity

“Ultimate” 7.5E34 $cm^{-2}s^{-1}$ luminosity

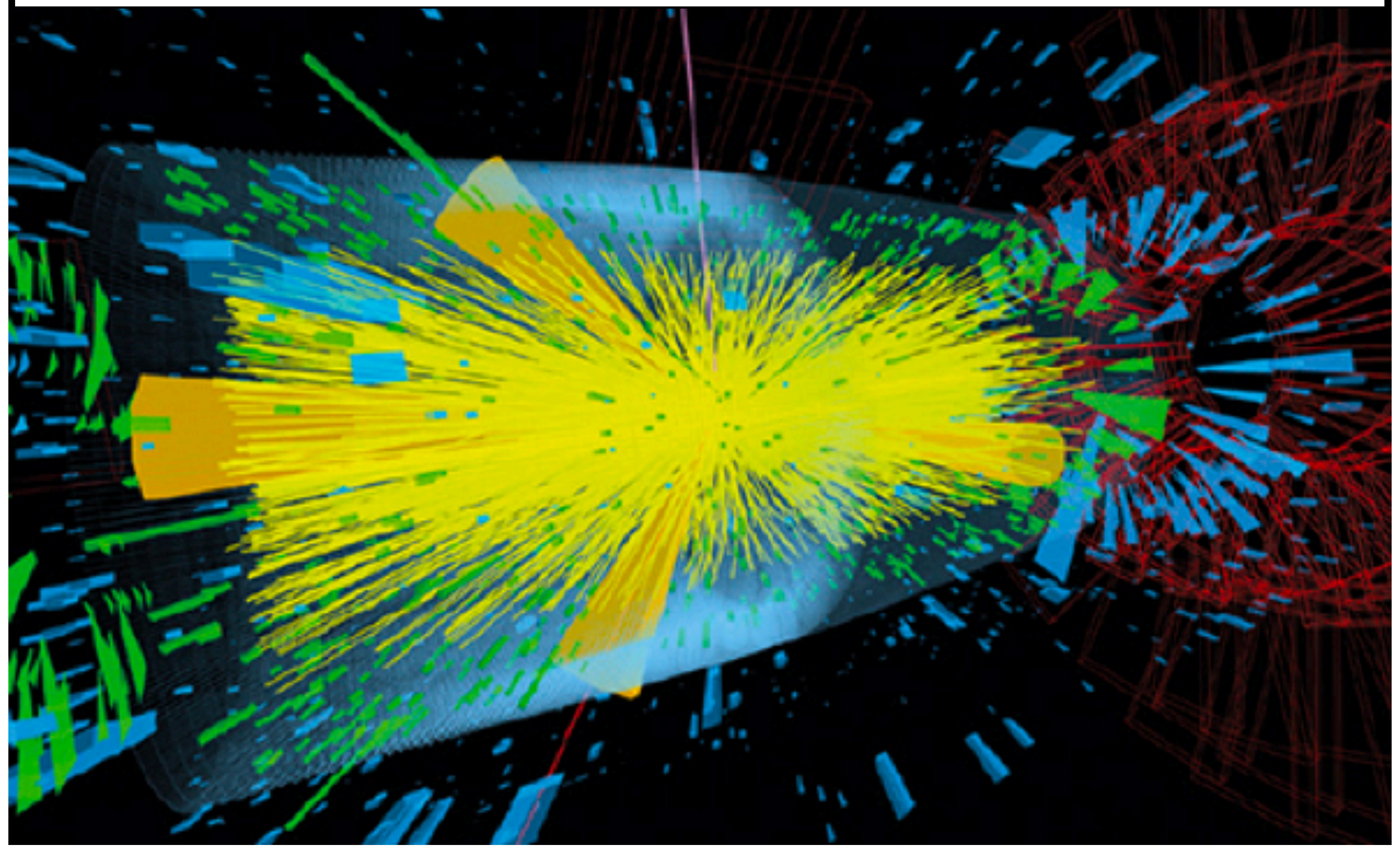
Increasing pile-up

- **140 - 200 collisions** per bunch crossing >> **3-5x** larger than in Run 2.
  - spread over few centimetres
  - spread over O(200) ps

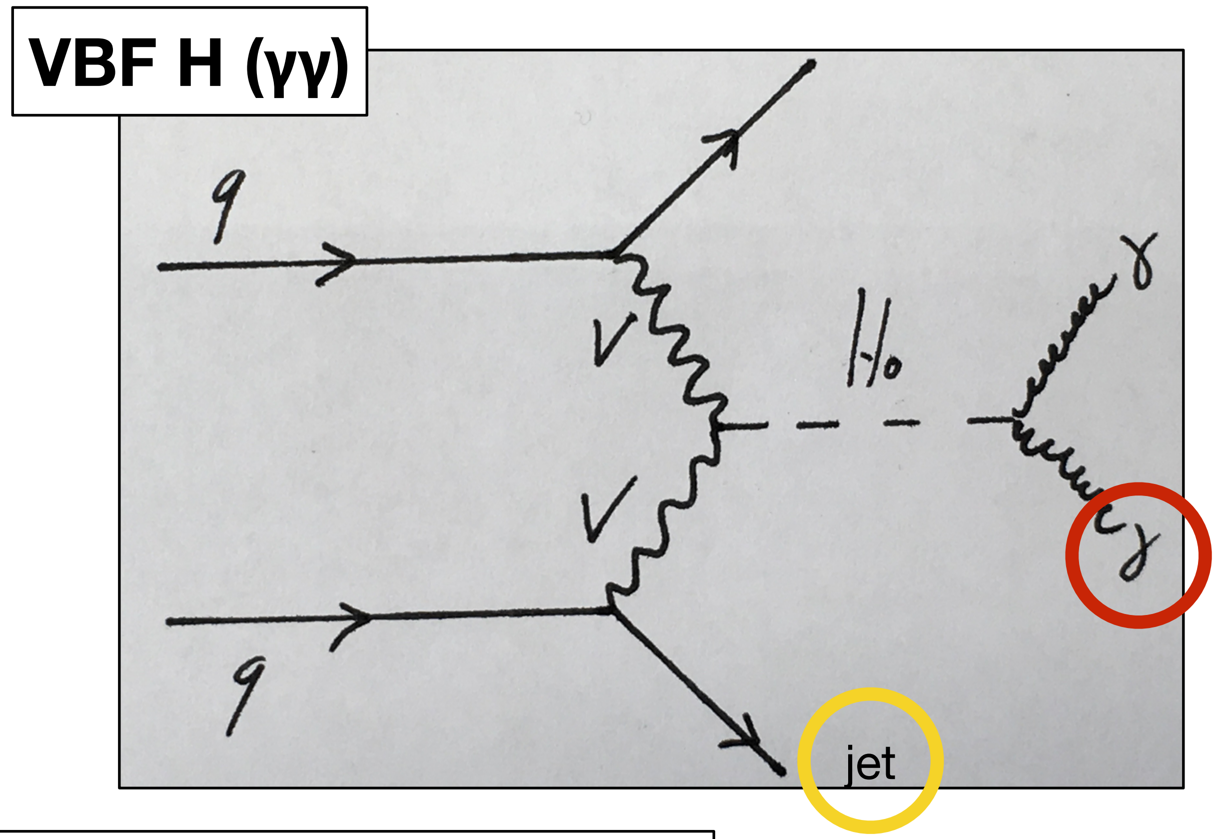
HL-LHC: O(140) p-p collisions in one bunch crossing



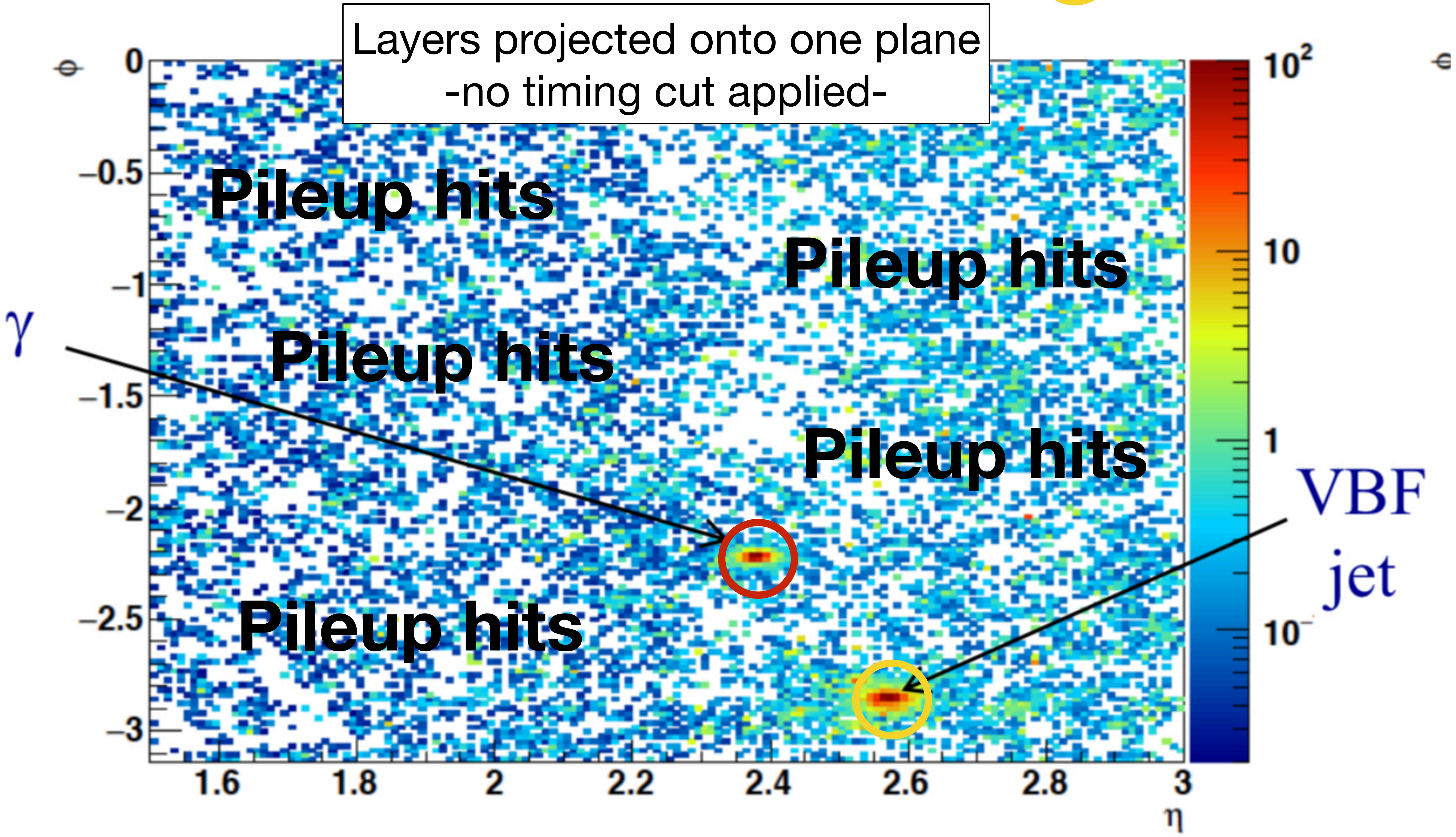
HL-LHC: A lot of activity in the CMS detector



Pile-up tends to hide the signal-of-interest

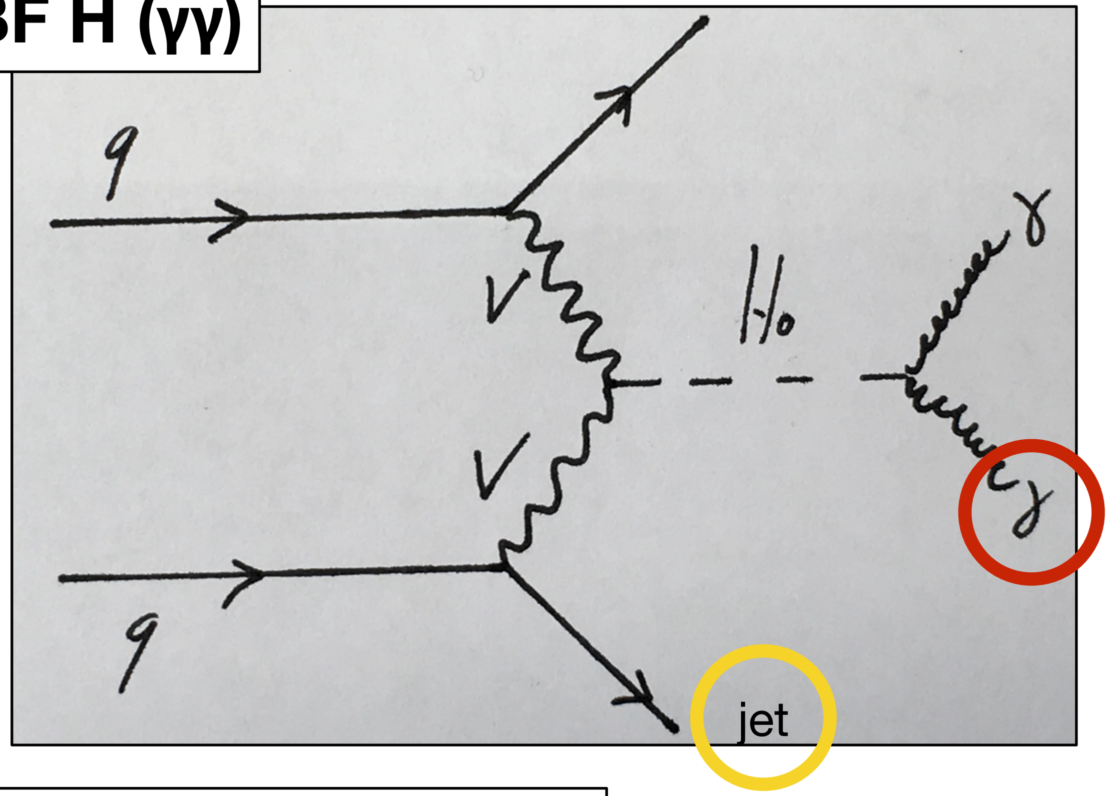


+ 200 PU

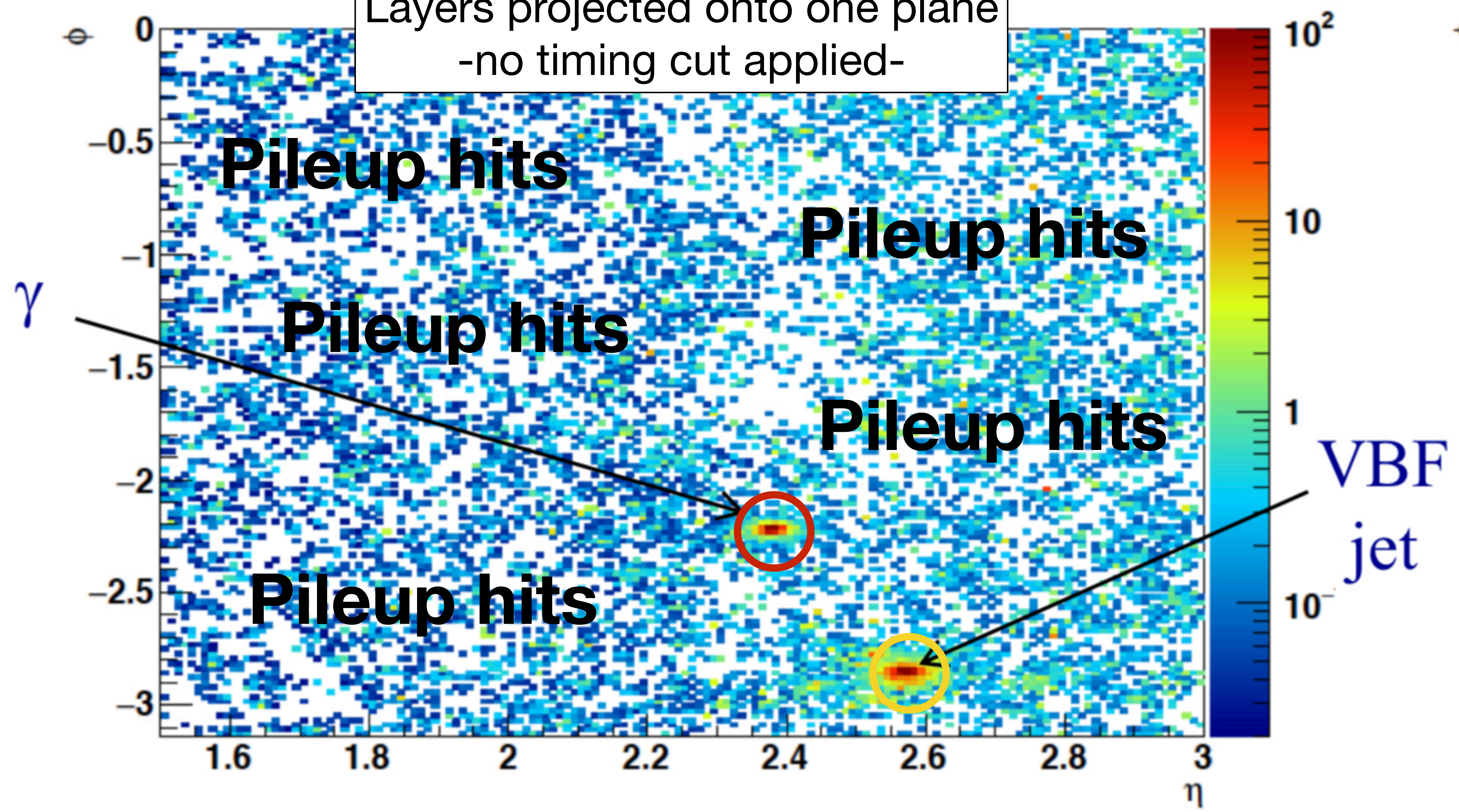


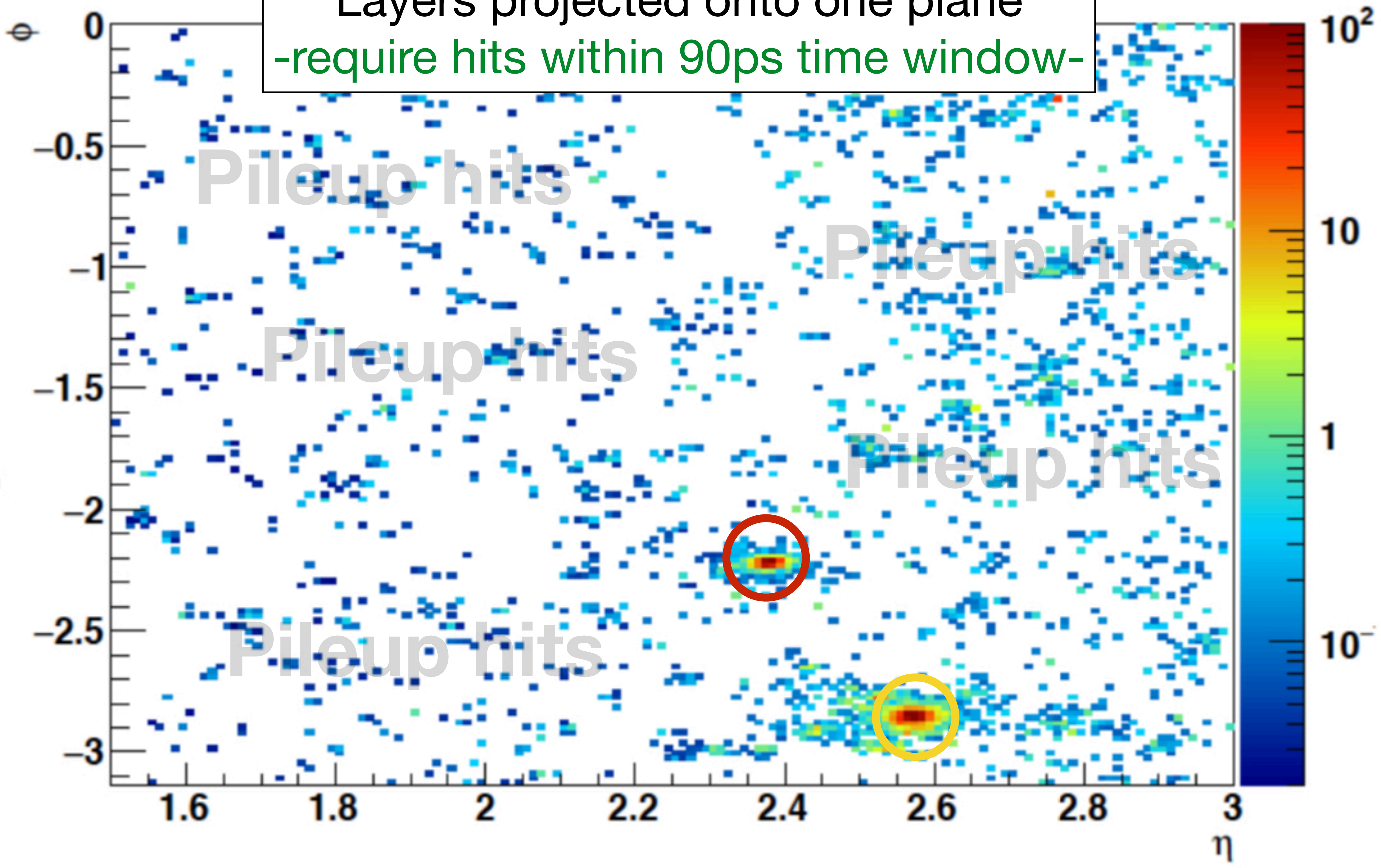
~~Idea: HGCAL will be 3D imaging calorimeter~~ **with timing capabilities**

VBF H (γγ)



+ 200 PU

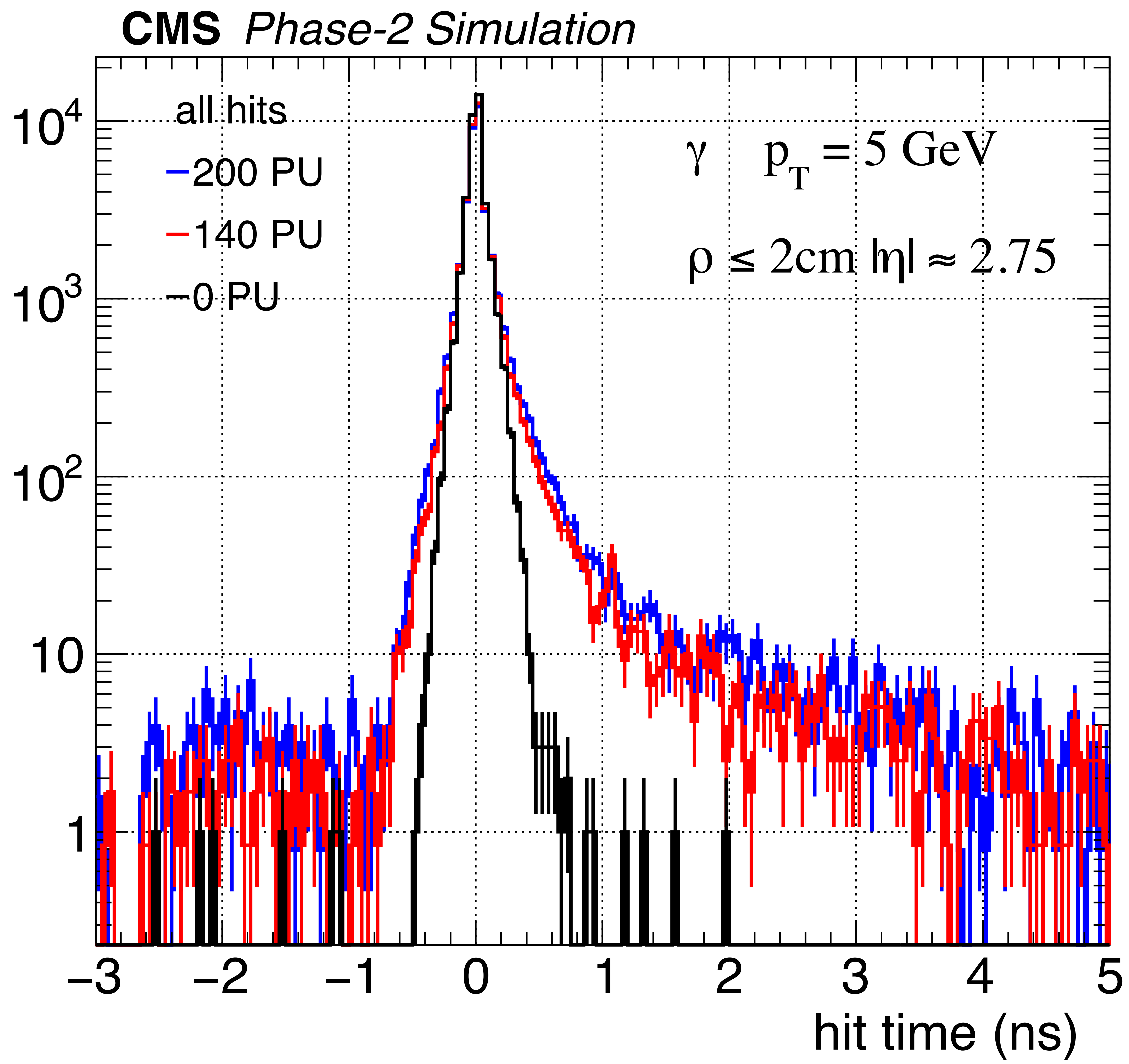




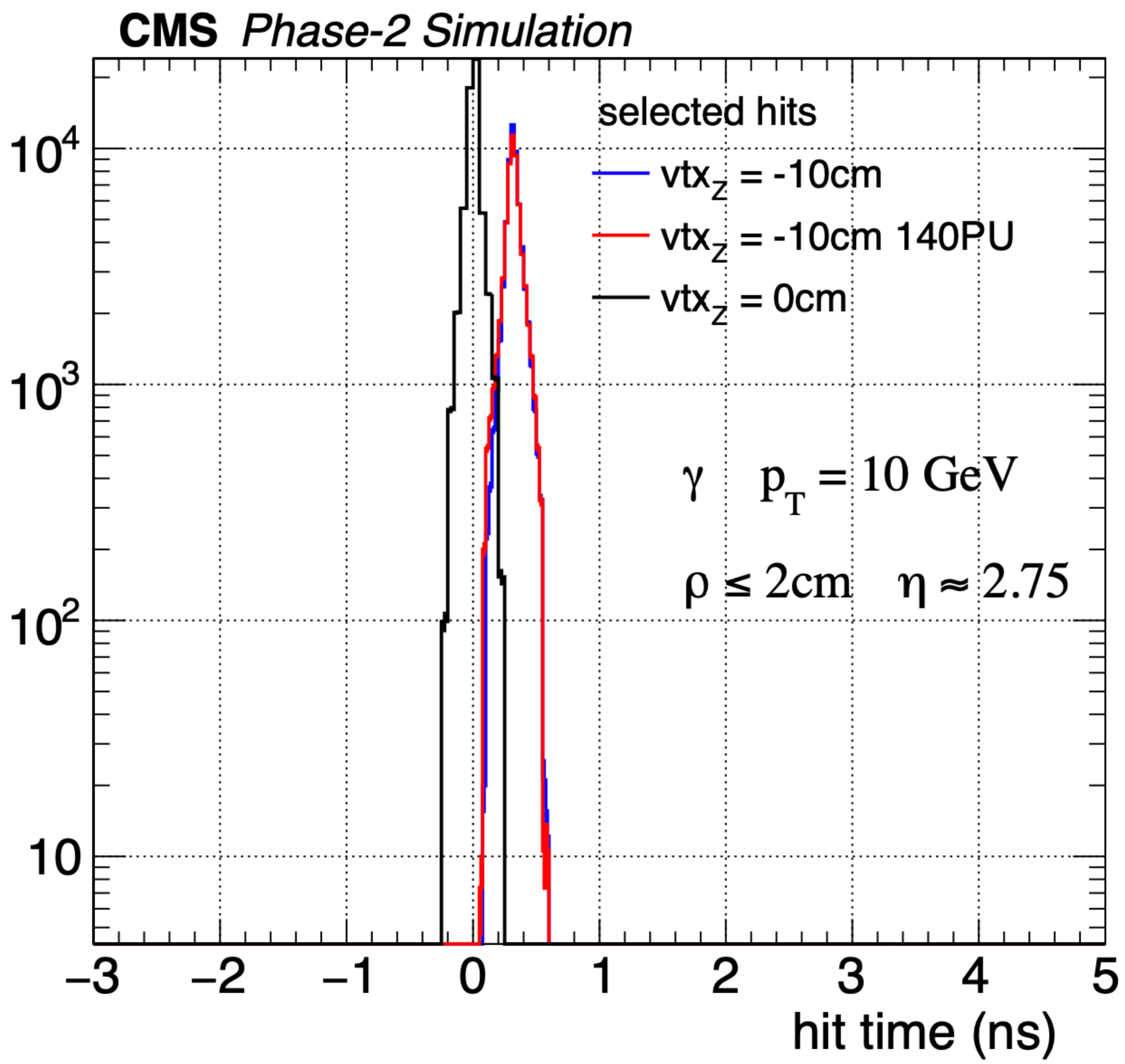
O(10ps) timing capabilities helpful

- Can expect timing resolution for silicon-based shower detections around a few 10 ps per channel.
- Extensive (however slightly outdated) simulation studies performed in the HGCAL technical design report.

➡Rejecting hits in the tails provides robustness in case of pileup.



➡Sensitivity to hits from displaced vertices even in case of pileup.



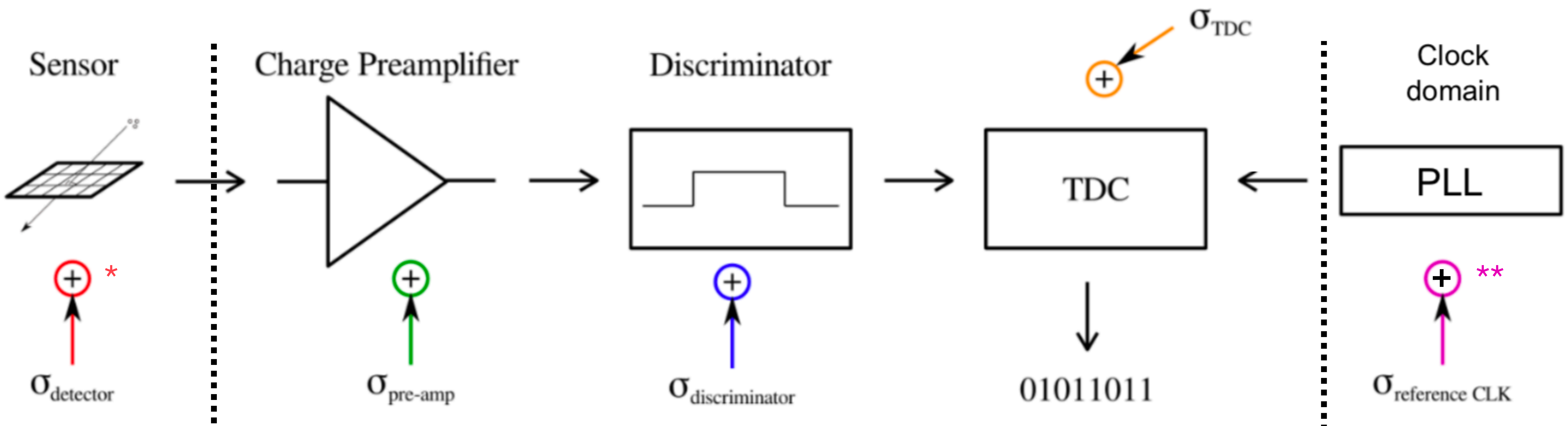
<u>Other take-aways on what can be expected:</u>

- O(10) - O(100) contributing hits with recorded timestamps per shower.

➡Can expect ~10ps resolution for showers with transverse momenta >5 GeV.

Realisation of such a timing resolution is not trivial

- Precision timing in such a complex, high granularity system is a great challenge for the electronics system:

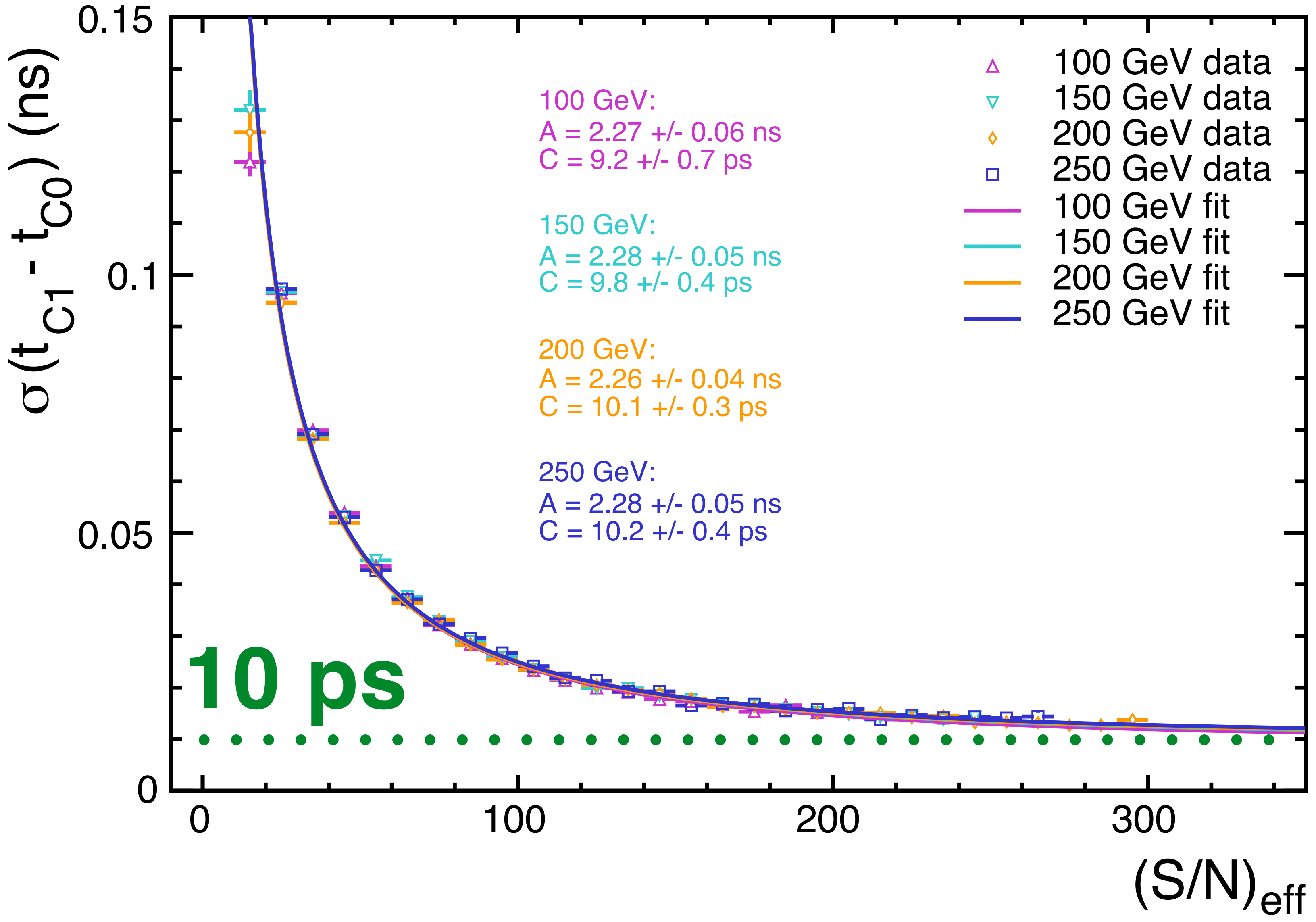


$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + ([TDC]_{RMS})^2$$

Preamplifier | Time walk | TDC quantization | noise and linearity

➡ **Front-end ASIC is key!**

Single planar silicon pad sensor timing performance evaluated in 2016 beam tests [JINST 13 (2018) P10023]



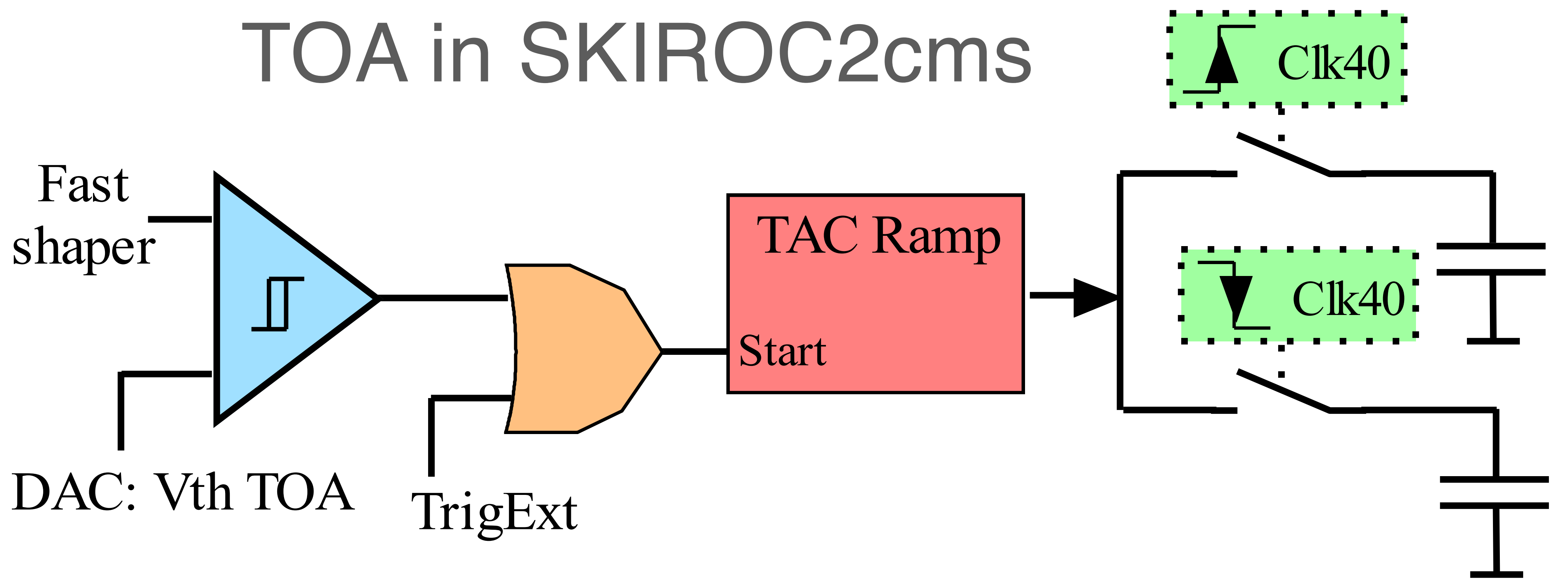
* Intrinsic silicon timing resolution is **~10 ps** for high-enough signals.

** The clock distribution system is *expected* to contribute **< *15 ps*** jitter.

2018 test beam with the SKIROC2-cms prototype ASIC

- Prototype ASIC:
  SKIROC2-cms with Time-of-Arrival (TOA) test block
  - TOA from fast shaper followed by discriminator and Time-to-Amplitude converter (TAC = TDC)
  - TAC based on voltage ramp stopped at clock edge (rising, falling)
    - Ramp saturation causes non-linearity in the response
  - TOA resolution measured to reach **50 ps** with single chip (*2017 JINST 12 C02019*)

TOA in SKIROC2cms



- Several HGCAL beam tests performed @ CERN SPS in 2018
  - e.g. *2021 JINST 16 T04001*, *2021 JINST 16 T04002*, *arXiv:2111.06855*
  - One of the goals: validate the timing performance of a prototype

- Reference timing device: MCP-PMT with less than 30ps contribution to the measured timing resolution.

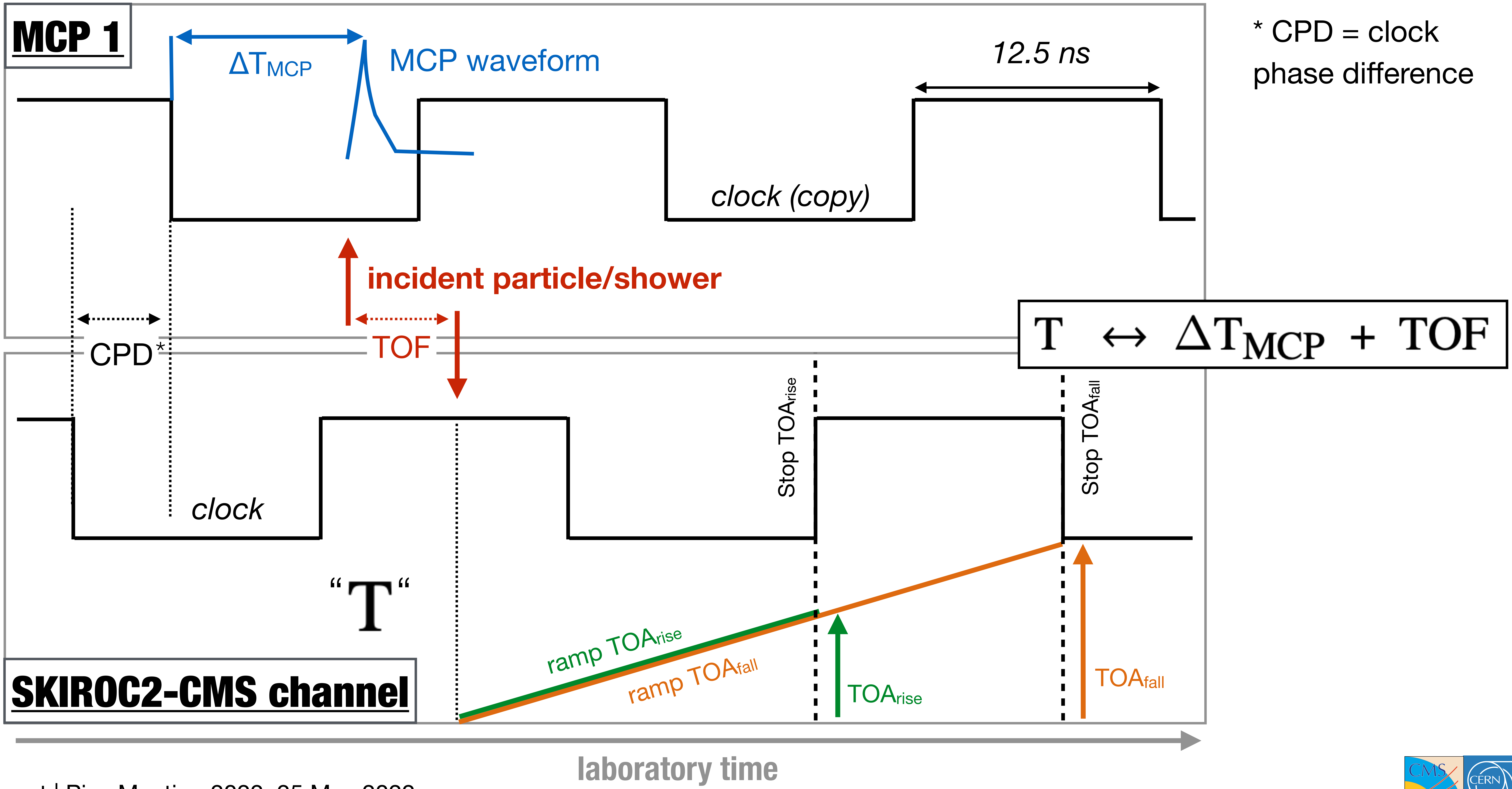
October 2018 @CERN SPS (H2)

Configuration 2:
28-layer EE setup
e$^+$ up to 300 GeV/c
delay wire chambers: incidence location reference
microchannel plates (MCP): incidence time reference

~28 X_0 (~50cm)

EE
28x1 modules

TOA calibration & reconstruction strategy



* CPD = clock phase difference

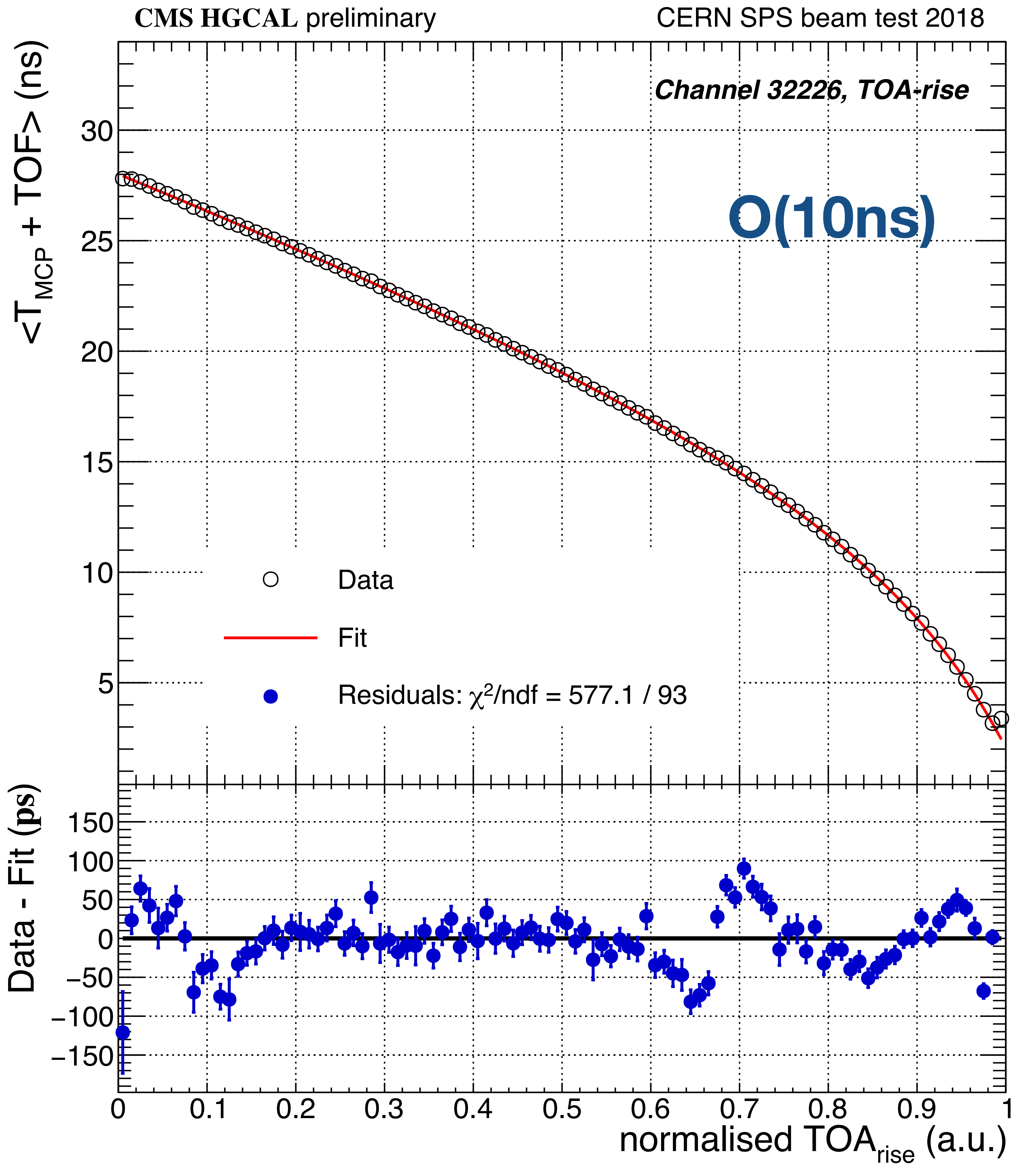
Three-step calibration procedure

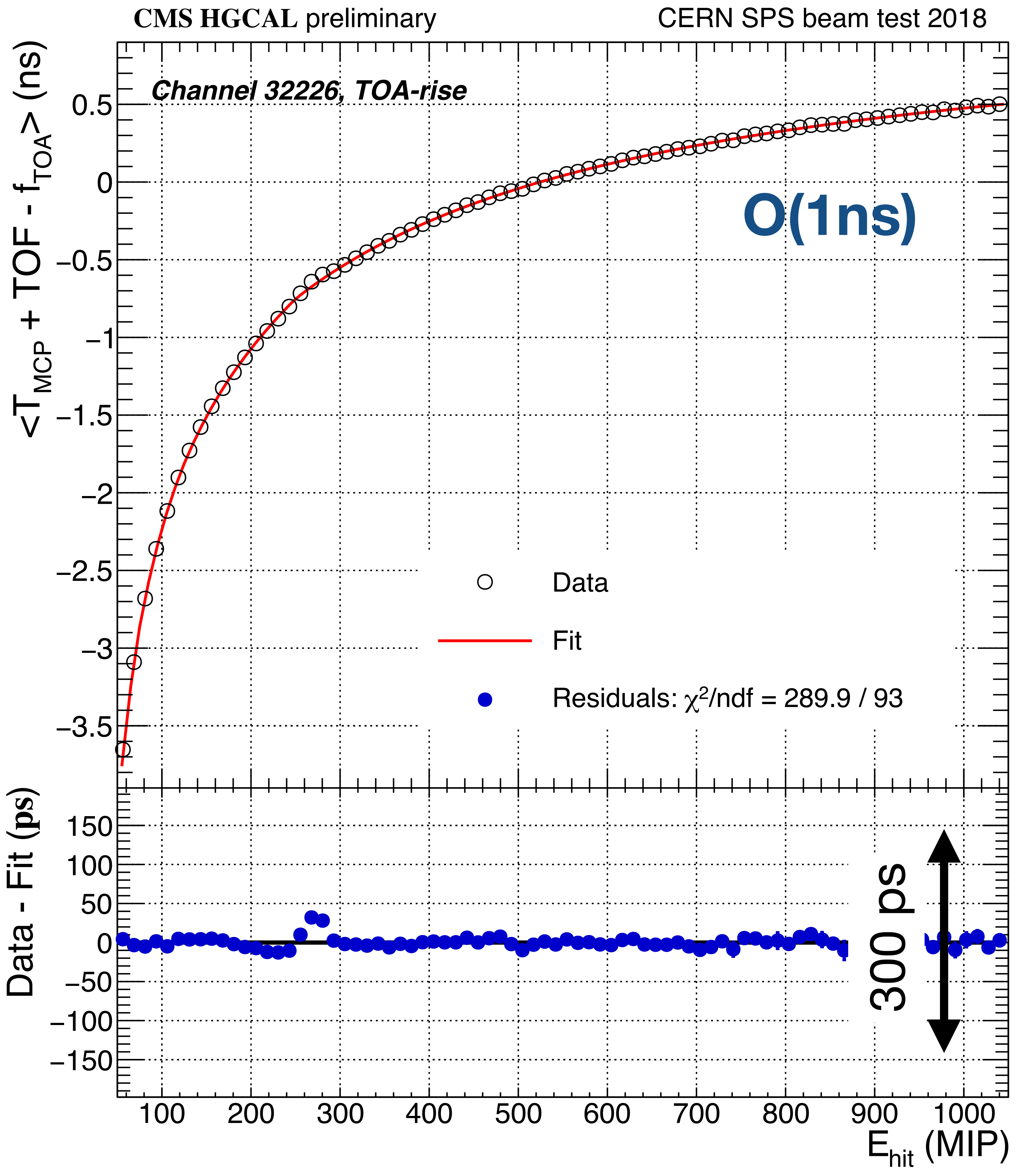
$$T = f_{TOA}(TOA_{rise/fall}) + f_{TW}(E_{hit}) + f_R(E_{module}, E_{hit})$$

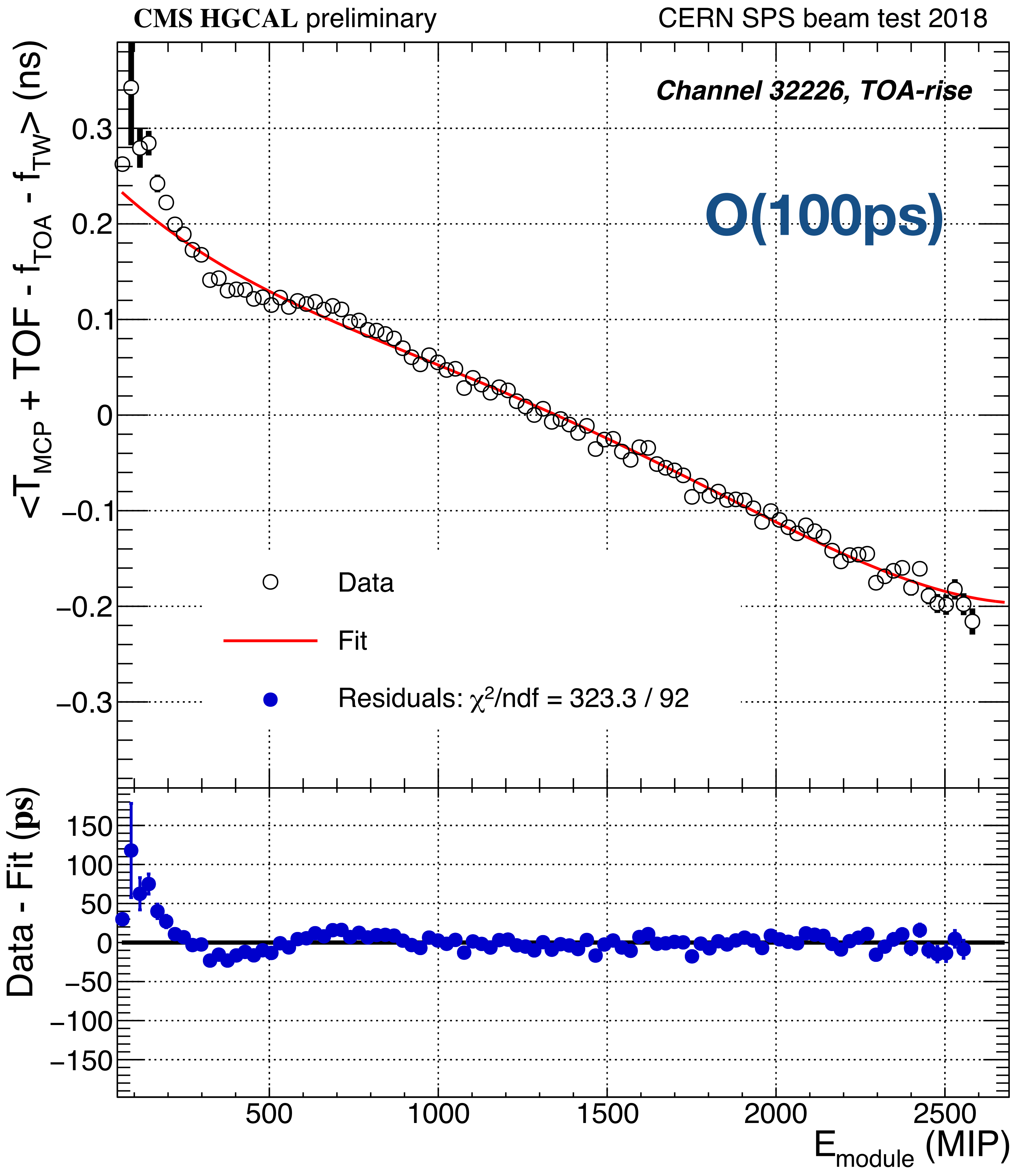
TOA non-linearity

Time-walk

Module energy time-walk



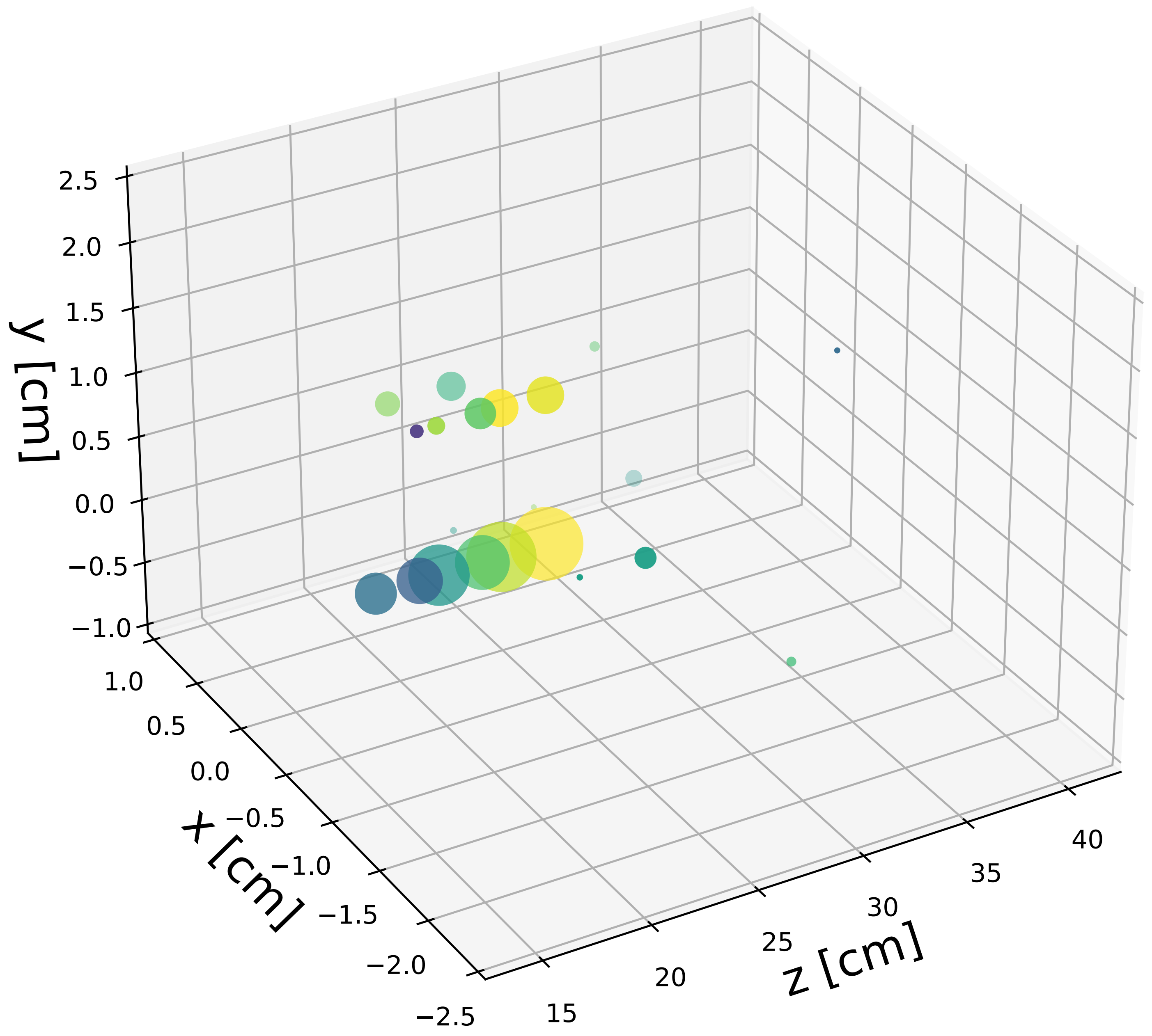




~~116 readout channels could be time-calibrated~~

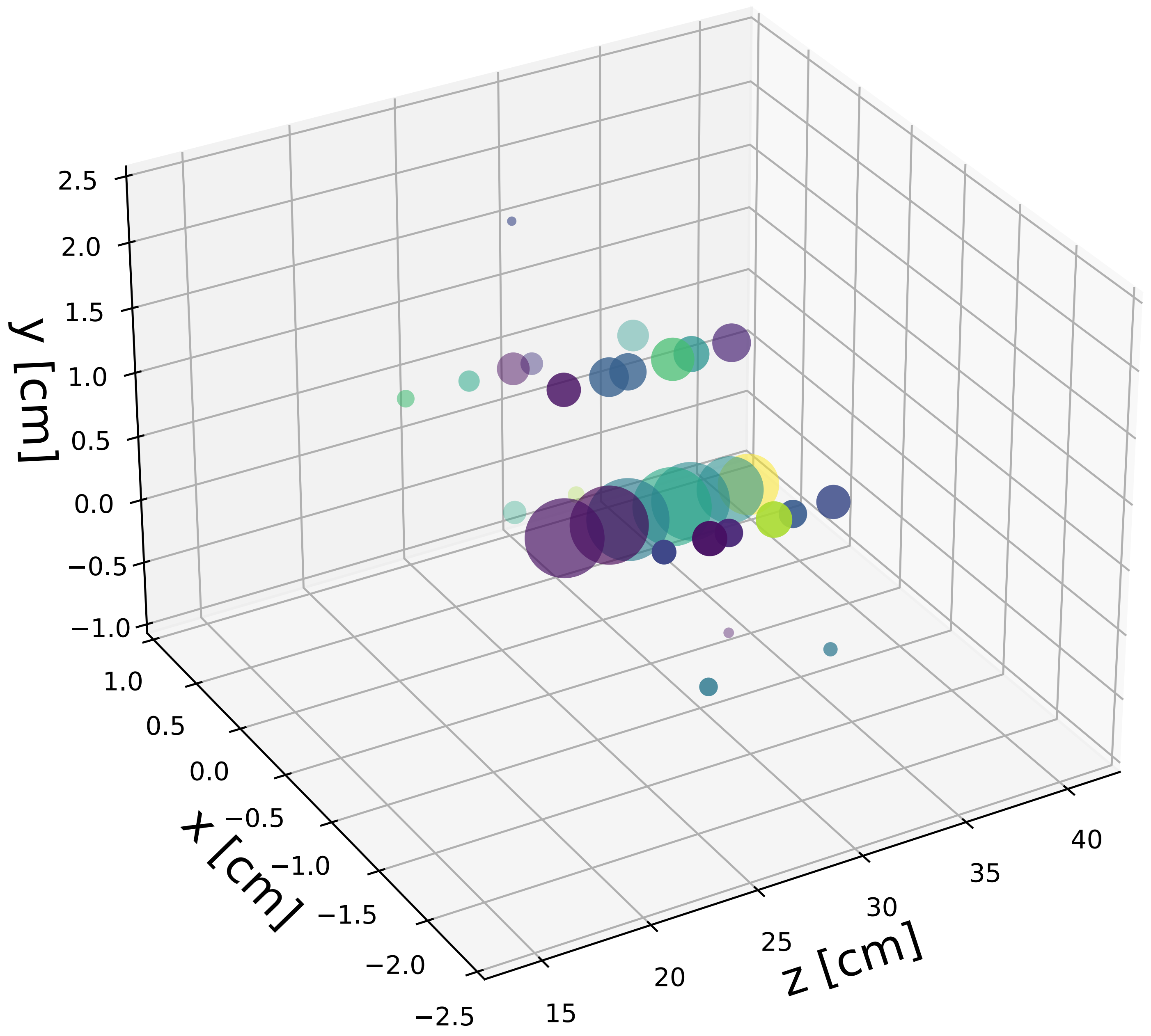
➡Demonstrated in test beam:
Resolve time evolution of real particle showers!

250 GeV/c e^+: 0.0-0.4 ns



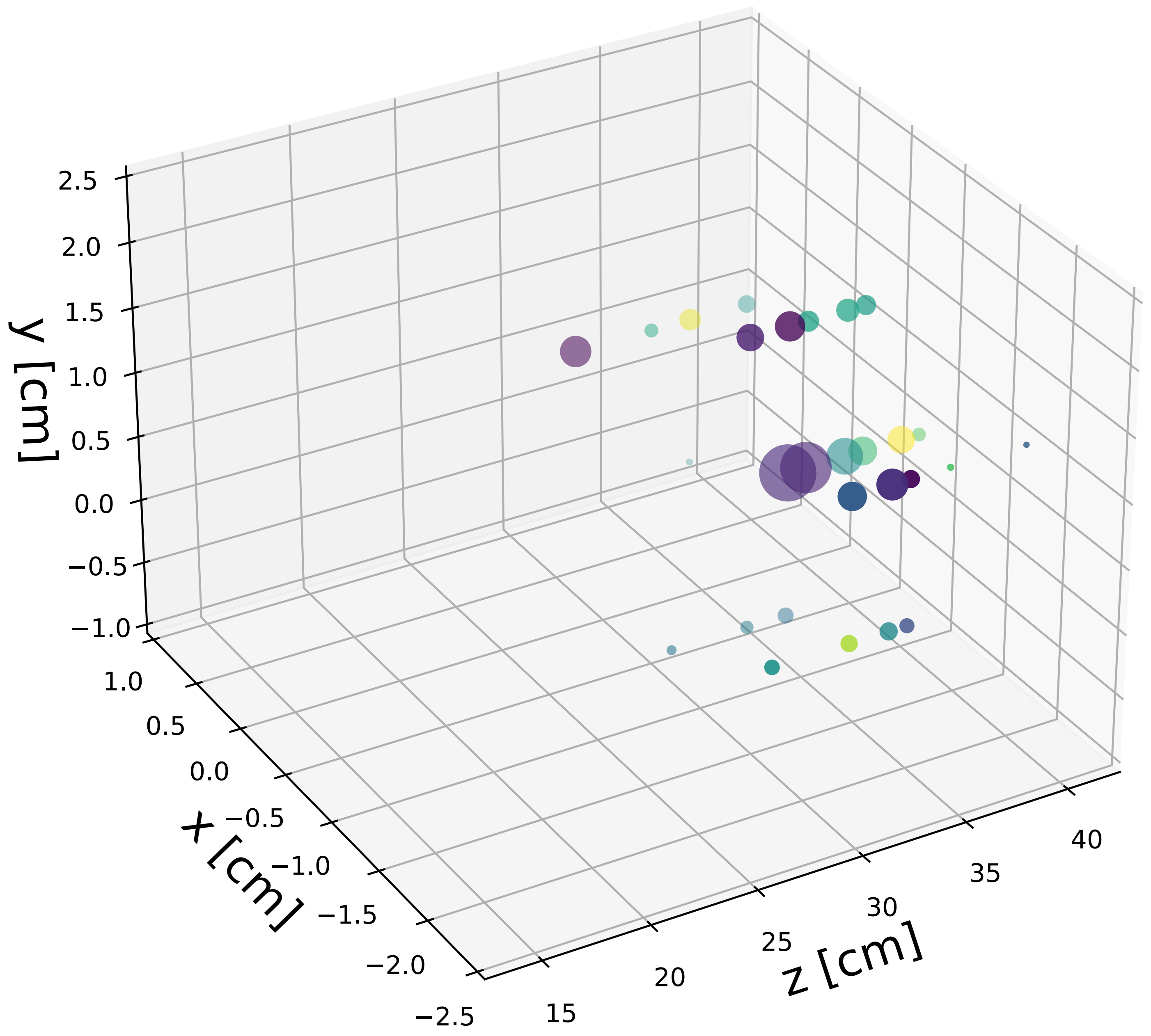
Early hit ⟶ **Late hit**

250 GeV/c e^+: 0.4-0.8 ns



Early hit ⟶ **Late hit**

250 GeV/c e^+: 0.8-1.2 ns

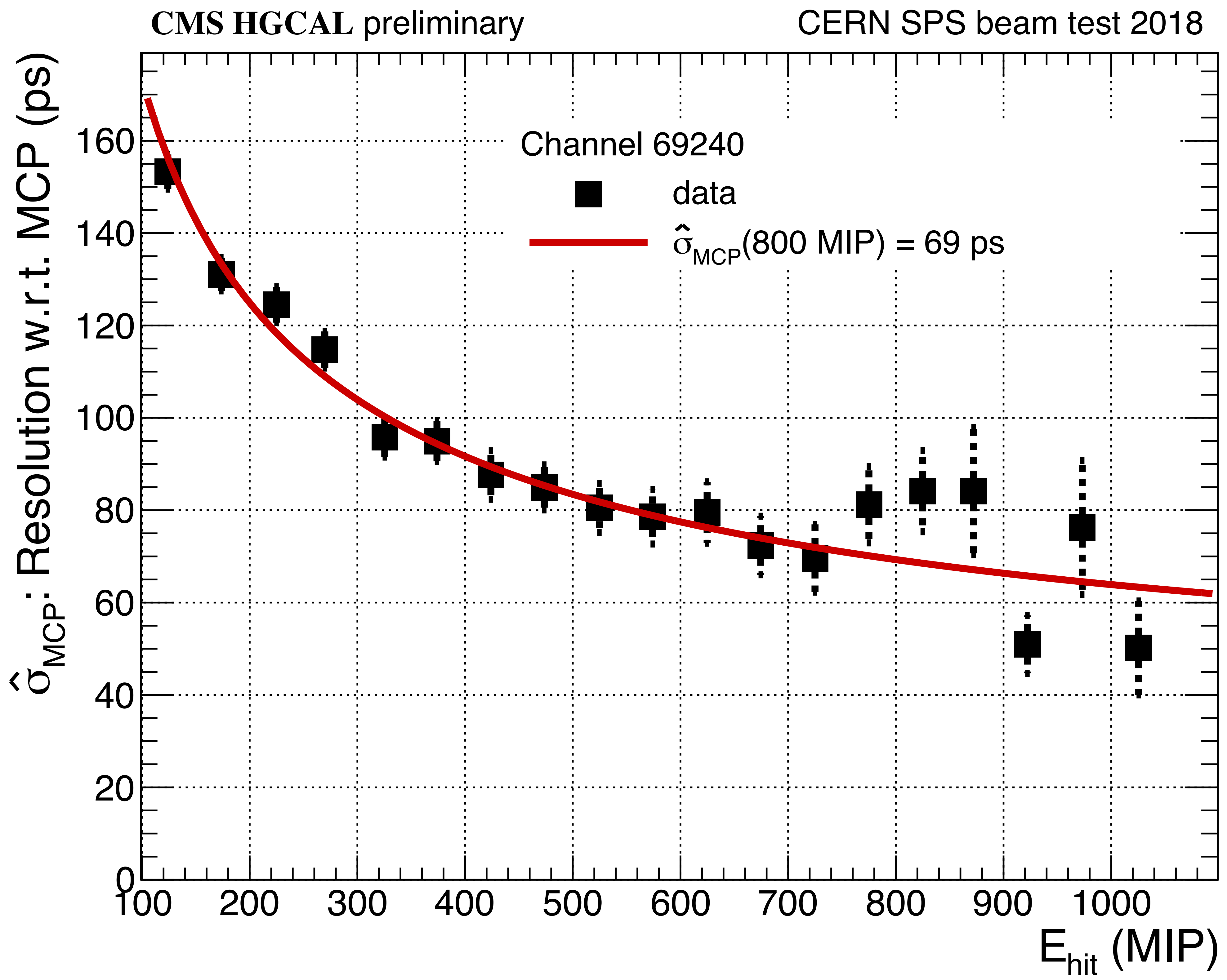


Early hit ⟶ **Late hit**

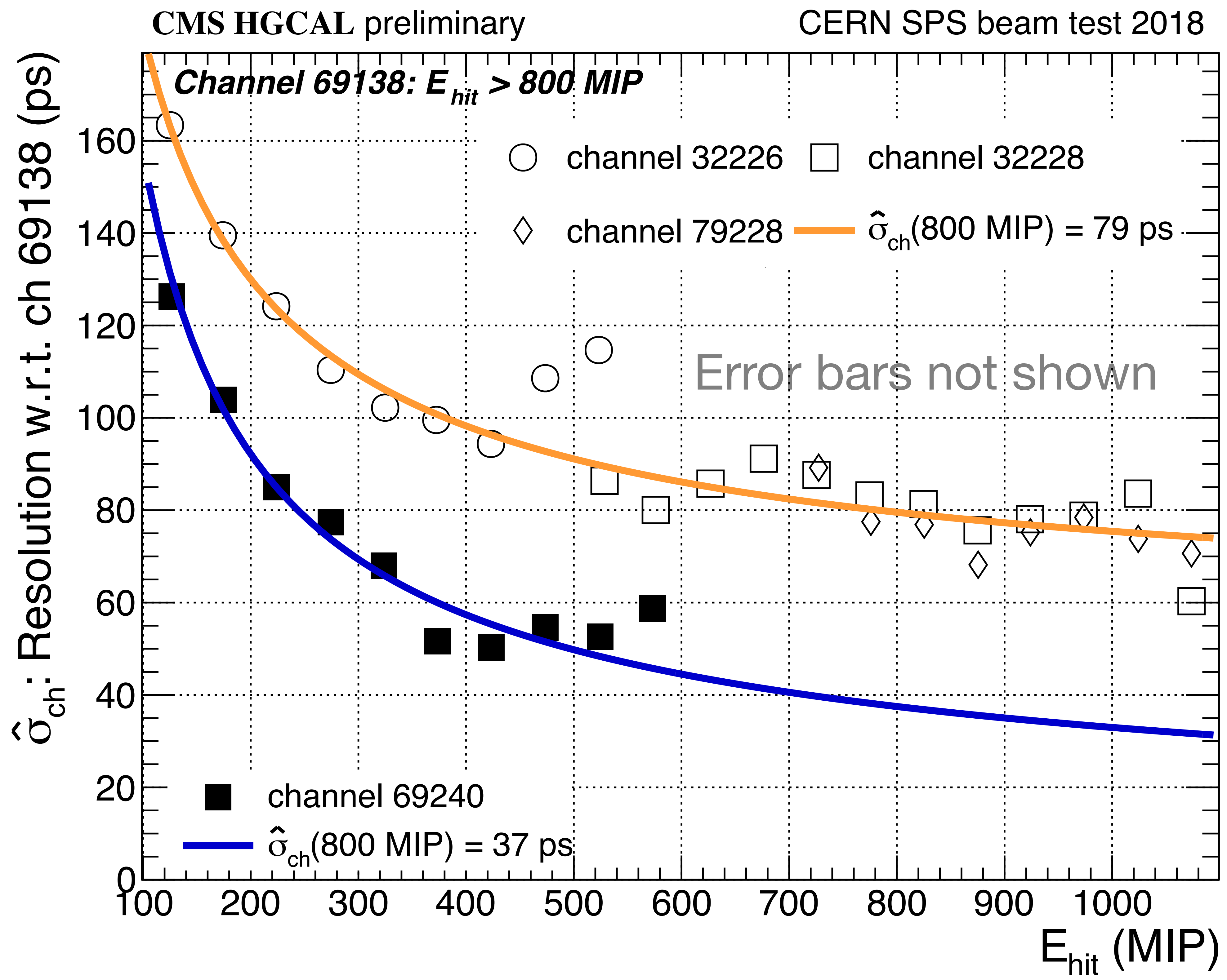
Per-channel timing resolution well below 100ps

- Expect ~50ps asymptotic timing resolution, dominated by Skiroc2-cms performance.

Resolution measured w.r.t. MCP



Resolution measured w.r.t. HGC channel

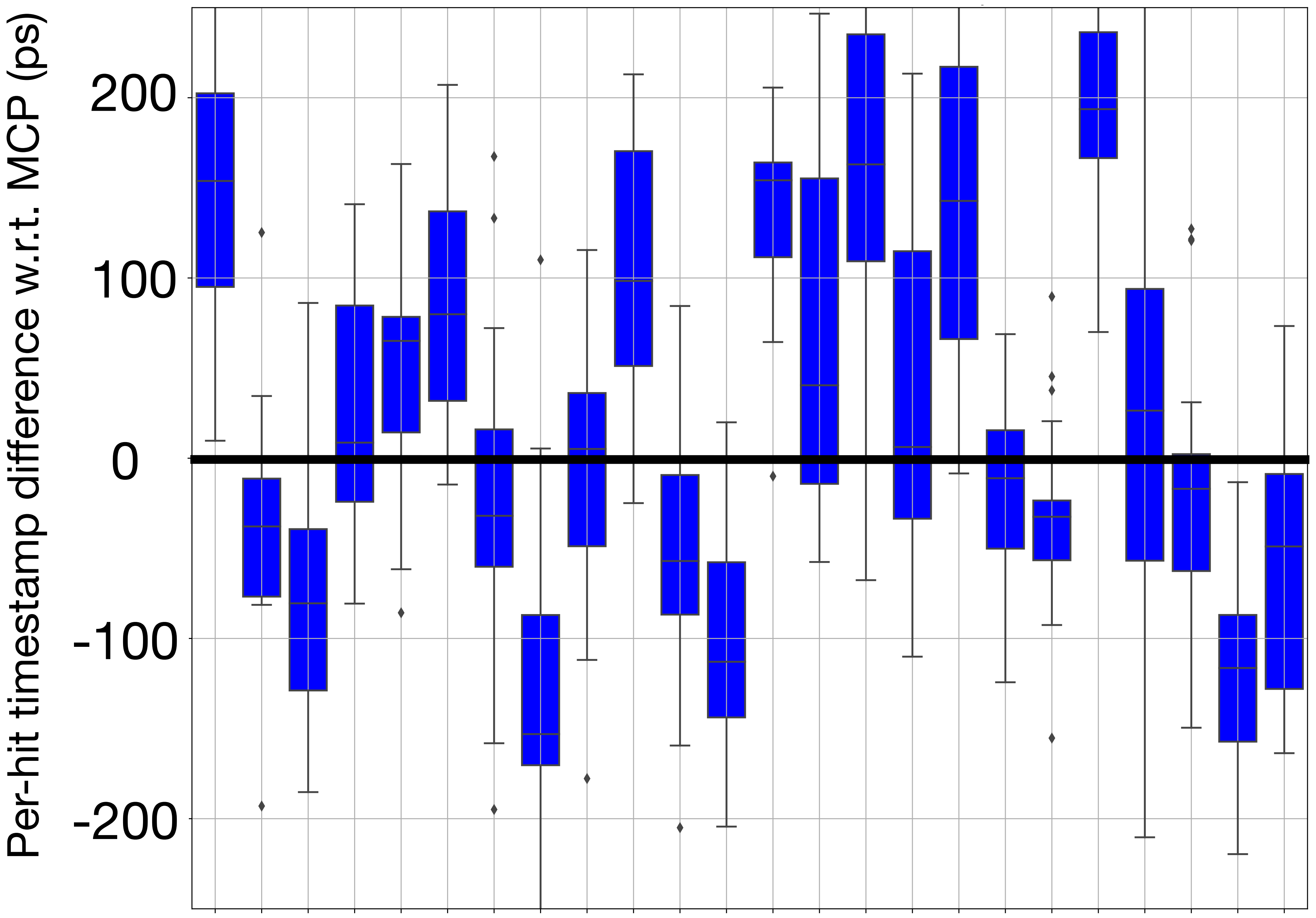


- Intrinsic MCP resolution already subtracted
- $\hat{\sigma}_{MCP}$(800 MIP) ~ **70ps**

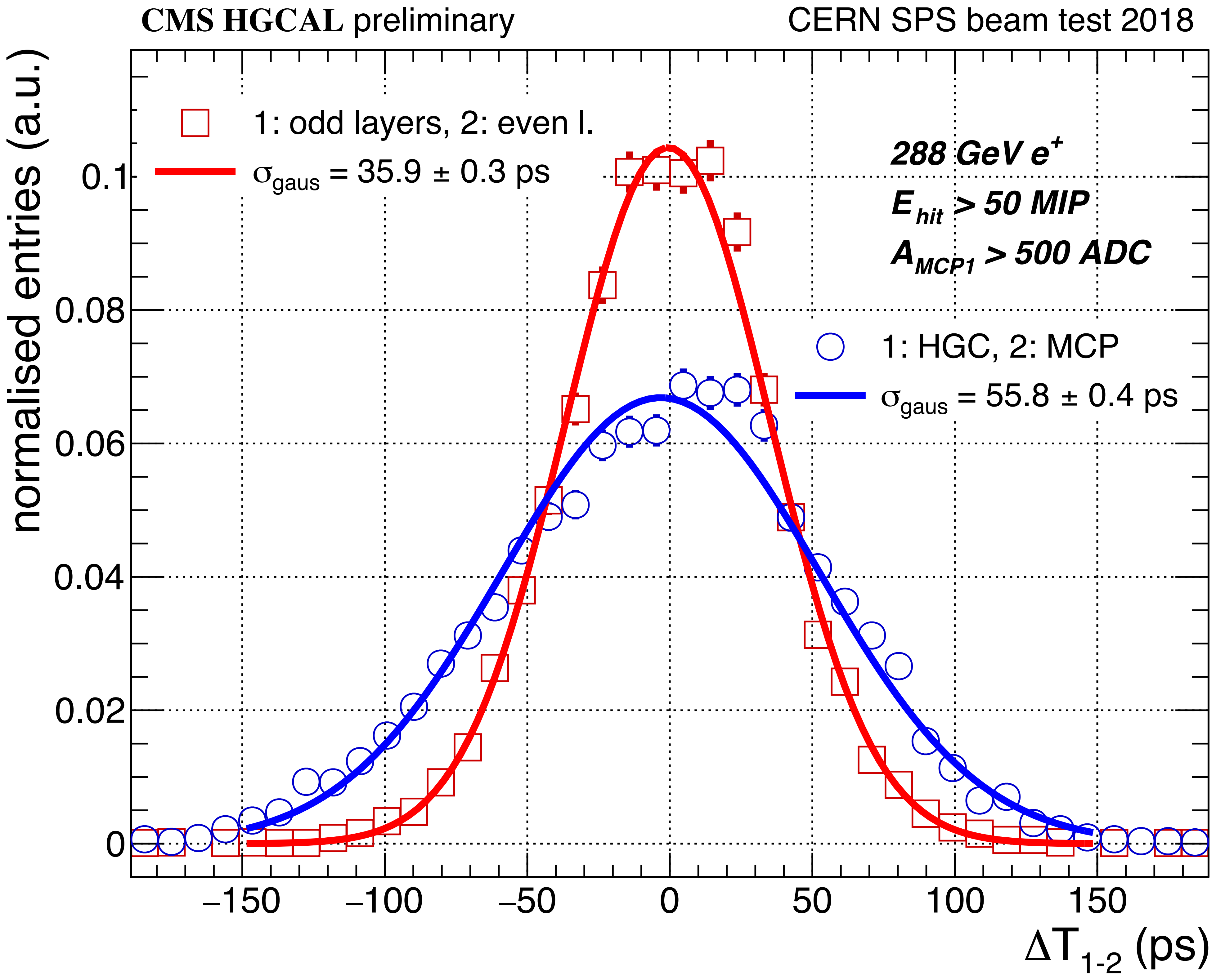
- Timestamp from channels on same module correlated
- $\hat{\sigma}_{ch}$(800 MIP) ~ 80ps
- Per-channel resolution of 80ps/√2 ~ **55ps**

Global jitter between HGC prototype and reference time

Per-shower distribution of hit timestamps



Resolution of 288 GeV EM showers w.r.t. different references



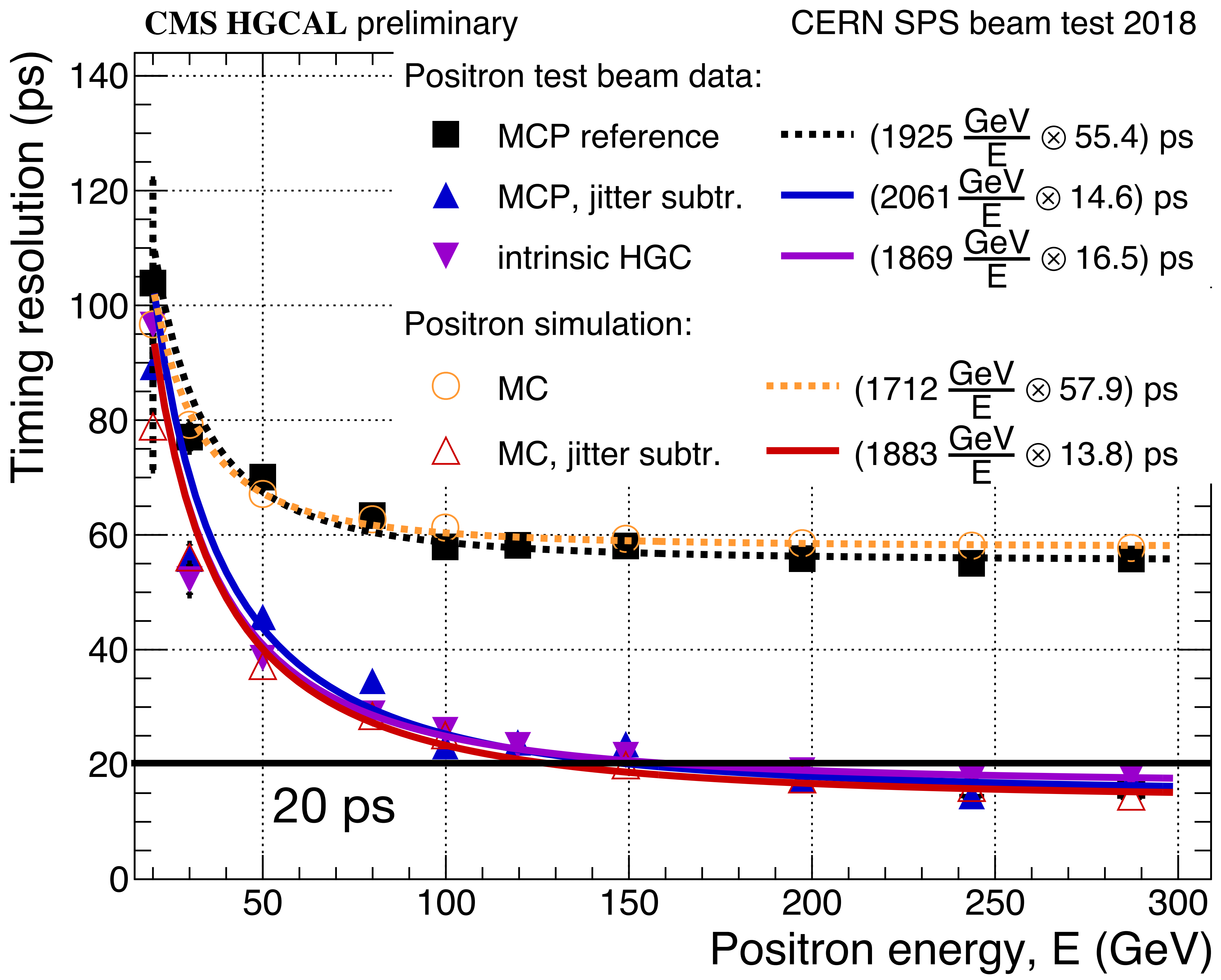
- Hit timestamps within one shower consistent w.r.t. each other
- Common shift w.r.t. the reference MCP
- ➡ **Indication of a global jitter between the HGC prototype and the reference MCP + clock copy system**
- Origin of this jitter is specific to the test beam setup

- Shower timestamp = energy-weighted sum of hit timestamps
- Blue: Shower timestamp w.r.t. MCP = **~56ps**
- Red: shower timestamp from half the layers w.r.t. each other = 2x shower timestamp of full HGC prototype = **~36ps**
- ➡ Assume uncorrelated global jitter: **~50ps** (independent on beam energy)

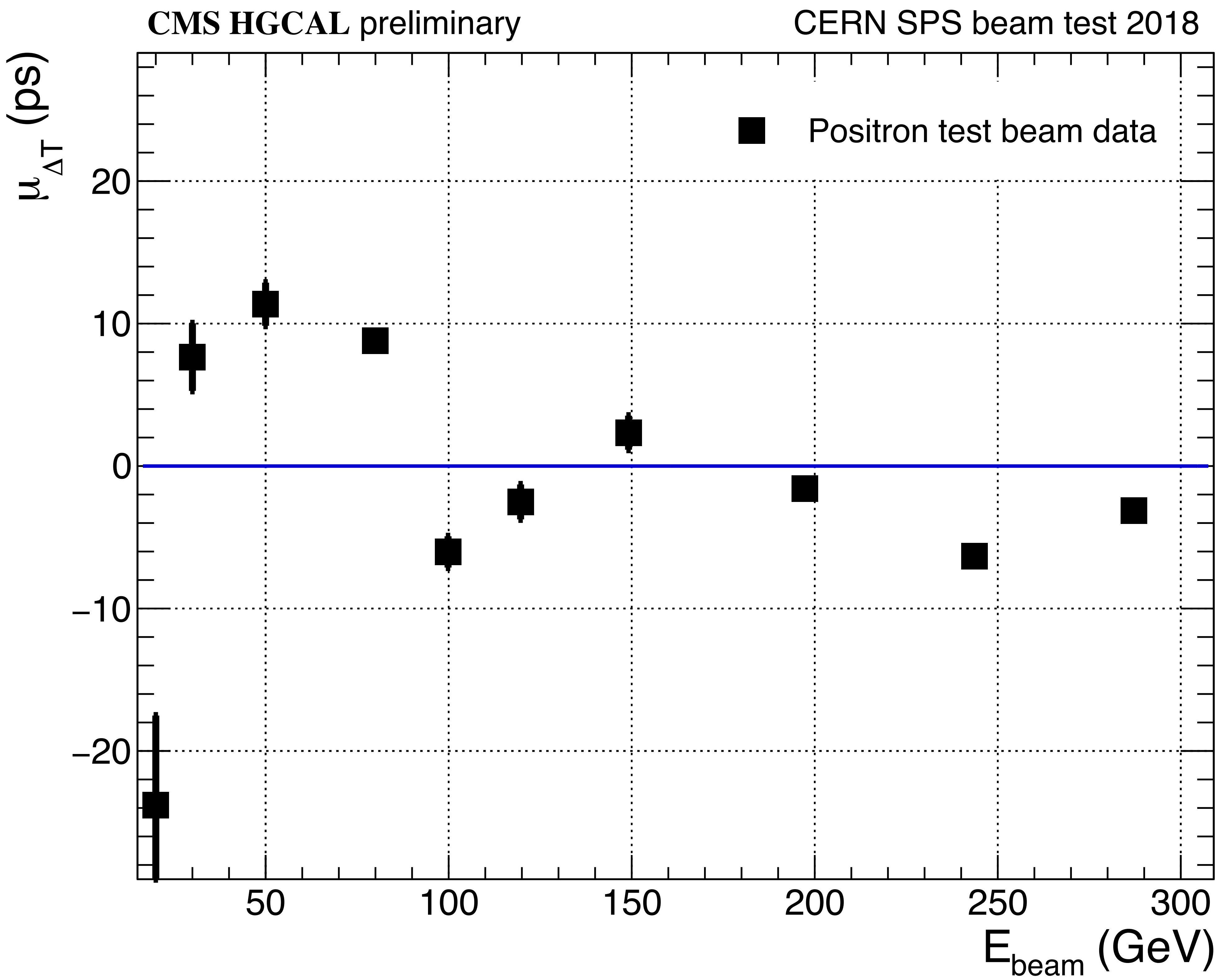
Shower timestamp: Resolution below 20ps & about 10ps bias

- Shower timestamp = energy-weighted sum of hit timestamps, TOF-subtracted from each hit time

Shower timing resolution:



Shower timing bias (w.r.t. MCP):



- Good agreement for all energies, between intrinsic HGC and HGC vs. MCP resolution after subtracting the global jitter.
- Good: MC reproduces data.

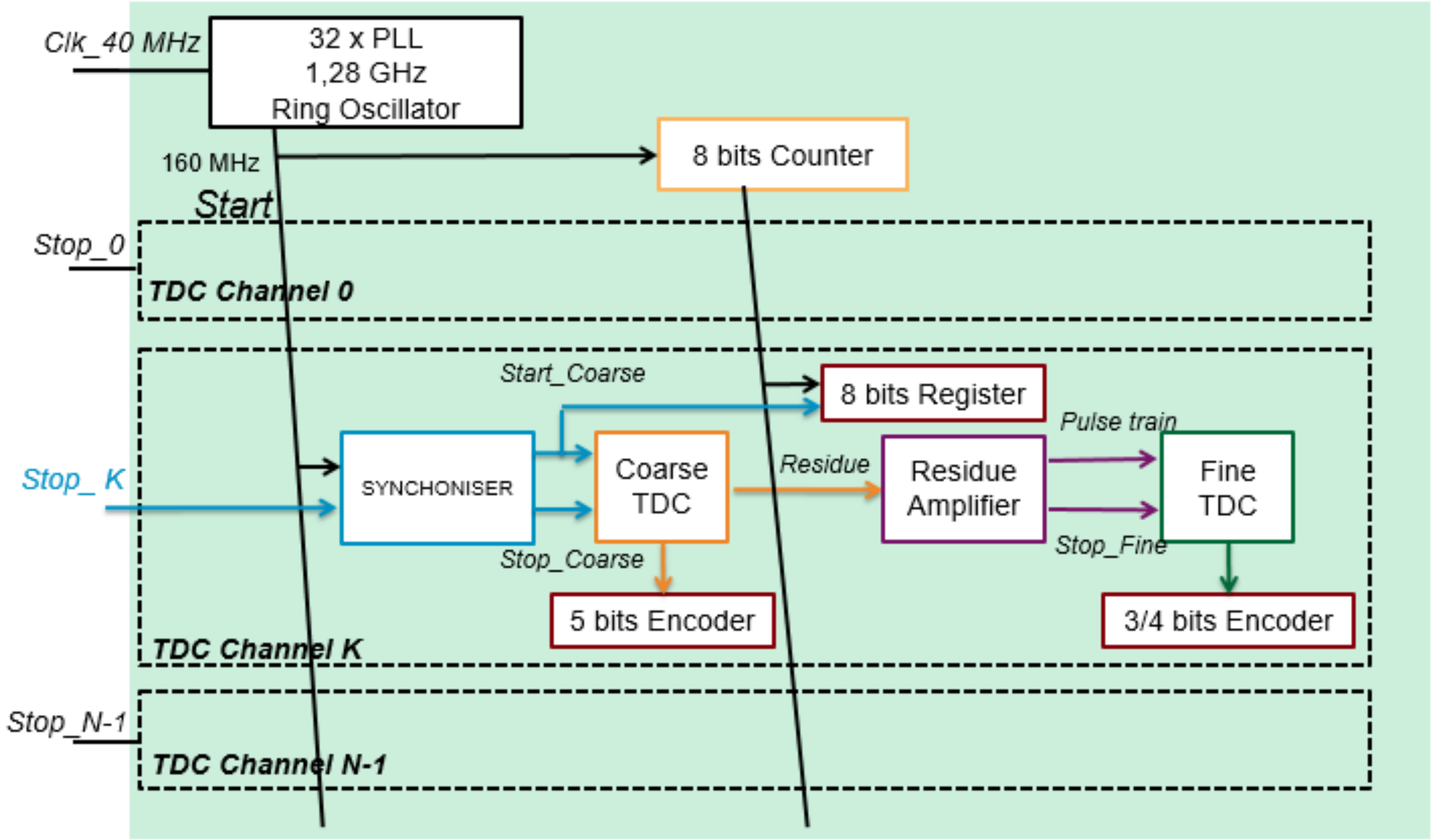
- **Bias of 10ps or less** for EM shower energies above **50GeV.**

➡ **Asymptotic resolution of less than 20 ps in tested range!**

Next: Ultimate ASIC will be the HGCROC

- HGCROC features a Time-of-Arrival block based on a **constant-threshold discriminator** and a **3-stage TDC**:
    - Gray counter on 160 MHz PLL
      Using 2 bits, LSB = **6.25 ns**
    - Coarse TDC (LSB = **195 ps**)
      classical DLL with start/stop signals
    - Fine TDC (LSB = **24.4 ps**)
      residue integrator based on a DLL line

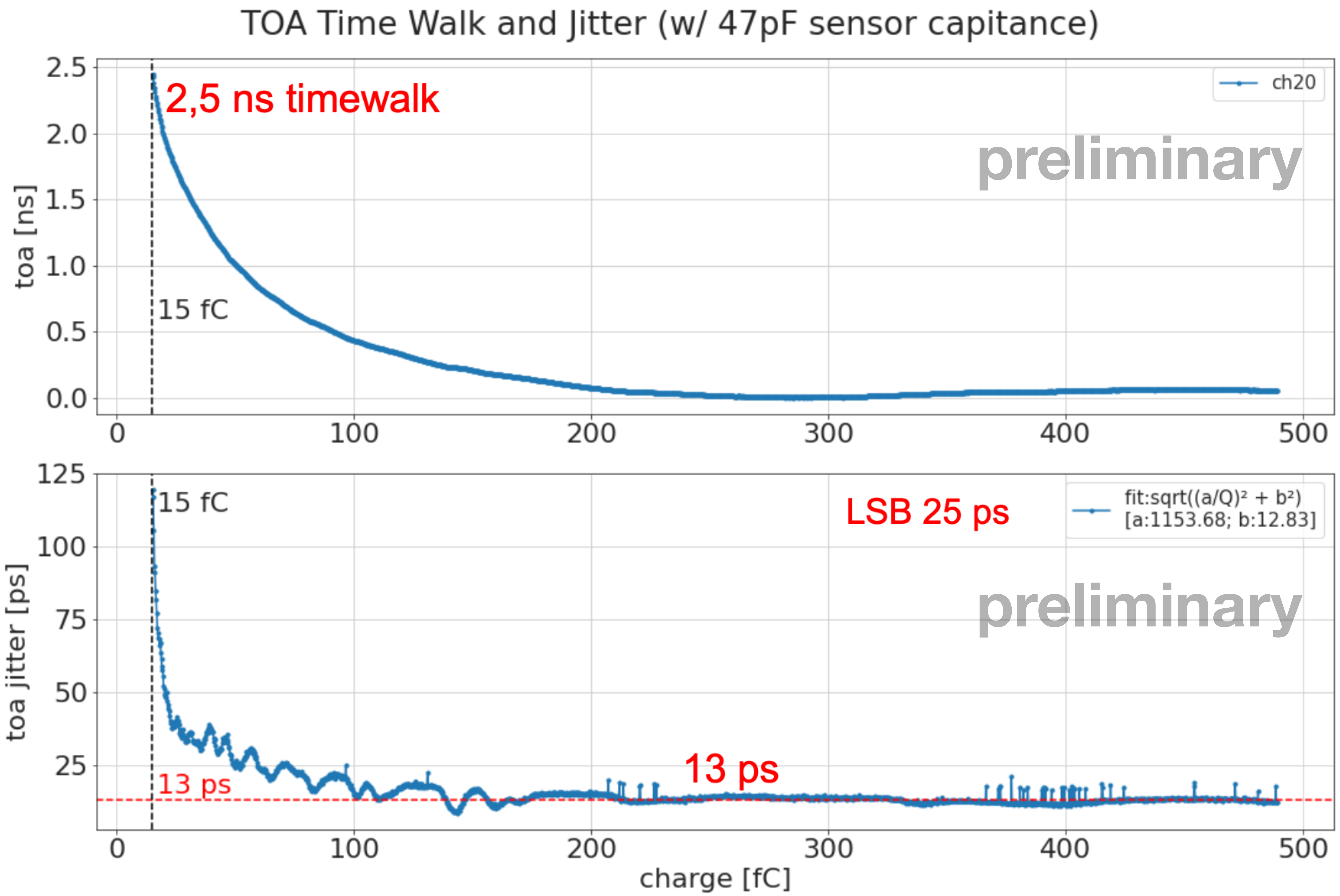
- Architectural advantages:
    - High-speed conversion and low power consumption
    - Large time range due to global counter
    - Keeps performance under temp. and process variations



TDC ToA specifications	
Resolution	< 25 ps rms
Range	10 bits over 25 ns
Conversion rate	> 40 MHz (bunch clock)
Power consumption	< 2 mW / channel
Area	Pitch 120 µm
Technology	TSMC 130 nm
Temperature	-30 °C

Timing performance of the final HGCROC version

- Significant improvements during the prototyping of the HGCROC ASIC from v1 to v3.
- Minimum threshold is now set to 15 fC (~5 MIPs in 300µm Si).
- Extremely promising results:
  - ➡**The measured jitter floor is about 13 ps…**
  - ➡**…which is about 3x better than the SKIROC2-cms.**



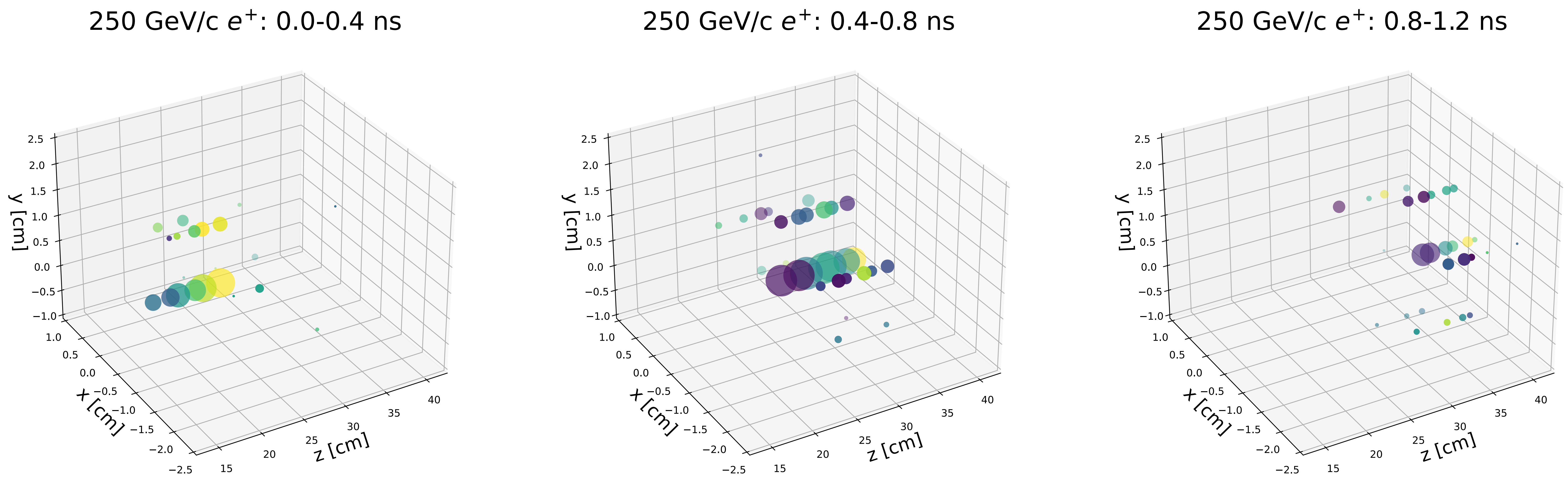
<u>Questions to answer in the comings months:</u>

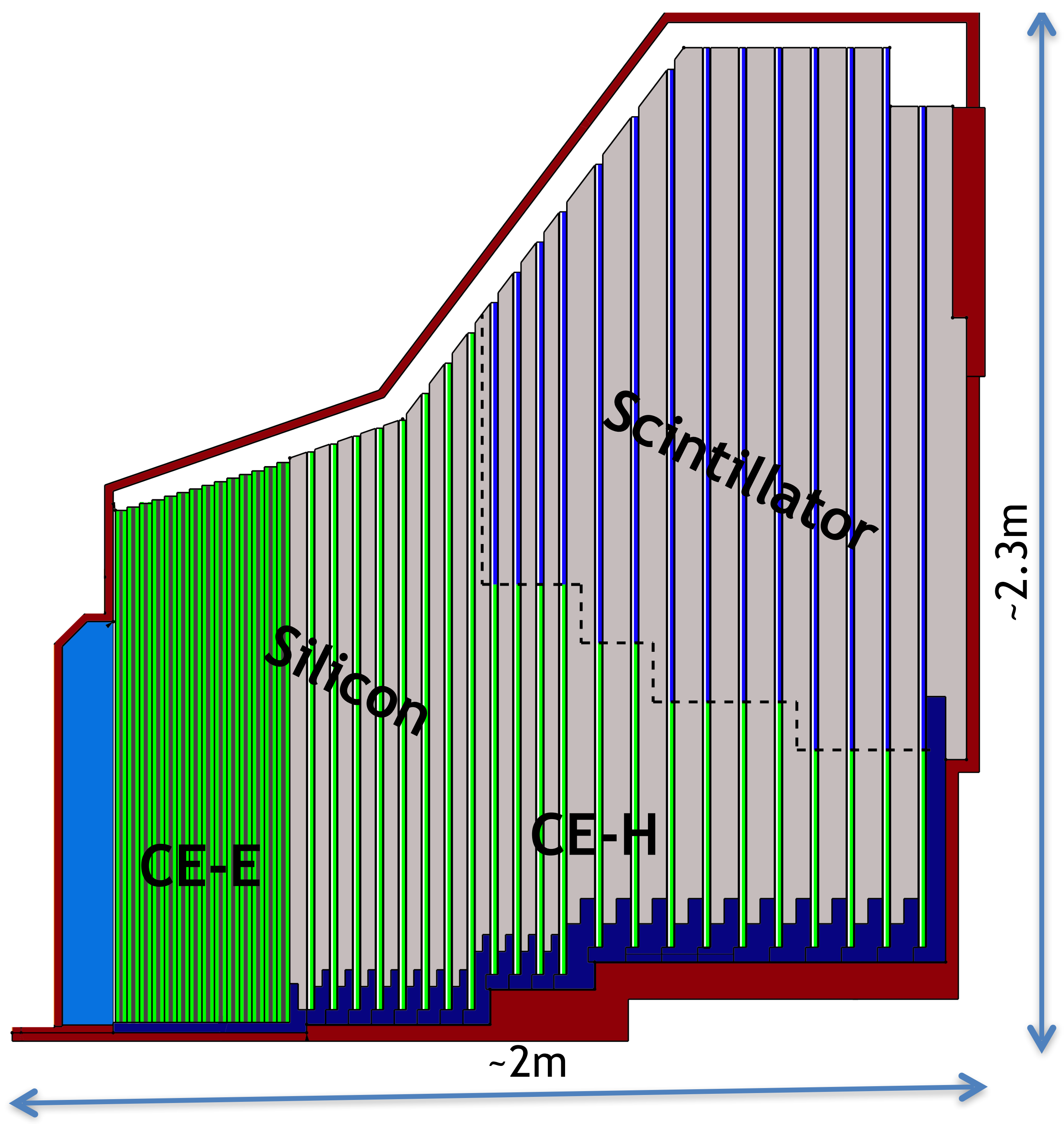
- Timing resolution of HGCROC-based silicon modules?
- Timing resolution of such modules operated with full electronics chain?

Summary - not a conclusion

HGCAL: where highly granular calorimetry comes to life at the energy frontier

- Silicon as sensitive material in high radiation region, scintillator+SiPMs elsewhere.
- 4D energy measurement of particle showers.



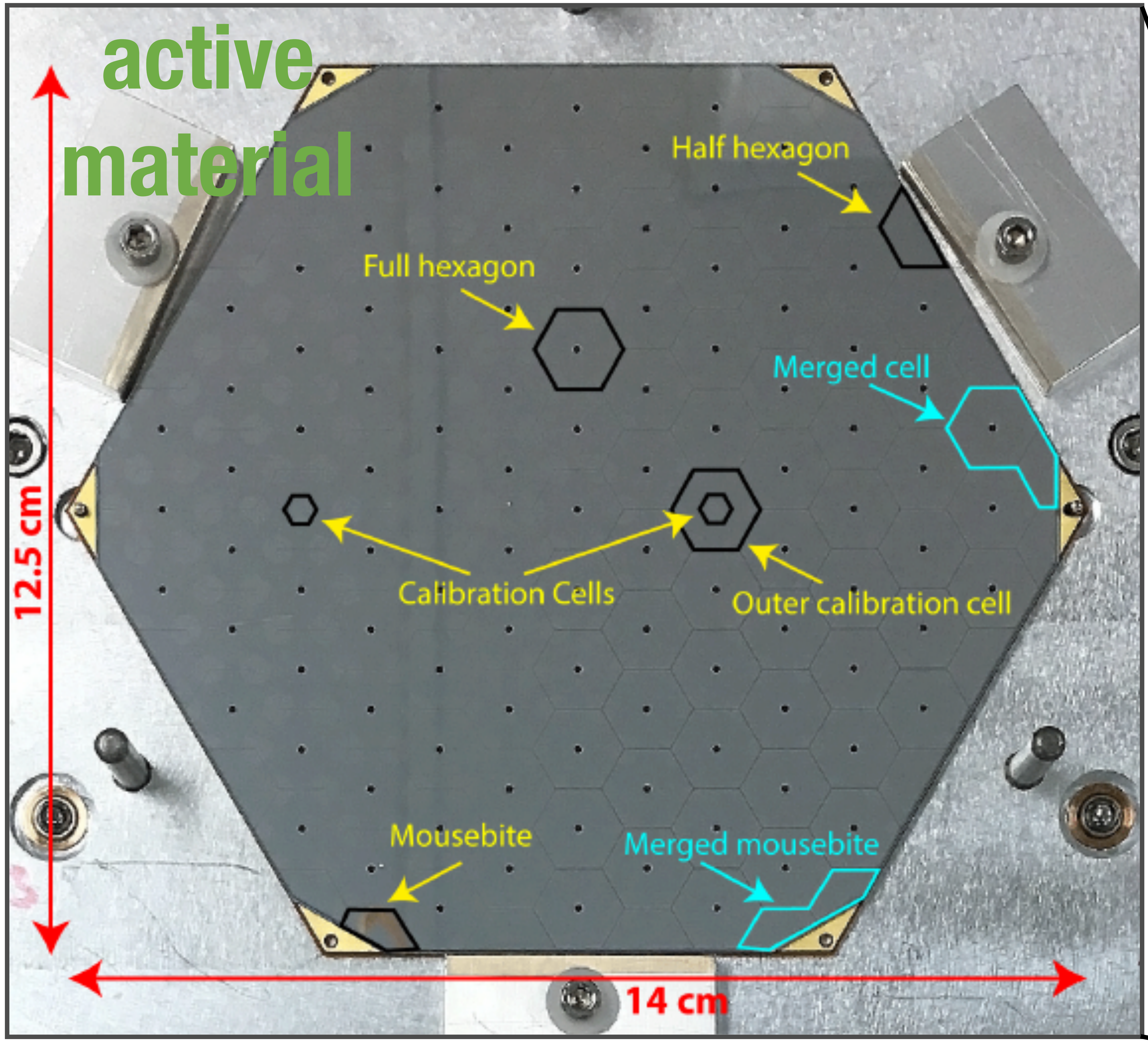


O(10ps) timing resolution targeted

- Integral for suppression of pile-up signatures, but non-trivial to achieve.
- 20 ps timing resolution + 10 ps bias for EM showers demonstrated in test beam experiment with prototype ASIC.
- Final ASIC should have x3 better timing resolution. *Tests with final modules and full electronics chain coming.*

Backup

HGCAL 2018 prototype module construction



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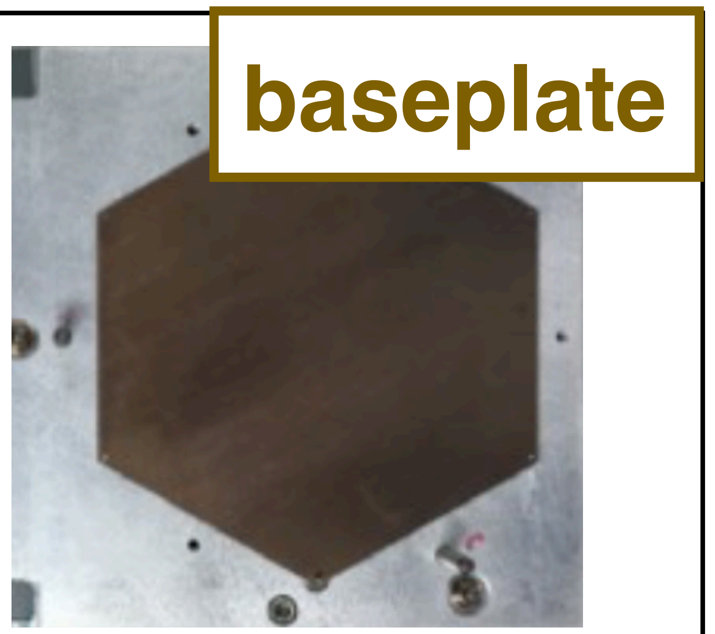
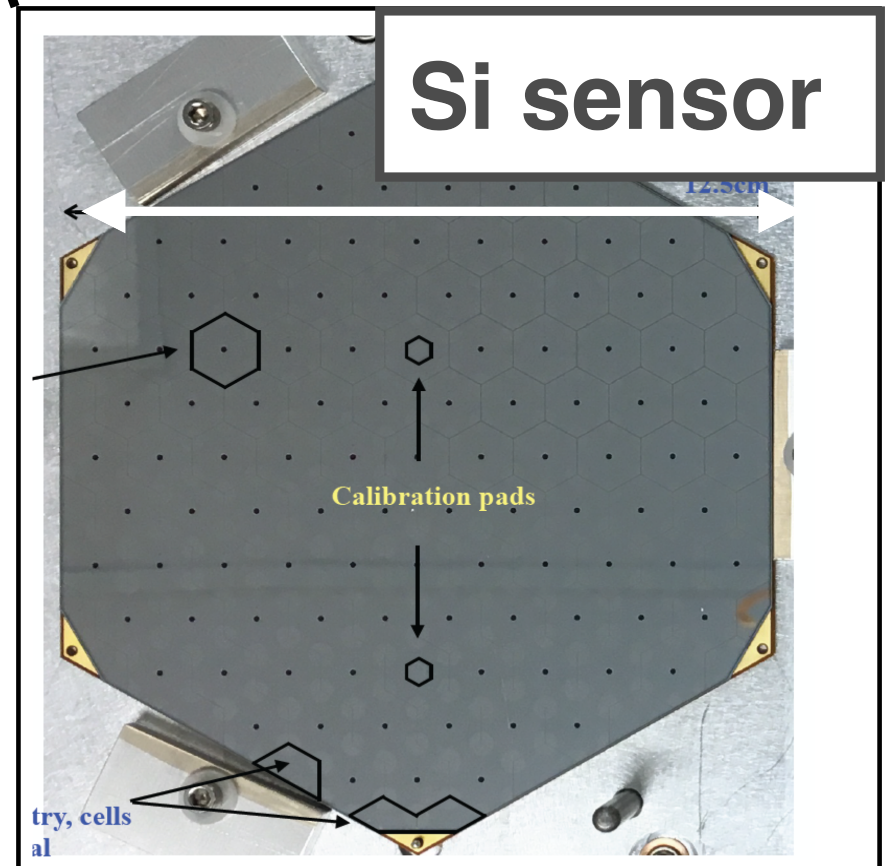
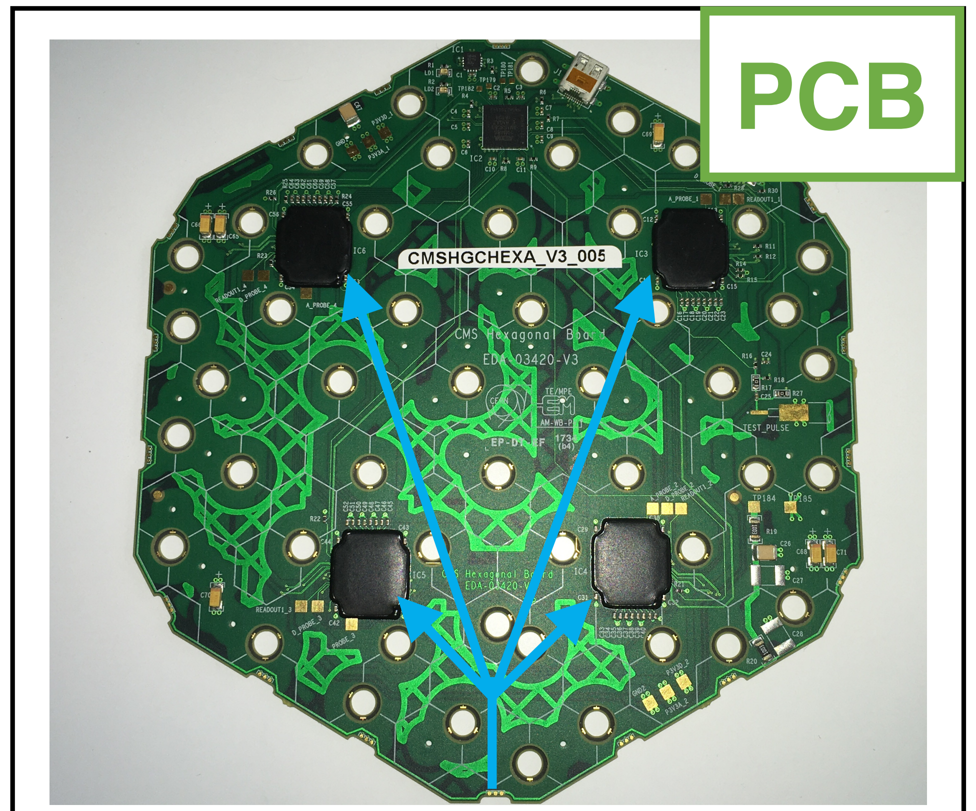


- CuW
- Cu

- Gold plated



6" silicon sensors:
- n-type, 128 cells
- 1 cm^2 cell-size
- depletion: 200 & 300μm



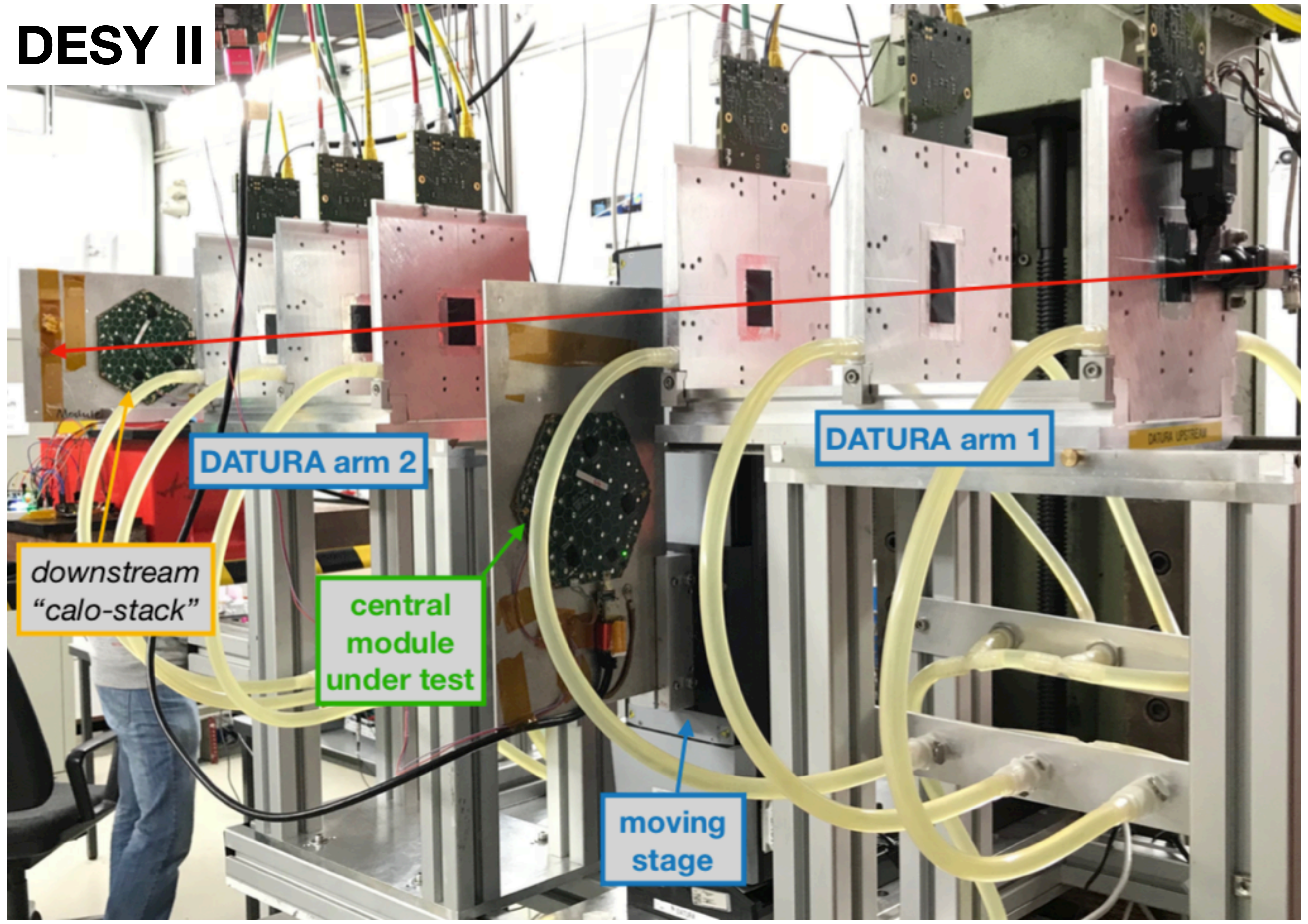
- SKIROC2-CMS ASIC, 64 ch., 4 chips/module
- Developed for CALICE (Skiroc2) & adjusted for HGCAL requirements

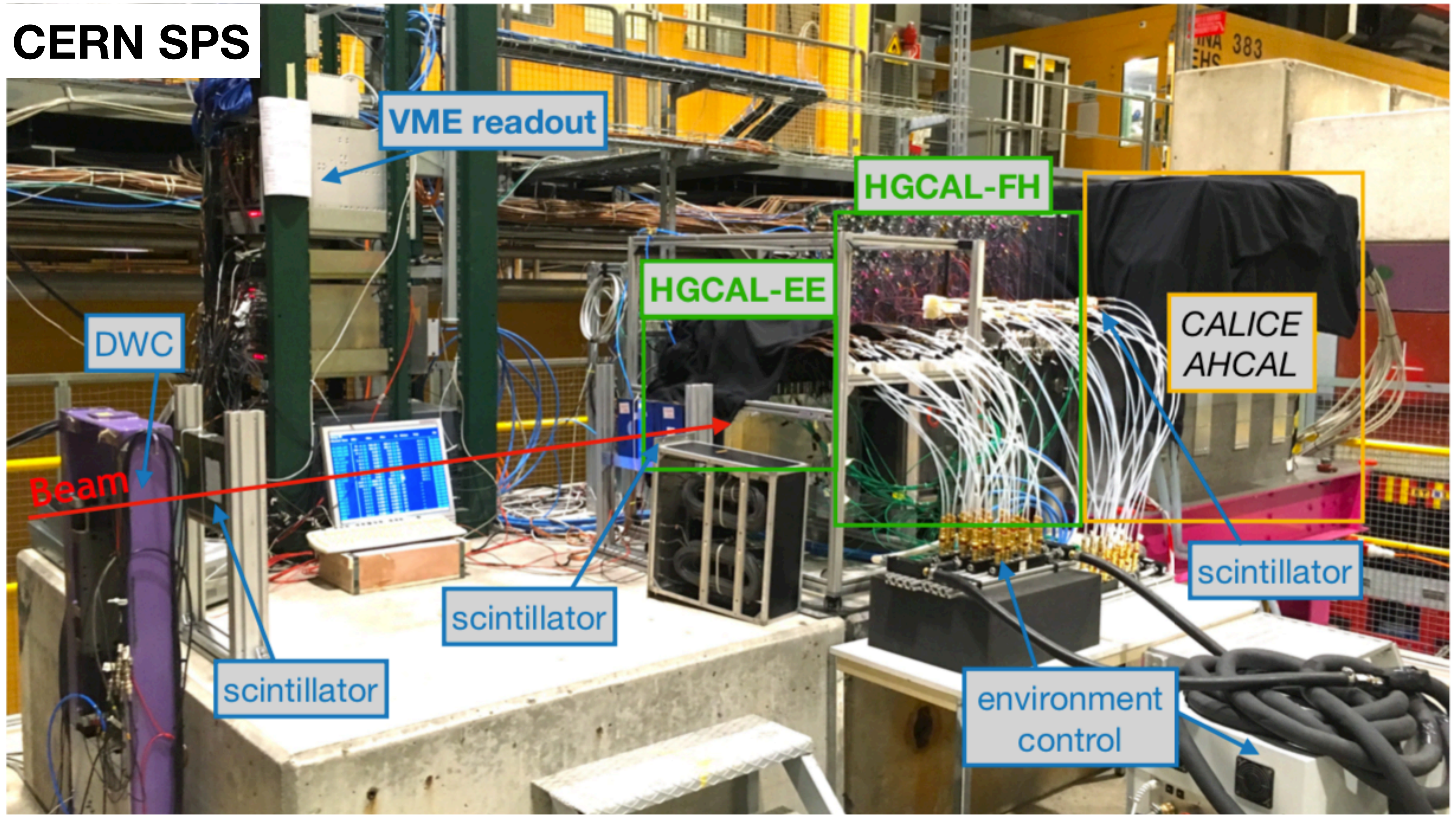
(b)

HGCAL 2018 test beams

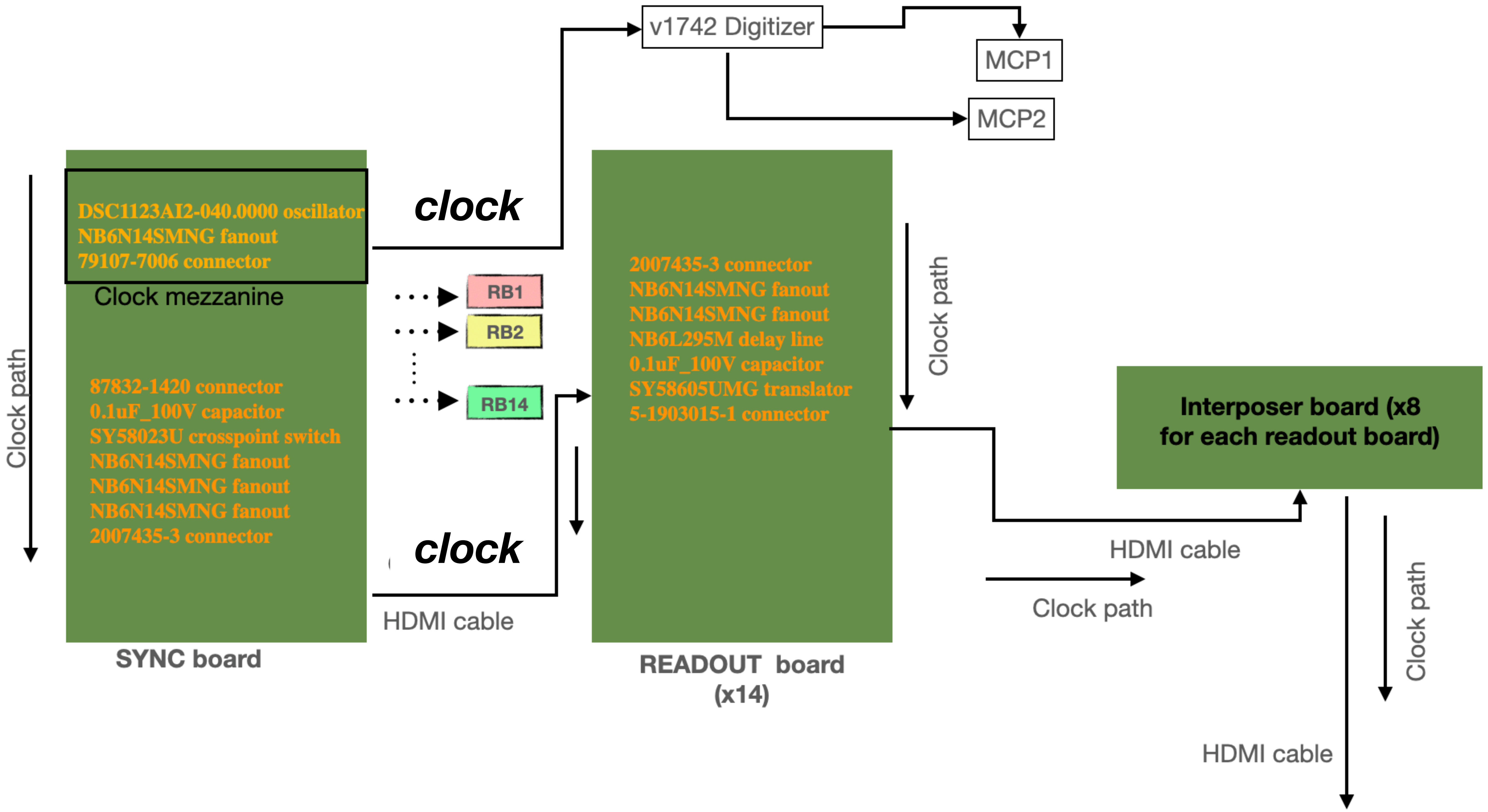
March 2018 @DESY II (T21) → **October 2018 @CERN SPS (H2)**

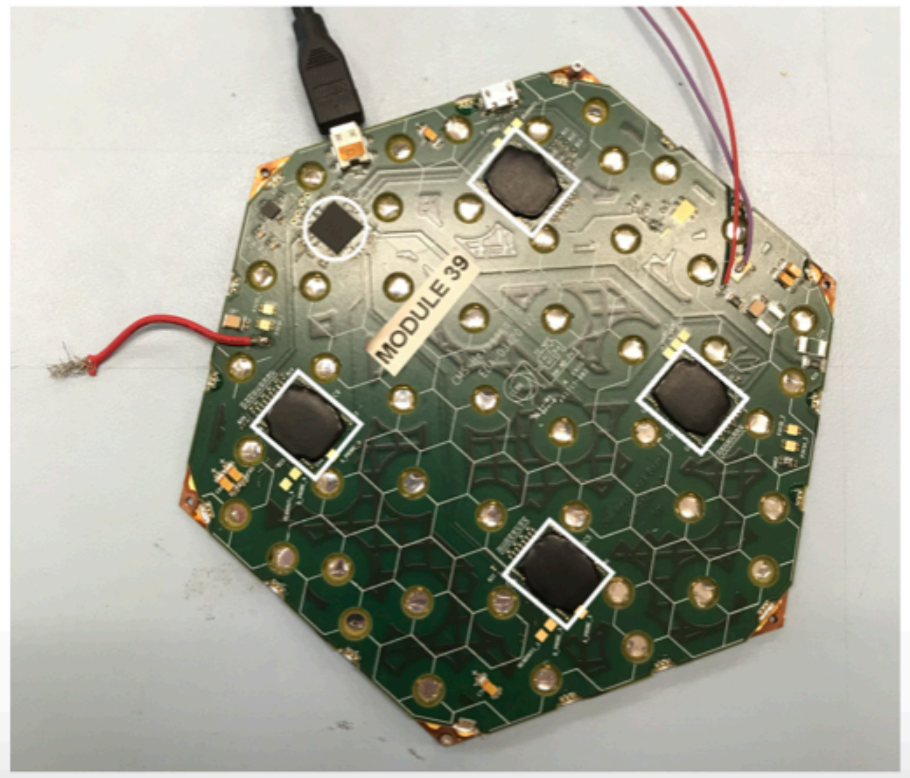
March 2018 @DESY II (T21)		October 2018 @CERN SPS (H2)
1 + 2 HGCAL modules: 1 module: mounted on moving stage	***Setup***	94 HGCAL modules: 28-layer EE setup + 12-layer FH setup
1.6 - 6 GeV/c e^-	***Particles***	e^+, μ^-, π^- up to 300 GeV/c
silicon module design qualification	***Goal***	full in-situ calibration, performance+comparison to simulation
DATURA beam telescope	***Aux. detectors***	delay wire chambers (DWC), microchannel plates, threshold Cherenkov detectors



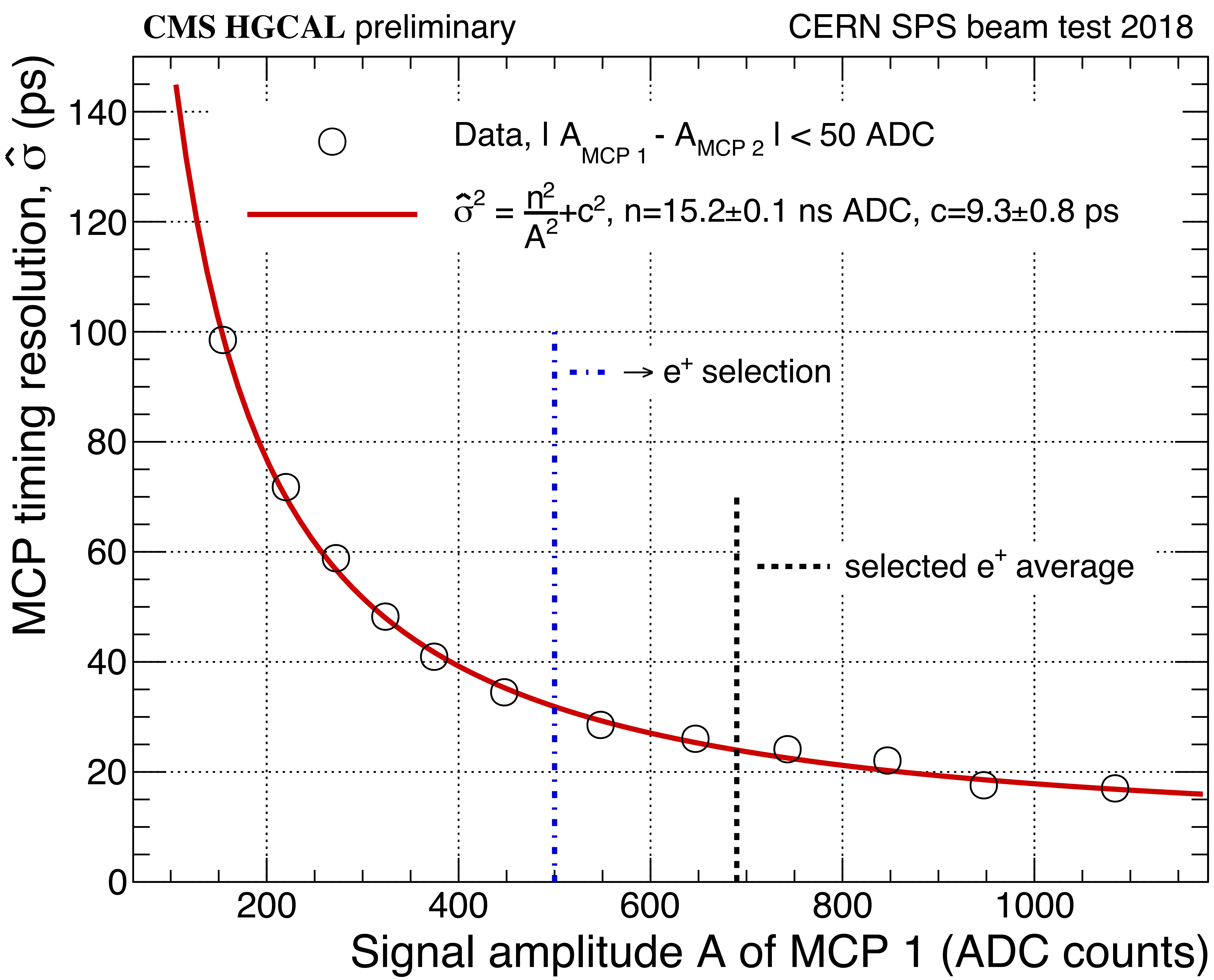


Clock path

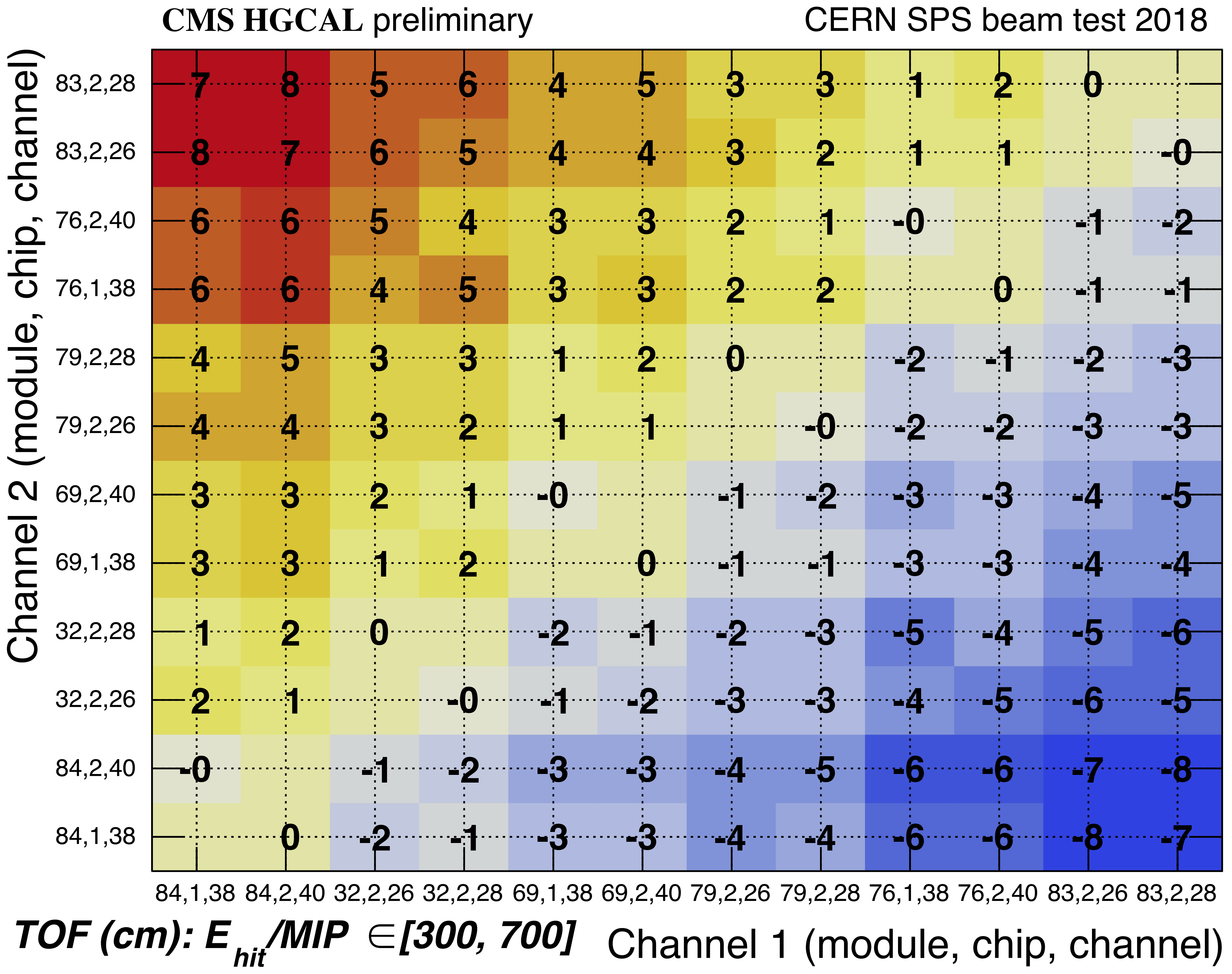

v1742 Digitizer
MCP1
MCP2
clock
DSC1123AI2-040.0000 oscillator
NB6N14SMNG fanout
79107-7006 connector
Clock mezzanine
87832-1420 connector
0.1uF_100V capacitor
SY58023U crosspoint switch
NB6N14SMNG fanout
NB6N14SMNG fanout
NB6N14SMNG fanout
2007435-3 connector
Clock path
SYNC board
RB1
RB2
RB14
clock
HDMI cable
2007435-3 connector
NB6N14SMNG fanout
NB6N14SMNG fanout
NB6L295M delay line
0.1uF_100V capacitor
SY58605UMG translator
5-1903015-1 connector
READOUT board
(x14)
Clock path
Interposer board (x8
for each readout board)
HDMI cable
Clock path
Clock path
HDMI cable

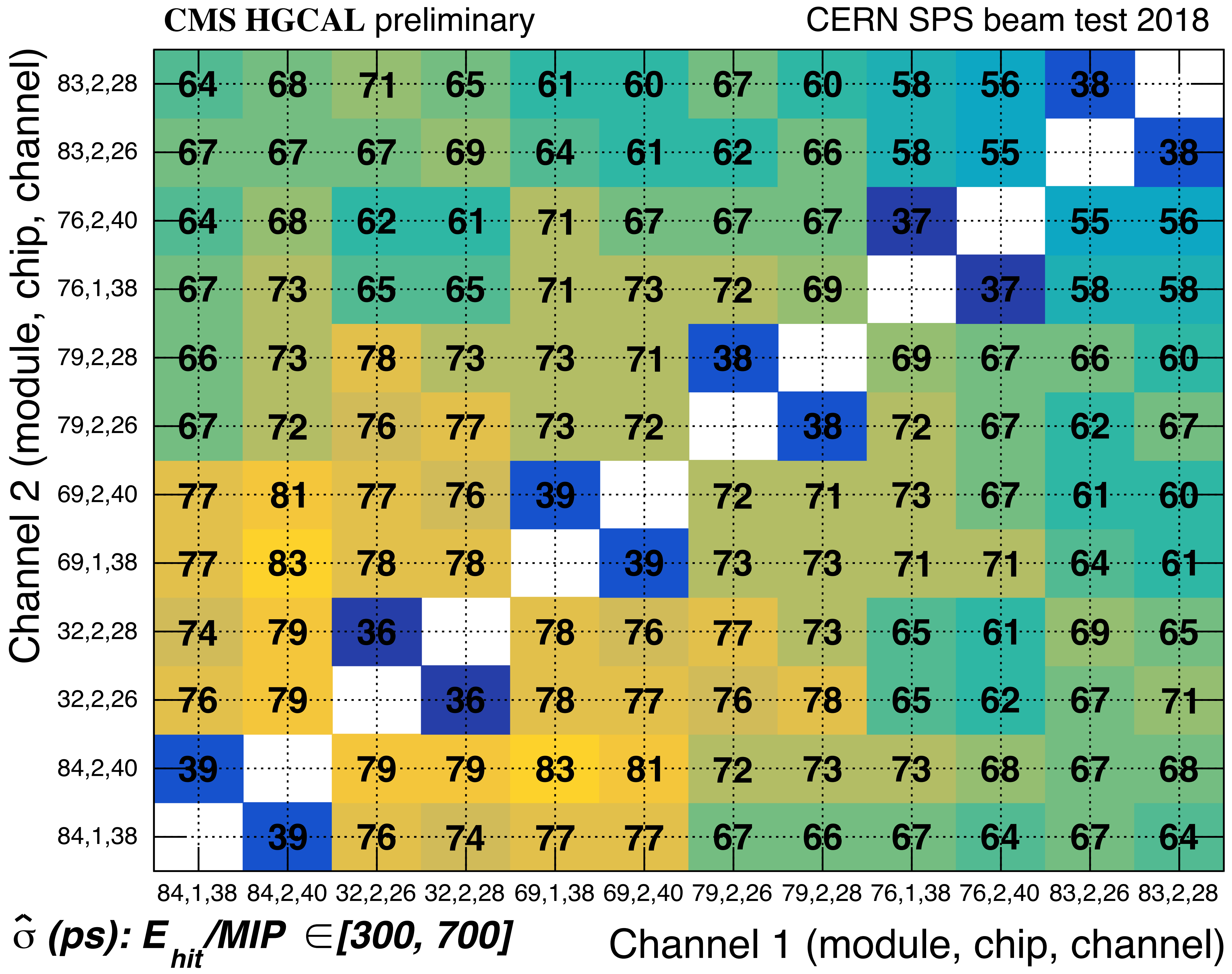


Intrinsic MCP timing resolution is ~25ps



Timestamp correlation between channels on the same module





Shower timing resolution dominated by high-energy hits

- Shower timestamp = energy-weighted sum of hit timestamps, TOF-subtracted from each hit time

Resolution vs. hit selection energy threshold