Fast Timing for Collider Detectors

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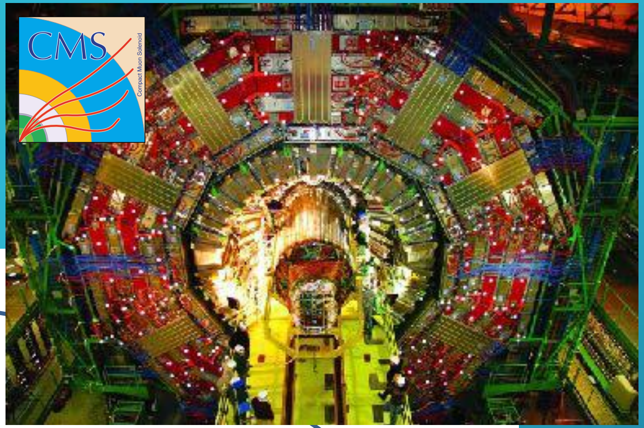
CERN Academic Training Lectures (3/3)

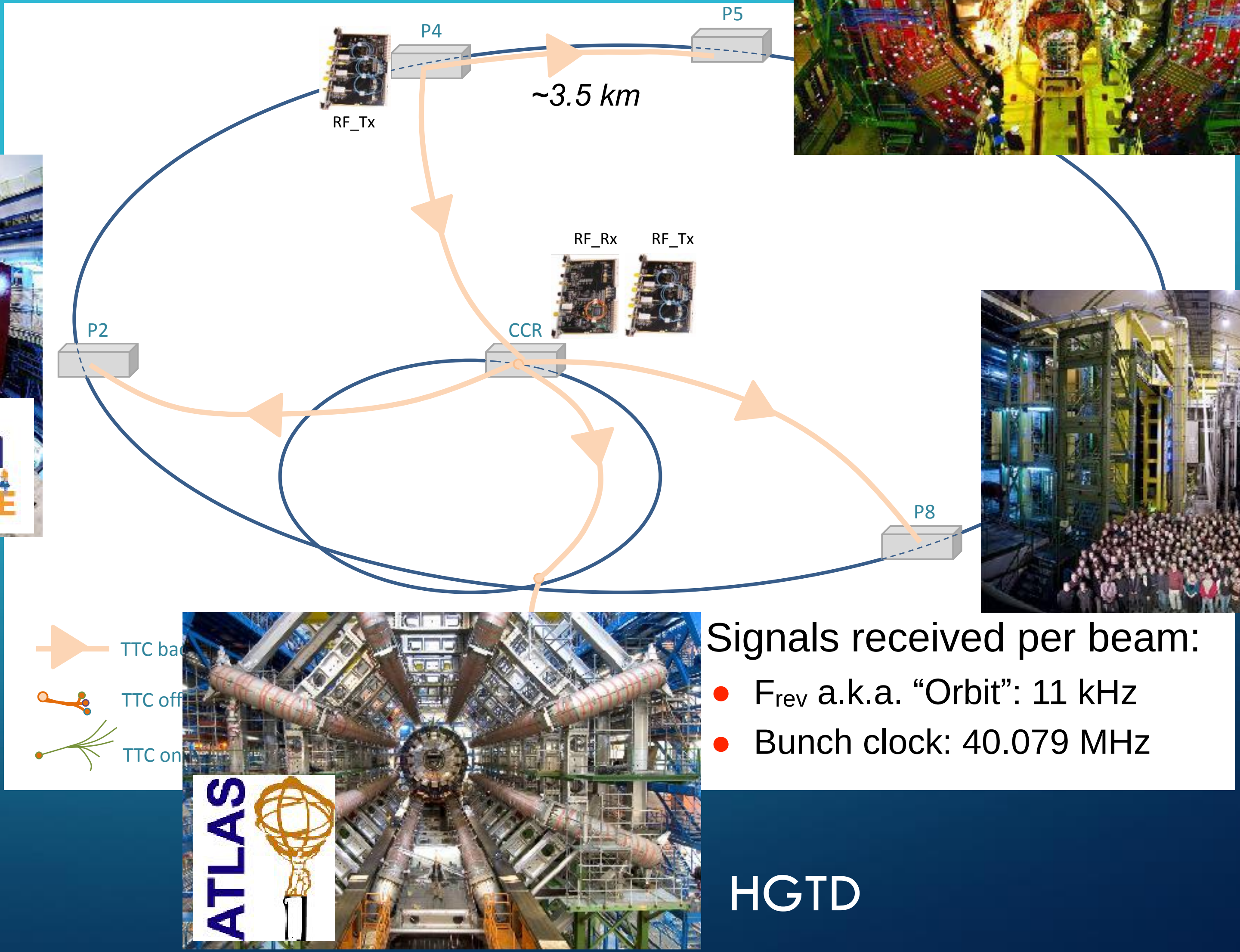
12 May 2017

Outline

- Detector implementations for HL-LHC
- Impact of fast timing on the HL-LHC physics program

Timing around the ring





BTL/ETL

TOF

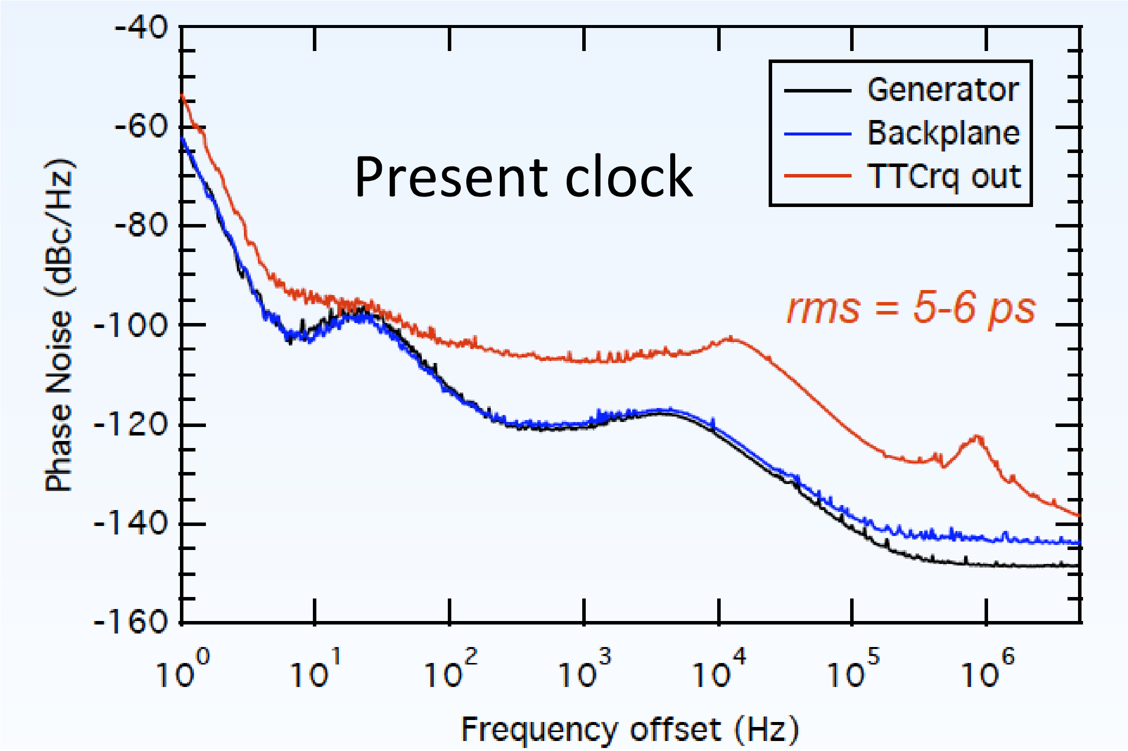
TORCH

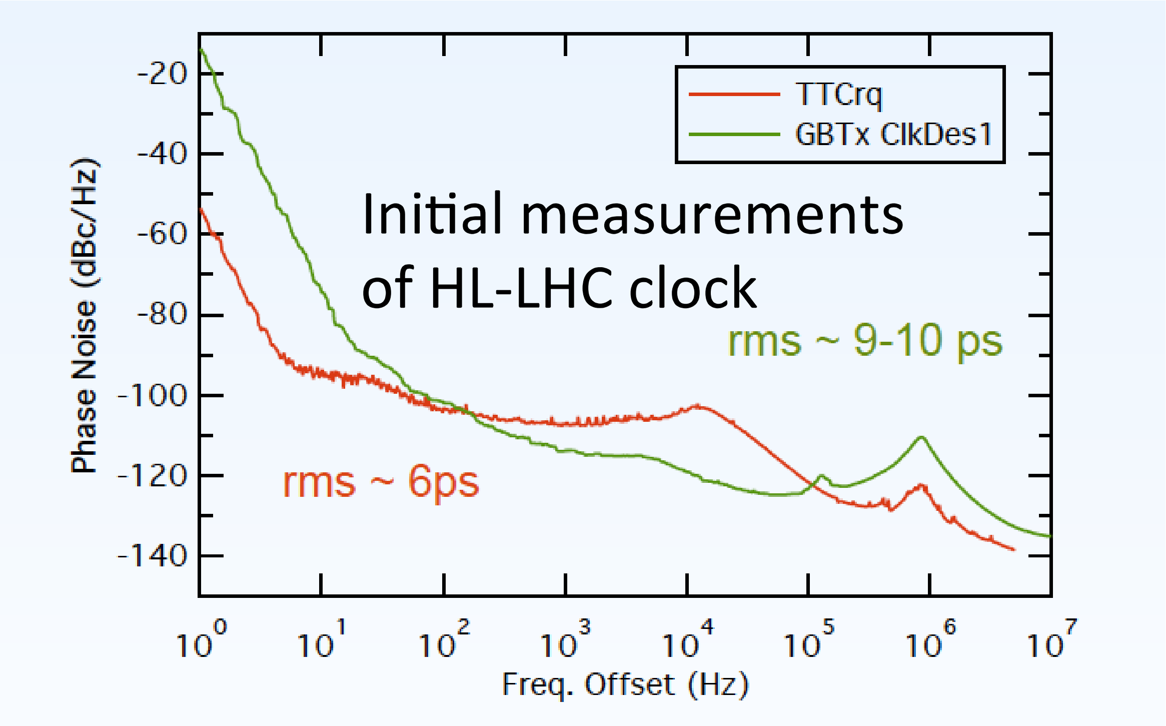
HGTD

Signals received per beam:

- F_{rev} a.k.a. “Orbit”: 11 kHz
- Bunch clock: 40.079 MHz

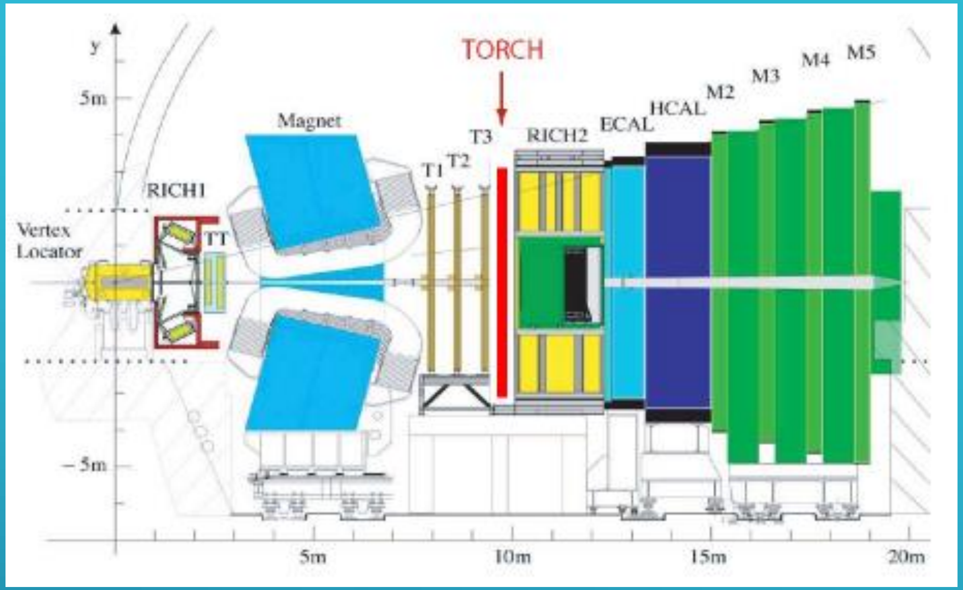
Clock distribution

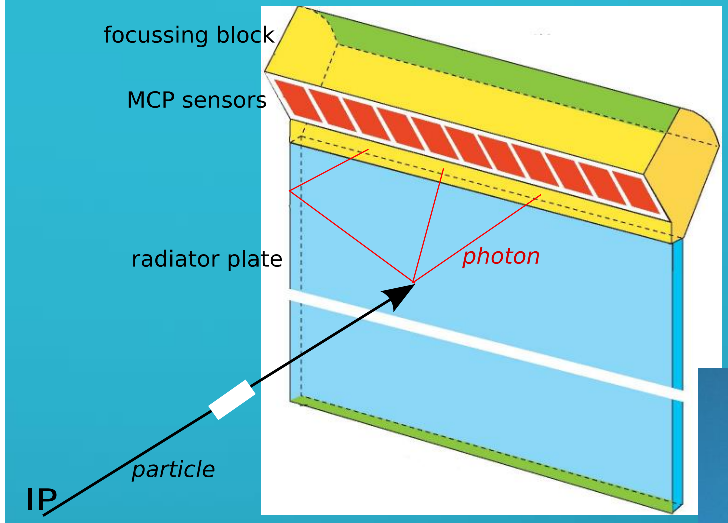


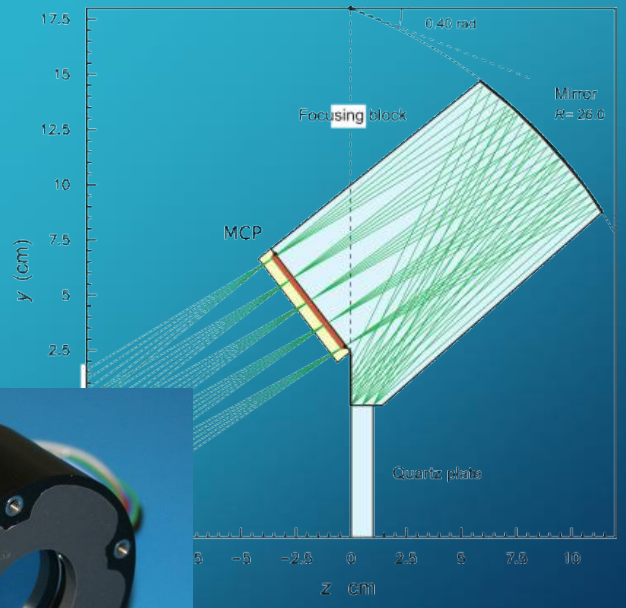


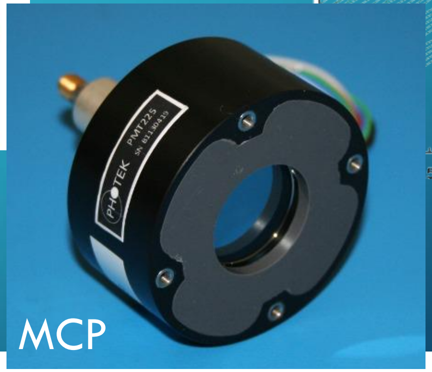
Clock source distributed around the ring with ~6ps jitter (may increase to ~10ps)

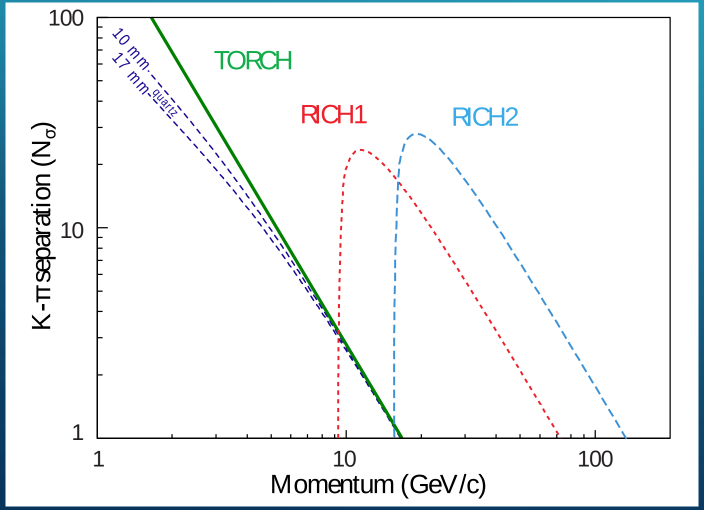
TORCH: Time Of internally Reflected CHerenkov light







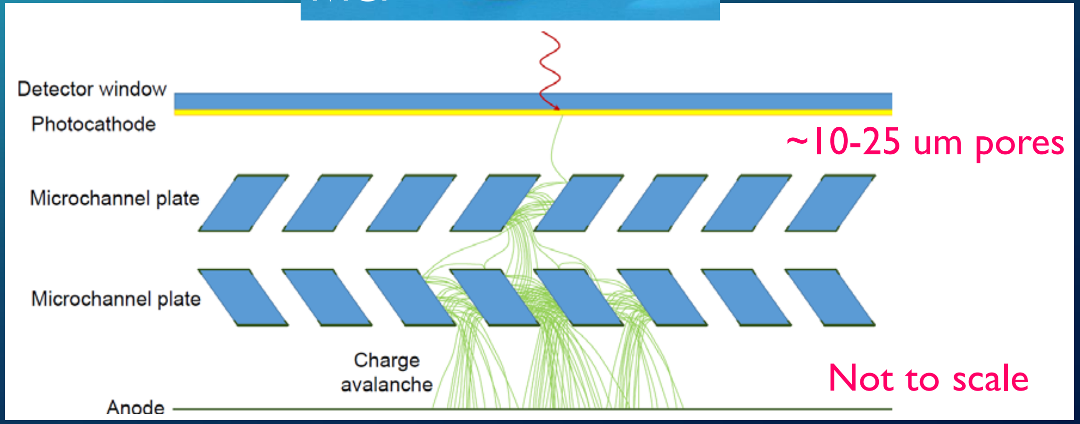




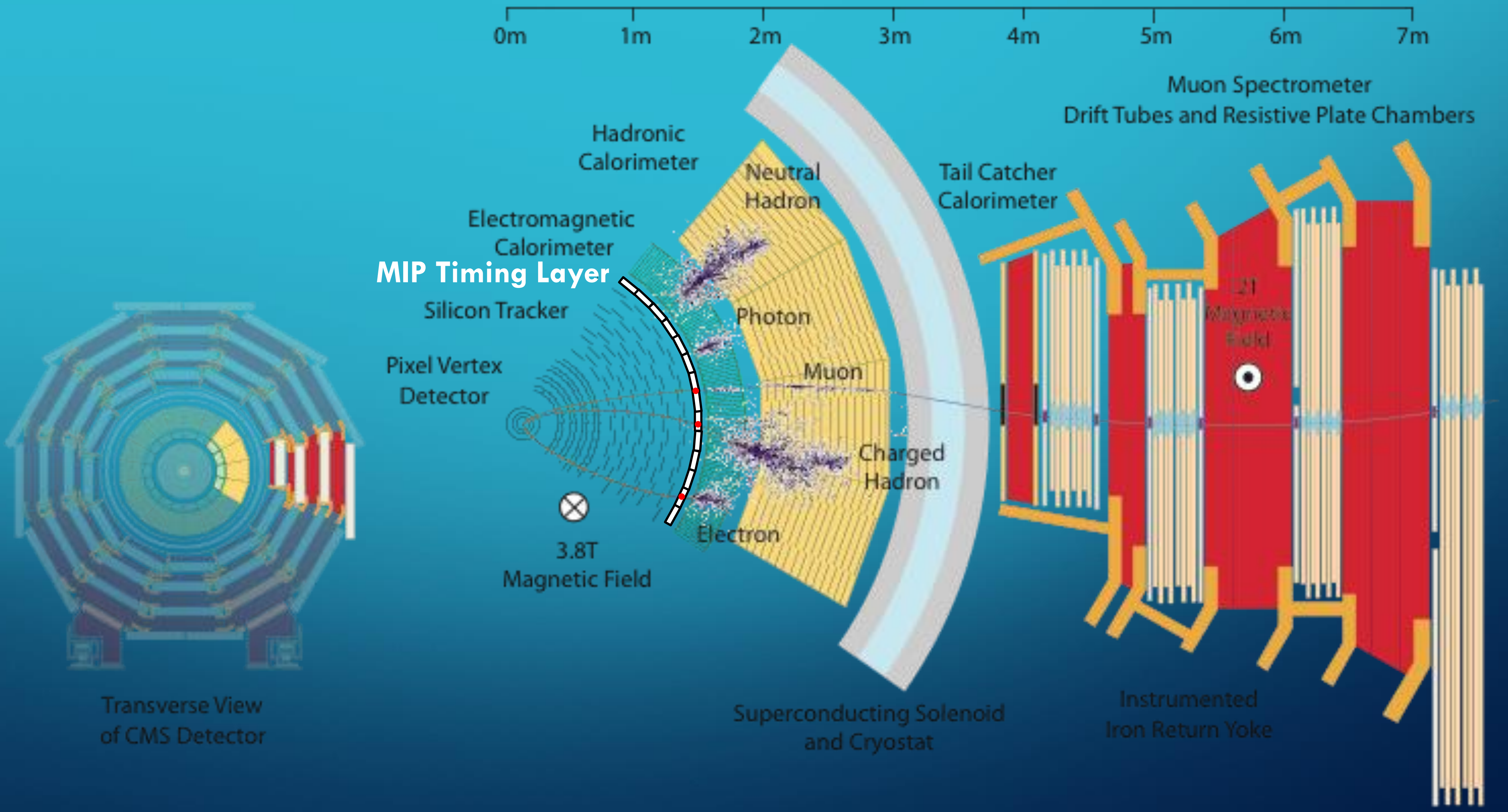
Goal: ~15ps/track

with ~30 photons/track
and ~70ps per single photon

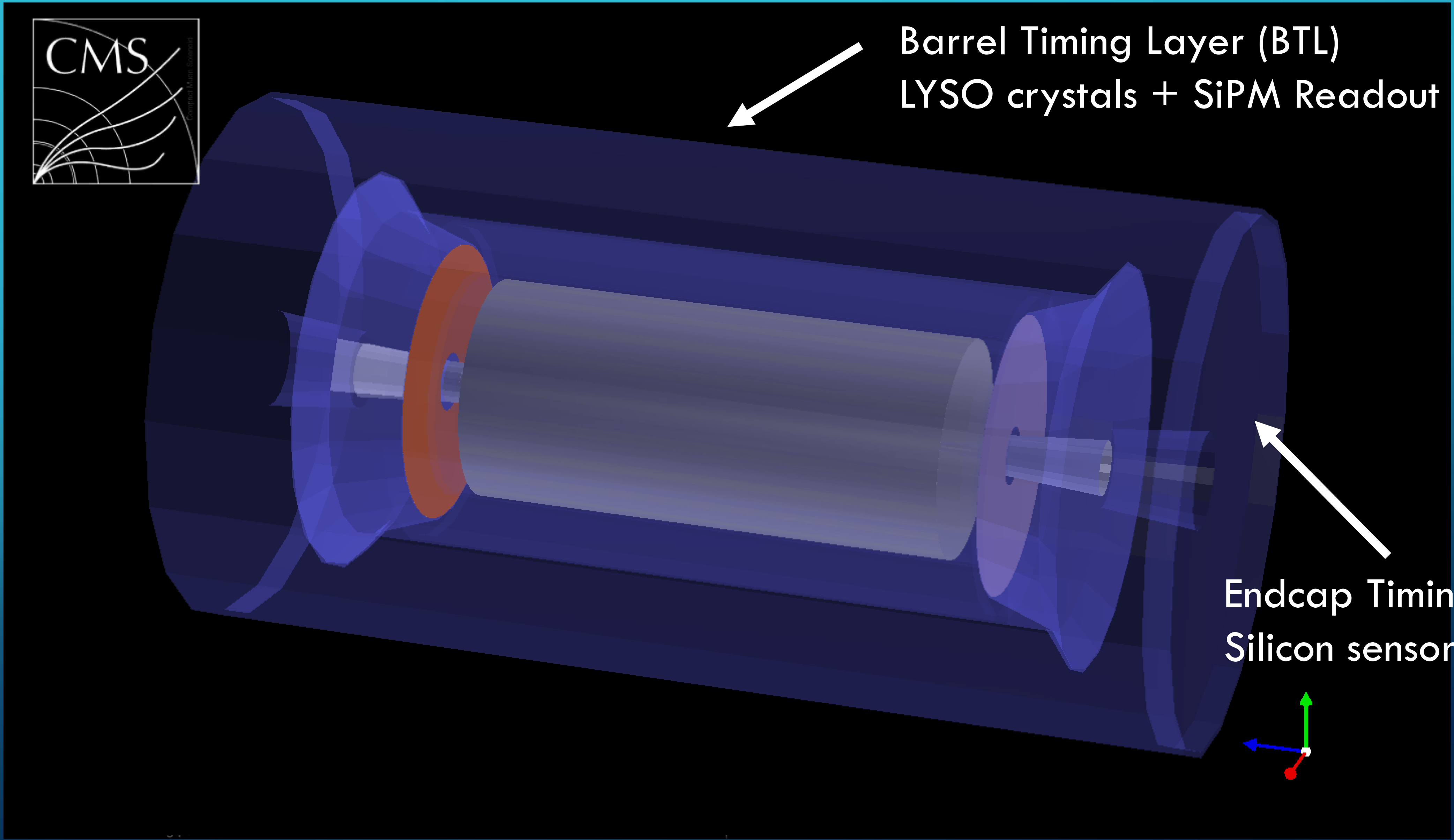
~70ps/√N → ~15ps



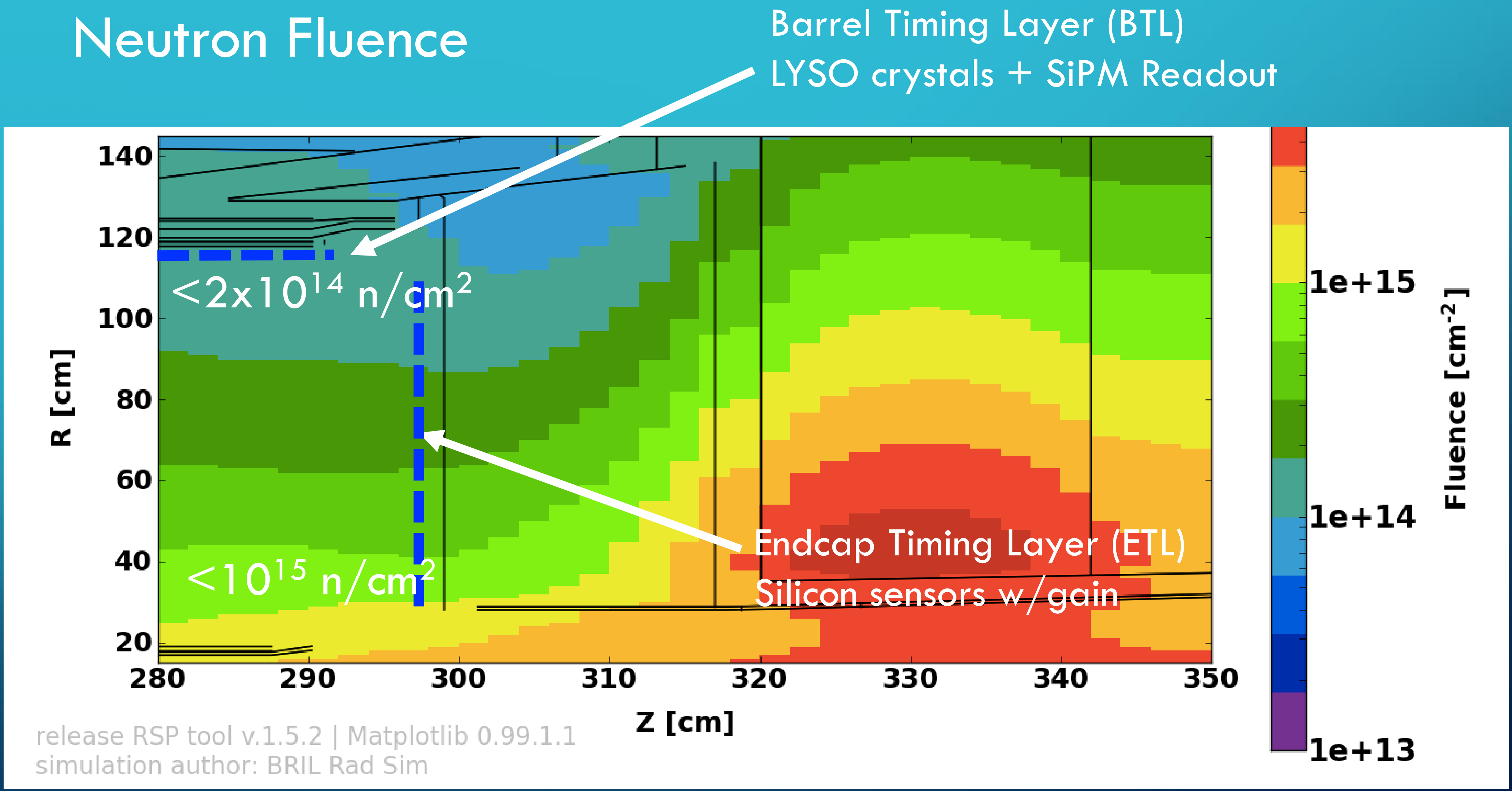
Particle-flow Event Reconstruction



Hermetic MIP timing layer



Neutron Fluence

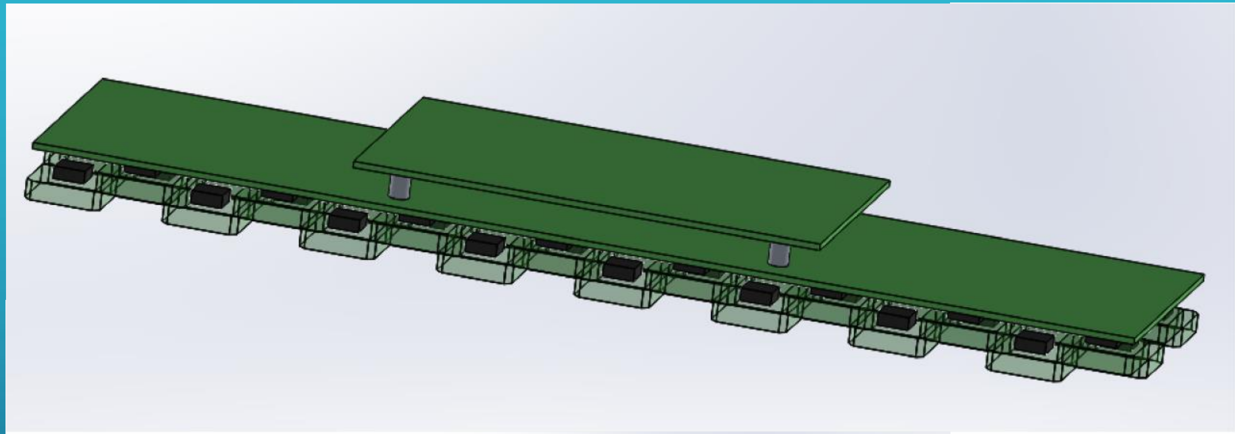


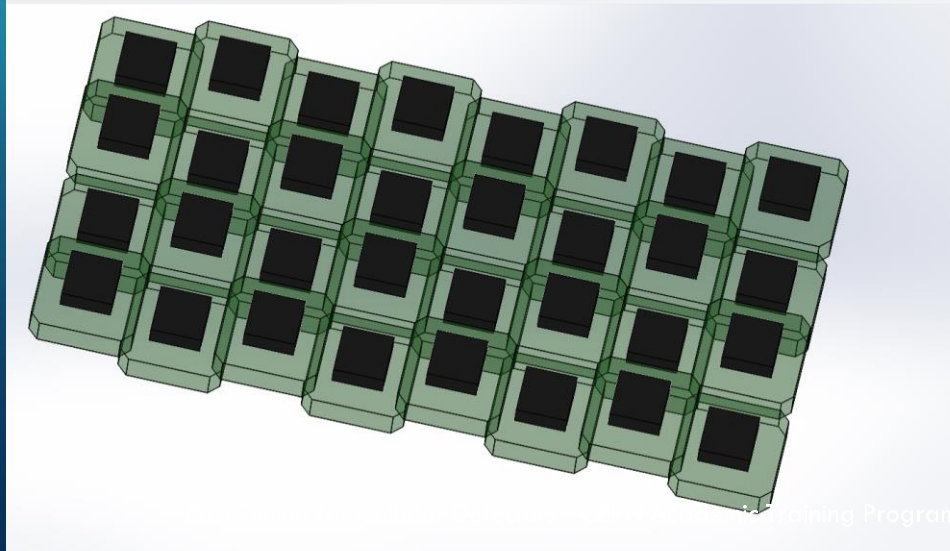
Barrel Timing Layer Module – Redesign from TOFPET

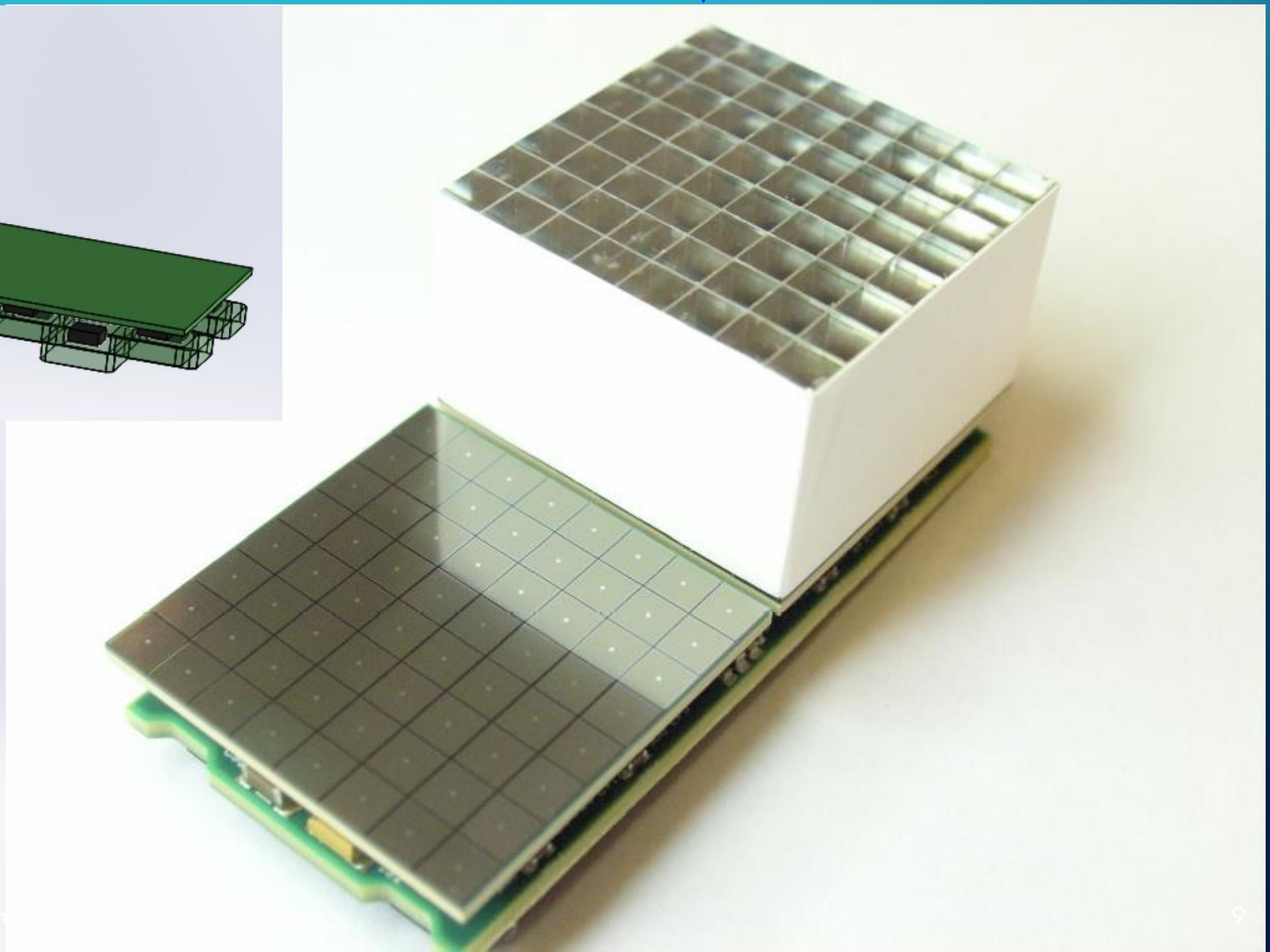
Basis for Design: TOFPET

→Reduce Crystal thickness to 3mm

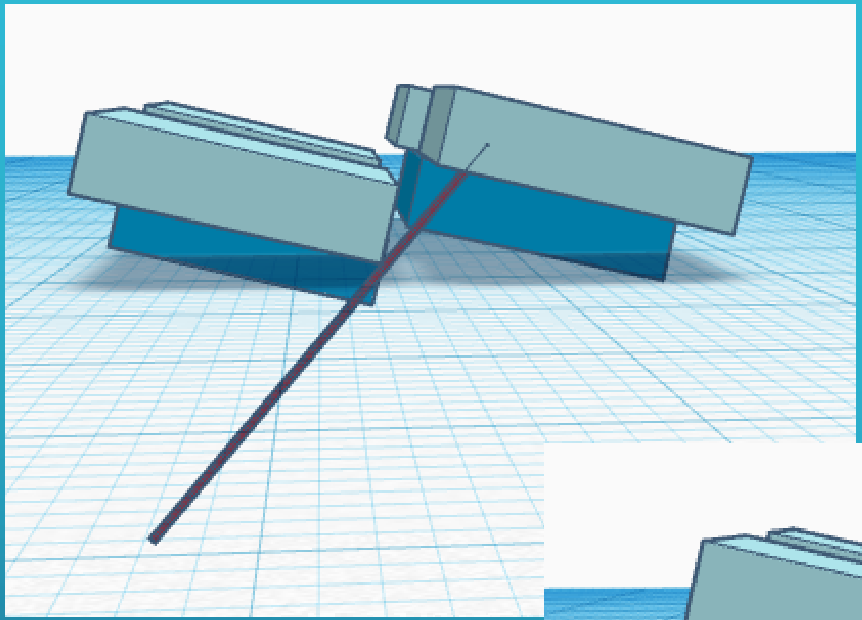
→Remove projective cracks with overlapping layers

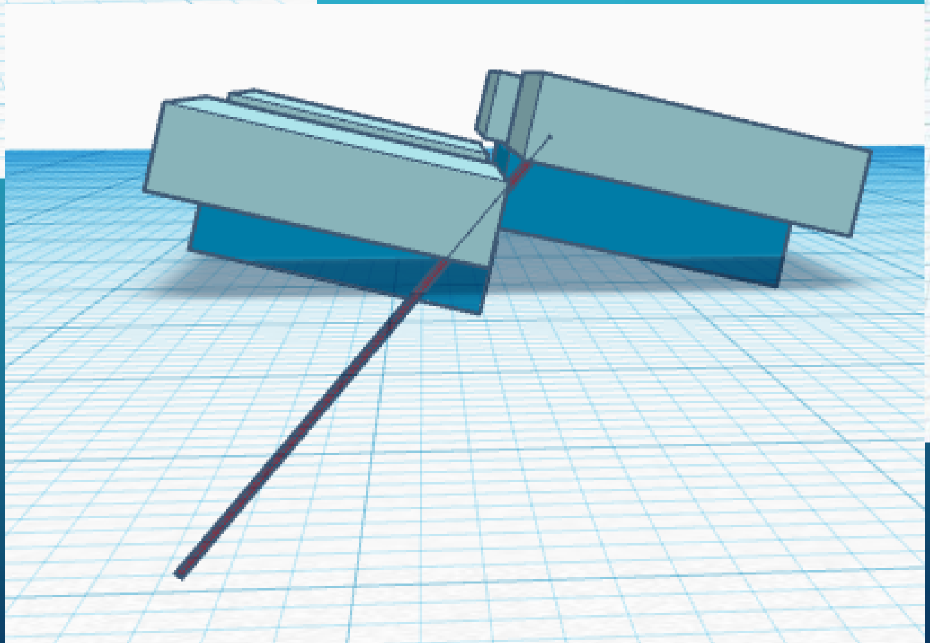


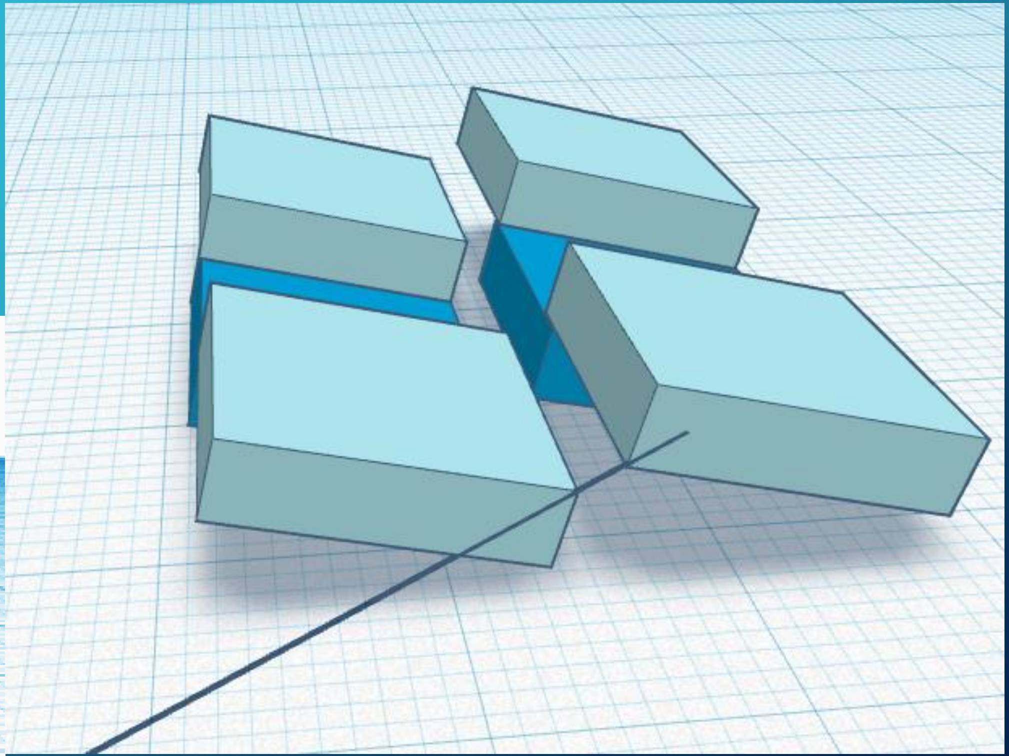




Tiling Crystals and Projective Cracks

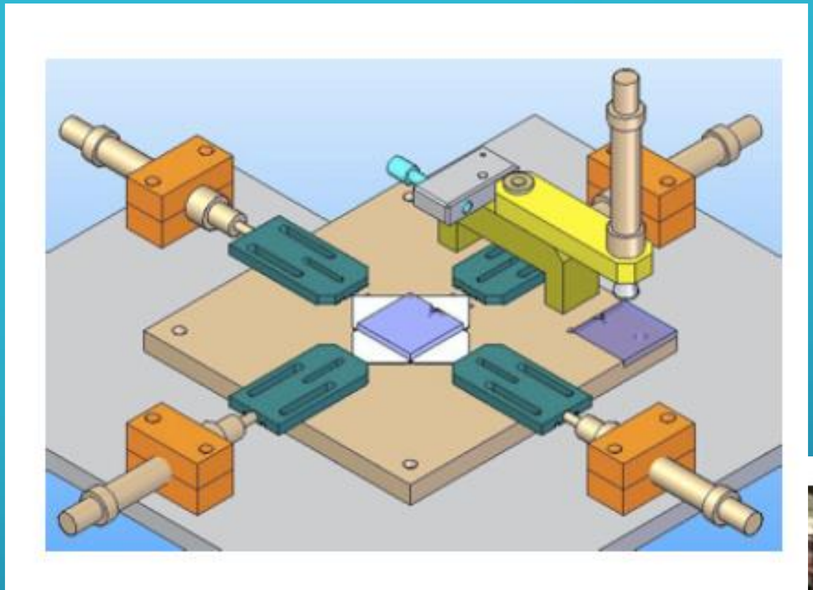


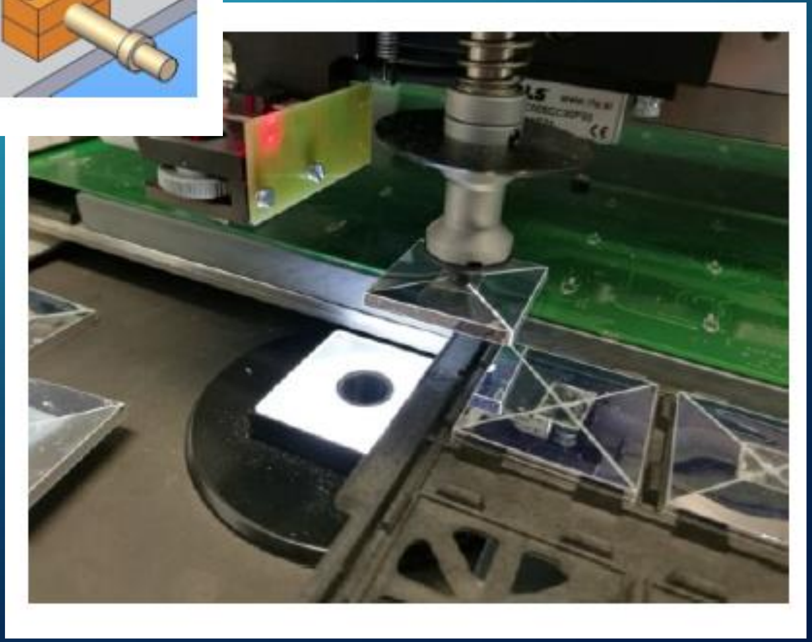




Sensor Module Construction Franzbrötchen

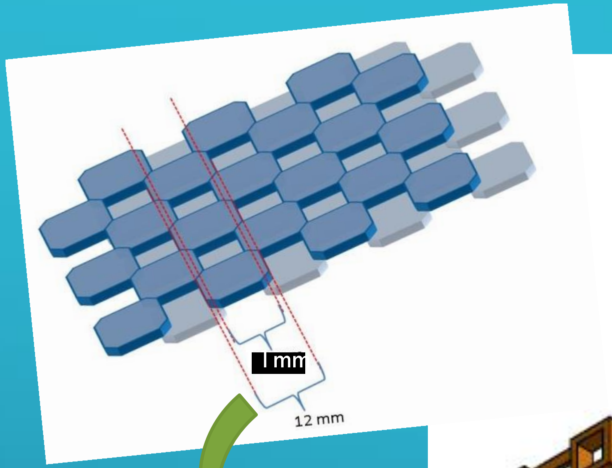
Wrap single crystals with a tile wrapping machine,
AHCAL building a pre-production version for 20k tiles



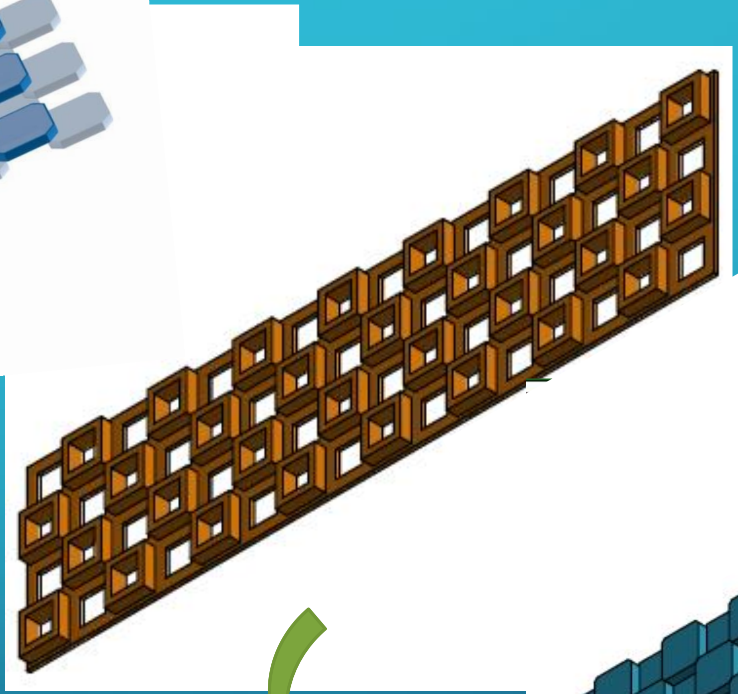


Pick and place wrapped tiles on SiPM board with a robot
72 tiles / 2.5 hours in AHCAL pre-production, can be accelerated significantly

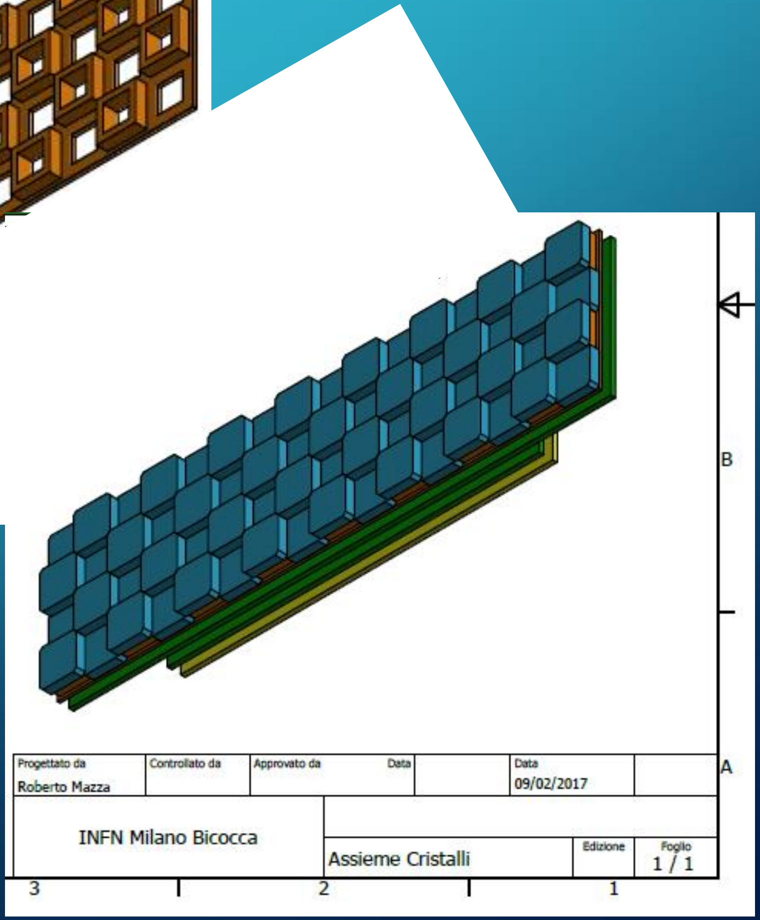
Sensor Modules Construction a la Milanaise



Mount crystals on alveola-like support structure

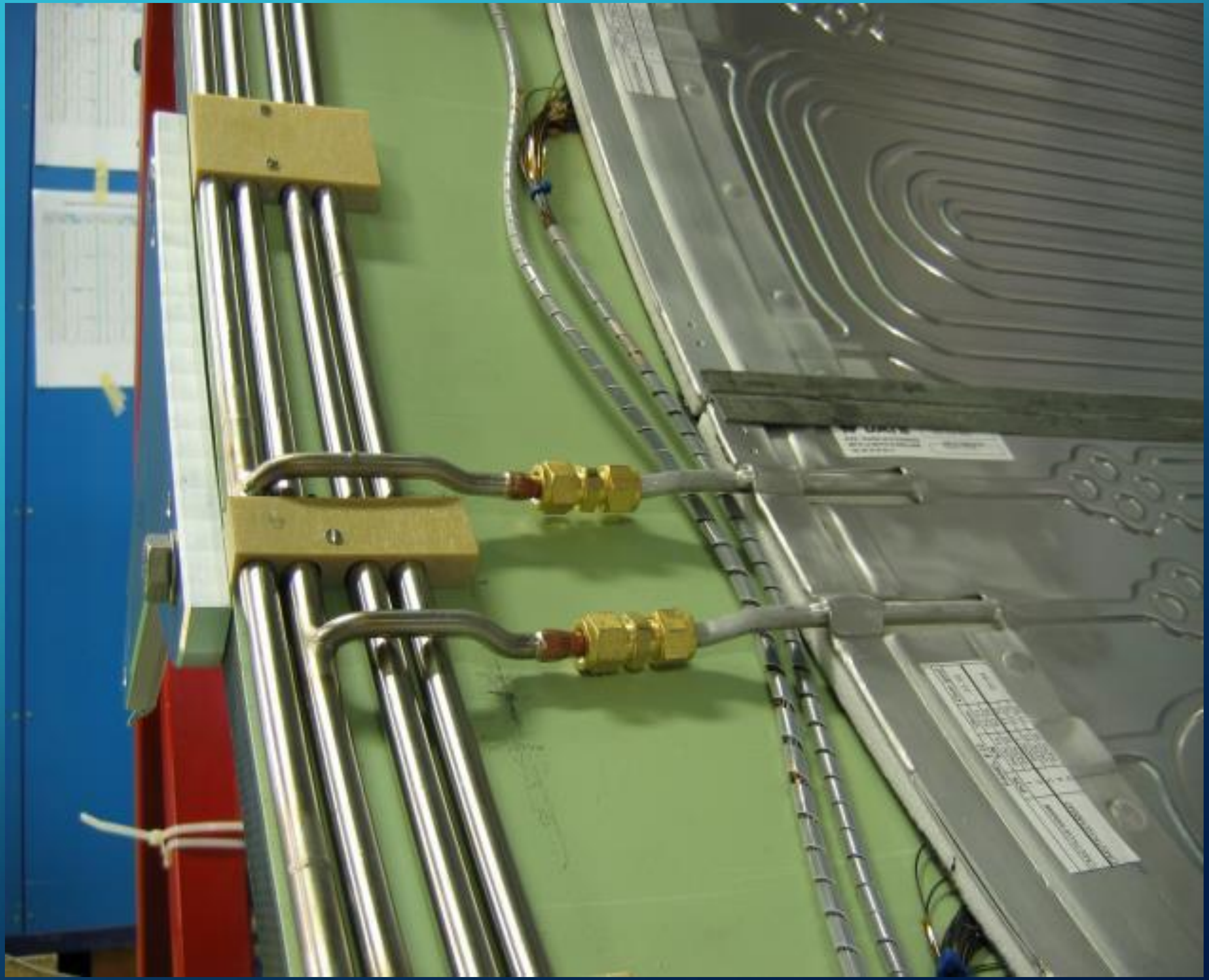


Mount crystal/alveola structure on SiPM mother board



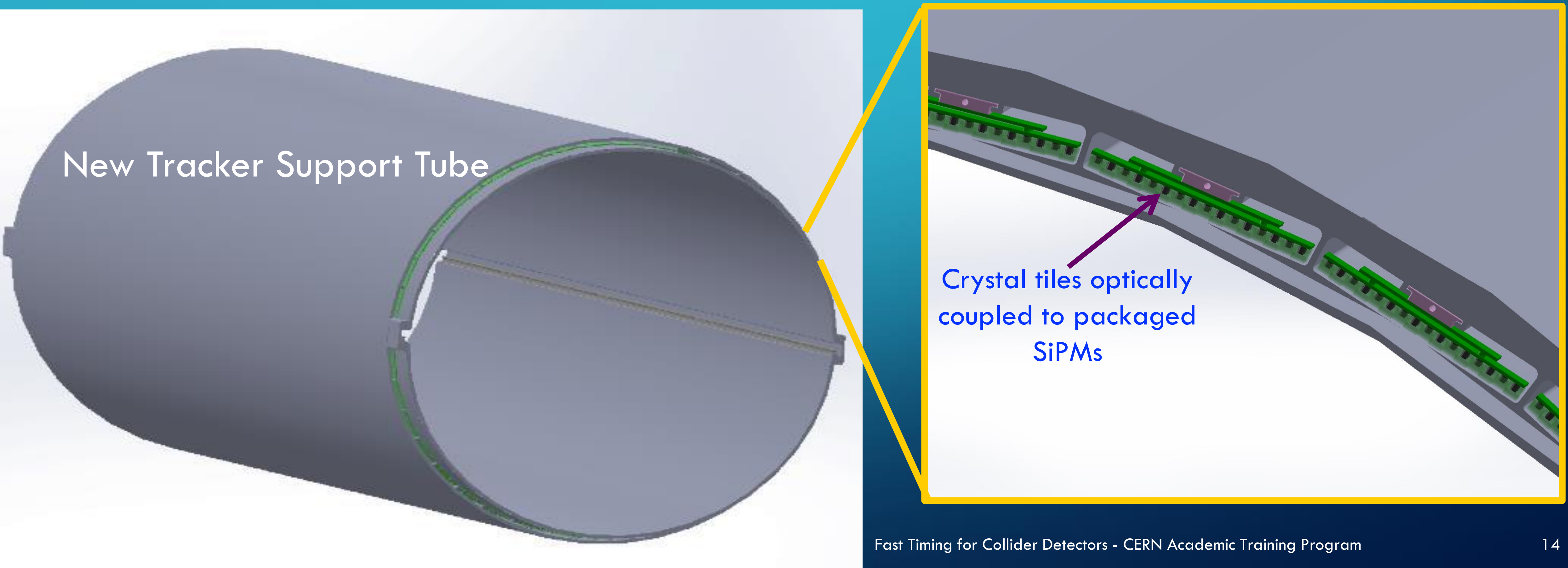
Tracker Support Tube and Thermal Screen

- Large carbon fiber cylinder – supported on 4 pins with a horizontal rail system to support the silicon trackers (TST at 20 C, Tracker at -20C → thermal screen)



Building Barrel Timing Layer into Track Support Tube

- Use thermal properties of carbon fiber tube with NoMex honeycomb filler to provide thermal screen (-35C inside → 20C outside) with active heating on the outer surface → run SiPMs at -35C



BTL Construction

~10mm x 10mm area LYSO crystals at R=1200mm → Hit occupancy few % at 200PU above 1/2 MIP threshold

36 trays in φ, 72 half trays :

- Number of crystals per module: 64

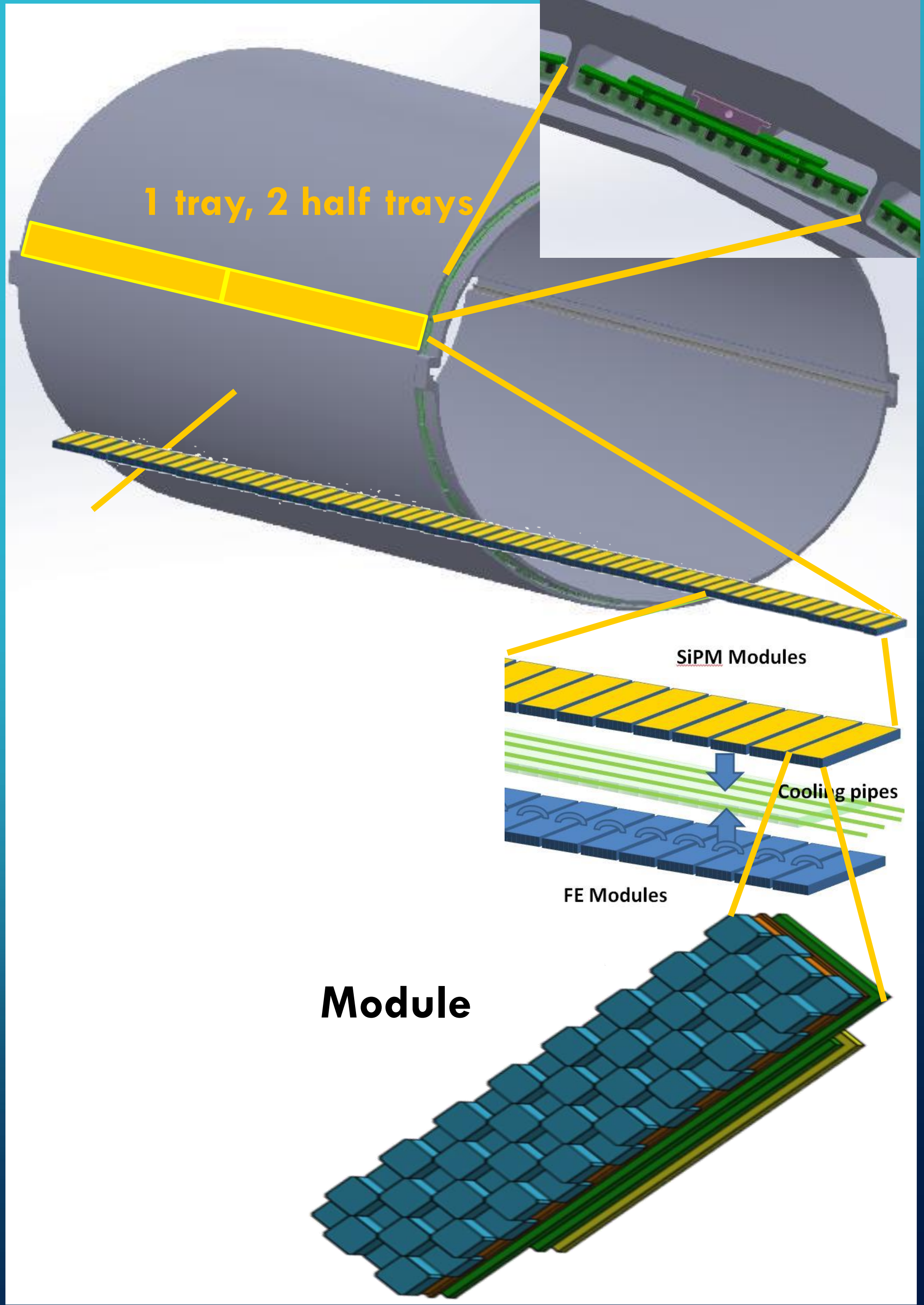
56 Modules per half tray (total 4032)

- Half-Tray length: 2604 mm (56x46.5 mm)
- Half-Tray width: 184.5 mm
- 1 Chip per module, 4 modules per link, 2 fibers per

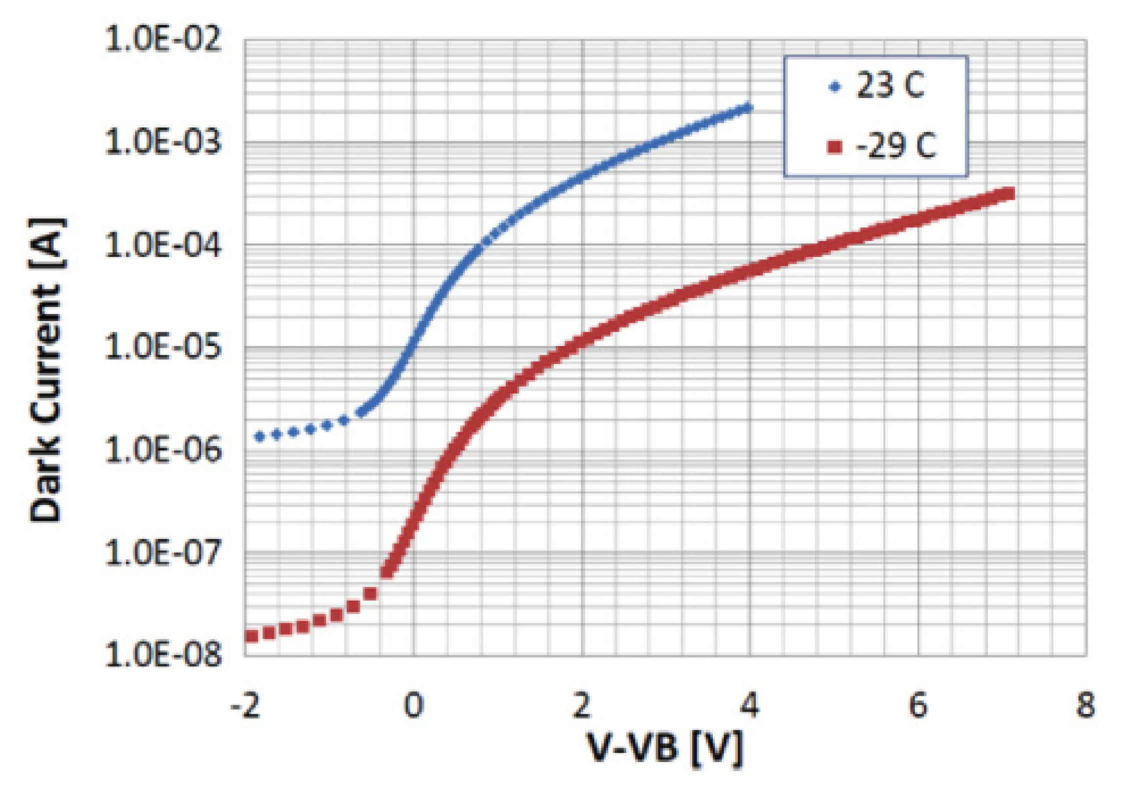
258048 channels in BTL

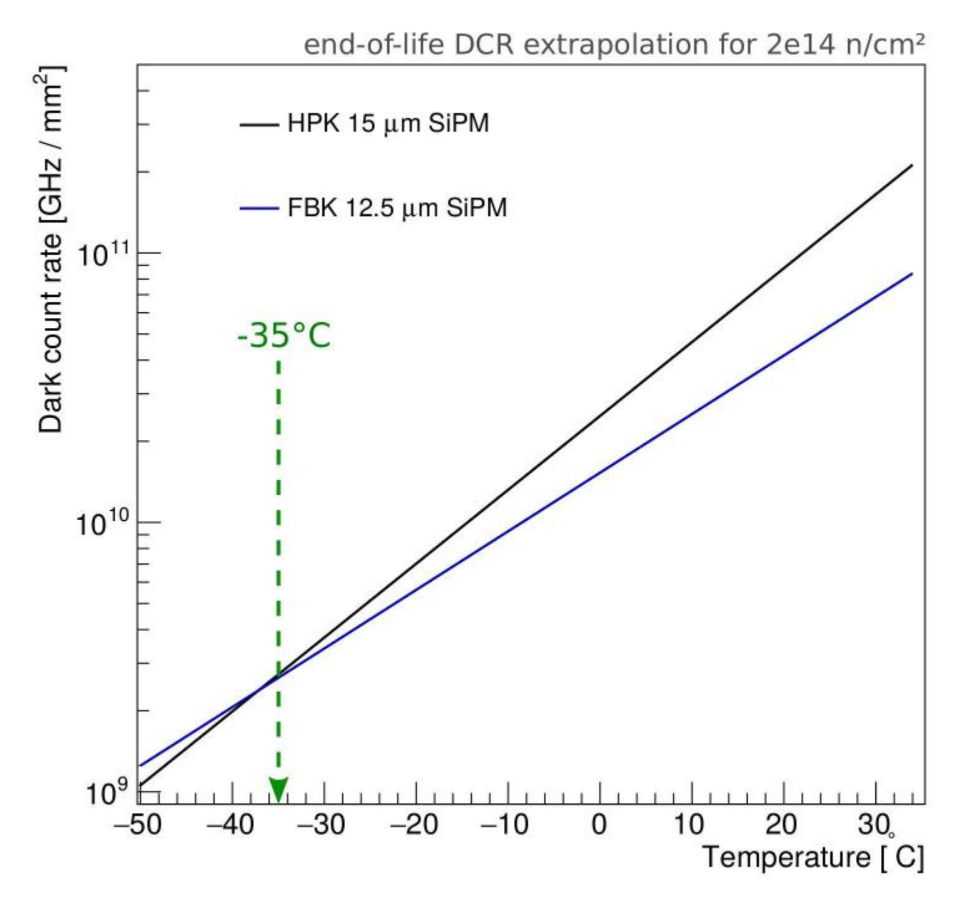
- Modules are the unit size for production of boards including crystal mounting.
- Half trays to be assembled from modules and inserted into TST.
- Total crystal weight ~11.2 kg per half tray.

~806 kg crystal weight of BTL

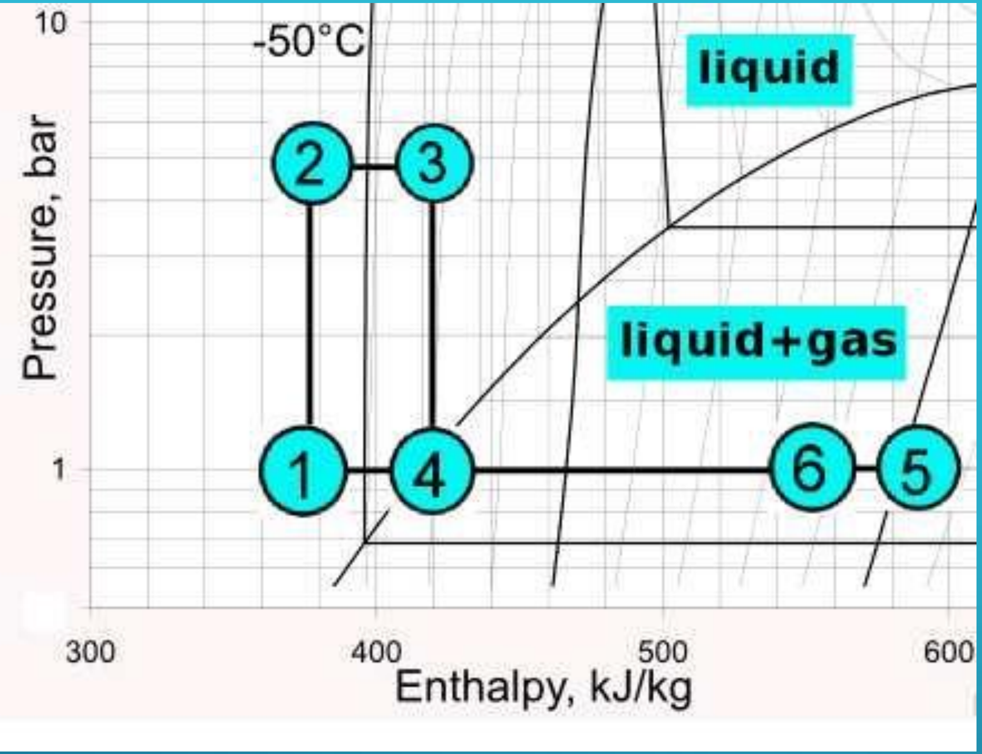


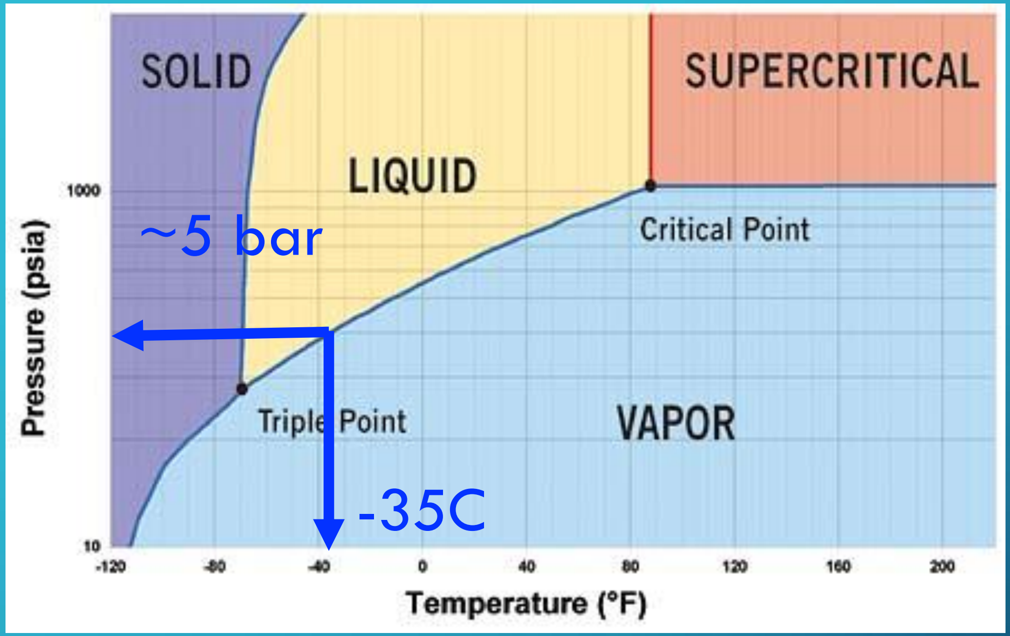
Dark Count Rate (DCR) drops with Temperature

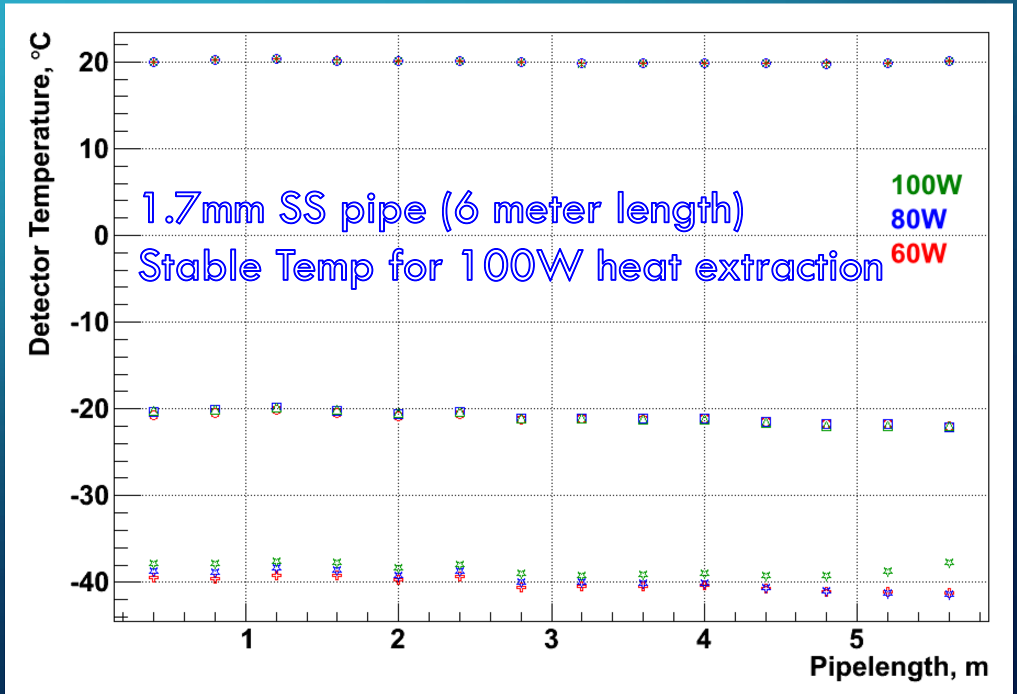




CO_2 Cooling







http://iopscience.iop.org/article/10.1088/1748-0221/6/01/C01091/pdf

L. Feld, W. Karpinski, J. Merz1 and M. Wlochal

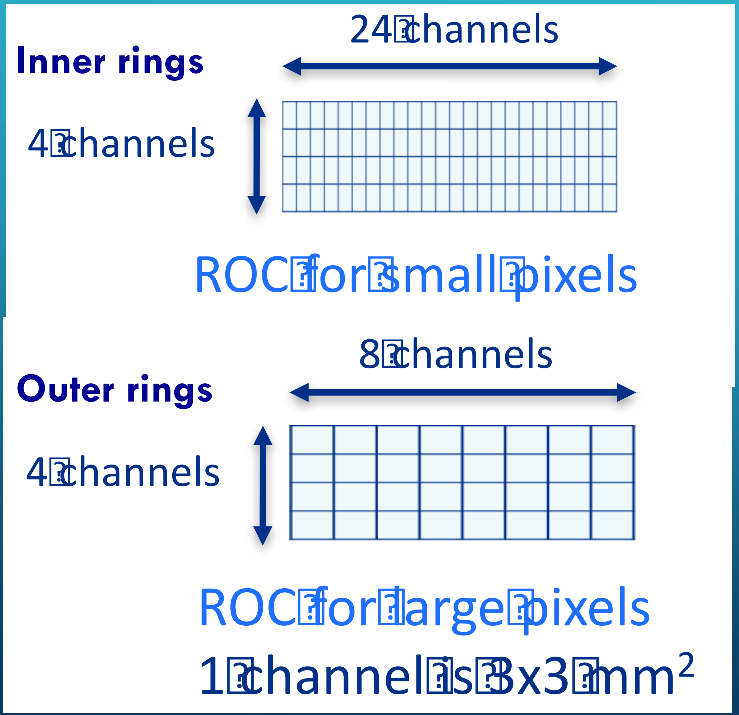
Self-heating of SiPM

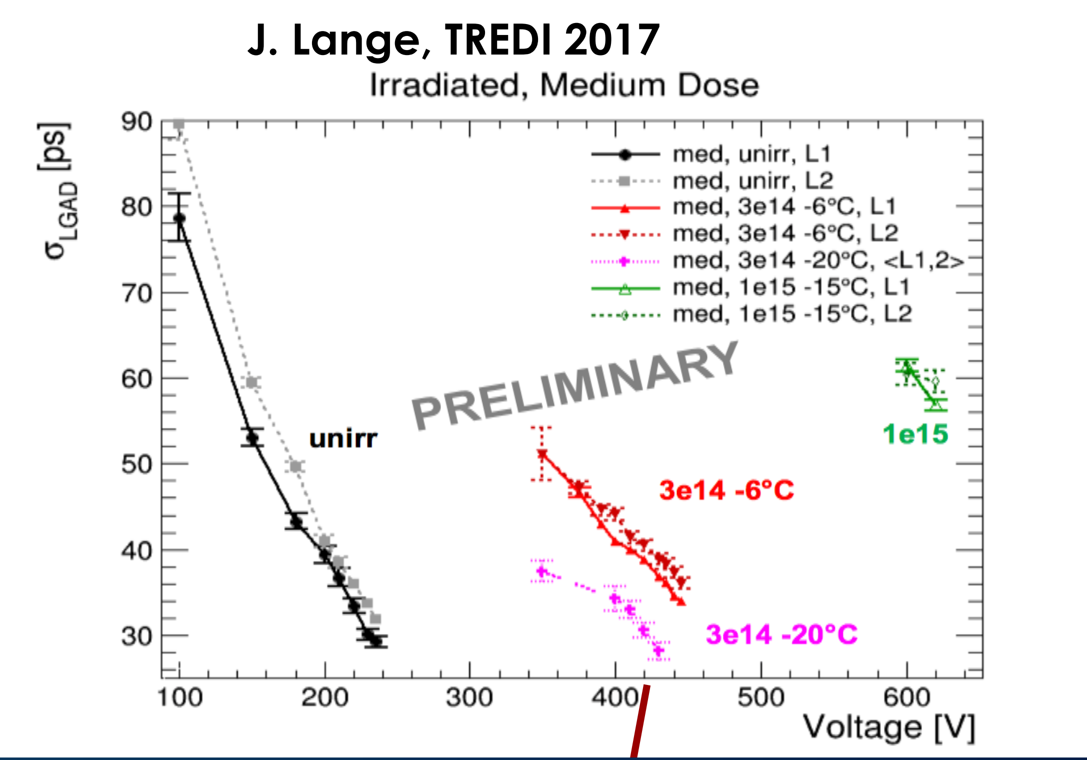
- Ultimately, it's the self-heating of the SiPM that limits the LYSO crystal+SiPM to use in the barrel ($<2\text{x}10^{14}$ n/cm^2)
  - The area is kept small to keep down the Dark Count Rate
  - The thickness of the crystal can vary 3mm→5mm to increase S/N, but too much material will degrade the EM (PbWO) calorimeter

Silicon sensor with gain

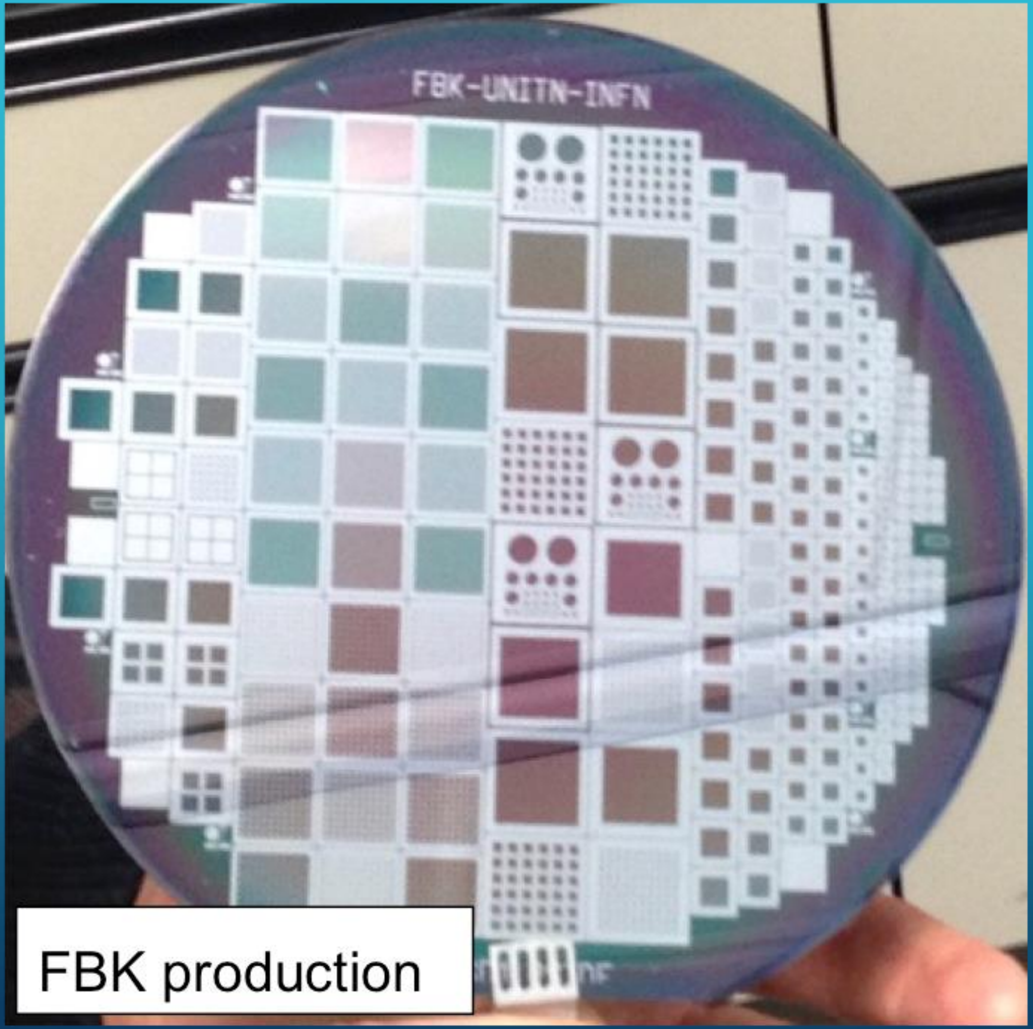
- Nominal geometry: 4.8 x 9.6 cm^2 modules with 1x3 mm^2 sensors
    - 16 ASICs bump-bonded to sensors
    - 3:1 ganging in the TDC at small η (3x3 mm^2 granularity)
- Readout ASIC in development
- Single sensor shown to have $\sigma_t \leq 50$ ps up to 10^{15} neq/cm^2

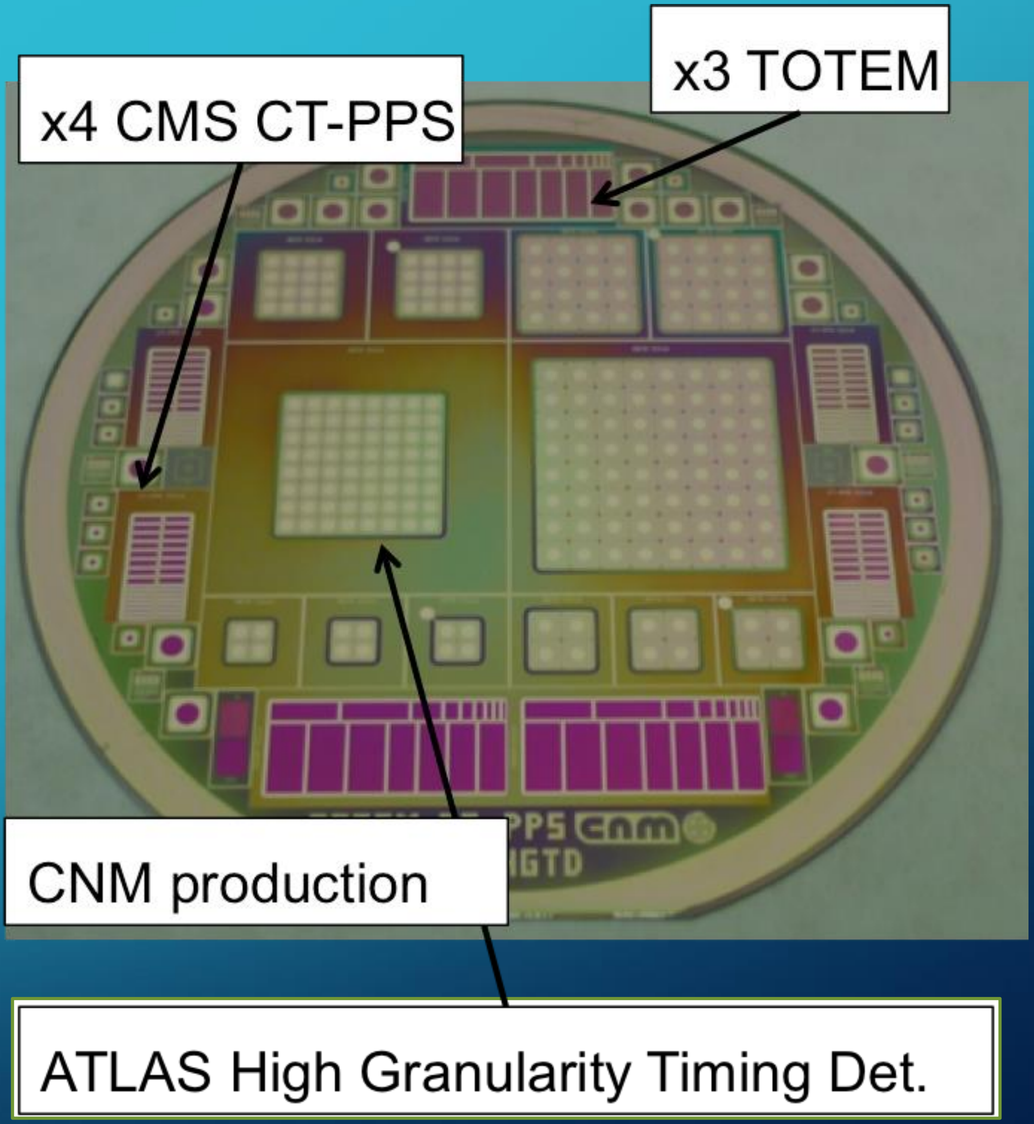
Eta	Fluence [10^{14} n_{eq}/cm^2]	Time resolution
1.6	1.1	~ 30 ps
2.0	2.1	~ 30 ps
2.5	4.1	~ 30 ps
2.6	6.5	~ 40 ps
3.0	10	~ 55 ps



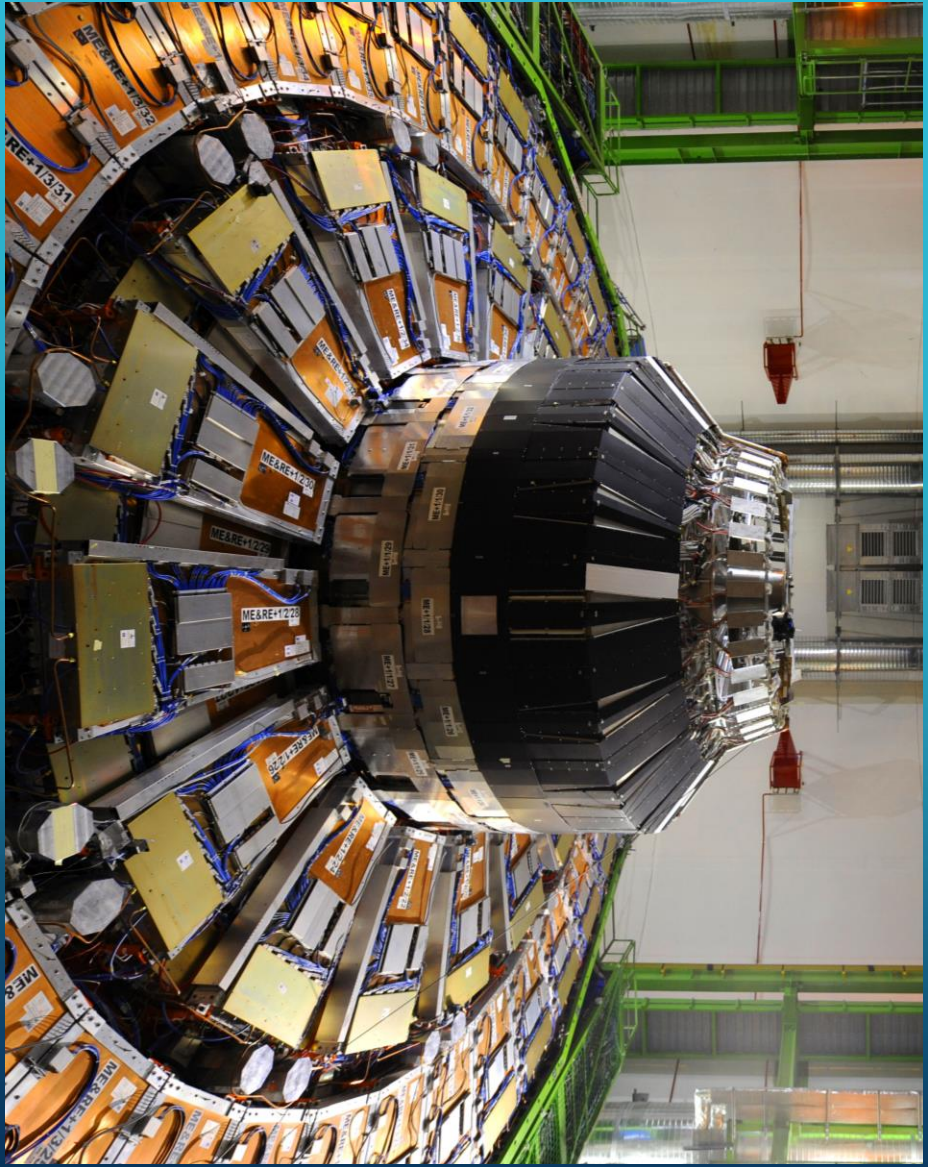


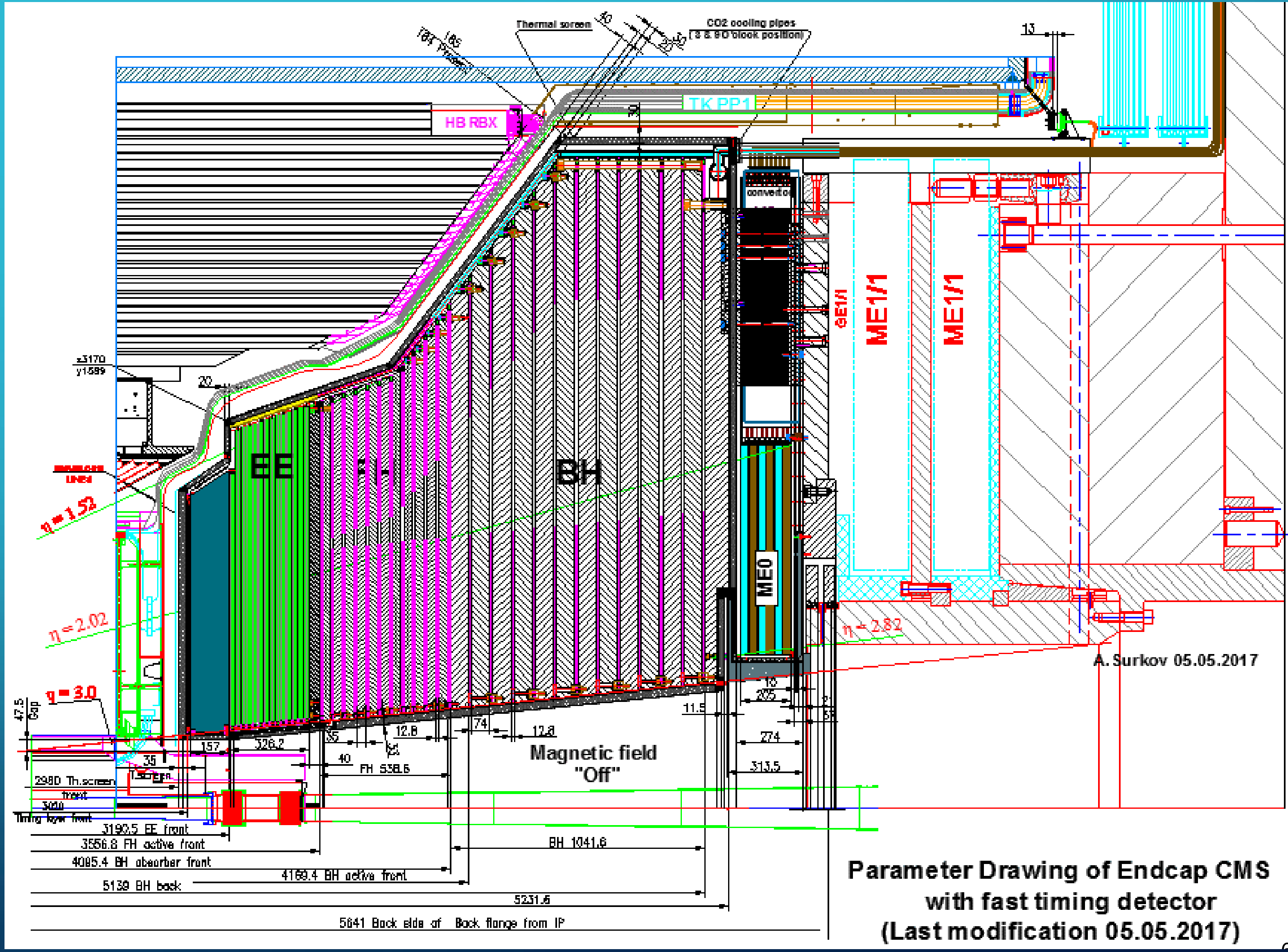
LGAD: Strong collaboration across experiments





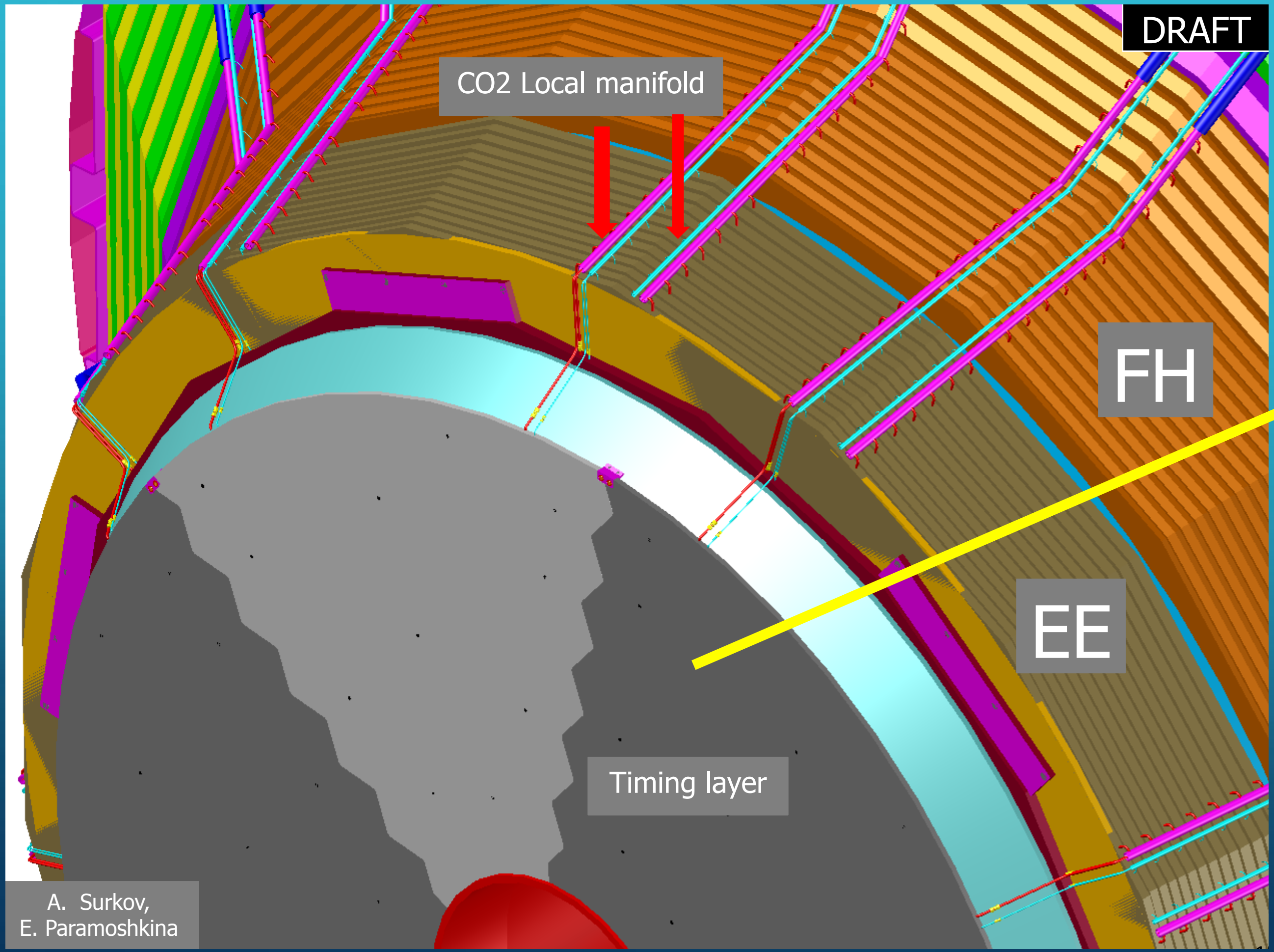
Endcap Timing Layer

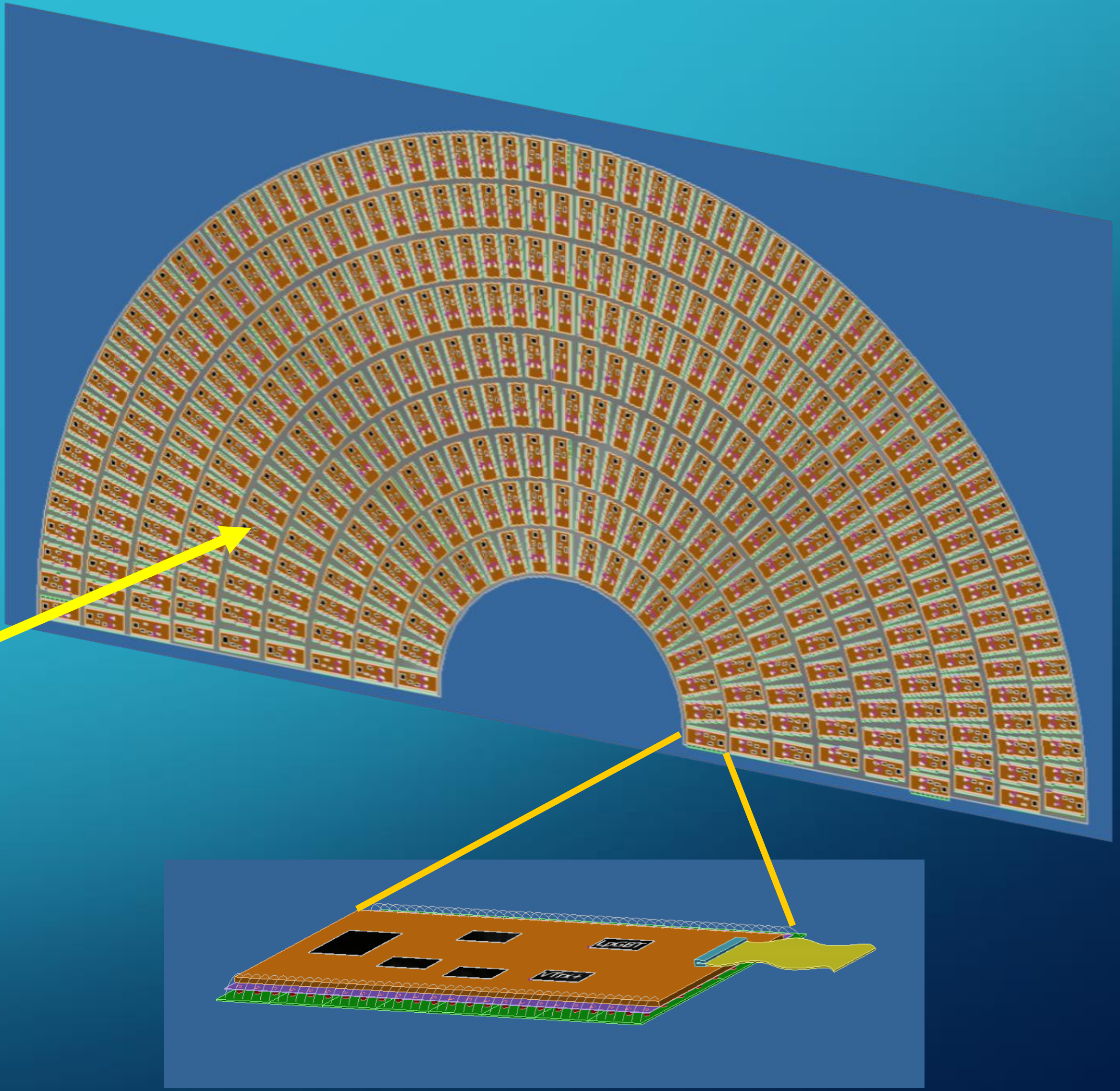




Parameter Drawing of Endcap CMS
with fast timing detector
(Last modification 05.05.2017)

Tiled Modules of Silicon Sensors



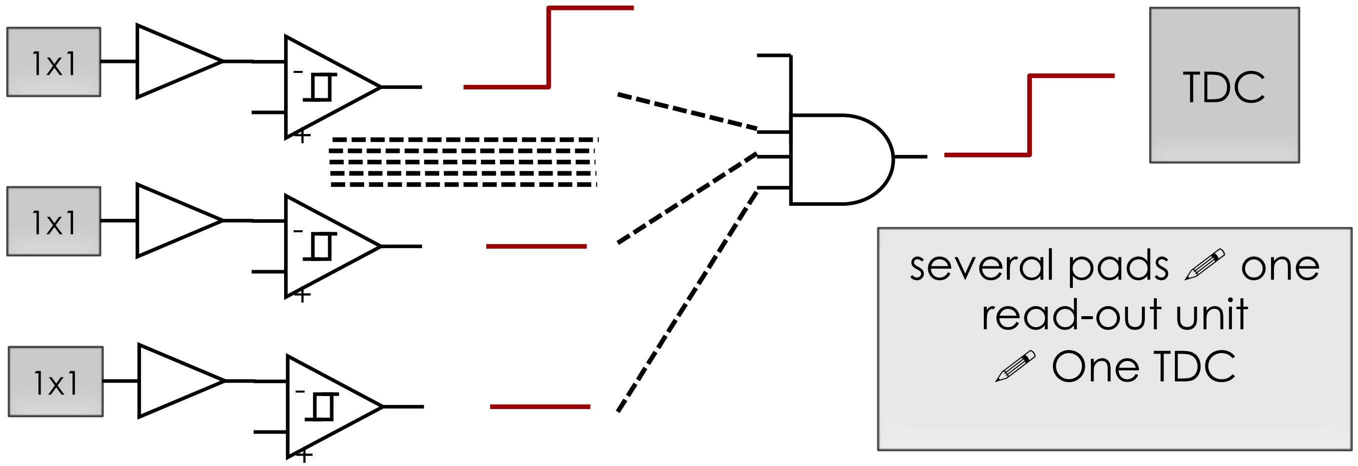


Decoupling of sensor size (PAD) and readout unit (TDC)

Sensor pad != read-out unit

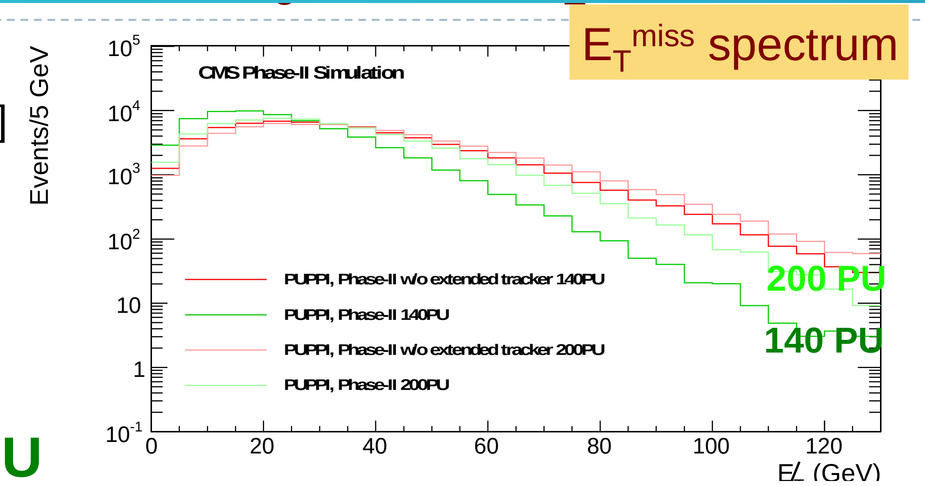
If not: merge n front-end channels after the discriminator to create a larger mm^2 read-out unit

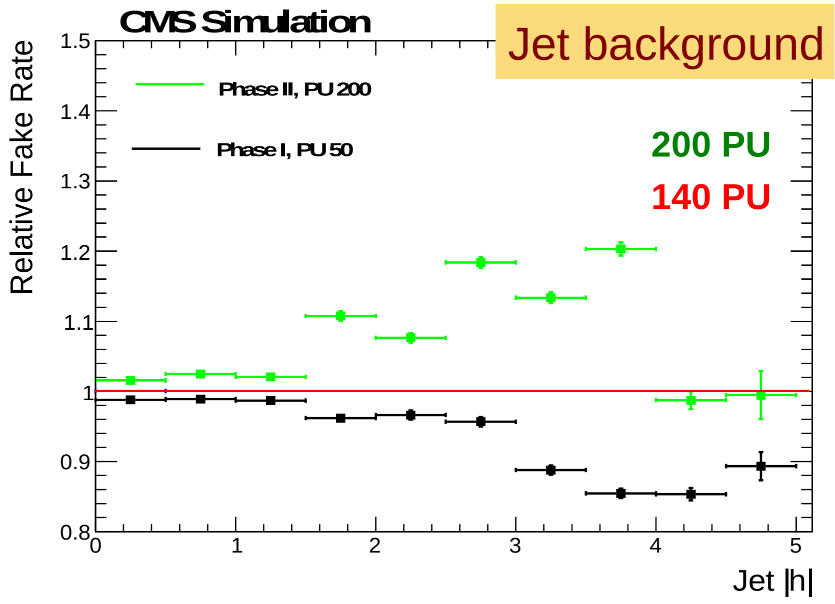
Digital summing retains all the benefits of small pads, while allowing for a reduced number of TDCs and read-out channels.

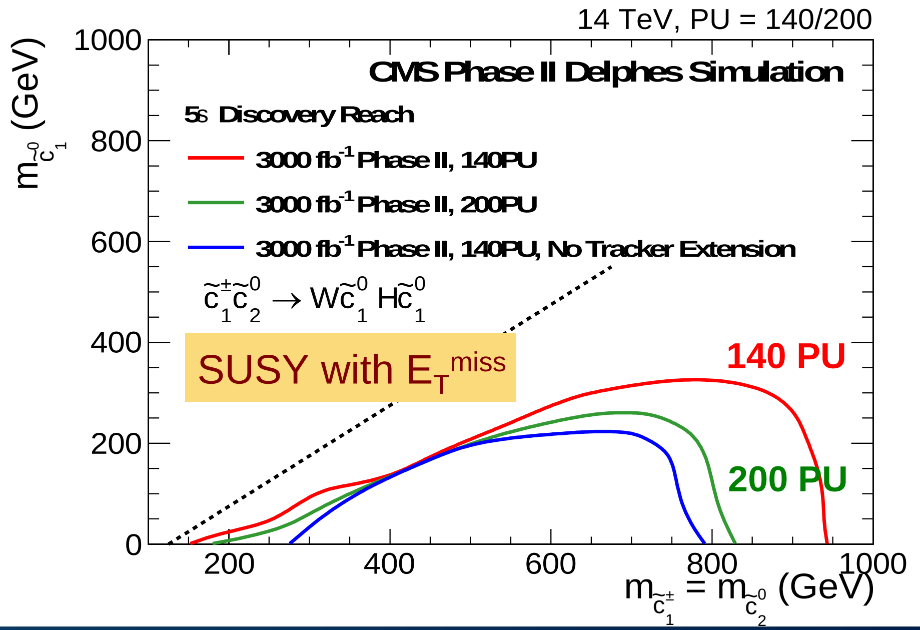


Countering the Anti-luminosity effect

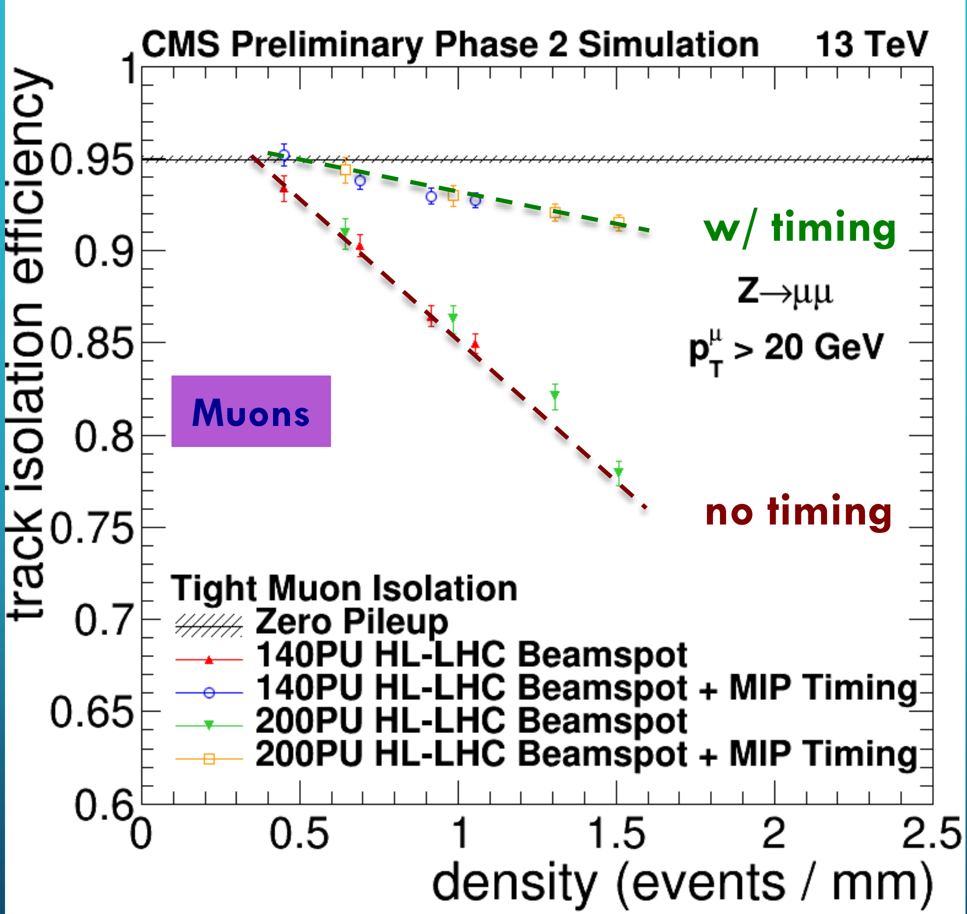
- CMS Upgrade Scope document:
  - [CERN-LHCC-2015-19, LHCC-G-165]
- **VBF $H \to \tau\tau$ requires 40% more luminosity at 200 than 140 PU**
  - E_T^{miss} resolution / Jet fake rate
- **Searches with E_t^{miss} less sensitive at 200 PU than 140 PU**

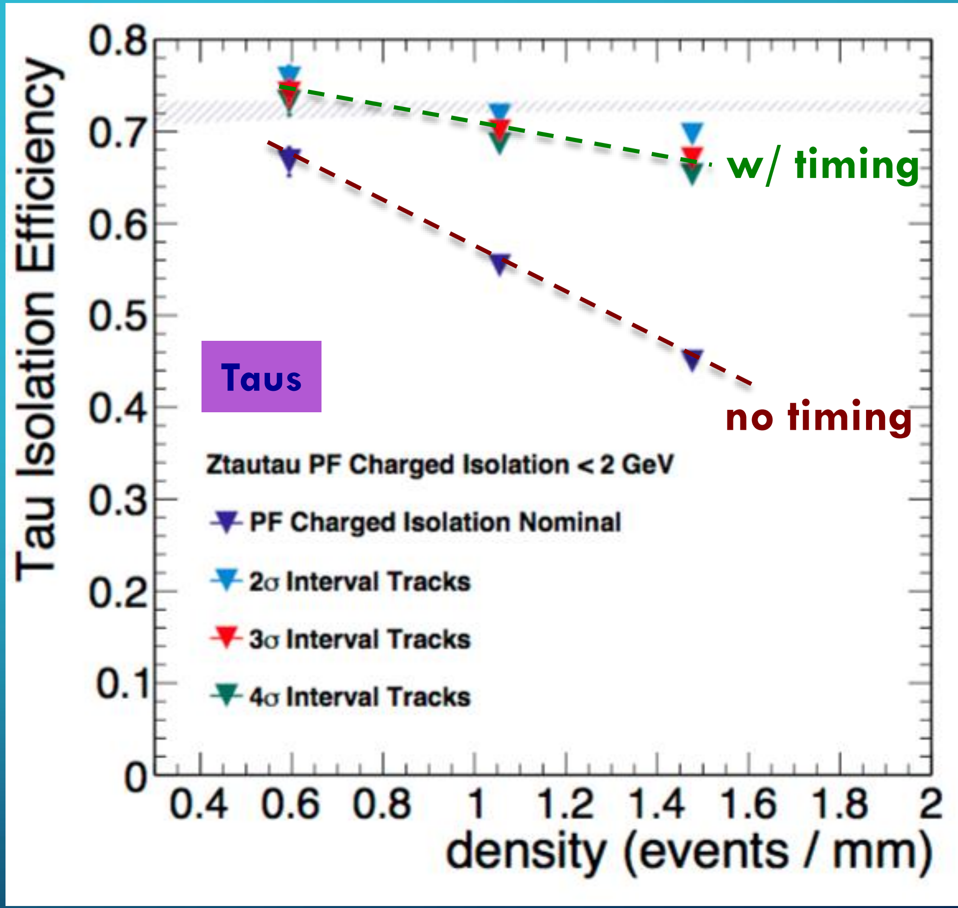






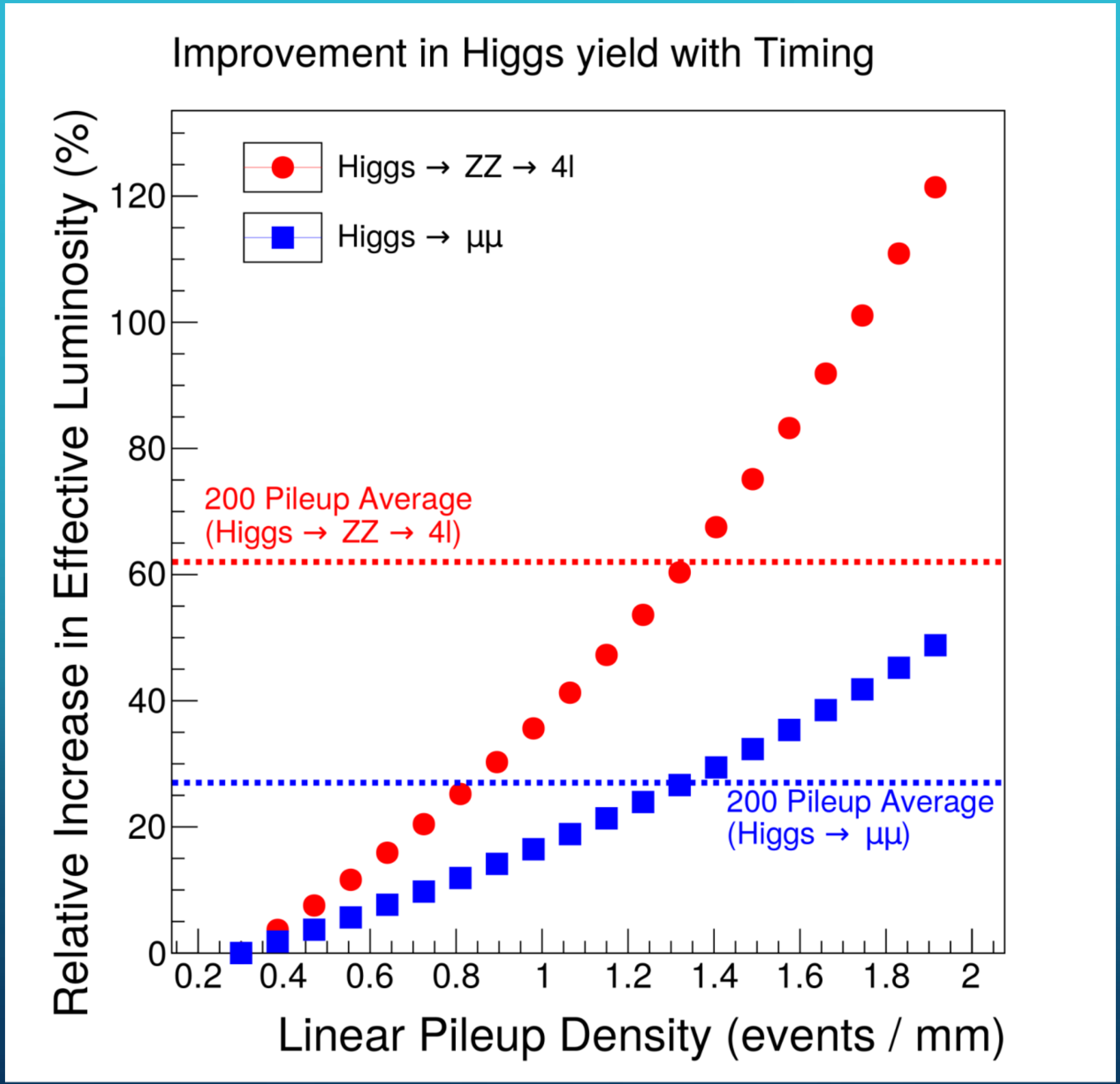
Muon and Tau Lepton Charged-Partcle Isolation Efficiencies

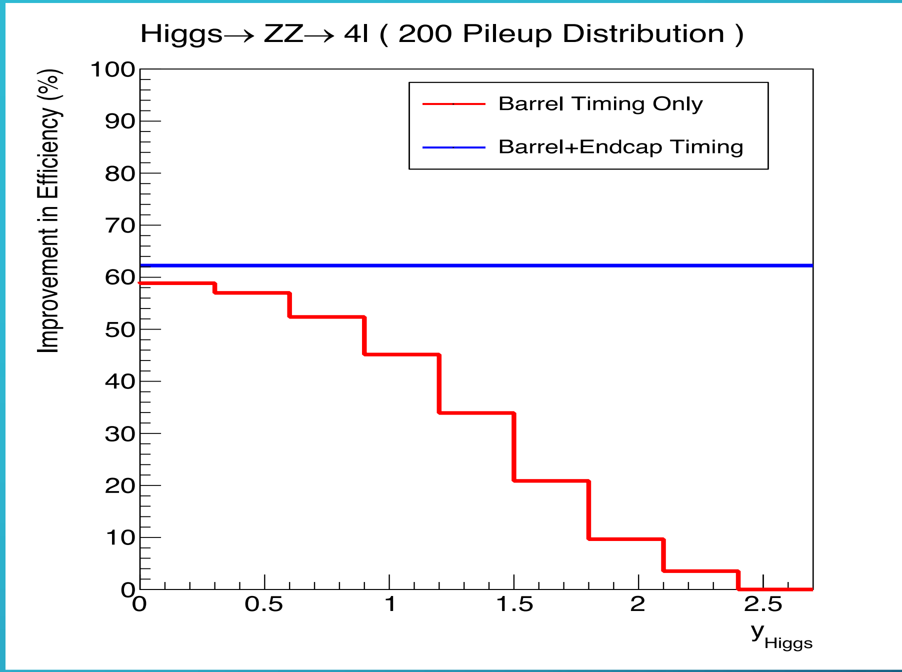


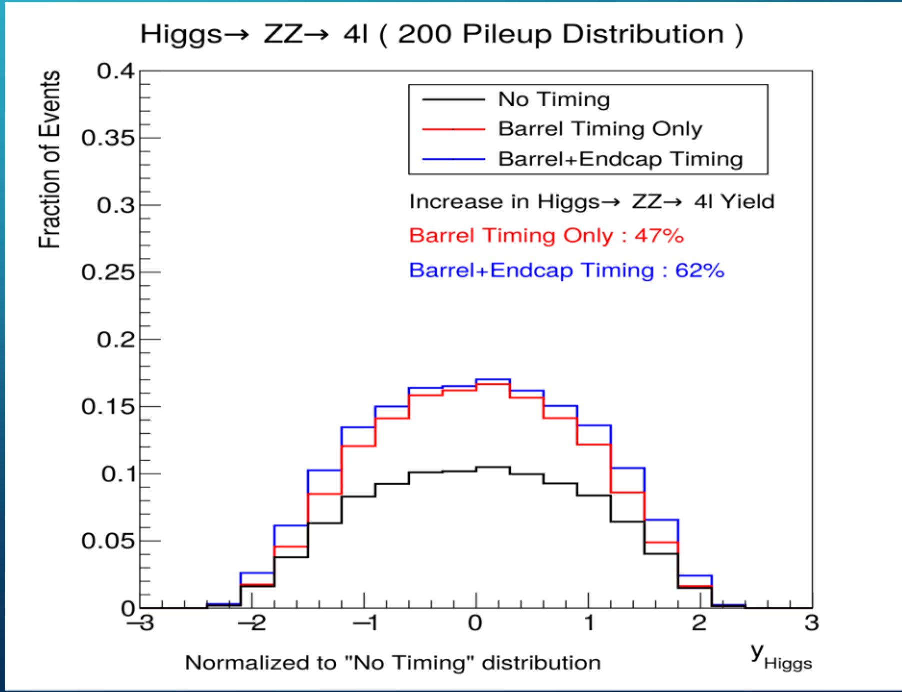


- Acceptance gain in searches and precision measurements

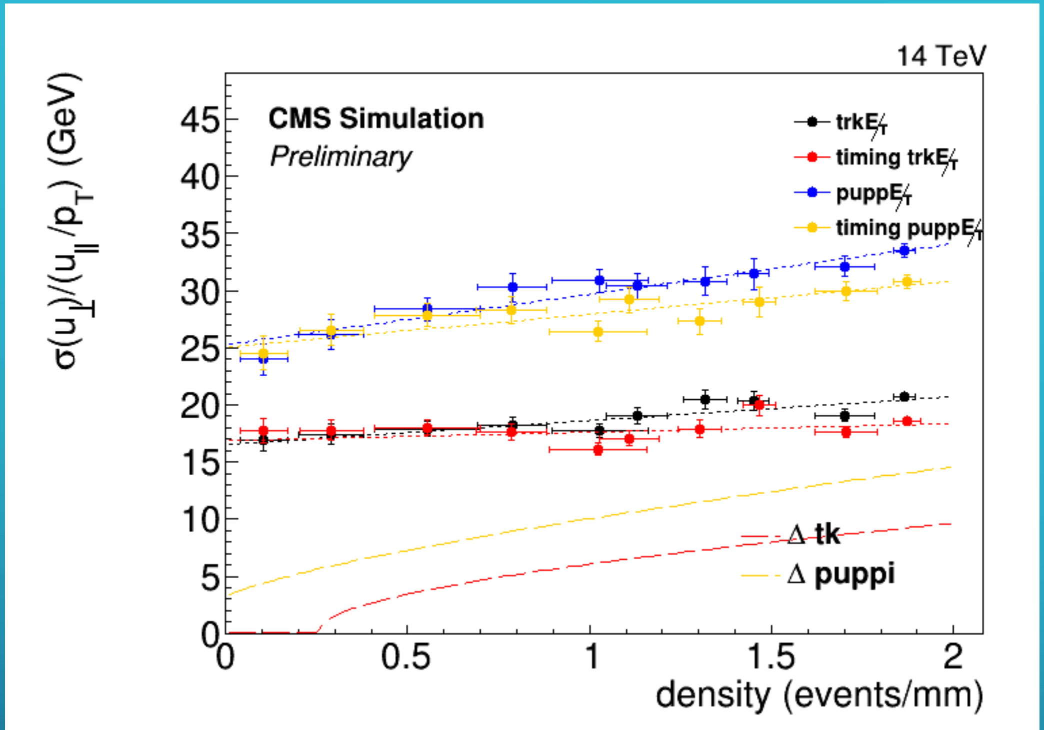
Higgs → μμ & Higgs → ZZ→ 4l

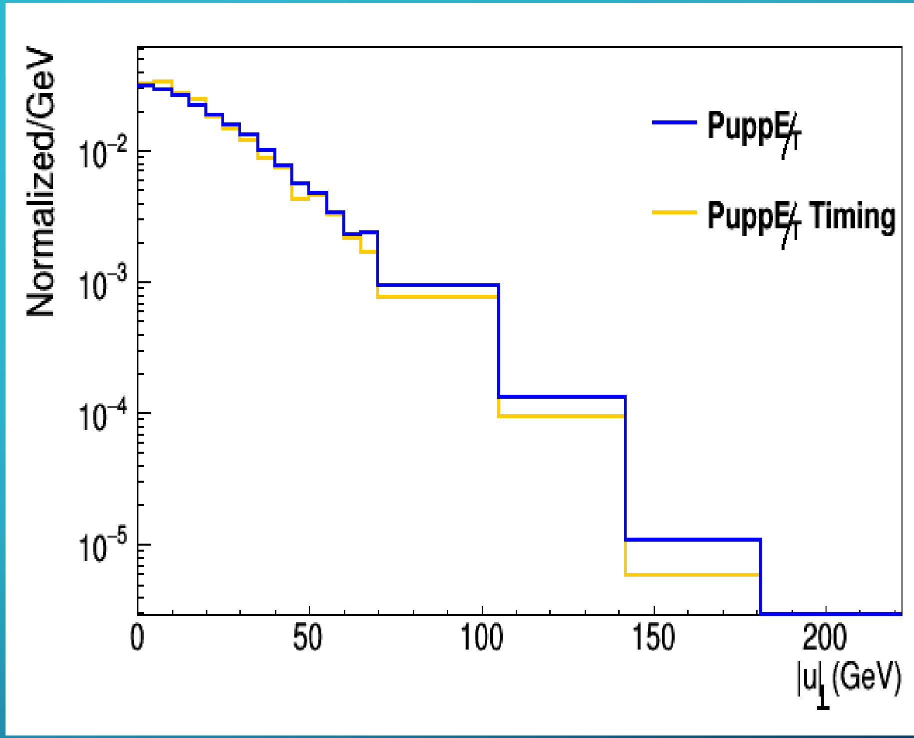






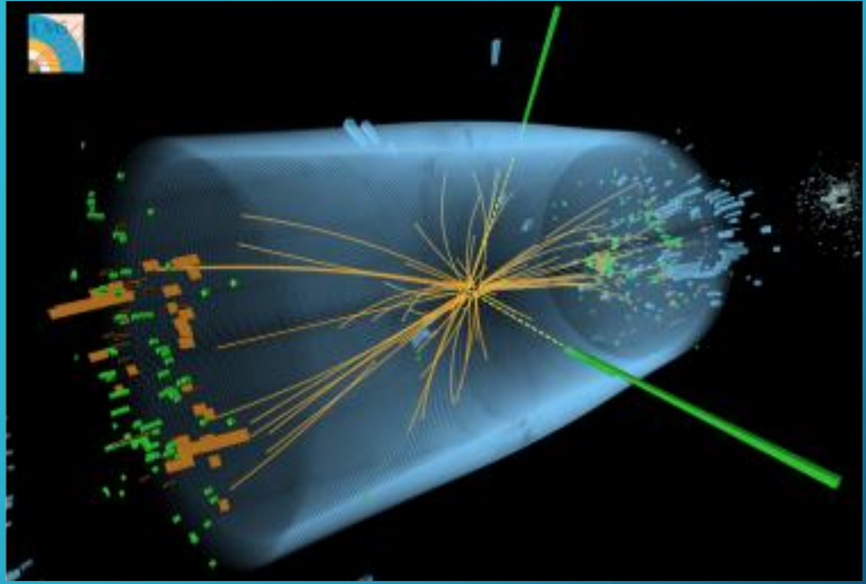
Missing Transverse Energy



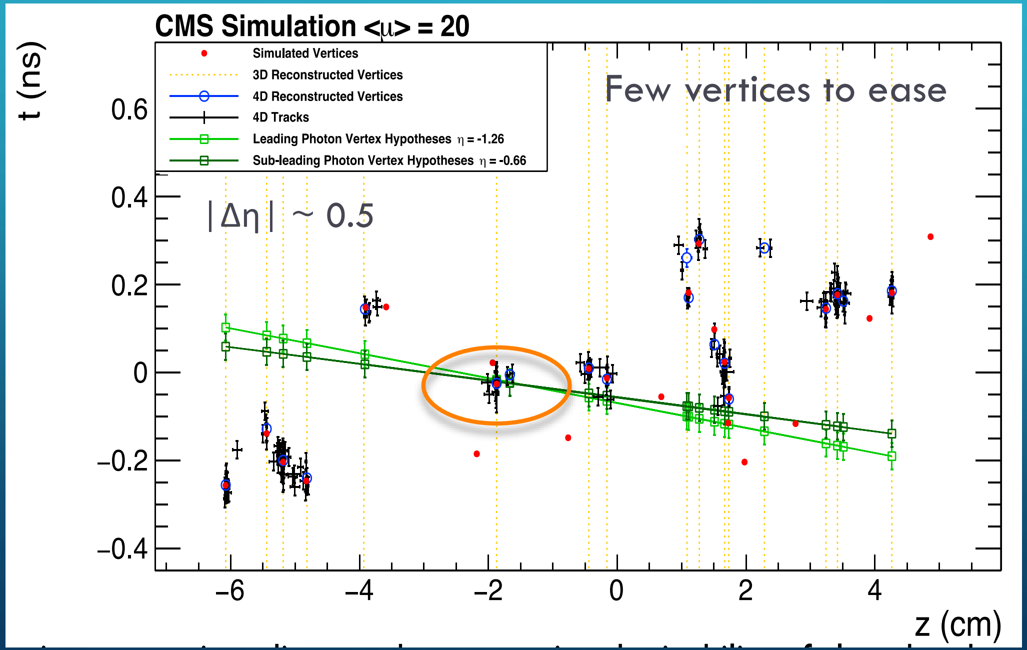


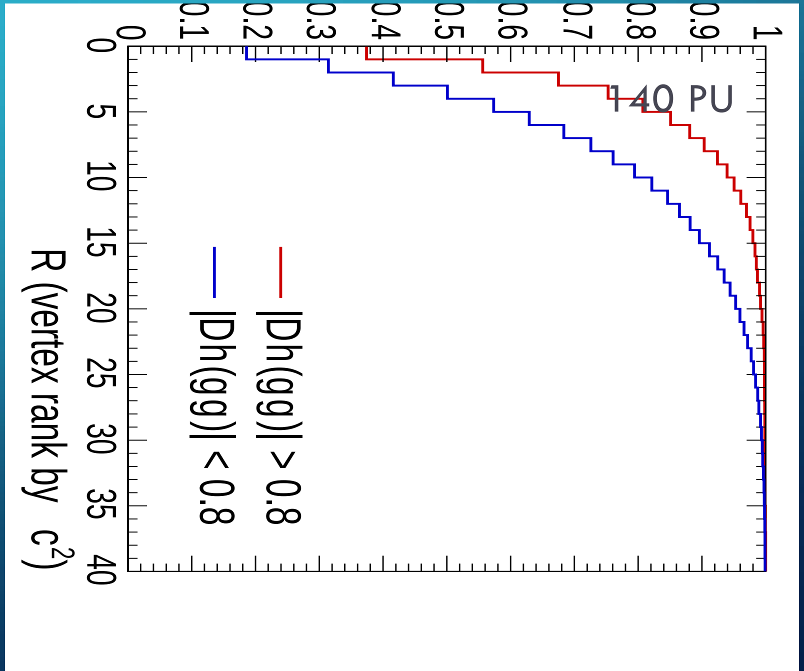
- MET Resolution study using Z→μμ events
  - PUPPI with track time information [photon timing not yet included]
- MET spectrum: tails reduced by a factor ~2
  - Offset [almost entirely] the performance degradation at 200 PU

H→γγ at HL-LHC



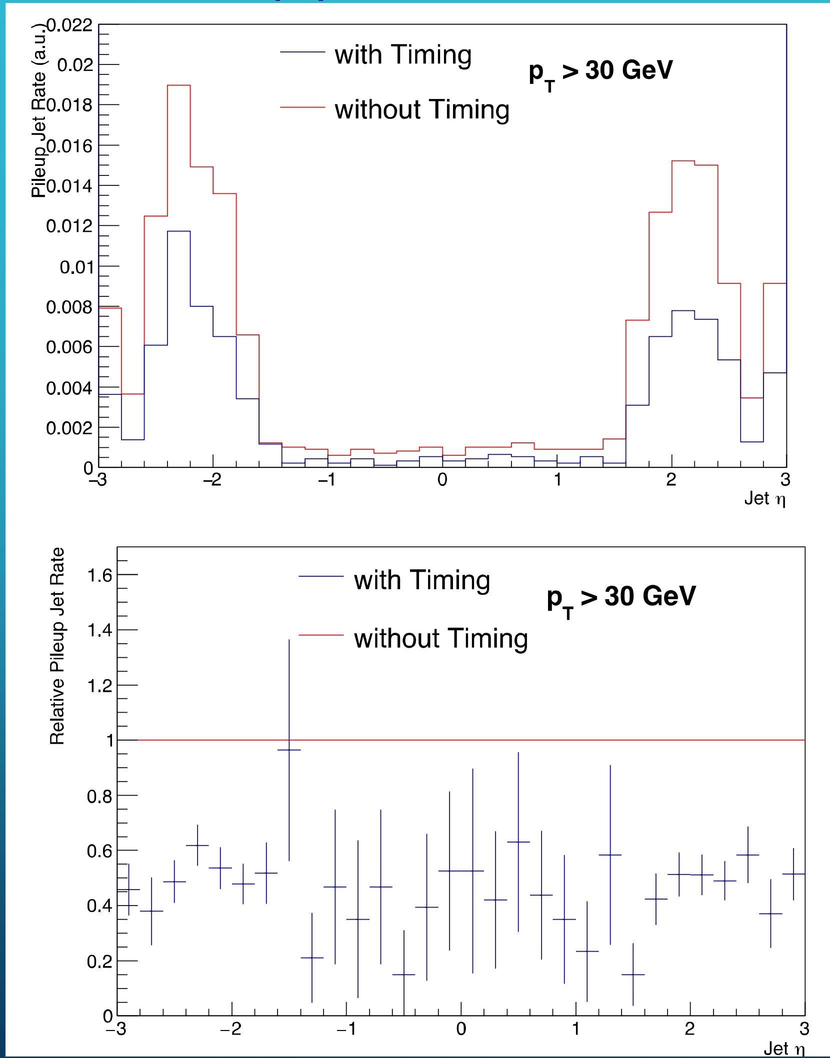
- Calorimeter timing-based triangulation matched to vertex time information
  - Resolve ambiguities of calorimeter timing-based triangulation
  - Simple χ^2 matching: 5X reduction in 'effective pileup'
- H→γγ at HL-LHC: substantial failure of kinematic vertex identification:
  - $\varepsilon(|z_{vtx}-z_{true}|) < 30\%$ at 200 PU (~ 80% in Run I)



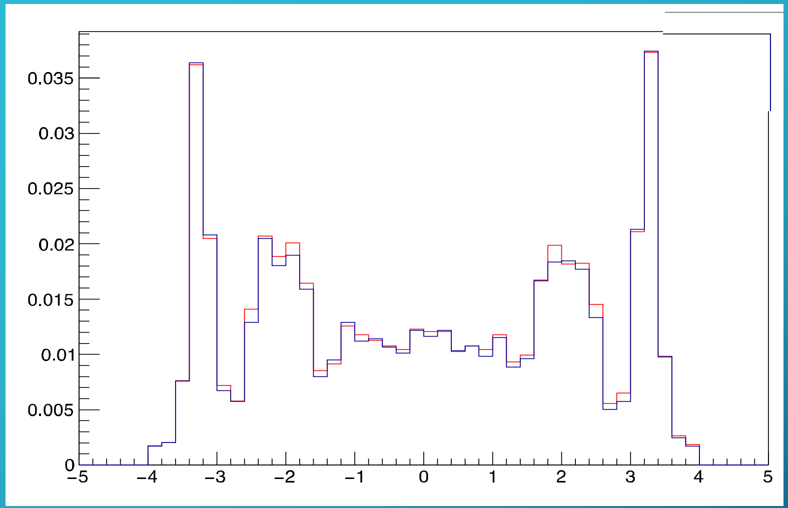


Pile-up Jet Suppression

- Pileup jets

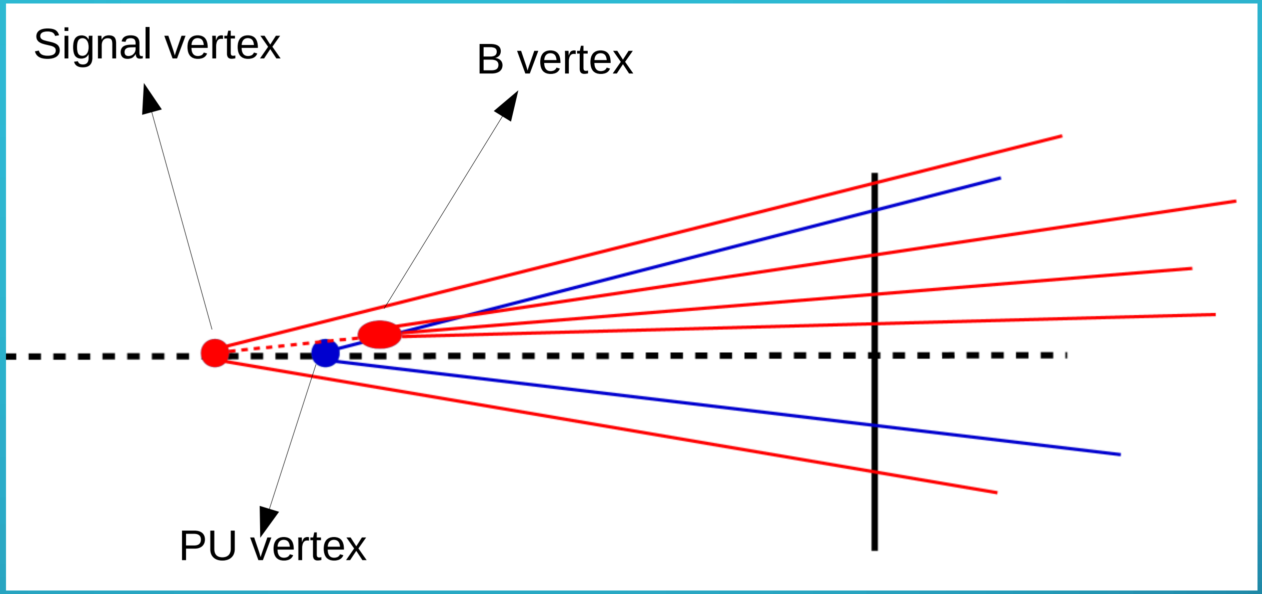


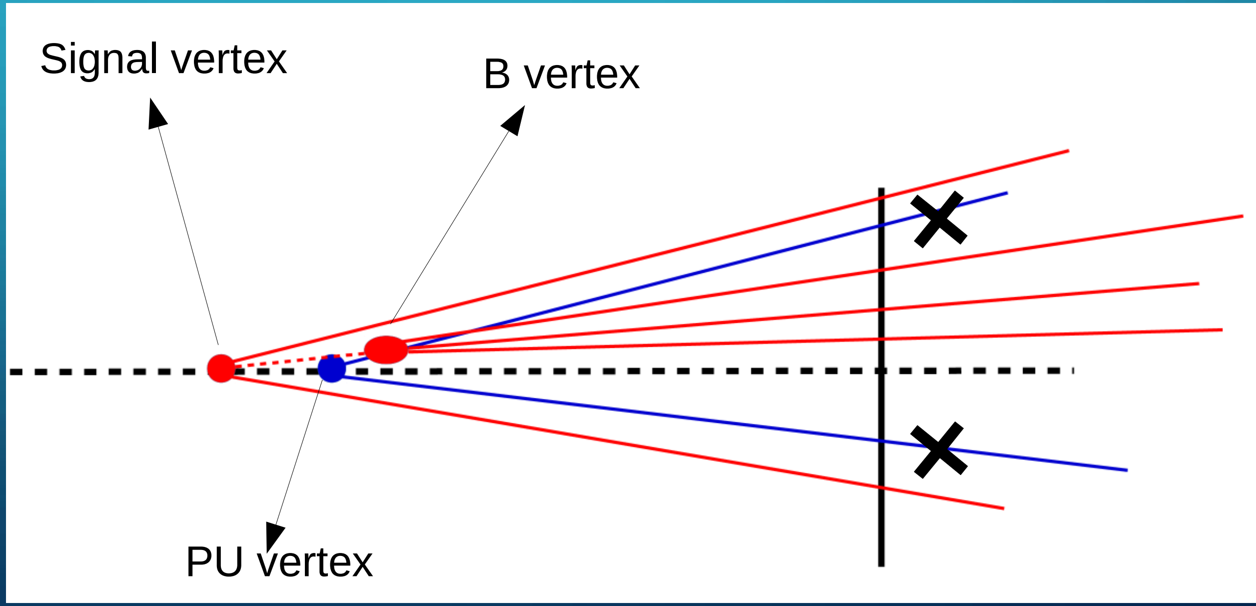
- Signal [generator matched] jets



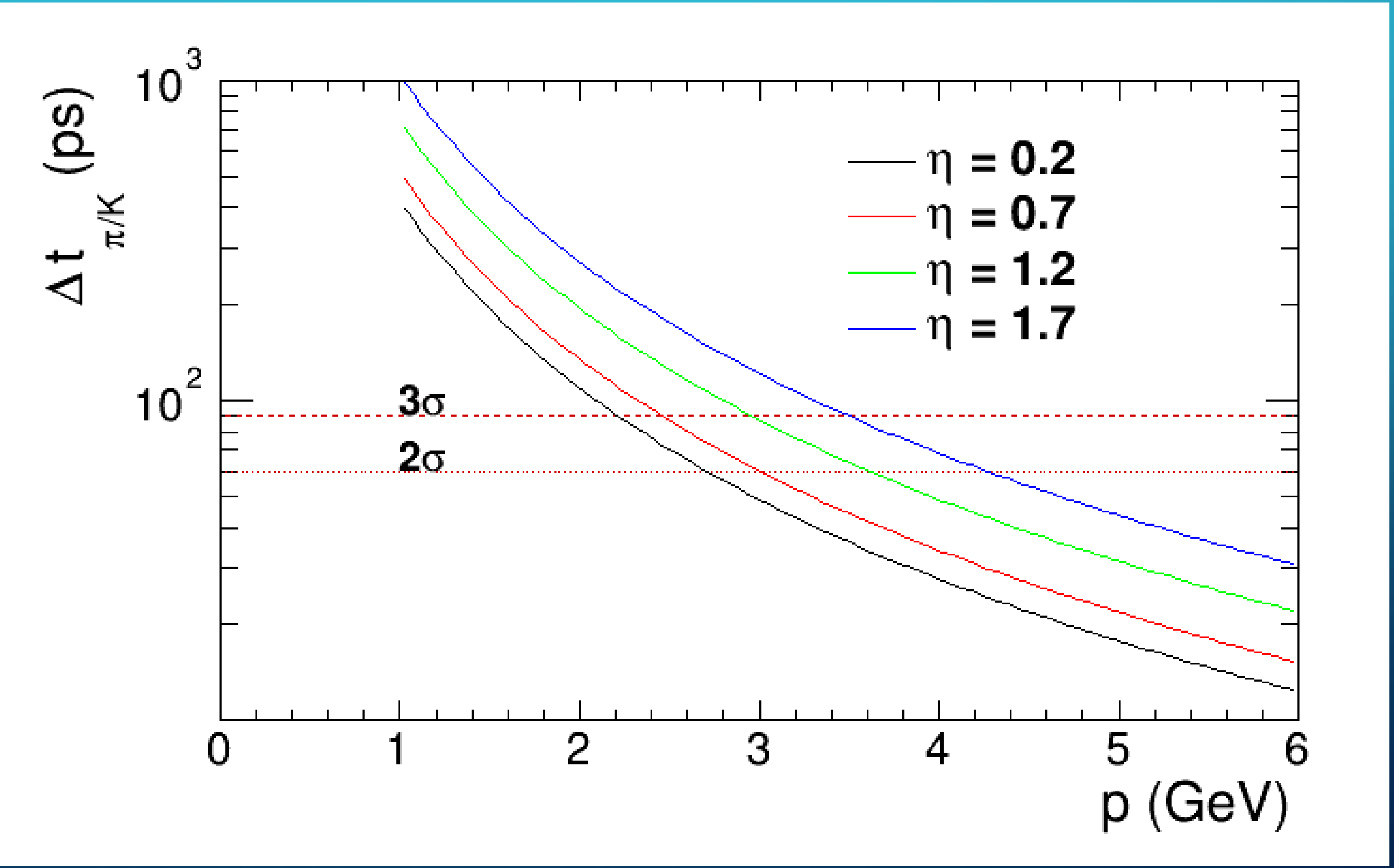
- Rate suppression from jet cleaning from pileup with timing
  - Key signature for jet tagging
- Efficiency for signal jets unaffected
  - Current baseline: |η|<3 coverage

Secondary Vertex Reconstruction





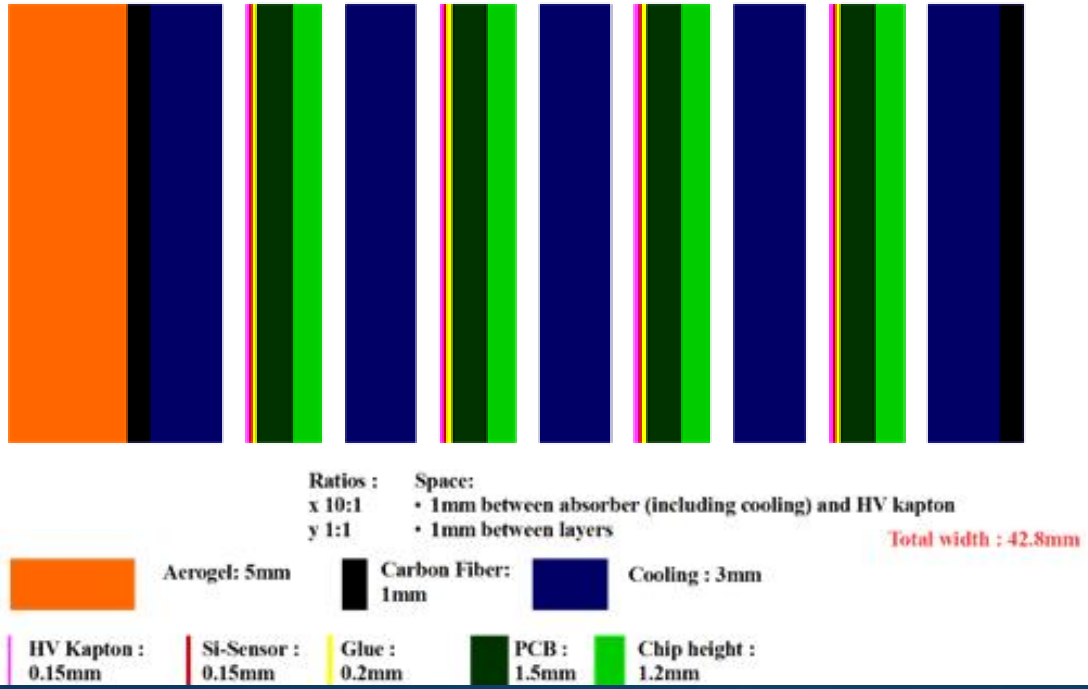
Time-of-Flight Particle Identification (π/K up to 2-3 GeV)

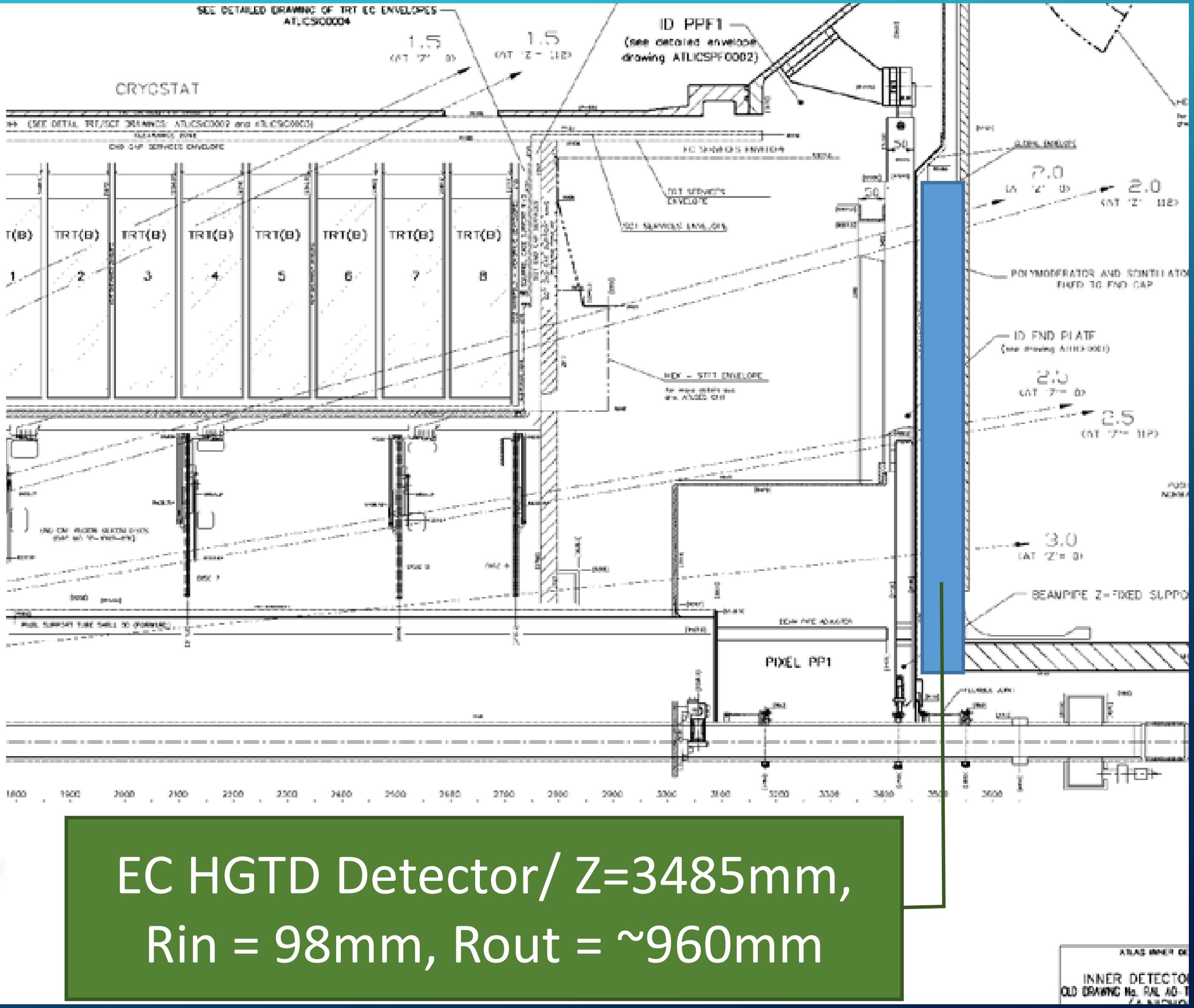


ATLAS HGTD proposed location

Common dimensions:
- **Insulation 5mm**
- **Carbon fibre 1mm**
- **Cooling 3mm**
- **SiSensor 0.15mm**
- **PCB+Electronics(Air)=2.7mm**
- **Tolerances 1mm**

Timing detector:
- **43mm**
- **4 Si sensor layers**



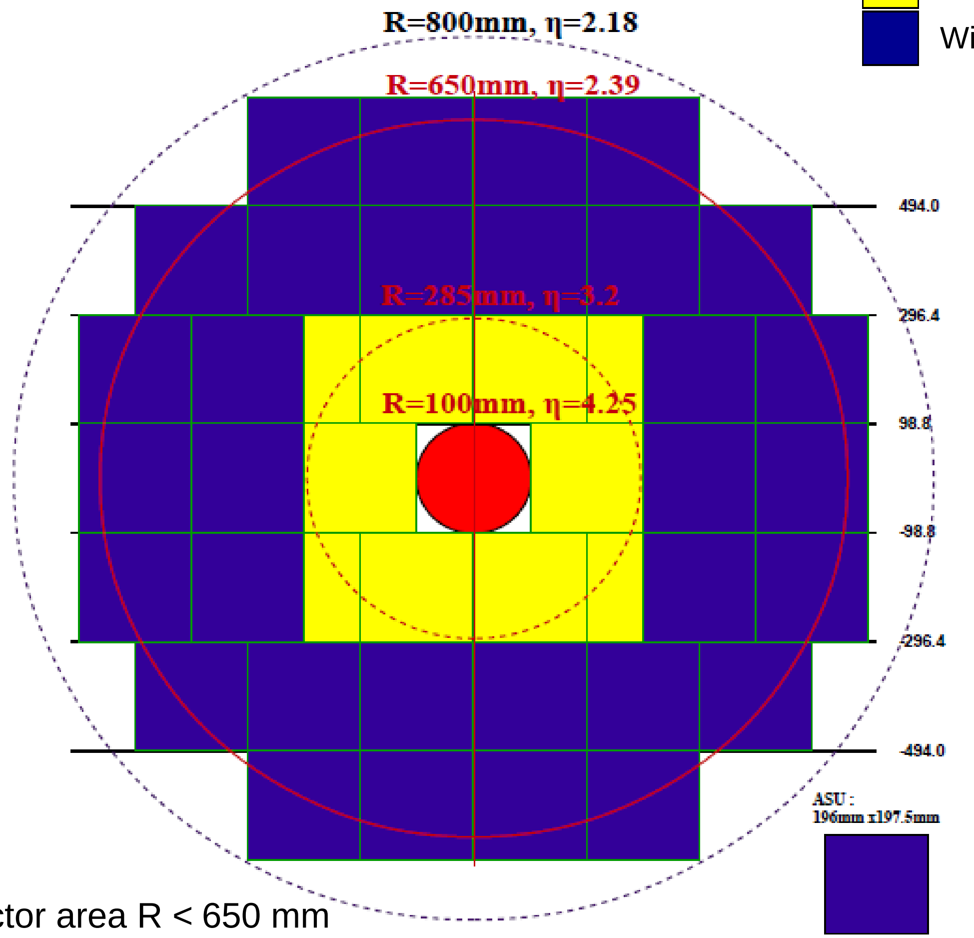


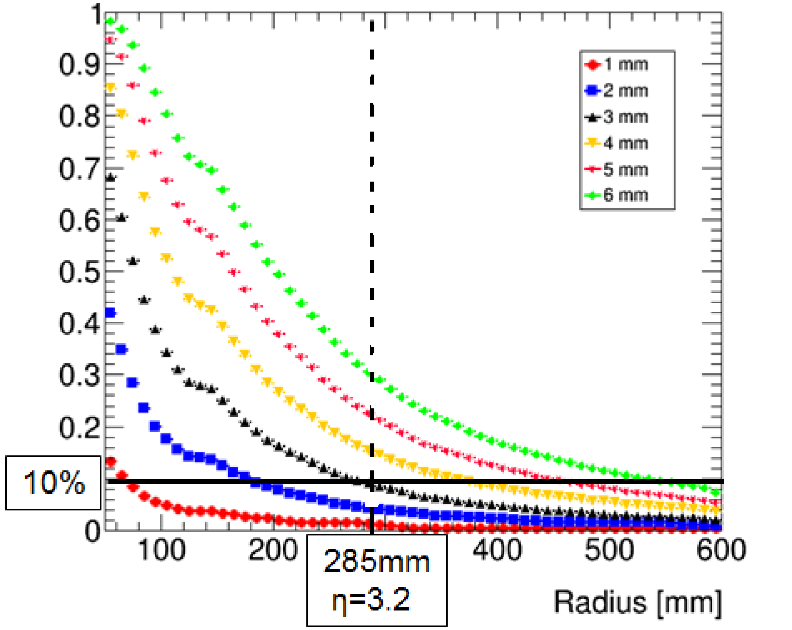
HGTD cell occupancy

Nothing is optimized yet

With 1· 1 mm² cell for R < 285 mm

With 3· 3 mm² cell for R > 285 mm





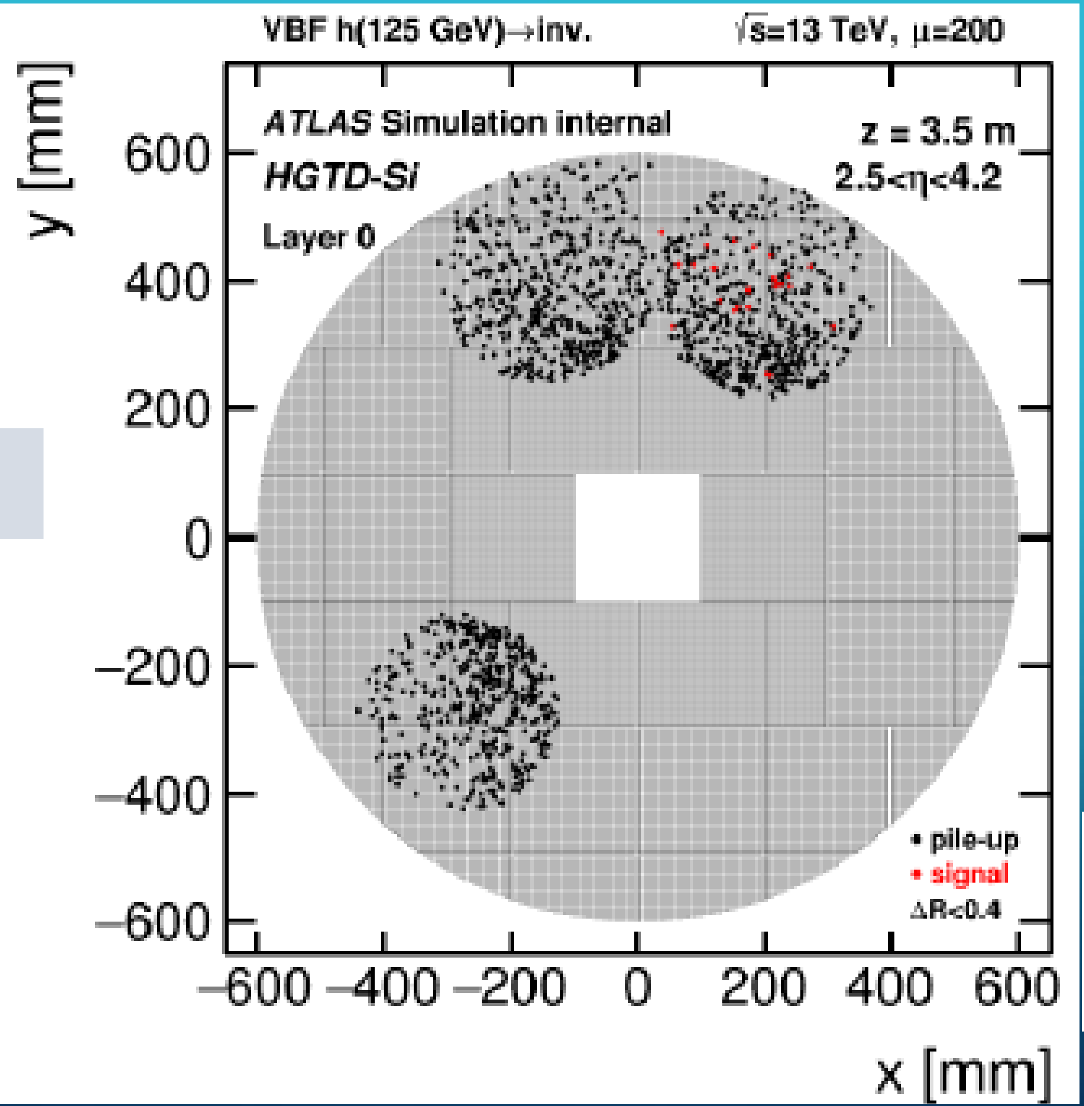
Occupancy plot for various cell sizes as a function of increasing (decreasing) radius (|□|)

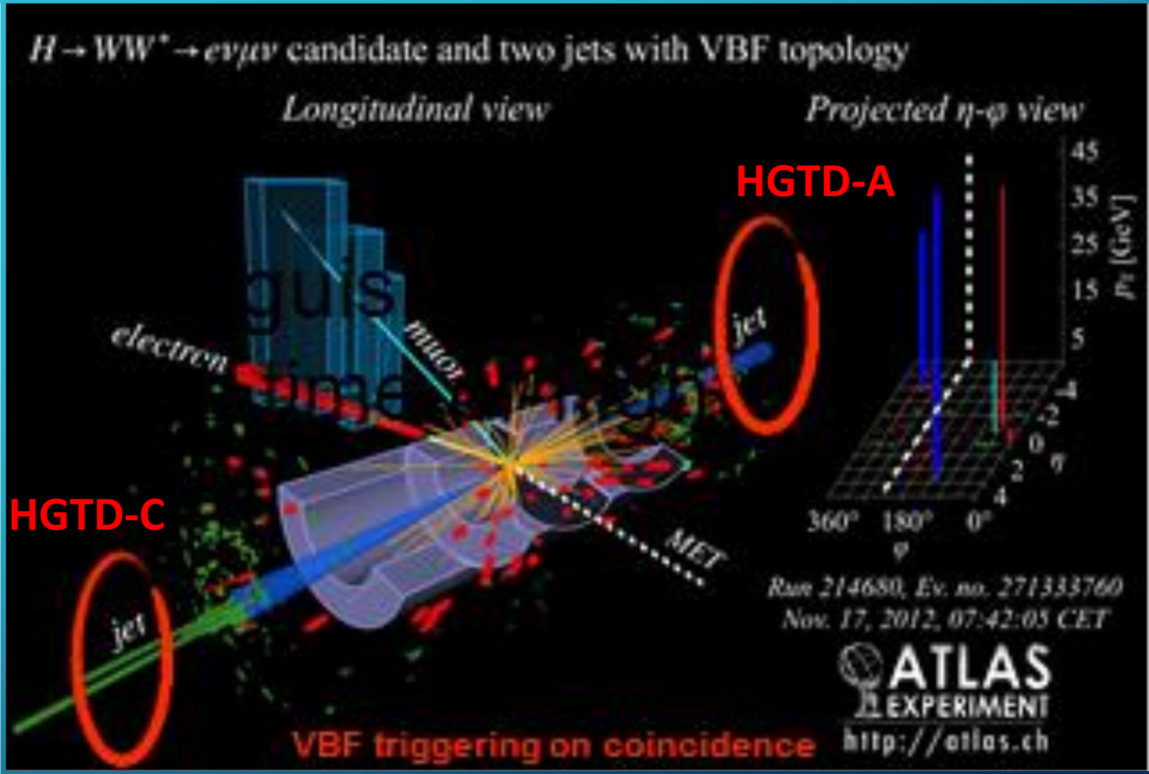
Detector area R < 650 mm
Maximum size R = 800 mm

6

Signal jet in high pileup

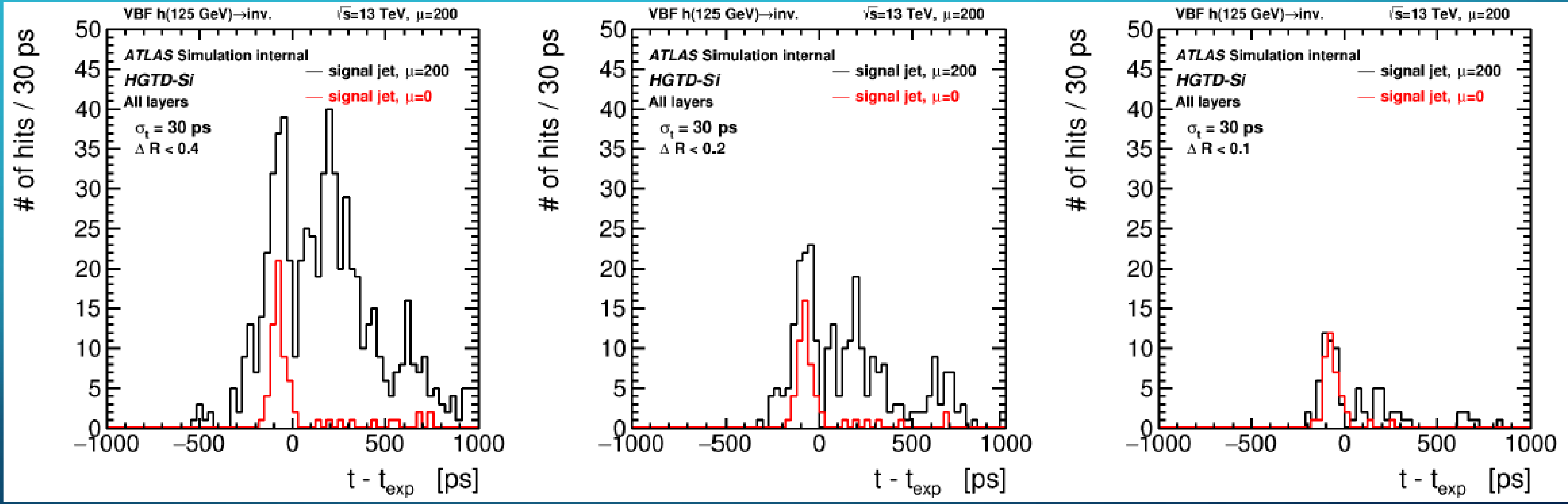
∝ = 200





L0 timing trigger for mitigation of pile-up Jets based on:
- Identification of cluster of track hits, from the same jet, with time coincidence within a bunch period
- Generation of L0 level trigger (40MHz) containing L0 Time object, to be combined with L0 Calo for a global trigger decision.

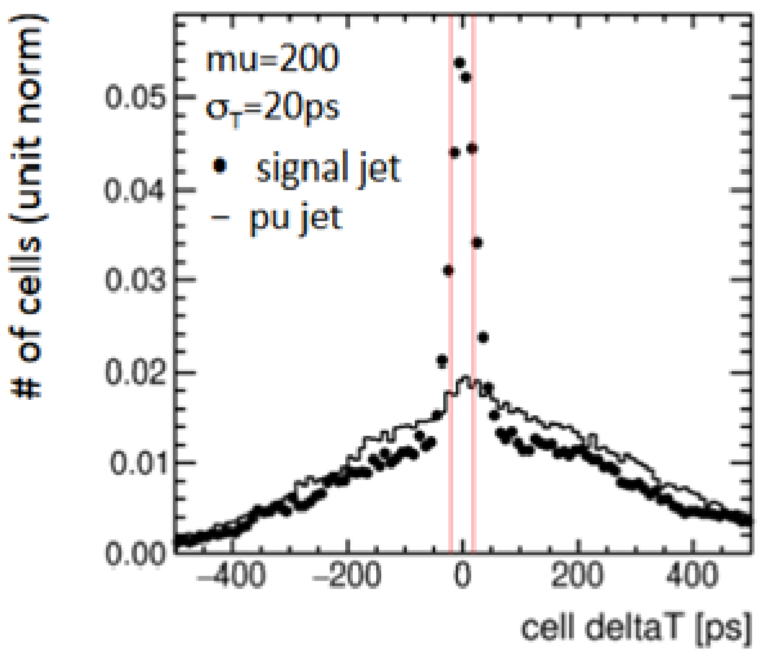
Timing of jet core

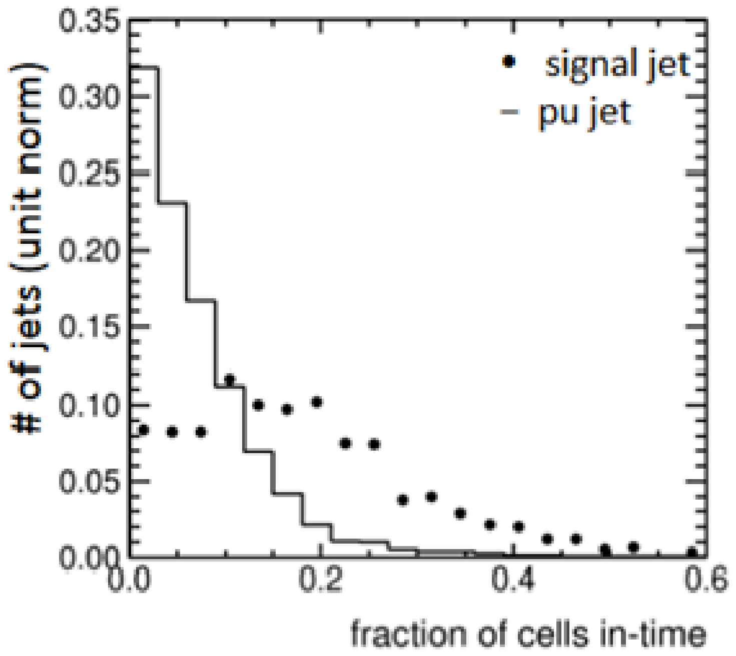


In-time fraction of cells within a jet

- Count number of in-time cells associated to each jet
  - cells with deltaR<0.05 to nearest cluster in jet
  - signal window = 1 σ_T

Sample with ~2k signal jets

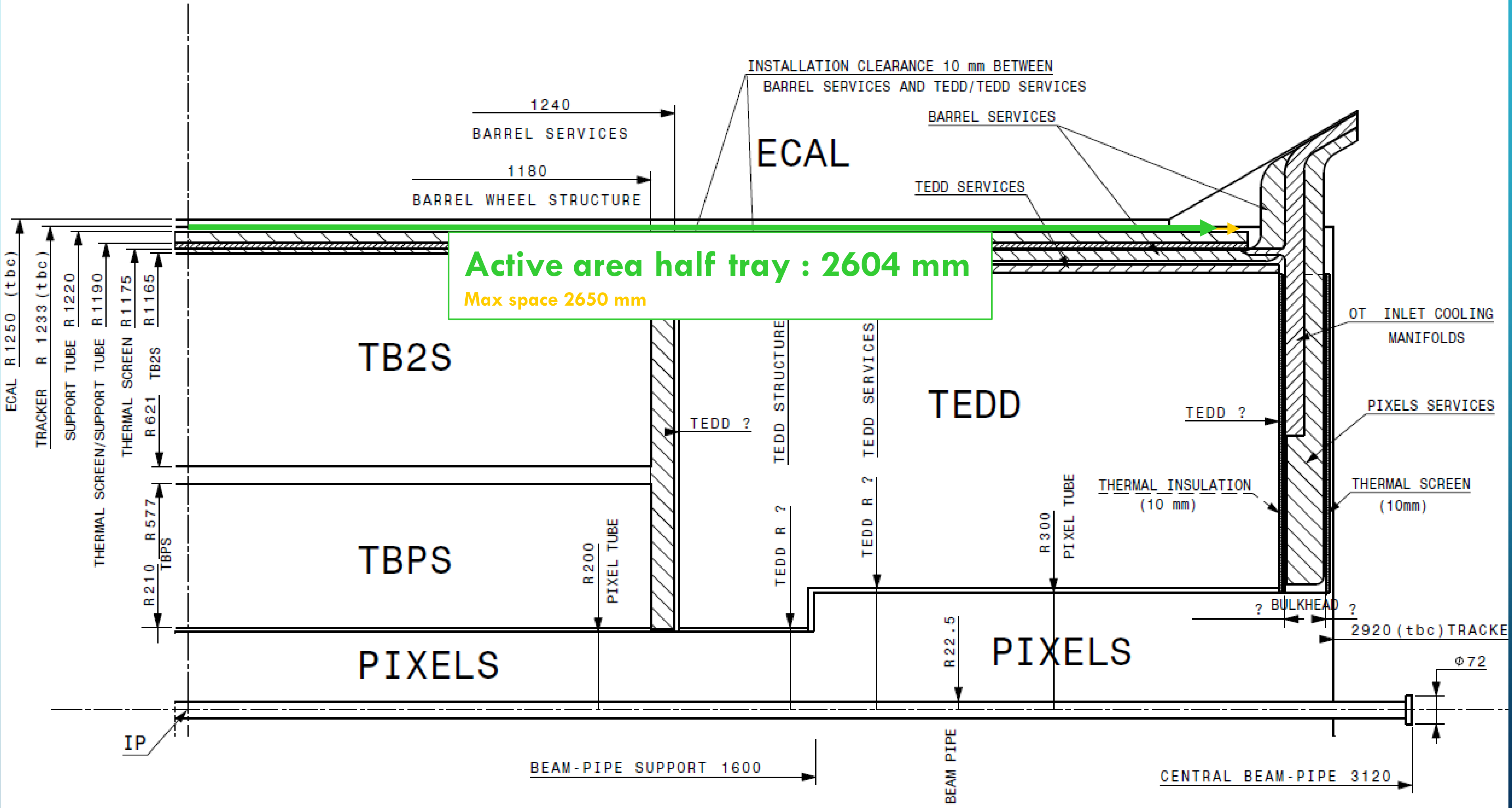




Summary – Lecture 3

- Fast timing has the potential to open up new possibilities for future machines - and it is very exciting to think about where that may lead.

Backup



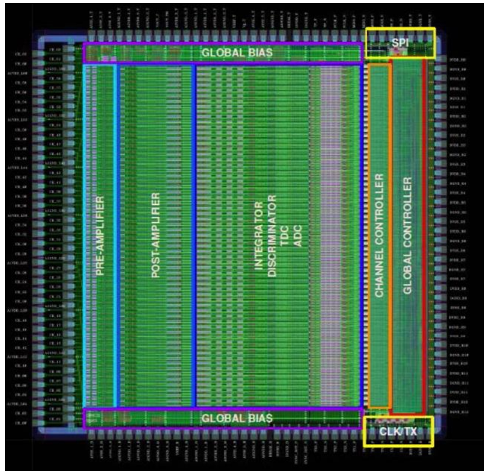
Unless otherwize stated all dimensions in this drawing represent the limits (envelopes) within which the component/assembly must fit.

For details of the structural parts, see the 3D model ST0579969_03 " CMS TRACKER PHASE 2 UPGRADE "

CMS phase 2 Tracker GEneral Parameters		DRAWN	P. LENOIR 2016-06-1
CMS PHASE 2 UPGRADE TRACKER ENVELOPES	SCALE 1:10	CONTROLLED	
		RELEASED	
		APPROVED	
		CAD Document Number	ST0764001_02
		REPLACES	
NON VALABLE POUR EXECUTION NOT VALID FOR EXECUTION	QAC -	CMS2TGEP0001	SIZE 3 IN

BTL Readout ASIC

- TOFPET2 chip seems to meet basic needs for BTL with minor changes needed to match expected SiPM gain and to reduce deadtime through time multiplexing
  - Timewalk correction is critical for TOFPET2, in particular timewalk correction for multiple hits needs to be understood.
  - TOFPET2 plans for submissions requires attention (see comments on schedule)



- Architecture based on TOFPET1
- 64 channel ASIC (CMOS 110 nm)
- timing and energy branch per channel
- dynamic range: configurable 150 to 1500 pC
- timing branch: amplifier, discriminators and TDC
- energy branch: amplifier, charge integrator and ADC
- time-over-threshold available
- 4-fold TAC per channel (de-randomization)
- TDC binning 40 and 20 ps
- energy measurement: 8 bit, noise ~1 LSB
- max rate per channel 0.6 M hits/s, limited by output links (3.2 Gb/s)
- power consumption ~5-8 mW/channel

Total power budget for BTL in the range between 12 kW and 18 kW

HGTD Electronics

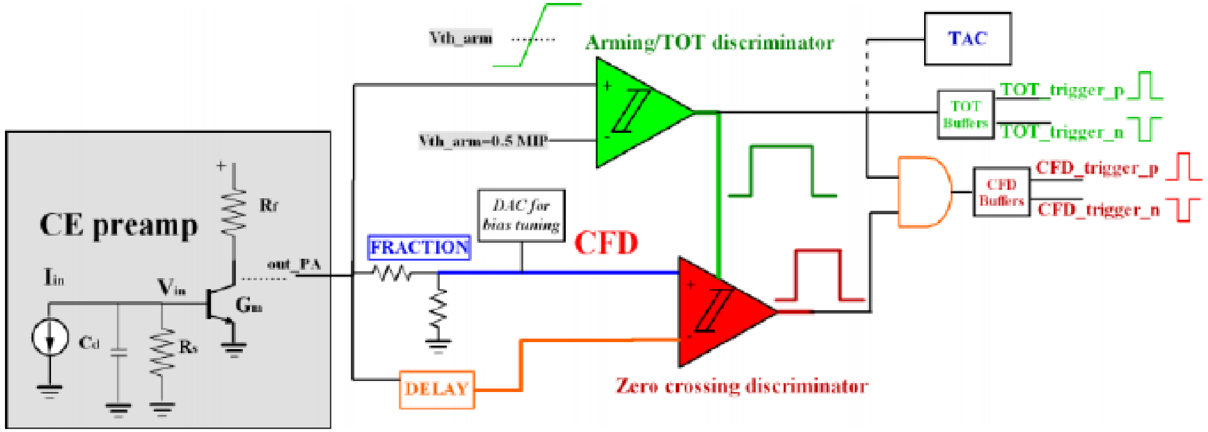
$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

Jitter — Time Walk — TDC

Electronics:
- 130nm TSMC
- 50mW/cm^2
- Cd= 2pF or 20pF
- Bump bonding or glueing
- ASIC foreseen in 2017

Time Walk Correction (HGTD-Si):
- TimeOverThreshold (TOT)
- ConstantFractionDiscriminator (CFD)
- <10-20ps from electronics simulation

Sensors:
- Short risetime: 500ps
- Large S/N and S
- Study in testbeam
- Dedicated electronics



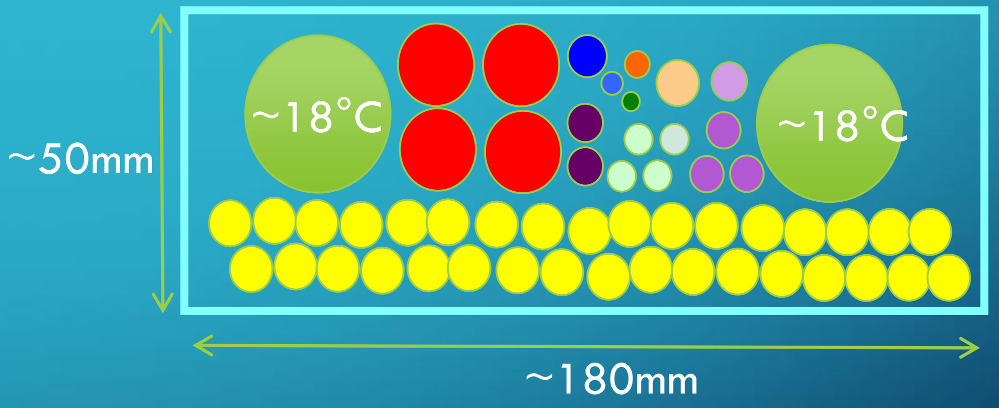
Services

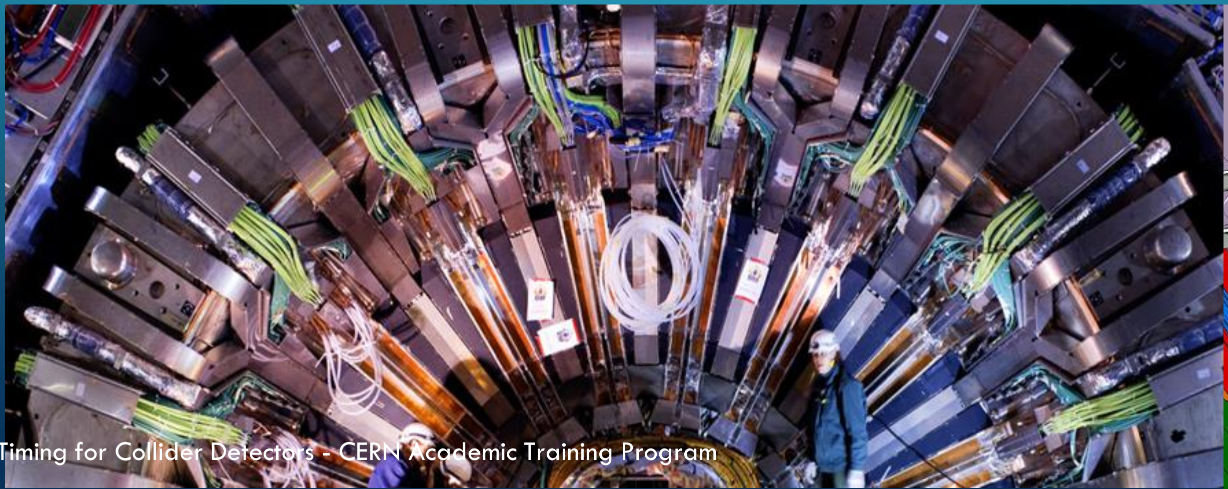
Each ECAL SM has one patch panel for the distribution of the services (18 per side)

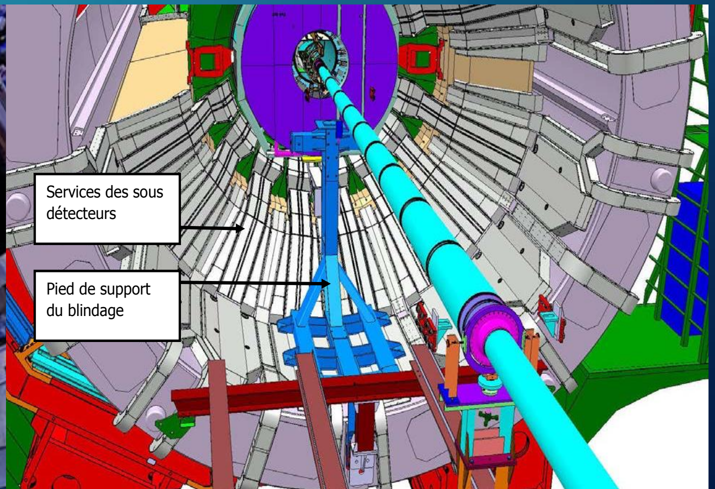
Service trays run out radially from each PP with a pair of adjacent SM trays run together (A/B)

Type	#(total)	Diameter
EB-HV	4	21.4
EB-DCS-PTM	1	11
EB-DCS-ESS	1	7.2
EB-DCS-HM	1	5.8
EB-LV-inhi	3	8.3
EB-LV-sen	1	8.3
EB-trunk	3	9.5
EB-LV	34	12.2
EB-sniffer/N2	2	10
EB-cooling-in flexible	1	41
EB-cooling-out flexible	1	41
EB-Mem-Hybrid	1	12
EB-Mem-Laser	1 per 2 SMs	10
EB-earth	1	4.9

~67% filled (75-85% practical max)



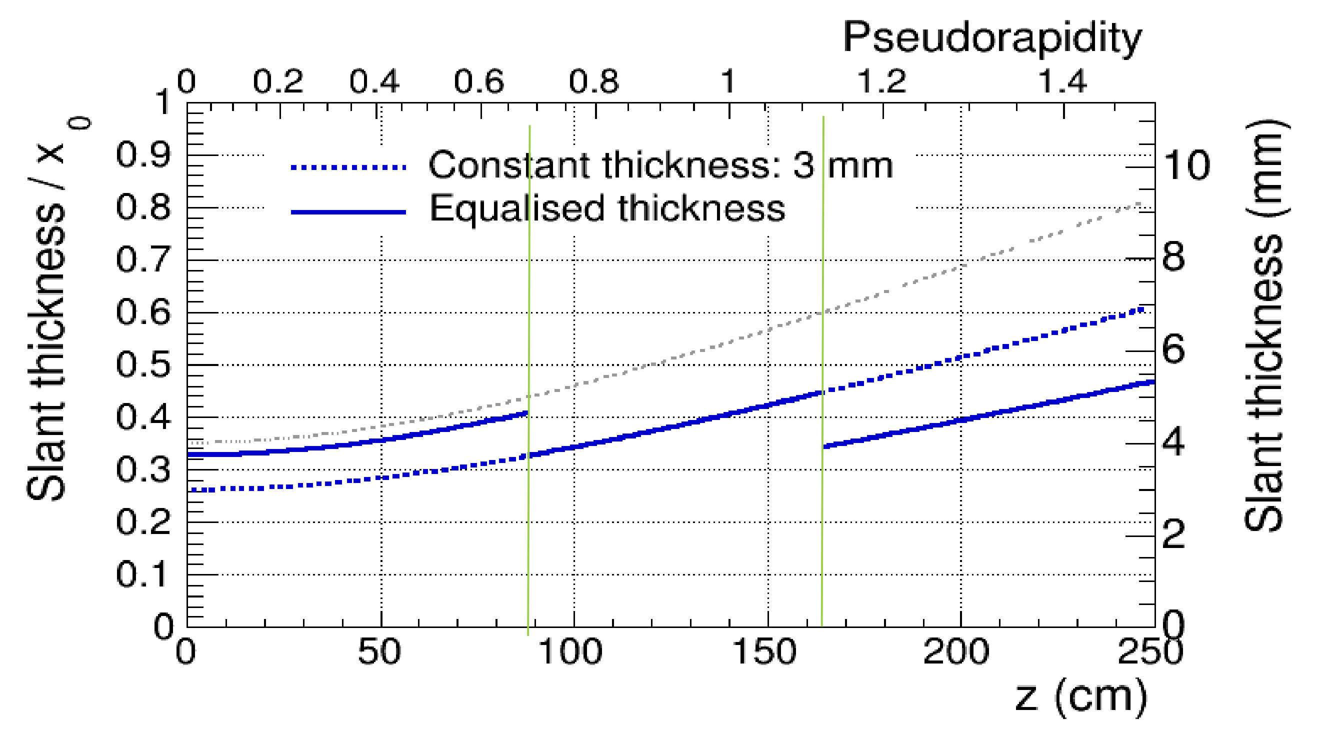




Equalized effective LYSO thickness

eta	Thickness [mm]	Volume [cm2]	Weight [g]	Module count	M_{xtal} per module [g]	
<0.6	3.75	0.54	3.9	1-19	250	4750
0.6 – 1.1	3.0	0.43	3.1	20-35	200	3200
>1.1	2.3	0.33	2.4	36-56	153	3213

crystal weight per tray ~11.2 kg



Impact of Out-Of-Time (OOT) Pile-up and backscatter from ECAL

- At <nPU>=200, probability to have total energy from PU in a cell above 0.1 keV is small (13.3% at eta=0 and 22.8% at eta=1.5)
- Most of the cells are unaffected by “in-time” PU at <nPU>=200 and have zero time jitter
- For typical discrimination thresholds of 20-200 phe contribution to time resolution <8ps