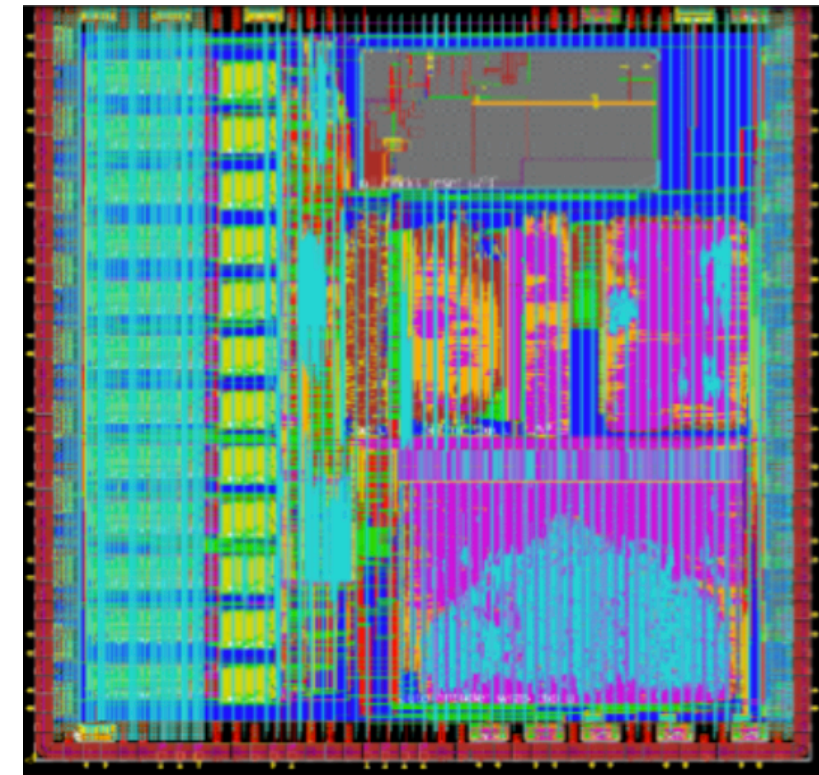
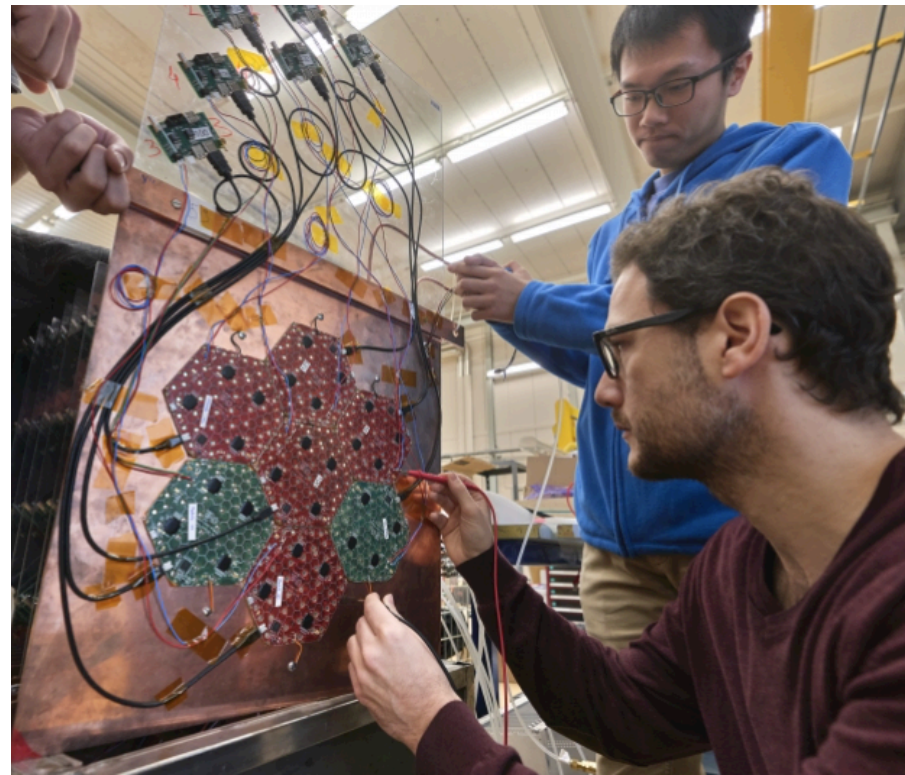
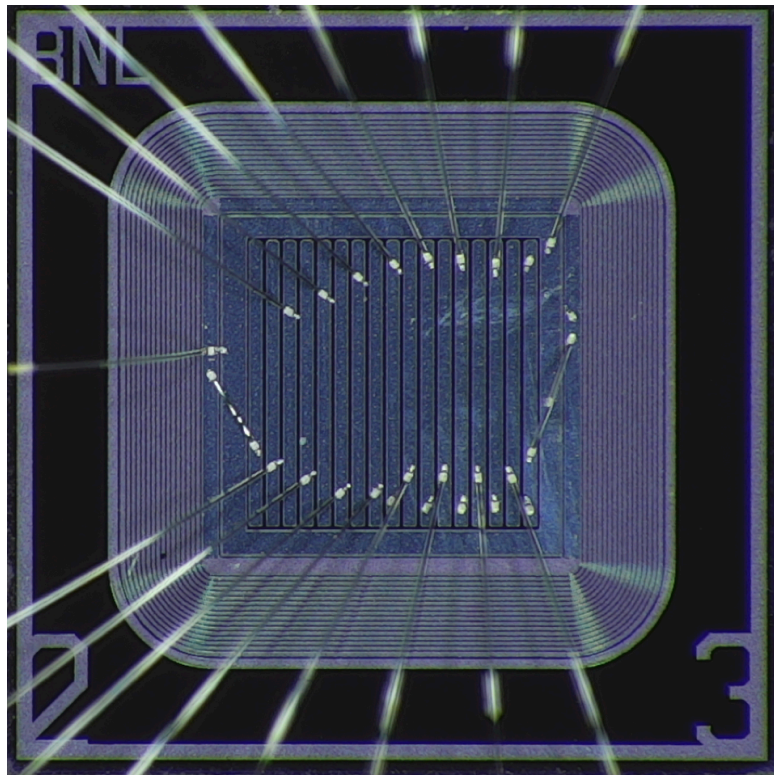


Detectors for Long-lived Particle Searches

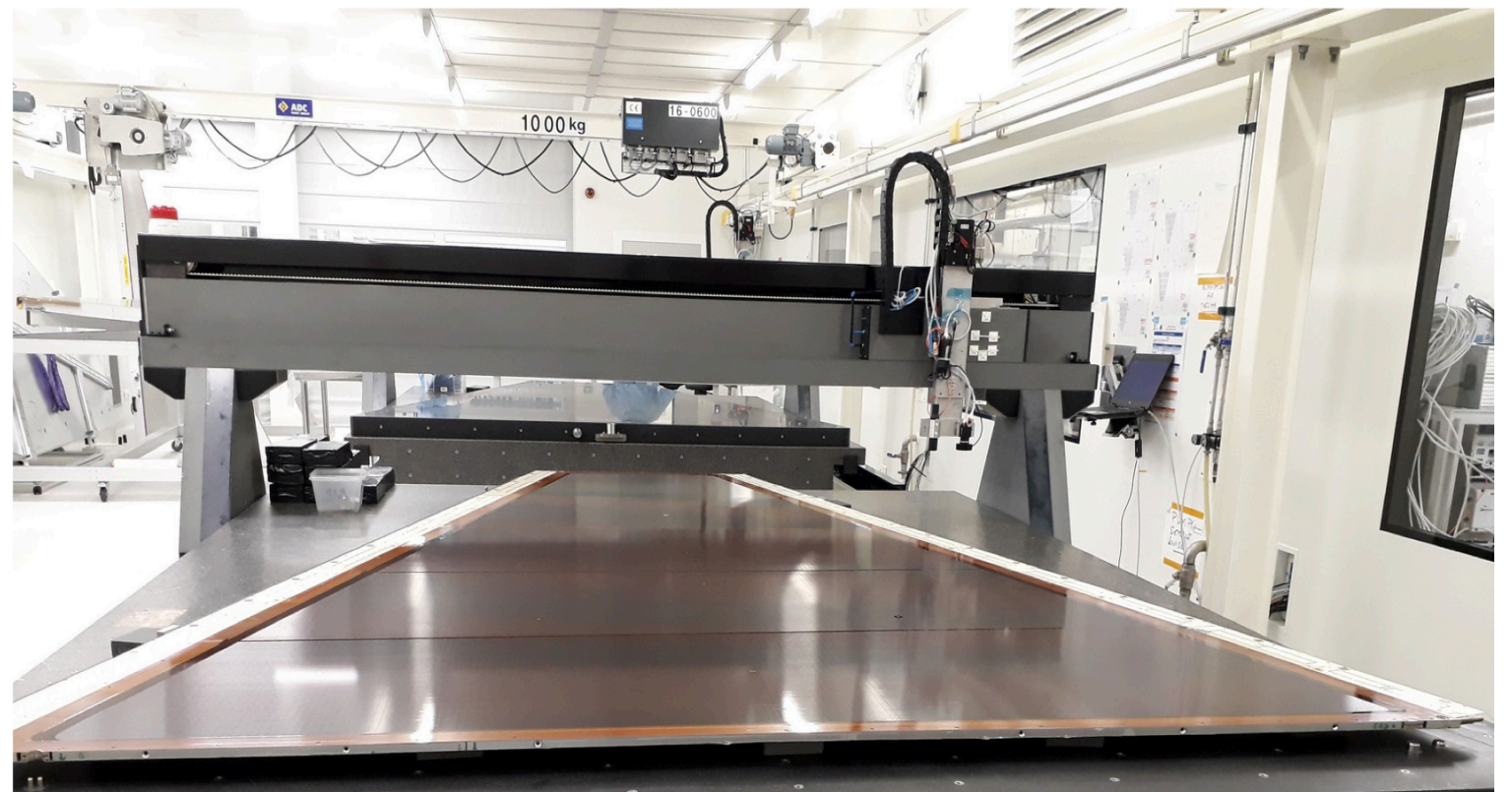
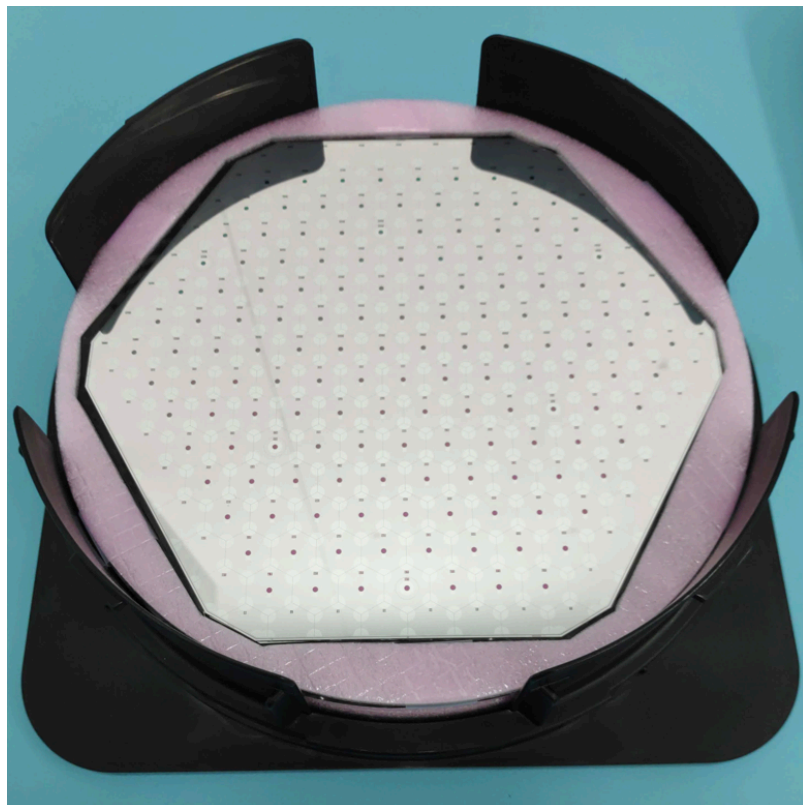
Cristián H. Peña
Fermilab



In collaboration with A. Apresyan, J. Duarte M. Papucci, N. Tran, S. Xie, C. Wang

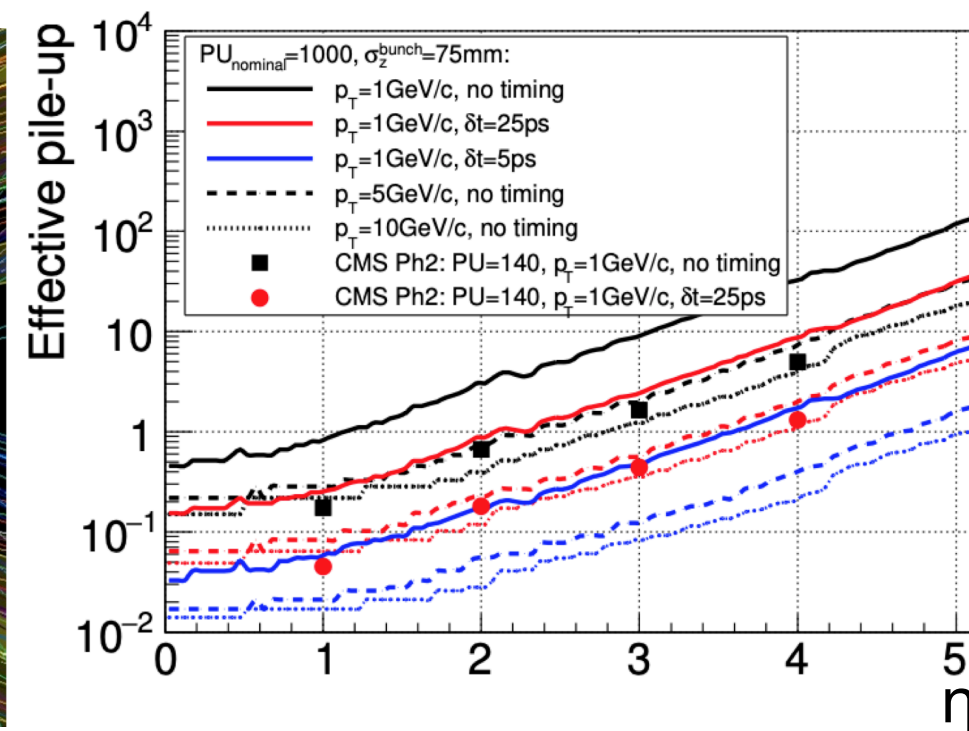
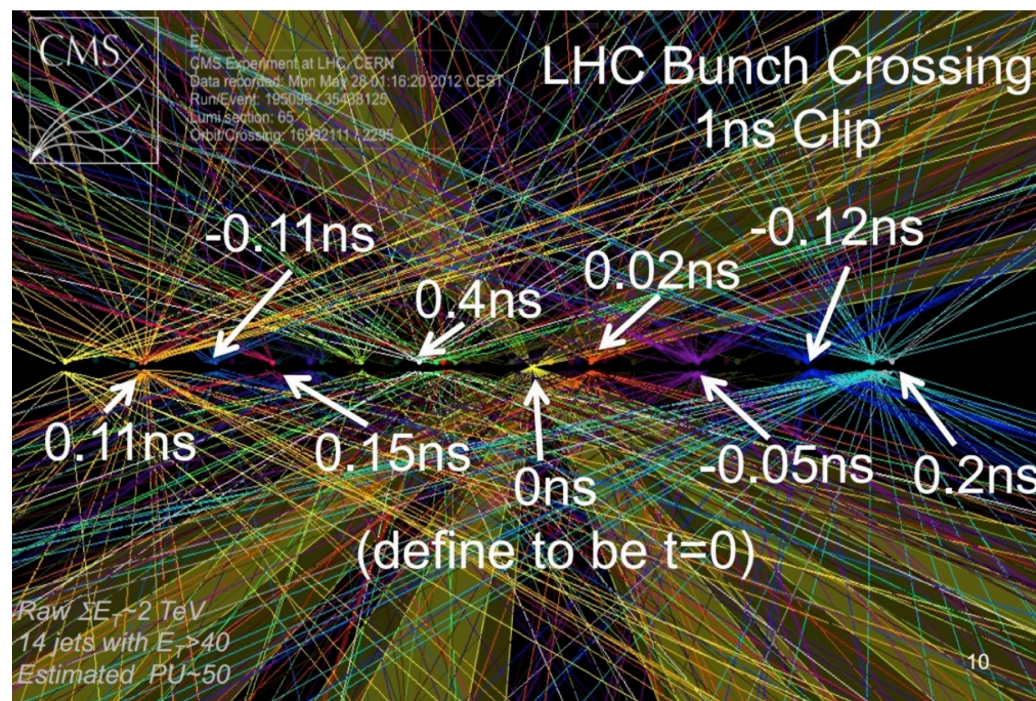
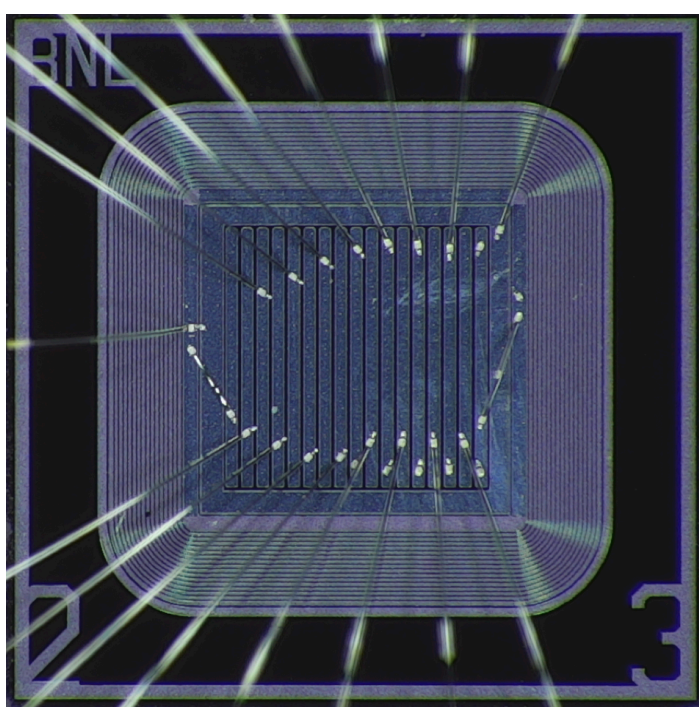


Cutting edge detector R&D for LLP searches



Tracker

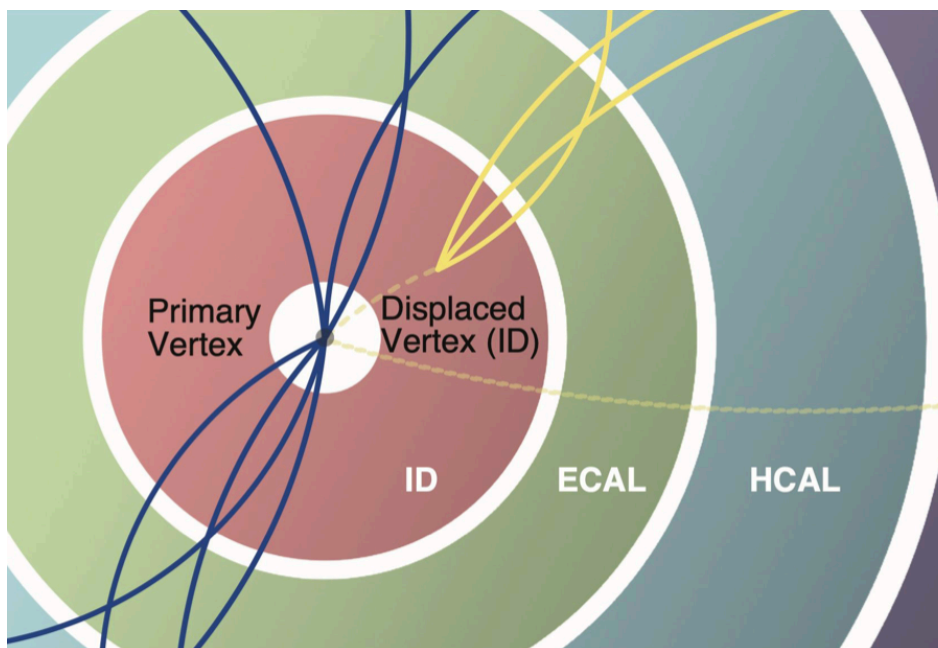
- 4D-Tracking: position+timing (x, y, z, t) in same sensor
- Momentum, 4D-vertexing, pileup and BIB rejection
- Specifications: ~ 10 ps and ~ 10 μm resolution: advance R&D for sensors and ASICs (IF03)



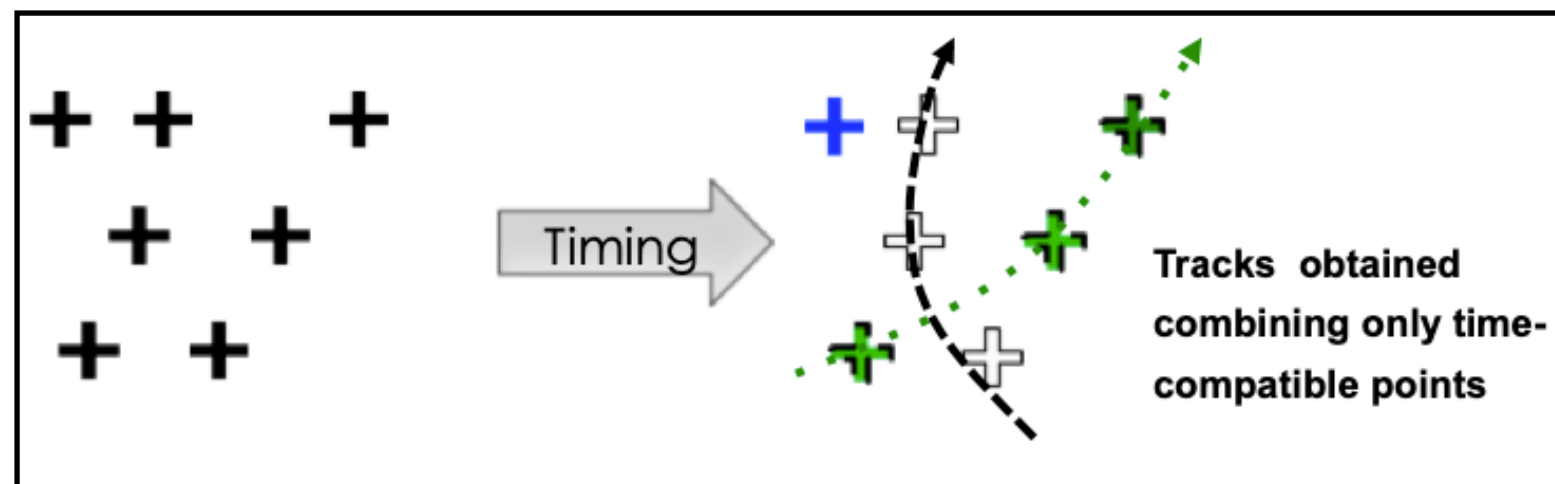
4D Tracking and DV

- 4D-Tracking: position+timing in same sensor
- Key capabilities: **4D-vertexing**
 - Pixels at large radii: enhanced DV capability
 - Smaller inner radius: sensitivity to lower $c\tau$

New capability: Large radii DV



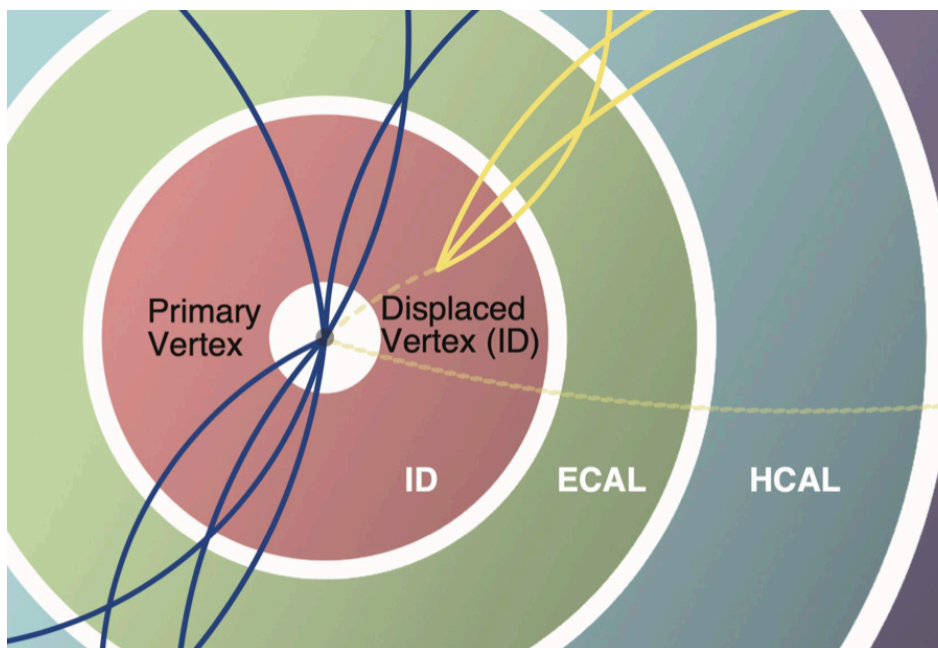
New capability: reduce hit combinatorics



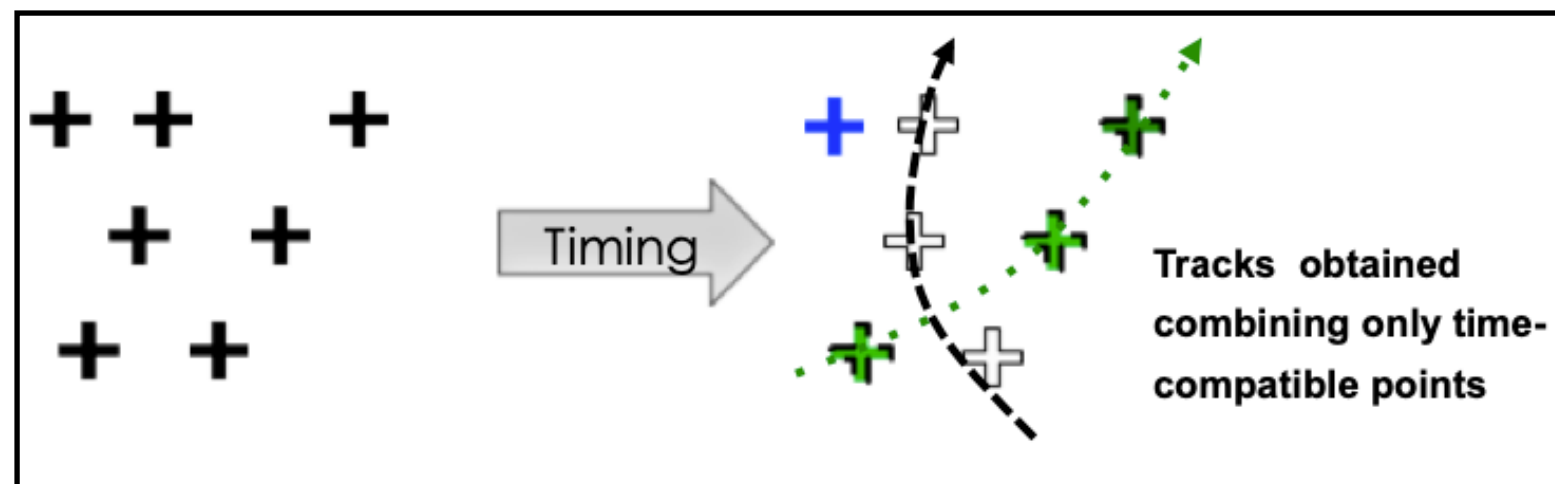
4D Tracking and DV

- 4D-Tracking: position+timing in same sensor
- Key capabilities: **4D-vertexing**
 - Pixels at large radii: challenge for ASIC design
 - Smaller inner radius: challenge rad hard sensor/ASIC

New capability: Large radii DV

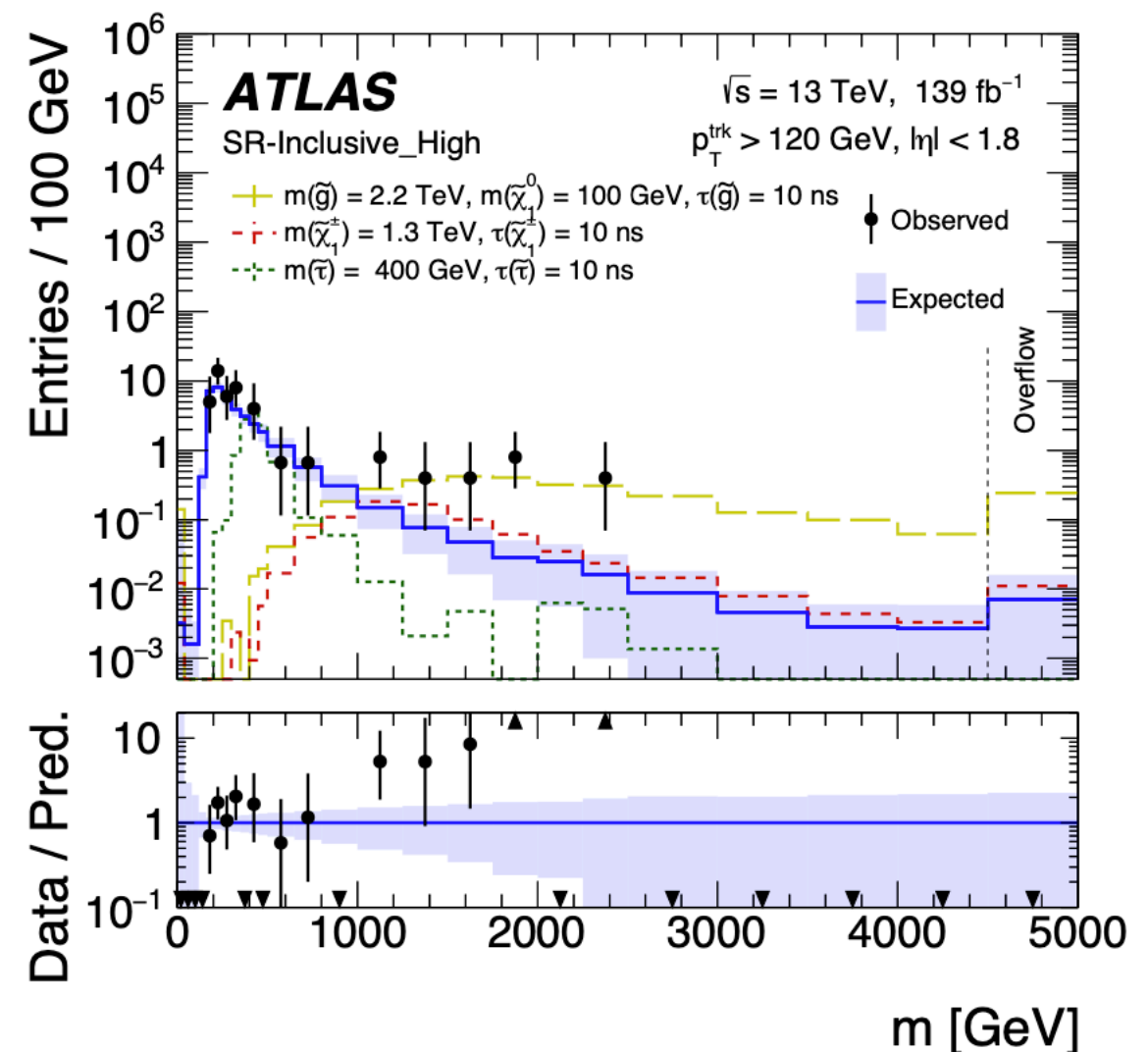
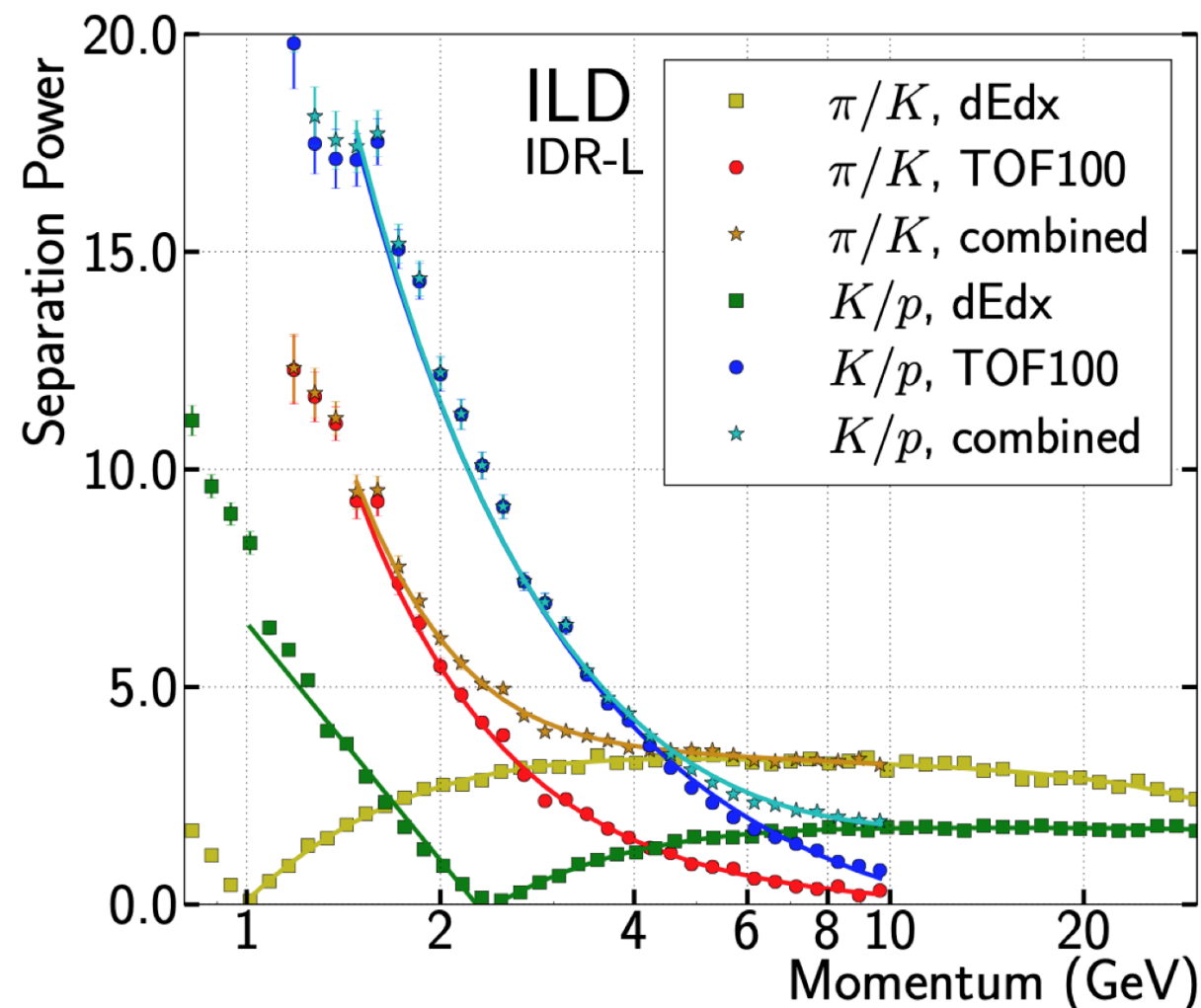


New capability: reduce hit combinatorics



Tracker: TOF and dE/dx

- **TOF** and **dE/dx** for **PID** and **HSCP** searches
 - PID: TOF and dE/dx measurements are complementary
 - Both information are critical for “signal” characterization



Tracker Technologies

- Several technology candidates for 4D-trackers in IF03:
 - AC-LGAD, LGAD optimizations (buried layer, double-sided, etc), 3D sensors, Induced Current sensors, Monolithic pixel sensor (IF03)
 - New materials, fabrication techniques: 4H-SiC, 3D silicon and diamond, 3D-sensors with gain, 3DIC SiPM, thin films, quantum dots (IF03)
- New approaches to front-end processing summarized in IF03 and IF07
 - Edge-computing, nanotechnologies to reduce power on the front-end, wireless

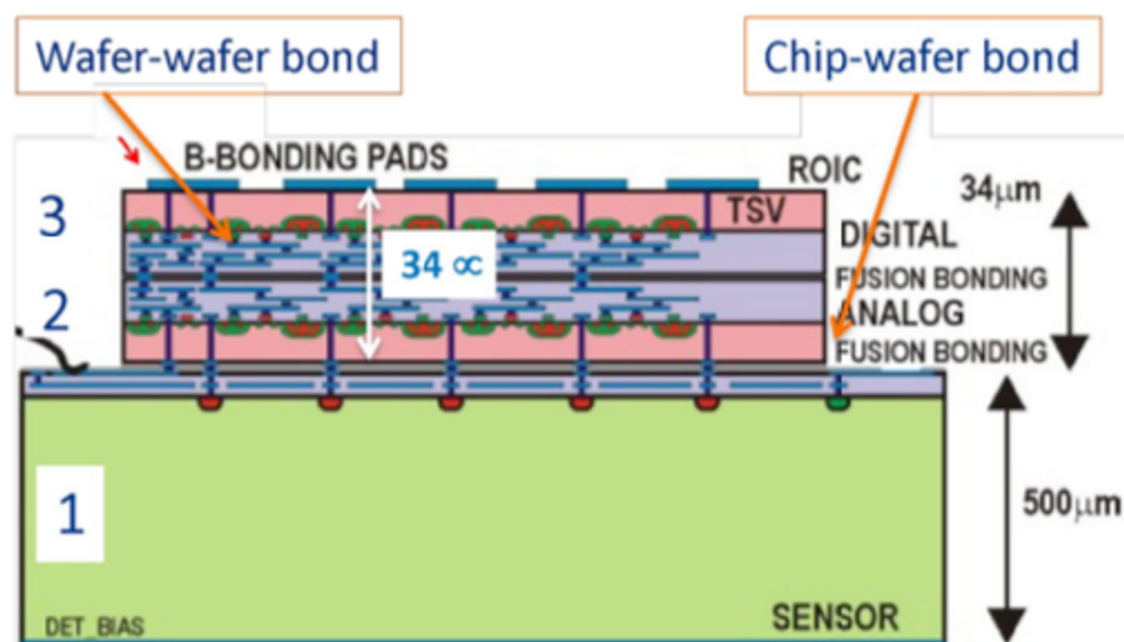
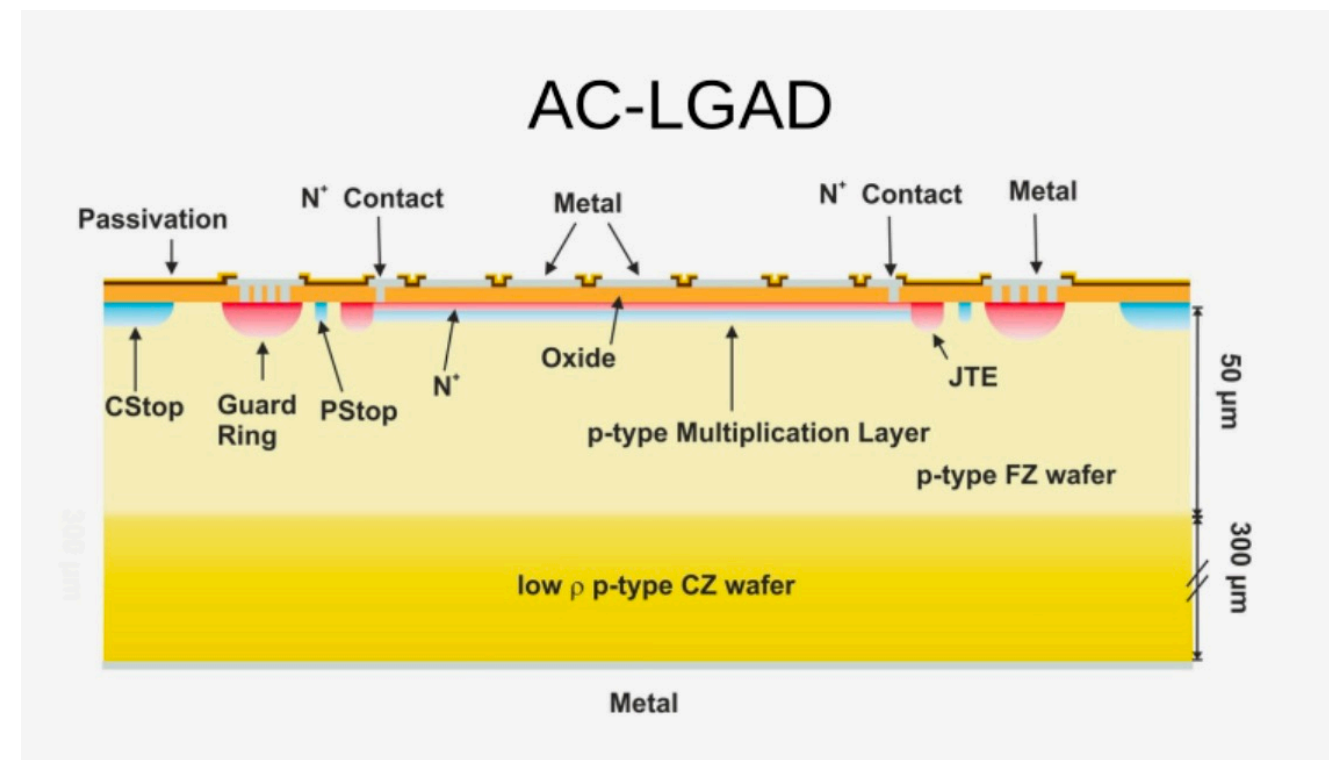
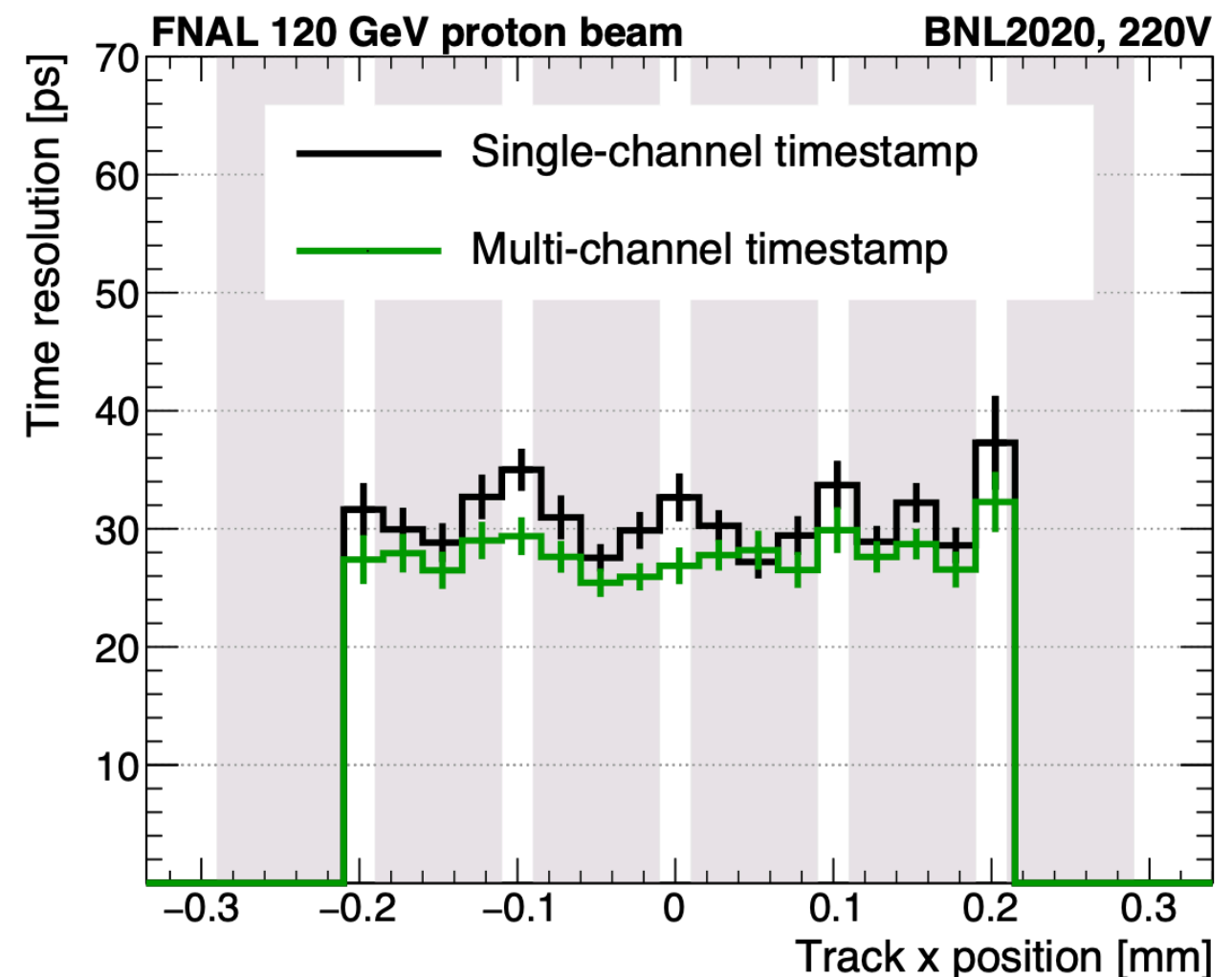
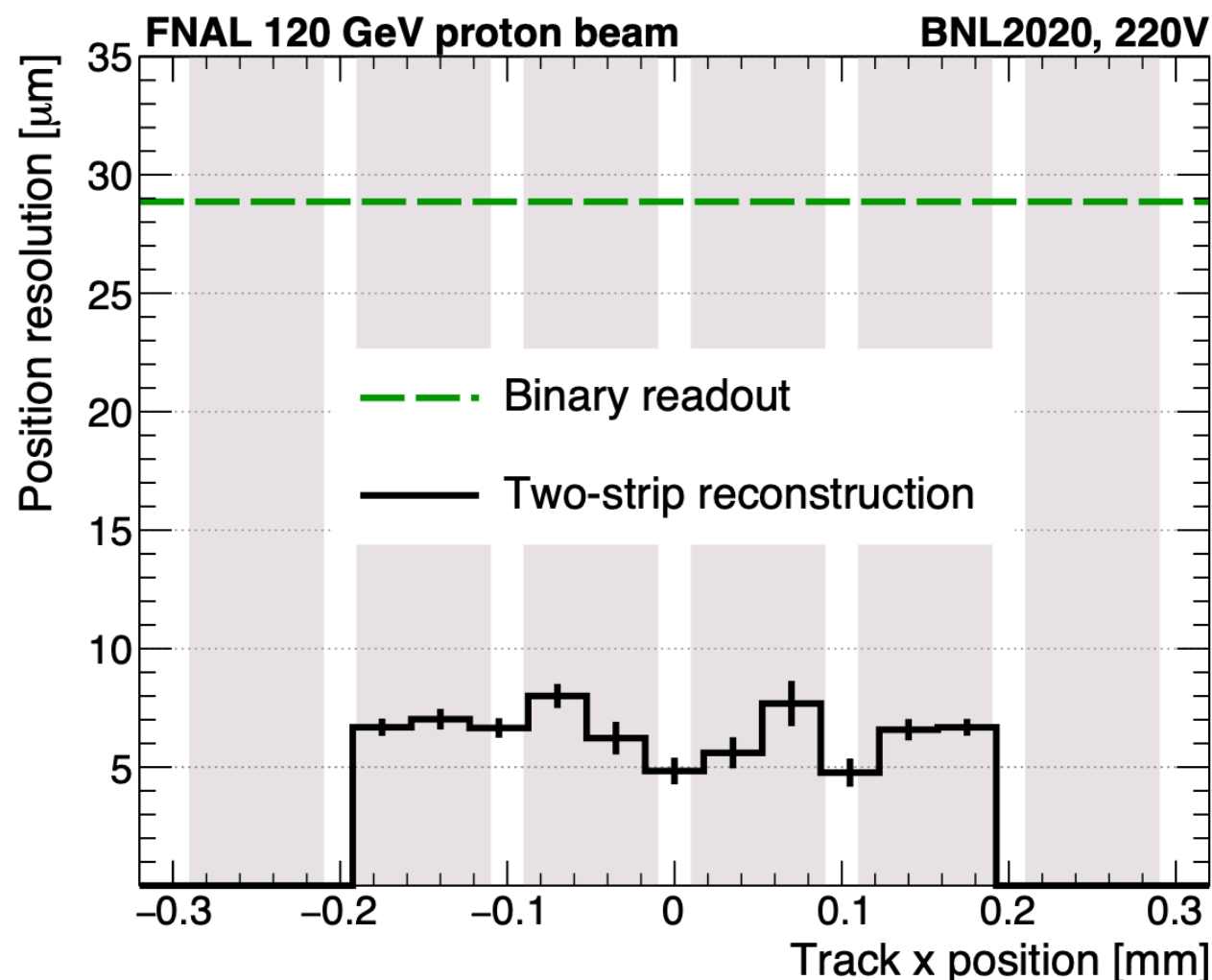


Figure 1: Example of 3D integration of sensor and readout chip.



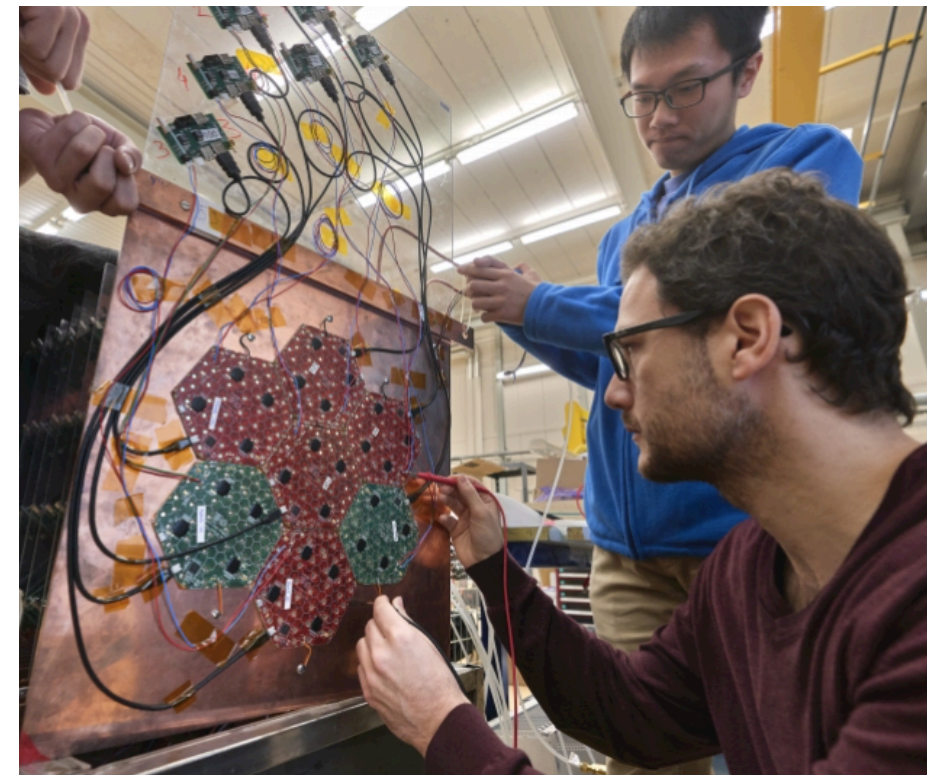
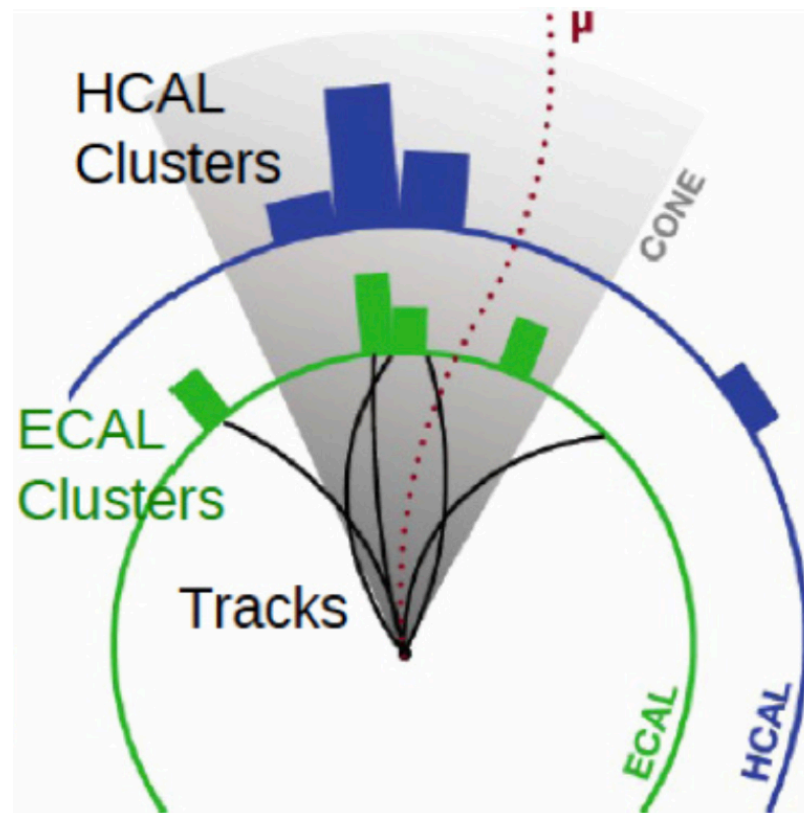
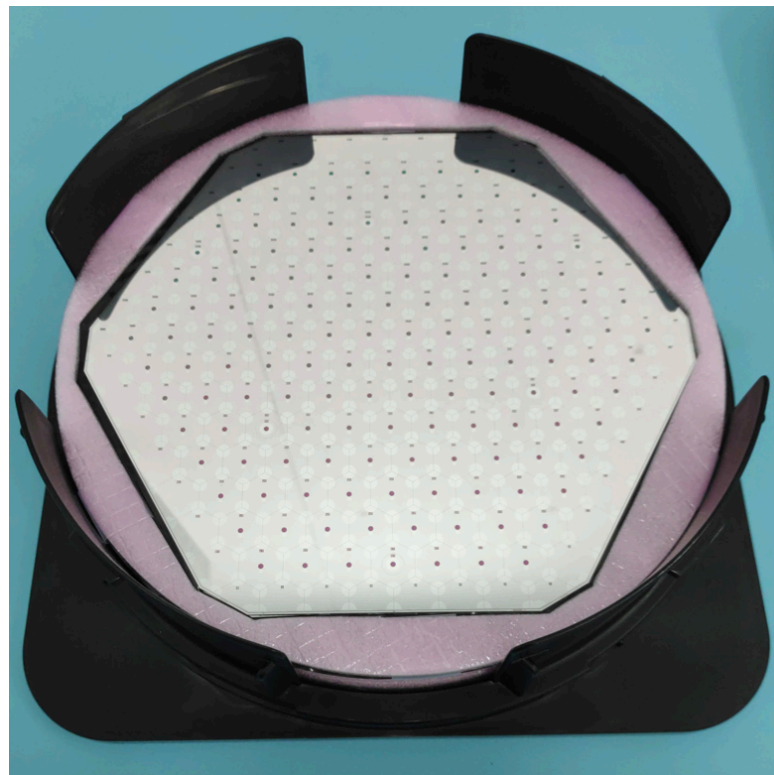
Tracker Technologies

- Several technology candidates for 4D-trackers in IF03:
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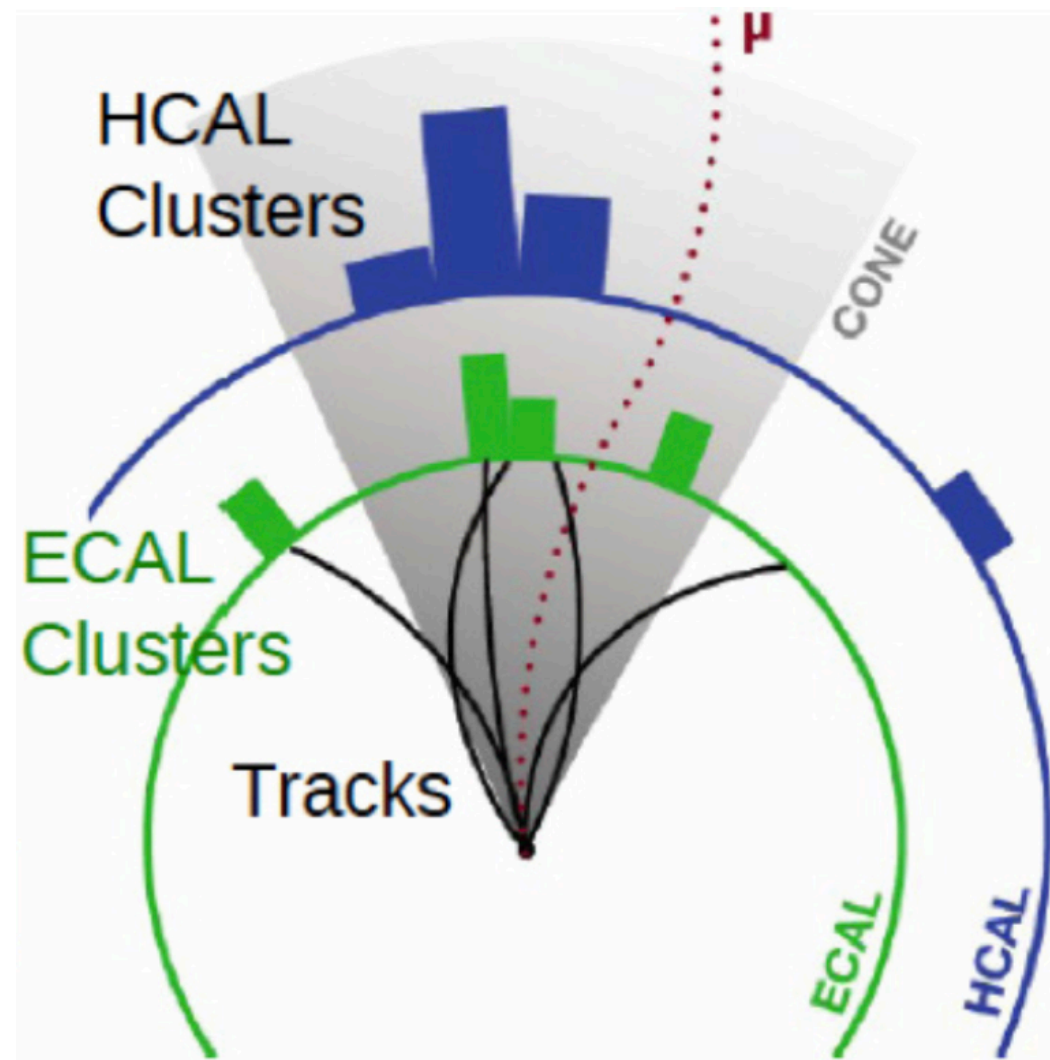
Calorimeters

- **5D-calorimeter:** measure (x, y, z, t, E)
 - Key capabilities: LLP vertex reconstruction and TOF
 - High transverse and longitudinal **segmentation**
 - Excellent timing resolution



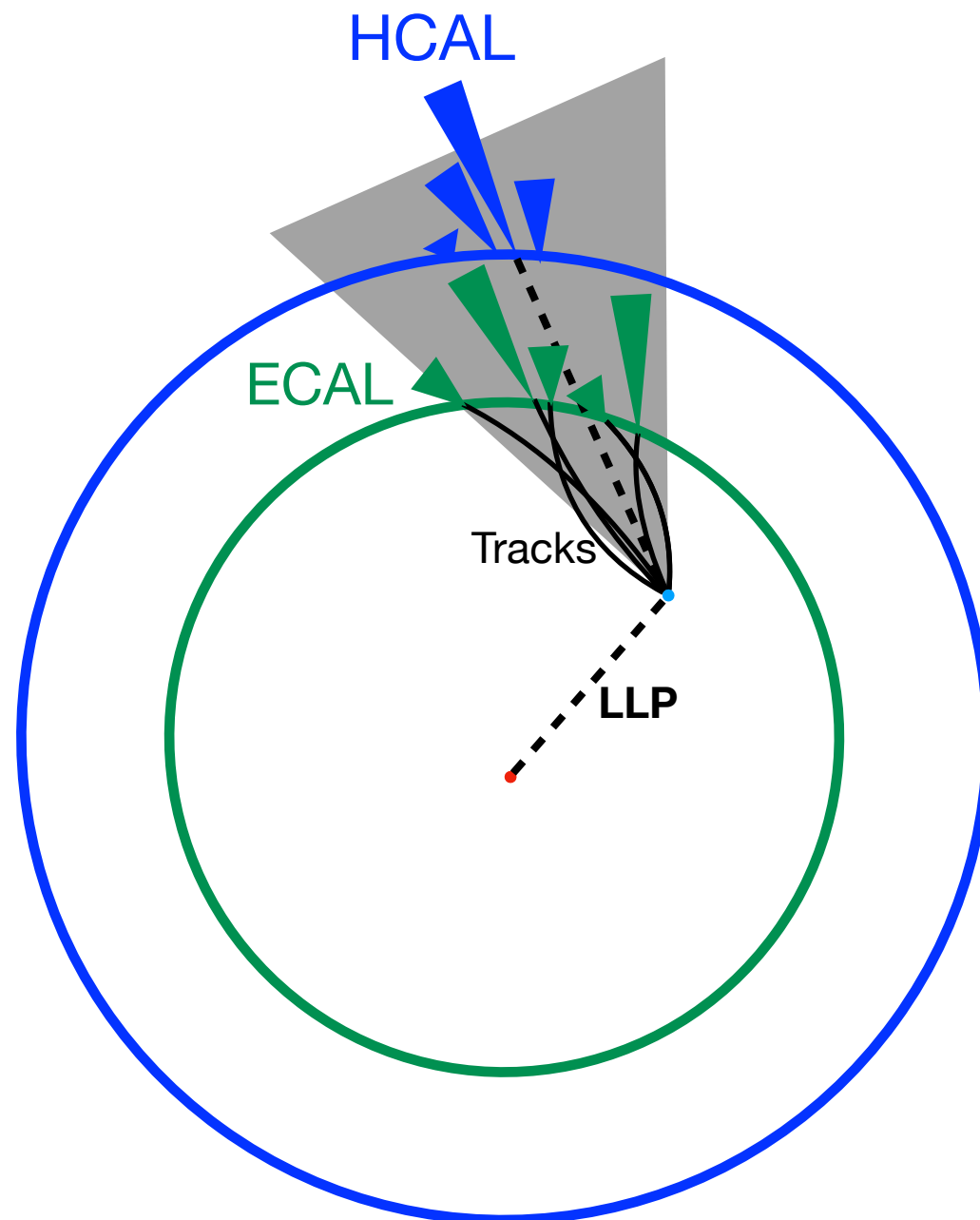
Particle Flow Detector

- Current experiments allow prompt particle flow reconstruction



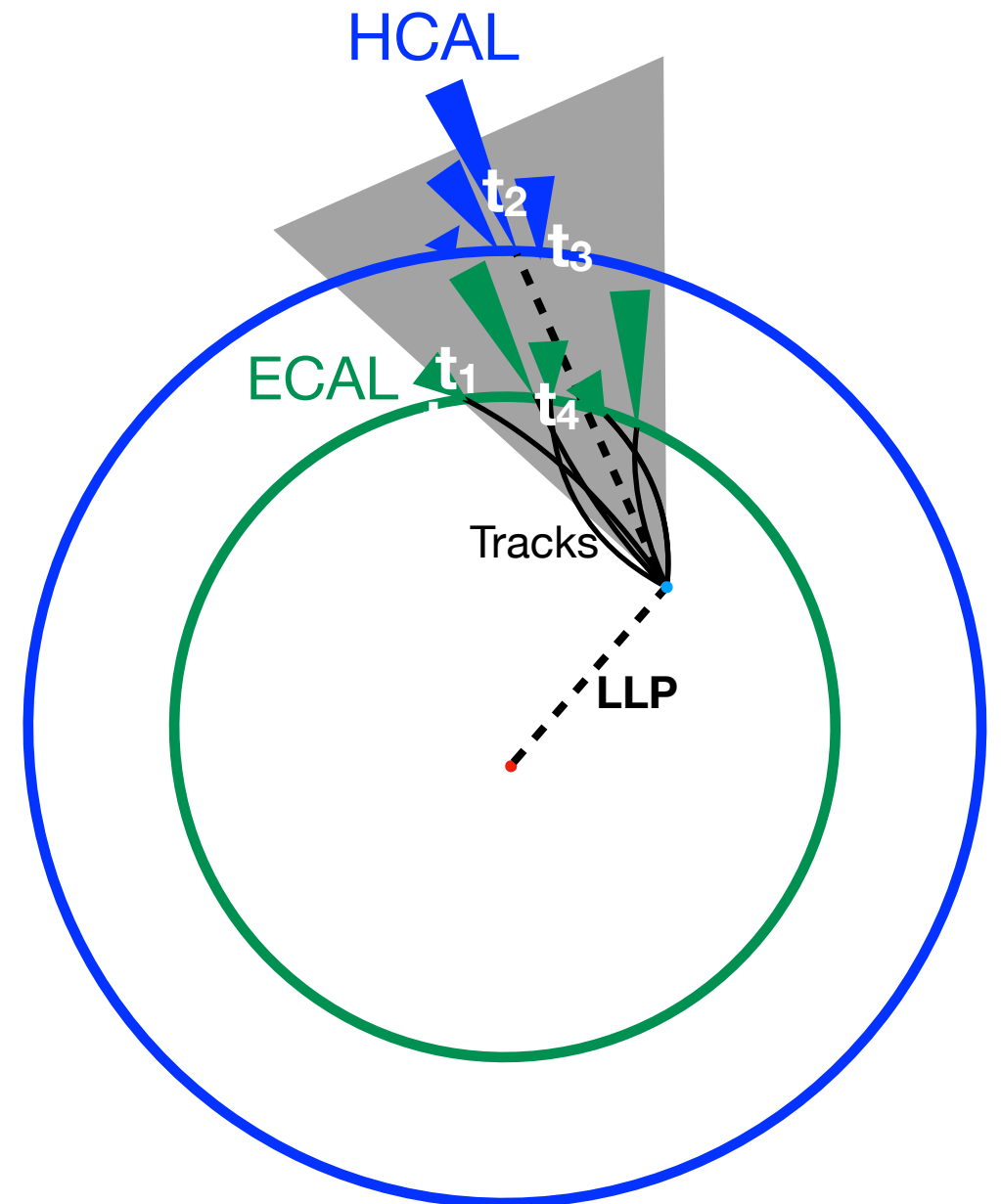
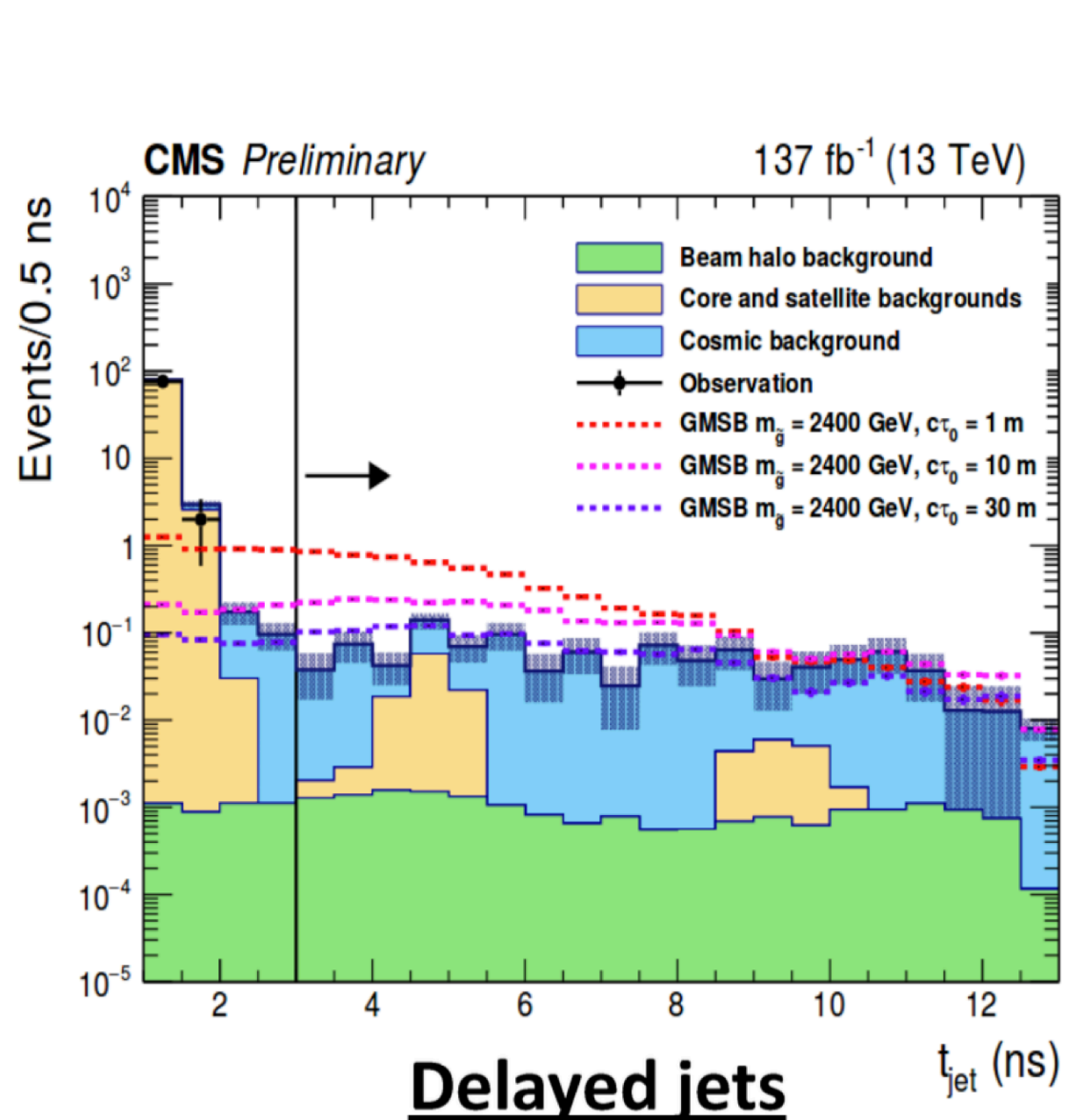
LLParticle Flow Detector

- 5D-calorimeter enables **LLPF** reconstruction



Calorimeter TOF

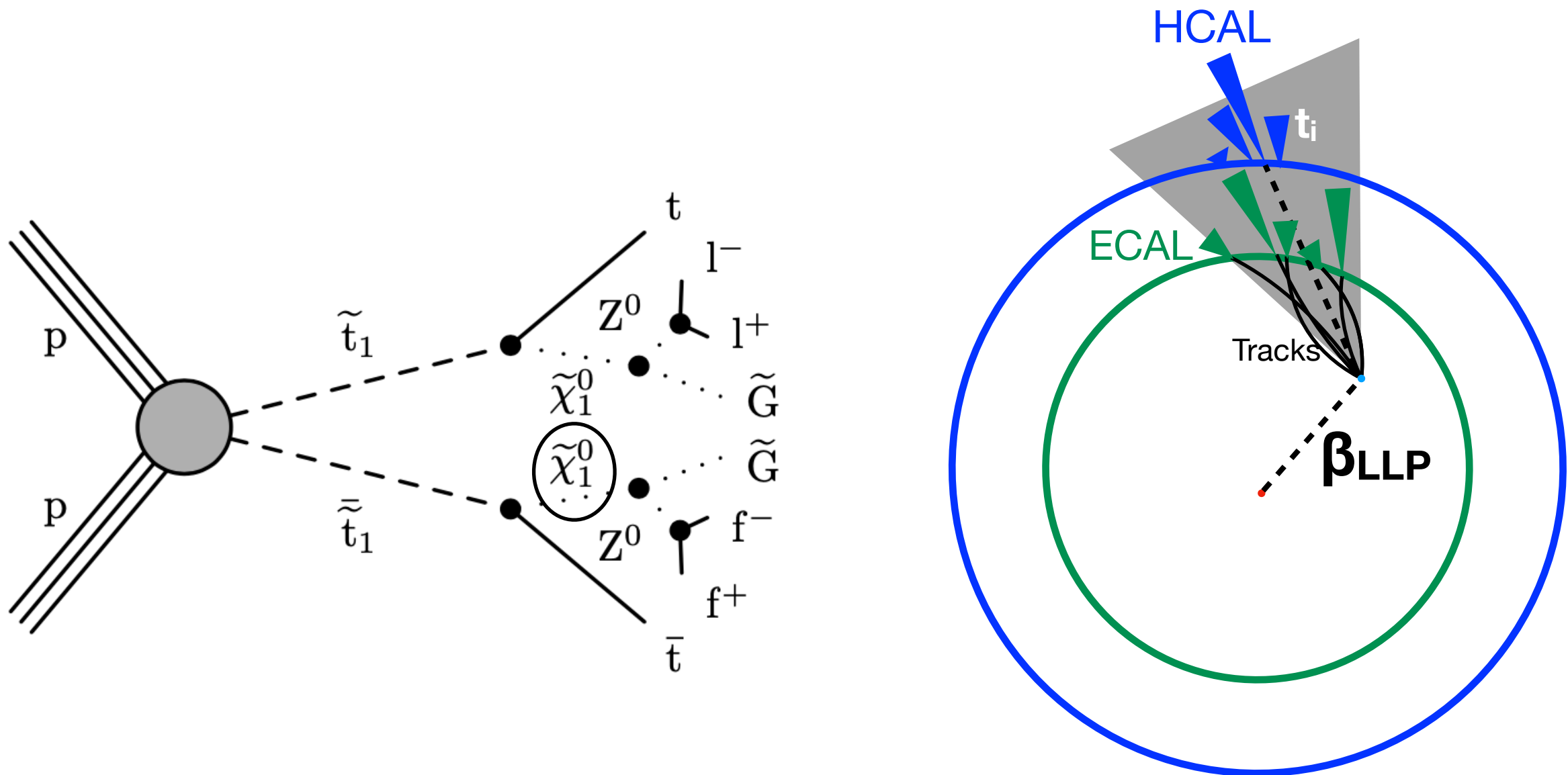
- Enables delayed photon and jet searches for LLPs



Ability to separate signal from backgrounds

Calorimeter TOF

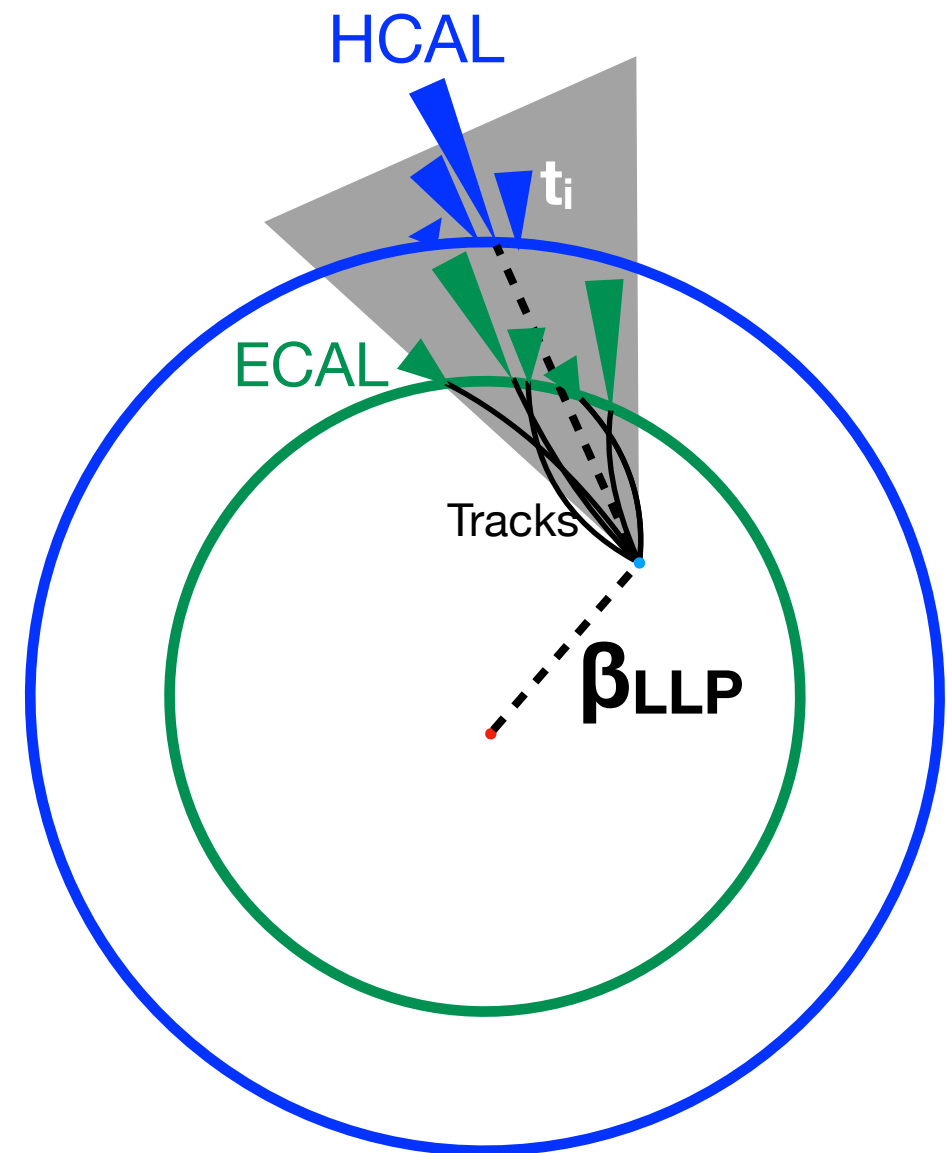
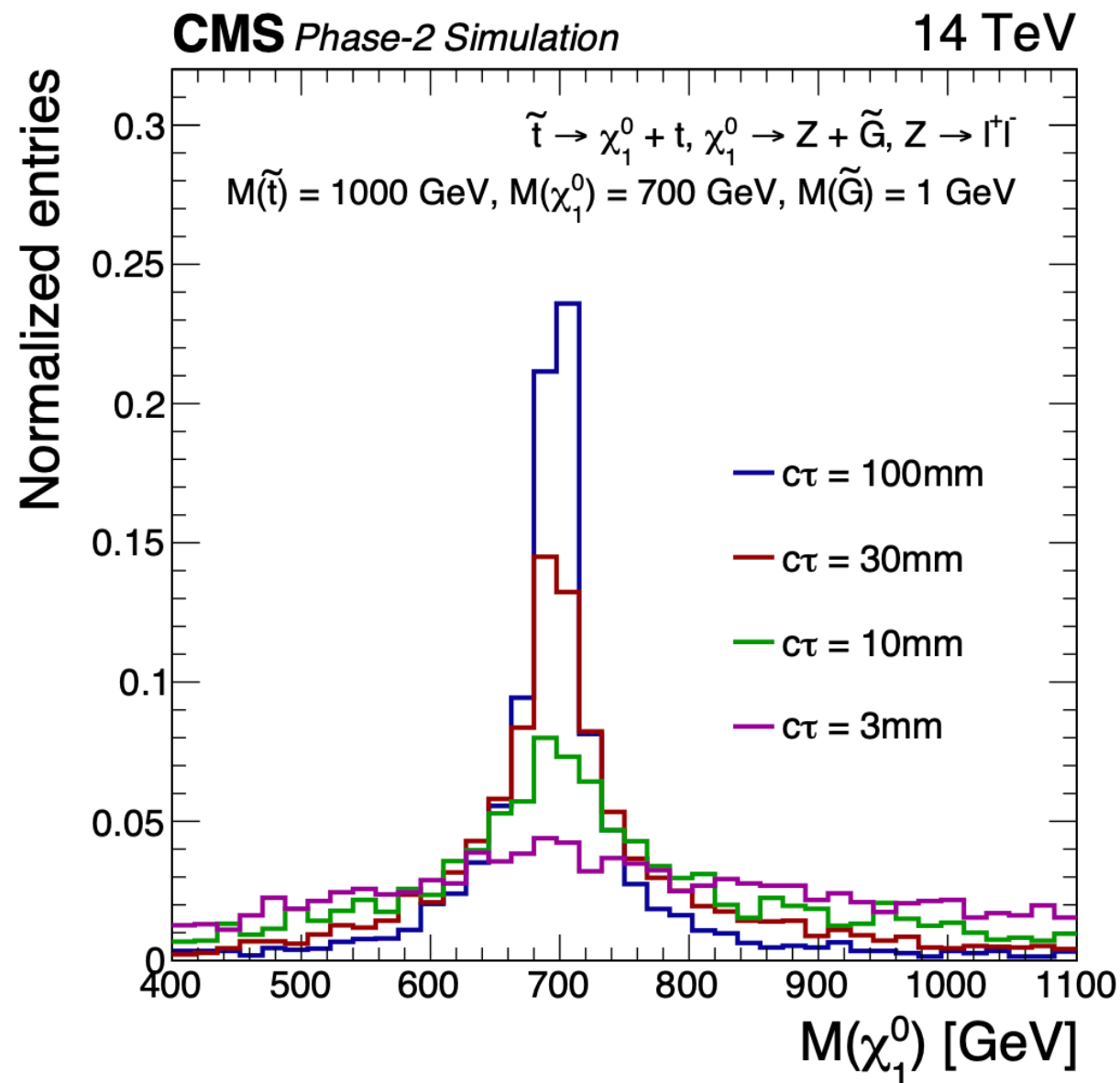
- Full LLP event reconstruction



5D calorimeter enables β_{LLP} measurement

Calorimeter TOF

- Full LLP event reconstruction

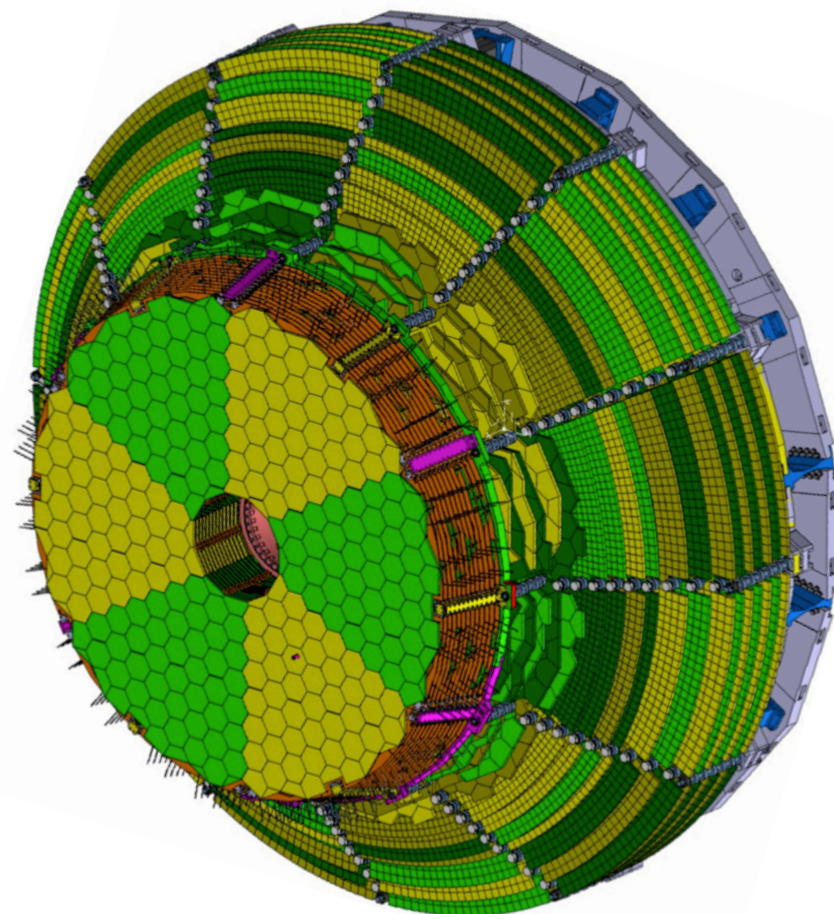
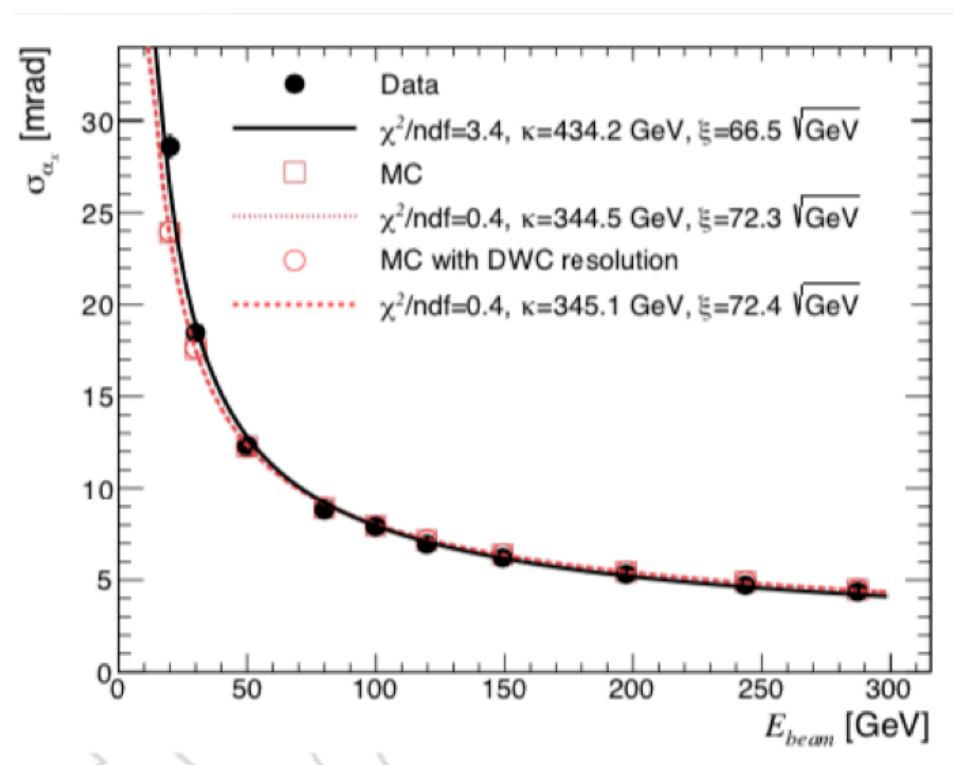
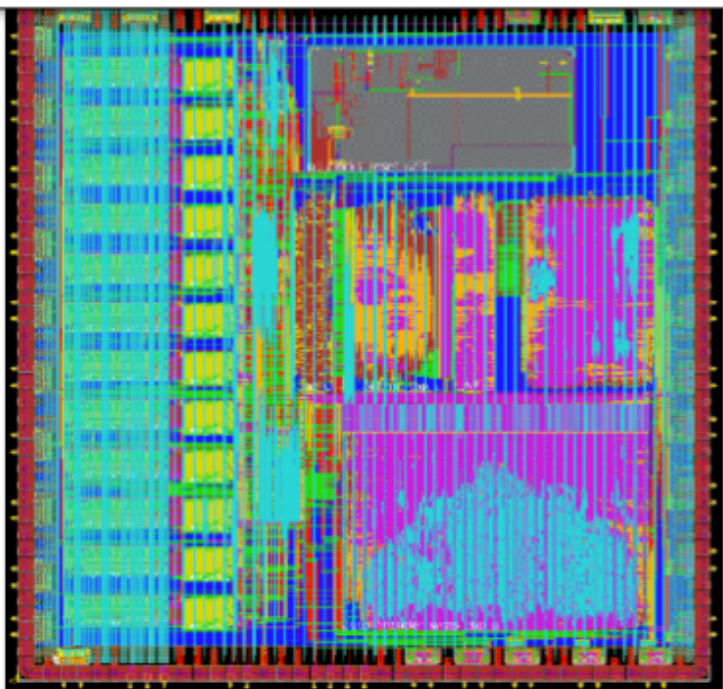


Ability to reconstruct LLP mass resonance

Calorimeter Technologies

- **Several 5D-calorimeters in construction or proposed in IF06:**
 - CALICE R&D, CMS HGCAL, ALICE FoCal (IF06)
 - **PF concept** (IF06) enhanced towards **LLPF**
- New front-end processing capabilities (e.g ECON) required for LLP triggering (IF07)

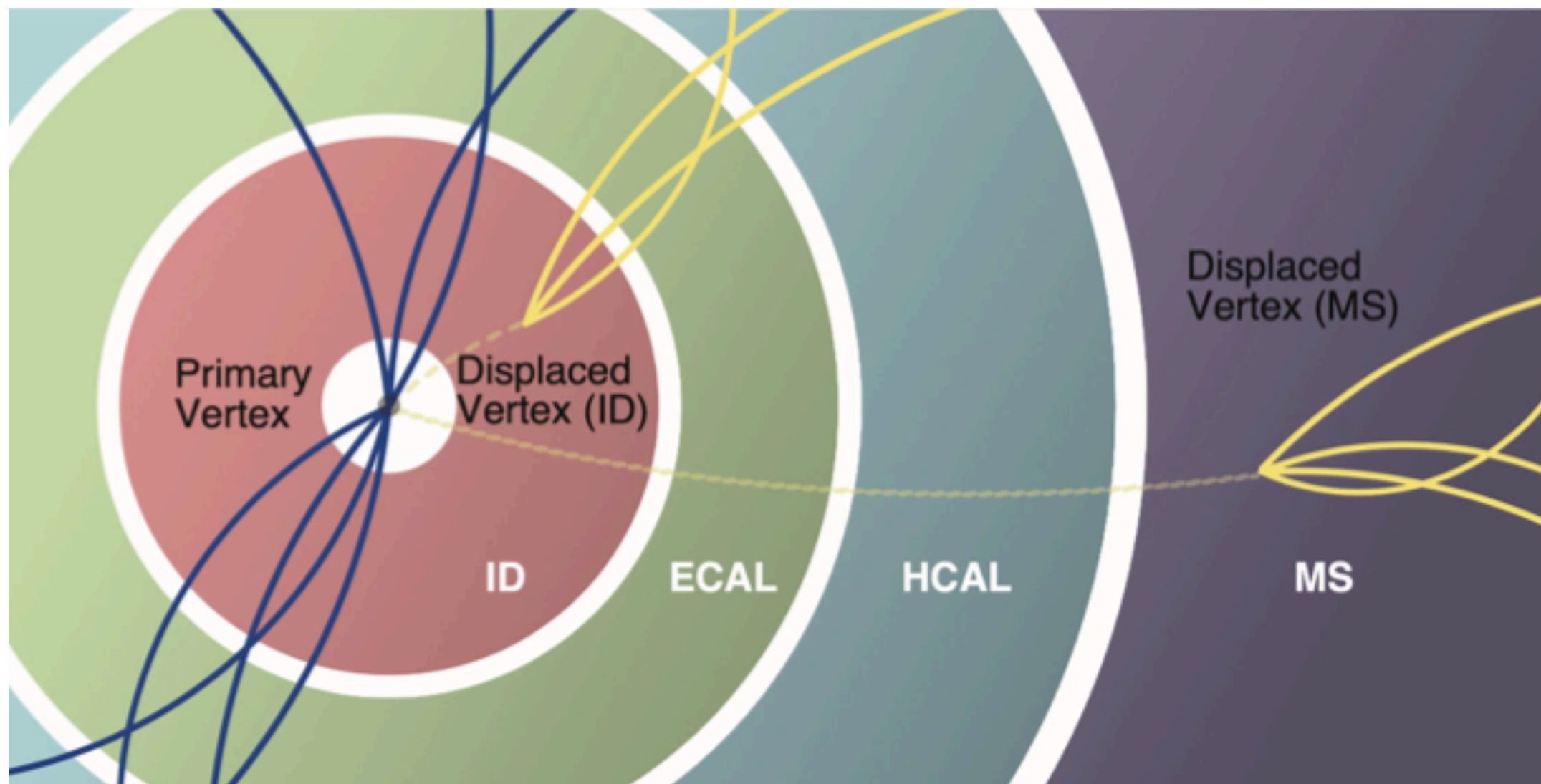
ECON as concentrator ASIC



Muon System

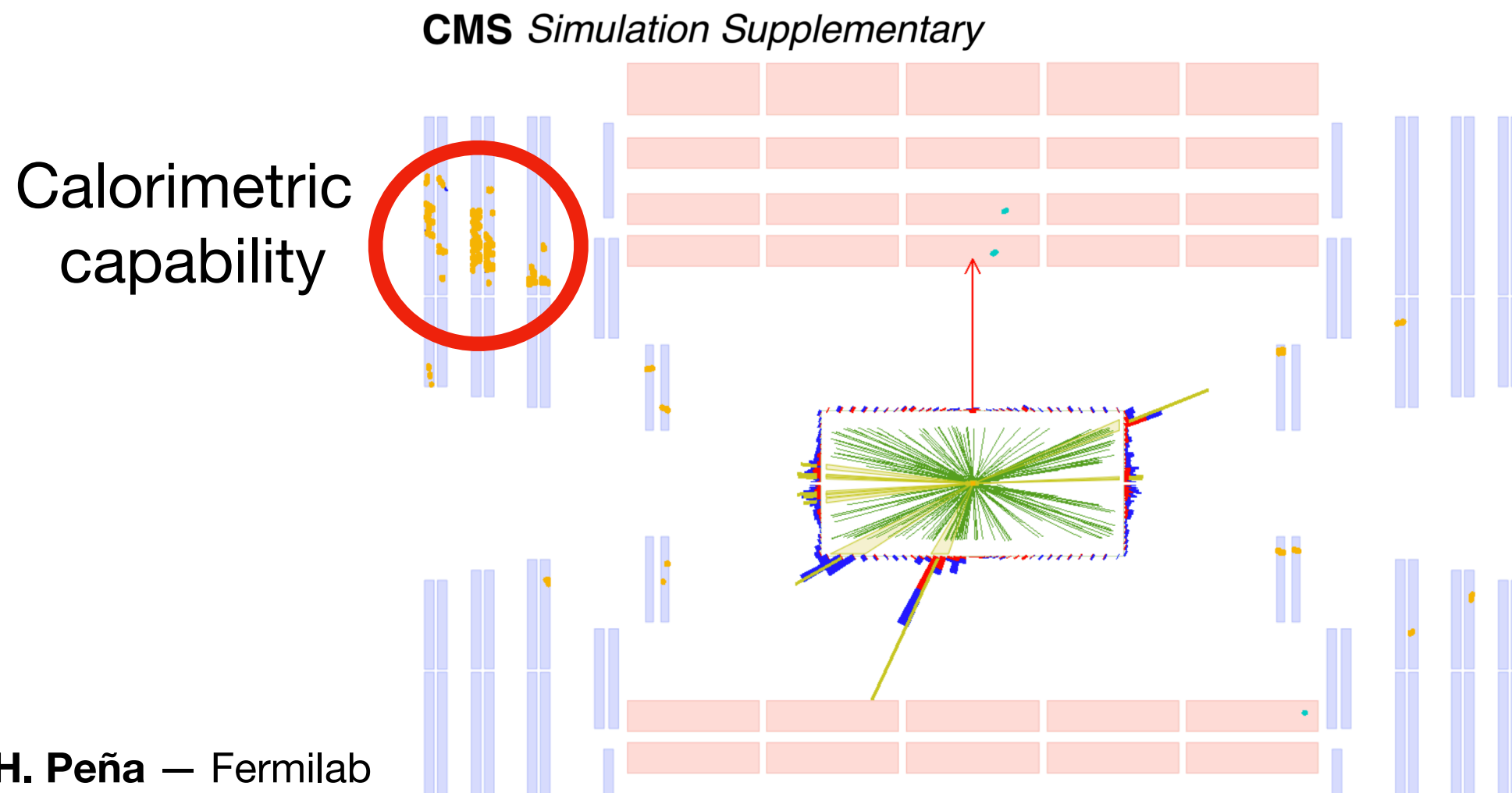
- **More active stations with improved granularity**
- **More shielding**

Displaced vertex capability



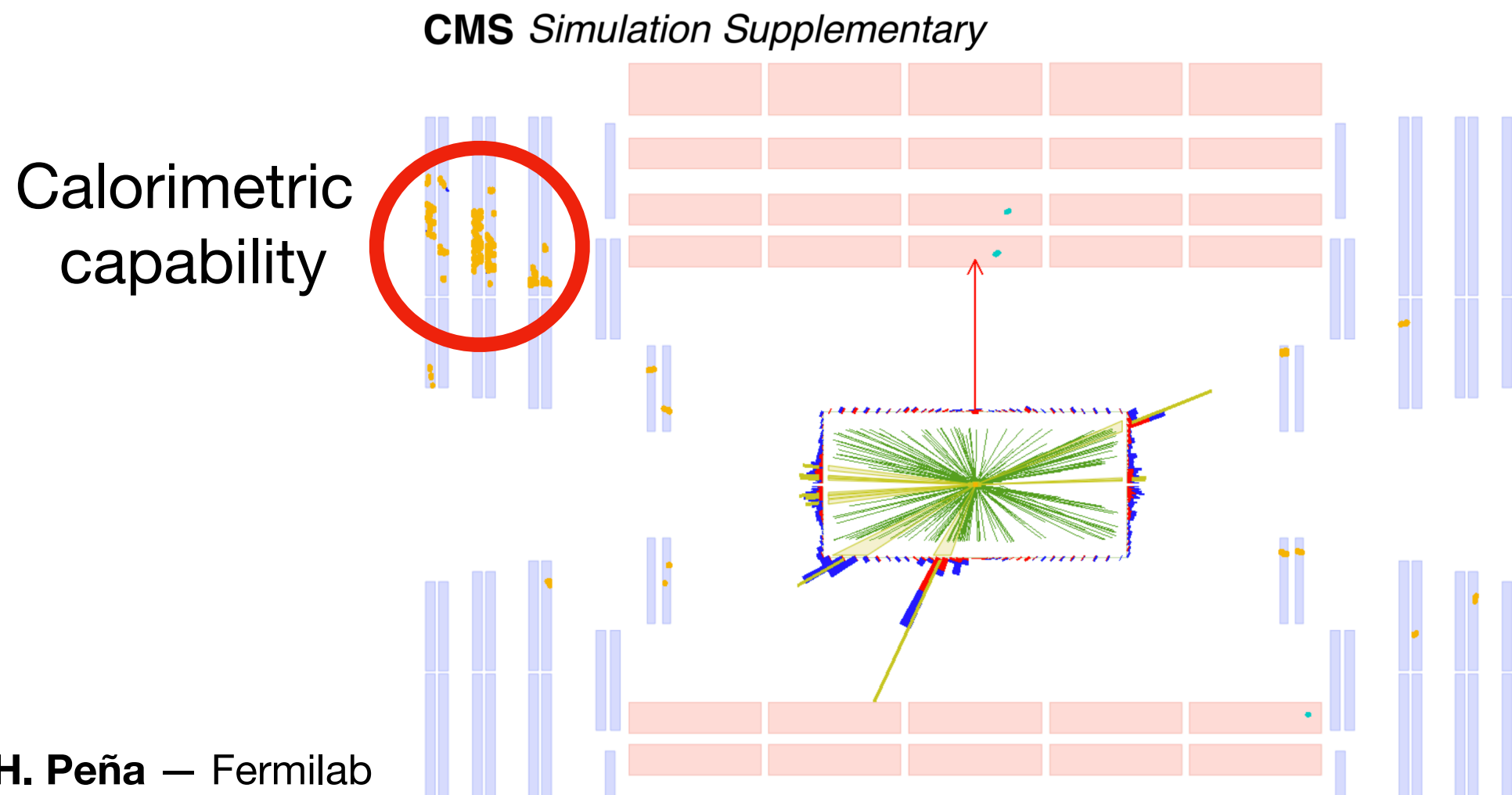
Muon System

- **More active stations with improved granularity**
- **More shielding**
- Embed active stations
→ calorimetric capability and increase fiducial volume



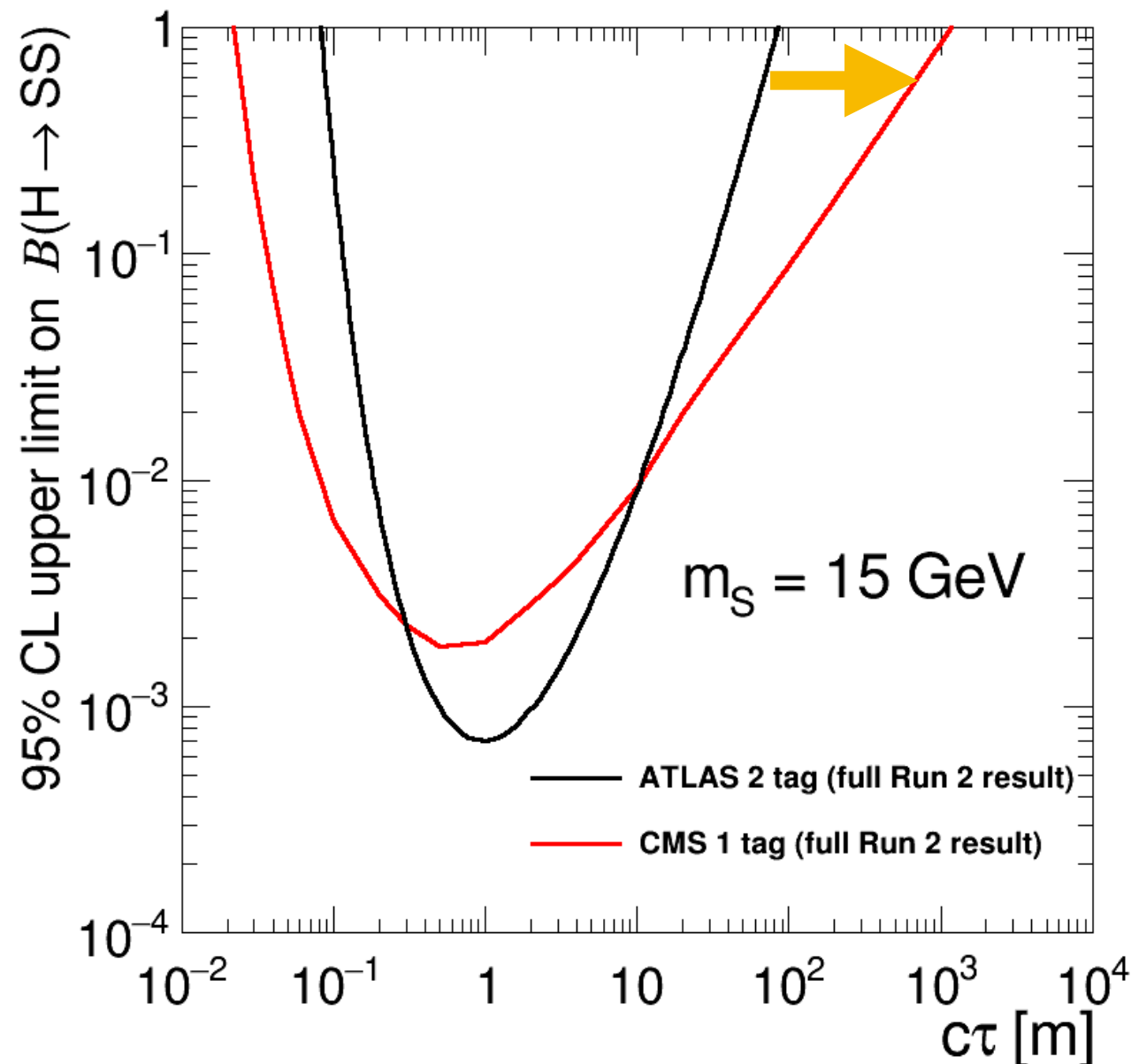
Muon System

- More active stations with improved granularity
- **Active** shielding
 - Embed active stations
→ Extra calorimetric capability and fiducial volume



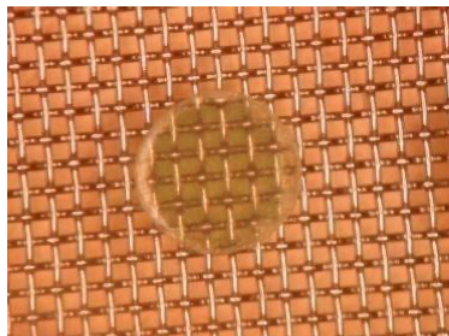
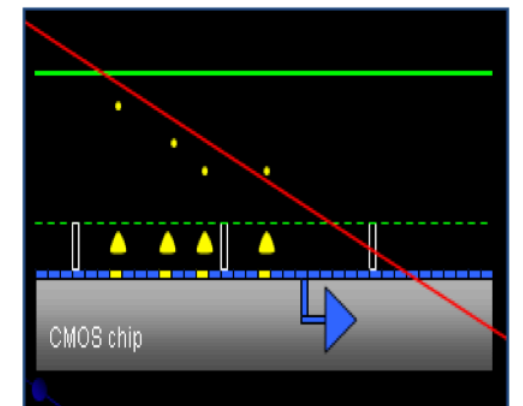
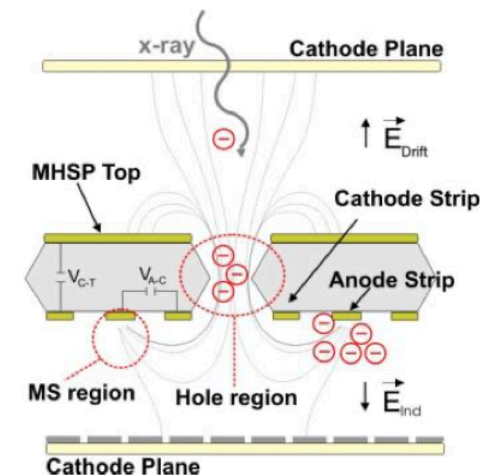
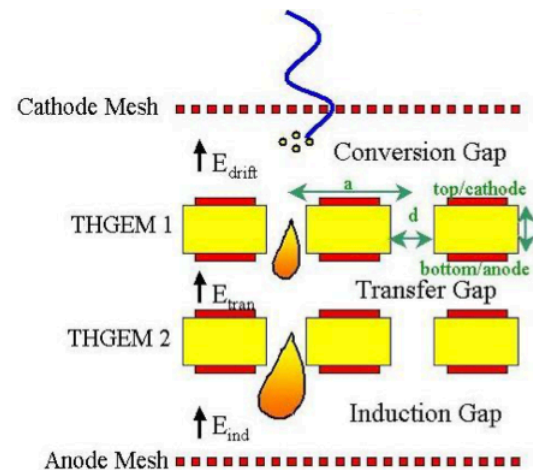
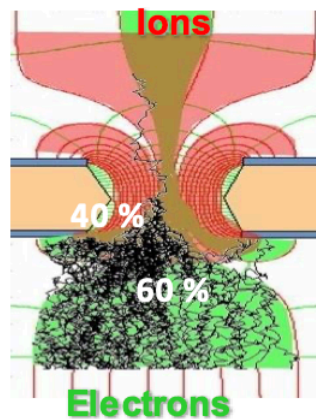
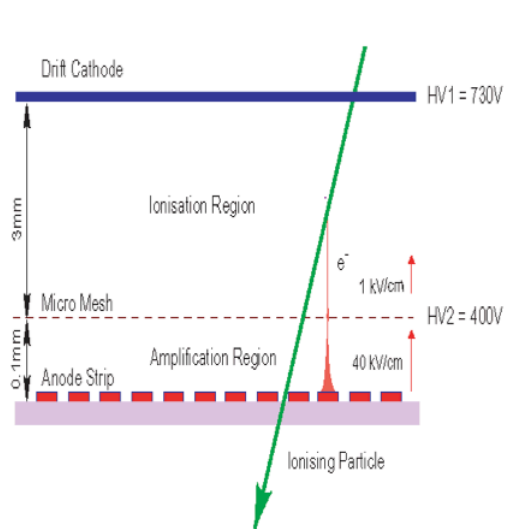
Muon System

- **Key features:** increased bkg suppression, increased target mass for stopped-particle searches
- **Better sensitivity for large LLP lifetimes**

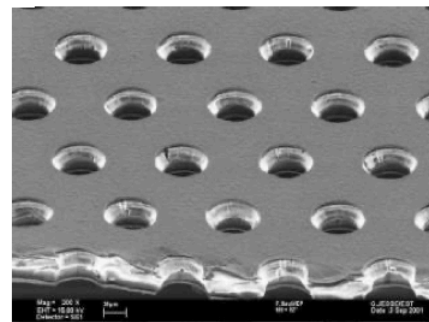


Muon System Technology

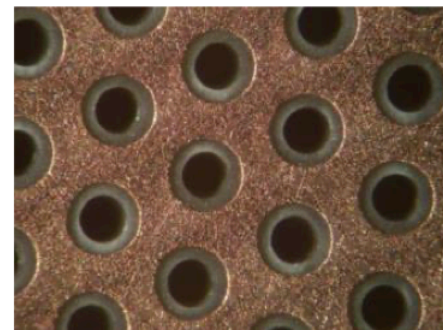
- Several technologies in construction or proposed in IF05:
 - MPGD: GEMs, MicroMegs, THGEMs, LEMs, RPWELL, micro-RWELL, μ -PIC, InGrid (IF05)
 - Currently in used in ATLAS, CMS, LHCb, TOTEM ...



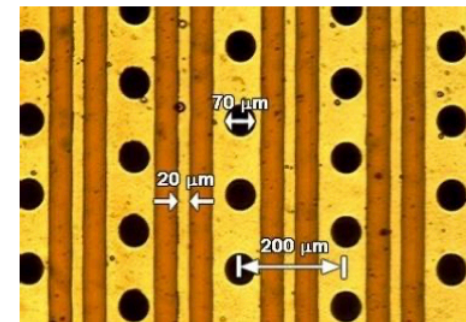
Micromegas



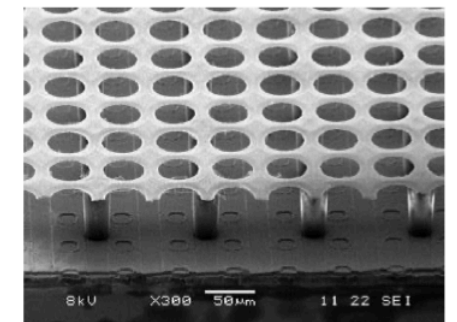
GEM



THGEM



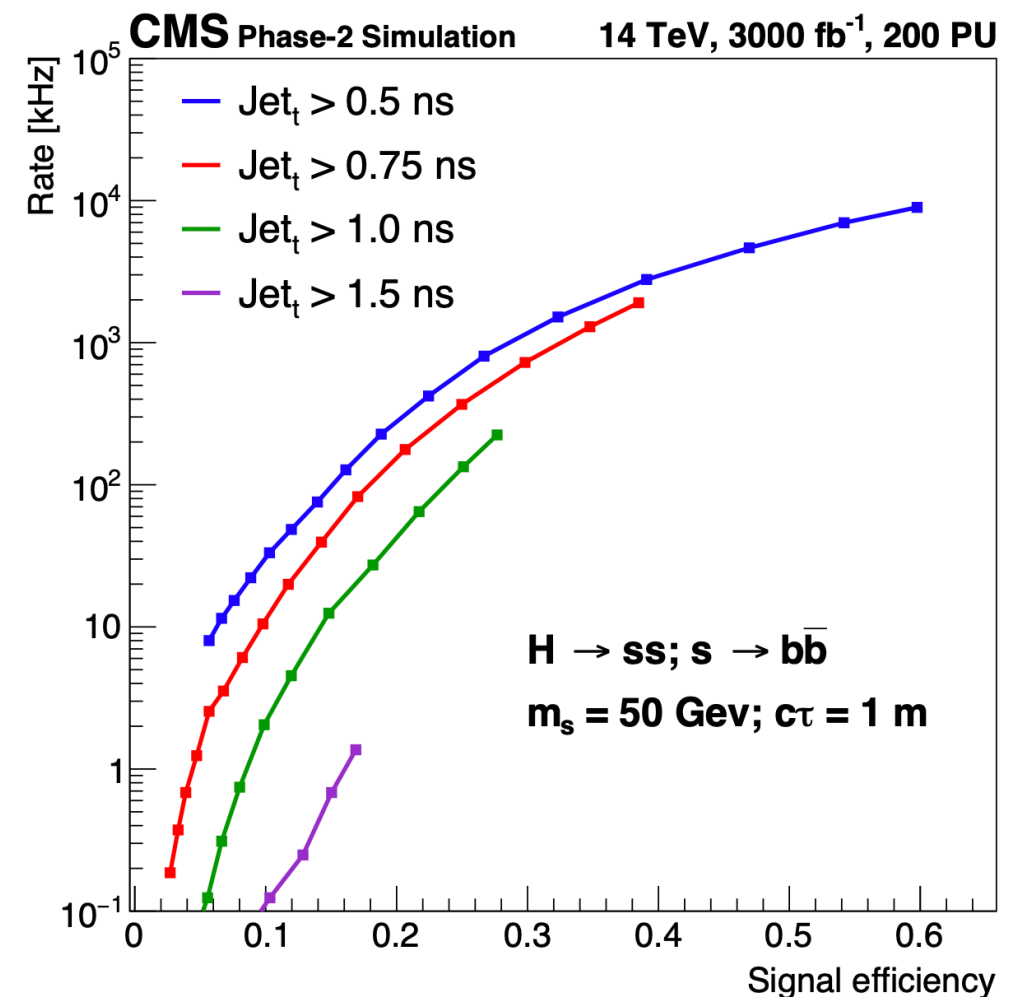
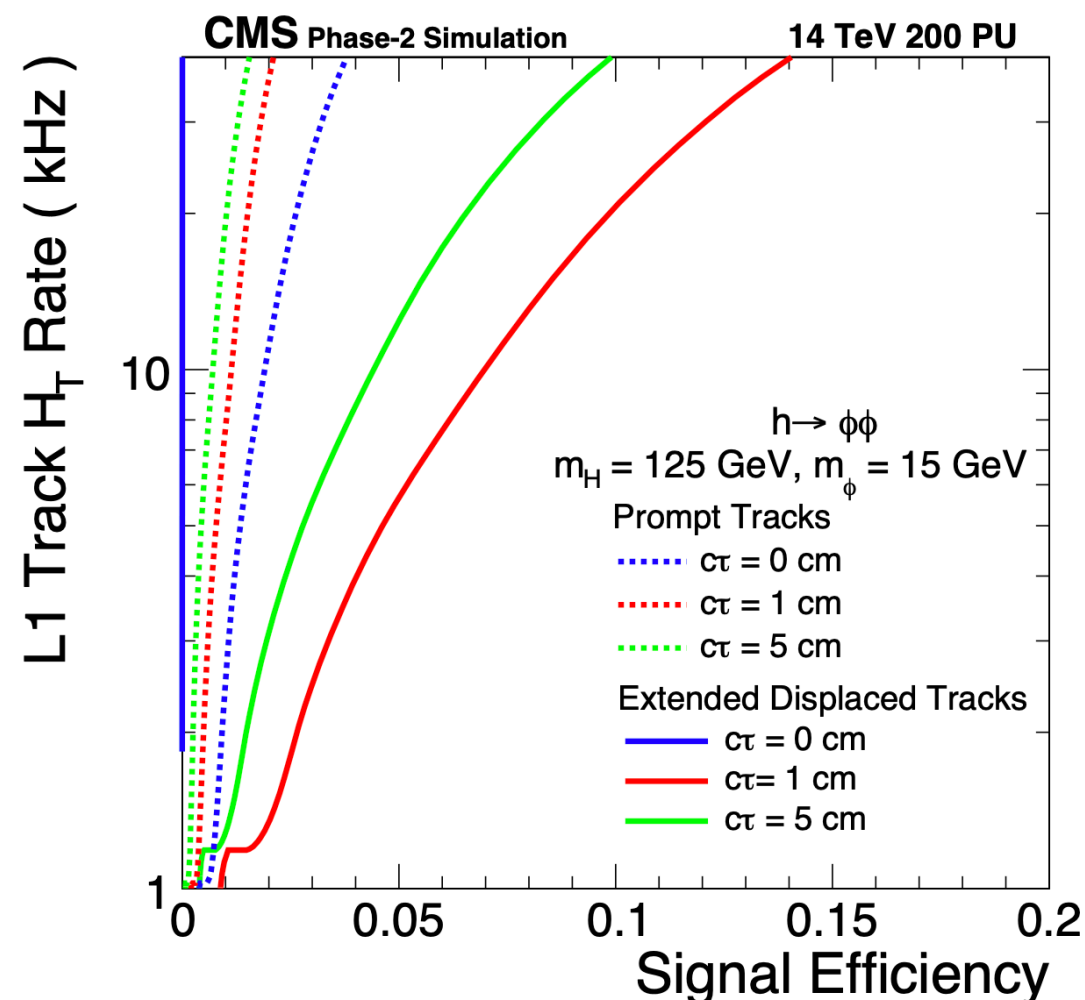
MHSP



Ingrid

Triggers

- LLP sensitivity of ATLAS and CMS LHC experiments currently limited at hardware trigger
- LLP aware 5D capabilities in each detector must be enabled in trigger hardware



Triggers

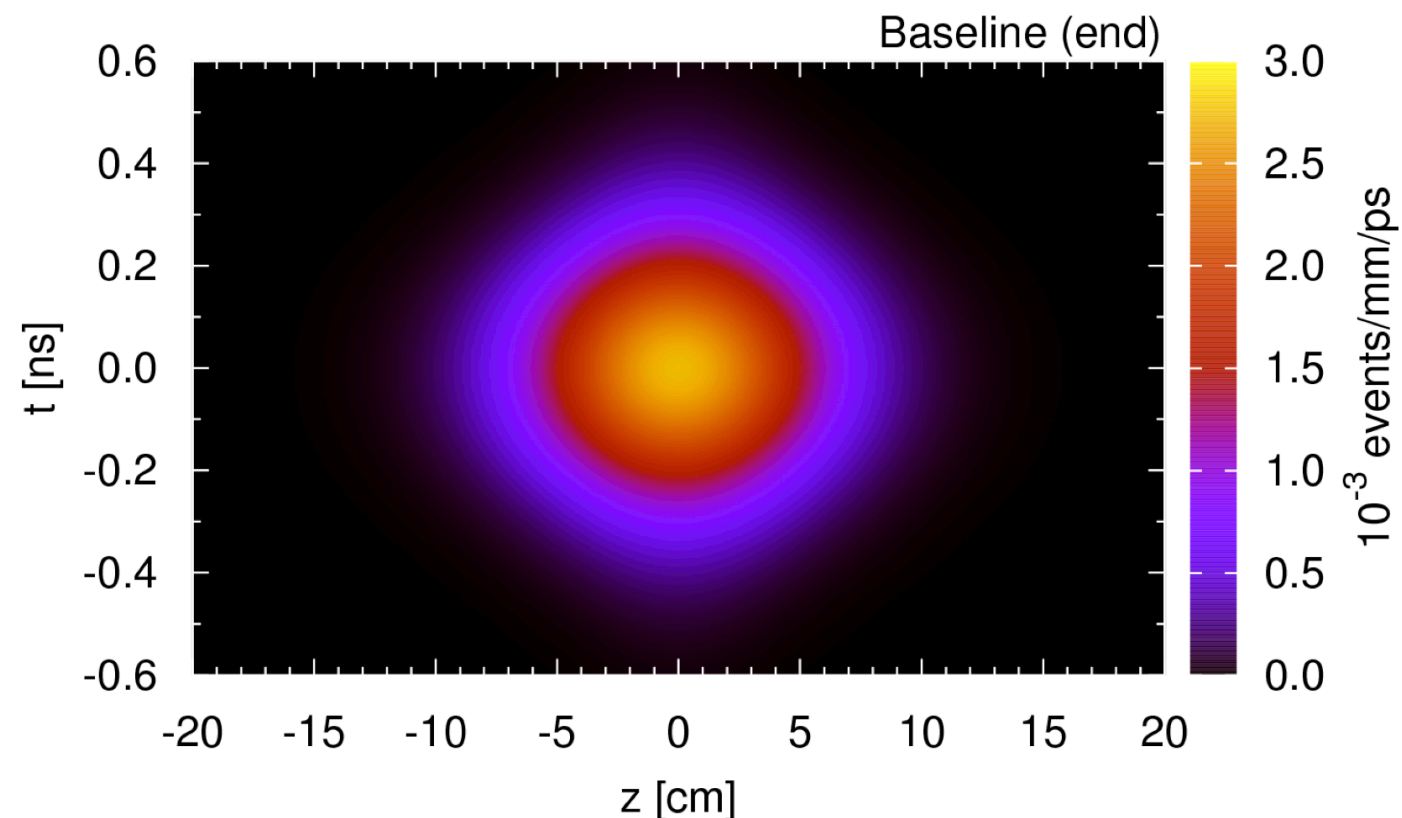
- LLP aware 5D capabilities in each detector must be enabled in trigger hardware
 - Displaced vertices, delayed objects, dE/dX ...
- Edge processing to enable readout in every collision
 - At the LHC: get energy (dE/dx), precision timing, and high spatial granularity measurements AT 40 MHz

summary

- Long lived Particle Flow (**LLPF**) through highly segmented 4D-tracking and 5D-calorimetry
- **Active Shielding** through embedded active muon stations to detect displaced decays and showers above background
- **Edge processing** to enable 4D displaced vertex triggering
- LLP aware **software and computing** model

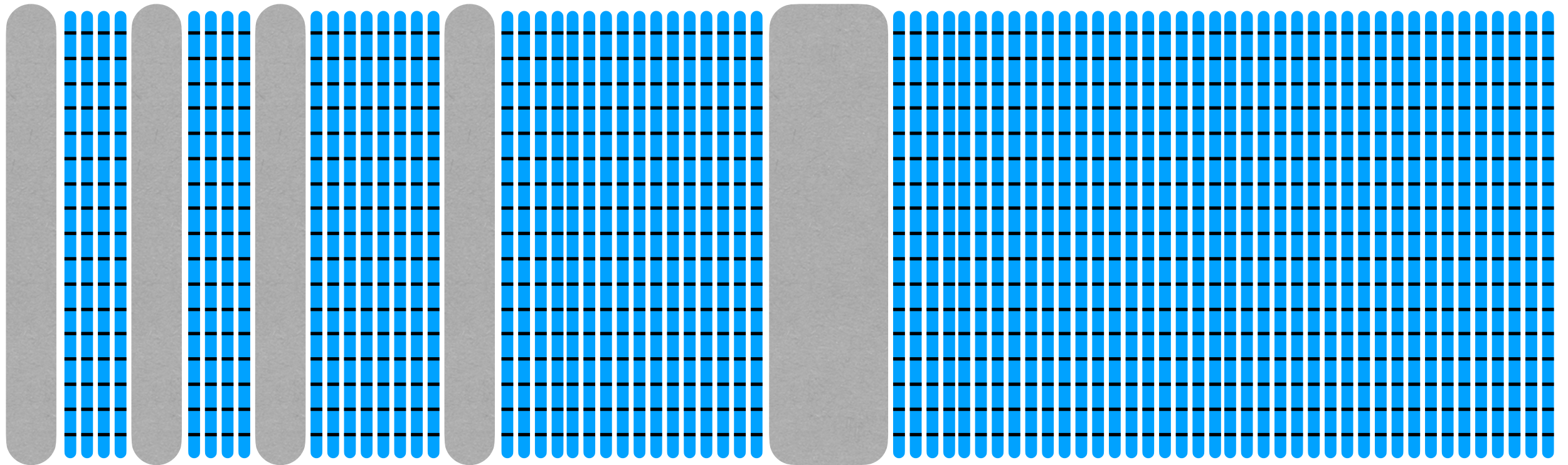
Tracker

- 4D-Tracking: position+timing in same sensor (pileup rejection, BIB, 4D displaced vtx reconstruction)
- ~ 10 ps and ~ 10 μm resolution: advance R&D for sensors and ASICs
- Capability to perform precision-vertexing including at large and small radius



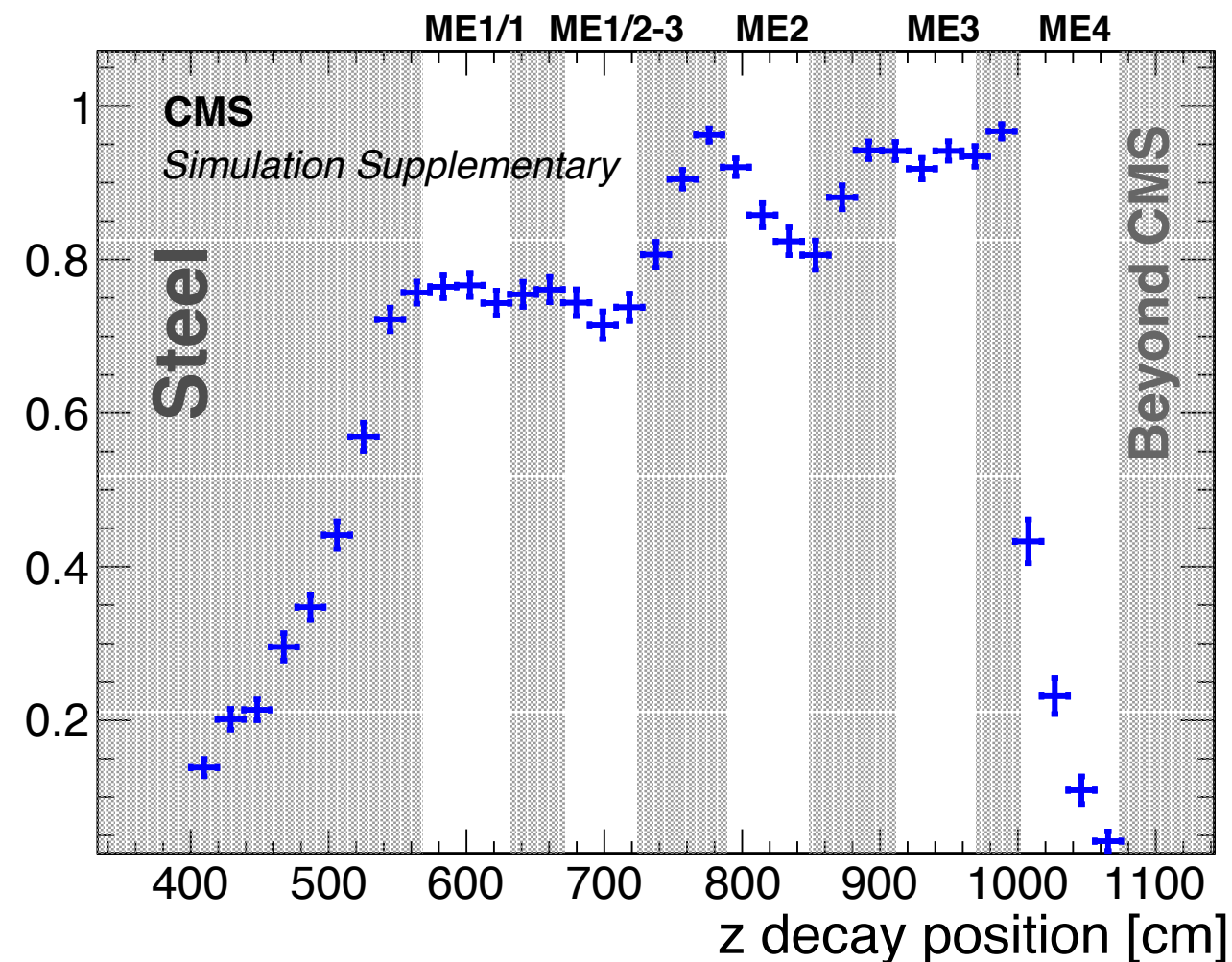
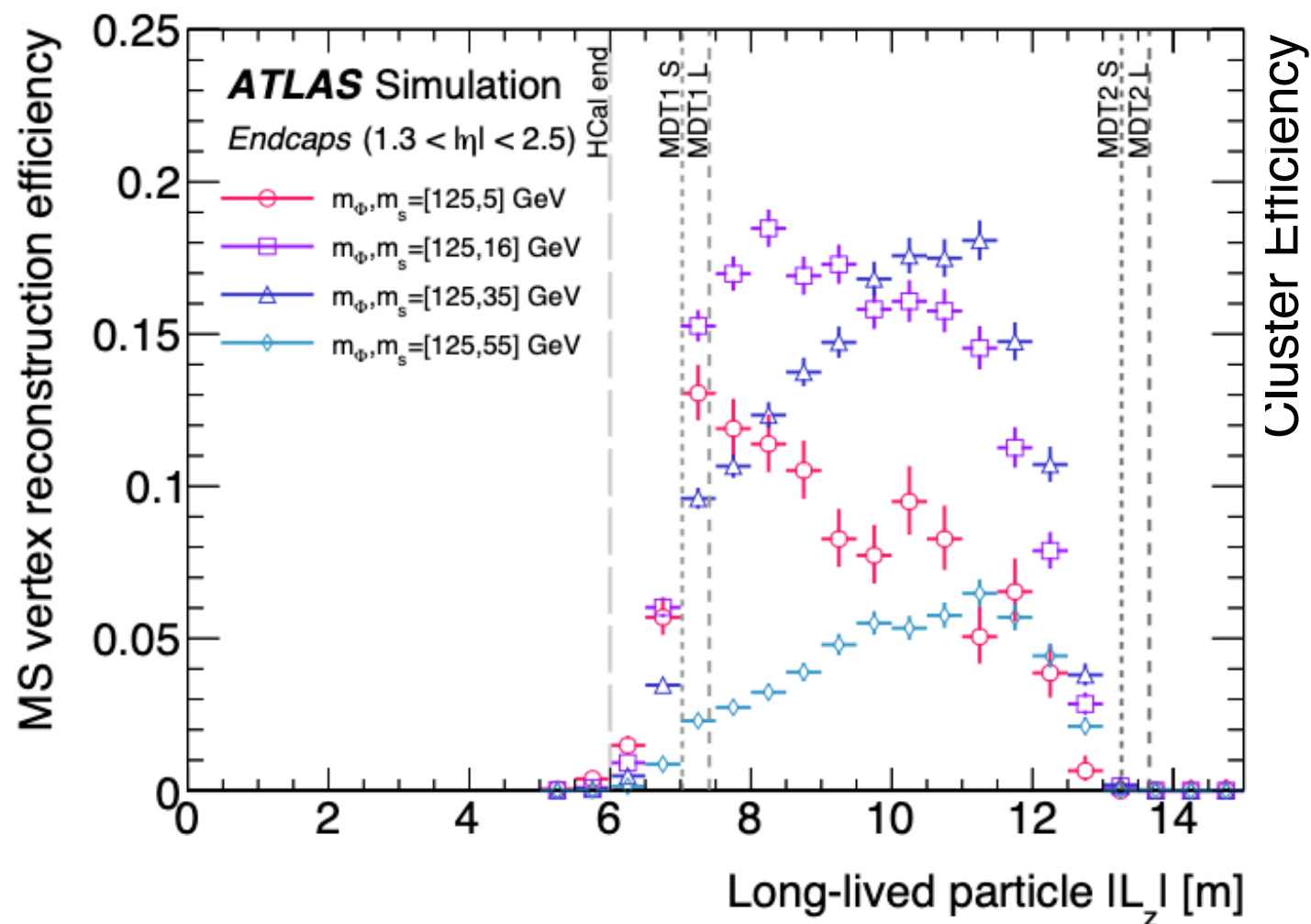
Muon System

- Hybrid MS system



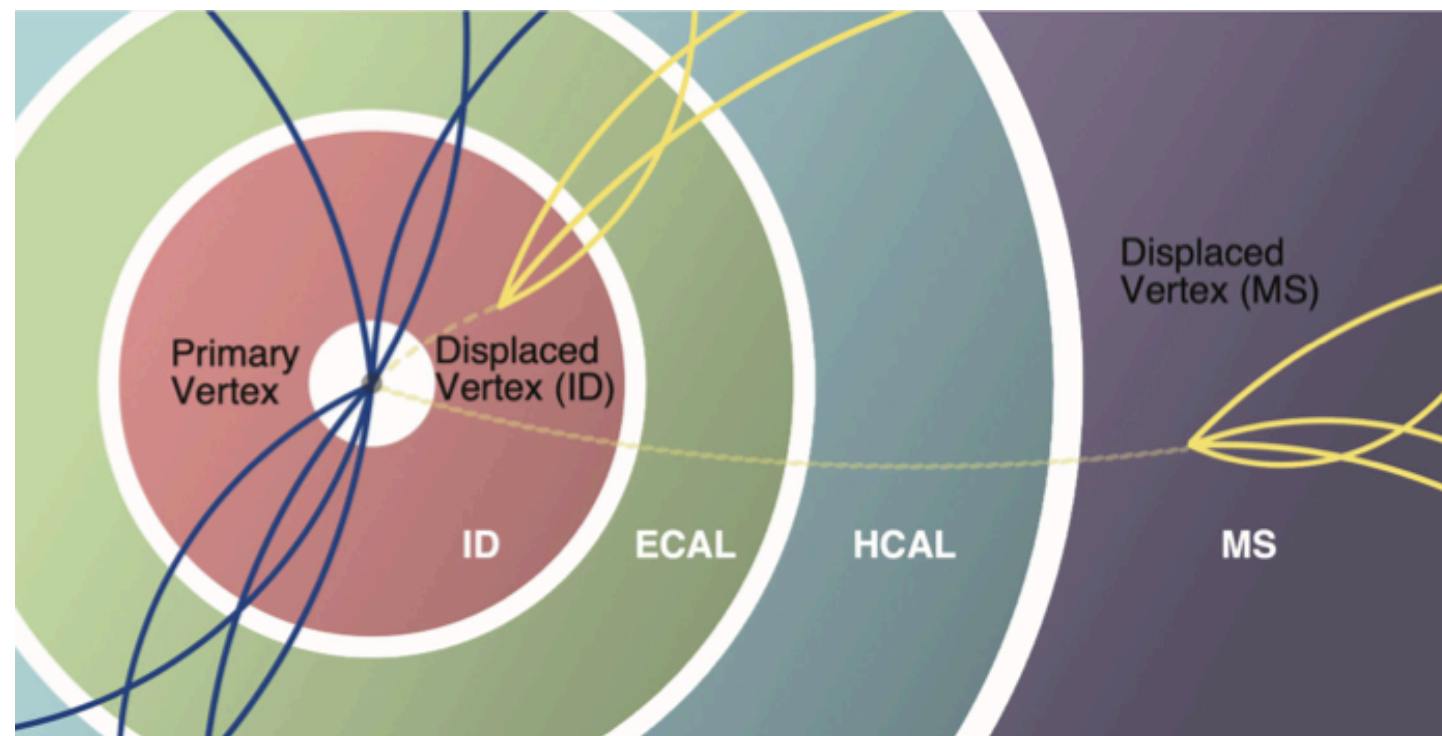
Muon System

- **Key capabilities:** LLP vertex reconstruction, TOF, LLP calorimetric signature



Muon System

- Need **larger number of active stations with improved granularity**
- Need **more shielding**
 - Interleaved layers of shielding and active stations provides LLP reconstruction through calorimetric signature and increases fiducial volume
- **Key capabilities:** LLP vertex reconstruction, TOF, LLP calorimetric signature
- **Key features:** increased bkg suppression, increased target mass for stopped-particle searches



CMS Simulation Supplementary

