Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science

4D trackers and precision timing

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IF03 Solid State Detectors

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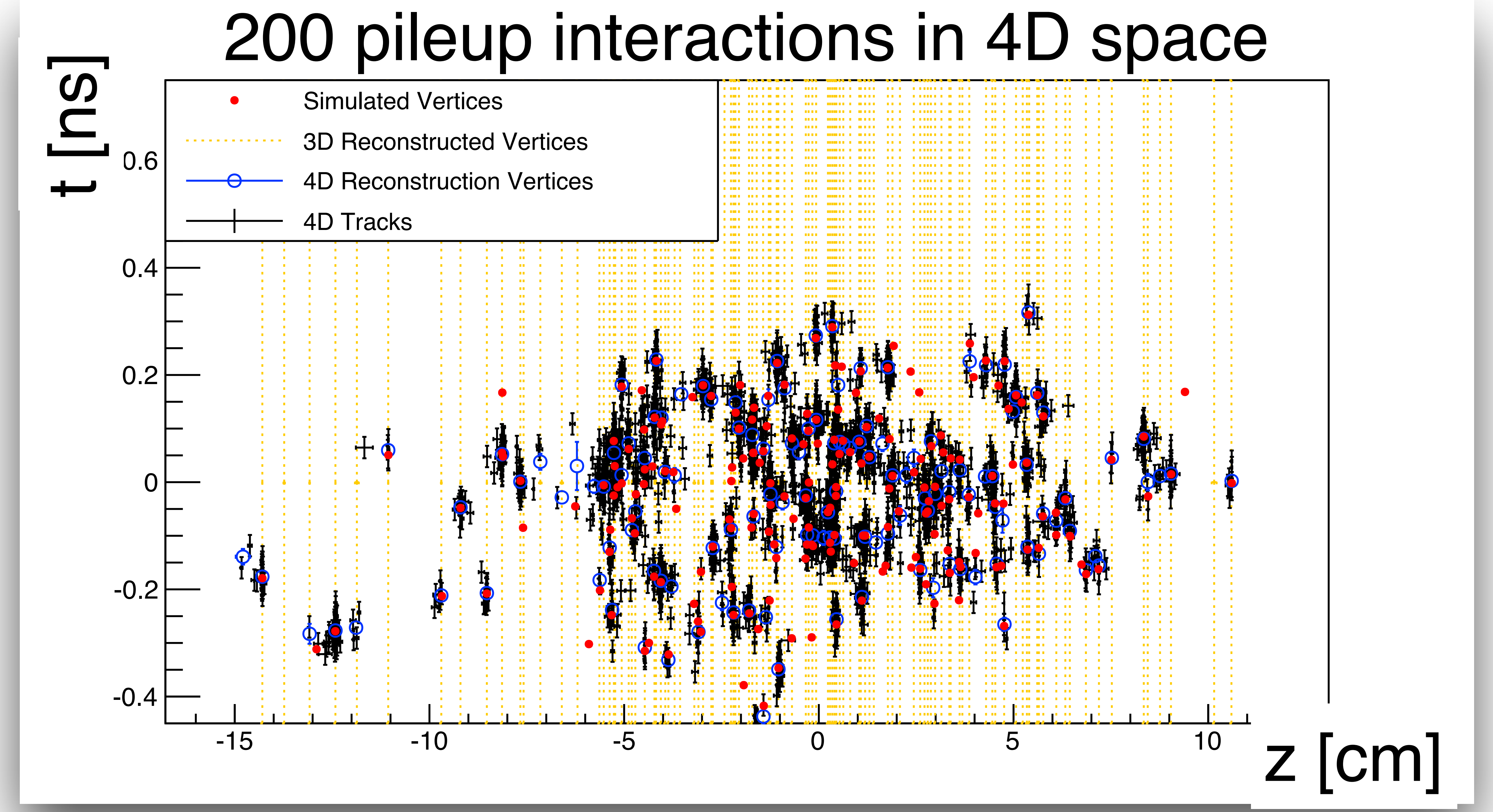
4D trackers and precision timing

- White paper covering 4D trackers and precision timing
  - LOIs #25, #37, #39

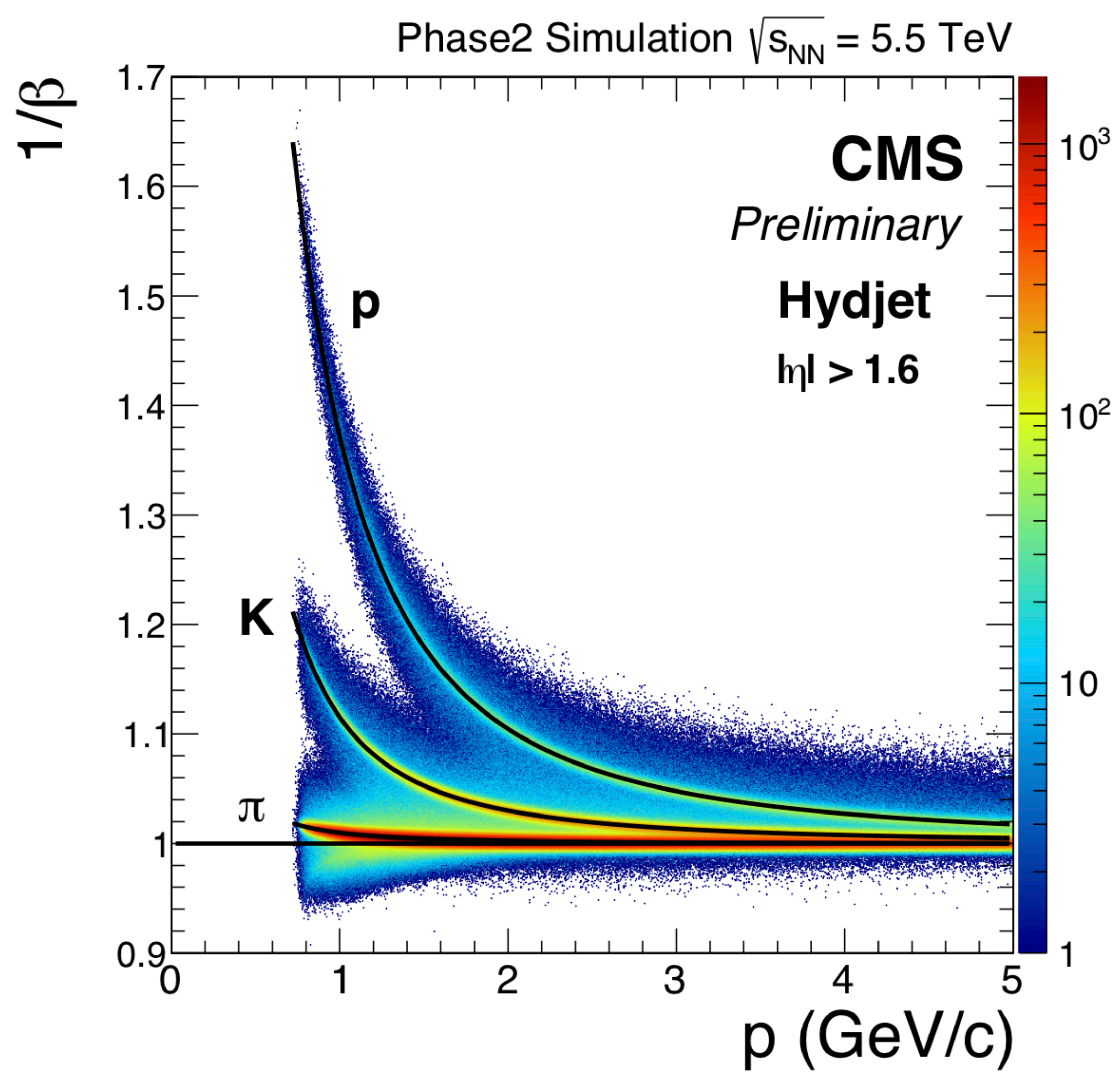
- Proposed structure
  - Motivation for 4D tracking & requirements for future collider experiments
    - FCC, ILC, EIC, muon collider
    - Resolutions approaching 5-10 microns & 5-10 ps in most extreme cases
    - Layout considerations
  - Sensor technologies, current status, key challenges, and R&D roadmap
    - Advanced LGADs (AC-LGADs, TI-LGADs, DJ, DG..) achieve excellent spatial resolution already
    - Concentrate R&D effort on radiation hardness and sub 20 ps resolution (ultra thin sensors?)
  - Electronics: challenges of density & power consumption, roadmap for future.

Motivation for 4D tracking

- ATLAS & CMS constructing timing layers for HL-LHC
  - 30-50 ps resolution, but coarse spatial resolution: “Zeroth” example of 4D tracker



Simplify complex environment
(Reject PU tracks)



Add ToF capability (PID, LLPs..)

Motivation for 4D tracking

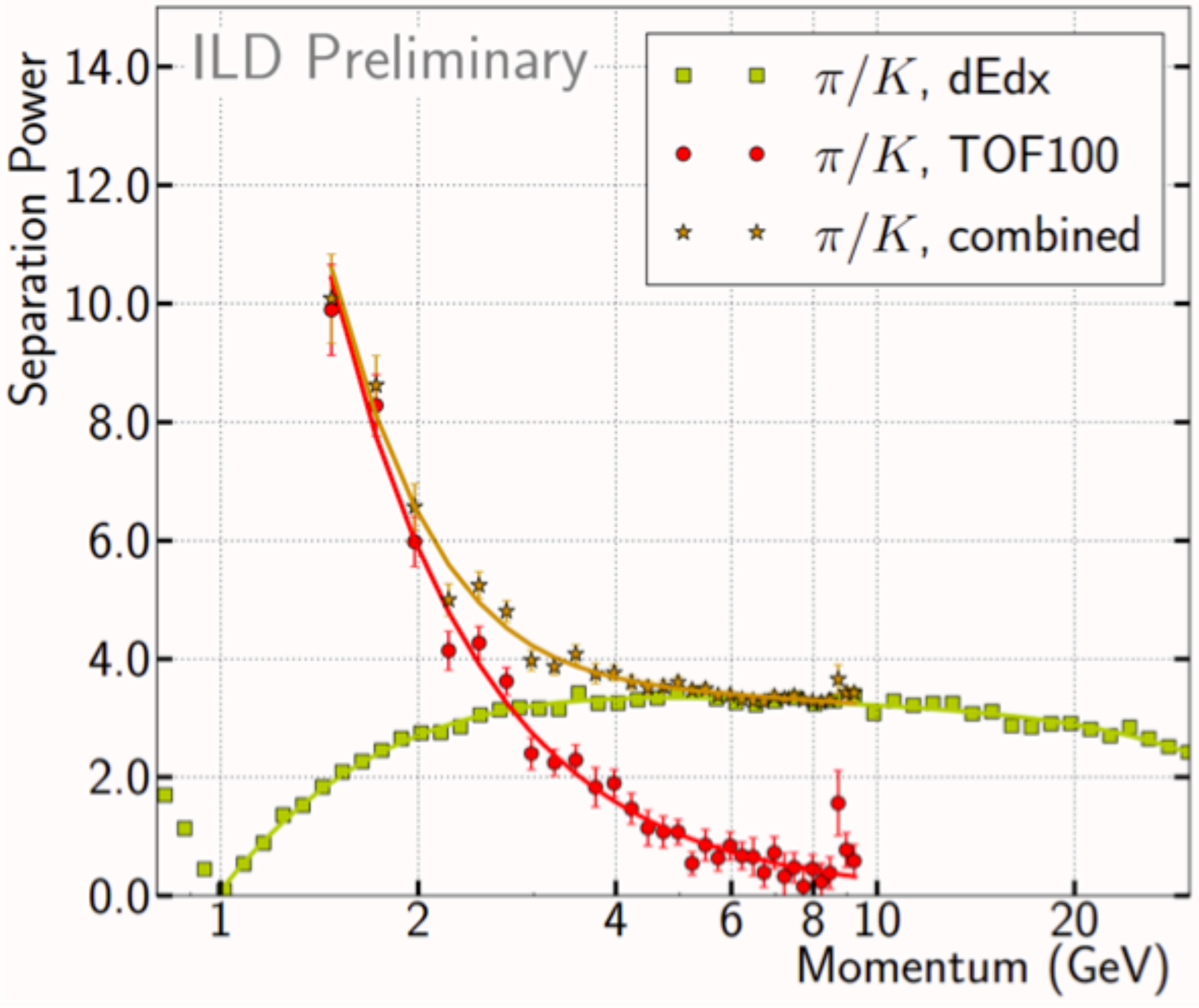
- FCC-hh
  - Need 10 um & 10 ps resolution in many layers
    - pattern recognition / track finding
    - PU rejection
  - Extreme rad hardness requirements

- ILC
  - Background rejection with modest timing ~ 1 ns (backscattered brems)
  - ToF capability important for PID & LLP

Detector requirements for future high-energy collider experiments, TREDI2020

Parameter \ Exp.	LHC	HL-LHC	FCC-hh	FCC-ee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G****)	20 G	20 M ***)	240k
Surface inner tracker [m^2]	2	10	15	1	1
Surface outer tracker [m^2]	200	200	400	200	140
Material budget per detection layer [X_0]	0.3%*) - 2%	0.1%*) - 2%	1%	0.3%	0.2%
Pixel size inner layers [μm^2]	100x150-50x400	~50x50	25x50	25x25	<~25x25
BC spacing [ns]	25	25	25	20-3400	0.5
Hit time resolution [ns]	<~25–1k*)	0.2**)–1k*)	~10^{-2}	~1k ***)	~5

Strange-tagging with TOF; V. Cairo, A. Schwartzman



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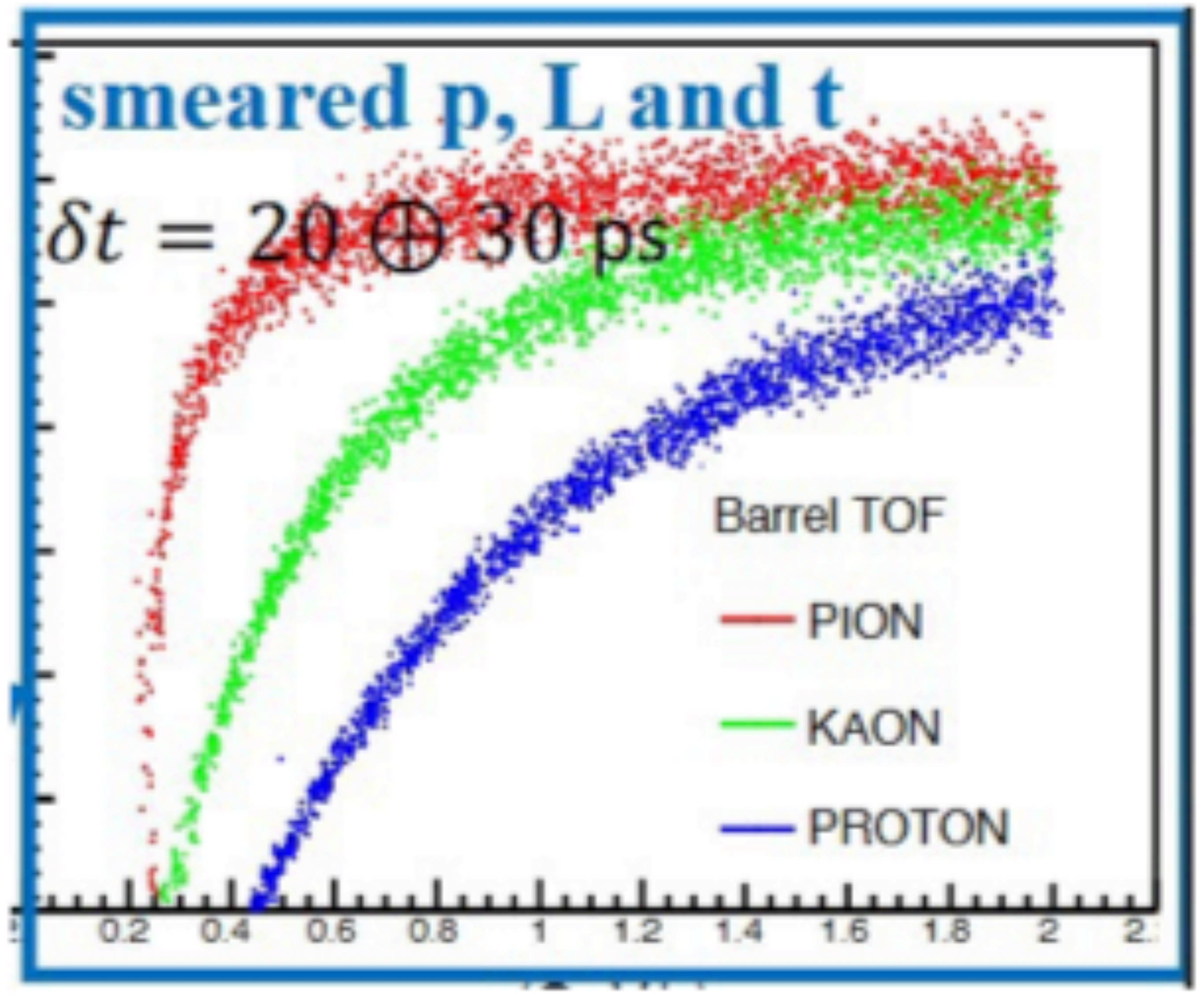
Motivation for 4D tracking

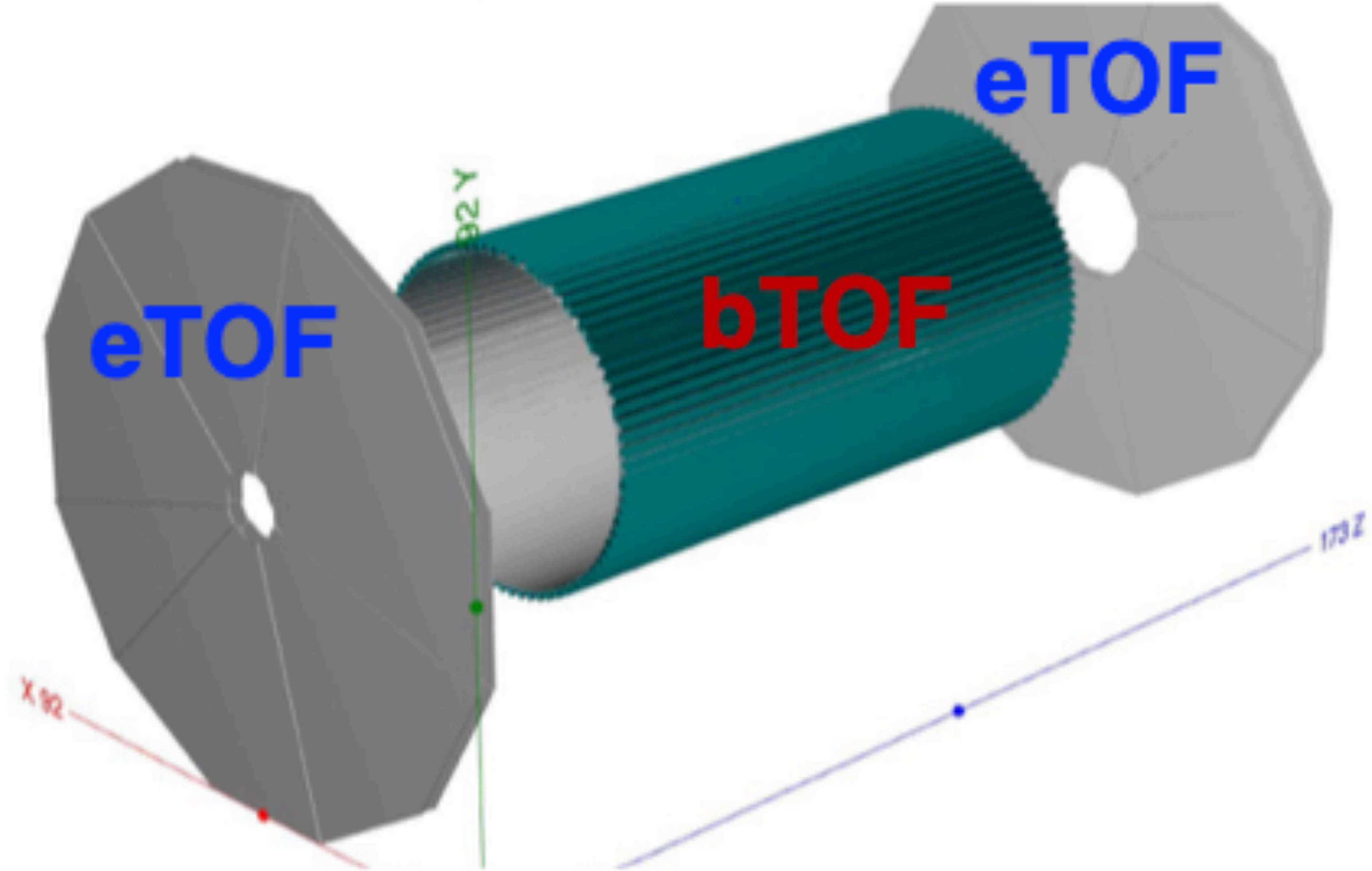
- EIC
  - ToF application: 30 ps & 30 um resolution
    - Don’t necessarily need timing in every layer.
  - Roman pots / forward application:
    - improve proton pT resolution
    - 50 ps and ~100 um resolution

- Muon collider
  - Reject beam-induced background in tracker with timing ~50 ps

https://muoncollider.web.cern.ch/tracking-detector

E.g. ToF in ATHENA detector





Layout considerations & compromises

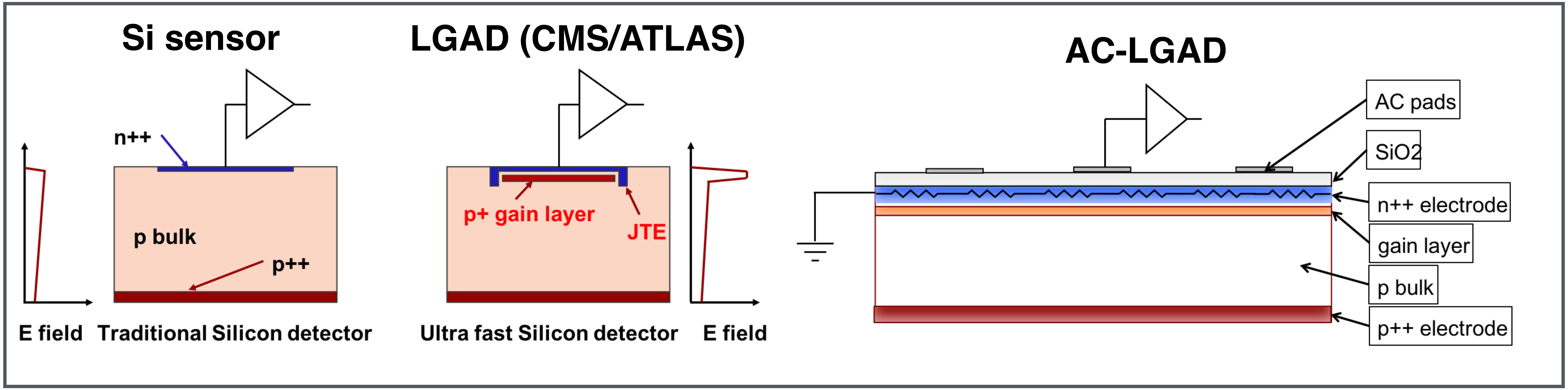
- Not all applications require cutting-edge performance in both time and space.

- Where can we make compromises to conserve resources ($$$, cooling power, material budget, etc..)? Some examples:
  - EIC roman pots: Need good timing, but only moderate space resolution
  - ILC: Only modest time resolution for BG rejection
  - How many layers really need ps timing? For TOF PID, LLP searches..
  - Forward / central coverage?
  - Segmentation: driven by occupancy, or spatial resolution?

- Applications exist for technologies that only check a few of the boxes.

Sensor technologies

- LGADs: thin sensors with moderate gain (30 ps resolution, ~mm granularity)
- Many concepts to introduce fine segmentation
  - AC-LGADs, Trench-isolated LGADs, Deep Gain LGADs, Deep Junction LGADs



Many successful prototypes produced by HPK, FBK, BNL, others.

Promising performance!

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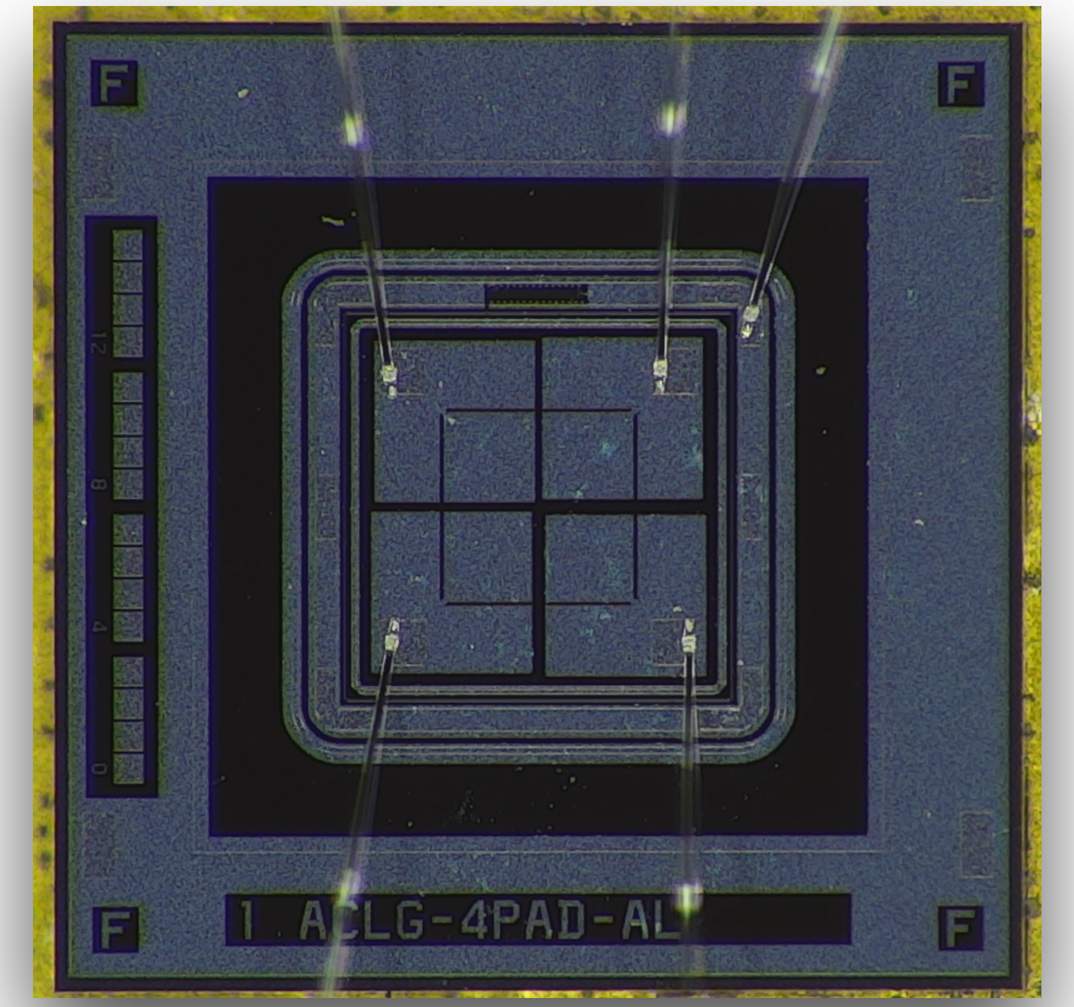
AC-LGAD demonstrations

C. Madrid, R. Heller (RD50)

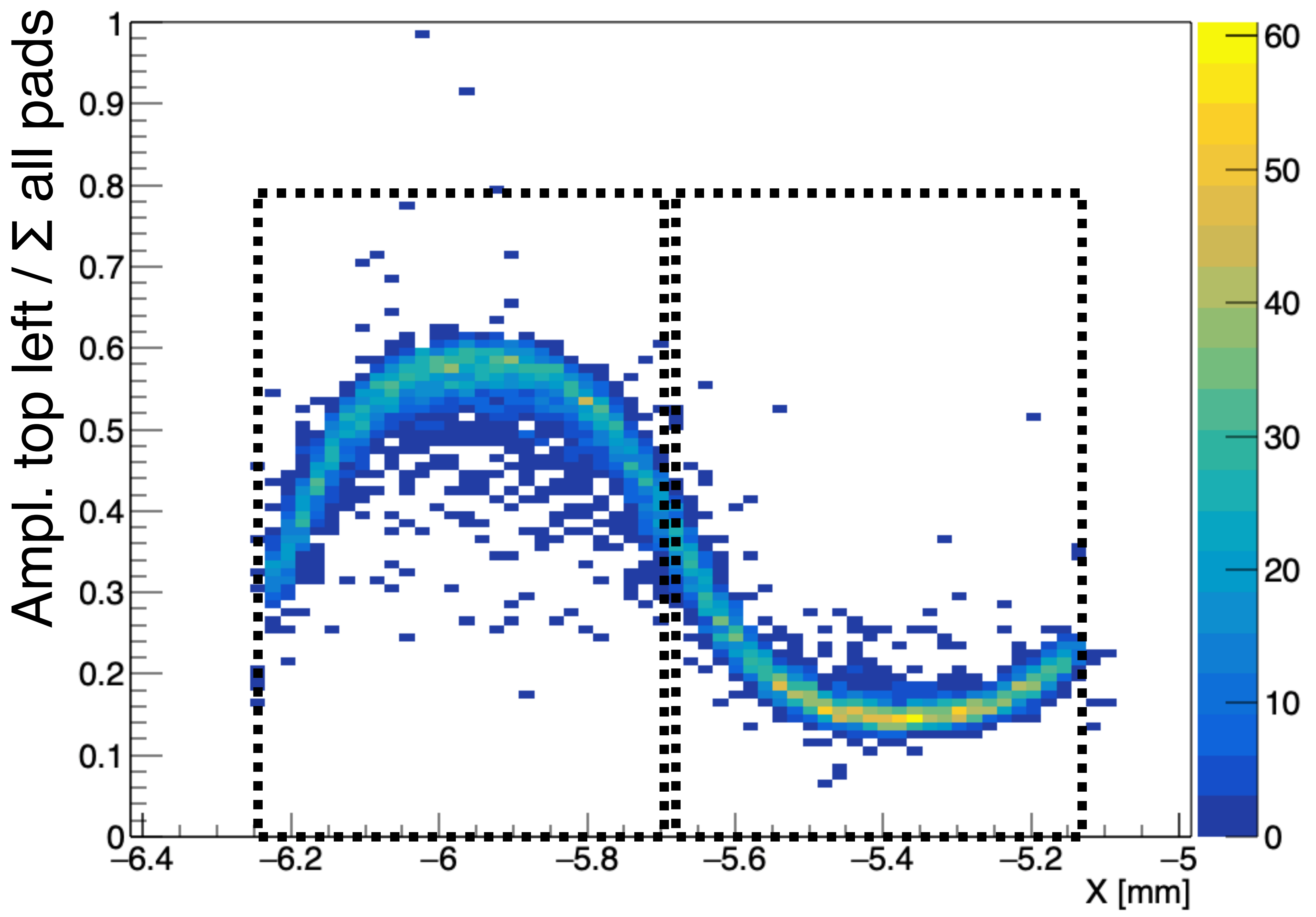
- AC-LGAD prototypes characterized at FNAL test beam, collaboration between FNAL, BNL, KEK, UCSC

AC-LGAD pads, HPK

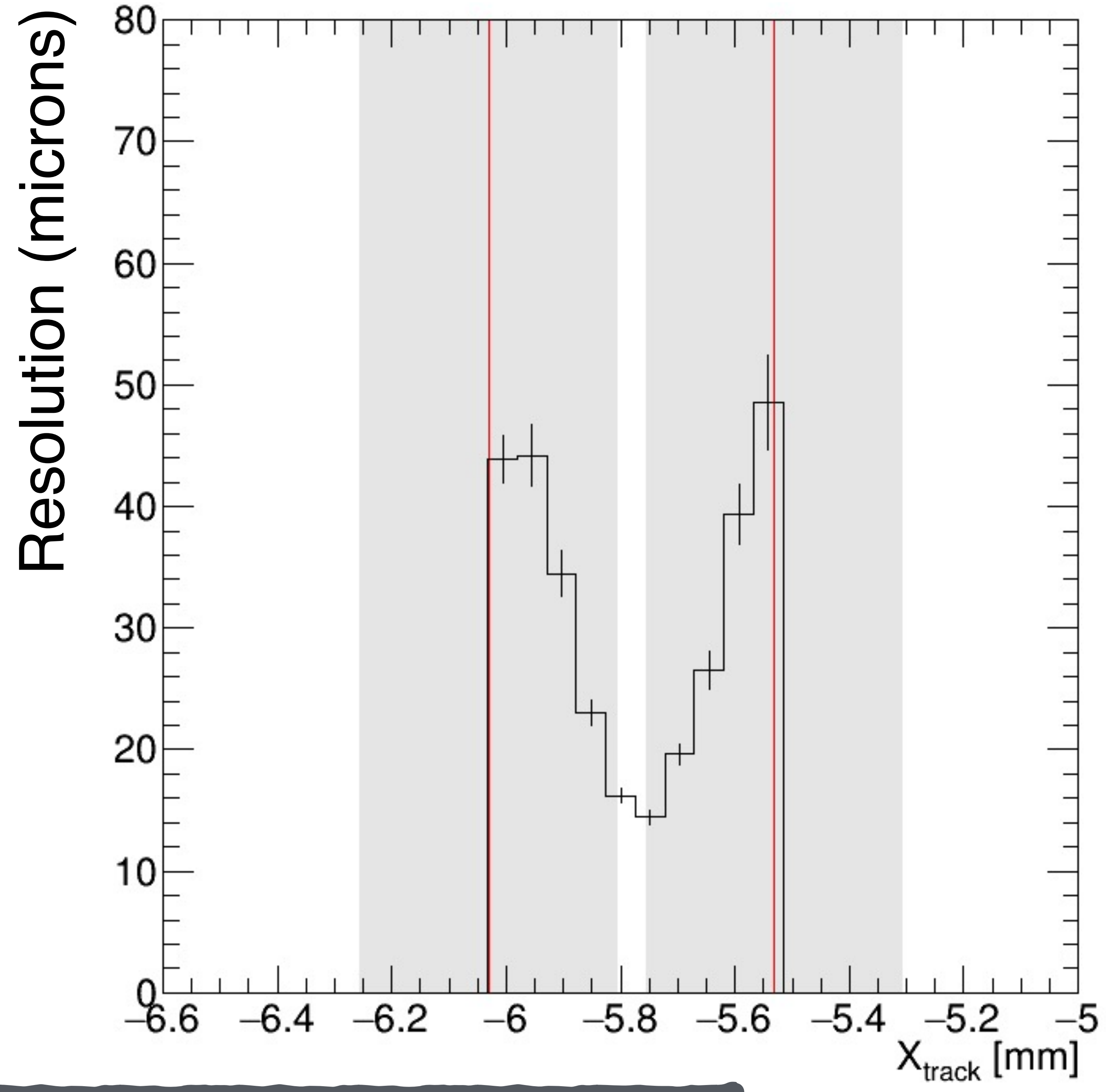
500 micron pitch



Signal sharing ratio between neighbors



Position resolution vs X



Signal sharing: achieve 5-10x better resolution than “pitch / sqrt(12)”!

Maintain 30 ps timing (limit for 50 micron thickness)

Spatial requirements already achievable, without relying on tiny pitch.

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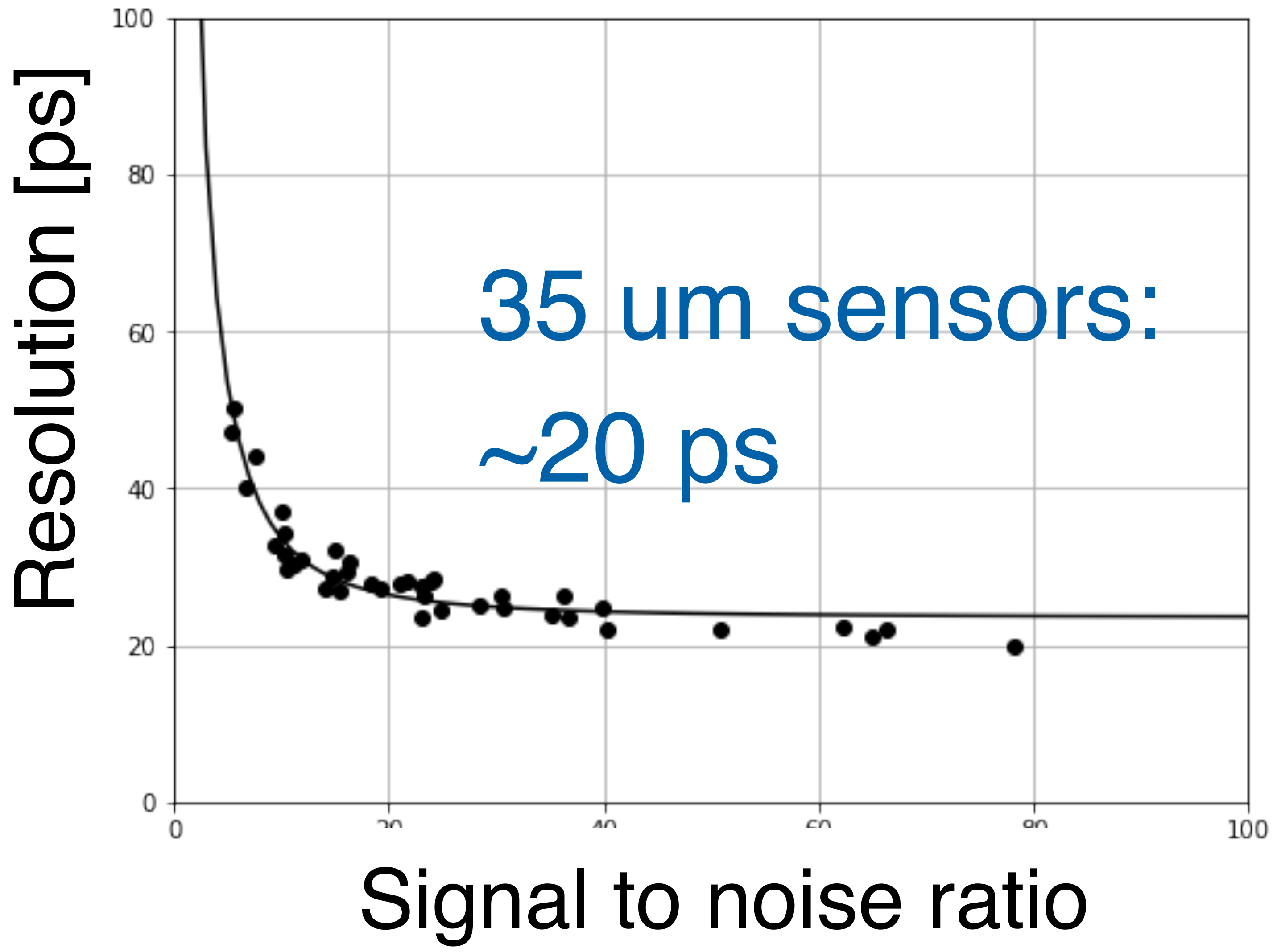
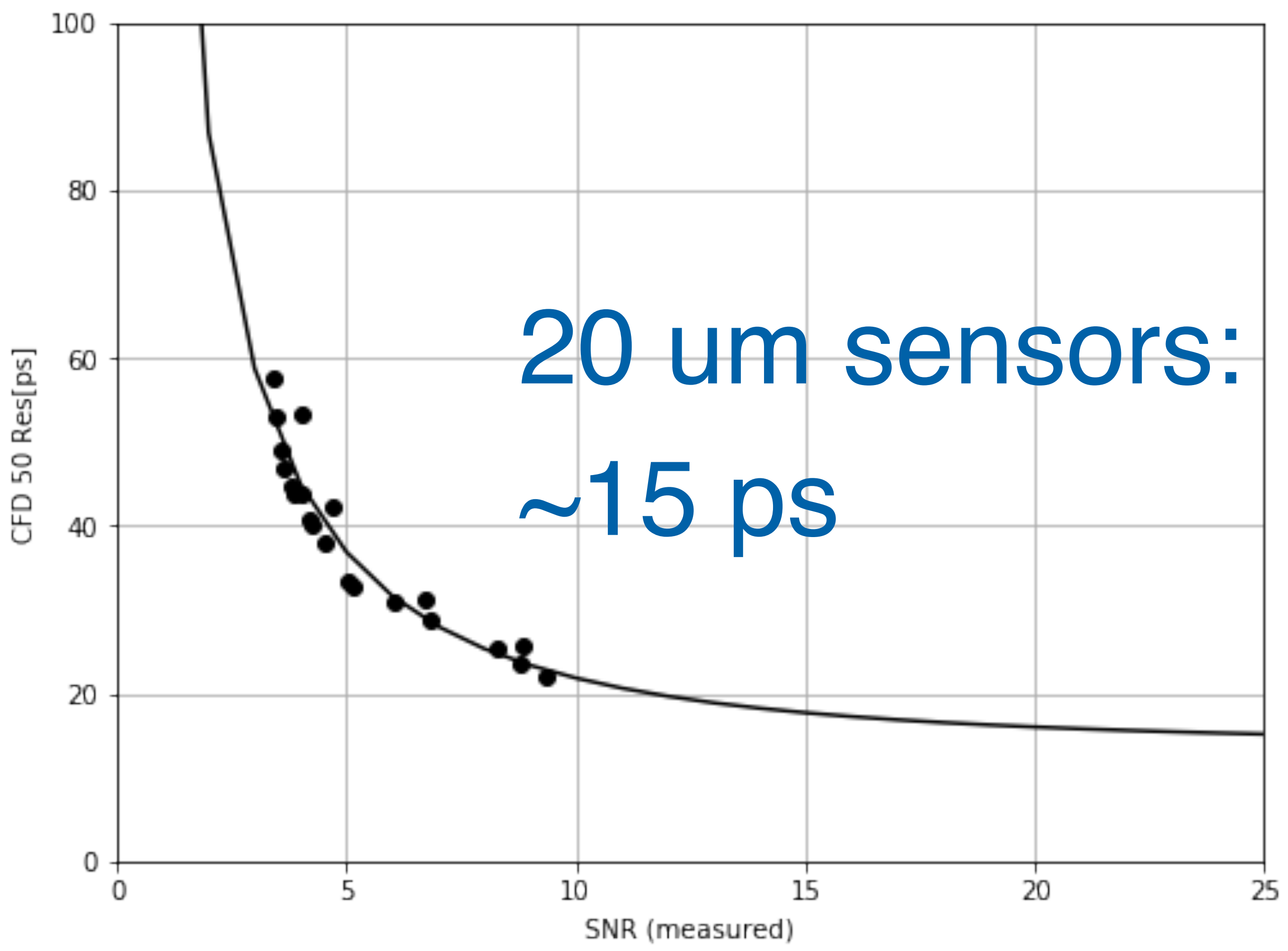
Key sensor challenges

- Improving time resolution: must go thinner!





[S. Mazza, LOI #25]

- Improving radiation hardness ($10^{17\text{-}18}$ neq/cm^2)
  - Thin sensors help: maintain gain & low depletion voltage to higher fluence
    - What about susceptibility to single event burnout? ([R. Heller, RD50])
  - Other techniques: Deeper gain implants (DJ and DG-LGADs), carbon co-implant

Electronics challenges

- 4D trackers place extreme demands on electronics
  - High bandwidth, low noise amplifier + high resolution TDC
  - Must fit in small area and use limited power

- HL-LHC LGAD chips (ETROC,ALTIROC):
  - 1-3 mW per channel, 1.3 mm pitch, 65 nm
  - Compare to RD53 (HL-LHC pixels): ~20 uW per channel, 50 micron pitch

- Significant R&D needed to keep power budget reasonable and shrink pitch!
  - SiGe readout for AC-LGADs
  - Monolithic LGADs

Conclusion

- 4D tracking capability will be a critical for all future collider detectors
  - Pattern recognition / PU rejection in dense environments
  - ToF capability for PID and LLPs

- Sensor technology already reaches specifications for some applications
  - Excellent spatial resolution achieved in various AC-LGAD designs

- Roadmap for future R&D:
  - Sensors:
    - Improve time resolution from 30 ps to 5-10 ps
    - Extend radiation hardness for FCC: $10^{17\text{-}18}$ neq/cm^2
  - Electronics:
    - Shrink pitch and reduce power usage per channel