Instrumentation

for energy frontier colliders

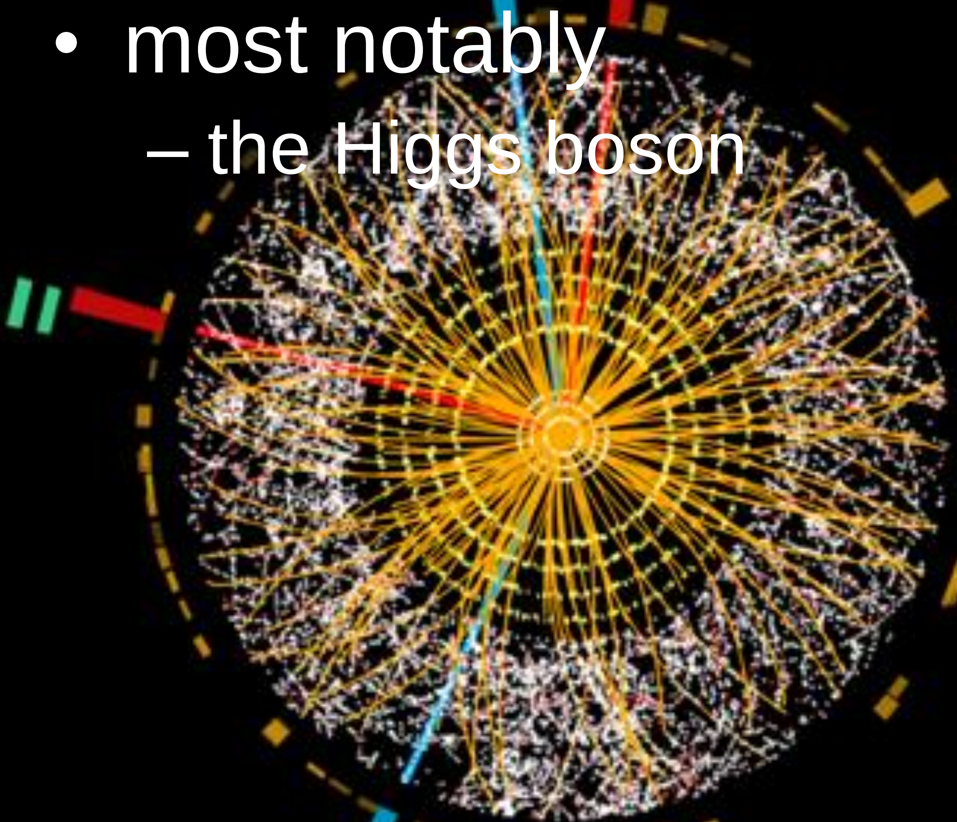
Ulrich Heintz
Brown University

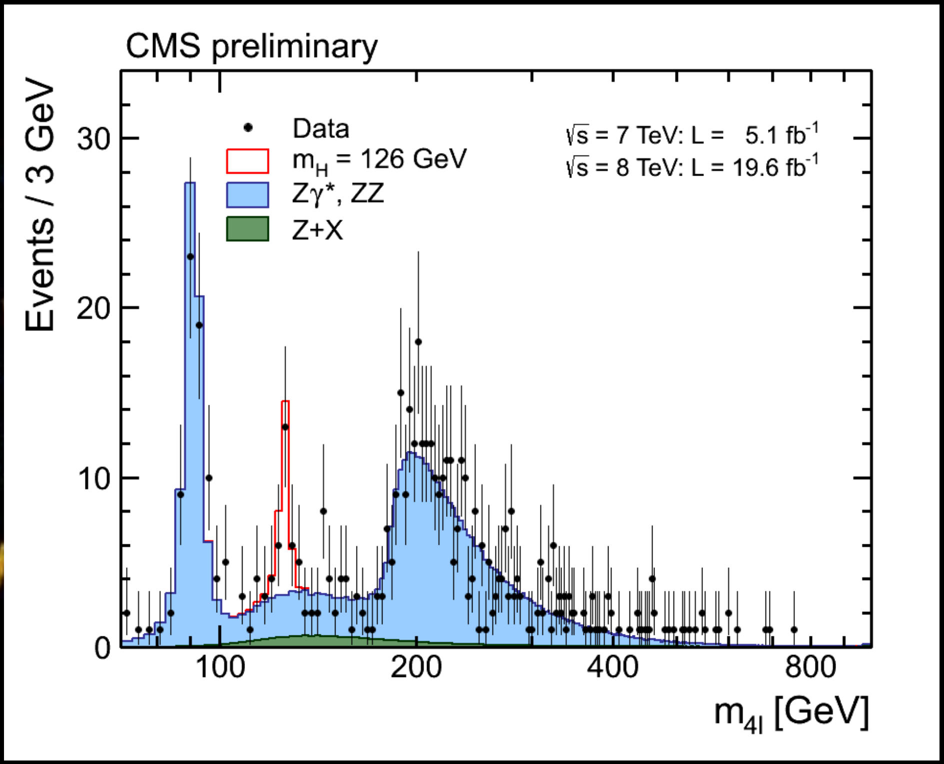
outline

- physics at the energy frontier
- instrumentation frontier
- request for input
- challenges for energy frontier machines
- technology R&D themes
- facilities
- conclusion

physics at the energy frontier

- we can look back on tremendous successes
- most notably
  - the Higgs boson





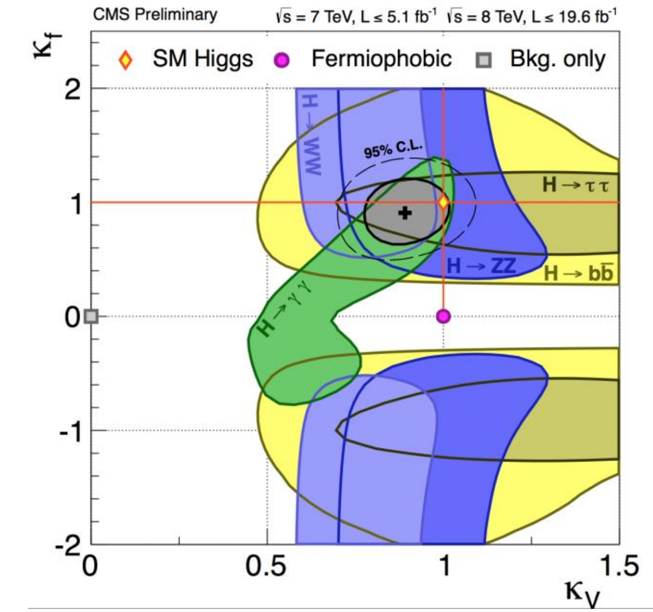
- made possible by advances in technology and instrumentation

physics at the energy frontier

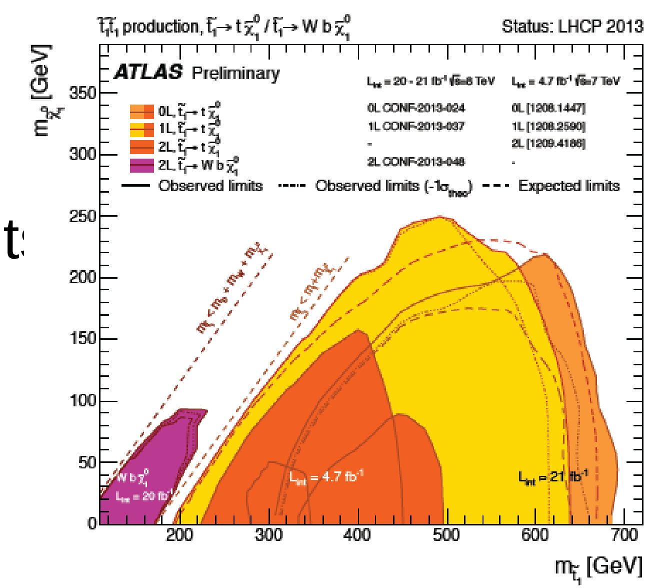
- large accelerators and collider detectors
- would like to do everything
  - measure position to microns
  - measure timing to picoseconds
  - measure energy deposit to eV
  - highly pixelated trackers and calorimeters
  - read it all out, all the time
- all at low cost, minimal power, and no mass …
- real detector designs driven by
  - constraints of the accelerator environment
  - physics needs
  - technical capabilities
  - cost

physics at the energy frontier

- characterize the Higgs boson
  - branching fractions
  - coupling constants, self-coupling
  - search for extended Higgs sector
- study vector-boson scattering



- search for new physics
  - SUSY
    - severely constrained by existing limits
    - light stop squarks (natural SUSY)
    - compressed spectra
  - exotic phenomena



physics at the energy frontier

- as beam energy increases, we are still looking at ewk scale phenomena involving W and Z bosons and their decay products
- maintain acceptance to relatively soft particles
- maintain large angular acceptance to minimize theoretical uncertainties and retain sensitivity to distinguish between different models should we find something new
- superior spatial and time resolution for pattern recognition in high occupancy environment

CPAD/Instrumentation Frontier

- to continue our success at the energy frontier we need to make technical and scientific innovation a priority as a field
- APS recognized this by
  - creating the Coordinating Panel for Advanced Detectors (CPAD) to study strategic issues in instrumentation
  - including the "Instrumentation Frontier" as one of the central thrusts of the 2013 Snowmass process
- Instrumentation Frontier workshops:
  - Argonne https://indico.fnal.gov/conferenceTimeTable.py?confId=6050
  - Boulder https://indico.fnal.gov/conferenceTimeTable.py?confId=6280

Instrumentation Frontier Organization

Conveners: M. Demarteau (ANL), H. Nicholson (Mt. Holyoke), R. Lipton (Fermilab)

Technologies	Energy Frontier	Intensity Frontier	Cosmic Frontier
	Ulrich Heintz	*David Lissauer*	*Juan Estrada*
Sensors *Marina Artuso* *Abe Seiden*	*Daniela Bortoletto (Purdue)* *Sally Seidel (New Mexico)* *Ren-yuan Zhu (Caltech)*	*Matt Wetstein (Chicago)* *Henry Frisch (Chicago)* *J. Va'vra (SLAC)*	*Andrei Nomerotksi (BNL)* *Clarence Chang (Chicago)* *Jim Fast (PNNL)*
Gaseous Detectors *Gil Gilchriese* *Bob Wagner*	*Andy White (UTA)* *Marcus Hohlmann (FIT)* *Vinnie Polychronakos (BNL)*	*James White (Texas A&M)* *Brendan Casey (FNAL)*	
Detector Systems *Ed Blucher* *David Lissauer*	*Roger Rusack (Minnesota)* *Adam Para (FNAL)*	*Bonnie Fleming (Yale)* *Bob Svoboda (UC Davis)*	*Karen Byrum (ANL)* *Peter Gorham (Hawaii)* *David Nygren (LBL)* *Dan Akerib (Case Western)* *Greg Tarle (Michigan)*
Electronics/DAQ/Trigger *Ulrich Heintz* *Ron Lipton*	*Dong Su (SLAC)* *Wesley Smith (Wisconsin)* *Maurice Garcia-Sciveres (LBNL)*	*Gary Varner (Hawaii)* *Yau Wah (Chicago)*	*Günther Haller (SLAC)* *Frank Krennrich (Iowa State)*
Novel/Emerging Technologies *Jim Alexander* *David MacFarlane*	*Ted Liu (FNAL)* *Julia Thom (Cornell)*	*Steve Ahlen (BU)*	*Juan Estrada (FNAL)*
Software *Norman Graf*	*Erich Varnes (Arizona)*	*Robert Kutschke (FNAL)*	*Salman Habib (ANL)*
Facilities	*Carsten Hast (SLAC)*	*Jae Yu (UTA)*	*Erik Ramberg (FNAL)*

Instrumentation Frontier Goals

- collected white papers (1 pagers)
  http://www.snowmass2013.org/tiki-index.php?page=Instrumentation+Frontier+Whitepapers
- summary white papers covering
  - energy, intensity, and cosmic frontiers
  - each instrumentation topic
- pull it all together in an instrumentation white paper
  - identify R&D themes that transcend the frontiers
  - connect R&D to physics needs
  - in which areas can the US play a lead role?
  - how do we best exploit the facilities and resources we have?

questions

- **can you identify benchmark physics goals that push the technology of current detectors?**
  - measurement of Higgs couplings
  - VBF production of Higgs boson (large η acceptance)
  - low mass stop searches (soft pT spectrum of decay products)
- **what is the performance that you are assuming for simulations?**
- **which aspects of detector performance are critical for each of these?**
  - which parameters are most important to improve on?
- **what improvements in the detector would be transformational for the physics reach?**
  - hadron calorimeter with em-like energy resolution?
  - ps timing of calorimeter signals?
  - ...???

questions

- **do you know how much the physics reach changes as certain detector properties are varied? Can you be quantitative: how much of an improvement is needed to make a difference?**
  - does a 10-20% improvement in resolution matter?
  - do we need factors of 2 or 10?
- **how important is fast time stamping of the signals from the detector? For which detector parts would this be most important?**
  - calorimeter? tracker?
- **how important is the forward region?**
  - how far in η do we need to cover?
- **how important is high b-tagging efficiency at low pT/at high pT?**
- **what are the requirements for triggers? In particular: how important are tau triggers, missing ET triggers and missing ET resolution? How important are inclusive lepton trigger thresholds ?**

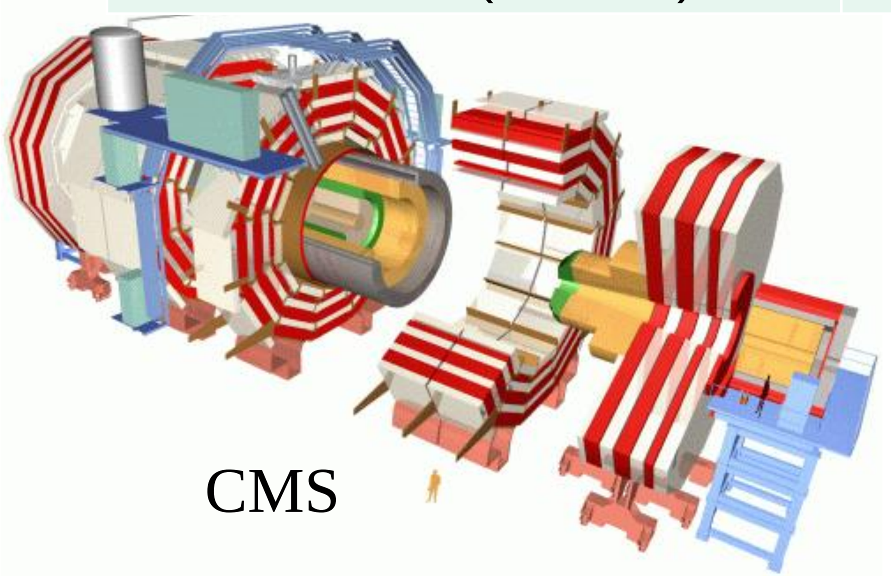
hadron collider facilities

facility	$\sqrt{s}$	L	$\int Ldt$	time scale
LHC	14 TeV	10^{34}	300/fb	2015-2021
HL-LHC	14 TeV	5×10^{34}	3000/fb	2023-2030
HE-LHC	26-33 TeV	2×10^{34}	300/fb/year	>2035
VHE-LHC	42-100 TeV			>2035

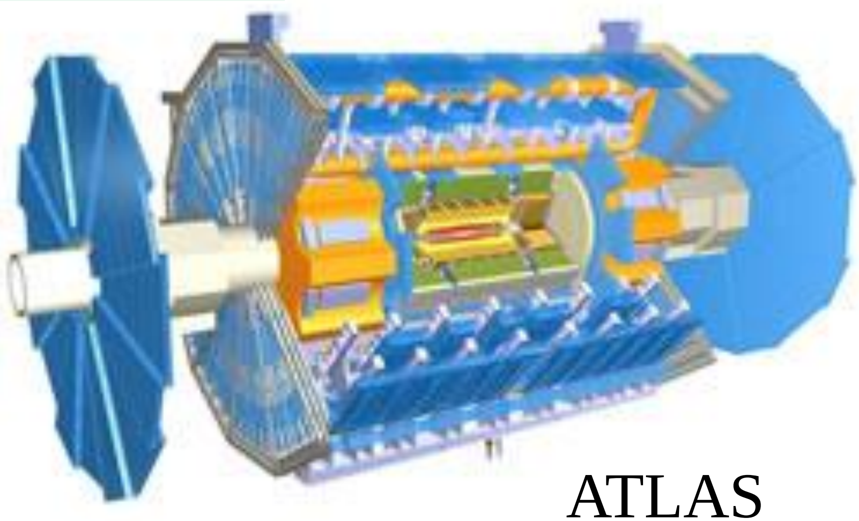
European Strategy for Particle Physics Preparatory Group:
Physics Briefing Book, CERN-ESG-005

environment at hadron colliders

	2012
beam energy	$4\ \mathrm{TeV}$
luminosity	$7.7 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$
integrated luminosity	$24/\mathrm{fb}$
number interactions/crossing	≈ 20
bunch spacing	$50\ \mathrm{ns}$
radiation dose (R≈5 cm)	$3 \times 10^4\ \mathrm{Gy}$



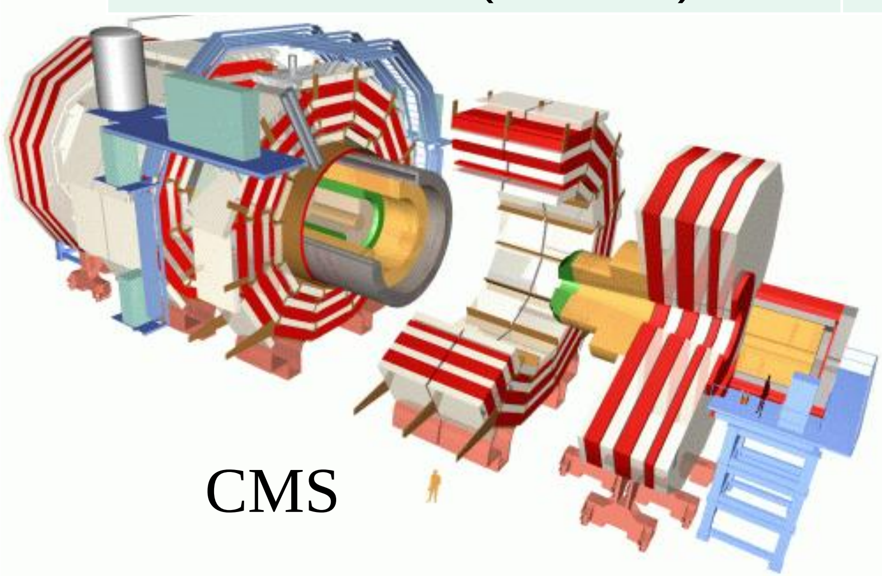
CMS

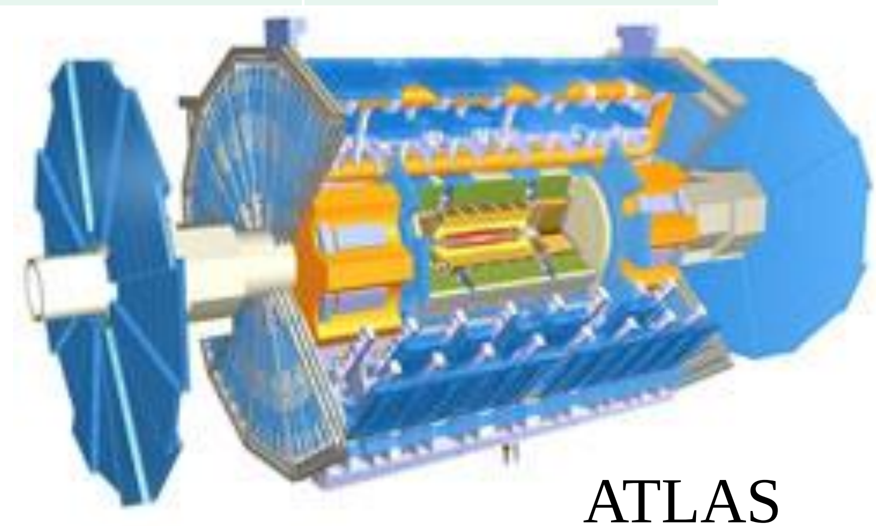


ATLAS

environment at hadron colliders

	2012	HL-LHC
beam energy	$4\ \mathrm{TeV}$	$7\ \mathrm{TeV}$
luminosity	$7.7 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$	$5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
integrated luminosity	$24/\mathrm{fb}$	$3000/\mathrm{fb}$
number interactions/crossing	≈ 20	≤ 140
bunch spacing	$50\ \mathrm{ns}$	$25\ \mathrm{ns}$
radiation dose (R≈5 cm)	$3 \times 10^{4}\ \mathrm{Gy}$	$5 \times 10^{6}\ \mathrm{Gy}$





environment at hadron colliders

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challenges: interaction rate

pileup

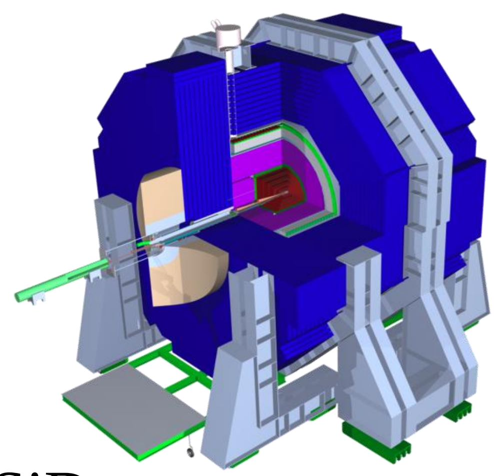
radiation damage

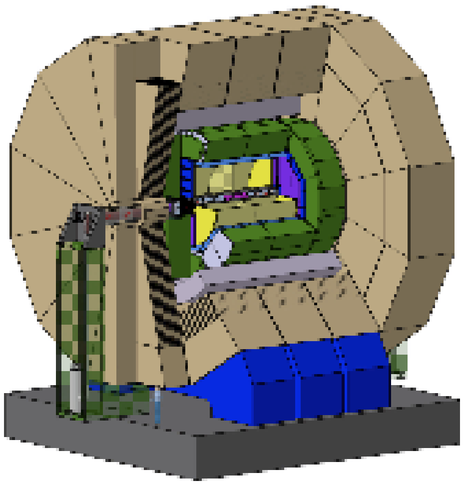
challenges

- interaction rate
  - increase rejection power of trigger system
  - low power, high bandwidth links
- pileup
  - pixelization
  - precision timing
- radiation damage
  - radiation hard detector technologies
  - operate at low temperatures

lepton collider facilities

facility	$\sqrt{s}$	L
ILC	$0.5\ \mathrm{TeV}$	1.5×10^{34}
CLIC	$3\ \mathrm{TeV}$	5.9×10^{34}
TLEP	$240 - 350\ \mathrm{GeV}$	
Higgs factory MuC	$\mathrm{m_H}$	$10^{31} - 10^{32}$
energy frontier MuC	$3 - 6\ \mathrm{TeV}$	$10^{34} - 10^{35}$


SiD


ILD

environment at e^+e^- colliders

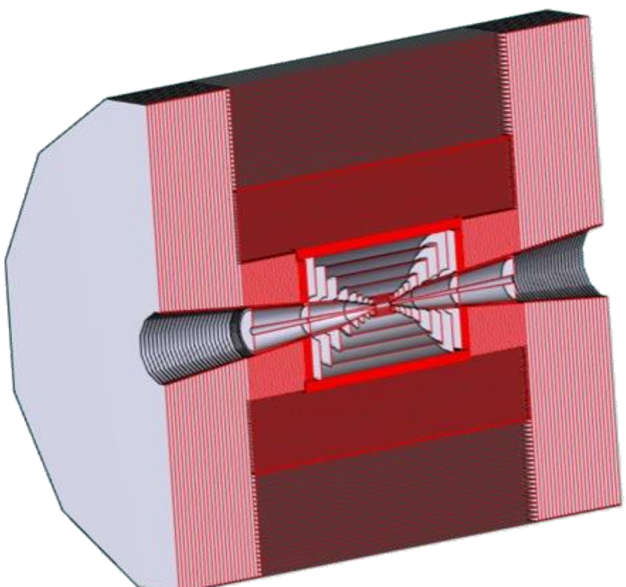
	ILC	CLIC
bunches/train	1312	312
length of bunch train	1 ms	156 ns
bunch spacing	762 ns	0.5 ns
interval between trains	199 ms	20 ms
collision rate	5 Hz	

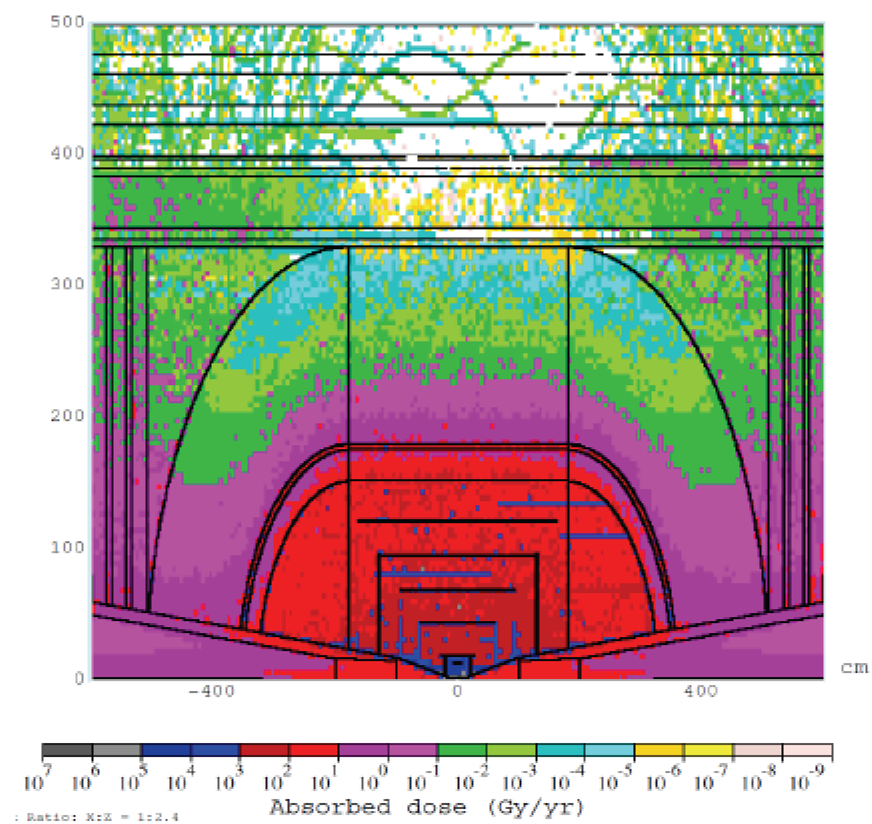
drive timing requirements for detector

detector performance driven by physics goals

environment at $\mu^+\mu^-$ colliders

- bunch spacing: 500 ns (Higgs factory), 10 μs (EF)
  - lots of time to read out detector
- backgrounds are large
  - 1.3 x 10^{10}/m/s muon decays for 2 beams @ 0.75 TeV
  - radiation dose $10^3 - 10^4$ Gy/year
  - detectors must be radiation hard
  - soft and out of time

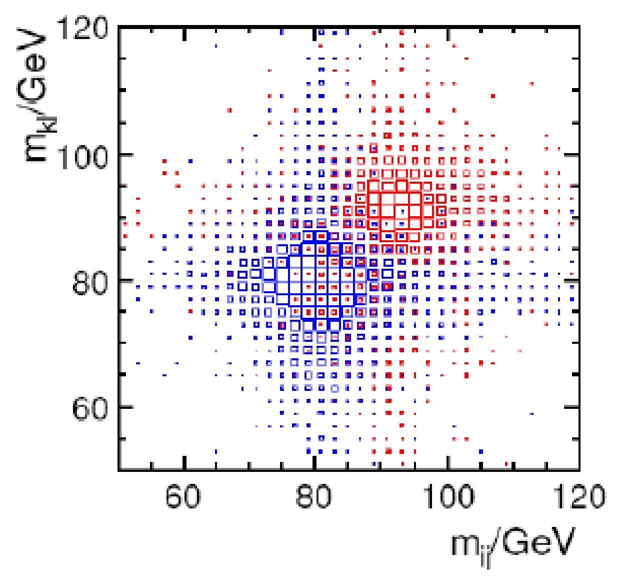


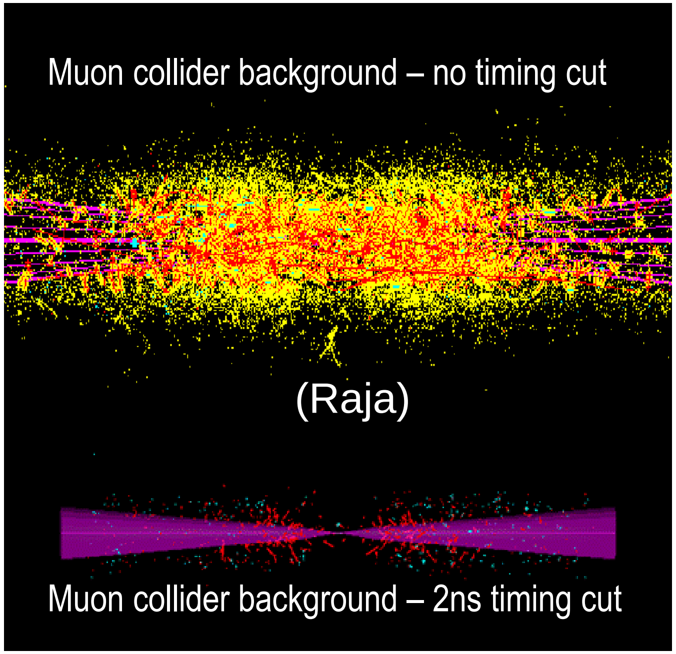


challenges

- separate hadronic W/Z decays
  - superior calorimeter resolution
  - high pixelization
- short bunch spacing (CLIC)
  - precise timing
- high background levels (MuC)
  - precise timing
  - radiation tolerance

H→WW/ZZ separation at ILC





enabling technologies

Pixelization
- Microelectronics feature size reduction
- New interconnect technologies
- Low power data transmission
- Technologies for 3D electronics

Speed
- Faster sensor technologies
- Low power, fast electronics
- Lower capacitance detectors (see pixelization, 3D silicon)

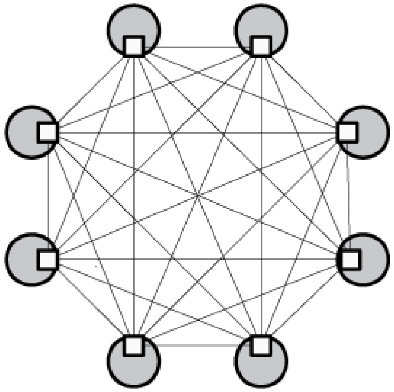
Resolution
- Smaller tracker elements (see pixelization)
- Improved understanding of hadron showers
- Imaging calorimetry (see pixelization)

Mechanics and Power
- Carbon fiber supports
- Foamed thermally conductive materials
- CO_2 cooling
- Power delivery using DC-DC conversion or serial powering

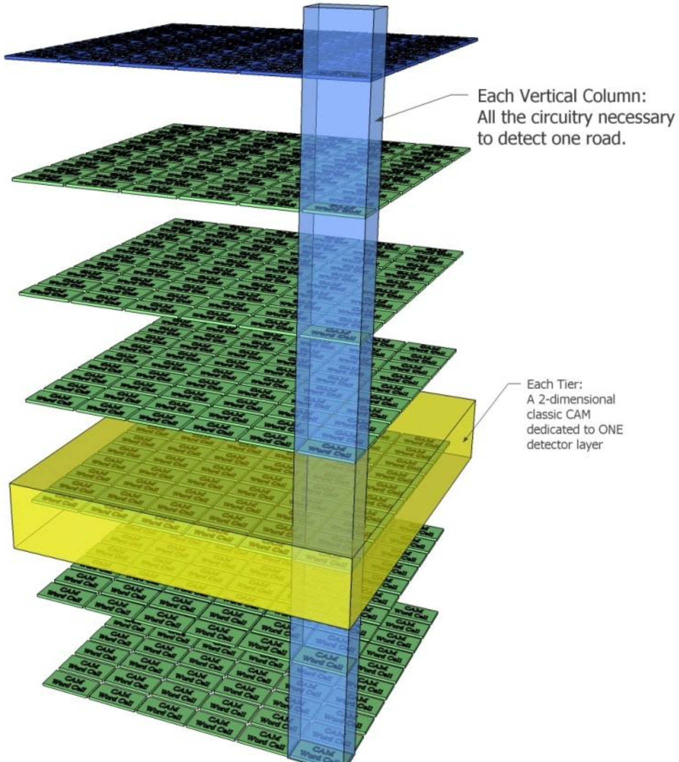
Data transmission
- Low power optical interconnects
- Wireless transmission
- Low power signaling
- Waveform digitization

Costs
- Large area arrays utilizing new technologies (LAPPD)
- Wafer scale integration (3D)
- High yield assembly techniques (active edge sensors)

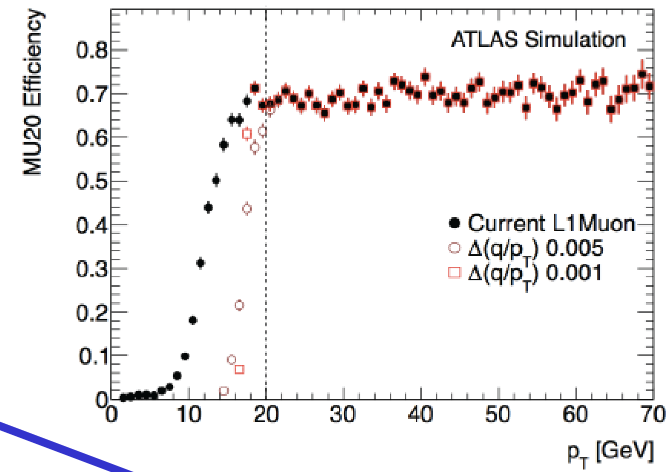
trigger for hadron colliders



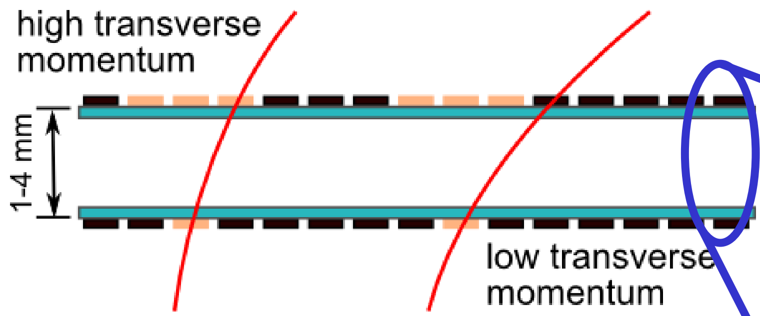
- instantaneous luminosity increases by O(10)
- increased pileup leads to non-linear increase in trigger rates
- improve rejection power of trigger
  - L1 track trigger
  - use full granularity of detector in trigger
  - compact high-density optical connectors and receivers
  - ATCA and μTCA crates with high-speed star and mesh backplanes
  - 3d technology for associative memory ASICs
  - exploit state of the art FPGAs and processing units such as GPUs

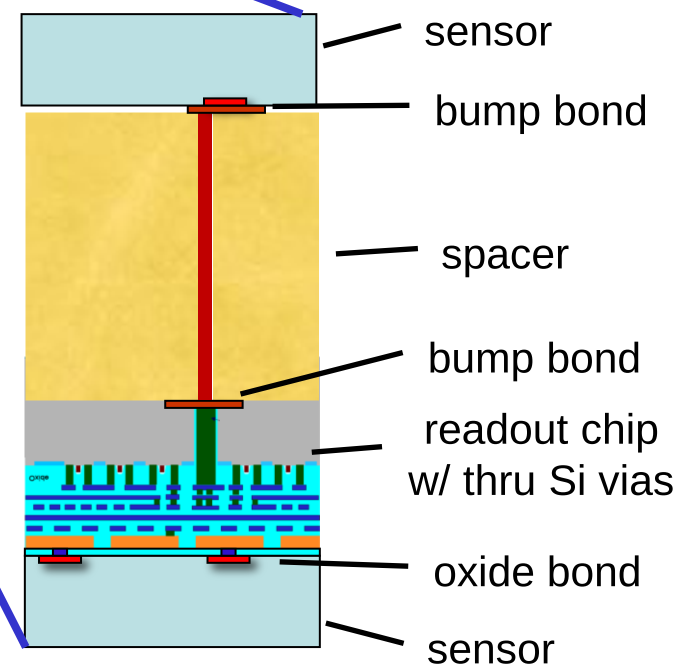


L1 track trigger for LHC



- region of interest trigger (ATLAS)
  - read out hits near L1 electron or L1 muon
  - sharpens pT turnon curve

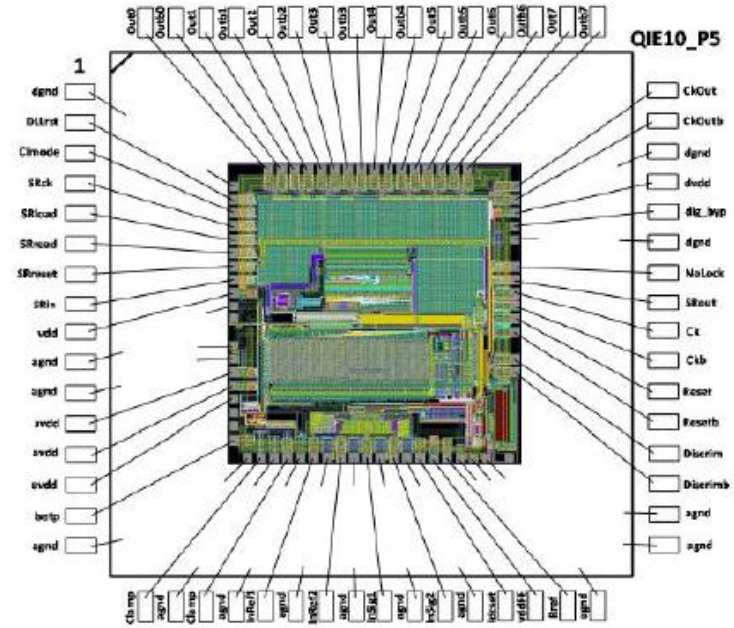




- self-seeded trigger (CMS/ATLAS)
  - requires on-detector data reduction
  - use closely spaced sensors to reject low pT tracks
  - find all tracks in a cone around L1 electron or L1 muon
  - associate tracks with vertices
  - track based isolation for L1 electron or L1 muon
  - vertical connection of sensor and readout chip

ASICs (application specific integrated circuits)

- ASICs
  - are fundamental component of instrumentation for all three frontiers
  - allow high channel density,
  - improve analog performance (e.g. noise, speed)
  - enable data reduction,
  - lower power dissipation, reduce cabling, mass
- R&D to develop
  - high-speed waveform sampling, pico-second timing
  - low-noise high-dynamic-range amplification and shaping
  - digitization and digital data processing
  - high-rate data transmission
  - low temperature operation
  - radiation tolerance

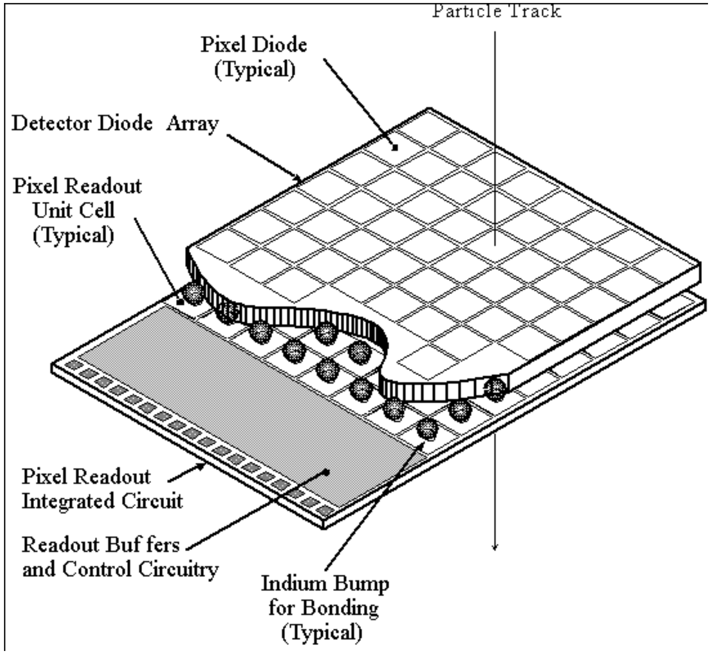


next generation trackers

- momentum and impact parameter resolution in high rate environment
  - improved two track separation
  - highly pixelated, thin sensors
- time measurement
  - thin sensors
- radiation hard
  - operate at low temperature
- low mass
  - power distribution for increased channel count and fast data links
  - multipurpose support structure
  - more efficient cooling

pixel tracker challenges

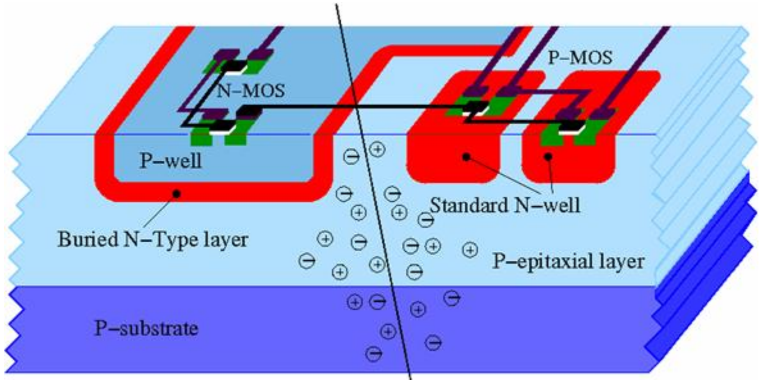
- hybrid pixel detectors (state of the art)
  - highest rate capability (300 MHz/cm^2)
  - radiation tolerance to 5x10^15 neq/cm^2
  - 130nm CMOS readout chip
- for HL-LHC
  - triple rate/dose requirements
    - need smaller feature size (65nm CMOS)
    - IC would contain 500M transistors → large design project
  - improve two track separation
    - smaller pixels
    - thinner sensor



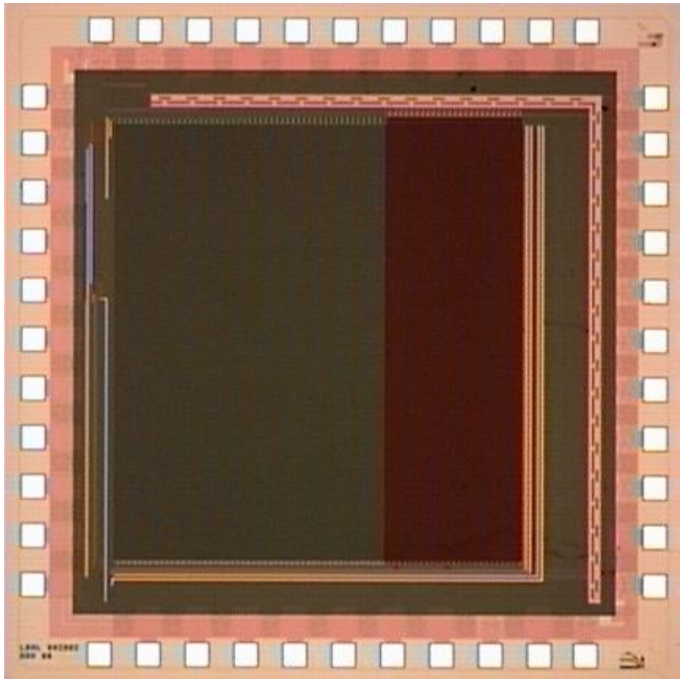
UC Davis Physics Department

MAPS (monolithic active pixel sensors)

- sensor and readout circuitry implanted in the same Si wafer
  - single chip solution without bump bonding
  - less mass than hybrid pixel detectors
  - lower capacitance
  - thin Si sensors (≈50 μm)
  - high granularity
- could include more functions in pixel cells
  - e.g. zero suppression at the pixel level
- 3D integration
  - allows combination of sensor and readout chip with different feature sizes/technologies
- sensor stitching
  - at thickness < 50 μm sensor no longer dominates mass
  - route signals and clocks through metals lines on the chip

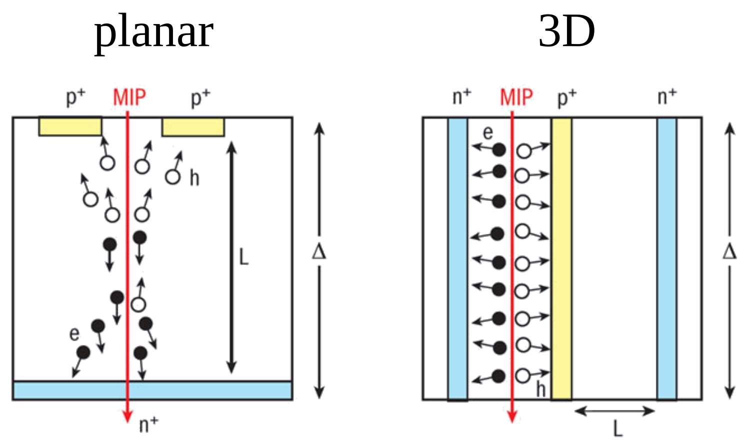


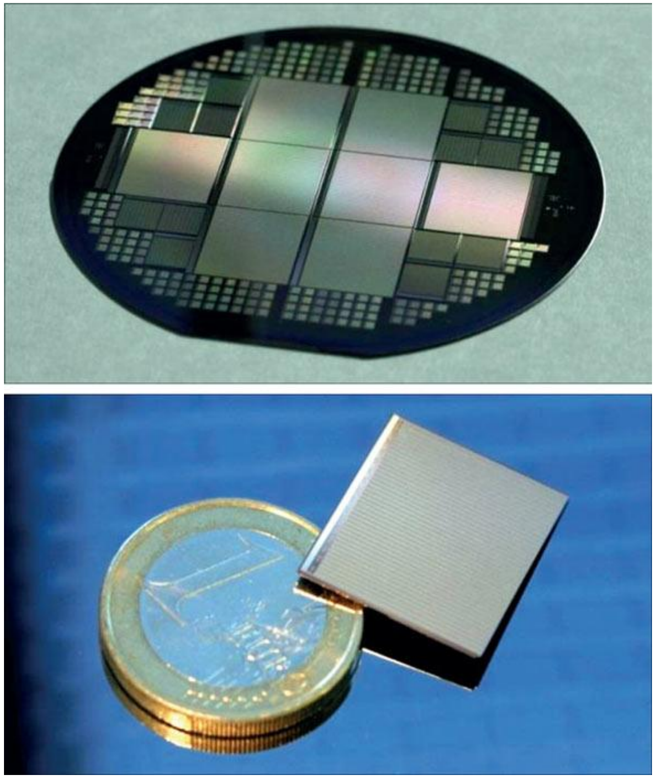
Electronic Instrumentation Lab, U Pavia


monolithic pixel sensor, LBL

3D pixel sensors

- planar sensors
  - collect charge with implant pixels on sensor surface
- 3D sensors
  - collect charge with implant columns in bulk
  - smaller depletion depth
  - faster charge collection
  - lower leakage current
  - lower depletion voltage
  - lower power dissipation
  - more radiation tolerant

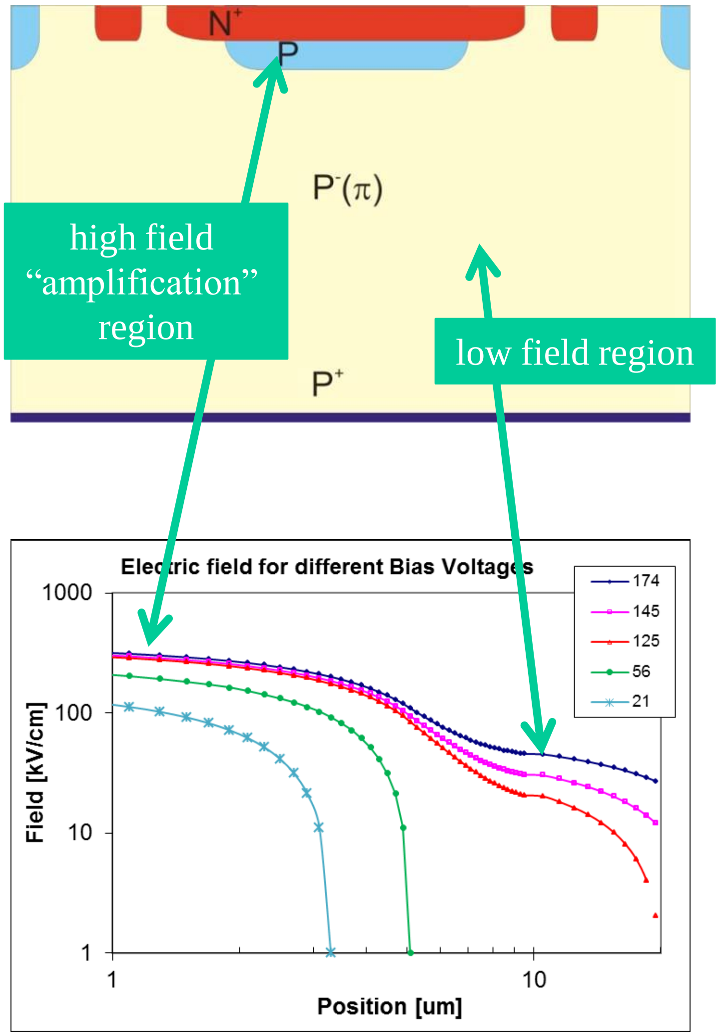




ATLAS IBL sensors - CERN

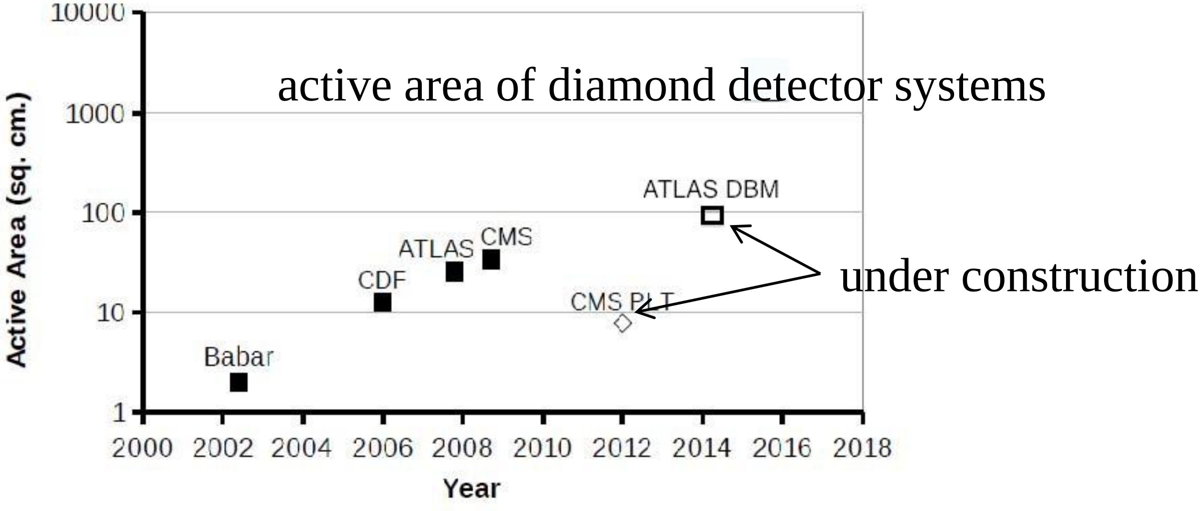
4D ultra-fast silicon detectors

- combine precise spatial resolution with ps time resolution
  - based on
    - thinned silicon (≈5 μm) to reduce charge collection time
    - increase charge collected using charge multiplication in bulk
    - develop readout system to match sensor rate, segmentation and time measurement capabilities
- R&D required
  - wafer processing options
    - n-bulk vs p-bulk,
    - planar vs 3D sensors
    - epitaxial vs float zone
    - depth and lateral doping profile



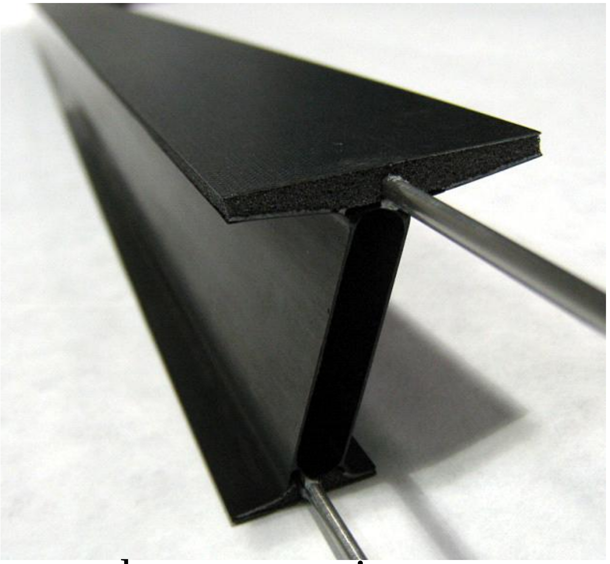
diamond sensors

- chemical vapor deposition (CVD) diamond
  – band gap 5.5 eV (silicon: 1.1 eV)
  – displacement energy 42 eV/atom (silicon: 15 eV)
  – only 60% as many charge carriers as silicon
  – radiation tolerant
  – low Z
  – do not require extensive cooling
- currently two viable industrial suppliers

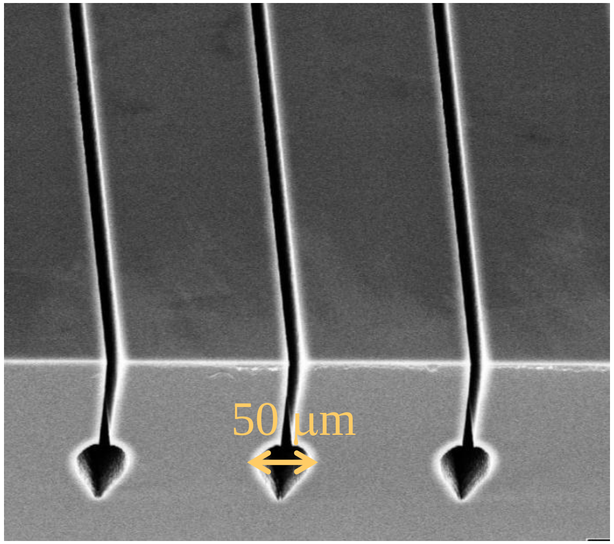


support, cooling, power

- next generation trackers will
  - have increased power density
    - high channel count
    - high speed data links
    - radiation damage
  - require
    - efficient cooling
    - low mass support and services
- R&D directions
  - new materials
    - low Z, stiff, thermally conductive, radiation hard
    - carbon foams/fibers, ceramics
  - multifunction structures
  - DC/DC converters
    - reduced power dissipation



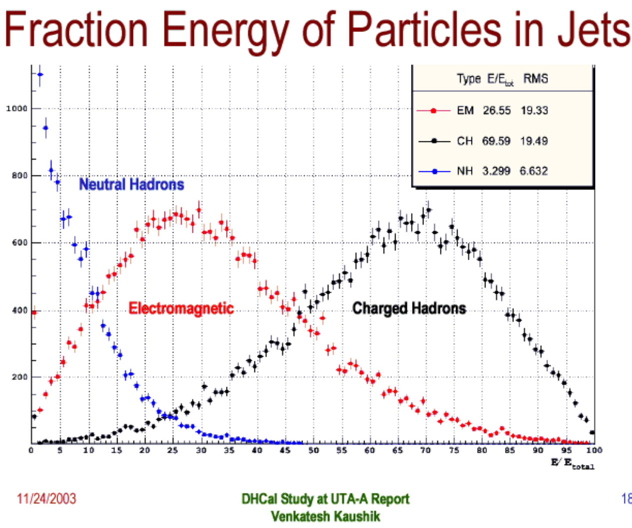
carbon composite structure

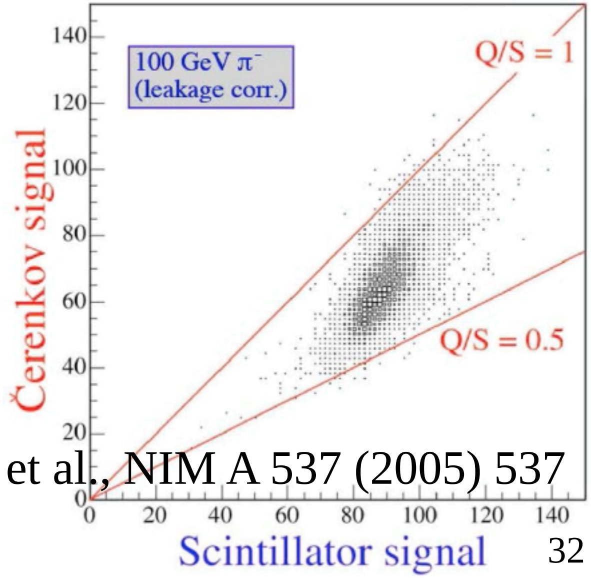


micro-machined cooling channel

high resolution hadron calorimeter

- need $\frac{\sigma}{E} \leq \frac{30\%}{\sqrt{E}}$ to separate W→qq and Z→qq
- resolution limited by fluctuations in hadronic showers
- compensating calorimeters
  - same response for EM and hadronic component
  - neutrons liberated in hadronic interactions → slow
- dual readout calorimeters
  - measure EM/had ratio using Cerenkov light (EM) and scintilation light (EM+had)
  - resolution limit $\frac{\sigma}{E} \leq \frac{15\%}{\sqrt{E}}$
  - Pb/Cu + scintillating fibers sampling calorimeter
  - homogeneous crystal calorimeter
    - needs dense and economical material

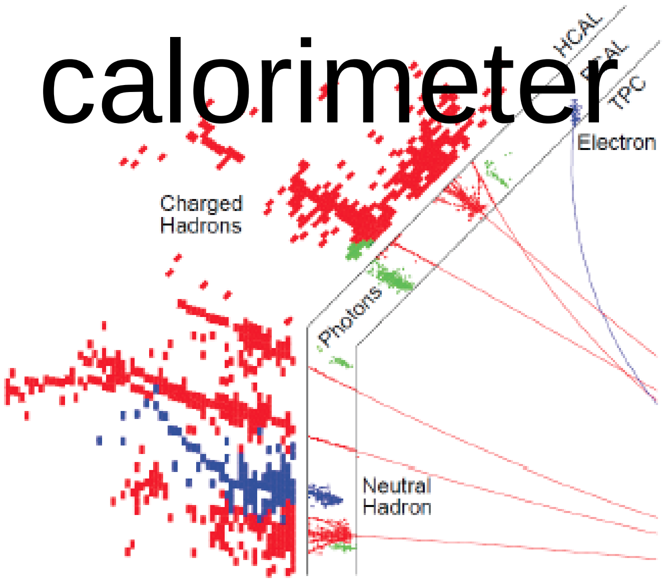




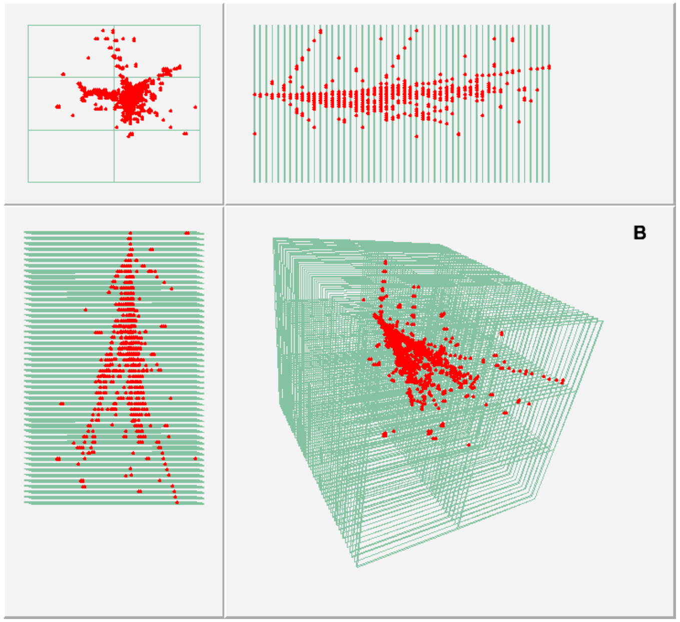
Akchurin et al., NIM A 537 (2005) 537

high resolution hadron calorimeter

- particle flow algorithm
  - reconstruct individual particles in shower
  - apply particle specific corrections
    - measure charged particles in tracker
    - measure photons in em calorimeter
    - measure neutral hadrons in hadron calorimeter
  - planned for e+e- collider detectors
- imaging calorimeters
  - particle flow requires detailed image of shower
  - requires high granularity detectors
  - micro-pattern gas detectors

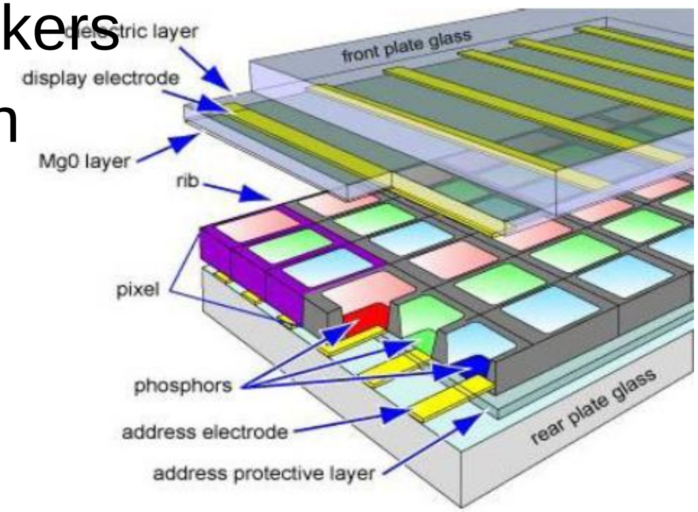


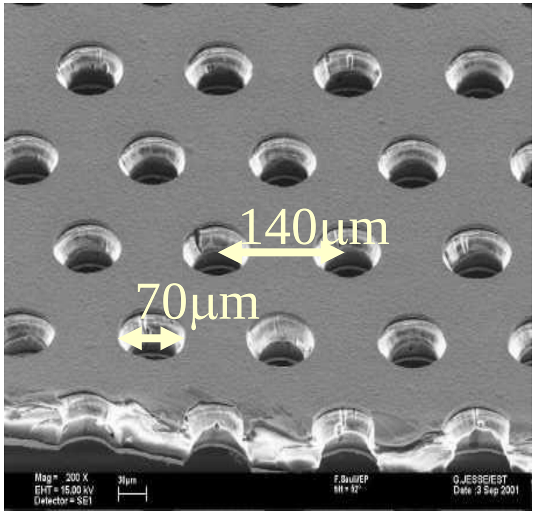
Typical topology of a simulated 250GeV jet in CLIC ILD



micro-pattern gas detectors

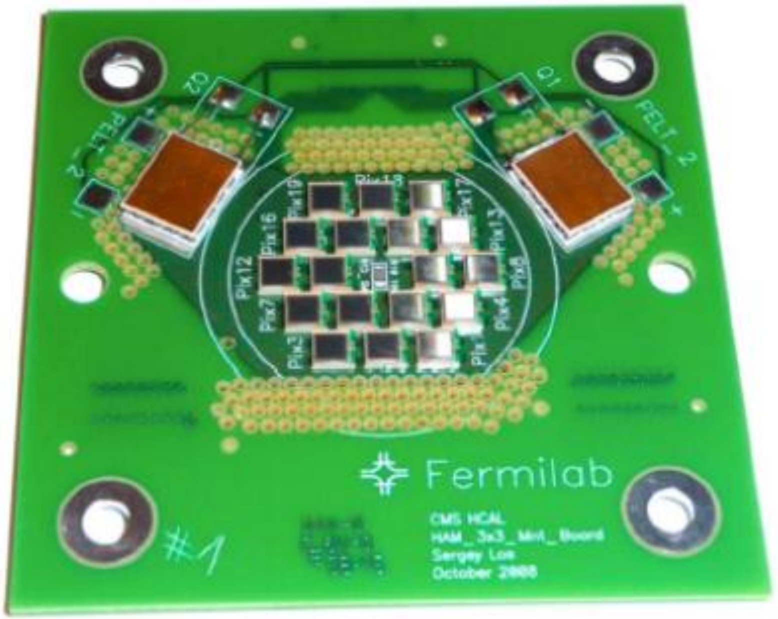
- applicable for calorimeters and trackers
- potentially low cost, large area, high granularity, fast, radiation hard
- plasma panel sensors (PPS)
  - resemble plasma-TV display panels, modified to detect gas ionization in the individual cells
- resistive plate chambers (RPC)
  - improve rate capabilities, granularity
- flat panel microchannels
- gas electron multipliers (GEMs)
- micromegas





solid state photo detectors

- Silicon Photomultipliers (SiPM)
  - Geiger-mode APDs
  - low power
  - low voltage
  - low noise (compared to APDs)
  - compact
  - excellent timing resolution
  - insensitive to magnetic fields
- R&D directions
  - Si is sensitive to radiation
    - need to cool devices to keep leakage current down
    - GaAs or InGaAs
  - Si has small attenuation length for UV light
    - needed to detect Cerenkov light
    - SiC (bandgap = 3.2 eV)



SiPM mounting card - CMS

facilities and resources

- national labs
- universities
  - interdisciplinary opportunities
  - nanofabrication facilities
- industry
  - piggy back on commercial developments
  - take advantage of SBIR program to fund R&D collaborations

conclusion

- in order to realize our physics goals, we need to invest in technology R&D
- the challenges at energy frontier facilities will be substantial
- there are many ideas for instrumentation that can address these challenges
- we need your input to identify the R&D avenues with the most promising physics potential

acknowledgements

- thanks to all white paper authors
  - see following two pages for listing

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  - “Instrumentation on the Energy Frontier”

White papers

- Level 1 Track Triggers at HL-LHC
  - E. Grunendahl, M. Johnson, R. Lipton, T. Liu, A. Ryd, L. Spiegel
- Tracker and Vertex Detector for a Muon Collider
  - V. Di Benedetto, C. Gatto, R. Lipton, A. Mazzacane, N.V. Mokhov, A. Para, S.I.Striganov, N.K. Terentiev, H. Wenzel
- Operation of Collider Experiments at High Luminosity
- Noble Liquid Calorimeters
- Triggers for hadron colliders at the energy frontier
  - W. Smith
- A Differential Time-of-Flight Technique for Collider Detectors
- Hadronic dual-readout calorimetry for high energy colliders
  - RD52 Collaboration
- Atlas Upgrade Instrumentation
  - G. Brooijmans, H. Evans, A. Seiden
- Combination of Active Edge and 3D Electronics Technologies
  - R. Lipton, C. Kenney, S. Parker, L. Spiegel, J. Thom
- Plasma Panel Detectors for Ionizing Particles
  - R. Ball, J. R. Beene, Y. Benhammou, E. H. Bentefour, J. W. Chapman, E. Etzion, C. Ferretti, P. S. Friedman, D. S. Levin, M. Ben Moshe, Y. Silver, R. L. Varner, C. Weaverdyck, and B. Zhou
- 3D Sensor Architecture
- Development of Resistive Plate Chambers
  - Burak Bilki, Kurt Francis, José Repond, Lei Xia (ANL)
- Powering Future Particle Physics Detectors
  - S. Dhawan (Yale), R. Sumner (CMCAMAC), R. Khanna (Texas Instruments)
- Imaging Calorimetry
- Future Crystal Electromagnetic Calorimetry

White papers

- Development of Cost-effective Crystals For Homogenous Hadron Calorimetry
- Application Specific Integrated Circuits (ASICs) for HEP applications
- The Next Generation of Crystal Detectors
  - Ren-Yuan Zhu (CalTech)
- Use of Flat Panel Microchannel Plates in Sampling Calorimeters with Timing
  - Anatoly Ronzhin (Fermilab) and Henry Frisch (EFI, Univ. of Chicago)
- Micro-Pattern Gas Detectors for Charged-Particle Tracking & Muon Detection
  - M. Hohlmann (Florida Inst. of Tech.), V. Polychronakos (BNL), A. White and J. Yu (UTA)
- Low Mass Support and cooling
  - William Cooper, Fermilab; Carl Haber, LBNL; David Lynn, Brookhaven National Lab
- Monolithic Pixel Sensors
  - M. Battaglia
- High speed, massively parallel, ATCA based Data Acquisition Systems using modular components
- The Next Generation of Photo-Detectors for Science in the Cosmic, Intensity and Energy Frontiers
  - K.Arisaka, J.Buckley, K.Byrum, H.Frisch, N.Otte, E.Ramberg, O.Siegmund, M.Sancheza, G.Varner, J.Va'vra, R.G.Wagner, M.Wetstein
- Future Developments in Gigasample-per-second Waveform Sampling Application Specific Integrated Circuits
  - Eric Oberla, Kurtis Nishimura
- Micro-Pattern Gas Detectors for Calorimetry
  - J. Yu (UTA), M. Hohlmann (Florida Inst. of Tech.), V. Polychronakos (BNL) and A. White
- Emerging Optical Link Technologies for HEP
- Opportunities for HEP Technology Evaluation in Smaller-Scale NP Experiments
  - P. Nadel-Turonski (JLAB) and G. Varner (University of Hawaii)
- Synergies Between Detector Development in Nuclear and Particle Physics
  - C. Woody (BNL), T. Hemmick (Stony Brook University), P. Nadel-Turonski (JLAB)