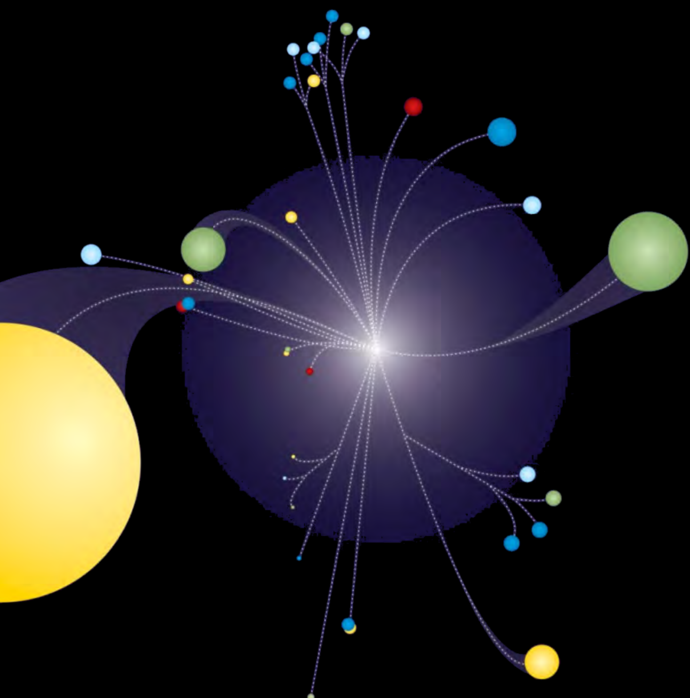
Blue Sky R&D



2017 CPAD Workshop

Albuquerque, New Mexico
October 12-14, 2017

With many thanks to all colleagues
for their contributions

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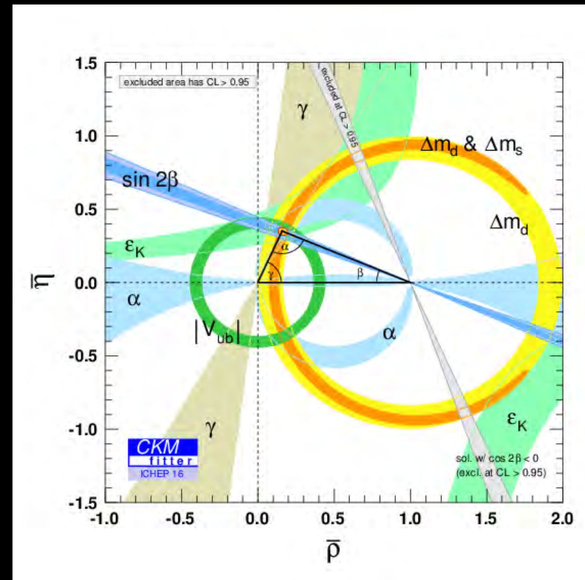
Argonne National Laboratory

Context

- The field of particle physics is changing dramatically, driven by:
  - Technology
  - Scale
  - Geopolitical reform
  - Fiscal realities
  - Discoveries
  - ....
- Increasingly the science we wish to pursue has demanded large, even mega-facilities
  - LHC, FCC, CEPC, CLIC, ILC
  - DUNE, HyperKamiokande
  - LSST, LZ, NEXO
  - ...
- Will this trend continue and what are the implications?
- What are the alternatives?

Context

- The Standard Model of particle physics is highly successful and measurements require higher and higher sensitivities to probe the fundamental interactions
  - B-factories like LHCb, Belle-II, g-2, Mu2e, Comet, …



- Theoretical guidance for observations outside the Standard Model is diffuse
  - Supersymmetry
  - Dark Matter, Dark Energy
  - Lepton Flavor Violation, …

We are very much in a data driven era !

That is, we need a tool-driven revolution to take the data with utmost precision and discover new things !

Blue Sky

- 'Blue Sky'
  - Not grounded in the realities of the present: visionary (Merriam-Webster)
  - Scientific research in domains where "real-world" applications are not immediately apparent (Wikipedia)
  - High-Risk / High-Gain research exploring new technologies (Ian & Marcel)
    - Unanticipated scientific breakthroughs are sometimes more valuable than the outcomes of agenda-driven research
    - Return on investment is inherently uncertain, but the field needs an appropriate infusion of blue sky R&D.

- Outline
  - One example of the need for high-risk / high-gain R&D
  - A few examples of innovative directions
  - Conclusions

Warning !

- This is a talk about ideas, suggestions, conjectures intended to spur dialogue; it is not a rigorous science presentation. So, ...

- There's some handwaving

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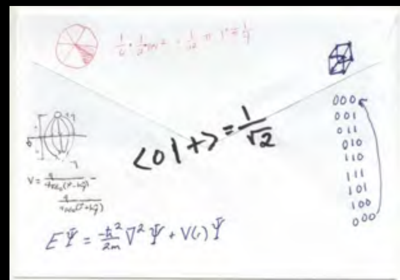

- back of the envelopes

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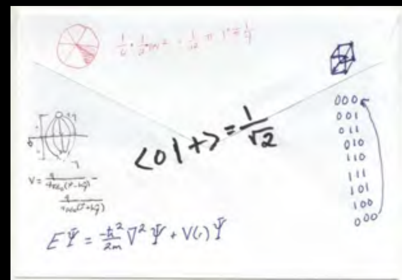
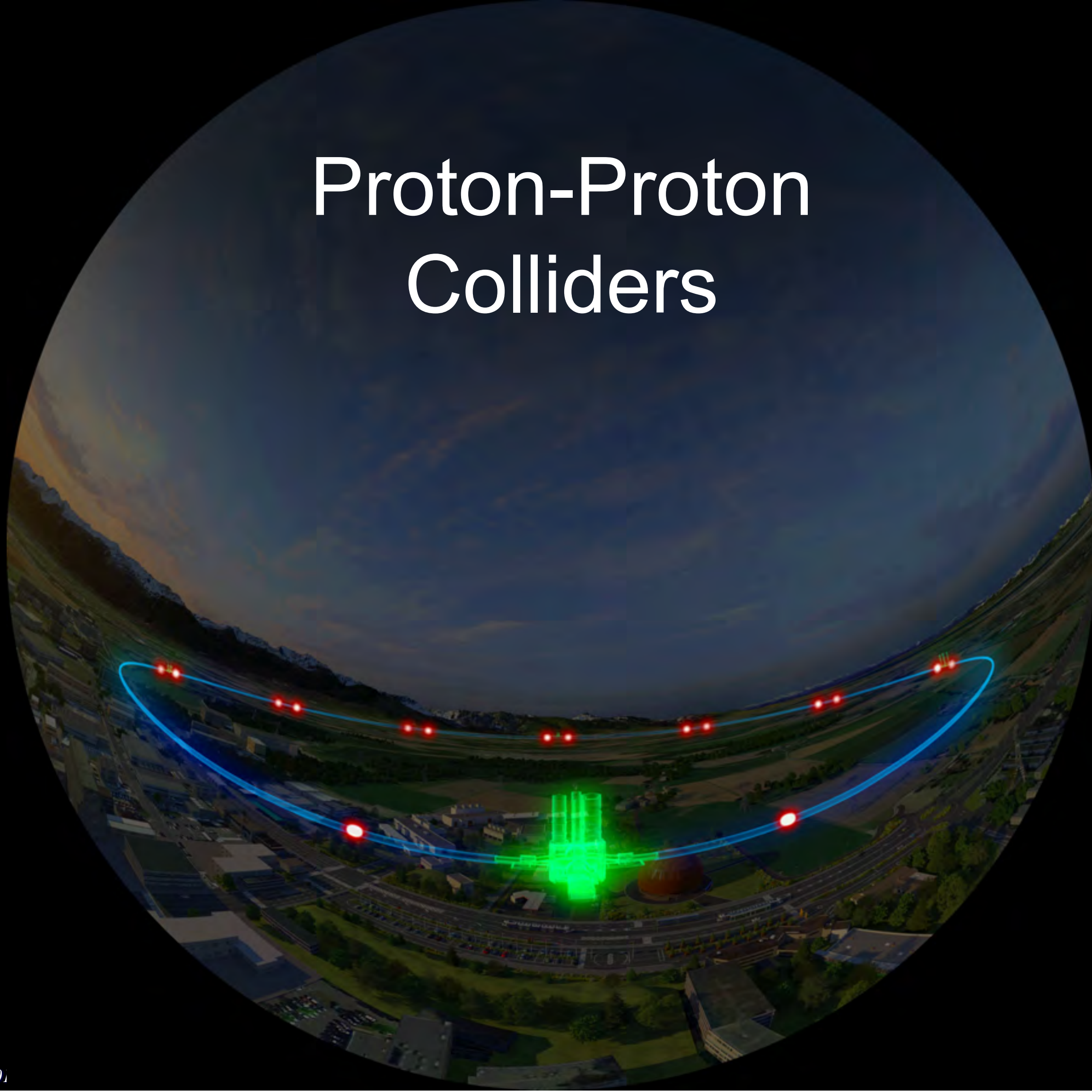


- And some wacky ideas

Proton-Proton Colliders



Proton Collider Parameters

parameter	FCC-hh	SPPC	HE-LHC*
collision energy [TeV]	100	71.2	>25
dipole field [T]	16	20	16
Circumference [km]	100	54	27
beam current [A]	0.5	1.0	1.12
bunch intensity [10^{11}]	1 (0.2)	2	2.2
bunch spacing [ns]	25 (5)	25	25
beta* [m]	0.3	0.75	0.25
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	20 - 30	12	>25
events/bunch crossing	<1020 (204)	400	850
stored energy/beam [GJ]	8.4	6.6	1.2
synchrotron. rad. [W/m/beam]	30	58	3.6

* HE-LHC is the High Energy upgrade of the LHC; challenges of this configuration included in the two new collider projects FCC and SPPC

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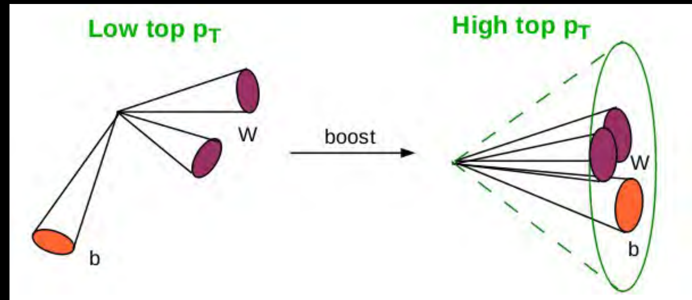
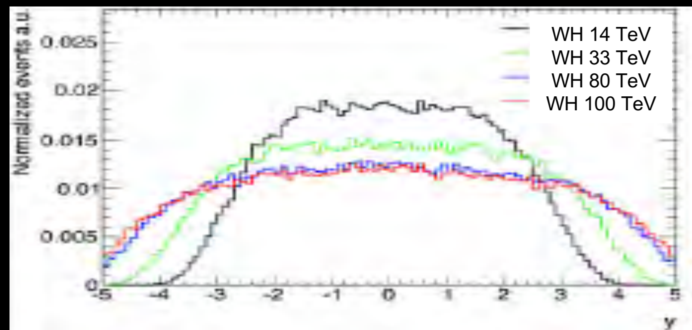
Life At 100 TeV

- Great physics potential
  - Enormous event rates
  - Pile-up 400 – 1000 events/bunch crossing
- Objects highly boosted
  - Measure jet-substructure: high granularity
  - Mitigate pile-up: high granularity
- High momentum particles
  - Depth and resolution required
- Uniform distribution in rapidity
  - Importance of forward regions

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

Lumi weight: 20 ab^{-1} / 20 fb^{-1} / 3 ab^{-1} (100 / 8 / 14 TeV)

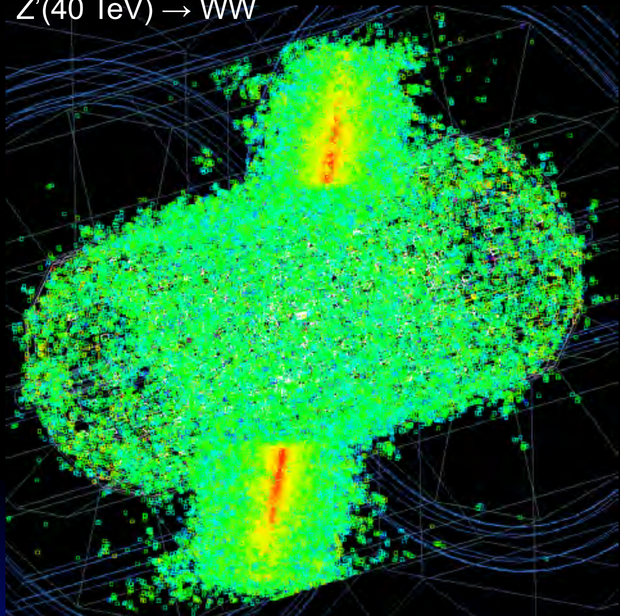




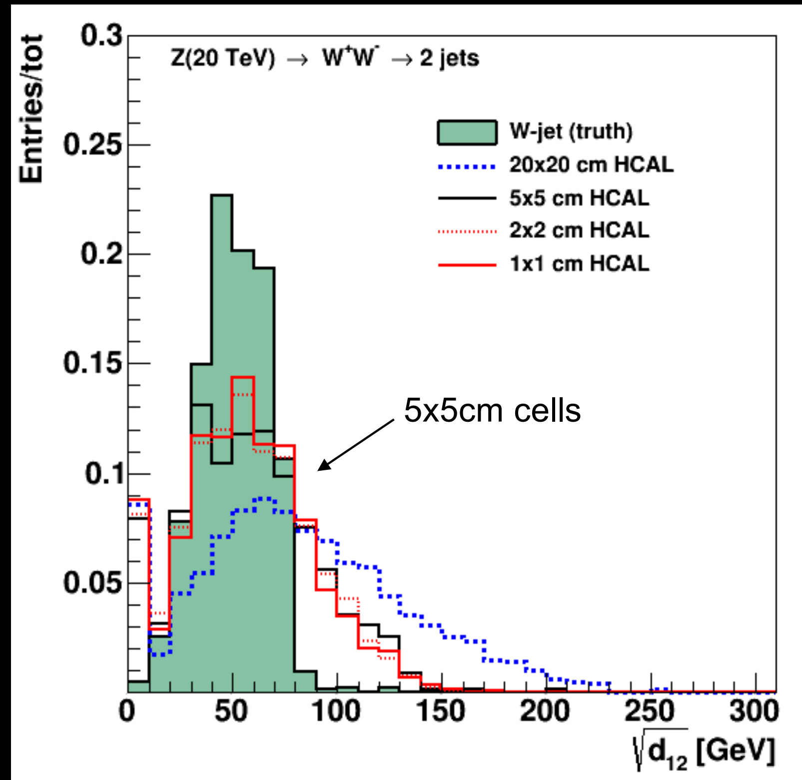
Calorimetry

- Challenges
  - Calorimeter transverse segmentation
  - Note:
    cell size λ/4 seems optimal

Z'(40 TeV) → WW



Single event, hard scatter only, no overlap !



A Sense Of Scale

- Challenges
  - Embedded readout electronics at 1mW/channel = 1.5MW of power
  - Timing on a system scale of millions of channels at the level of 50ps
  - Pile-up reaching 1000 events

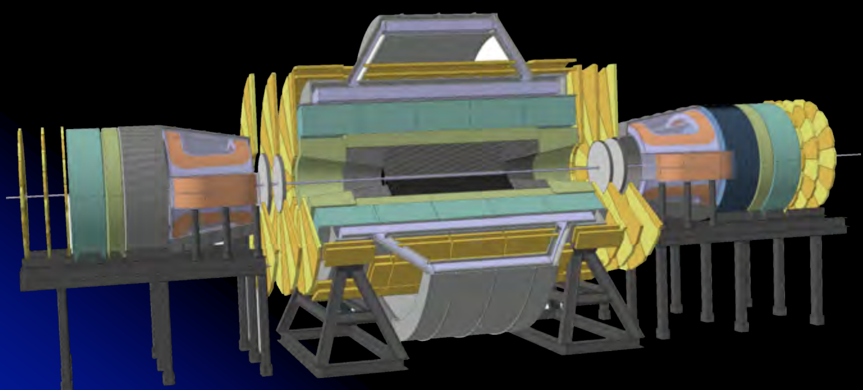
	CMS	ATLAS	CMS HGCal		FCC/SPPC
Diameter (m)	15	25			~27m
Length (m)	28.7	46			~70m
B-Field (T)	3.8	2/4			6
EM Cal channels	~80,000	~110,000	4.3M		70M (2x2cm^2)
Had Cal channels	~7,000	~10,000	1.8M		80M (5x5cm^2)

- Simply scaling CMS High-Grained calorimeter would require >5,000 m^2 of silicon

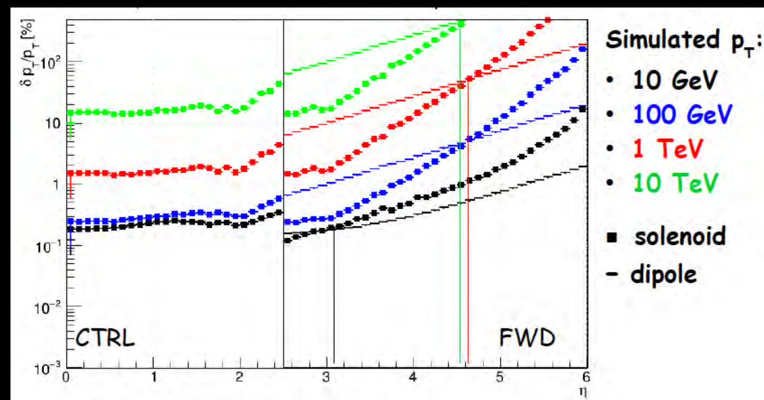
Tracking And B-Field

- Momentum Resolution: $$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$
- Challenge:
  - A factor 7 in energy from 14 TeV → 100 TeV, requires a gain of a factor 7 in σ/BL^2 to retain LHC p_T resolution, down to $|\eta|<6$!
    - B=4T → B=6T
      L=1.1m → 2.4m
    - σ=20μm → 5μm
      L increase by $\sqrt{7/4} \approx 30\%$

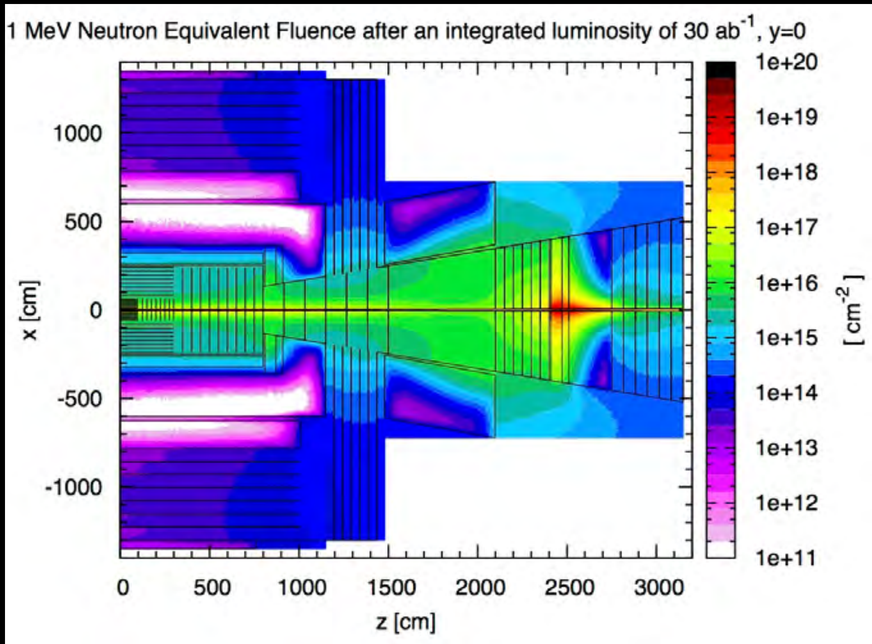
Magnet: 6T/12m bore
System: 20-30 m diameter, 30-50 m long
Stored Energy: 50-60 GJ.

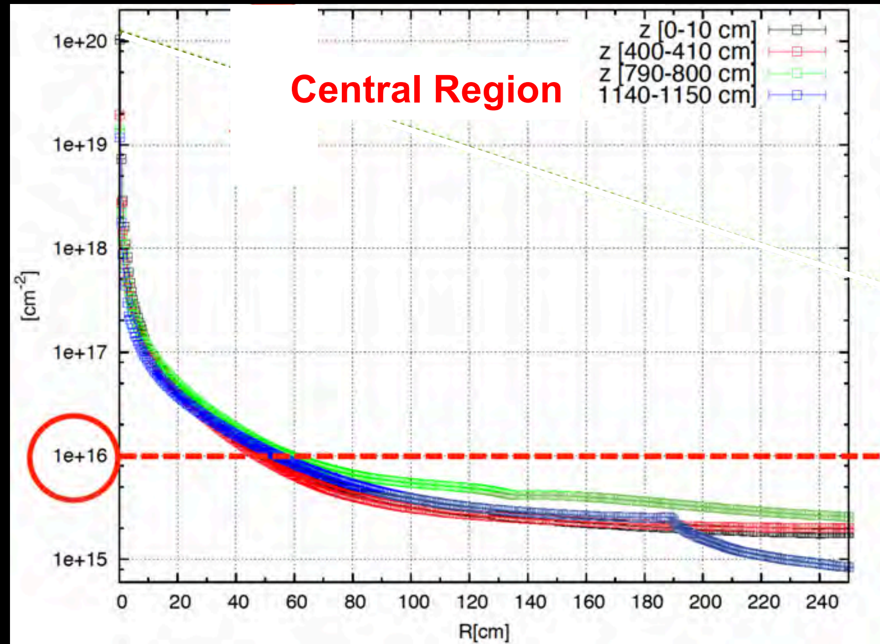


Dipole or solenoid in forward region



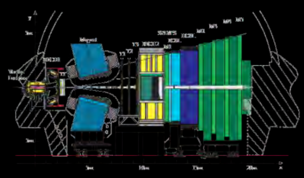
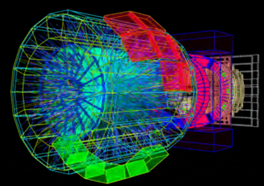
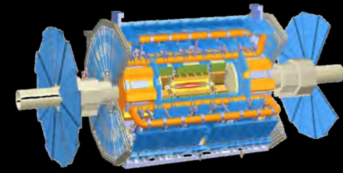
Radiation Damage



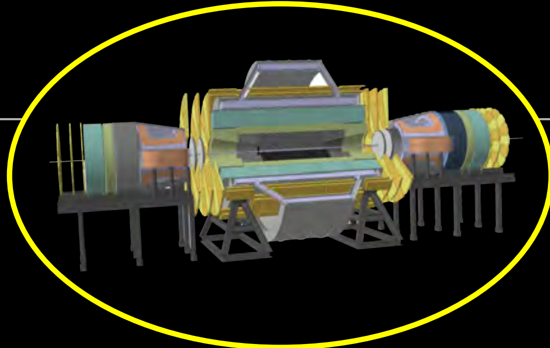


- For radii < 50 cm (well into the tracker) the fluence exceeds the value expected at HL-LHC (10^{16} cm^{-2}) by up to 2 orders of magnitude
- Forward region even worse!

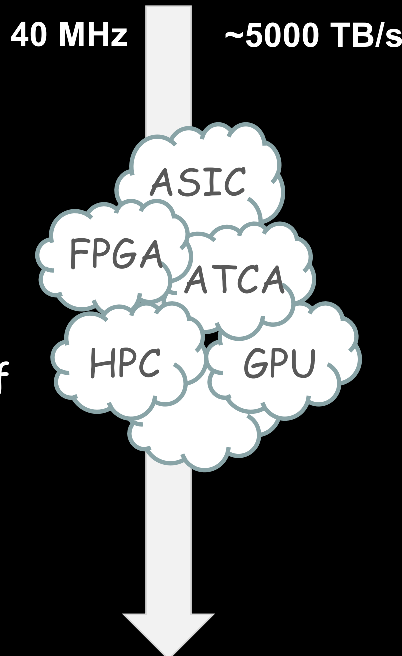
Trigger and Data Rates (after Upgrades)

LHCb	ALICE	ATLAS	CMS
			
40 MHz / 40 Tb/s	50 kHz / 1 TB/s	40 MHz / 20 Tb/s	40 MHz / 40 Tb/s
DAQ	DAQ	DAQ	DAQ
LLT μ, e, γ, h	Reco + Compression	Level 0/1	Level 1
5 - 40 MHz		0.5 - 1 MHz	1 MHz
HLT Event reco		Level 2	Level 2
20 – 100 kHz	50 kHz	5 - 10 kHz	7.5 – 10 kHz
Offline	Offline	Offline	Offline
2 GB/s	75 GB/s	10 - 20 GB/s	40 GB/s

At 100 TeV

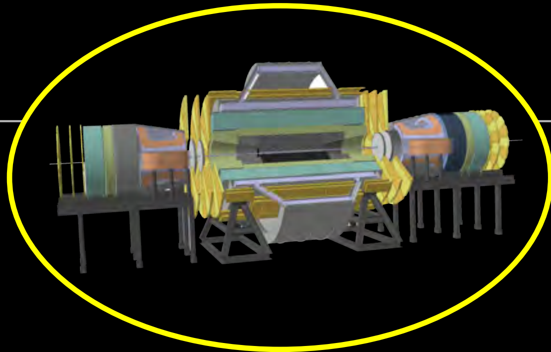


Larger detectors
Higher granularity
More data



- Tracking and calorimeter each have raw data rates of ~2,000 TB/s
- Using 10Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Pb/s

At 100 TeV



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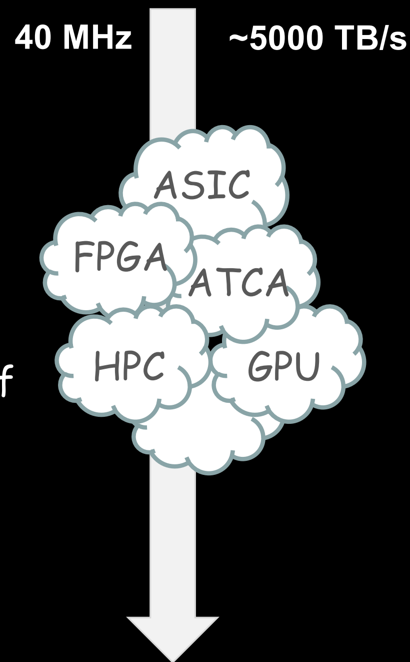

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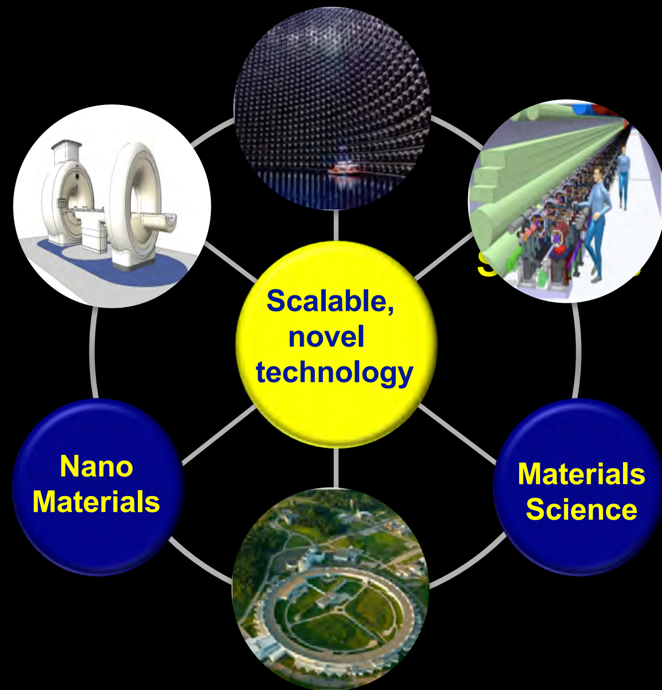
- Power budget for links, based on best current devices (~500mW for 5Gb/s): 2MW for links alone
- Substantial R&D required for low-mass, rad-hard, low cost devices with no commercial applications

New Tools !

- The new generation of detectors will not be our “grandparents” sensors and detectors.
- New techniques, technologies and possibly a whole new paradigm needs to be considered

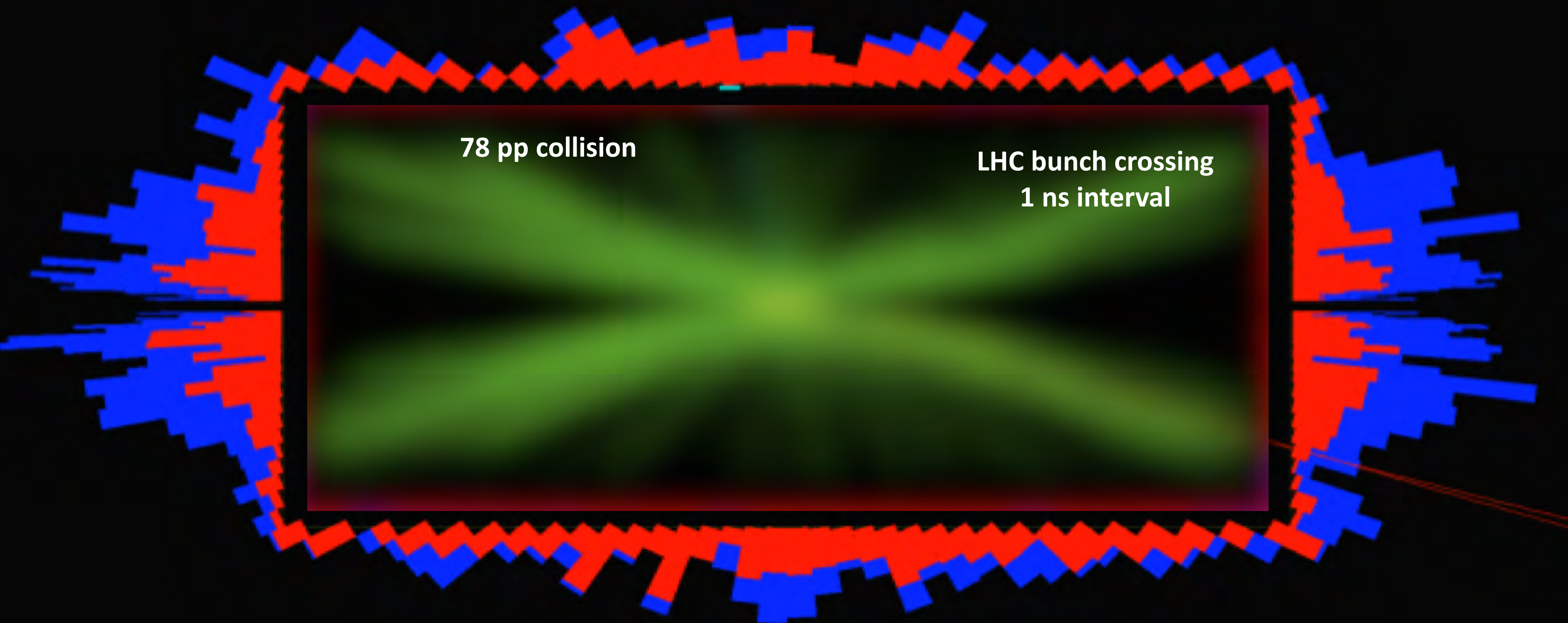
- Arguably, the most successful new techniques will be interdisciplinary efforts working across science disciplines with multiple partners.

- Some ideas …



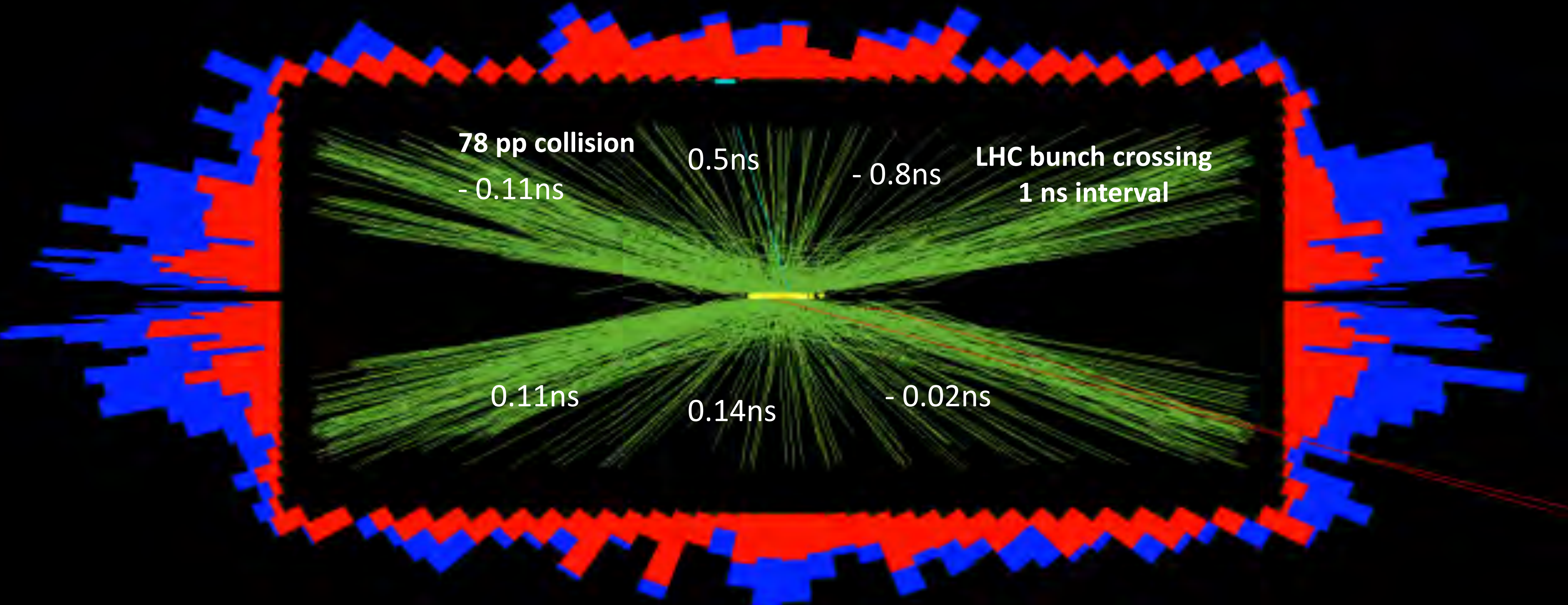
Mitigating Pile-Up

- By adding timing, as being planned for the HL-LHC upgrades



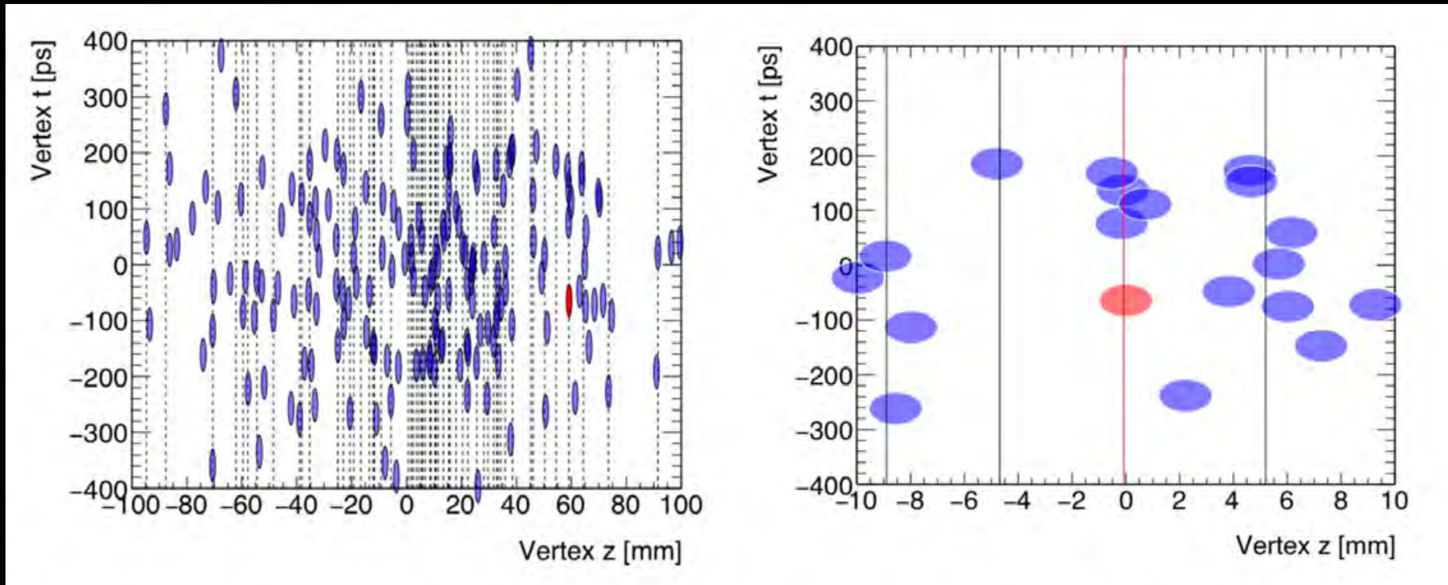
Viewing collisions in 3D

Mitigating Pile-Up



Viewing collisions in 4D

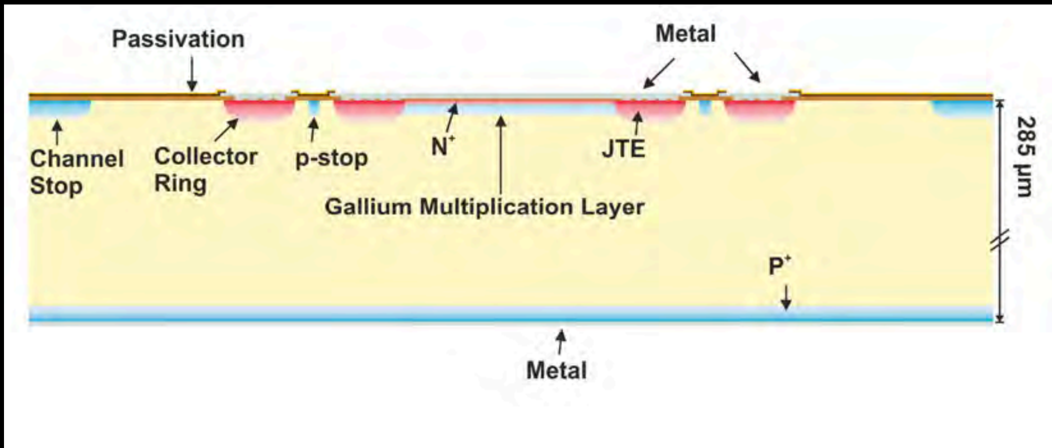
Mitigating Pile-UP



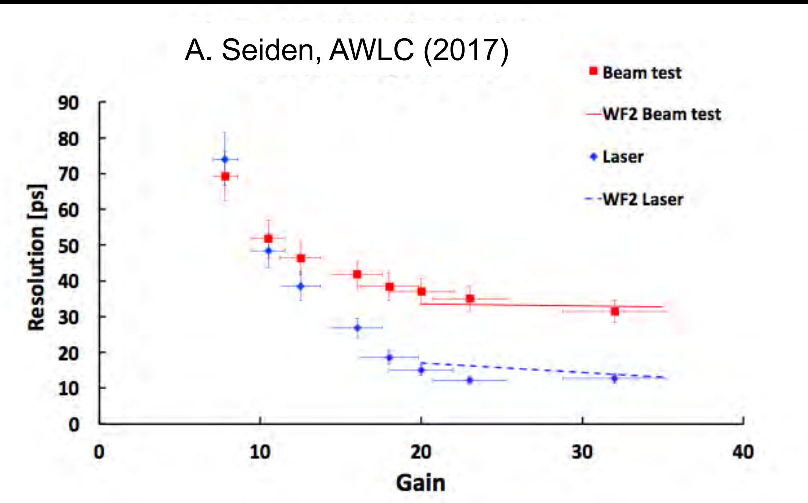
Event display of 200 additional interactions: ellipses correspond to truth vertices (red=hard scatter). The dotted lines indicate the position of the reconstructed vertices in the event.

- Pile up of event vertices in space can be separated if a timing resolutions of ~30-60 ps is obtained in a high rate, radiation intense environment

Low Gain Avalanche Detectors (LGAD)



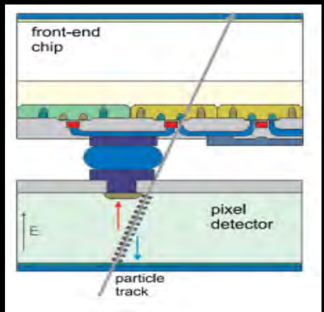
N. Cartiglia, C. Pellegrino AIDA Workshop (2017)



- Goal to obtain good timing resolution; introduce multiplication layer close to junction
  - Gain field ~ 300 kV/cm over a few μm near junction
  - Bulk field ~ 20 kV/cm; saturated electron drift velocity ~10^7cm/sec.
  - Gain for electrons but not holes, leads to gain ~ 20.

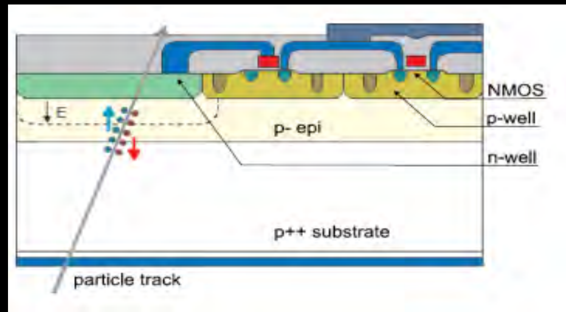
Technologies

Hybrid Pixel



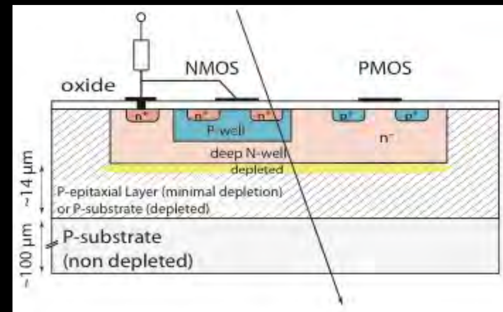
- Q collection by drift

CMOS-MAPS



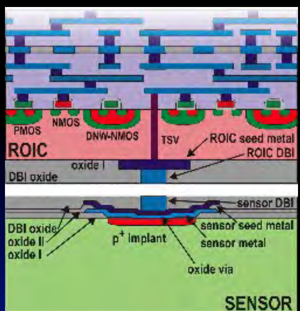
- Charge collection by diffusion

HV-CMOS



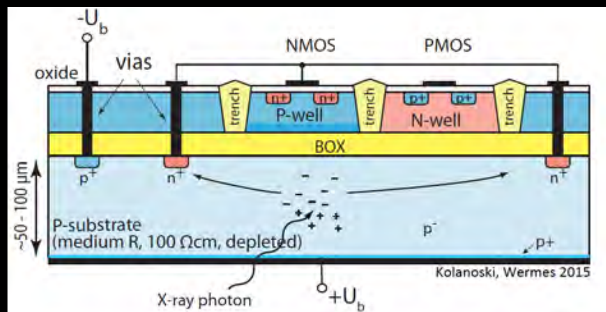
- HV process, 10 – 15 µm depletion region under deep N-well

3D Tiered



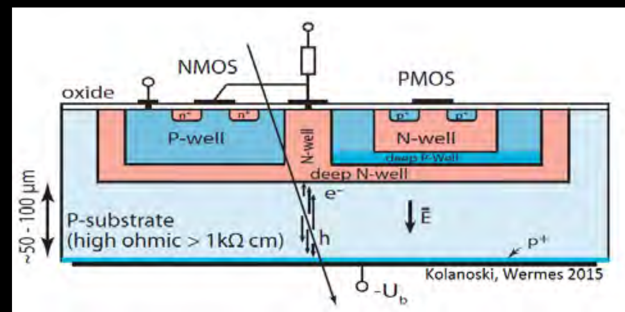
- Fully depleted

SOI-CMOS



- Fully depleted or HV process

HR-CMOS



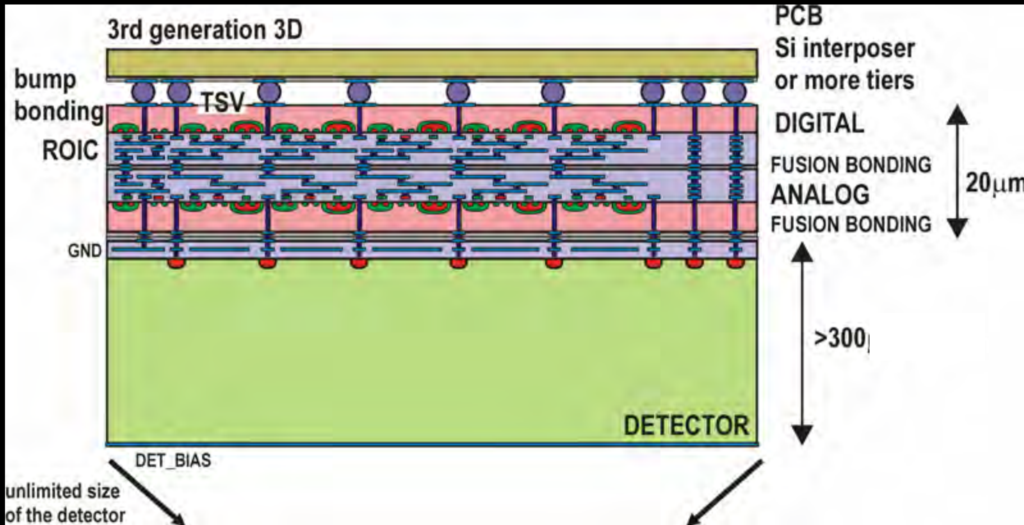
- Can be fully depleted

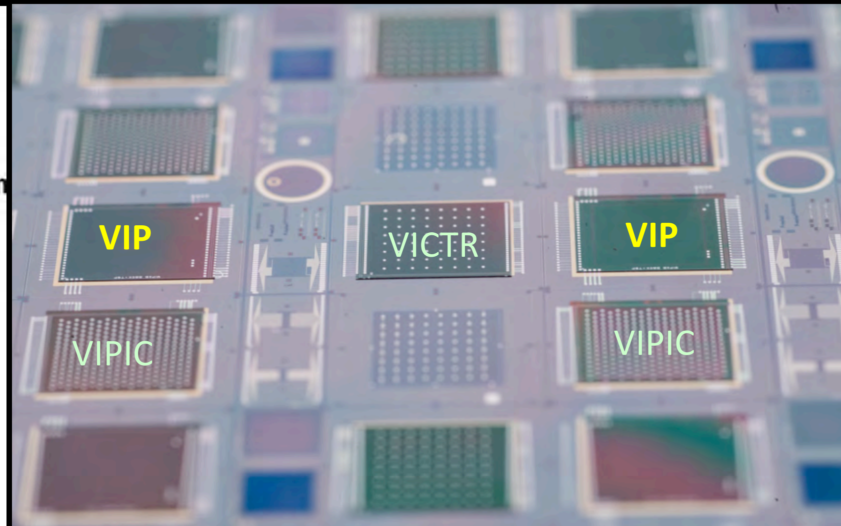
Tiered Silicon

Tier 3: digital

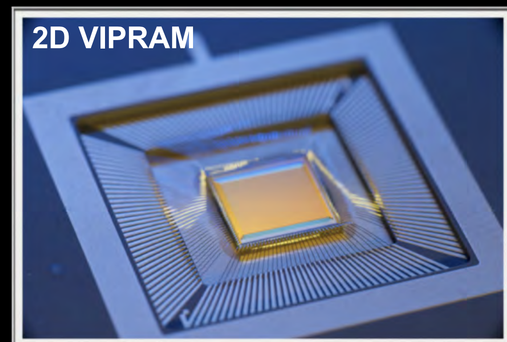
Tier 2: analog

Tier 1: sensor





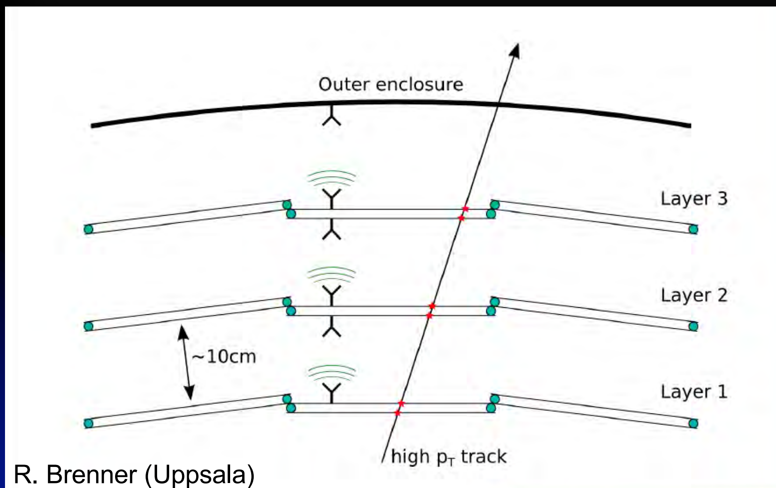
- Tremendous progress being made in wafer bonding technologies and through-silicon-via (TSV) technology
- 2D building blocks could be ready for 3D integration, for example for pattern recognition (arXiv:1709.08303v1)



The Curse of Cables

Wadapt: "Wireless Allowing Data And Power Transmission"

In the process of applying for RD Status at CERN

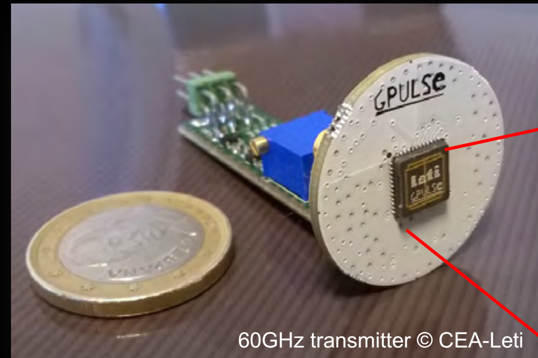


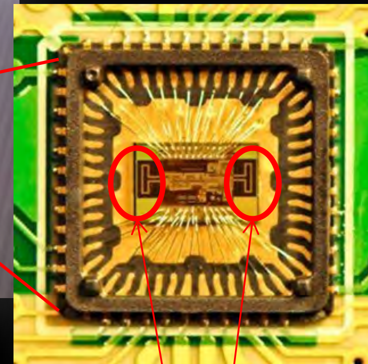
- Wireless readout concept:
  - Radial transfer of data provides communication between layers
  - Signals cannot penetrate layers; reusability of frequency channels
  - Truly transformational

Millimeter-wave Technology

- 30 to 300 GHz
- Wavelength (λ) of few mm (eg. 5mm @60GHz)
- Multiple Gbits/s (Several GHz of bandwidth)
- Compact and low power systems with high integration and high density

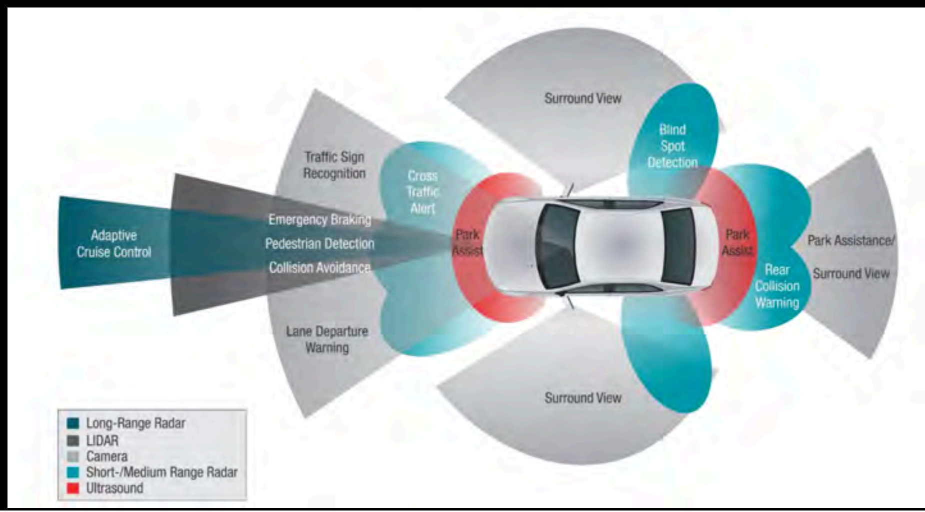
Cedric Dehos (CEA/LETI)





Antennas

- A current key application: 24, 79 GHz automotive radar

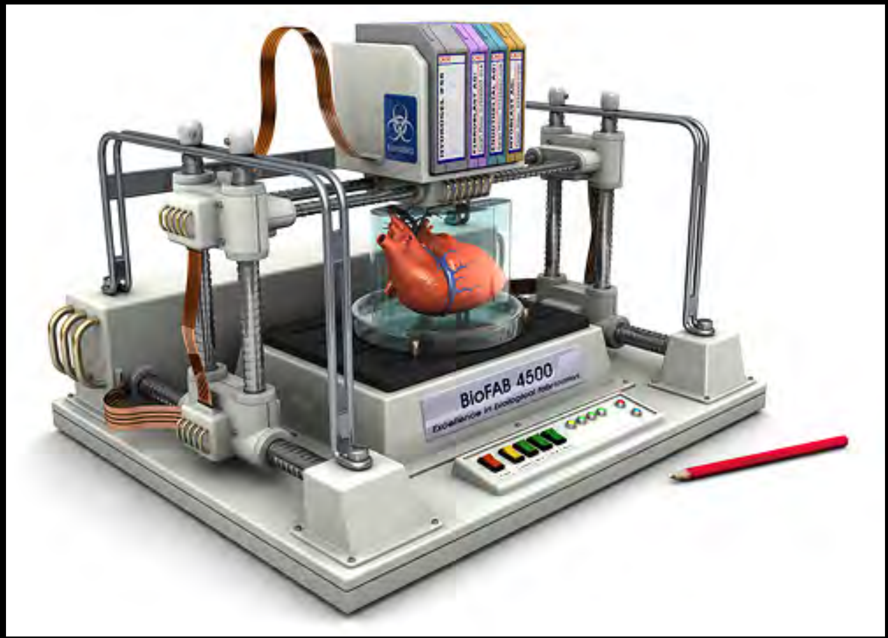


Rohde & Schwartz

Additive Manufacturing

3D Bioprinting

A New Era of Possibilities

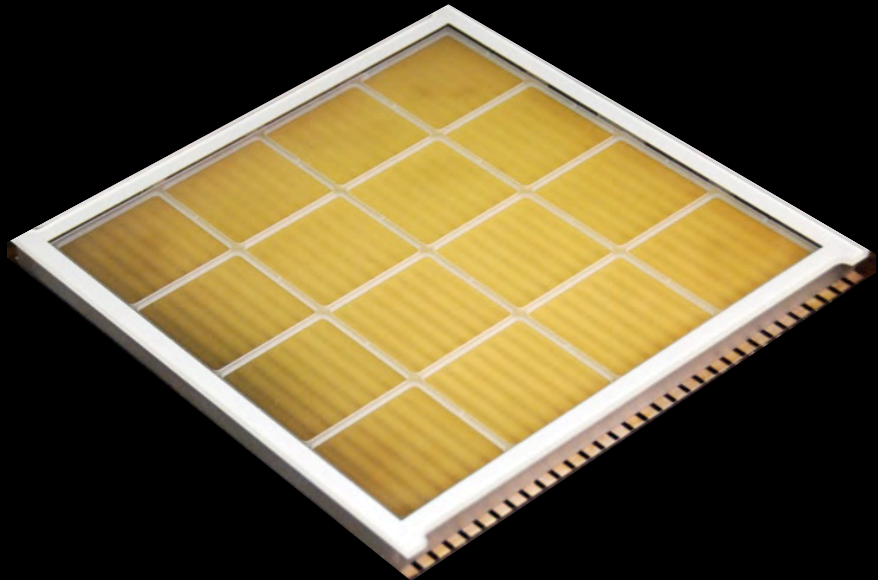


Advances medicine ...

http://www.organovo.com/

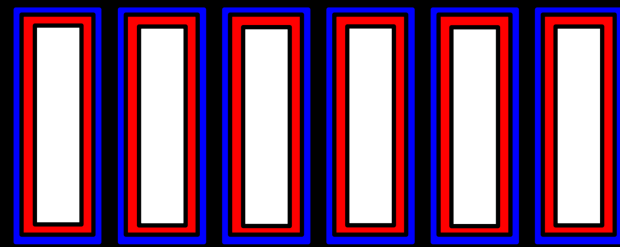
Photodetectors

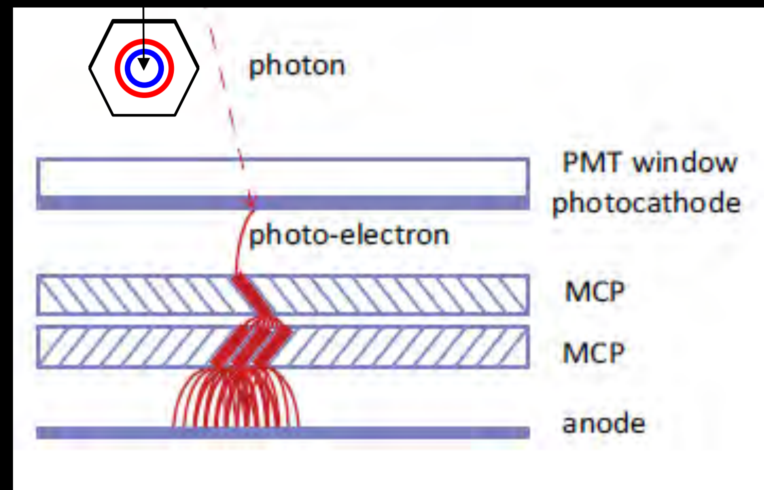
- Large Area Photodetectors



- Key innovations
  - Glass Package
  - Glass microcapillary arrays
  - Atomic Layer Deposition for functionalization
  - Fast waveform sampling readout

Atomic Layer Deposition

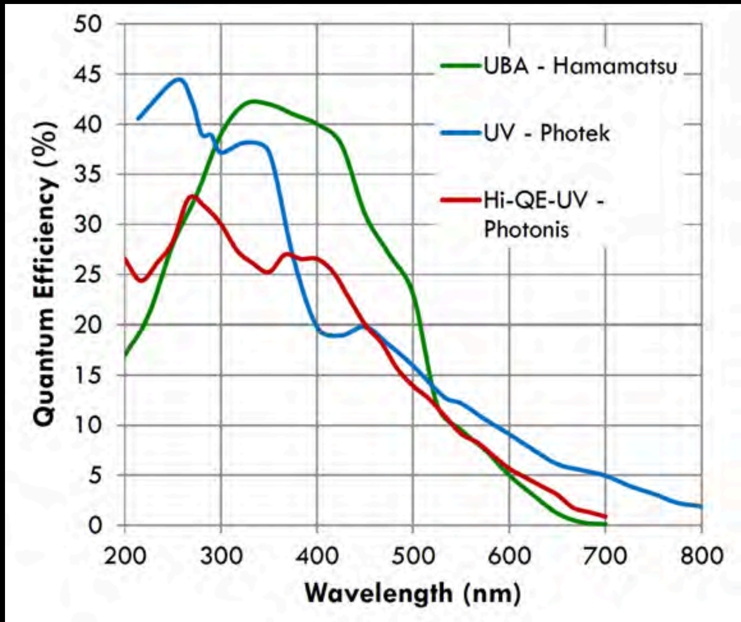




Schematic MCP-based PMT

Photocathodes

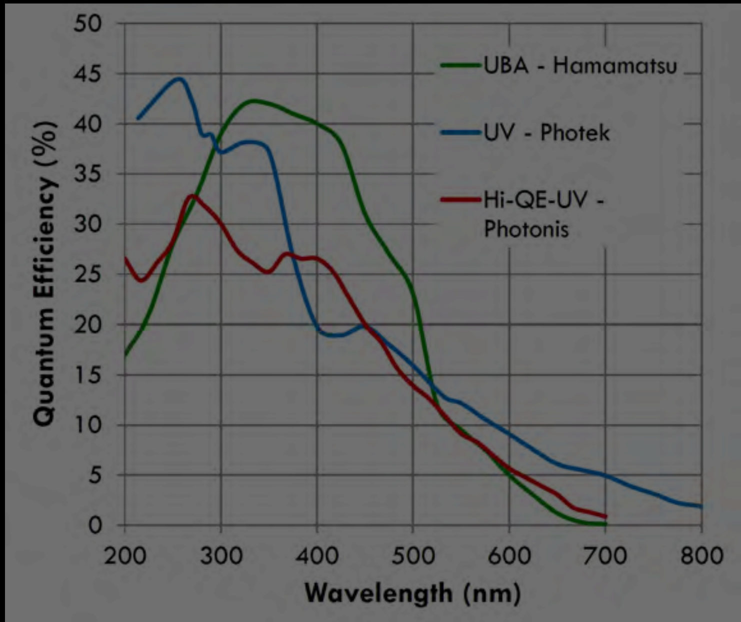
- Alkali-Antimonide Photocathodes



- Alkali Antimonides:
  - Cs_3Sb
  - K_2CsSb
  - Na_2KSb
  - Rb_2CsSb
  - $Na_2KSb:Cs$

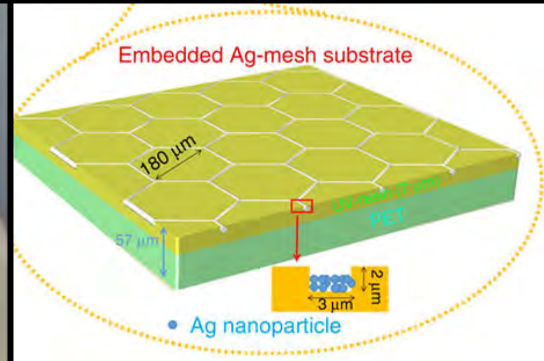
Photocathodes

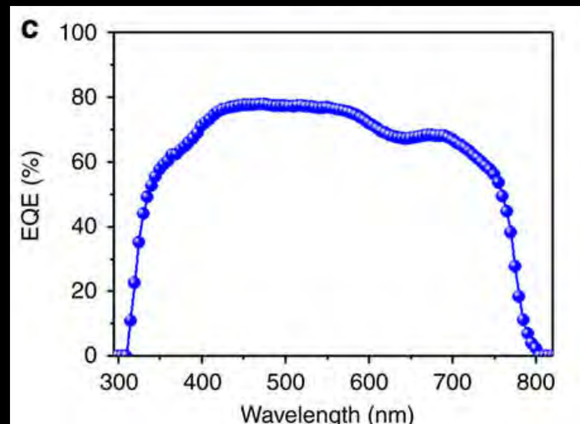
- Alkali-Antimonide Photocathodes



- Alkali Antimonides:
  - Cs_3Sb
  - K_2CsSb
  - Na_2KSb
  - Rb_2CsSb
  - $Na_2KSb:Cs$

- Perovskites for photocells





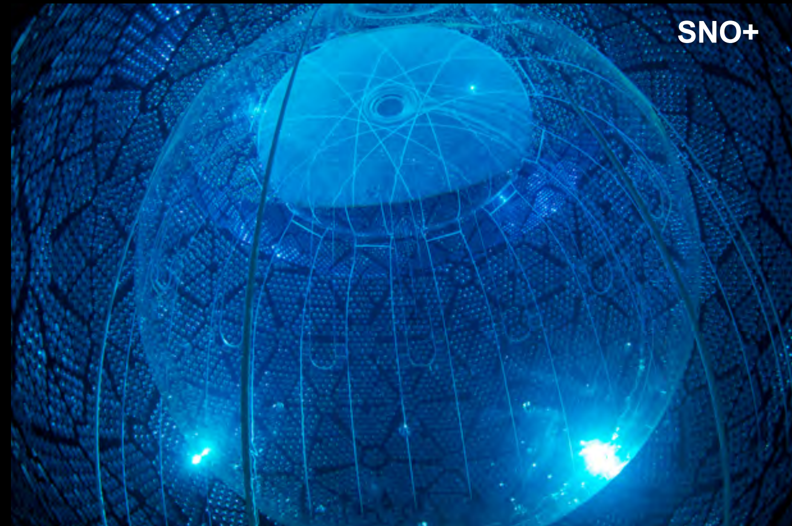
planar heterojunction perovskite solar cells constructed on highly flexible and ultrathin silver-mesh/conducting polymer substrates.

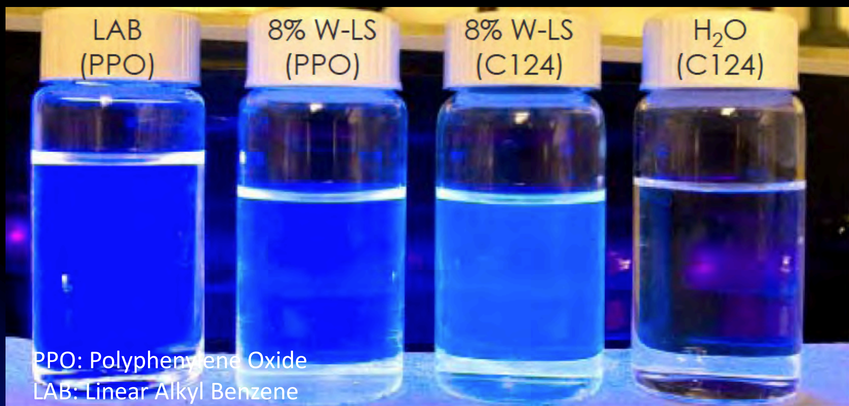
http://dx.doi.org/10.1038/ncomms10214

Loading

- ^{130}Te-loaded scintillator to look for NLDBD
- Loading with Te-diol complex
- Loading with TeBD + amine
- Hybrid loading: TeEG + surfactants

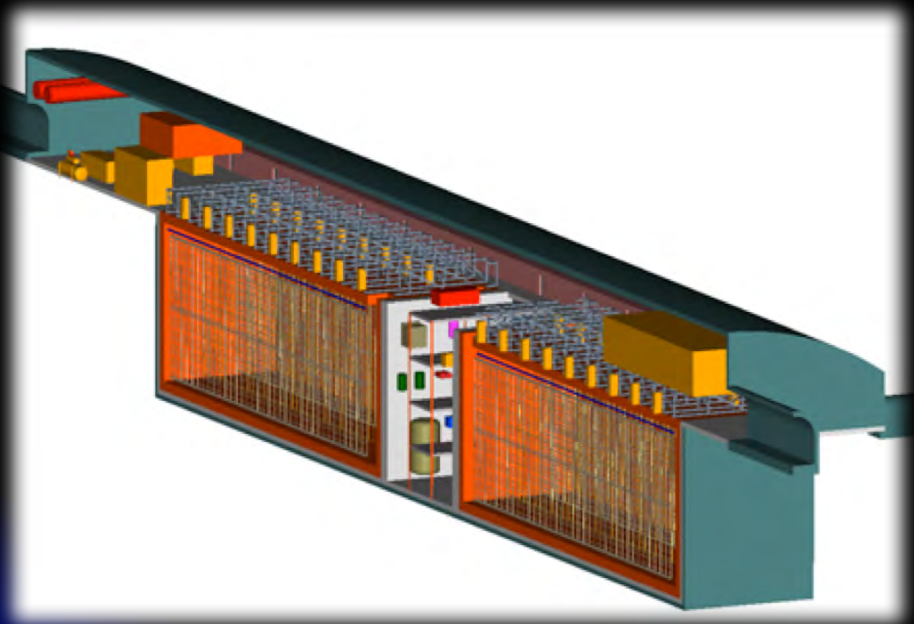
- Gd doping of water detectors
- Water-based Liquid Scintillator as alternative to organic liquid scintillators





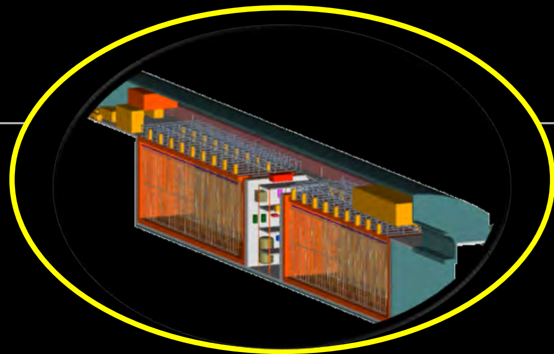
Loading

- One 10 kton neutrino detector for DUNE is the equivalent of 3.5 Olympic swimming pools of liquid Argon

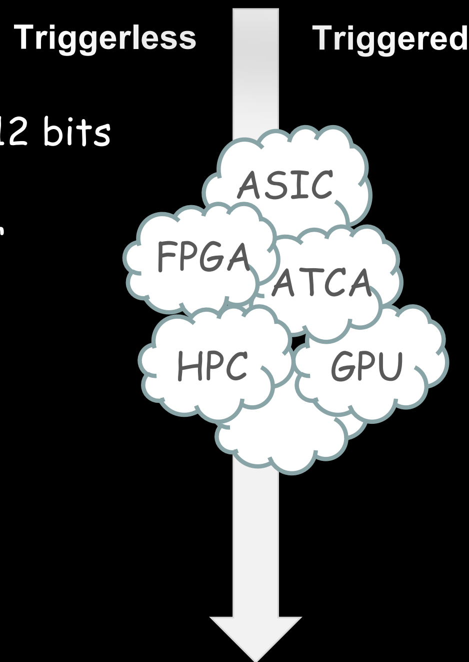


- Can these huge volumes be used in a different way than just measuring small and slow electron charges and UV scintillation signals?

At 120 GeV



Larger detectors
Higher granularity
More data



- DUNE (SP): 2 MHz sampling x 12 bits x 1536000 channels = 37 TB/s
- For all data this is 145 EB/year

- DUNE (SP): 2 MHz sampling x 12 bits x 1536000 channels = 37 TB/s
- For just data during beam spill, this is 436 PB/year

- Take all data continuously and analyze all data on the fly
  - Data compression
  - Smart, fast online algorithms
  - Advanced mixed architectures
  - …

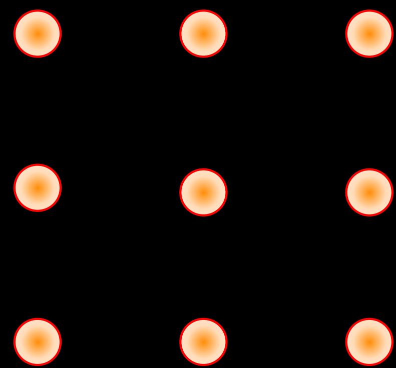
Other Ideas …

- Session on Friday Afternoon at 18:00 !!

- Unorthodox Musings toward True 3-D readout for a Multi-kiloton LAr TPC
- Barium tagging for neutrinoless double-beta decay
- Scintillating Bubble Chambers
- Development of detectors and readout for light dark matter search
- Development of metamaterials for future detector optics
- Prospects for a 10x reduction in the cost of superconducting sensors. Prospects for bringing superconducting sensors to a scale comparable to semiconductor devices.

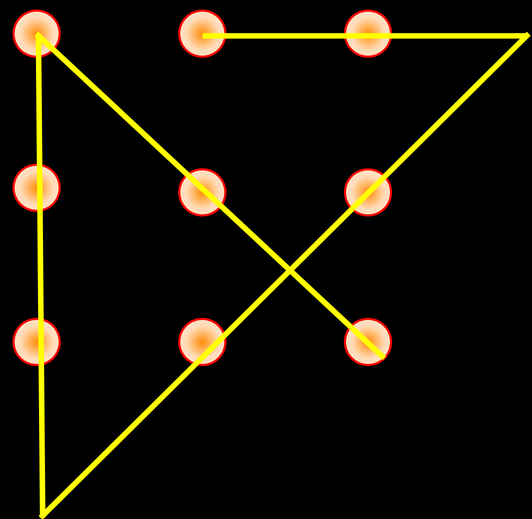
Thinking Out Of The Box

- Connect the dots by drawing four straight, continuous lines that pass through each of the nine dots, and never lift the pencil from the paper.



Thinking Out Of The Box

- …… can only be solved by "*going outside the box*".



Innovation

Innovation

The light bulb would never have been invented through incremental changes to a candle !

Innovation

... And the same holds true for the LED light

New Ideas !

- We have asked the conveners of all the working groups to come up with multiple, innovative, ideas with at least:
  - One 'evolutionary' research program
  - One 'revolutionary' research program
- Each submitted research program is expected to have:
  - A clearly stated objective
  - Set of deliverables and milestones
  - Anticipated project duration
  - List of collaborators


Thank you !