Detectors Of The Future

Higgs Couplings Workshop

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Oak Ridge National Laboratory

Oxford, October 4, 2019

The Future

The Pensieve

https://www.pottermore.com/writing-by-jk-rowling/pensieve

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Today: The Edifice of the Standard Models

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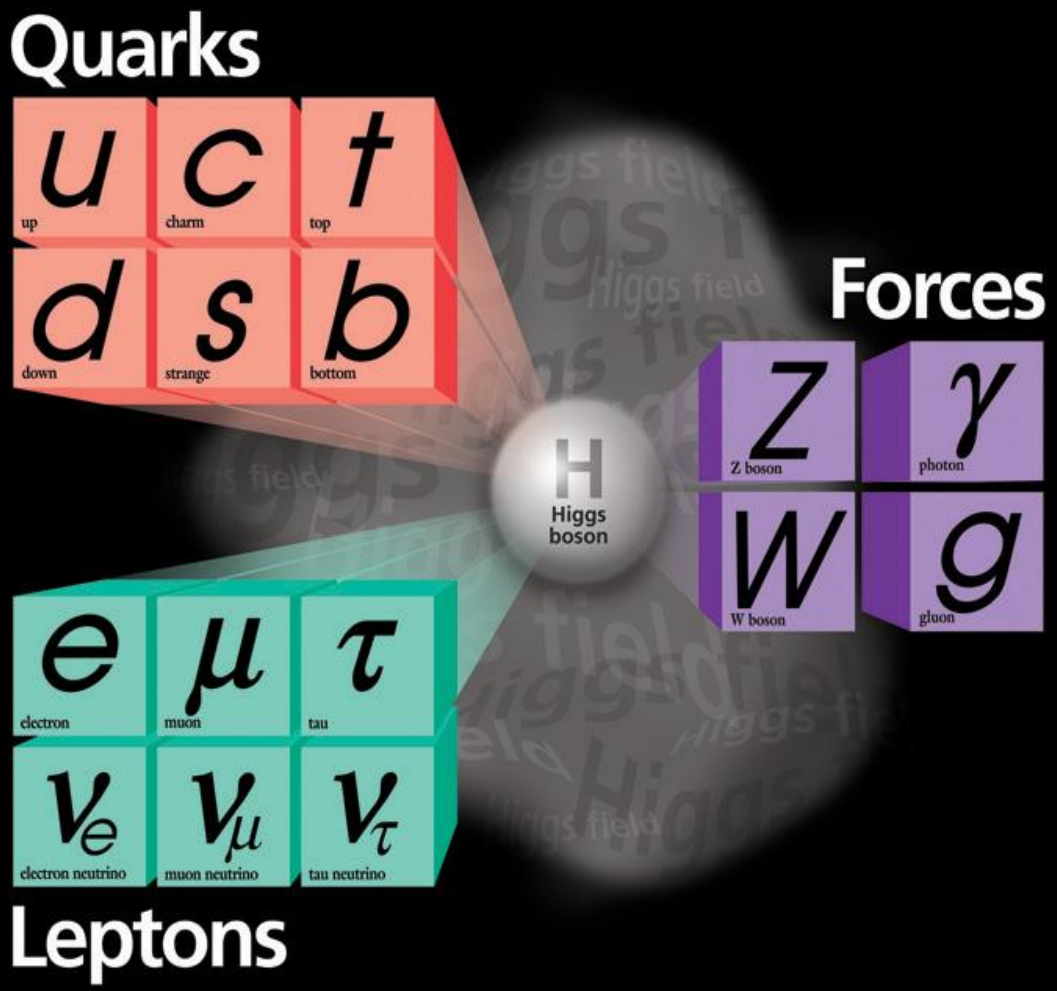
Particle Standard Model



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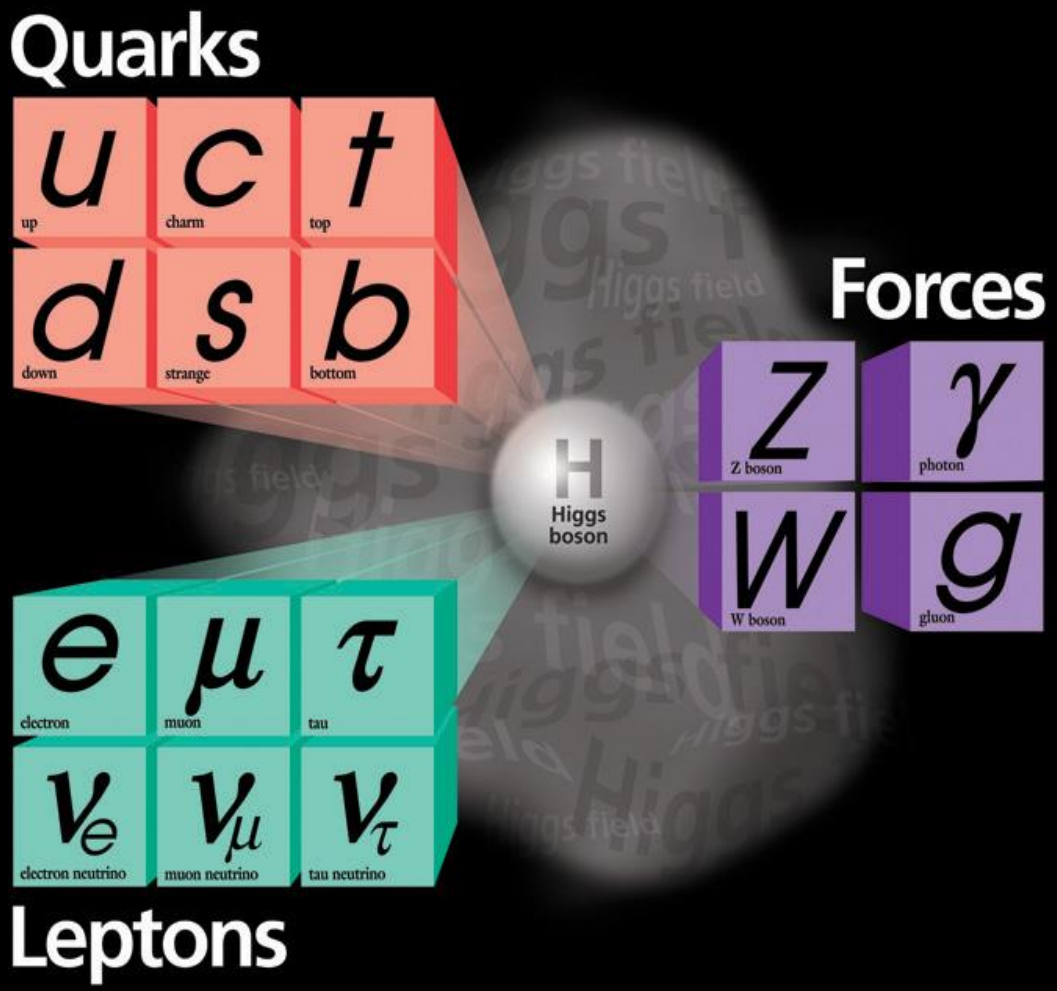
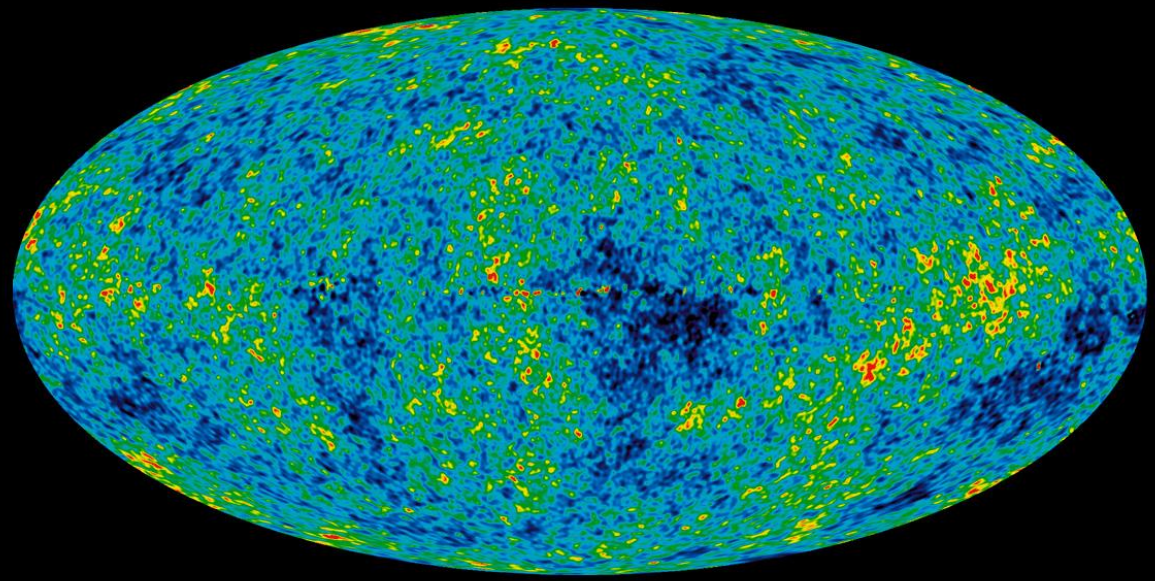


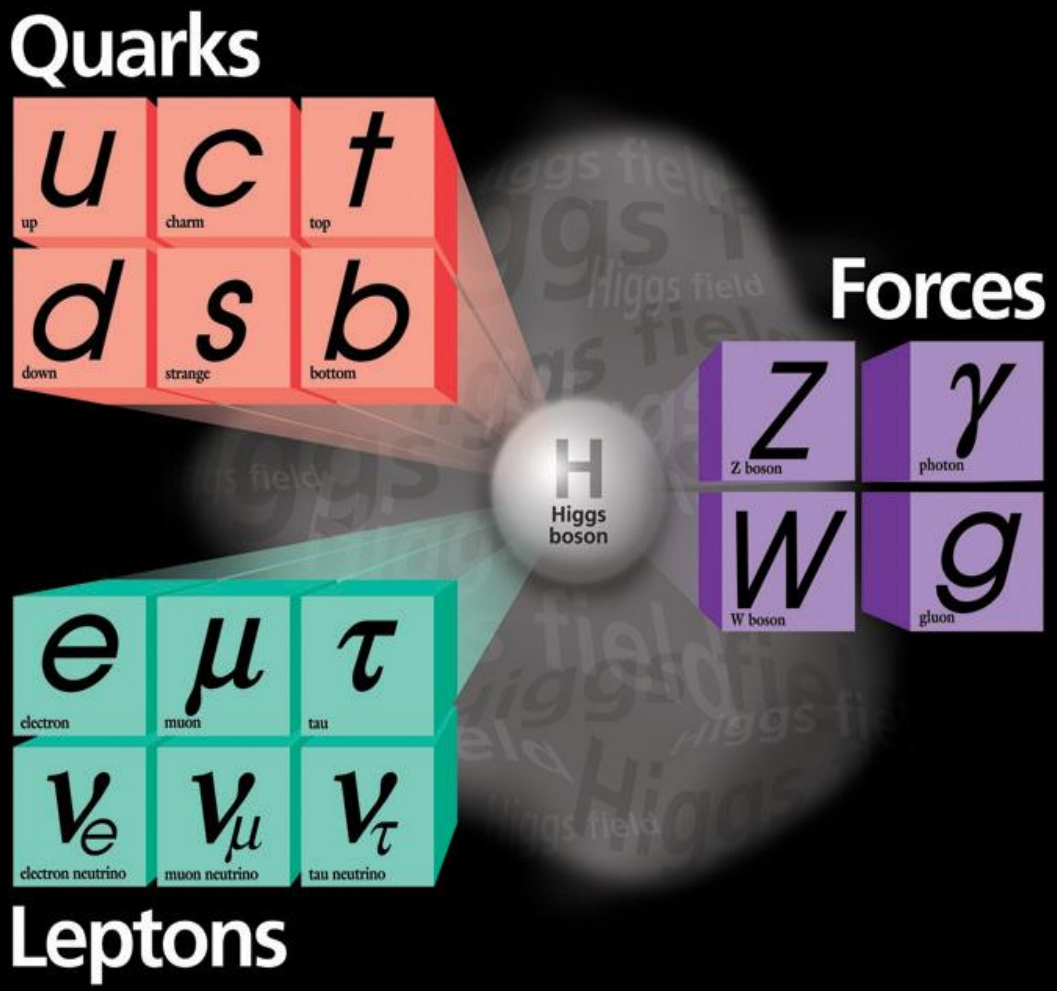
Cosmology Standard Model



Λ_{CDM}

An Edifice Hundred Years In The Making

Particle Standard Model



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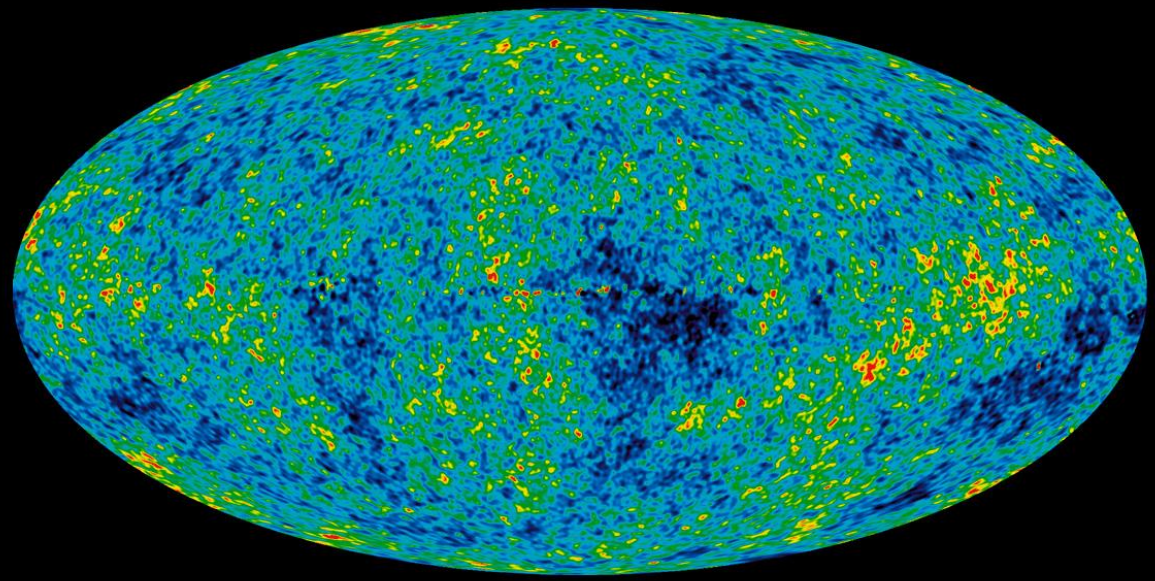


Λ_{CDM}

… it is highly predictive and has been rigorously tested (in QED to 1 part in 10 billion)

Tribute: Nobel Prizes

- Nobel Prize winners in experimental high-energy and particle astro-physics since 1960; two prizes for instrumentation; in addition, 17 winners in HEP theory

The Enablers

- Discovery of Big Bang Theory
- Weak Neutral Currents
- J/Psi discovery
- Discovery of the Tau-Neutrino
- Discovery of the top quark
- Discovery of the Higgs Boson
- Discovery of the Quark Gluon Plasma
- Discovery of Neutrino Oscillations
- Accelerated Expansion of the Universe
- Gravitational Wave Detection
- Definition of SI unit for time

The Enablers

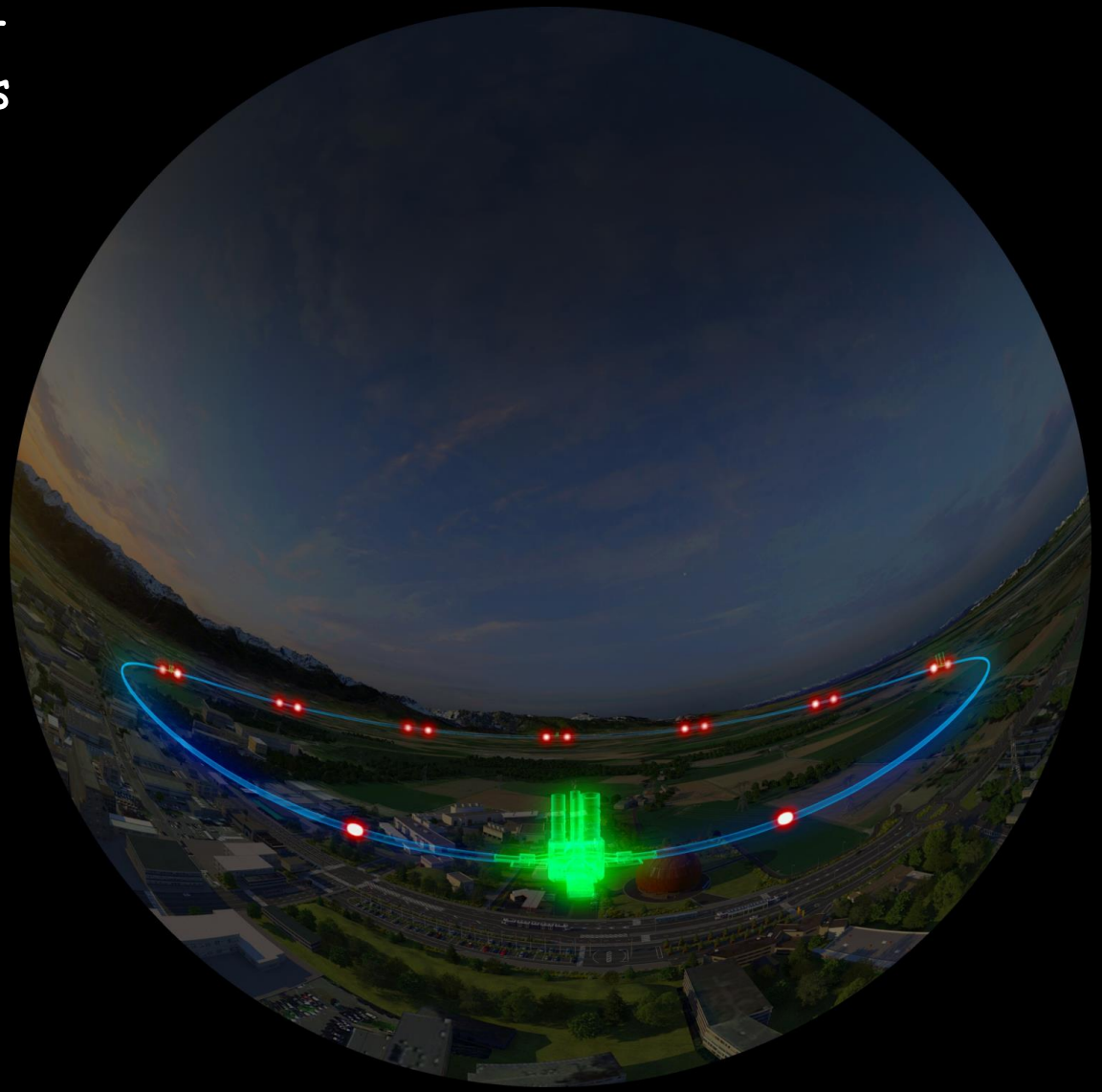
Discovery of Big Bang Theory	Radio Telescopes
Weak Neutral Currents	Bubble Chambers
J/Psi discovery	Multi-wire Proportional Chambers
Discovery of the Tau-Neutrino	Emulsions
Discovery of the top quark	Silicon Strip Detectors
Discovery of the Higgs Boson	Silicon Pixel Detectors, PWO, LHC
Discovery of the Quark Gluon Plasma	Time Projection Chamber
Discovery of Neutrino Oscillations	Liquid Scintillator and Photodetectors
Accelerated Expansion of the Universe	Charged Coupled Devices
Gravitational Wave Detection	Decoupled Interferometer + Lasers
Definition of SI unit for time	Atomic Clocks

Our Current Quest …

- Creation of the Universe: Cosmic Inflation
- Matter – Antimatter Asymmetry
- Higgs Sector – Scalar Fields
- Dark Matter
- Dark Energy
- Mass Hierarchy of Fundamental Particles
- Fine-tuning Problem
- Proton Puzzles: spin, radius
- Electric Dipole Moments
- …

New Tools !

- Colliders are a choice to further our current understanding and address the shortcomings of the current theories

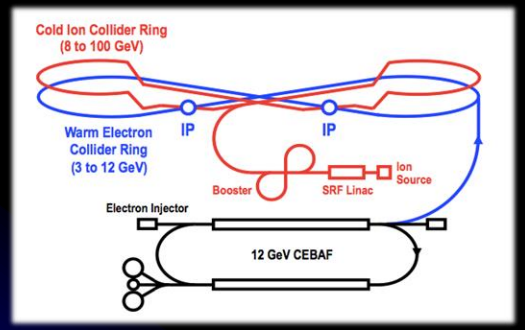


Outline:

- The landscape of future colliders
  - Their operating parameters
- Instrumentation challenges for:
  - e^+e^- Colliders
  - pp Colliders
- Conclusions

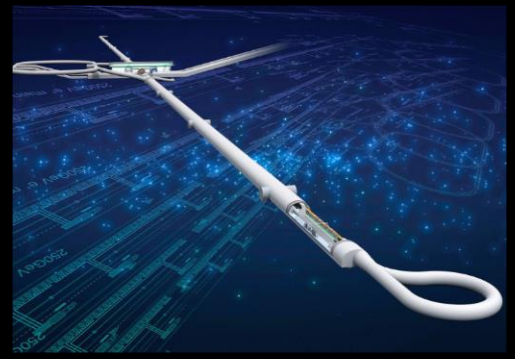
Colliders Proposed

2025



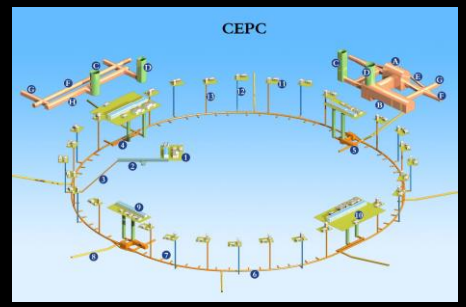
Electron Ion Collider (EIC)
e < 25 GeV, p < 250 GeV

2030



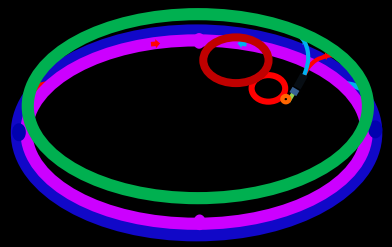
International Linear Collider (ILC)
e^+e^- E_{cms} < 1 TeV

2035

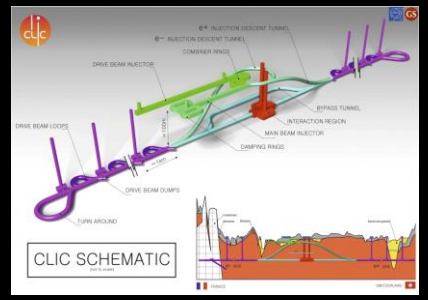


Circular Electron Positron
Collider (CepC) E_{cms} < 250 GeV

2040

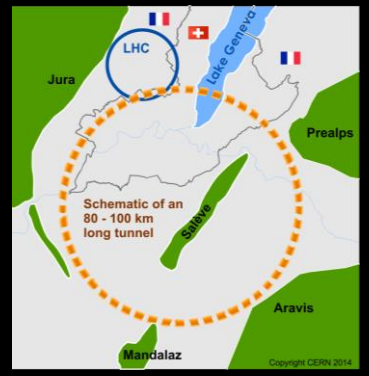


Super pp Collider (SppC)
E_{cms} ~100 TeV



Compact Linear Collider (CLIC)
e^+e^- E_{cms} < 3 TeV

2045



Future Circular Collider (FCC)
pp, E_{cms} ~100 TeV
e^+e^- E_{cms} < 350 GeV
AA E_{cms} ~40TeV

Proton Collider Parameters

parameter	FCC-hh	SPPC	HE-LHC*
collision energy [TeV]	100	75 - 125	>25
dipole field [T]	16	20	16
Circumference [km]	100	100	27
beam current [A]	0.5	1.0	1.12
bunch intensity [10^{11}]	1 (0.2)	1.5	2.2
bunch spacing [ns]	25 (5)	25	25
beta* [m]	0.3	0.71	0.25
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	<30	10	>25
events/bunch crossing	<1020 (204)	490	850
stored energy/beam [GJ]	8.4	6.6	1.2
synchrotron. rad. [W/m/beam]	24	11	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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Electron-Positron Collider Parameters

parameter	FCC-ee				CEPC		ILC	CLIC	LEP2
Physics working point	Z	WW	ZH	tt_{bar}	Z	H	all	all	Z / WW
energy/beam [GeV]	45.6	80	120	182.5	45.5	120	<500	<500	105
bunches/beam (train)	16640	2000	328	48	12000	242	1312	354	4
bunch spacing [ns]	19.6	163	994	3396	25	680	554	0.5	22000
bunch intensity [10^{11}]	1.7	1.5	1.8	2.3	0.8	1.5	0.2	0.068	4.2
beam current [mA]	1390	147	29	5.4	461	17.4	5.8	0.019	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	230	28	8.5	1.55	32.1	2.93	2.0	2.3	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.21	0.036	1.73	0	0	3.34

Circular

Linear

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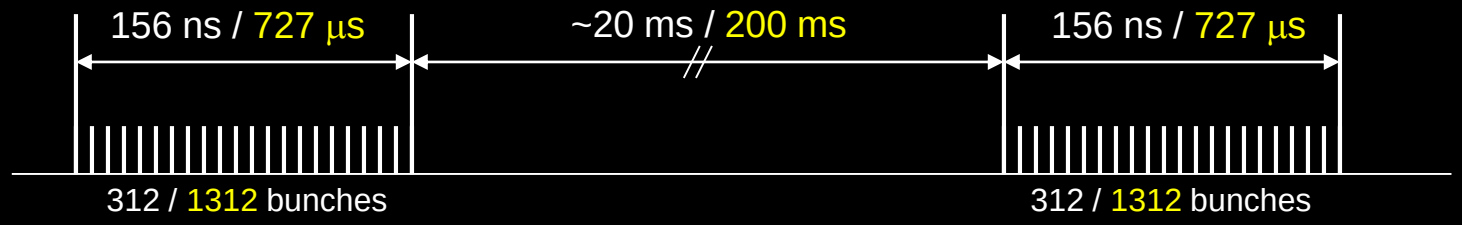
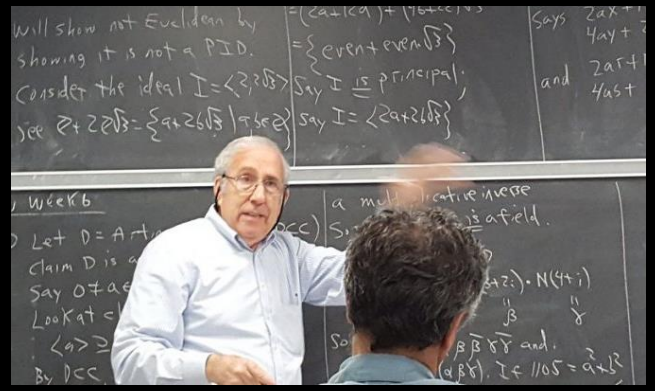
Beam Structure: CLIC, duty cycle 50 Hz

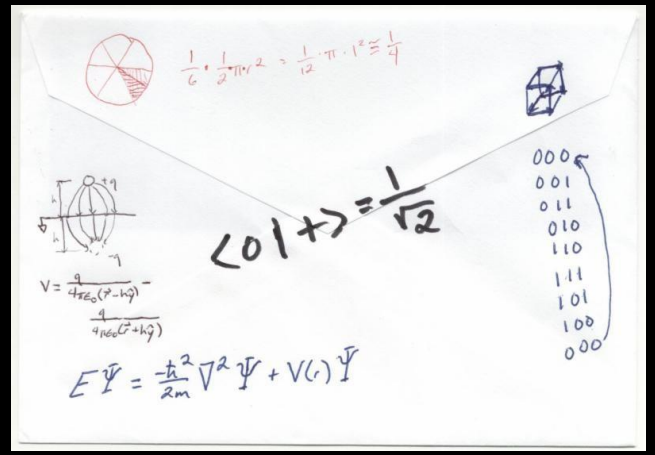
ILC, duty cycle 5 Hz



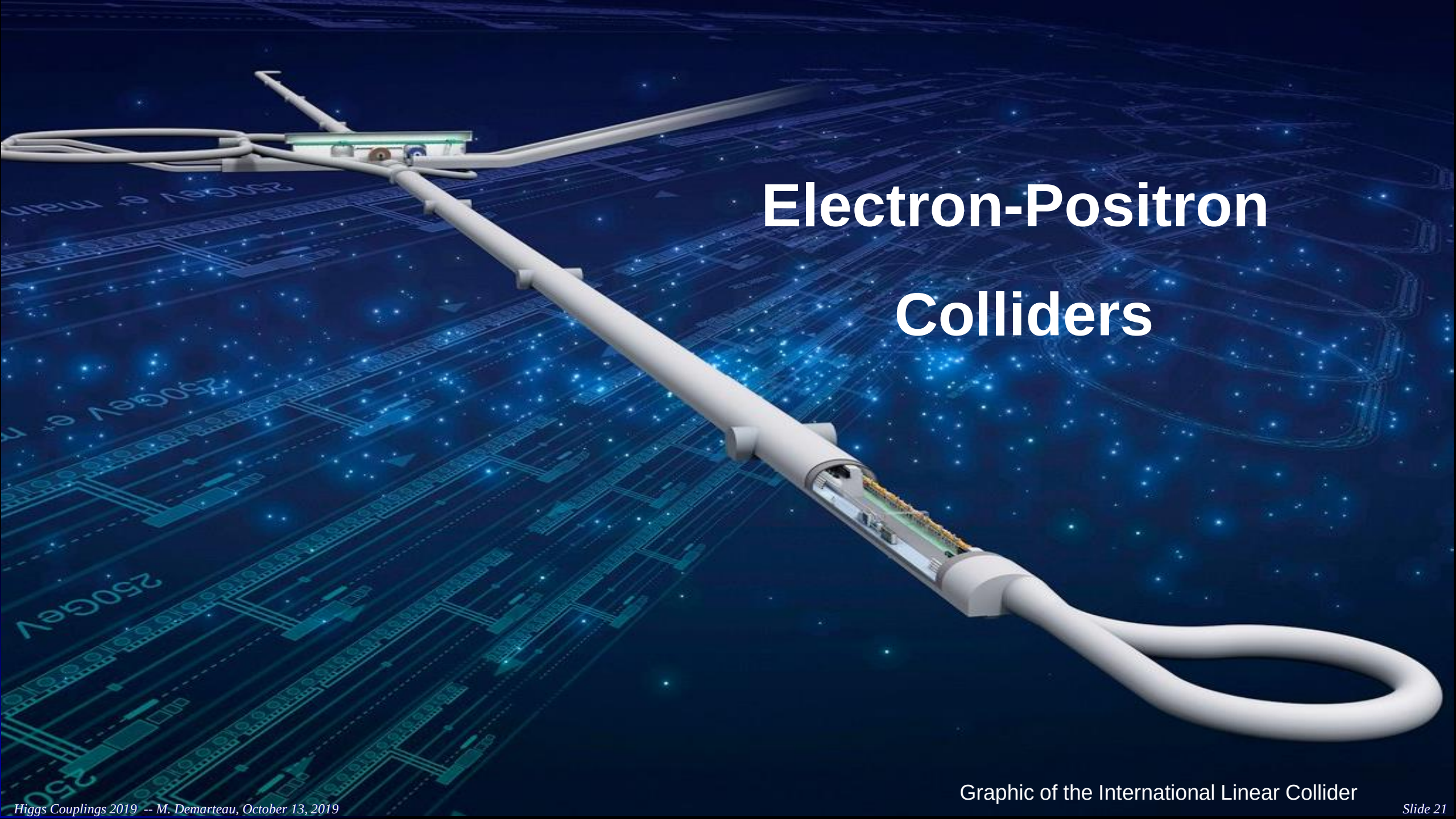
Warning !

- It is tough to make predictions so far ahead. So, …
- There's some handwaving
- And back of the envelopes
- And, I will show my bias!





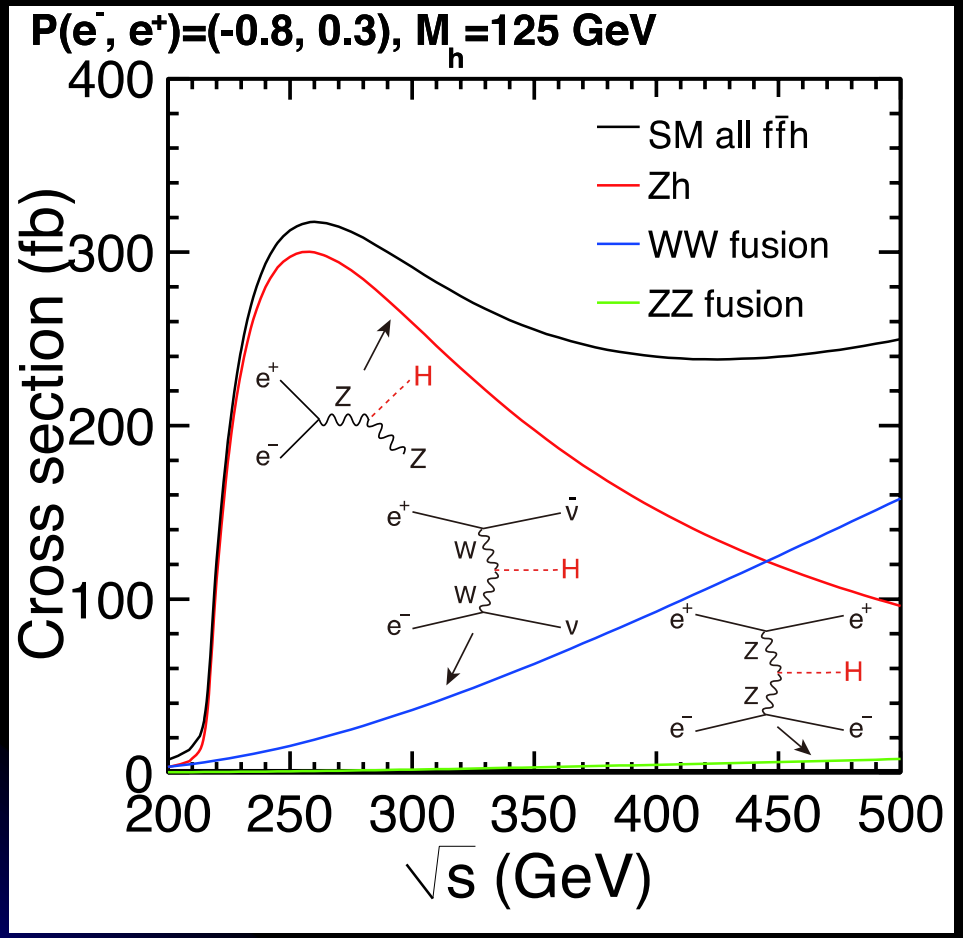
Electron-Positron Colliders



Graphic of the International Linear Collider

e^+e^- Is Precision Physics

- Proposed e^+e^- colliders are intended to deliver precision physics, notably of the Higgs



- ZH-channel allows for
  - Most precise Higgs mass measurement through mass recoil
  - Model independent measurement of branching ratios / couplings

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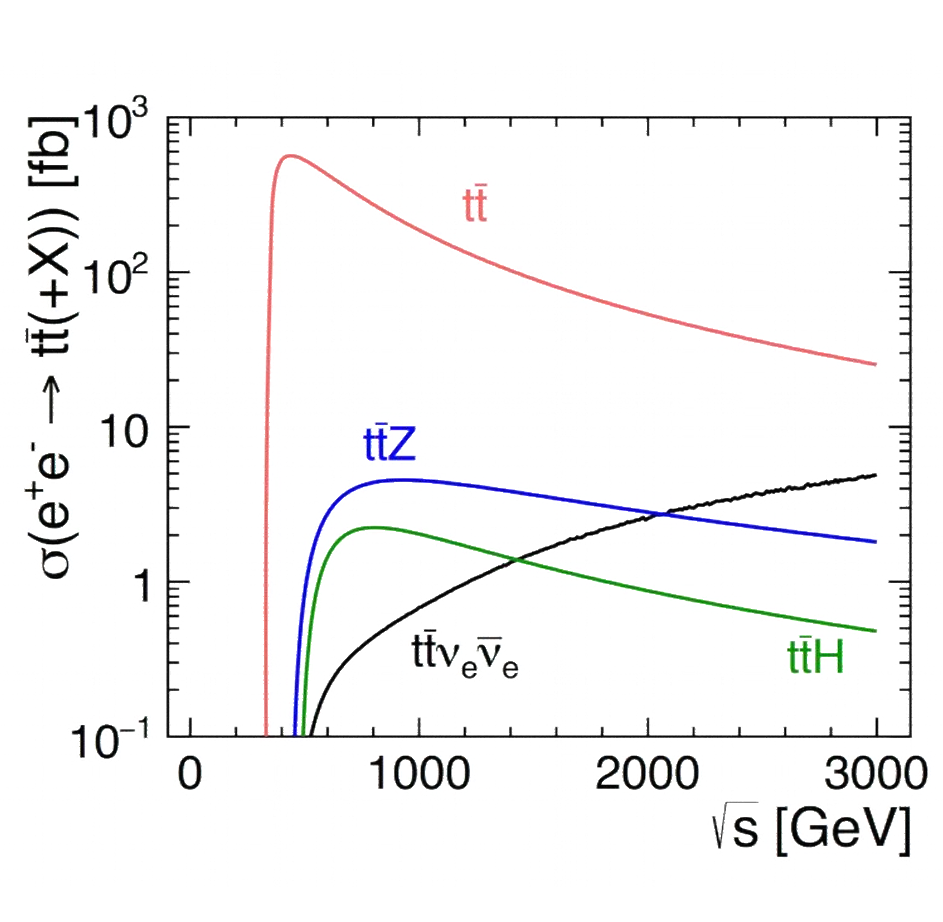

- ZH-channel allows for
  - Most precise Higgs mass measurement through mass recoil
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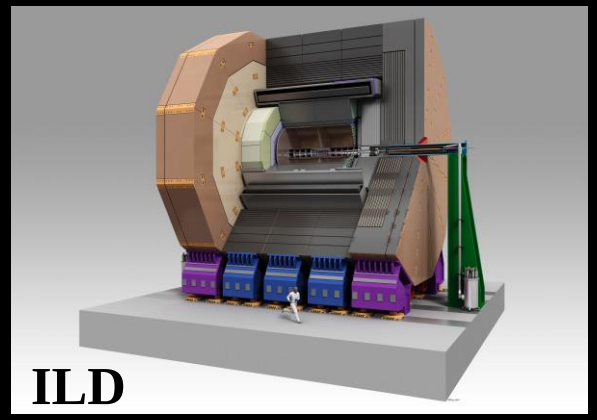
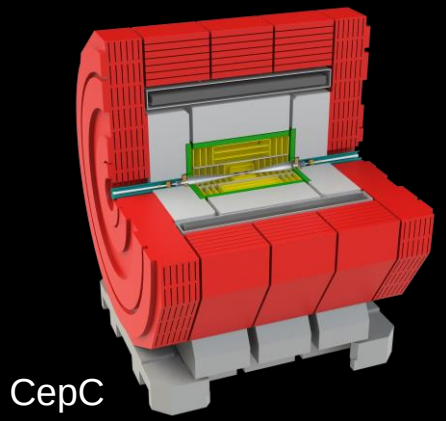
- With increasing energy, fusion channels open up, ttbar threshold and Higgs self coupling measurement to fully map the Higgs potential

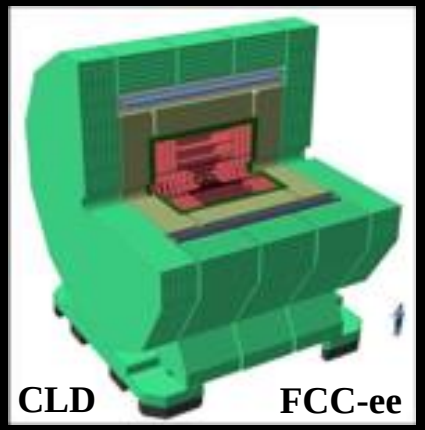
Proposed e^+e^- Detectors



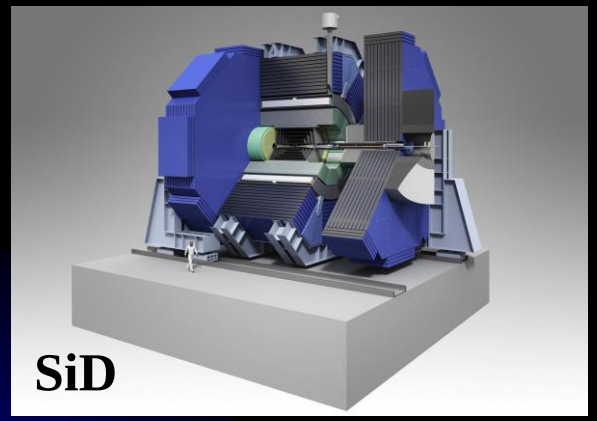
3.5(4) T Solenoid, 8.8 x 8 m
Si Pixel + TPC Tracker R = 1.8(1.5) m



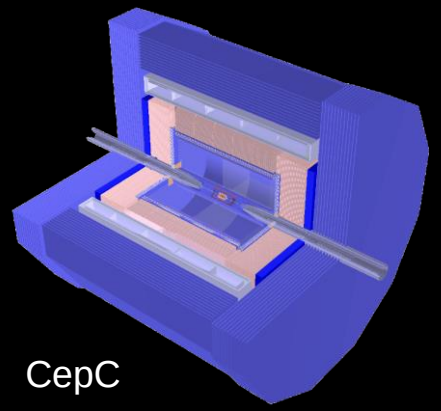
4 T Solenoid, 7 x 8.3 m
Full Si-Tracker R = 1.5 m



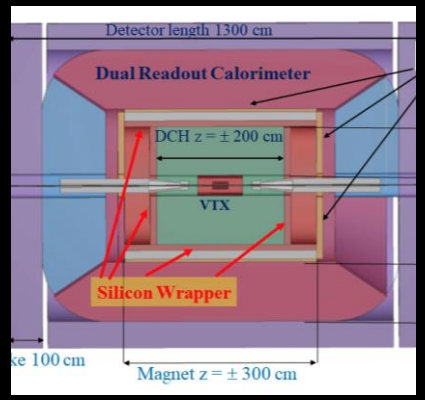
2T Solenoid 7.4 x 7.4 m
Full Si-Tracker R = 2 m



5 T Solenoid, 6 .8 x 6 m
Full Si-Tracker R = 1.2 m



3 T Solenoid 6.4 x 7.8 m
Si Pixel + TPC tracker R = 1.8 m



IDEA
FCC-ee
CepC

2 T Solenoid 4.2 x 6 m
Si Pixel + Drift Chamber R= 2 m

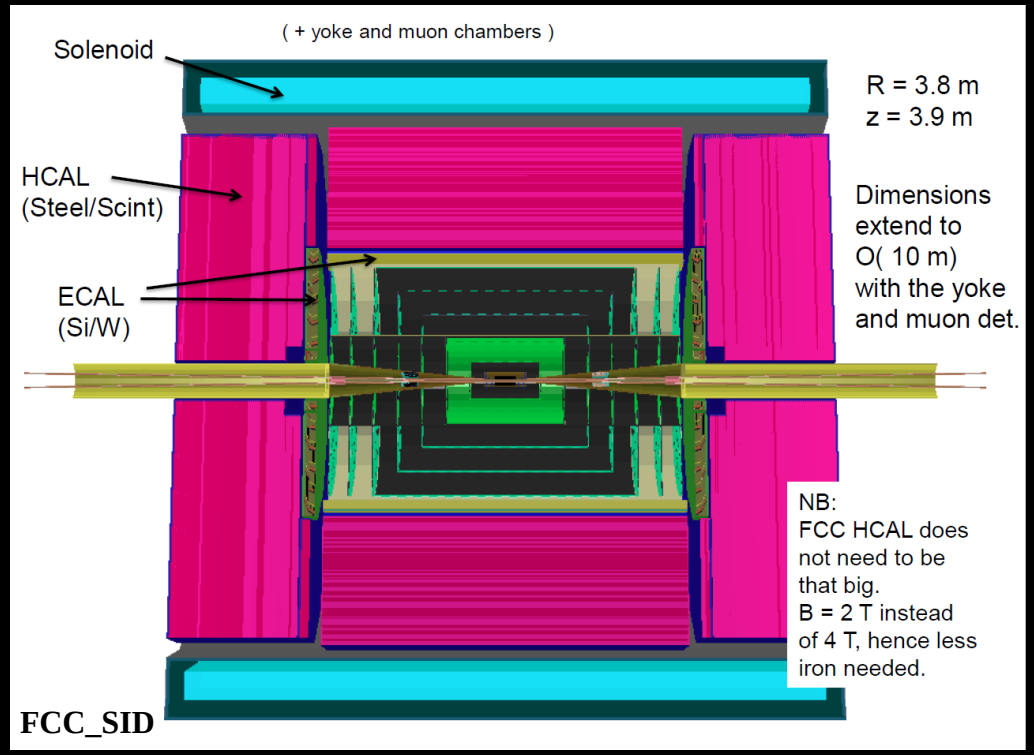
Proposed e^+e^- Detectors

- For the ILC and CLIC and CepC and FCC-ee

- Based on TPC for main tracking or based on Silicon

- CLIC detectors have deeper calorimeters for running at $\sqrt{s}$ = 3 TeV

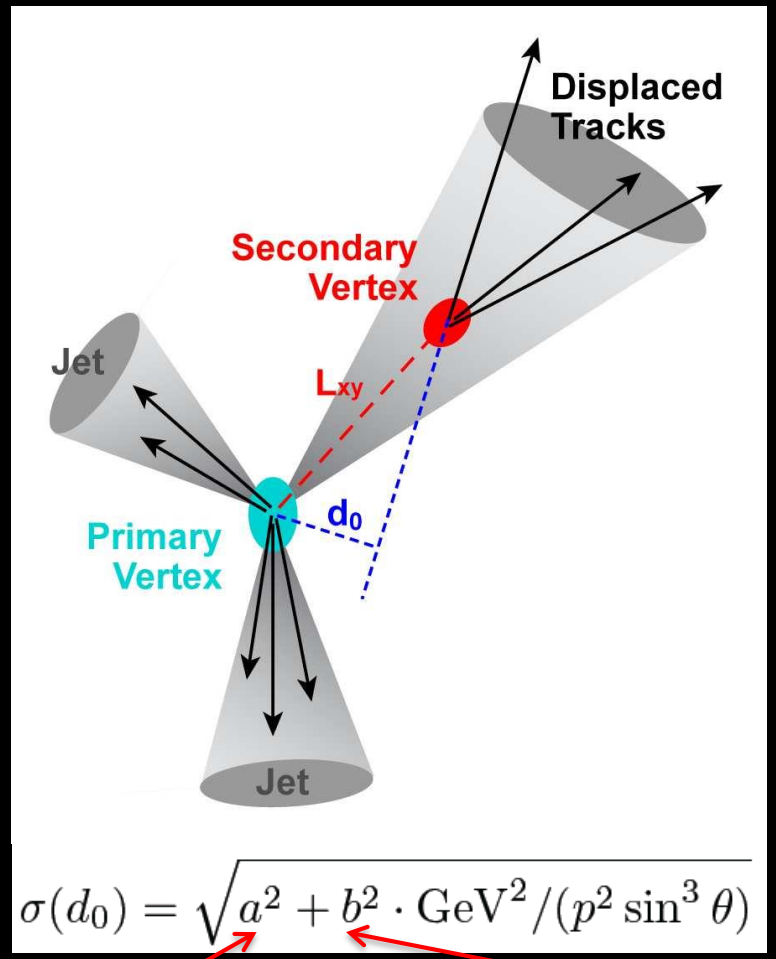
- Central magnetic field requirements and calorimeter depth relaxed for CepC, FCC-ee



Vertex Detector

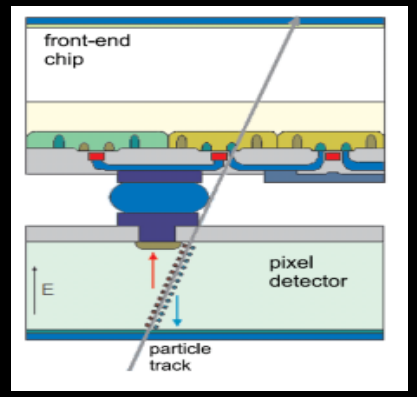
- Measure point of origin of tracks as accurately as possible
  - Impact parameter resolution
  - Single hit resolution
  - Primary vertex resolution

- Challenges:
  - Lowest possible mass budget
  - Low power, low occupancy
  - Best position resolution
  - Timing information for each hit
  - As close as possible to the interaction point
  - Forward region
  - Radiation hard



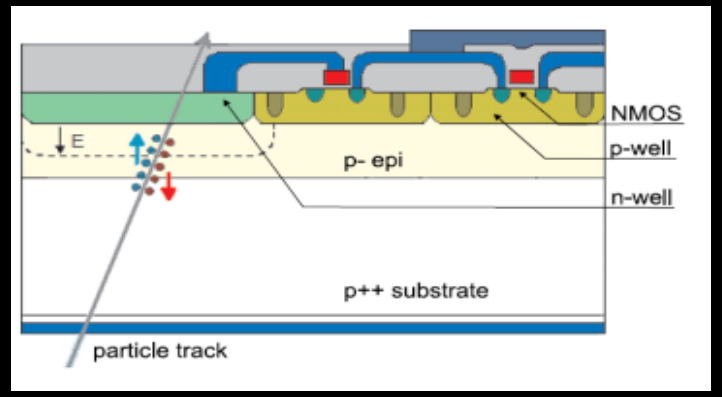
Technologies

Hybrid Pixel



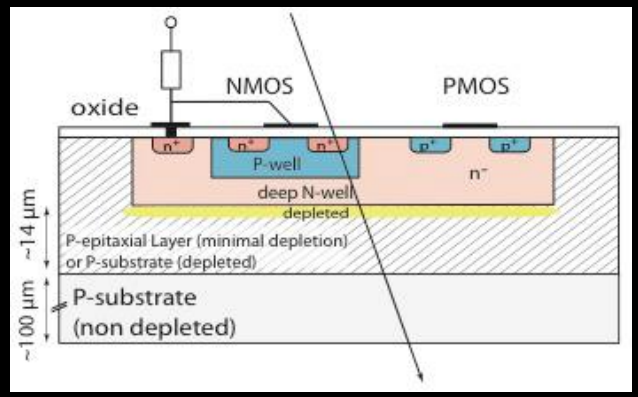
- Q collection by drift

CMOS-MAPS



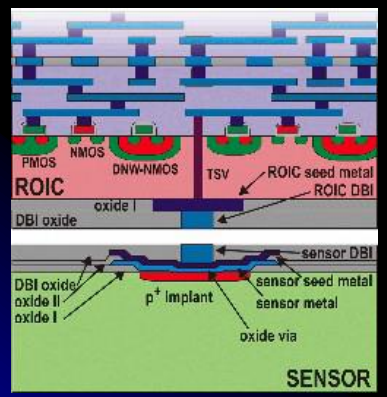
- Charge collection by diffusion

HV-CMOS



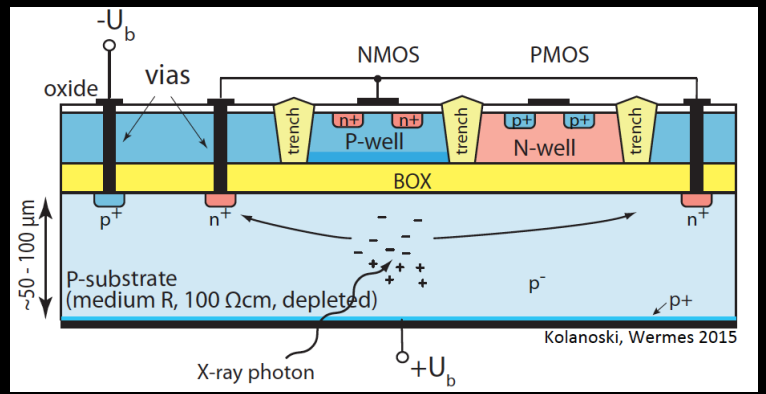
- HV process, 10 – 15 µm depletion region under deep N-well

3D Tiered



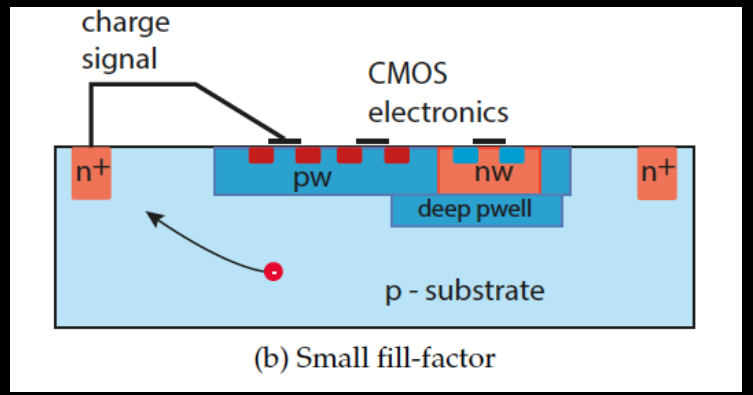
- Fully depleted

SOI-CMOS



- Fully depleted or HV process

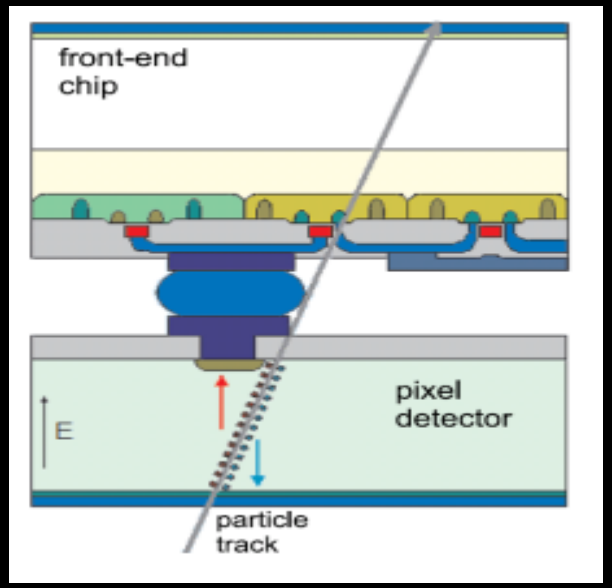
Depleted-CMOS



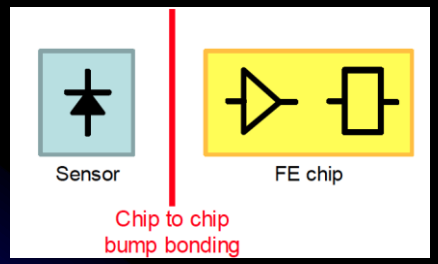
- Fully depleted, low C

Two Pixel Technologies

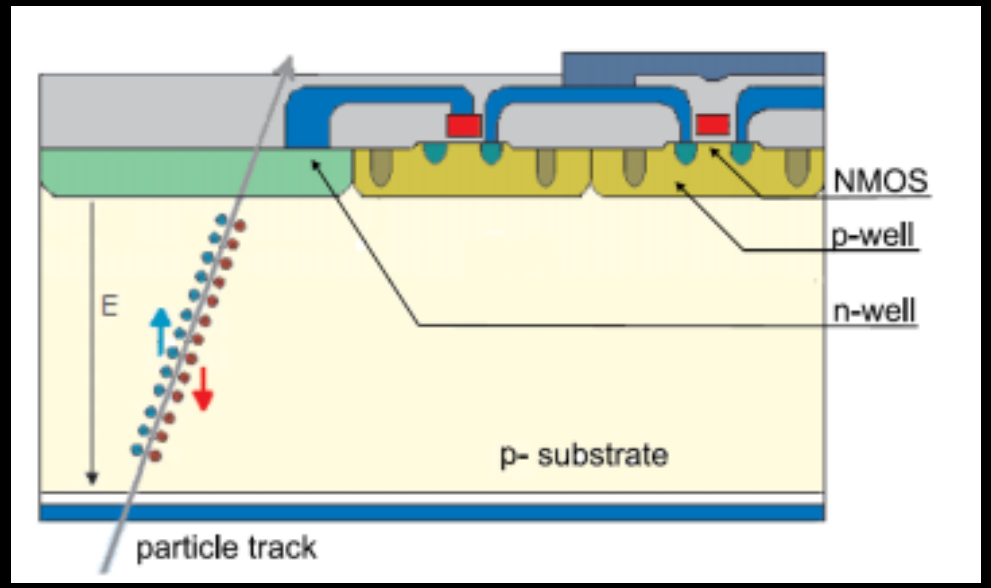
Hybrid Pixels



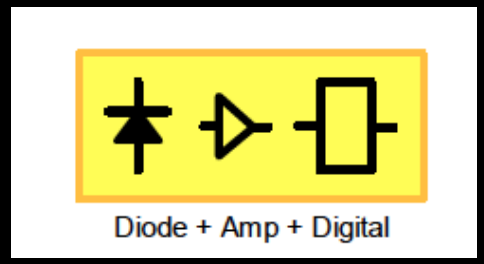
~300 μm



Depleted CMOS MAPS



~100 μm

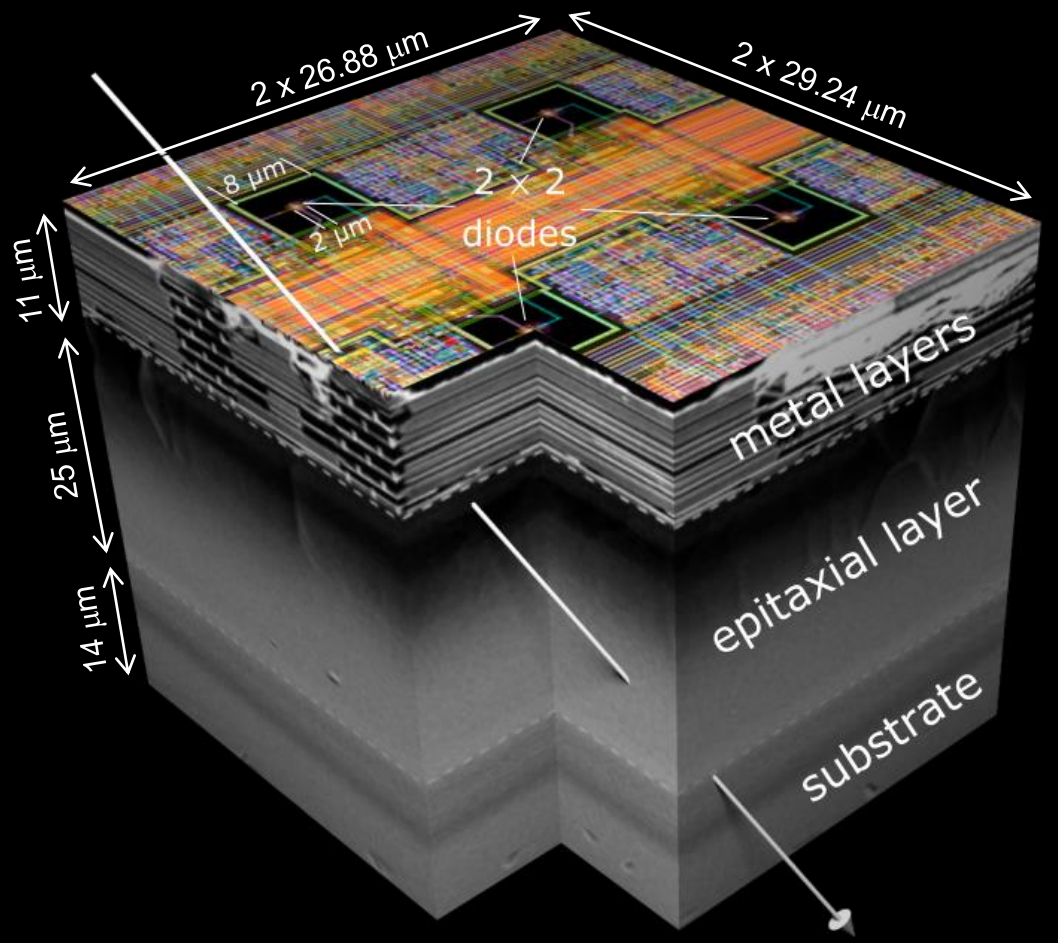


MAPS = Monolithic Active Pixel Sensor

Peric et al., NIM A582 (2007) 876-885 & NIM A765 (2014) 172-176

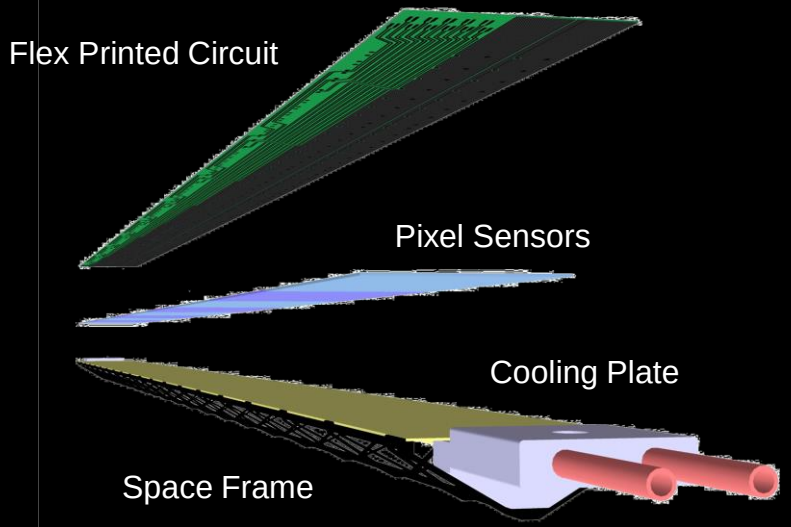
Mattiazzo, Snoeys et al., NIM A718 (2013) 288-291

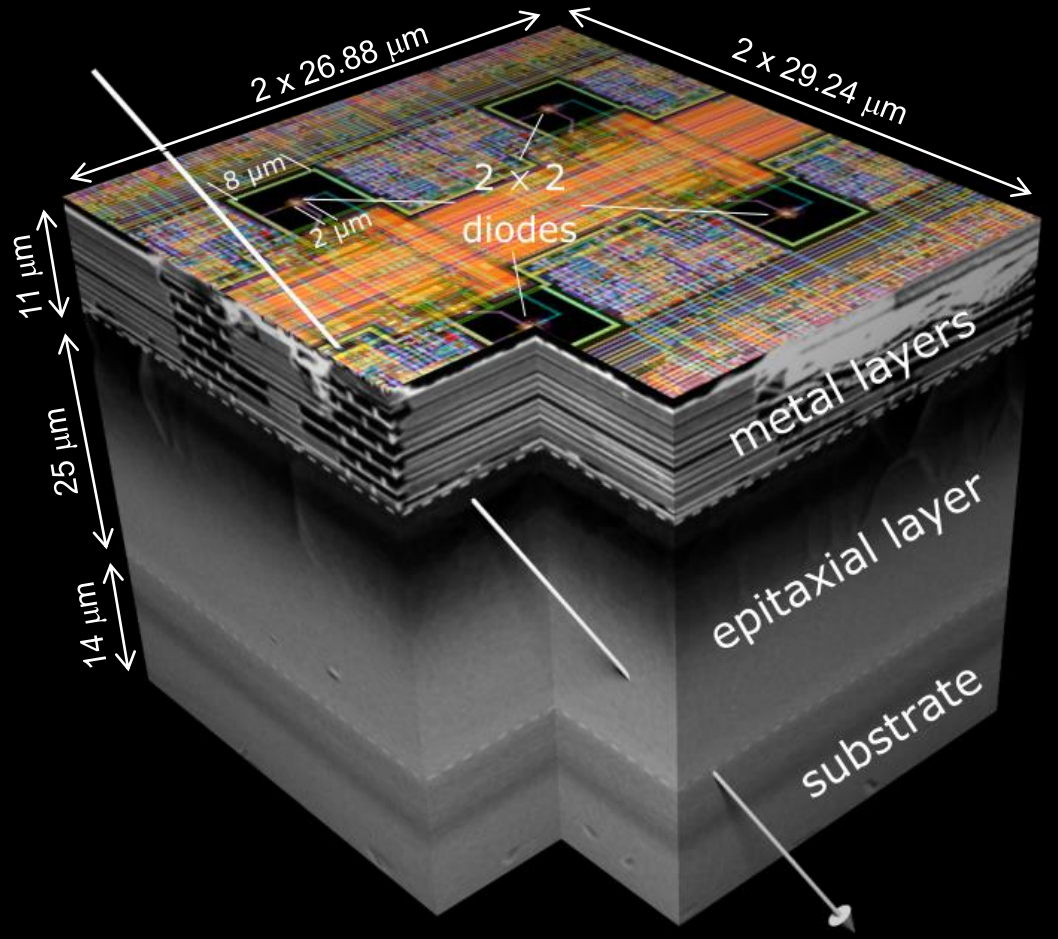
CMOS Pixel Chips



ALPIDE (ALICE)

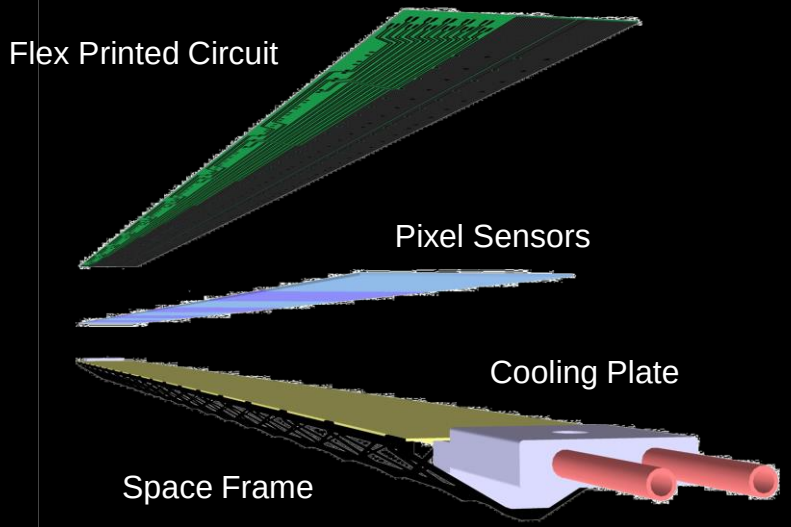
CMOS Pixel Chips

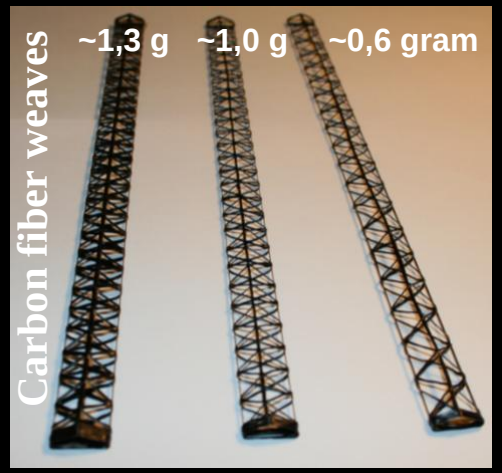


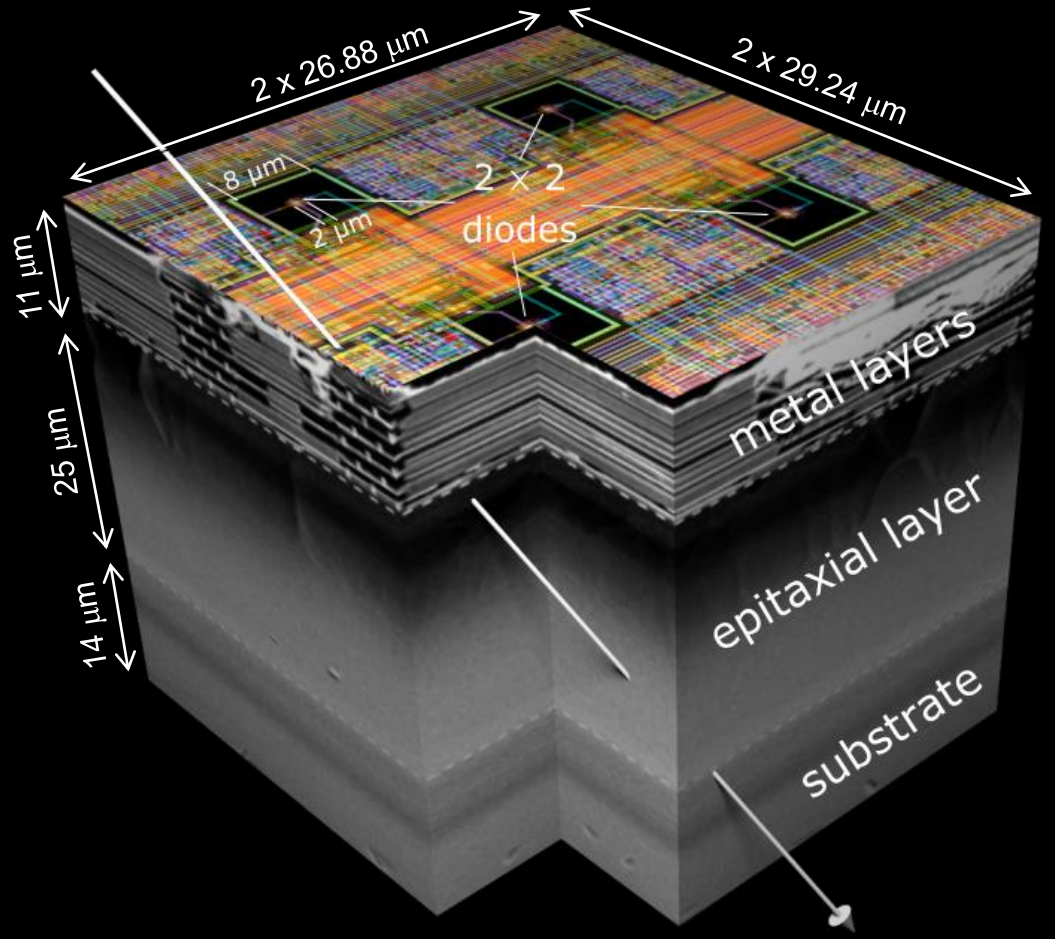


ALPIDE (ALICE)

CMOS Pixel Chips







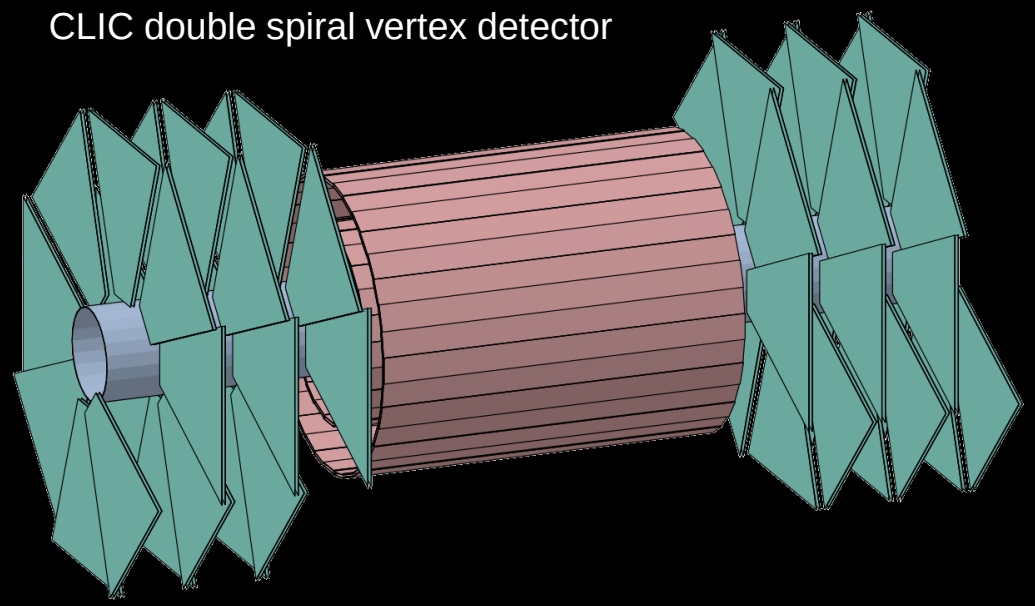
ALPIDE (ALICE)

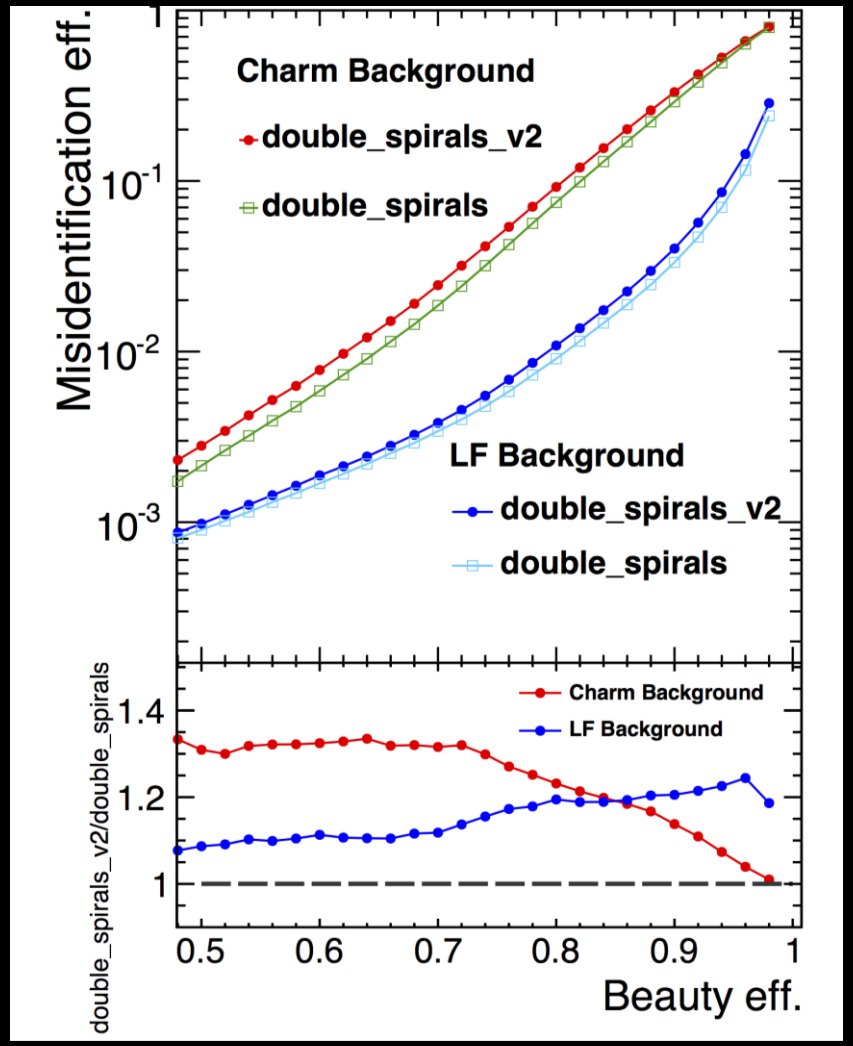
- Tremendous progress in CMOS pixel designs
  - E.g. Alpide: pixel pitch: 29µm x 27µm
  - Power < 40mW/cm^2
  - Integration time <10µs
  - Recall: 0.1% X_0 = 100 µm Si
- Many incompatible performance requirements remain !

Impact Of Mass Budget

- Double mass budget from 0.2%X_0 to a more realistic 0.4%X_0 for CLIC detector

CLIC double spiral vertex detector

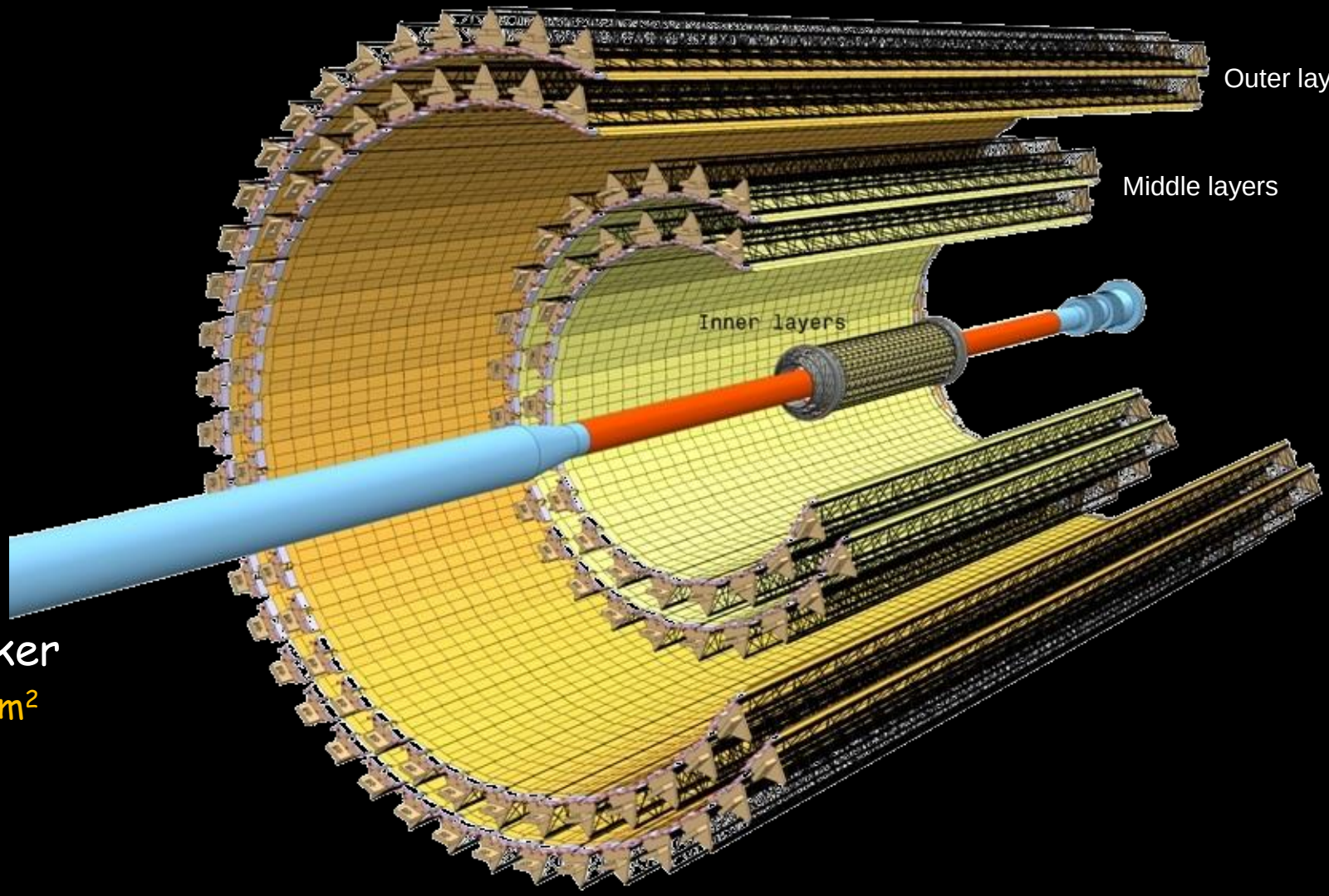




- Charm mis-identification increase up to 35%
- Strongly dependent on
  - Angle (forward nearly an order of magnitide)
  - Energy (7x for 90GeV – 1TeV jets)

Silicon Tracking

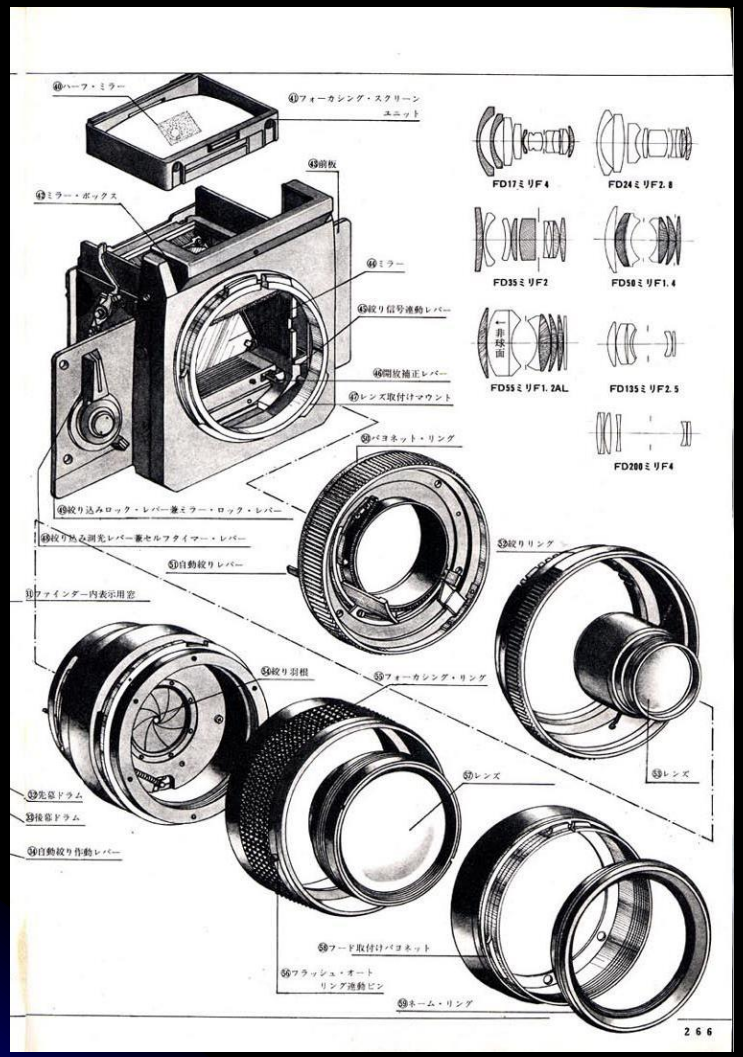
- All silicon pixel tracking becoming possible



- ALICE MAPS-CMOS Tracker
  - 7-layers, 12.5 Giga pixels, 10m^2
  - R coverage: 23 – 400 mm
- Material/layer:
  - 0.3% X_0 (IB)
  - 1.0% X_0 (OB)

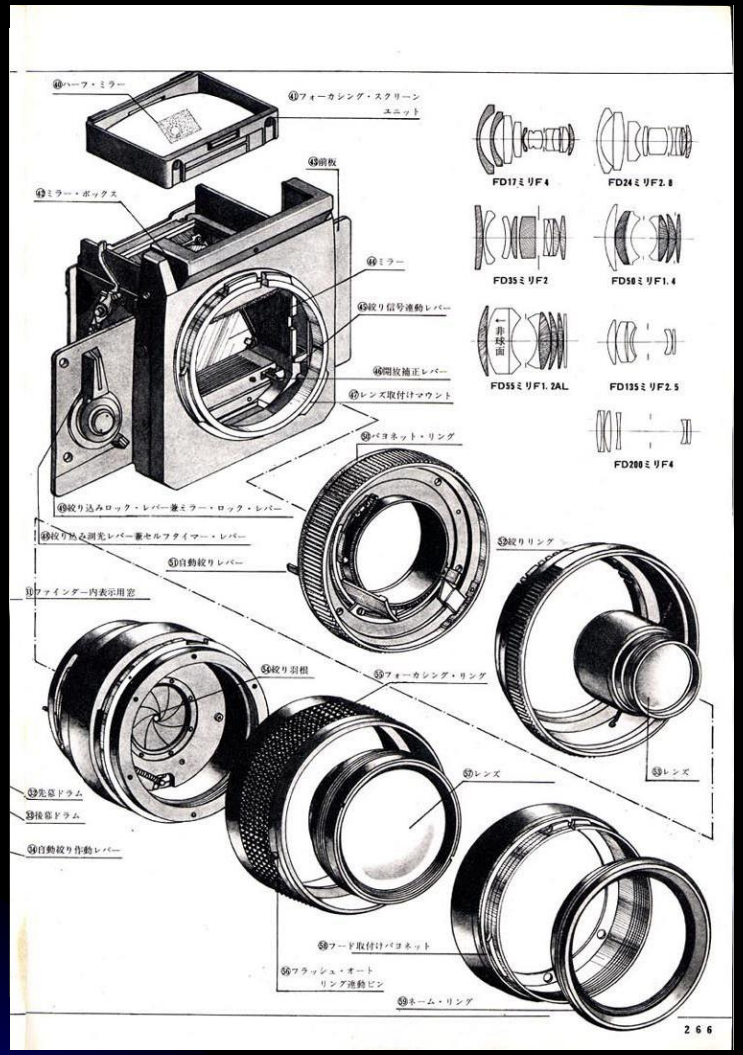
A Side Note: Perspective

A Side Note: Perspective



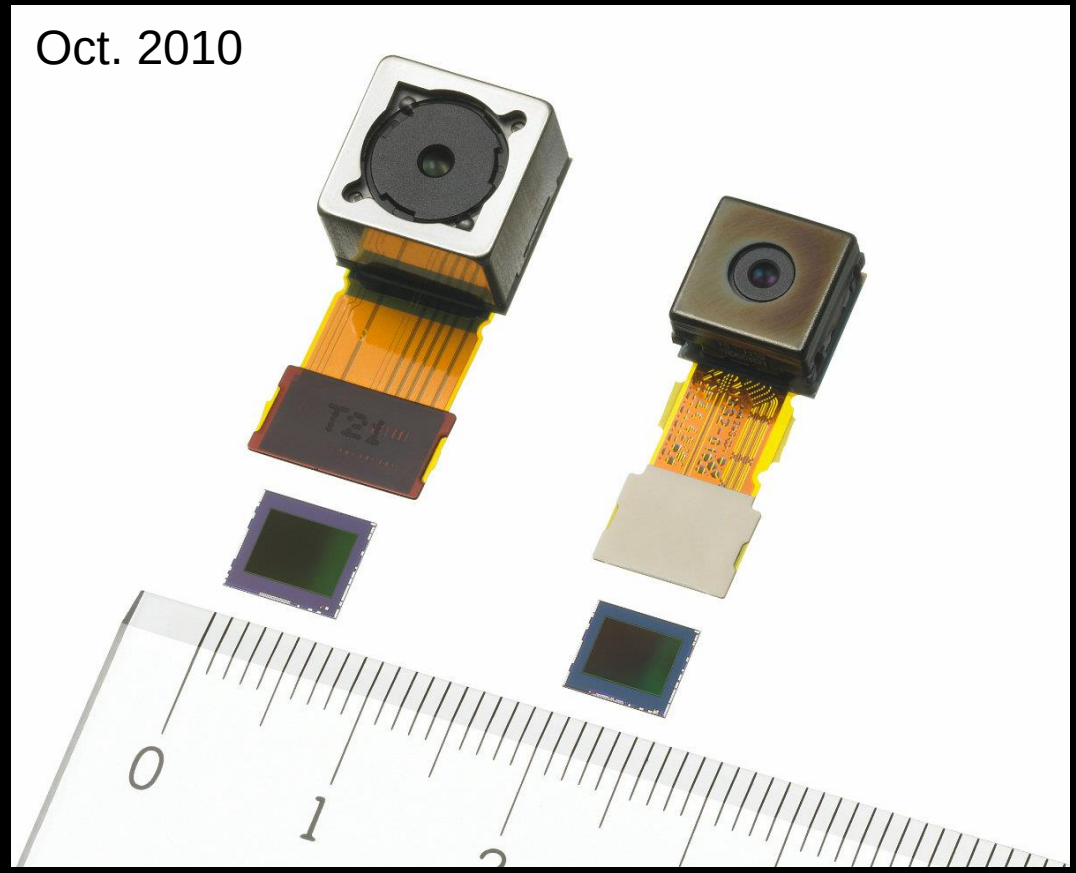
~ 1985 – 1990

A Side Note: Perspective



~ 1985 – 1990

Oct. 2010

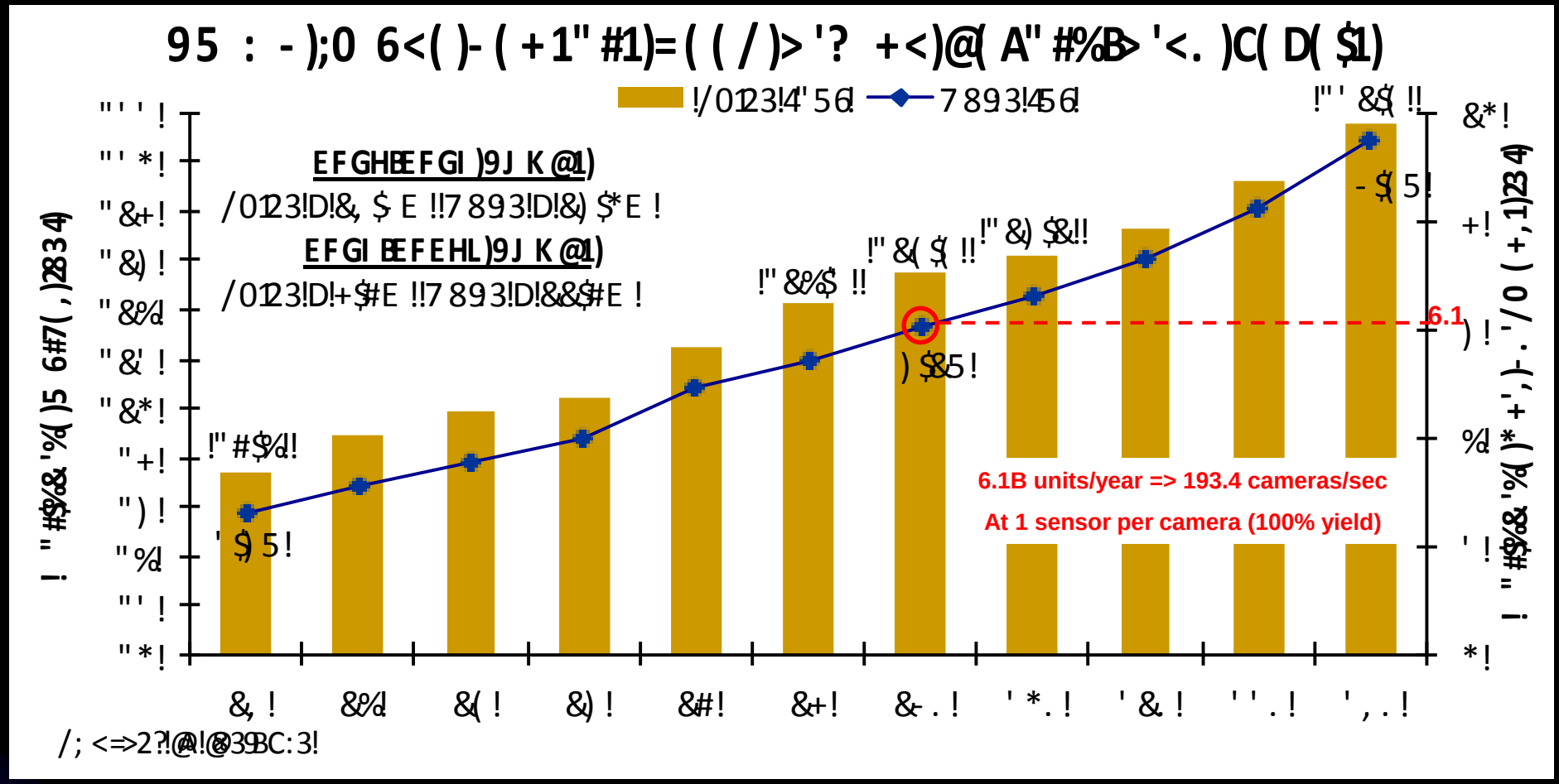


Sony IMX081PQ, 16.2 MPixel
W = 6.52mm, pixel 1.12μm
15 fps, back-illuminated

Sony IMX105PQ, 8.13 MPixel
W = 5.76mm, pixel 1.4μm,
15fps, back-illuminated

https://www.sony.net/SonyInfo/News/Press/201010/10-137E/index.html

A Side Note: Perspective

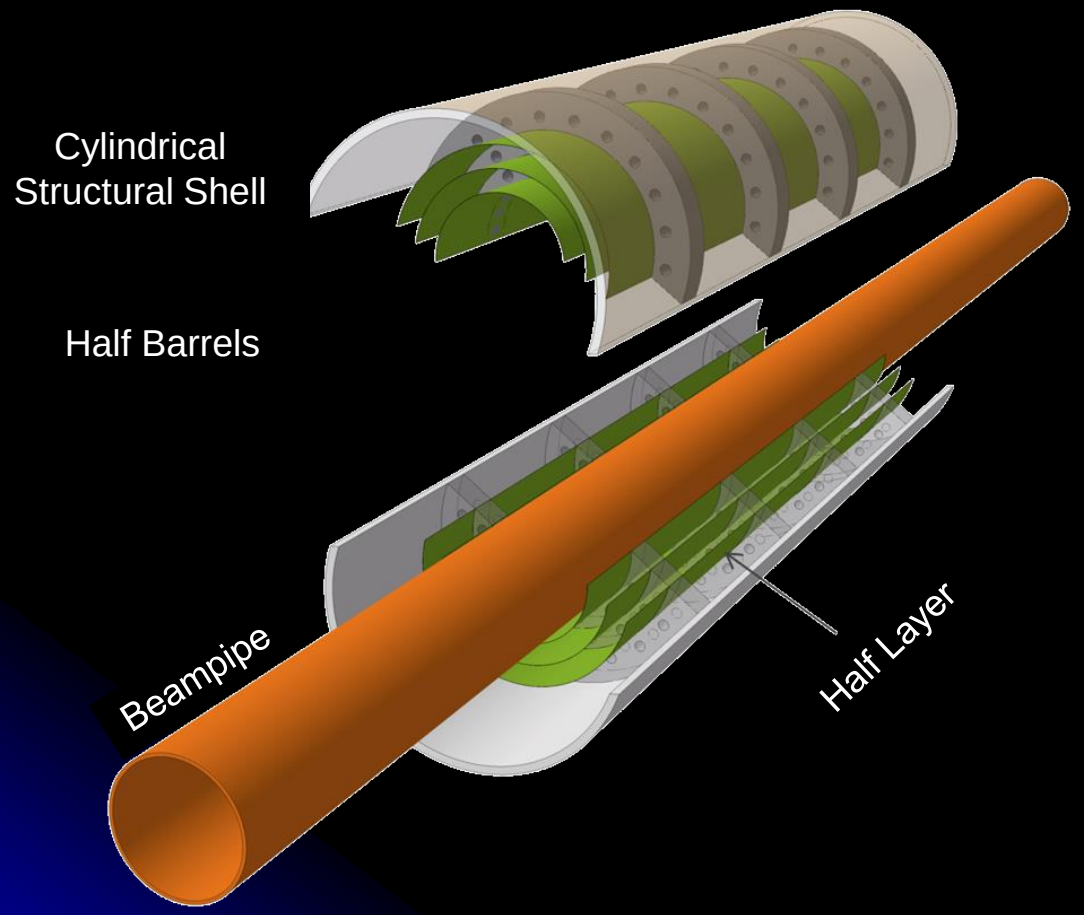


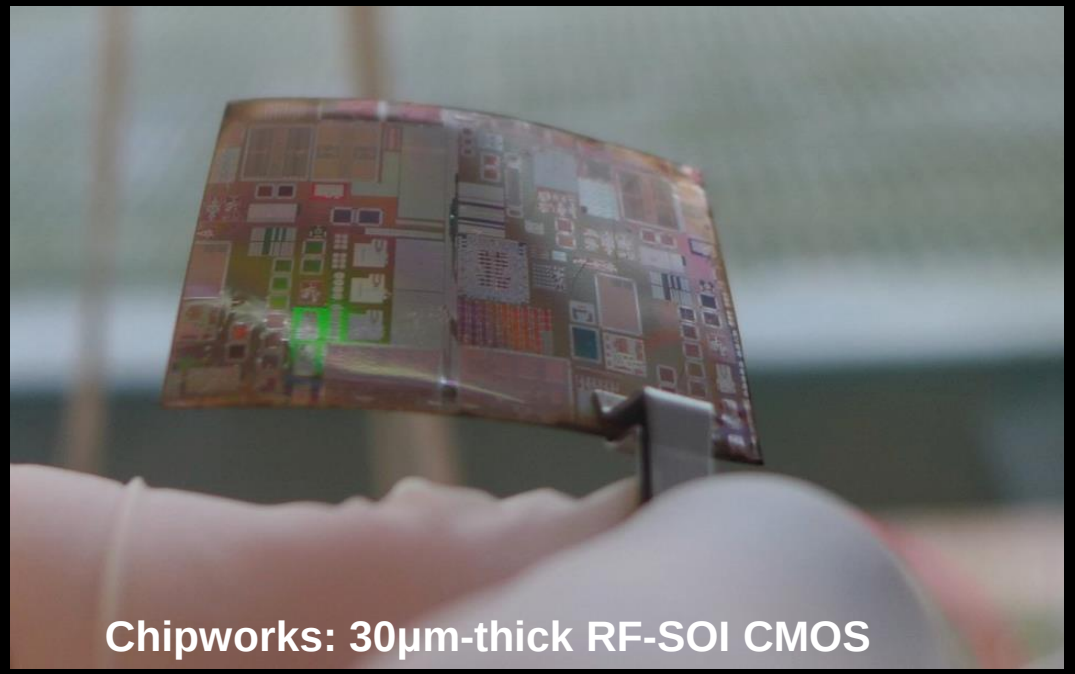
- Almost 200 CMOS imagers per second produced!

CAGR = Compound Annual Growth Rate

Depleted CMOS Sensors

- The requirements of the field are very demanding; our market share is infinitesimally small. But, …

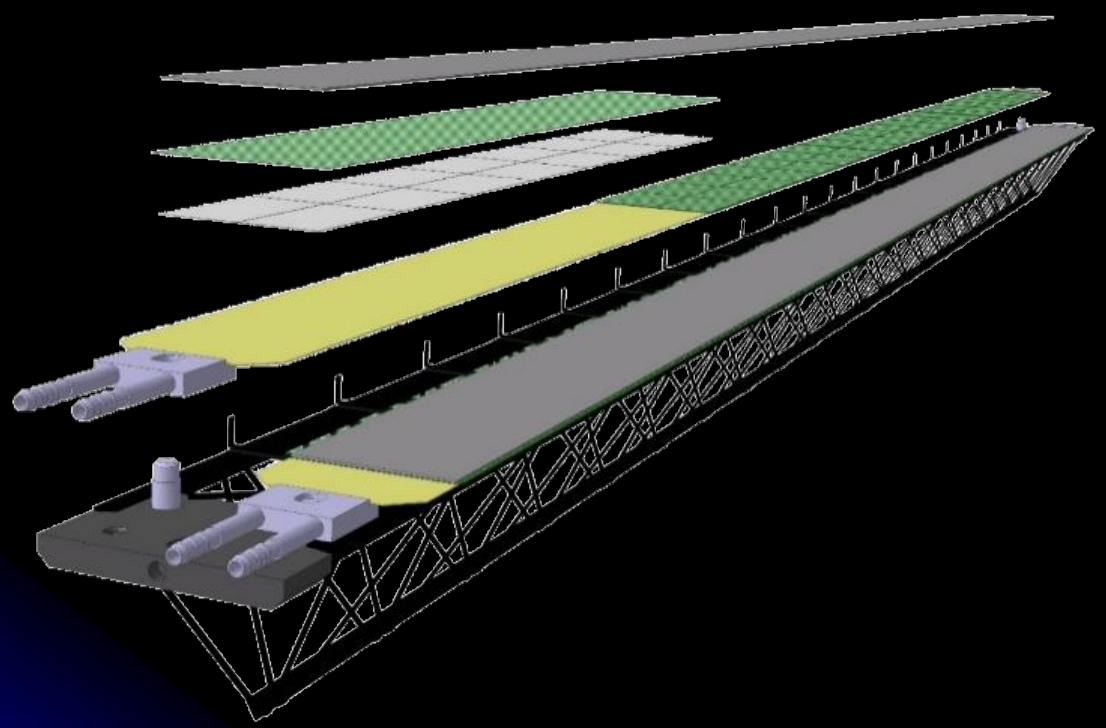




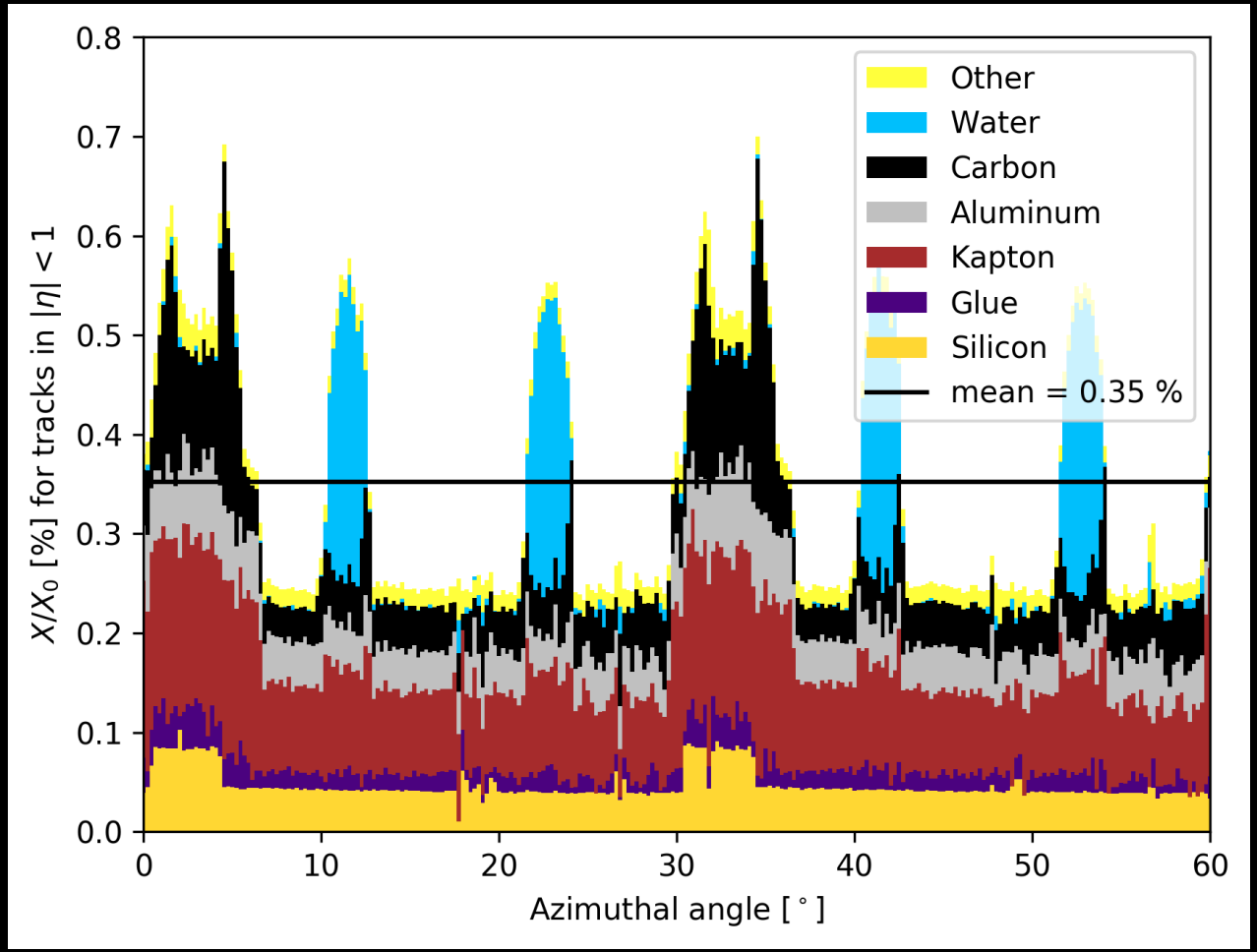
ALICE Note: https://cds.cern.ch/record/2644611

Depleted CMOS Sensors

- Minimize the material budget



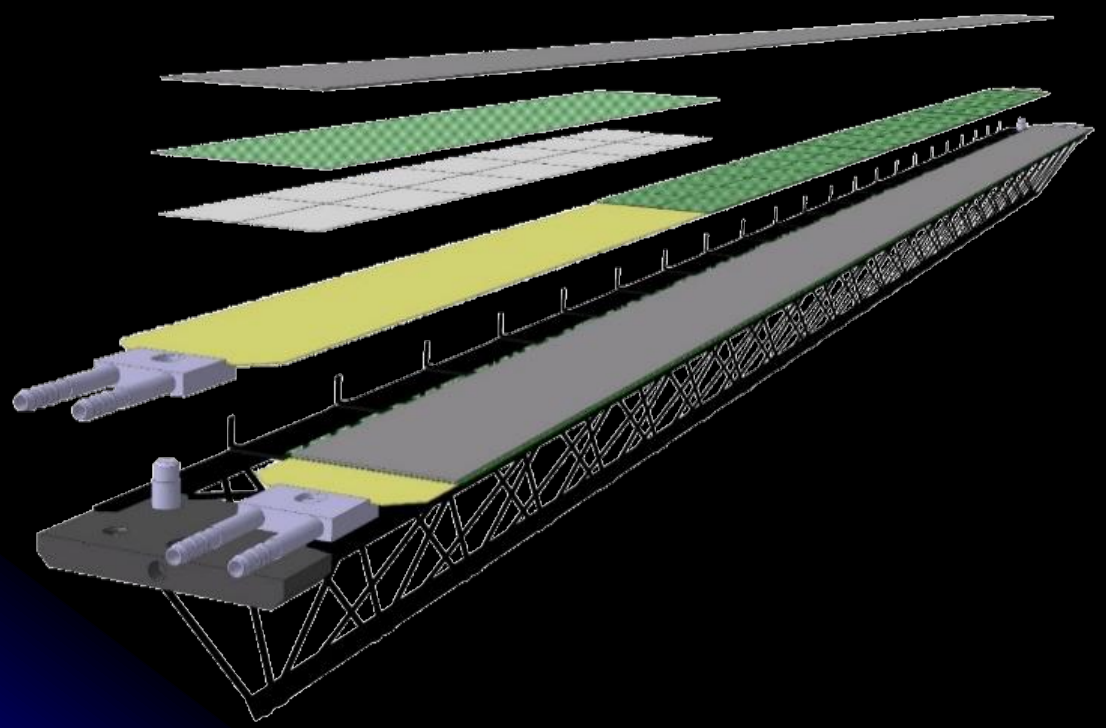
Overall Material Budget



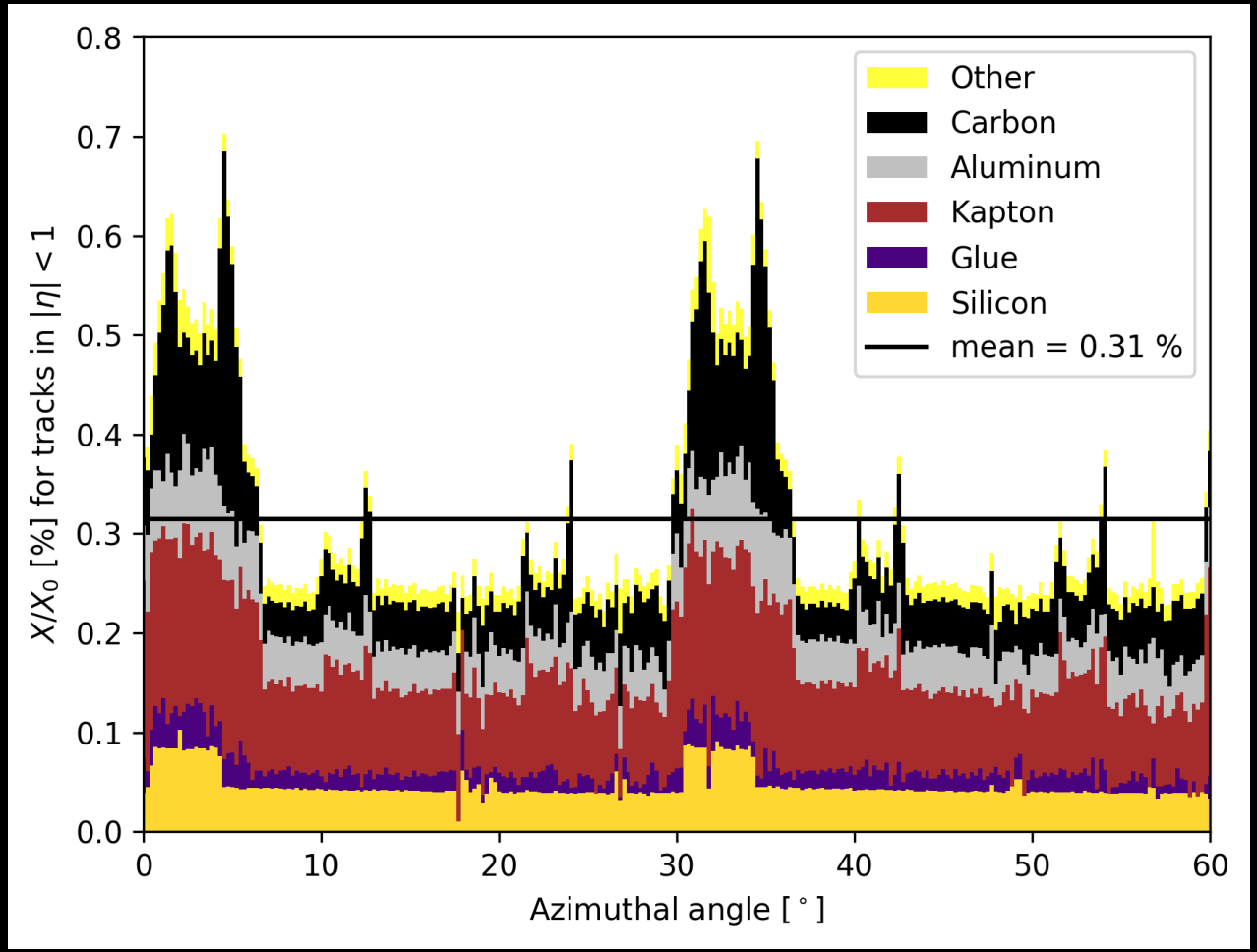
Luciano Musa, Bergen, August 2019: https://indico.cern.ch/event/836343/

Depleted CMOS Sensors

- Minimize the material budget



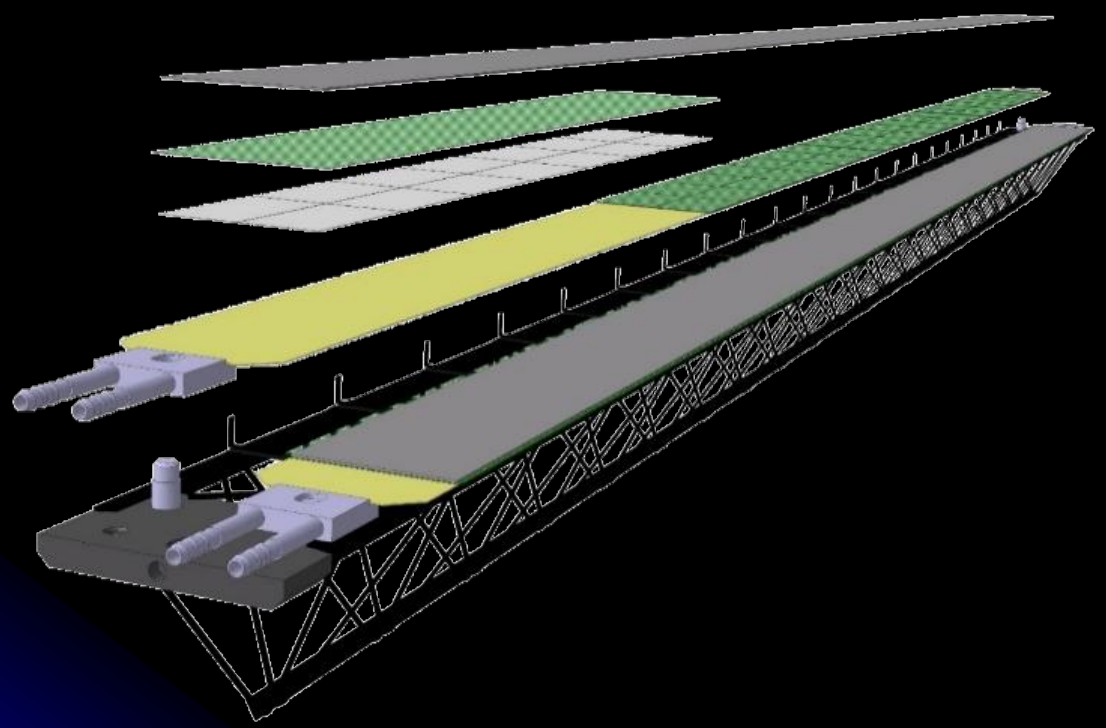
Reduce Power Budget, Remove Cooling



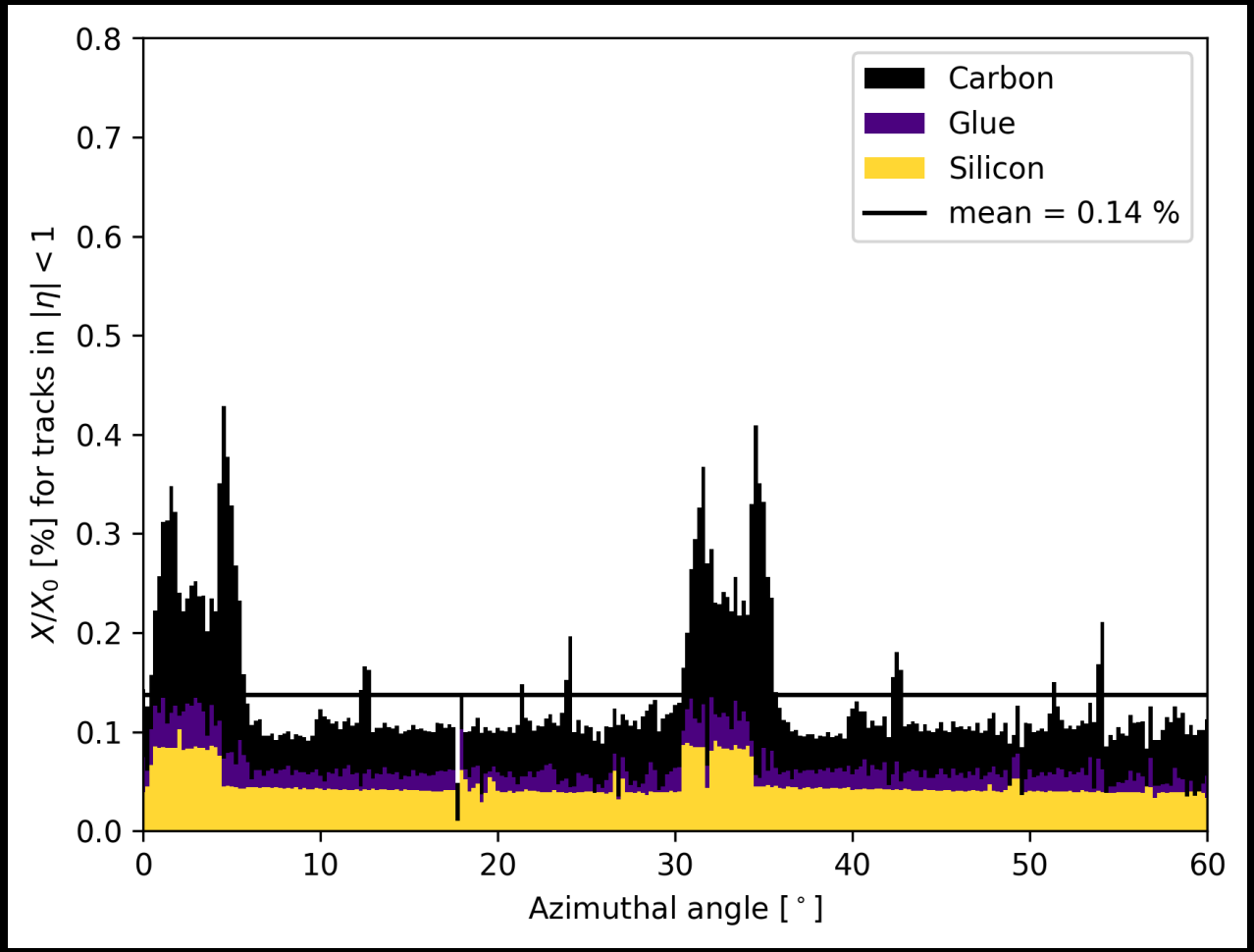
Luciano Musa, Bergen, August 2019: https://indico.cern.ch/event/836343/

Depleted CMOS Sensors

- Minimize the material budget



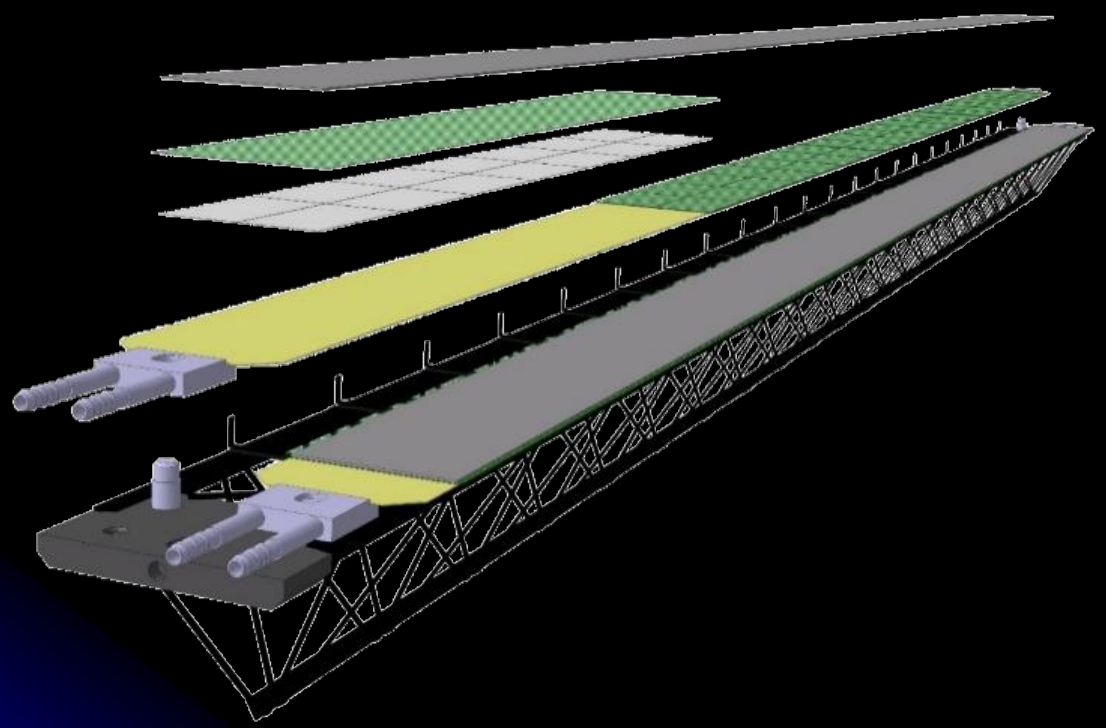
Stich Sensors, Reduce Power and Bus Lines



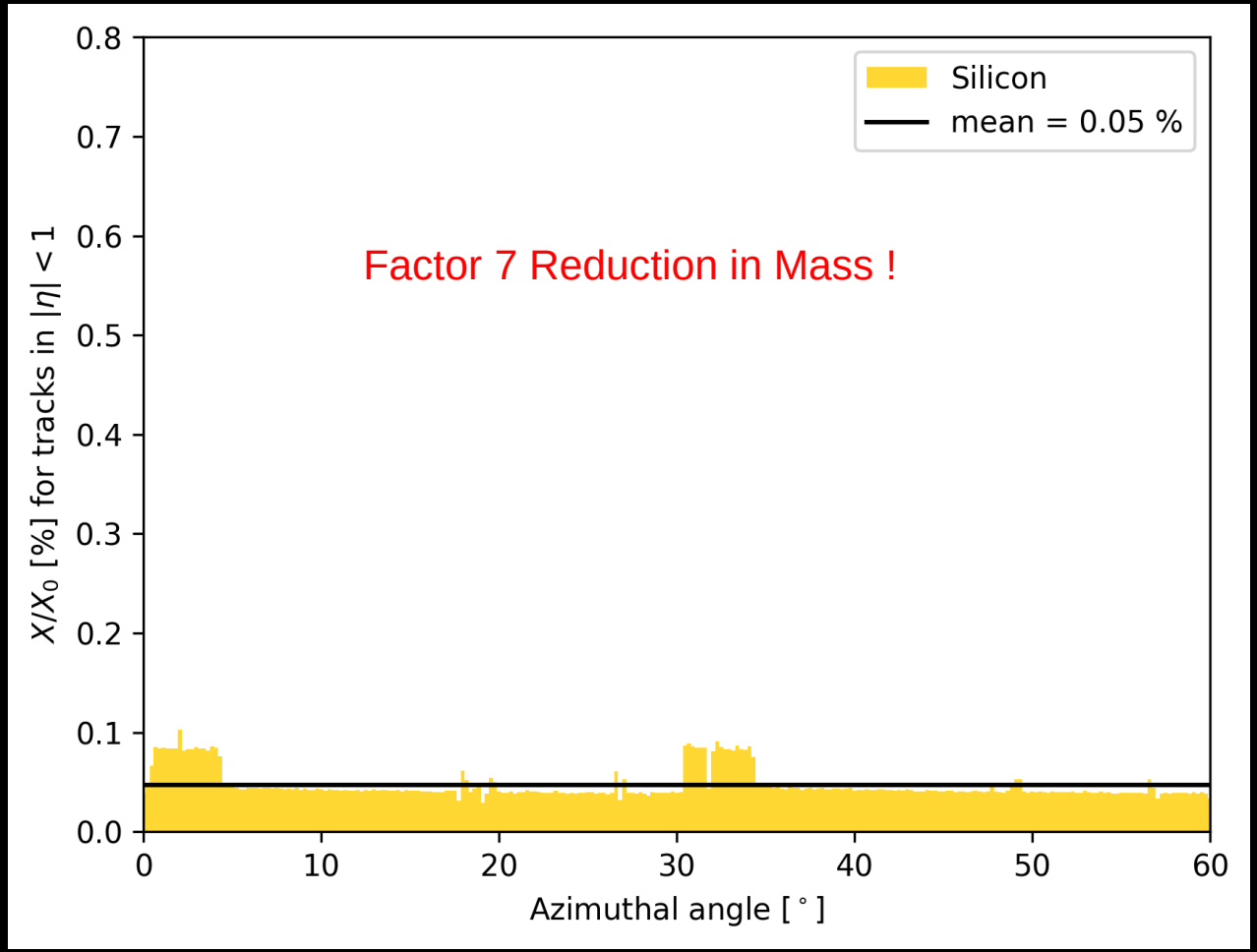
Luciano Musa, Bergen, August 2019: https://indico.cern.ch/event/836343/

Depleted CMOS Sensors

- Minimize the material budget



Mechanical Support Outside Active Volume



Luciano Musa, Bergen, August 2019: https://indico.cern.ch/event/836343/

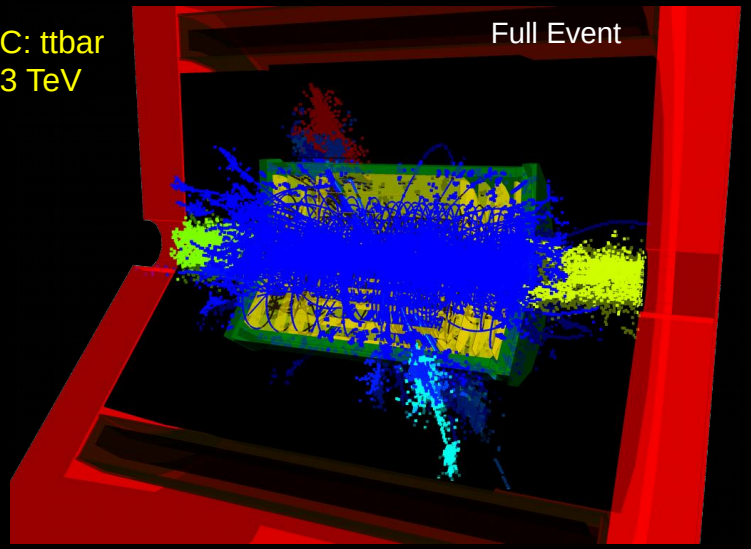
Calorimetry

- Measure the energy of EM and hadronic showers with excellent precision in high pile-up environment
- Approach: high segmentation for 3D reconstruction

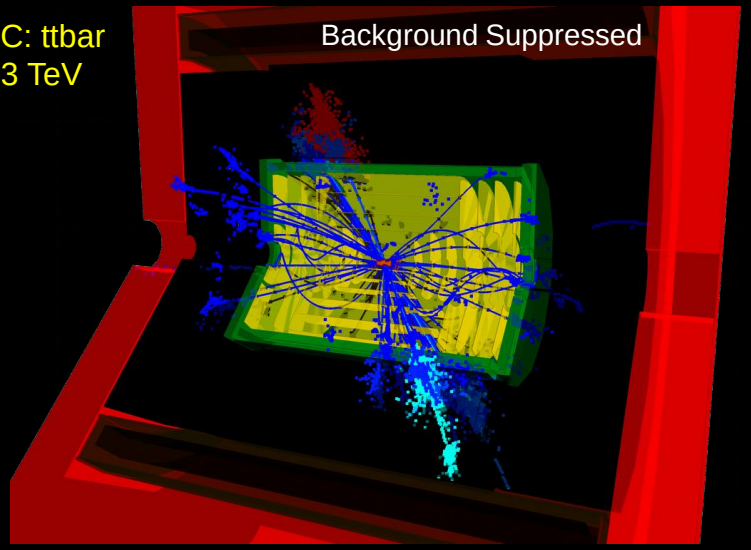
- Challenges
  - Good resolution for jets and electrons
  - Embedded Cooling
  - Scale

- CLIC Background rejection:
  - Reconstruction window
    - 10 ns before, 30 ns after event
  - Building physics objects
  - Timing requirements, particle type and p_T

CLIC: ttbar at 3 TeV

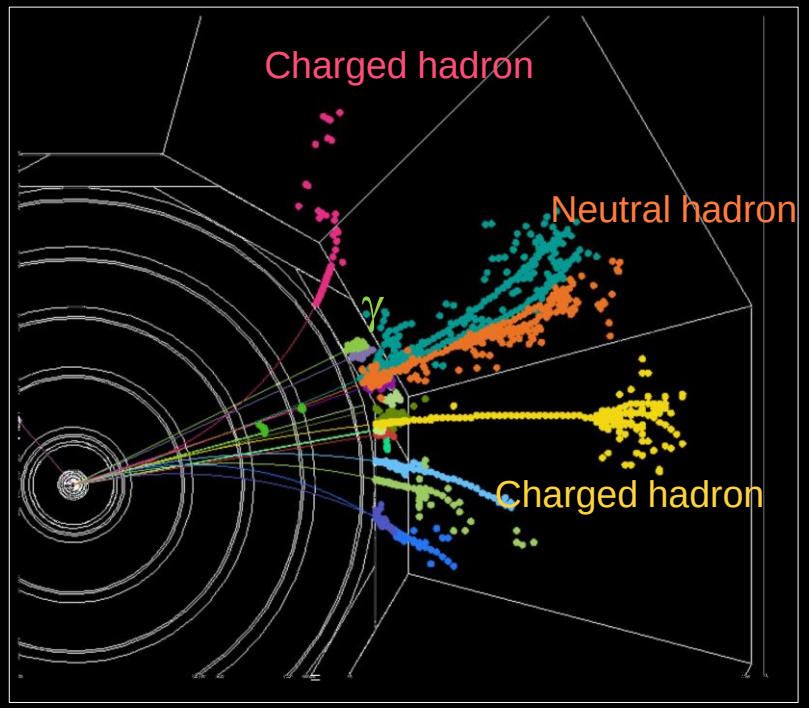


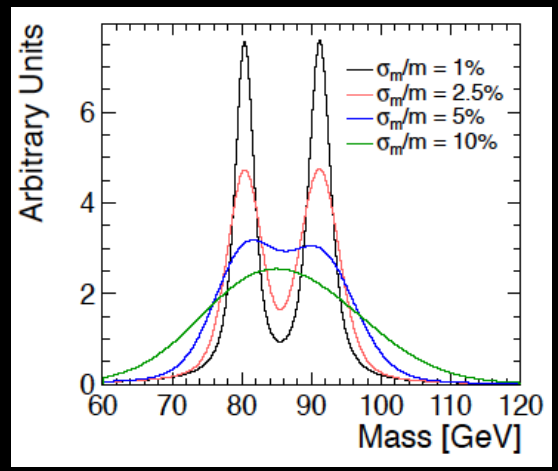
CLIC: ttbar at 3 TeV



Particle Flow Calorimetry

- Obtain the best jet energy resolution to distinguish hadronic decays of W and Z-boson: particle flow
- Measure energy of each particle separately
  - Charged particle: by tracker
  - γ: by EM Calorimeter
  - Neutral hadron: by EM and Hadron Calorimeter
- Calorimeter measures energy of neutrals
- Key to particle flow calorimetry is very high granularity → large channel count with embedded readout electronics

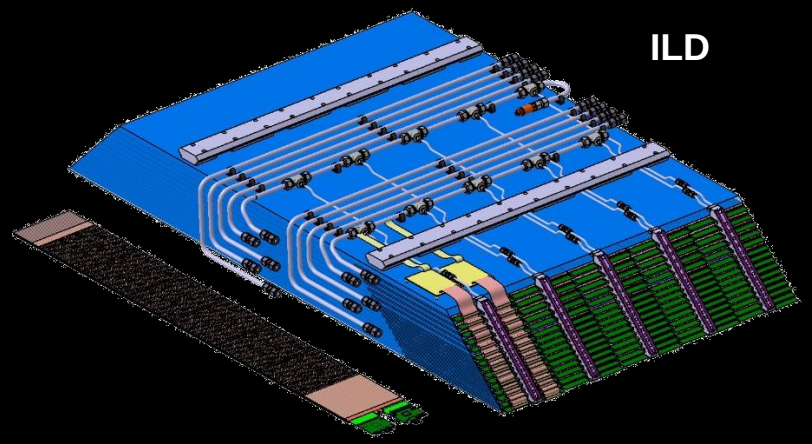




W/Z separation

Scale

ILD HGC Configuration	EM Section	Hadronic Section	
Active Layer/Absorber	Si/W	Scint Tile/Steel	Glass RPC/Steel
Number of Layers	30	48	48
Cell Size (cmxcm)	0.5 x 0.5	3 x 3	1 x 1
Depth (X_o /λ_{int})	24	5	5
Readout	Analog	Analog	Semi-Digital
# of Channels (x10^6)	100	8	70
Total area (m^2)	2500	7000	7000



Scale

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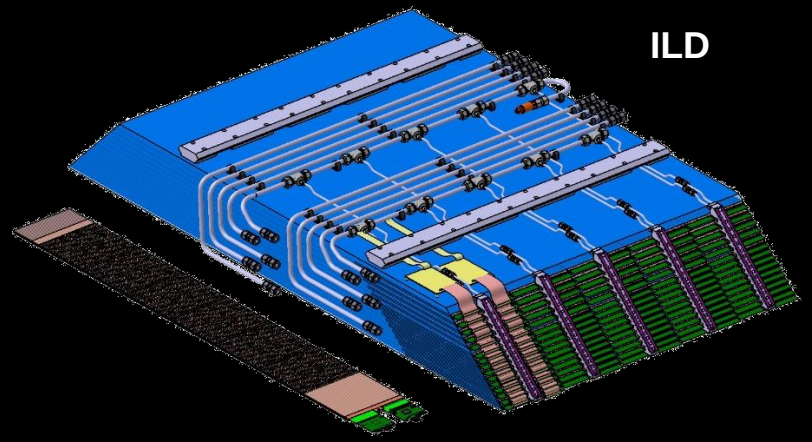

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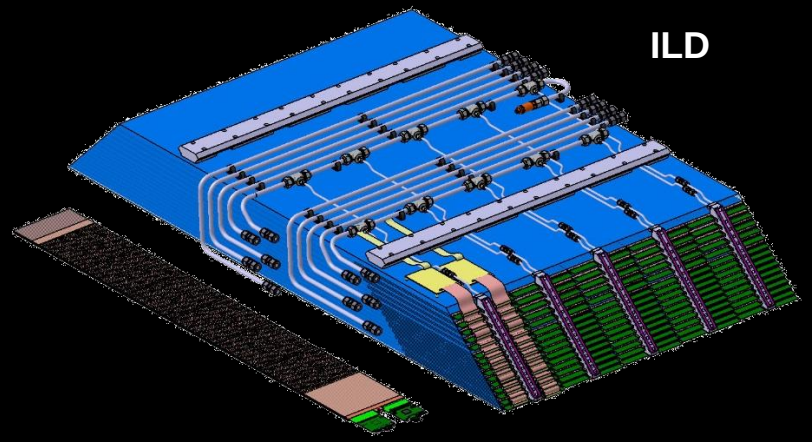
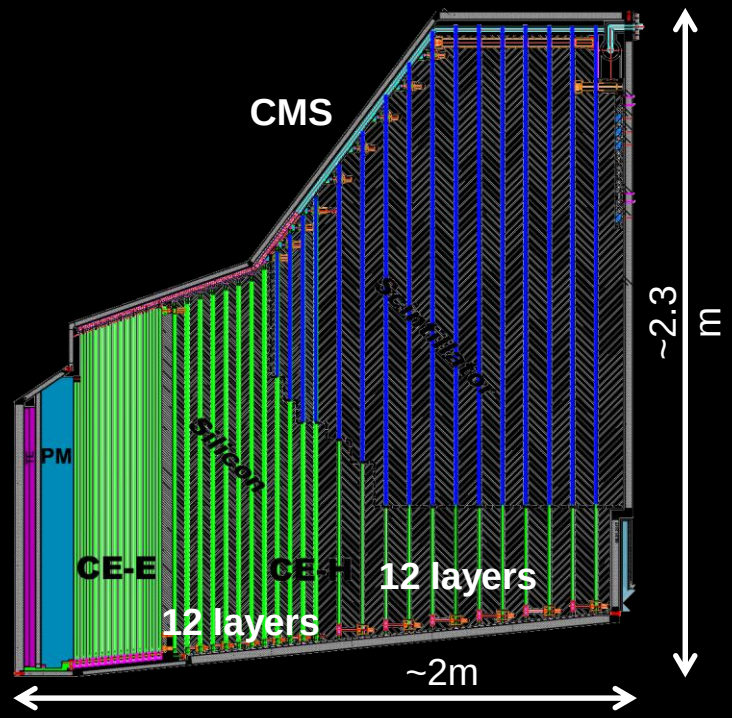
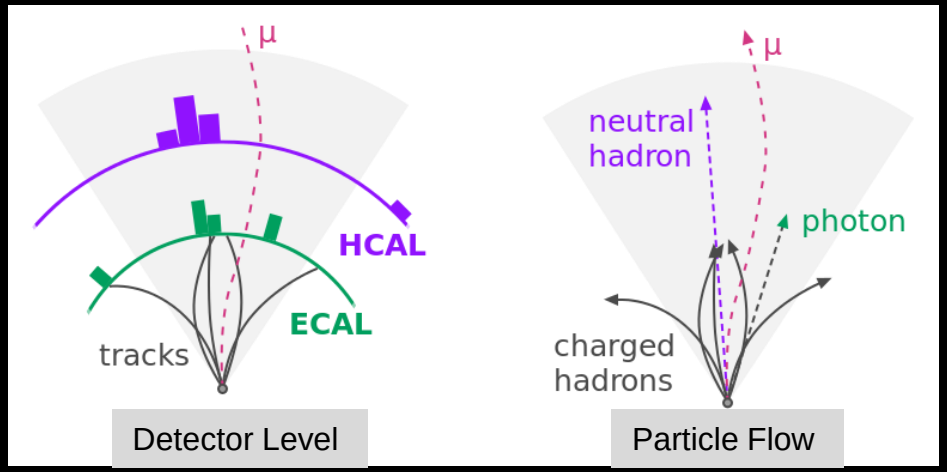


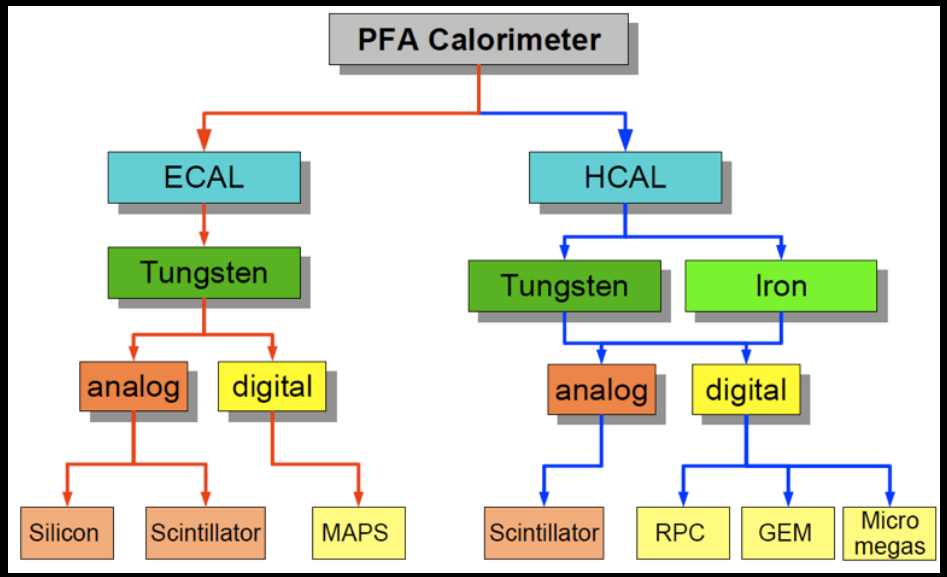


- CMS High-Grain Calorimeter (HGCAL):
  - Full system maintained at -30°C
  - ~600m2 of silicon sensors
  - ~500m2 of scintillators
  - 6M Si channels, 0.5 or 1.1 cm2 cell size
  - 400k scint-tile channels
  - Data readout from all layers

Calorimetry

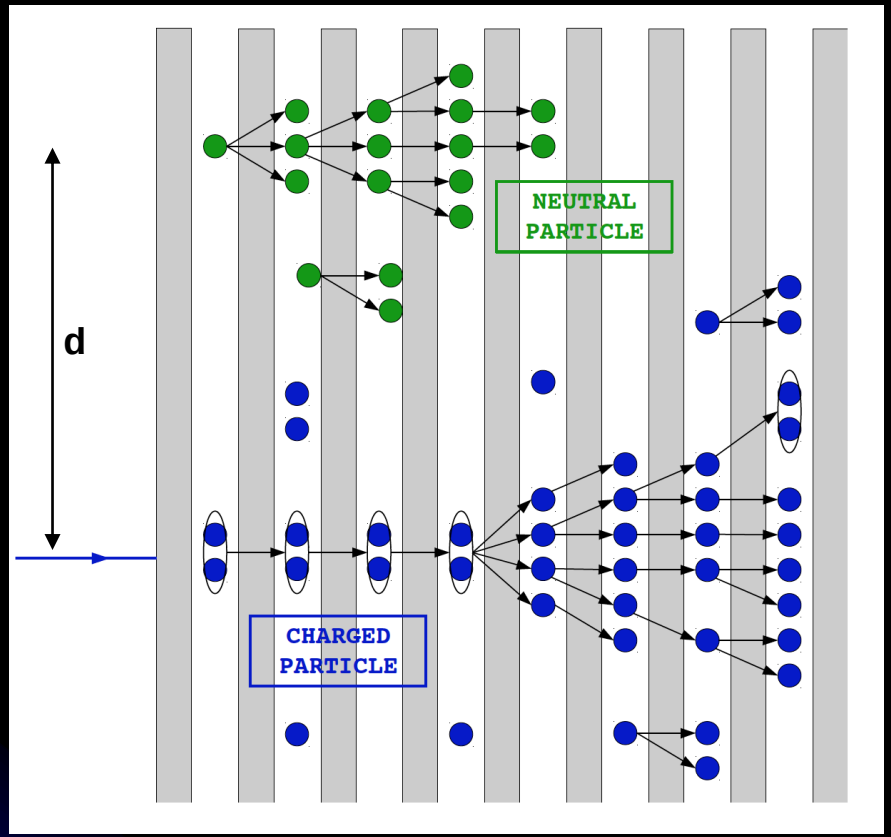
- Challenges:
  - Intricate interplay of magnetic field, radius and cost:
    - Want good separation of particles:
      - Large detector radius and depth
      - Large magnetic field to separate
      - High granularity
    - Compact showers to minimize overlap
      - Small Molière radius
  - Absorber, active medium and readout choice
  - Integrated readout electronics and cooling
  - Timing information
  - Linearity of response
  - Calibration
  - …

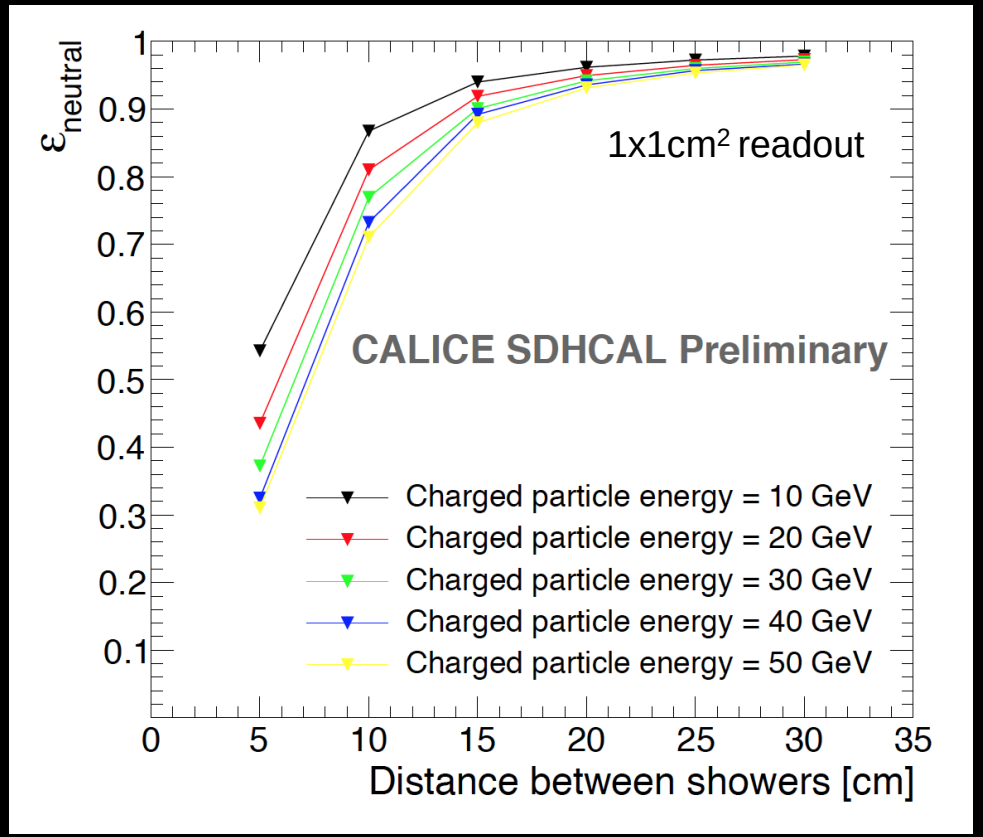




Identification of Neutrals

- Monte Carlo simulation semi-digital hadron calorimeter, 1x1cm^2 RPC; 10 GeV neutral



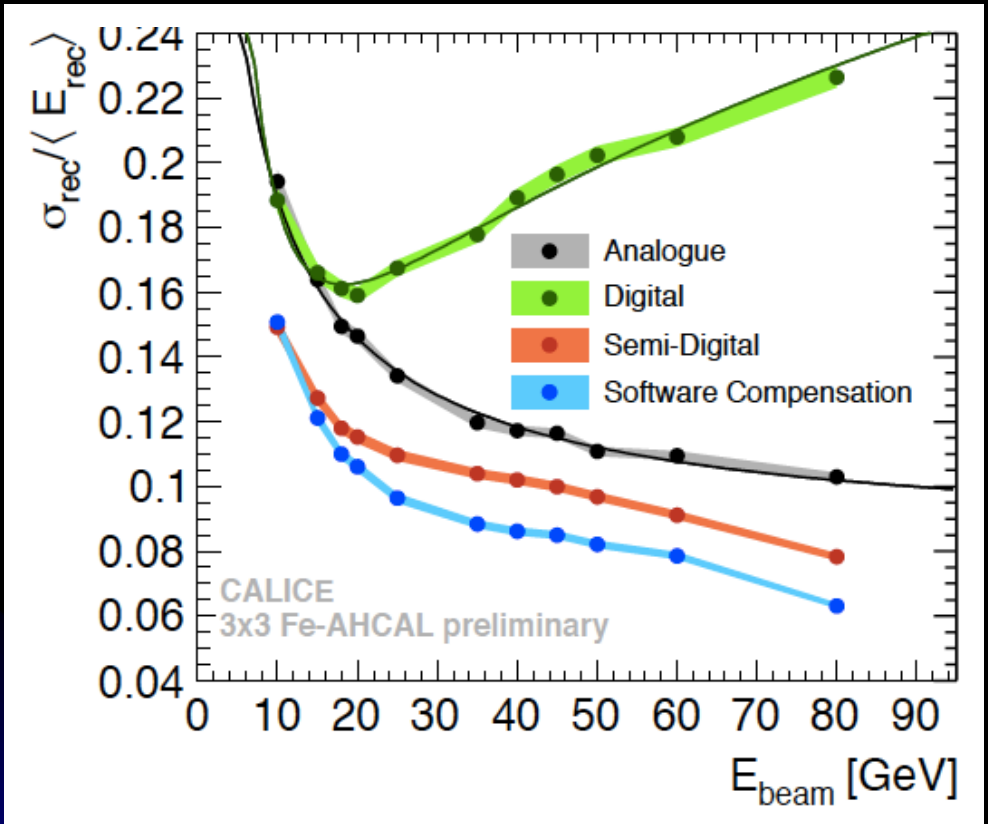


$\varepsilon_{neutral}$ = N_{hits} (reco) / N_{hits} (initial)

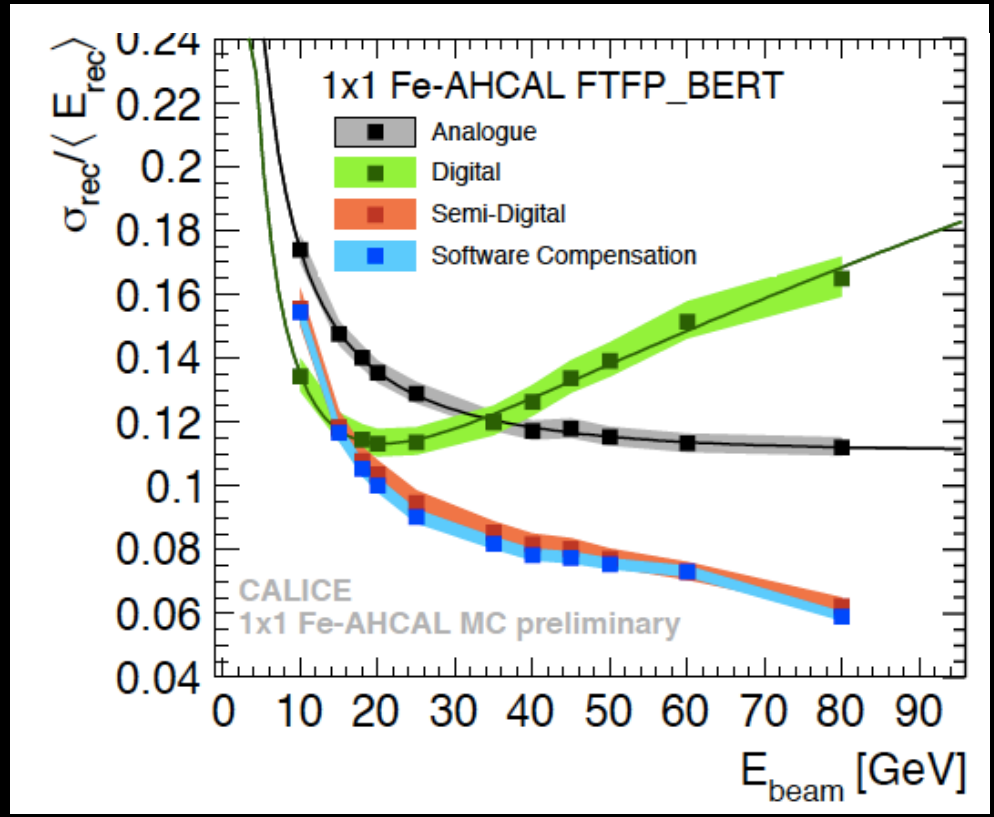
Segmentation

- Fe as absorber; Active medium: scintillator (analogue), RCP (digital, semi-digital)

Segmentation: 3x3cm^2

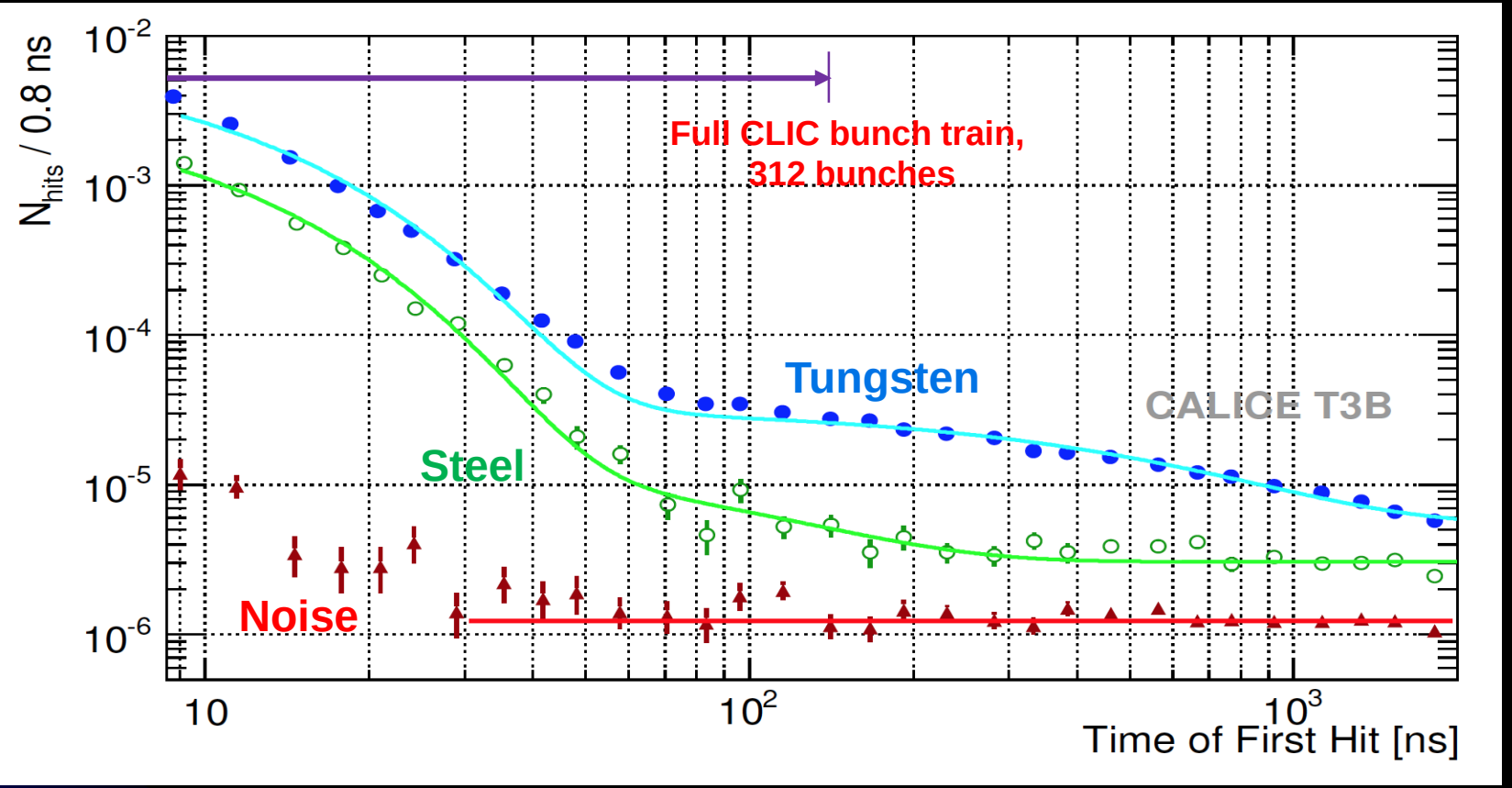


Segmentation: 1x1cm^2



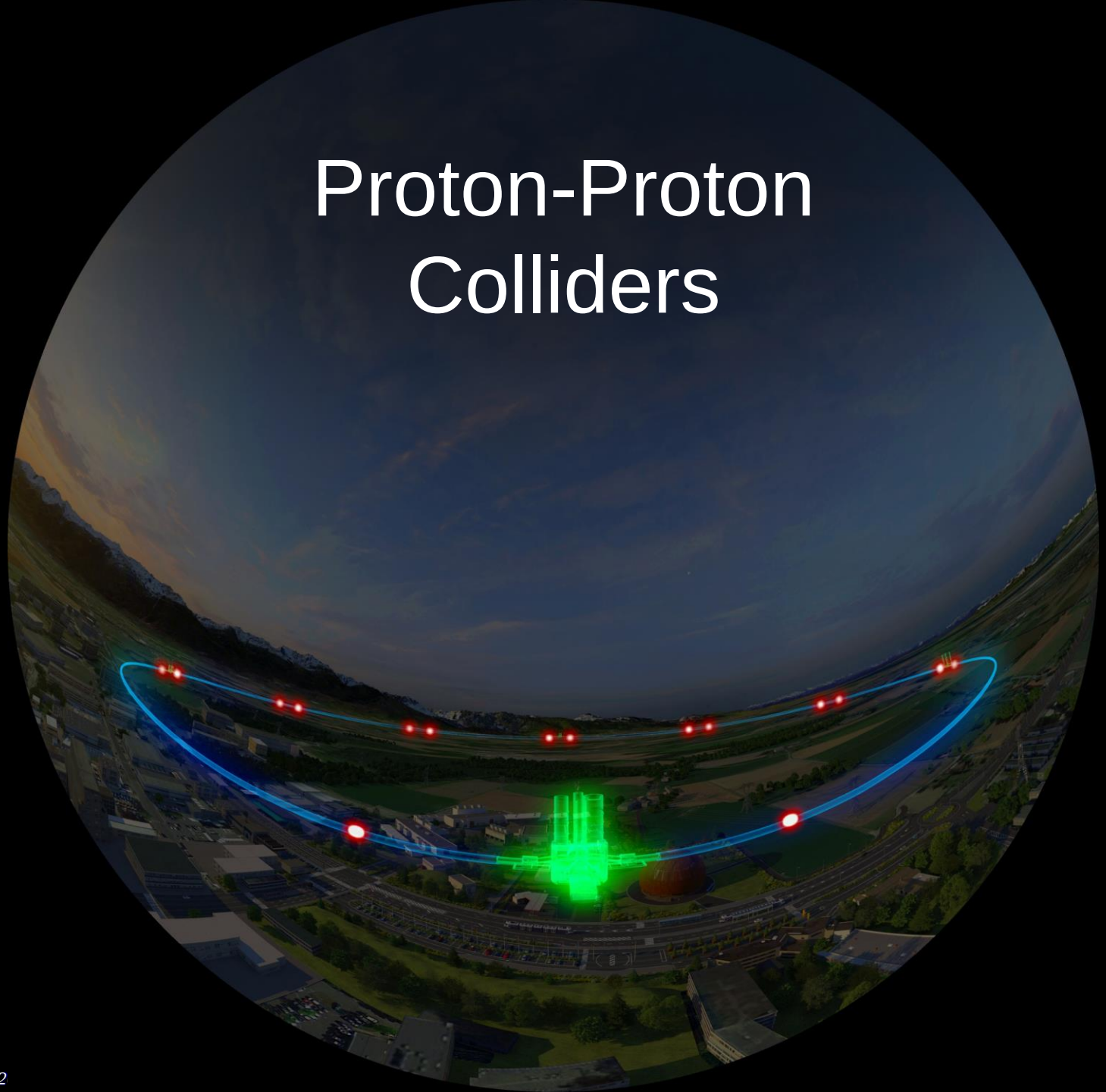
Time Structure of Hadronic Showers

- Denser absorbers show slower shower time evolution
- CLIC bunch crossing 0.5ns; Key reconstruction challenge is the pile-up of hadronic background from several bunch crossings (E_{cal} / train = 19 TeV)
- Hit time stamping of 300ps considered



JINST 9 (2014) P07022

Proton-Proton Colliders

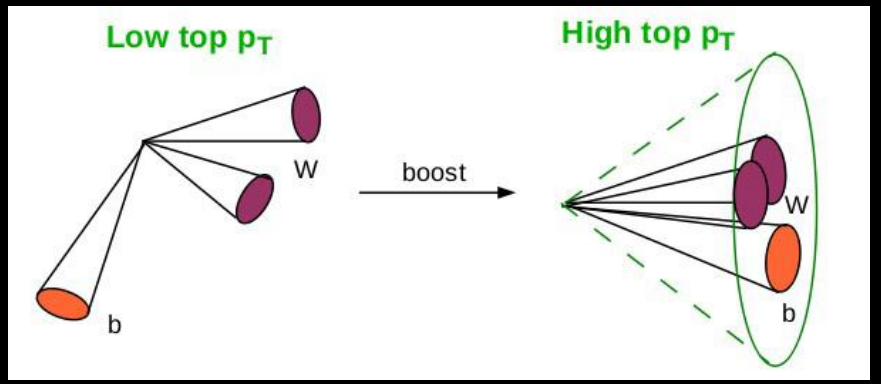


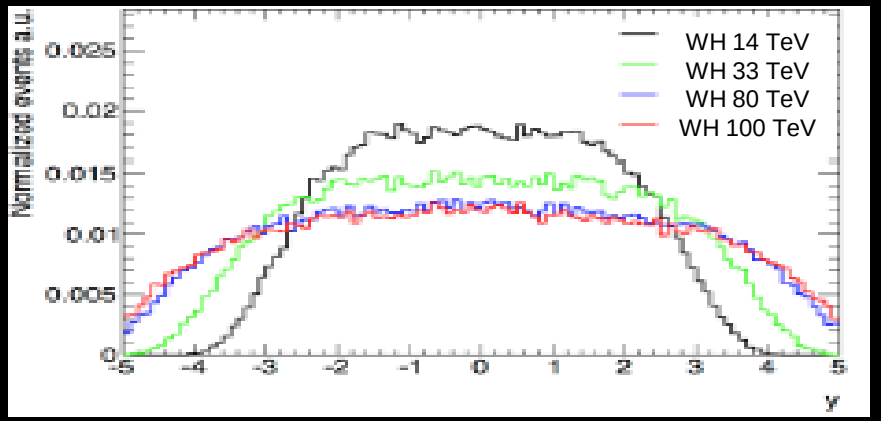
Life At 100 TeV

- 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

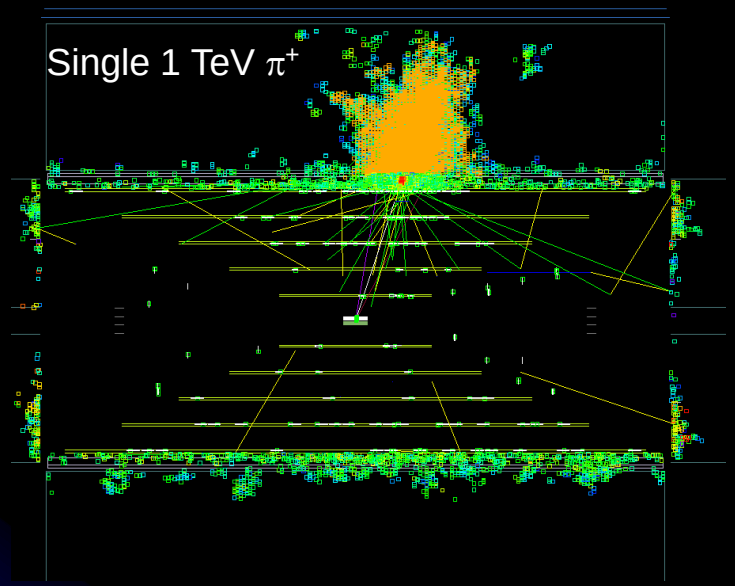
Lumi weight: 20 ab^{-1} / 20 fb^{-1} / 3 ab^{-1} (100 / 8 / 14 TeV)



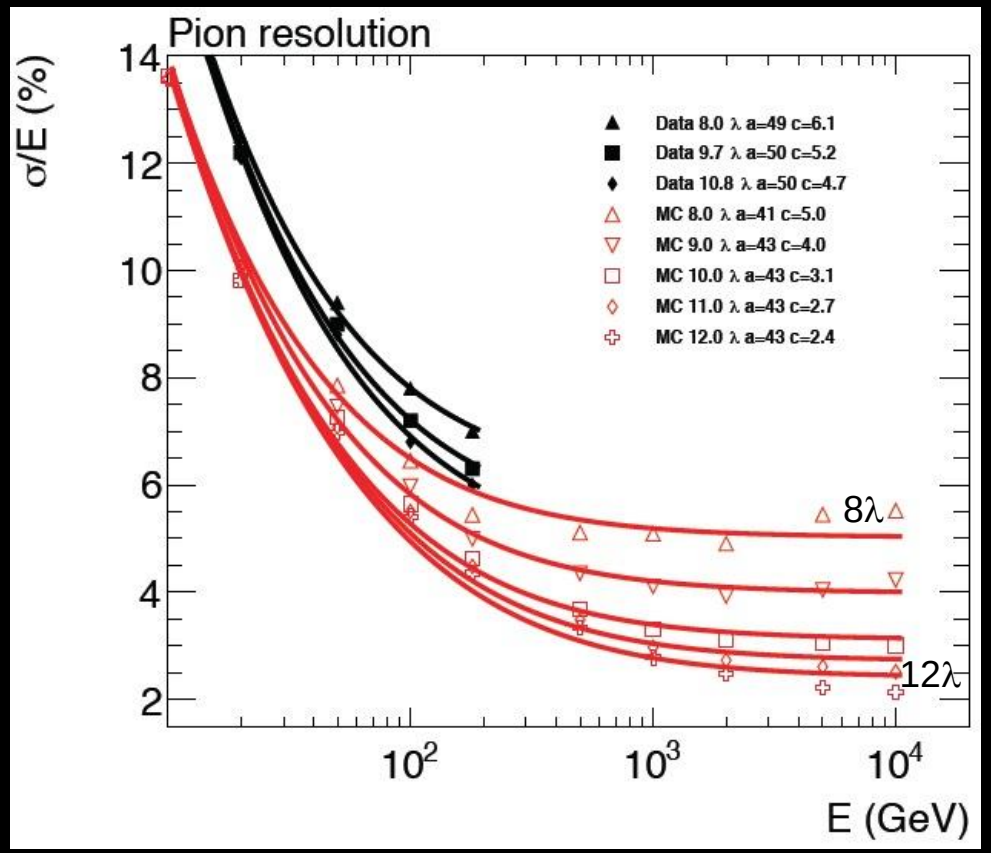


Calorimetry

- Challenges
  - Calorimeter depth: need 12λ to contain jets with reasonable energy resolution
  - Note:
    For p_T(jet) > 30 TeV about 10% of hadrons in jet will have energy > 1 TeV

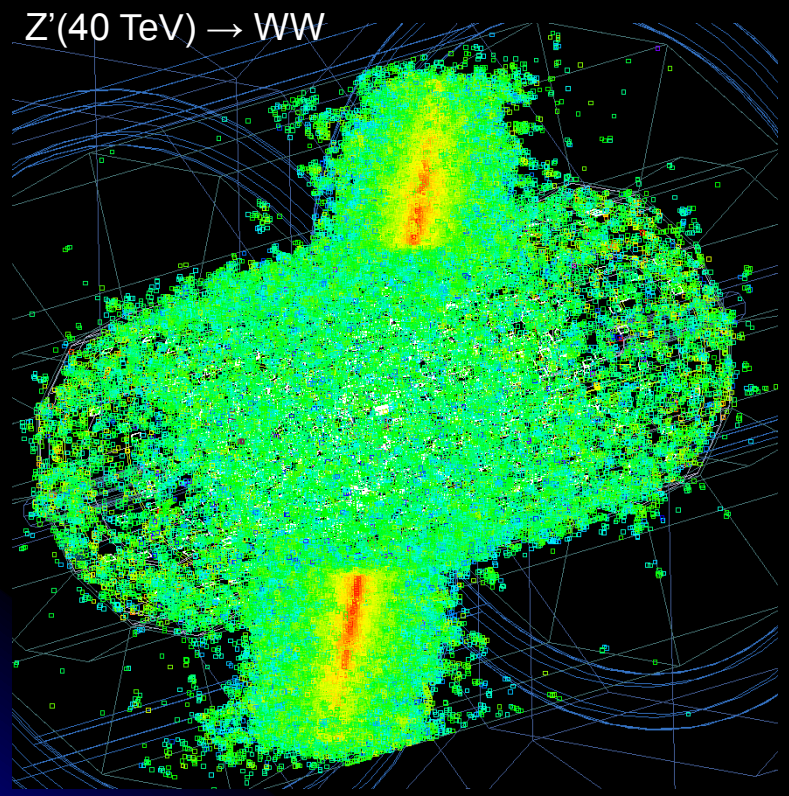


7300 calorimeter hits
440 Si Tracker hits

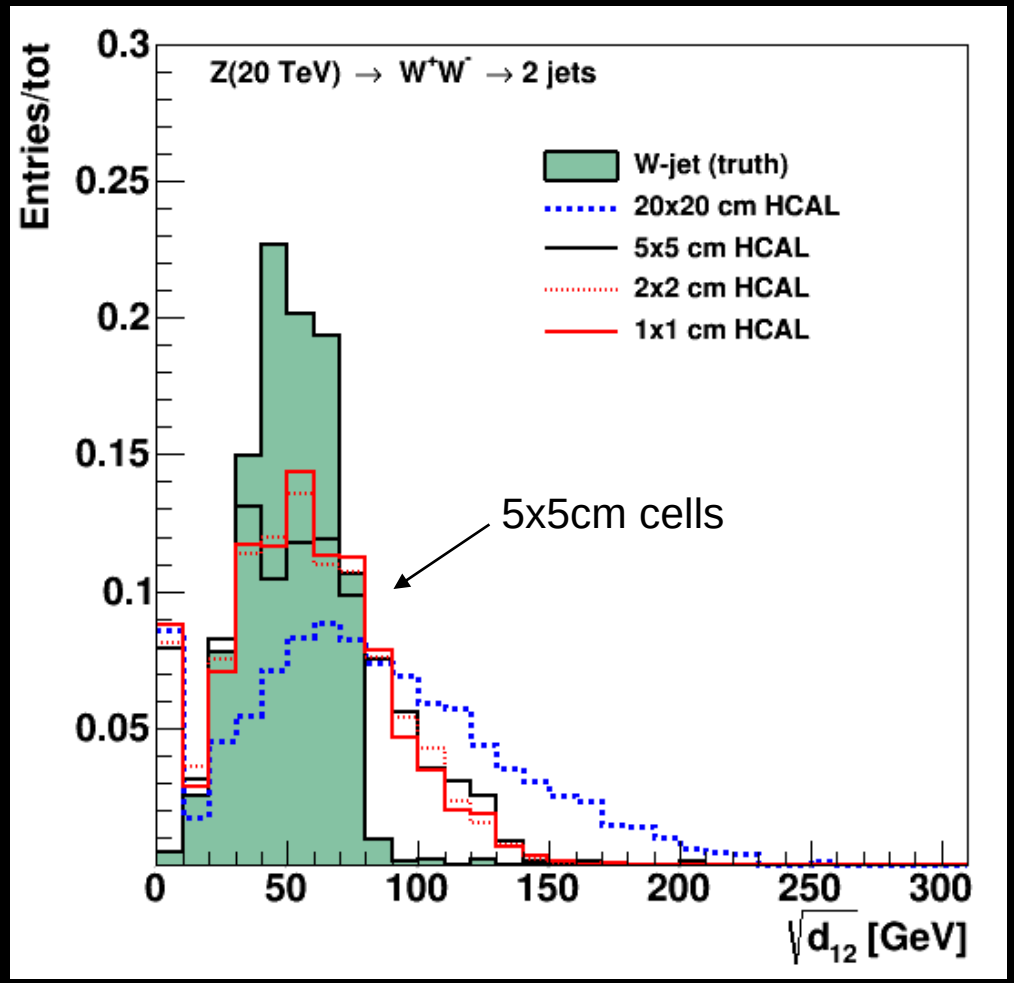


Calorimetry

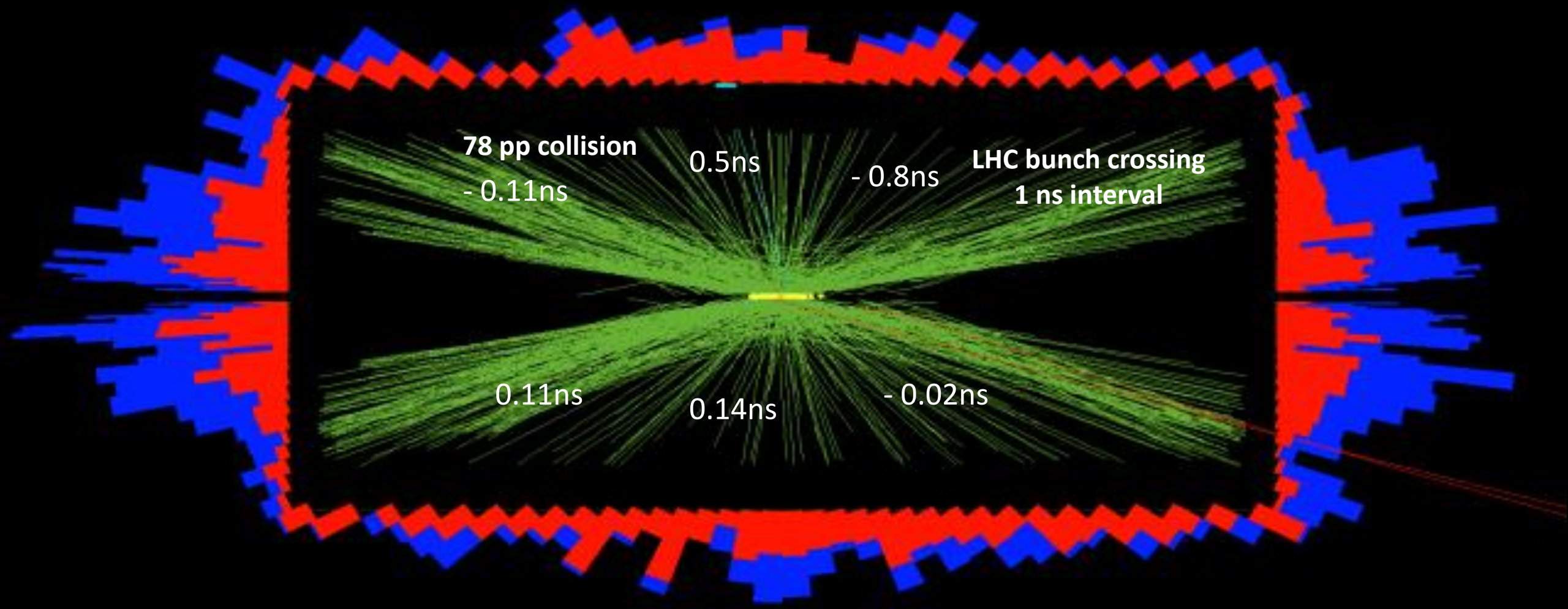
- Challenges
  - Calorimeter transverse segmentation
  - Note:
    cell size $\lambda/4$ seems optimal



Single event, hard scatter only, no overlap !



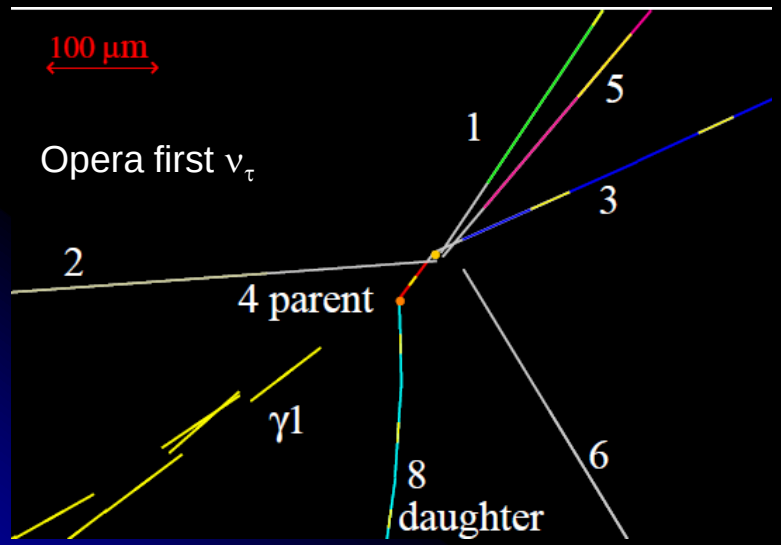
Mitigating Pile-Up

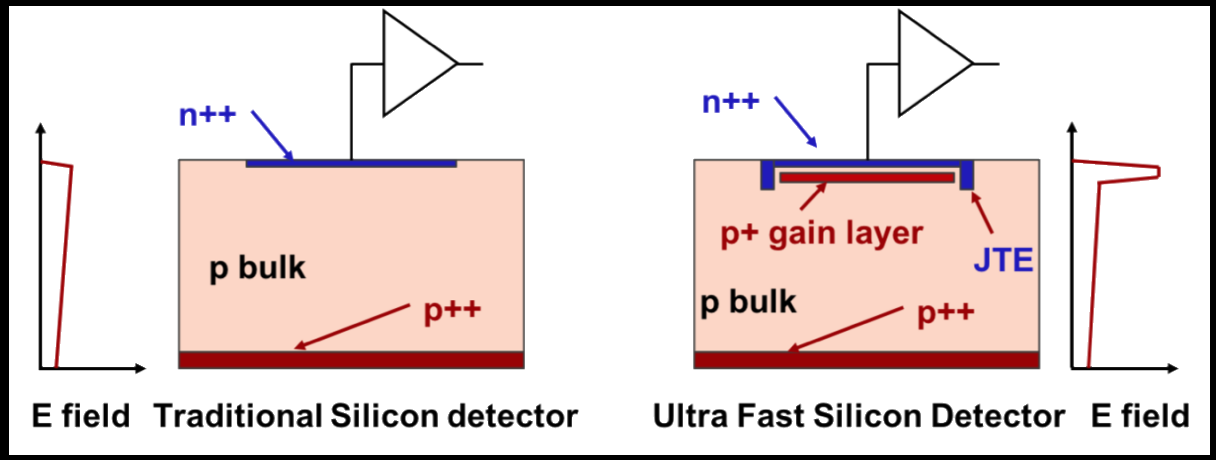


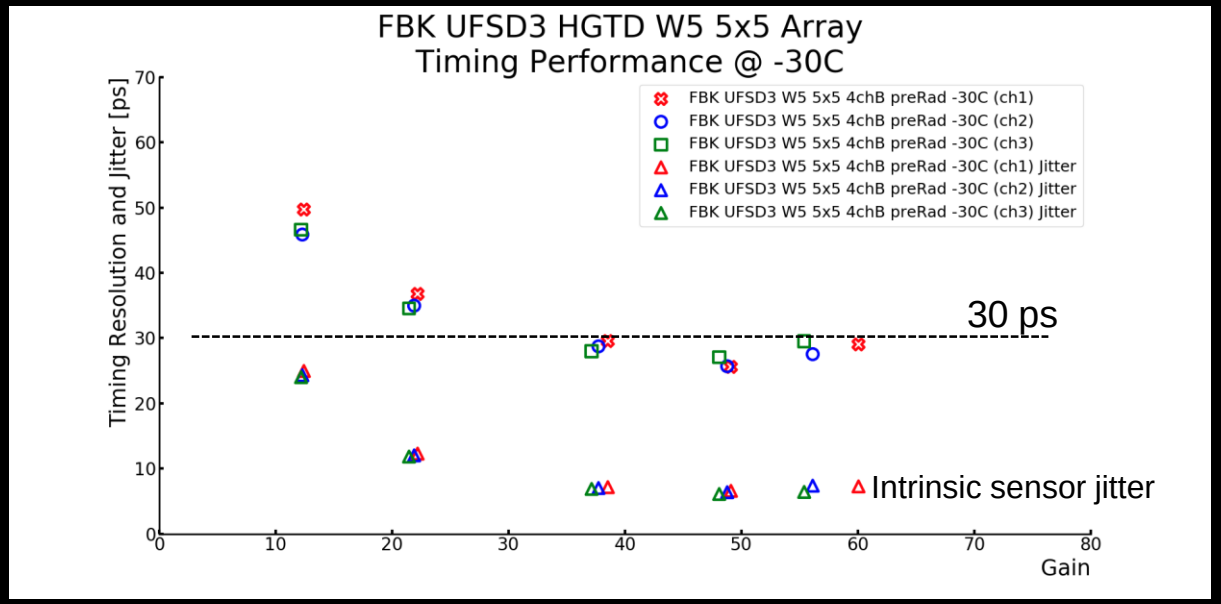
Viewing collisions in 4D

Timing Detectors

- 5-Dimensional Calorimetry
- Reconstruct true 4-vectors: (x,t), (E,p)
  - Fully map the event and aid in pile-up mitigation
- Challenge
  - Clock distribution
  - 50ps timing resolution on a system level
  - Radiation hardness and cooling
  - Scale of the system







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 ($2\times2cm^2$)
Had Cal channels	~7,000	~10,000	1.8M	80M ($5\times5cm^2$)

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

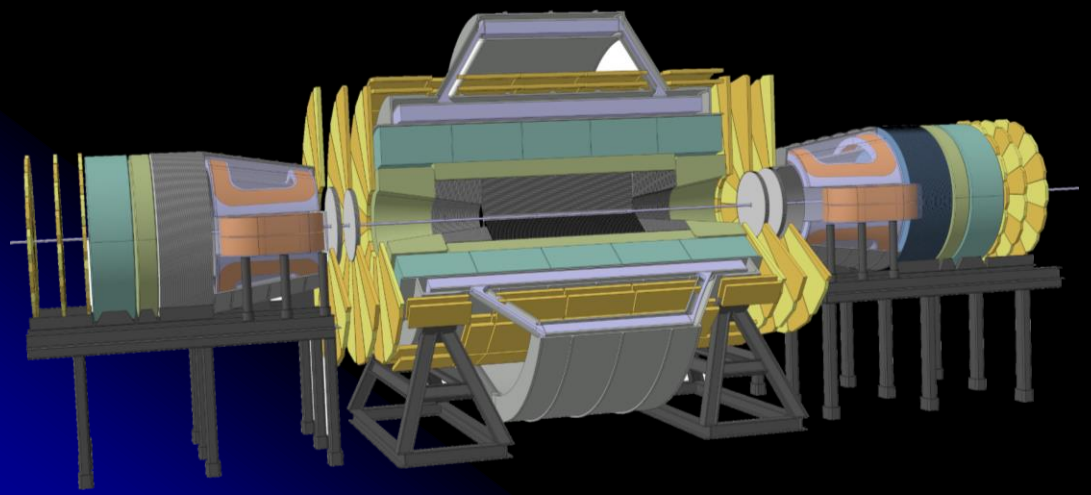
Tracking And B-Field

- Momentum Resolution:

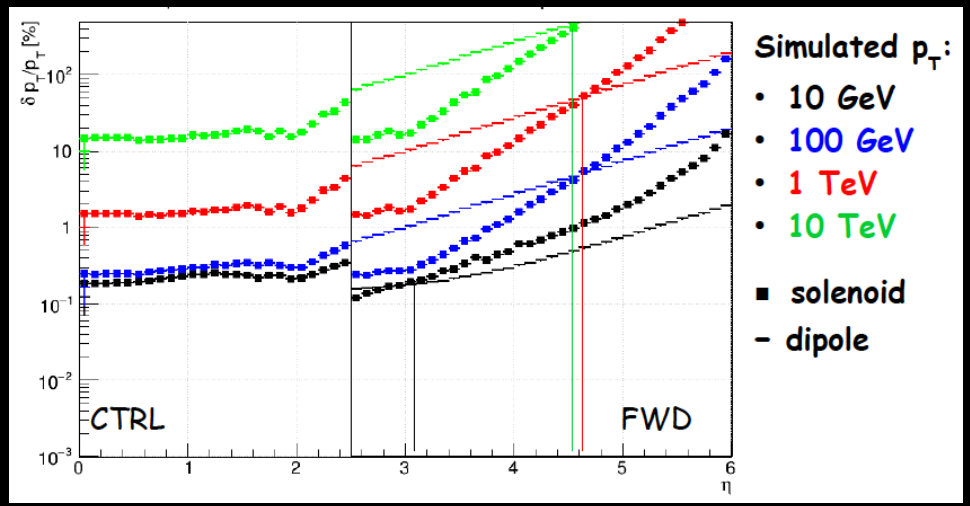
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

- 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 $\sqrt{7/4} \approx 30\%$

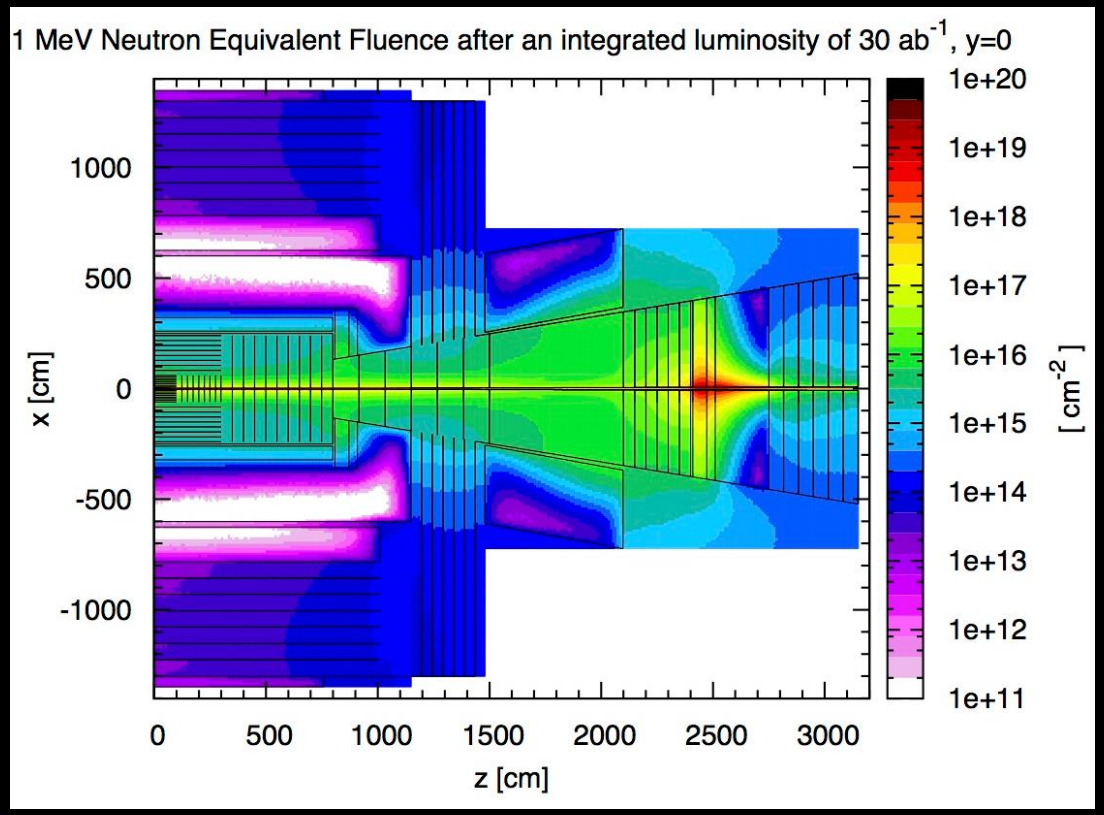
Magnet: 6T/12m bore
System: 20-30 m diameter, 30-50 m long
Stored Energy: 50-60 GJ.

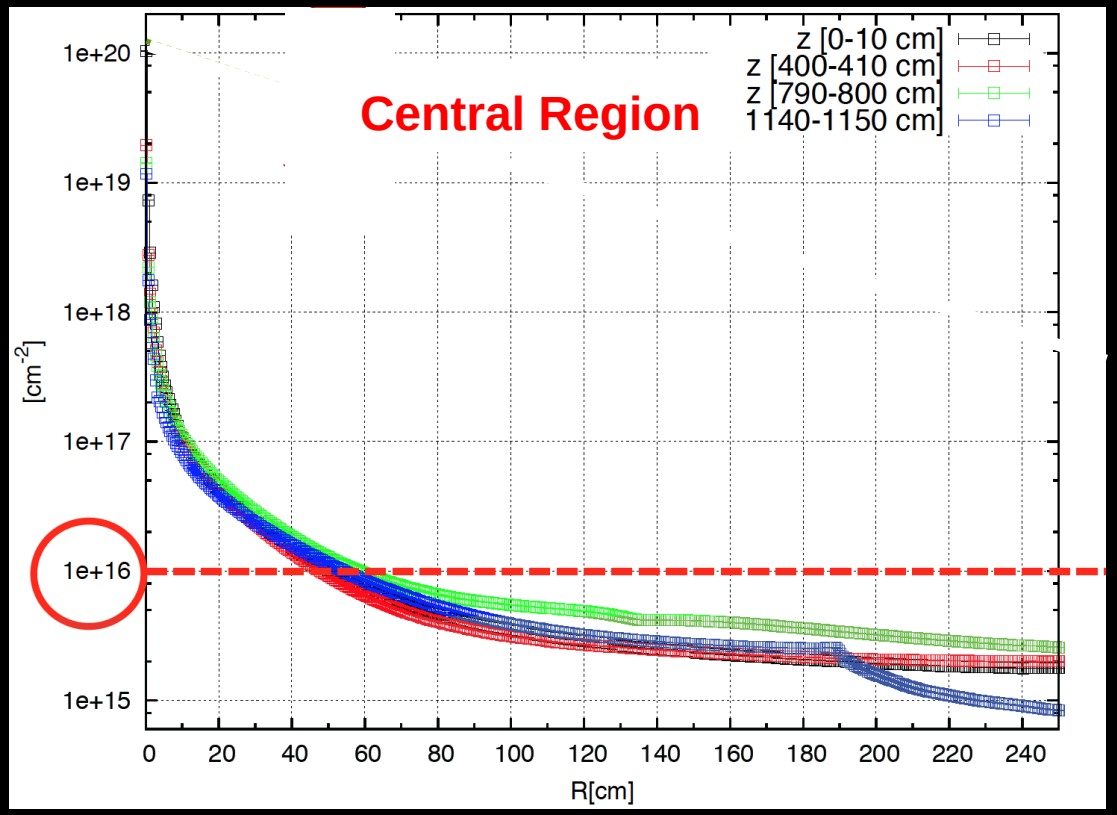


Dipole or solenoid in forward region



Radiation Damage

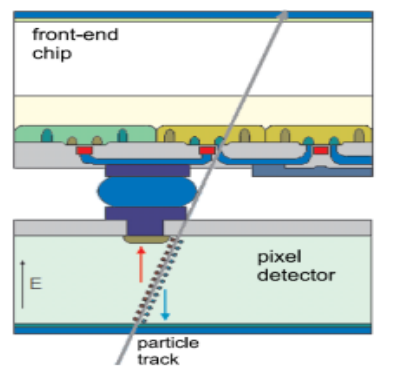




- For radii < 50 cm (well into the tracker) the fluence exceeds the value expected at HL-LHC (10^{16} cm^{-2}) by up to 2 orders of magnitude
- Forward region even worse!

ASIC Technology

Hybrid Pixel

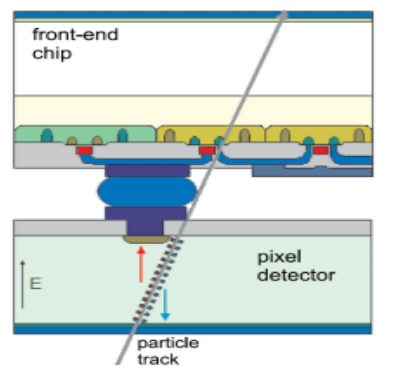


- Q collection by drift

- Hybrid pixels currently only viable technology for vertex detectors for pp colliders

ASIC Technology

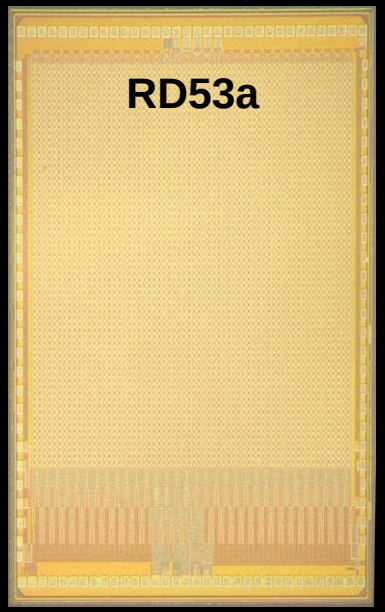
Hybrid Pixel



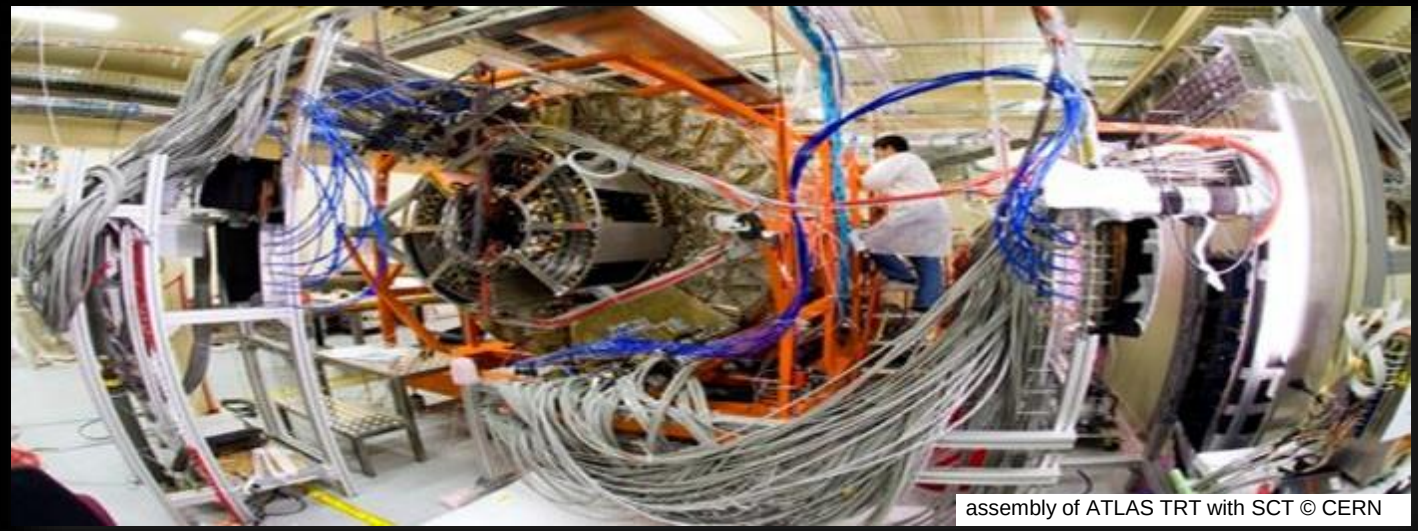
- Q collection by drift

- Hybrid pixels currently only viable technology for vertex detectors for pp colliders
- Huge amount of work done to make pixel readout chip radiation hard for HL-LHC
- FCC requires additional two orders of neutron damage radiation resistance, more performance, in increasingly difficult technology

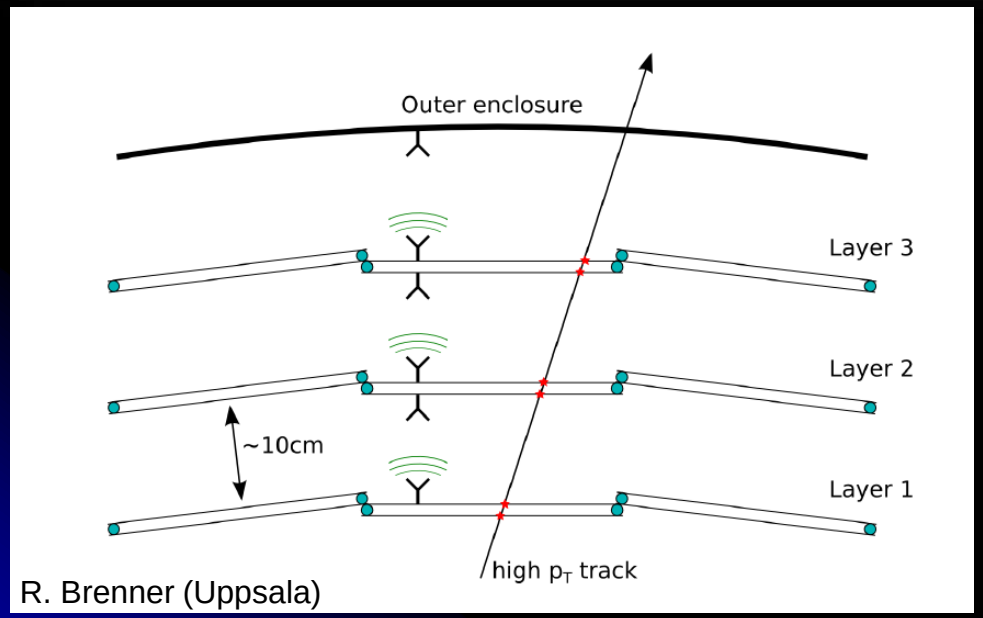
Chip	Technology	Readout Rate
FEI3 / PSI46	250 nm	40 Mb/s/cm^2
FEI4	130 nm	80 Mb/s/cm^2
RD53a	65 nm	~1 Gb/s/cm^2
FCC ASIC	?	~10-50 Gb/s/cm^2



The Curse of Cables


assembly of ATLAS TRT with SCT © CERN

Wireless Allowing Data And Power Transmission

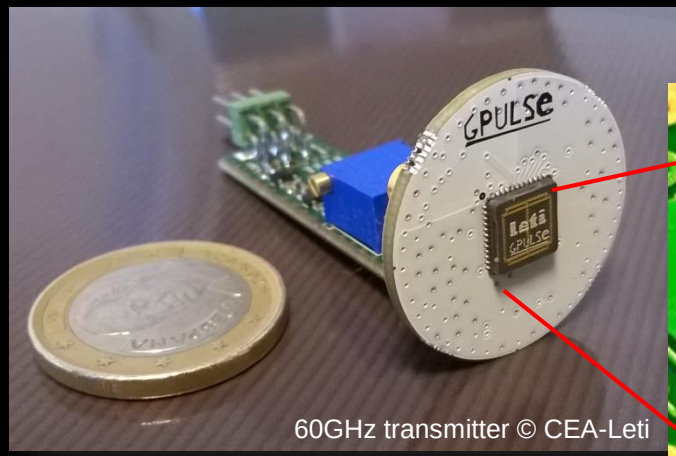


R. Brenner (Uppsala)

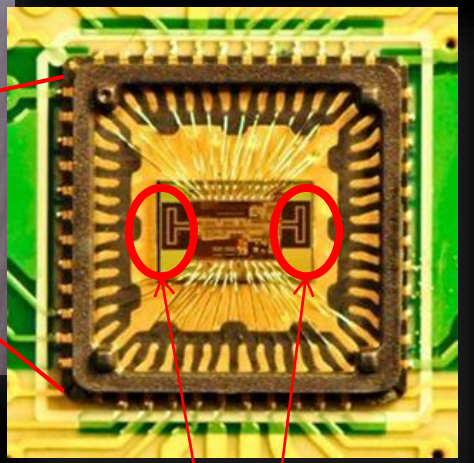
- Wireless readout concept:
  - Radial transfer of data provides communication between layers
  - Signals cannot penetrate layers; reusability of frequency channels
  - Truly transformational

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

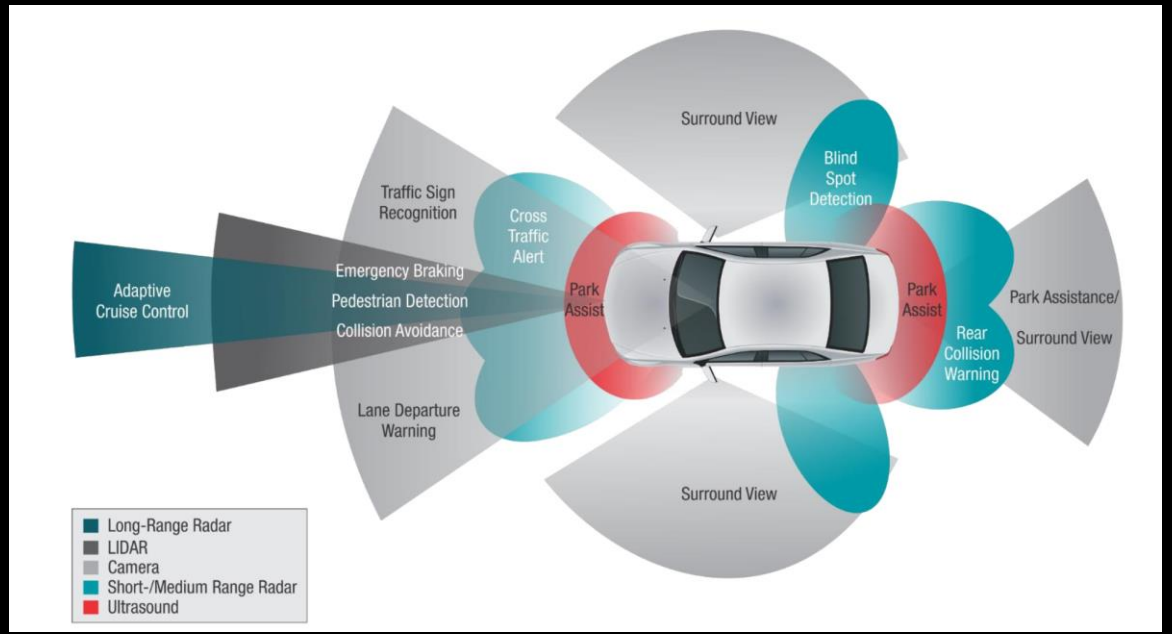


Cedric Dehos (CEA/LETI)



Antennas

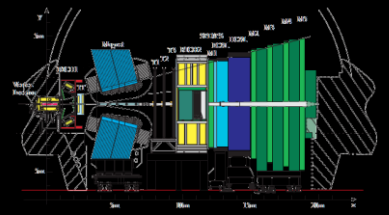
- A current key application: 24, 79 GHz automotive radar



Rohde & Schwartz

Trigger and Data Rates

LHCb



40 MHz — 40 Tb/s

DAQ

LLT
μ, e, γ, h

5 - 40 MHz

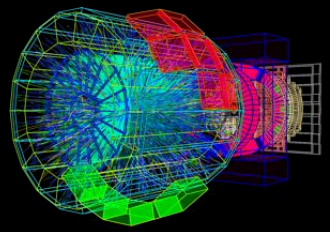
HLT
Event reco

20 – 100 kHz

Offline

2 GB/s

ALICE



50 kHz — 1 TB/s

DAQ

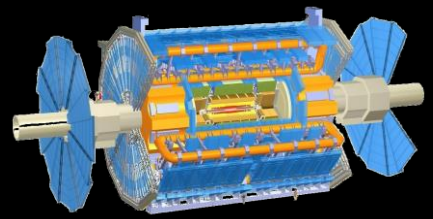
Reco
+
Compression

50 kHz

Offline

75 GB/s

ATLAS



40 MHz — 20 Tb/s

DAQ

Level 0/1

0.5 - 1 MHz

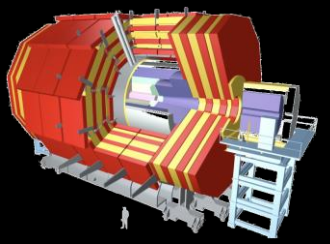
Level 2

5 - 10 kHz

Offline

10 - 20 GB/s

CMS



40 MHz — 40 Tb/s

DAQ

Level 1

1 MHz

Level 2

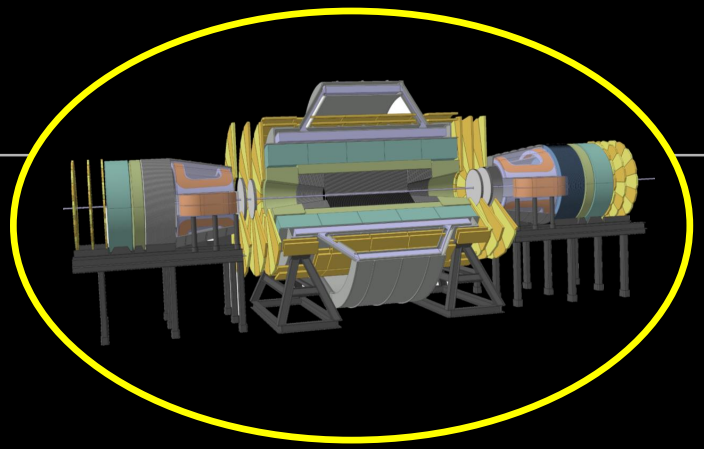
7.5 – 10 kHz

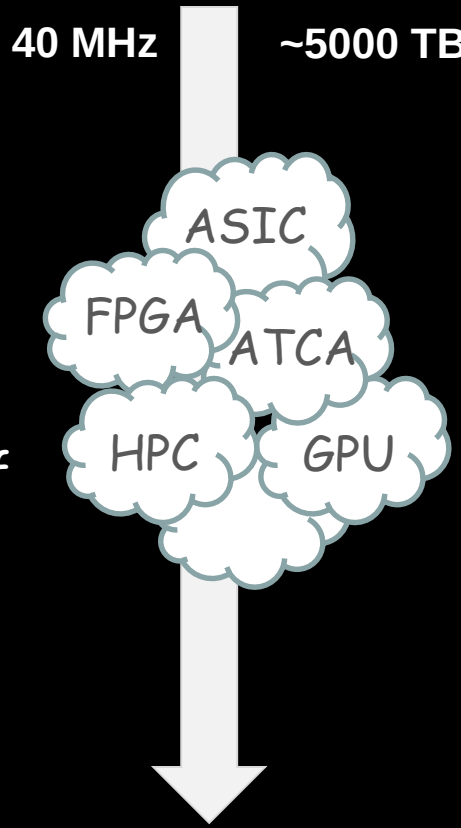
Offline

40 GB/s

At 100 TeV

Larger detectors
Higher granularity
More data

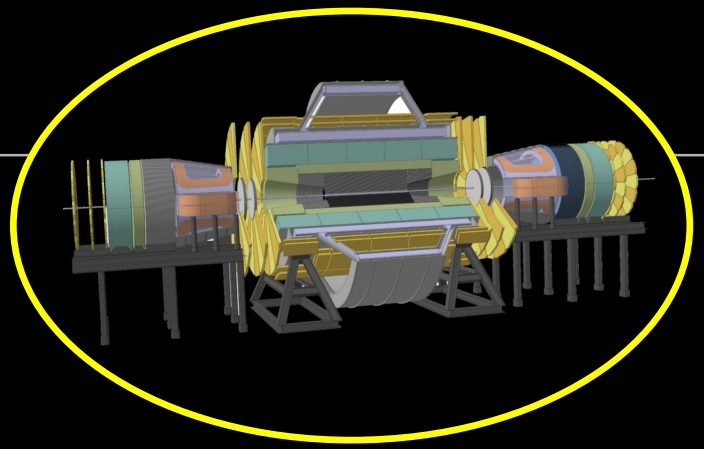


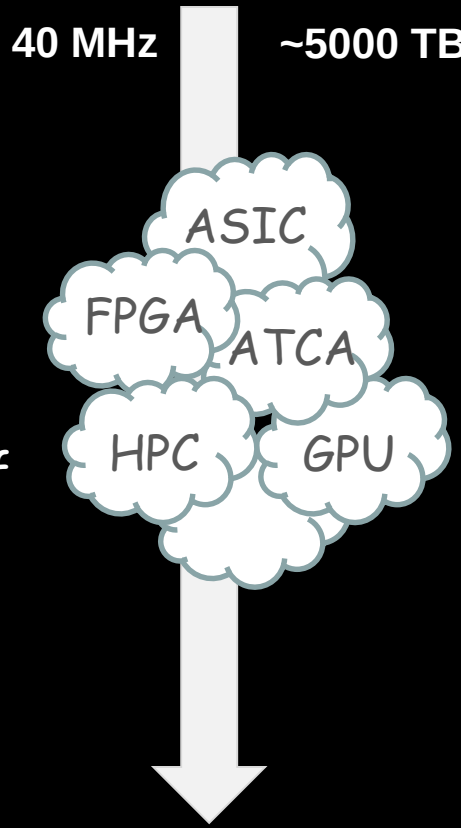


- Tracking and calorimeter each have raw data rates of ~2,000 TB/s
- Using 10Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Eb/s

At 100 TeV

Larger detectors
Higher granularity
More data





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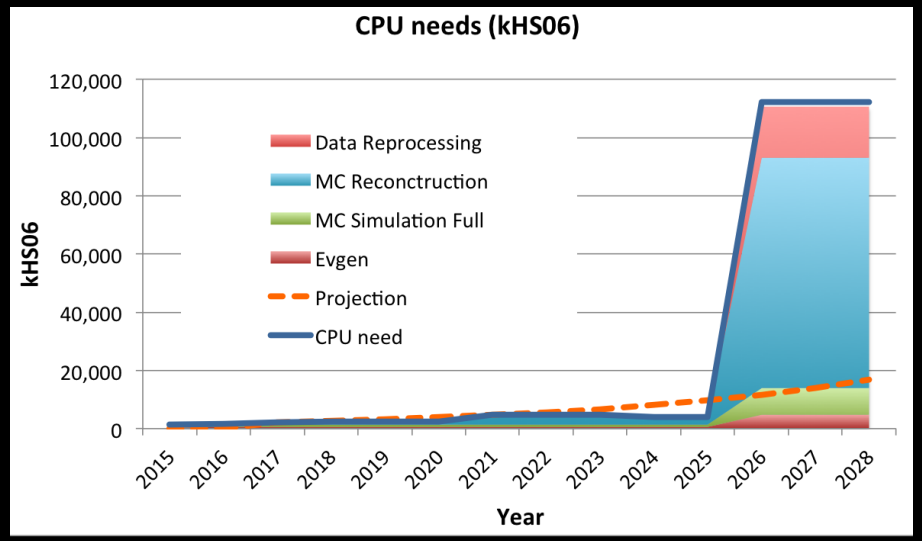
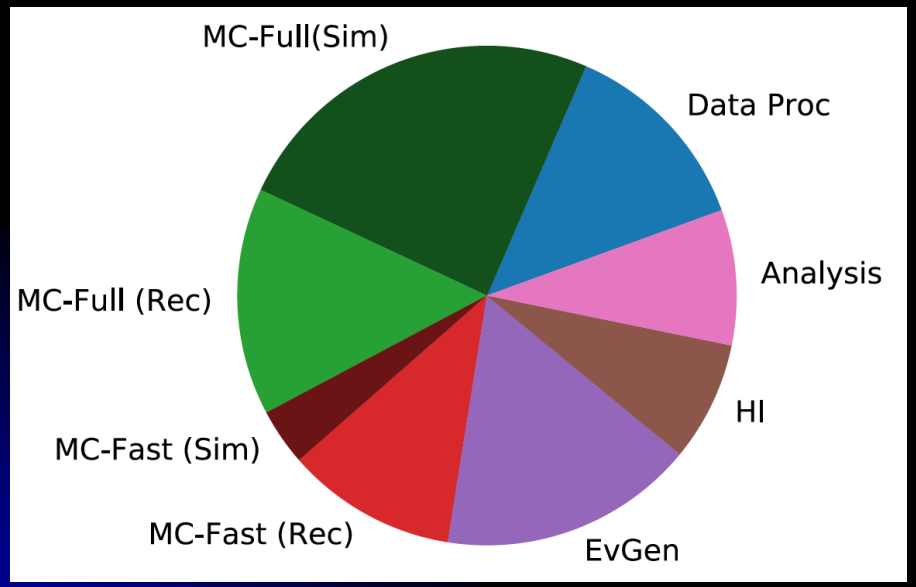
- Using 10Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Eb/s

- 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

Simulation

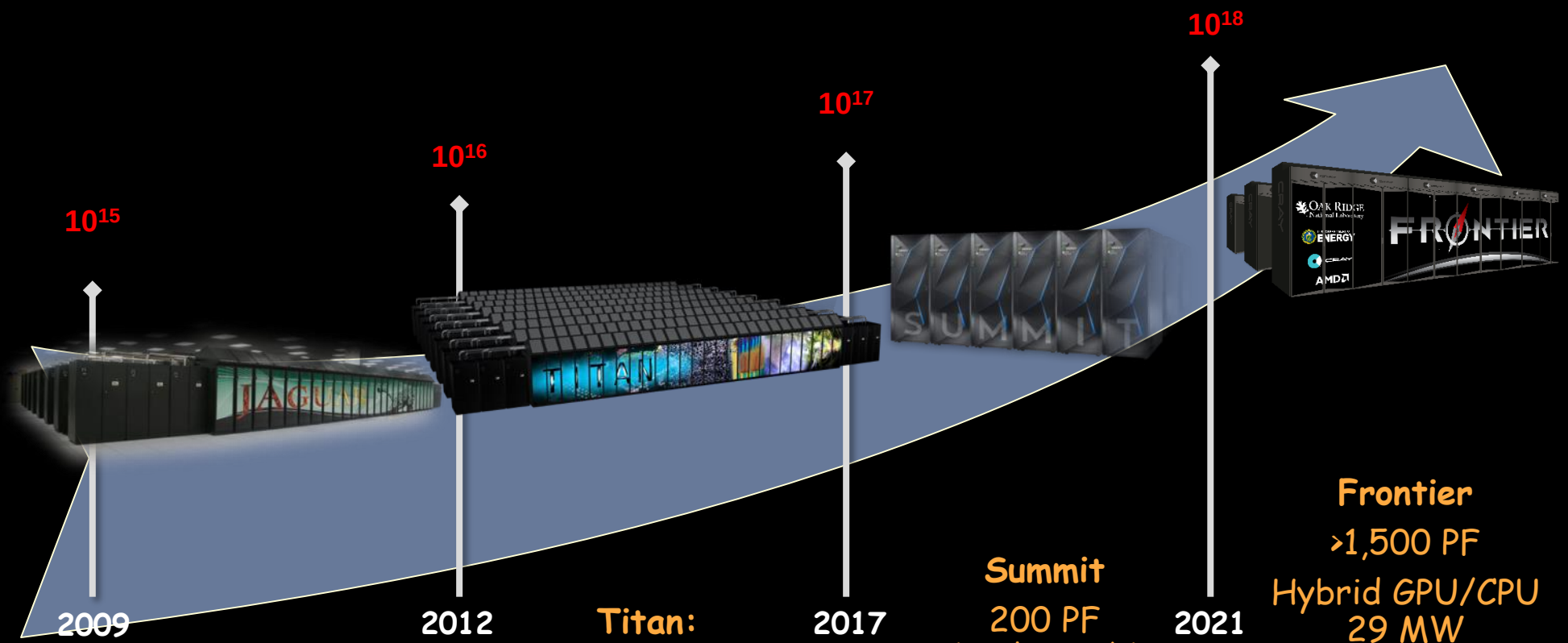


S. Vallecorsa, Big Data Summit, July 2018

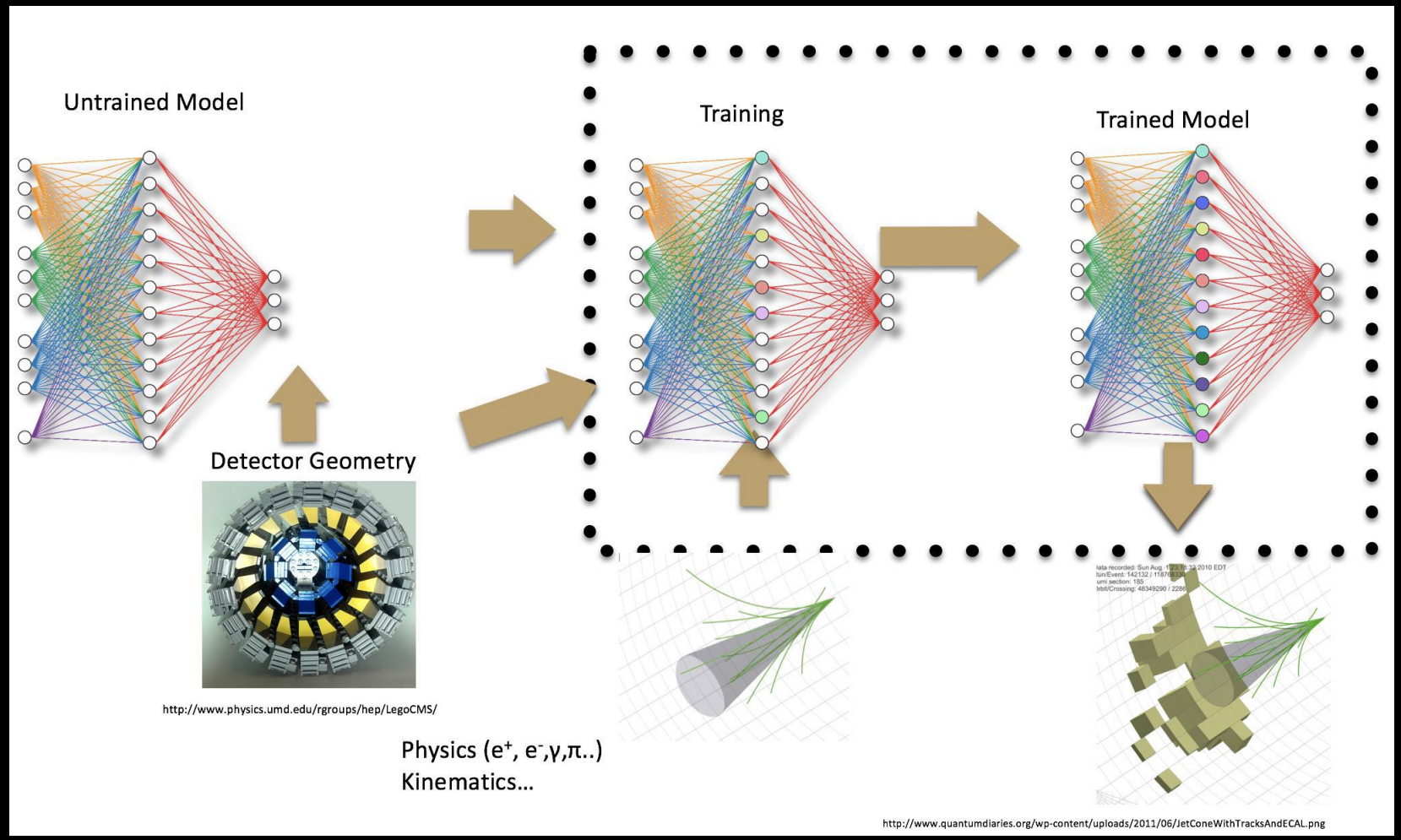


- HL-LHC already unprecedented event rate and complexity
- Current computing models predict a significant shortfall in resources
- Resource budget assumes that fast Monte Carlos and Event generators have been sped up by x2
- Will FCC-hh require another factor 5 increase?

Road to Exascale Computing and ML

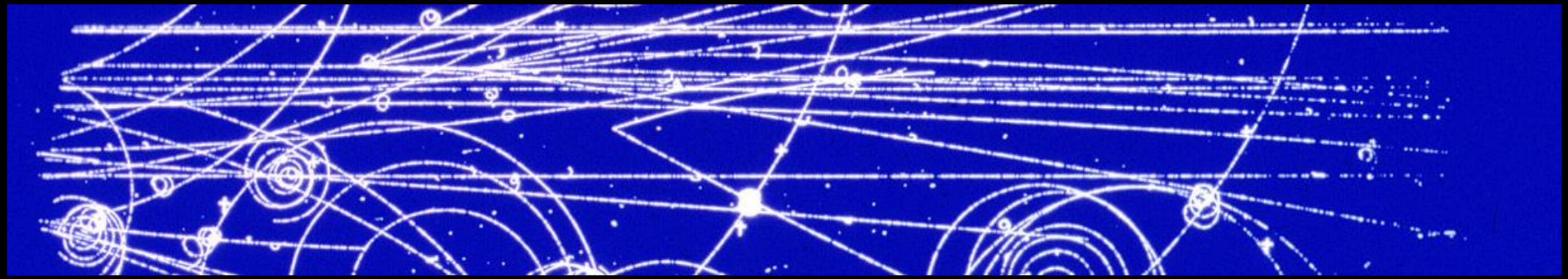


Generative Adversarial Networks

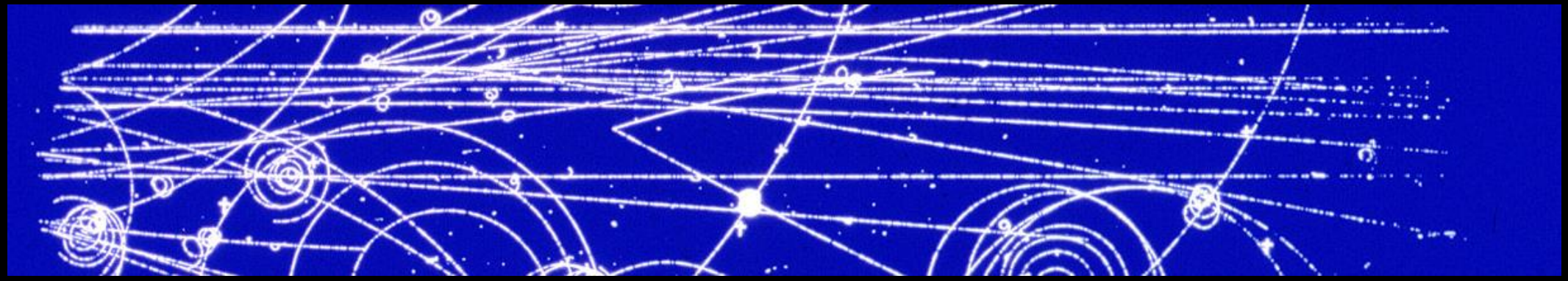


- Claimed speedup of factor 17,000; but still need to train GAN and ensure tails are correctly modeled.

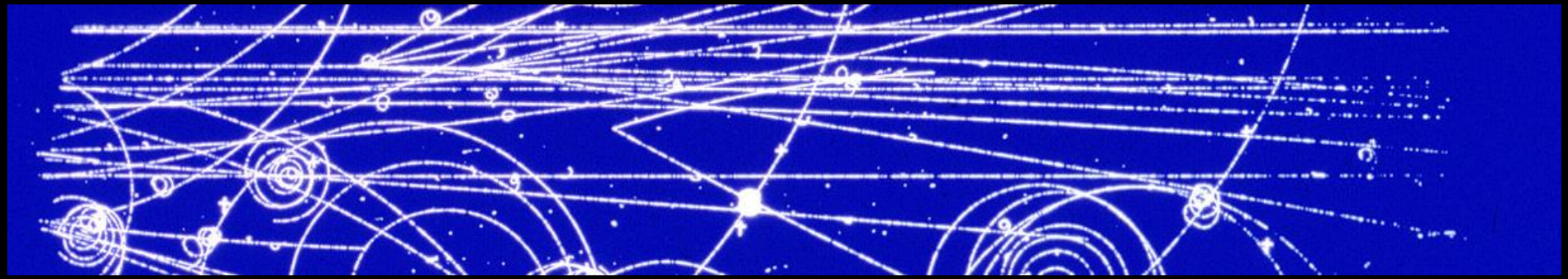
Perspective

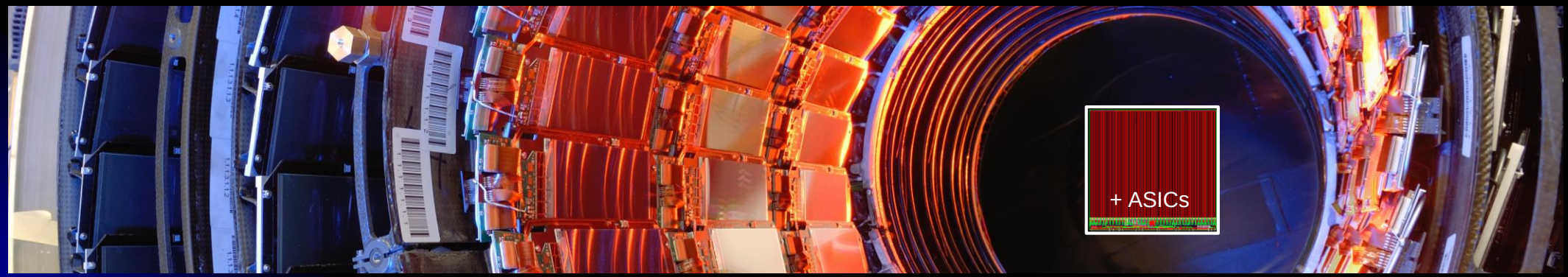


Perspective



Perspective





Innovation

Innovation

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

Summary

- We are living in a most fascinating time, faced and at the verge of answering some of the most profound questions about the origin, and destination, of the world and universe we live in.
- To answer these questions we need new tools. These tools, however, are daunting in many respects.
- Technological advances are absolutely critical for realizing future colliders and enabling the Higgs as a tool for discovery.

- **There is an urgent need for creativity!**
- **It is time for another experimental transformational development!**

- **The future ain't, and cannot be, what it used to be!**

Thank You