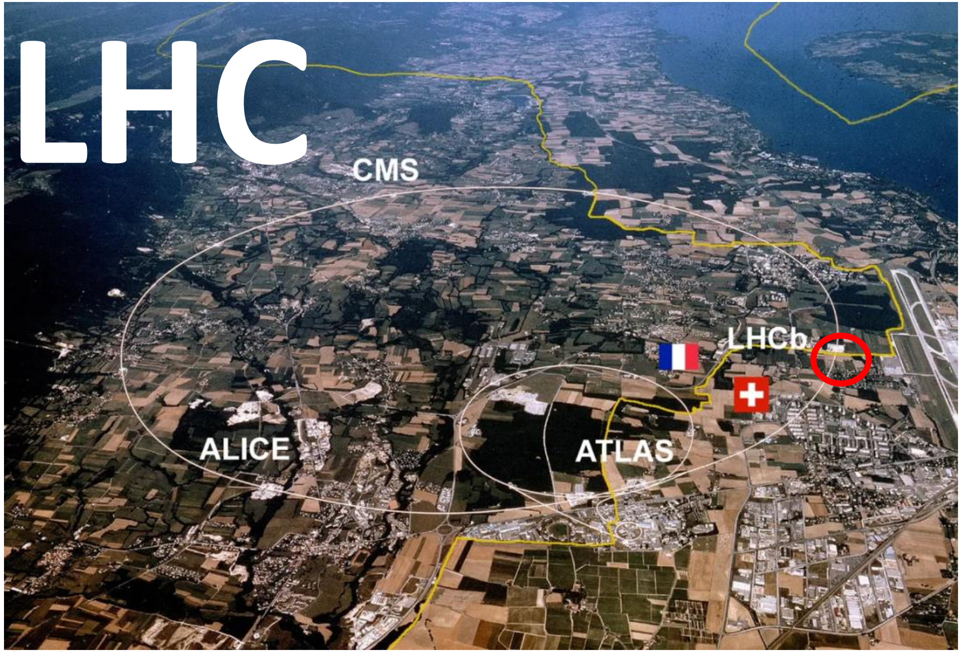
Challenges for High Luminosity LHC

Kazu Akiba
Nikhef

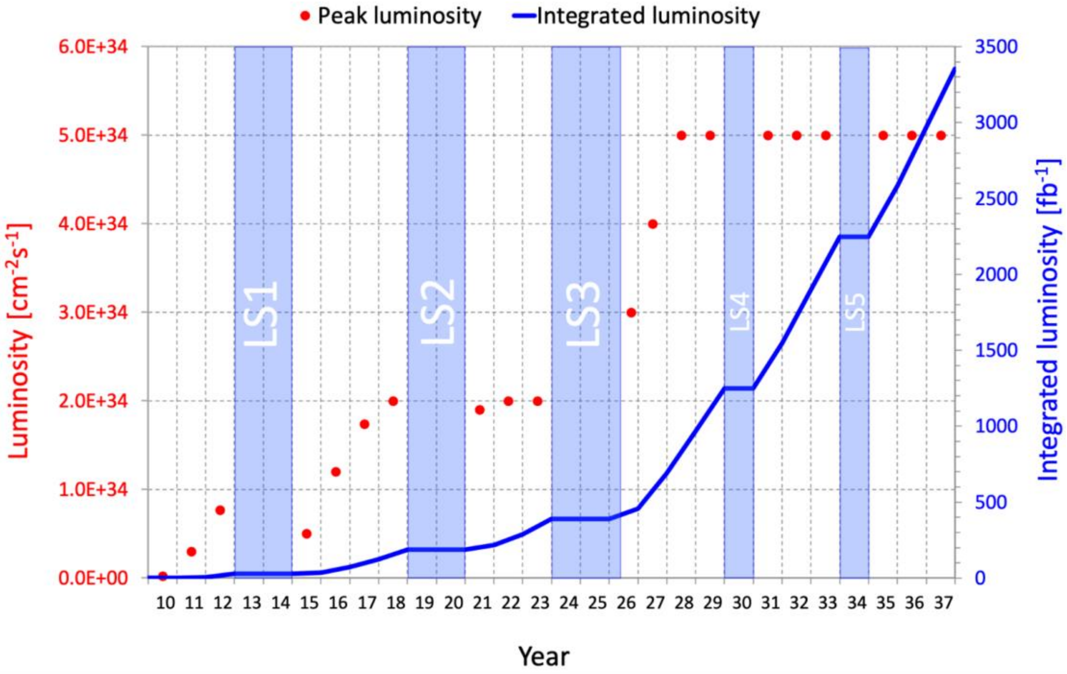
Kinetic energy of a proton (K)	Speed (%c)	Accelerator
160 MeV	52	Linac 4
2 GeV	94.8	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV (design energy)	99.9999991	LHC

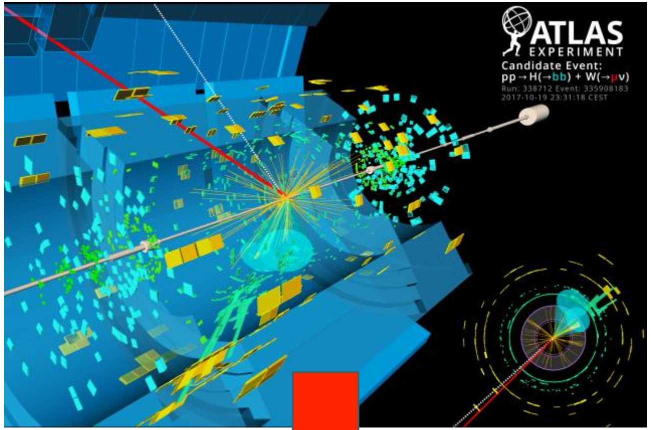
Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2

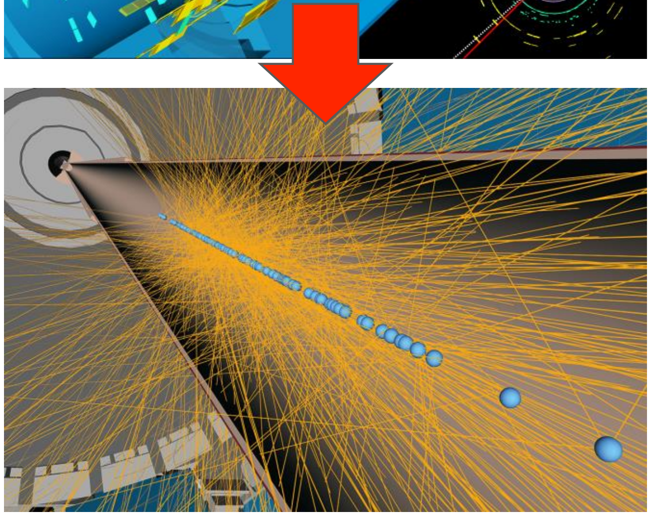


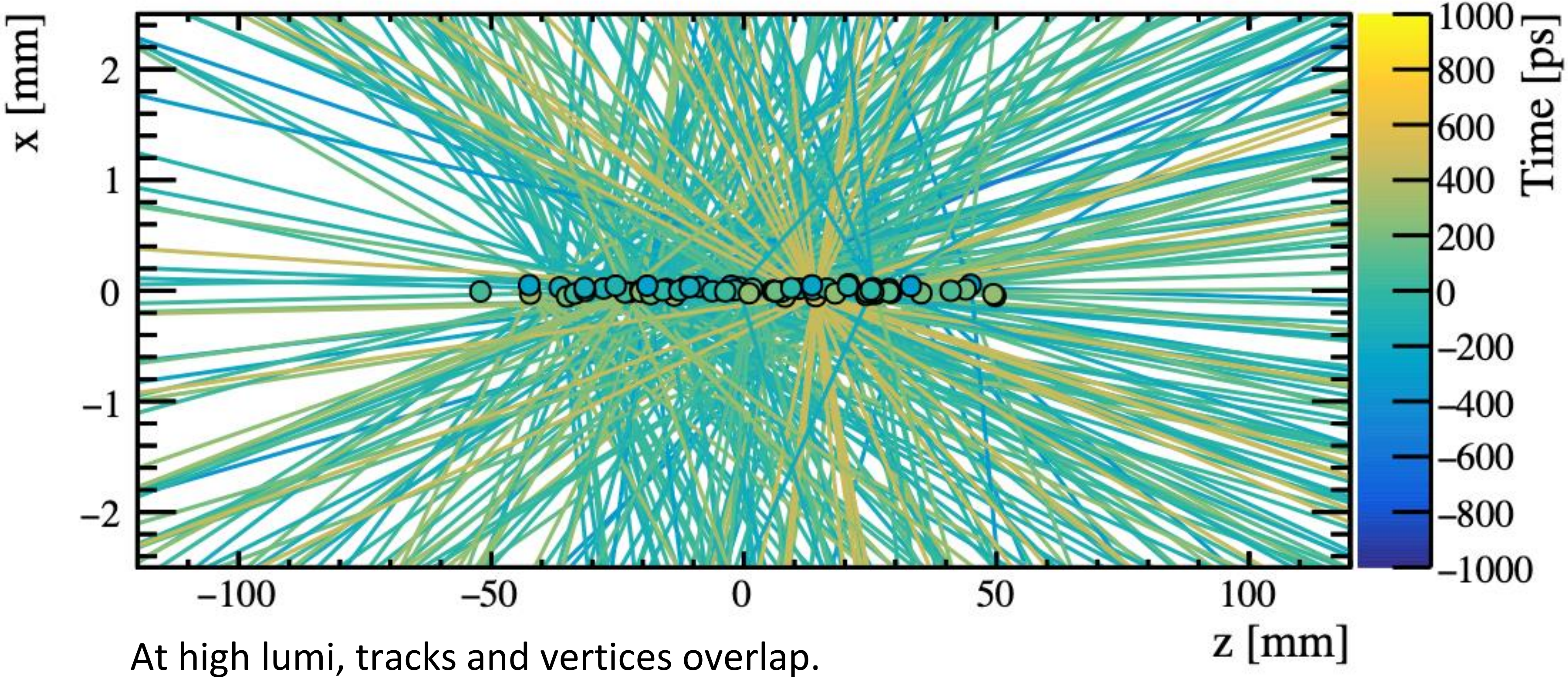
Design parameters	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3 °C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per direction
Energy, protons	7 TeV*
Energy, ions	2.76 TeV/u (**)
Peak magnetic dipole field	8.3 T
Distance between bunches	~7.5 m
Luminosity (protons)	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	1 billion

How LHC can provide more data/second?
→ Luminosity

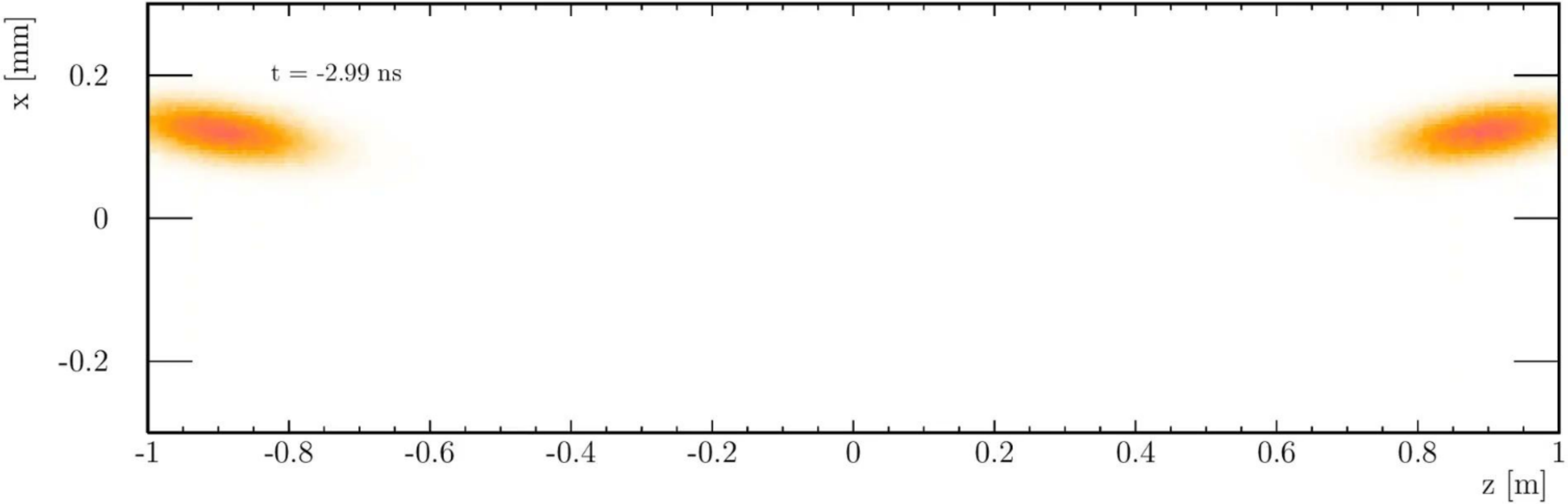




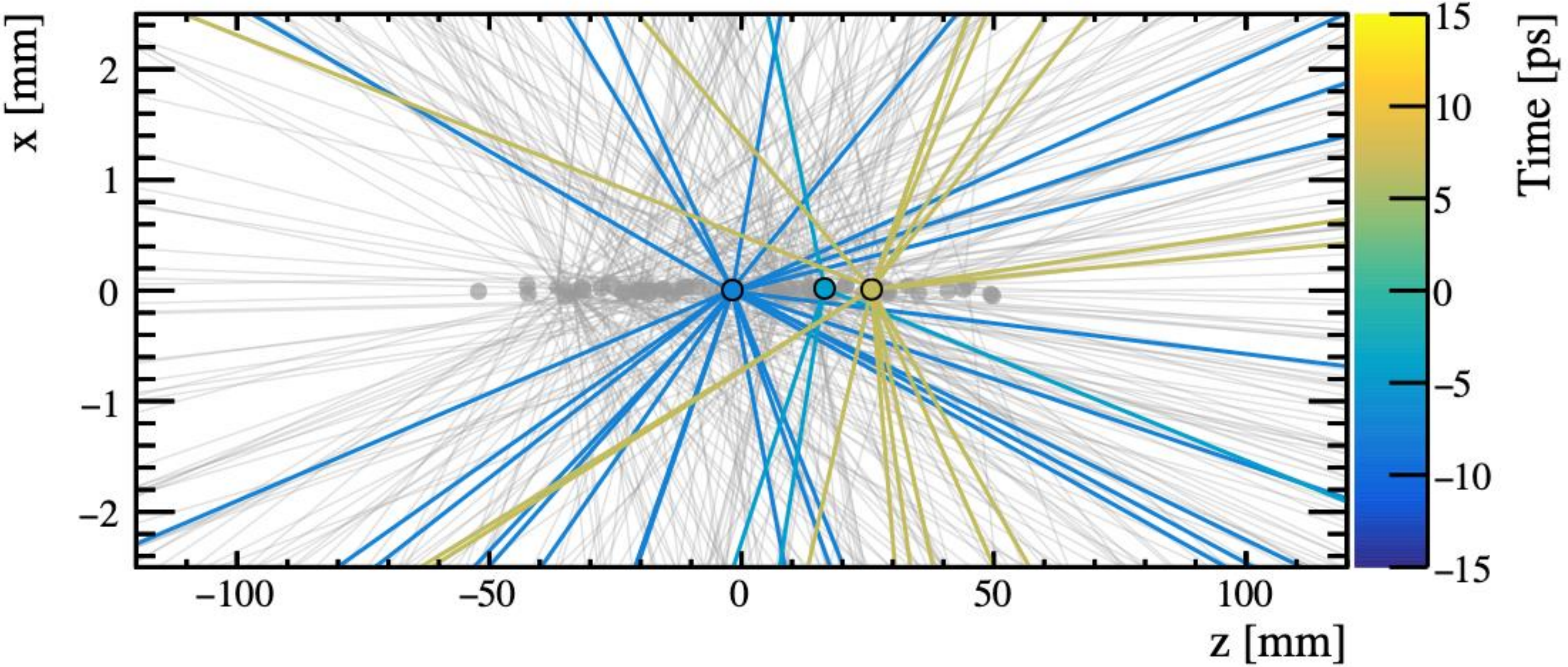




At high lumi, tracks and vertices overlap.
Reconstruction for physics events becomes difficult.



Nevertheless the bunch crossing time takes longer than **200 ps in time** (and 44 mm in z)



Applying temporal cuts could result in a problem less complex than the current detector

Long/short lived particles

A lot of High Energy Physics is based on selecting/identifying the presence of long lived particles. Lifetimes give a clear signature:

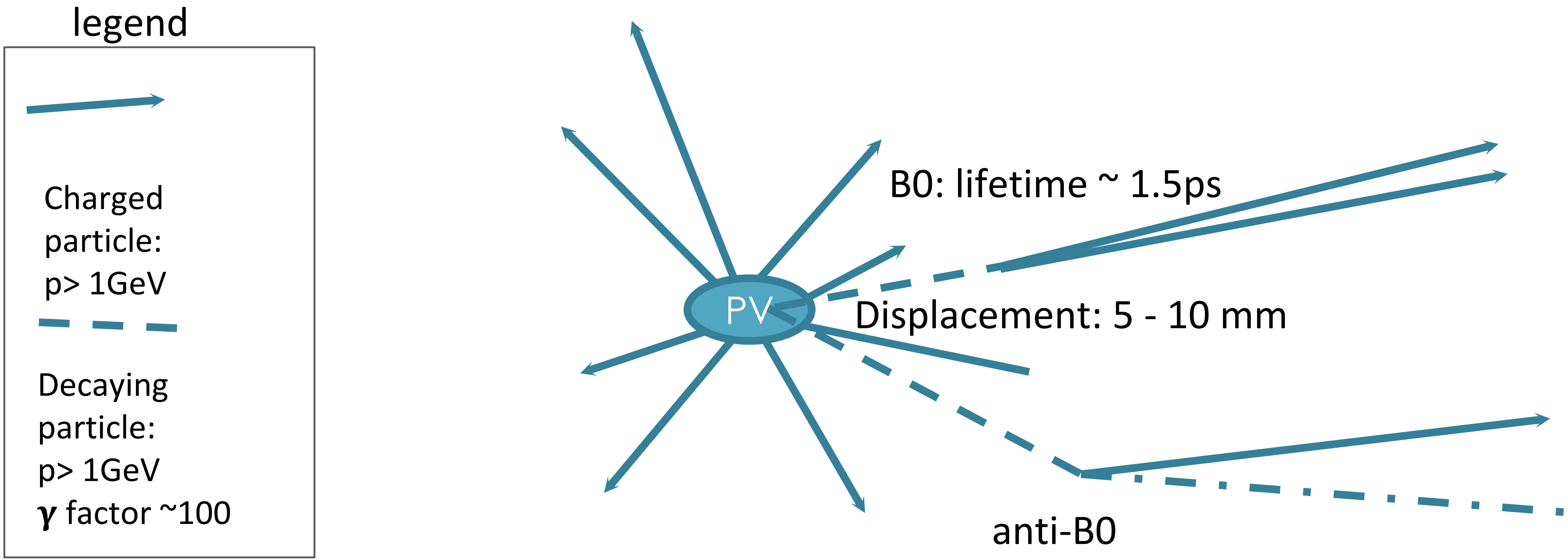
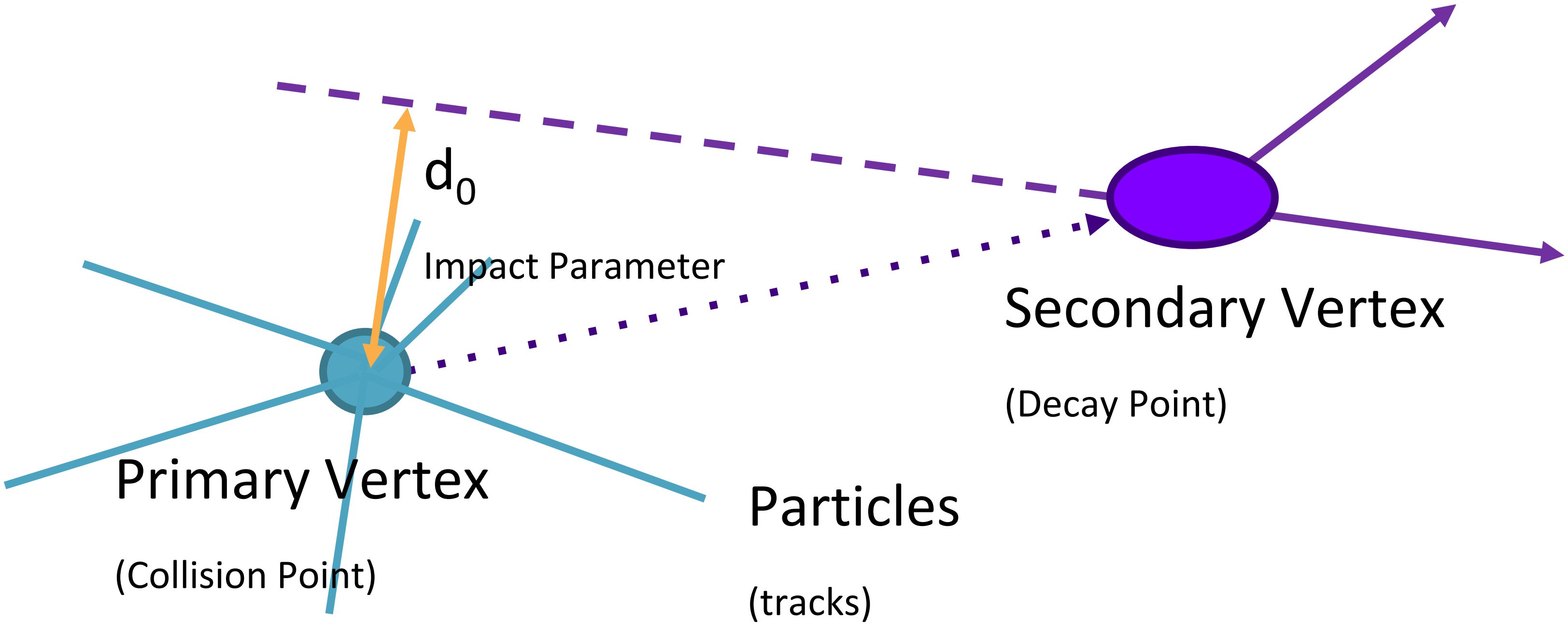


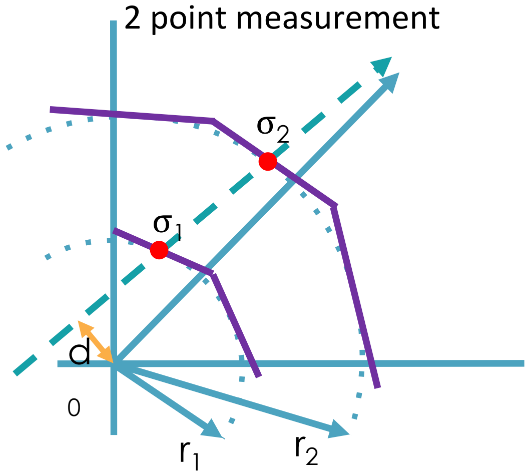
Figure of Merit: Impact parameter



$$\sigma_{d_0}^2 \propto \sigma_{hit}^2 + \sigma_{ms}^2$$

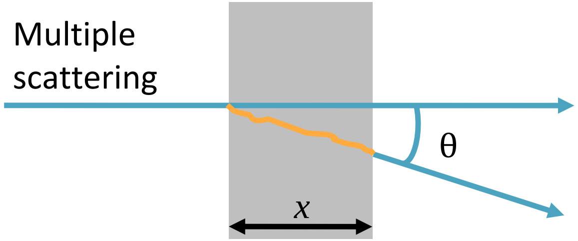
Impact Parameter - Figure of Merit of a Vertex Detector

- Depends on 3 main parameters
  - Intrinsic ***hit resolution***
  - Distance to the ***first measured*** point and lever arm
  - Multiple scattering in ***detector material***, worse at low p_T



$$\sigma_{d_0} = \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \equiv \sigma_{geom}$$

Pixel Detectors

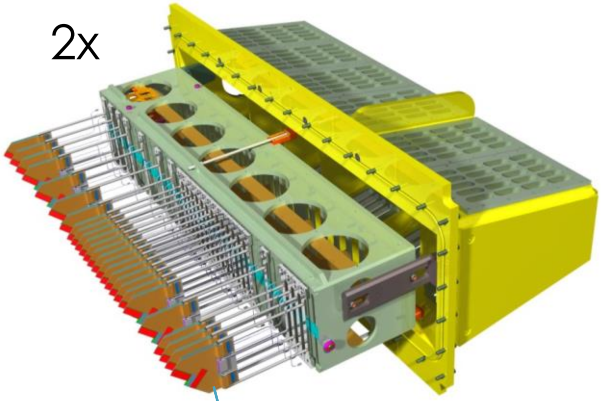


$$\sigma_{d_0} = \frac{r}{p} 13.6\ MeV \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log\left(\frac{x}{X_0}\right)\right]$$

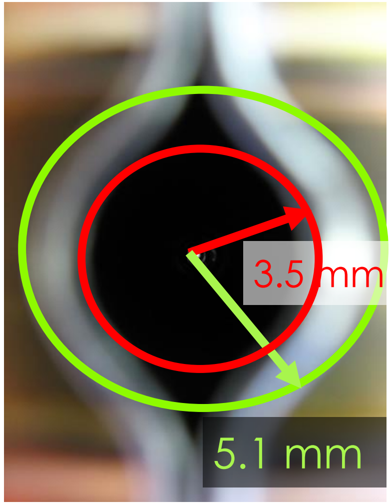
Sensor and cooling material

$$\sigma_{d_0}^2 \approx \sigma_{geom}^2 + \left(\frac{f(x/X_0)}{p_T\sqrt{\sin\theta}}\right)^2$$

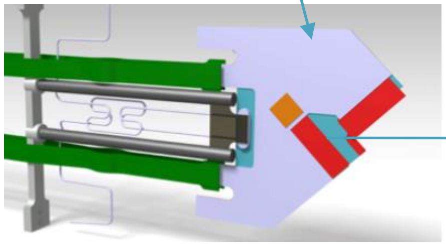
Overview of the Current Detector

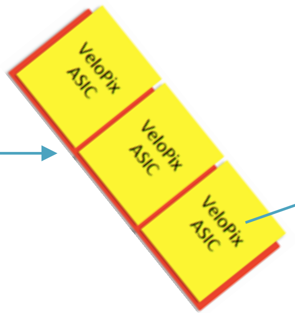


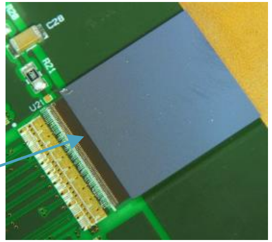
- 52 modules, 55 µm pitch sensors
- 40M pixels
- Data driven readout
- 5.1 mm sensitive distance to beam.
- Operate in Vacuum
- Innovative micro-channel cooling (-20 °C)
- Separated from the beam by an milled foil



Substrate thickness ~ 500µm Si







A successful experiment @ high luminosity

Main assumption:

Impact Parameter Resolutions will yield same signal selection performance
IF timing resolution of **20 ps/track** is achieved.

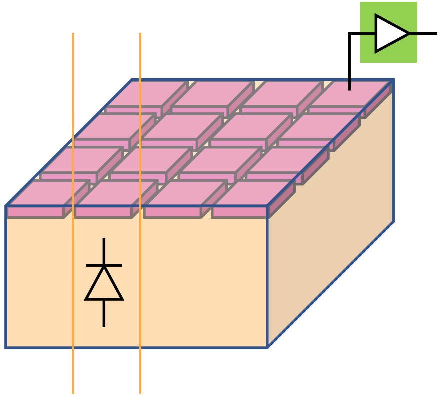
Timing of 50 ps/hit is a global requirement.

Radiation Hardness needs to be up to 6 times larger than now

An extensive R&D program was launched to find the achievable limits

Silicon pixel detectors

- Fast silicon sensors consist e.g. of p-type silicon bulk with n-type pixel implants
- Particles traverse the detector leaving a small charge
- The charge needs to be collected and amplified by a front-end circuit.

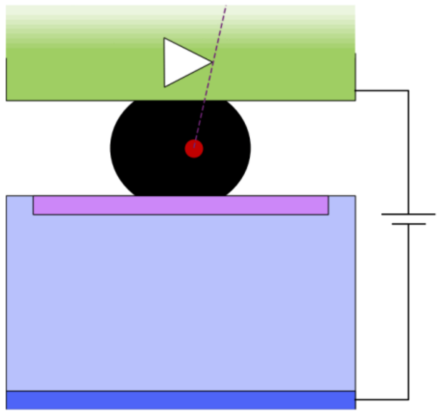


- Typical pixel size 20 – 50 μm
- Typical sensor thickness 20 – 300 μm

How to get good time resolution (electronics viewpoint)

- Time resolution
  - α,β > γ

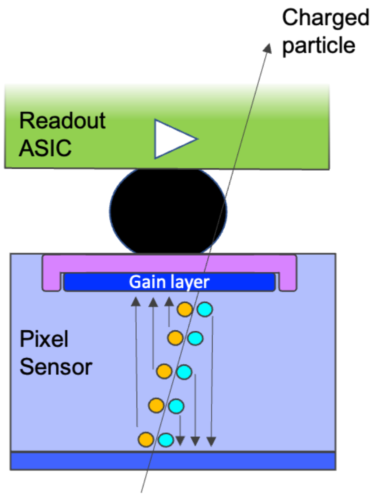
$$\sigma_t \sim \frac{C^{\alpha}}{Q^{\beta} P^{\gamma}}$$



- Minimise capacitance C
  - Small pixel -> can fit less functionality per pixel
  - Small electrode -> less uniform fields
- Maximise signal Q in shortest possible time (dQ/dt = current)
  - Short drift distance (thin), high drift speed (large bias voltage), avalanche gain
- Large power P (transistor transconductance, g_m)
  - Last resort, ‘costly’ in terms of material needed to provide power and cooling

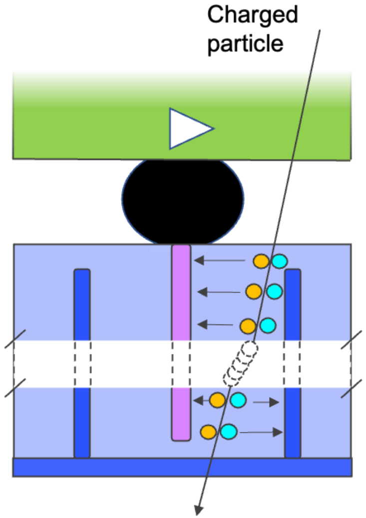
Sensor candidates

Low Gain Avalanche Detector (LGAD)



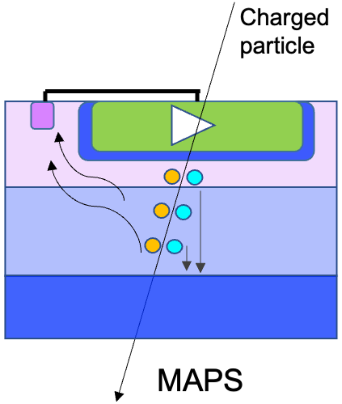
- Large signal (gain)
- Medium capacitance
- Modest rad. hard

3D



- Large signal (thick)
- Rad. Hard (shown 3E16)
- High capacitance
- More material

Monolithic Active Pixel Sensor (MAPS)



- Very low capacitance
- Low material
- Small signal
- Challenge to operate at high rate and high radiation doses.

Electronics Challenges

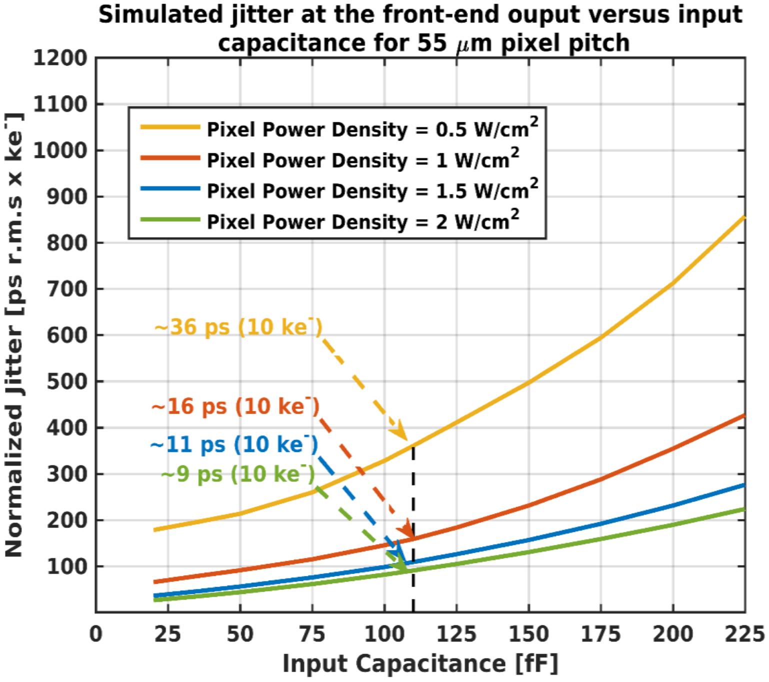
The increased luminosity brings proportional data rates and radiation damage. Data rate > 100 GB/s/cm2

To cope with this, additional processing at the frontend (pixel) is required.

Fast-timing amplification (on-pixel) also requires more powerful analog design (better cooling)

Current prototyping (CERN+Nikhef) a chip (PicoPix) to achieve <30 ps RMS (TDC <40 ps) in 28 nm CMOS.

Clock distribution and stability is a major challenge for detector operation.

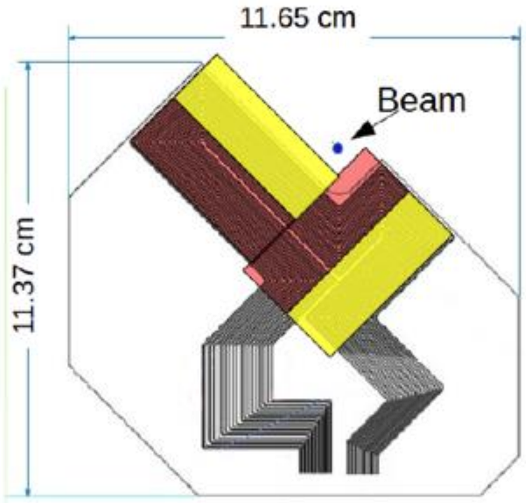


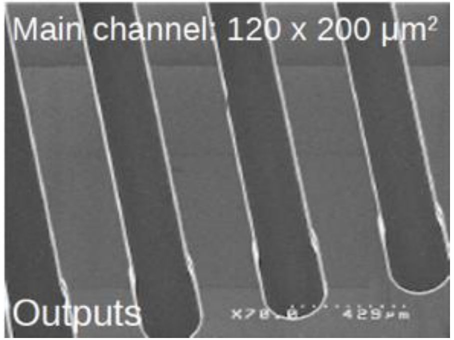
PicoPix -- 2026

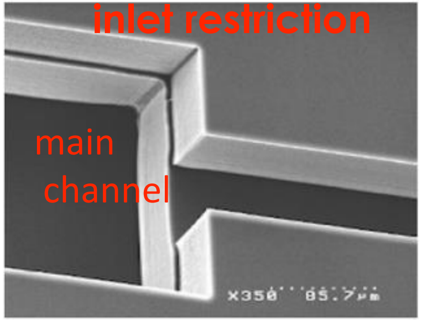
Minimising material

Microchannel cooling

- Efficient cooling solution is required to maintain the sensors at < -20^{o}C
- No CTE mismatch
- This is provided by the novel technique of evaporative CO_2 circulating in 120 µm x 200 µm channels within a silicon substrate.



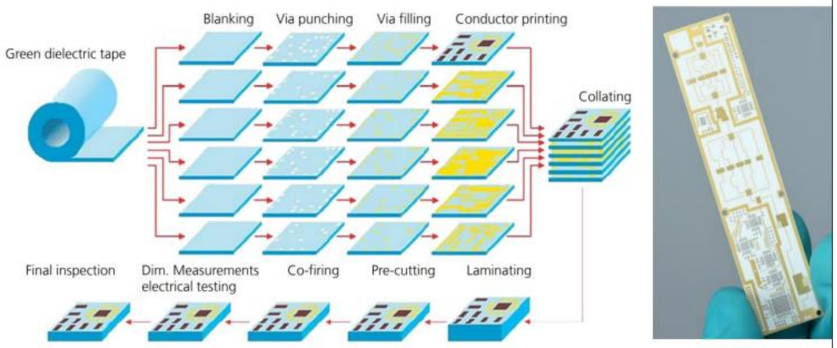


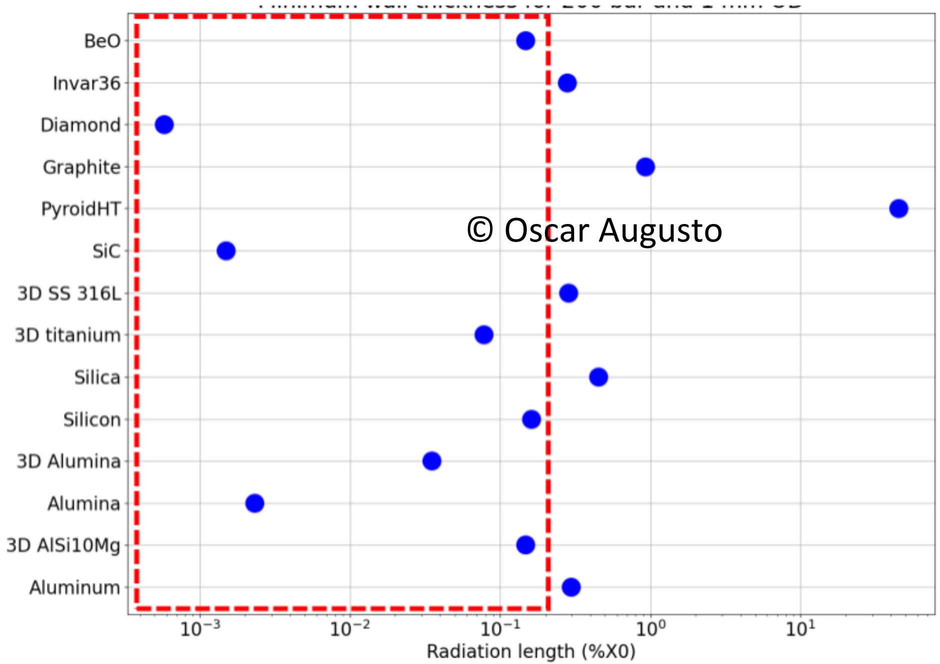


SEM images of etched wafer before bonding

Minimising material

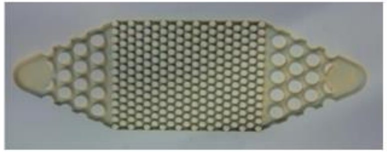
A lot of research is ongoing in using alternative solutions to provide much lighter signature for the substrate, which can include electronics.

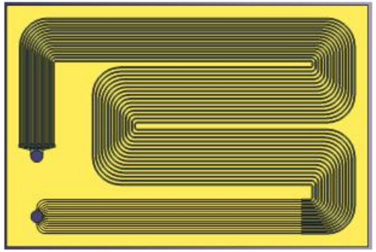




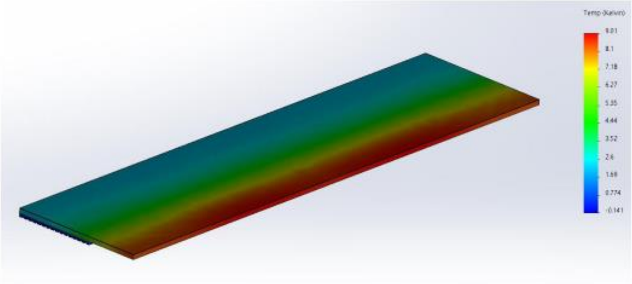
3D printed Ceramics or metals

Substrate needs to be made of very little material but also provide sufficient heat extraction and a low operating temperature



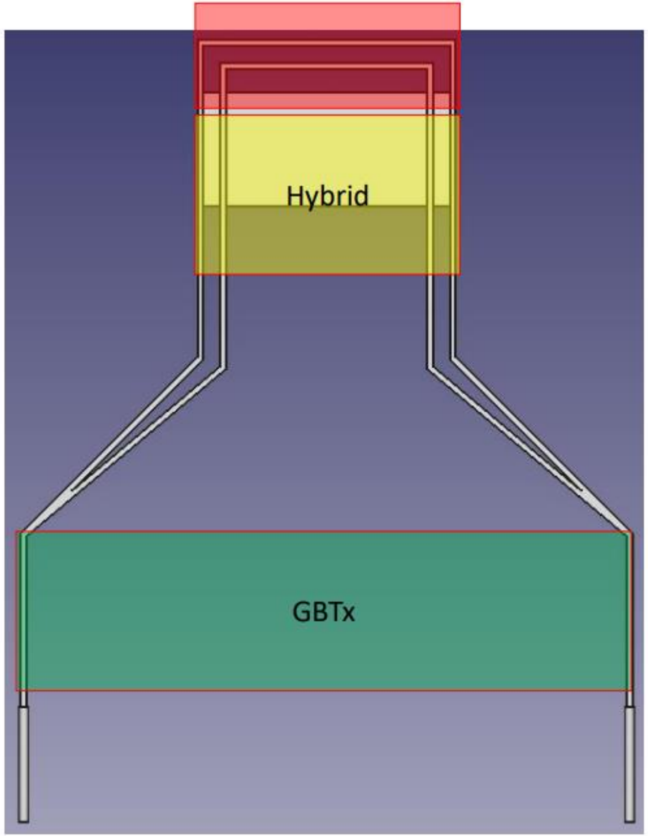


SNAKEI based design to optimize printing parameters/test feasibility



Simplified FEA focusing on the 5 mm overhang. Substrate in alumina and heat conduction on one side of the cooling plate and Stycast (100um). For $2\mathrm{W/cm}^2$, $\Delta\mathrm{T} \sim 9$ C.

Sensor tile



Summary

LHC can provide more luminosity = collisions/s = physics discovery potential.

However collisions overlap in space, **requiring separation in time**.

Time resolutions of 50 ps on each pixel are desired.

Further requirements remain:

Spatial resolutions better than 10µm

Minimum material to scatter trajectories.