How To Design A Silicon Tracking Detector

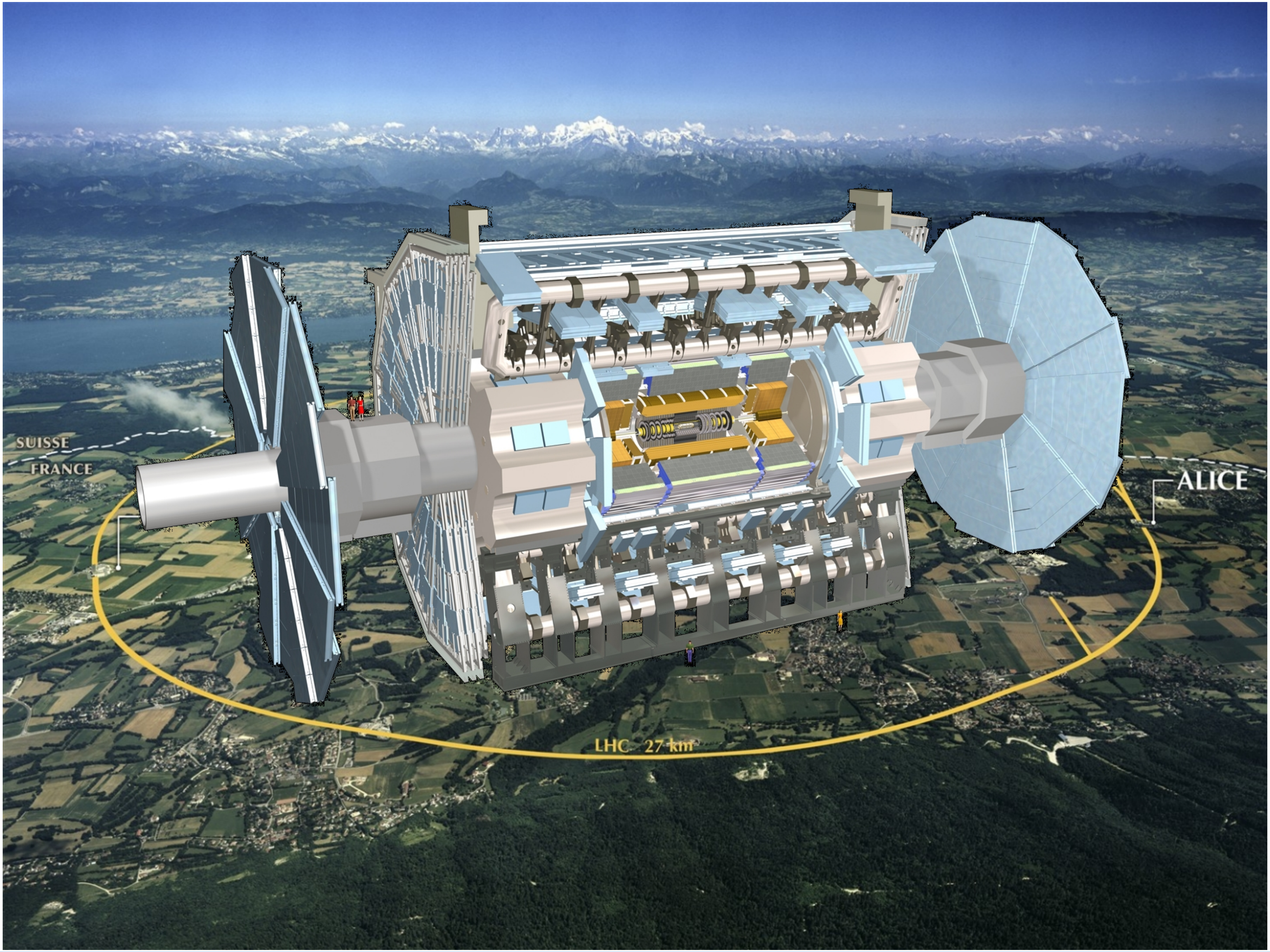
Insights from the ITk upgrade for the ATLAS Detector at CERN

Ben Smart

- First, let me set the scene...

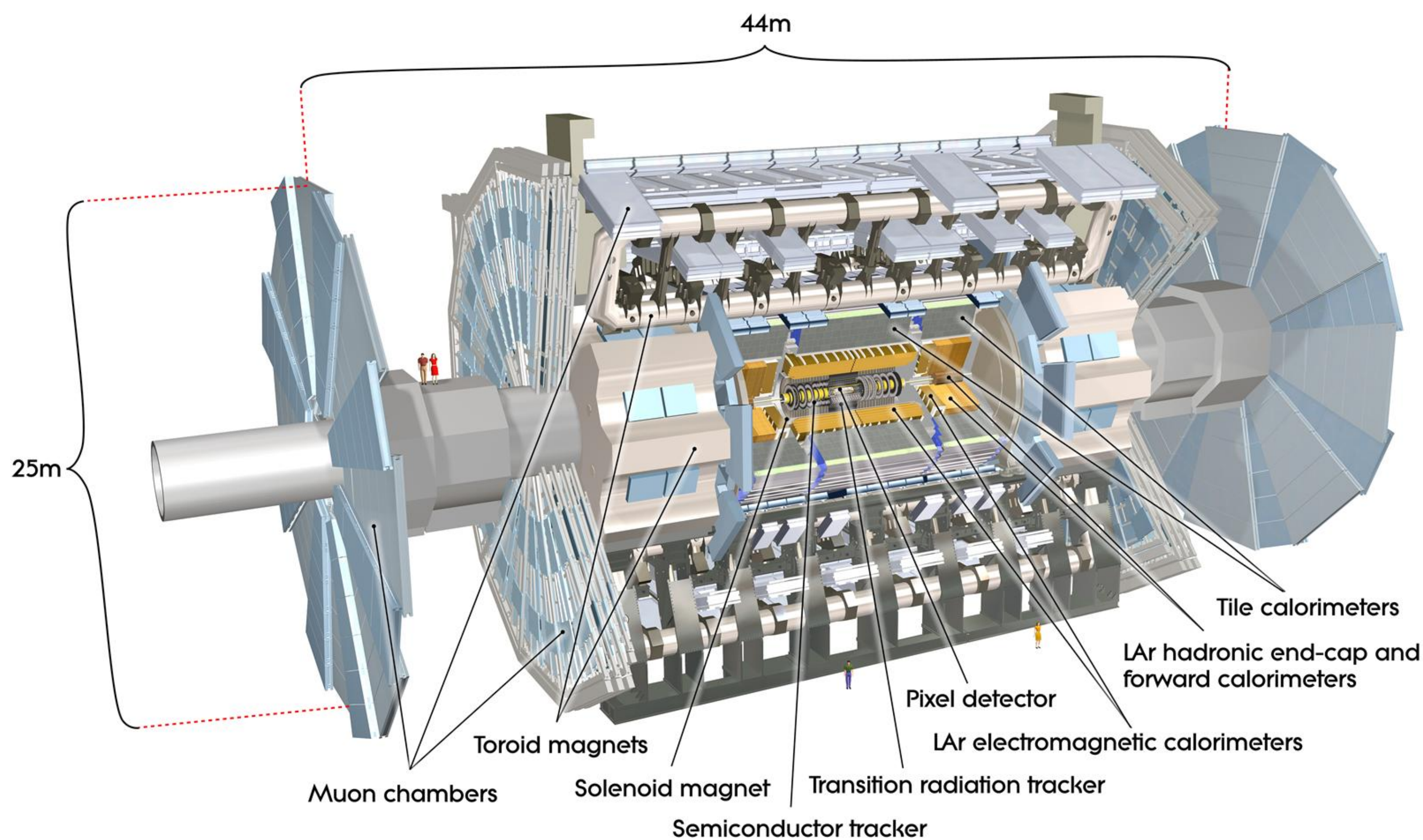
The Large Hadron Collider At CERN

The ATLAS Detector At CERN

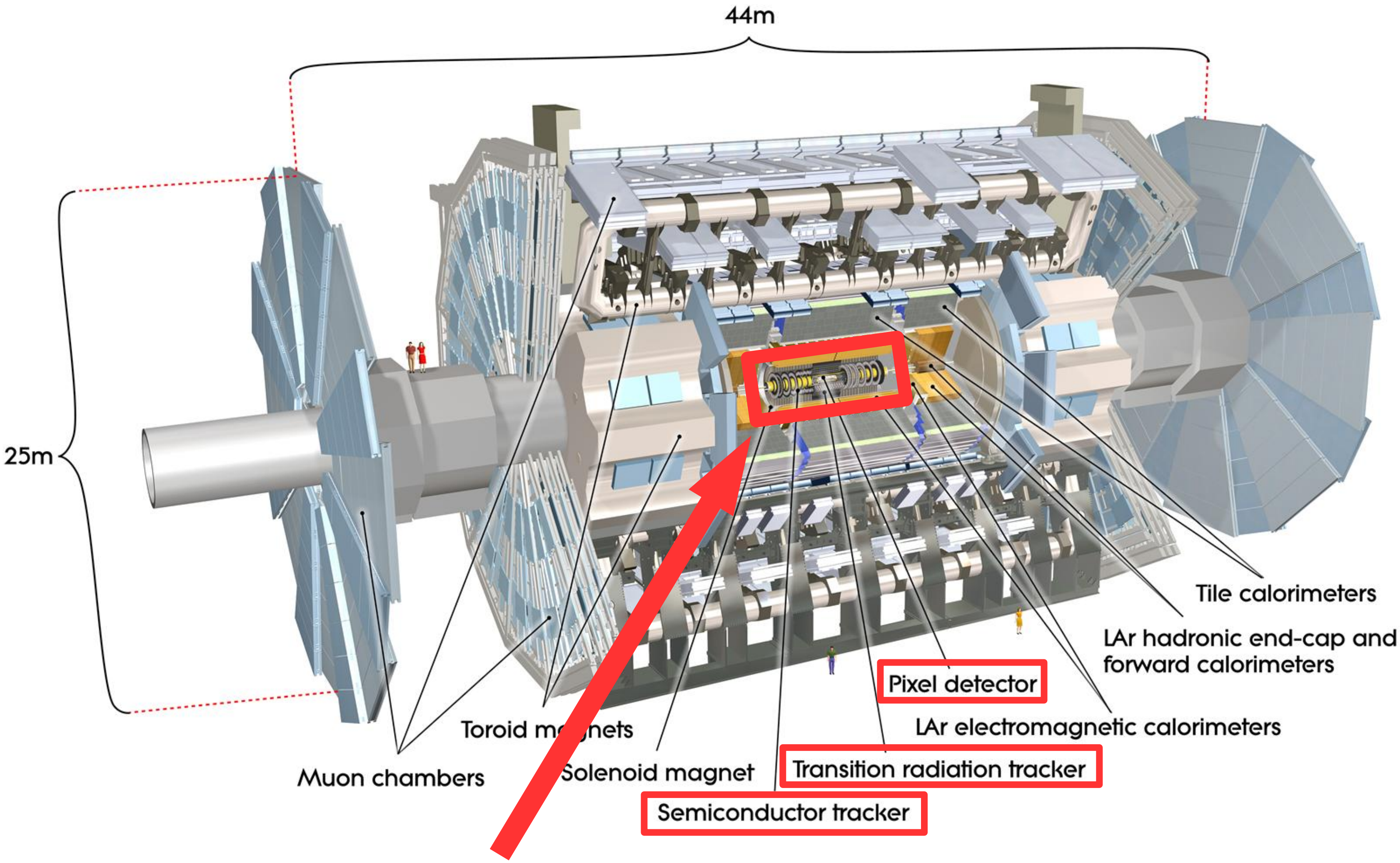


Great Things Have Been Achieved So Far… But We Strive For More

The ATLAS Detector At CERN



The ATLAS Detector At CERN



This is the tracking detector ('Inner Detector') of ATLAS.
It will be upgraded, and that is what I will talk about today.

- What LHC and ATLAS upgrades and why?
- Tracking detector performance and how to achieve it.
- Physics studies with the upgraded LHC and ATLAS
  – the ultimate goal.

- What LHC and ATLAS upgrades and why?
- Tracking detector performance and how to achieve it.
- Physics studies with the upgraded LHC and ATLAS – the ultimate goal.

In the future, the LHC will go to higher energy and luminosity

This will be called the 'High-Luminosity LHC' (HL-LHC)

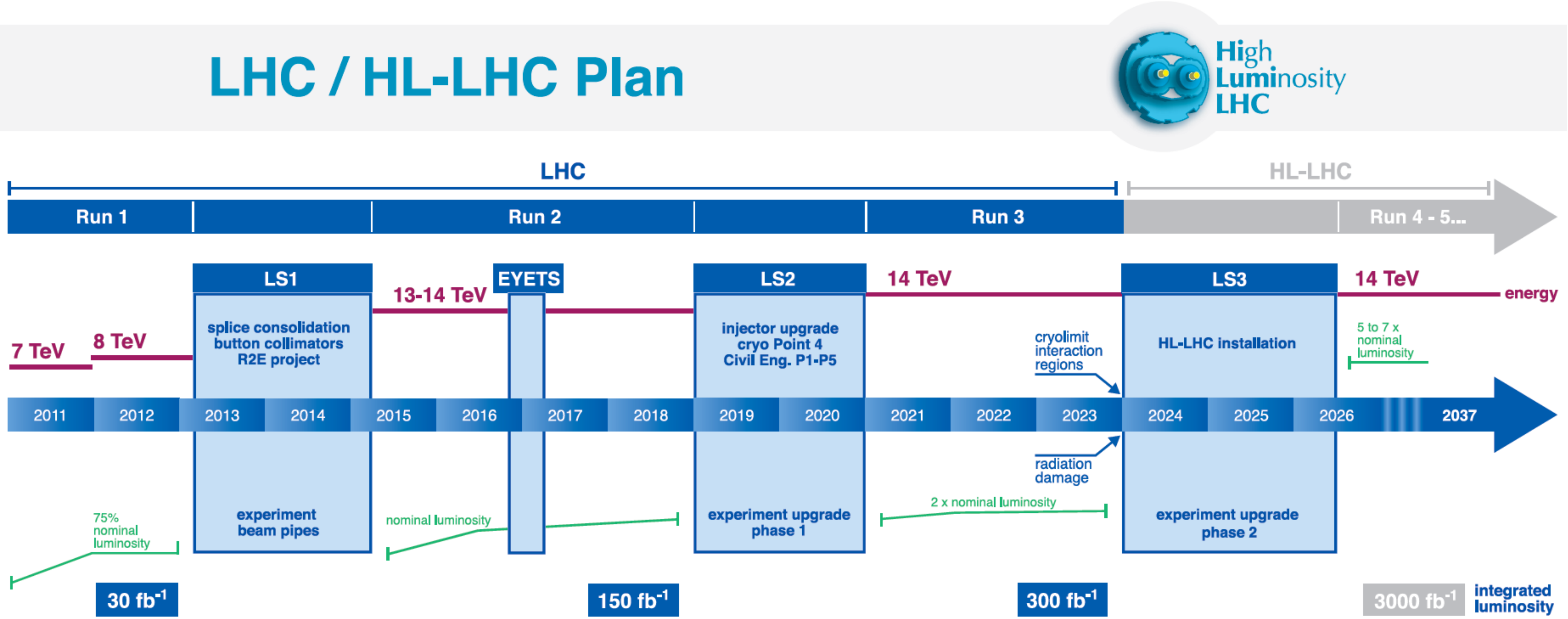
The ATLAS detector will also be upgraded

The current ATLAS Inner Detector will be removed, and replaced with a new, all-Silicon sensor, inner tracker

This new Inner Tracker will be called the ITk

The Plan For The Future: LHC

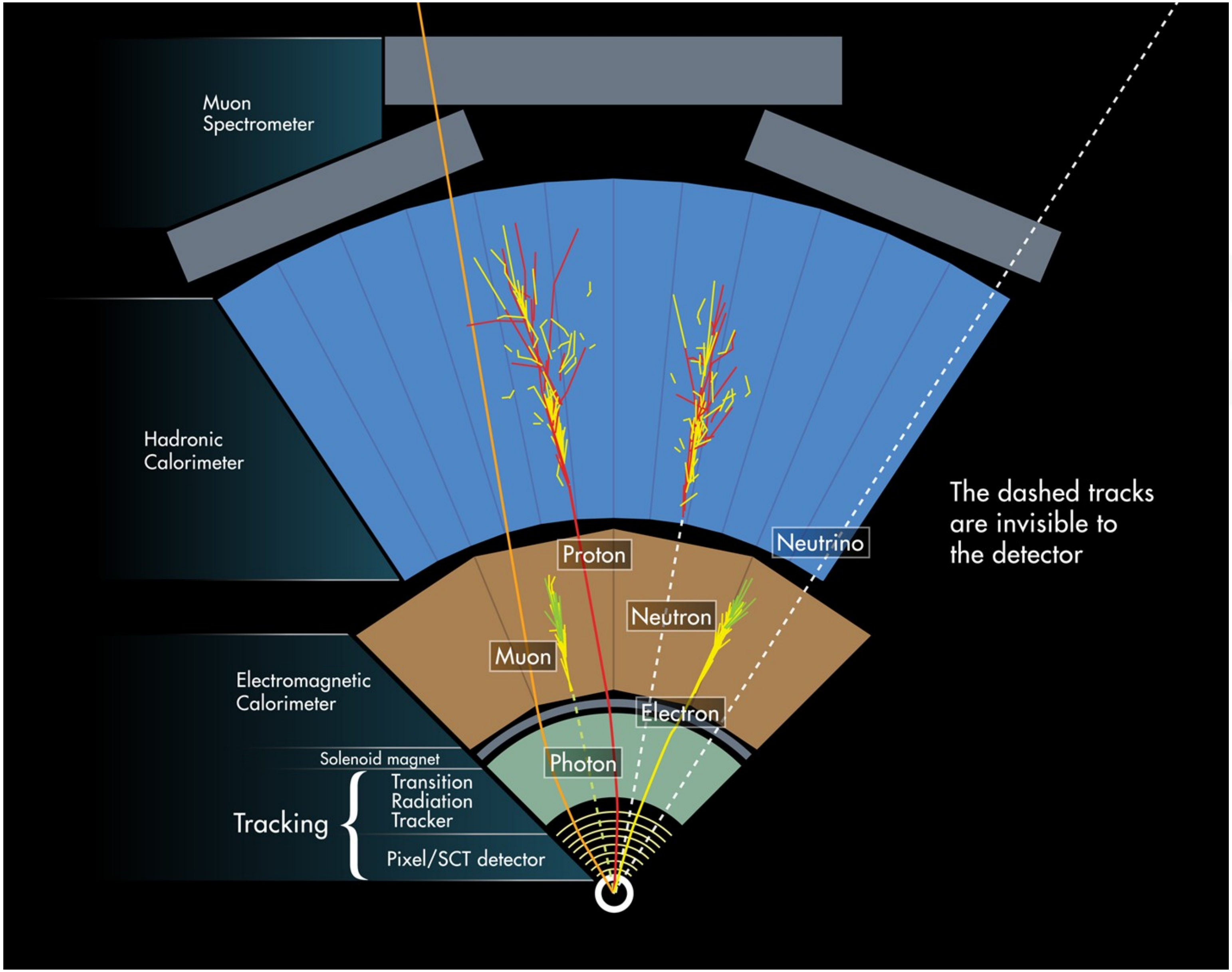
- To improve our measurements and searches, the LHC and ATLAS will be upgraded:



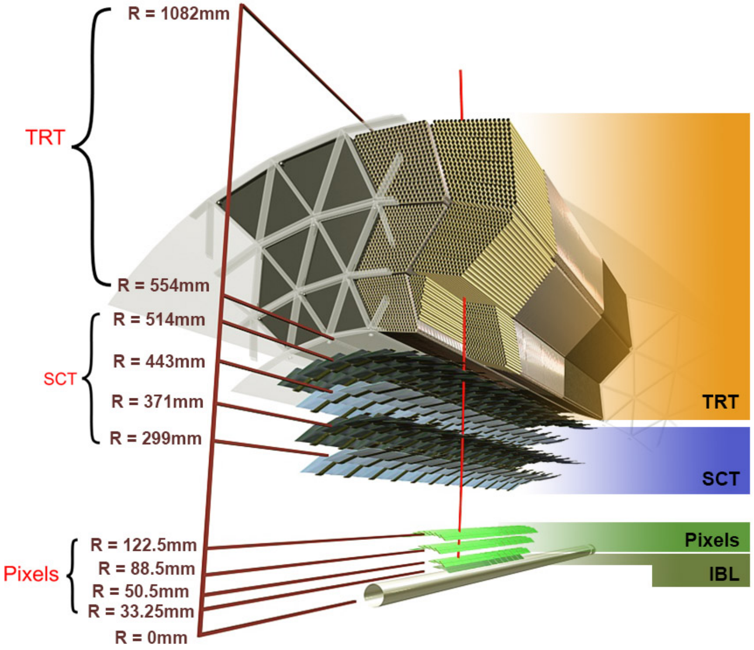
- The LHC will become the High-Luminosity-LHC, to produce 3000 fb^{-1} of integrated luminosity by 2035.
  Higher Energy → benefits searches for new particles.
  Higher integrated luminosity → benefits precision measurements and studies of rare processes.

- Instantaneous luminosity x5-7
  → Particle densities x5-7
- Integrated luminosity x10
  → Radiation damage x10

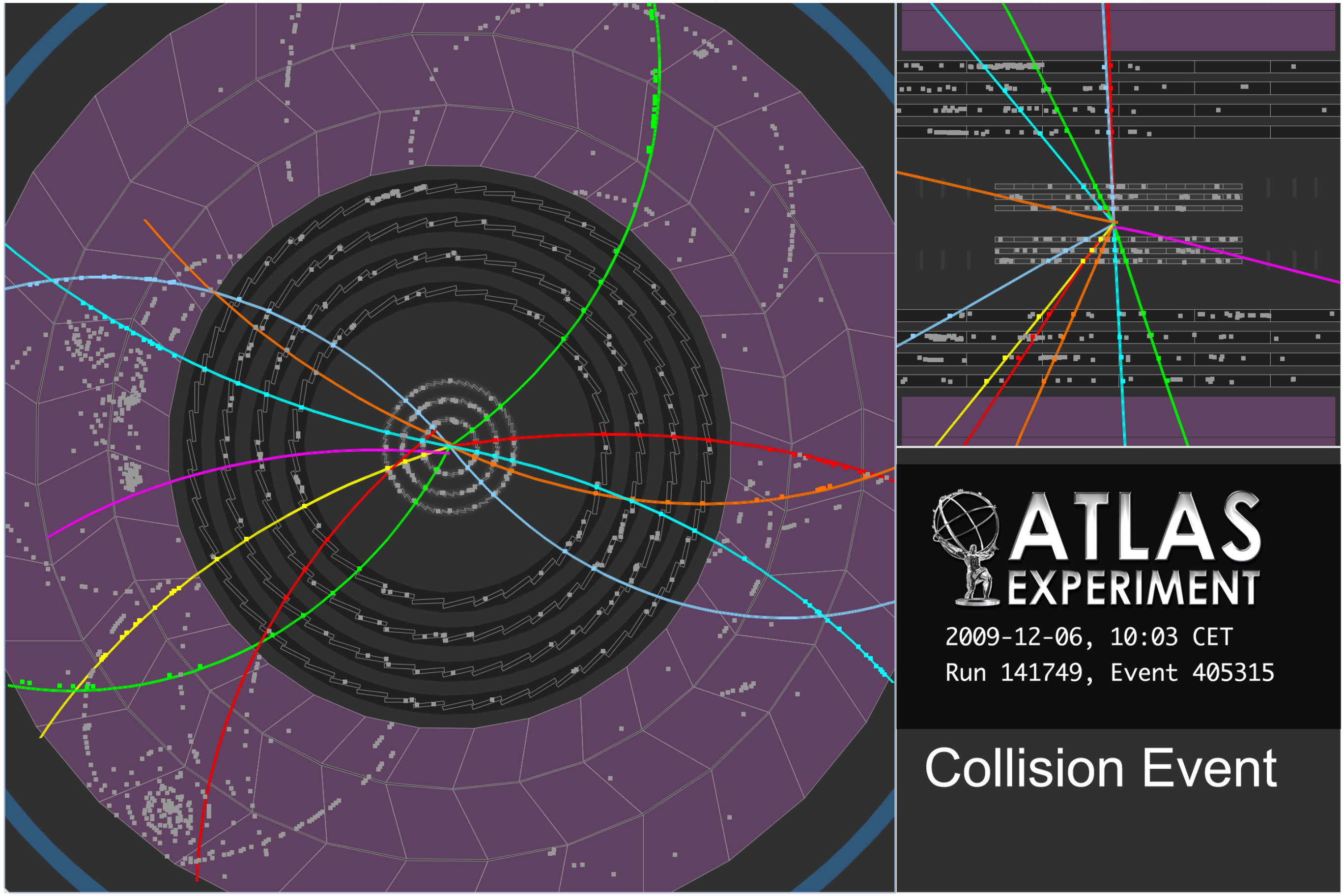
- First, let us understand what a tracking detector is for in ATLAS:



- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.

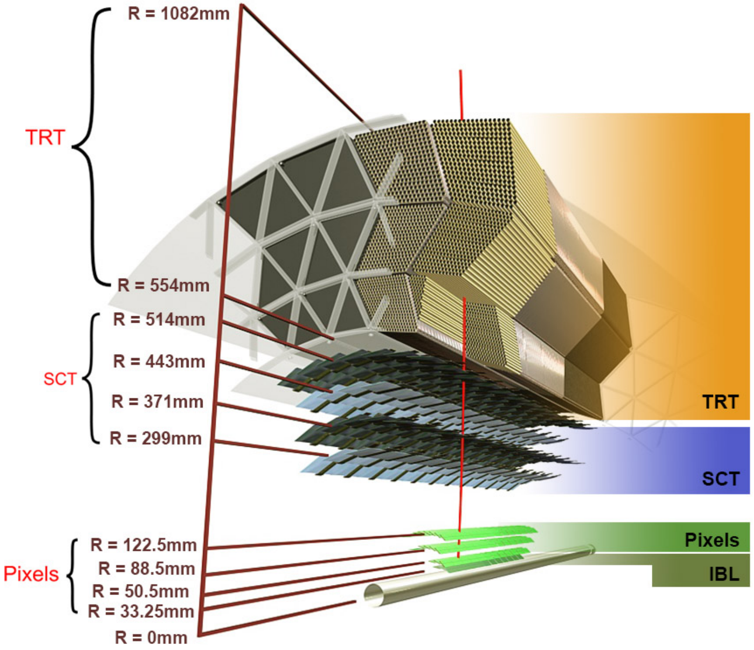


Current ATLAS Inner Detector

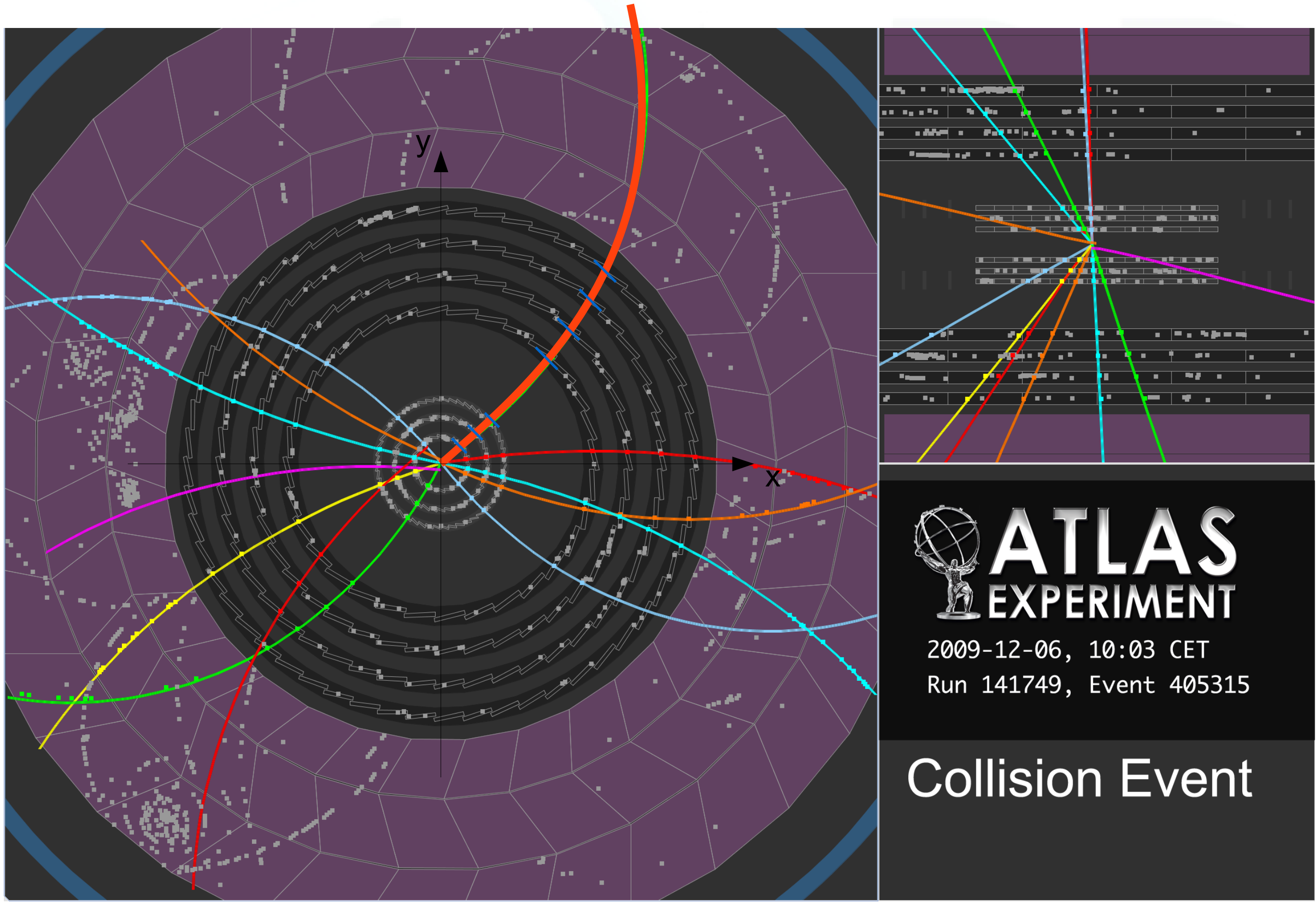


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.



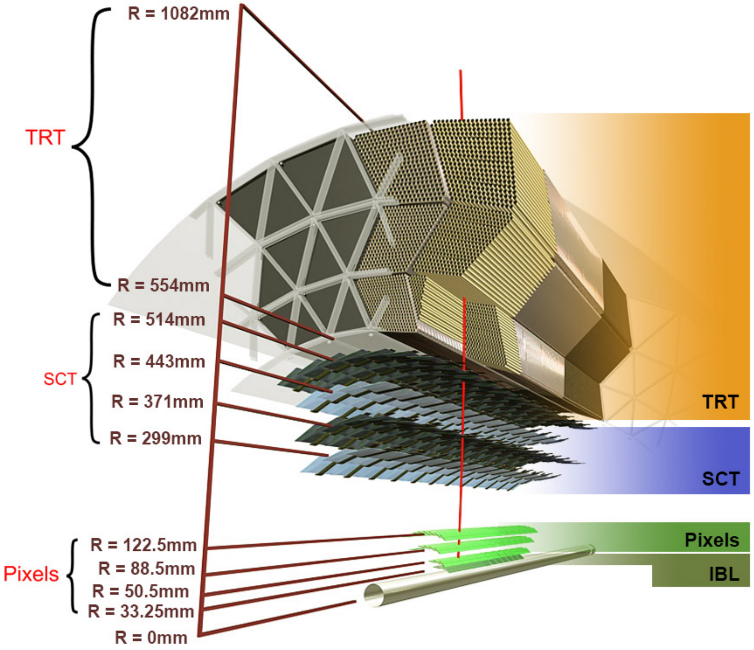
Current ATLAS Inner Detector



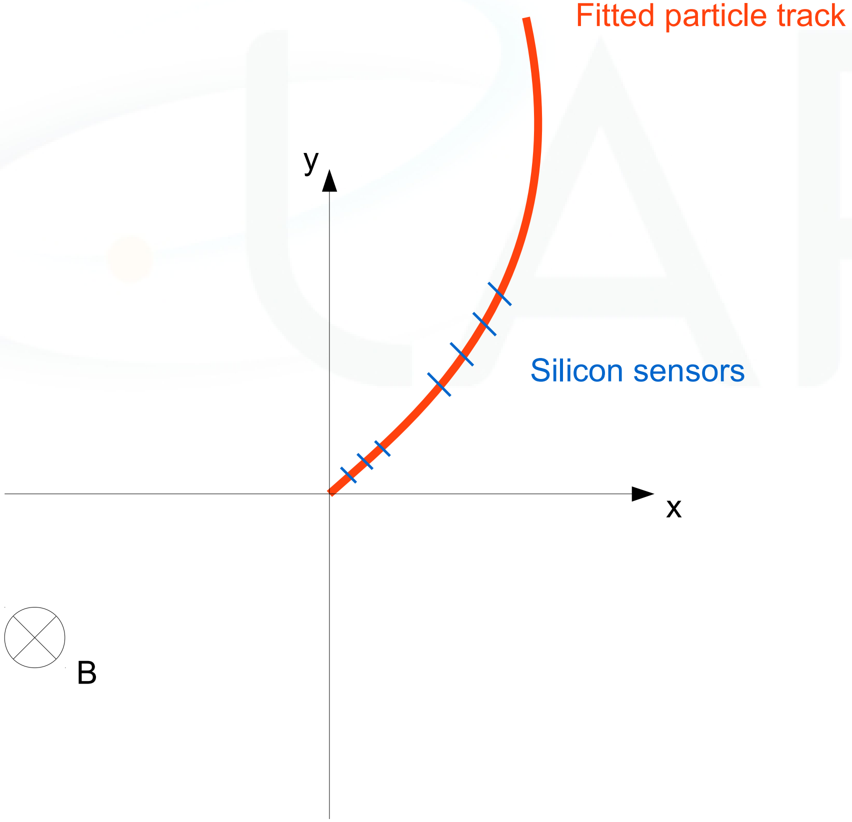
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Why Upgrade The ATLAS Tracking Detector?

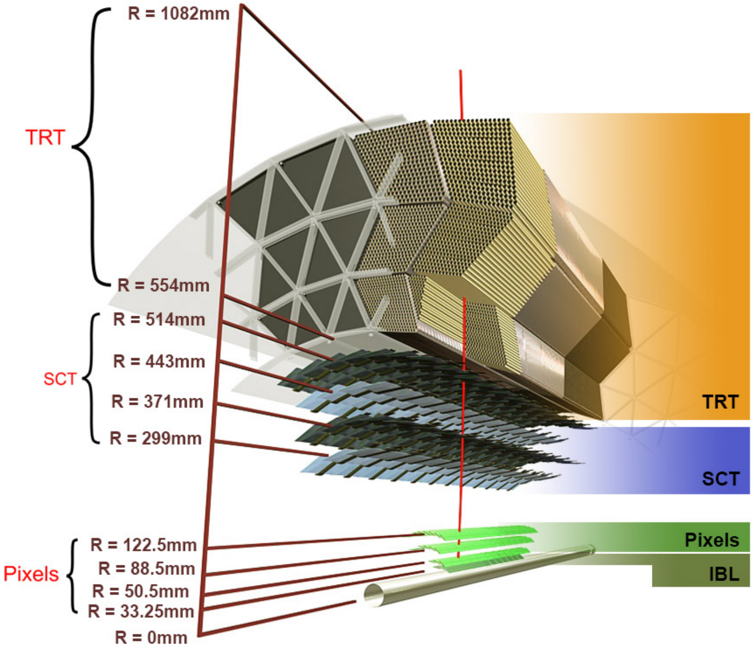
- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.



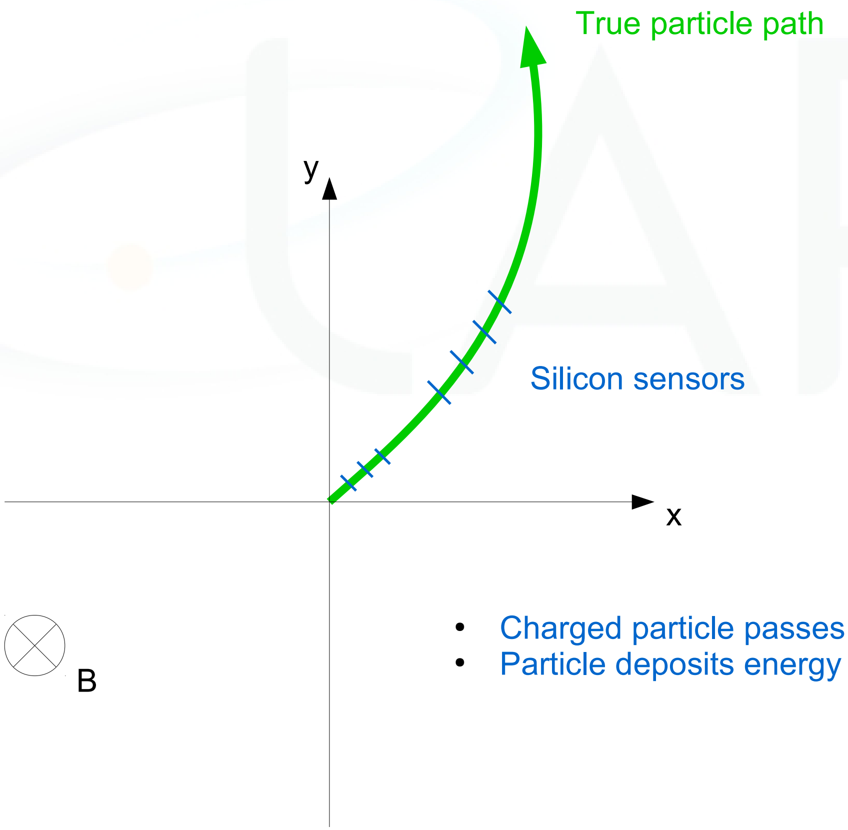
Current ATLAS Inner Detector



- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.

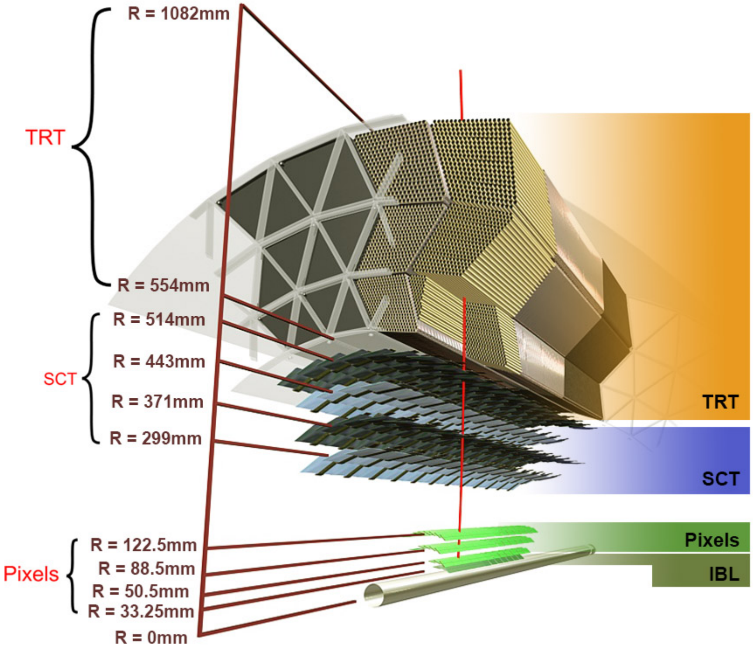


Current ATLAS Inner Detector

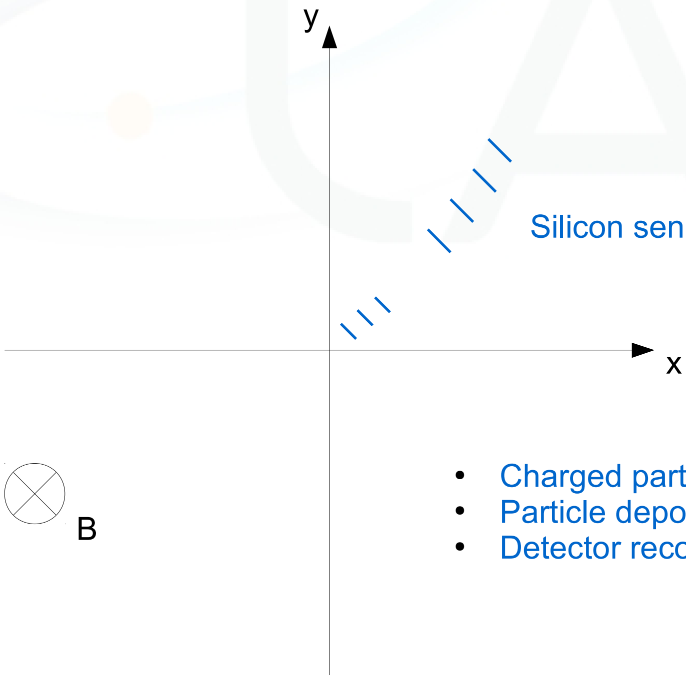


- Charged particle passes through detector.
- Particle deposits energy in each sensor it hits.

- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.



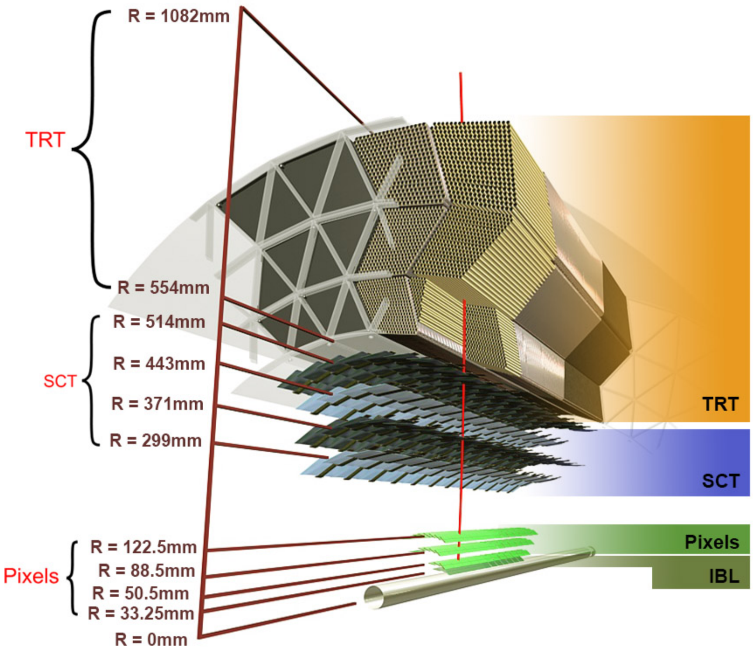
Current ATLAS Inner Detector



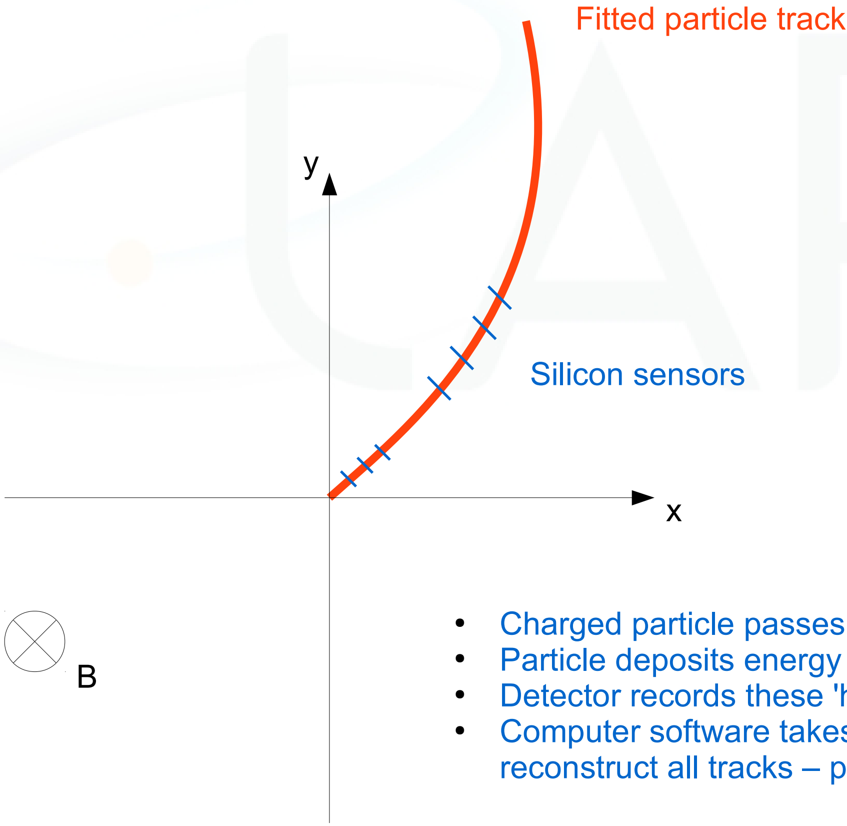
- Charged particle passes through detector.
- Particle deposits energy in each sensor it hits.
- Detector records these 'hits'.

Why Upgrade The ATLAS Tracking Detector?

- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.

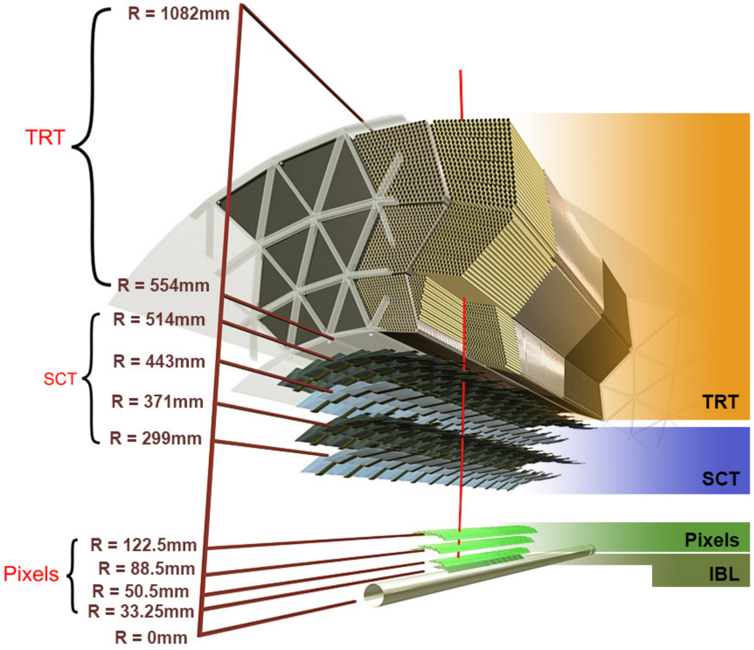


Current ATLAS Inner Detector

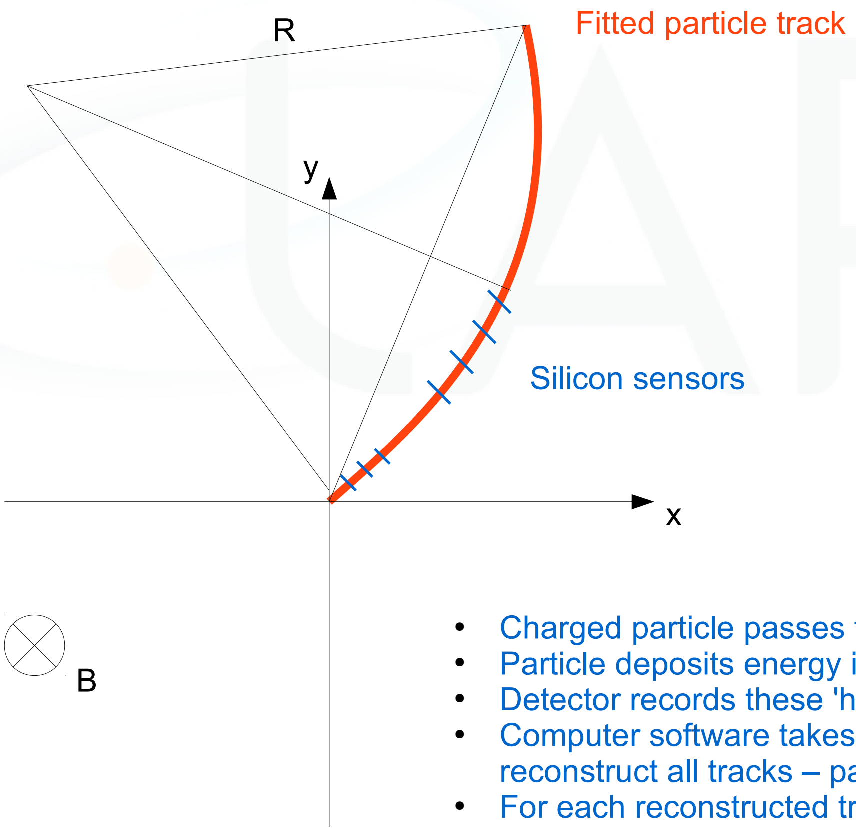


- Charged particle passes through detector.
- Particle deposits energy in each sensor it hits.
- Detector records these 'hits'.
- Computer software takes all 'hits', and tries to reconstruct all tracks – pattern matching.

- First, let us understand what a tracking detector is for in ATLAS:
- The ATLAS tracking detector allows for the identification of electrically charged particles.
- It is immersed in a magnetic field, allowing for momentum measurement.



Current ATLAS Inner Detector

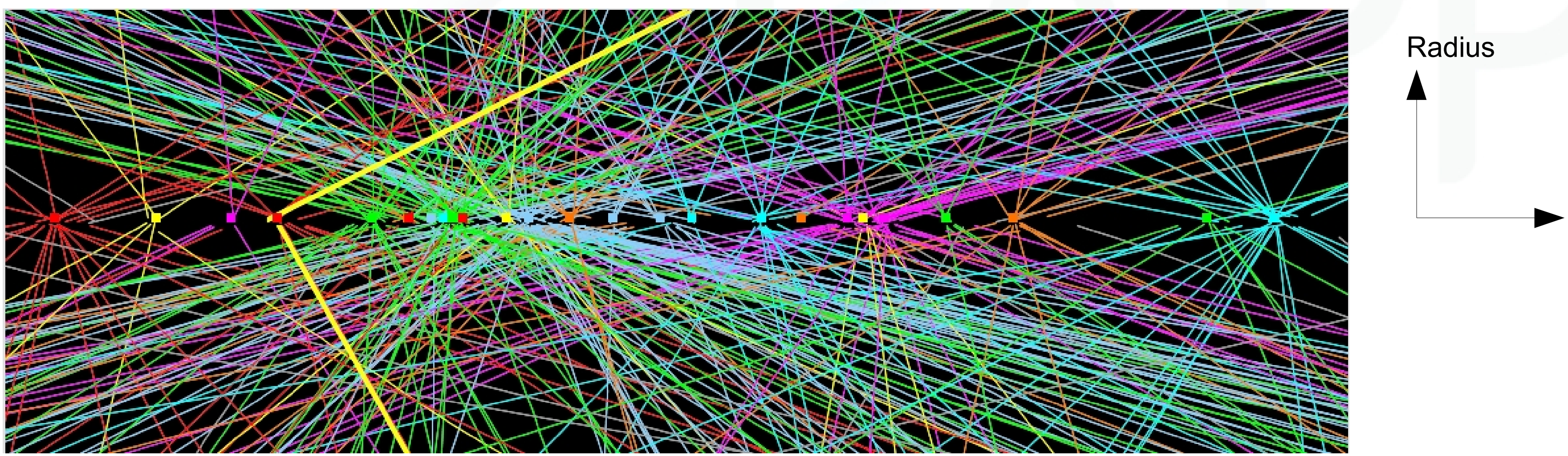


- Charged particle passes through detector.
- Particle deposits energy in each sensor it hits.
- Detector records these 'hits'.
- Computer software takes all 'hits', and tries to reconstruct all tracks – pattern matching.
- For each reconstructed track, the curvature can be calculated, and the transverse momentum computed.

$$p_T = qRB$$

- By the end of LHC Run 3 in 2023, the current ATLAS Inner Detector will be heavily radiation damaged.
- It will also be more than 15 years old by then – newer technology is available with which to build a better tracking detector.
- The HL-LHC will provide a more challenging environment for tracking…

2012 ATLAS event, with 25 reconstructed vertices (μ=25)



Beam spot length: σ_z = ~5cm

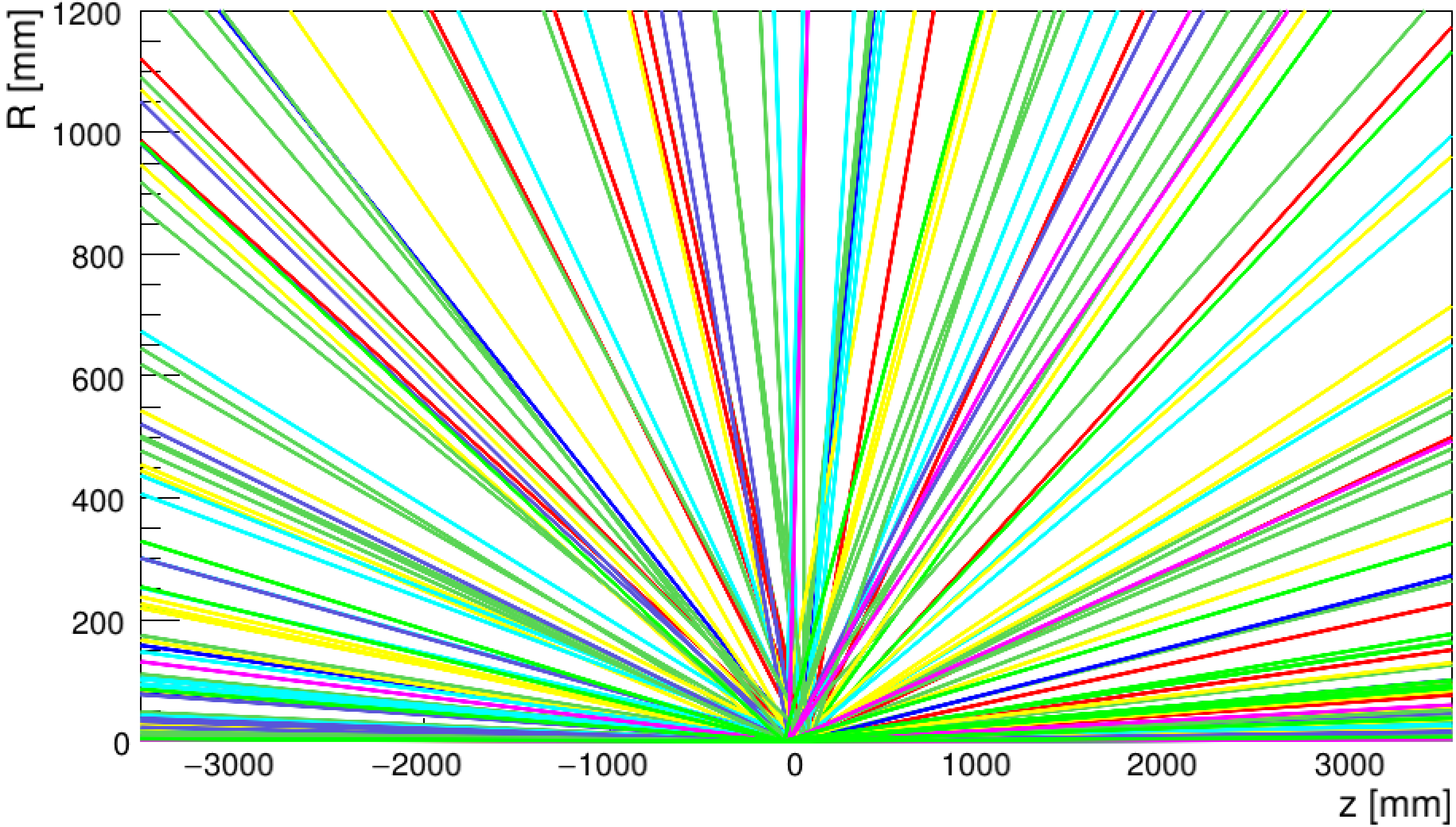
- At the HL-LHC we expect μ=200 within a similar space.

2012 ATLAS event, with 25 reconstructed vertices (μ=25)

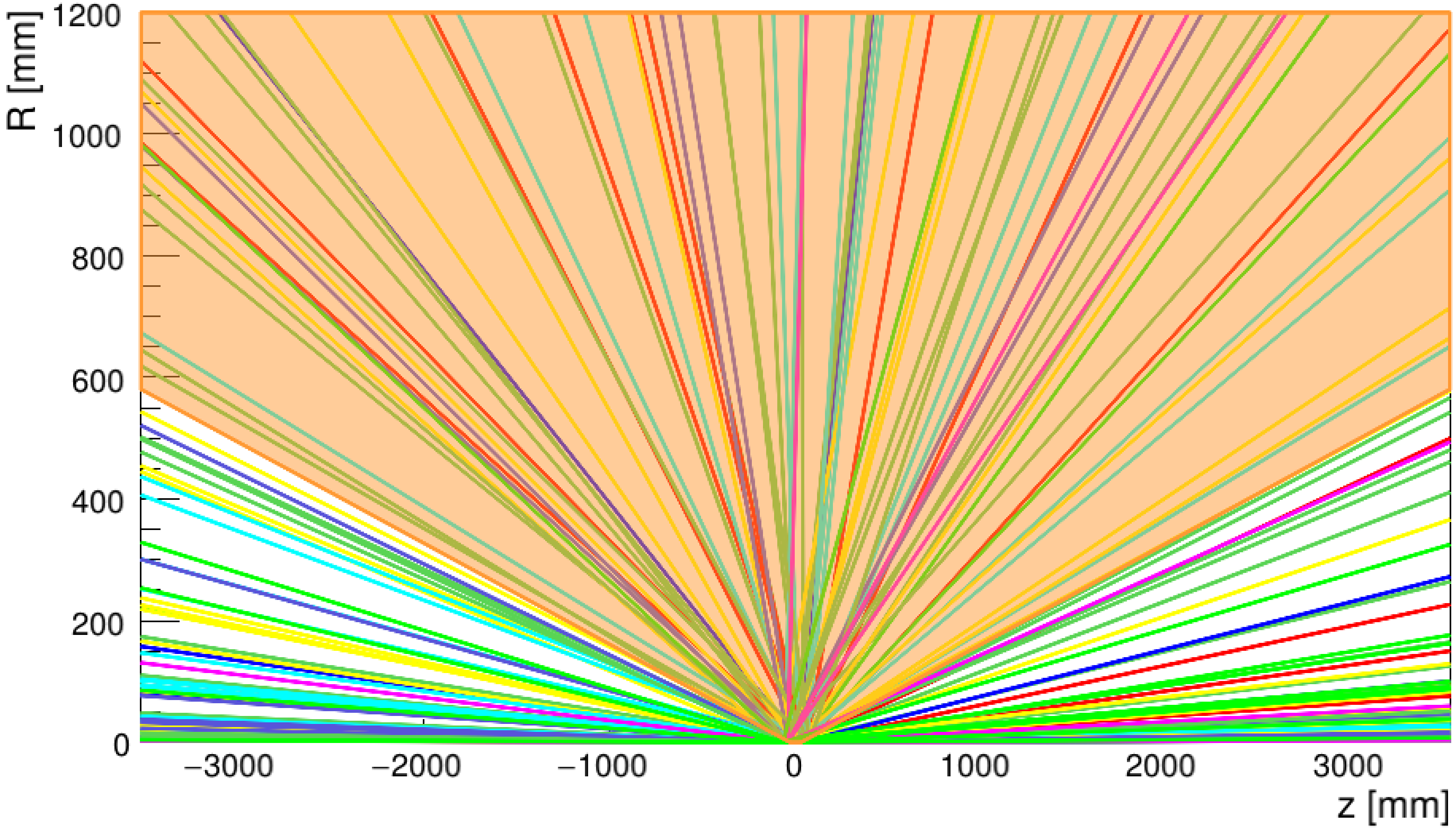
Beam spot length: σ_z = ~5cm

Why Upgrade The ATLAS Tracking Detector?

- μ=25

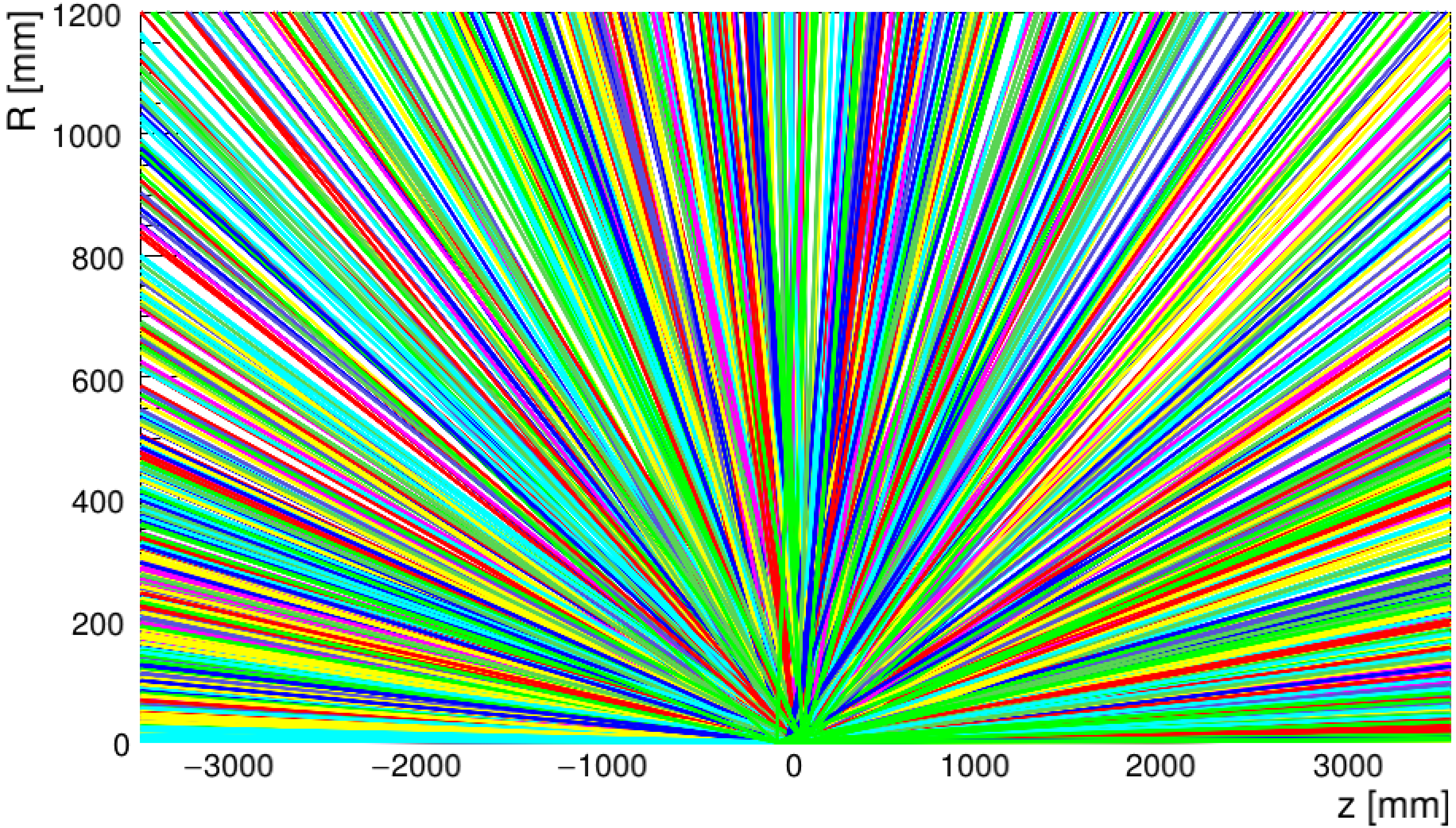


- μ=25
- Angular acceptance of current ATLAS Inner Detector shown (orange).



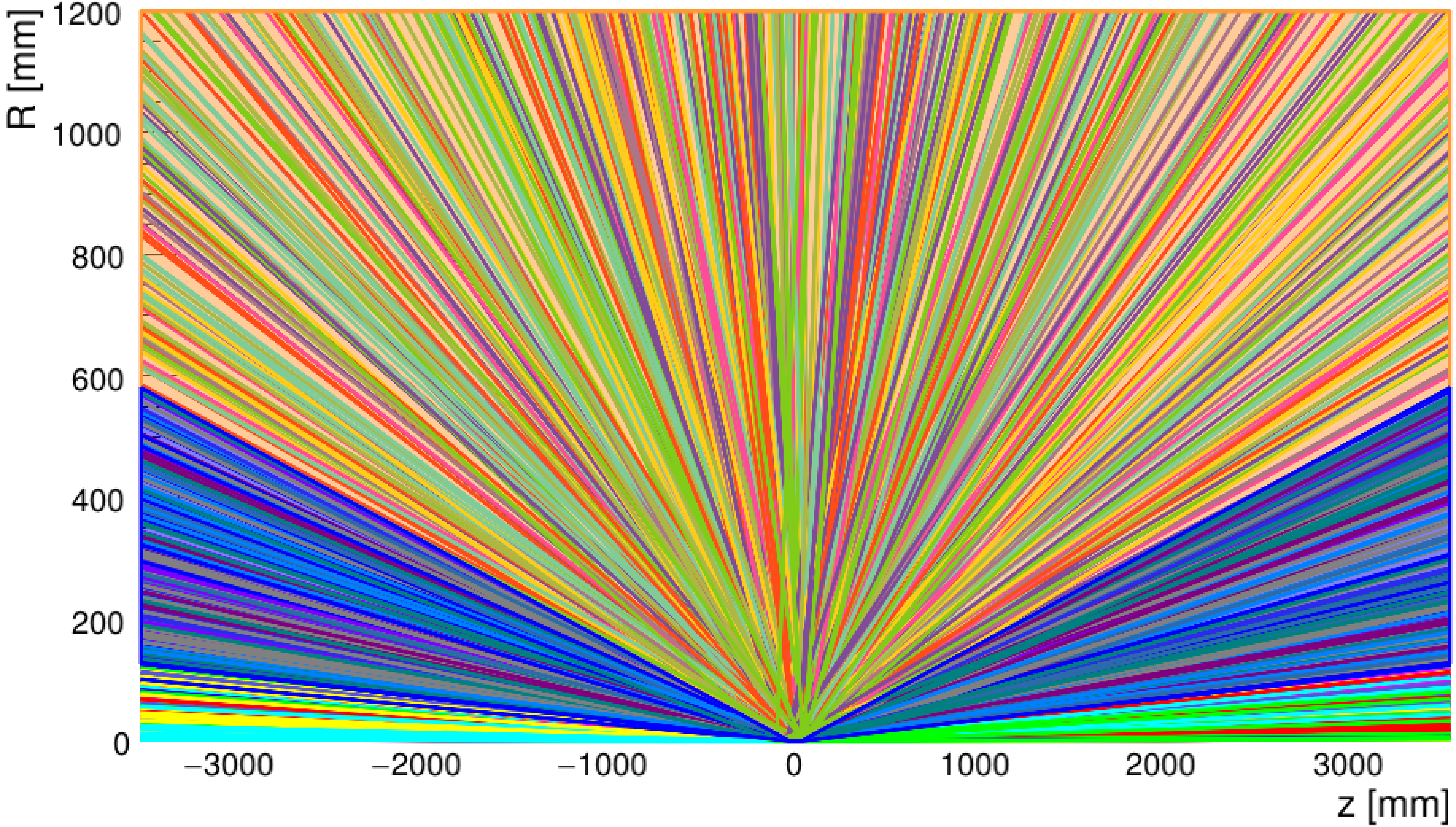
Why Upgrade The ATLAS Tracking Detector?

- μ=200.

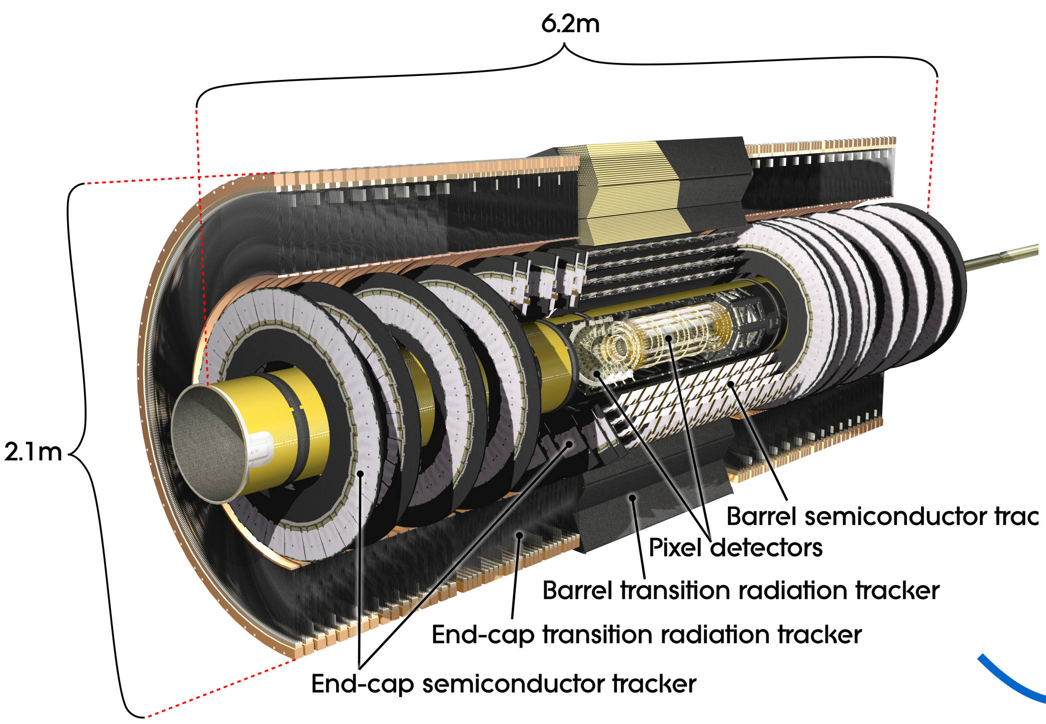


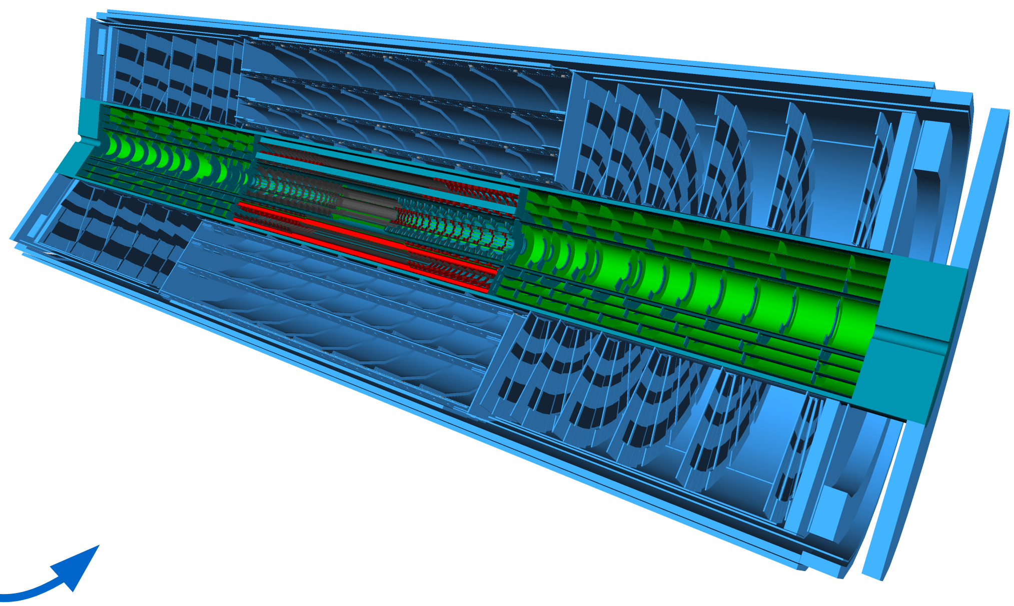
Why Upgrade The ATLAS Tracking Detector?

- μ=200.
- Angular acceptance of current ATLAS Inner Detector shown (orange), and extra coverage of ITk (blue).



- LHC will be upgraded, providing new physics opportunities, but also a challenging environment to work in.
- Existing components will be heavily radiation-damaged by 2023.
- ITk will use newer technology, have increased angular acceptance, and have better performance, than the current Inner Detector.





Current Inner Detector

Inner Tracker (ITk)

- What LHC and ATLAS upgrades and why?
- Tracking detector performance and how to achieve it.
- Physics studies with the upgraded LHC and ATLAS – the ultimate goal.

Tracking Detector Performance

- What parameters should we consider for tracking detector performance?

- What parameters should we consider for tracking detector performance?
- The ultimate goal is to improve physics analysis performance.
  - How precisely could we measure known phenomena?
    - Higgs mass.
    - Known Higgs couplings.
  - What limits could we set on processes, models, phenomena, etc.?
    - Higgs self-coupling.
    - Beyond the standard model...

- What parameters should we consider for tracking detector performance?

- The ultimate goal is to improve physics analysis performance.

  - How precisely could we measure known phenomena?
    - Higgs mass.
    - Known Higgs couplings.

  - What limits could we set on processes, models, phenomena, etc.?
    - Higgs self-coupling.
    - Beyond the standard model...

- Unfortunately, if we change some aspect of the ITk design, it is a slow and laborious process to accurately test its effects on the performance in a given physics analysis.

- What parameters should we consider for tracking detector performance?

- Instead, we should think about what aspects of tracking detector performance will most affect physics analysis performance.

    - d_0 resolution → strong indicator of b-tagging performance

    - z_0 resolution → strong indicator of pile-up rejection.

    - Tracking efficiency → how likely are we to detect a particle track?

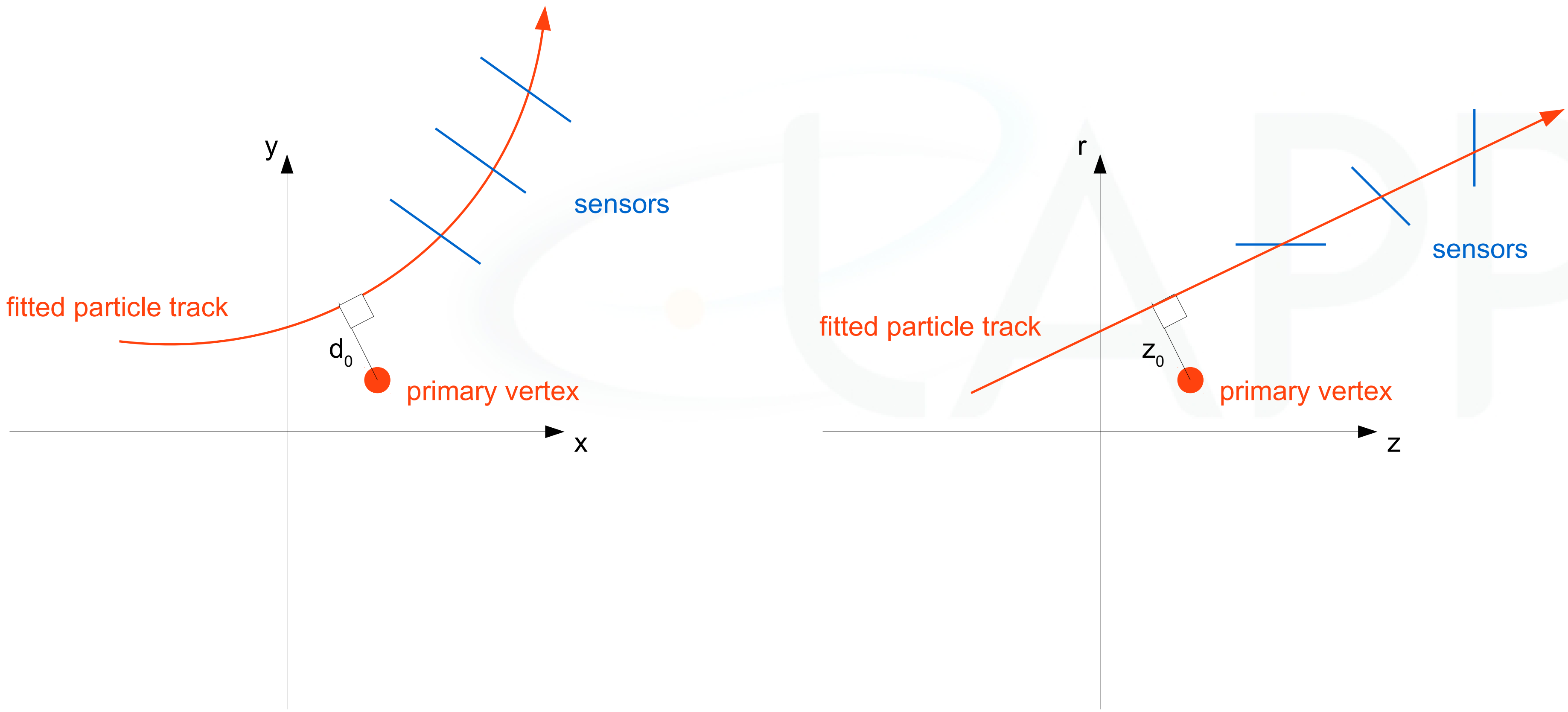
    - p_T resolution → how well can we measure particle momentum.

- Let us look at each of these parameters,
  and understand how our detector design affects them,
  so that we can understand how to optimise our detector.

  - d_0 resolution → strong indicator of b-tagging performance
  - z_0 resolution → strong indicator of pile-up rejection.
  - Tracking efficiency → how likely are we to detect a particle track?
  - p_T resolution → how well can we measure particle momentum.

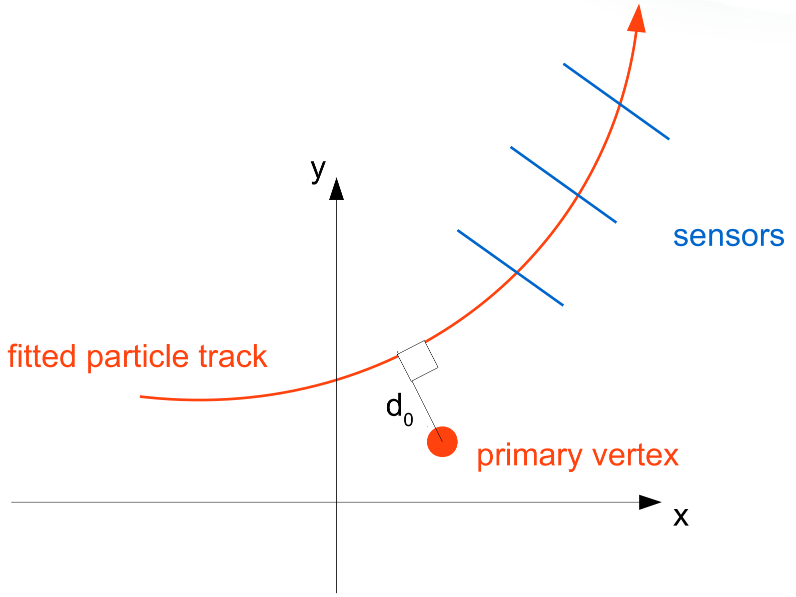
d_0 And z_0 Resolutions – What Are They?

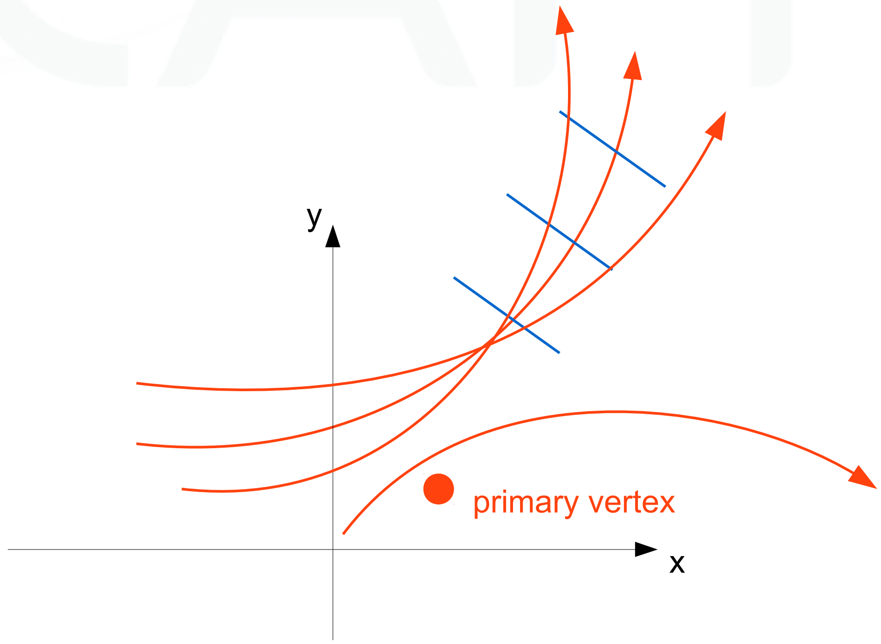
- For each reconstructed track, d_0 and z_0 are measures of how close the track comes to the 'primary vertex' – the location where the nearest proton-proton collision is predicted to have occurred.



- d_0 and z_0 resolutions are the accuracy to which these parameters can be measured – important for correctly associating tracks to the correct vertex.

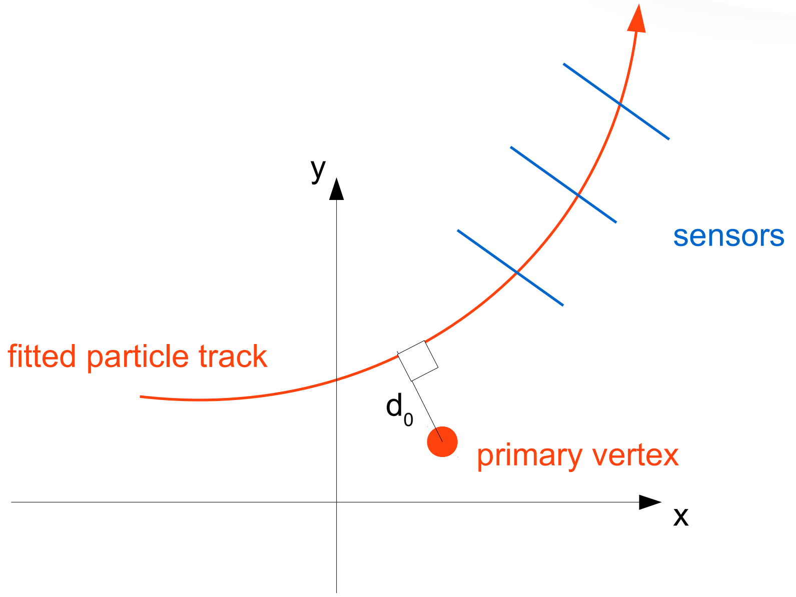
- d_0 resolution is a good predictor of b-tagging performance.
  - 'b-tagging' is the identification of hadronic jets coming from b-quarks.
  - b-quarks form B-hadrons, which can travel ~cm before decaying.
  - Good d_0 resolution allows for tracks to be accurately associated with primary or secondary vertices – important for identifying B decays.
  - b-tagging is vital for physics analyses involving b quarks ($H \to b\bar{b}$).

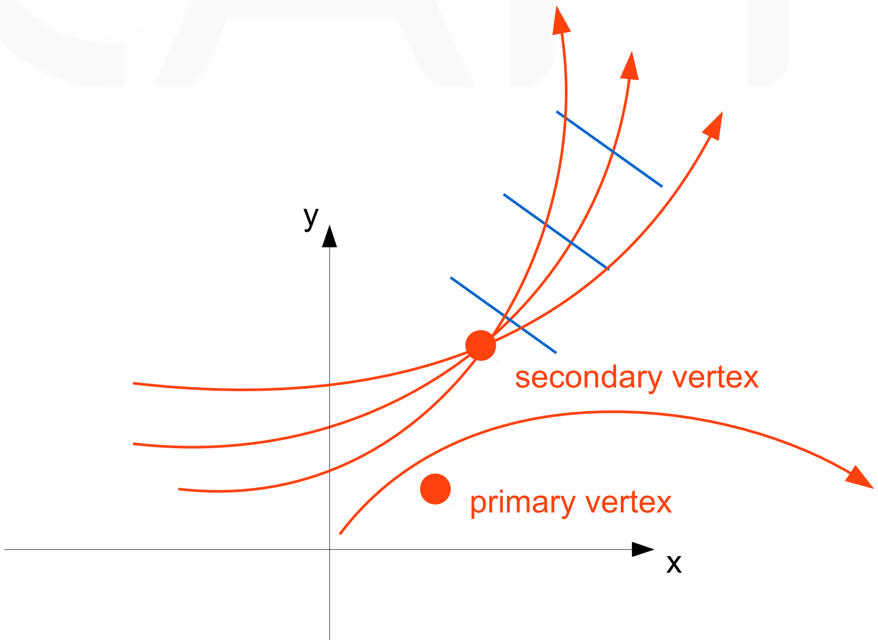




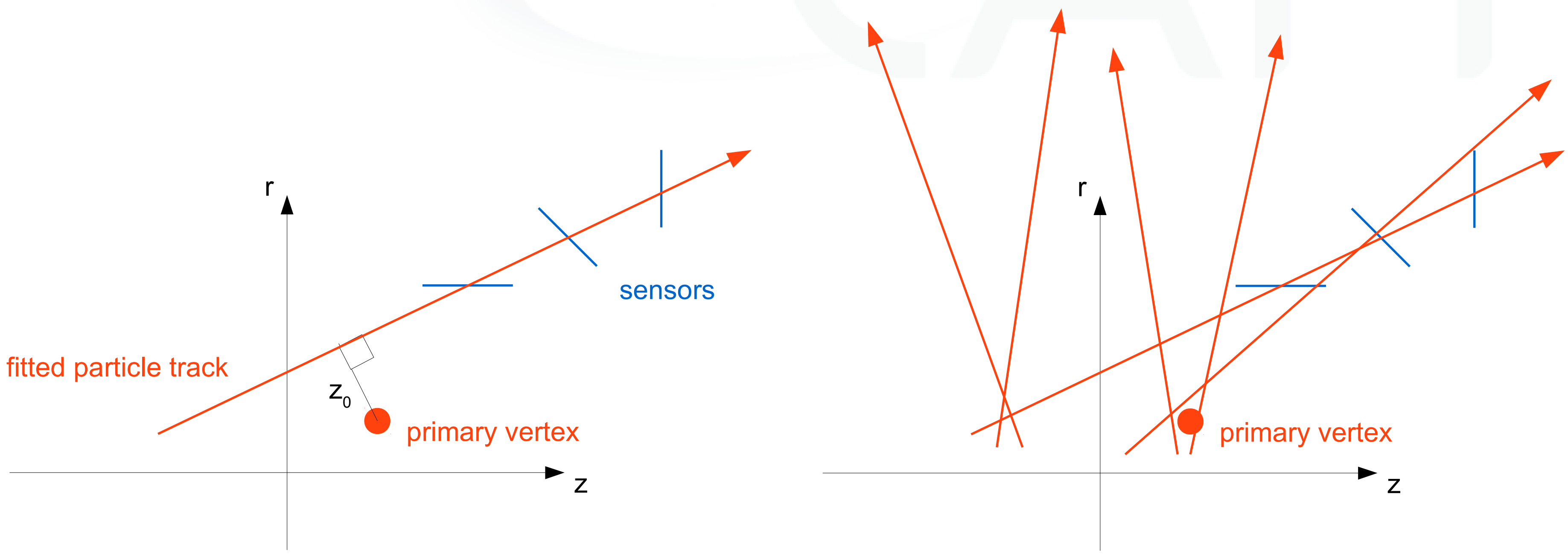
d_0 Resolution – Why Is It Important?

- d_0 resolution is a good predictor of b-tagging performance.
  - 'b-tagging' is the identification of hadronic jets coming from b-quarks.
  - b-quarks form B-hadrons, which can travel ~cm before decaying.
  - Good d_0 resolution allows for tracks to be accurately associated with primary or secondary vertices – important for identifying B decays.
  - b-tagging is vital for physics analyses involving b quarks ($H \to b\bar{b}$).

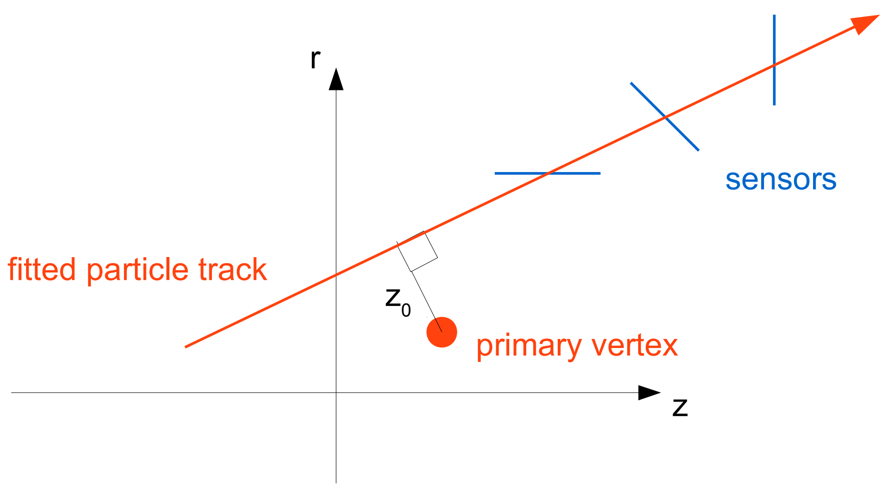


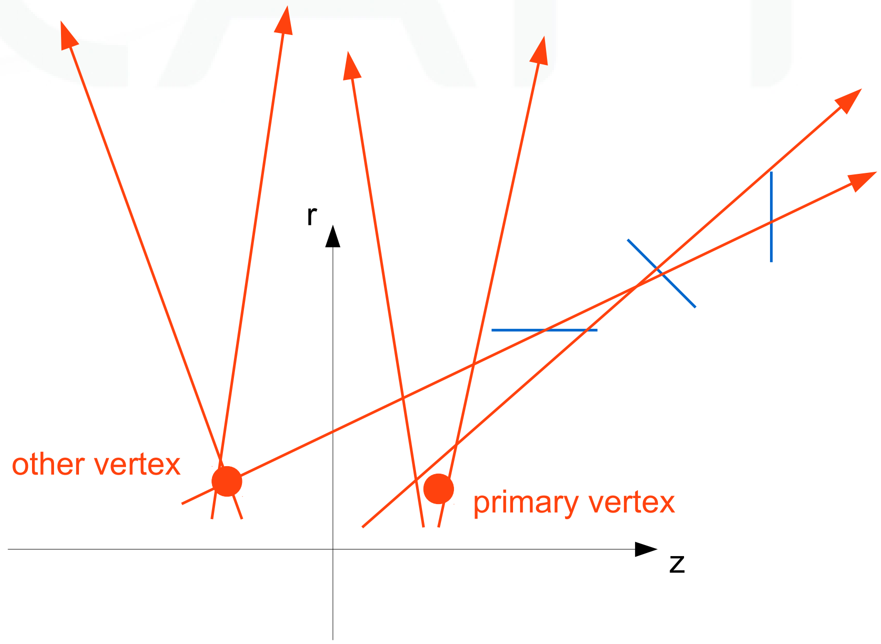


- z_0 resolution is a good predictor of pile-up rejection.
  - Pile-up rejection: isolating what has come from one specific proton-proton collision of interest,
    and rejecting what has come from other proton proton collisions.
  - Good z_0 resolution allows for accurate association of tracks to proton-proton collisions.
  - Good pile-up rejection leads to more accurate physics measurements.

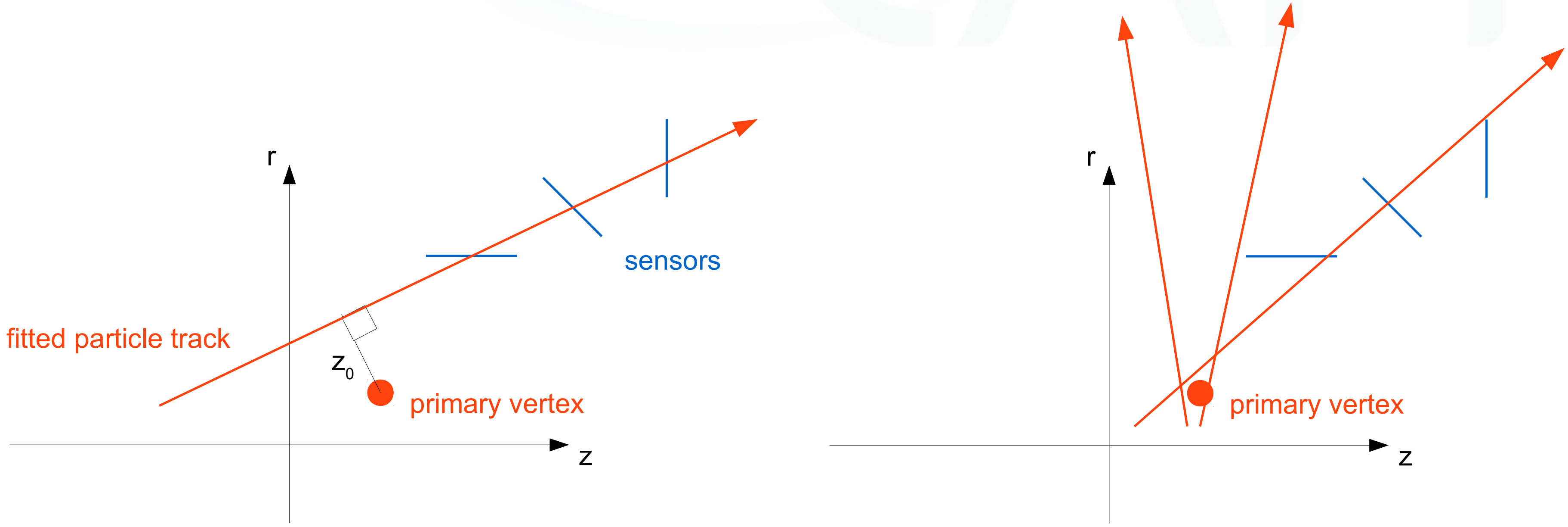


- z_0 resolution is a good predictor of pile-up rejection.
  - Pile-up rejection: isolating what has come from one specific proton-proton collision of interest,
    and rejecting what has come from other proton proton collisions.
  - Good z_0 resolution allows for accurate association of tracks to proton-proton collisions.
  - Good pile-up rejection leads to more accurate physics measurements.





- z_0 resolution is a good predictor of pile-up rejection.
  - Pile-up rejection: isolating what has come from one specific proton-proton collision of interest,
    and rejecting what has come from other proton proton collisions.
  - Good z_0 resolution allows for accurate association of tracks to proton-proton collisions.
  - Good pile-up rejection leads to more accurate physics measurements.



- d_0 and z_0 resolutions are most dependent on the first two hits.
- They can be approximated in the following type of form, taking only these first two hits into account:

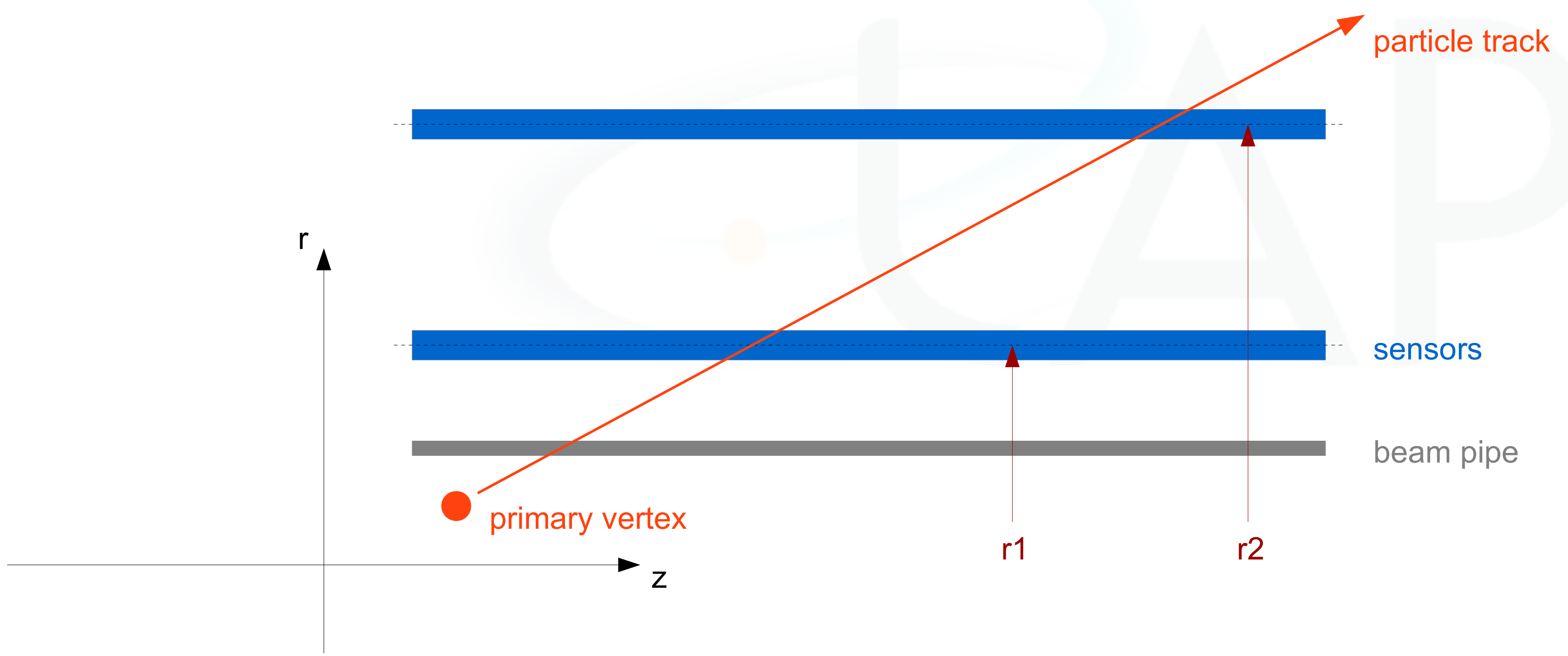
$$\sigma_{z0} = \frac{r_1\sigma_{2z} + r_2\sigma_{1z}}{r_2 - r_1} + \frac{k_{1z}r_1}{p_T}$$

- d_0 and z_0 resolutions are most dependent on the first two hits.
- They can be approximated in the following type of form, taking only these first two hits into account:

$$\sigma_{z0} = \underbrace{\frac{r_1\sigma_{2z} + r_2\sigma_{1z}}{r_2 - r_1}}_{\text{constant term}} + \underbrace{\frac{k_{1z}r_1}{p_T}}_{p_T\text{ dependent term}}$$

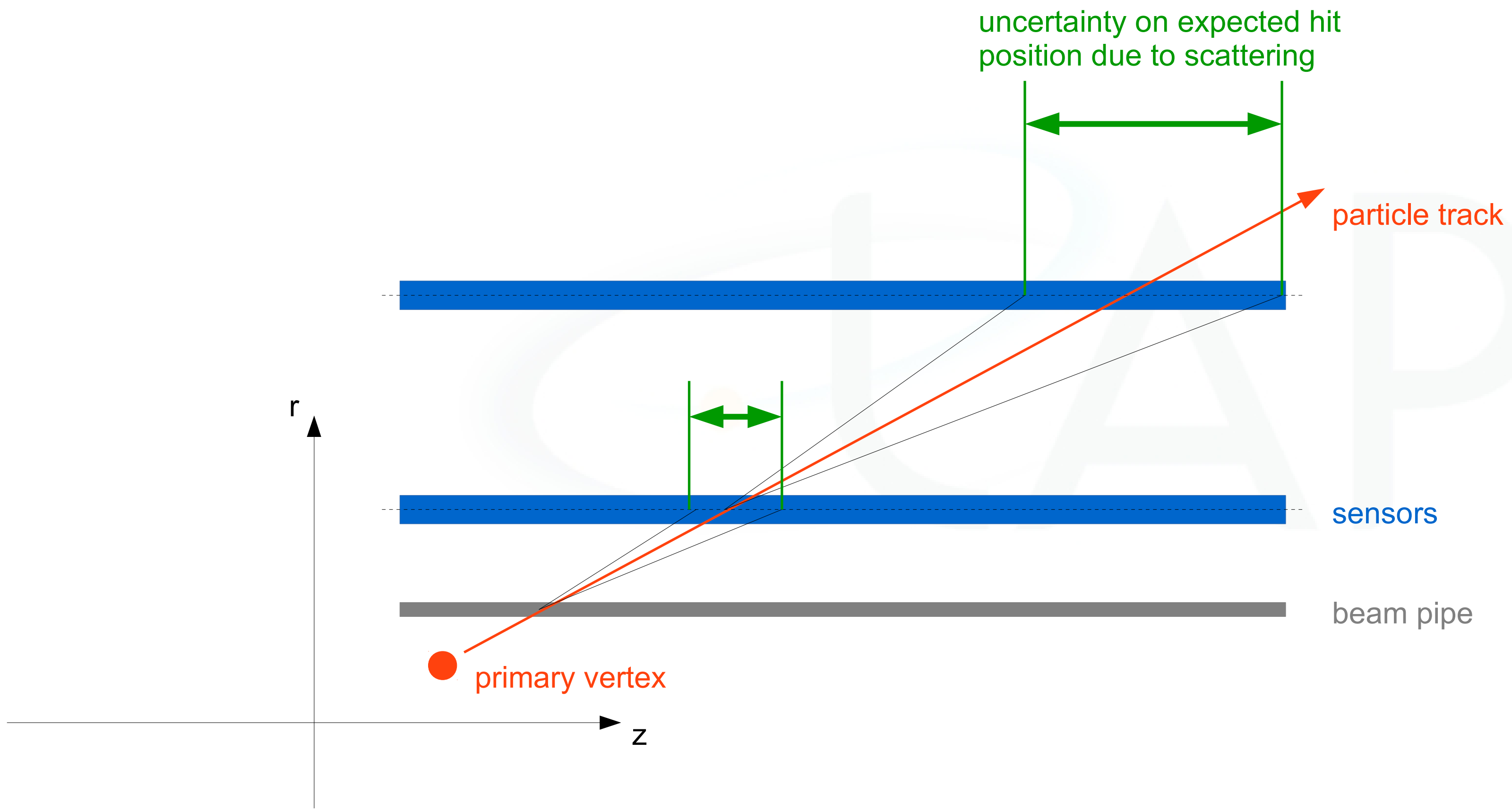
where:
σ_{z0}: z_0 resolution
r_n: radius of nth hit
σ_{nz}: intrinsic resolution in z of nth layer
k_{1z}: scattering component in z

- From this we learn that:
  we should have the first hit as close to the interaction point as possible,
  and have a large distance between the first and second,
  to provide a good 'lever arm' for the track fitting.



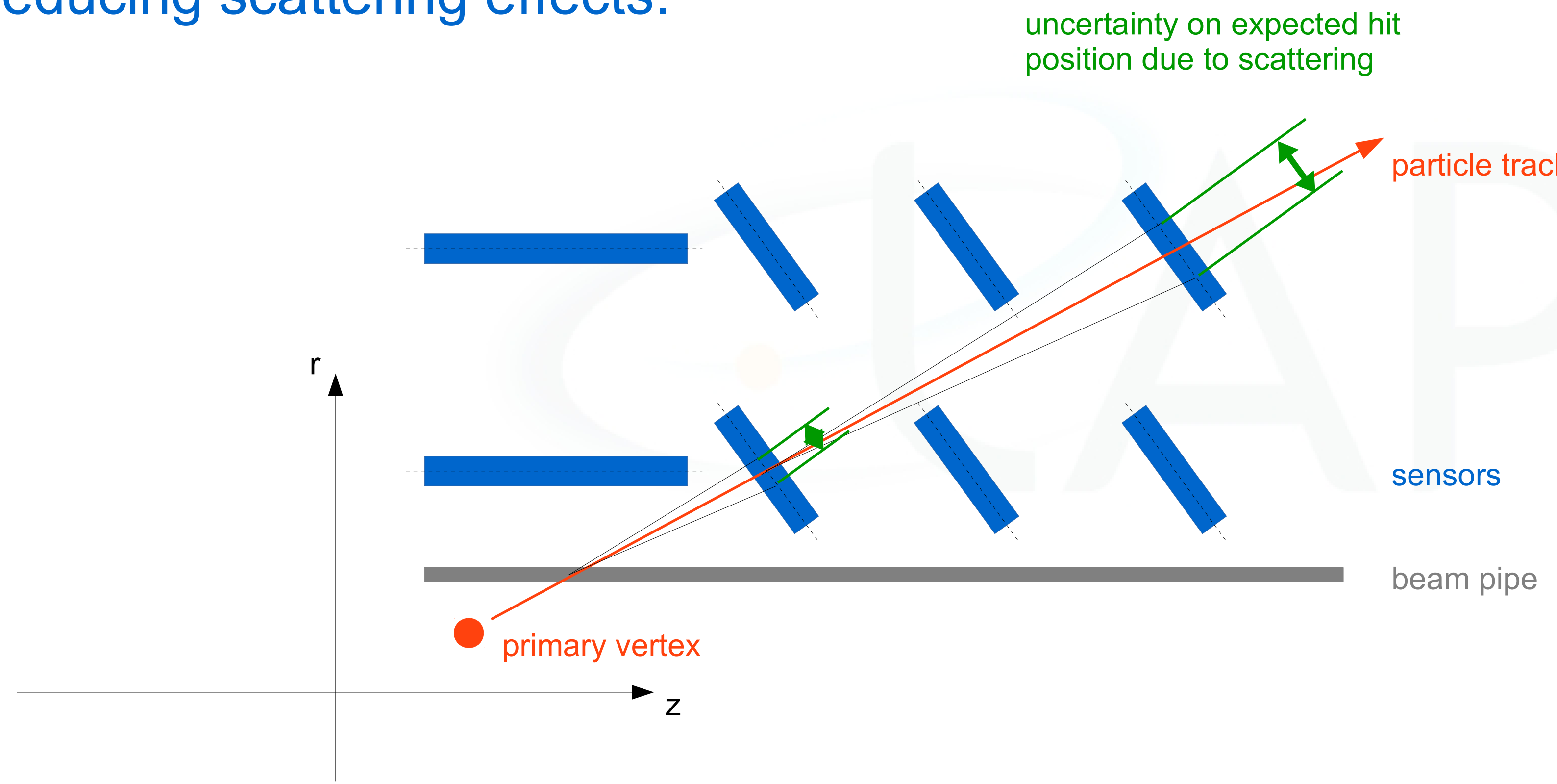
$$\sigma_{z0} = \frac{r_1\sigma_{2z} + r_2\sigma_{1z}}{r_2 - r_1} + \frac{k_{1z} r_1}{p_T}$$

- But, passing through Silicon sensors at high incident angles leads to a longer particle path-length through the Silicon, increasing scattering.



$$\sigma_{z0} = \frac{r_1 \sigma_{2z} + r_2 \sigma_{1z}}{r_2 - r_1} + \frac{\boxed{k_{1z}} r_1}{p_T}$$

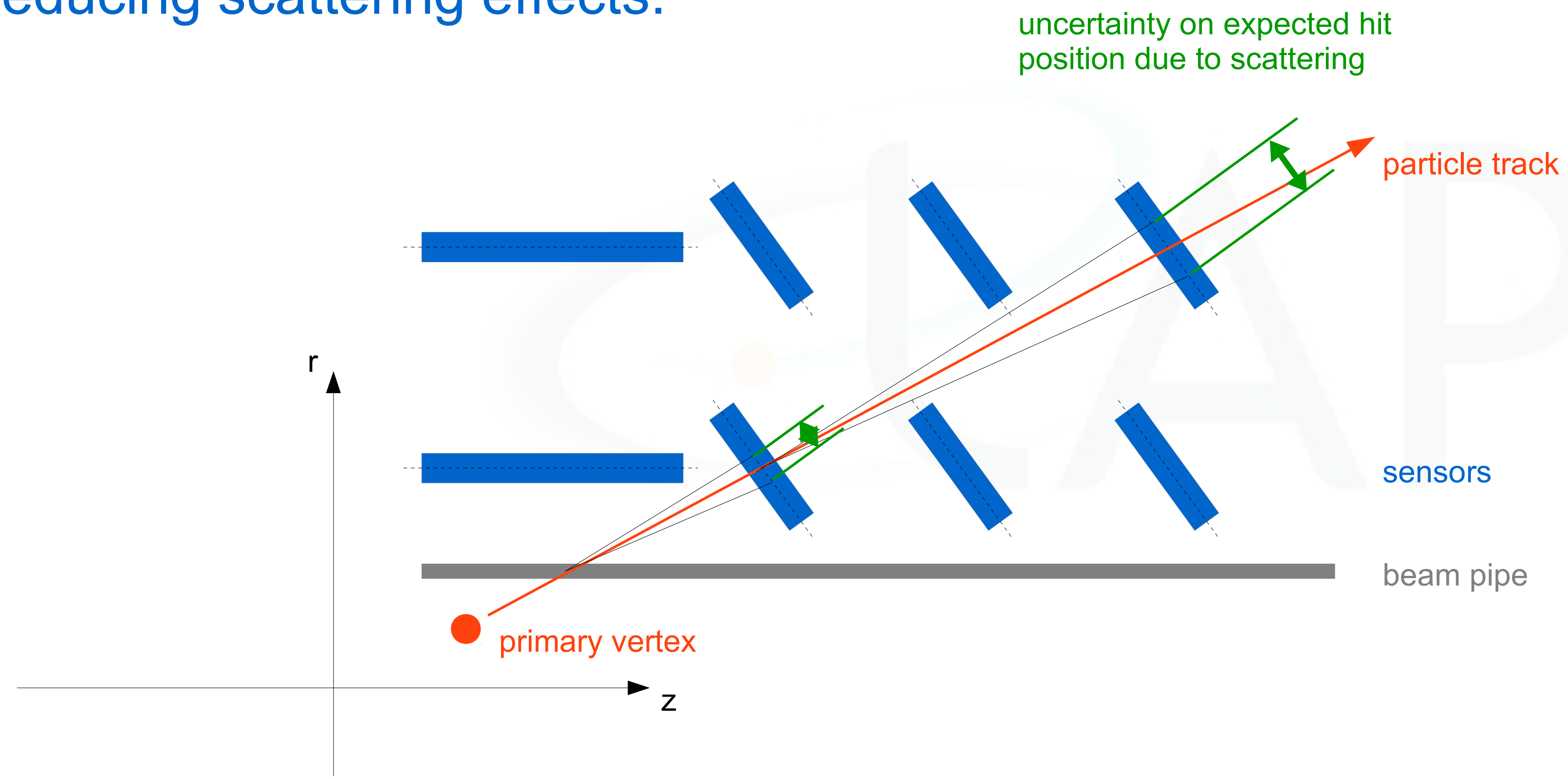
- One solution is to incline sensors
  to be more perpendicular to incident particle paths,
  thus reducing the path-length through the Silicon,
  so reducing scattering effects.



$$\sigma_{z0} = \frac{r_1\sigma_{2z} + r_2\sigma_{1z}}{r_2 - r_1} + \frac{\boxed{k_{1z}}r_1}{p_T}$$

d_0 And z_0 Resolutions – Scattering

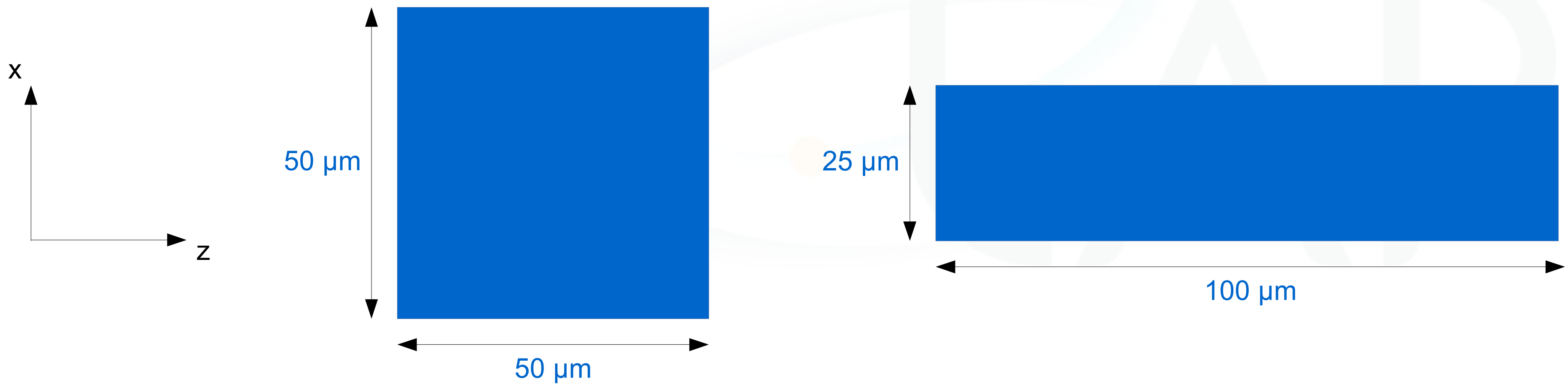
- One solution is to incline sensors
  to be more perpendicular to incident particle paths,
  thus reducing the path-length through the Silicon,
  so reducing scattering effects.



$$\sigma_{z0} = \frac{r_1 \sigma_{2z} + r_2 \sigma_{1z}}{r_2 - r_1} + \frac{k_{1z} r_1}{p_T}$$

- Minimising all material in front of
  first few hits also reducing scattering.
- A light-weight detector is thus important.

- The size of the individual pixels will affect the intrinsic resolutions of the sensors.
- The smaller the pixel pitch along a given axis, the better the resolution along that axis.
- Choice to be made for ITk pixel size:



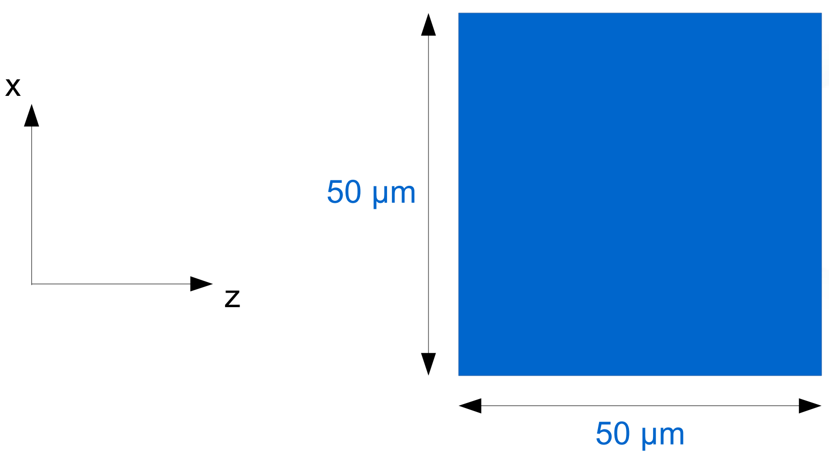
- Each pixel sensor is ~2cm by ~2cm, divided up into many pixels.

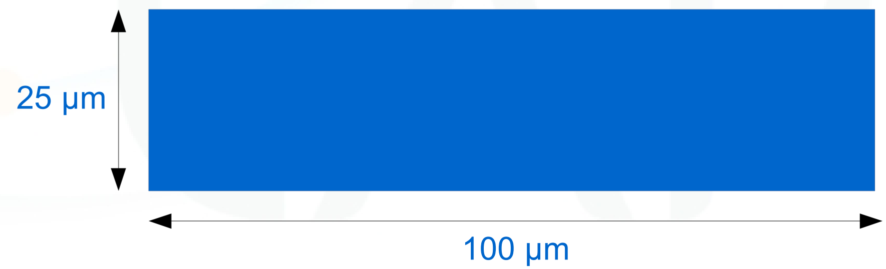
$$\sigma_{z0} = \frac{r_1 \boxed{\sigma_{2z}} + r_2 \boxed{\sigma_{1z}}}{r_2 - r_1} + \frac{k_{1z} r_1}{p_T}$$

(current ATLAS Inner Detector has $50\text{x}400\mu m^2$ and $50\text{x}250\mu m^2$ pixels)

- The size of the individual pixels will affect the intrinsic resolutions of the sensors.
- The smaller the pixel pitch along a given axis, the better the resolution along that axis.
- Choice to be made for ITk pixel size:

$$\sigma_{z0} = \frac{r_1 \boxed{\sigma_{2z}} + r_2 \boxed{\sigma_{1z}}}{r_2 - r_1} + \frac{k_{1z} r_1}{p_T}$$





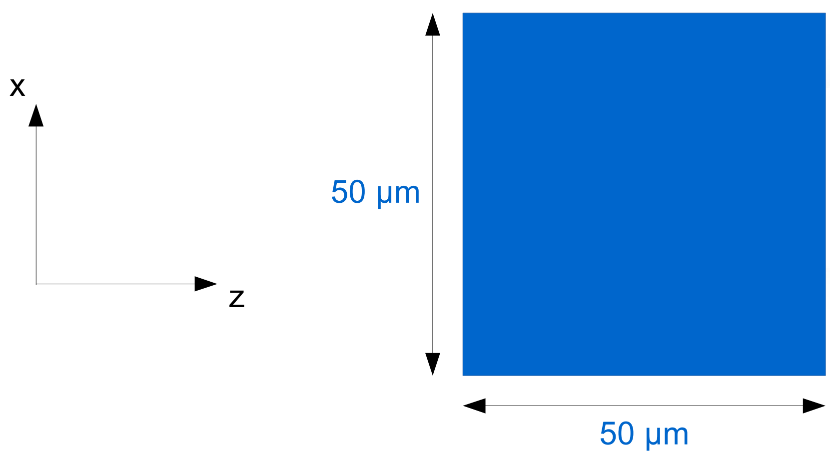
- 50×50 µm²
- Smaller pitch along z
  → better z_0 resolution*
  → better pile-up rejection*
- Larger pitch in x-y plane
  → worse d_0 resolution
  → worse b-tagging

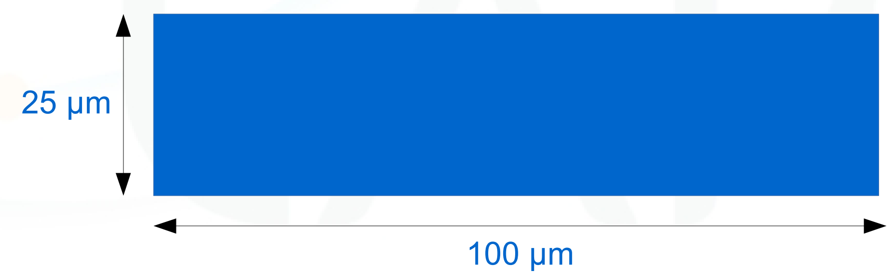
- 25×100 µm²
- Larger pitch along z
  → worse z_0 resolution*
  → worse pile-up rejection*
- Smaller pitch in x-y plane
  → better d_0 resolution
  → better b-tagging

d_0 And z_0 Resolutions – Pixel Pitch

- The size of the individual pixels will affect the intrinsic resolutions of the sensors.
- The smaller the pixel pitch along a given axis, the better the resolution along that axis.
- Choice to be made for ITk pixel size:

$$\sigma_{z0} = \frac{r_1\boxed{\sigma_{2z}} + r_2\boxed{\sigma_{1z}}}{r_2 - r_1} + \frac{k_{1z} r_1}{p_T}$$





- 50x50 µm^2
- Smaller pitch along z
  → better z_0 resolution*
  → better pile-up rejection*
- Larger pitch in x-y plane
  → worse d_0 resolution
  → worse b-tagging

- 25x100 µm^2
- Larger pitch along z
  → worse z_0 resolution*
  → worse pile-up rejection*
- Smaller pitch in x-y plane
  → better d_0 resolution
  → better b-tagging

*At high η, sensor misalignment effects are likely to wash out differences in z0 resolutions.

d_0 And z_0 Resolutions – Conclusions

- d_0 and z_0 resolutions are most dependent on the first two hits.

$$\sigma_{z0} = \frac{r_1 \sigma_{2z} + r_2 \sigma_{1z}}{r_2 - r_1} + \frac{k_{1z} r_1}{p_T}$$

- First layer of sensors (first hit) should be as close to the collision interaction point as possible.

- Second layer of sensors (second hit) should be a reasonable distance away from the first, in order to provide large lever arm,
  – but this should be balanced against scattering effects and intrinsic resolutions – requires optimisation.

- Detector should be as light as possible to minimise scattering effects.

- Optimal orientation of sensors also minimises scattering effects,
  – inclined sensors come with additional engineering challenges.

- Choice to be made on pixel size,
  – different sizes have different advantages.

Tracking Efficiency

- Tracking efficiency: what is the probability that a charge track will be correctly identified and reconstructed?

- Requires high efficiency of all active detector hardware and software.

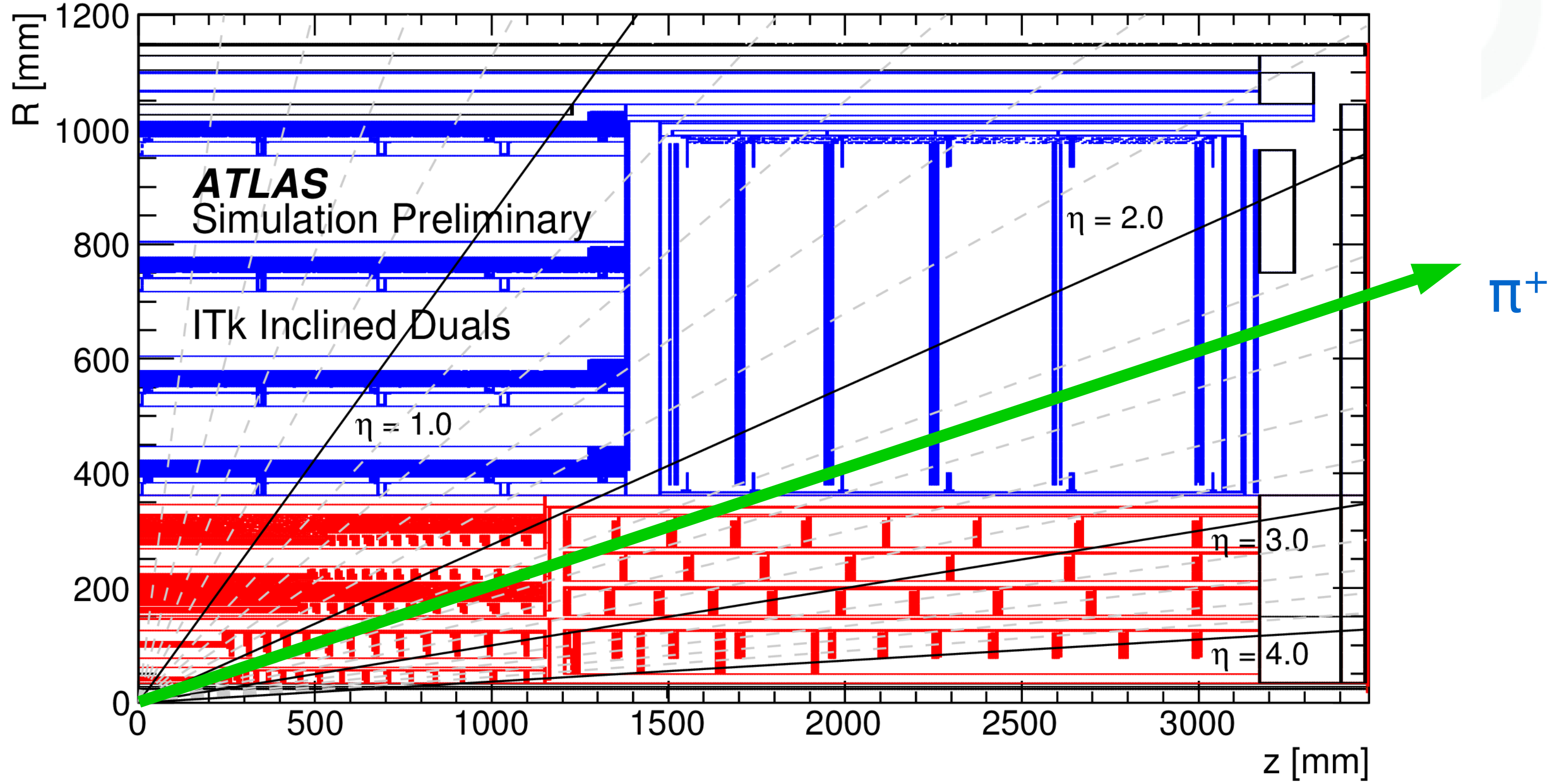
  - If a particle passes through a sensor, the probability for that sensor to register a hit must be close to 100%.
  - Detector design must incorporate redundancy (extra sensor layers):
    - even if one or two sensors on a track do not register hits (these are called 'holes'), there must still be enough hits on track to accurately reconstruct the track.
  - Software must be capable of accurately reconstructing tracks even with missed hits (holes).

- With high-efficiency detector components and software, tracking efficiency is then mostly dependent on material interactions.

- Interactions between particles and the nuclei of detector material are the dominant cause of 'lost' tracks, (assuming high-efficiency sensors).

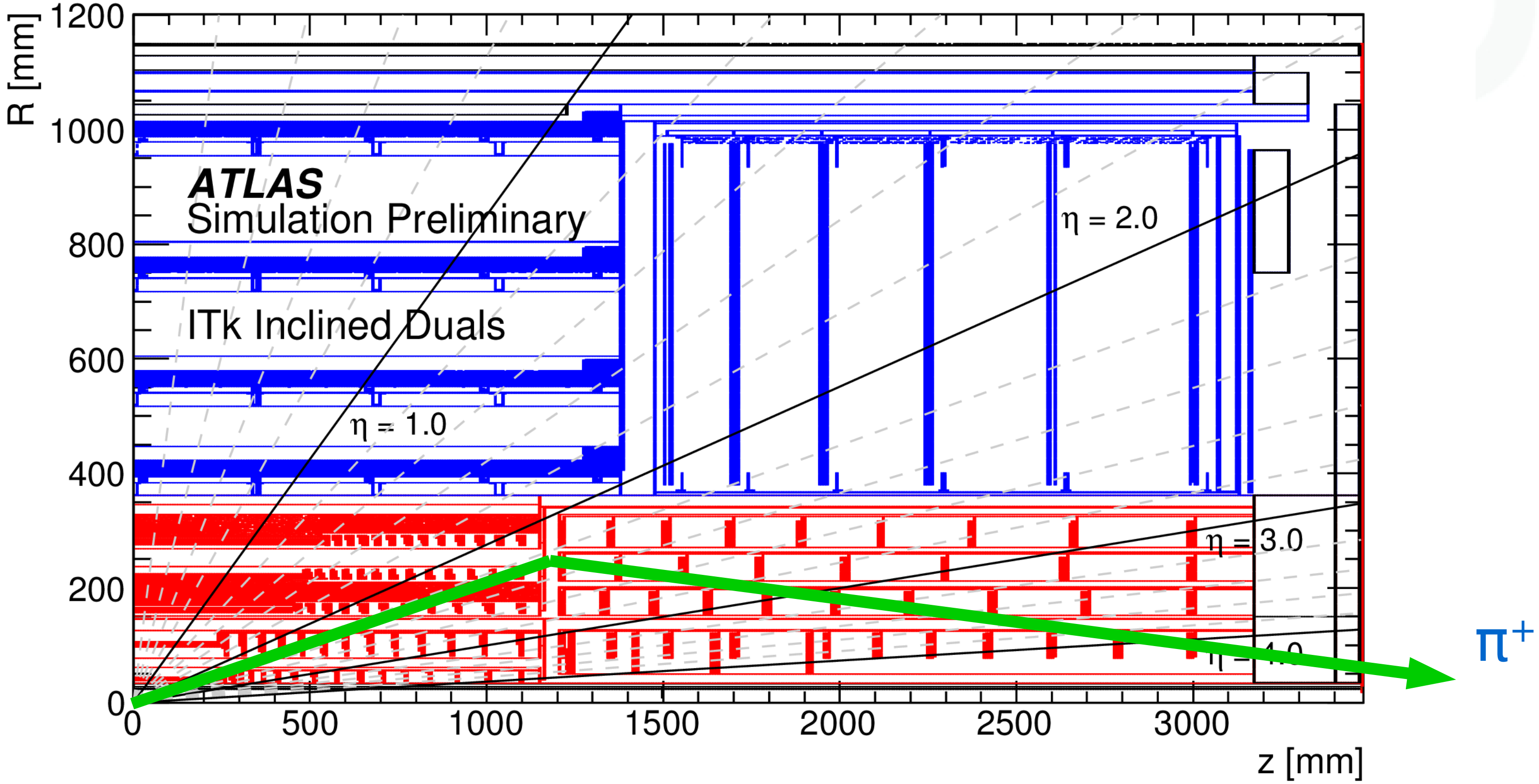
- Imagine a single pion, travelling through a detector…

- Ideally it travels through the detector with minimal material interaction.
- Then it interacts with all available active sensors, and thus can have its path reconstructed as a track.



- For a pion, electromagnetic radiation losses should have minimal impact on tracking.
- Interactions with nuclei will have a larger effect, even for E > 1 GeV.

- Such an interaction would cause the pion to be absorbed or deflected, causing its path to not be reconstructed.



- The probability for an incident particle to interact with a nucleus is related to the nuclear interaction length, λ_0.

- Here I only consider particles with E > 1 GeV, since below this energy additional effects come into play.

- The probability P(n) to not have nuclear interaction, after passing through n nuclear interaction lengths of material ($n = x/\lambda_0$), is given by $P(n) = e^{-n}$.

- We can then make the approximation that $\varepsilon_{Detector} \approx P(n) = e^{-n}$.

- n should then be the number of nuclear interaction lengths passed through in order to reach the minimum number of hits required.

(If you want to remind yourself of the full derivation of P(n), see for example; *Experimental Techniques in Nuclear and Particle Physics – Stefaan Tavernier – Springer*.)

- Highly efficient sensors and software are required for good tracking efficiency.

- Interactions between particles and the nuclei of detector material are the dominant cause of 'lost' tracks, (assuming high-efficiency sensors).

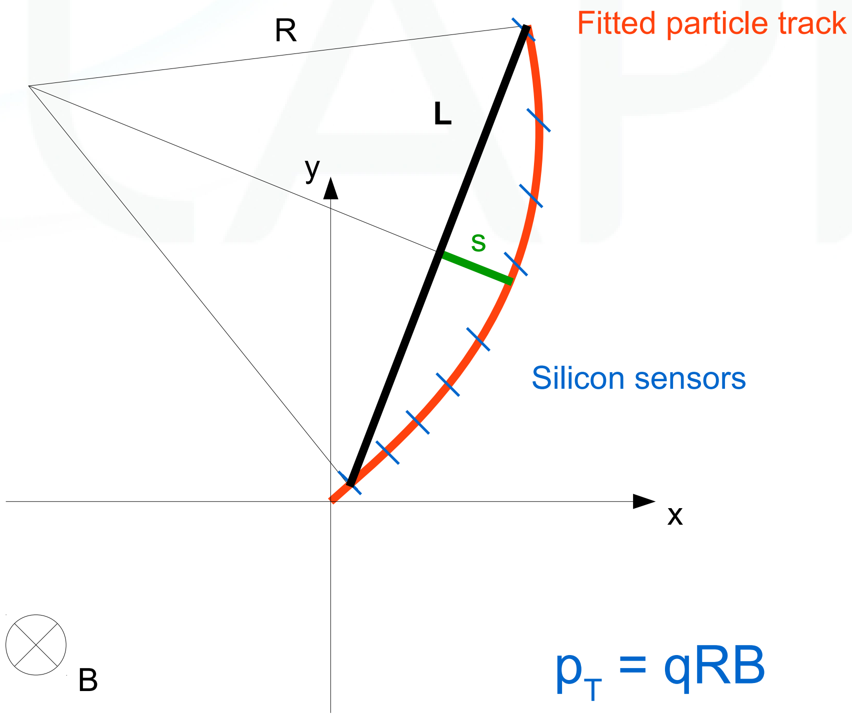
- Tracking detector efficiency can be approximated as,

$$\varepsilon_{Detector} \approx P(n) = e^{-n}$$

where n is the number of nuclear interaction lengths passed through in order to reach the minimum number of hits required.

- It is therefore important to have as little material in the detector as possible – have it be as light-weight as possible.

- The distance between the first and last hit is called the 'lever arm' (**L**).
- The better the sagitta (s) can be measured, the better the curvature of the track can be estimated.
- The longer the lever arm, the better the sagitta can be measured.



$p_T = qRB$

- The distance between the first and last hit is called the 'lever arm' (**L**).
- The better the sagitta (s) can be measured, the better the curvature of the track can be estimated.
- The longer the lever arm, the better the sagitta can be measured.

At high p_T:

intrinsic resolution

$$\frac{\sigma_{p_T}}{p_T} = \frac{p_T \, \boxed{\sigma_{\text{hit}}}}{qBL^2} H_N^{\text{equiv}}$$

where,

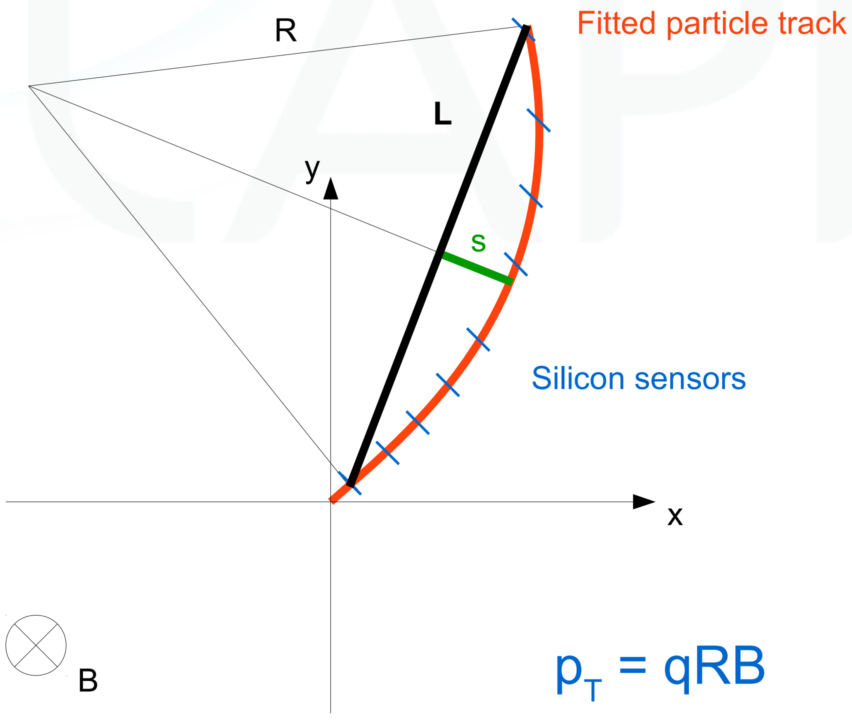
equivalent number of hits

$$H_N^{\text{equiv}} = \sqrt{\frac{720(N-1)^3}{(N-2)N(N+1)(N+2)}}$$

At low p_T:

scattering component

$$\frac{\sigma_p}{p} = \frac{2p\,\boxed{k}}{qBL}$$



$p_T = qRB$

- From this we learn that for good p_T resolution we need:
  - Strong magnetic field
  - Good intrinsic resolution in x-y plane
  - Large number of hits on track
  - Light-weight detector (reduces scattering component)
  - Long lever arm

At high p_T:

intrinsic resolution

$$\frac{\sigma_{p_T}}{p_T} = \frac{p_T \, \boxed{\sigma_{\text{hit}}}}{qBL^2} H_N^{\text{equiv}}$$

where,

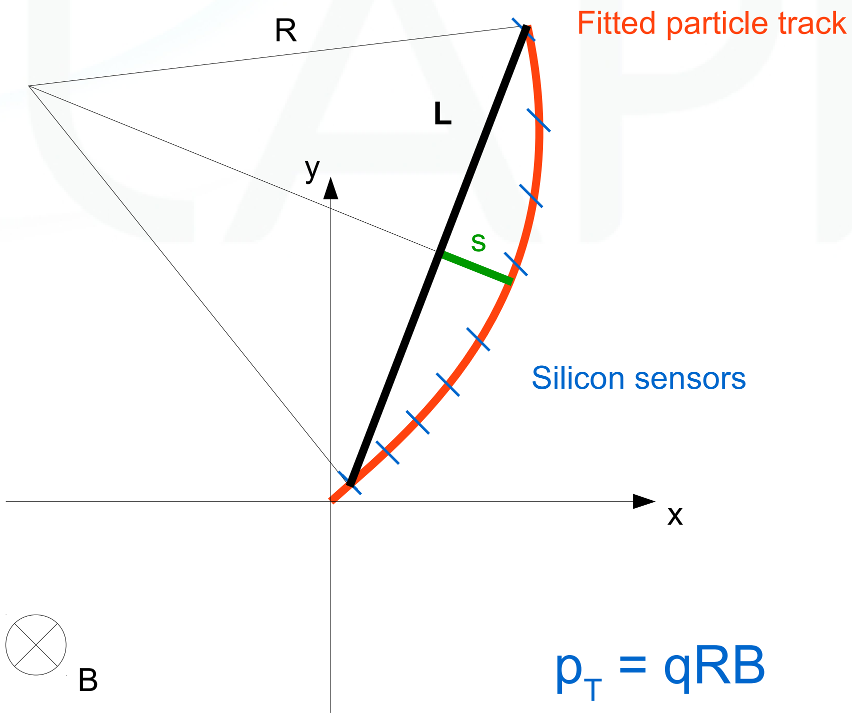
equivalent number of hits

$$H_N^{\text{equiv}} = \sqrt{\frac{720(N-1)^3}{(N-2)N(N+1)(N+2)}}$$

At low p_T:

scattering component

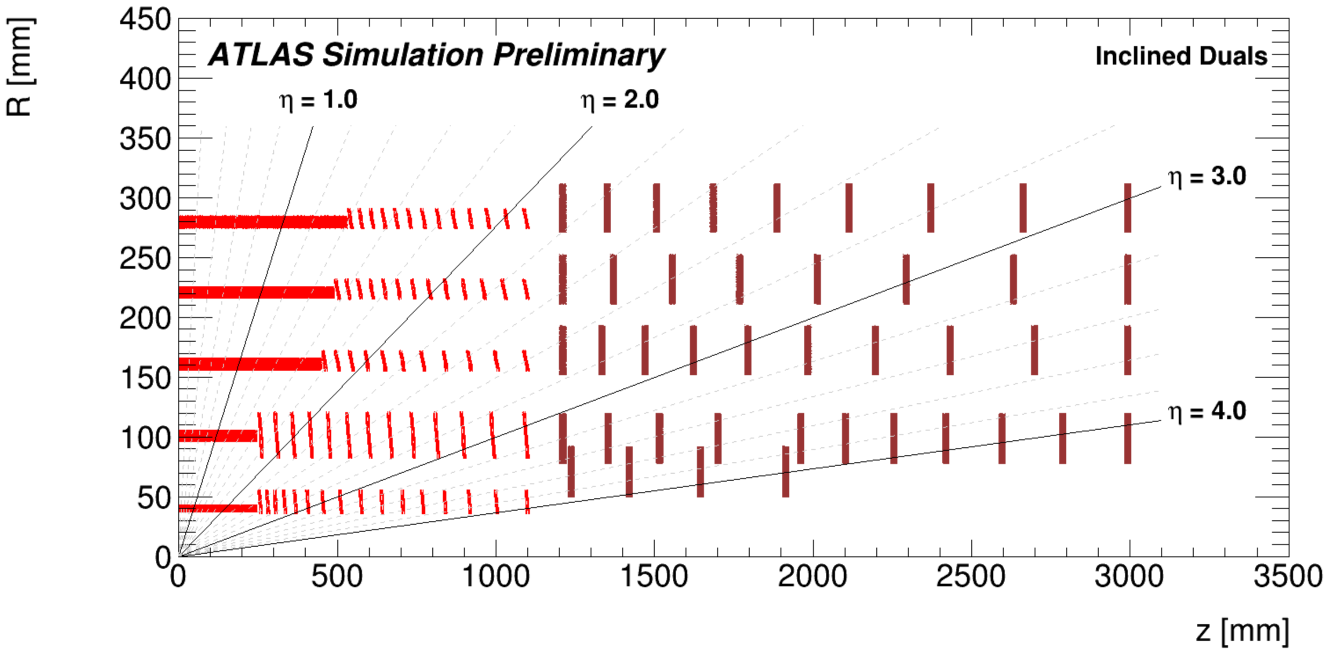
$$\frac{\sigma_p}{p} = \frac{2p\,\boxed{k}}{qBL}$$



$p_T = qRB$

- For good p_T resolution we need:
  - Strong magnetic field.
    - Can't really change this for the ITk.
  - Good intrinsic resolution in x-y plane.
    - Smaller pixel pitch will improve this ($25 \times 100 \mu m^2$).
  - Large number of hits on track.
  - Light-weight detector (reduces scattering component)
    - More hits on track requires more sensors, which adds more material to the detector, increasing scattering.
    - Optimisation required to balance these two requirements.
  - Long lever arm.
    - As large a distance as possible between the first and last hits.
    - For ITk we can not change the volume available to us, so we must make optimal use of the volume we have.
    - First hit as close to the interaction point as possible.
    - Last hits as close to the limits of the volume as possible.

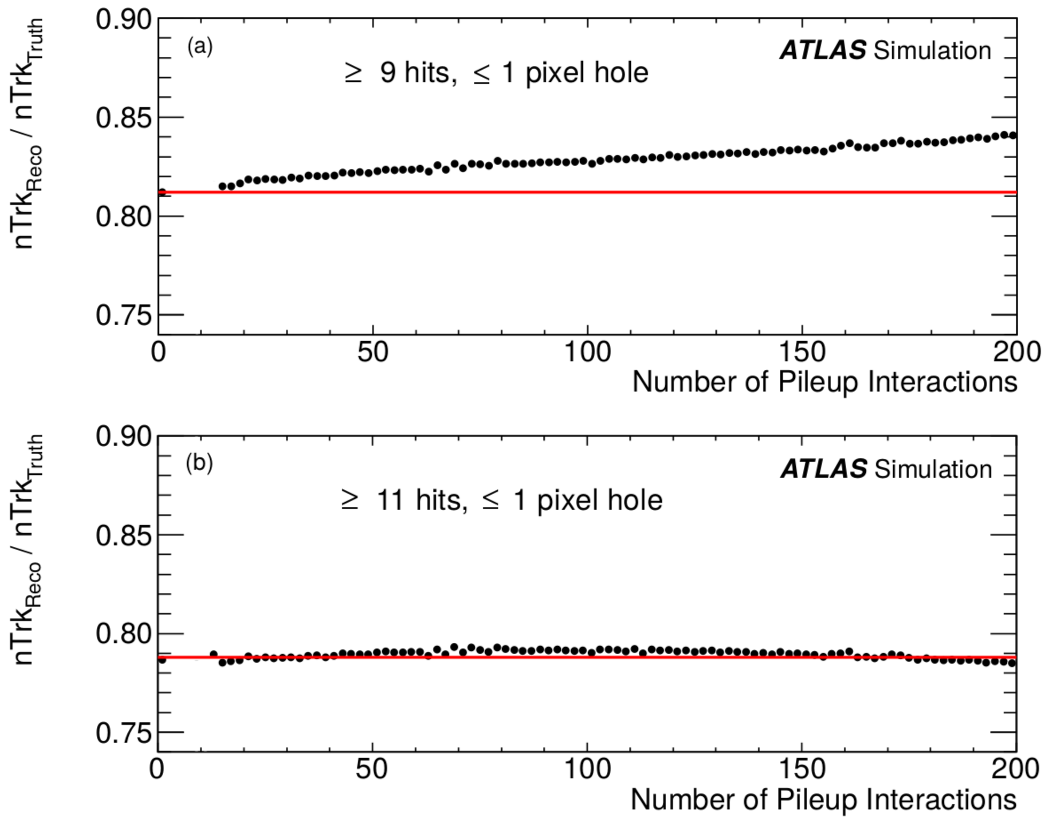
- The aforementioned tracking performance parameters are not the only things that we should consider.
- Hermeticity
  - Each layer of sensors should be hermetic.
  - Any particle originating from within the 30cm-long beam spot should not be able to pass through a detector layer without hitting a sensor. – Geometric puzzle requiring optimization.
  - Needed for good tracking efficiency.



- Number of hits
  - More hits means more measurements on track (good), but adds more material, resulting in more scattering (bad).
  - Need to find the minimum number of hits that ensures robust tracking.

- Flat tracking efficiency versus pile up is a good indicator of a sufficient number of hits.
- Do not want fraction of tracks reconstructed to change depending on the number of proton-proton collisions per bunch crossing.

- Latest ITk layout includes 2 extra hits to allow for detector defects – 13 hits.
- Also allows up to two holes on track.

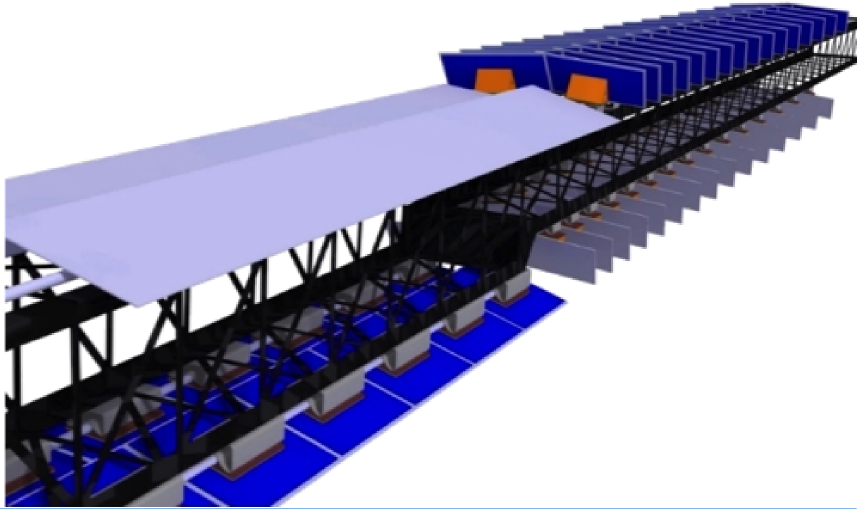


What Else Should We Consider?

- Electrical services
  - Electrical cabling is one of the largest contributors to material in the detector, and thus scattering.
  - Services should be routed so as to minimise the material particles must pass through, to reduce scattering.

- Cooling
  - Silicon sensors must be kept cold to avoid thermal runaway.
  - Thermal runaway temperature decreases with radiation damage.
  - Sensors closest to the interaction point will receive most radiation damage.
  - For the ITk, it is cooling that limits how close we can put sensors to the interaction point.

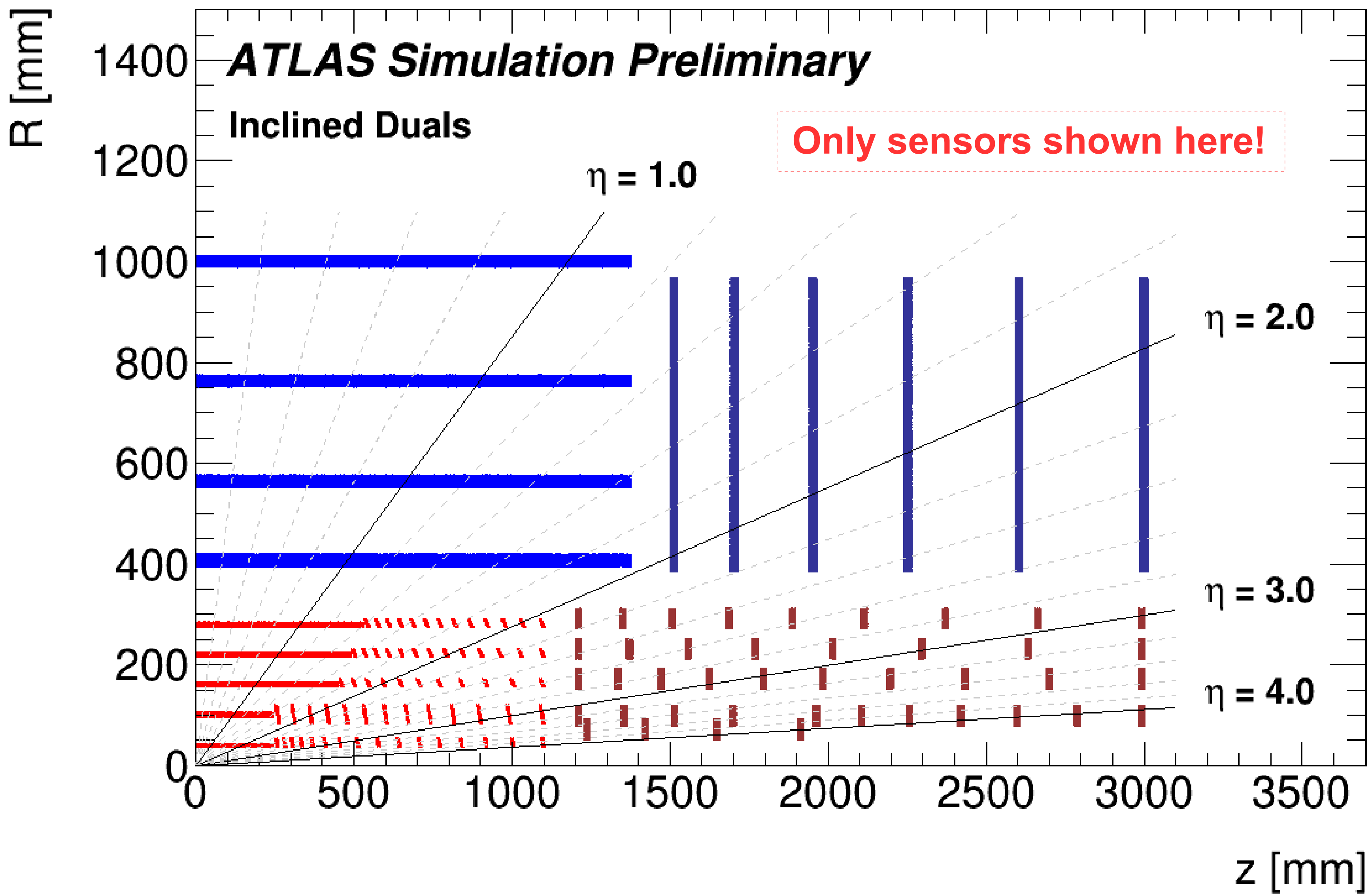
- Support structures
  - Must be light-weight and rigid.



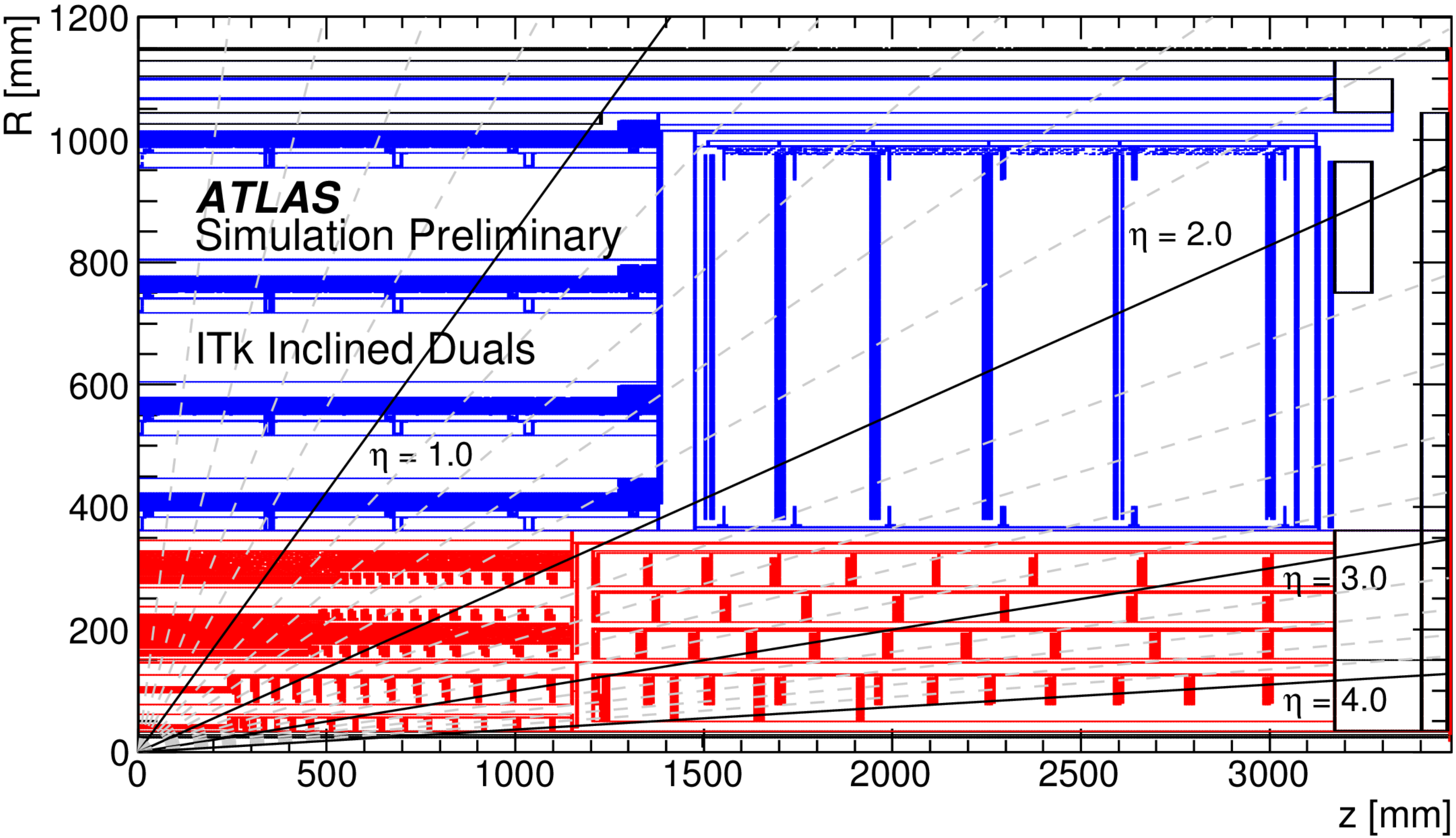
Design Conclusions

- Need a light-weight detector.
- Inclining sensors reduces material and scattering.
- Enough sensors, (to have enough hits on track), to ensure no pile-up dependence for tracking.
- First layer of sensors as close to interaction point as cooling will allow.
- Second layer of sensors an optimal distance from first, for σ_{d0} and σ_{z0}.
- Outermost sensors as far away from interaction point as possible.
- Small pixel pitch – choice to be made on what to prioritise.
- Cost, and time available, are always important factors.
  Must aim for best achievable performance with time and funding available.

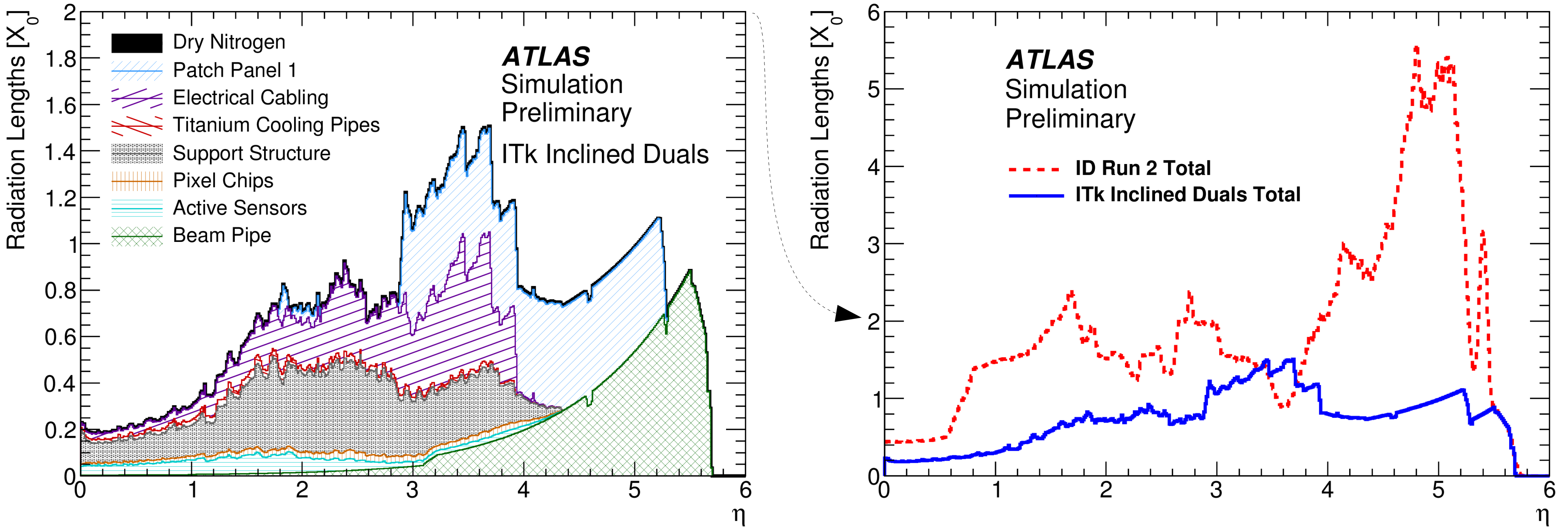
- Taking all this into account, this is the latest (public) ITk layout:



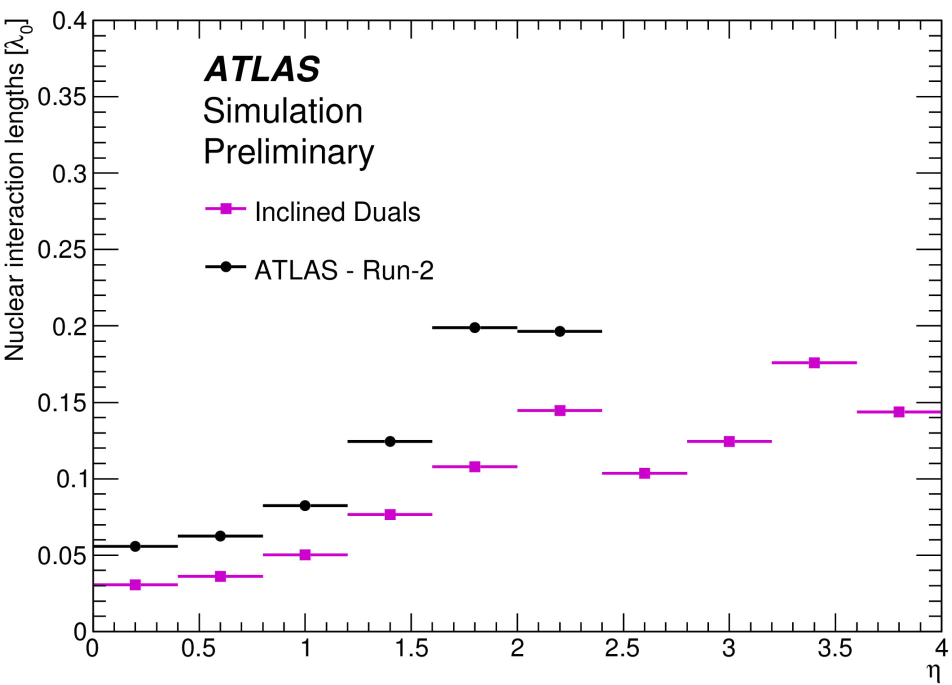
- This is the latest (public) ITk layout, showing all simulated material:

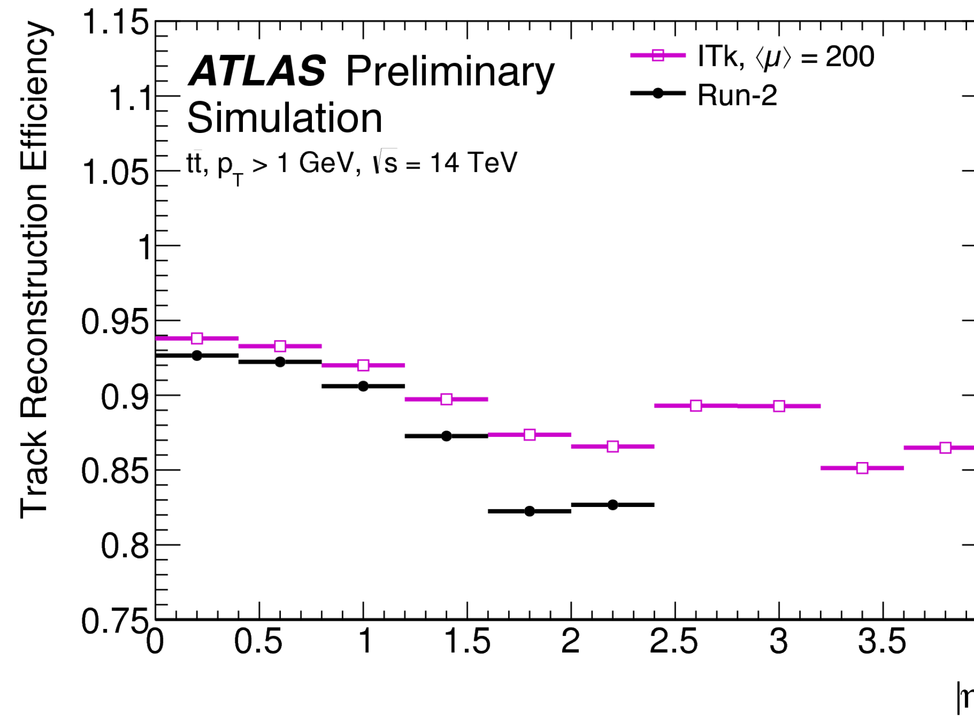


- Detector is light-weight.
- Less material than current ATLAS Inner Detector.



- Detector is light-weight.
- Less material than current ATLAS Inner Detector.
- This leads to better tracking efficiency.

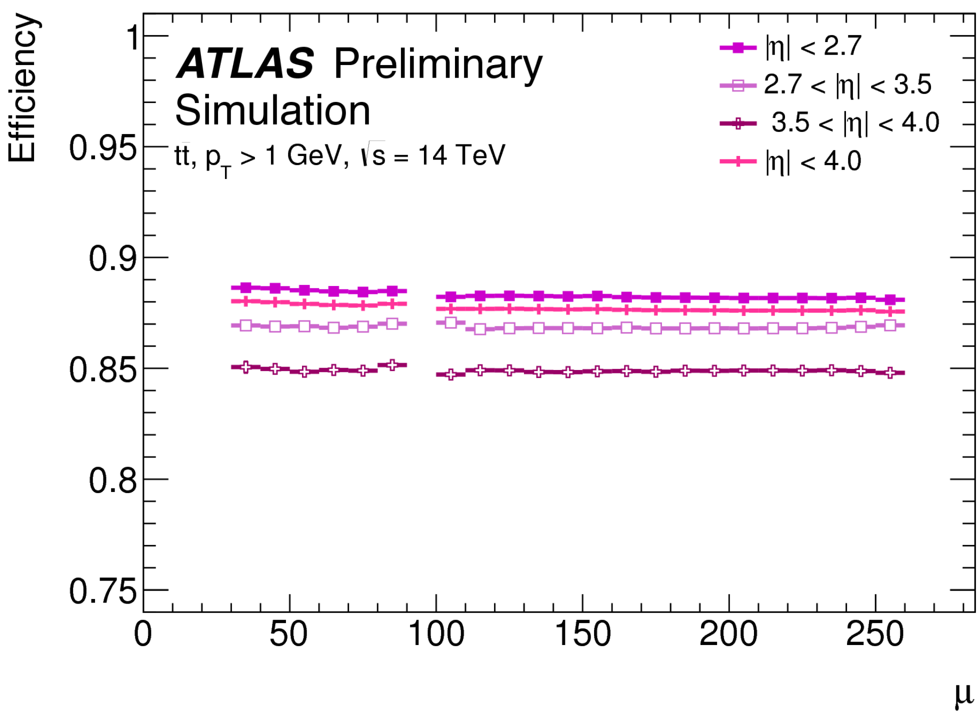


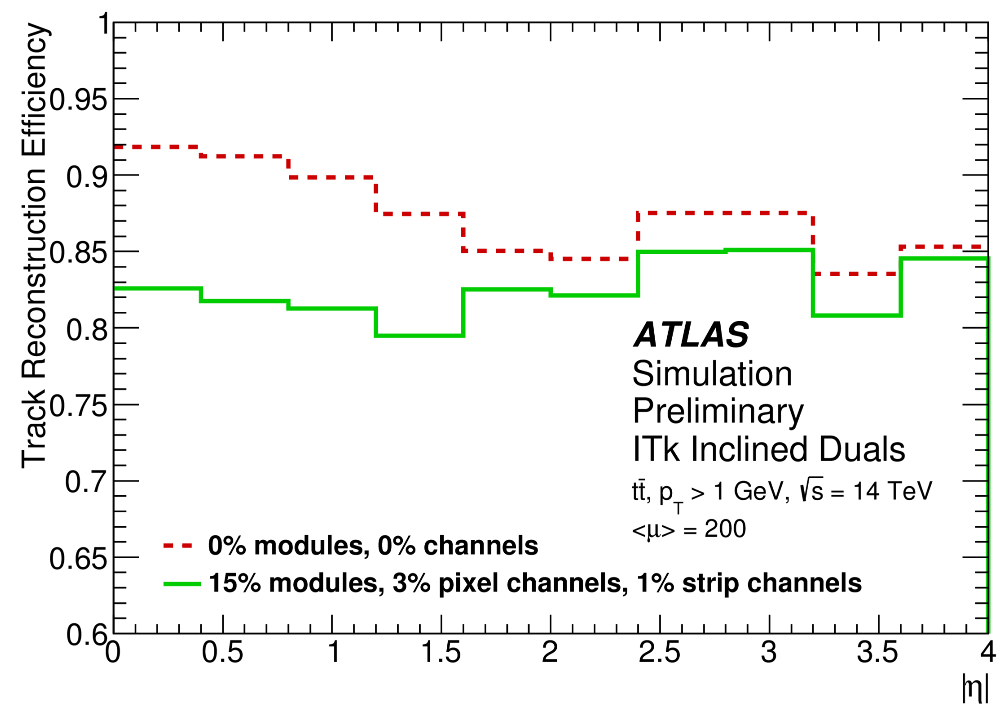


Number of nuclear interaction lengths seen by a particle as a function of η up to the position where sufficiently many sensors have been crossed such that the reconstruction hit requirements are met.

- Tracking efficiency is not dependent on pile-up μ,
  – this indicates that we have a sufficient number of hits on track.

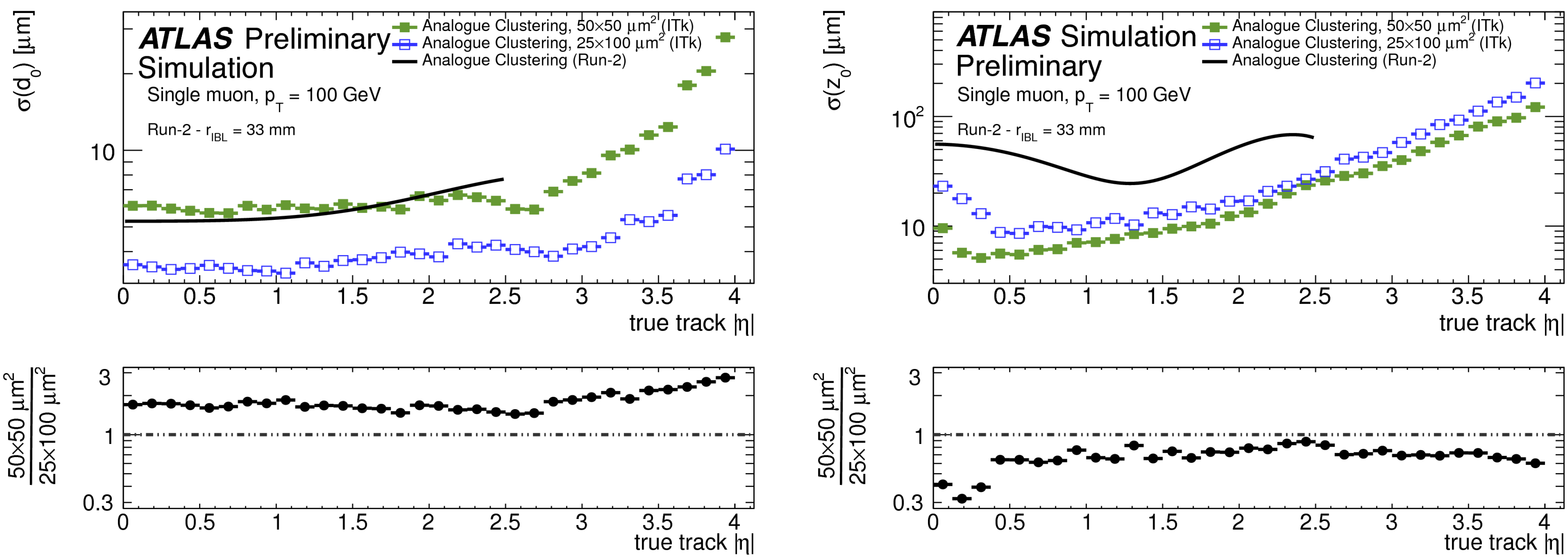
- Tracking efficiency drops in end-of-life scenario with radiation-damaged detector components, (right-hand plot).





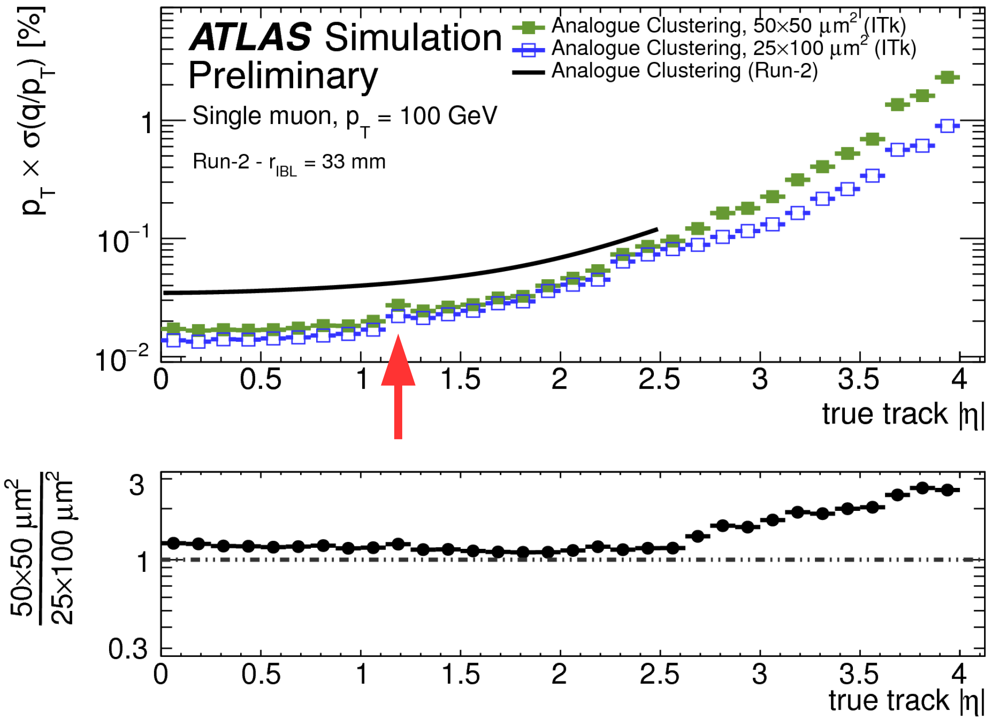
- d_0 and z_0 resolutions for different pixel sizes:

- As expected,
  50x50μm² pixels give better z_0 resolution,
  25x100μm² pixels give better d_0 resolution.

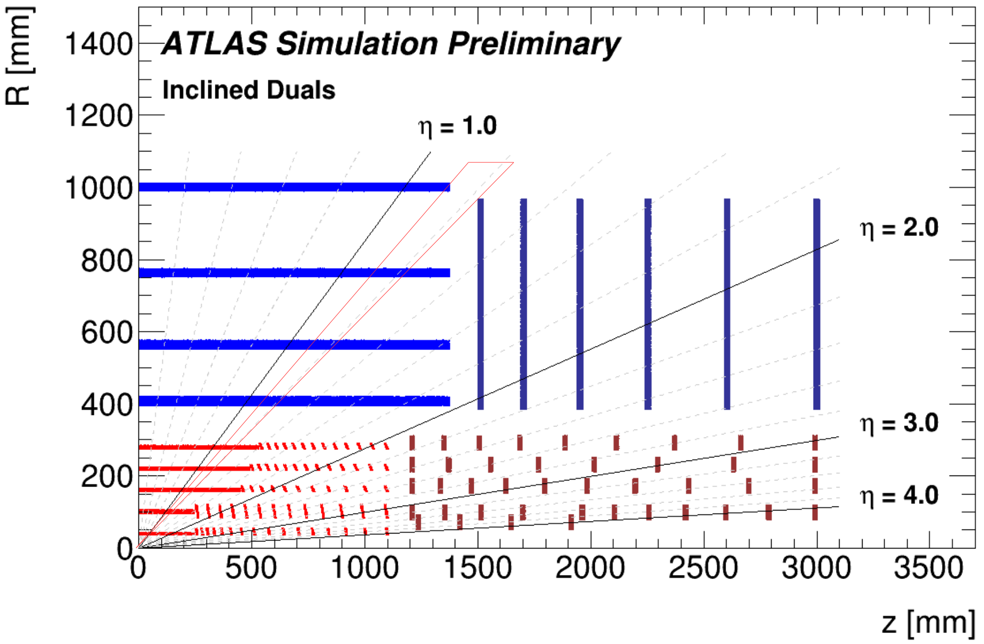


(current ATLAS Inner Detector has 50x400μm² and 50x250μm² pixels)

- p_T resolution is, as expected, slightly better with 25x100μm² pixels.
- Slight worsening of p_T resolution at |η| ≈ 1.2 due to gap in strip outer layer, – reduces lever arm in this region.
- Effect is somewhat washed-out in left plot due to 30cm-long beam spot.



Only sensors shown here!



Outline Of Today's Seminar

- What LHC and ATLAS upgrades and why?
- Tracking detector performance and how to achieve it.
- Physics studies with the upgraded LHC and ATLAS – the ultimate goal.

Physics Gain Of Increased Angular Acceptance Of ITk

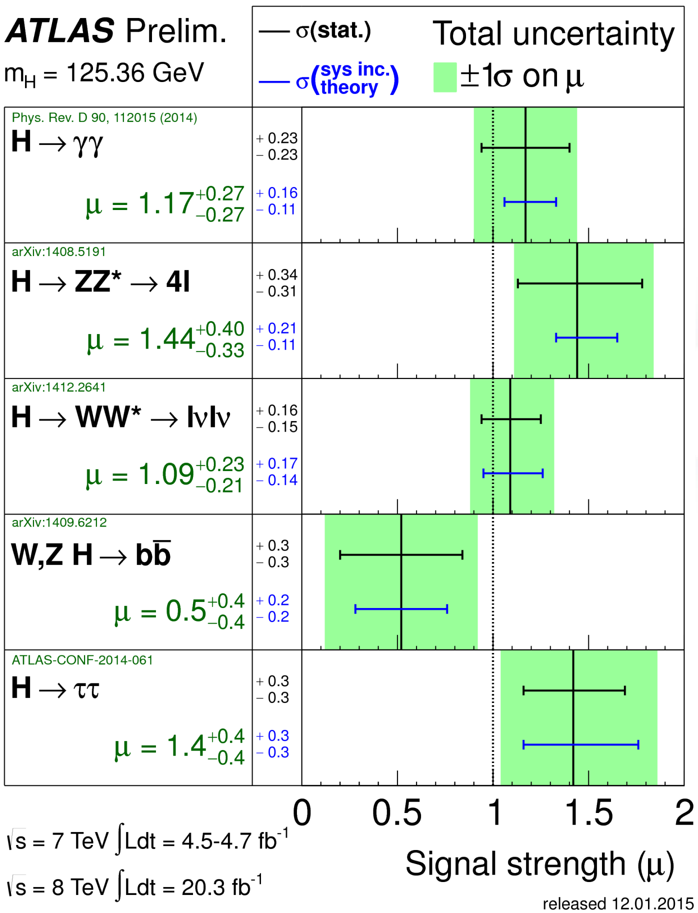
- Increased angular acceptance of ITk benefits pile-up rejection, and thus robustness against pile-up effects, for all analyses.
- Analyses with forward physics especially benefit from from increased angular acceptance:

	Measurement precision		
Physics channel	$\|\eta\|<2.7$	$\|\eta\|<4.0$	
VBF $H \rightarrow WW^*$	22%	12%	(ATLAS-TDR-025)
Same-sign WW scattering	4.5%	4.0%	(ATL-PHYS-PUB-2017-023)

ATLAS Higgs Prospects – Higgs Couplings

- Run-1 Higgs coupling analyses have been extrapolated to future runs:

Run-1



Run-1 Δμ/μ
Run-2 Δμ/μ

Δμ/μ = 0.23
Δμ/μ = 0.14

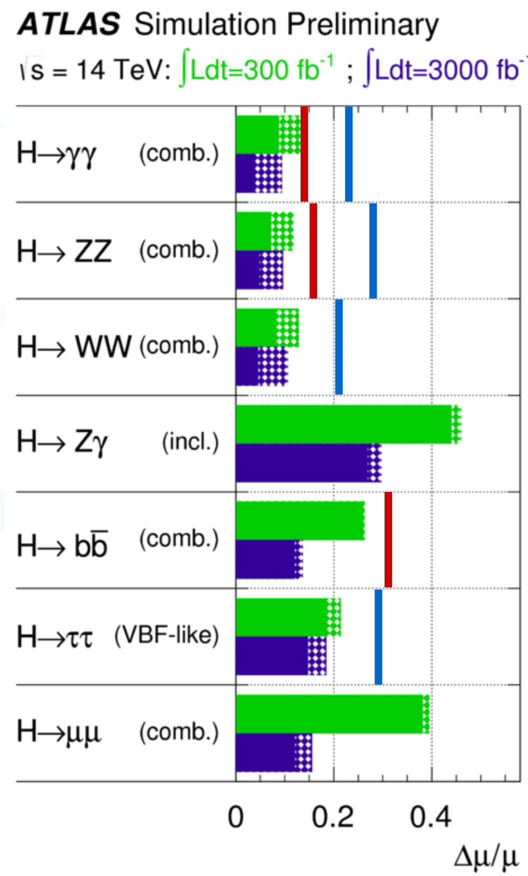
Δμ/μ = 0.28
Δμ/μ = 0.16

Δμ/μ = 0.21
Δμ/μ = 1.63*

Δμ/μ = 0.8
Δμ/μ = 0.31

Δμ/μ = 0.29

Run-3 and HL-LHC



Dashed areas indicate Δμ/μ
with current theory uncertainties.

Vertical blue lines are Run-1 values.
Vertical red lines are Run-2 values.

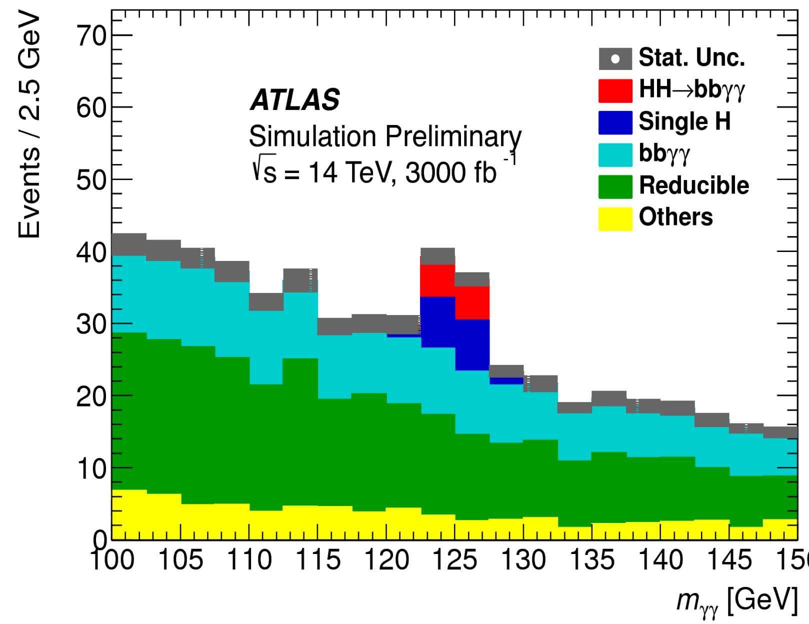
(ATLASHiggsSummaryPlots)
(ATLAS-CONF-2017-045)
(ATLAS-CONF-2017-043)
(ATLAS-CONF-2016-112 *not all prod modes)
(ATLAS-CONF-2017-041)

(ATL-PHYS-PUB-2014-016)

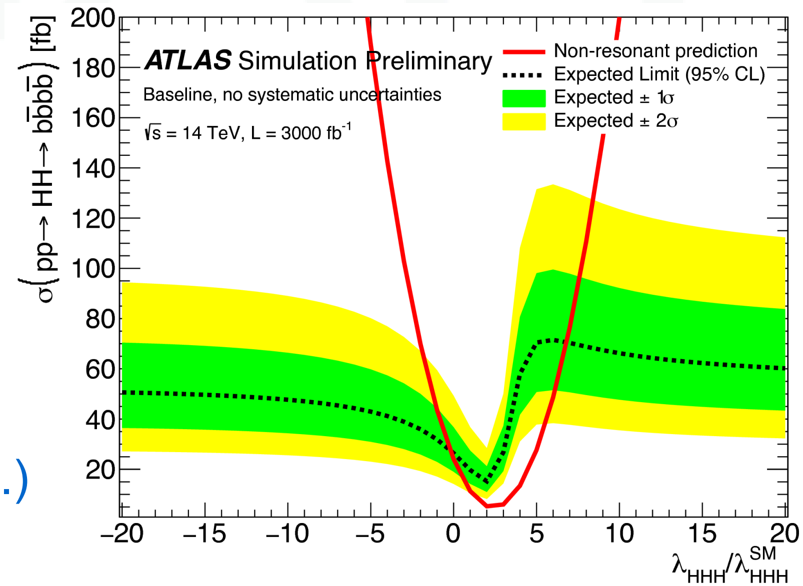
- Full HL-HLC dataset required to measure Higgs self-coupling.

- HH → $\gamma\gamma b\bar{b}$
  - Analysis using simulated / smeared HL-LHC ATLAS+ITk Monte Carlo.
  - Significance: 1.5 σ
  - $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ (95% CL. no syst.)

(ITK-2017-001)



- HH → $b\bar{b}b\bar{b}$
  - Extrapolation from Run-2 analysis.
  - Main background: multijet QCD, estimated from Run-2 data.
  - $-1.2 < \lambda_{HHH}/\lambda_{SM} < 8.0$ (95% CL. no syst.)
  - $-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ (95% CL. 2016 syst.)



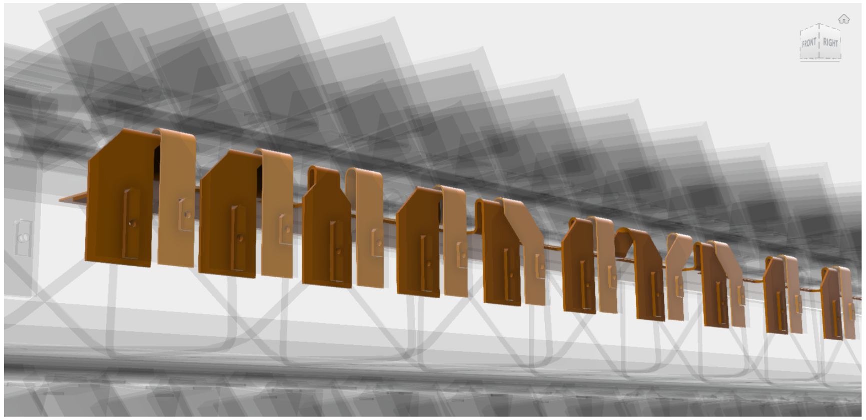
(ITK-2017-001)

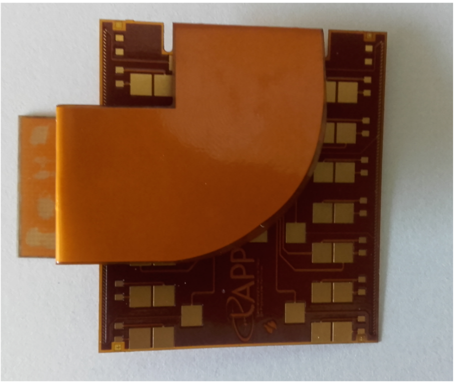
- In the future, the LHC and ATLAS will be upgraded.
  ATLAS will get a new tracking detector, the ITk.
- While physics analysis performance is the ultimate goal, tracking detector design can be optimised by considering tracking performance metrics.
- One can determine how basic design parameters affect these tracking performance metrics, and from there how to optimise a detector design.
- The latest ITk design involves novel solutions, such as inclined sensors, and expects to match or exceed the performance of the current ATLAS Inner Detector, while working in a more challenging environment.
- All these developments will benefit searches for new particles, precision measurements, and studies of rare processes, with the ATLAS Detector.

Backup

- Data rates
  - Sensor positions and electronics will determine data rates.
  - Sensors closer to interaction point will have higher data rate.
  - Higher data rate requires more electrical cables to read out data, – thus more material in detector.

- Electrical services
  - Should be as light as possible while still being able to transmit data over the required cable length.
  - Generally, lighter cables mean less conducting material and thus more attenuation (so shorter transmission length).
  - Services should be routed so as to minimise material particles must pass through, to reduce scattering.





- Cooling
  - Silicon sensors are not perfect insulators - some leakage current will always be present.
  - Leakage current heats the sensors.
  - The hotter the sensors are, the larger the leakage current will be.
  - If a sensor goes above some temperature, this becomes a thermal runaway process, and the sensor will be destroyed.
  - Sensors must therefore be cooled,
    – for ITk, this will be (bi-phasic) liquid CO_2 cooling.

  - Radiation damage also increases leakage current, thus lowering the thermal runaway temperature.
  - Cooling systems must be able to sufficiently cool sensors when they are most radiation damaged at the end of their lifetime.

  - The closer sensors are to the interaction point, the more radiation damage they will receive, thus requiring more cooling.
  - <u>For the ITk, it is cooling that limits how close we can put sensors to the interaction point.</u>

- Support structures
  - Must be light-weight and rigid.
  - Light-weight to reduce scattering.
  - Rigid to ensure sensor positions are well-known over time, with temperature changes etc.
  - Must allow 're-working' during construction – if a sensor fails after it has been attached to a support structure, it must be possible to replace that sensor without damaging anything.
  - Must be buildable with the time and money available.