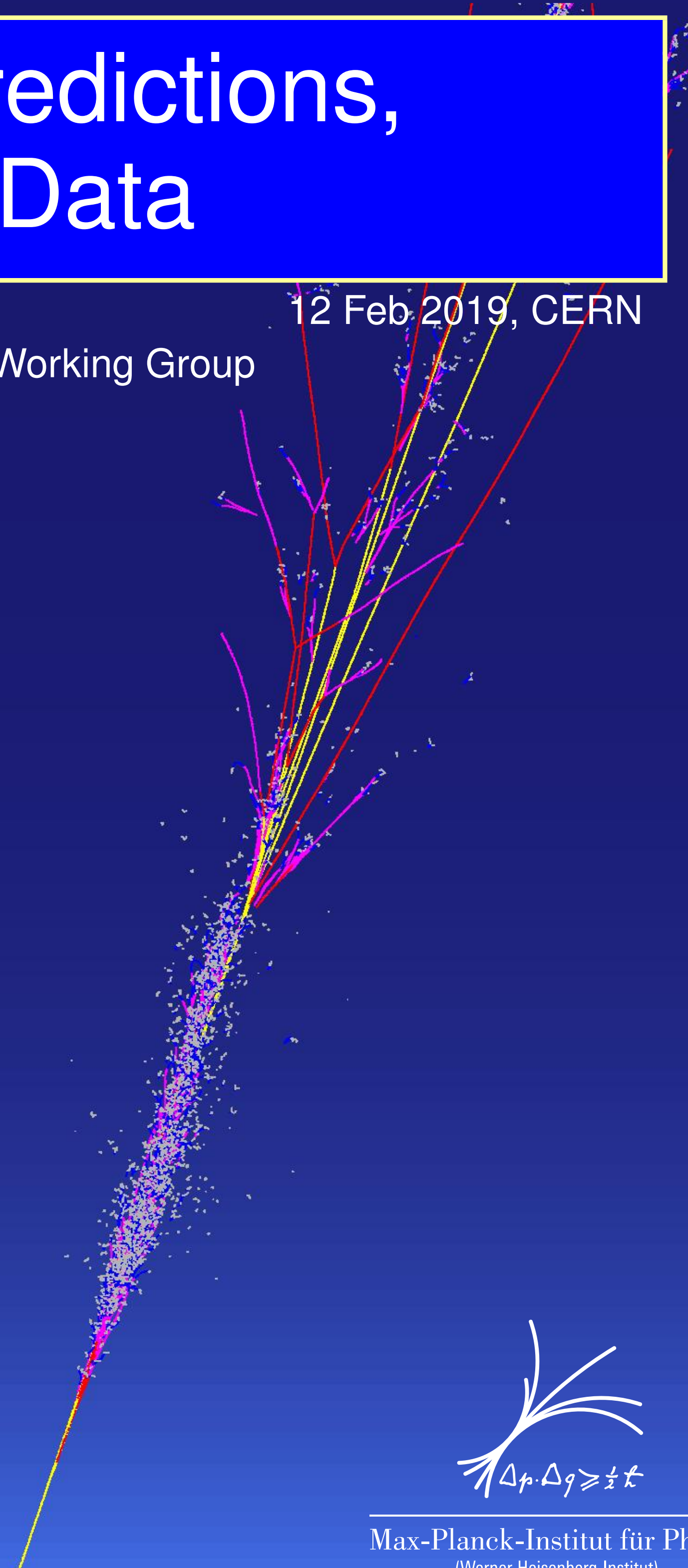
ATLAS Simulations, Predictions, Comparison with Data

Radiation Workshop Sven Menke, MPP München 12 Feb 2019, CERN
on behalf of the ATLAS Radiation Simulation Working Group



- Introduction
  - ATLAS and Simulation requirements
- Simulations
  - FLUKA
  - GCalor
  - FLUGG
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- Predictions
  - Radiation backgrounds for Phase-II
  - Radiation damage in the IBL
  - Radiation damage in the Tile Calorimeter Scintillators
- Conclusions & Outlook

ATLAS EXPERIMENT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

- ATLAS needs simulations for radiation backgrounds in several contexts
  - Predictions for ageing/performance degradation of already installed parts
  - Limit-setting for parts to be installed for upgrades
  - Benchmarking with radiation detectors installed in ATLAS
  - Activation and residual dose rate studies for radiation protection assessments of interventions and radioactive waste estimates
- Especially the last one (but also the second) require quick changes in geometry
  - Open/Closed Detector
  - Removed/Added parts
  - New detector components
- For already installed detector parts and long-term benchmarking the focus is on accuracy
  - Material composition
  - Structure in space including holes and non-uniformities
  - Positioning
  - Service and support material
- The strategy of ATLAS has been to use different programs and geometries for different tasks
- Comparison of these with each other is extremely helpful in identifying areas with wrong assumptions about the detector material

Simulations in use

FLUKA

- Standalone proprietary `FORTRAN` code to simulate particle cascades in matter
- Widely used since decades for the purpose of radiation background predictions
- Requires registration in order to use it and older versions expire
- Physics can not be modified by users
- For ATLAS simplified detector geometries exist for all phases of the experiment

FLUGG

- A program that allows to use Geant4 geometries with FLUKA
- Needs specific versions of both

GCalor

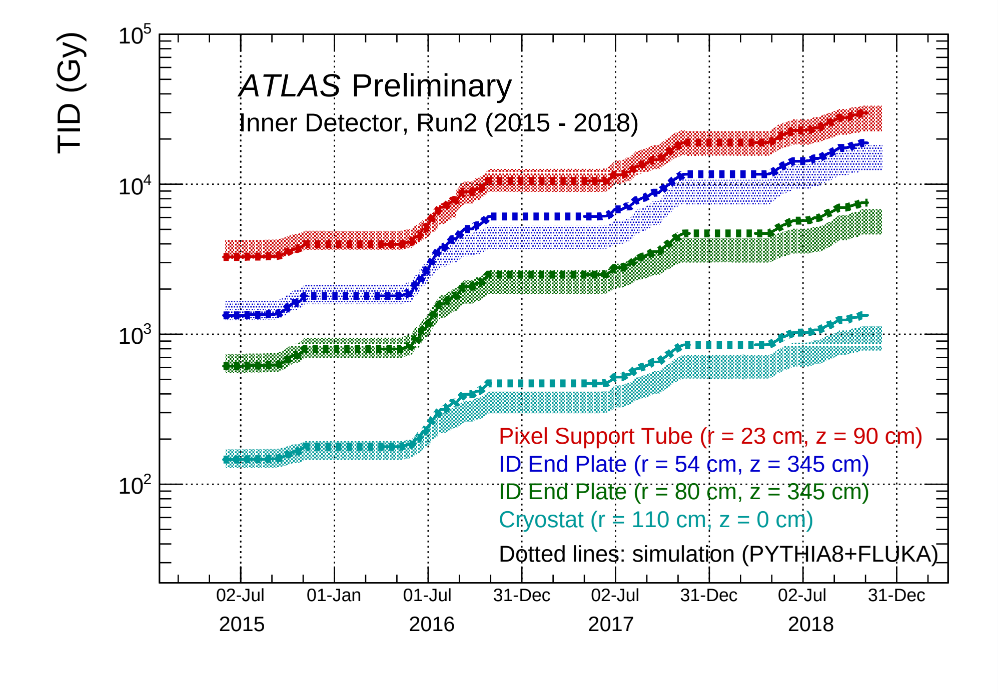
- `FORTRAN` code that combines `CALOR` transport code for low energy hadrons with geometry from `Geant3`
- Simplified geometries in `Geant3` exist for ATLAS

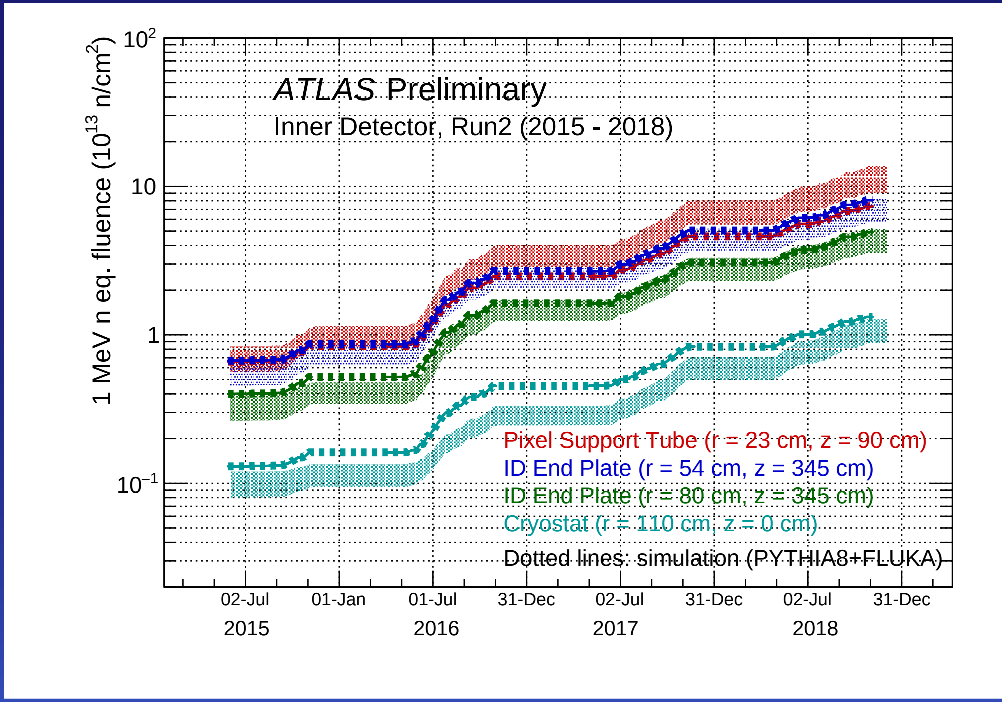
Geant4

- Open source toolkit in `C++` for multi-purpose simulations of particle interactions
- Most widely used by HEP experiments for their simulation of physics events
- For ATLAS has the most detailed geometry description of the sensitive detectors
- Verified detector descriptions with test-beam and collisions data
- Lacks description of special cases (like open detector)
- Added radiation map user code in 2017/18

Comparison to ATLAS data

- FLUKA has been used to compare radiation simulations for TID and NIEL with measurements from radiation monitors installed at several positions inside the ATLAS detector
- REM RadFETs with $0.13\mu m$ oxide thickness (left) measure total ionisation dose (bands) compared to FLUKA predictions (dots)
- BPW34 diodes (right) measure via forward bias the 1 MeV equivalent neutron fluence (bands) compared to FLUKA (dots)



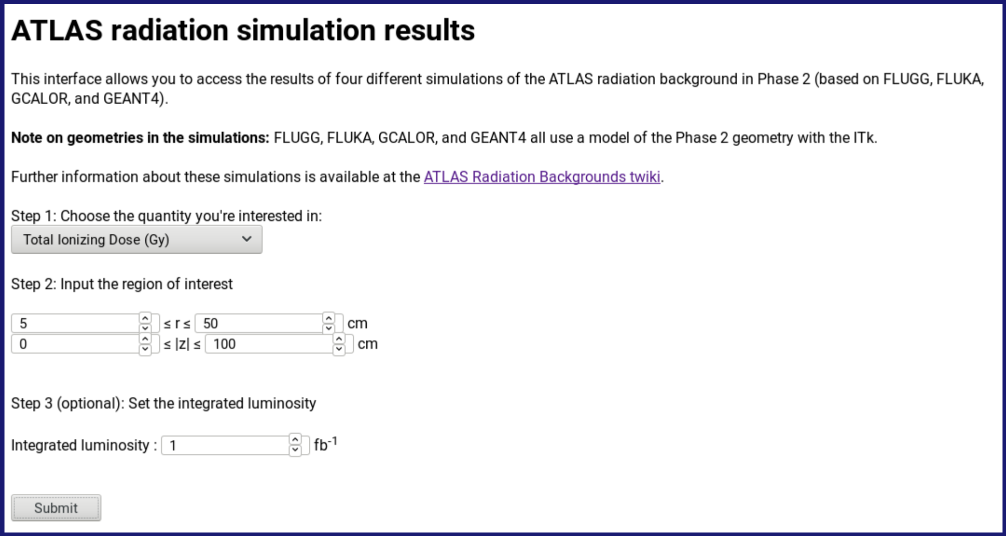


- In general the agreement between measurements and simulations is quite good in the ATLAS inner detector systems, especially the SCT and RadMons. Some interesting differences are emerging in the pixel measurements which are currently under study (see Monday's morning session)

Predictions

- For the various Phase-II TDRs of ATLAS we used all 4 simulation approaches to predict the radiation backgrounds
- Agreement between them (or lack thereof) depends mostly on the implemented detector geometries and materials
  - For the inner detector material is mostly light and very φ-uniform
    - ► all four approaches agree reasonably well
  - Behind the calorimeters modest differences are visible
  - Most dramatic differences occur in areas with holes/shafts/service-channels that are implemented differently in the geometries
- Based on case-by-case considerations we either used an average of all 4 codes or individual results in case there was a reason to prefer one description over the other
- Dedicated Web-tool with averages, maxima, uncertainties and graphical representation is in place to compare all 4 codes in terms of TID, NIEL and flux of hadrons above 20 MeV (see next slide)

Web-Tool



ATLAS radiation simulation results

This interface allows you to access the results of four different simulations of the ATLAS radiation background in Phase 2 (based on FLUGG, FLUKA, GCALOR, and GEANT4).

Note on geometries in the simulations: FLUGG, FLUKA, GCALOR, and GEANT4 all use a model of the Phase 2 geometry with the ITk.

Further information about these simulations is available at the ATLAS Radiation Backgrounds twiki.

Step 1: Choose the quantity you're interested in:

Total Ionizing Dose (Gy)

Step 2: Input the region of interest

5 ≤ r ≤ 50 cm

0 ≤ |z| ≤ 100 cm

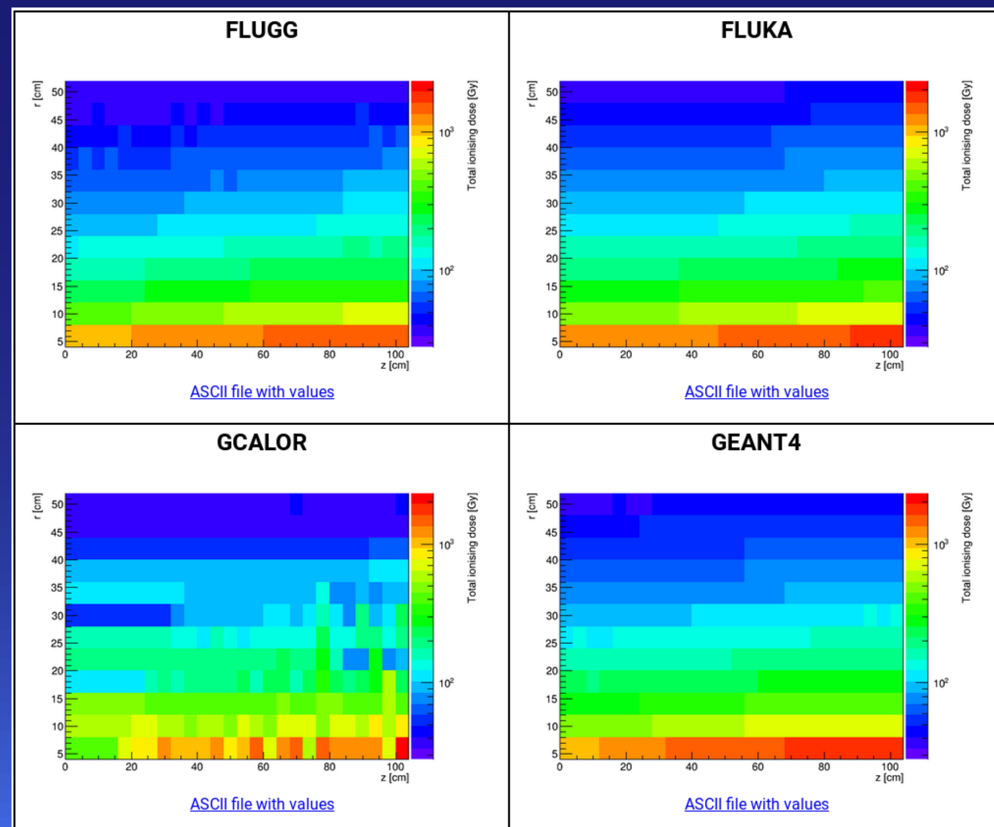
Step 3 (optional): Set the integrated luminosity

Integrated luminosity : 1 fb^{-1}

Submit

All values are calculated from the cells in the selected R-Z region, assuming an integated luminosity of 1 fb^{-1} and minbias cross section of 80 mb.

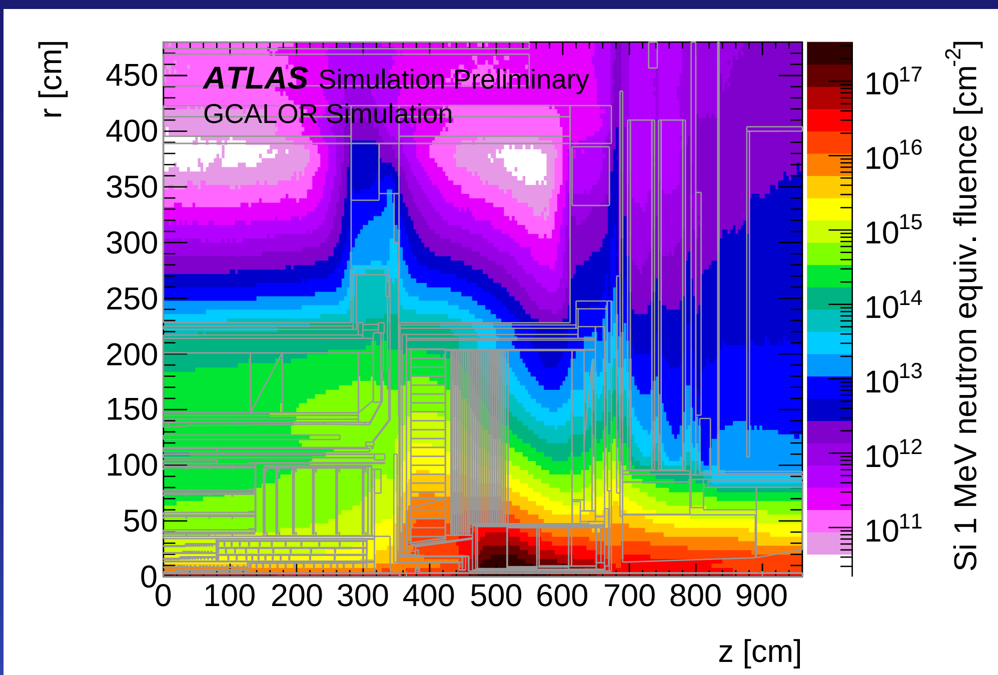
	Total ionizing dose [Gy]			
	FLUGG	FLUKA	GCALOR	GEANT4
Average:	244.76 +/- 0.26	268.13 +/- 0.19	248.82 +/- 0.15	285.31 +/- 0.21
Standard deviation:	347.28	372.94	299.21	400.61
Maximum:	1.55e+03 +/- 1.06e+01	1.72e+03 +/- 1.03e+01	1.93e+03 +/- 1.14e+01	1.86e+03 +/- 1.12e+01
R-Z location of maximum	4 < r < 8 cm 100 < |z| < 104 cm	4 < r < 8 cm 100 < |z| < 104 cm	4 < r < 8 cm 100 < |z| < 104 cm	4 < r < 8 cm 100 < |z| < 104 cm

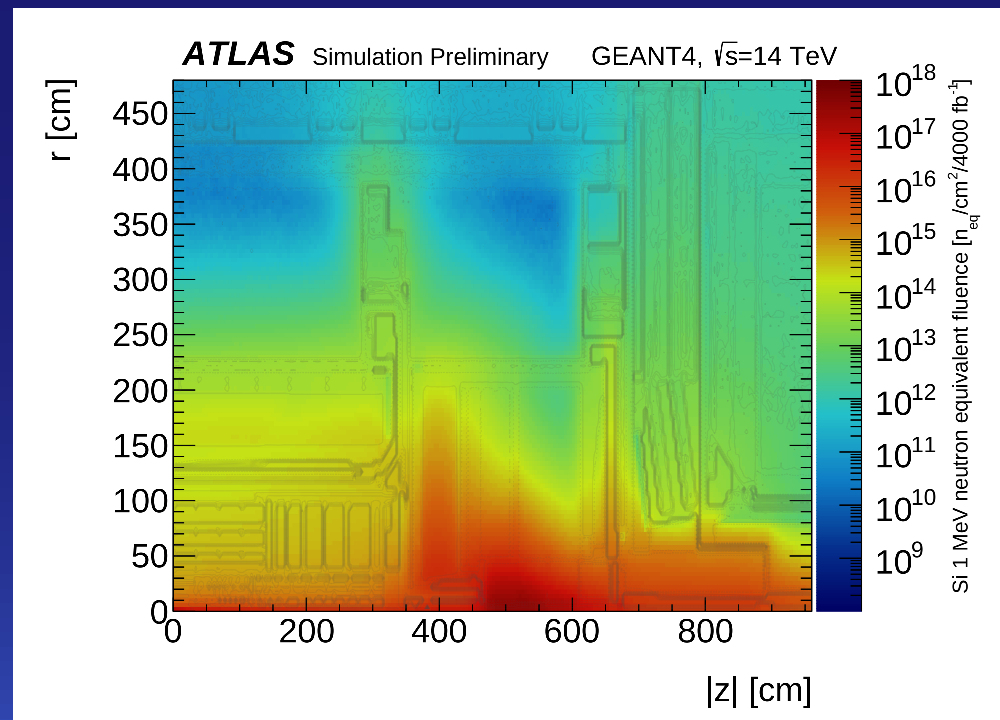


- Input Web-Form (top left) to choose r and $|z|$ ranges, radiation map type (TID, NIEL, SEE) and integrated luminosity
- Output table (top right) with averages, maxima, uncertainties
- Comparison graphic of selected radiation type in given area for all four codes (right)

GCalor and Geant4 in Calorimeter regions

- $1\ \mathrm{MeV}$ equivalent neutron fluence in calorimeter regions from GCalor (left) and Geant4 (right) for a Phase-II detector
  - $50\mathrm{k}$ inelastic proton-proton events generated with PYTHIA 8
  - A2 ATLAS tune & MSTW2008LO PDF @ $\sqrt{s} = 14\ \mathrm{TeV}$
  - Assumed cross-section: $\sigma_{\mathrm{inel}} = 80\ \mathrm{mb}$
  - Normalised to an integrated luminosity of $L = 4000\ \mathrm{fb}^{-1}$

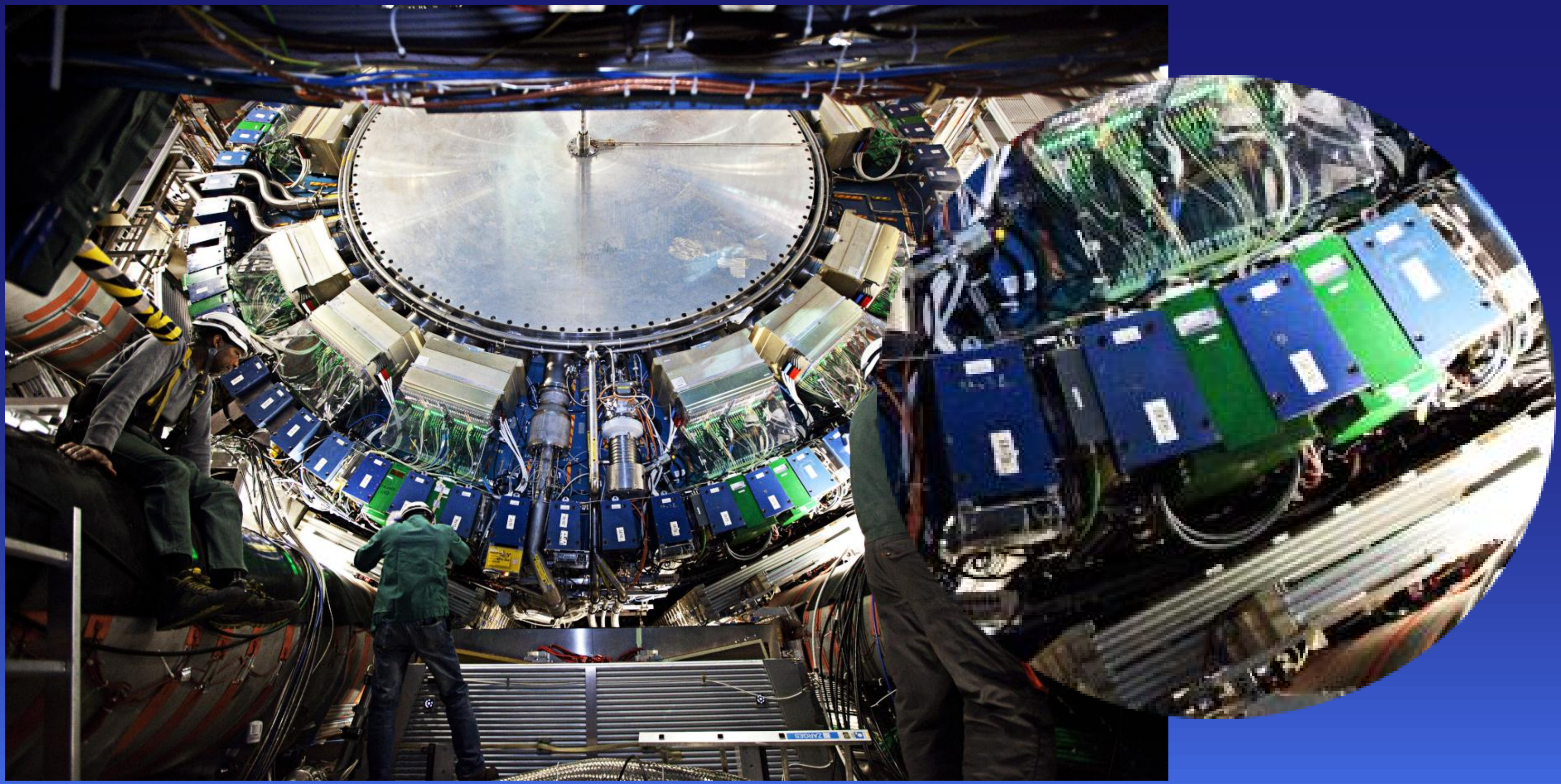




- Good overall agreement

3D Geant4 predictions

- For some regions the 2D results are not sufficient
  - Barrel: $284\,\text{cm} < |z| < 320\,\text{cm}$, $388\,\text{cm} < r < 424\,\text{cm}$
  - Endcap: $616\,\text{cm} < |z| < 652\,\text{cm}$, $388\,\text{cm} < r < 424\,\text{cm}$
  - 40% of the volume is steel
  - Electronics located in air-gaps between the 64 steel “Tile Fingers”
- φ-averaged numbers include shielded values inside steel
- Photo below shows endcap regions with the Tile Fingers in blue and end-plates of electronics in green

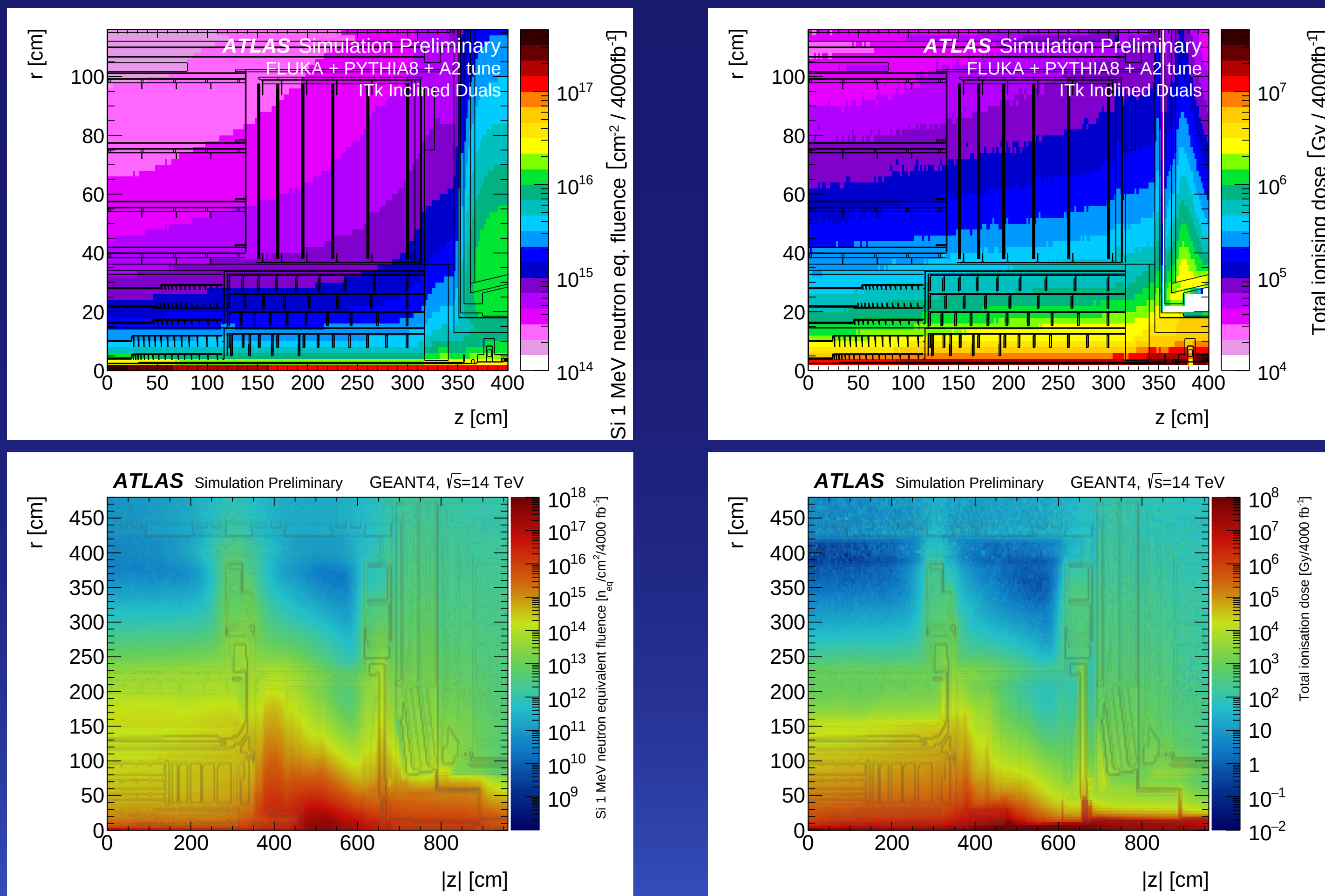


3D Geant4 predictions

- Since the geometry model in Geant4 is in 3D and has the detailed structure of Tile Fingers implemented it is straight forward to evaluate radiation maps in 3D here
- 1.125° small bins in φ were needed to separate air-gaps from steel
  - Mapped to $1/16^{\text{th}}$ segment in φ to keep the statistics (and memory consumption) reasonable
- Differences of the 3D simulation w.r.t. the 2D results:
  - Si-NIEL: unchanged – as for the full 2D maps NIEL is least disturbed by details in the material since neutrons dominate in these areas
  - TID: $\sim 50\%$ larger in gaps between the Tile Fingers (less shielding)
  - SEE: in between Si-NIEL and TID with $\sim 30\%$ increase
- These are the differences for the maxima in the Tile Finger region
  - Since the exact location of the weakest radiation tolerant piece is unknown ...
  - Maxima are evaluated in a “fluctuation protected” mode by taking the values for which value minus statistical uncertainty is largest

FLUKA and Geant4 in Inner Detector region

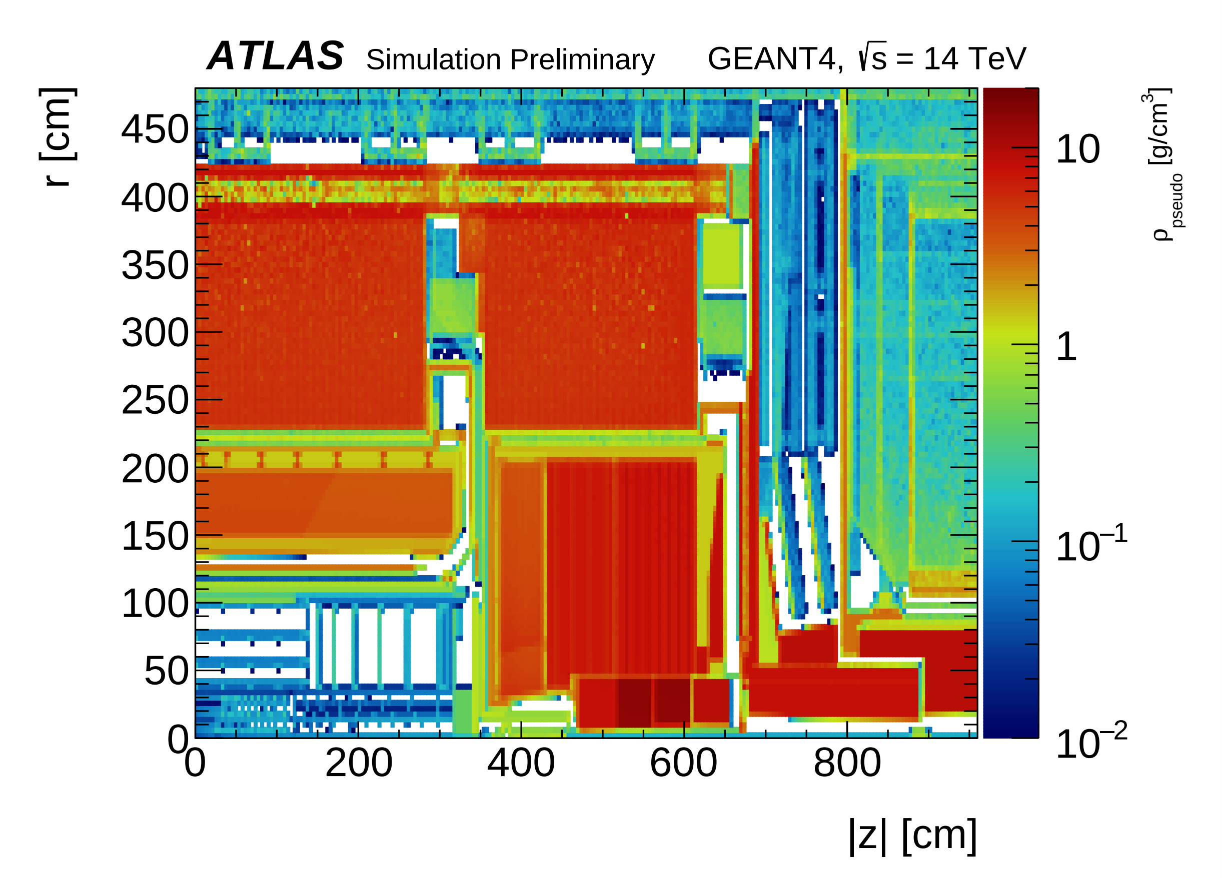
- 1 MeV eq. neutron fluence (left), TID (right) in inner detector region from FLUKA (top) and up to calorimeters from Geant4 (bottom) for Phase-II
- Same generator/normalisation as before for GCalor/Geant4 comparison



- Excellent agreement in inner detector region

Pseudo Density

- Plot below shows $\rho_{\text{pseudo}} \equiv \text{ELOSS}/\text{Volume}/\text{TID}$ from Geant4
- Can be generated from all four simulations in use and shows the actual geometry used (no extra run!)

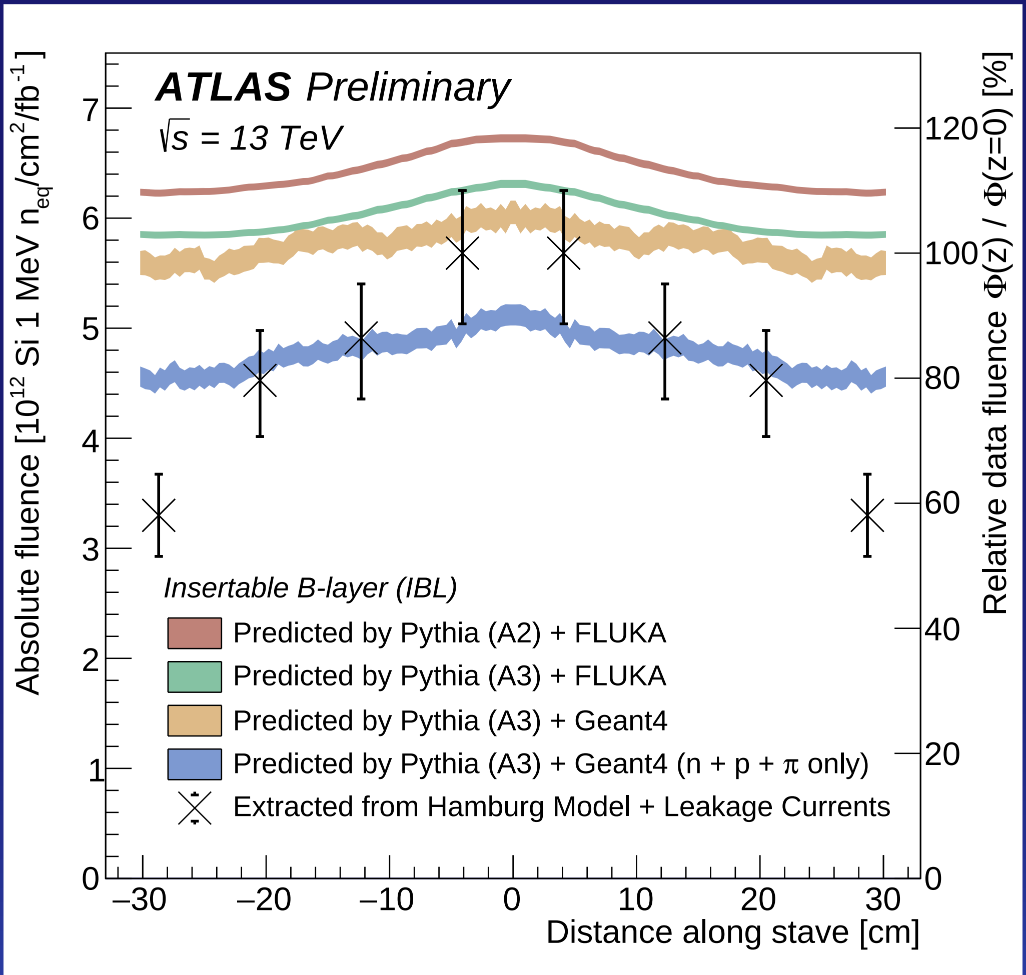


- This "pseudo density" is close to the average density for homogenous detectors
- It differs from average density for non-φ-uniform detectors
- Is a great debugging tool to identify mistakes in geometry implementations

- ATLAS uses this to compare (and adjust) the different implemented geometries

Comparison of Geant4 and FLUKA with FLUKA for IBL@Run-2

- Geant4 and FLUKA were used for Run-2 geometry to predict Si-NIEL in the IBL area ($|z| < 30\,\text{cm}$, $3.2\,\text{cm} < r < 3.6\,\text{cm}$)

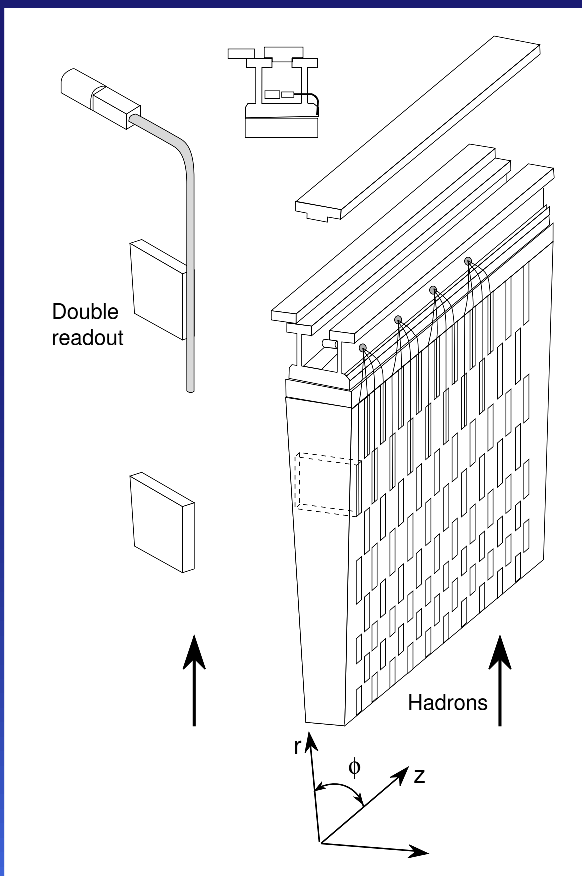


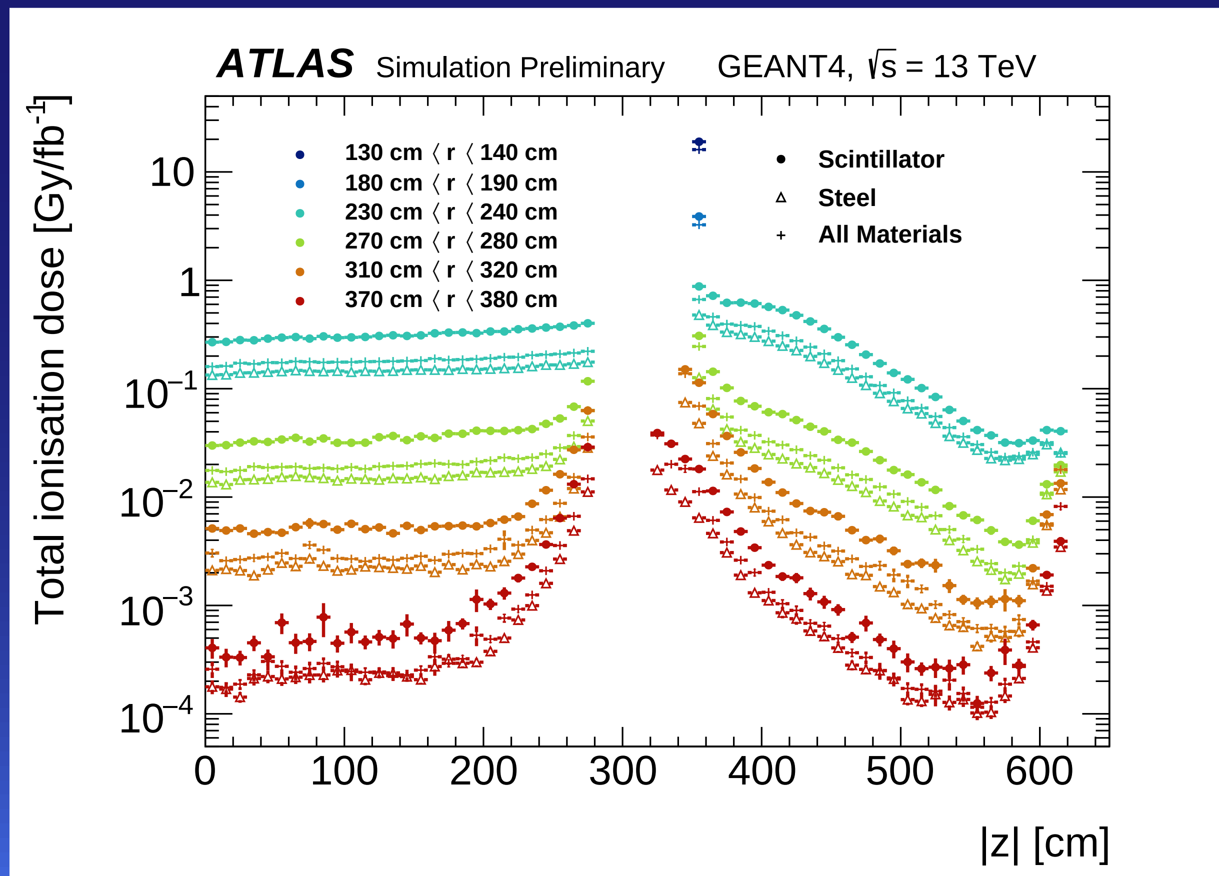
- A3 ATLAS tune & NNPDF23LO PDF @ $\sqrt{s} = 13$ TeV
- Assumed cross-section: $\sigma_{\text{inel}} = 78.42$ mb
- Normalised to an integrated luminosity of $L = 1$ fb^{-1}
- FLUKA and Geant4 agree well if same MC tune is used
- Kaons, ions, baryons contribute 20% in IBL area

- IBL leakage current measurements are converted to Si-NIEL and compared to the simulations
  - see Mika's talk for discussion on accuracy of damage factors

Predictions for Tile Scintillator radiation damage with Geant4

- ATLAS Tile Calorimeter has thin alternating sheets of steel- and scintillating-tiles
- In FLUKA the geometry is modelled as homogenous mixture
- Need Geant4 geometry to evaluate TID separately in steel and scintillators as function of position along the beam axis ($|z|$) for different distances from the beam axis (r)





Conclusions & Outlook

- ATLAS uses different simulation codes and various geometry implementations for radiation predictions
  - Codes agree well when identical geometries are used
  - Flexibility and level of detail in the geometry implementations differ substantially
- FLUKA has been the main tool in the past
  - Simplified geometries allow for fast implementation of special configurations
  - Emphasis in the geometry was on shielding
- Geant4 is most recent addition in terms of radiation predictions
  - Benefits from high level of detail/accuracy for sensitive detectors
  - Not so flexible in terms of detector configuration
  - Started recently to also add activation studies to Geant4
- Comparisons of FLUKA and Geant4
  - Benefits both sides in terms of implementing more accurate geometries
  - Currently calorimeters are being refined in FLUKA and shielding is getting corrected in Geant4
  - Aim for comparisons of particle spectra with identical toy detector in FLUKA and Geant4 to quantify residual differences
  - Could use a simplified ATLAS geometry in Geant4 as well for special situations like an open detector, etc.
- Availability of at least two independent implementations is a great advantage and helped converging on predictions in difficult detector regions!