High-Luminosity LHC formally approved by CERN Council in June 2016

High priority of worldwide subatomic physics community

- Significant **detector challenges** in this environment with up to 200 separate proton-proton collisions per 25 ns bunch-crossing (pileup) ... see slides ahead...

**First:** physics prospects —>
1. Prospects for Higgs Couplings

Estimates for Run 3 and HL-LHC based on Run-1

\[ \kappa = \frac{\sigma}{\sigma_{SM}} \]

\[ \kappa_V = \frac{m_V^2}{v^2} \]

ATLAS Simulation Preliminary
\[ \sqrt{s} = 14 \text{ TeV} \]

Particle mass
\[ m_i \text{ [GeV]} \]

Gauge interaction
Vector Bosons \( V=W,Z \)

Yukawa interaction
\( f = \text{fermions} \)

Updates planned for SNOMASS, see also European Strategy Update
2. Probe Higgs Self Coupling

\[ V = \frac{m_h^2}{2} h^2 + \frac{\lambda_3}{4} v h^3 + \frac{\lambda_4}{4} h^4 \]

\[ \lambda_3 = \lambda_4 = \frac{m_h^2}{(2v^2)} \]

- Channel bbγγ

- Channel bbττ. Most sensitive

\[ \kappa = \frac{\lambda_3}{\lambda_3^{SM}} \]

\[ \sigma \sim 40 \text{ fb} @ 14 \text{ TeV} \]

O(100k) HH produced

destructive interference

**Di-Higgs**

\[ \text{ATL-PHYS-PUB-2018-053} \]
3. Find Supersymmetry?

Supersymmetry entries in Spires:

1974 1982 2012

D. Treille 2019

3000 fb⁻¹: Extend discovery potential

ATLAS Simulation Preliminary
\(|\sqrt{s}|=14\) TeV, 3 ab⁻¹

All limits at 95% CL

Wino \(\tilde{\chi}_1^+\rightarrow W^\pm \tilde{\chi}_1^0\rightarrow 2L+MET\) final state

ATLAS Simulation Preliminary
\(|\sqrt{s}|=14\) TeV, 3000 fb⁻¹

ATLAS 13 TeV, 80 fb⁻¹

95% CL exclusion (±1 \(\sigma_{exp}\)), multi-bin
5\(\sigma\) discovery, inclusive
All limits at 95% CL

\(\tilde{\tau}^+\tilde{\tau}^- \rightarrow 2 \times \tilde{\tau}_1^0\)

ATL-PHYS-PUB-2018-048
4. Detect Dark Matter?

- Mono-jet searches projected to end of Run 3 & HL-LHC
- Systematic uncertainties extrapolated from current analyses under different scenarios
5. Measure Vector Boson Scattering

The study of the scattering of two massive vector bosons $V = W, Z$ (vector boson scattering, VBS) provides a key opportunity to probe the nature of the electroweak symmetry breaking (EWSB) mechanism as well as physics beyond the Standard Model. It is still unknown whether the Higgs boson preserves unitarity of the longitudinal $VV$ scattering amplitude at all energies, or if other new physics processes are involved.

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ pp \rightarrow W^\pm W^\pm jj \]

- **Expected total uncertainty of 6% is achieved @ HL-LHC**
—> 10x the luminosity reach of first 10 years of LHC operation

<table>
<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Instantaneous $\mathcal{L}$</th>
<th>Integrated $\mathcal{L}$</th>
<th>Pileup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2 LHC</td>
<td>13 TeV</td>
<td>$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>300 fb$^{-1}$</td>
<td>37</td>
</tr>
<tr>
<td>HL-LHC (Nominal)</td>
<td>14 TeV</td>
<td>$5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>3000 fb$^{-1}$</td>
<td>140</td>
</tr>
<tr>
<td>HL-LHC (Ultimate)</td>
<td>14 TeV</td>
<td>$7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>4000 fb$^{-1}$</td>
<td>200</td>
</tr>
</tbody>
</table>

Integrated $\mathcal{L}$ per year: 250 fb$^{-1}$ (baseline), > 300 fb$^{-1}$ (ultimate)
The inner tracker must continue to perform up to 4000 fb\(^{-1}\) (except Pixel Inner System replaced @ 2000 fb\(^{-1}\).):

➢ **Detector Sensor technologies** (Si planar, 3D, diamond) qualified for: \((3-19 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2, 2-10 \text{ MGy})\)
   - NIEL (Non-Ionizing Energy Loss)
     —> bulk damage (trapping centres), depletion voltage and leakage current increase

➢ **Front-End Readout ASICs** (Application Specific Integrated Circuits) qualified for:
   - TID (Total Ionising Dose) —> surface effects, transistor damage and ageing effects
   - SEE (Single Event Effects) induced by heavy ions and hadrons —> either soft errors (no permanent damage: Single Event Upsets,… ) or hard errors (permanent damage: Single Event Latchup)

➢ **Material (cable, glue, composite…)** must be qualified
   - TID can compromise chemical/mechanical integrity
## ATLAS Upgrades

### System | Phase-I | Phase-II
--- | --- | ---
**Muon** | New Small Wheels (NSW) | Muon chambers for inner barrel Continuous readout.

**Tracking**

**Calorimeters** | Level-1 (L1) trigger electronics Liquid Argon (LAr): | LAr: Continuous readout Tile Calorimeter (TileCal): Continuous readout

**Timing**

**Trigger / DAQ** | Trigger hardware | L1 rate increased: 1 MHz
- Higher purity e/γ triggers
- Lower forward muon fake rate
High Level Trigger increased: 10 kHz

+ luminosity monitor upgrades
• New Small Wheels will replace current inner muon endcap wheels

• Thin-Gap Chambers, primary trigger, < 1 mrad resolution

• MicroMegas, primary tracking, resolution < 100 microns

• Now commissioning at CERN —>
Construction of sTGC and Micromegas modules for both NSW-A and C is nearing completion. Sector installation and commissioning well underway.
Phase 2: Muons

- New readout + trigger electronics
- Inner barrel RPC new layer
- New TGC triplet module EIL4
- Combine trigger NSW-TGC
- MDT data at L1: better resolution

ATLAS Simulation Preliminary

Barrel, Large sectors $p_T^{\text{trigger}} > 20$ GeV

- Offline
- Phase-II RPC
- Phase-II RPC & MDT

ATLAS Simulation
Single muons, $<\mu> = 0$
$2.0 < h_{\mu} < 2.7$

- ITk
-Muon Spectrometer
-Combined

Combined performance $\geq$ Run 2 $p_T$ [GeV]

MDT = Monitored Drift Tubes
• **Phase-1**: LAr trigger electronics with higher granularity “Super Cells”, longitudinal shower information
  
  • Electrons: high efficiency & reduced trigger rate
  
  • Jets: Improved resolution
  
  • **Phase 2**: LAr and TileCal data streaming at 40 MHz, radiation-tolerant electronics
Upgrades to LAr Calorimeter

Front-end crates

Back-end crates

See poster by Marcos Oliveira
ITk Pixels
- 5 barrel layers + 5 EC (EndCap)
- Inclined sensors
- Covers $|\eta| < 4$ (was 2.5)
- 1st layer 35 mm from beam line
- Higher resolution than Inner Detector (ID) pixels

ITk Strips
- 4 barrel layers + 6 EC (Endcap) rings
- Silicon microstrip modules with small stereo angle provide 2D measurements
- Higher resolution than Run 2 TRT

ATLAS Simulation Preliminary

ATLAS-TDR-025, ATLAS-TDR-030
ITk Tracking Performance

✓ ITk layout designed to guarantee **hermetic** coverage within $|\eta| < 4$
  - Provides at least 9 hits for all particles with $p_T > 1$ GeV within $|z_{\text{vertex}}| < 150$ mm
    - Allows for **tighter track selection** without compromising reconstruction efficiency
  - Maintain efficiency over 85% up to $|\eta| < 4$, comparable to Run2 ID at $<\mu> = 20$
  - Improves the **fake rate** over Run2 ID, even with a 10x increase in pile-up.

Overall significant improvement thanks to
- Reduced material budget $\rightarrow$ minimize material interactions
- Increase in overall hit counts $\rightarrow$ tighter track selection
- Improved hermeticity $\rightarrow$ more hits, fewer holes
**ITk Pixel Overview**

**ITk Layout – ATLAS-P2-ITK-23-00-00**

**ATLAS Simulation**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Sensor Type</th>
<th>Thickn. [µm]</th>
<th>Sensor Size [µm²]</th>
<th>Module Type</th>
<th>Modules installed</th>
<th>Replacement (2000 fb⁻¹)</th>
<th>Fluence w/ SF [1e15 nₑq/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 barrel</td>
<td>3D n-in-p</td>
<td>150</td>
<td>25x100 1E</td>
<td>Triplet</td>
<td>288</td>
<td>Yes</td>
<td>18</td>
</tr>
<tr>
<td>L0 rings</td>
<td>3D n-in-p</td>
<td>150</td>
<td>50x50 1E</td>
<td>Triplet</td>
<td>900</td>
<td>Yes</td>
<td>18</td>
</tr>
<tr>
<td>L1</td>
<td>Planar n-in-p</td>
<td>100</td>
<td>50x50</td>
<td>Quad</td>
<td>1160</td>
<td>Yes</td>
<td>4</td>
</tr>
<tr>
<td>L2-4</td>
<td>Planar n-in-p</td>
<td>150</td>
<td>50x50</td>
<td>Quad</td>
<td>6816</td>
<td>No</td>
<td>4-1</td>
</tr>
</tbody>
</table>

**Local supports:**

- Inner System (IS)
- Outer End-Cap (EC)
- Outer Barrel (OB)

**Pixels: transition from R&D to pre-production**
**ITk Strip Overview**

**Barrel:** 4 barrel layers instrumented with modules on the two sides of the stave local support

**Endcap:** 6 disks instrumented with modules on the two sides of the petal local support

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td># of modules</td>
<td>10976</td>
<td>6912</td>
</tr>
<tr>
<td># of Local Support</td>
<td>392</td>
<td>384</td>
</tr>
<tr>
<td>Surface [m²]</td>
<td>104.8</td>
<td>60.4</td>
</tr>
</tbody>
</table>

**Barrel:** Stave is loaded with 28 modules → Length ~ 140 cm

**Endcap:** Petal is loaded with 18 modules → Length ~ 60cm

Strips: transition pre-production -> production
Phase 2: ITk
Silicon Microstrips

Sensor charge collection efficiency
NIM A 983 (2020) 164422

Spec: > 6.4k e-

Max dose expected + safety 1.6x10^{15} \text{n/cm}^2
• LGADS (Low-Gain Avalanche Detectors) located on cryostat wall between barrel and endcap calorimeters \(2.4 < |\eta| < 4.0\)

• Timing information enhances pileup jet rejection combined with ITk

• Req. resolution: 30-50 ps/track

• Constraints: thickness < 12.5 cm, Fluence \(2.5 + 15\text{n/cm}^2\), TID 2 MGy

See talk by C. Ohm
The Phase-II TDAQ upgrade enables lowering the single lepton Level-0 threshold to 20 GeV from 50 GeV, (projected threshold w/o upgrade).

Trigger in 3 systems:
1) Level-0 Trigger
2) Readout & Dataflow
3) Event Filter

1) L0Trigger Data from the detectors @ 40 MHz
   Latency: within 10 μs (2.5 μs today)

2) Complete event-data then transmitted through Readout & Dataflow into Event-Filter @ 1 MHz (100 kHz today)

3) Event Filter performs event reconstruction & selection + info from HW-based tracking (HTT).
   Final selected events (5 vs 2 MB today) then transferred to permanent storage @ 10 kHz
   (1 kHz today)
Luminosity and Beam Protection

1. Beam Conditions Monitor Upgrade (BCM’)
   - Provides Fast (bunch-by-bunch) safety system for ATLAS, Luminosity measurement and Background monitoring

2. Inner Pixel system: Separate ring; 4 stations per side with abort, lumi BCM’ and BLM.

2. LUCID (LUminosity Cherenkov Integrating Detector) Upgrade
   - Replace all PMTs with MOD-PMTs (modified: Aluminum ring deposited on inside of windows)
   - Reduce PMT acceptance
     - avoid saturation @ high $\mu$
   - Move detectors to region w. lower flux

BCM TOF concept
- Collisions: in-time
- Background: out-of-time

5” pCVD diamond wafer with test dots
pCVD diamond chosen as sensor material
- robustness (no cooling), low $C$, negligible $I$, fast signal, radiation hard
Conclusion and Outlook

• ATLAS Upgrades well underway (despite many challenges of covid)

• Phase 1 - Installation & Commissioning

• Phase 2 - Prototypes
  —> Preproduction
  —> Construction

• Will meet challenges of HL-LHC

• Open range of physics possibilities

We will be going here

ITk Barrel stave

90% of the data to be produced by the LHC will come during the HL-LHC phase

We are here
HL-LHC will probe gluino masses up to 3.2 TeV, R-parity conserving scenarios. This is about 0.8 – 1 TeV above the Run-2 g̃ mass reach for 80 fb⁻¹. Top squarks can be discovered (excluded) up to masses of 1.25 (1.7) TeV for massless neutralinos, i.e. $\Delta m(t_\tilde{g}, \tilde{\chi}_0^0) \gg m_t$, under realistic uncertainty assumptions. This extends by about 700 GeV the reach of Run-2 for 80 fb⁻¹. The reach in m degrades for larger $\chi_0^0$ masses. If $\Delta m(t_\tilde{g}, \tilde{\chi}_0^0) \sim m_t$, the discovery (exclusion) reach is 650 (850) GeV.
<table>
<thead>
<tr>
<th>Model</th>
<th>spin</th>
<th>95% CL Limit (solid), 5 $\sigma$ Discovery (dash)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KK \rightarrow 4b$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$HVT \rightarrow VV$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$G_{RS} \rightarrow W^+W^-$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$G_{RS} \rightarrow t\bar{t}$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Z_{TC2} \rightarrow t\bar{t}$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Z_{SSM} \rightarrow t\bar{t}$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Z' \rightarrow \ell^+\ell^-$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Z'^{SSM} \rightarrow \ell^+\ell^-$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Z'^{SSM} \rightarrow \tau^+\tau^-$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$W_{SSM} \rightarrow \tau\nu$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$W'_{SSM} \rightarrow \ell\nu$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$W_R \rightarrow t\bar{b} \rightarrow b\ell\nu$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Q^* \rightarrow jj$</td>
<td>1\2</td>
<td></td>
</tr>
<tr>
<td>$\nu_{Majorana} \rightarrow \ell q\bar{q}'$</td>
<td>1\2</td>
<td></td>
</tr>
<tr>
<td>$\nu_{Heavy} (m_N = m_E)$</td>
<td>1\2</td>
<td></td>
</tr>
<tr>
<td>$\ell'^* \rightarrow \ell'\gamma$</td>
<td>1\2</td>
<td></td>
</tr>
<tr>
<td>$LQ(pair \ prod.) \rightarrow b\tau$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$LQ \rightarrow t\mu$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$LQ \rightarrow t\tau$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$H^{++}H^{-} \rightarrow \tau_h\ell^+\ell^-\ell^+\ell^-$ (NH)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$H^{++}H^{-} \rightarrow \tau_h\ell^+\ell^-\ell^+\ell^-$ (IH)</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

($\ell = e, \mu$)

Section
HL/HE-LHC

6.1.1
6.4.4 6.4.4
6.4.6
6.2.2 6.2.2
6.2.3 6.4.6
6.4.6
6.2.5 6.2.5
6.2.5 6.2.4
6.2.4
6.2.7
6.2.6
6.2.6

$\sqrt{s} = 27$ TeV, $L = 15$ ab$^{-1}$

5.2.3 5.2.4
5.2.1
5.2.1
5.2.1 5.1.1
5.1.1 5.1.1

$\sqrt{s} = 14$ TeV, $L = 3$ ab$^{-1}$

5.1.1 5.1.1

arXiv:1812.07831

Mass scale [TeV]
Long-Lived Particles?

"Disappearing track"

ATLAS Simulation Preliminary
$\sqrt{s}=14$ TeV, 3000 fb$^{-1}$, $\mu = 200$
All limits at 95% CL

Expected Limit ($\pm 1\sigma_{exp}$)
5$\sigma$ discovery
Theory
Run 2 Limit (arXiv:1712.02118)
Detect Dark Matter?

Evidence for Dark Matter (DM): Cosmic Microwave Background, gravitational lensing, galaxy rotation curves, large scale structure...

\[ \Omega_b \approx 0.05, \quad \Omega_{DM} \approx 0.25, \quad \Omega_{\Lambda} \approx 0.70 \]

Methods of Detection:

- **Annihilations** (Indirect Detection)
  - DM \(\rightarrow\) SM
  - DM \(\rightarrow\) SM

- **Scattering** (Direct Detection)
  - DM \(\rightarrow\) SM
  - DM \(\rightarrow\) SM

- **Production** (Accelerators)
  - SM \(\rightarrow\) DM
  - SM \(\rightarrow\) DM
Dark Matter Prospects

HL-LHC
3000 fb$^{-1}$
- here: scalar mediator

$X + E_T^{miss}$
$X = t\bar{t}, dijets$

JHEP 1905 (2019) 142

SI=spin-independent

$\sigma_SI \simeq 6.9 \times 10^{-43} \text{ cm}^2 \cdot \left( \frac{g_{qfDM}}{1} \right)^2 \left( \frac{125 \text{ GeV}}{M_{mod}} \right)^4 \left( \frac{\mu_X}{1 \text{ GeV}} \right)^2$.

Scalar model, Dirac DM

$g_{DM} = 1, g_{SM,f} = 1$

Collider limits at 95% CL, direct detection limits at 90% CL

LHC

$\chi \sim m_{DM}$

Complementary searches

CRESST III

XENON1T

PRL 121 (2018) 111302

PRL 117 (2016) 121303

DarkSide-50

PRL 121 (2018) 081307

LUX

PRL 118 (2017) 021303

Argo-3000 (proj.)

DarkSide-Argo EPPSU submission

DARWIN-200 (proj.)

JCAP 11 (2016) 017

HL-LHC, 14 TeV, 3 ab$^{-1}$


HE-LHC, 27 TeV, 15 ab$^{-1}$


FCC-hh, 100 TeV, 1 ab$^{-1}$

PRD 93 (2016) 054030

FCC-hh, 100 TeV, 30 ab$^{-1}$

Rescaling of PRD 93 (2016) 054030

[1] Physics Briefing Book
CERN-ESU-004 Sept.2019
**ATLAS Preliminary**

Projection from Run 2 data

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

- $\text{BR}_{bb} \pm 0.076 (\pm 0.020 \pm 0.073)$
- $\text{BR}_{\tau\tau} \pm 0.060 (\pm 0.017 \pm 0.057)$
- $\text{BR}_{WW} \pm 0.058 (\pm 0.010 \pm 0.057)$
- $\text{BR}_{\gamma\gamma} \pm 0.060 (\pm 0.012 \pm 0.059)$
- $\text{BR}_{ZZ} \pm 0.053 (\pm 0.016 \pm 0.051)$
- $\text{BR}_{\mu\mu} \pm 0.149 (\pm 0.127 \pm 0.075)$
- $\text{BR}_{Z\gamma} \pm 0.242 (\pm 0.203 \pm 0.131)$
\begin{align*}
V &= \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \\
\lambda_3 &= \lambda_4 = \frac{m_h^2}{2v^2}
\end{align*}

\begin{align*}
\kappa_\lambda &= \lambda_3 / \lambda_3^{SM} \\
&= 1 \text{ in SM}
\end{align*}

**Di-Higgs**

\[ \sigma \approx 40 \text{ fb} @ 14\text{TeV} \]

O(100k) HH produced
destructive interference

**ATLAS and CMS**

3000 fb\(^{-1}\) (14 TeV)

**HL-LHC prospects**

-2\text{ab}^{-1} (14 TeV)

**SM HH significance:** 4\(\sigma\)

0.1 < \(\kappa_\lambda\) < 2.3 [95% CL]

0.5 < \(\kappa_\lambda\) < 1.5 [68% CL]

**A challenge!**
ITk Strips Module

Front-End (FE) **ASICs**: ABC + HCC

**Hybrid**: PCB containing ASICs reading out silicon microstrip sensor

**Sensors**: Silicon microstrip sensors, 10x10cm, ~300 μm thick, 75 μm pitch

**Module** = hybrid + sensor groups of modules -> barrel stave or EC “petal”
ITk Strips Front-End ASICs

Wafer with pre-production ASICs

ABCStar (ATLAS Binary Chip) die showing I/O and 4 rows of front-end pads

Technology: GF (ex IBM) 130nm CMOS8RF technology
Strip Sensors

- n-in-p float-zone sensors with p-stop isolation, ~320 µm thickness
- 8 different sensor types (2 barrel, 6 EC)

Sensor produced by Hamamatsu.
All pre-production has been delivered including all EC sensors.
  - Mini sensors and other test structures on each wafer. First test results are as expected from new Test Chip structures
Qualification of sites on going.

Charge collection efficiency vs fluence
Table 2.9: The maximal 1 MeV neutron equivalent fluences and total ionising dose for different parts of the Pixel Detector, for the baseline replacement scenario for the inner section. All values have been multiplied by a safety factor of 1.5.

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>Layer</th>
<th>Location</th>
<th>$R$ (cm)</th>
<th>$z$ (cm)</th>
<th>Fluence ($10^{14} \text{ n}_{eq}/\text{cm}^2$)</th>
<th>Dose (MGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 fb$^{-1}$</td>
<td>0</td>
<td>flat barrel</td>
<td>3.9 *</td>
<td>0.0</td>
<td>131</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>incline barrel</td>
<td>4.0</td>
<td>24.3</td>
<td>-</td>
<td>9.9</td>
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<tr>
<td></td>
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<td>end-cap</td>
<td>3.7</td>
<td>25.9</td>
<td>123</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.7</td>
<td>110.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.1</td>
<td>123.8</td>
<td>68</td>
<td>6.3</td>
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<tr>
<td>2000 fb$^{-1}$</td>
<td>1</td>
<td>flat barrel</td>
<td>9.9</td>
<td>24.3</td>
<td>27</td>
<td>1.5</td>
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<td></td>
<td></td>
<td>incline barrel</td>
<td>8.1</td>
<td>110.0</td>
<td>35</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>end-cap</td>
<td>7.9</td>
<td>299.2</td>
<td>38</td>
<td>3.2</td>
</tr>
<tr>
<td>4000 fb$^{-1}$</td>
<td>2-4</td>
<td>flat barrel</td>
<td>16.0</td>
<td>44.6</td>
<td>28</td>
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<td>15.6</td>
<td>110.0</td>
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<td></td>
<td></td>
<td>end-cap</td>
<td>15.3</td>
<td>299.2</td>
<td>38</td>
<td>3.5</td>
</tr>
</tbody>
</table>

* Updated in 2020: 3.9 -> 3.4 cm, Fluence -> 188 E+14 neq/cm**2
Pixel 3D sensors

3D sensor technology has matured in the last 20 years and is now becoming a standard choice where extreme radiation hardness is critical. In ATLAS, part of the Insertable B-Layer (IBL) relies on 3D pixel sensors.

Figure 4.7: Schematic view of electrode arrangement and charge collection in planar and 3D pixel sensors.

1E: 1 electrode / pixel
2E: 2 electrodes / pixel
3E: 3 electrodes / pixel
Pixel Planar Si sensors

- Thin n-in-p planar sensors: IBL (Insertible B-Layer) in ID today uses 200 µm n-in-n planar sensors with 50x250 µm² pixel cells.
- ITk will use n-in-p technology (single side process) with 50x50 µm² pixel cells: 150 µm for the outer layers; 100 µm for the inner Layer-1

✓ Required performance
  - First results show clear operating hit efficiency >97%
  - Bias voltage at end of lifetime up to:
    - 600 V for 150 µm active thickness
    - 400 V for 100 µm active thickness

✓ Market Survey almost finalized
  - Tender issued by the end of the year

✓ Vendors are optimizing the final design
  - Different biasing solutions allowed
    - Punch through (PT)
    - Bias Rail (BR) and bias resistor
    - Temporary Metal (TM)
  - Dimension of the n⁺ implant
Several module prototype stages have helped to reach maturity in several aspects:

- General module design explored with FEI4 prototypes
- Extensive studies with ~ 250 RD53A module prototypes: thermal cycling, serial powering, new demonstrator to explore system aspects, ...
- ITkPixV1 modules coming.

✓ Hybridization
- Demonstration of fine-pitch bump-bonding on RD53A successful.
- Market survey of vendors running for different process steps: bump deposition, UBM, flip-chip.
- Concern: Thermal cycling causes bump stress, in case of large CTE mismatch between flex (Cu) and Si. Observed in inter-chip regions of FEI4 quads.
  - Improves with parylene coating of the assembled modules and mitigations in interfaces and flex design.

✓ Flex-Hybrid
- Designs for common flex hybrids finished (RD53A)/ongoing (ITkPixV1).
- Reduced Cu content to mitigate CTE mismatch with Si
ITk Material Budget

✓ With the increased surface and granularity wrt ID, $X_0$ mitigation thanks to:

• Strip: DC-DC powering and data transmission with optical links and lpGBT
• Pixel: Thinned sensors and FE, Serial powering, inclined region in the Outer Barrel, increased readout speed
• Common (ITK and Strip): Light structures, cooling designs optimized as well as material choice wrt the requirements (precision, stability, contain the thermal run away, ...)
• NB: Material budget is regularly updated as the engineering design evolves

Reduced material budget versus current ID in Run 2.
→ Minimize effects of multiple-scattering and energy losses before outer detectors.


HGTD Time resolution

• Test beam results: https://arxiv.org/abs/1804.00622

Single Pad LGA
• LHC pilot beam weeks 42/43 (preliminary schedule)
• Updates to ATLAS software in preparation including multi-threading, speed-up tracking