The Standard Model (SM) works very well: too well?
→ SM does not explain everything: e.g. no Dark Matter candidate
→ Naturalness & low-mass of the Higgs boson suggest physics beyond the SM (BSM)

High Lumi-LHC: x100 LHC data at TeV scale
• Measure Higgs properties in detail
• Probe rare SM processes
• Search for new physics: none @LHC yet!
From the LHC to the HL-LHC

LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3 | Run 4 - 5...

<table>
<thead>
<tr>
<th>LS1</th>
<th>13 TeV</th>
<th>13.5-14 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>splicing consolidation button collimators</td>
<td>EYETS</td>
<td>injector upgrade cryo Point 4 DS collimation P2-P7(11 T dip.) Civil Eng. P1-P5</td>
<td>HL-LHC installation</td>
</tr>
<tr>
<td>experiment beam pipes</td>
<td>nominal luminosity</td>
<td>experiment upgrade phase 1</td>
<td>experiment upgrade phase 2</td>
</tr>
<tr>
<td>7 TeV</td>
<td>8 TeV</td>
<td>30 fb⁻¹</td>
<td>14 TeV</td>
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10/20/2017

Yangyang Cheng | CMS Upgrade@LLP
Challenges from HL-LHC

Radiation Dose

Detector elements and electronics exposed to high radiation dose → limits equipment lifetime & degrades signal

Pile-up

140 - 200 additional pp collisions on top of process of interest

Display of a 140 PU event

7.5 x 10^{34} \text{ Hz/cm}^2, \ Pile-up <\mu> = 200
HL-LHC Upgrade: Objectives

• Replace components:
  – parts too damaged by the time of HL-LHC
  – parts that will not survive HL-LHC environment

• Extend coverage:
  – tracker, muon extension etc.

• Improve function:
  – higher granularity pixels, endcap cal; L1 tracking etc.

• New detector(s):
  – Fast timing layer

• Increase bandwidth:
  – trigger & DAQ
HL-LHC Upgrade: Overview

**Trigger/HLT/DAQ**
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output =7.5 kHz

**Barrel EM calorimeter**
- Replace FE/BE electronics
- Lower operating temperature (8°C)

**Muon systems**
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region 1.5 < |η| < 2.4
- Muon tagging 2.4 < |η| < 3

**Replace Endcap Calorimeters**
- Rad. tolerant - high granularity
- 3D capability

**+Timing layer**
( outside tracking volume)
- Radiation tolerant; high granularity
- Extend |η| coverage up to 4
Tracker Upgrade: Pixel

- Increased coverage w/ more disks:
  - $|\eta| \approx 2.5 \rightarrow |\eta| \approx 4$

- Radiation hardness w/ thinner pixels:
  - $285\mu m \rightarrow 150\mu m$

- Improved resolution w/ smaller pixels:
  - Also maintains occupancy $\sim 0.1\%$

- Reduced material budget
Tracker Upgrade: OT & L1 Track Trigger

- Six layers + five disks of pixels-strip/strip-strip modules
- Two-sided sensor modules → stubs → enable track finding at L1 for tracks w/ pT > 2GeV: ~15k stubs @ 14MHz

For more on LLP prospects w/ L1 Track Trigger, see Yuri Gershtein’s talk later today!
Excellent tracking performance with increased coverage and better resolution!

Vertexing resolution almost independent of pile-up; longitudinal resolution only ~50% worse than transverse (with 25x100x150 pixels)
Tracker Upgrade: LLP Prospects

- Heavy stable charged particles (e.g. split SUSY): high dE/dx in silicon sensor
- Phase2 inner pixel has analogue readout:
  - 4 (maybe more?) bit time-over-threshold info provides good resolution
- Phase2 outer tracker has digital readout + dedicated overthreshold bit (HIP flag) with programmable threshold (currently set at 1.4MIP)

Good separation between background and signal in dE/dx and number of overthreshold clusters per track
Calorimetry Upgrade: Barrel

- The crystals in the ECAL will be kept for duration of LHC.
- The FE & BE electronics will be replaced for more precise timing, useful in both pile-up mitigation and searches for new physics.
- Target (hardware fundamental limit): \(~30\text{ps for } E > ~30\text{GeV}\) (1/10 of current limit).
- Current studies on HCAL Barrel radiation damage suggest no need for replacement at HL-LHC: pending further study.

Expected dose in HCAL Barrel at HL-LHC, in 4500fb-1 ultimate scenario.
Calorimetry Upgrade: Endcap

The endcap calorimeter will be replaced with a silicon-based calorimeter:

- high granularity and 3D imaging to help mitigate PU
- Fast signal collection (<10ns) and **fast timing capability** (few tens of ps)

⇒ **4D info in space-time to reconstruct showers**

- **EM Endcap**: Pb/W/Cu + Si
- **Front Hadronic endcap**: SS + Si
- **Backig Hadronic endcap**: brass + plastic
- **Hexogonai silicon sensors**
  - 100/200/300μm thick: per radius
  - CO2 cooling to operate at -30C to minimize radiation damage

*Leakage current @ 1000V*
Calorimetry Upgrade: Performance

Results shown for barrel calorimetry upgrade: HGCAL results in progress

- **H → γγ:**
  - Precision timing improves vertexing resolution;
  - Expect degrade in energy resolution

- **H → ττ:**
  - Maintain performance for mass resolution at HL-LHC vs Run2

- Good jet performance: significant improvement with upgrades
- PUPPI works well for PU mitigation
- Aging effect minimal w/ recalibration
HL-LHC Upgrade: Muon System

Muon system upgrade scope for HL-LHC:
• Existing detectors:
  • upgrade barrel DT and endcap CSC electronics for 40MHz readout
• Extend forward coverage:
  • GEM & RPC detectors: 1.6<\eta<2.4
  • ME0 (for trigger): 2.4<\eta<2.9

Standalone muon trigger at L1:
• Keep rate under control:
  • single muon threshold 20-25GeV @ HL-LHC
• Provide good resolution and efficiency
• Provide capabilities not covered by L1 track trigger, e.g. displaced tracks & slow moving particles
Muon Upgrade: Performance

Improved performance with HL-LHC upgrade:
- Higher efficiency: minimal dependency on pile-up
- Lower rate: better measurement $\rightarrow$ much purer sample
- Improved timing resolution w/ electronics upgrade
  - 12.5 ns $\rightarrow$ 1 ns in DT
- Extended forward coverage: $|\eta|<2.4$ $\rightarrow$ $|\eta|<2.8$
- Benefits from the L1 track trigger for prompt muons

Prospects on LLP searches:
See Henning Keller’s excellent talk on Wednesday!
• Calorimeter upgrades (ECAL electronics + HGCAL) will provide precise (a few 10s of ps) timing for high energy photons in barrel and high energy hadrons/photons in endcap
• Additional timing layer (outside tracker volume) can provide precision timing for charged hadrons & converted photons down to a few GeV.
• Traditional 3D vertex fit upgraded to a 4D fit
Timing Upgrade: LLP Prospects

(Illustrations c/o A. Ledovskoy)
For more info, see dedicated talk later today!

Scenario 1: Long-lived particle (neutral or charged) is produced at IP, & at secondary vertex (SV), decays into two observable particles (neutral or charged). With timing info (t1,2→T1,2; T0=T1=T2) the scenario has unique solution for SV → full reconstruction!

Scenario 2: LLP decays to visible + invisible particles. If the invisible particle mass is known + additional timing info → enough constraints for unique solution → applicable for GMSB, iDM dark photon etc.
HL-LHC Upgrade: Trigger

- **L1 Trigger:**
  - Increase output: $100\text{kHz} \to 750\text{kHz}$,
  - Increase latency: $3.4\,\mu\text{s} \to 12.5\,\mu\text{s}$
  - New track trigger at L1 (+ calo, muon, global)

- **High-Level Trigger:**
  - Processing power scales with pile-up and L1 rate
  - Output rate increase to 7.5kHz (up to 10kHz)
HL-LHC Upgrade: Timeline

- **Tracker TDR**
  - May 2017: pre-view document; end of June 2017: provide CMS approved version - including cost and responsibilities
  - Nov. 2017: final approval of the Tracker TDR

- **Barrel Calorimeters and Muons TDRs**
  - Sep. 2017: provide CMS approved TDRs - including cost and responsibilities
  - Feb. 2018: final approval of the BC and Muons TDRs

- **Endcap Calorimeter TDR**
  - Nov. 2017: provide CMS approved TDR - including cost and responsibilities
  - May. 2018: final approval of the Endcap Calorimeter TDRs

<table>
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<tr>
<th>Calendar Year</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<th>2024</th>
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<tbody>
<tr>
<td><strong>Long Shutdowns</strong></td>
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<td></td>
<td></td>
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<td>LS2</td>
<td></td>
<td></td>
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<td><strong>Tracker:</strong> Pixel</td>
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<td>Engin.</td>
<td>ED/SR</td>
<td>Production - Assembly - Float</td>
<td>Install. Comm.</td>
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Conclusions and Outlook

• The High-Luminosity LHC brings exciting physics potential #MoarData and many experimental challenges:
  – high radiation, high pile-up, high data-rate

• Comprehensive upgrade program to address these challenges and meet physics potential
  – improved spacial resolution: tracker; HGCAL; ...
  – increased forward coverage: pixel extension; muon; ...
  – improved timing information: HGCAL; MIP; electronics; ...
  – L1 tracking & other trigger/DAQ upgrades

• Higher luminosity + a more powerful machine + improved techniques \(\rightarrow\) new possibilities for LLP searches
THANK YOU!

Keep looking with a magnifying glass; you never know what you might find...