BSM Physics at the HL-LHC

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Improved detectors

• Higher granularity tracking & calorimetry
• Extended $\eta$ coverage for tracker and muons
• Improved triggering (tracks, vertices, muons)
• Improved timing
• Improved readout
• Improved radiation hardness

versus

• High pile up
• High beam-induced background
• High radiation
BSM @ HL-LHC

- Long lived particles
- Vector-like quarks
- SUSY
- Heavy resonances
- Others
- Dark sectors
- Dark matter

Flavor

- in this talk
BSM searches at HL-LHC

- Continue and improve current searches to extend sensitivity
- Design new searches exploiting the new detector improvements.
- Develop new analysis strategies.

→ access scenarios with lower cross sections, lower acceptance.

→ open new search channels
  - e.g., in SUSY: focus on EWK sector, staus, compressed scenarios
  - e.g., long lived particles: explore improvements in muon systems, tracking, triggers and dedicated timing detectors to expand searches.

2 current methods to establish sensitivity

- Projections from a present analysis
  - Use existing samples, scale results to a higher luminosity considering different systematic scenarios

- Full analysis with parametrized detector performance
  - New simulation of the detectors, new/improved analysis design
Stau pair searches

- Direct $\tilde{\tau}\tilde{\tau} \rightarrow \tilde{\tau}_1^{0}\tilde{\tau}_1^{0}$
- $m(\tilde{\tau}) \sim m(\tilde{\chi}_1^{0}) \rightarrow \Omega_{\tilde{\chi}_1^{0}}h^2 \sim$ observed.
- Low cross sections, low acceptance
- 2 OS $\tau_{\text{had}} + E_{\text{Tmiss}}$ final state.
- Used $\Delta R(T_1, T_2)$, $m_{T_2}$, $m_{T(\tilde{\tau}_1)} + m_{T(\tilde{\tau}_2)}$.

Current reach, $\tilde{\tau}_L\tilde{\tau}_L, \tilde{\tau}_R\tilde{\tau}_R$ combined:
- Excl: $m(\tilde{\tau}) < 109\text{GeV}$ for $m(\tilde{\chi}_1^{0}) = 0$.

HL-LHC reach, $\tilde{\tau}_L\tilde{\tau}_L, \tilde{\tau}_R\tilde{\tau}_R$ combined:
- 5$\sigma$ disc: $\sim 400 - 500\text{GeV}$
- Exclusion: $\sim 700\text{GeV}$ depending on systematics.
C2N4 in same sign dilepton search

- SUSY EWK sector with $\mu < M_1 < M_2$.
  -> wino like degenerate $\tilde{\chi}_2^\pm \tilde{\chi}_4^0$ mass $\sim M_2$.
- 2 SS Ws (leptons) + $E_T^{\text{miss}}$ final state.
  <— NEW search channel.
- Used $m_{T,\text{min}} = \min[m_{T(\text{lep}_1, P_T^{\text{miss}})}, m_{T(\text{lep}_2, P_T^{\text{miss}})}]$.

HL-LHC has potential to probe most of natural SUSY space with EW naturalness $\Delta EW < 30$. 

Excl.: 900 GeV

Sensitivity only at HL-LHC
Exotic states with $HH \rightarrow b\bar{b}b\bar{b}$

- Heavy resonances $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$
- KK excitation of graviton in bulk RS
- Heavy neutral Higgs in 2HDMs
- Tag boosted $H \rightarrow b\bar{b}$ using jet mass, finding sujets, and subjet b-tagging.
- Look for bumps in di-boosted jet invariant mass distribution.

Sensitivity to bulk gravitons: $\sim 2.5$ TeV.
Current excl.: 500-720 GeV.

Similar CMS study studied VBF production of $X \rightarrow HH$
Used forward jets, and found sensitivity up to $m_G \sim 3$ TeV.
Z’ and W’ searches

- Z’ → tt → WbWb → ℓνbqqb.

TopColour model with a spin-1 Z’.

- Boosted t or resolved t with 1e/μ.

- Reconstruct tops and check m_{tt}.

- Current/300fb^{-1} excl.: m_{Z’} ~2.1/3TeV.

- HL-LHC excl.: m_{Z’} ~4TeV.

(boosted search dominates)

- Heavy W’ → tb → e/μ + νbb

  - e.g. sequential SM.

  - e/μ + jets + b jets + E_T^{miss}.

- Search for signal in inv mass m_{tb}.

  - Current excl: 2.7TeV.

  - HL-LHC excl: m_{W’} beyond 4TeV.

  - HL-LHC discovery: m_{W’} up to 4TeV.
VLQ top partner search

- EWK production (Wb/Zt fusion) of VLQ top partner $gq \rightarrow Tbq'/Ttq$ with $T \rightarrow tH$.
- 1lep + jets + b jet(s) + boosted H + $E_{T\text{miss}}$ + forward jet.
- Reconstruct $m_T$ with a $\chi^2$ minimization.
- HL-LHC greatly extends sensitivity and opens access to these models.

A versatile HL-LHC VLQ and VLL search program being designed:
Production in heavy Higgs decays, measurement of chiral structure, ...
Displaced muon search

- Model independent search for displaced muons decaying outside the tracker.
- Trigger and reconstruction only in the muon system (standalone muons)
  - Additional hits in new muon layers + improved algorithms improve efficiency.

- Interpretation in terms of GMSB smuons: \( \tilde{\mu} \rightarrow \tilde{\chi} \mu \) (low cross sections)
- Exclude smuons with mass < 220GeV.
- Discovery wrt \( \tau \) significantly improved.
- Interpretations ongoing for other models (e.g. dark photons).
Disappearing tracks, displaced vertices

- Long lived $\tilde{\chi}_1^\pm$ when $m(\tilde{\chi}_1^\pm) \simeq m(\tilde{\chi}_1^0)$
  $\rightarrow \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$ (very soft $\pi^\pm$)
- Disappearing track + $E_T^{\text{miss}}$.
- ATLAS: Benefit greatly from the new inner tracker strip detector (ITk).
- Wino $\tilde{\chi}_1^\pm$ excl: 400 (Run2) $\rightarrow$ 800GeV.
- Pure higgsino $\tilde{\chi}_1^\pm$: 150 (Run2) $\rightarrow$ 260GeV.

- Displaced photons from $\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$
- CMS MTD: MIP timing with 30ps precision. Acceptance of $|\eta| < 3$ for $p_T$, $p < 0.7$ GeV in barrel/endcap.
- Use time of arrival of photons to MTD to discriminate signal $\rightarrow$ determine $\tilde{\chi}_1^0$ time of flight.
  $\rightarrow$ increased sensitivity with MTD to short lifetimes and high masses.

Current HL-LHC
**Dark matter searches**

Simplified models with few free parameters:
- \( m_{\text{mediator}}, m_{\text{DM}}, \text{couplings} \)
- \( g_{\text{mediator-SM}}, g_{\text{mediator-DM}} \).

**DM at HL-LHC:**
- Mainly projection studies
  - Monojet
  - DM + heavy flavor (DM+t, tt, bb, tttt)
  - DM + mono Z, \( \gamma \), VBF DM
  - ...

Example: Monojet + \( E_T^{\text{miss}} \) search

![Graph showing CMS Preliminary Simulation 3000 fb\(^{-1}\) (14 TeV)](attachment:Graph.png)
Summary

• HL-LHC offers an unprecedented amount of data and novel detector capabilities.
• BSM reach to be extended and new models and signatures to be explored.
• Rare processes become accessible.
• Many projection studies and full analyses are ongoing.
• A CERN yellow report including all recent studies by the LHC experiments and theorists being prepared for the end of 2018 as input to the European Strategy Group.
The SUSY saga will continue

- **Gluinos** and **squarks** have the highest cross sections.  
  \( \rightarrow 5\sigma \) discovery reach up to \(~2.5\) and \(~2\) TeV.

- Conventional **sbottom** and **stop** searches  
  \( \rightarrow 5\sigma \) discovery reach up to \(~1.3\) and \(~1\) TeV.

- Improving searches with **refined methods**.

**Focus on difficult scenarios:**
- EWK gauginos in various decays
- Compressed EWK gauginos, sleptons
- Chargino pair production
- Light Higgsinos
- Stau pair production
- Compressed stop
- Heavy stops/sbottoms
- …
Z’ and W’ searches

- Z’ → tt, t → leptonic and hadronic
- Narrow width Z’ ; RS KK graviton.
- Discovery sensitivity for hadronic channel on RS KK graviton.
- HL-LHC excl: 3.3TeV (narrow Z’), 4TeV (RS KK graviton)

- W’ → μν
- Assessed the impact of upgrade of ATLAS trigger system, i.e. addition of barrel inner RPCs.
- Increase in muon trigger acceptance gain: 70% → 90%.
Long lived particle signatures

• Neutral or charged particles decaying a macroscopic, measurable distance away from the interaction point.
• Many models with LLPs.
• Non standard signatures, non standard objects.
• Signature based searches
• Need dedicated triggers and algorithms.
• Track triggers, improvement in muon systems and dedicated timing detectors will improve sensitivity.
Disappearing tracks, displaced vertices

- LLP decaying in inner tracker to stable particles forming displaced tracks / vertices.
- Larger volume and increased number of silicon layers in ITk significantly improve displaced vertex acceptance for an R hadron case study.

- ATLAS High granularity timing detector.
- Located at \( z = 3.5\text{m} \), \( 2.4 < |\eta| < 4 \).
- 30ps/track timing resolution.
- Improves sensitivity to slow forward charged long lived particles.