Future Searches for New Physics at the LHC with ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

Snowmass on the Mississippi, Minneapolis, July 31st 2013
Introduction
LHC Run 1

- 25 fb\(^{-1}\) of 7+8 TeV pp data
- Higgs boson found!
  - Looks like SM at first glance
- Stringent limits set on physics beyond the SM
- Many precise measurements of SM processes
# ATLAS Supersymmetry Searches

**Model** | \(e, \mu, \tau, \gamma, J_{ets} \) | \( \mathcal{E}^{\text{miss}} \) | \( L \) | \( \mathcal{L} \) | \(| \mathcal{L} \mathcal{L} | \) | \( \text{mass} [\text{TeV}] \) | \( \text{Reference} \) |
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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are obtained minus 1\sigma theoretical signal cross-section uncertainty.

**Similar results obtained by CMS**
CMS Exotics Searches

CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)

- q* (qg), dijet
- q* (qW)
- q* (qZ)
- q*, dijet pair
- q*, boosted Z
- e*, Λ = 2 TeV
- μ*, Λ = 2 TeV
- Z'SSM (ee, μμ)
- Z'SSM (tt)
- Z' (tt hadronic) width=1.2%
- Z' (dijet)
- Z' (tt lep+jet) width=1.2%
- Z'SSM (ll) fbb=0.2
- G (dijet)
- G (jet+MET) k/M = 0.2
- G (γγ) k/M = 0.1
- G (ZllZqq) k/M = 0.1
- W' (lv)
- W' (dijet)
- W' (td)
- W' → WZ(leptonic)
- WR' (tb)
- WR, MNR=MWR/2
- WKK μ = 10 TeV
- pTC, nTC > 700 GeV
- String Resonances (qg)
- s8 Resonance (qg)
- E6 diquarks (qg)
- Axigluon/Coloron (qgbar)
- gluino, 3jet, RPV
- gluino, Stopped Gluino
- stop, HSCP
- stop, Stopped Gluino
- stau, HSCP, GMSB
- hyper-K, hyper-p=.12 TeV
- neutralino, cr<50cm
- Long Lived

Heavy Resonances:

- Z'SSM (ee, μμ)
- Z'SSM (tt)
- Z' (tt hadronic) width=1.2%
- Z' (dijet)
- Z' (tt lep+jet) width=1.2%
- Z'SSM (ll) fbb=0.2
- G (dijet)
- G (jet+MET) k/M = 0.2
- G (γγ) k/M = 0.1
- G (ZllZqq) k/M = 0.1
- W' (lv)
- W' (dijet)
- W' (td)
- W' → WZ(leptonic)
- WR' (tb)
- WR, MNR=MWR/2
- WKK μ = 10 TeV
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Compositeness:

- q* (qg), dijet
- q* (qW)
- q* (qZ)
- q*, dijet pair
- q*, boosted Z
- e*, Λ = 2 TeV
- μ*, Λ = 2 TeV
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- Z'SSM (tt)
- Z' (tt hadronic) width=1.2%
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LeptoQuarks

- b' → tW, (3l, 2l) + b-jet
- q', b'/t' degenerate, Vtb=1
- b' → tW, l+jets
- B' → bZ (100%)
- T' → tZ (100%)
- t′ → bW (100%), l+jets
- t′ → bW (100%), l+l

4th Generation

- C.I. Λ , X analysis, Λ+ LL/RR
- C.I. Λ , X analysis, Λ- LL/RR
- C.I., μμ, destructive LLIM
- C.I., μμ, constructive LLIM
- C.I., single e (HnCM)
- C.I., single μ (HnCM)
- C.I., incl. jet, destructive
- C.I., incl. jet, constructive

Contact Interactions

- Ms, γγ, HLZ, nED = 3
- Ms, γγ, HLZ, nED = 6
- Ms, ZL, HLZ, nED = 3
- Ms, ZL, HLZ, nED = 6
- MD, monojet, nED = 3
- MD, monojet, nED = 6
- MD, mono-γ, nED = 3
- MD, mono-γ, nED = 6
- MBH, rotating, MD=3TeV, nED = 2
- MBH, non-rot, MD=3TeV, nED = 2
- MBH, boil. remn., MD=3TeV, nED = 2
- MBH, Quantum BH, MD=3TeV, nED = 2

Extra Dimensions & Black Holes

- *similar results obtained by ATLAS*
Run-1 Publications

- ATLAS and CMS have published 510 papers based on run-1 collision data to date
  - Split about 50/50 between searches and measurements
  - Expect >100 more per experiment on run-1 data
    - as 7 and 8 TeV analyses finish
  - Behind every paper there is a PhD thesis!
    - Often more than one…
- Huge interest in the field
  - Higgs observation papers have >1300 citations each
    - they are merely one year old!
US role in LHC, ATLAS and CMS

- US has made critical contributions to LHC machine
  - E.g. Inner Triplet magnets
- US is single biggest collaborator in both ATLAS and CMS
  - ATLAS: 583 US authors (20% of total)
    - 175 US graduate students
  - CMS: 678 US authors (31%)
    - 247 US graduate students
- US Contributions
  - Major contributions to design, construction and operation of most subdetectors
  - Making major impact on physics analyses
  - Providing leadership in all areas
Future Plans for LHC and ATLAS and CMS Detector Upgrades
LHC Roadmap

2009
LHC startup, $\sqrt{s}$ 900 GeV

2010
$\sqrt{s}=7+8$ TeV, $L \sim 6 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$, bunch spacing 50ns

2011
Go to design energy, nominal luminosity - Phase 0

2012
$\sqrt{s}=13\sim14$ TeV, $L \sim 1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, bunch spacing 25ns

2013
LS1

2014
LS2
Injector + LHC Phase I upgrade to ultimate design luminosity

2015
$\sqrt{s}=14$ TeV, $L \sim 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, bunch spacing 25ns

2016

2017

2018
LS3

2019

2020

2021

2022
HL-LHC Phase II upgrade: Interaction Region, crab cavities?

2023

...?

2030?

$\sqrt{s}=14$ TeV, $L \sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, luminosity levelling

Run 1
$\sim 25 \text{ fb}^{-1}$

Run 2
$\sim 75-100 \text{ fb}^{-1}$

$\sim 350 \text{ fb}^{-1}$

$\sim 3000 \text{ fb}^{-1}$
LHC Roadmap

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$\sqrt{s}=14$ TeV, $L\sim 5\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, luminosity levelling

2020

2021

2022
LS3

2023

2030?

Average # of simultaneous pp collisions

- 20
- $\sim 25$
- $\sim 50-80$
- $\sim 140$
Detector Upgrades

- Detectors will need to be upgraded to be able to cope with higher luminosity, e.g.
  - Improve trigger capabilities
    - better discriminate the desired signal events from background as early as possible in trigger decision
  - Upgrade and/or replace detectors as they e.g.
    - Cannot handle higher rate due to bandwidth limitations
    - Suffer from radiation damage making them less efficient
Detector Upgrades: Phase-0, Phase-I and Phase-II

- **Phase-0**
  - 4th Si Pixel layer (IBL)
  - Complete muon coverage
  - Repairs (TRT, LAr and Tile)
  - New beampipe and infrastructure updates

- **Phase-I**
  - Fast Track Trigger (FTK)
  - Muon New Small Wheel (NSW)
  - LAr cal. electronics

- **Phase-II**
  - New pixel and strip tracker
  - Calorimeter
  - Muon system
  - Trigger system
  - Computing
  - ...
Tracking during Phase-2

- New inner trackers needed after 300 fb\(^{-1}\)
- Performance as good or better than current detectors even for 140 pp interactions per crossing

b-tag \(\varepsilon=70\%\) light q rejection: 120
Jet and $E_T^{\text{miss}}$ resolution degrades moderately with increasing pileup

- Performance still sufficient for physics measurements and searches

more details: see talk by A. Schwartzman in QCD parallel session Saturday
Jet counting and substructure at high pileup

- Jet multiplicity is controlled with clever pileup suppression techniques.
- Jet substructure can still be resolved thanks to “trimming” techniques.
  - Important for searches with boosted massive objects (e.g. top, W, H)
Future Prospects for New Physics Searches
Many questions follow from Higgs discovery!

- **Is it the Higgs boson?**
  - Does it couple to matter exactly as predicted?
  - Does it couple to gauge bosons exactly as predicted?
  - Are there more Higgs bosons?
- **Does the Higgs boson decay to non-SM particles?**
  - E.g. to Dark Matter?
- **How do bosons interact with each other?**
  - Does Higgs boson contribute as expected in SM?
  - Are there new gauge groups?
- **What protects the Higgs mass from being $m_{\text{Planck}}$?**
  - Is Nature Supersymmetric?
    - Is Dark Matter a SUSY particle?
  - Are there new generations of fermions?
  - Is there some other new dramatic physics coming in at the TeV scale
    - Are there extra dimensions of space?
    - Is there a new strong interaction?
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Studies of Future Physics Prospects

- Studies have been performed for $\sqrt{s}=14$ TeV for integrated luminosities of 300 fb$^{-1}$ (LHC) and 3000 fb$^{-1}$ (HL-LHC)
  - Many were done a year ago for European Strategy study
  - Many new studies done newly for this Snowmass meeting
- Studies should be considered conservative
  - Analyses were based on parametric simulation (ATLAS) or extrapolated from Run-1 (CMS) for a given set of cuts
    - Much less elaborate than current Run-1 analyses
    - Better results can be obtained when cuts are reoptimized
      - Gain by making cuts harder to reject more background
  - Various treatments of systematic uncertainties studied to provide range of predictions
    - See talk by M. Klute

CMS and ATLAS white papers: arXiv:1307.7135 and 1307.7292
How do bosons interact with each other?

- In SM there is an exact cancellation between terms for longitudinal vector boson scattering
  - Cross section does not grow with energy due to Higgs
- Long history of studying trilinear gauge couplings at LEP and Tevatron
  - Excellent probe of structure of EWK interaction
- LHC allows for the first time study of quartic couplings
  - Understand if Higgs boson plays the expected role in this area
Probing Quartic Gauge Boson Couplings

- Vector boson scattering: ZZ, WZ, W^±W^±,...
- 3-boson production, e.g. Zγγ
Quartic Gauge Boson Couplings

- Use framework of effective operators to parameterize new physics as quartic coupling, e.g.
  - $ZZ$: dimension-6 operator
  - $Z\gamma\gamma$: dimension-8 operator

- If new physics discovered with $300 \text{ fb}^{-1}$ can measure coupling with 5% accuracy with $3000 \text{ fb}^{-1}$
What protects Higgs mass from being $m_{\text{Planck}}$?

- **Known possible answers:**
  - SUSY: top squark at $m \lesssim 1$ TeV
    - ... and gluino with $m \lesssim 3$ TeV
  - vector-like top quarks
    - e.g. Little Higgs theories
  - extra spatial dimensions or some other dramatic new physics at a mass scale of a few TeV

- **Can directly search for these particles at LHC!**
  - If we see nothing at LHC the electroweak scale is finetuned at $\sim 1\%$ level
SUSY particles and processes

- Top squarks
  - Produced directly or in gluino decays
    - if gluino mass low enough
  - Decay via top quarks or via charginos to final states of W’s and b’s

- Gluinos
  - Decay via jets + $E_T^{\text{miss}}$
  - Meta-stable case

- Charginos and neutralions
  - Trilepton signature
Run-1 constraints on top squarks

- Vigorously probed using many different analyses
- However, **pretty natural** scenarios still allowed, e.g.
  - \(M(g)=1.5 \text{ TeV}, \ m(t)=300 \text{ GeV}, \ m(\text{LSP})=150 \text{ GeV}\)
- LHC (and HL-LHC) will be able to discover such scenarios
Gluino reach if decay via top/bottom

- With 300 fb$^{-1}$ will reach about 2 TeV in gluino mass both in top- and b-decay signatures
  - 3000 fb$^{-1}$ study ongoing
Top squark discovery potential

- Challenging analysis due to large top background
  - Systematic uncertainties matter
- 300 fb\(^{-1}\):
  - Discovery up to 800-900 GeV in direct production
- 3000 fb\(^{-1}\):
  - Reach improved by \sim 140 GeV in \textit{m}(\text{stop}) and \sim 100 GeV in \textit{m}(\text{LSP})
- Expect further improvements with reoptimization
- Sbottom also supposedly light due to mixing with stop
- Discovery with 300 fb\(^{-1}\) for masses up to 600-700 GeV
  - Scenario A: syst. errors as today
  - Scenario B: syst. errors scaled with \(1/\sqrt{L}\) (but at least 10%)
Search for large $E_T^{\text{miss}}$ and large $M_{\text{eff}}$

Current limit $\sim 1.2$ TeV at 95% CL:
- Will be extended to $2.3$ ($2.7$) TeV with LHC (HL-LHC) if we don’t discover it
- Discovery potential extended by 400 GeV with HL-LHC
Weak SUSY Production

- Further motivations for new physics at weak scale
  - Unification of couplings, Dark Matter, ...
  - E.g. in “split-SUSY” squarks are heavy but gauginos are at ~low mass
    - Search for those directly
- Classic search
  - Chargino+neutralino production

Current limits not yet very restrictive, e.g. no constraints for m(LSP)>100 GeV
Future Prospects for Weak SUSY Production

- Probe chargino masses of \( \sim 500 \text{ GeV} \) with \( 300 \text{ fb}^{-1} \)
  - for \( m(\text{LSP})<100-200 \text{ GeV} \)
- Dramatic improvement with HL-LHC:
  - Reach >800 GeV for \( m(\text{LSP})<300 \text{ GeV} \)
Metastable Gluinos and Staus

- Metastable sparticles occur in many scenarios of new physics
  - E.g. Split-SUSY $\tilde{g}$, GMSB stau, …

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<td>Run-1 data 95% CL limit</td>
<td>&gt;1.0</td>
<td>0.27</td>
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<td>300 fb$^{-1}$ 5$\sigma$ discovery</td>
<td>1.8-2.0</td>
<td>~0.8</td>
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<tr>
<td>3000 fb$^{-1}$ 5$\sigma$ discovery</td>
<td>2.1-2.3</td>
<td>~1.2</td>
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Vector-like Top Quarks

- Colored spin-1/2 fermions
  - transform the same for left- and right-handed under EW gauge group
- Provide alternative solution to little hierarchy problem
- Appear in many BSM models, e.g.
  - Little Higgs, Extra Dimensions,…
Vector-like Top: Present

Currently probing up to about 600-800 GeV
Vector-like Top: future

CMS projection $\sqrt{s}=14$ TeV $\geq 1$ leptons

- Probe $>1.5$ TeV with 3000 fb$^{-1}$
### Rare decays of the top quark

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<th>SM</th>
<th>QS</th>
<th>2HDM</th>
<th>FC 2HDM</th>
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<th>$\mathcal{R}$</th>
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<td>$t \to uy$</td>
<td>$3.7 \times 10^{-16}$</td>
<td>$7.5 \times 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
<td>—</td>
<td>$\sim 10^{-11}$</td>
</tr>
<tr>
<td>$t \to uZ$</td>
<td>$8.0 \times 10^{-17}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>$2 \times 10^{-6}$</td>
<td>$3 \times 10^{-5}$</td>
<td>—</td>
<td>$\sim 10^{-9}$</td>
</tr>
<tr>
<td>$t \to ug$</td>
<td>$3.7 \times 10^{-14}$</td>
<td>$1.5 \times 10^{-7}$</td>
<td>—</td>
<td>—</td>
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<td>$4.6 \times 10^{-14}$</td>
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</tr>
<tr>
<td>$t \to cZ$</td>
<td>$1.0 \times 10^{-14}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-5}$</td>
</tr>
<tr>
<td>$t \to cg$</td>
<td>$4.6 \times 10^{-12}$</td>
<td>$1.5 \times 10^{-7}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-8}$</td>
<td>$8.5 \times 10^{-5}$</td>
<td>$2 \times 10^{-4}$</td>
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</table>

- LHC is a top factory
  - In 3000 fb$^{-1}$ 0.5 billion observed $tt\bar{t}$ events per experiment
- In SM top quark decays to $Wb$ nearly 100%
  - Observing decays to other modes clear sign of new physics
- Interesting region starts at $\sim 10^{-4}$
- HL-LHC will probe $\sim 3 \times 10^{-5}$ at least
Is there some other new physics coming in dramatically at the TeV scale?

- E.g. large or warped extra dimensions provide alternative solution to naturalness problem
  - Bring Planck scale down to TeV scale
- Main signatures
  - Resonances of dilepton, diphoton, ditop production
    - via KK graviton or KK gluon exchange
    - Also common signatures for extended gauge groups (Z’)
  - Monojet or monophoton
    - Due to graviton emission
  - Many hard particles
    - Black holes
- All of them are pursued in run-1 data analyses
  - Future prospects for dilepton and ditop resonances
Dilepton resonances: limits

- Current limits are on $\sigma \times \text{BR}$ are $\sim 0.3$ fb
  - Expect to improve by a factor of $\sim 100$ with HL-LHC
  - Probe $Z'_{\text{SSM}}$ up to masses of 7.8 TeV

<table>
<thead>
<tr>
<th>95% CL limits on:</th>
<th>$Z'\rightarrow ee$ (TeV)</th>
<th>$Z'\rightarrow \mu\mu$ (TeV)</th>
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<tbody>
<tr>
<td>Run-1 data</td>
<td>2.79</td>
<td>2.48</td>
</tr>
<tr>
<td>300 fb$^{-1}$</td>
<td>6.5</td>
<td>6.4</td>
</tr>
<tr>
<td>3000 fb$^{-1}$</td>
<td>7.8</td>
<td>7.6</td>
</tr>
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</table>
Dilepton resonances: discovery potential

<table>
<thead>
<tr>
<th></th>
<th>$Z'_{SSM, ee}$</th>
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<tr>
<td>300 fb$^{-1}$</td>
<td>5.1 TeV</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>3000 fb$^{-1}$</td>
<td>6.2 TeV</td>
<td>6.4 TeV</td>
</tr>
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</table>
Ditop resonances: limits

- Current limits are on $\sigma \times \text{BR}$ are $\sim 0.1$ pb
  - Expect to improve by a factor of $\sim 100$ with HL-LHC
  - Probe KK gluons up to masses of $\sim 6.7$ TeV

<table>
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<tr>
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<th>$g_{KK}$ (TeV)</th>
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<td>Run-1 data</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>300 fb$^{-1}$</td>
<td>3.3</td>
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<td>3000 fb$^{-1}$</td>
<td>5.5</td>
<td>6.7</td>
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Many questions follow from Higgs discovery!

- **Is it the Higgs boson?**
  - Does it couple to matter exactly as predicted?
  - Does it couple to gauge bosons exactly as predicted?
  - Are there more Higgs bosons?

- **Does the Higgs boson decay to non-SM particles?**
  - E.g. to Dark Matter?

- **How do bosons interact with each other?**
  - Does Higgs boson contribute as expected in SM?
  - Are there new gauge groups?

- **What protects the Higgs mass from being $m_{Planck}$?**
  - Is Nature Supersymmetric?
    - Is Dark Matter a SUSY particle?
  - Are there new generations of fermions?
  - Is there some other new dramatic physics coming in at the TeV scale
    - Are there extra dimensions of space?
    - Is there a new strong interaction?
Do we have to know results from 13 TeV run to decide on HL-LHC?

- Compare scenarios depending on what we know by 2017
  - Assume about 50 fb\(^{-1}\) by 2017 analyzed

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<tr>
<th>Observation in 2017</th>
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<td>B  Found 3(\sigma) excess in data in at least one BSM signature</td>
<td></td>
</tr>
<tr>
<td>C  Found no excess in data &gt;2(\sigma) but deviation in Higgs by 3(\sigma)</td>
<td></td>
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**Do we have to know results from 13 TeV run to decide on HL-LHC?**

- Compare scenarios depending on what we know by 2017
  - Assume about 50 fb$^{-1}$ by 2017 analyzed

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Do we have to know results from 13 TeV run to decide on HL-LHC?

- Compare scenarios depending on what we know by 2017

  - Improve precision on Higgs couplings by factor 2-3
  - First chance to study Higgs self coupling
  - Significantly extend reach for new physics in many areas
  - Capitalize on major past investment and incrementally upgrade working machine and detectors

A   B   C   D

Want HL-LHC?

- Found no excess in data and no deviation in Higgs either
European Strategy

- In 2012 European Strategy convened to plan the future of particle physics in Europe
  - Endorsed by CERN council in May 2013

Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.
Conclusions

- LHC run-1 has been tremendous success
  - Higgs discovery and severe constraints on BSM physics
    - >500 publications on vast range of topics
- Future LHC running will be even more exciting
  - Probe Higgs boson precisely (see M. Klute’s talk)
  - Significantly extend discovery reach for BSM physics
    - Is EWK scale natural?
- HL-LHC natural next step to fully exploit LHC
  - Capitalize on major past investments
  - Significantly extends LHC potential
    - Regardless of additional LHC discoveries!
  - Upgrades needed to LHC machine and ATLAS and CMS
    - Construction should start in 2017 to be ready for 2022
  - US is a very important partner in this global endeavor
Backup Slides
Monoleptons: $W'$ and Dark Matter

- $W'$ discovery potential increased to 6 TeV for 3 ab$^{-1}$
- Also probe dark matter cross section:
  - Improvement from 300 fb$^{-1}$ to 3000 fb$^{-1}$: factor 3-5
- 3000 fb\(^{-1}\) delivered in the order of 10 years
- High “virtual” luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen (Linac 4, Booster 2GeV, PS and SPS)

\[
L \left[ 10^{34} \text{ cm}^{-2}\text{s}^{-1} \right]
\]

- no leveling w peak \(2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\)
- leveling at \(5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- nominal

\[
5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ levelled luminosity}
\]
\[
3 \text{ fb}^{-1} \text{ per day}
\]
\[
\sim 250 \text{ fb}^{-1} /\text{year}
\]
- Increase in cross section by factor $\sim 10$ for $M \sim 2$ TeV
- Discovery of TeV scale particles possible with a few fb$^{-1}$