Beyond the Standard Model
Searches @ the LHC

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August 15 – August 26
Islamabad

5th School on LHC Physics - 2016
Overview of the 3 lectures in the next days

• Lecture 1:
  – Introduction to searches for new physics
  – Searches for exotica and new phenomena

• Lecture 2:
  – Searches for supersymmetry
  – Searches for real exotic particles

• Lecture 3:
  – The hunt for dark matter
  – Outlook for the LHC and for the Future
After the discovery of the Higgs particle @ the LHC: Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.
Astronomers found that most of the matter in the Universe must be invisible Dark Matter.

‘Supersymmetric’ particles?
Particle Dark Matter?

The Dark Matter Candidate Zoo

- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Snuetrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (ie. “WIMPzillas”)
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPs (charged massive particles)
- Cryptons, mirror matter, and many, many, many others…
WIMPs

- Perhaps Dark Matter is a particle with weak-scale mass?
  - *Weakly Interacting Massive Particles (WIMPs)*
  - Produced in the Big Bang, interact via $\chi + \chi \rightarrow q + q$

- As the universe expands and the temperature drops...
  - WIMPs become diluted, interact less often and ‘freeze out’.
  - Higher cross-section ($<\sigma v>$) yields lower relic density

*Weakly-interacting massive particles naturally provide the right relic abundance - “WIMP miracle”*
Direct Searches for Dark Matter

Underground low noise experiments

No non-ambiguous signal yet!!

There is a very large number of projects which are under construction or being planned for the future.

Monroe at EPS-HEP, Adapted from Snowmass community summer study, 2013

New 8/9/15: XMASS experiment (Japan) does not confirm the periodical effect seen by DAMA/LIBRA
Direct Searches for Dark Matter

New results from PandaX and LUX
The Generic Dark Matter Connection

Searches for mono-jets and mono-photons etc. can be used to search for Dark Matter (DM).

Use effective theory or better simplified models to relate measurements to Dark Matter studies.
Dark Matter Searches

Convert collider search results into limits on DM quantities
Two ways:

- Effective field theory (EFT):
  - Mediator too heavy to be generated directly
  - Contact interaction with suppression scale \( M_\star \sim \frac{M}{\sqrt{g_\chi g_{SM}}} \), with \( g_\chi \) and \( g_{SM} \) the couplings to Standard Model (SM) and DM, and M the mediator mass

- Simplified models: Popular in SUSY
  - Specified massive mediator
  - UV-complete (no validity issue)

Types of interactions chosen in the early studies

Discussions on the region of validity became a major issue...
Mono-object Searches @ LHC

- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Example Monojets

Effective Field Theories for DM interpretation has been criticised!
Alternative SMS now more popular...

arXiv:1407.8257
arXiv:1411.0535
arXiv:1408.3583
arXiv:1410.8812
Collider Dark Matter Signatures

**ET^{miss} + X a.k.a. Mono-X**
- X from ISR jet, b, t, γ, W, Z

**S.C. Shu**

- X from mixing with mediator

- X from paired t̅, b̅
Monojets/top/bb/tt Searches

- Key observables - imbalanced transverse momentum ETmiss
- Irreducible background: Z(vv)+jets
  - jets might be mis-reconstructed as b-jets, γ, W, Z

ETmiss+jet

ETmiss+t

ETmiss+b̄b/ť

S.C. Shu

[Graphs and data plots related to monojet, ETmiss, and ATLAS conference papers]

- ATLAS-CONF-2016-050
- ATLAS-CONF-2016-076
- ATLAS-CONF-2016-077
- ATLAS-CONF-2016-086
Monophoton/W/Z/H Searches

S.C. Shu

Boosted jet substructure technique is used in hadronic W/Z/H
Spin-0 mediator exclusion is at the 100-200 GeV level
Spin-1 mediator exclusion is at the 1-2 TeV level
Dark Matter Searches: Evolution

Dark Matter hunt is one of the new main physics goals for the LHC!

- Mono-object searches are not yet giving better sensitivity compared to 8 TeV
- But new developments with Simplified Models, allow including many more search channels such as dijets (aka “In Search for the Mediator”)

ArXiv:1507.00966
Dark Matter Searches: Evolution

CMS Preliminary

Mono-Z(\ell\ell)

Mono-Photon

Mono-jet/Mono-V

Z' \rightarrow (jj)+j

Z' \rightarrow j+j

Run1

Run2

SM

DM

SM

DM

SM

Med

SM

SM

SM

SM

DM

DM

Dark Matter Summary ICHEP 2016

Axial-vector mediator, Dirac DM

\( g_q = 0.25, g_{\text{DM}} = 1 \)

Observed exclusion 95% CL

\( \text{D} | \text{jet} \); [EXO-16-038]

\( + [\text{arXiv:1604.08807}] \)

Bosonized dijet

[EXO-16-030]

DM + J/V_{\text{jet}}

[EXO-16-037]

DM + j

[EXO-16-039]

DM + Z_{\ell\ell}

[EXO-16-038]

M_{\text{Med}} [GeV]

m_{\text{DM}} [GeV]

Low mass dijet

Dijet

Mono-jet/W
Comparison with Direct Detection

CMS Preliminary
Axial-vector med., Dirac DM
$g_q = 0.25$, $g_{DM} = 1$

90% CL limits

ICHEP 2016

CMS observed exclusion 90% CL
- CMS DM+$\gamma$
  [EXO-16-037]
- CMS DM+$Z_\gamma$
  [EXO-16-038]
- CMS DM+$j/\gamma$
  [EXO-16-037]

DDAD observed exclusion 90% CL
- Pico 2L
  [arXiv:1601.03729]
- Pico 60
  [arXiv:1510.07078]
- Super-K $\tau^+\tau^-$
  [arXiv:1503.04858]
- IceCube $\tau^+\tau^-$
  [arXiv:1601.00653]

90% CL limits
Comparison with Direct Detection

ICHEP 2016

CMS Preliminary

Vector mediated, Dirac DM

$g_q = 0.25$, $g_{DM} = 1$

CMS observed exclusion 90% CL

- CMS DM+$j/V_{q}$ [EXO-16-037]
- CMS DM+$\gamma$ [EXO-16-039]
- CMS DM+$Z_{q}$ [EXO-16-038]

DD observed exclusion 90% CL

- CRESST-II [arXiv:1509.01515]
- CDMS Lite 2015 [arXiv:1509.02448]
- PandaX 2016 [arXiv:1607.07400]

90% CL limits
Cite: “Why should 5% of the mass density have all the fun?”

Visible Sector

Portal

Dark Sector

Can motivate alternative searches to MET + X from dark sector
Discussions on Dark Matter Interpretation

ATLAS/CMS Dark Matter Forum:
experiment/theory discussion towards Run-2 DM searches

Many possibilities to be used as building blocks:

- Prioritized set of simplified models
- Common model implementation and details (e.g. matching, scales) towards MC generation of benchmarks
- EFT validity assessment procedure

This Forum will document:
models and choices
arXiv:1506.03116

https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
Mailing list: lhcdmf@cern.ch

=> Now an ATLAS/CMS +TH working group: arXiv:1603.04156
Dark Matter and the Higgs

“higgs portal models”
Eg: arXiv:1205.3169
Invisible Higgs Decay Channel

Search for invisible Higgs decays using

\[ Z + H \rightarrow 2 \text{ leptons} + \text{missing } E_T \]
\[ VBF \: H \rightarrow 2 \text{ jets} + \text{missing } E_T \]

Possible decay in Dark Matter particles (if \( M < M_H/2 \)): Higgs Portal Models

Combined result from the three channels

\[ \text{BR}(H \rightarrow \text{invisible}) < 58\% (44\% \text{ exp}) \] at 95\% CL.
for a Higgs with a mass of 125 GeV

\[ \sqrt{s} = 8 \text{ TeV} \: (\text{VBF} + \text{ZH}) \]
\[ L = 18.9 - 19.7 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \: (Z(\ell\ell)H \text{ only}) \]
\[ L = 4.9 \text{ fb}^{-1} \]

\[ \sigma \times B(H \rightarrow \text{invisible}) / \sigma_{\text{SM}} \]
95\% CL limits

CMS

Combination of VBF and ZH, H \rightarrow \text{invisible}

arXiv1404.1344
Invisible Channels Combination

Combination of all channels including also the mono-jet channel gives for a 125 GeV Higgs a limit of 24% (23% expected) at 95% CL.
Looking Forward @ the LHC
Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - Colorons
  - Dark photons
  - String balls/T balls
  - Bi-leptons
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….

Have to keep our eyes open for all possibilities: Food for MANY PhD theses!!
A Global View!

Model independent search
- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class:
- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles

Probability distribution as expected for 35 pb$^{-1}$ for CMS
→ muons, electrons, photons, (b)jets, MET

ATLAS for 20 fb$^{-1}$
Are we leaving no stone unturned?

- The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics.

- But if we still do not see more than a 2 sigma at the end of run-III, the HL-LHC will be likely mostly a precision physics machine.

- Are we looking at the right place? Time for more effort in thinking of complementary searches?

Are we looking at the right place? Leave no stone unturned!!
LHCb New Physics in Rare Decays?

Analysis of the $B_0 \to K^* \mu^+ \mu^-$ decay (full run-I data-set)

http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#P5p

arXiv:1512.04442

Angular observable

2.9$\sigma$ for each point
3.7$\sigma$ naive combination

See LHCb lecture
Particles with Milli-Charges?

CMS search for fractional charged particle:

\[ Q = 1/3e > 140 \text{ GeV}; \quad Q = 2/3e > 310 \text{ GeV} \] (95% CL. dE/dx)

A “new” idea -> Hunting for particles with charges \( \sim 0.1 - 0.001e \)

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

arXiv:1607.04669

MilliQan experiment proposal
Particles with Long Lifetimes?

New Detectors to Explore the Lifetime Frontier

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Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854

David Curtin†
Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742 USA

H. J. Lubatti‡
Department of Physics, University of Washington, Seattle, WA 98195
(Dated: June 22, 2016)

arXiv:1606.06298

MATHUSLA
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

Aim to cover the range

\[ cT \lesssim 10^7 - 10^8 \text{ m}. \]

\( \sim \) BBN constrained inspired

Possible detector surface array eg above ATLAS or CMS:

\( (200m)^2 \)

\( 8 \times (70m)^2 \)
How does it feel to be a (BSM) Theorist?
The Future @ The LHC
The Future: Studying the Higgs...

Many questions are still unanswered:
- What explains a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- The Higgs is the new particle that may give us crucial insight into the new physics world. We will have to study it!!

Higgs as a portal
- Having discovered the Higgs?
- Higgs boson may connect the Standard Model to other “sectors”
Approved program at CERN to collect 3000 fb$^{-1}$ with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (eg Higgs)
Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach.

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb$_3$Sn magnets)
   → Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
   → Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

**HE-LHC** (part of FCC study): ~16 T magnets in LHC tunnel ($\rightarrow \sqrt{s} \sim 30$ TeV)
- uses existing tunnel and infrastructure; can be built at fixed budget
- strong physics case if new physics from LHC/HL-LHC

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**F. Gianotti**
FCC meeting
Rome April 2016
Example: Searches for New Particles

Searches for pair produced SUSY particles

Energy is key for searches for massive particles!!
Can LHC answer all questions?: Likely not

Some/all New Particles out of mass range?
Need for higher energies at colliders?

Higher precision measurements needed
Need for higher luminosity or e+e-?

Measuring details of the Higgs?
Need for a Higgs factory?

Many ideas are emerging for new accelerators since June 2012
So far only projects being studied, none is approved yet
International FCC collaboration (CERN as host lab) to study:

- **pp-collider** $O(100)$ TeV ($FCC-hh$) → main emphasis, defining infrastructure requirements
  - $\sim 16$ T → 100 TeV $pp$ in 100 km

- 80-100 km tunnel infrastructure in Geneva area

- $e^+e^-$ collider ($FCC-ee$) as potential intermediate step

- $p-e$ ($FCC-he$) option

- HE-LHC with $FCC-hh$ technology
The LHC has entered a new territory. The ATLAS and CMS experiments are heavily engaged in searches for new physics. The most popular example is Supersymmetry, but many other New Physics model searches are covered.

No sign of new physics yet in the first 20 fb$^{-1}$ at 8 TeV and the first 13 TeV data… This starts to cut into the ‘preferred regions’ for a large number of models, like SUSY.

More exotic channels are now being covered: monopoles, fractional or multiple charged particles, long lived particles… Still many unexplored channels left to explore.

The LHC did its part so far with a great run-1 and is strong in run-2. Collected over 20 fb$^{-1}@ 13$ TeV… And maybe one day soon:
End of Lecture II