Lake Louise and Aspen Winter Conferences 2018

PPD seminar

23rd May 2018

Fergus Wilson
Outline

- Holiday snaps
- SUSY (ATLAS/CMS)
- Long Lived Particles
- Dark Photons
- $g-2$
- Dark Matter
- Flavour - Neutrinos
- Flavour – Leptons and quarks
- Gravitational Waves

Lake Louise and Aspen conferences, Fergus Wilson
Lake Louise (Canada) and Aspen (USA)

23-May-2018  Lake Louise and Aspen conferences, Fergus Wilson
Lake Louise, Alberta
Aspen, Colorado
SUSY
Three Miracles of SUSY

- Elegant solution to the hierarchy problem (i.e., why the Higgs boson mass is not found at the Planck scale)
- Gauge unification
- Dark matter candidate with the right abundance
The majority of searches were inclusive. They targeted strongly-produced SUSY particles that cascade decay to WIMPS (DM candidates) and generic models like MSUGRA/MSSM/GMSB.

Searches for the 3rd generation were emerging (e.g. arXiv:1101.1963)
Contemporary search program

- The 125 GeV Higgs is considered as “SUSY model killer” (tension with high-scale theories). However, the discovery of Higgs inspired a number of searches for $m \sim O(1 \text{ TeV})$ 3rd generation squarks.
- Overall, the search program is more exciting than ever before.
- Goes even beyond the R-parity conserving models and in the corners of phase space where the mass differences are small (compressed and long-lived).
- Caveat: The data are often interpreted for simplified models so the limits need to be translated carefully for your model of choice.
  - The simplified models may give overly high or low exclusion.

Hidetoshi will discuss this later on.
Direct stop production pair-production: Overview

- Huge improvement in sensitivity in comparison to Run 1
- Decays with neutralinos heavier than 300-400 GeV are difficult to probe.
- What is happening with m(stop)~220 GeV and m(LSP)~50 GeV?
The $M_{T2}$ Variable

- $M_{T2}$: "transverse mass" - a generalization of the transverse mass in case of a pair of invisible particles
- For a simplified case of no extra jets and zero masses for visible and invisible systems:
  \[(M_{T2})^2 \approx 2p_T^{\text{vis}(1)}p_T^{\text{vis}(2)}(1 + \cos\phi_{12})\]
  - $M_{T2} \sim \text{MET}$ for symmetric SUSY-like topologies
- $M_{T2}$ kills QCD background very efficiently:
  - $M_{T2} \sim 0$ for dijets
  - $M_{T2} < \text{MET}$ in case of mismeasured dijets

Lesters & Summers, hep-ph/9906349
## Contemporary search program

### ATLAS SUSY Searches

**ATLAS SUSY Searches** - 95% CL Lower Limits

#### Model
- \( t, \bar{t}, \gamma, \) Jets
- \( \sqrt{s} = 7, 8 \) TeV
- \( \sqrt{s} = 13 \) TeV
- Reference

**Mass limit**

<table>
<thead>
<tr>
<th>Model</th>
<th>( \sqrt{s} = 7, 8 ) TeV</th>
<th>( \sqrt{s} = 13 ) TeV</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t, \bar{t}, \gamma, ) Jets</td>
<td>719 GeV</td>
<td>1.37 TeV</td>
<td>ATLAS CONF-2017-480</td>
</tr>
<tr>
<td>( \sqrt{s} = 7, 8 ) TeV</td>
<td>1.37 TeV</td>
<td>1.37 TeV</td>
<td></td>
</tr>
<tr>
<td>( \sqrt{s} = 13 ) TeV</td>
<td>1.37 TeV</td>
<td>1.37 TeV</td>
<td></td>
</tr>
</tbody>
</table>

#### ATLAS Preliminary

- \( \sqrt{s} = 7, 6, 13 \) TeV
- Reference

**Mass scale [TeV]**

<table>
<thead>
<tr>
<th>Model</th>
<th>ATLAS Preliminary</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t, \bar{t}, \gamma, ) Jets</td>
<td>310 GeV</td>
<td>ATLAS CONF-2017-675</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, i.e. refs. for the assumptions made.*

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Supersymmetry or Supercremery?

Summary of all recent results:

Selected CMS SUSY Results* - SMS Interpretation

ICHEP ’16 - Moriond ’17

CMS Preliminary
\[ \sqrt{s} = 13\text{TeV} \]
\[ L = 12.9 \text{ fb}^{-1} L = 35.9 \text{ fb}^{-1} \]

*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for \( m_1 > 0 \) GeV unless stated otherwise

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Summer_Conferences_2017_36_fb_1

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Physics behind long-lived particles

SUSY

- Long-lived $\tilde{g}$: Heavy squark, $\tilde{g}$-Bino co-annihilation
- Long-lived $\tilde{\chi}^\pm$: Wino/Higgsino Lightest Stable Particle (LSP)
- Long-lived $\tilde{\chi}^0$: Gravitino LSP, R-parity violation, Wino-Bino co-annihilation

Hidden/dark sector scenario

- Long-lived dark photon: Higgs portal model
- Long-lived neutral scalar: Heavy neutral boson portal model

Others

- Long-lived right-handed neutrino: Left-right symmetry extension of SM
- Long-lived multi-charged particle: Monopole, Micro black hole, Q-ball

And many more!!
Signatures of long-lived particles

- Muon system (MS)
  - RPC, MDT, TGC, CSC
- Calorimeter (Calo)
  - LAr, Tile
- Inner detector (ID)
  - Pixel, SCT, TRT

- Displaced late photon from LLP
- Large dE/dx (and low velocity) track of LLP
- Disappearing track of LLP
- Displaced vertex from LLP
- Decay of (stopped) LLP inside Calo
Long Lived Particles

\[ \tilde{g} (R-hadron) \rightarrow q\bar{q} \tilde{\chi}^0_1 ; m(\tilde{\chi}^0_1) = 100 \text{ GeV} \]

March 2018

- **Expected**
- **Observed**

95% CL limits

**ATLAS** Preliminary

- **RPC 0L 2-6 jets arXiv:1712.02332 (f=13 TeV, 36 fb⁻¹)**
- **RPC 0L 2-6 jets ATLAS-CONF-2018-003 (f=13 TeV, 36 fb⁻¹)**
- **Displaced vertices arXiv:1710.04501 (f=13 TeV, 33 fb⁻¹)**
- **Pixel dE/dx arXiv:1604.04520 (f=13 TeV, 3.2 fb⁻¹)**
- **Stable charged arXiv:1606.05129 (f=13 TeV, 3.2 fb⁻¹)**
- **Stopped gluino arXiv:1310.6584 (f=7.8 TeV, 5.0, 23 fb⁻¹)**

Displaced Vertex in ID

**Interpretation from prompt decay search**

**Pixel dE/dx only + Hadron Calo Timing**

ATLAS-CONF-2018-003

23-May-2018 Lake Louise and Aspen conferences, Fergus Wilson
DARK/HIDDEN SECTOR
Dark Sector

\[ \alpha' = \varepsilon^2 \alpha \]

See Okun, 1982; Galison, Manohar, 1984; Holdom, 1986; etc.; Arkani-Hamed, Finkbeiner, Slatyer, Weiner; 2008; Pospelov, Ritz, 2008; etc.
Recasting for other Models

Dark photon searches provide sensitivity to (many) other models.

Ilten, Soreq, MW, Xue [1801.04847]

We developed a data-driven way to easily recast any dark photon search to obtain limits on any other vector model (auto-calculates hadronic decay rates for all masses).
G-2
\[ \vec{\mu} = g \frac{q}{2m} \vec{S} \]

External Magnetic Field

\[ g = 2(1 + a) \]

Muon anomalous magnetic moment

\[ a_{\mu}^{SM} = (g - 2)/2 = a_{QED} + a_{EW} + a_{QCD} \]
The uncertainty source $\delta a_\mu$ is shown in the table below:

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Status 2015 [ppb]</th>
<th>Projected after FNAL [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Theory</td>
<td>420</td>
<td>310</td>
</tr>
<tr>
<td>HVP</td>
<td>360</td>
<td>215</td>
</tr>
<tr>
<td>HLbL</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>Total Exp.</td>
<td>540</td>
<td>140</td>
</tr>
</tbody>
</table>

Theory uncertainty remains the same, both the theoretical and experimental central values are unchanged, but the experimental uncertainty is reduced.

> $7 \sigma$ for unchanged central values

New Physics!

$5 \sigma$ discrepancy
Outline

- Muon g-2 Physics
- Muon g-2 Experiment
- Muon g-2 Status
- Conclusions

BNL experiment was statistically limited.

Need more muons!

Lets move to Fermilab!

Reduce the 480 ppb statistical uncertainty to 100 ppb! → 10 x BNL data
\[ a_\mu(\text{Expt}) = \frac{g_e \omega_a m_\mu \mu_p}{2 \tilde{\omega}_p m_e \mu_e} \]

- **Magnetic Field**: 1.4513 T
- **Current**: 5176 A
- **Dimensions**: 3 x 15 m
- **Yokes**: 700 tons, 12 yokes: C shaped flux

**g-2 Magnet in Cross Section**

- **Detectors**
  - inner coil
  - top hat
  - thermal insulation
  - wedge
  - edge shim
  - muon region
  - fixed NMR probes
  - surface correction coil
  - outer coil

- **Results of Shimming the Magnet**

**Fermilab**

- **3/27/2018**
- Walton I Aspen 2018
Dark Matter

The Dark Matter Landscape

- Axions
  \( \sim 10^{-9} \text{-} 10^{-3} \text{ eV} \)

- Sterile Neutrinos
  \( \sim 1 \text{-} 10 \text{ keV} \)

- Primordial Black Holes
  \( \sim 10 \text{-} 100 \text{ M}_\odot \)

- The "Classical WIMP"
  \( \sim \text{MeV} \text{-} 100 \text{ TeV} \)

- Proton mass
  \( m_{\text{proton}} = 1 \text{ keV} \)

- Planck mass
  \( M_{\text{Planck}} = 10^{28} \text{ eV} \)

- Solar mass
  \( 100 \text{ M}_\odot = 10^{68} \text{ eV} \)
Recent Results From XENON1T, PandaX-II, CRESST-III
Dark Matter

The Future of Direct Detection

23-May-2018
Lake Louise and Aspen conferences, Fergus Wilson
An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams

3) Interaction which suppress elastic scattering with nuclei by powers of velocity or momentum

4) Dark matter that is lighter than a few GeV (evading direct constraints)

5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter’s relic abundance

6) The dark matter annihilates to unstable non-Standard Model states (ie. hidden sector models)

Although potentially invisible to both underground detectors and colliders, many of these scenarios are testable with indirect searches

In this sense, the lack of such signals has strengthened the motivation for gamma ray, cosmic ray and neutrino searches for dark matter
A dark matter event in silicon

In Si, create one additional $e^-/h^+$ pair for each 3.6 eV of recoil energy

Here $Q = 3$
Rates increase dramatically for lower $Q$

$E_e$ [eV]

$E_e$ [eV]

$m_\chi = 10$ MeV
$m_\chi = 1$ GeV

Best threshold for a Si detector before June 2017:
$\sim 11e^-$ (40 eV)

A recent technological breakthrough enables much lower thresholds:
SENSEI

$\sigma_e = 10^{-37}$ cm$^2$
$F_{DM}(q) = 1$

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SENSEI’s target material are special silicon CCDs

“Skipper CCDs”

~million pixels
Skipper CCD

- has a *modified readout stage* that allows multiple sampling of the same pixel without corrupting the charge packet:

\[
\text{pixel value} = \frac{1}{N} \sum_{i}^{N} (\text{pixel sample})_i
\]

- developed in collaboration with LBNL MicroSystems Lab
- successfully demonstrated in a Fermilab LDRD project (2016)

Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

Achieved rms noise \(~ 0.06 \text{ e}^- \)  \(\rightarrow\) Dramatic reduction in threshold!
Counting Electrons

Tiffenberg, Sofo-Haro, Drlica-Wagner, R.E. Guardincerri, Holland, Volansky, Yu (1706.00028)

rms noise ~ 0.06 e-
NEUTRINOS
Neutrinos

Still many profound unknowns

- Are there more than 3 neutrino flavors?
  - do light sterile neutrinos exist?
- Is CP violated in the leptonic sector?
  - understanding matter - anti-matter asymmetry?
- What is the Neutrino mass hierarchy?
  - which neutrino is the lightest?

Several anomalies that don't fit in the 3 oscillation scenario:
A New Neutrino?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>DAR</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC</td>
<td>3.8$\sigma$</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>$\nu_\mu \rightarrow \nu_\tau$ CC</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC</td>
<td>2.8$\sigma$</td>
</tr>
</tbody>
</table>

KM3NetT detector design

- Detection principle: Optical Cherenkov radiation
- 6 orders of magnitude in energy (GeV-PeV)
- All flavour detection
- A 3D array built with a modular design
- Optical sensor: multi-PMT (DOM)
- Detection units (DU): vertical slender strings host 18 DOMs
- Building blocks of 115 DUs each
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Sea network of submarine cables and Junction Boxes connected to shore via a main e/o cable
- All data to shore

<table>
<thead>
<tr>
<th></th>
<th>ARCA</th>
<th>ORCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Italy</td>
<td>France</td>
</tr>
<tr>
<td>DU distance</td>
<td>90m</td>
<td>20m</td>
</tr>
<tr>
<td>DOM spacing</td>
<td>36m</td>
<td>9m</td>
</tr>
<tr>
<td>Instrumented mass</td>
<td>2*500Mton</td>
<td>5.7 Mton</td>
</tr>
</tbody>
</table>
KM3Net

KM3NeT DOM and DU

Optical module

- 31 x 3” PMTs
- Light reflector rings around PMTs
- LED & acoustic piezo inside
- Tiltmeter/compass
- Gbit/s fibre DWDM
- Hybrid White Rabbit

- Digital photon counting
- Directional information
- Wide angle of view
- Improved background rejection
- Compact and cost effective design:
  1 DOM equivalent to 3 Antares OMs

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First ORCA DU preliminary results

First event with recorded track reconstructed by ORCA (down-going muon)

A bright muon bundle
IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments – essential for constraining new physics
Atmospheric Oscillation Parameters

- Currently unclear whether $\sin^2 \theta_{23}$ is maximal
  - 3rd mass state made up of equal parts $\nu_\mu$, $\nu_\tau$
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6$\sigma^*$
- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)
The Future: IceCube-Gen2

- High Energy Array
  - 120 strings x 80 sensors/string
  - \(\sim 8 \text{ km}^3\) volume, wider string spacing

- PINGU
  - Low energy infill
  - 26 strings (incl. IC Upgrade)

- Also investigating surface arrays, UHE radio detection

- Cost scale similar to IceCube
MicroBooNE:
Status & Recent Results

Sowjanya Gollapinni
University of Tennessee, Knoxville
(On behalf of MicroBooNE Collaboration)

Aspen Winter Conference
March 29, 2018
MicroBooNE is paving way for the three-detector SBN program to more definitively address the sterile neutrino question where we have existing hints:

- Well understood BNB beam
- Same detector technologies, same beam = reduced systematics!
MicroBoone

The MicroBooNE Experiment

- **Linac**
  - Length: 150m
  - Proton Energy: 400 MeV

- **Booster (BNB)**
  - Circumference: 468m
  - Proton Energy: 8 GeV

- MicroBooNE
  - 470 m baseline

- Short-Baseline Oscillation Experiment
- Located on the Booster Neutrino Beam (BNB) at Fermilab

23-May-2018
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The LArTPC Principle

- Argon makes a desirable target (dense, abundant, ...)
- Two signals: Ionization signal & Scintillation light
- Finely (mm-scale) segmented anode wires — excellent resolution!
- Bubble chamber quality images in HD!
- Technology allows for scalability — can build massive detectors

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Upgrades: Cosmic Ray Tagger System

• Plastic Scintillator Modules & SiPM readout
• Design & Construction paper under preparation for JINST
• Currently developing matching techniques between TPC and CRT
MicroBooNE

A neutrino event in MicroBooNE LArTPC

"Imaging" detectors digitized Bubble chambers with Calorimetry!
Reconstruction & Particle ID

Muon tracking efficiency

Deep Learning techniques

Pandora Pattern Recognition Algorithms

Developing multiple approaches for the flagship oscillation analysis
FLAVOUR
BEAST II (Phase 2 Commissioning Detector inside Belle II)

A system of radiation detectors: beam background monitors, first responders

FANGS: “LHC/ATLAS style” silicon pixel sensors,
CLAWS: scintillator tiles read-out by silicon PMTs,
PLUME: “ILC style” MIMOSA silicon pixel sensors,
micro-TPC nuclear recoil (fast neutrons) detectors,
He-3 tube thermal neutron detectors,
Scintillators + PIN diodes,
diamond sensors

Now
End of 2018

BEAST II
Includes two PXD and four SVD ladders

VXD = PXD + SVD

Understanding beam-related backgrounds (and physics backgrounds!) is of great importance. There is only that much of radiation hardness...
Belle II Had Been Recording Cosmic Events Until Recently

Summer 2017

standalone cosmic ray test (single high energy shower)

KLM

TOP

ECL

KLM

February 2018

Beam view layout of 16 TOP slots

Clean standalone TOP triggering on cosmic muons

Back-to-back top-to-bottom TOP-based two-slot triggers
Belle II

τ Leptons Provide a Unique Laboratory to Search for LFV

Upper limits for LFV τ decays with the full 50 ab⁻¹ data sample at Belle II

90% C.L. upper limits for LFV τ decays

B2TiP report / to be submitted to PTEP (2018)
CP violation - $\gamma$

Almost all the best channels for the determination of the CKM angle $\gamma$ have now been analysed for run 1. For example, suppressed ‘ADS’ mode, $B^- \rightarrow (\pi^- K^+)_{D} K^-$ (+CC).

Combination of LHCb $B \rightarrow DK$ results obtained so far

**LHCb-CONF-2017-004**

$\gamma = (76.8^{+5.1}_{-5.7})^\circ$

Uncertainty significantly better than that obtained with combined B-factory results.

Agrees with prediction from rest of triangle

$\gamma_{\text{indirect}} = (65.3^{+1.0}_{-2.5})^\circ$
Flavor Anomaly in R(D) and R(D*)

\[ \mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^{-}\bar{\nu}_{\tau})}{\mathcal{B}(\bar{B} \to D^{(*)} \ell^{-}\bar{\nu}_{\ell})} \quad (\ell = e, \mu) \]

[\tau helicity provides a handle to investigate the new (virtual) particle (if confirmed)]

If the current 4.1\sigma deviation is real, Belle II should be able to make a discovery with 5/ab (i.e. around 2021)
GRAVITATIONAL WAVES
Ground based detectors

- Initial observatories, and instruments, constructed starting in mid-90’s
  - NSF Physics for LIGO; Virgo’s support from CNRS and INFN
- Observed, setting upper limits until 2011
- Both Virgo and LIGO undertook a complete rework of the instruments
- Advanced LIGO came on line in 2015 – First discovery 15 Sept 2015
- Advanced Virgo came on line in 2017 – First signal 14 August 2017
Stellar-mass Binary Black Holes

- 5 events published to date; 1 with both LIGO and Virgo detectors
- Consistency with GR in extremes of compactness and $v/c \sim 0.6$
- Revealed an unexpected class of heavier Stellar-mass BH
GW170814: Virgo and LIGO detectors, enabling triangulation, polarization sensing

LIGO-Hanford and Livingston have similar orientations -> little information about GW polarizations

Virgo is not aligned with LIGO – giving polarization information

Sky localization improves ~20x; Uncertainty in volume reduced ~34x
GW170817: Binary Neutron Star Coalescence

https://doi.org/10.1103/PhysRevLett.119.161101
GRB 170817A occurs $(1.74 \pm 0.05)$ seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is $5.0 \times 10^{-8}$ (Gaussian equivalent significance of 5.3σ)

-> BNS mergers are progenitors of (at least some) SGRBs
Multimessenger Observations

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = $t_0$

GRB 170817A
$t_0 + 2$ sec

LIGO signal found
$t_0 + 6$ minutes

LIGO-Virgo GCN reporting
BNS signal associated with the time of the GRB
$t_0 + 41$ minutes

SkyMap from LIGO-Virgo
$t_0 + 4$ hours

Optical counterpart found
$t_0 + 11$ hours

- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event
- And…: transmutation of common elements (pure neutron matter) into gold!
5-year plan

- **LIGO**
  - O1: 60-80 Mpc
  - O2: 60-100 Mpc
  - O3: 120-170 Mpc
  - O4: 190 Mpc

- **Virgo**
  - O2: 25-30 Mpc
  - O3: 65-85 Mpc
  - O4: 65-115 Mpc
  - O5: 125 Mpc

- **KAGRA**
  - 25-40 Mpc
  - 40-140 Mpc
  - 140 Mpc

Years:
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
The advanced GW detector network

- Advanced LIGO
  - Hanford, Livingston 2015

- Advanced Virgo
  - 2017

- LIGO-India
  - 2025

- KAGRA
  - 2019
THE END