# Theory developments related to IPP projects

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## Purpose of this talk

- Update on recent developments in theory that might affect current IPP projects, or stimulate new experiments or measurements

- "Physics directory" of Canadian theory community: who to call when you want to talk to a theorist

- I focus here on theorists who are doing things directly related to IPP projects. There are several more who work on more formal physics, cosmology, etc., whom I haven't mentioned here.

I will try to be comprehensive, but will surely fail – apologies to those whose work I'm not aware of!

Email me if I missed you and I'll add you to the archival version of the slides.

⇒ slides updated as of June 12, 2017: changes are in magenta

## Outline

Dark matter and dark sectors

Improved SM predictions

Precision Higgs tests for BSM physics

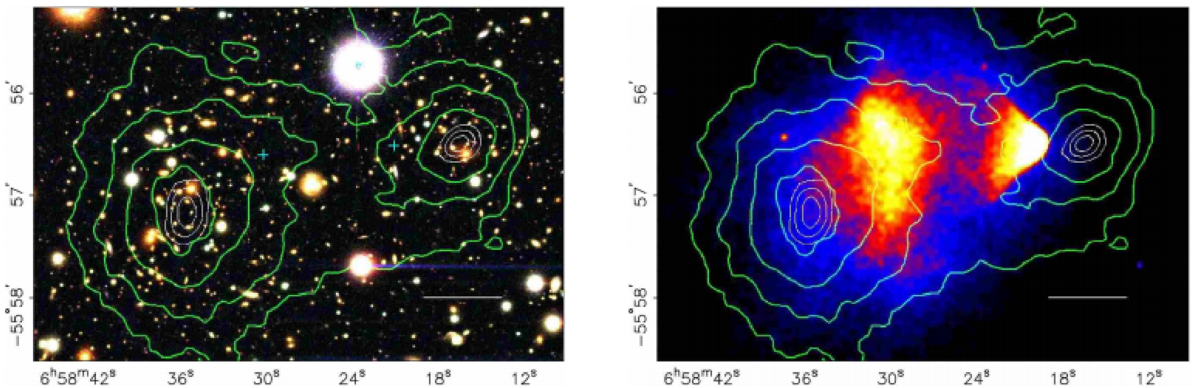
New LHC signals with a focus on naturalness

Neutrinos

Final thoughts

# Dark matter and dark sectors

Dark matter's gravitational effects provide direct observational evidence for particle physics beyond the Standard Model.
→ has attracted intense theorist interest

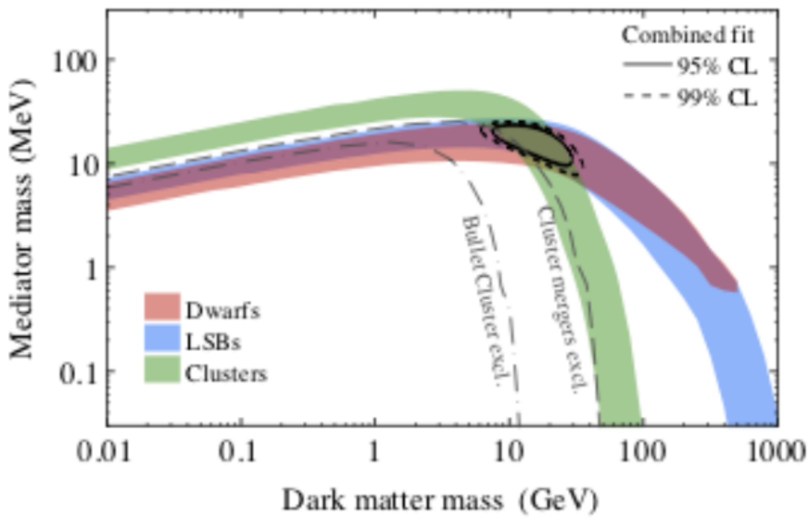



Collided galaxy-clusters: dark matter is not modified gravity
CMB power spectrum + BBN: dark matter is non-baryonic

Absence of (unequivocal) dark matter discovery in direct, indirect, or collider searches
→ interest in non-minimal models & new avenues to detection
→ possible connection to other open questions / anomalies
→ refinement of direct-detection theory calculations

## Dark matter and dark sectors – self-interacting dark matter

There is some evidence for dark matter self-interactions from small-scale structure problems and other astrophysical hints




Models for and constraints on self-interacting DM: Sean Tulin (York), Jim Cline (McGill), Steve Godfrey & H.L. (Carleton)

## Dark matter and dark sectors – composite dark matter

The SM is not very simple: most of stable matter is composite (protons, neutrons, nuclei, atoms).
$\rightarrow$ What if dark matter is similarly complicated?

Dark matter as "hadrons" from a dark non-abelian gauge force: David Morrissey (TRIUMF) & Kris Sigurdson (UBC), Randy Lewis & Sean Tulin (York)

Dark "atoms" from dark-sector leptogenesis (linked to our baryon asymmetry); can have ionized component, interesting astrophysical implications: Jim Cline (McGill)

## Dark matter and dark sectors – looking for dark-sector signals

Dark sectors contain additional particles (light mediators, states very feebly coupled to SM) that may show up in other types of experiments.

- Beam-dump experiments (& accelerator neutrino expts)
- Neutrino beam experiments (e.g., "trident" final states)
- Quarkonium decays at Belle-II
- "Emerging jets" at LHC

Low-mass dark sector states can have dramatic effects on lower-energy precision measurements; could be linked to SM anomalies, e.g. muon $g-2$ (light $Z'$ link now excluded by direct searches!), $b \to s\ell^+\ell^-$

Maxim Pospelov, Adam Ritz (UVic), Mina Arvanitaki (Perimeter), Daniel Stolarski (Carleton), Sean Tulin (York), David Morrissey (TRIUMF), Jim Cline (McGill), David London (UMontreal), Rainer Dick, Tom Steele (Saskatchewan)

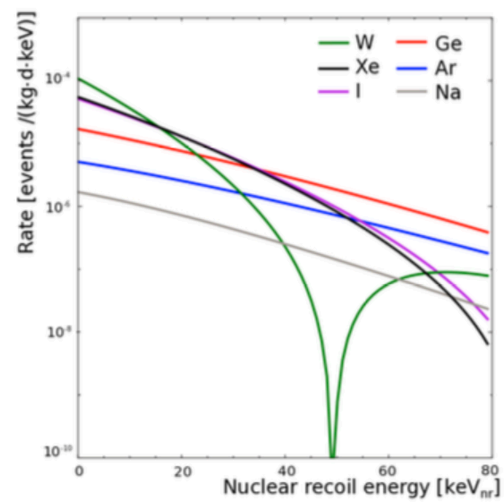
## Dark matter and dark sectors – nuclear scattering cross sections

Precision calculation of the "SM side" of DM-nucleus scattering cross sections

DM-nucleon interaction:
- nucleon form factors; renormalization group running from weak scale down to hadronic scale; quantifying hadronic uncertainties: Richard Hill (visiting PI this year; at TRIUMF last year)

DM-nucleus interaction:
- nuclear form factor varies with target material, recoil energy: coherence loss at high energies as DM compton wavelength probes nuclear substructure; inelastic scattering.

Matrix elements: Jason Holt (TRIUMF) has done some similar work



## Improved SM predictions

Muon-electron conversion & bound-muon background spectrum: Andrzej Czarnecki (Alberta)
Hadronic vacuum polarization for muon $g - 2$: Kim Maltman (York)

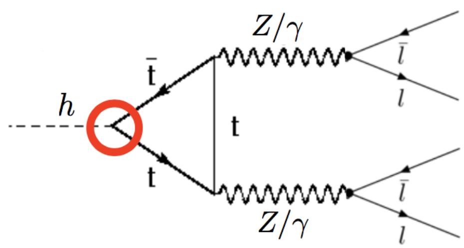
Precision electroweak and BSM contributions to polarized electron-proton scattering (MØLLER), NLO EW corrections to 4f processes at Belle-II: Svetlana Barkanova (Acadia $\rightarrow$ Memorial), Aleksandrs Aleksejevs (Memorial)
2-loop EW corrections Bhabha scattering: Alexander Penin (Alberta)

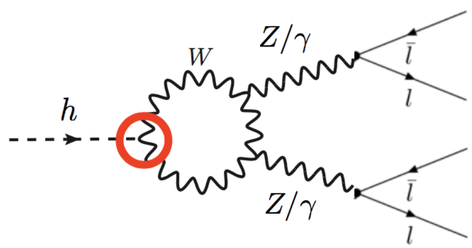
QCD jet structure; kinematics in inclusive B decays: Michael Luke (Toronto)

Hadron spectroscopy & properties (bottomonium, charmonium, etc; understanding recently-discovered exotic states): Steve Godfrey (Carleton), Randy Lewis, Kim Maltman (York), Richard Woloshyn (TRIUMF)

## Precision Higgs tests for BSM physics – Higgs couplings

Probe modified couplings via loop effects in $H \to 4\ell$ (modified top Yukawa, modified HWW/HZZ couplings – interference gives sensitivity to relative sign): Daniel Stolarski (Carleton)




Constraining extended Higgs sectors from (tree-level) Higgs coupling modifications: Steve Godfrey, H.L. (Carleton), Mariana Frank (Concordia), Gilles Couture, Cherif Hamzaoui (UQAM)

Model-independent parameterization of heavy BSM physics via dimension-6 effective operators, constrain using Higgs observables at LHC: Thomas Gregoire, Daniel Stolarski (Carleton)

## Precision Higgs tests for BSM physics – exotic Higgs decays

"Higgs portal": a hidden sector could interact with the SM only through Higgs-mediated processes.

Light hidden-sector particles can lead to exotic Higgs decays, e.g. $H \to$ MET, $H \to X+$ MET, $H \to aa \to bb\mu\mu$, etc.
Exotic Higgs Decays Working Group (subgroup of LHC HXSWG)

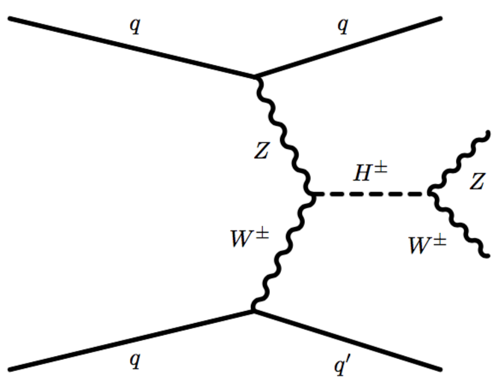
David Curtin (Toronto new hire); also David Morrissey (TRIUMF), Daniel Stolarski (Carleton)

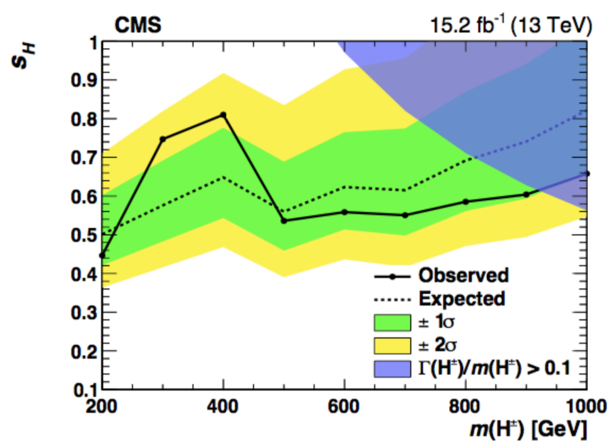
# Precision Higgs tests for BSM physics – search for extra Higgses

Direct searches for the additional Higgs bosons in extended Higgs sectors

- charged Higgs from exotic sources of EW symmetry breaking
- search strategies for compressed spectra in inert-doublet model
- virtual effects of 2HDM in quarkonium decays
- global combinations of constraints from different sources

H.L., Steve Godfrey (Carleton), David Morrissey (TRIUMF), Jim Cline (McGill), Mariana Frank (Concordia), Bob Holdom (Toronto)



## New LHC signals with a focus on naturalness – nonminimal

Usual approach to naturalness: have "top partners" that cancel the divergent contribution to the Higgs mass coming from the top quark.
- SUSY: top squarks
- Little Higgs, etc: fermionic top partner

But LHC constraints on the usual signatures push top-partner masses close to a TeV, reintroducing fine-tuning.

Non-minimal versions of these models can relax constraints by introducing new decay modes, reducing production cross sections
- SUSY: Dirac gauginos, broken R-parity
- Top partners: decays to light quarks instead of $t, b$

Thomas Gregoire (Carleton), Mariana Frank (Concordia), David Morrissey (TRIUMF)

# New LHC signals with a focus on naturalness – weird stuff

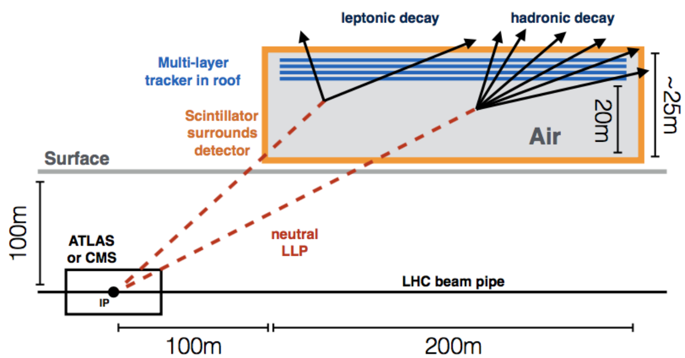
New approach to naturalness in past few years: what if the "top partners" do not carry colour? → "Neutral Naturalness"

Realistic model-building necessitates rather complicated hidden sector, can produce very novel signatures:

- emerging jets: jet produced in hidden-sector dark-QCD, displaced decays back to SM particles

- "quirks": exotic, maybe electrically-charged fermions tied together with a very stretchy QCD-like string

- long-lived particles: proposal for simple large-volume tracking detector on the surface above an LHC collision point




David Curtin (Toronto new hire), Daniel Stolarski, Thomas Gregoire (Carleton), David Morrissey (TRIUMF), Sean Tulin (York)

## Neutrinos – models and experimental probes

Nonzero neutrino masses are technically physics beyond the Standard Model. How are they generated?
- Very high scale – not much we can do to probe mechanism.
- Weak scale or below – mechanism can be probed at colliders!

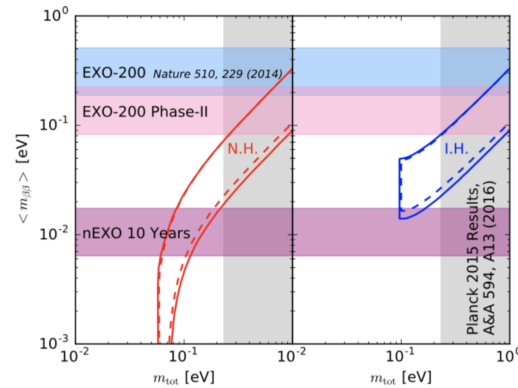
Vectorlike leptons; weak-scale right-handed neutrinos; Higgs Triplet model; left-right symmetric models
$\rightarrow$ predict collider signals; links to other problems like dark matter

John Ng (TRIUMF), Mariana Frank (Concordia)

# Neutrinos – improved nuclear theory

EXO limits on $\langle m_{\beta\beta} \rangle$ are a band, not a line, due to nuclear matrix element uncertainty

T2K's largest sources of systematics are nuclear model uncertainties in cross sections




Need better nuclear theory (also experiments with different target materials for neutrino-nucleus scattering, and/or water near-detector NuPRISM)

- Neutrinoless double beta decay nuclear matrix elements calculations for various nuclei: Jason Holt (TRIUMF)

- Medium energy neutrino-nucleus cross sections: Sonia Bacca (TRIUMF), Richard Hill (visiting PI this year)

## Final thoughts

- Theorists make SM predictions: essential for testing the SM, measuring its parameters, and searching for deviations due to new physics

- Theorists propose new searches & new experiments: motivated by plausible new answers to open physics questions

- Theorists make connections between different experiments: anomaly in one place $\rightarrow$ ways to test it elsewhere $\rightarrow$ motivation for new analyses

- Theorists synthesize results: combine signals and constraints from multiple experimental approaches to build a global view $\rightarrow$ ultimately the whole reason we do physics

Interaction and cross-fertilization between theorists and experimentalists energizes this program.