Particle theory for the LRP period (2017-2021)

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IPP Town Hall meeting, June 15, 2015

Outline

Part I:
- Higgs
- Precision SM
- Naturalness

Part II:
- Neutrinos
- Flavour

Part III:
- Dark matter
- Hidden sectors
- Baryogenesis

Summary

Many of these topics are intimately interlinked.

The continual interplay between theory and experiment is vital for progress.

We are living in an increasingly data-rich era, in which information from multiple experimental approaches is being combined to learn more about the Universe.

Understanding the Higgs sector

Key questions:

- Is the Higgs we've discovered the only source of electroweak symmetry breaking?
  - → Extended Higgs sector with new scalars? Strong dynamics?

- What solves the naturalness problem?
  - → SUSY? Top partners? Compositeness? Something else?

- Can Higgs dynamics explain the baryon excess of the Universe?
  - → Electroweak baryogenesis facilitated by an extended Higgs sector?

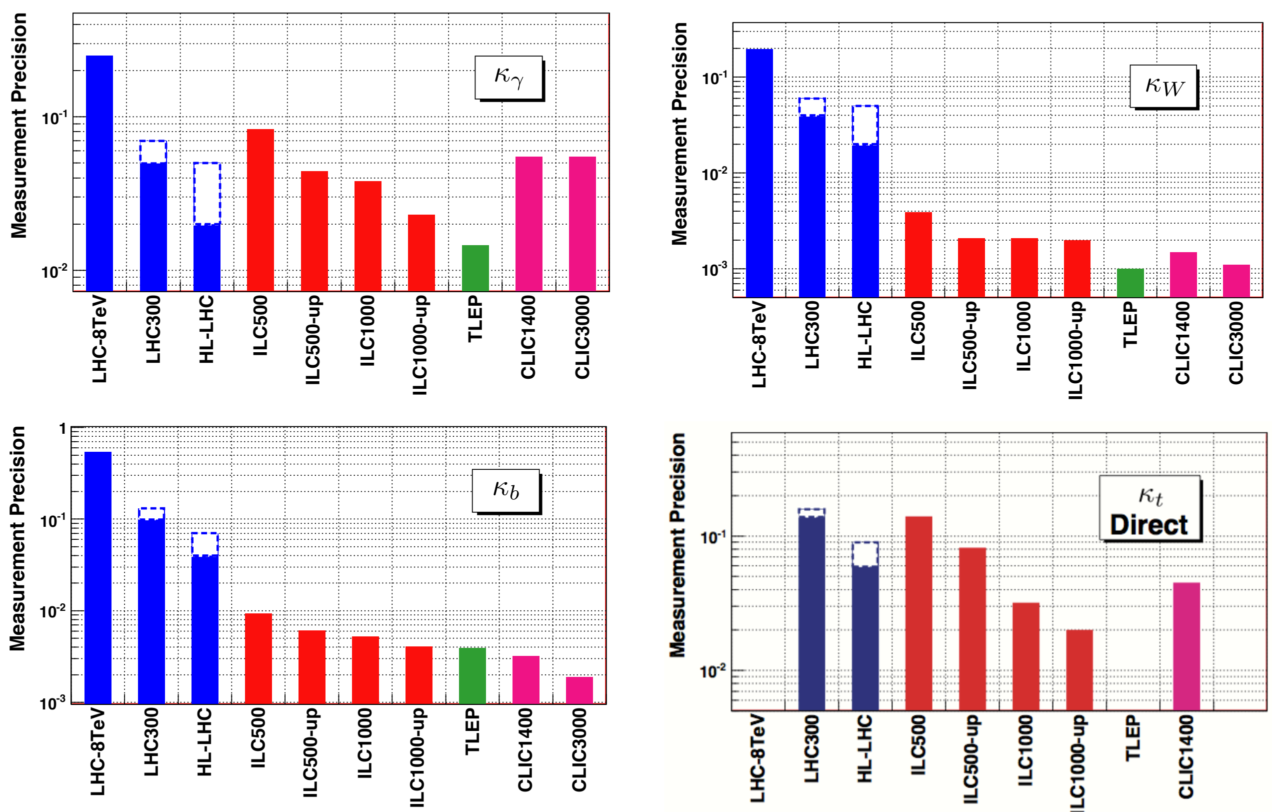
- Is the Higgs a "portal" to a hidden sector?
  - → Higgs portal to dark matter? Twin Higgs hidden valley? Rare decays?

Measure couplings of 125 GeV state: LHC, ILC

- probe for extended Higgs sector: mixing effects

- probe for new physics in loops: may be related to naturalness

- rare exotic decays: Higgs-portal hidden sector, light SUSY

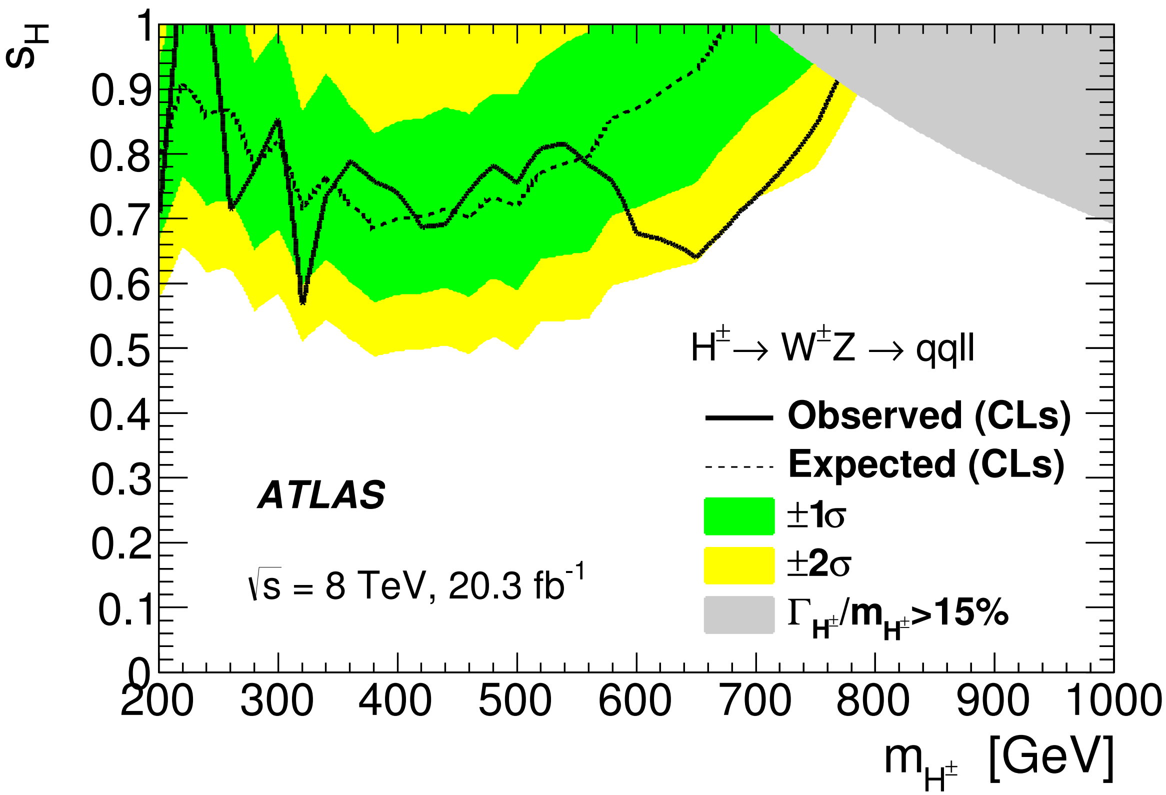


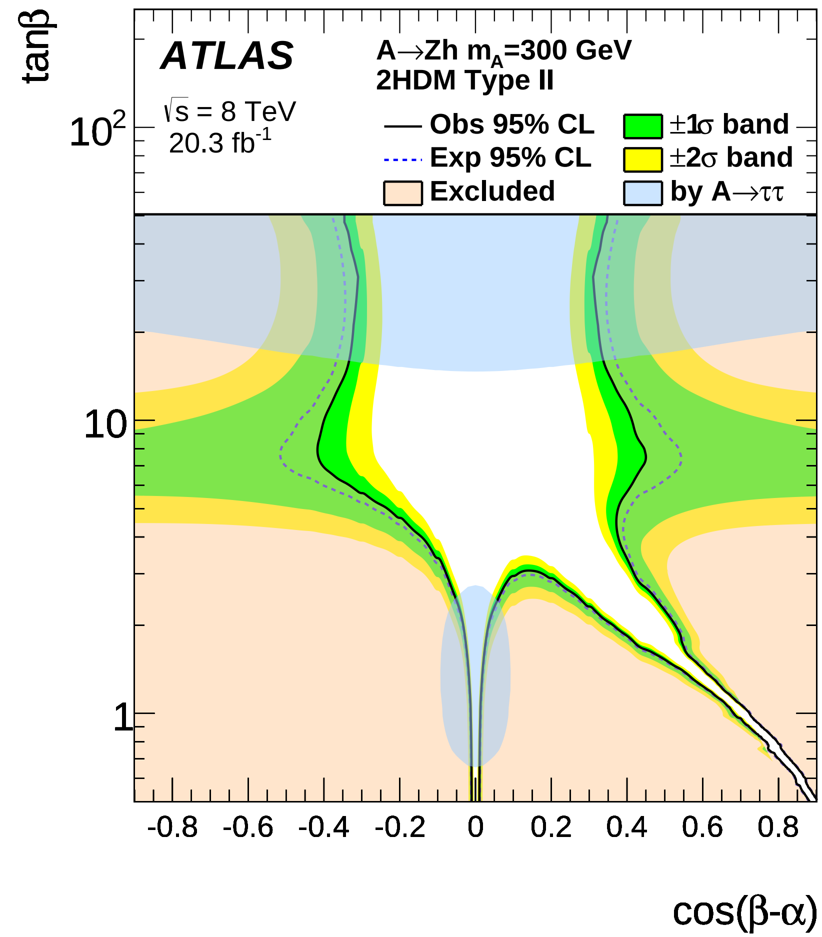
Snowmass
Energy Frontier report,
arXiv:1401.6081

Search for additional Higgs particles: LHC, ILC

- a direct probe for a neutral or charged extended Higgs sector and the best way to learn its nature

VBF prod'n of $H_5^\pm$ in Georgi-Machacek model





Role of theory:

- model-building: extended Higgs sectors, models for naturalness, hidden-sector models

- pheno: indirect constraints from B-physics, etc.

- calculation: precision calcs of cross sections and backgrounds

- tools: MadGraph files, benchmark points, cross-section tables

Many Canadian theorists heavily involved in Higgs physics:

Frank, Grégoire, Godfrey, Holdom, Logan, Morrissey, Ng, Yavin, ...

Precision measurements of Standard Model physics (electroweak)

(QCD and hadronic physics $\Rightarrow$ Randy Lewis' talk)

Key questions:

- Are there deviations in vector boson scattering at high energies?

  $\rightarrow$ Composite Higgs? Exotic scalars? Complementary window to EWSB

  LHC (especially high lumi)

- Are there any diboson resonances?

  $\rightarrow$ W'/Z'? Exotic scalars?

  LHC, ILC (including below resonance)

- Are there deviations in top quark couplings to $W/Z/h$?

  $\rightarrow$ Partially composite top $\leftrightarrow$ warped extra dimensions?

  LHC, ILC $\sqrt{s} \geq 350$ GeV

- Are there deviations from precision SM at lower energies?

  $\rightarrow$ Light hidden states? Higher-dim. operators from new heavy states?

  $(g-2)_\mu$, PIENU, ALPHA, ILC, QWeak/Møller, ...

Role of theory:

- model-building: little Higgs, left-right sym. models, RS, . . .

- pheno: indirect constraints on model parameters

- calculation: precision determinations of observables

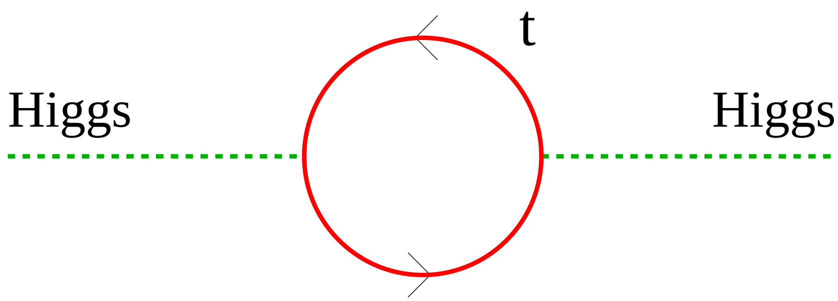
Canadian theorists involved in precision, diboson, or top physics:

Aleksejevs, Barkanova, Czarnecki, Frank, Grégoire, Godfrey, Logan, Ng, Penin

Naturalness

Key question: is naturalness a good guide for theories of Nature?

Suppose the SM is valid up to energies $E = \Lambda \gg v = 174\,\text{GeV}$:



$$\Rightarrow \Delta v^2 \simeq \frac{3\,y_t^2}{16\pi^2}\Lambda^2$$

Puzzle: $\Delta v^2 \gg v^2$ unless $\Lambda \lesssim 1000\,\text{GeV}$.

Solutions: 1. Loop cancellations from new particles.
e.g. Supersymmetry, Little Higgs, Twin Higgs

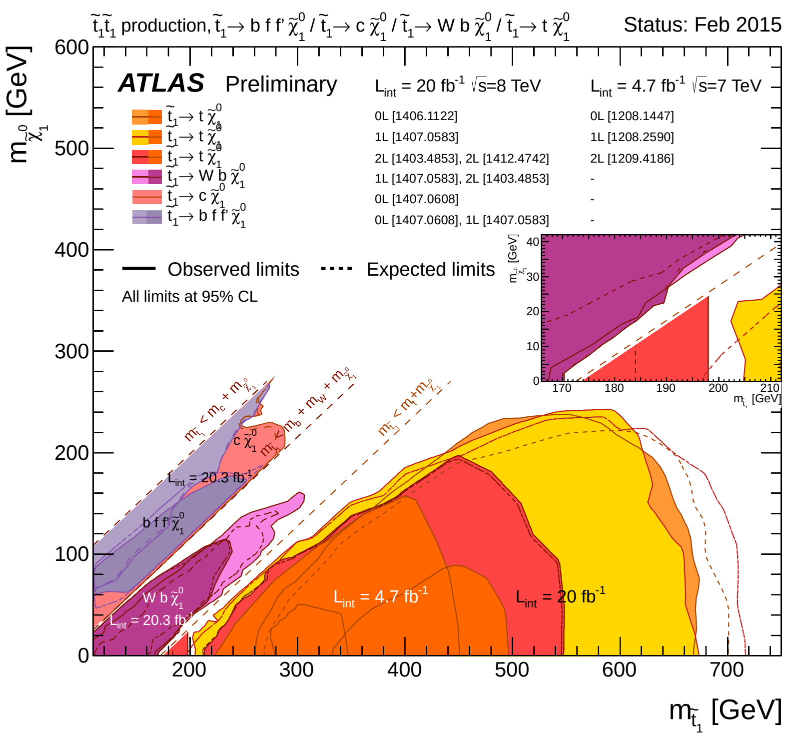
2. Something radical happens at $E = \Lambda$.
e.g. Extra Dimensions ($R = \Lambda^{-1}$), Composite-Higgs

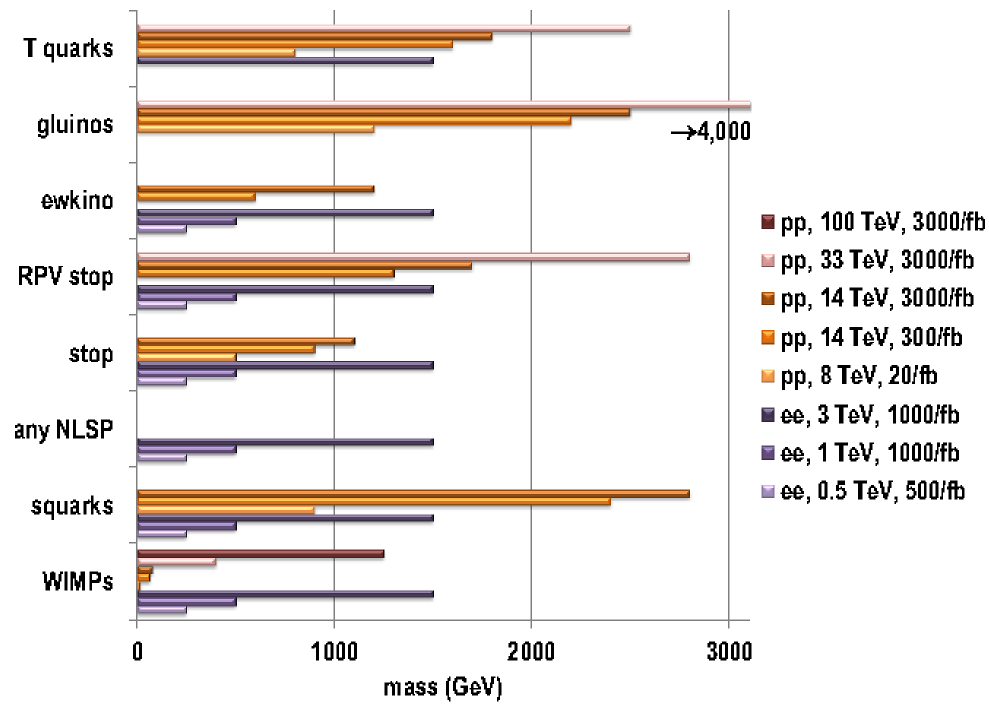
With SUSY:

$$\Delta v^2 \simeq \frac{y_t^2}{16\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda}{m_t}\right) .$$

$m_{\tilde{t}}$ is the mass of the scalar top (stop) superpartners.

Stop searches: LHC, ILC

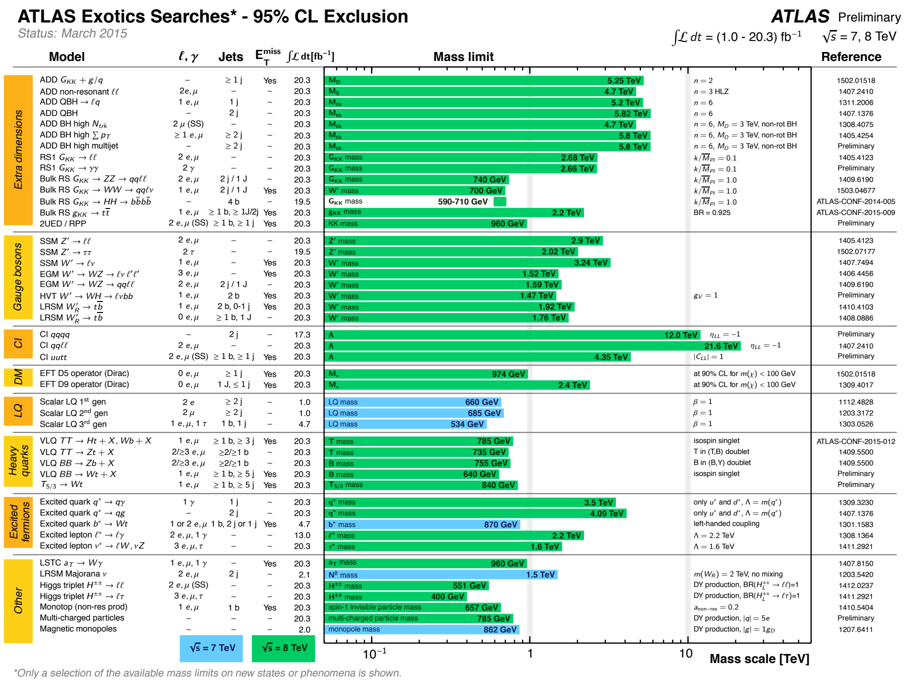


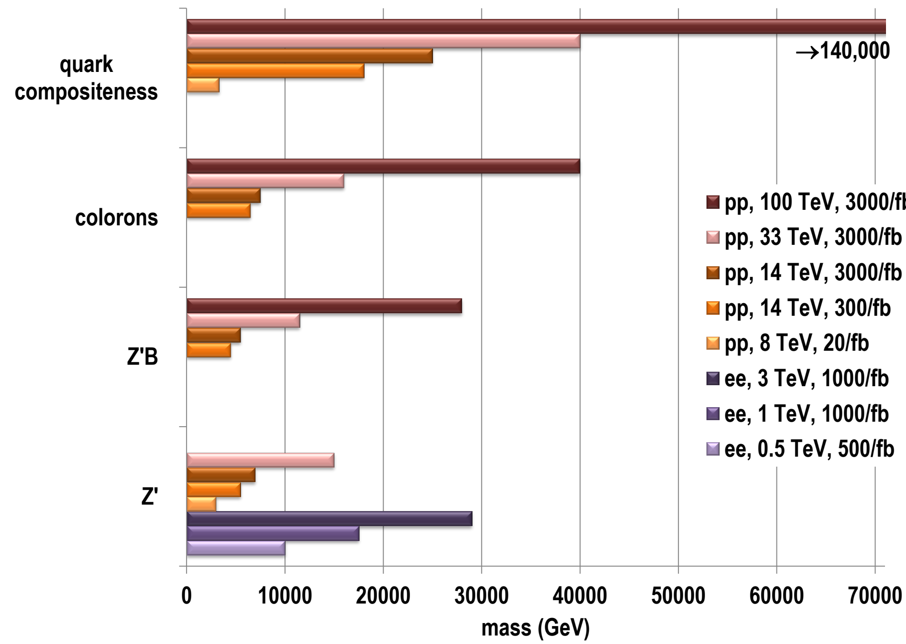


Snowmass New Particles WG report, 1311.0299

"Something radical" at $E = \Lambda \Rightarrow$ new states with mass $m \sim \Lambda$.

Naturalness suggests $\Lambda \lesssim 1000\,\text{GeV}$.





Snowmass New Particles WG report, 1311.0299

Upcoming searches will strongly test naturalness! LHC, ILC

Why haven't we already seen new states for naturalness?

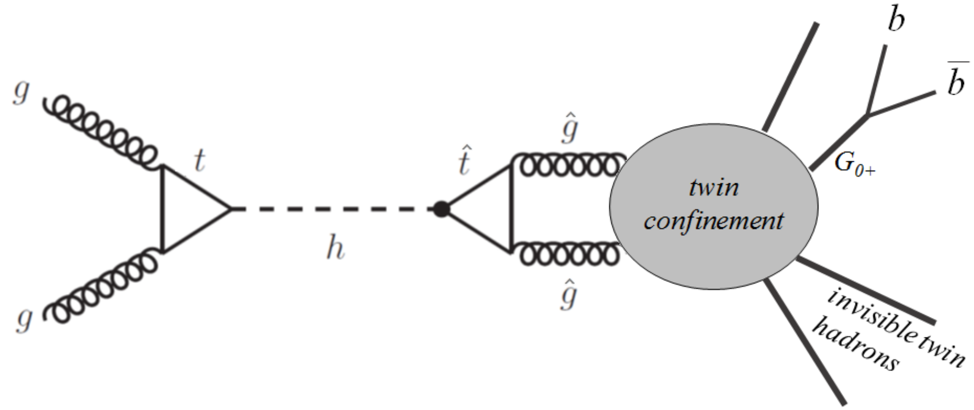
"Neutral Naturalness": new states do not have $SU(3)_c$ charge.
e.g. Twin Higgs, Folded SUSY, Quirky Little Higgs

Neutral partner states usually arise as (super-) copies of the SM.

SM-like Higgs acts as a connector.

$\rightarrow$ deviations in Higgs rates from SM LHC, ILC

$\rightarrow$ complicated hidden states connected to the Higgs LHC, ILC



Role of theory:

- model-building: new models of naturalness (or alternatives)

- pheno: predicting signals of models, recasting existing searches, connecting bounds from different experiments

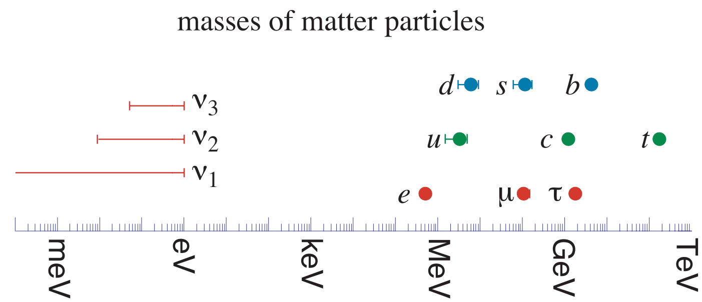
- calculations: constraints from electroweak precision data, loop processes, lattice techniques for strongly-coupled models

- tools: MadGraph files, benchmark points, cross-section tables

Many Canadian theorists involved with naturalness models:

Arvanitaki, Burgess, Campbell, Cline, Frank, Grégoire, Lewis, Logan, Morrissey, Ng, Schuster, Toro, ...

Neutrinos

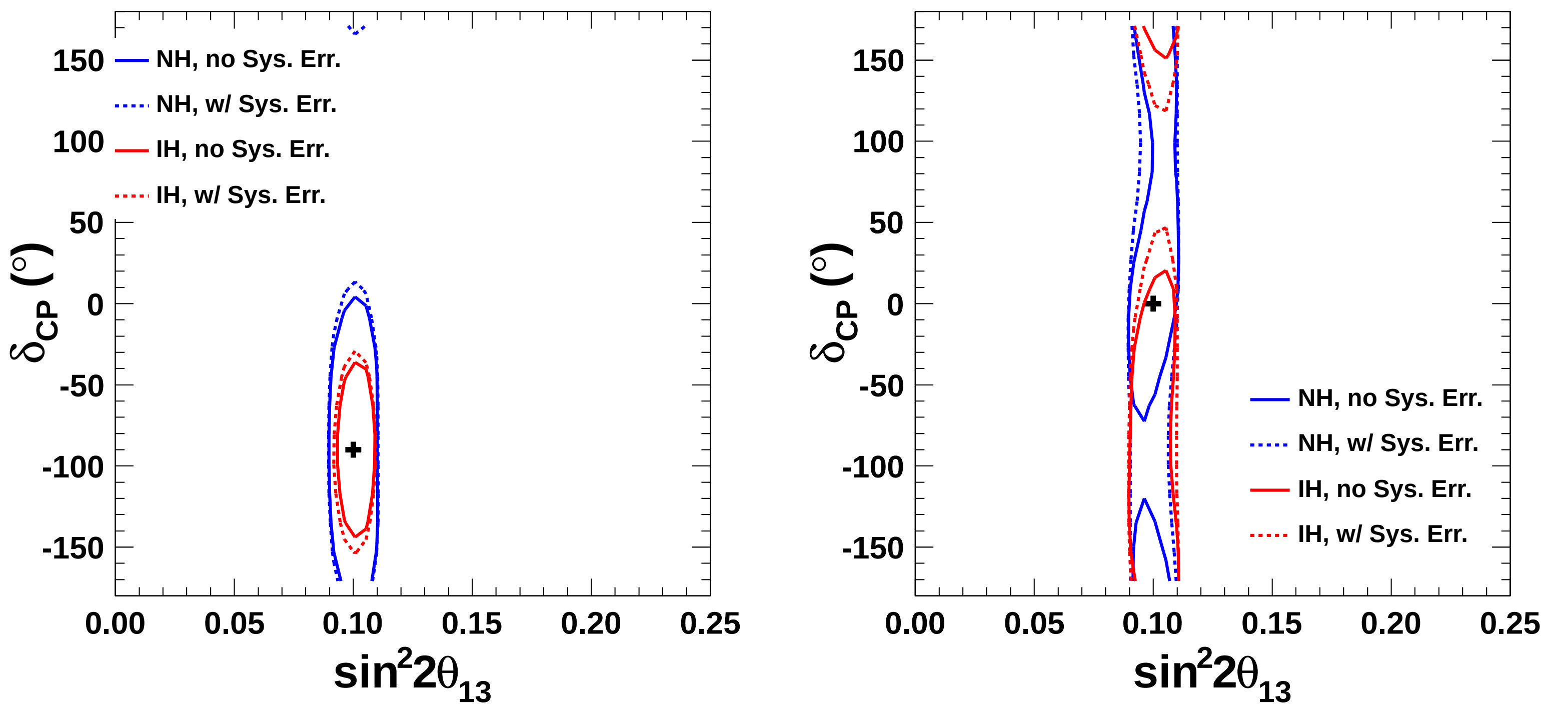


Key questions:

- Where do the masses and mixings come from?
  - $\rightarrow$ singlet neutrinos, seesaw types I,II,II, . . .
  - T2K, SNO+, EXO, IceCube. . .
- What are the absolute neutrino masses?
  - $\rightarrow$ normal vs. inverted hierarchy, cosmological effects
  - EXO, SNO+, T2K,. . .
- Do neutrinos give new CP or L violation?
  - $\rightarrow$ $\delta_{CP} \neq 0, \pi$, Majorana or Dirac
  - T2K, EXO, SNO+,. . .
- Are there new light neutrinos or exotic neutrino interactions?
  - $\rightarrow$ light steriles, new $U(1)$ forces,. . .
  - IceCube, . . .

Is neutrino mixing a new source of CP violation? T2K

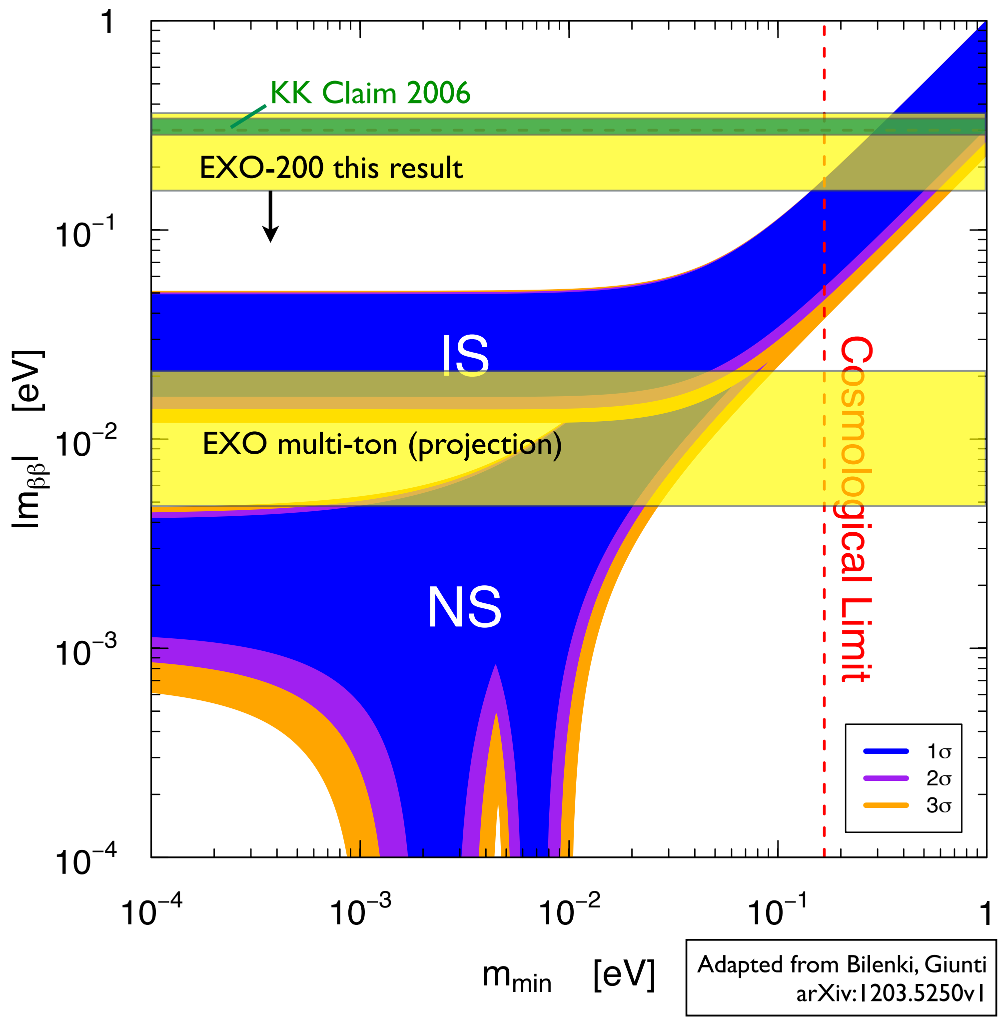
Compare $P(\nu_\alpha \to \nu_\beta)$ to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$:



Projection w/ full T2K stats + ultimate reactor precision on θ_{13}, arXiv:1409.7469

Are neutrino masses a source of L violation? EXO, SNO+

Test by looking for $0\nu\beta\beta$ decay:



2012 talk by J. Farine

Role of theory:

- models: new mass mechanisms, investigate new ν forces

- pheno: compare results from different experiments, relate to cosmology (DM and baryogenesis), connect with LHC searches

- calculation: improve neutrino-nucleus cross-sections

Canadian theorists involved in neutrino physics:

Burgess, Ng, Pospelov, Ritz, Yavin, nuclear theorists

Flavour physics

Key questions:

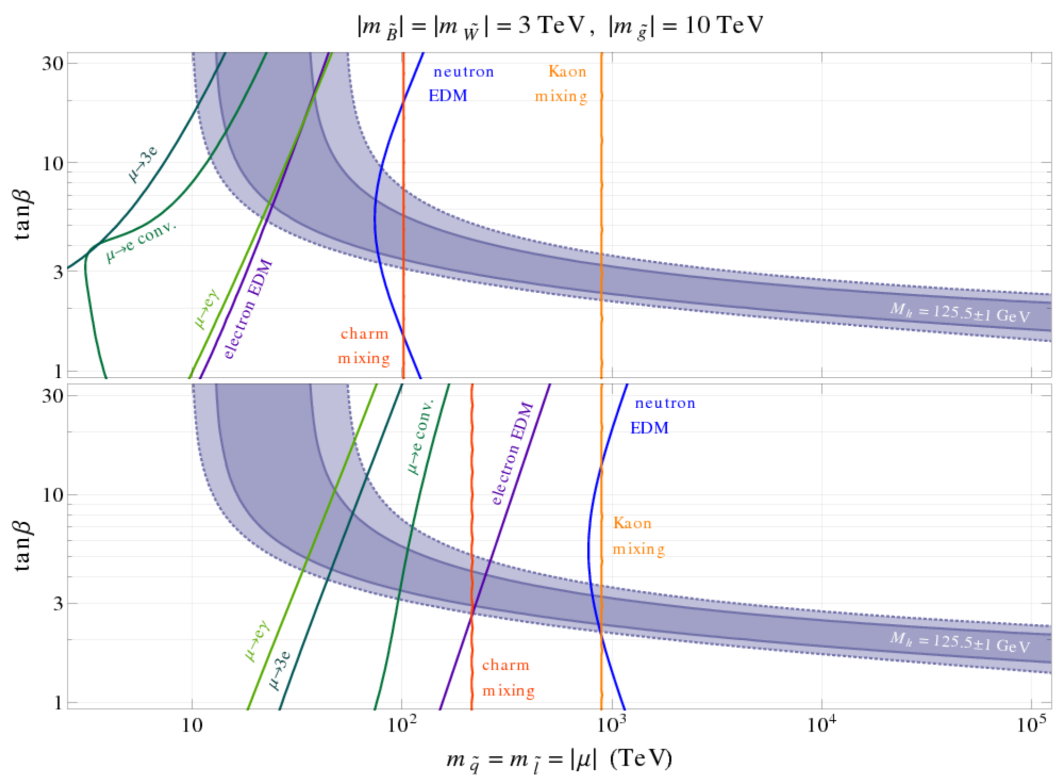
- What sets the fermion masses and CKM mixing angles?
  - $\rightarrow$ Froggatt-Nielsen mechanism? Radiatively-induced masses?
- Are there any new particles that distinguish among flavours?
  - $\rightarrow$ Squarks/sleptons? Leptoquarks? A second Higgs doublet?
- Is there new flavour physics in charged leptons?
  - $\rightarrow$ $(g-2)_\ell$, $e/\mu/\tau$ universality violation, $\mu \rightarrow e$ flavour violation
- Are there new sources of CP violation?
  - $\rightarrow$ neutron and electron electric dipole moments

General Theme: flavor tests vs. flavor-mixing new physics.

If naturalness means $\Lambda \lesssim 1$ TeV, why haven't we seen deviations from the SM in charged flavor?

$\rightarrow$ Minimal flavour violation? Alignment?

No new physics below generic flavour scale $\Lambda \gtrsim 100$ TeV (split SUSY??)?



Current

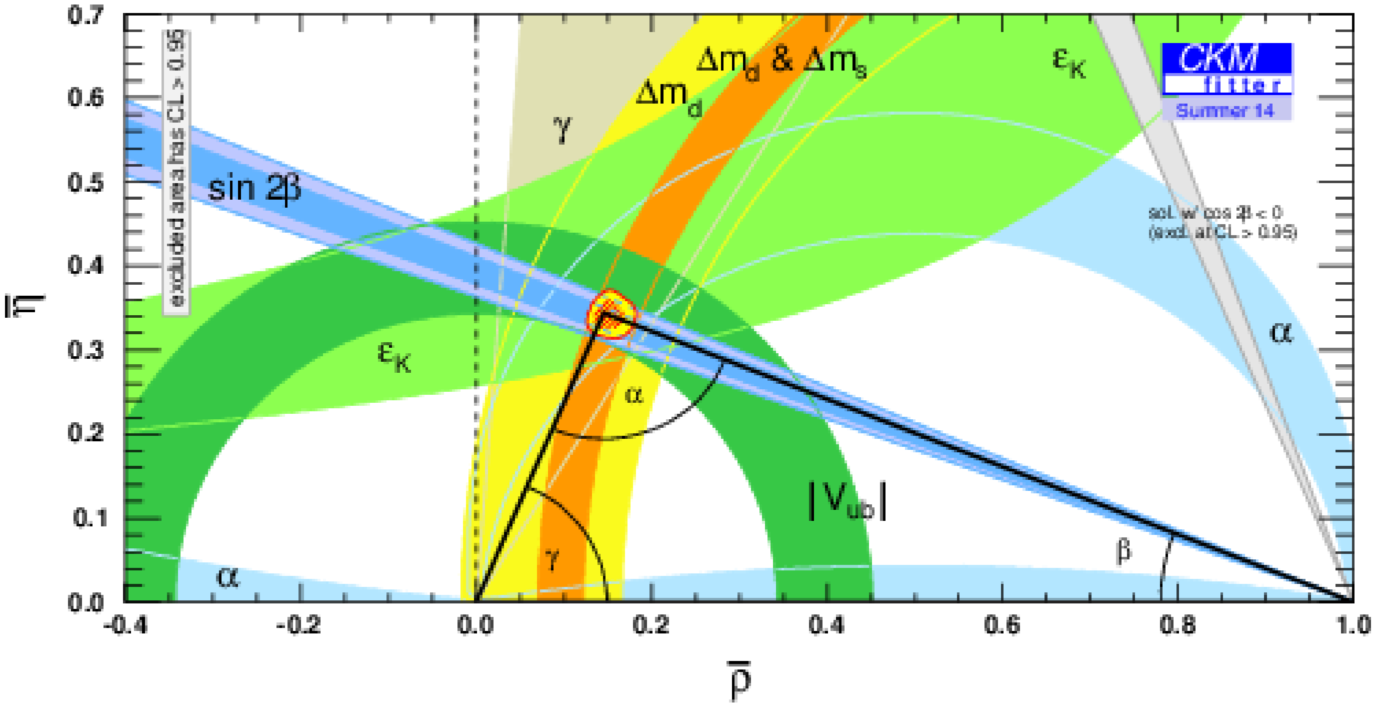
Projected

SUSY with large flavour mixing and CP violation, Altmannshofer *et al.* arXiv:1308.3653

Precision tests of the CKM paradigm: Belle II, LHC, ILC, NA62 indirect search for new flavour-distinguishing particles

- Compare tree-level and loop-induced probes of CKM parameters: can have New Physics in loops

- Next generation of sensitivity at Belle II aims to probe MFV squarks at TeV scale ⇒ complementarity with direct searches



Search for new flavour-distinguishing int's of charged leptons

- Charged lepton universality violation: $e/\mu/\tau$ ratios

PIENU, Belle II, LHC, ILC

- Charged lepton flavour violation: $\mu \to e\gamma$, $\tau \to \mu\gamma$, etc.

MEG, Mu2e; Belle II

- Assorted new physics coupled to leptons?

JPARC $(g-2)_\mu$

- Leptoquarks?

LHC, ILC direct; PIENU, Belle II, etc indirect

- Rare Higgs decays: $h \to \tau\mu$? 2.4σ excess at CMS...

LHC, ILC

Role of theory:

- model-building: flavour theories, gauged $(L_\mu - L_\tau)$, models motivated by experimental anomalies

- pheno: global constraints on model parameters, CKM fits with BSM operators, recasting LHC searches to constrain models

- calculation: precision calculations of B-physics observables, new-physics effects from loops

Several Canadian theorists involved in flavour and CP physics:

Couture, Frank, Hamzaoui, London, Ng, Pospelov, Ritz, Tulin, Yavin, ...

The search for dark matter

Key questions:

- What is it?!?

  → WIMP or axion? Fermion? Scalar? Vector? What mass?

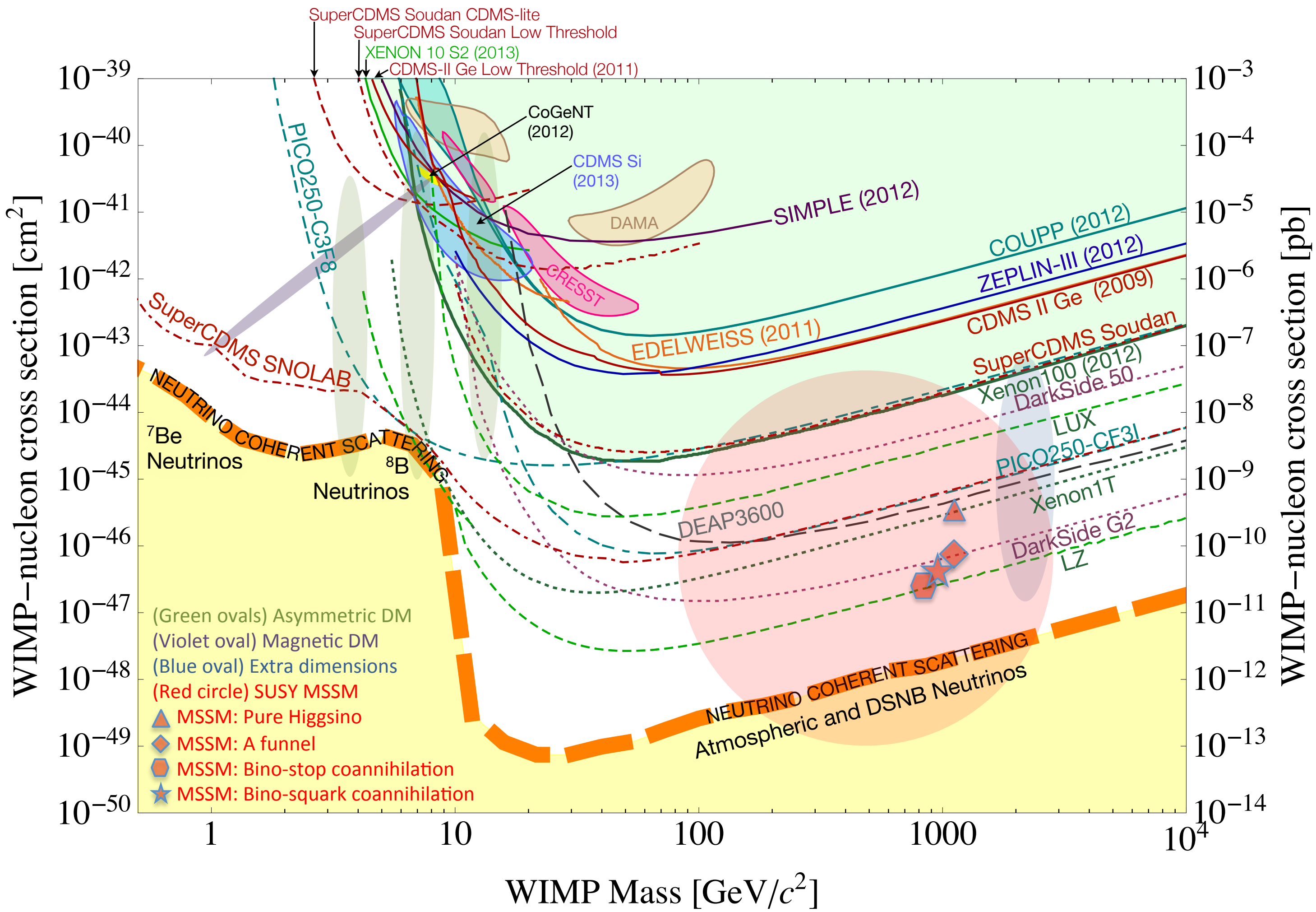
- How does it interact with the rest of the Standard Model?

  → Weak-charged? Higgs portal? New-physics mediator?

- What mechanism fixed the relic density?

  → Thermal freeze-out? Thermal freeze-*in*? Decay of a heavier particle? Asymmetry like for the baryons? Resonant oscillations (axions)?

Direct searches for dark matter: DEAP, SuperCDMS, PICO



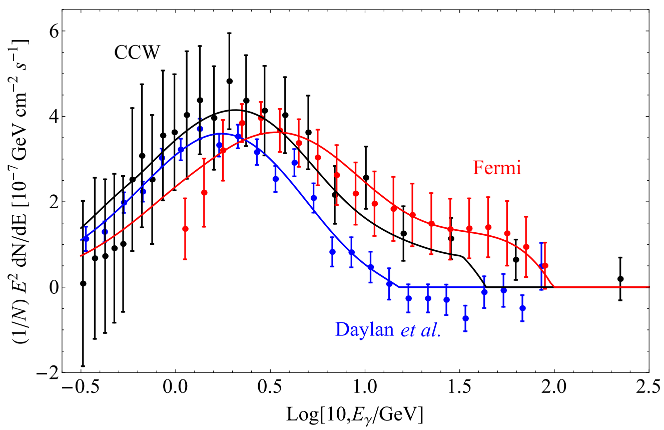
Snowmass WIMP direct detection report, arXiv:1310.8327

- Measure cross section; some sensitivity to WIMP mass

Indirect searches for dark matter: look for annihilation products

- gamma rays from galactic centre, nearby dwarf galaxies, ...

Fermi, VERITAS



Cline et al, arXiv:1503.08213

Longstanding few-GeV gamma-ray excess from galactic centre (but it may be pulsars)

← best-fit multimediator models

Dwarfs constrain annihilation cross sections to various final states

- neutrinos from DM captured in the Sun

IceCube, SuperK, SNO+(?)

Constrain couplings of DM to nucleons

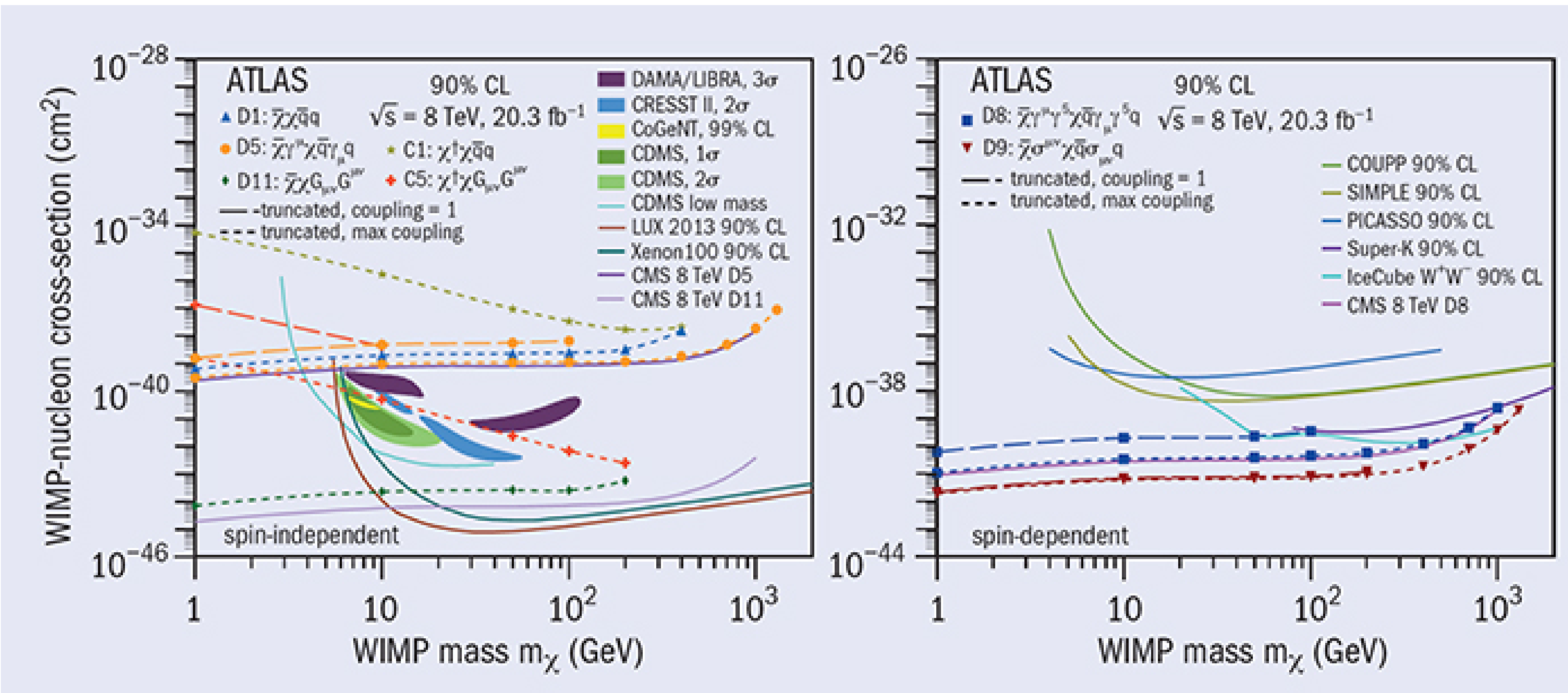
- DM-induced antimatter in local galactic neighbourhood AMS

Constrain annihilation cross sections to various final states

Collider searches for new invisible particles: LHC, ILC
Low-mass “hidden sector”: + Belle II, T2K, . . .

- X + MET: could be DM, or just long-lived on collider scale

- constrain coupling of DM to nucleons



Role of theory:

- model-building: often motivated by expt "hints"

- pheno: constraints, complementarity of collider/direct/indirect

- expt proposals: e.g. beam-dump expts for low-mass DM models

Many Canadian theorists heavily involved in dark matter physics:

Arvanitaki, Burgess, Cline, Dick, Grégoire, Godfrey, Logan, Moore, Morrissey, Ng, Pospelov, Ritz, Schuster, Toro, Tulin, Yavin, . . .

Hidden Sectors

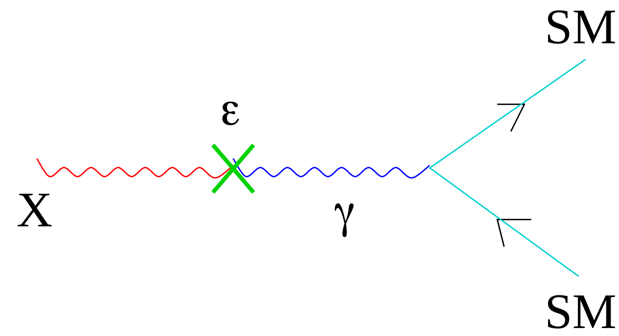
Key questions:

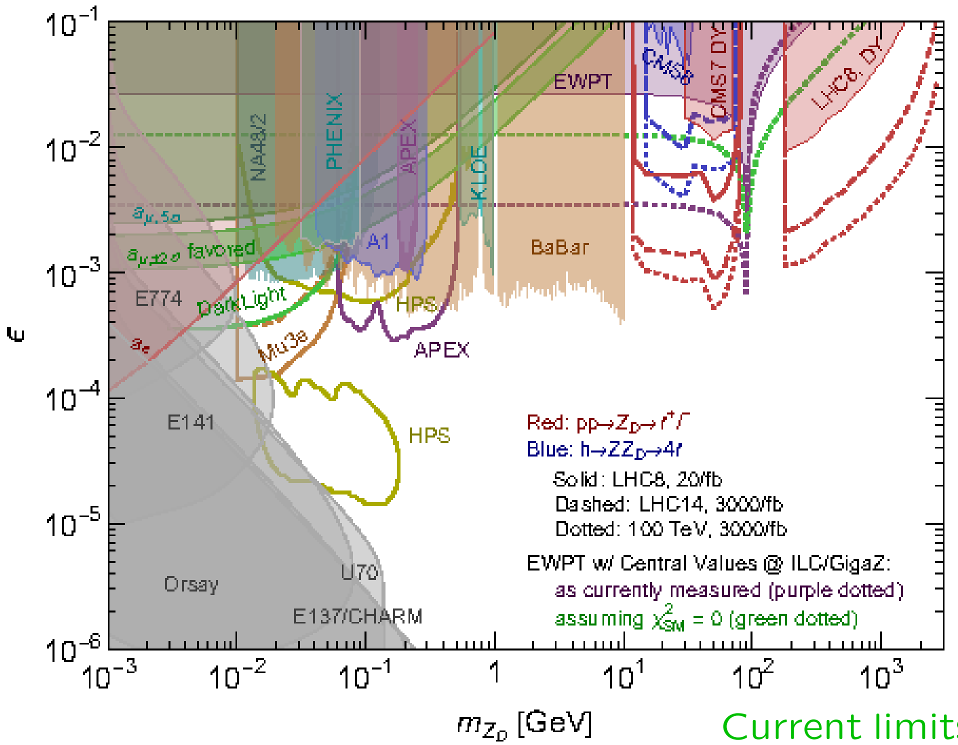
- Are there new hidden particles or forces below the weak scale?
  - → dark vectors? axion-like-particles, Higgs-portal states, singlet fermions
- Do new hidden states connect to other puzzles?
  - → dark matter, baryogenesis, strong CP, naturalness, neutrino mass
- Can such states be probed using existing experiments?
  - → precision SM measurements, meson factories, beam dumps, astrophysics, accelerator neutrino experiments, LHC
- Are there new experimental opportunities to pursue?
  - → APEX, SHIP, HPS, DarkLight, ARIEL(?), . . .

e.g. Hidden Photon A' with Kinetic Mixing ϵ to Hypercharge

If $A' \to SM + SM$ dominates:

$$\to \epsilon\, A'_\mu\, j^\mu_{em}$$



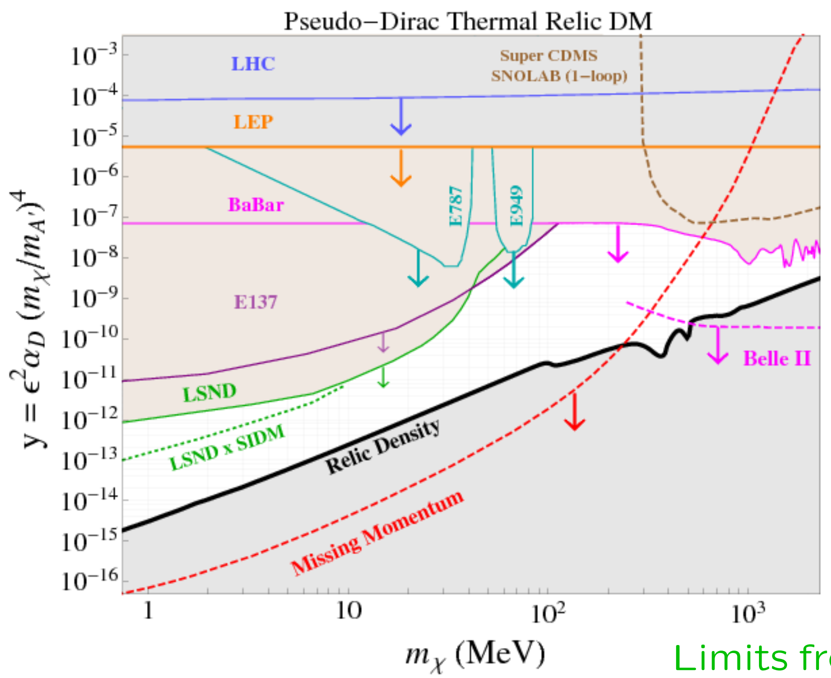


Current limits from Curtin *et al.*, 1412.0018

Many experiments can be sensitive: Belle II, LHC, APEX, . . .

e.g. Hidden Photon A' with Kinetic Mixing and Dark Matter χ

If $A' \to \chi\chi$ dominates:



Limits from Izaguirre *et al.*, 1505.00011

New contributions to invisible final states: Belle II, NA62

Elastic χ scattering downstream of a target: E137, LSND, T2K

Dedicated fixed-target "missing momentum" experiments:
Izaguirre, Krnjaic, Schuster, Toro, 1411.1404

Role of theory:

- model-building: what sorts of things should we look for?

- pheno: limits old experimental data, connections to DM

- new experiments: *e.g.* fixed-targets, neutrino runs

Several Canadian theorists involved in hidden sector physics:

Arvanitaki, Cline, Frey, Morrissey, Pospelov, Ritz, Schuster, Toro, Yavin, ...

Baryogenesis

Key questions:

- Why is there more matter than antimatter in the Universe?
  - $\rightarrow$ electroweak baryogenesis, leptogenesis, hidden dark baryons, . . .
- Is the asymmetry related to the Higgs?
  - $\rightarrow$ electroweak baryogenesis
- Is the asymmetry related to observable CP violation?
  - $\rightarrow$ electroweak baryogenesis, other low-scale mechanisms
- Is the asymmetry related to dark matter?
  - $\rightarrow$ asymmetric dark matter, $\rho_{DM} \simeq 5\rho_b$
- Is the asymmetry connected to the source of neutrino masses?
  - $\rightarrow$ leptogenesis, baryons via neutrino oscillations
- Is the asymmetry related to observable B violation?
  - $\rightarrow$ GUT baryogenesis, some low-scale mechanisms

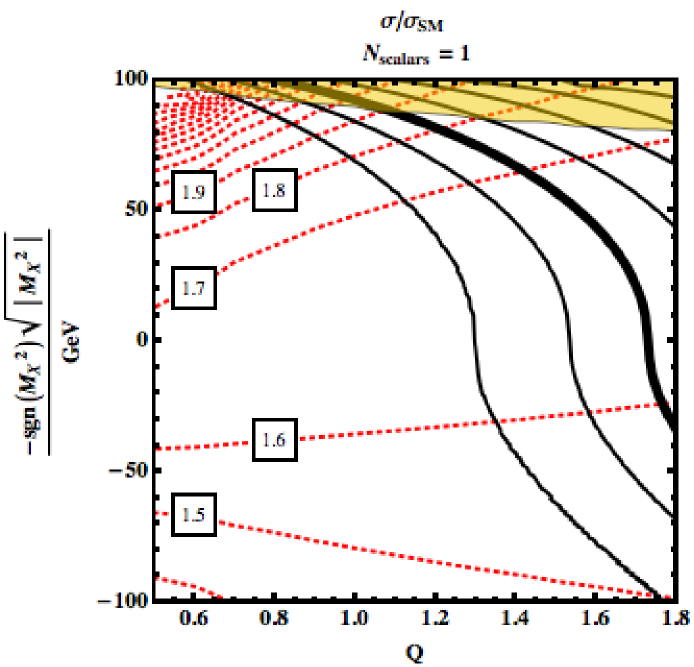
e.g. Electroweak Baryogenesis: baryon creation during the electroweak phase transition

Ingredient #1: new physics that couples to the Higgs

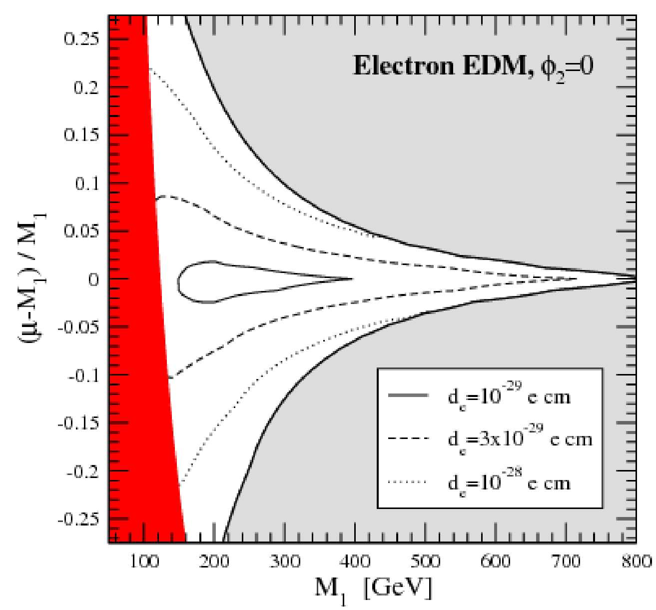
$\rightarrow$ constrained by precision Higgs measurements LHC, ILC

Ingredient #2: new CP violation that connects to the Higgs

$\rightarrow$ searches for electric dipole moments EDM with UCN, Fr



Higgs rates in SUSY EWBG, 1203.2924



EDM limits on EWBG, Li *et al* 0910.4589

Role of Theory:

- mechansisms: find new ways to create the baryon asymmetry

- pheno: relate mechanism models to experimental observables, connect to dark matter, Higgs physics, neutrinos, flavor, . . .

- calculation: improve predictions of existing mechanisms

Many Canadian theorists involved in baryogenesis:

Burgess, Cline, Moore, Morrissey, Tulin, Yavin, . . .

Summary

We are in an era of unprecedented data.

Discovery of the Higgs confirmed the Standard Model,
but it also sharpened the puzzle of Naturalness.

Neutrino oscillations, dark matter, and the baryon asymmetry
give experimental evidence of new physics beyond the SM.

Data from the LHC will probe the Higgs and test naturalness.

Searches for dark matter will cover most of the WIMP region.

Testing of neutrinos and flavour will cover higher energies.

Searching at low energies may uncover surprises.

Interplay between theory and experiment will be vital
to get the most out of both.