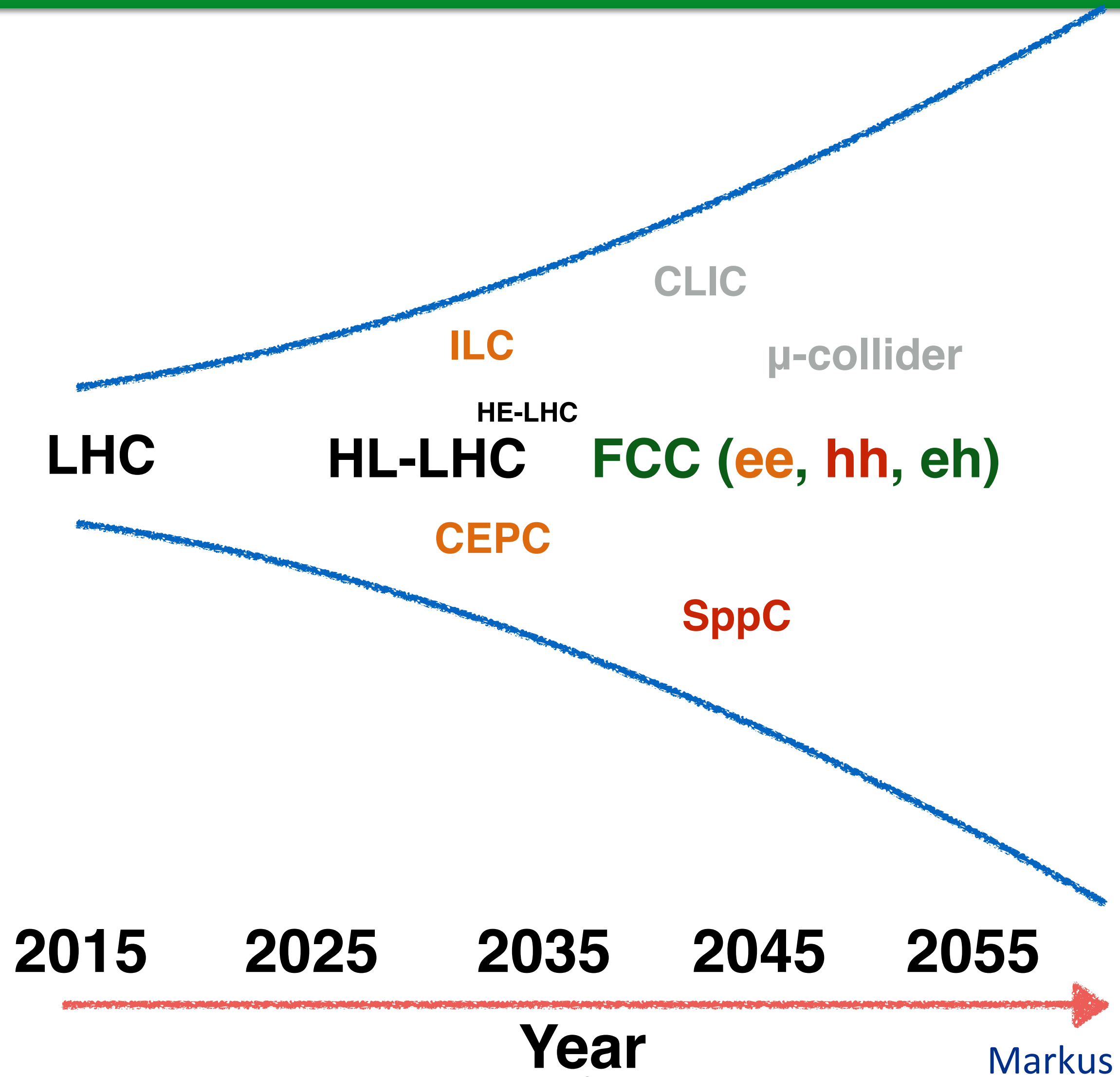
Physics motivation for the next generation of Energy and Intensity Frontier machines

Joe Lykken

GARD-SRF Roadmap Workshop

9 February 2017

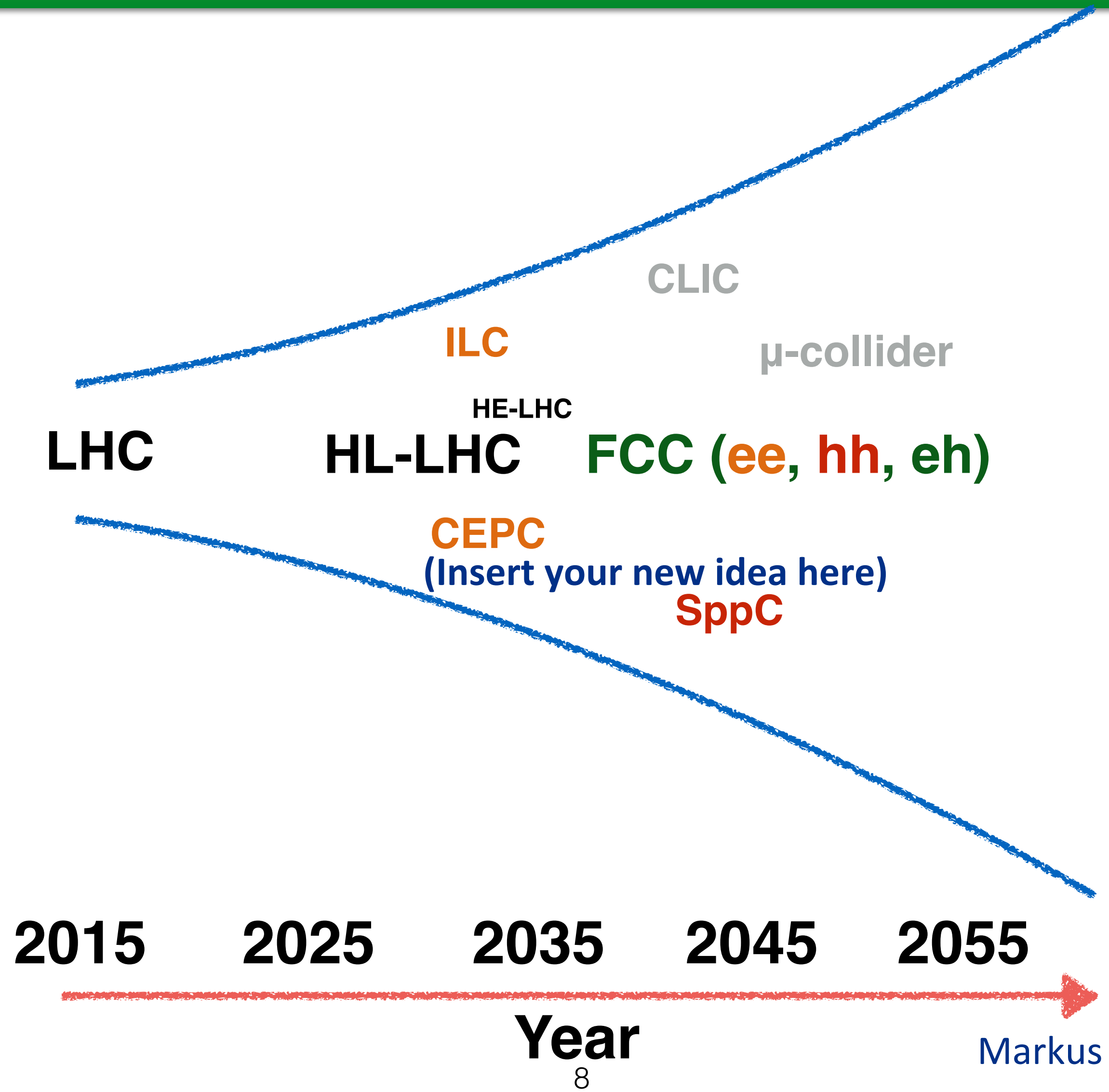
The Road Ahead



8

Markus Klute, HC16

The Road Ahead



Markus Klute, HC16

Standard Model rules on earth, if not in the heavens

- The last seven particle colliders (three B factories plus LEP, SLC,Tevatron, and LHC) have so far seen no conclusive evidence of Beyond the SM phenomena in the laboratory
- This is at least somewhat surprising for LHC, since strong arguments based on naturalness imply that the Higgs boson should be accompanied by BSM physics at a similar scale, ~<TeV
- The only BSM physics observed so far *in the lab* is neutrino mass (from neutrino flavor change)
- Theorists are getting nervous and impatient…

Reality-based theory guidance for HEP

At this point it is probably a good idea for we theorists to be humble and keep our arguments simple. Let me attempt to do that.

Question: Physics motivation for the next generation of Energy and Intensity Frontier machines?

Answer:

Reality-based theory guidance for HEP

At this point it is probably a good idea for we theorists to be humble and keep our arguments simple. Let me attempt to do that.

Question: Physics motivation for the next generation of Energy and Intensity Frontier machines?

Answer:

- Higgs
- Neutrinos
- Dark matter

Higgs

A Higgs boson like particle was discovered at LHC in 2012

It is the first of its kind ever observed

Its existence implies the Higgs mechanism, a very sophisticated property of the quantum vacuum

And it implies a phase transition in the early universe of unknown origin (why did the Higgs field turn itself on?)

Obviously it should be a top priority of HEP to detect, measure, and understand the detailed physics tied to the Higgs

Higgs challenges

Detect and measure with precision the various decay modes of the Higgs boson, including “invisible” decays into undetected particles

Detect the Higgs self-coupling, and constrain directly the Higgs potential

Detect evidence of Higgs compositeness

Find heavier (or lighter?) cousins of the Higgs boson

Higgs challenges

Detect and measure with precision the various decay modes of the Higgs boson, including “invisible” decays into undetected particles

Detect the Higgs self-coupling, and constrain directly the Higgs potential

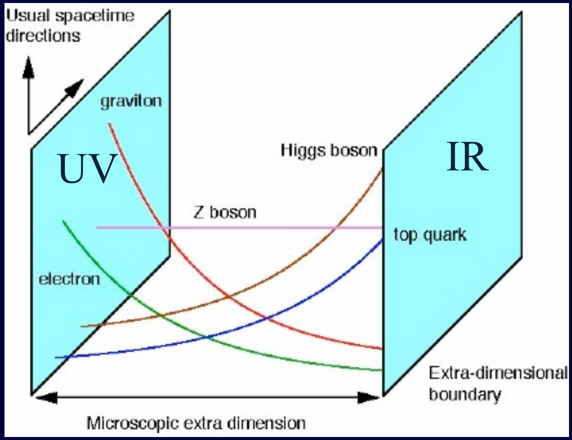
Detect evidence of Higgs compositeness

Find heavier (or lighter?) cousins of the Higgs boson

LHC and HL-LHC can tell us a lot, but will **not** be definitive for any of these challenges

Composite Higgs?

The Standard Model in Warped Extra Dimensions



- Elegant solution to the Hierarchy problem: it is possible that the otherwise mysterious mass scale of the Higgs boson is precisely an IR cutoff scale in a warped extra dimension
- The Higgs boson is really a pion-like composite

Hierarchical SM fermion masses from localization [masses and degree of compositeness depend on overlap with Higgs/TeV scale]

KK modes (weak bosons, gluons, fermions, gravitons) localized towards the IR with Masses ≥ 1 TeV from precision measurements (Higgs induced mixing with SM particles)

Gauge-Higgs Unification Models: A dynamical origin of the Higgs Field

Enlarge the SM gauge symmetry in the bulk such that additional zero mode/s of the 5D gauge field (scalars) are identified with the Higgs degrees of freedom

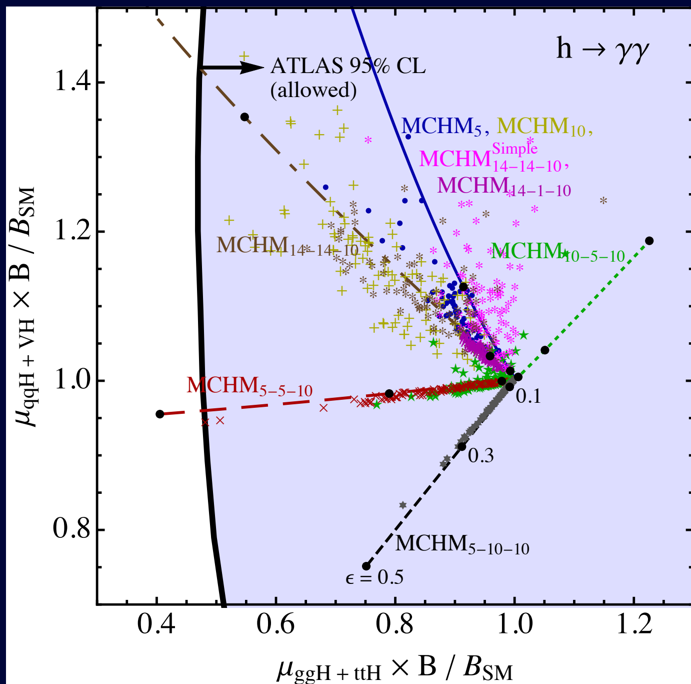
➔ No tree-level Higgs Potential ==> Induced at one-loop level

➔ Dynamical EWSB: driven by the top Yukawa

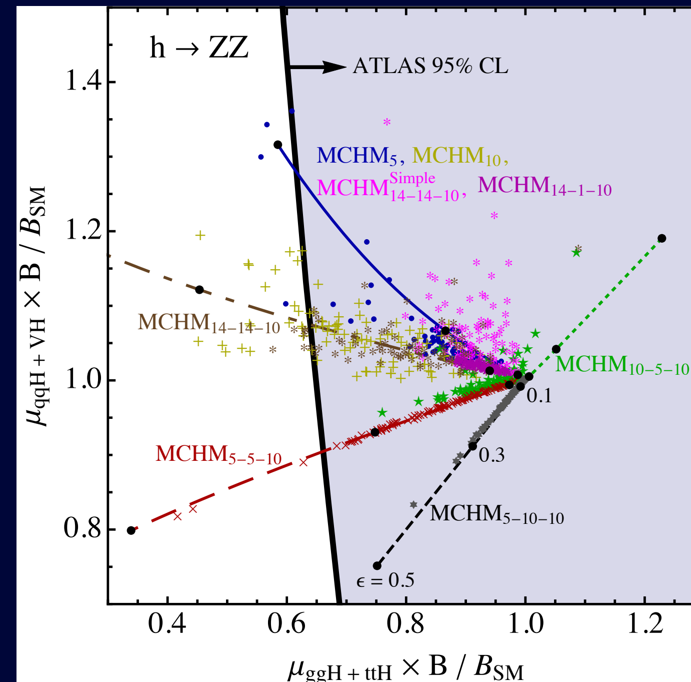
Talk by M. Carena

Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



Talk by M. Carena

M.C., Da Rold, Ponton'14

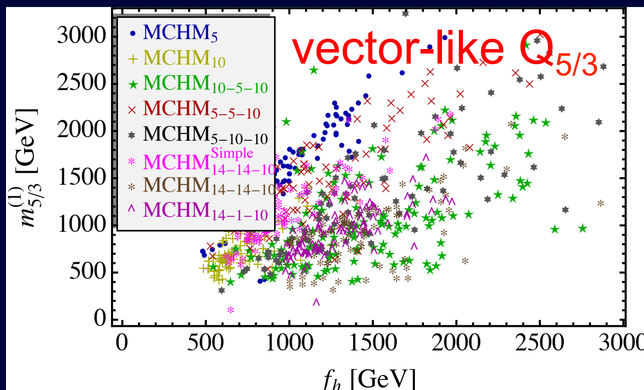
After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands f > 500 GeV

More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

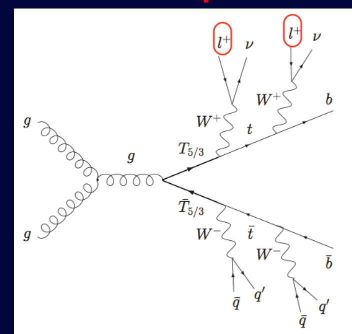
Other global symmetry patterns allow for additional Higgs Bosons in the spectrum

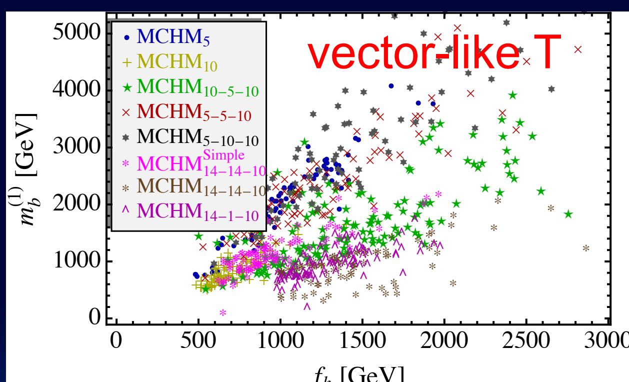
Composite pNGB Higgs Models predict light Fermions

Pair production, single production, or exotic Higgs production of vector-like fermions
[masses in the TeV range and possibly with exotic charges: Q = 2/3,−1/3, 5/3,8/3,−4/3]

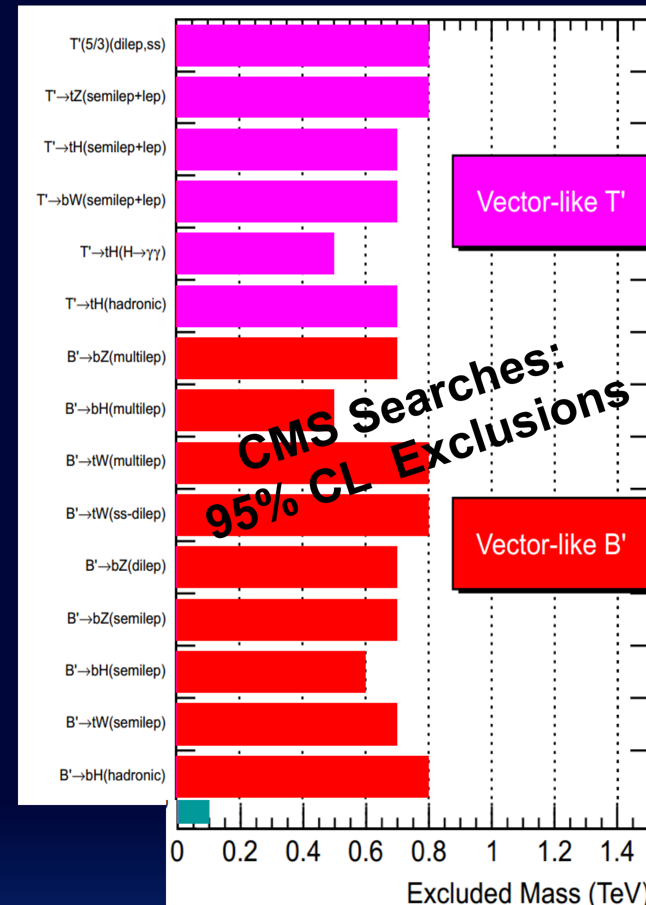


SS di-leptons





Large variety of signatures, many with energetic leptons



M.C., Da Rold, Ponton'14

Talk by M. Carena

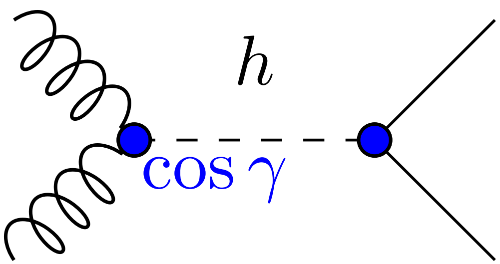
LHC exclusion for M_f < 800 GeV]

Hunting the singlet Higgs bosons

Dario Buttazzo, FCC Physics Workshop

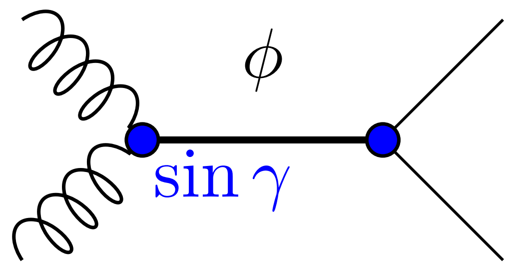
Two complementary ways to look for the extra Higgs:

Higgs signal strengths



$\mu_h \sim c_\gamma^2 \times \mu_{\rm SM}$

Direct searches



$\mu_\phi \sim s_\gamma^2 \times \mu_{\rm SM}$

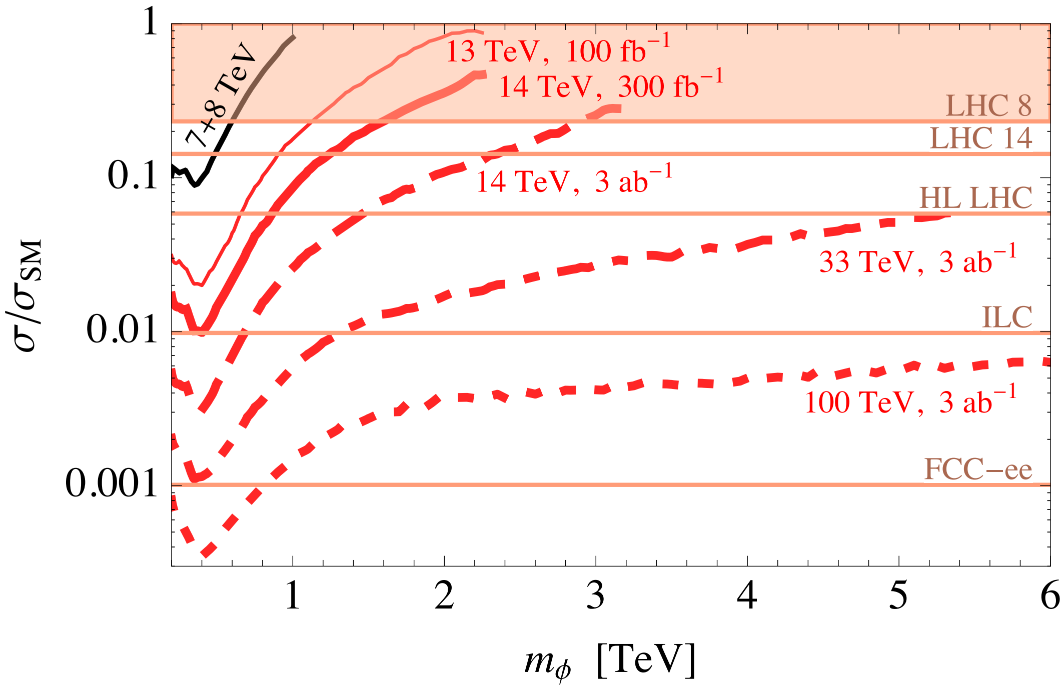
This is a very generic possibility

A Singlet Higgs with Higgs-like decays via mixing

Direct vs indirect

Dario Buttazzo, FCC Physics Workshop

We can now compare the reach of direct and indirect searches.
$\sigma/\sigma_{\rm SM} \propto \sin^2\gamma$ (ignore $\mathrm{BR}_{\phi\to hh}$ for the moment...)



Direct searches dominate for lower masses ($\lesssim 1$ TeV) at each stage of the experimental program

Neutrinos

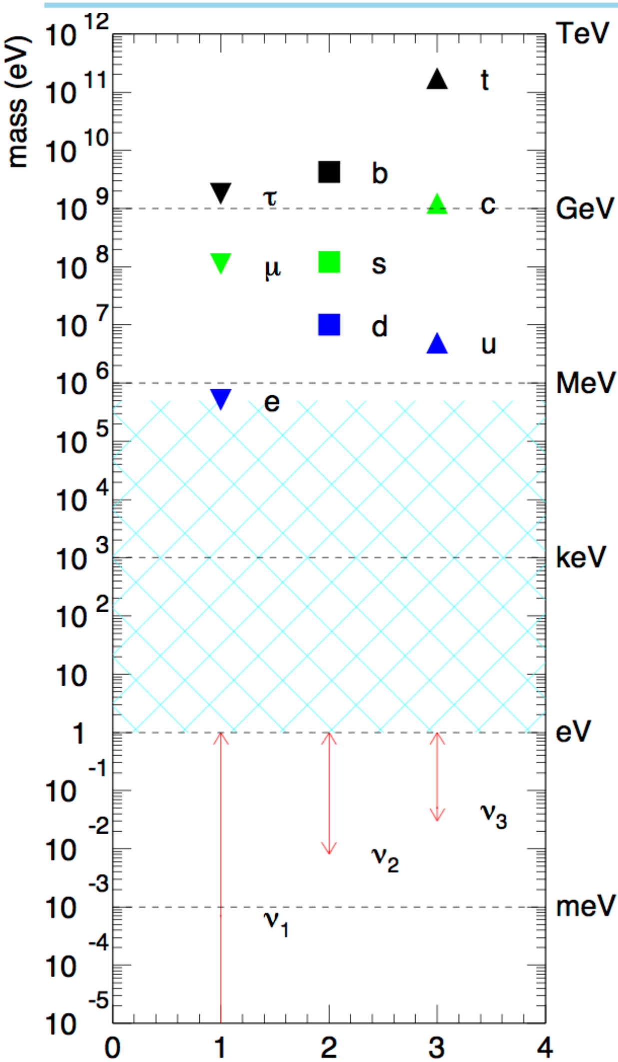
Neutrinos were discovered a long time ago, but they are very difficult to study

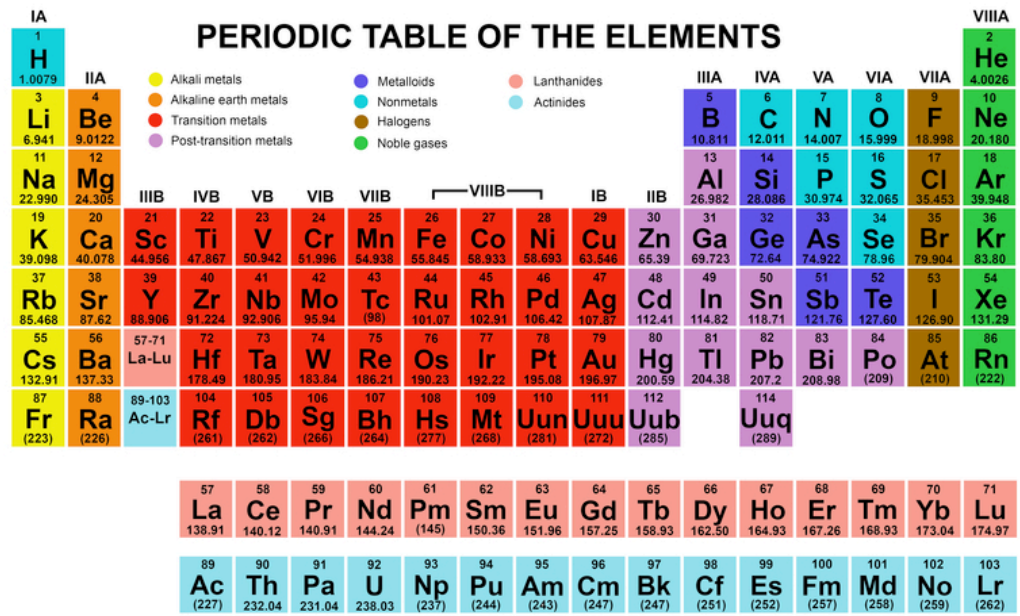
So far their known properties are surprising and mysterious, including/especially neutrino mass

We know that they play a major role in cosmology, perhaps even in the origin of baryonic matter itself

Obviously it should be a top priority of HEP to detect, measure, and understand the detailed physics tied to the neutrinos

What is the underlying dynamics of flavor?





Saying that the Standard Model with the Higgs mechanism is a successful theory of fermion masses is like saying that the Periodic Table is a successful theory of atoms

Neutrinos are especially strange – understanding them better may be a clue to this whole puzzle

Fermilab

How little we know: which see-saw? what scale?

Smallness of neutrino mass can be "explained" by:

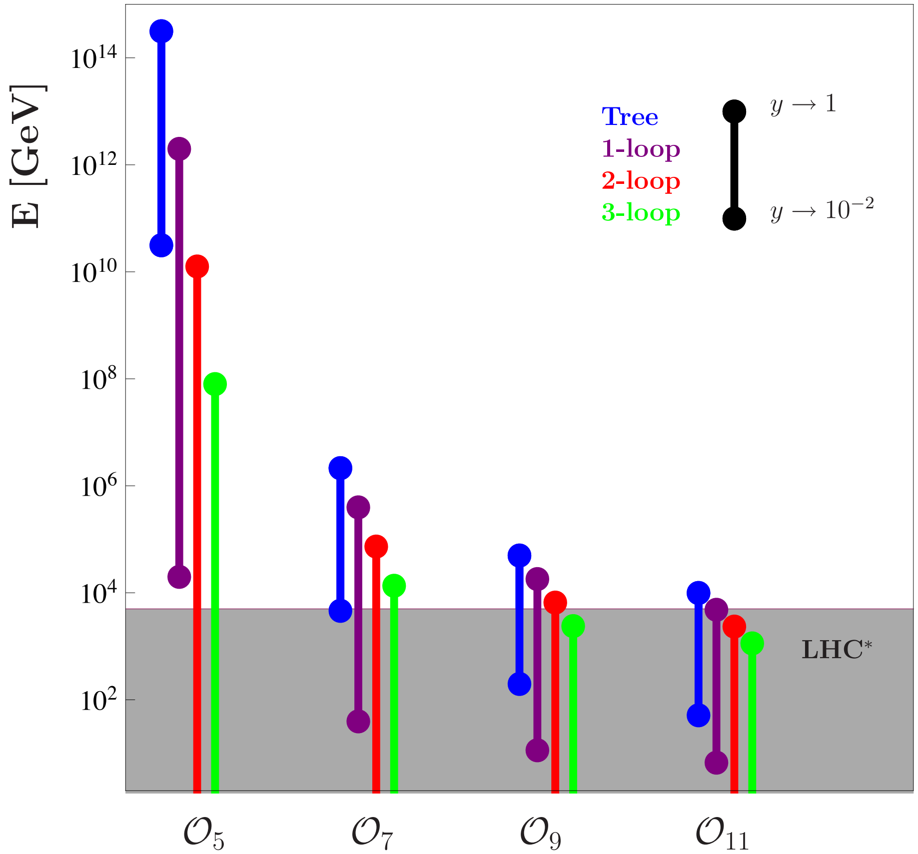
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

$\Rightarrow$ Loop factor: $n \geq 1$
+ "smallish" $Y \sim \mathcal{O}(10^{-3} - 10^{-1})$

$\Rightarrow$ Higher order: $d = 7, 9, 11$

$\Rightarrow$ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

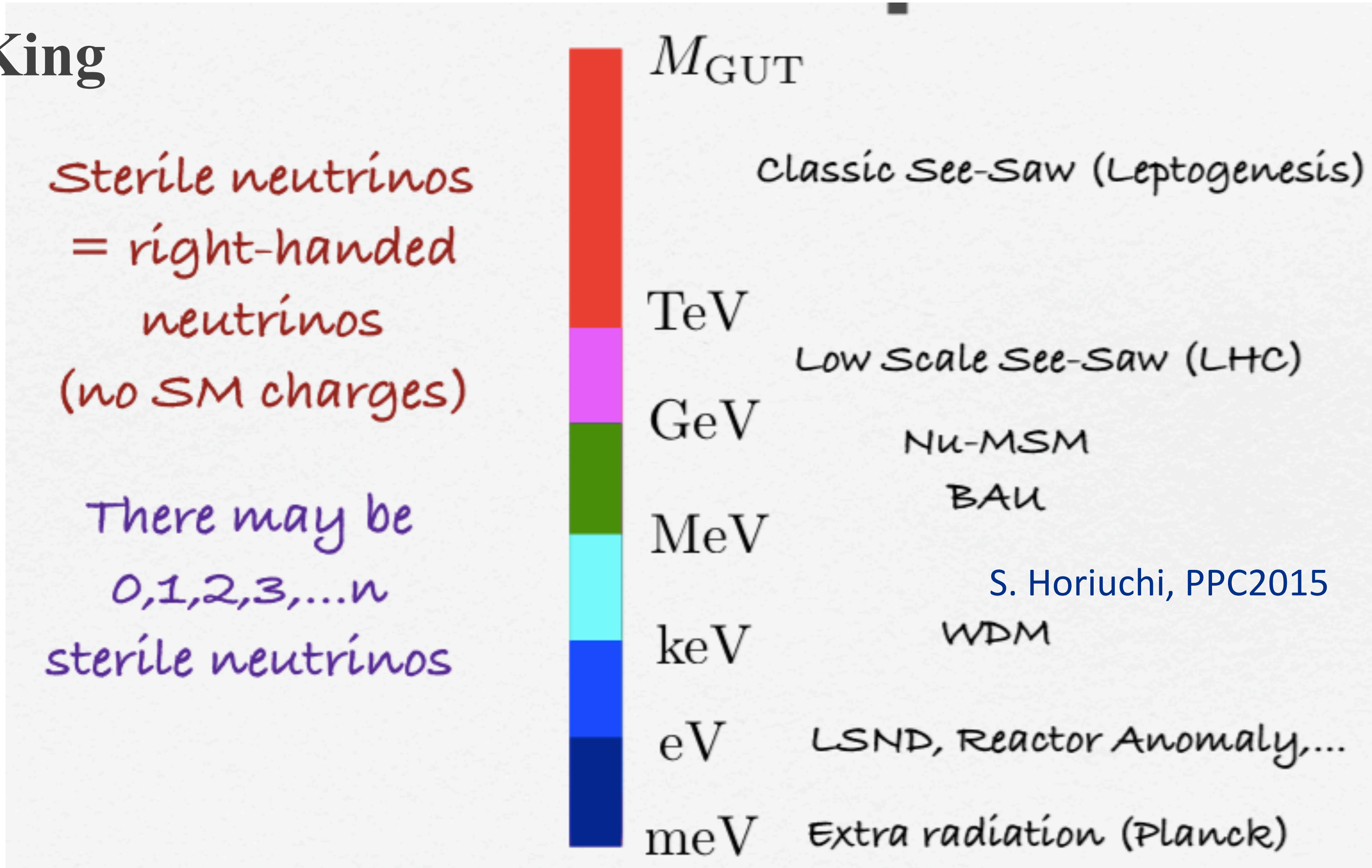
$\cdots$ or combination thereof



M. Hirsch, WIN2015

How little we know: sterile neutrinos

S. King



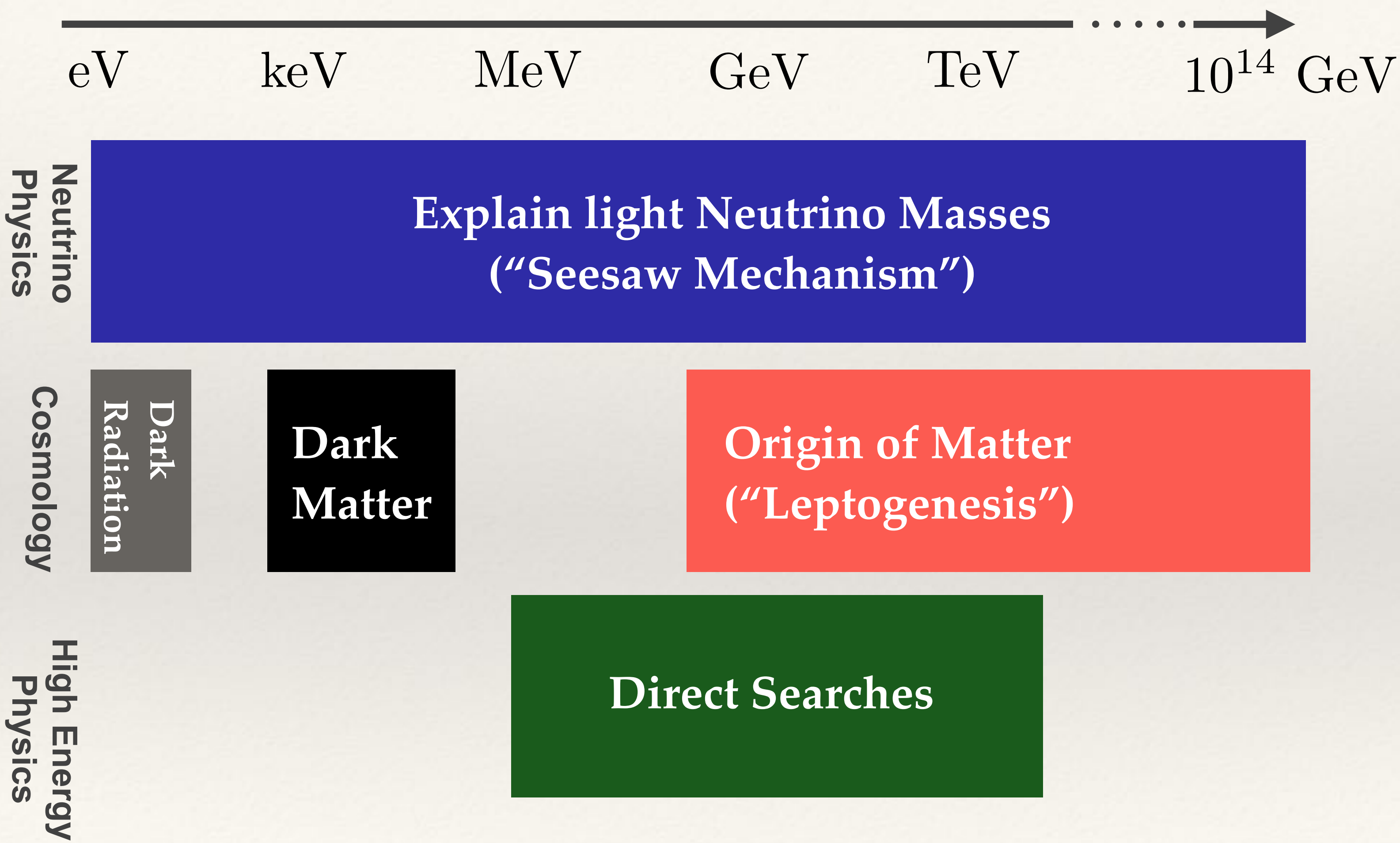
Fermilab

Neutrinos and accelerators

Even with massive sophisticated detectors such as DUNE, long baseline neutrino oscillation experiments require pushing the Intensity Frontier to more powerful beams

Our ignorance of the scales of new physics associated to neutrinos also poses challenges to Energy Frontier colliders

Direct Searches



Marco Drewes, FCC Physics Workshop

Direct Searches

Fixed Target Experiments

SHiP
Search for Hidden Particles

NA62

b Factories

LHCb

Belle II

High Energy Colliders

FCC
hh ee he

CEPC

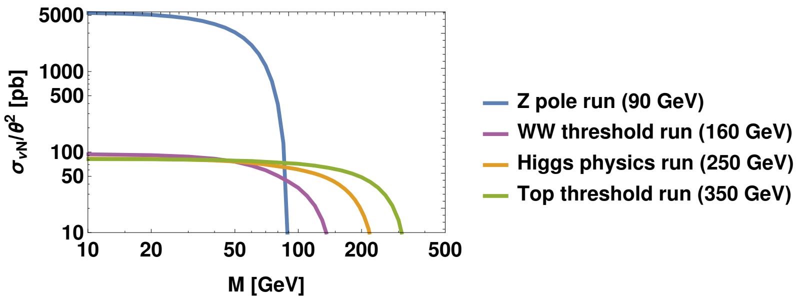
ilc
international linear collider

Direct Searches

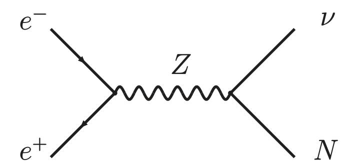
High Energy Physics

Marco Drewes, FCC Physics Workshop

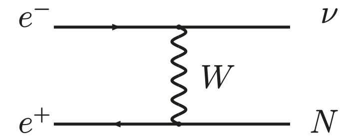
Heavy neutrinos at the FCC-ee



production channel: $\mathbf{Z_s} \propto |\theta|^2$



production channel: $\mathbf{W_t} \propto |\theta_e|^2$



Always one light ν in the final state, no unambiguous LNV signature at the leading order.

Signatures of heavy ν for e^-e^+ colliders at leading order

Name	Final State	$\lvert\theta\rvert$, Z pole	$\lvert\theta\rvert$, $\sqrt{s} > m_Z$
lepton-dijet	$\ell_\alpha \nu jj$	$\lvert\theta_\alpha\rvert^2$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$
mixed flavour dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$\lvert\theta_\alpha\rvert^2$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$
same flavour dilepton	$\ell_\alpha \ell_\alpha \nu\nu$	$\lvert\theta\rvert^2$	$\lvert\theta_e\rvert^2$
dijet	$\nu\nu jj$	$\lvert\theta\rvert^2$	$\lvert\theta_e\rvert^2$
invisible	$\nu\nu\nu\nu$	$\lvert\theta\rvert^2$	$\lvert\theta_e\rvert^2$

Modify WW production

Modifies mono-Z, mono-h production

Eros Cazzato, FCC Physics Workshop

Fermilab

Dark matter

Modulo some very fancy cosmic trick, we know that dark matter particles exist, and that cold dark matter dominates

But we only have evidence so far for gravitational interactions between dark matter and baryonic matter

We do not know how many varieties of dark matter there are, or their origins

Dark matter may interact with baryonic matter via the exchange of one or more kinds of dark mediator particles; these could be e.g. Higgs-like or photon-like

Wide range of possible masses for both the dark matter and dark mediator particles

Incomplete list how to receive echoes from dark sectors
It depends on **nature of mediator** and **dark sector structure**

Gravity	• **direct**, e.g. Planck, velocity of galaxies • **indirect**, e.g. grav. waves from first-order phase transition
vector mediator (new gauge group)	• **direct**, e.g. hidden valley phenomenology, comp. dark matter, ... • **indirect**, e.g. running of gauge coupling
scalar mediator	• **direct**, e.g. hidden valley phenomenology, ... • **indirect**, e.g. running of mixing angles,...

See talks by D. Curtin, S. Iwamoto, A. Katz, M. McCullough, J. Zurita

Dark matter and accelerators

Both Intensity Frontier and Energy Frontier accelerators could produce dark matter particles or dark mediator particles

Intensity Frontier dark matter searches include repurposing neutrino experiments, or beam dump based experiments, or precision measurements (e.g. the muon g-2 anomaly could be caused by the dark sector)

Energy Frontier dark matter searches include missing energy searches and direct searches for dark mediators; in both cases lepton accelerators offer obvious advantages

Fermilab

Direct dark sector spectroscopy at e+e- colliders

- Can we access the quantum numbers of the mediator and dark sector particle, e.g. spin or masses?

[Dreiner, Huck, Kraemer, Schmeier, Tattersall '12]
[Andersen, Rauch, MS '13]
[Chacko, Cui, Hong '13]

- Let us pick a benchmark simplified model

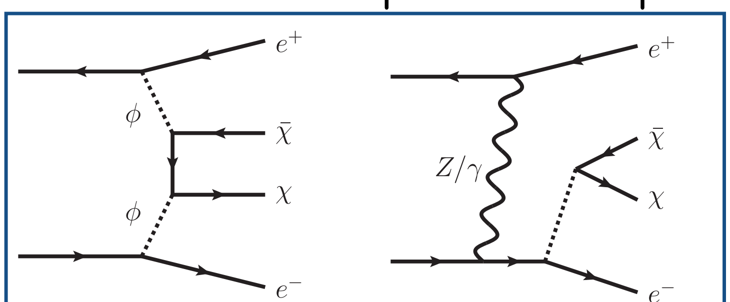
assume mediator couples between electron and dark sector particle

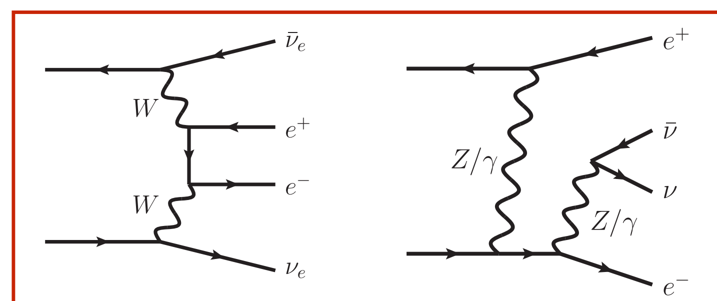
	scalar	vector
e	$i\, g_{ee\phi,S}\ \bar{e}e\ \phi_S$	$i\, g_{ee\phi,V}\ \bar{e}\gamma_\mu e\ \phi_V^\mu$
χ	$i\, g_{\chi\chi\phi,S}\ \bar{\chi}\chi\ \phi_S$	$i\, g_{\chi\chi\phi,V}\ \bar{\chi}\gamma_\mu\chi\ \phi_V^\mu$

$$M_* = \frac{M_\phi}{\sqrt{g_{ee\phi}g_{\chi\chi\phi}}}$$

model	mediator mass	mediator spin	WIMP mass	M_*
LSL	8 GeV	0 (scalar)	5 GeV	30 GeV
LVL	8 GeV	1 (vector)	5 GeV	30 GeV
LSH	8 GeV	0 (scalar)	120 GeV	27.4 GeV
LVH	8 GeV	1 (vector)	120 GeV	21 GeV
HSL	200 GeV	0 (scalar)	5 GeV	1250 GeV
HVL	200 GeV	1 (vector)	5 GeV	1250 GeV
HSH	200 GeV	0 (scalar)	120 GeV	332.4 GeV
HVH	200 GeV	1 (vector)	120 GeV	511.8 GeV

- In VBF-like final state possible to exploit kinematic distributions



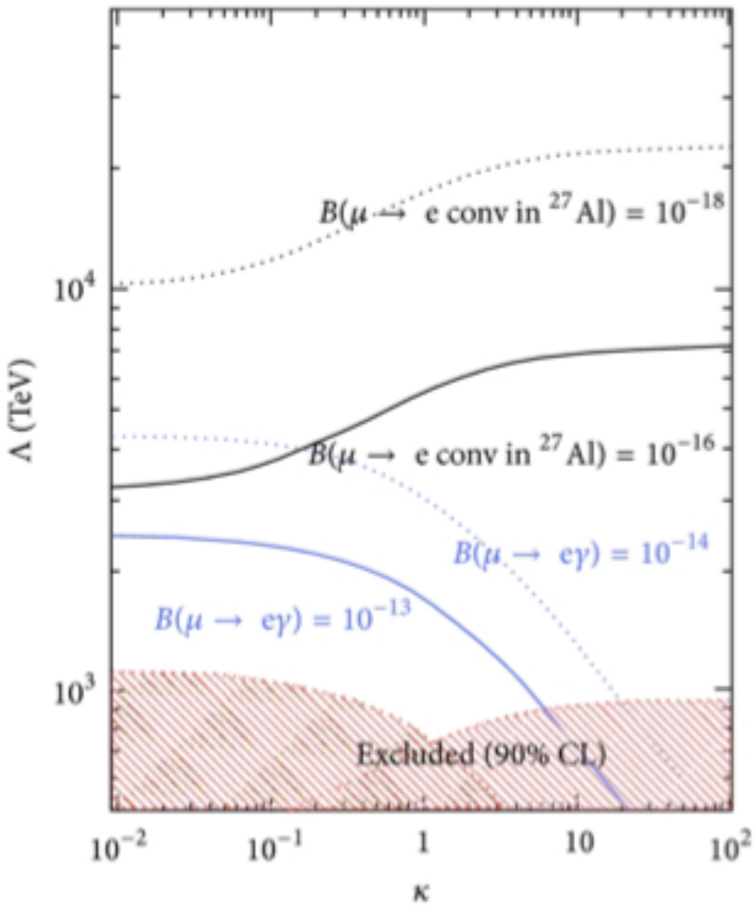


FCC Physics Workshop CERN 5 Michael Spannowsky 20.01.2016

The power of intensity

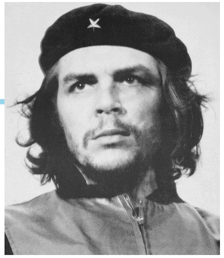
The Mu2e experiment is a perfect example of how beam intensity can be translated into unprecedented reach for new physics through a rare process or precision measurement

Surely we can do more of this!



Fermilab

The BSM revolution: when? where? how?



"The revolution is not an apple that falls when it is ripe. You have to make it fall" -- Ernesto Guevara de la Serna

- It is not enough just to discover new physics - this we already have (dark matter, dark energy, inflation, baryogenesis, and neutrino masses)
- It is also not sufficient to build BSM frameworks – we already have these too
- We seem to be missing some key clues that will propel us into new ways of thinking and new connections
- We need to keep shaking the tree
- We probably need new technologies to do the shaking!

Thank You