First ECFA WORKSHOP.

Highlights & Plans
WG1-SRCH

Roberto Franceschini (Rome III), Rebeca Gonzalez (Uppsala),
Aleksander Filip Zarnecki (Warsaw)

ecfa-whf-wg1-srch-conveners@cern.ch

WG1-SRCH
Feebly interacting particles, direct low mass searches

Outline:

- Introduction
- Highlights of the workshop
- Goals and plans

Recent Snowmass EF BSM report: arXiv:2209.13128

Introduction

Physics Beyond the Standard Model (BSM) of particle physics is unavoidable.

We need fundamental level description for phenomena like:

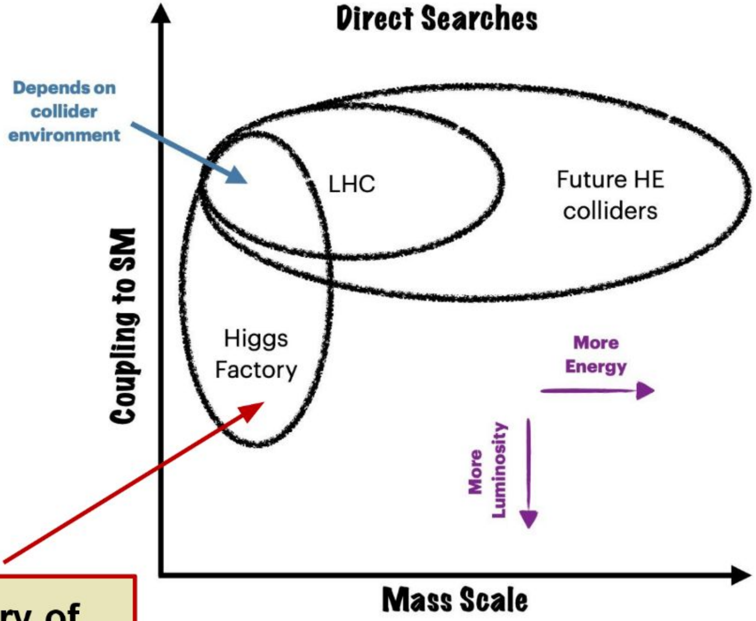
- Dark matter and its abundance in the Universe
- Matter-antimatter asymmetry and the source of the required CP violation
- Neutrino masses
- Flavour structure of the Standard Model
- Description of gravity on the particle/quantum level
- Explanation of observed anomalies in precision measurements
    - Muon g-2
    - Measurements of (semi)leptonic B decays
    - W-boson mass

Energy Frontier Machines: energy and precision

New physics can be at low and at high mass scales: Naturalness would prefer mass scale close to the EW scale, but direct searches of specific models have placed stronger bounds around 1-2 TeV.

Depending on the mass scale of new physics and the type of collider, the primary method for discovery new physics can vary.

We need to use both energy and precision to push beyond the 1 TeV scale



Focus of this talk: some highlights and a summary of the vision emerged from Snowmass EF studies

Introduction

Negative results of direct BSM searches at the LHC suggest that we need to change the perspective. BSM scales does not need to be large.

- new particle interactions can be very week, the signal could be below our experimental sensitivity,
- long-lived or feebly-interacting particles can give exotic signatures, beyond traditional BSM searches

⇒ We need to be sure that our searches are not biased by particular model assumptions

⇒ We should try to be as model-independent as possible.

Introduction

Two approaches to BSM searches possible:

- Exploring well **established theoretical models**, looking at model predictions for various **benchmark** scenarios. Different signatures possible.
- Looking rather at **particular signatures**

Significant overlap possible between WG1-SRCH and WG1-HTE, WG1-GLOB. Also for BSM scenarios with directly accessible new states, significant deviations in precision measurements, Higgs couplings in particular, usually expected.

Introduction

Types of contributions submitted to the WG1-SRCH session

- Suggesting theory/model, which should be considered at future e^+e^-
- Studies based on particular theoretical scenarios
- Studies looking at particular experimental signatures
- *Physics beyond colliders - beam dump experiments*

Total of 15 talks: 10 presentations in two WG1-SRCH parallel sessions,

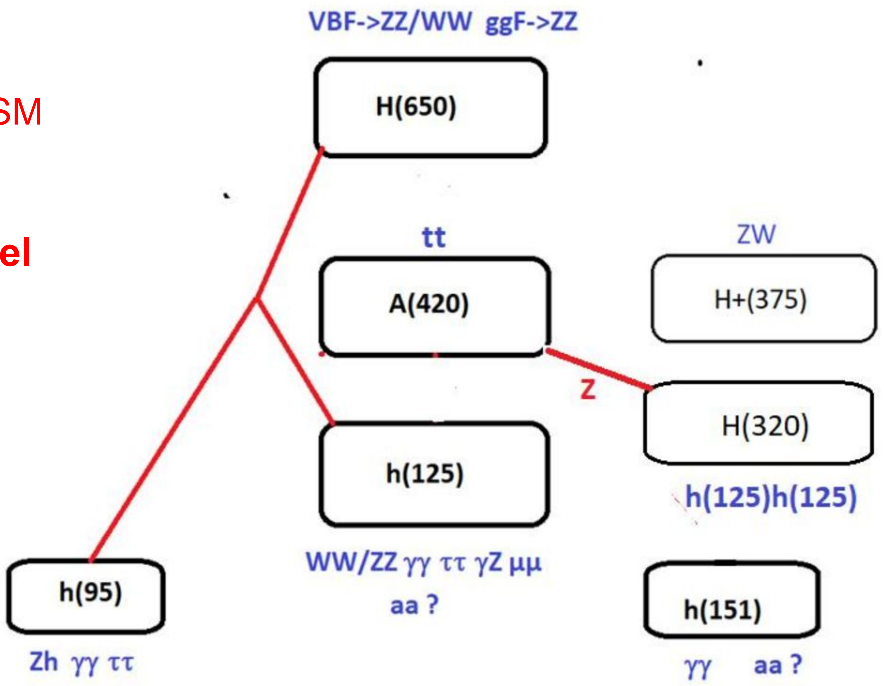
5 presentations in the joint WH1-HTE+SRCH session

Francois Richard
Searches for light scalars at LHC
and interpretation of the findings

SUMMARY ON BSM CANDIDATES

VBF→H(650)→WW is inconsistent with MSSM

various indications from LHC can be described in the **Georgi Machacek model**



Highlights

Case study: Search for $pp \to \phi \to \gamma\gamma$: excess at $m_\phi \sim 95$ GeV

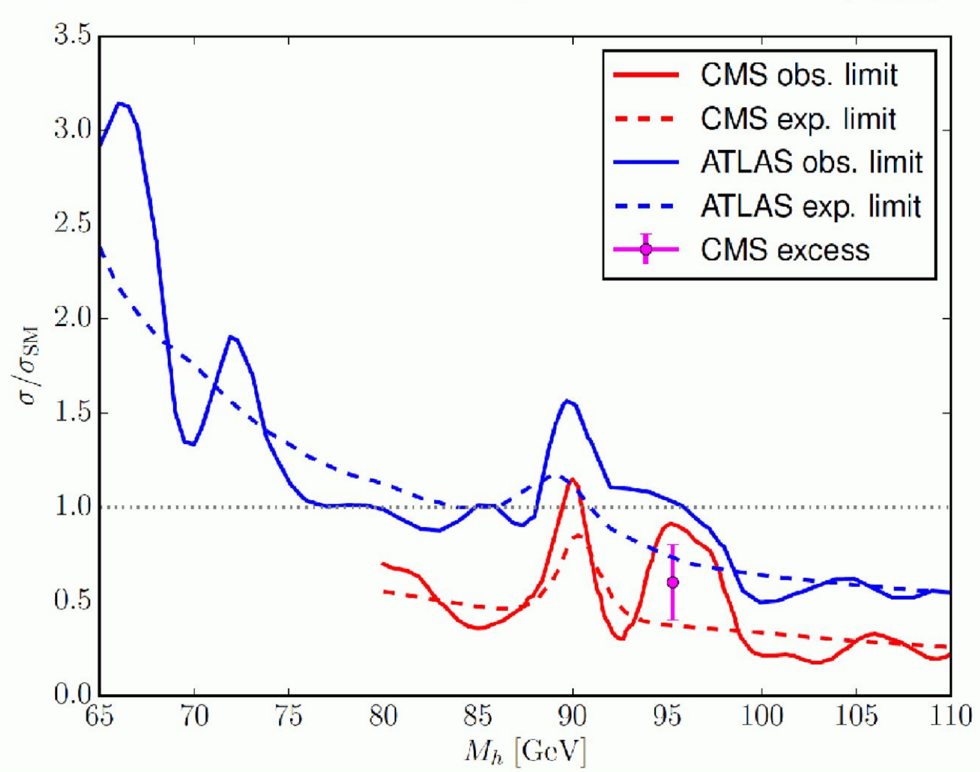
[CMS '17, ATLAS '18, S.H., T. Stefaniak '18]

$\mu_{\rm CMS} = 0.6 \pm 0.2$

Possible scenario:

Next-Two Higgs Doublet Model (N2HDM)

Opening also many other observation possibilities at e^+e^- Higgs Factory

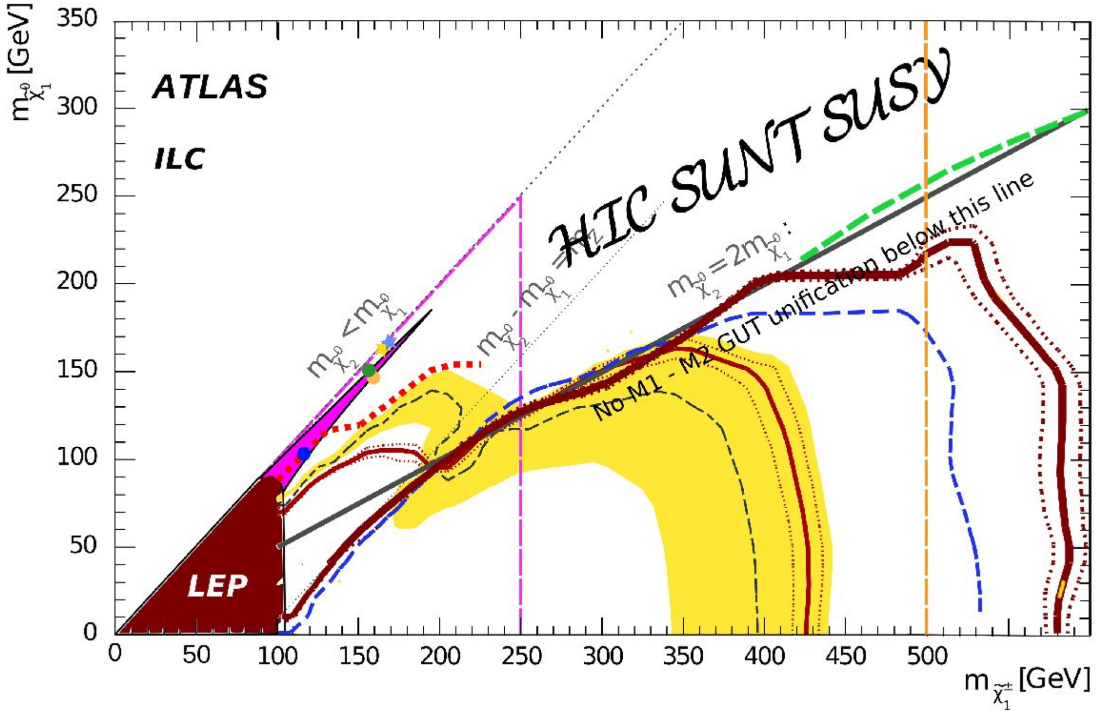


⇒ if there is something, it would look exactly like this!

Summary: SUSY - All-in-one

Highlights

Many regions in the SUSY parameter space remain and will remain unexplored by LHC…



ATLAS Eur Phys J C 78,995 (2018), Phys Rev D 101,052002 (2020), arXix:2106.01676;

ATLAS HL-LHC ATL-PHYS-PUB-2018-048; ILC arXiv:2002.01239; LEP LEP LEPSUSYWG/02-04.1

Highlights

Constraints from Dark Matter observables

Two Higgs Doublet Model with a Complex Scalar Singlet

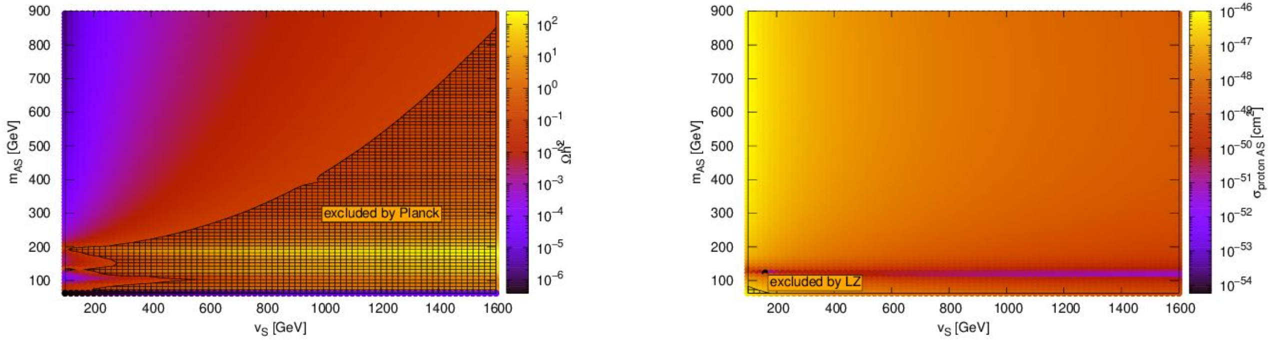


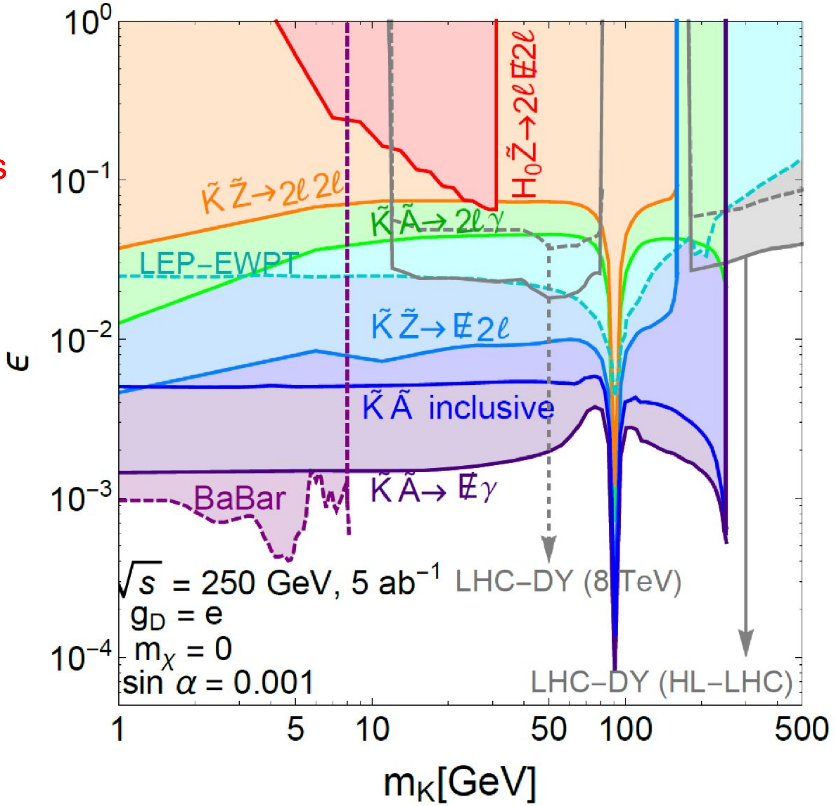
Figure: Variation of the DM mass and v_s against relic density and direct detection cross-section.

Dark photon sensitivity

Highlights

Double Dark Portal model
simultaneous vector and scalar portals

Rich e^+e^- collider phenomenology with new light hidden particles…

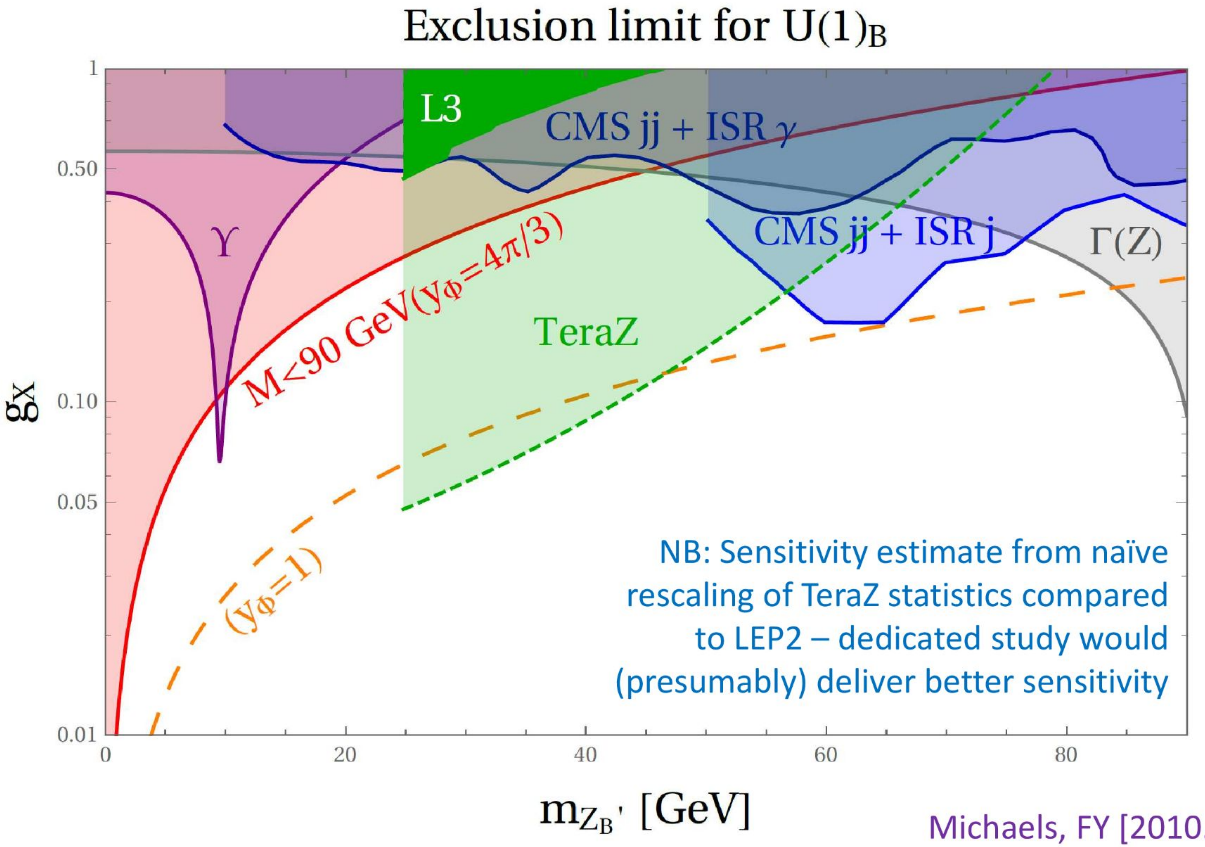


Future prospects with TeraZ collider

Highlights

Light Z' still not excluded, if new gauge coupling small

⇒ look for exotic Z decays at Tera-Z



Michaels, FY [2010.00021]

Motivation

In the 2HDM, triple Higgs couplings $\lambda_{h_i h_j h_k}$ can be large while respecting all the relevant theoretical and experimental constraints

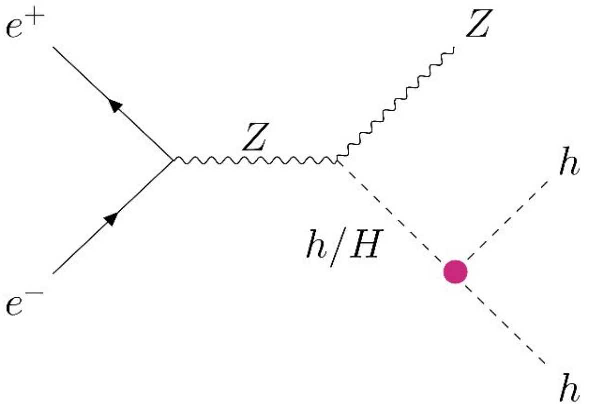
(Eur.Phys.J.C 80 (2020) 9, 884 [arXiv:2005.10576] and Eur.Phys.J.C 82 (2022) 6, 536 [arXiv:2203.12684])

↓

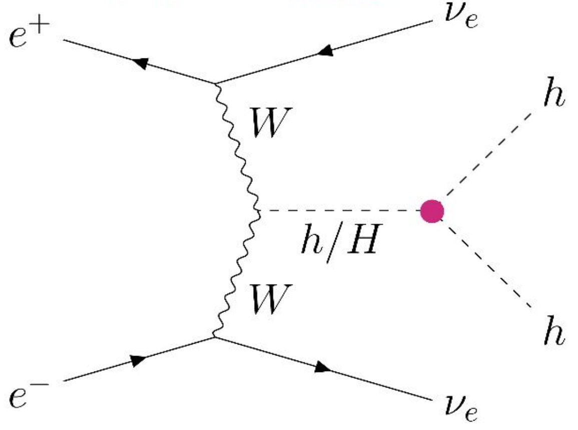
Di-Higgs production could access to $\lambda_{h_i h_j h_k}$ at tree level

Two channels of interest: $e^+e^- \to hhZ$ and $e^+e^- \to hh\nu\bar{\nu}$

hH, HH and AA production was also studied at *(Eur.Phys.J.C 81 (2021) 10, 913 [arxiv:2106.11105])*



More important at low energies (ILC)



More important at large energies (CLIC)

Higgs Physics

Chris Verhaaren, Higgs Naturalness at a HTE factory

Supersymmetric partners do not need to carry SM charges

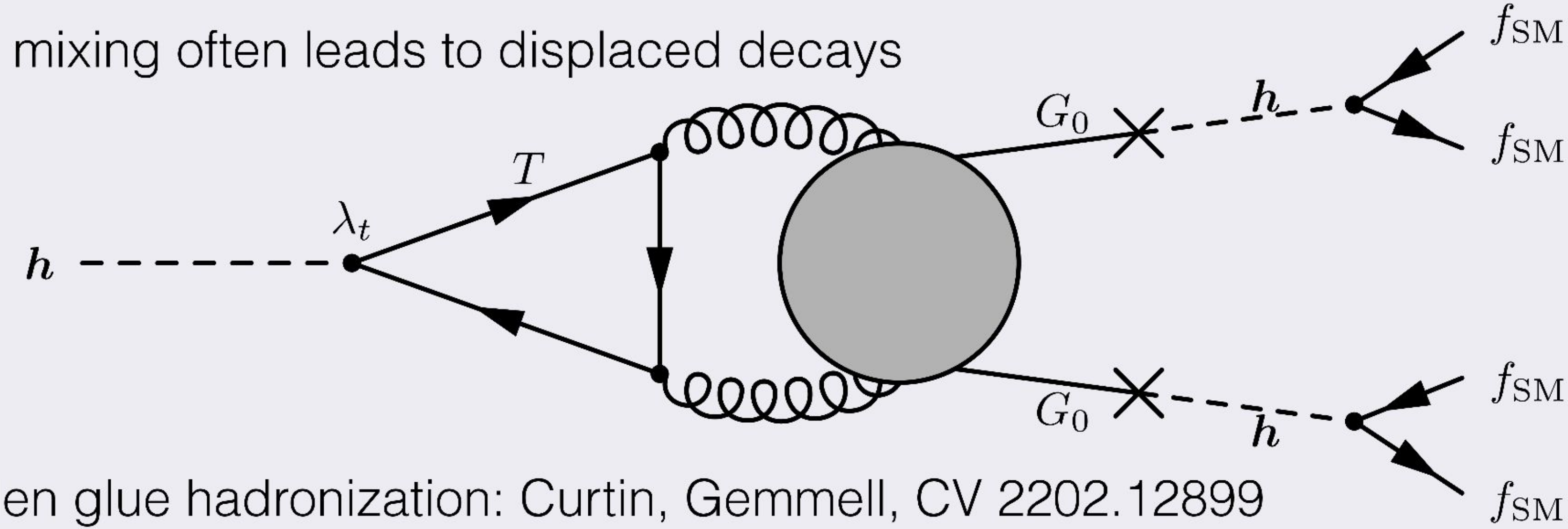
Exotic Higgs Decays

BSM states that are stable become part of the Higgs invisible width

Lightest hidden glueball mixes with the Higgs

$$h \to G_0 G_0 \to \bar{f} f \bar{f} f$$ (Mostly to b-quarks)

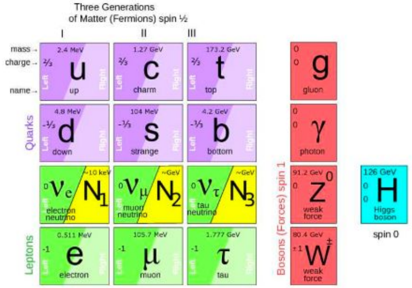
Small mixing often leads to displaced decays



Hidden glue hadronization: Curtin, Gemmell, CV 2202.12899

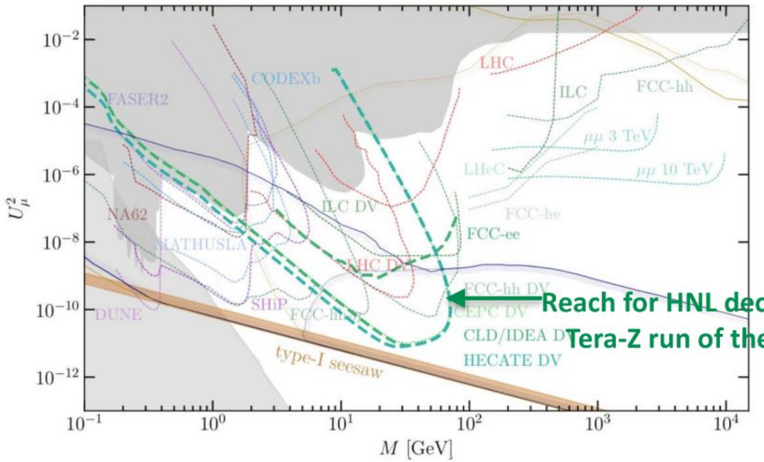
1st Physics Case: LL Heavy Neutral Leptons

- Right-handed, sterile neutrinos
- Dirac or Majorana fermions
- Lifetimes that don't disrupt the simplest BBN bounds and/or unstable on cosmological timescales
- Could shed light some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter
- FCC will probe space not constrained by astrophysics or cosmology, complementary to other accelerator and neutrino prospects
- HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! arXiv:2106.16226
- See Saw type I is simplest way we can probe HNLs at the FCC, but not only one



long-lived HNLs when coupling and mass are small

arXiv:2203.05502



Juliette Alimena, Long-Lived Particles at the FCC-ee

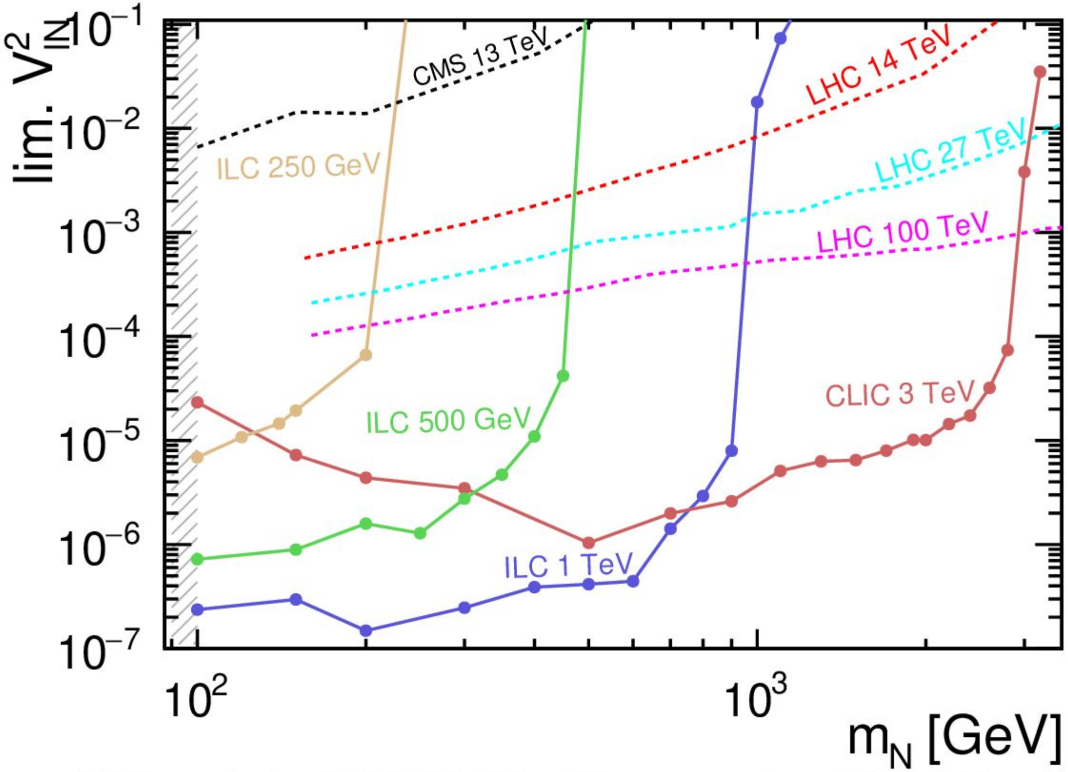
Final results

Highlights

The cross section limits can be translated into limits on the V_{lN}^2 parameter.

Heavy Neutral Leptons

Above M_Z prompt decays seem to be more promising

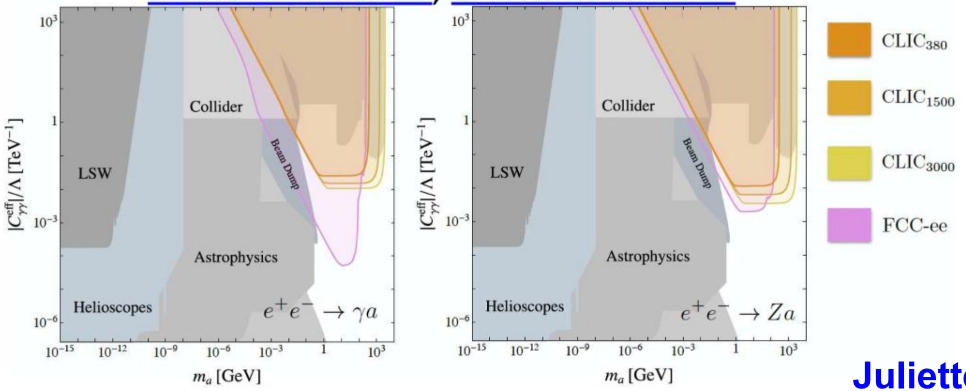


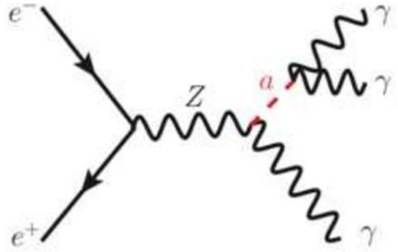
LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

2nd Physics Case: LL Axion-Like Particles

- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
  - Orders of magnitude of parameter space accessible
  - Especially sensitive to final states with at least 1 photon
- **Privately generated ALPs in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card,** $\sqrt{s} = 91\ \text{GeV}$ **(arXiv:1808.10323)**

arXiv:1808.10323, arXiv:2108.08949

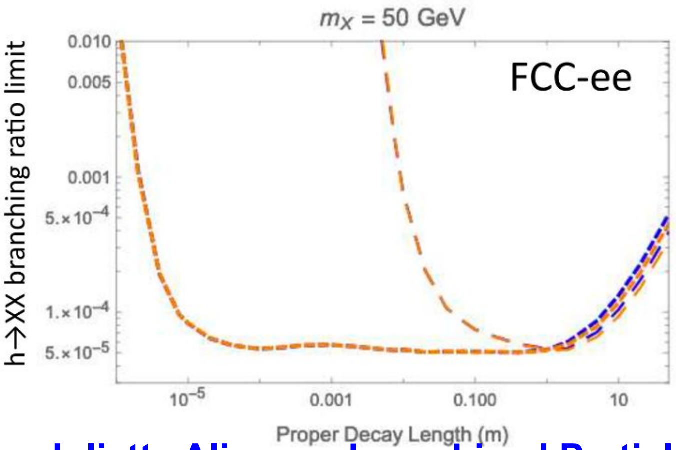




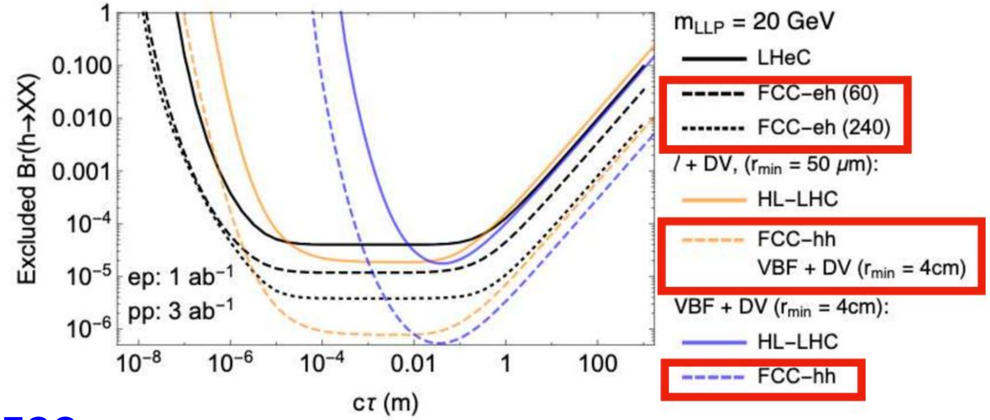
3rd Benchmark: Exotic Higgs decays to LLPs

- Higgs bosons could undergo exotic decays to e.g. scalars that could be long-lived
- Exotic Higgs decays to LLPs could be explored at future colliders
  - Twin Higgs models with displaced exotic Higgs boson decays, Hidden Valley models with Higgs bosons decaying to neutral LLPs (arXiv:1812.05588)
  - LLPs from Higgsinos or exotic Higgs decays (arXiv:1712.07135)
- **New personpower starting** with generating this model in Madgraph, then will incorporate into FCC framework

arXiv:1812.05588



arXiv:1712.07135

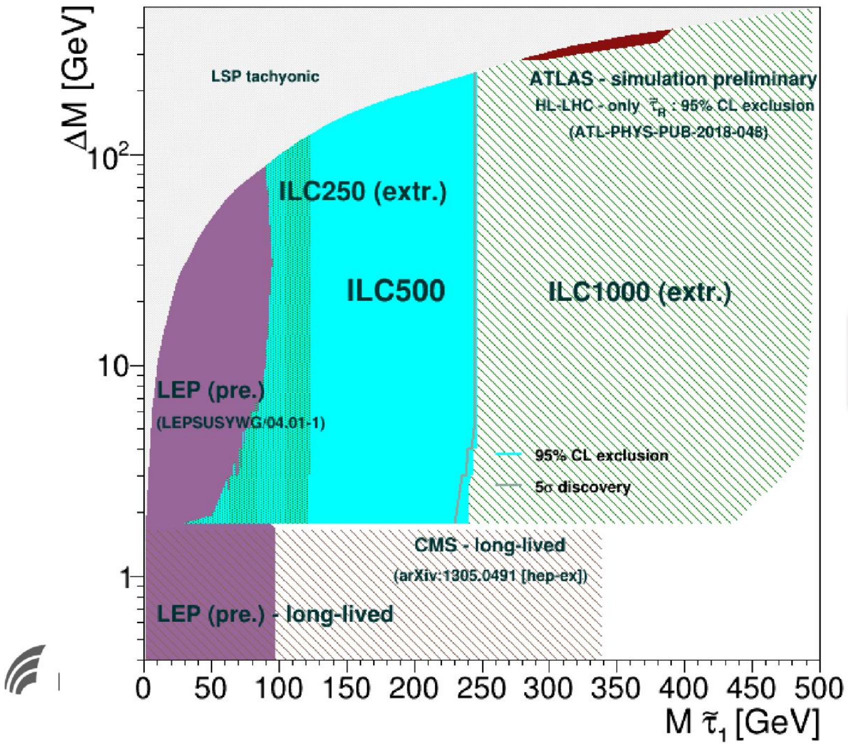


Highlights

ILC expected limits

Maria Teresa Nunez Pardo De Vera

Stau searches and measurement prospects at future Higgs factories



At ILC discovery and exclusion are almost the same

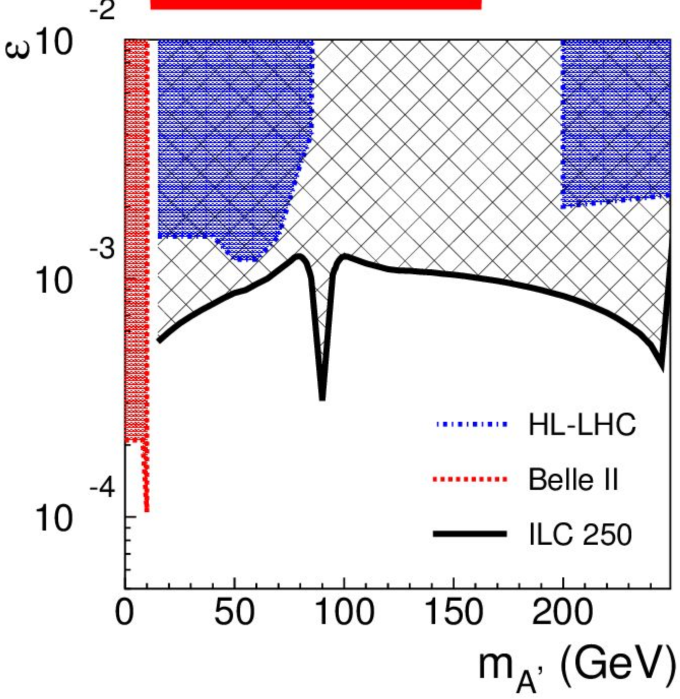
arXiv:2105.08616

A minimal model of the dark sector

- Dark photon ,A'_D, is a hypothetical gauge boson in the dark sector
  - The A'_D is produced as a resonance if an ISR photon removes just the right amount of energy from the e^+e^- system:

    $$E_{ISR} = (E^2_{CMS} - M^2_{A'_D})/2E_{CMS}$$
- In this study, we therefore look for
  - $e^+e^- \to A'_D + \gamma_{\text{ISR}} \to f\bar{f} + \gamma_{\text{ISR}}$
    - γ_{ISR} is always at the low angles
    - The $\mu\bar{\mu}$ final state is the best measured one, so we concentrate on that channel

arXiv:2111.09928

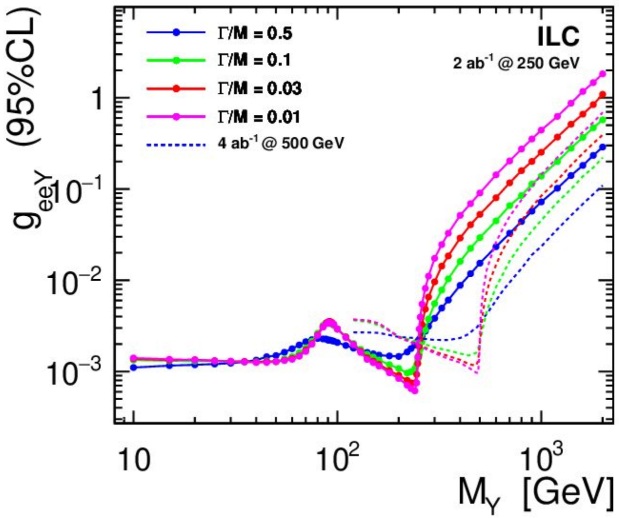


Highlights

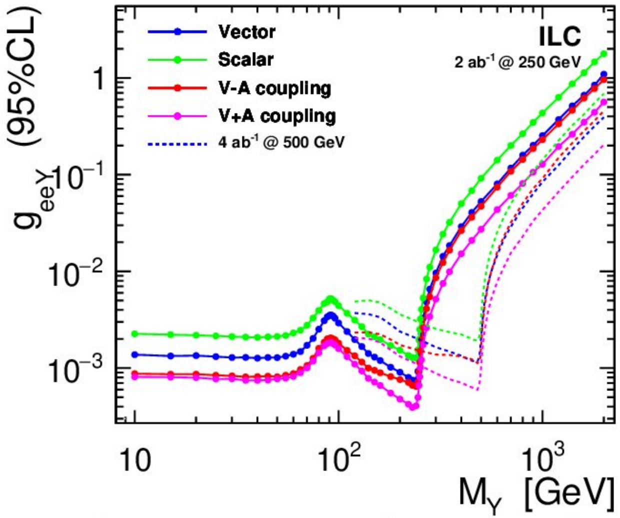
Coupling limits for mediator coupling to SM fermions
$\mathcal{O}(1)$ mediator coupling to DM, fixed by mediator width

Combined limits for ILC @ 250 GeV (compared to ILC @ 500 GeV)

Vector mediator



Mediators with $\Gamma/M = 0.03$



Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit

Possible signatures at e^+e^- colliders – X pair production

Assuming generic **long-lived particle X** and one **DM candidate***, the signatures can be categorised based on the possible production and decay channels:

production \ decay	X → SM SM	X → SM SM DM	X → SM DM	X → DM DM
$e^- e^+$ → X X	• 2 displaced vertices ◆	• 2 displaced vertices • $\not{E}$ ◇	• 2 displaced tracks/jets/γ • $\not{E}$ ◇	Invisible ◆
$e^- e^+$ → X X DM	• 2 displaced vertices • $\not{E}$	• 2 displaced vertices • $\not{E}$	• 2 displaced tracks/jets/γ • $\not{E}$	Invisible
$e^- e^+$ → X X Z/h/γ	• 2 displaced vertices • Z/h/γ ◆	• 2 displaced vertices • Z/h/γ • $\not{E}$ ◇	• 2 displaced tracks/jets/γ • Z/h/γ • $\not{E}$ ◇	• Z/h/γ • $\not{E}$ ◆

(red box) - predicted by models mentioned on the slides 5-9

If Z_2 is imposed:

◇ - X odd under Z_2

◆ - X even under Z_2

* branches with neutrinos also marked as DM

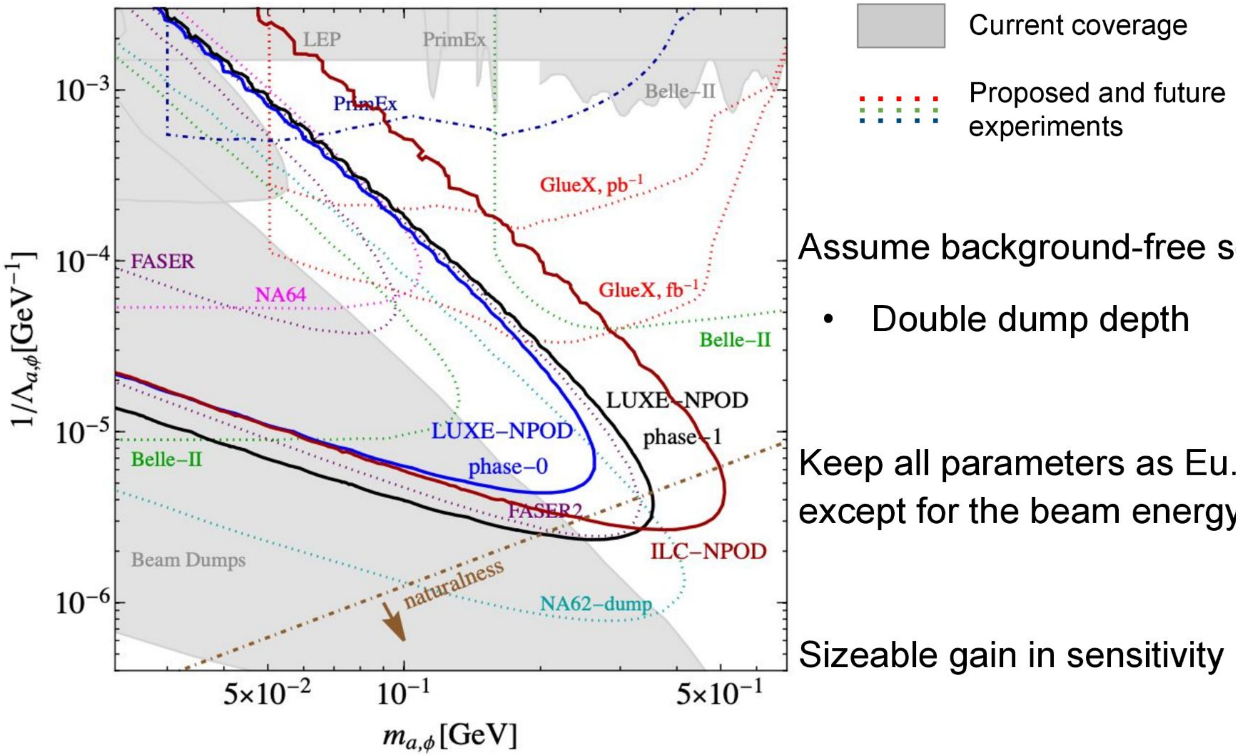
- The cells in the table can be referred back to signatures in particular models
- Mixed channel $(XX \to 2SM + 2DM)$ also possible

Expected sensitivity gain from energy

Highlights

LUXE concept
at ILC beam dump

Yotam Soreq's
talk at ILCX2021



Assume background-free scenario

- Double dump depth

Keep all parameters as Eu.XFEL, except for the beam energy

Sizeable gain in sensitivity

Impressions from the session

While LHC limits are often in the TeV range, many “holes” in the parameter space remain unexplored for different scenarios, including SUSY.

Many interesting, motivated scenarios with low scale BSM possible, both standard and exotic signatures can be looked for.

Dedicated studies show high sensitivity of future e^+e^- machines to different theoretical scenarios and signatures, often going orders of magnitude below current and expected limits from LHC.

Goals and plans

Our initial goal was to get the overview of the activities and construct a map of activities, linking different theoretical models/approaches with experimental methods/signatures.

We do think we are about to complete this task.

> More input is clearly very welcome, but we believe that we all relevant studies are already on our list…

Goals and plans

The next step is to propose benchmarks for the future studies and comparisons.

Two types of test scenarios possible:

- Theory motivated benchmarks
  allow for referring to indirect searches and precision measurements
- Signature oriented benchmarks
  more directly related to detector and reconstruction challenges/requirements

We do have some initial ideas, but some more discussions are still needed…

Goals and plans

We need to make sure that all relevant signatures are addressed properly:

- do detector designs take into account possible non-standard signatures?
- are reconstruction and analysis tools flexible enough to identify also "unexpected" signals?
- what additional/new detector features could be used to enhance search sensitivity
  eg. higher timing resolution, better dE/dx ?

We should be open for non-standard search approaches to maximize physics output and search coverage → new ideas are always welcome

Additional experiments (beyond collider mode):
physics reach gain has to be well understood

Goals and plans

There are still a lot of challenges working for us in the next months.

Everyone is invited and very welcome to make a contribution.

Indico: https://indico.cern.ch/category/14866/

e-group: ecfa-whf-wg1-srch@cern.ch

Many thanks to all speakers for their contributions
and many interesting discussions

Thank you!

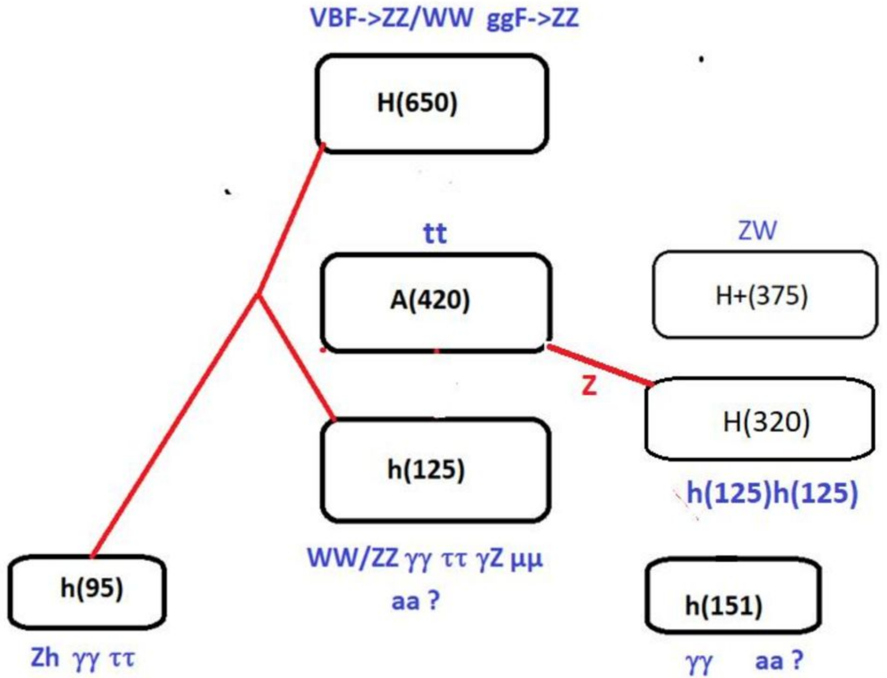
Backup slides

More on highlights

Highlights (1)

Theory aspects / model presentations

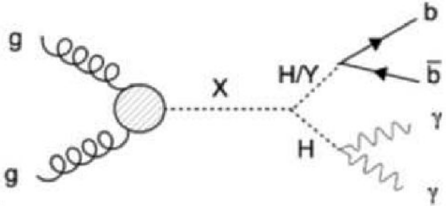
SUMMARY ON BSM CANDIDATES

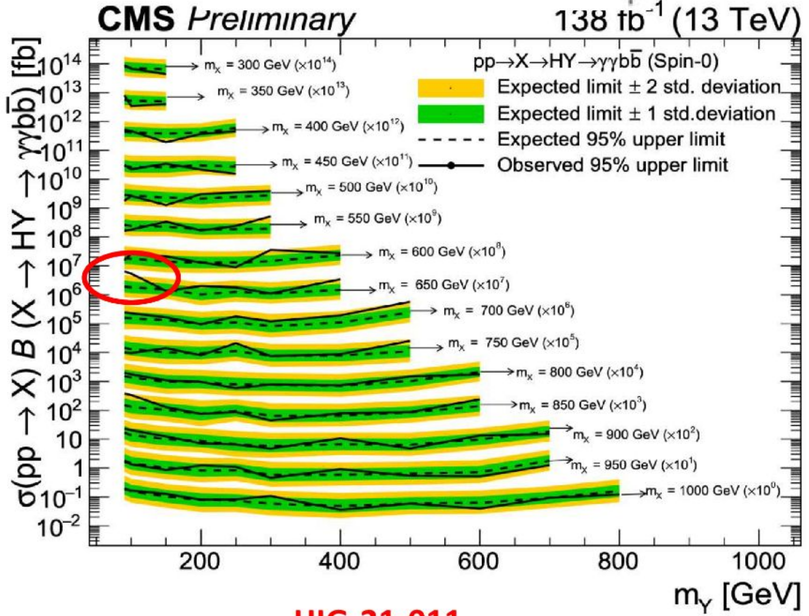


Francois Richard
Searches for light scalars at LHC and interpretation of the findings

Evidence for gg+VBF->H(650)->Y(90)+h(125)->bb+γγ

- 3.8 s.d. at mH=650 GeV and mY=90 GeV at ICHEP22
- Mass resolution on Y does not allow to distinguish between Z and h(95) [2203.13180](2203.13180)
- CP says that bb cannot come from Z->bb but could be h(95)
- The cross section is dominant over other processes ~200 fb
- Suggests that H(650) could be an



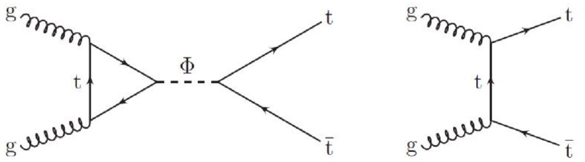


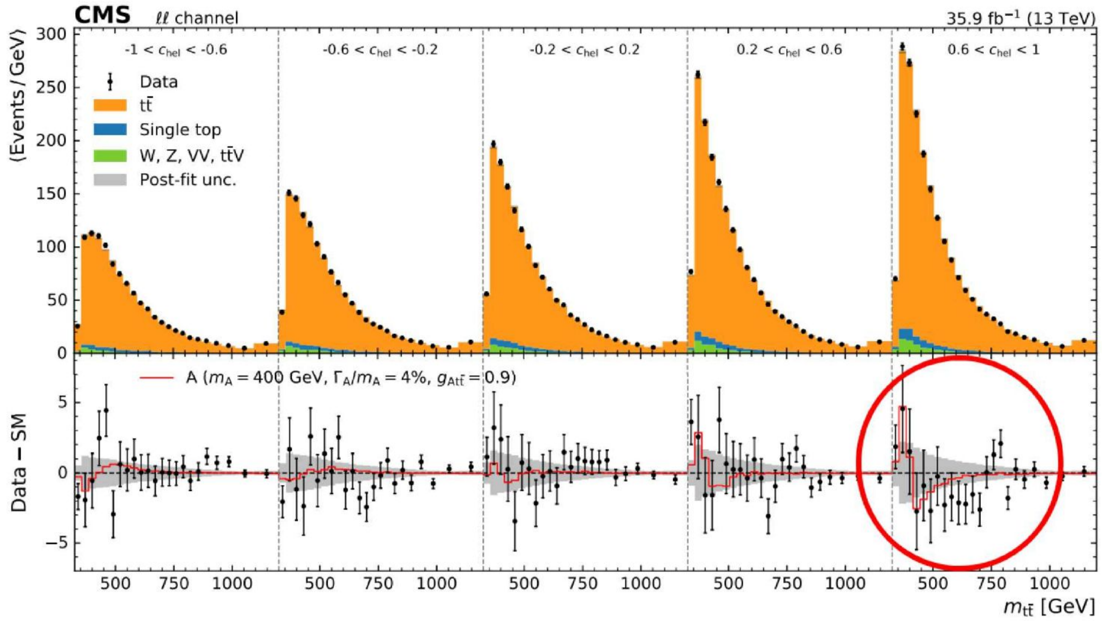
HIG-21-011

Highlights

Possible hint for heavy Higgses at the LHC:

CMS Higgs-boson search in $pp \to \phi \to t\bar{t}$ at $m_\phi \sim 400$ GeV

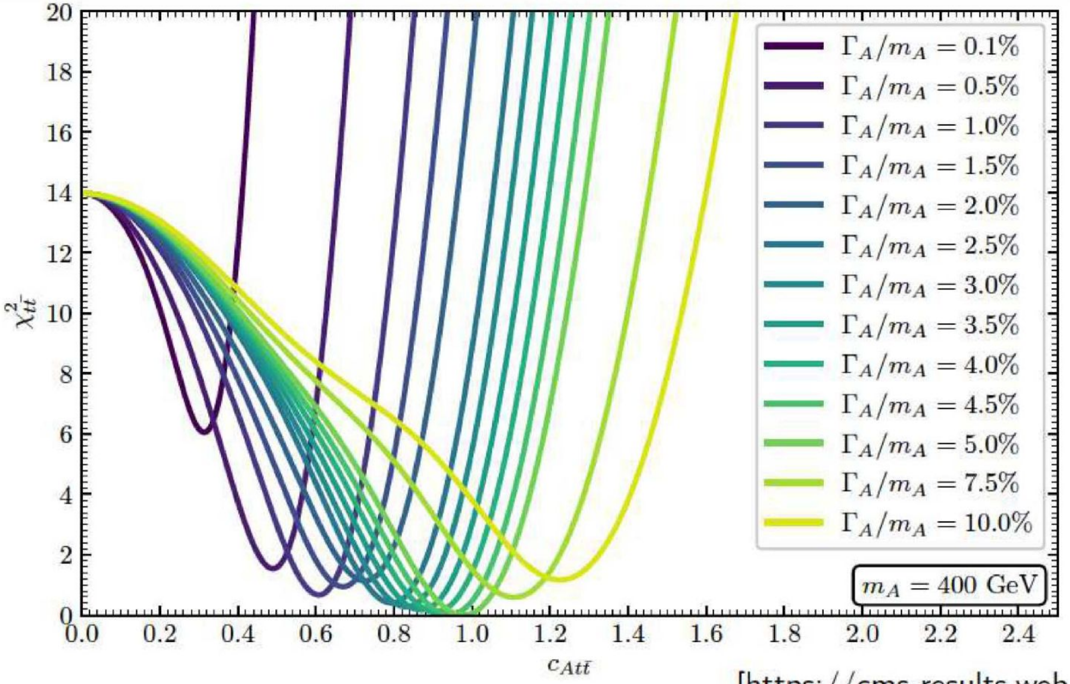




[CMS: 1908.01115]

Highlights

χ^2 distribution from the excess: local: $3.5\,\sigma$, global: $\lesssim 2\,\sigma$



[https://cms-results.web.cern.ch]

$\Rightarrow$ can be explained in the N2HDM/NMSSM for $\tan\beta \sim 1.5$ $\Rightarrow$ in ILC reach

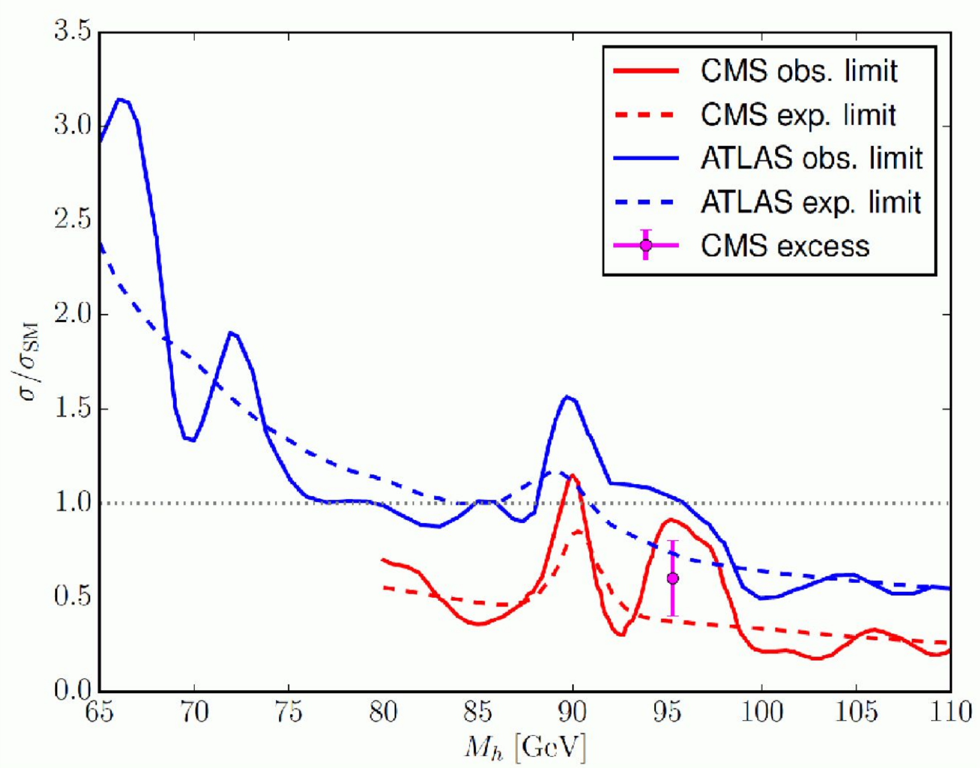
[T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21]

Highlights

Case study: Search for $pp \to \phi \to \gamma\gamma$: excess at $m_\phi \sim 95$ GeV

[*CMS '17, ATLAS '18, S.H., T. Stefaniak '18*]

$\mu_{\rm CMS} = 0.6 \pm 0.2$



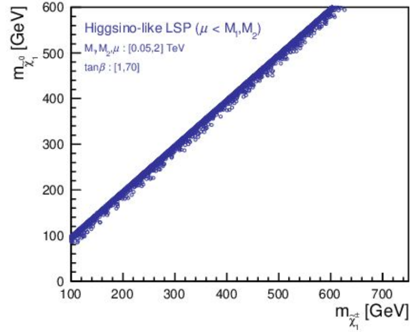
$\Rightarrow$ if there is something, it would look exactly like this!

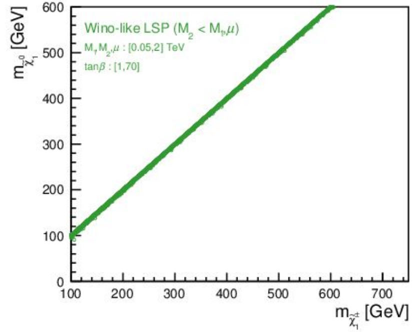
Highlights

SUSY: What *do* we know ?

Naturalness, hierarchy, DM, g-2 all prefers light electro-weak sector.

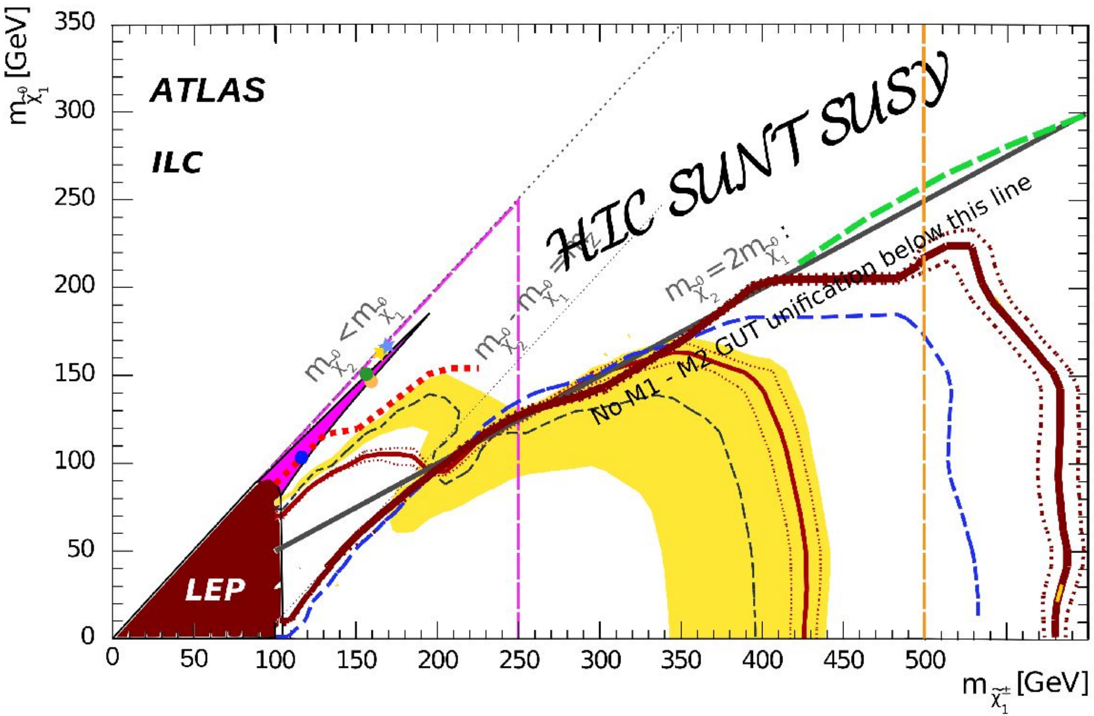
- Except for 3d gen. squarks, the coloured sector - where pp machines excel - doesn't enter the game.
- If the LSP is higgsino or wino, EW sector is "compressed". Only for bino-LSP can the difference be large.
- So, most sparticle-decays are via cascades, with small $\Delta(M)$ at the end.
- For this, current limits from LHC are only for specific models, and LEP2 sets the scene.





Highlights

Summary: SUSY - All-in-one



ATLAS Eur Phys J C 78,995 (2018), Phys Rev D 101,052002 (2020), arXix:2106.01676;

ATLAS HL-LHC ATL-PHYS-PUB-2018-048; ILC arXiv:2002.01239; LEP LEP LEPSUSYWG/02-04.1

Highlights

The Model: 2HDMS

- We consider a softly broken Z_2 symmetric Type II Two Higgs Doublet Model (2HDM) (Branco et.al,hep-ph/1106.0034) and Z_2' symmetric singlet complex scalar potential.

- The quantum numbers of the fields are

Particles	Z_2	Z_2'
Φ_1	+1	+1
Φ_2	-1	+1
S	+1	-1

Table: The quantum numbers of the Higgs doublets Φ_1, Φ_2 and complex singlet S under $Z_2 \times Z_2'$.

Highlights

Constraints from Dark Matter observables

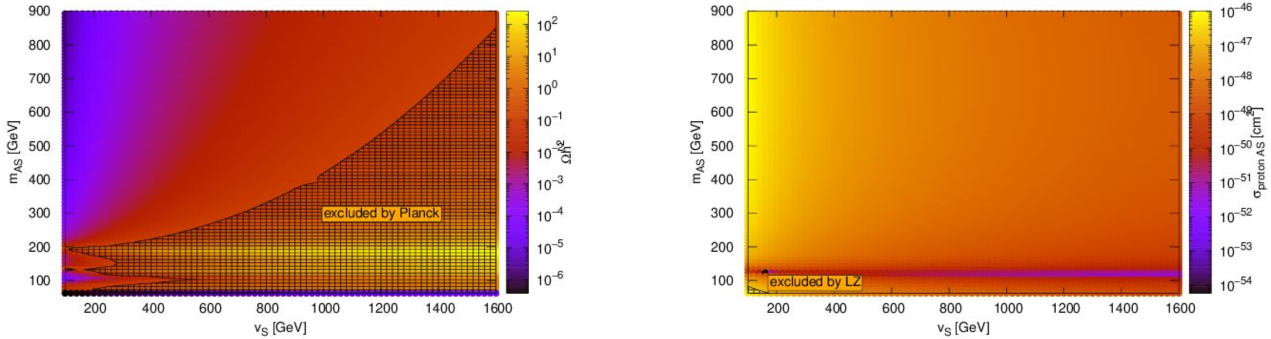


Figure: Variation of the DM mass and v_s against relic density and direct detection cross-section.

Highlights

Introduction – Portals to dark sectors

- Soft principle of quantum theories: anything that is not **forbidden** (by symmetry) is **mandatory**
- Special relevance: portal couplings to dark sectors
  - Given DM is SM gauge singlet, leading coupling to SM would be lowest dimension possibility
    - Scalar Higgs portal $(\mu\phi + \lambda\phi^2)H^\dagger H$
    - Neutrino portal $y_n LHN$
    - Kinetic mixing portal $-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
    - Axion portal (dim. 5) $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$

Consider both simultaneously! Generic for UV fermions to generate both

Highlights

Prospects for dark photon

- Many possible visible and invisible final states

$$e^+e^- \to \tilde{Z}H_0 \text{ Study } \tilde{Z} \to \ell\ell \text{ and semi-visible } H_0 \to (\ell\ell)_Z\chi\chi$$

$$e^+e^- \to \tilde{Z}\tilde{K} \text{ Study } \tilde{Z} \to \ell\ell \text{ and } \tilde{K} \to \bar{\chi}\chi \text{ or } \ell\ell$$

$$e^+e^- \to \gamma\tilde{K} \text{ Study } \tilde{K} \text{ inclusive decays, and exclusive } \tilde{K} \to \bar{\chi}\chi \text{ or } \ell\ell$$

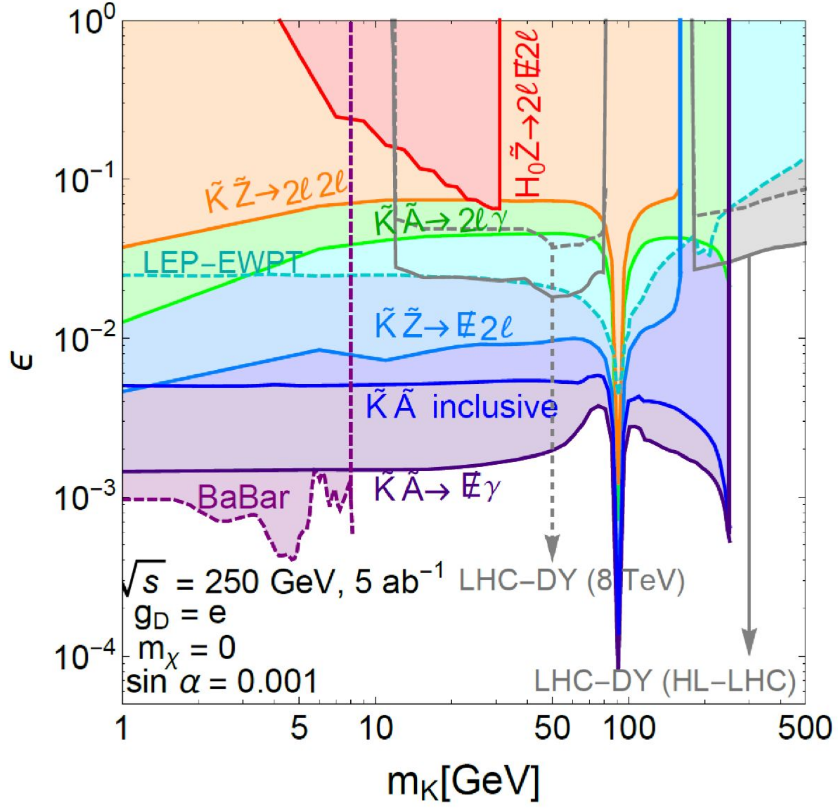
$$e^+e^- \to \tilde{Z}S \text{ Study } \tilde{Z} \to \ell\ell \text{ and } S \to 4\chi$$

  - Event simulation using MG5+Pythia+Delphes
  - SM backgrounds and cuts driven by e^+e^- environment
- Rates for visible states are lower by $(\varepsilon/g_D)^2$, best sensitivity from requiring missing energy threshold
  - LEP direct constraints ($\varepsilon < 0.03$) not competitive

Hook, Izaguirre, Wacker [1006.0973]

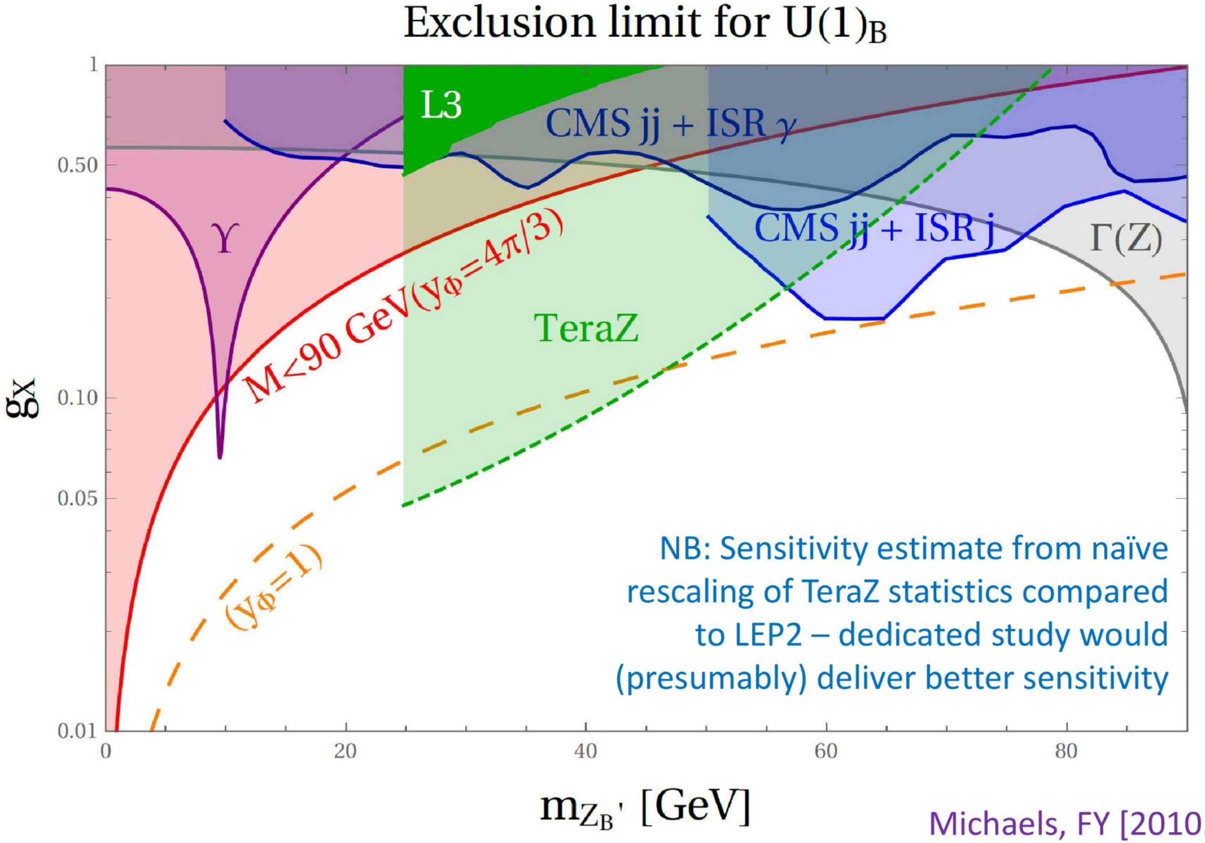
Highlights

Dark photon sensitivity



Highlights

Future prospects with TeraZ collider



Michaels, FY [2010.00021]

Motivation

In the 2HDM, triple Higgs couplings $\lambda_{h_i h_j h_k}$ can be large while respecting all the relevant theoretical and experimental constraints

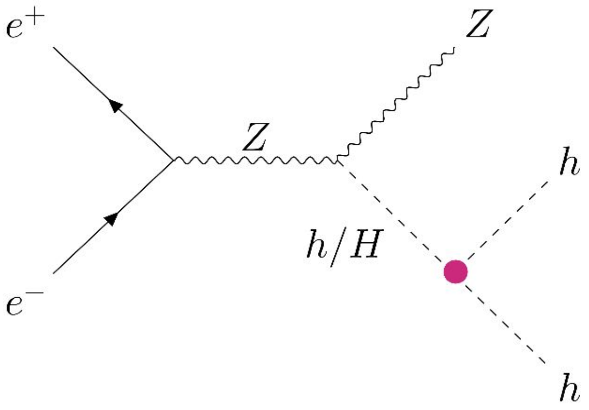
(Eur.Phys.J.C 80 (2020) 9, 884 [arXiv:2005.10576] and Eur.Phys.J.C 82 (2022) 6, 536 [arXiv:2203.12684])

↓

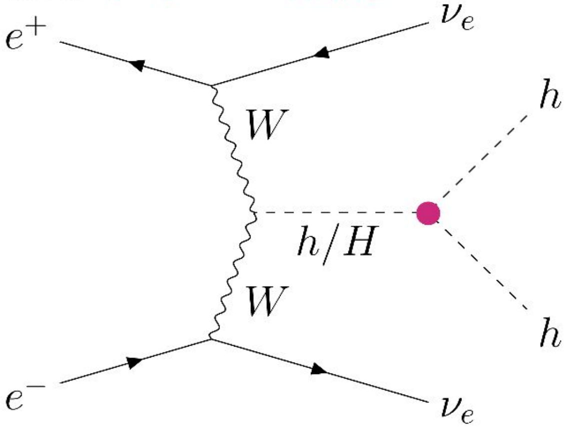
Di-Higgs production could access to $\lambda_{h_i h_j h_k}$ at tree level

Two channels of interest: $e^+e^- \to hhZ$ and $e^+e^- \to hh\nu\bar{\nu}$

hH, HH and AA production was also studied at (Eur.Phys.J.C 81 (2021) 10, 913 [arxiv:2106.11105])



More important at low energies (ILC)



More important at large energies (CLIC)

4-$b$jets events from hh production: λ_{hhH} "sensitivity"

We define our theoretical sensitivity as: $R = \frac{\bar{N}^R - \bar{N}^C}{\sqrt{\bar{N}^C}}$

$\bar{N}^{R/C}$ are the events nearby the H resonance from diagrams with λ_{hhH} and diagrams without THC resp.

Considered reduction factors:

- $h \to b\bar{b}$ decays + 80% of b-jet tagging efficiency
- Detection acceptance with the following cuts:

$$p_T^b > 20\text{ GeV},\ |\eta^b| < 2,\ \Delta R_{bb} > 0.4,\ \begin{cases} p_T^Z > 20\text{ GeV} \\ \not{E}_T > 20\text{ GeV} \end{cases}$$

hhZ	$\sqrt{s}$ [GeV]	$\sigma_{2\text{HDM}}$ / σ_{SM} [fb]	$\bar{N}^R_{4bZ}$ / $\bar{N}^C_{4bZ}$ / $\bar{N}^{\text{SM}}_{4bZ}$	R_{4bZ}
BP1	500	1.063 / 0.158	193 / 10 / 3	58
	1000	0.913 / 0.120	206 / 1 / 4	205
	1500	0.493 / 0.077	22 / < 1 / 1	-
	3000	0.147 / 0.033	1 / < 1 / < 1	-
BP2	1000	0.156 / 0.120	20 / 1 / 1	19
	1500	0.106 / 0.077	4 / < 1 / < 1	-
	3000	0.042 / 0.033	< 1 / < 1 / < 1	-
BP3	1000	0.254 / 0.120	29 / 5 / 2	11
	1500	0.218 / 0.077	8 / 1 / < 1	7
	3000	0.086 / 0.033	1 / < 1 / < 1	-
BP4	1500	0.075 / 0.077	1 / < 1 / < 1	-
	3000	0.038 / 0.033	< 1 / < 1 / < 1	-

$hh\nu\bar{\nu}$	$\sqrt{s}$ [GeV]	$\sigma_{2\text{HDM}}$ / σ_{SM} [fb]	$\bar{N}^R_{4b\not{E}_T}$ / $\bar{N}^C_{4b\not{E}_T}$ / $\bar{N}^{\text{SM}}_{4b\not{E}_T}$	$R_{4b\not{E}_T}$
BP1	500	0.404 / 0.034	119 / 4 / 1	58
	1000	2.391 / 0.097	1510 / 24 / 0	303
	1500	4.423 / 0.239	794 / 13 / 2	217
	3000	9.098 / 0.819	2425 / 46 / 6	351
BP2	1000	0.234 / 0.097	79 / 3 / 1	44
	1500	0.625 / 0.239	70 / 3 / 1	39
	3000	1.850 / 0.819	282 / 28 / 9	48
BP3	1000	0.208 / 0.097	85 / 5 / 3	36
	1500	0.709 / 0.239	111 / 5 / 3	47
	3000	2.422 / 0.819	577 / 30 / 11	100
BP4	1500	0.428 / 0.239	4 / < 1 / < 1	-
	3000	1.523 / 0.819	72 / 4 / 3	34

More sensitivity to λ_{hhH} (i.e. larger R) in $hh\nu\bar{\nu}$, specially at **CLIC 3 TeV** but good prospects for **BP1 at ILC**

more details in [arXiv:2106.11105]

Higgs Physics

Exotic Higgs Decays

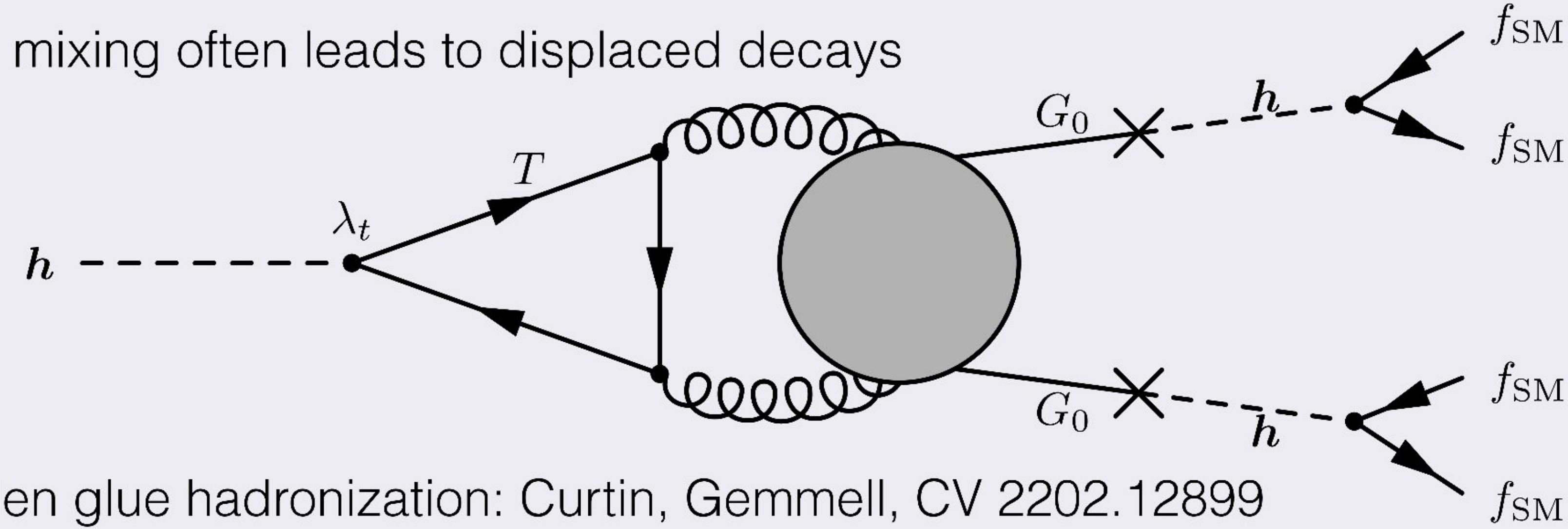
Chris Verhaaren, Higgs Naturalness at a HTE factory

BSM states that are stable become part of the Higgs invisible width

Lightest hidden glueball mixes with the Higgs

$$h \to G_0 G_0 \to \bar{f} f \bar{f} f$$ (Mostly to b-quarks)

Small mixing often leads to displaced decays

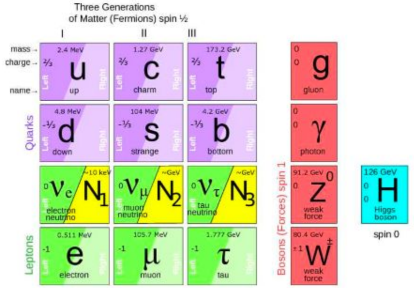


Hidden glue hadronization: Curtin, Gemmell, CV 2202.12899

Highlights (2)

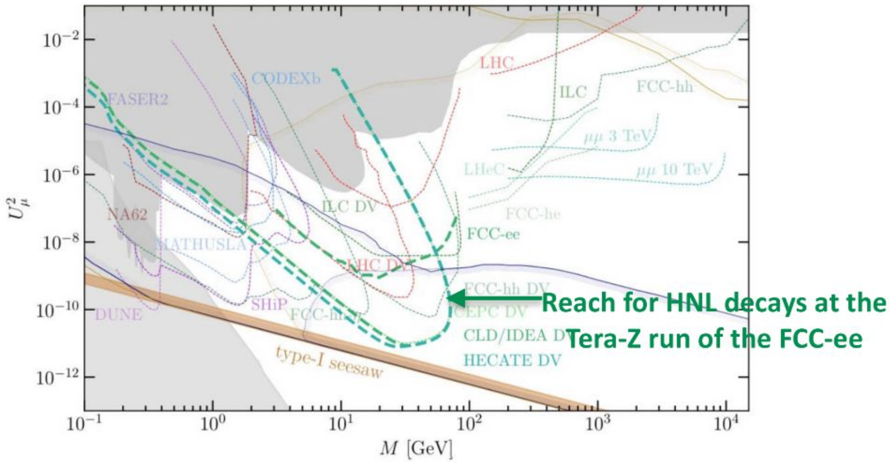
Studies based on particular theoretical scenarios

1st Physics Case: LL Heavy Neutral Leptons



- Right-handed, sterile neutrinos
- Dirac or Majorana fermions
- Lifetimes that don't disrupt the simplest BBN bounds and/or unstable on cosmological timescales
- Could shed light some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter
- FCC will probe space not constrained by astrophysics or cosmology, complementary to other accelerator and neutrino prospects
- HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! arXiv:2106.16226
- See Saw type I is simplest way we can probe HNLs at the FCC, but not only one

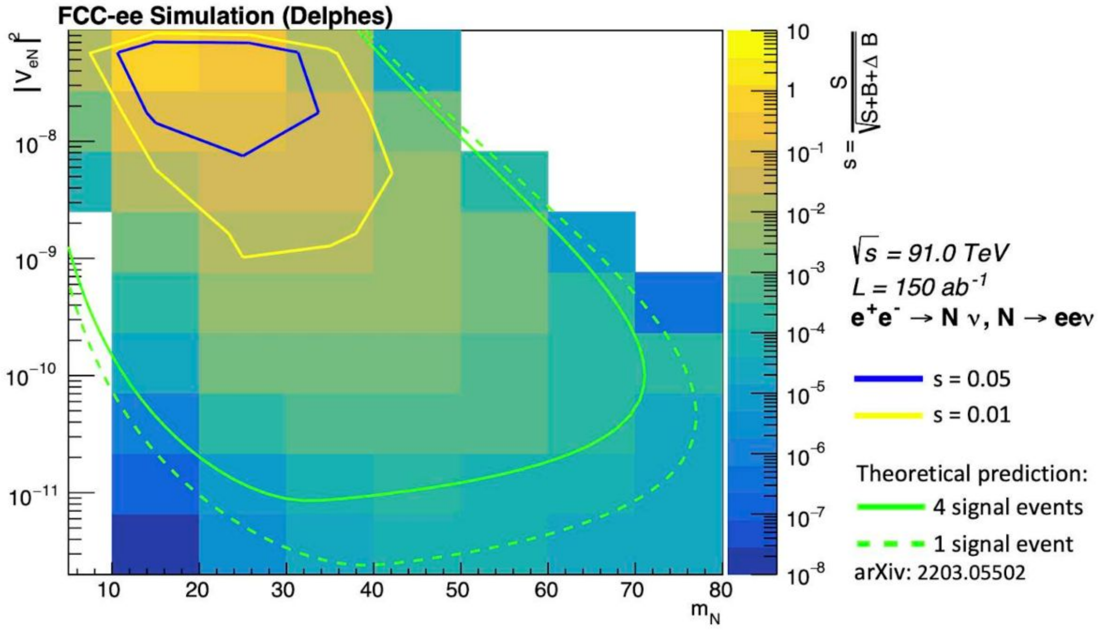
arXiv:2203.05502



Lovisa Rygaard

Sensitivity

New!



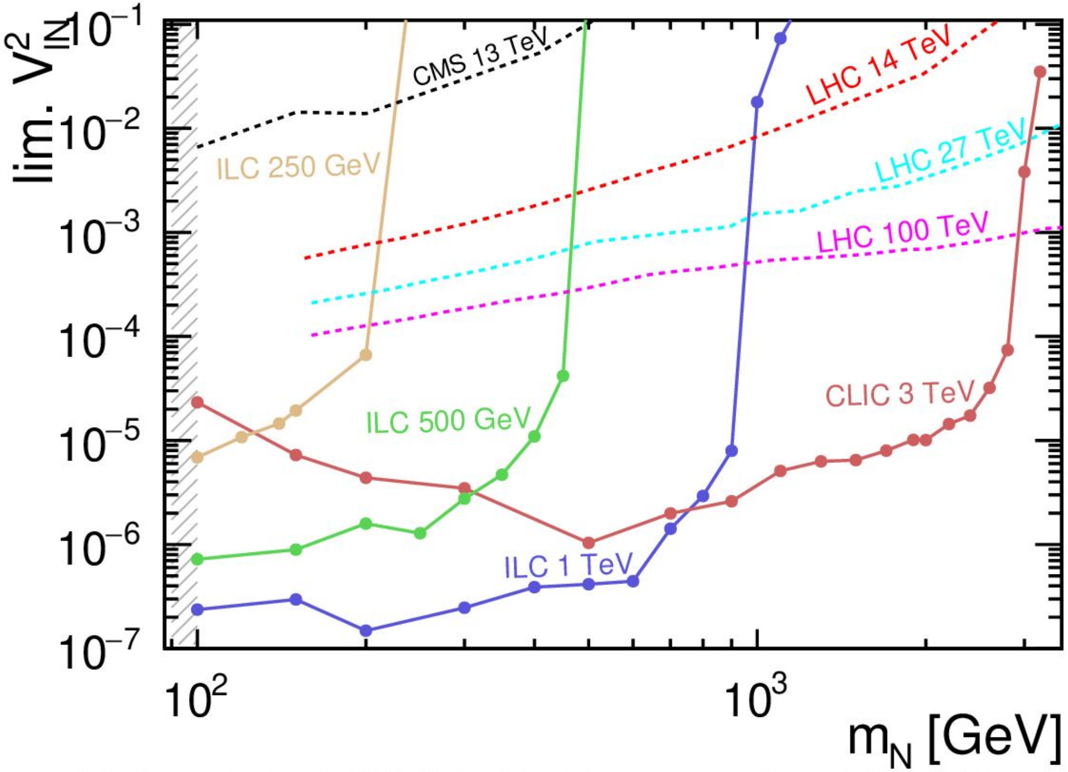
- $s = \frac{S}{\sqrt{S+B+\Delta B}}$
- **Experimental analysis:** $N \rightarrow ee\nu$
  - Contours show where s = 0.01 and 0.05
  - Sensitivity limited by background statistics
- Theory prediction from arXiv:2203.05502
  - For 1 and 4 signal events
  - Includes all HNL decay modes, not only electrons
  - Assumes no background
  - Displaced vertex between 400 μm and 1.22 m
- **Next step:** add more decay modes, particularly $N \rightarrow ejj$

Highlights

The cross section limits can be translated into limits on the V_{lN}^2 parameter.

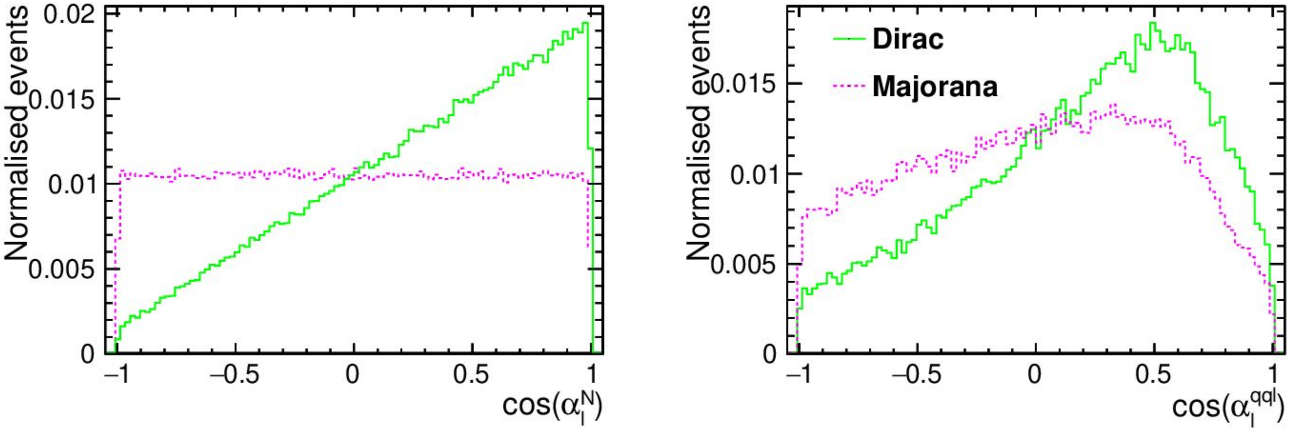
Heavy Neutral Leptons

Above M_Z prompt decays seem to be more promising



LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

Dirac vs. Majorana – l emission angle



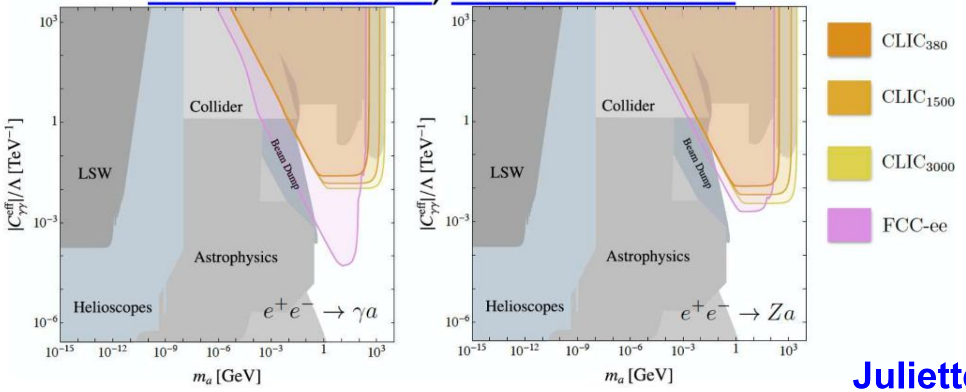
generator vs. detector

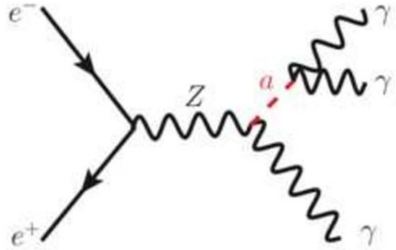
→ dedicated study in progress

2nd Physics Case: LL Axion-Like Particles

- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
    - Orders of magnitude of parameter space accessible
    - Especially sensitive to final states with at least 1 photon
- **Privately generated ALPs in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card,** $\sqrt{s} = 91\ \text{GeV}$ **(arXiv:1808.10323)**

arXiv:1808.10323, arXiv:2108.08949

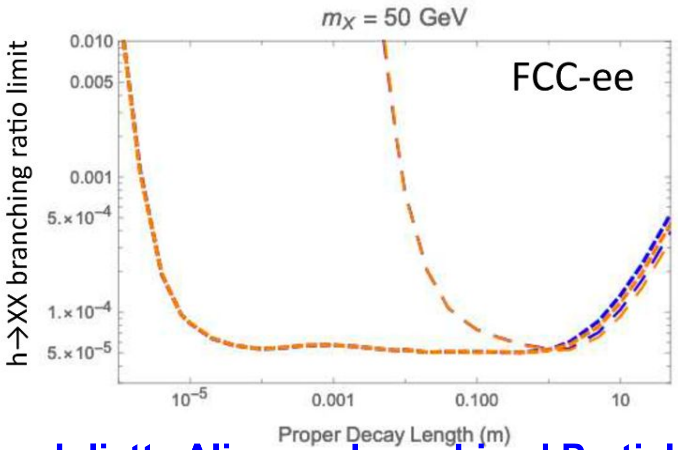




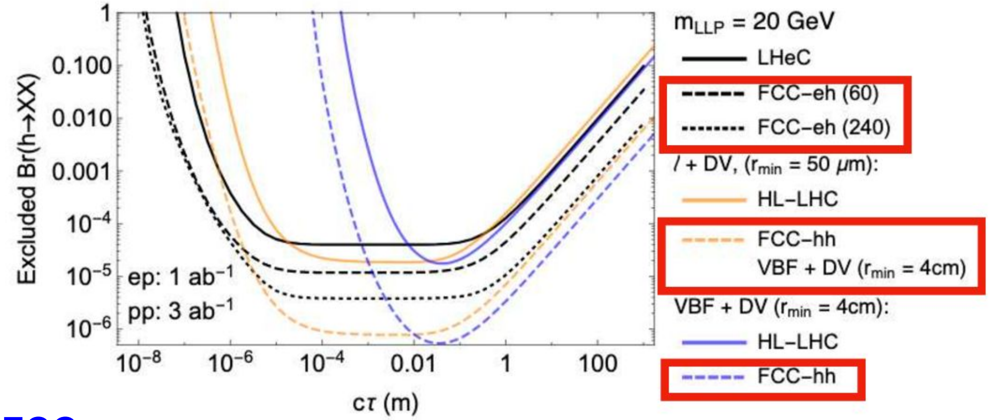
3rd Benchmark: Exotic Higgs decays to LLPs

- Higgs bosons could undergo exotic decays to e.g. scalars that could be long-lived
- Exotic Higgs decays to LLPs could be explored at future colliders
  - Twin Higgs models with displaced exotic Higgs boson decays, Hidden Valley models with Higgs bosons decaying to neutral LLPs (arXiv:1812.05588)
  - LLPs from Higgsinos or exotic Higgs decays (arXiv:1712.07135)
- **New personpower starting** with generating this model in Madgraph, then will incorporate into FCC framework

arXiv:1812.05588



arXiv:1712.07135



Highlights

Maria Teresa Nunez Pardo De Vera

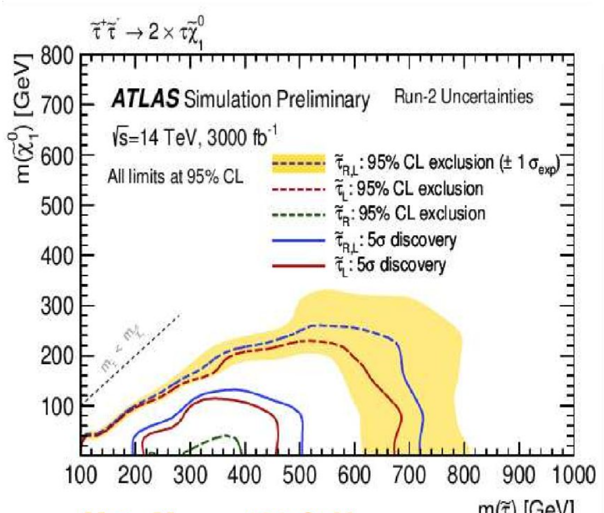
Stau searches and measurement prospects at future Higgs factories

Limits at LEP and LHC (ctd.)

$\tilde{\tau}$ prospects at HL-LHC

Expected gain in sensitivity to direct $\tilde{\tau}$ production

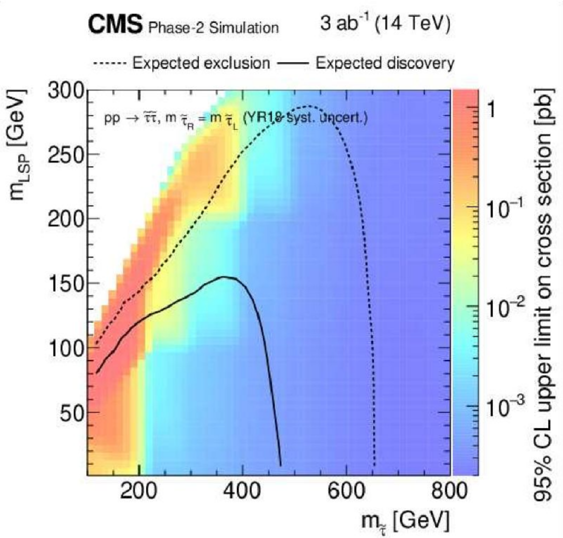
- Two models: $\tilde{\tau}_R$ and $\tilde{\tau}_L$
- No mixing



M $\tilde{\tau}$ - M_{LSP} > 120 GeV

ATL-PHYS-PUB-2018-048

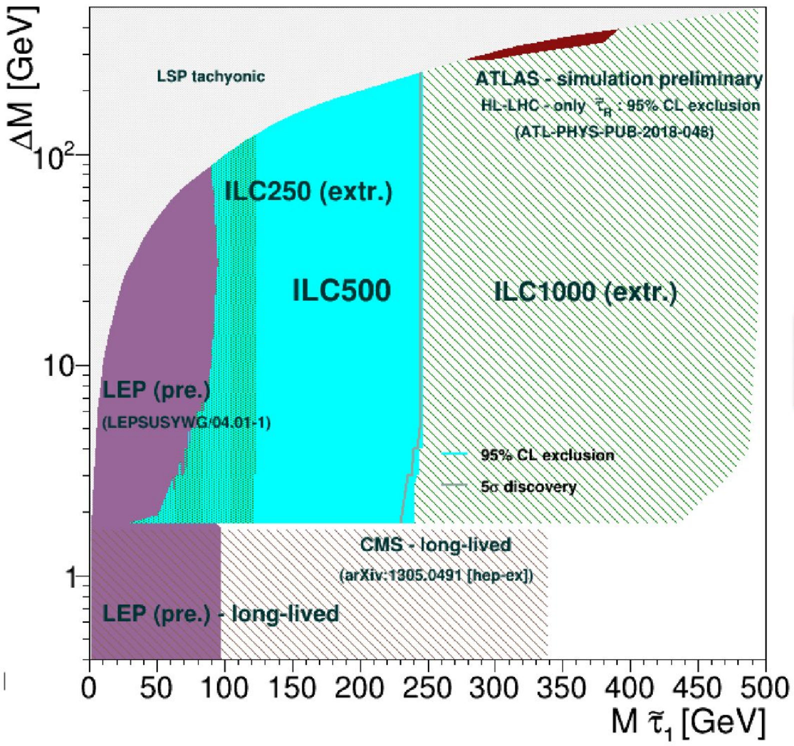
- Two $\tilde{\tau}$ assumed to be mass-degenerate
- No mixing



CMS PAS FTR-18-010

No discovery potential for $\tilde{\tau}$ coannihilation scenarios or $\tilde{\tau}_R$ pair production

ILC expected limits



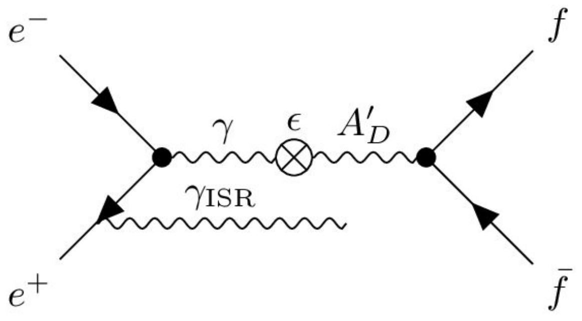
At ILC discovery and exclusion are almost the same

arXiv:2105.08616

A minimal model of the dark sector

- Dark photon ,A'_D, is a hypothetical gauge boson in the dark sector
  - The A'_D is produced as a resonance if an ISR photon removes just the right amount of energy from the e^+e^- system:

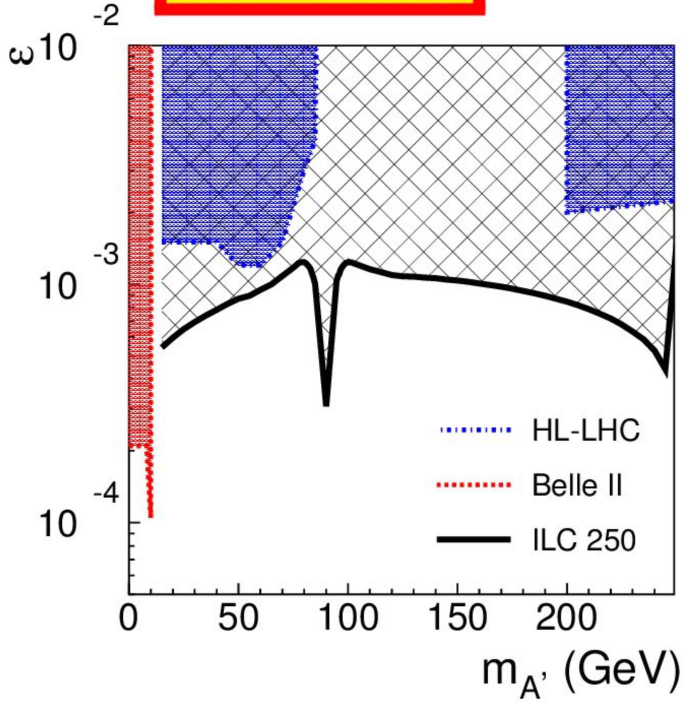
    $E_{ISR} = (E^2_{CMS} - M^2_{A'_D})/2E_{CMS}$
- In this study, we therefore look for
  - $e^+e^- \to A'_D + \gamma_{\text{ISR}} \to f\bar{f} + \gamma_{\text{ISR}}$
    - γ_{ISR} is always at the low angles
    - The $\mu\bar{\mu}$ final state is the best measured one, so we concentrate on that channel



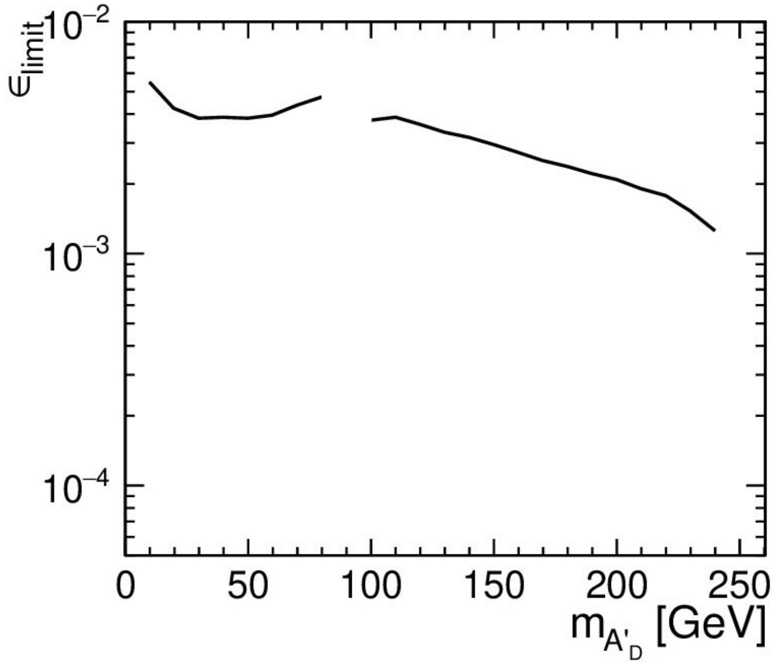
$$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

exclusion limit ϵ_{limit}

arXiv:2111.09928



Theoretical study, ($\sigma_{m_{\mu\bar{\mu}}} = m_{\mu\bar{\mu}}^2 \times 10^{-5}$ for all $m_{\mu\bar{\mu}}$)



Our study

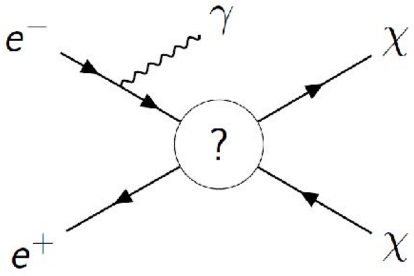
Highlights (3)

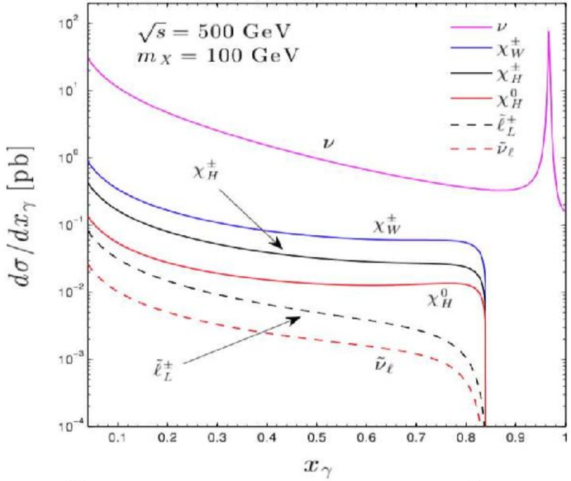
Signature motivated studies

Highlights

Mono-photon signature

The mono-photon signature is considered to be the most general way to look for DM particle production in future e^+e^- colliders.





DM can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

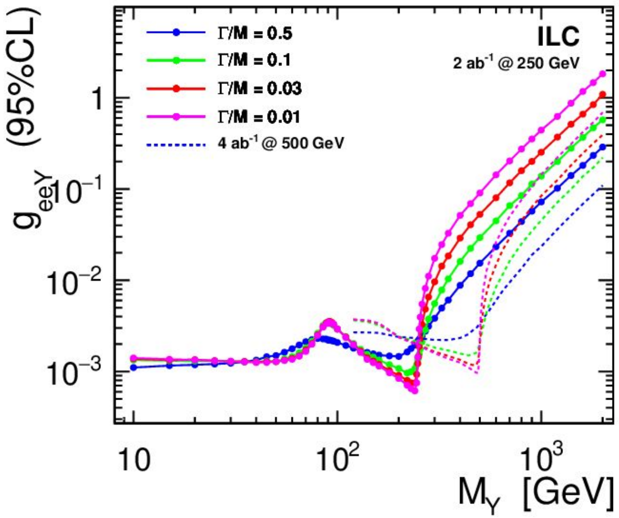
This process can be detected, if additional hard photon radiation from the initial state is observed in the detector...

Highlights

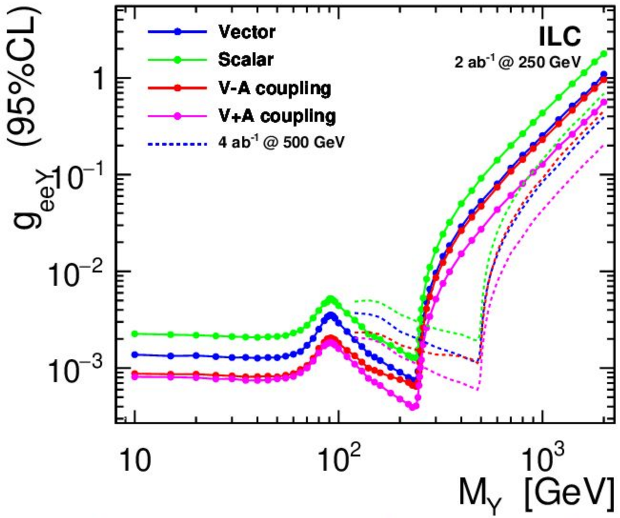
Coupling limits for mediator coupling to SM fermions
$\mathcal{O}(1)$ mediator coupling to DM, fixed by mediator width

Combined limits for ILC @ 250 GeV (compared to ILC @ 500 GeV)

Vector mediator



Mediators with $\Gamma/M = 0.03$



Almost uniform sensitivity to mediator coupling g_{eeY} up to kinematic limit

Signature examples in models with FIMPs

SUSY + axino DM (arXiv:1506.07532)

- Long-lived higgsino $\tilde{h}^0$ and frozen-in LSP axino $\tilde{a}$
- A higgsino pair-production with $\tilde{h}^0 \to Z\tilde{a}, h\tilde{a}$ gives a signature of two displaced vertices + $\not{E}$

Singlet-Doublet DM (arXiv:1805.04423)

- Additional fermions: long-lived $\chi_{2,3}$ and stable χ_1 DM FIMP (Z_2 symmetry)
- Pair production of $\chi_{2,3}$ and decays $\chi_{2,3} \to \chi_1 h, \chi_1 Z$ lead to a signature of two displaced vertices + $\not{E}$

Higgs portal (arXiv:1908.05685)

- Long-lived dark Higgs S that decays into DM or SM by mixing with SM Higgs
- With $h \to SS$ and $S \to \mathrm{SM\,SM}, \mathrm{DM\,DM}$ possible signatures of 2 (or 1) displaced vertices + Z boson (or Z + $\not{E}$)

Possible signatures at e^+e^- colliders – X pair production

Assuming generic **long-lived particle X** and one **DM candidate***, the signatures can be categorised based on the possible production and decay channels:

decay / production	X → SM SM	X → SM SM DM	X → SM DM	X → DM DM
e^-e^+ → X X	• 2 displaced vertices ◆	• 2 displaced vertices • $\not{E}$ ◇	• 2 displaced tracks/jets/γ • $\not{E}$ ◇	Invisible ◆
e^-e^+ → X X DM	• 2 displaced vertices • $\not{E}$	• 2 displaced vertices • $\not{E}$	• 2 displaced tracks/jets/γ • $\not{E}$	Invisible
e^-e^+ → X X Z/h/γ	• 2 displaced vertices • Z/h/γ ◆	• 2 displaced vertices • Z/h/γ • $\not{E}$ ◇	• 2 displaced tracks/jets/γ • Z/h/γ • $\not{E}$ ◇	• Z/h/γ • $\not{E}$ ◆

▭ - predicted by models mentioned on the slides 5-9

If Z_2 is imposed:

◇ - X odd under Z_2

◆ - X even under Z_2

* branches with neutrinos also marked as DM

- The cells in the table can be referred back to signatures in particular models
- Mixed channel $(XX \rightarrow 2SM + 2DM)$ also possible

Highlights (4)

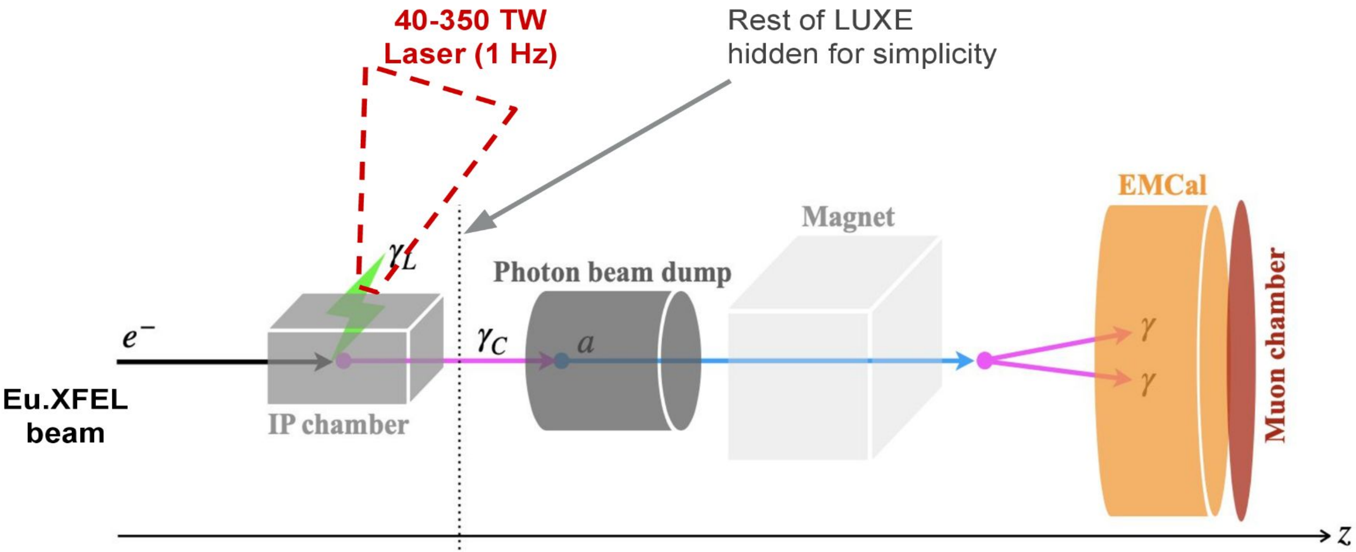
Physics beyond collider mode

Highlights

LUXE NPOD

New Physics search with Optical Dump

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, Santra, Soreq, Tal Hod, 2107.13554

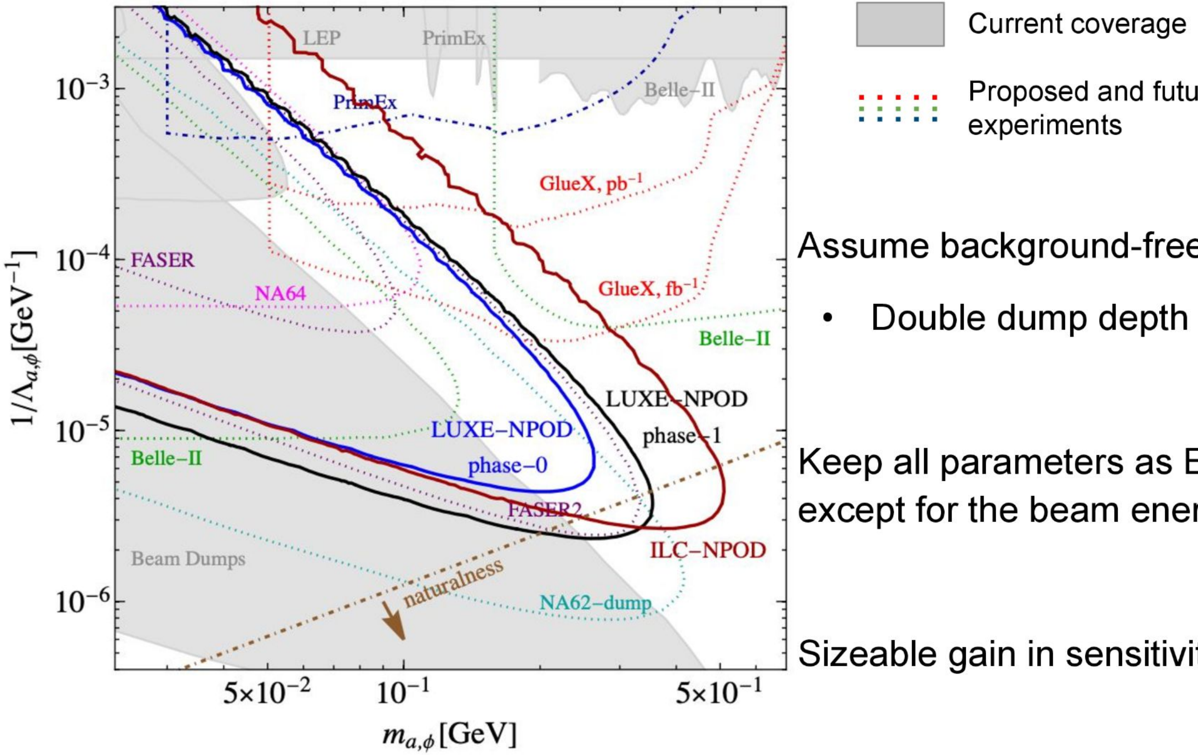


Expected sensitivity gain from energy

Highlights

LUXE concept
at ILC beam dump

Yotam Soreq's
talk at ILCX2021



Assume background-free scenario

- Double dump depth

Keep all parameters as Eu.XFEL, except for the beam energy

Sizeable gain in sensitivity