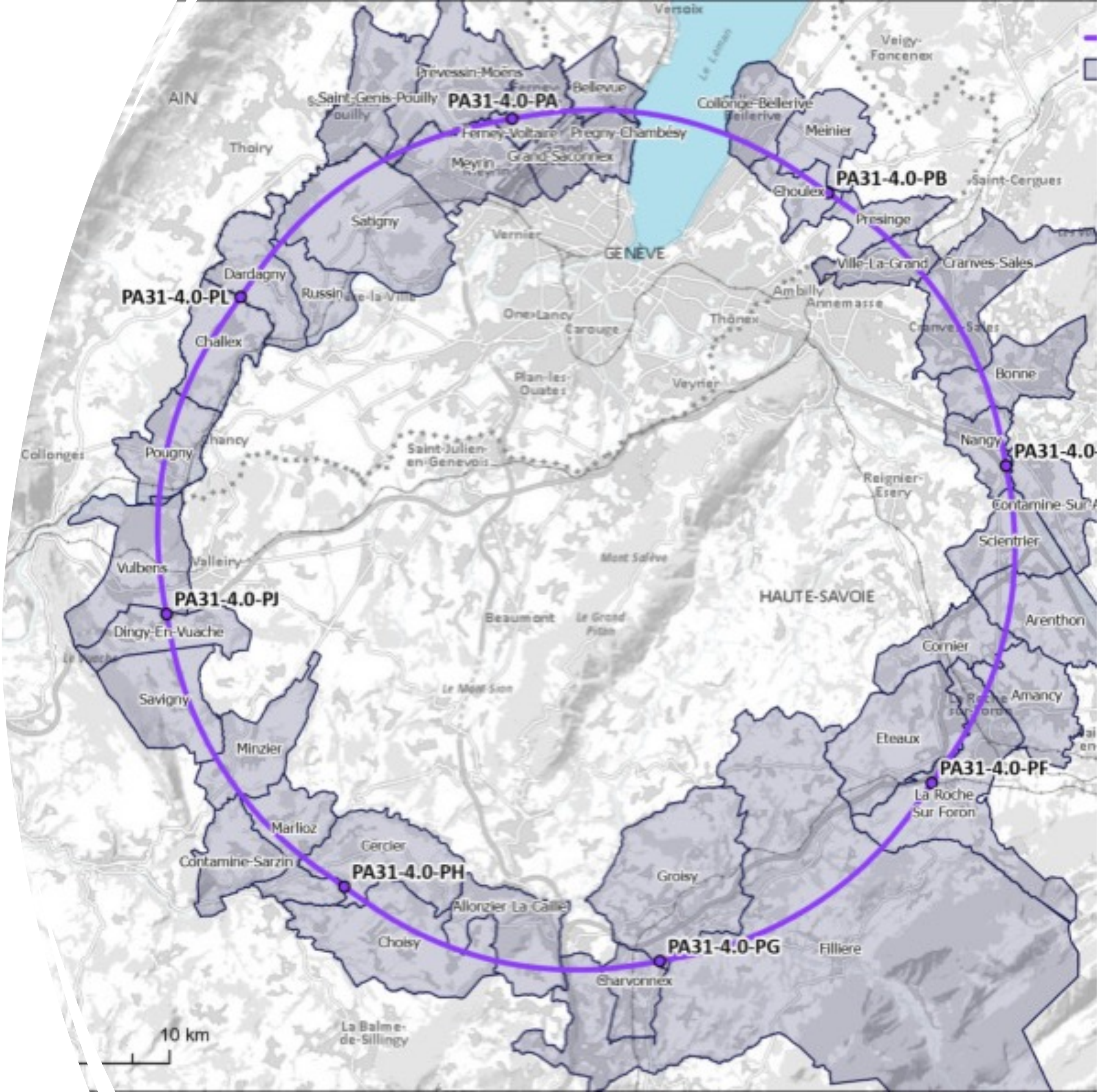
BSM in FCC

Zeynep Demiragli

(Boston University)

FCC Week 2024, San Francisco



Where the wild things are?

BOSTON UNIVERSITY

Illustrator: Maurice Sendak

FCC-ee opportunity: Precision and Exploration

- Explore indirectly using precision measurements.
- Explore directly & discover: ALPs, dark photons, HNLs, exotic Higgs any of which could be feebly interacting particles

Where the wild things are?

BOSTON UNIVERSITY

Illustrator: Maurice Sendak

FCC-ee opportunity: Precision and Exploration

- Explore indirectly using precision measurements.
- Explore directly & discover: ALPs, dark photons, HNLs, exotic Higgs any of which could be feebly interacting particles

Where the wild things are?

BOSTON UNIVERSITY

Illustrator: Maurice Sendak

FCC-ee opportunity: Precision and Exploration

- Explore indirectly using precision measurements.
- Explore directly & discover: ALPs, dark photons, HNLs, exotic Higgs any of which could be feebly interacting particles

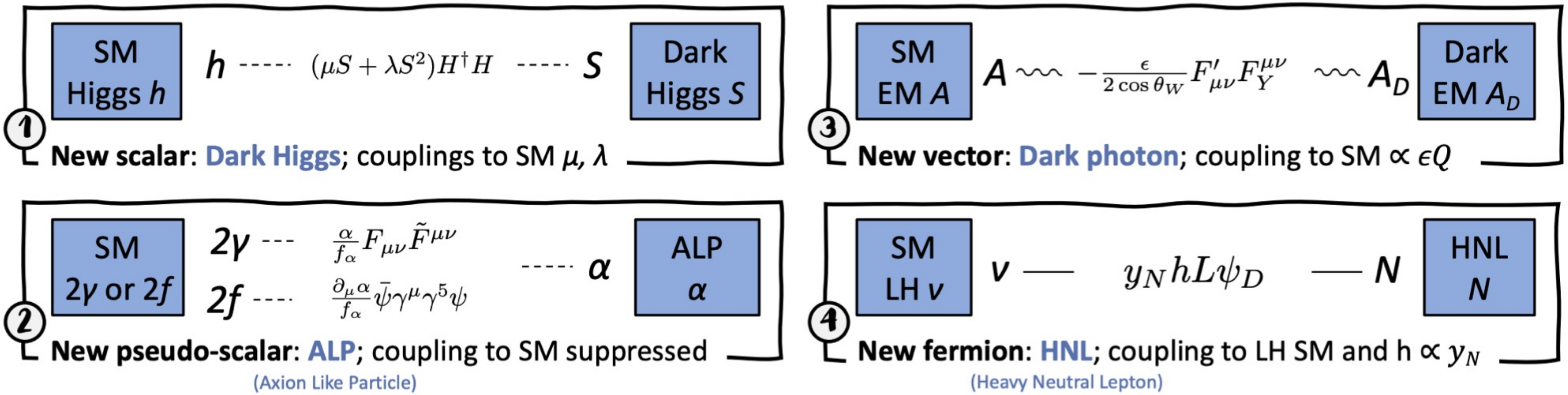
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

Personal Favorite Motivator: Dark Sector

BOSTON UNIVERSITY

While the dynamics of the dark sector could be complicated…

to observe a dark sector, *we need a portal interaction*:

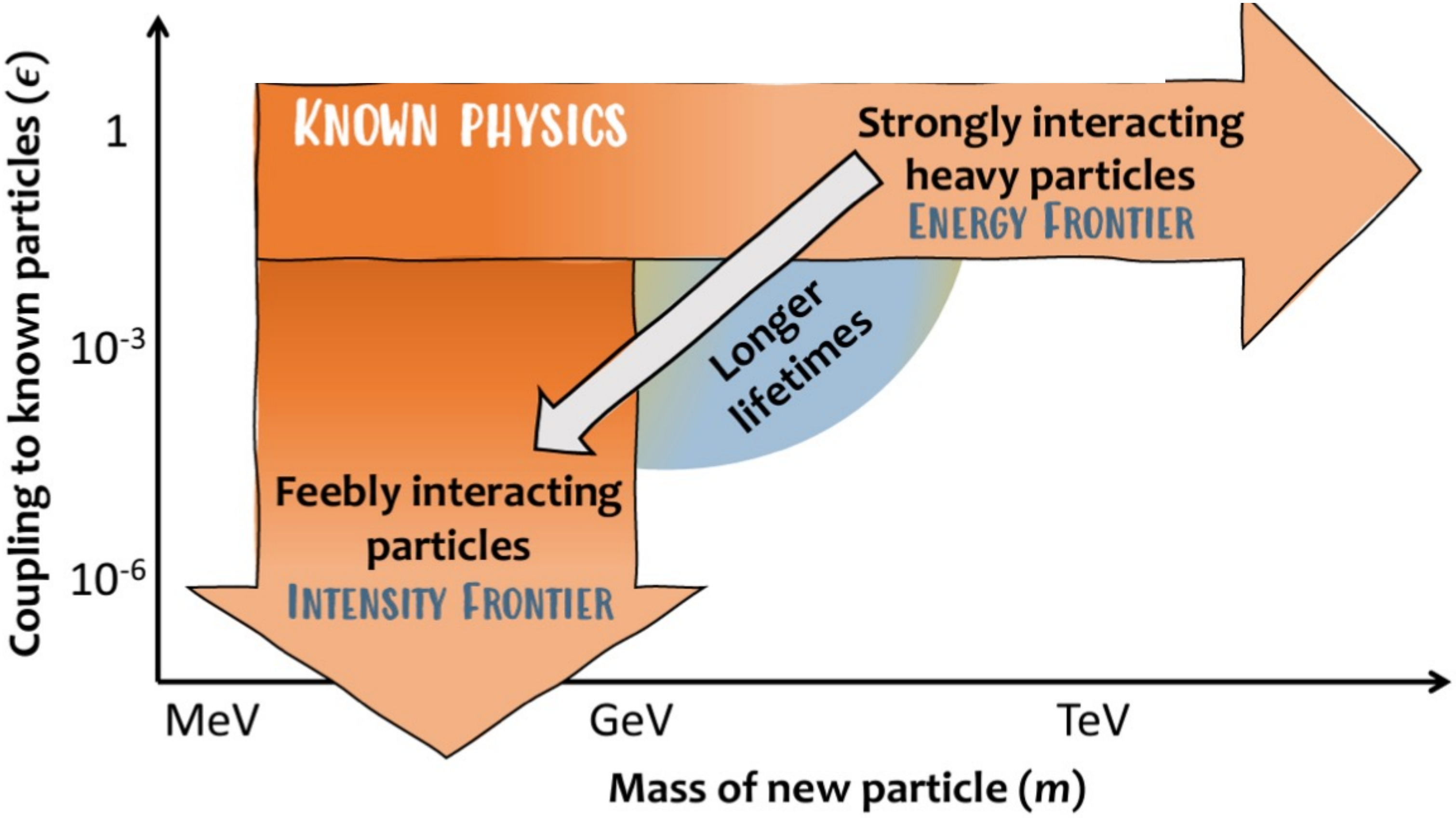


New Physics could be light and feebly interacting with SM

Personal Favorite Motivator: Dark Sector

BOSTON UNIVERSITY

Feebly interacting Particles: From Energy Frontier to Intensity Frontier



A paradigm shift has already started at the LHC

Distance travelled by particles:

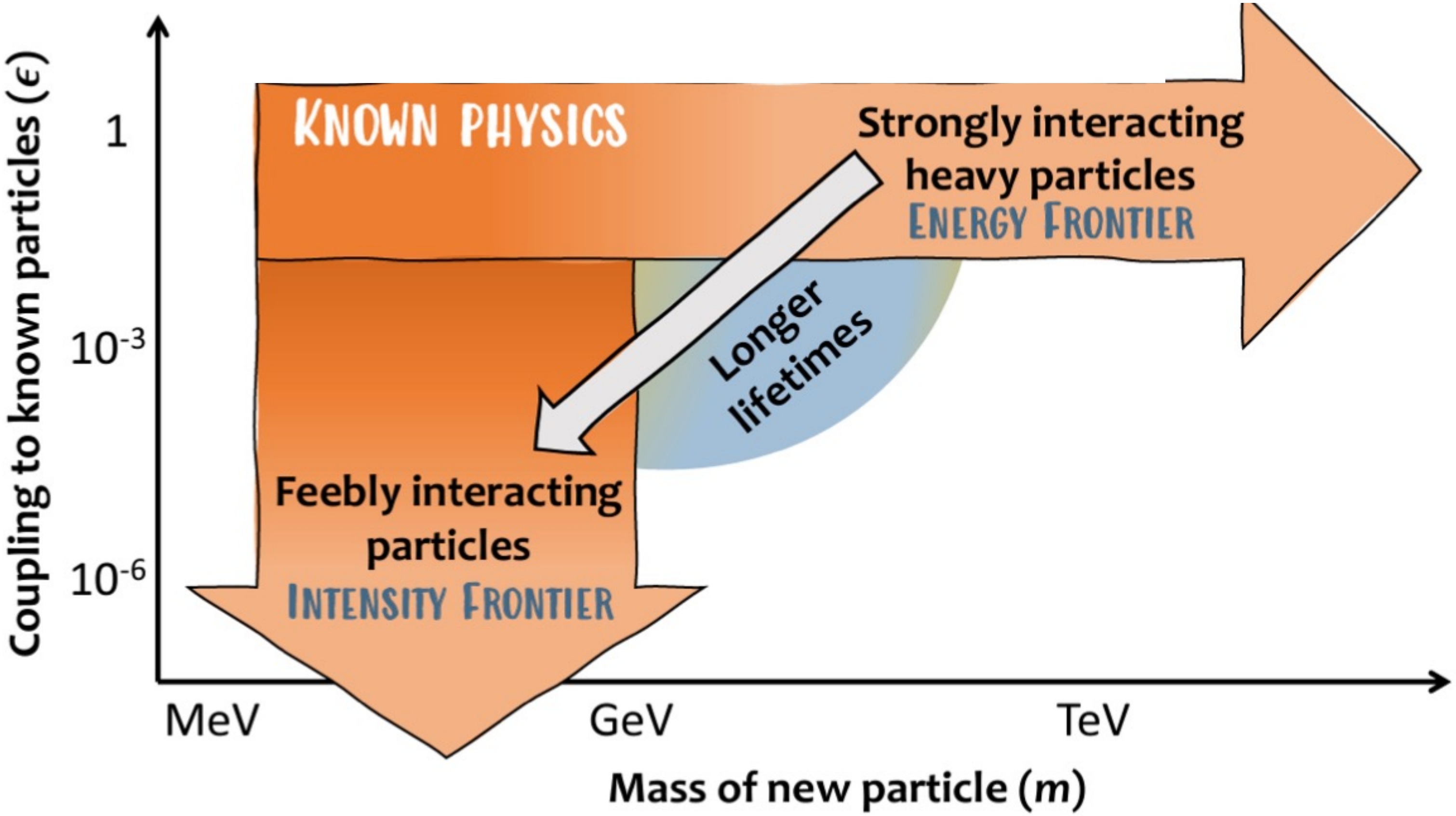
$$L = v\,\tau\,\gamma \propto c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$

Diagram credit to A. Sfyrla

Personal Favorite Motivator: Dark Sector

BOSTON UNIVERSITY

Feebly interacting Particles: From Energy Frontier to Intensity Frontier



A paradigm shift has already started at the LHC

... but LHC experiments weren't designed for this:

Distance travelled by particles:

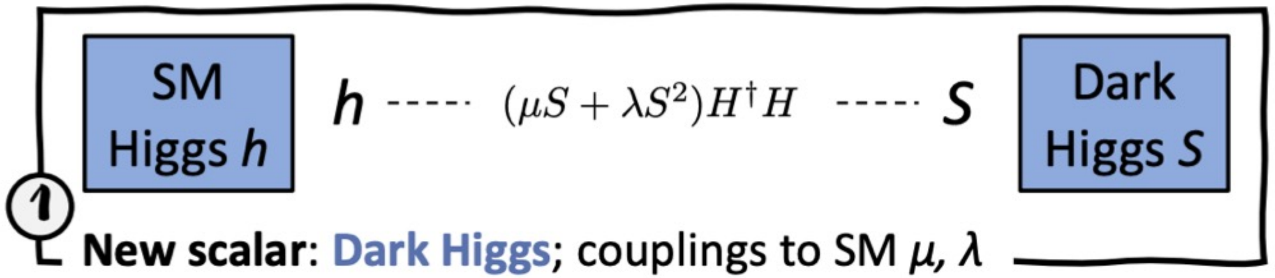
$$L = v\,\tau\,\gamma \;\propto\; c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$

Diagram credit to A. Sfyrla

See L. Skinnari's talk for detector requirements!

Scalar Portal: Dark Higgs, BSM Higgs

BOSTON UNIVERSITY



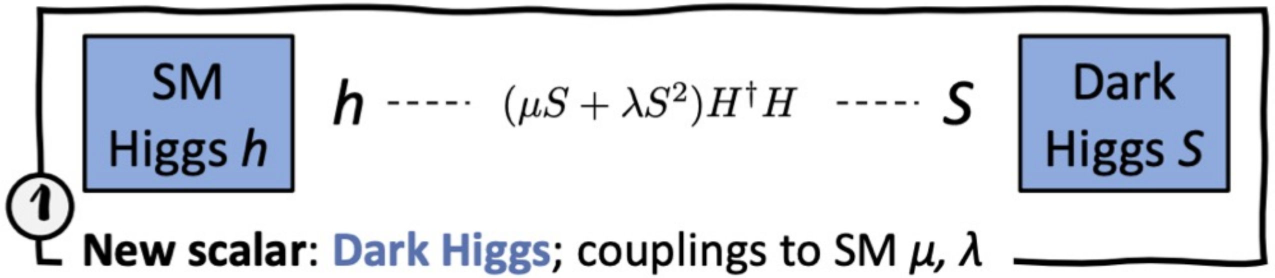
μ: Higgs-S mixing mass term → $\sin\theta$

The mixing implies that the SM couplings of the Higgs deviate from their SM values

https://arxiv.org/pdf/1612.09284

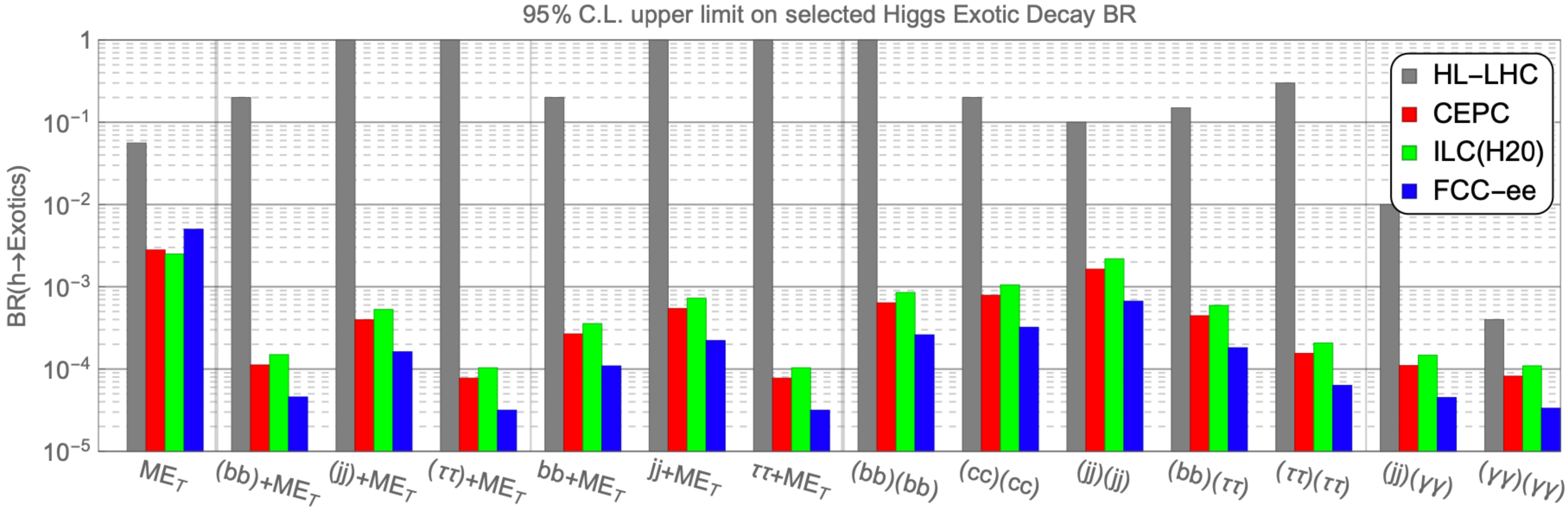
Scalar Portal: Dark Higgs, BSM Higgs

BOSTON UNIVERSITY



μ: Higgs-S mixing mass term → sinθ

λ: H → S S production with coupling λ

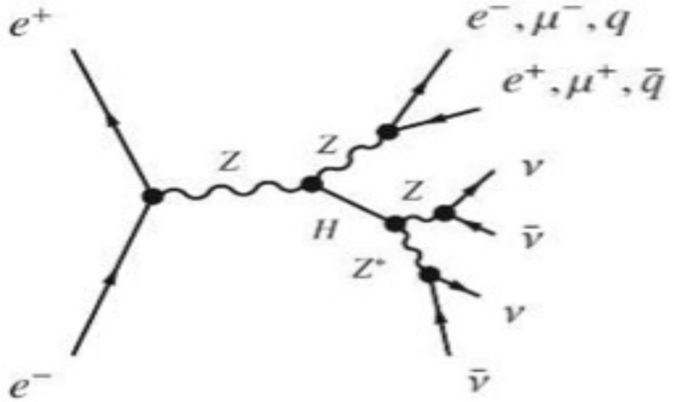


https://arxiv.org/pdf/1612.09284

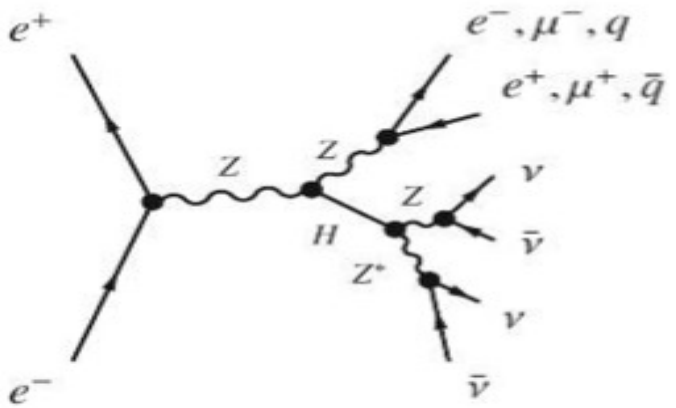
Case Study: Higgs Invisible

In SM $H \rightarrow ZZ \rightarrow (\nu\bar{\nu})(\nu\bar{\nu})$ process has a BR of about 10^{-3}

- Current ATLAS/CMS sensitivity: ~10-15% BR observed
- Inv BR would be significantly enhanced in presence of New Physics



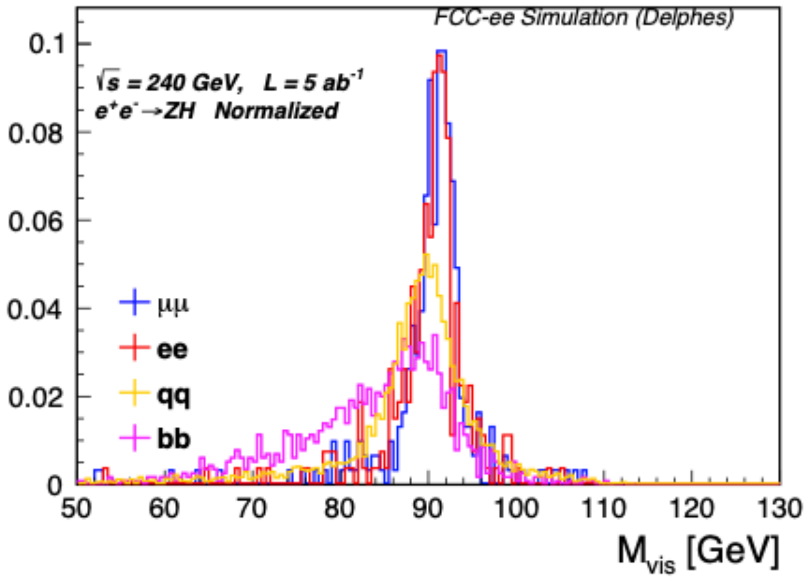
Case Study: Higgs Invisible

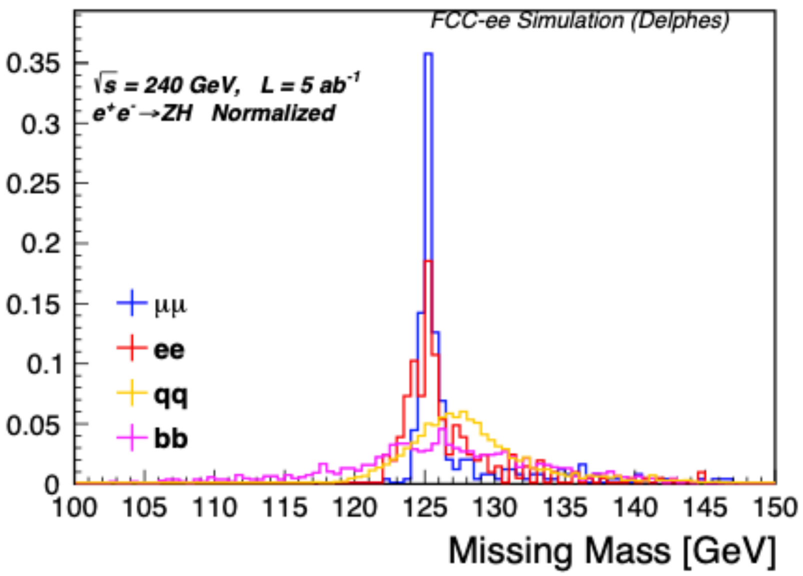


In SM $H \to ZZ \to (\nu\bar{\nu})(\nu\bar{\nu})$ process has a BR of about 10^{-3}

- Current ATLAS/CMS sensitivity: ~10-15% BR observed
- Inv BR would be significantly enhanced in presence of New Physics

Signal (H→ inv)	Energy	Luminosity	Channels	Backgrounds
ZH	240 GeV	5 ab^{-1}	$ee, \mu\mu, bb, qq$	Z, ZZ, ZH, WW





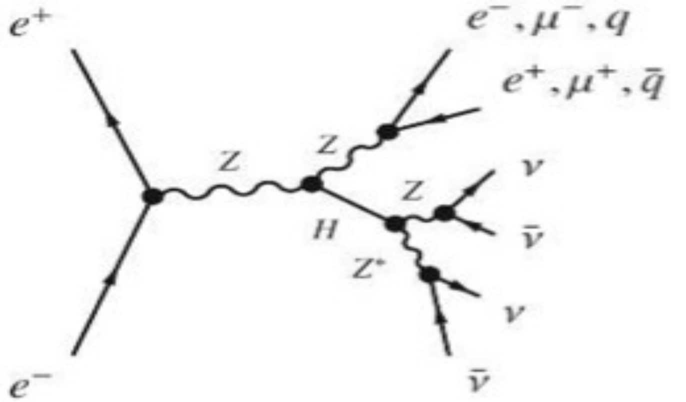
Using Delphes simulation

- qq resolution worse than ee/mm
- M_{miss} resolution best for mm
- Mass resolution for bb worst due to neutrinos in b hadron decays

Case Study: Higgs Invisible

In SM $H \rightarrow ZZ \rightarrow (\nu\bar{\nu})(\nu\bar{\nu})$ process has a BR of about 10^{-3}

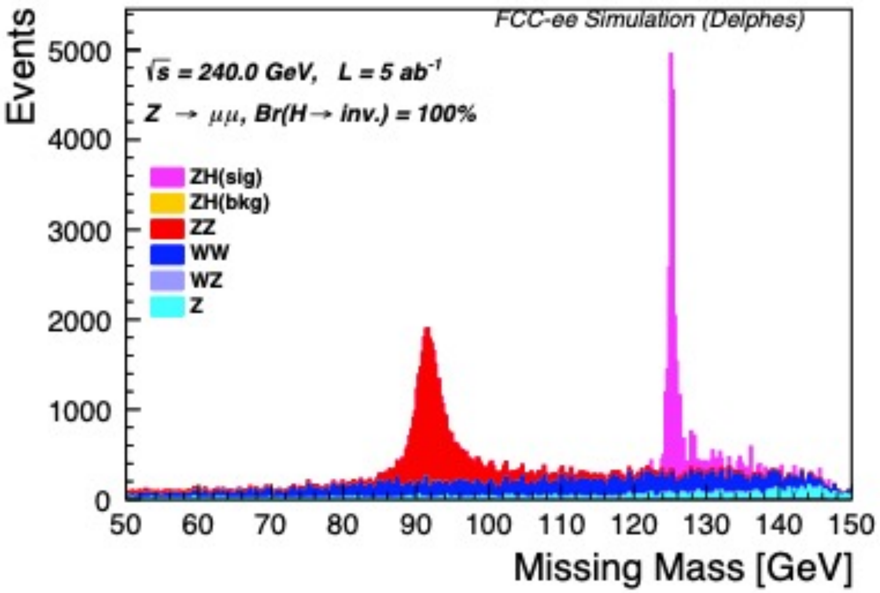
- Current ATLAS/CMS sensitivity: ~10-15% BR observed
- Inv BR would be significantly enhanced in presence of New Physics

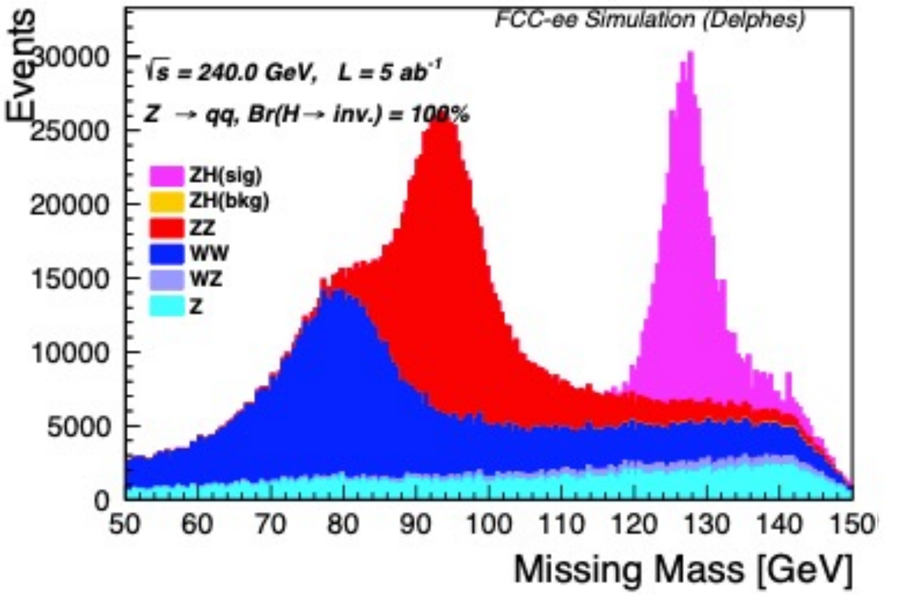


Signal (H→ inv)	Energy	Luminosity	Channels	Backgrounds
ZH	240 GeV	5 ab^{-1}	$ee, \mu\mu, bb, qq$	Z, ZZ, ZH, WW

Additional requirements for Z(bb) channel, to cope with worse resolution of bb system

Use distribution of M_{miss} in likelihood fit.

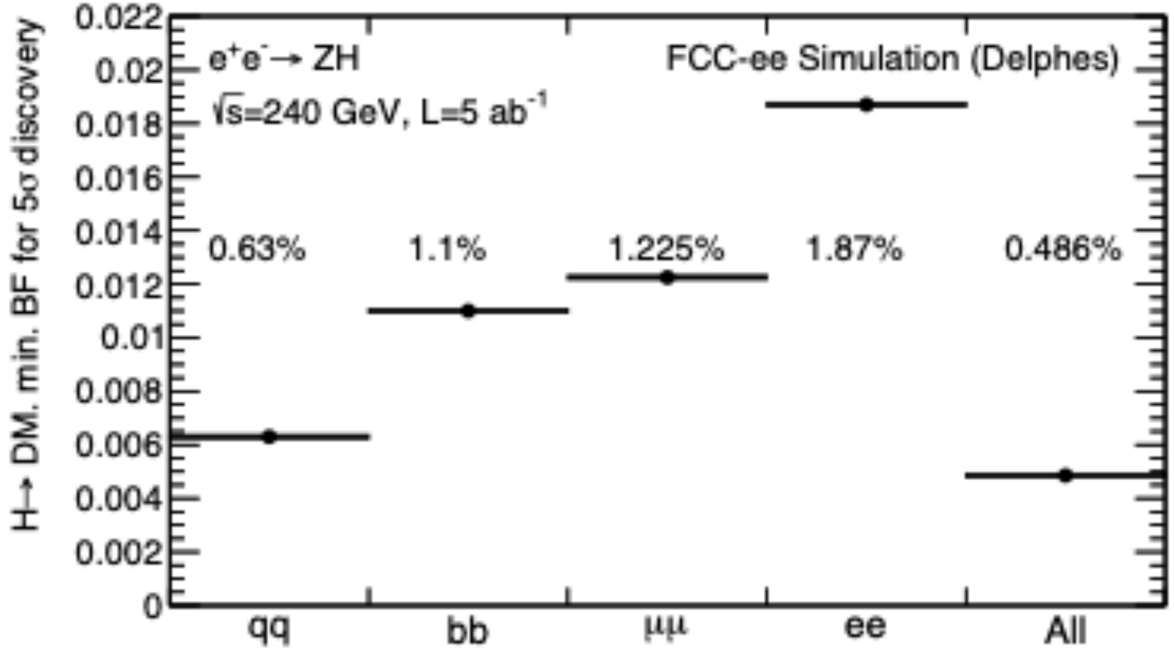




Case Study: Higgs Invisible

Reach **SM precision of ≃ 0.1%**

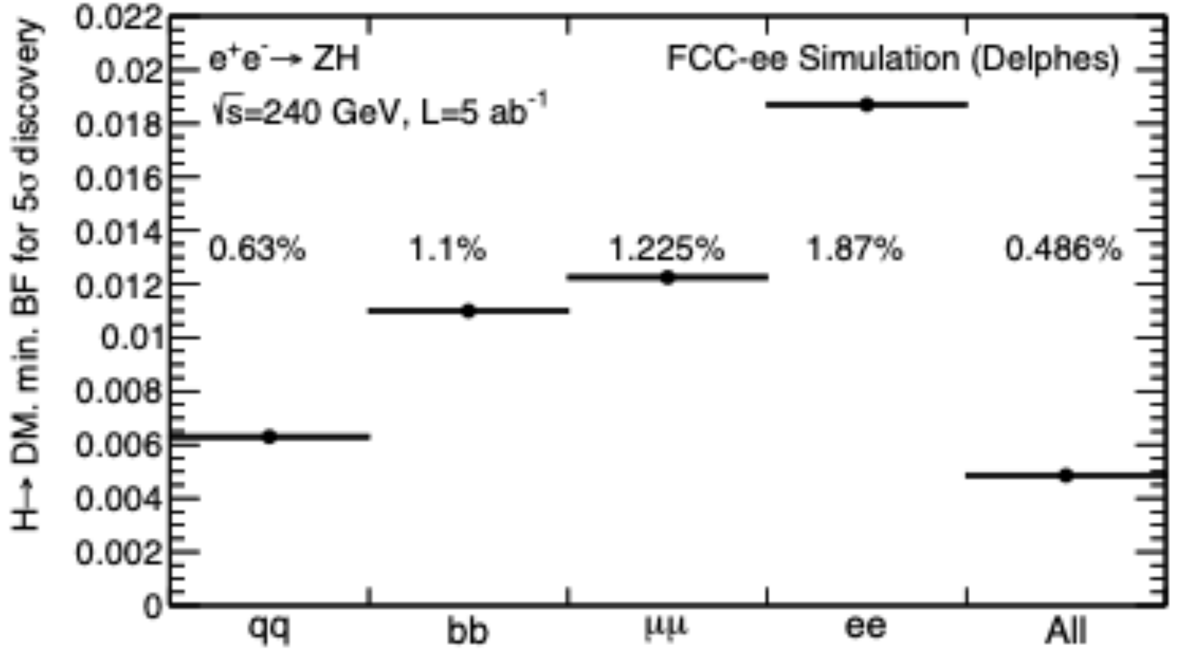
Could discover **NP** with $H \rightarrow inv$ above SM background **with BF ~ 0.5%**

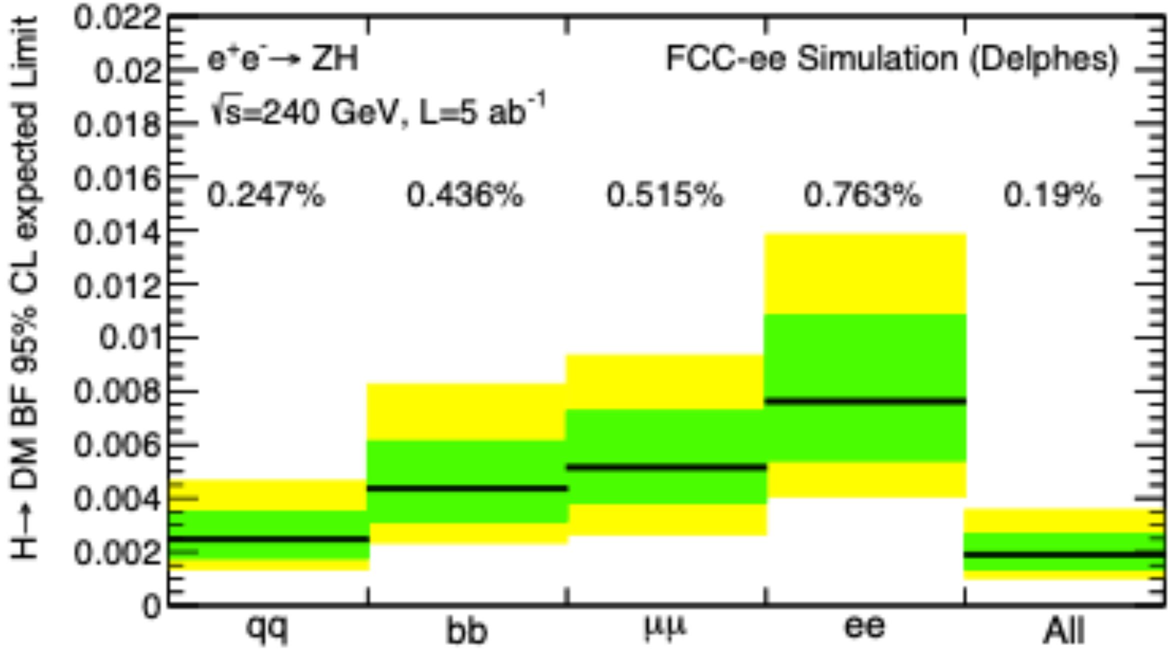


Case Study: Higgs Invisible

Reach **SM precision of ≃ 0.1%**

Could discover **NP** with $H \rightarrow$ inv above SM background **with BF ~ 0.5%**



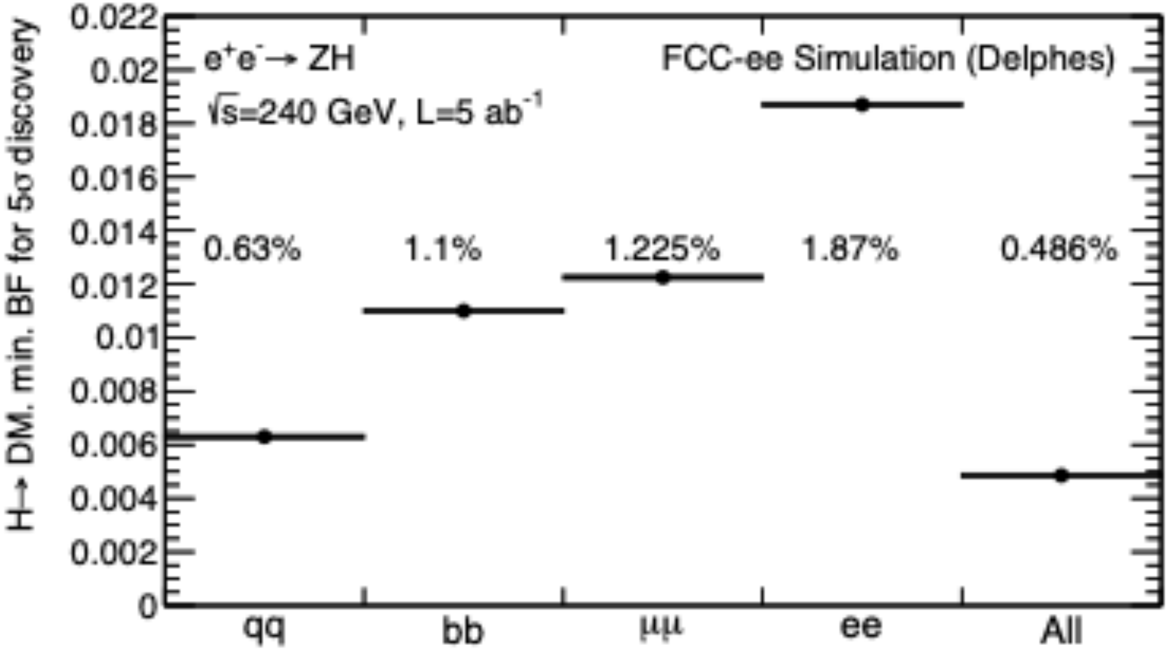


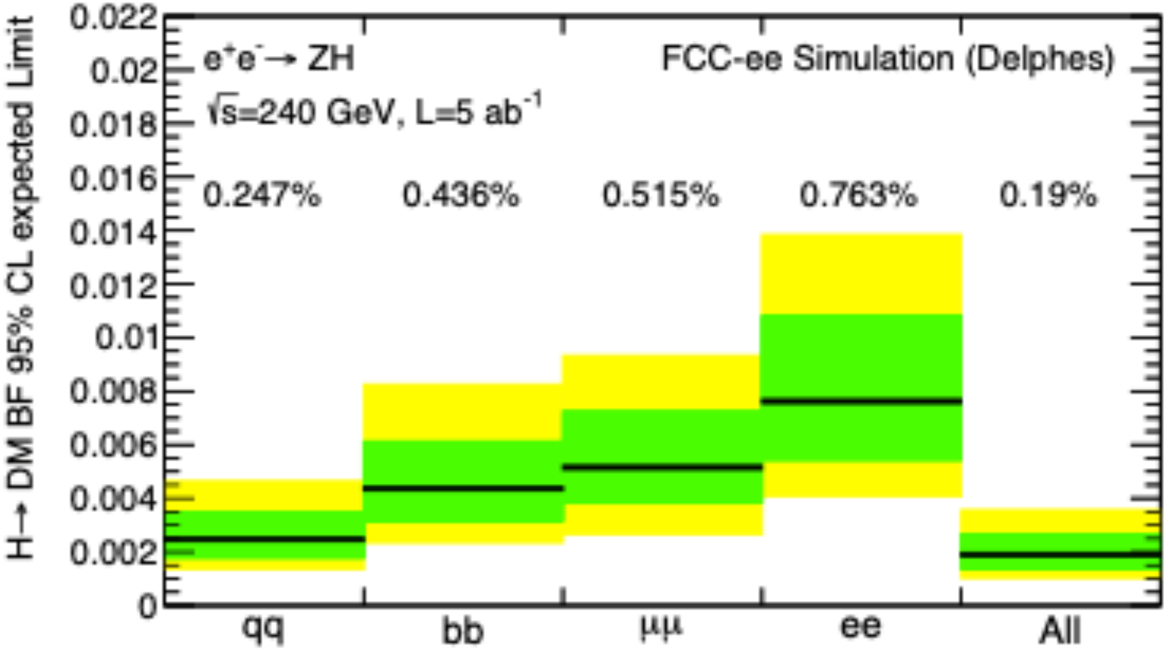
Case Study: Higgs Invisible

BOSTON UNIVERSITY

Reach **SM precision of ≃ 0.1%**

Could discover **NP** with $H \rightarrow inv$ above SM background **with BF ~ 0.5%**



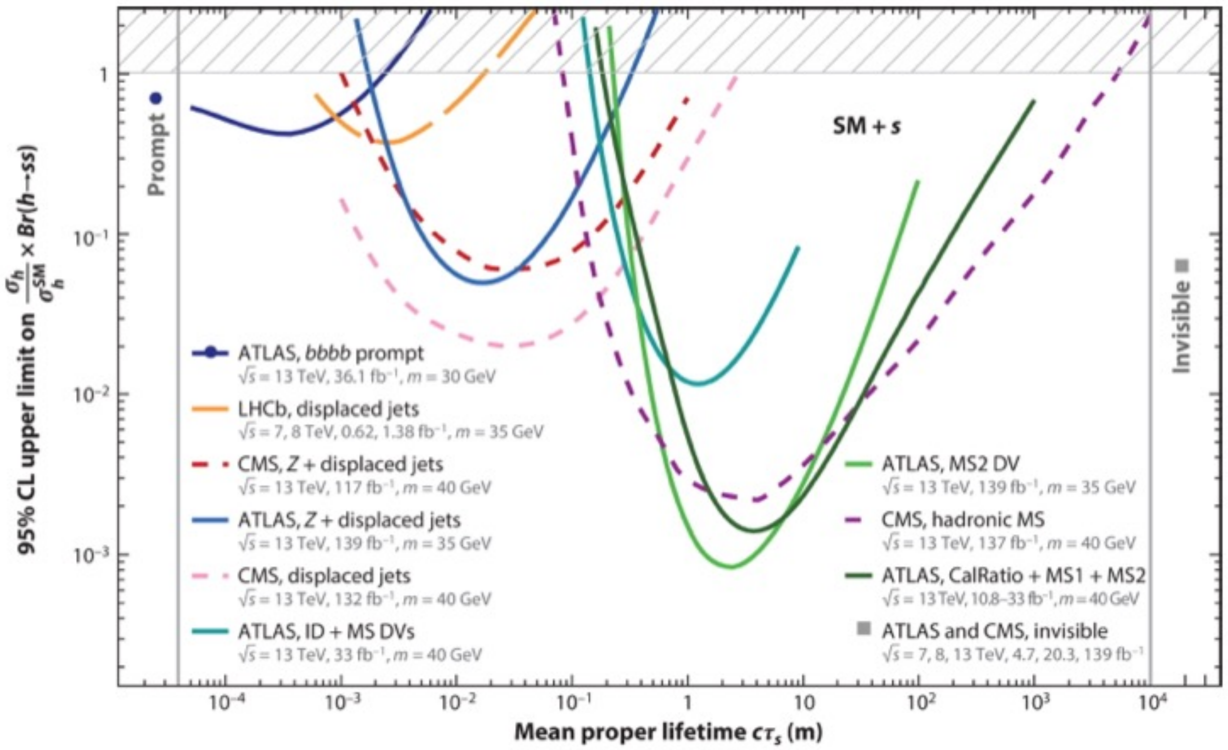


Recent work (FCC MIT Workshop) compares CLD full sim and CLD & IDEA Delphes fast sim.

- Efficiency is ~identical for IDEA and CLD fast simulations!
- Electron eff is worse for full sim than for fast sim & Muon eff is very similar for full & fast sim.

Case Study: Exotic Higgs Decay

Review: Exotic Higgs Decays arXiv:2111.12751

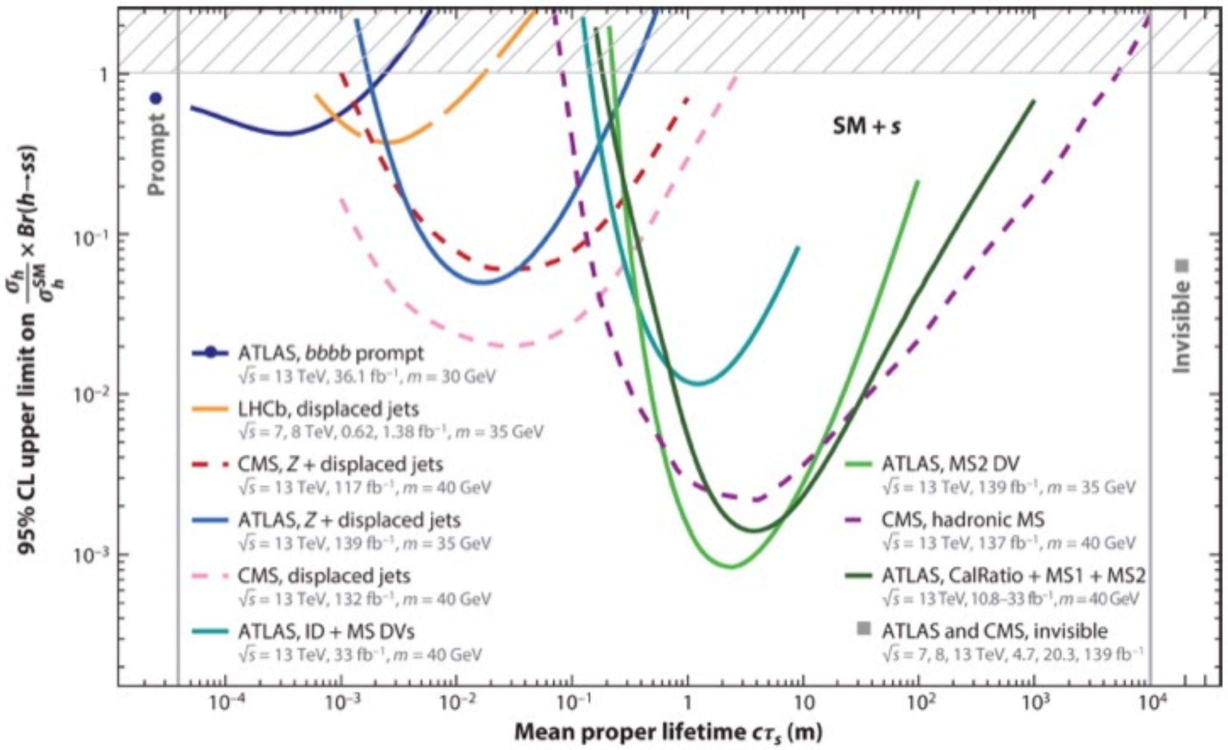


For sufficiently small mixing, the scalar can be long-lived: cτ ~ meters if θ < 1e-6

ZH → Z (ee/mm) + H → s s

Case Study: Exotic Higgs Decay

Review: Exotic Higgs Decays arXiv:2111.12751



For sufficiently small mixing, the scalar can be long-lived: cτ ~ meters if θ < 1e-6

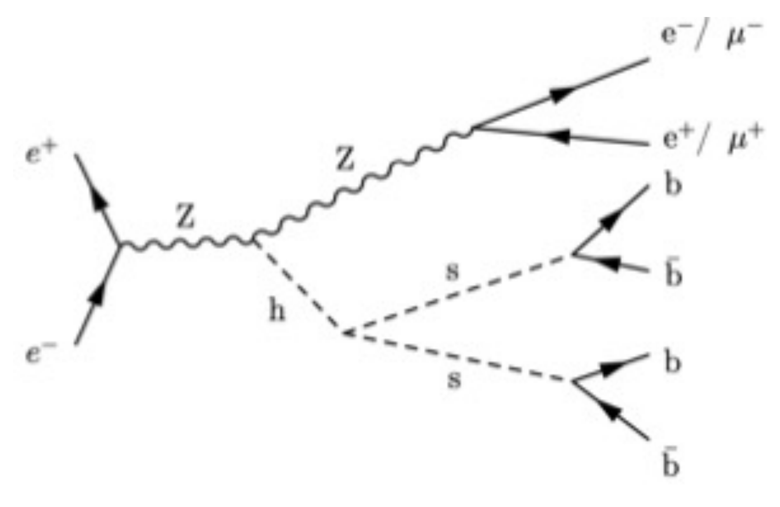
ZH → Z (ee/mm) + H → s s → 4b

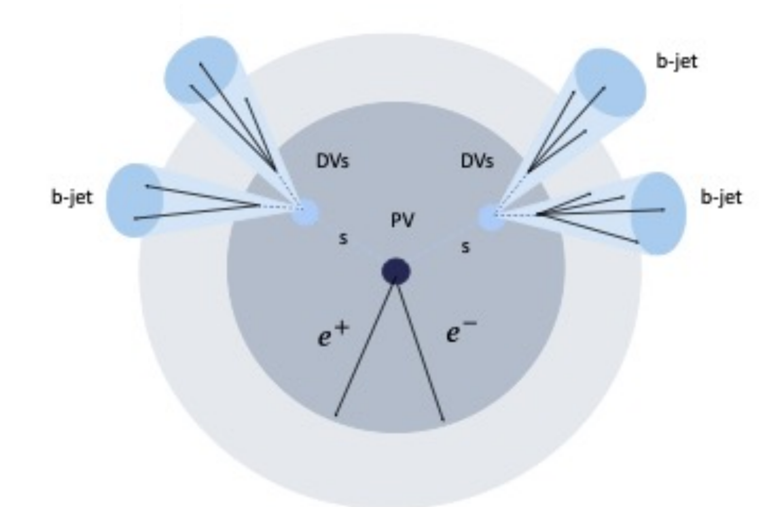
Full chain:
MadGraph v3.4.1 (for parton level) +
Pythia8 (parton shower / hadronization) +
Delphes (winter2023 IDEA)

Signal (H→ inv)	Energy	Luminosity	Channels	Backgrounds
ZH	240 GeV	5 ab^{-1}	$4b$	WW, ZZ, ZH

Case Study: Exotic Higgs Decay

Pre-selection: 2 opposite sign, same flavor leptons (invariant mass within Z) + 2 displaced vertex



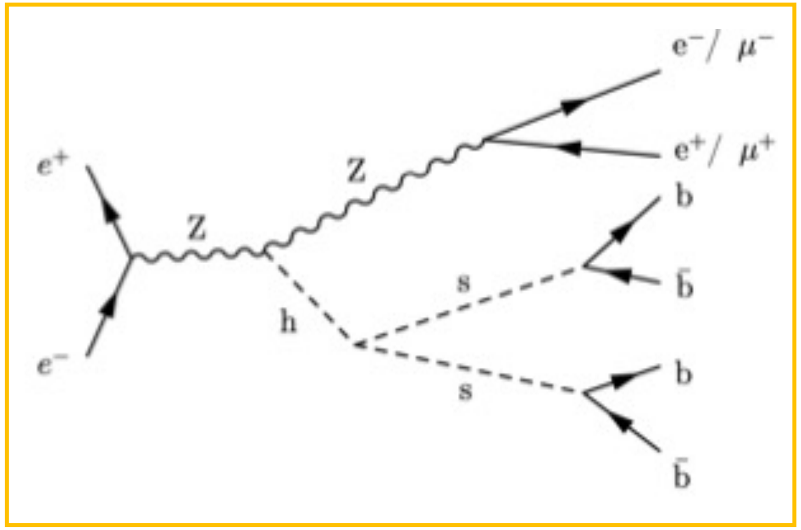


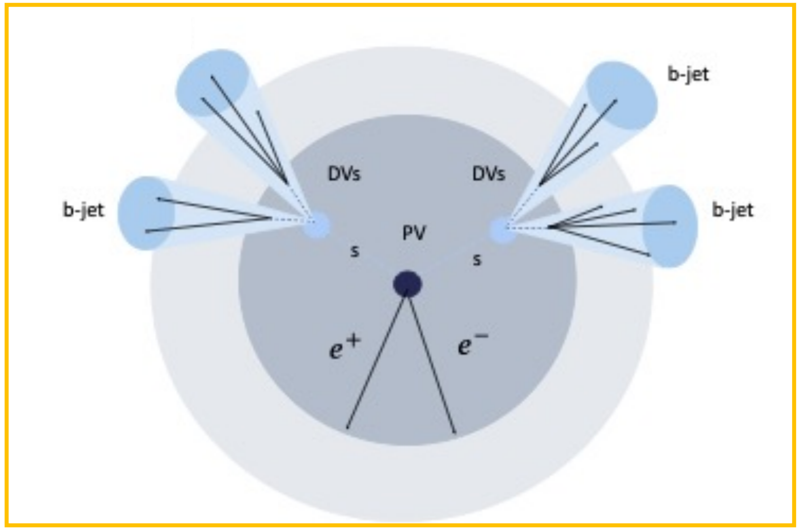
Type	Parameter	Value
Track Selection	Min p_T	1 GeV
	Min $\lvert d_0 \rvert$	2 mm
Vertex Reconstruction	V^0 rejection	True
	Max χ^2	9
	Max M_{inv}	40 GeV
	Max χ^2 added track	5
	Vertex merging	False
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV

Case Study: Exotic Higgs Decay

BOSTON UNIVERSITY

Pre-selection: 2 opposite sign, same flavor leptons (invariant mass within Z) + 2 displaced vertex



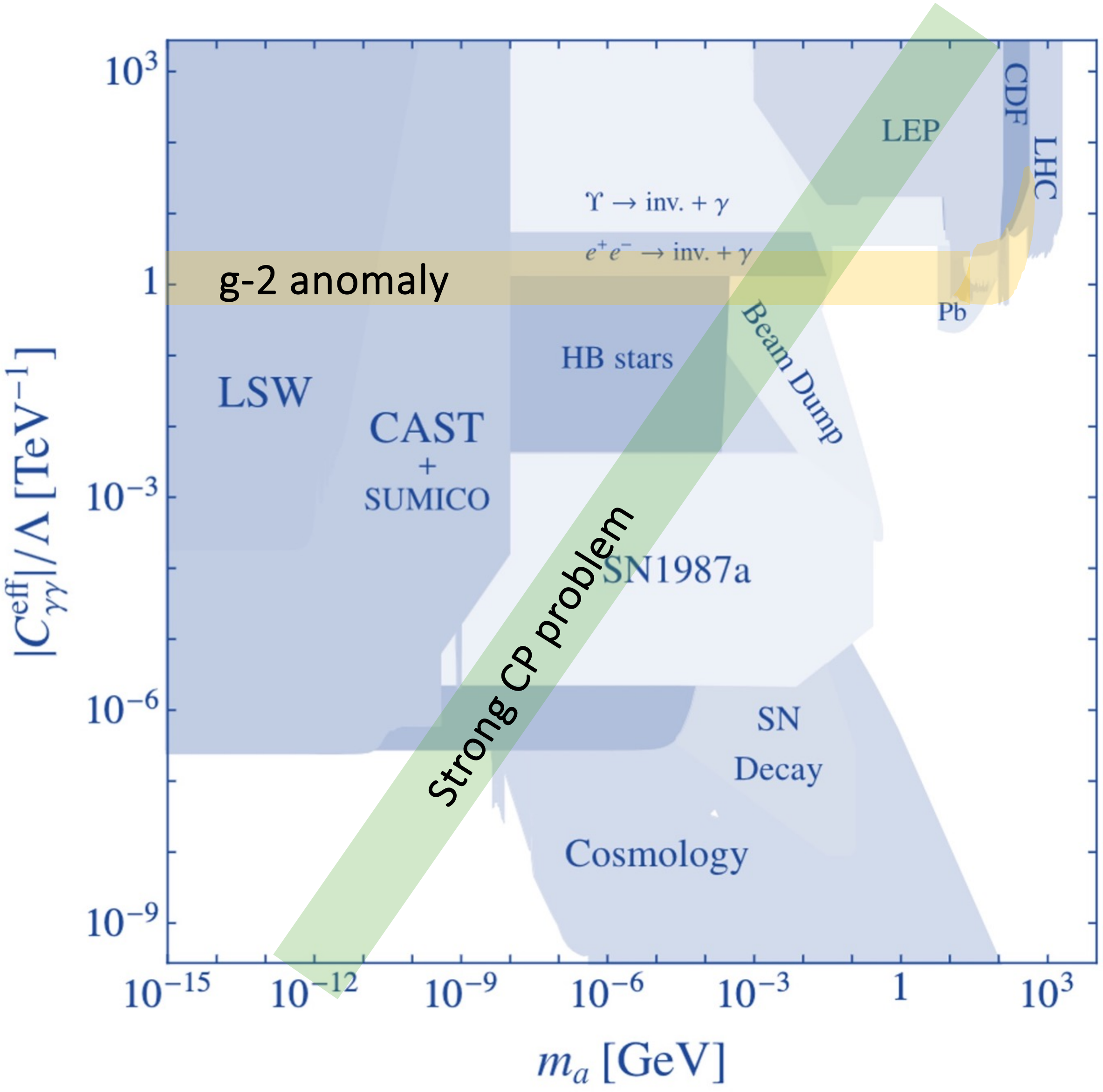


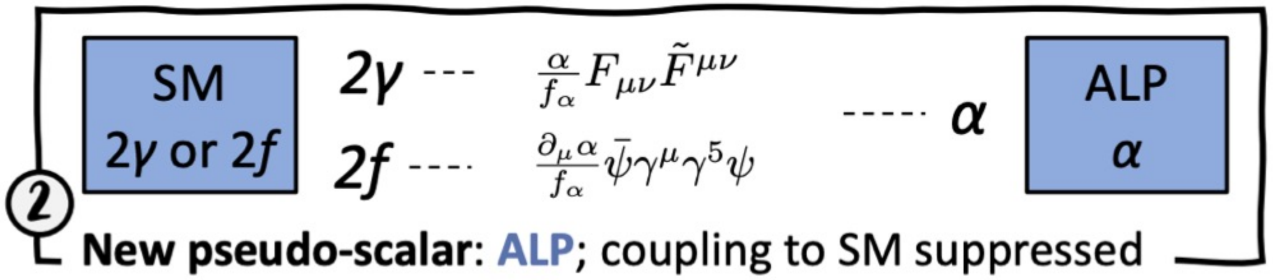
Type	Parameter	Value
Track Selection	Min p_T	1 GeV
	Min $\|d_0\|$	2 mm
Vertex Reconstruction	V^0 rejection	True
	Max χ^2	9
	Max M_{inv}	40 GeV
	Max χ^2 added track	5
	Vertex merging	False
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV

Zero background search => 3 events is 95% CL exclusion

m_s, $\sin\theta$	$c\tau$ [mm]	BR($h \to ss$)	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	3.4	6.98×10^{-4}	55.2 ± 0.552	52.84 ± 0.538	49.02 ± 0.520	5.0 ± 0.166
20 GeV, 1e-6	341.7	6.98×10^{-4}	55.2 ± 0.552	52.44 ± 0.538	49.02 ± 0.521	37.1 ± 0.453
20 GeV, 1e-7	34167.0	6.98×10^{-4}	55.2 ± 0.552	52.38 ± 0.540	49.68 ± 0.524	0.8 ± 0.067
60 GeV, 1e-5	0.9	2.06×10^{-4}	16.32 ± 0.163	15.62 ± 0.127	14.59 ± 0.154	0.0033 ± 0.0023
60 GeV, 1e-6	87.7	2.06×10^{-4}	16.32 ± 0.163	15.62 ± 0.196	14.61 ± 0.196	10.96 ± 0.167
60 GeV, 1e-7	8769.1	2.06×10^{-4}	16.32 ± 0.163	15.52 ± 0.159	14.62 ± 0.155	6.49 ± 0.103

Pseudo-scalar Portal: Axion-like Particles

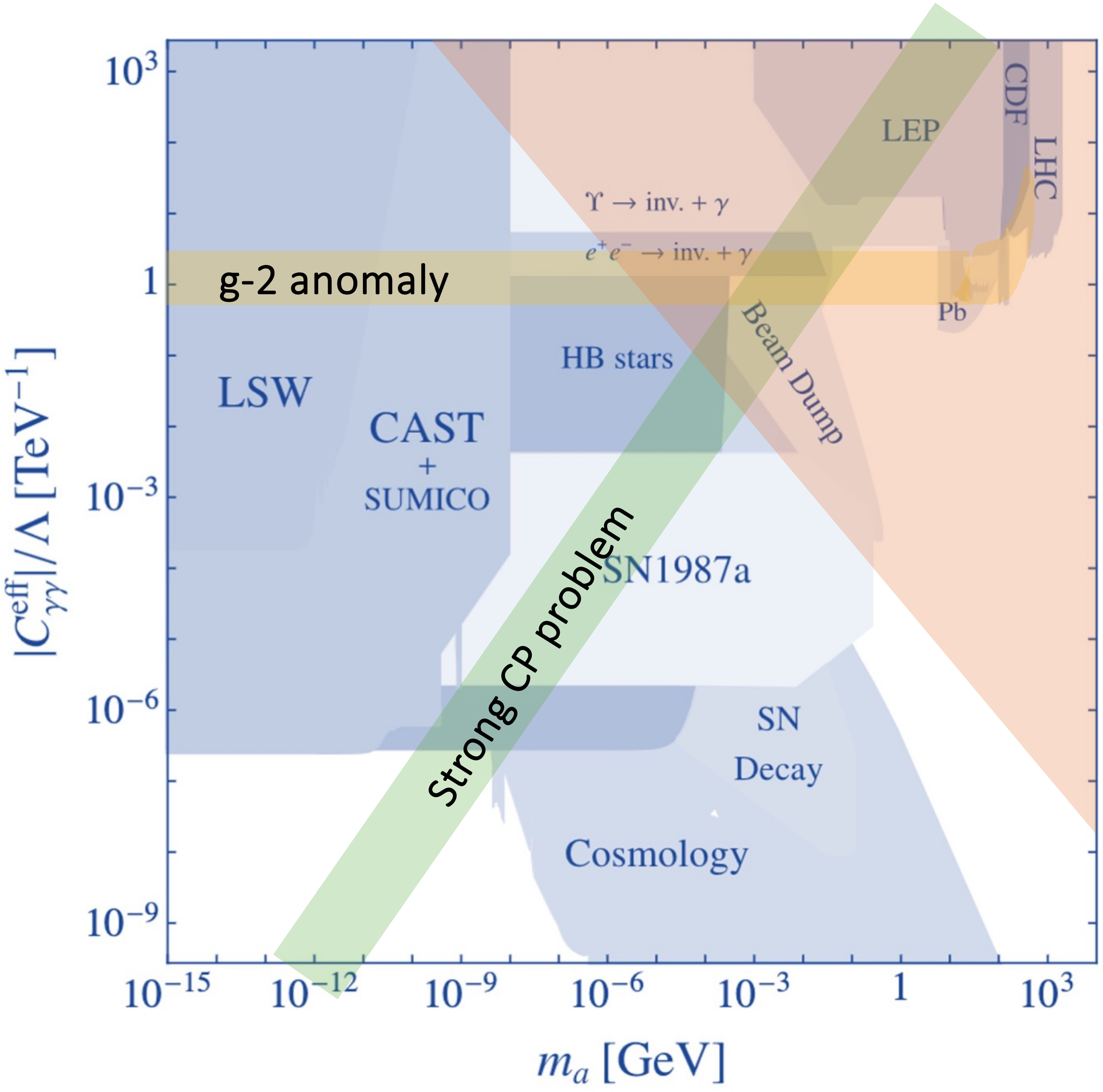


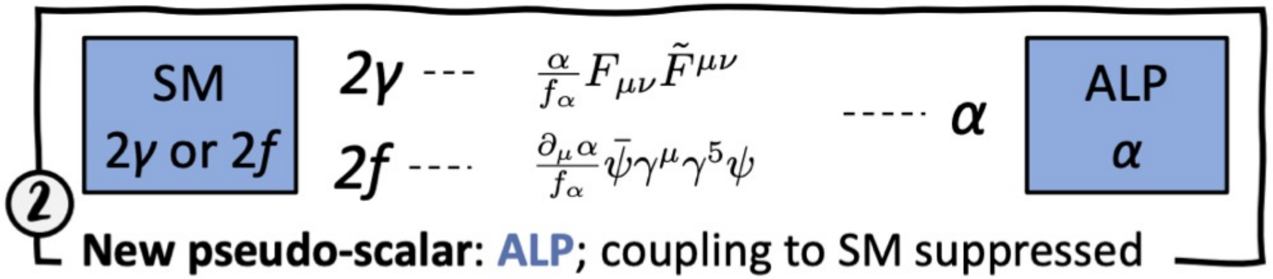


(Axion Like Particle)

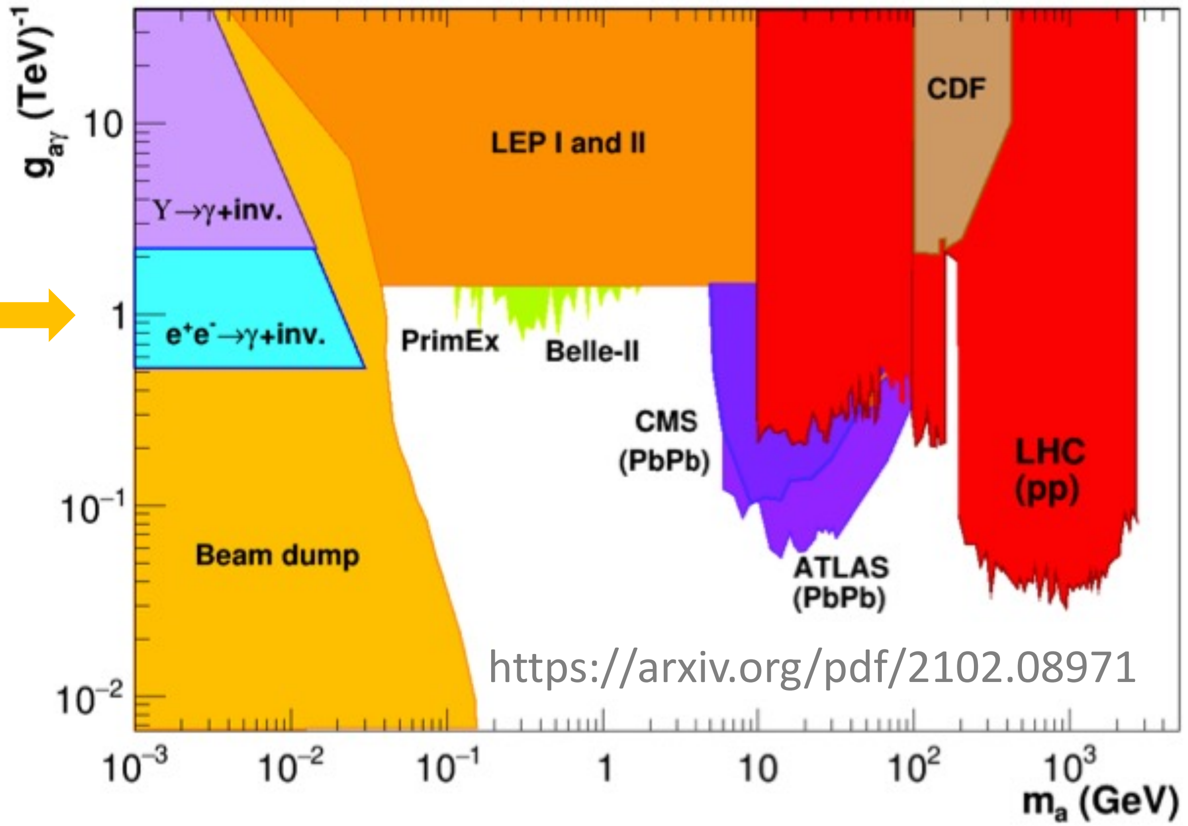
Pseudo-scalar Portal: Axion-like Particles

BOSTON UNIVERSITY





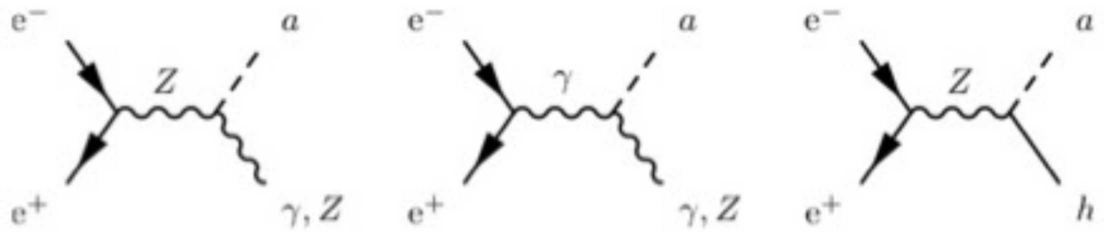
(Axion Like Particle)



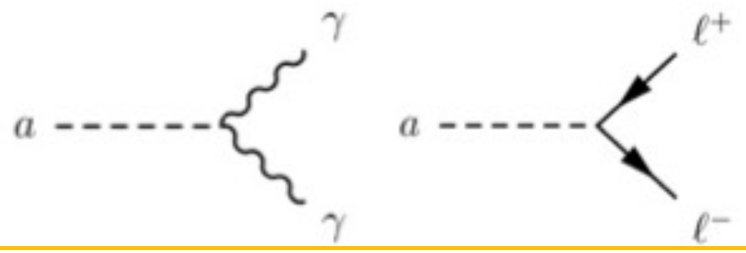
https://arxiv.org/pdf/2102.08971

Case Study: Axion-like Particles

"Standard" approach:

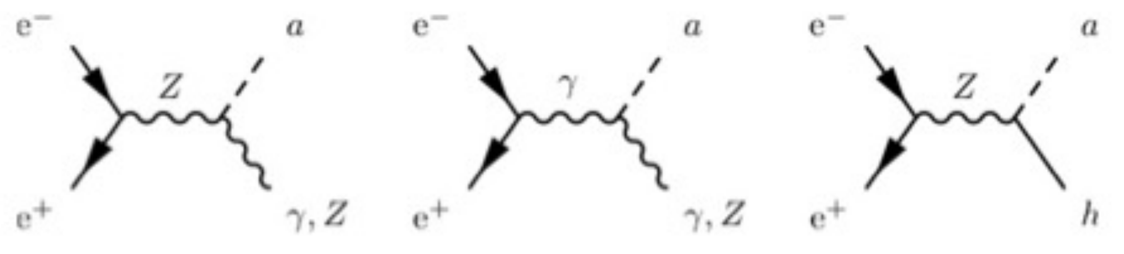


With decays:

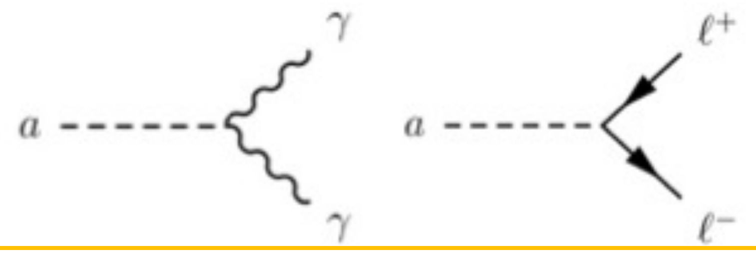


Case Study: Axion-like Particles

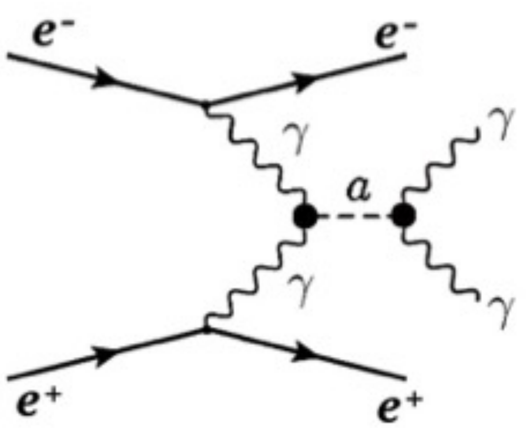
"Standard" approach:

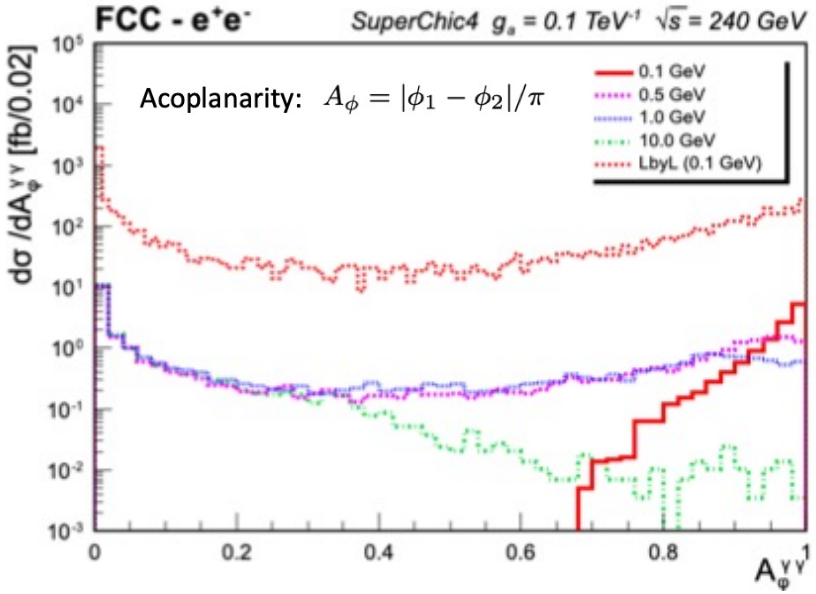


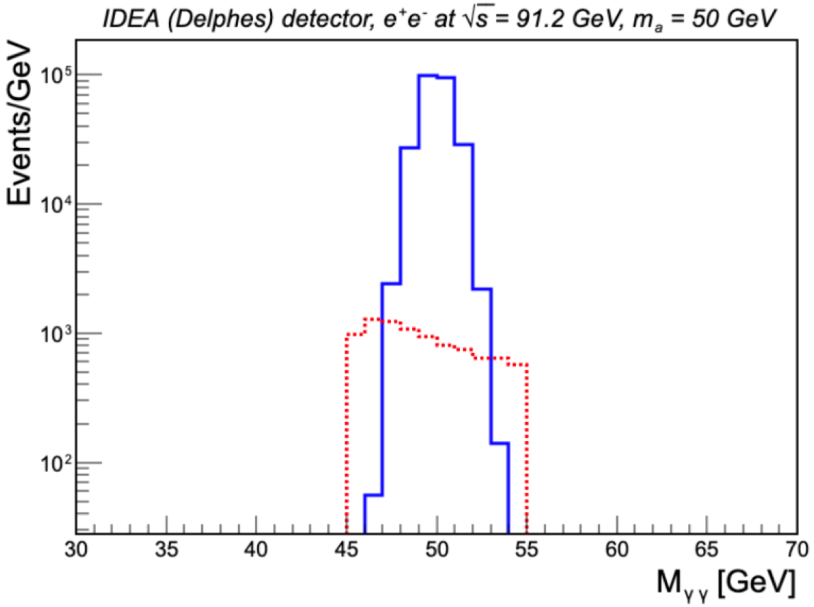
With decays:



ALP production via photon-photon fusion: Using SC4 MC generator for the ALP signal and Light-by-Light continuum background (irreducible background) + IDEA sim



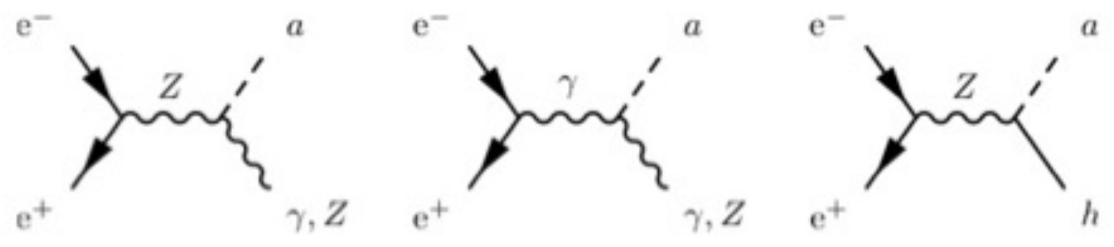




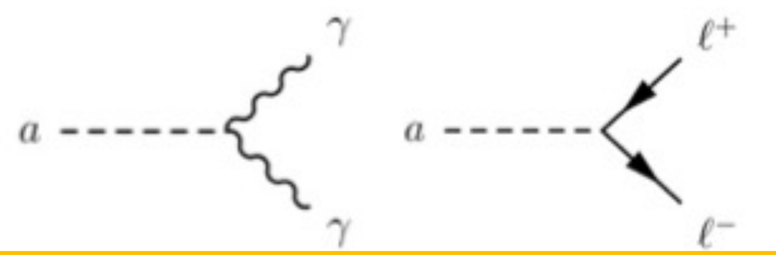
Case Study: Axion-like Particles

BOSTON UNIVERSITY

"Standard" approach:

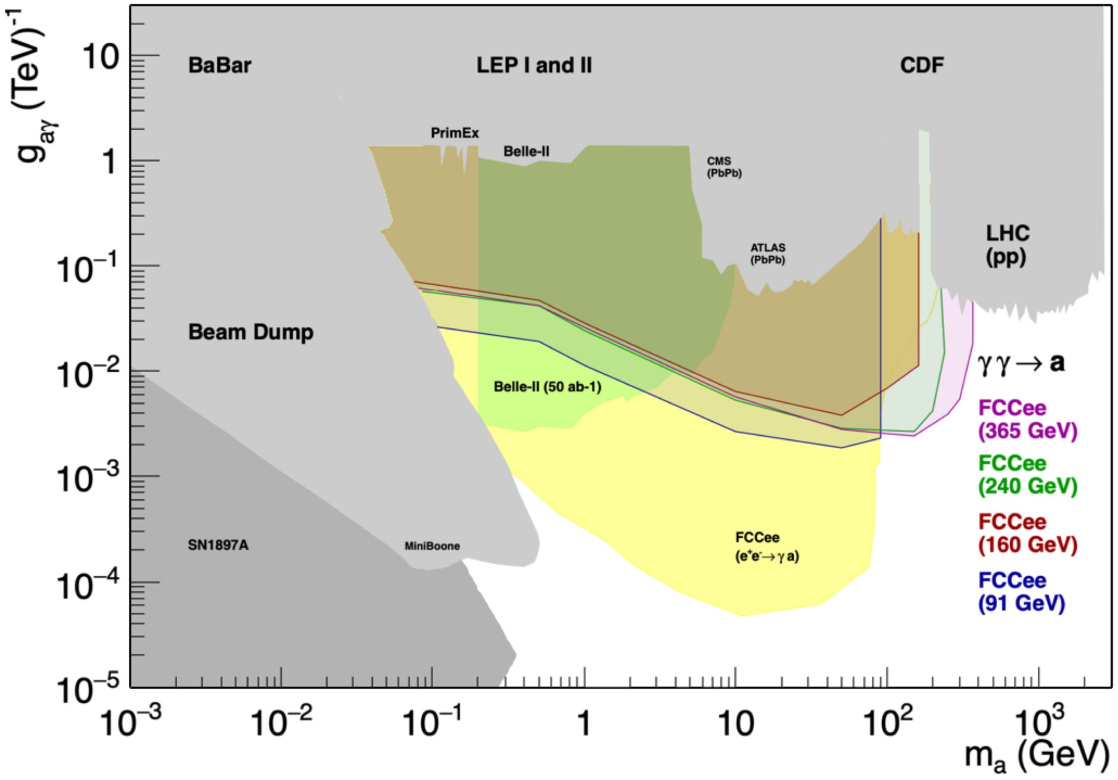


With decays:



- $\gamma\gamma \rightarrow a$ extends current LHC limits for m_a = 5 – 350GeV by 2(O) magnitude
- $e^+ e^- \rightarrow Z \rightarrow \gamma a$ extends current LHC limits for m_a = 0.1 – 90 GeV by 3(O) magnitude

For low ALP mass, sophisticated detectors & techniques are needed to isolate the overlapping photons



Neutrino Portal: Heavy Neutral Leptons

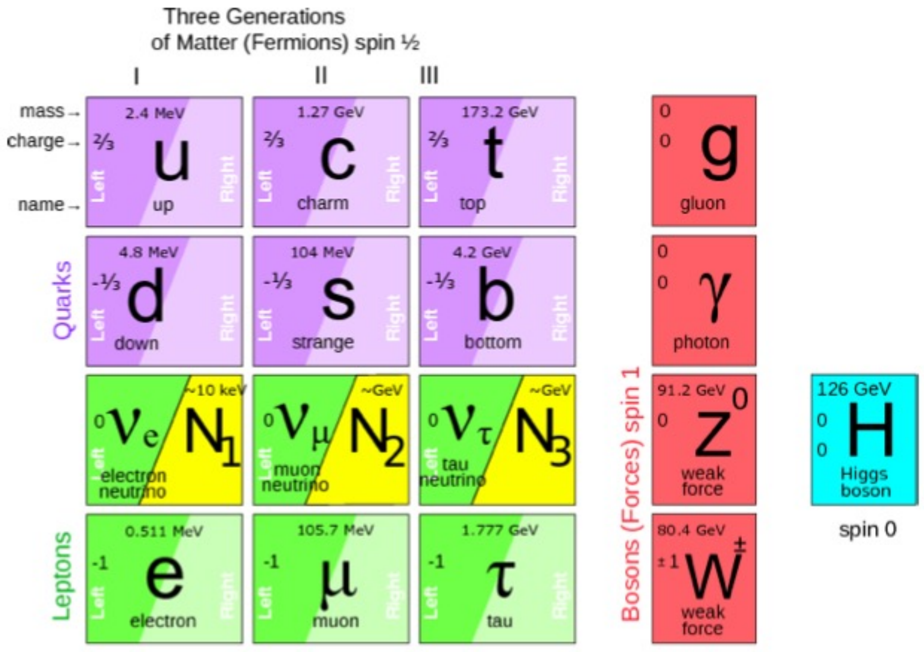
BOSTON UNIVERSITY

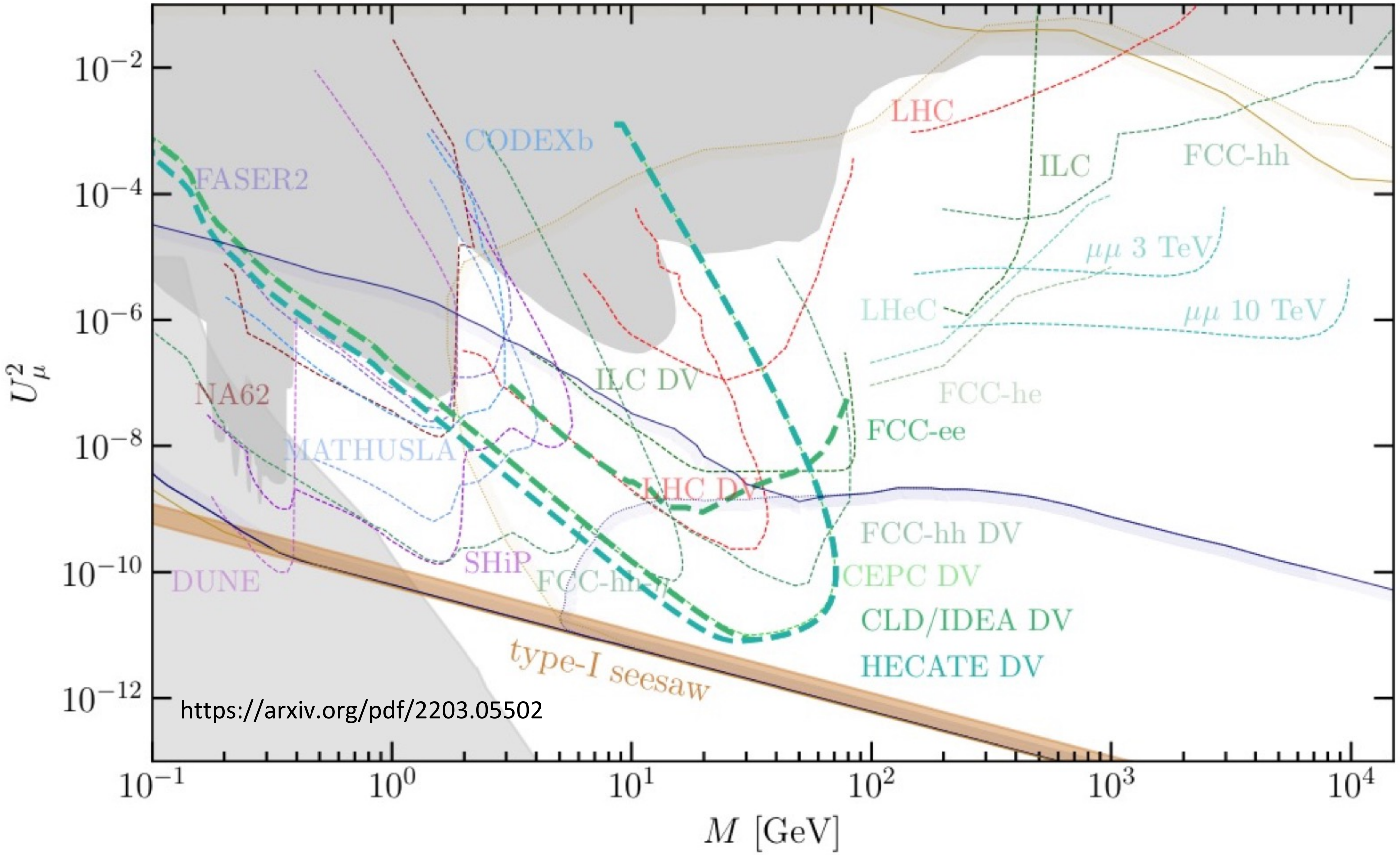
SM LH ν — ν — $y_N h L \psi_D$ — N — **HNL** N

④ **New fermion: HNL; coupling to LH SM and h ∝ y_N**

(Heavy Neutral Lepton)

One of the renormalizable portals to dark sectors. Could also address : Neutrino masses via seesaw mechanism, Baryogenesis via leptogenesis and oscillation anomalies…

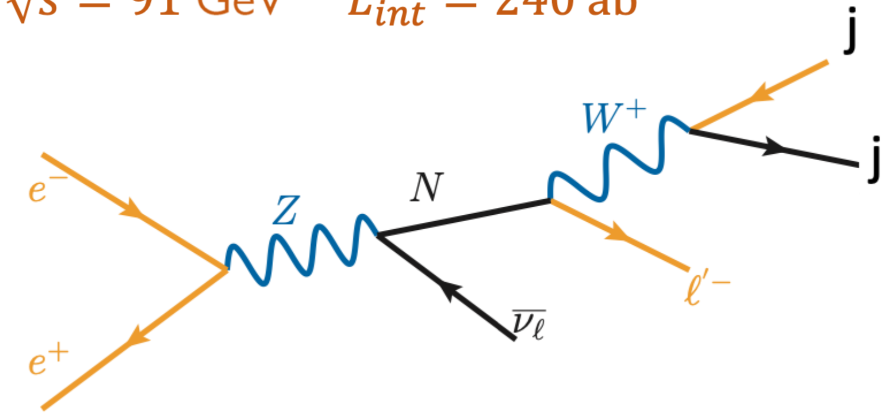




Case Study: Prompt & Displaced HNL- μjj

BOSTON UNIVERSITY

$\sqrt{s} = 91$ GeV $L_{int} = 240\ \text{ab}^{-1}$



High production rate. (~50% of the BR)

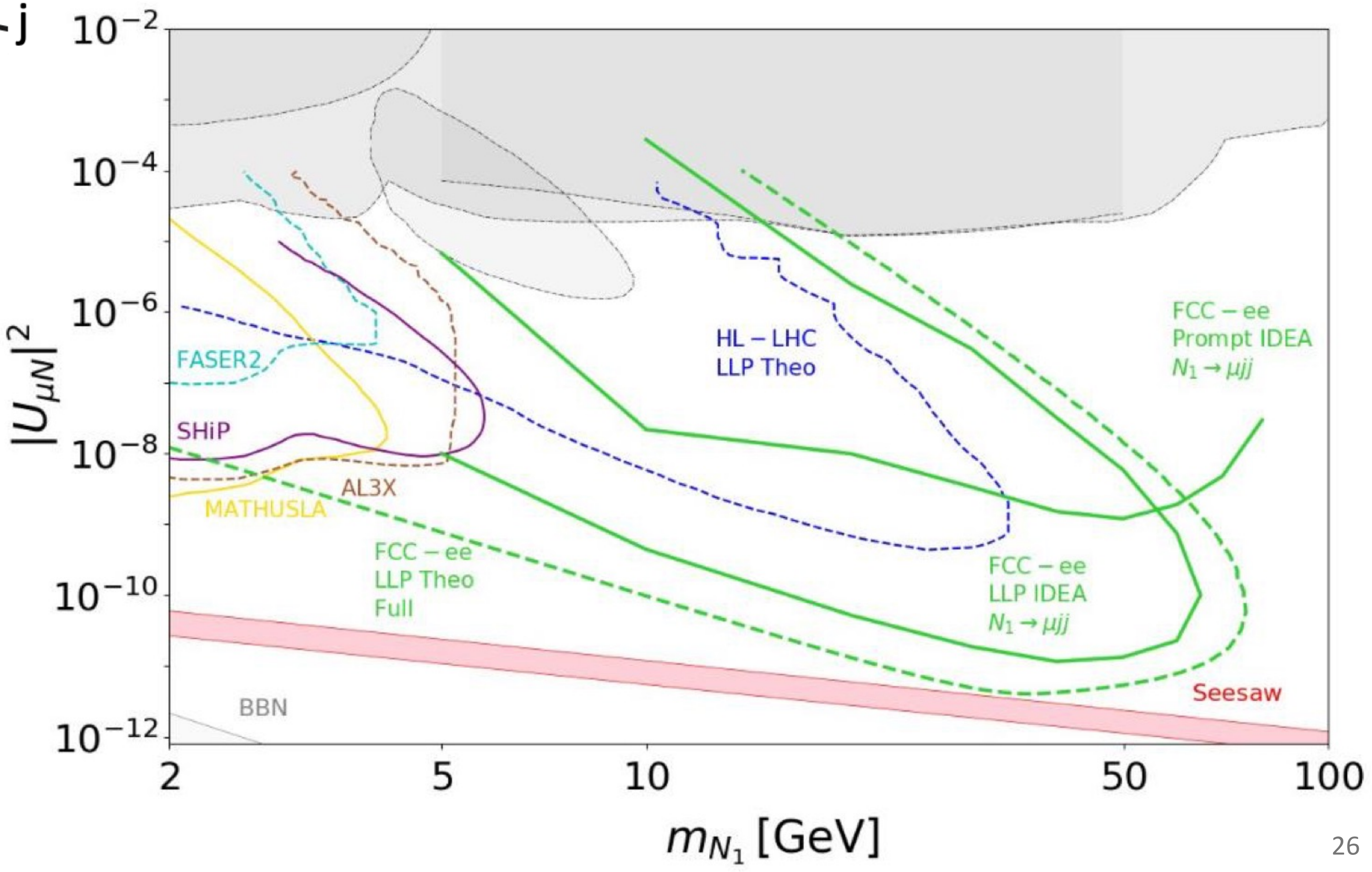
Jets can be well separated or collimated.

Primary backgrounds from Z :

- $Z \to bb/cc/uds,\ Z \to \mu\mu\ /\ \tau\tau$
- $e\ e \to \mu\nu qq$ => irreducible

Prompt selection: 1 muon, 1 or 2 jets, good PV

Displaced selection: Radial vertex position > 0.5 mm

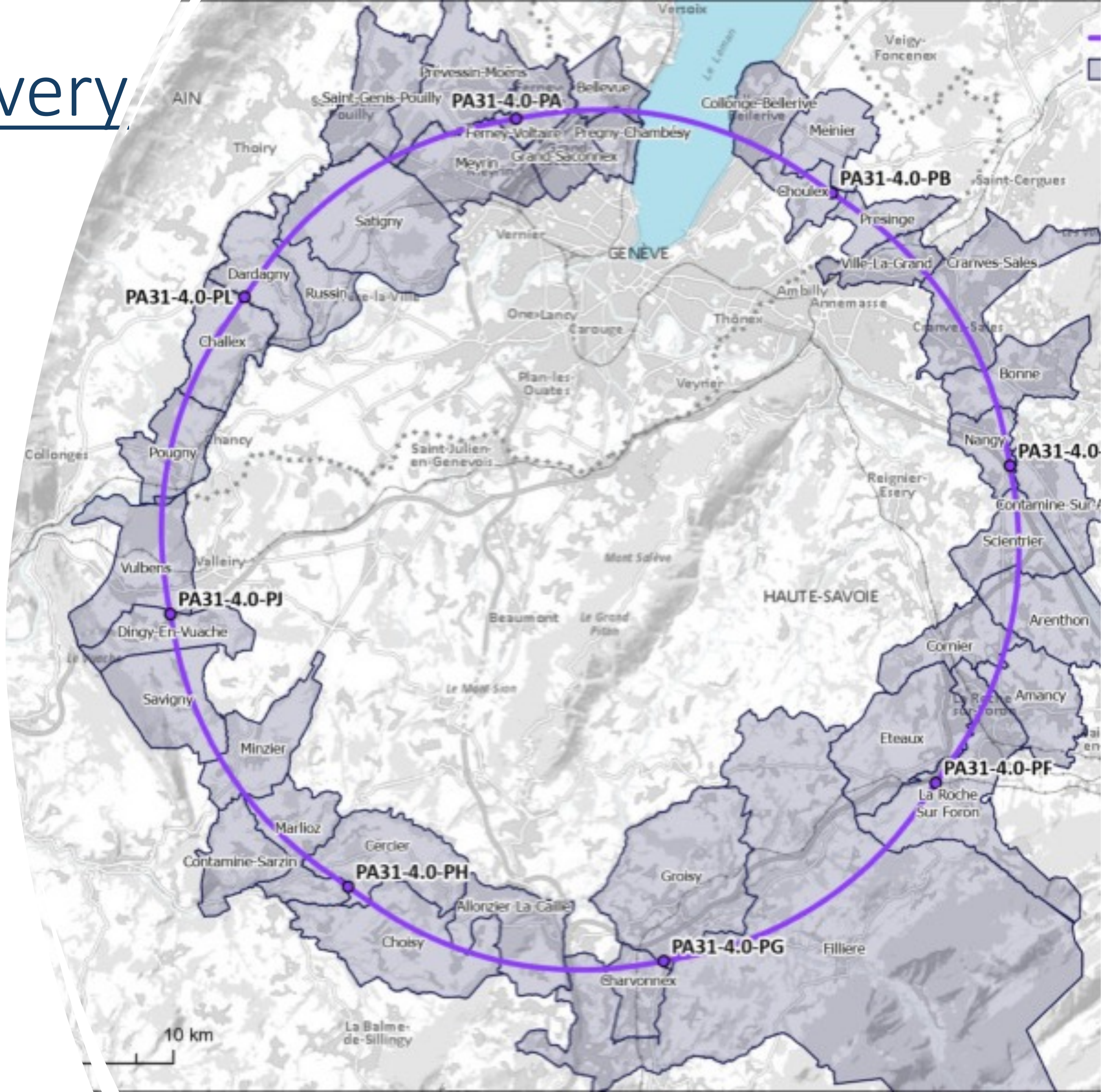


FCC: A Gateway to Discovery

Today's Focus: Dark sector signals, including Heavy Neutral Leptons, Axion-like particles, and exotic Higgs decays.

Beyond the Dark Sector: The FCC offers numerous Beyond Standard Model (BSM) opportunities, with the Z pole and ZH pole runs being especially crucial. The FCC presents a large and unique phase space for exploration.

Let's design our detectors to maximize these opportunities!



From P. Azzi's slides

FCC 10

arXiv:2106.13885

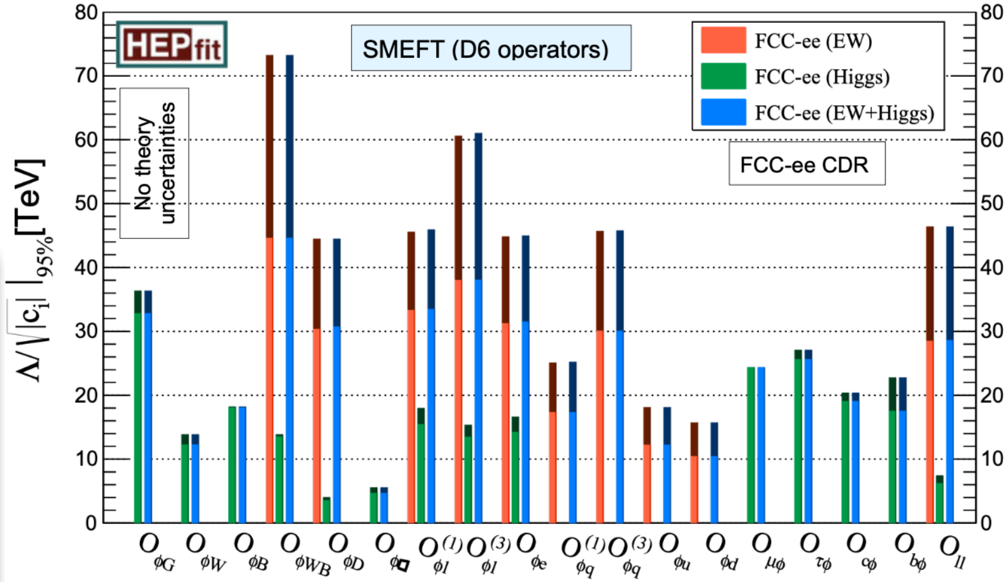
Indirect BSM sensitivity from EWPO

- **Target: reduce syst. uncertainties to the level of statistical**
- Exquisite √s precision (100keV@Z, 300keV@WW)
- ~50 times better precision than LEP/LSD on EW precision observables

Need TH results to fully exploit Tera-Z

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement†
m_Z Γ_Z $\sin^2\theta^\ell_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to4f$ or EFT frame-work)	NNLO for $ee\to WW$, $W\to f\bar{f}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
$m_{\rm top}$	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

†The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.



Indirect sensitivity to 70TeV-scale sector connected to EW/Higgs

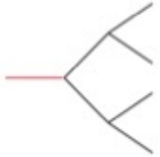
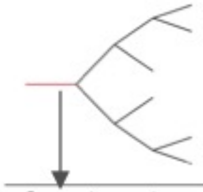
M. Carena Slides

BOSTON UNIVERSITY

Higgs exotic decays: a rich variety of possibilities

- Focus on 2-body Higgs decays to BSM particles with subsequent decays to BSM or SM particles
- These processes are well-motivated by SM + Scalar singlets, 2HDMs (+ Scalar), SUSY models, gauge SM extensions (e.g. dark photons), SM + Fermion/s (e.g. Heavy Neutral leptons), etc.

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

HL-LHC has large number of Higgs produced (0.2 Billion), having great sensitivity to exotic decays into leptons and photons

All the rest: challenging at the LHC due to missing energy and/or hadronic background

(HL-)LHC will provide valuable first-hand information on these challenging channels

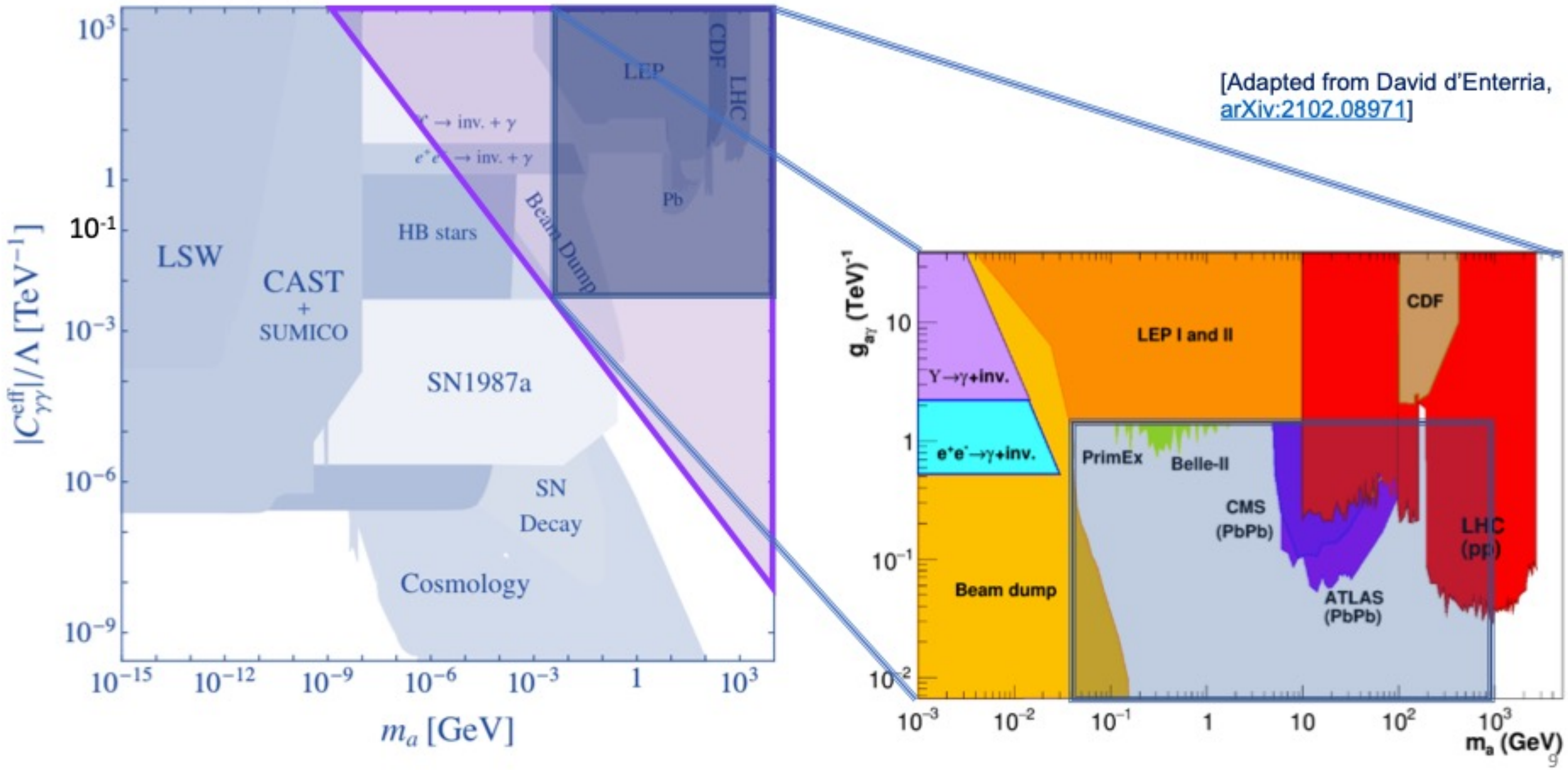
FCC-ee will have great opportunities to cover these searches

Z. Liu et al. arXiv:1312.4992 ; arXiv:1612.09284

21 03-25-2024 Marcela Carena I BSM FCC-ee opportunities Fermilab

BOSTON UNIVERSITY

Zooming in the colliders region



HNL Full Cuts

1. Event Filter	2. Event Selection	3. Vertex selection
1 muon ≥ 3 tracks $E_\mu \geq 3$ GeV $E_{miss} \geq 5$ GeV	1 lepton (muon) Cuts on p_{miss}, jets, μ and visible mass	$N_{tracks} - N_{tracks}^{primary} < 5$ $\chi^2_{vtx,primary} < 10$
4. Mass-dependent kin. selection	**5a. Displacement: prompt**	**5b. Displacement: LL**
M_{vis} within $2 \times 10\%\sqrt{M}$ E_{miss} within $2 \times 10\%\sqrt{p_\nu}$	$r_{vert}^{primary} > 0.5$ mm $D_{0,\mu} < 8\sigma$ if $M_{N_1} > 70$	$r_{vert}^{primary} < 0.5$ mm