Direct BSM searches at FCC
An overview

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BSM potential of FCC

Approaches:

- Direct detection of signals for new particles
- Precision measurements: deviations from SM expectation

Machines:

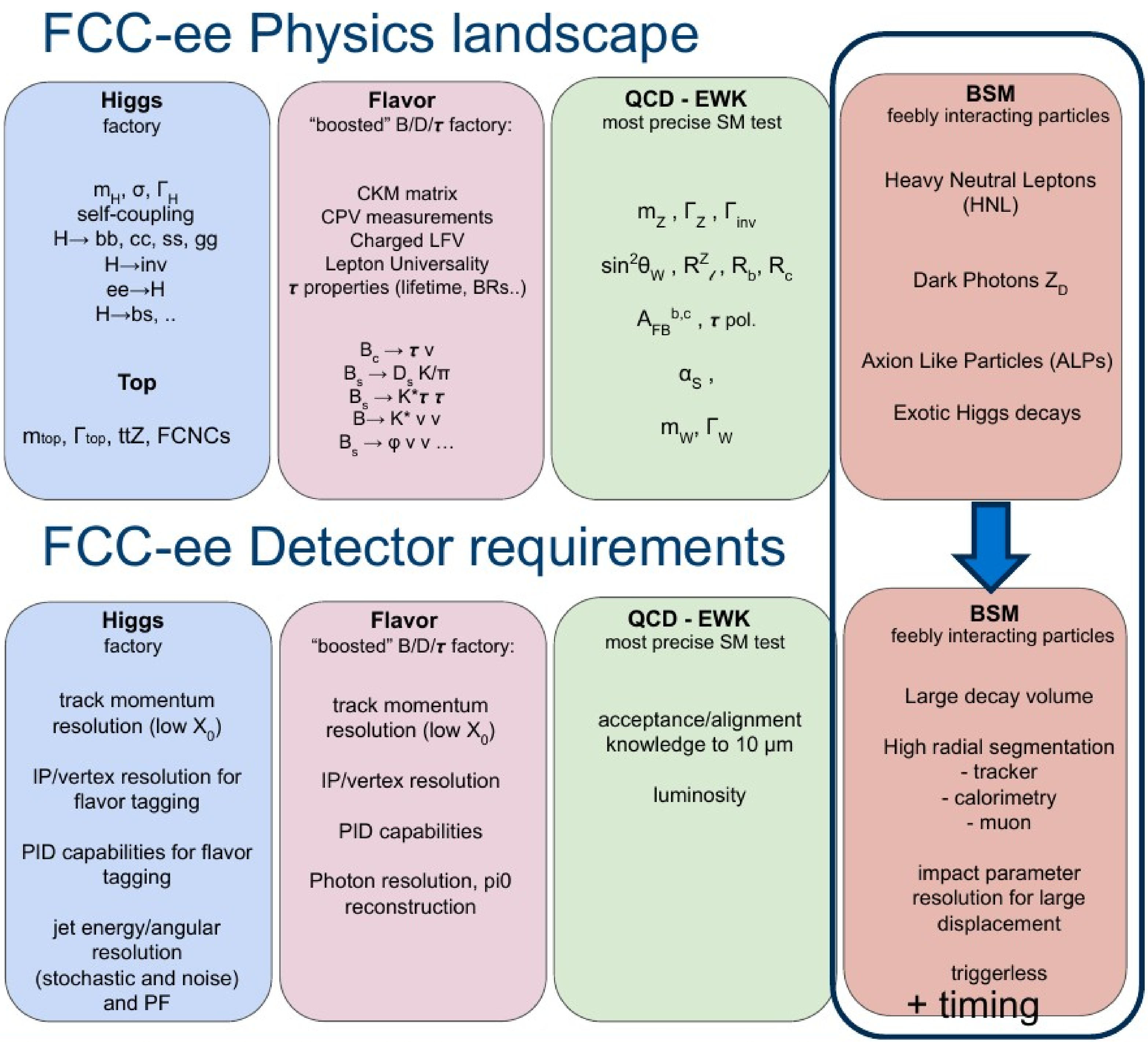
- FCC-ee: precision machine: clean environment, limited CMS range, very high statistics
- Fcc-hh: discovery machine: explore new energy regime

Main experimental thrust of PED BSM group:

- Define promising scenarios for direct BSM search at FCC-ee
- Requirements on detector design on the basis of detailed physics studies: recent work focused towards midterm report

Topic brilliantly reviewed at last FCC week by S. Williams and N. Valle. I'll heavily rely on these two talks

FCC-ee: physics vs detector requirements



FCC-ee Physics landscape

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \rightarrow \tau\nu$
$B_s \rightarrow D_s K/\pi$
$B_s \rightarrow K^* \tau\tau$
$B \rightarrow K^* \nu\nu$
$B_s \rightarrow \varphi\nu\nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

FCC-ee Detector requirements

Higgs
factory

track momentum
resolution (low X_0)

IP/vertex resolution for
flavor tagging

PID capabilities for flavor
tagging

jet energy/angular
resolution
(stochastic and noise)
and PF

Flavor
"boosted" B/D/τ factory:

track momentum
resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0
reconstruction

QCD - EWK
most precise SM test

acceptance/alignment
knowledge to 10 μm

luminosity

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

impact parameter
resolution for large
displacement

triggerless

\+ timing

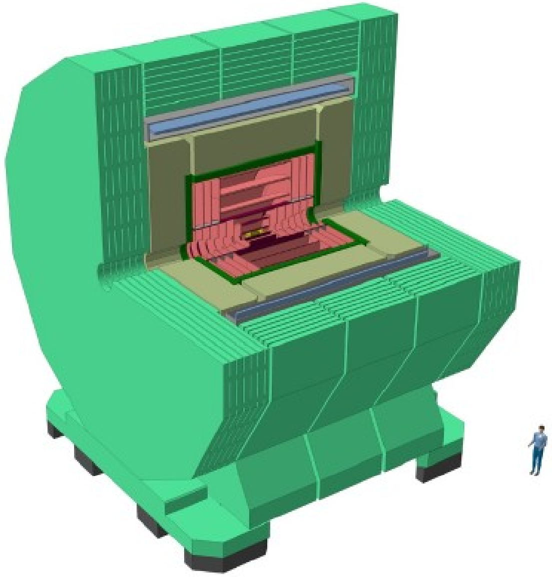
FCC has very large menu of physics topics

Each of these poses a specific experimental challenge and pushes detector optimisation

Unique challenges from BSM: long-lived particles

Detector concepts at FCC-ee

CLD ("CLIC-like Detector")

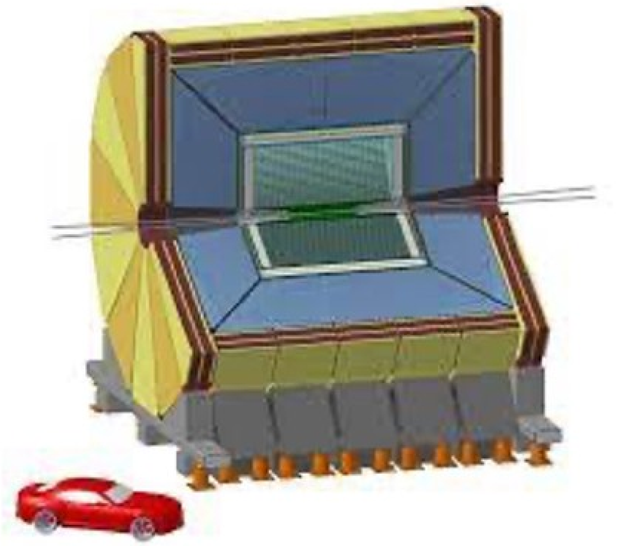


Full silicon vertex-detector+ tracker

3D high-granularity calorimeter

Solenoid outside calorimeter

IDEA ("Innovative Detector for Electron-positron Accelerator")



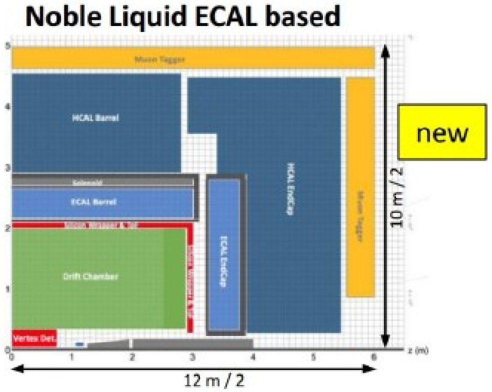
Silicon vertex detector

Short-drift chamber tracker.

Dual-readout calorimeter (solenoid inside)

…Plus new proposals …

(easy to test in FCCSW setup)

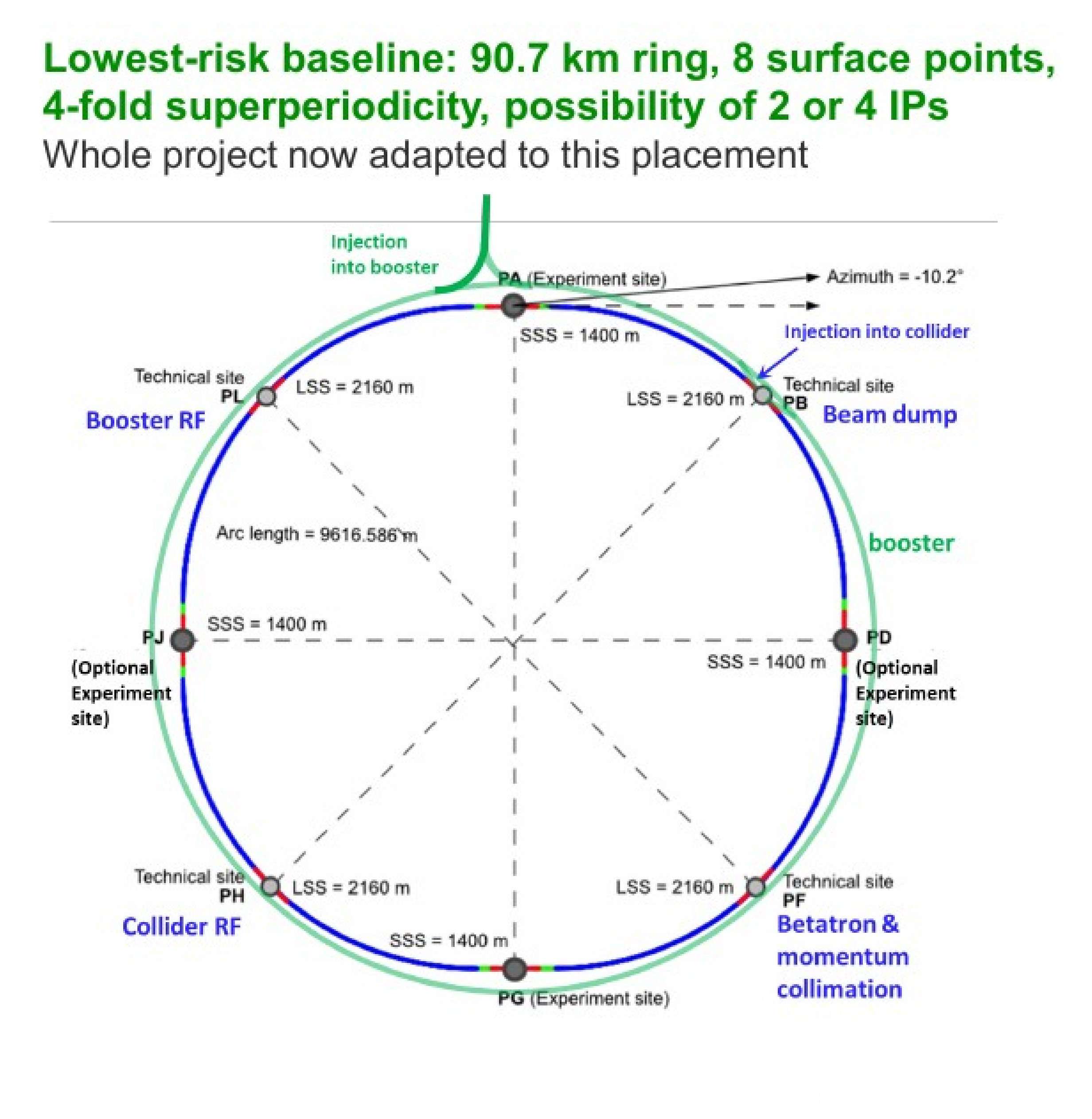


Note: all studies in this talk use the IDEA detector card in Delphes

Luminosity scenario

4 Interaction points (IP):
For Z pole run assume an Integrated luminosity of 240 ab-^{1}, corresponding to 8 10^{12} Z

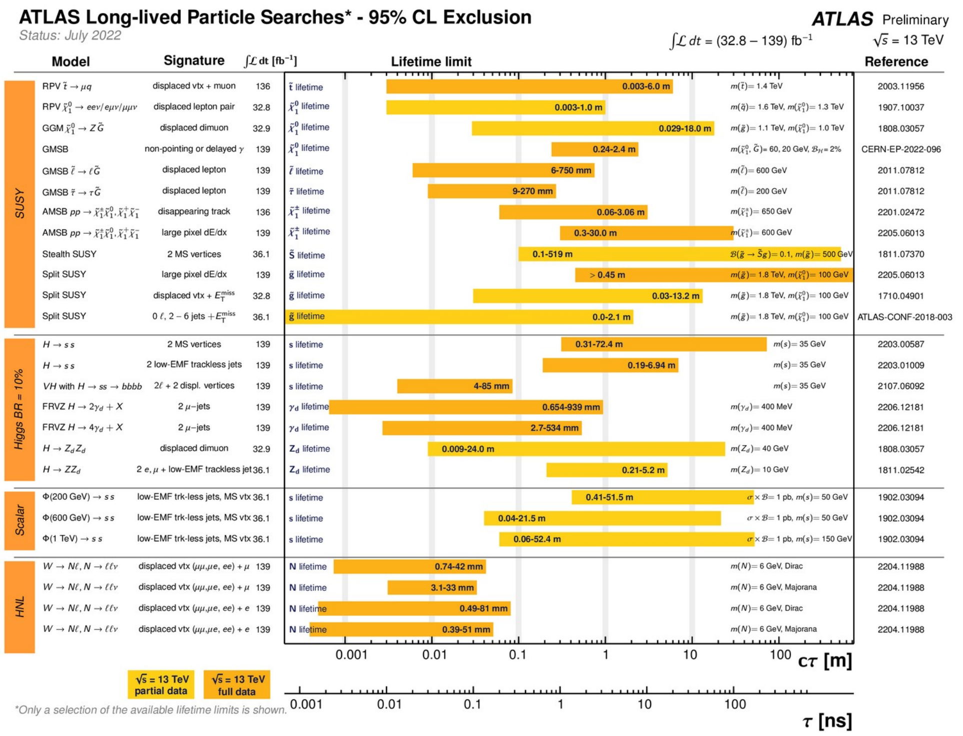
Most studies still based on old benchmark: 2 IP, 150 ab^{-1}



Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs

Whole project now adapted to this placement

BSM:The broader research goal



At the end of the HL-LHC, if no BSM found:

Top -down approach (theo):

Develop solutions to big issues:

naturalness, etc. compatible with LHC data

Bottom-up approach (exp):

Among well-motivated models: FCC-ee signatures to which LHC not sensitive

- Low mass: obligated, but also opportunity, LHC typically reduced sensitivity at low masses
- Low couplings: profit from TeraZ statistics, and better analysis efficiency because of cleaner environment

→ Long lived particles

List of topics

Cross-check the list of ECFA-WRG1-SRCH (Rebeca Gonzalez-Suarez is convener both for us and for that group)

- Heavy Neutral Leptons *
- Exotic Higgs boson decays *
- Light SUSY scenarios and scenarios with light scalars
- Axion-like particles (ALP) *
- Z’, dark photons and other light mediator scenarios

For items with * organised activity in our community, which I will review in this talk

Group organisation

Exp Conveners:

Rebeca Gonzalez-Suarez, GP

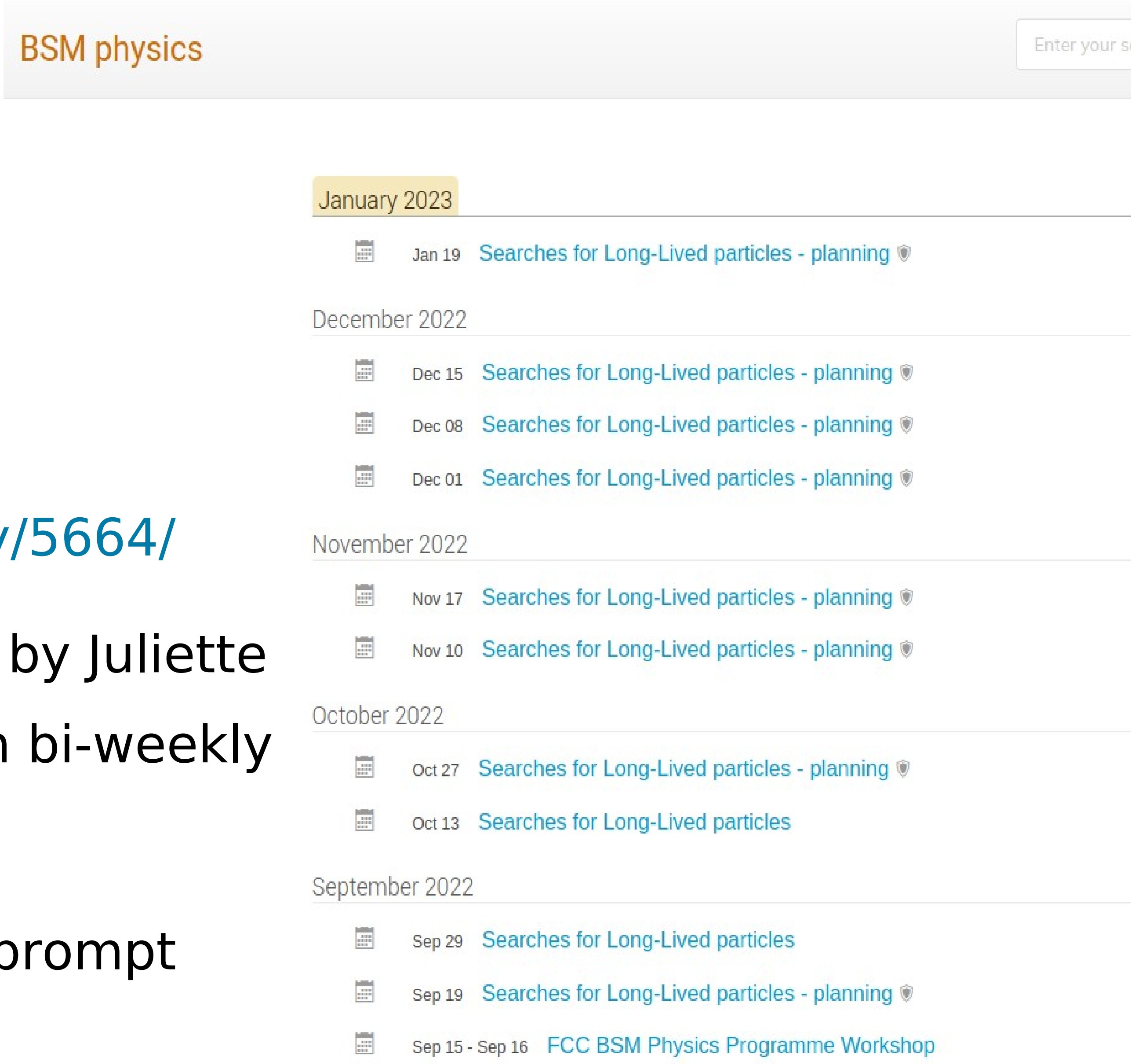
MC contact: Sarah Williams

Indico category:

https://indico.cern.ch/category/5664/

Very active LLP group chaired by Juliette Alimena (~10-15 people) with bi-weekly working meetings

Approaching critical mass for prompt signatures



BSM physics

January 2023

Jan 19 Searches for Long-Lived particles - planning

December 2022

Dec 15 Searches for Long-Lived particles - planning

Dec 08 Searches for Long-Lived particles - planning

Dec 01 Searches for Long-Lived particles - planning

November 2022

Nov 17 Searches for Long-Lived particles - planning

Nov 10 Searches for Long-Lived particles - planning

October 2022

Oct 27 Searches for Long-Lived particles - planning

Oct 13 Searches for Long-Lived particles

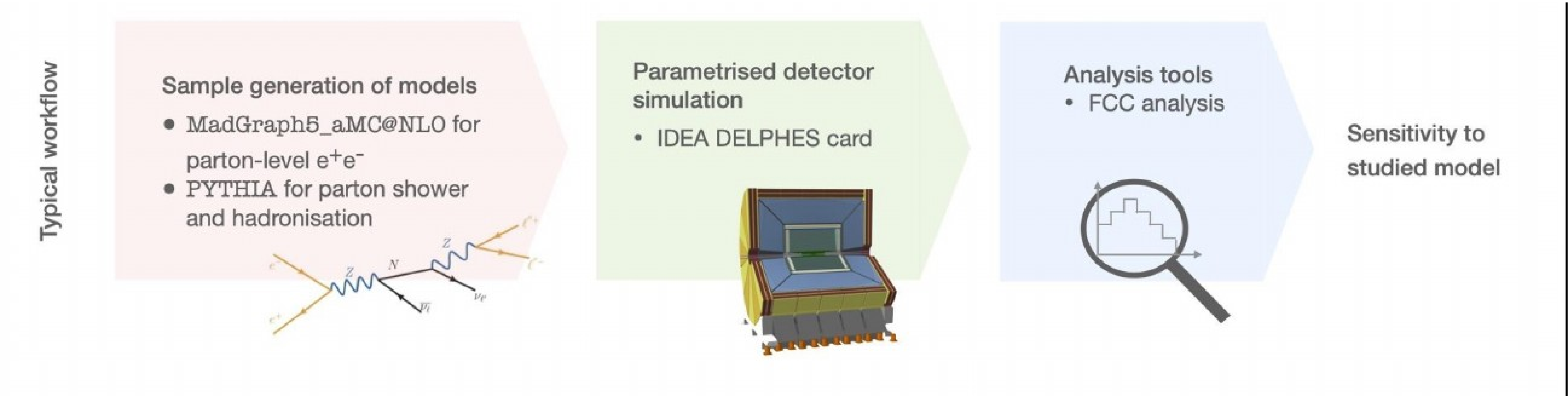
September 2022

Sep 29 Searches for Long-Lived particles

Sep 19 Searches for Long-Lived particles - planning

Sep 15 - Sep 16 FCC BSM Physics Programme Workshop

Workflow



Typical workflow

Sample generation of models
- MadGraph5_aMC@NLO for parton-level e^+e^-
- PYTHIA for parton shower and hadronisation

Parametrised detector simulation
- IDEA DELPHES card

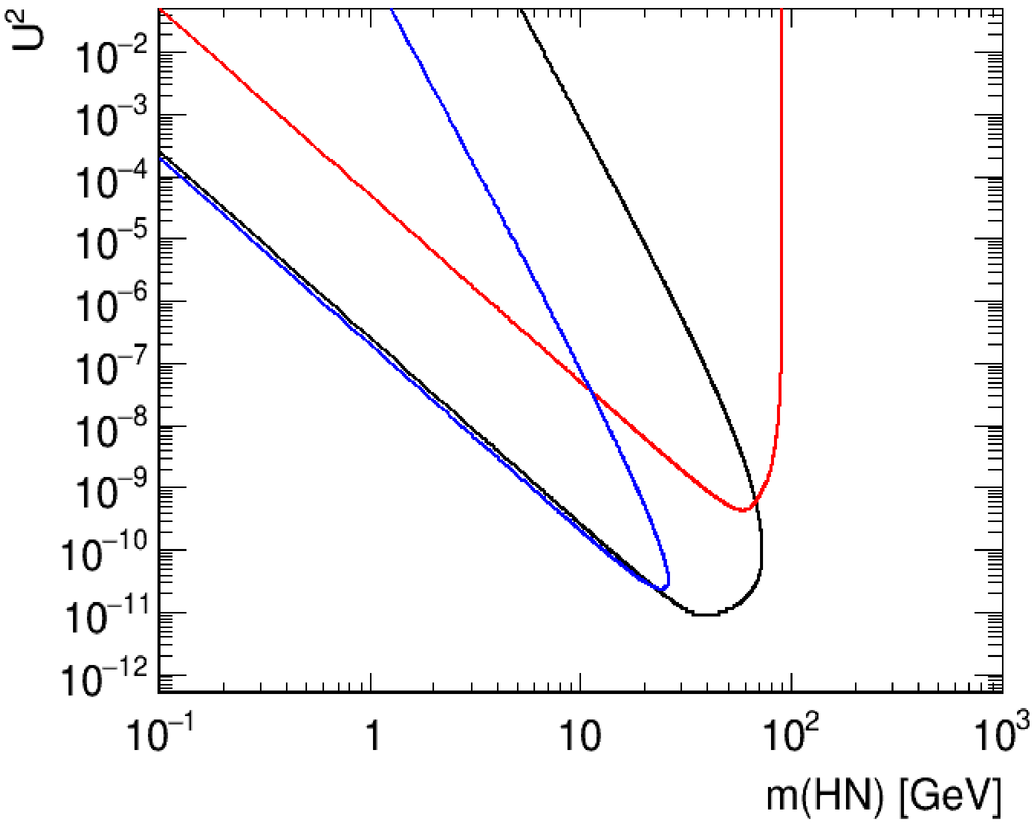
Analysis tools
- FCC analysis

Sensitivity to studied model

- Background files produced centrally based on FCC software.
- Signal files produced either centrally or by analysis group.
- DELPHES output stored in EDM4HEP format
- Use FCCsoftware to produce ntuples for analysis based on FCCanalysis package
- Two large production campaigns, spring2021 and winter2023
    - Main limitation: statistics at peak

Prompt vs LLP

Generically reach is defined in m(new physics)-coupling plane
True e.g for ALP, HNL



Complementary reach of three different signatures:

- Prompt
- Decay in inner detector
- Decay in calo/muon detector

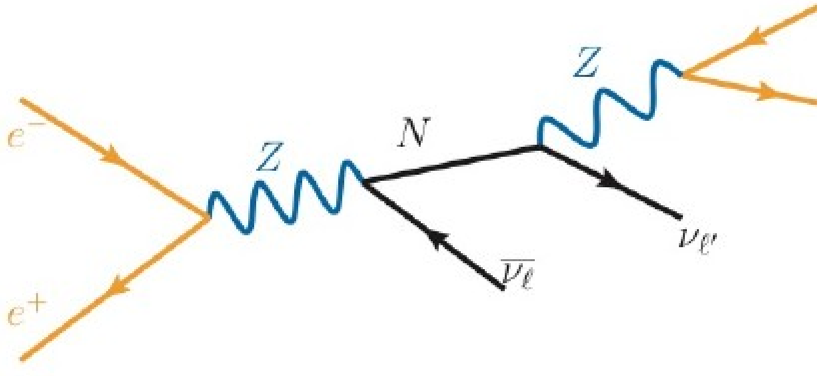
Study of coverage for a given model should address all three signatures.

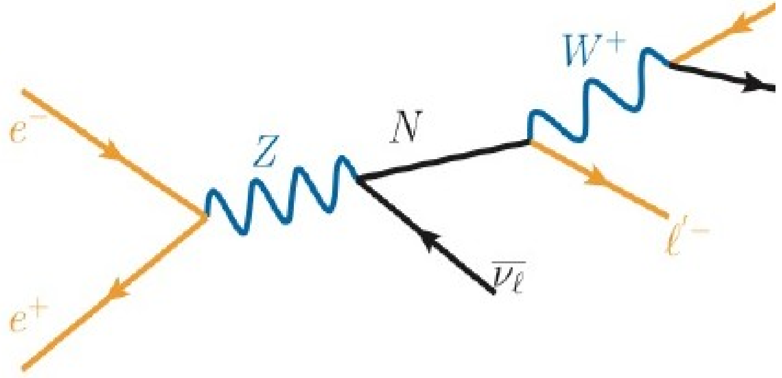
Very different experimental requirements

At present only first two exploited

HNL potential

Production of HNL in Z decay through mixing with light neutrinos





If only 1 HNL flavour assumed, model defined in terms of two parameters: m_N and U, mixing parameter

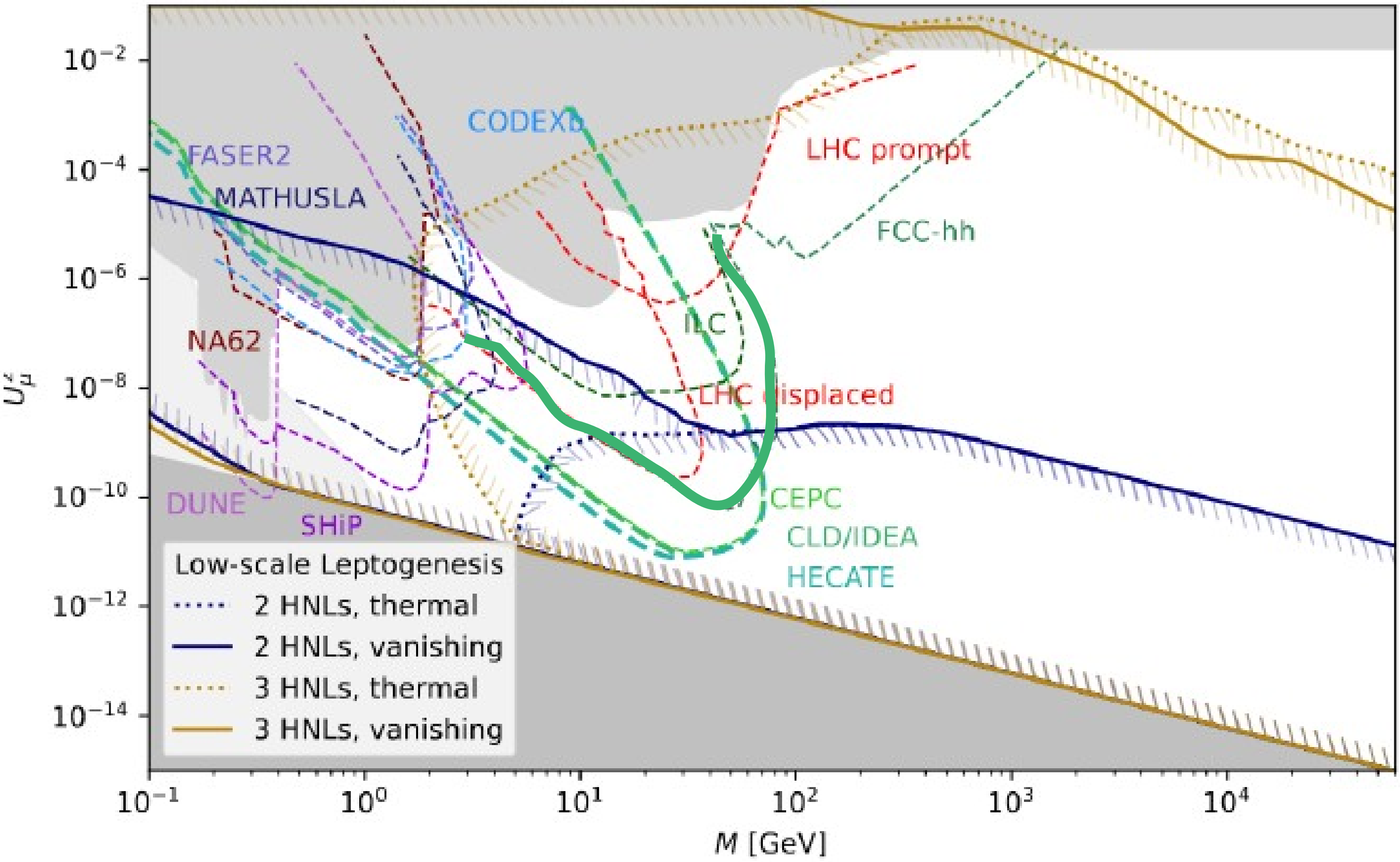
Production BR:
$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2\,\mathrm{BR}(Z \to \mathrm{invisible})\left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right)\left(1 - \frac{{m_N}^2}{{m_Z}^2}\right)$$
$$|U_N|^2 \equiv \sum_{\ell=e,\mu,\tau}|U_{\ell N}|^2$$

Decay width:
(m_{HN}<80 GeV)
$$\Gamma_N \simeq c_{\mathrm{dec}}\frac{a}{96\pi^3}U^2M^5G_F^2$$

a~12
M.Drewes arXiv:2210.17110

Expectations

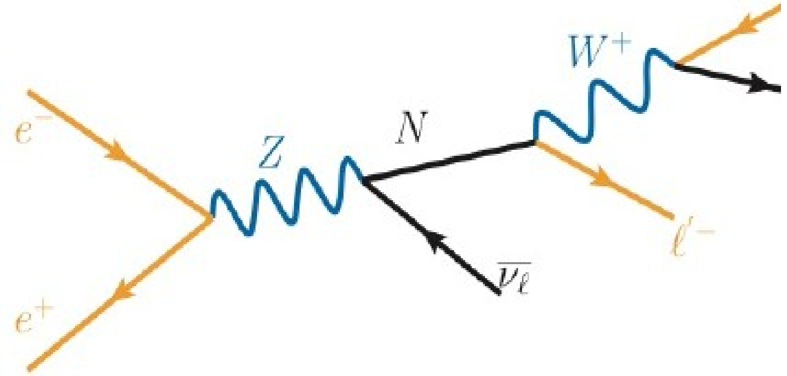
ArXiv:2203.05502



Assume for FCC-ee 5x10^{12} Z produced (to update)

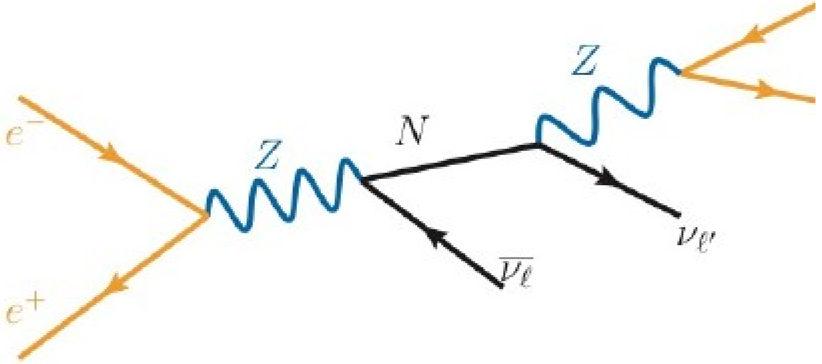
Thick green line: approximate CEPC reach

Decay signatures



l^+ q

ν q’



l^+ q

l^- q

Analysis matrix: for HNL

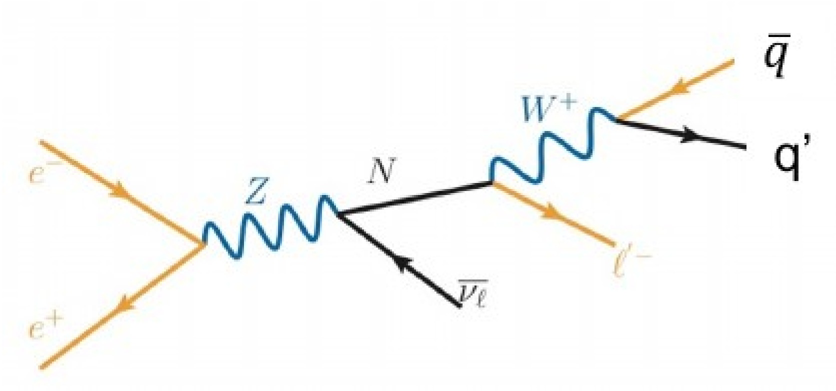
- Decay final state (l=e,μ):
  - j j l ~50% *
  - j j’ nu ~20%
  - l l nu ~5% *
  - l l’ nu ~9%
  - l τ nu ~9%

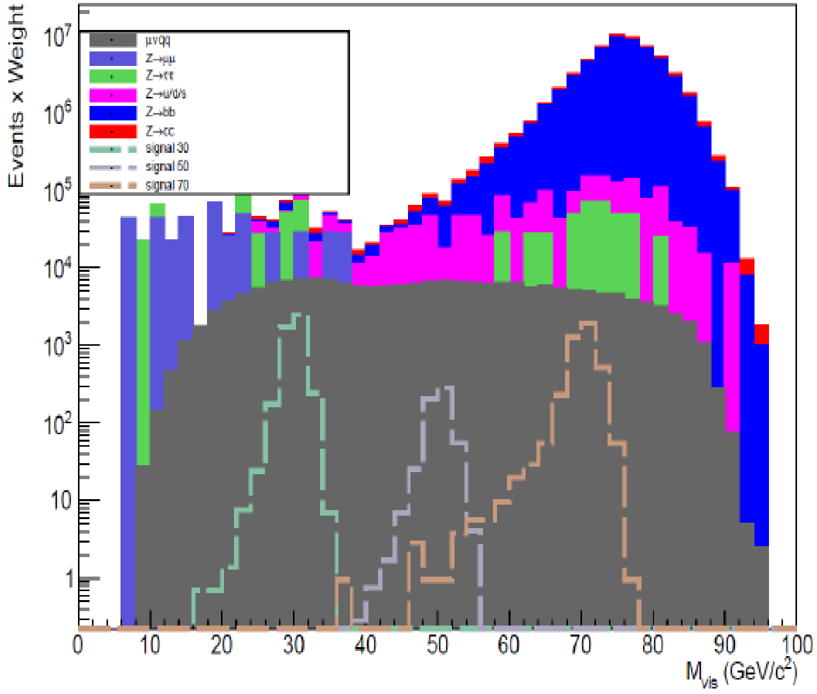
  (BRs for m_{HN}<80 GeV)
- Decay lengths
  - Prompt
  - LL decay In ID
  - LL decay in Calo

Signatures with * studied in group

HNL→ μjj (prompt+LL)

GP, Nicolò Valle





- Most favourable decay: 50% cross-section
- Full reconstruction of HNL possible.
- Momentum of neutrino recoiling against HNL fixed by recoil formula:

$$p_\nu(M_{N_1}) = \frac{M_Z^2 - M_{N_1}^2}{2\,M_Z}$$

Strong kinematic constraints allow background suppression

Prompt analysis at Z peak:

Reducible backgrounds:

Z decays, dominated by Zbb

Irreducible background:

4-body μ ν qq

GP, Nicolò Valle

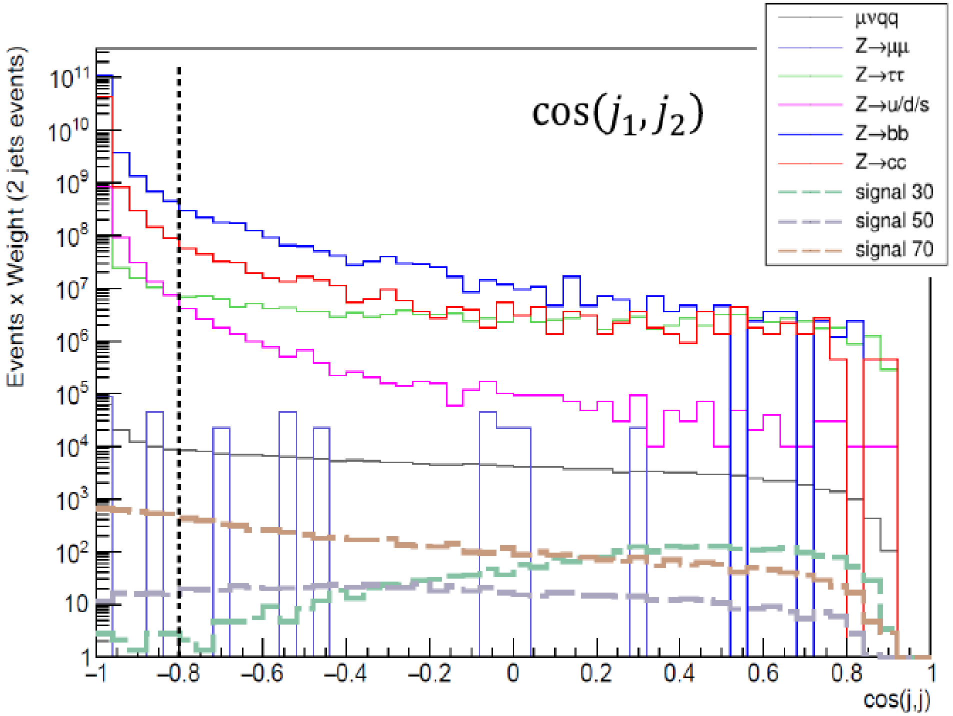
HNL→ μjj (prompt+LL)

Require one or two jets and one muon

Reject backgrounds using cuts on kinematic variables

Example: for 2-jet events, the two jets are dominantly back to back, this is not the case for the signal

After cuts, for each test mass require



$$M_{vis} \in M_{HNL} \pm \Sigma \text{ and } E_{miss} \in p_{\nu,nominal} \pm \Sigma$$

Σ = 2 × 20% × M HNL

Finally, require muon from HNL to come from interaction point:

$$D_{0,\mu} < 8\,\sigma$$

With $D_{0\mu}$ impact parameter of muon wrt center of detector in Plane transverse to the beam

More details on selection in the talk by N. Valle referred in first slide

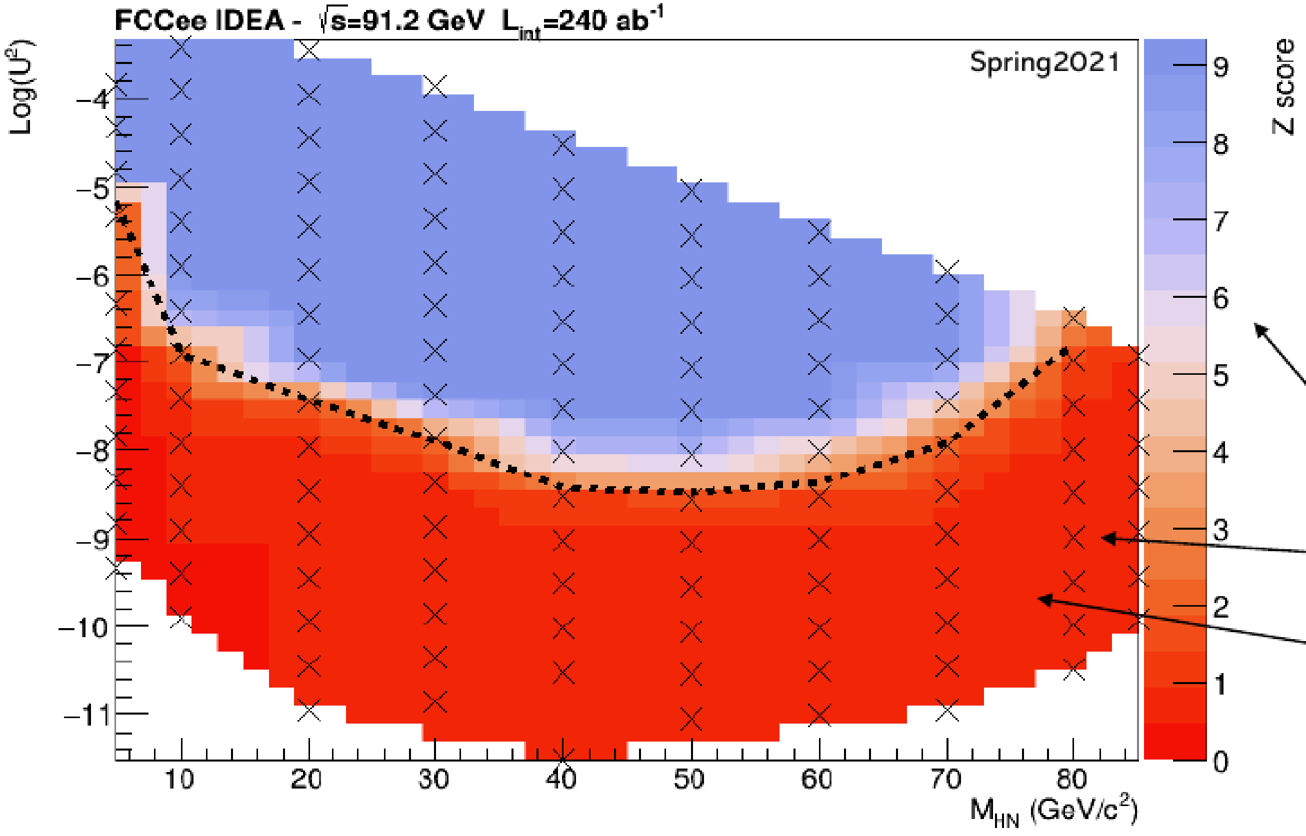
Prompt results

GP, Nicolò Valle

- Baseline: Integrated Lumi = **$240\ \mathrm{ab}^{-1}$** $\leftrightarrow 8\times10^{12}$ Z boson events
- Looking for U^2 producing 95% CL excess of events

For each HNL mass M: $P[n < b \mid HNL(M, U^2)] = 1 - \mathrm{CL}$

b = #background events



CL converted in gaussian quantile

Simulated signal data points

Delaunay interpolation in the plane

LL results

GP, Nicolò Valle

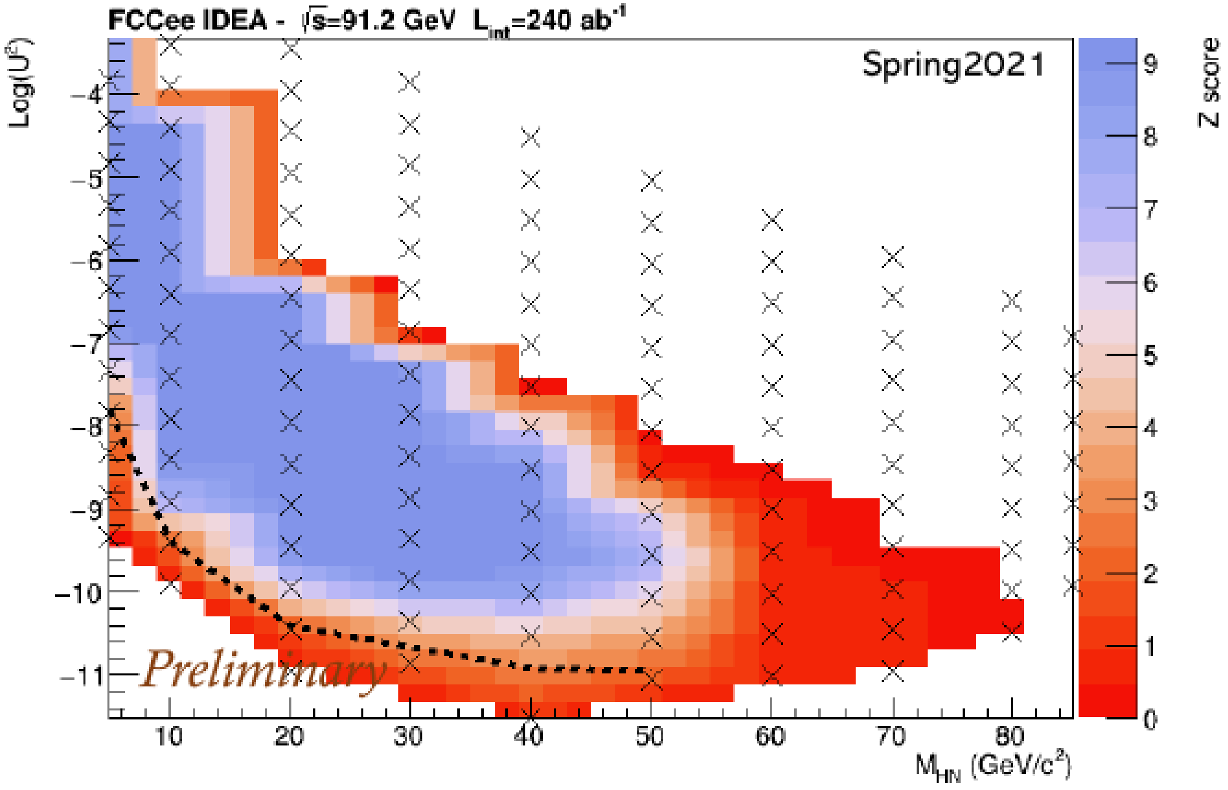
Low mass (≲ 40 GeV/c 2) HNL long-lived for couplings of interest, loss of efficency when requiring muon prompt

Background highly suppressed

Use detailed parameterization of IDEA tracking performance in DELPHES-FCC

Kinematic selection not modified, prompt background suppressed by D_μ > 1 mm

Signal efficiency kept > 50% at low mass and weak coupling



Work in progress on approach exploiting detailed HNL vertex reconstruction

A. Sfyrla, D. Moulin, P. Kontaxakis

HNL→ ejj prompt

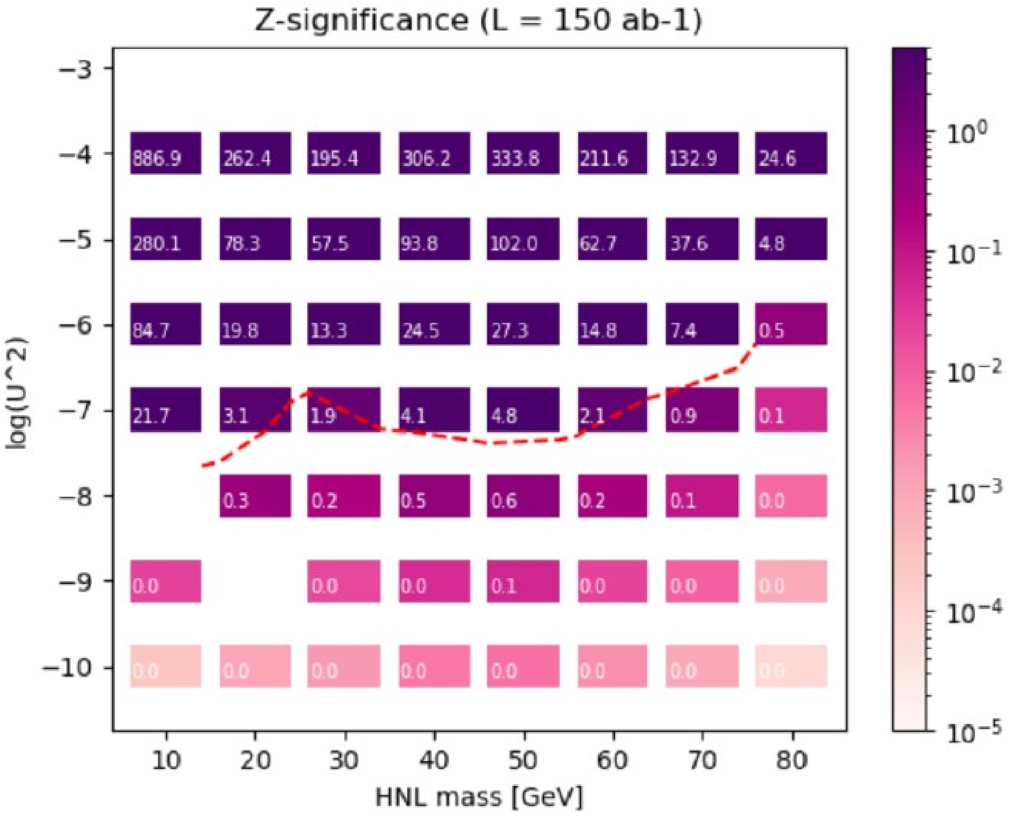
Selection: Require 2 jets and an electron

- $E_{miss} > 12$ GeV, accounts for neutrino fixed energy in 3-body decay
- Leading electron energy > 35 GeV, to remove most of the electron from jets
- $\theta(j_1\, j_2) < 2.4$ rad, distance electron dijet $\Delta R(e,jj) < 3$

- Official Winter2023 FCCee samples + samples generated with official data cards
- Jets built at the analysis level with the Durham algorithm in #jet = 2 mode

$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} = 2$$

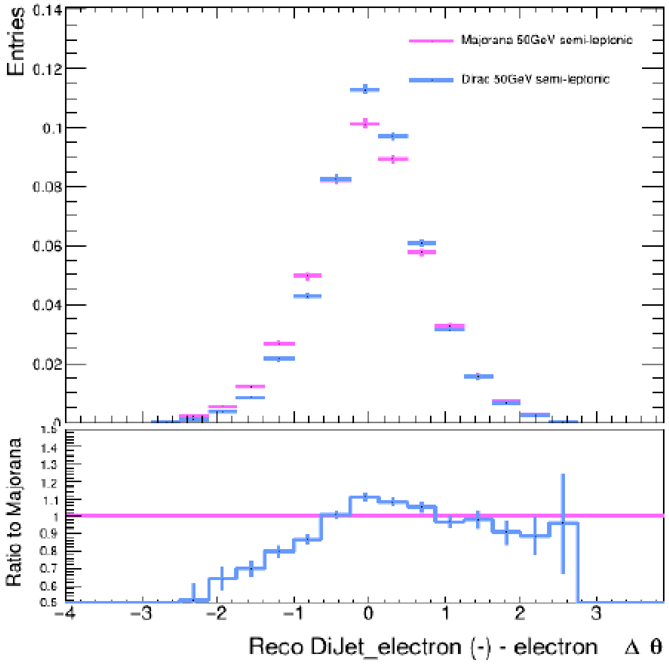
With 10% syst. uncertainty

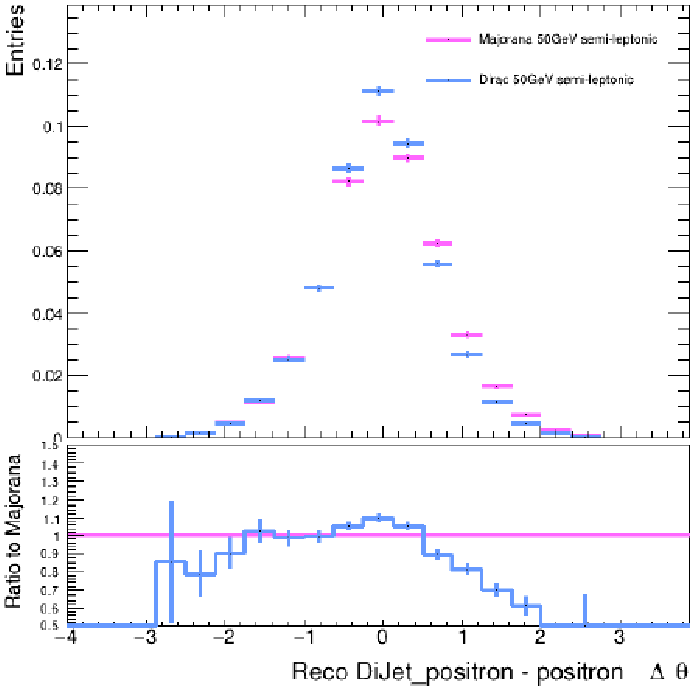


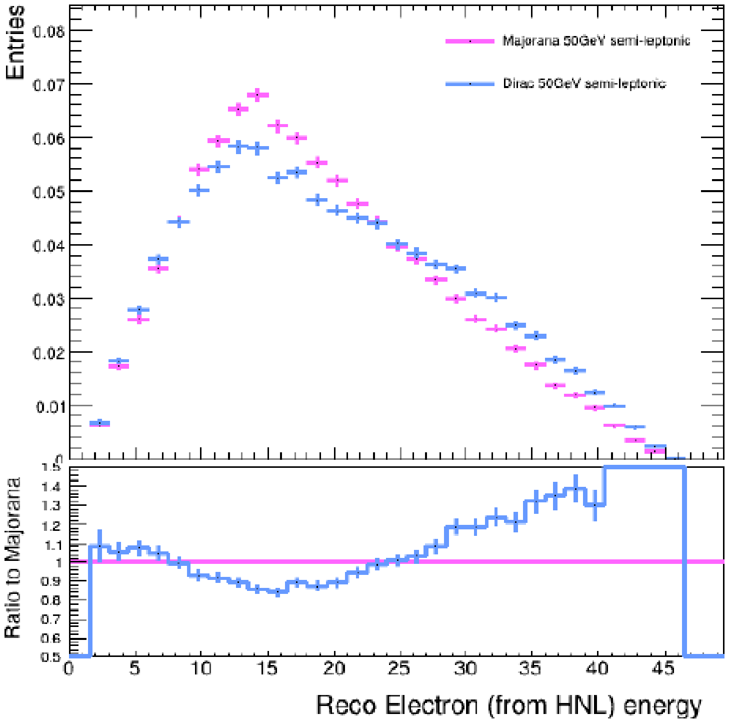
A. Sfyrla, D. Moulin, P. Kontaxakis

HNL→ ejj: Dirac vs. Majorana

- Define final state variables for which difference Dirac-Majorana can be observed [1]
- Ex: Electron energy, HNL (dijet) energy, Electron-HNL angle:
- Studied both at the generation → MG5 and reconstruction level → DELPHES
- Good discrimination coming from electron/positron distributions separately







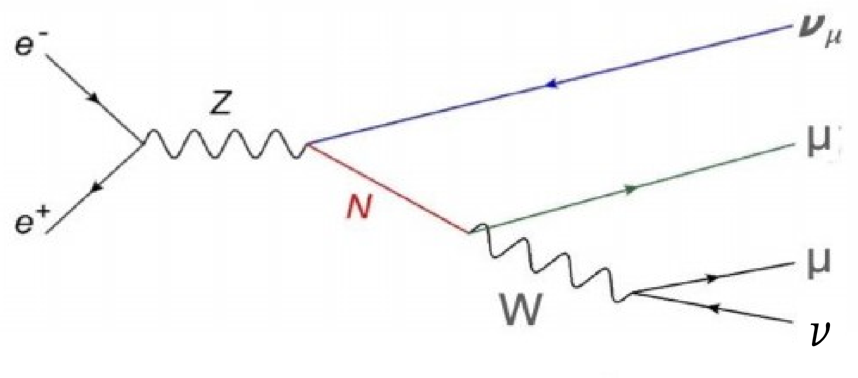
[1] https://arxiv.org/pdf/2105.06576.pdf

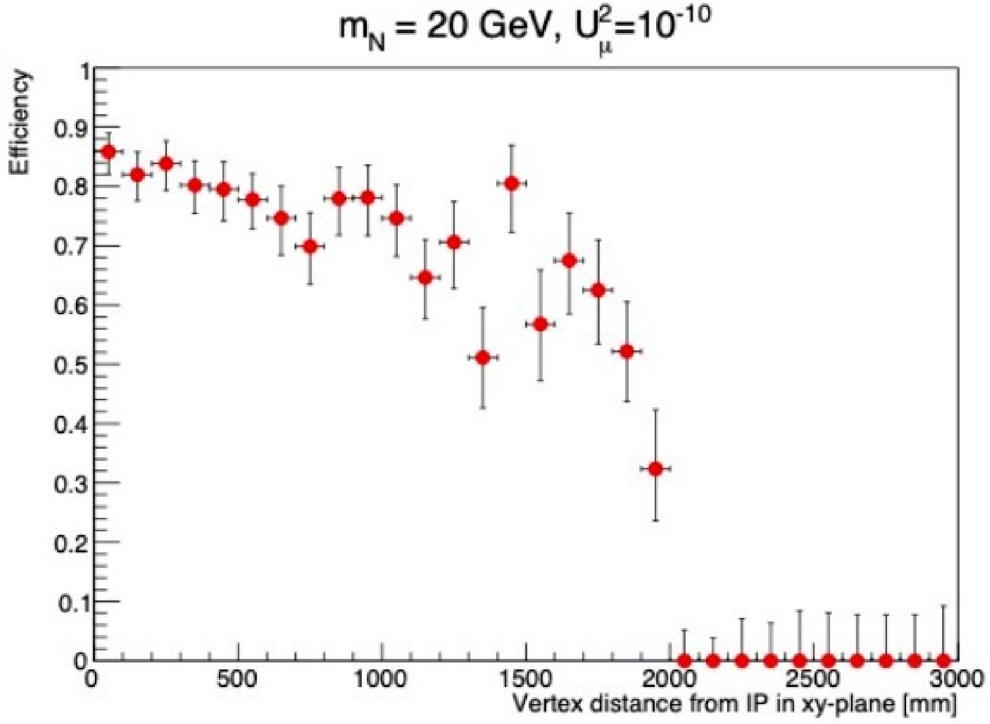
HNL→ μμν LL

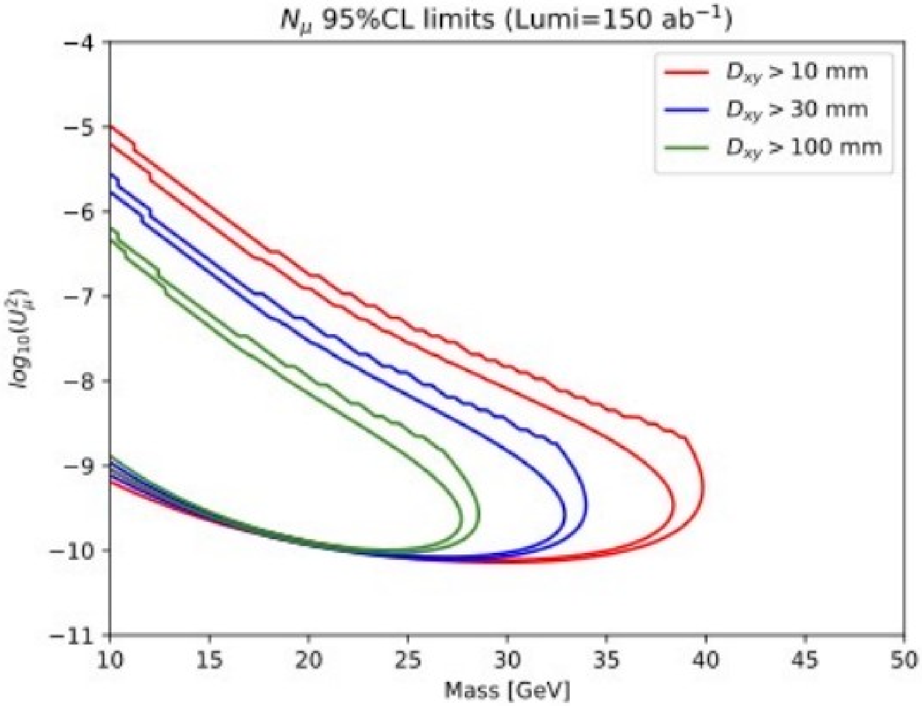
Lorenzo Bellagamba

Early studies of sensitivity with N→$\mu\mu\nu$ channel looking for DV

Optimise search based on the distance from the 2-muon decay vertex to the IP







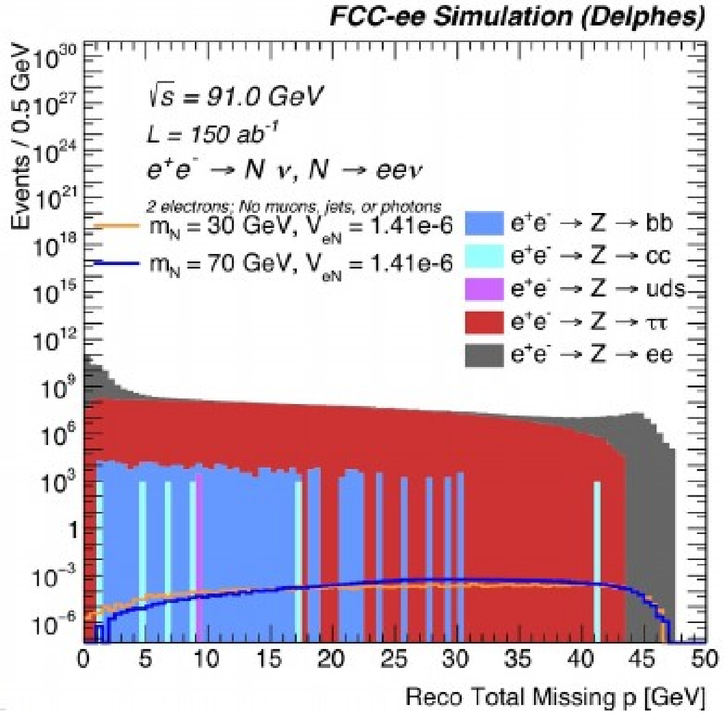
Published in Front. Phys. 10:967881 (2022)

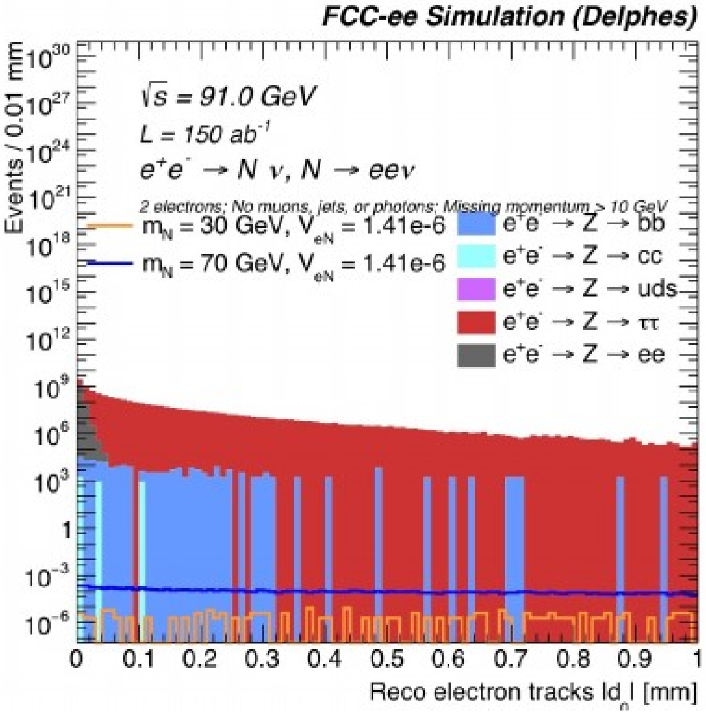
HNL→ eeν LL

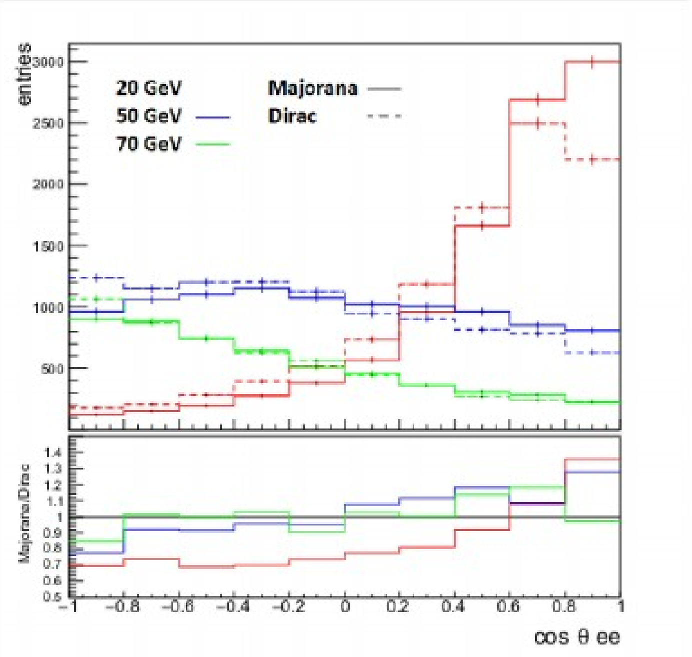
Initial study developed a selection to reduce backgrounds

- 2 electrons with a veto on additional photons, jets, muons.
- p^{Miss}> 10 GeV to reduce the Z→ee background with instrumental missing momentum.
- Electron $|d_0|$>0.5 mm

Also studied variables Sensitive to Dirac/Majorana nature of HNLs

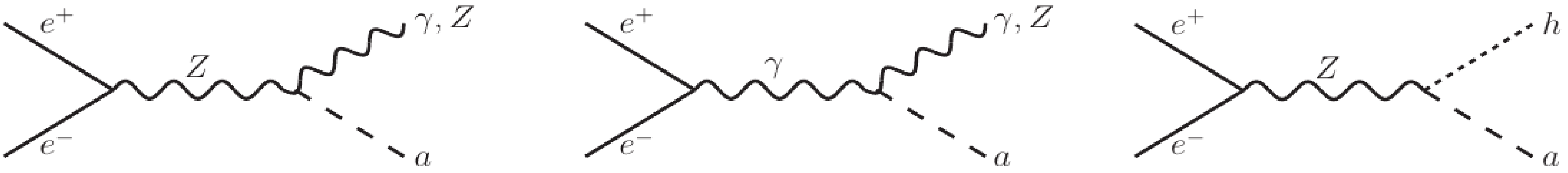






Being reevaluated on the basis of winter2023 production (S. Williams)

ALP



Simplified model with

many possible signatures, e.g.

- γa, a→γγ
- γa, a→ ll
- ha, h→bb, a→ γγ

Different decays of a, depending

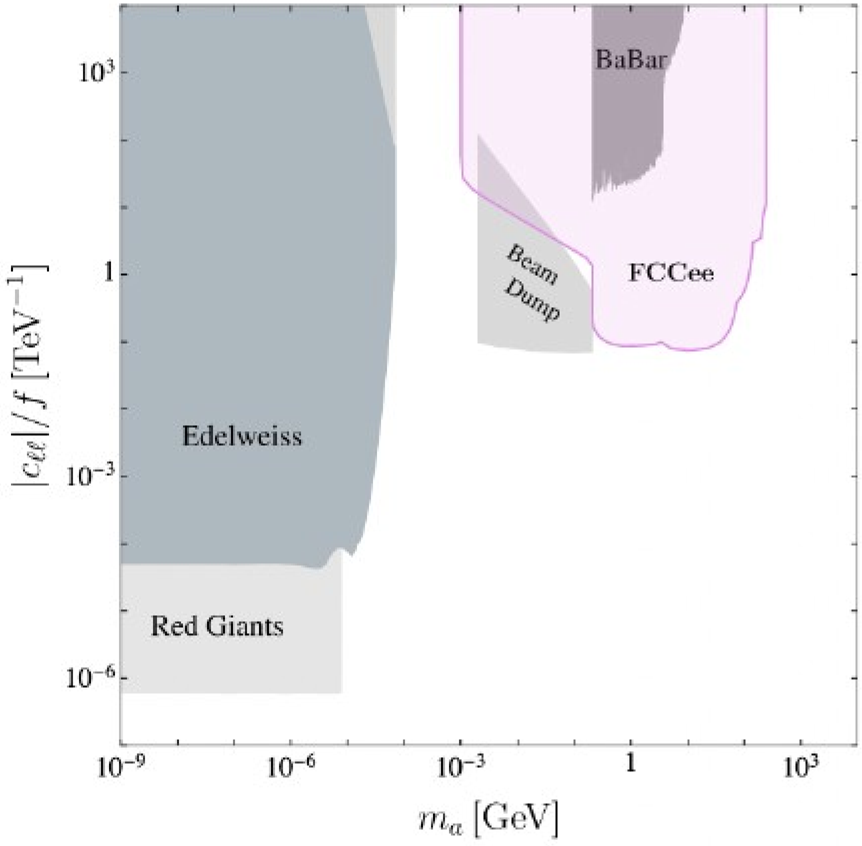
which couplings non-zero

Both long-lived and prompt

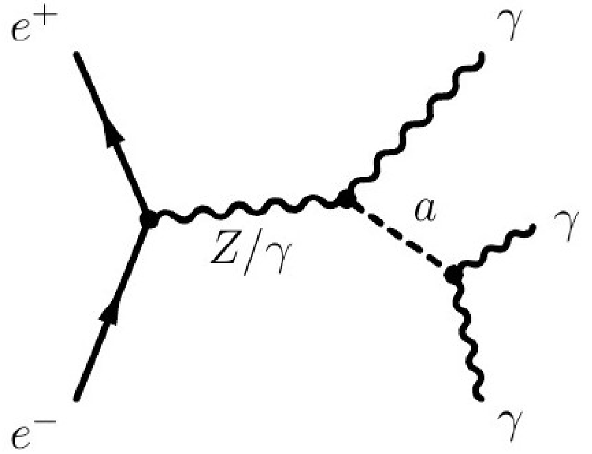
signatures, would be useful to

define benchmarks beyond 3γ

arXiv:2203.05502



ALP: 3γ final state



3 photon state considered in preliminary detailed studies,

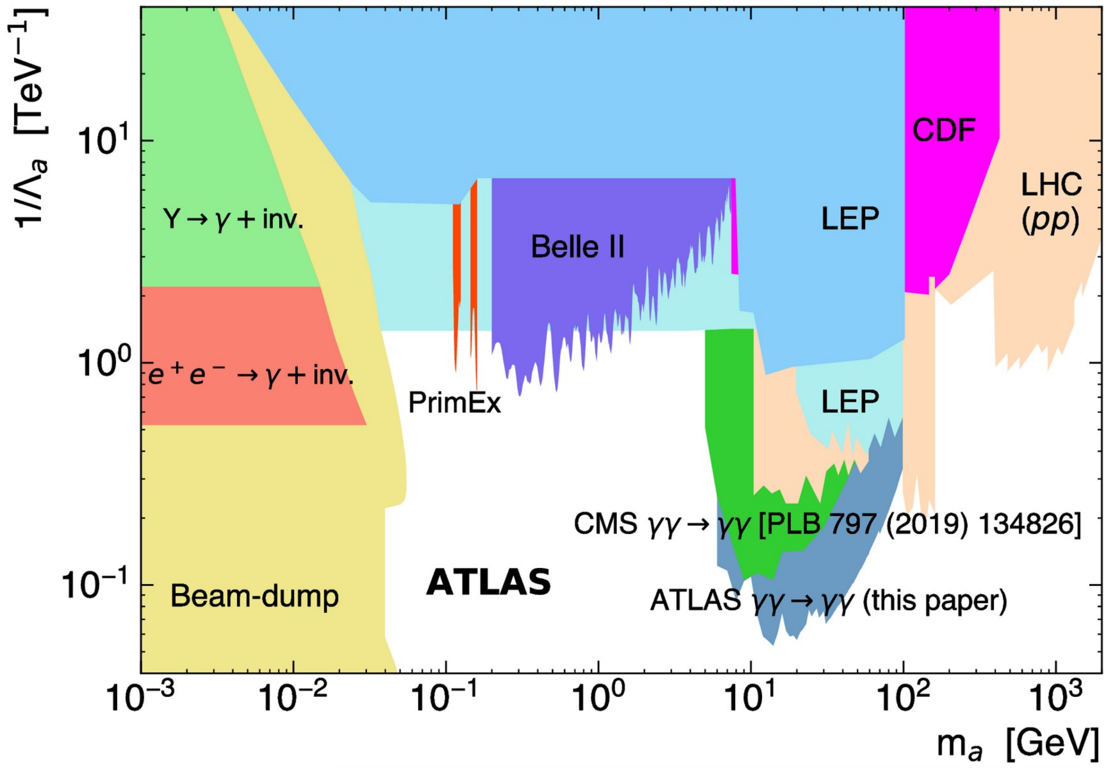
- Prompt
- Long-lived

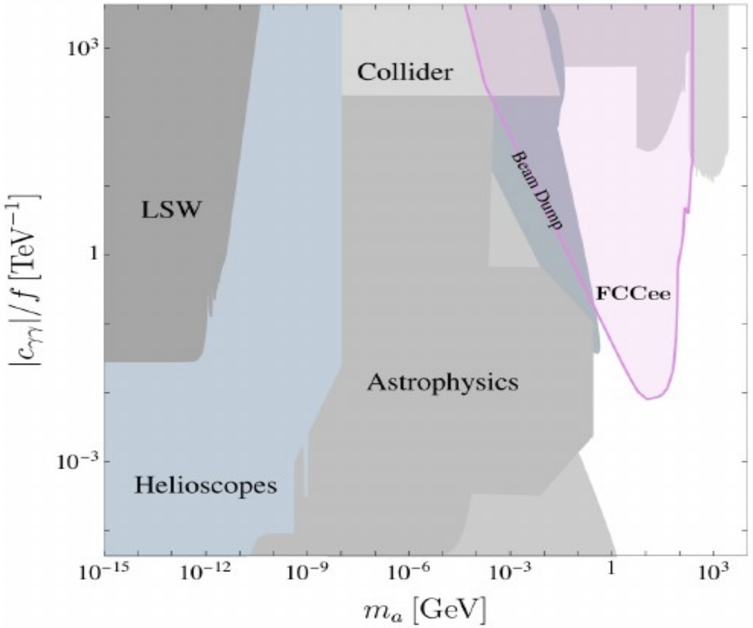
Experimental implications:

- Mass reconstruction for very collimated photons
- Timing of photons for LLP

Key role of preshower?

Existing constraints from JHEP 12 (2017) 044

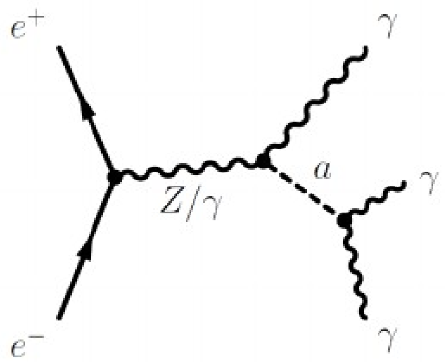




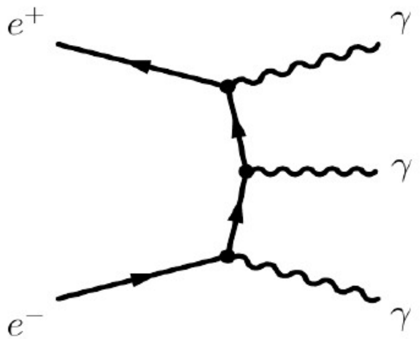
ALP Prompt analysis

Thesis L. Pezzotti

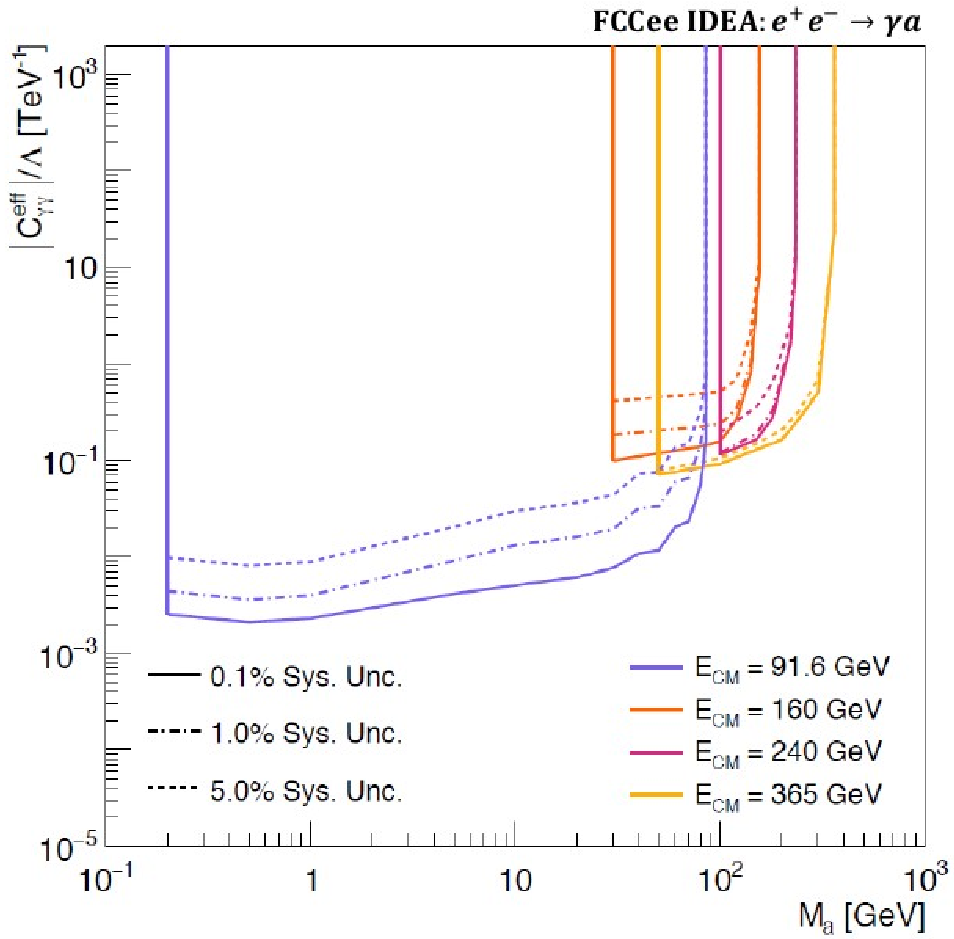
Based on samples produced with MG5+ IDEA DELPHES card before the full software chain available



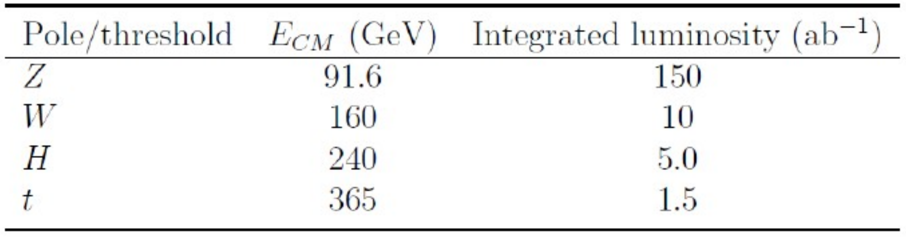
Signal



Background



For each test mass select events with two photons near the mass, and third photon with momentum defined by recoil formula

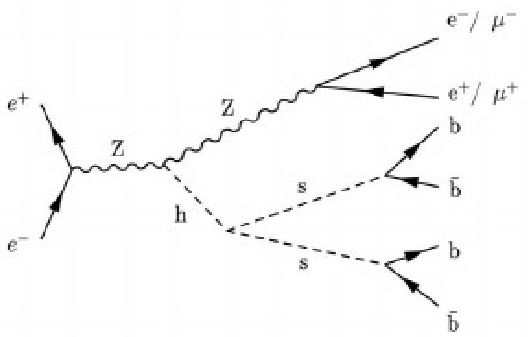


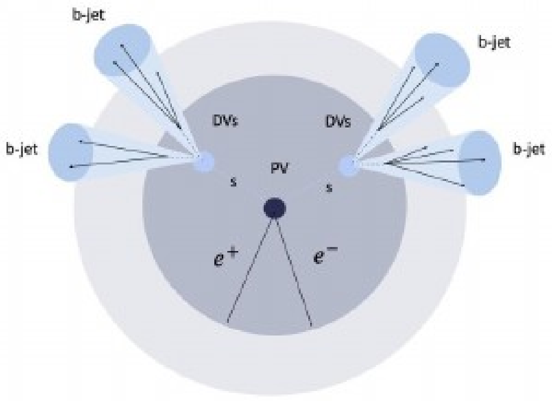
Pole/threshold	E_{CM} (GeV)	Integrated luminosity (ab^{-1})
Z	91.6	150
W	160	10
H	240	5.0
t	365	1.5

Further suppress background with angular selection on two photons form ALP decay

Magdalena Vande Voorde, Giulia Ripellino

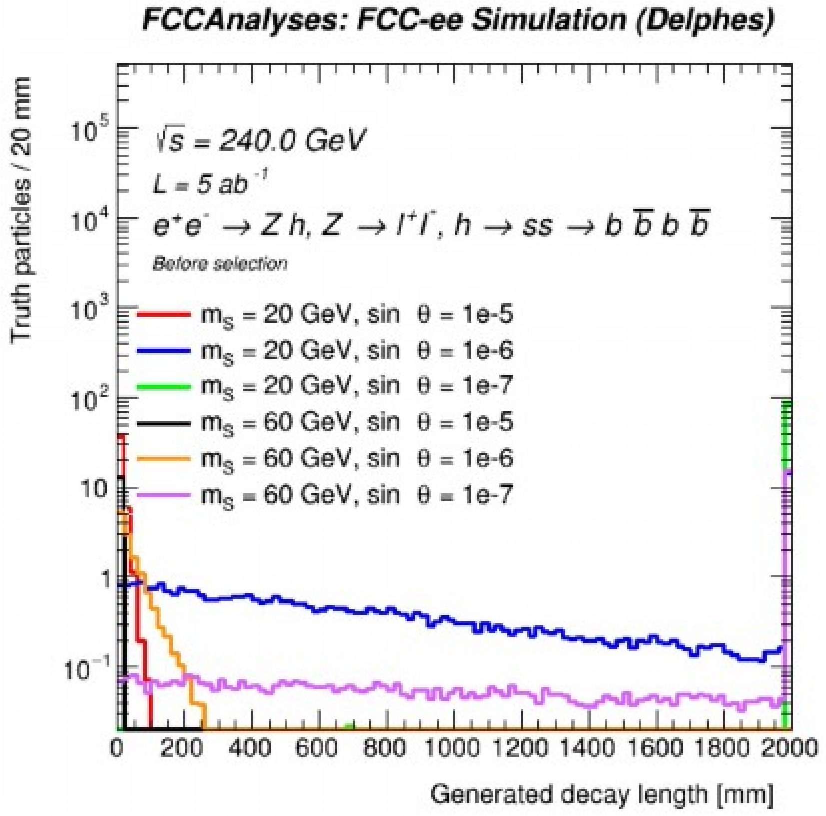
Exotic Higgs decays





- Extend SM with additional scalar.
- Probe h → ss → bbbb in events with 2 displaced vertices, tagged by Z

$$e^+e^- \to Z \to Zh,\, Z \to l^+l^-,\, h \to ss,\, s \to b^+b^-$$

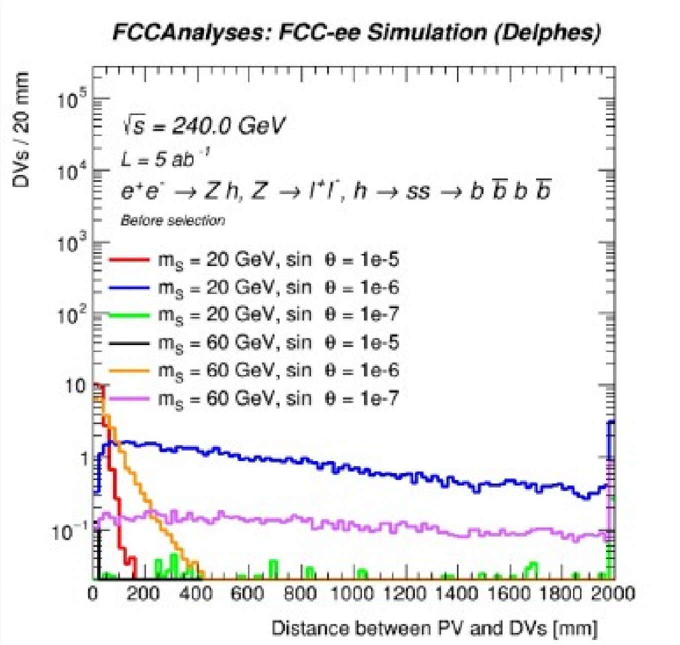


- Look at events with at least one scalar within acceptance region 4 mm < r< 2000mm
- Aim to develop event selection and perform early sensitivity study.

Magdalena Vande Voorde, Giulia Ripellino

Vertexing

Studied two options of DV reconstruction implemented in FCCAnalysis framework with additional constraints inspired by ATLAS DV analysis

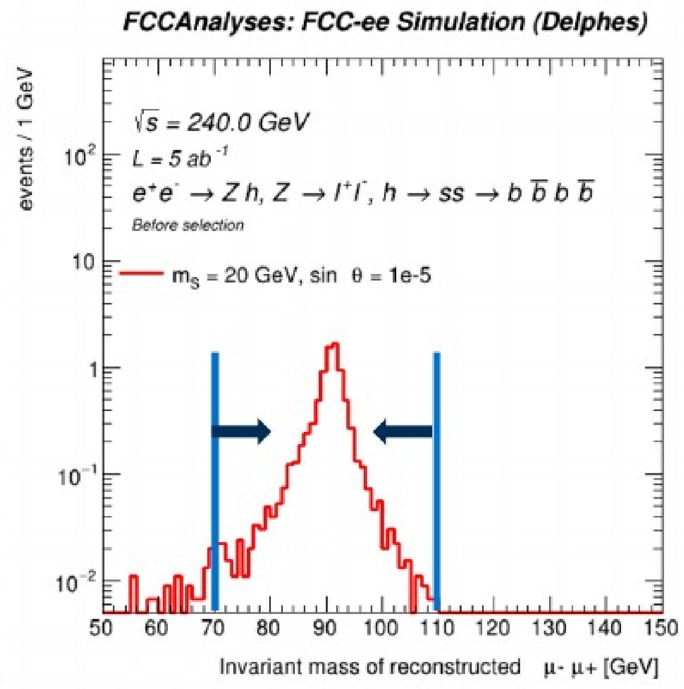


1. SV finder of LCFI+ algorithm (https://arxiv.org/abs/1506.08371)
2. Add vertex merging to recover some DVs from scalars, work in progress to understand goodness-of-fit results

Magdalena Vande Voorde, Giulia Ripellino

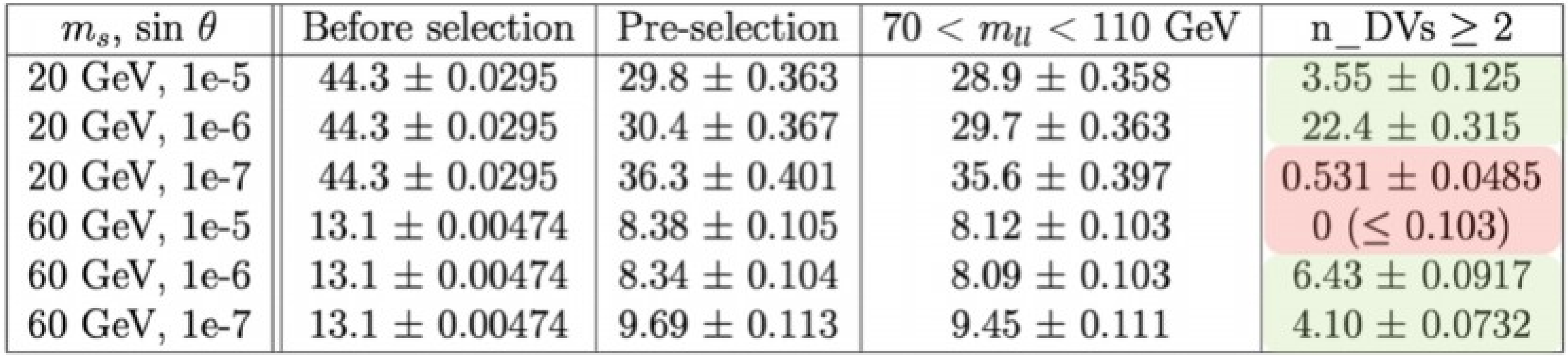
Results

	Selection
Pre-selection	≥ 2 oppositely charged electrons or muons
Z boson tag	$70 < m_{ll} < 110$ GeV
Multiplicity of DVs	n_DVs ≥ 2



Secondary vertex selection

Vertex Selection		
	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV



m_s, sin θ	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	44.3 ± 0.0295	29.8 ± 0.363	28.9 ± 0.358	🟩 3.55 ± 0.125
20 GeV, 1e-6	44.3 ± 0.0295	30.4 ± 0.367	29.7 ± 0.363	🟩 22.4 ± 0.315
20 GeV, 1e-7	44.3 ± 0.0295	36.3 ± 0.401	35.6 ± 0.397	🟥 0.531 ± 0.0485
60 GeV, 1e-5	13.1 ± 0.00474	8.38 ± 0.105	8.12 ± 0.103	🟥 $0\ (\leq 0.103)$
60 GeV, 1e-6	13.1 ± 0.00474	8.34 ± 0.104	8.09 ± 0.103	🟩 6.43 ± 0.0917
60 GeV, 1e-7	13.1 ± 0.00474	9.69 ± 0.113	9.45 ± 0.111	🟩 4.10 ± 0.0732

All but 2 considered signals could be excluded at 95% CL in background-free search

Conclusions

Rich menu of BSM final states available for discovery at FCC-ee

Focus on models involving low-mass particles with feeble couplings to SM

Benchmark in these models are being identified

Present work mostly focused on detailed analyses of reach for long lived exotic particles

→ important detector challenges to exploit the signatures

Backup

Previous LL publication

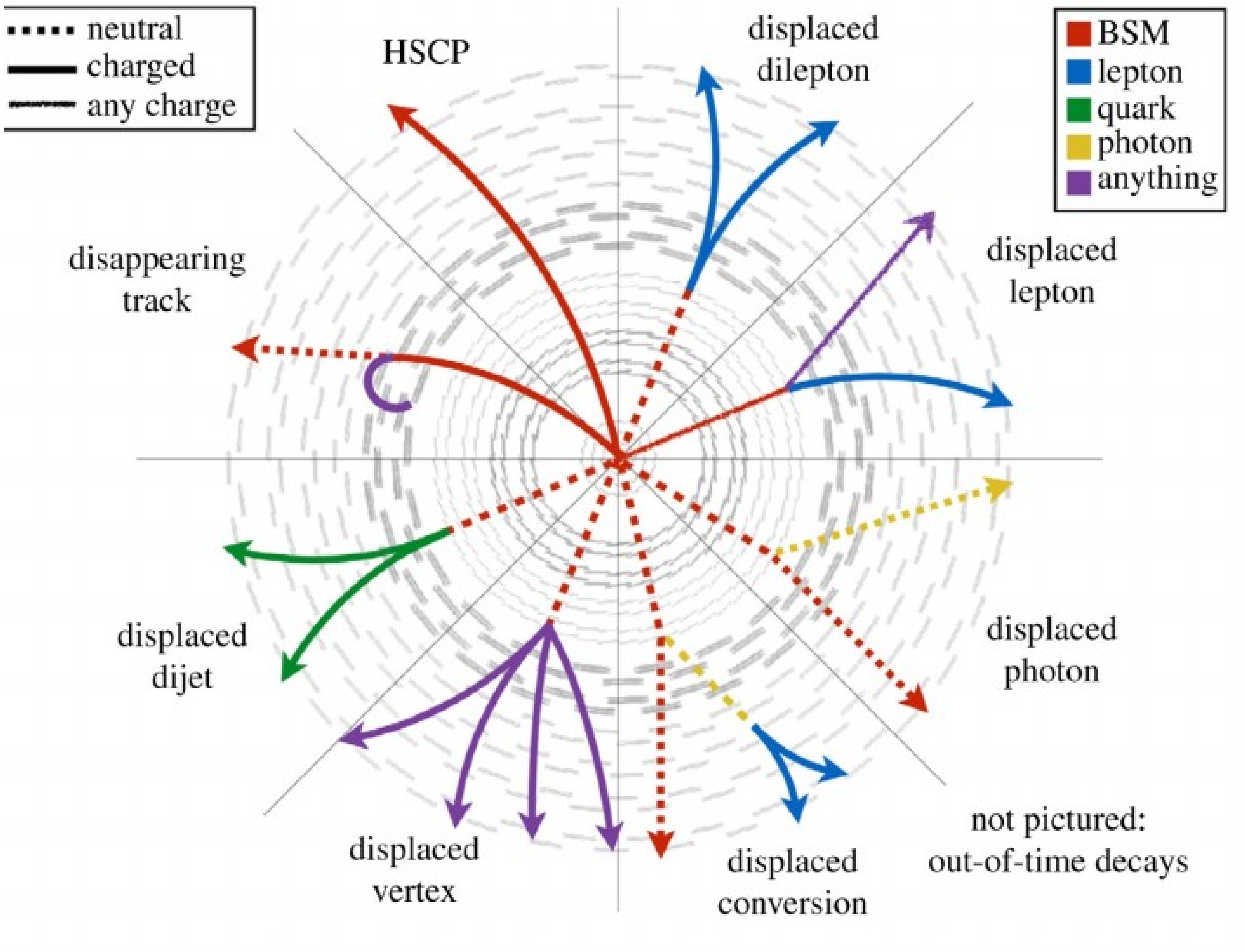
Searches for long-lived particles at the future FCC-ee

C. B. Verhaaren[1], J. Alimena[2]*, M. Bauer[3], P. Azzi[4], R. Ruiz[5], M. Neubert[6,7], O. Mikulenko[8], M. Ovchynnikov[8], M. Drewes[9], J. Klaric[9], A. Blondel[10], C. Rizzi[10], A. Sfyrla[10], T. Sharma[10], S. Kulkarni[11], A. Thamm[12], A. Blondel[13], R. Gonzalez Suarez[14] and L. Rygaard[14]

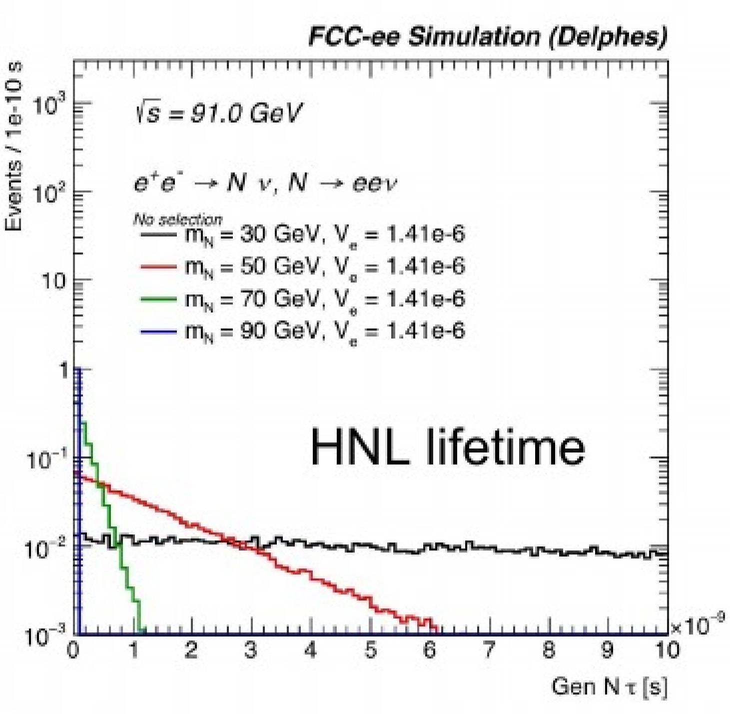
[1]Department of Physics and Astronomy, Brigham Young University, Provo, UT, United States, [2]Experimental Physics Department, CERN, Geneva, Switzerland, [3]Department of Physics, Durham University, Durham, United Kingdom, [4]INFN, Section of Padova, Padova, Italy, [5]Institute of Nuclear Physics, Polish Academy of Sciences, Kracow, Poland, [6]Johannes Gutenberg University, Mainz, Germany, [7]Cornell University, Ithaca, NY, United States, [8]Leiden University, Leiden, Netherlands, [9]Université Catholique de Louvain, Louvain-la-Neuve, Belgium, [10]University of Geneva, Geneva, Switzerland, [11]University of Graz, Graz, Austria, [12]The University of Melbourne, Parkville, VIC, Australia, [13]LPNHE, Université Paris-Sorbonne, Paris, France, [14]Uppsala University, Uppsala, Sweden

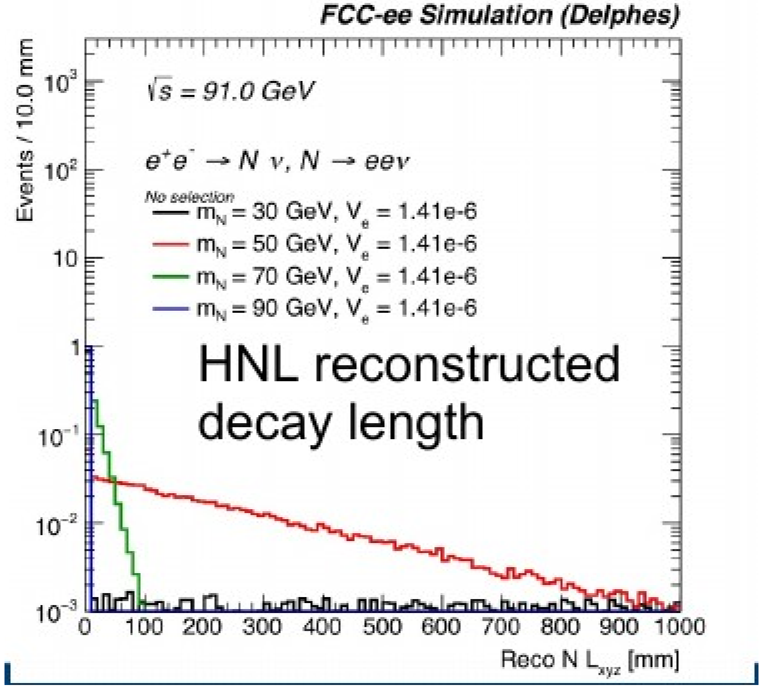
Published in Front. Phys. 10:967881 (2022)

Long Lived searches



HNL→ eeν



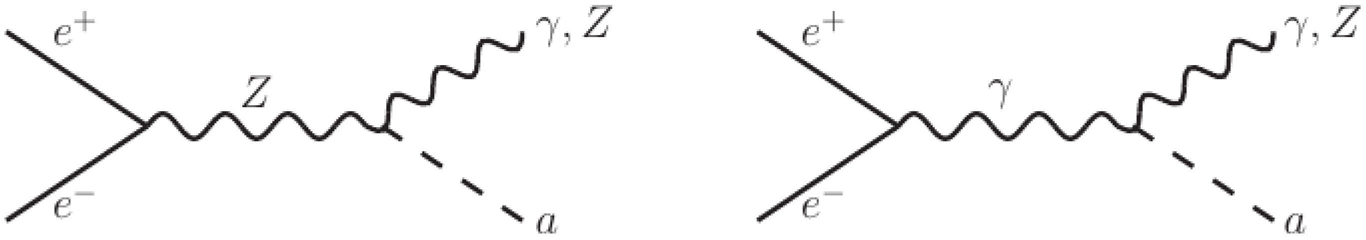


Lifetime and reconstructed length

ALP: the model

$$\mathcal{L}_{\rm eff} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}\,.$$

We are interested in the associate production of a and γ



- Assume a only couples to hypercharge and not to SU2

$$C_{\gamma Z} = -s_w^2\, C_{\gamma\gamma}$$

- Assume BR(a→ γγ)=100%

Experimental reach can be represented in 2-d M_a-$C_{\gamma\gamma}$ plane

Implemented in two UFOs:

Brivio et al.:arXiv: 1701.05379

Bauer et al:arXv:1808.10323

Checked that the two UFOs give the same results, use Bauer et al. for generation

Existing limits

Two mass ranges:

<~100 MeV – ~5 GeV:
Can we cover this difficult region?

>~5 GeV
Are we sensitive to lower couplings than the ones explored at the LHC in photon-photon collisions?

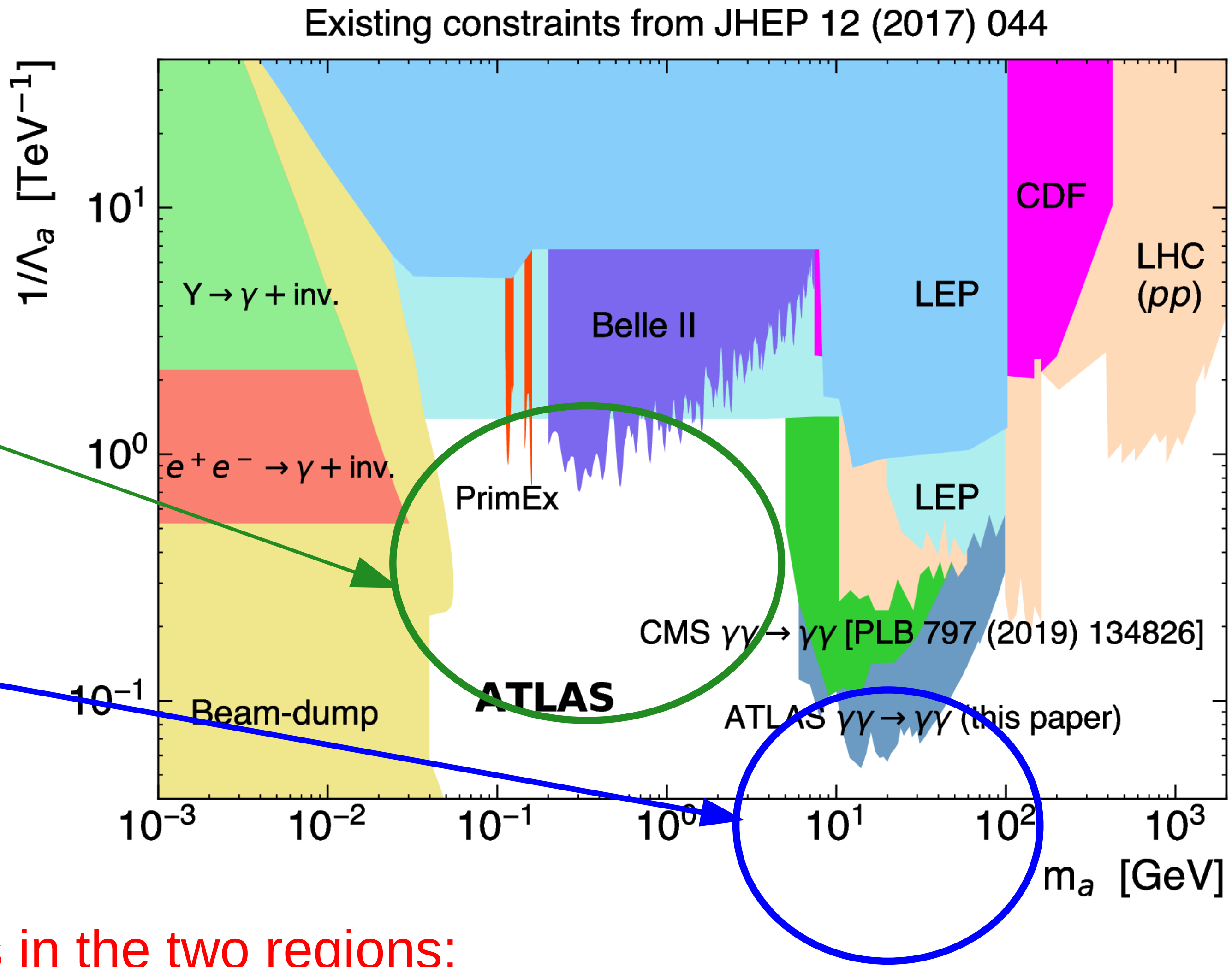


Figure from:

ATLAS:arXiv 200805355

Different experimental issues in the two regions:

- >5 GeV: energy resolution
- <5 GeV: separation of two very collimated photons, resolution on position measurement

Comparison with existing limits and projected reach

In the 10-100 GeV region FCC-ee reach in the same ballpark as projected PbPb LHC result

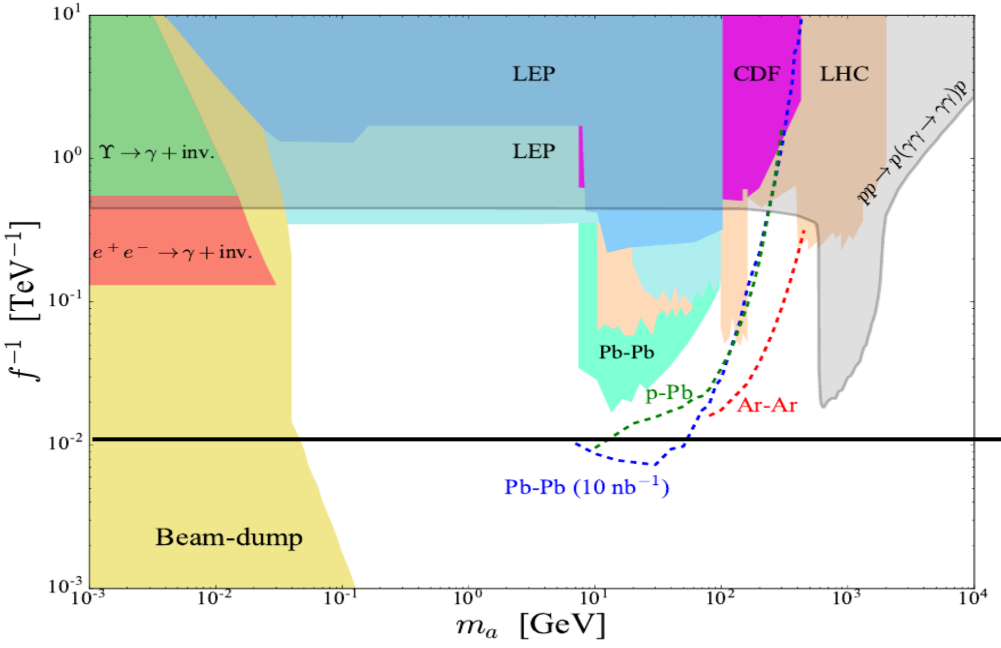
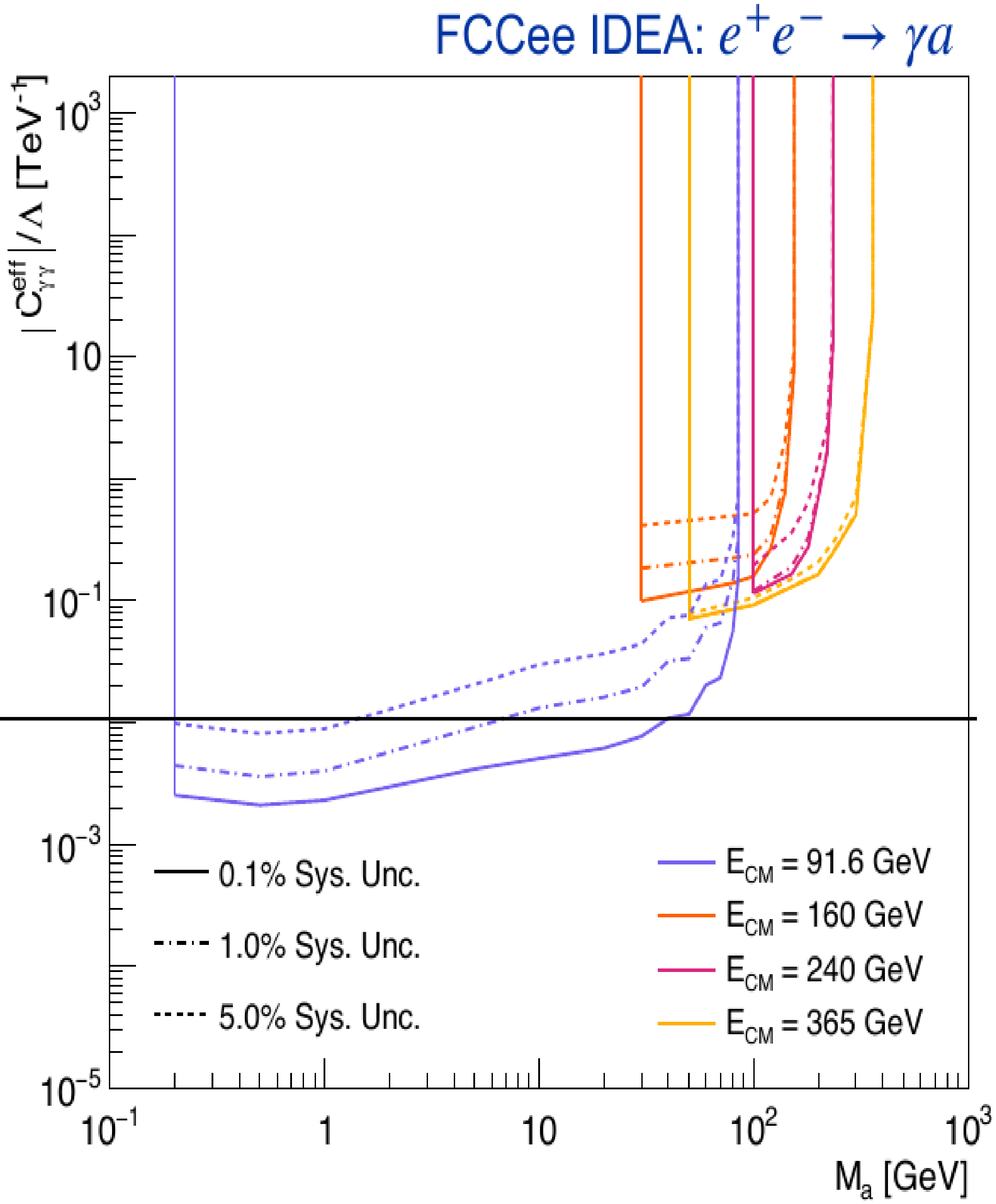


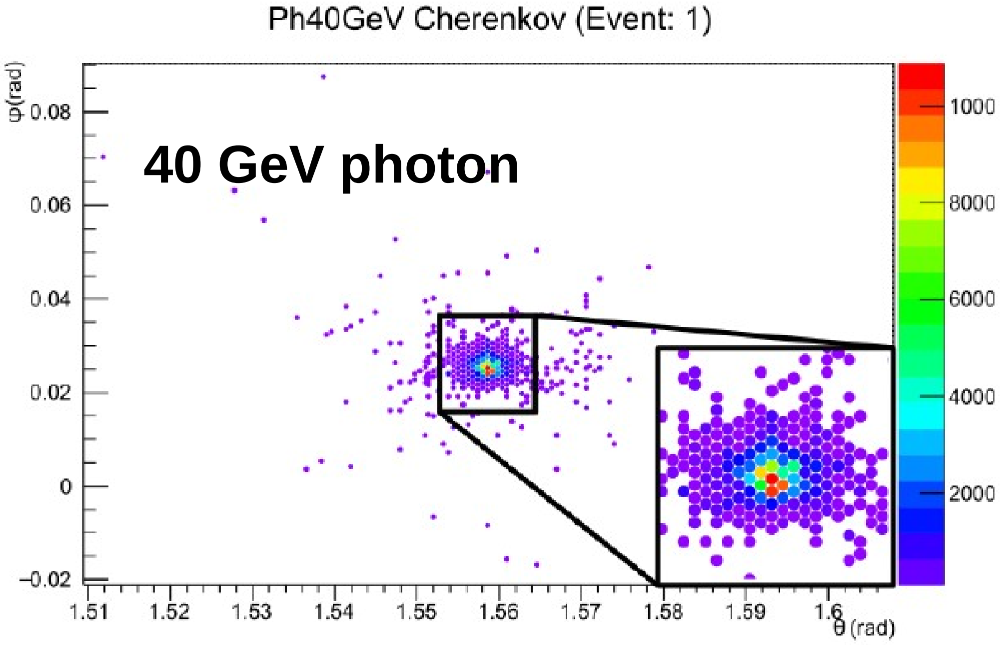
Figure from

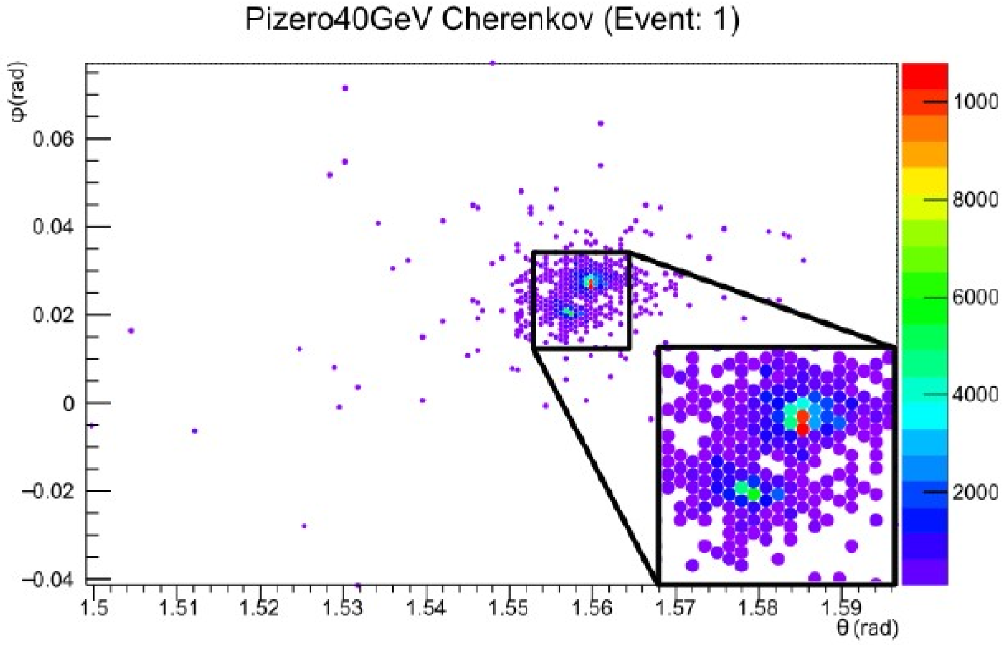
Schoeffel at al. arxiv:2010.07855



Example: exploiting the full granularity of IDEA DR Calo

With Silicon PMs it is possible to read one by one all of the fibers in the calorimeter → possibility to separate very close photons and to precisely measure invariant mass





Ideal field of application for ML image recognition, work ongoing in Pavia (master thesis A. Villa)

SUSY

Not very popular anymore, but holes in LHC offer opportunity for FCC-ee.

Two obvious examples:

- Compressed slepton
- Higgsino

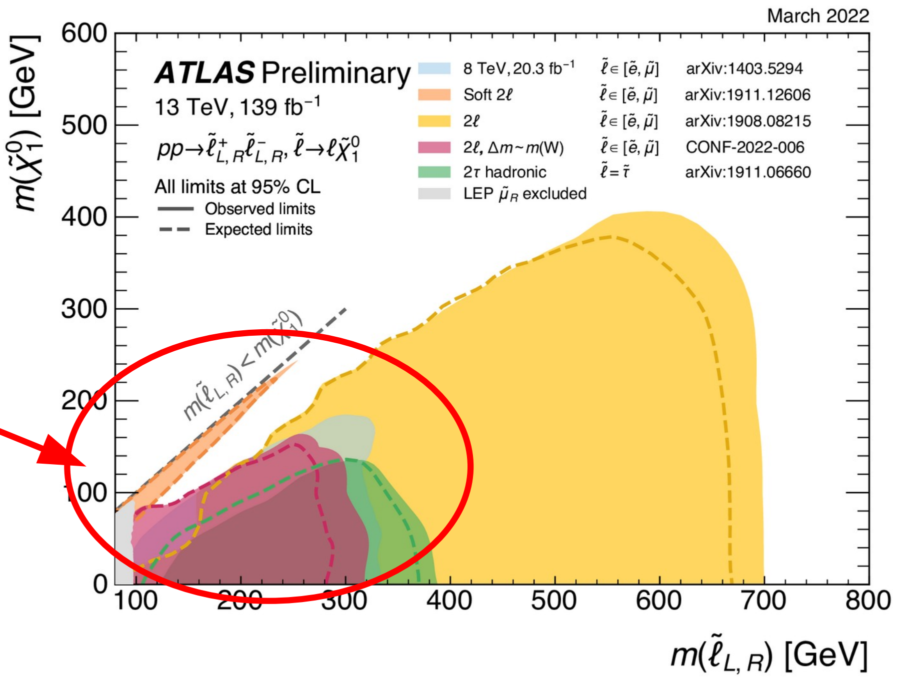
Need to verify what kind of challenges for detector design these signatures provide.

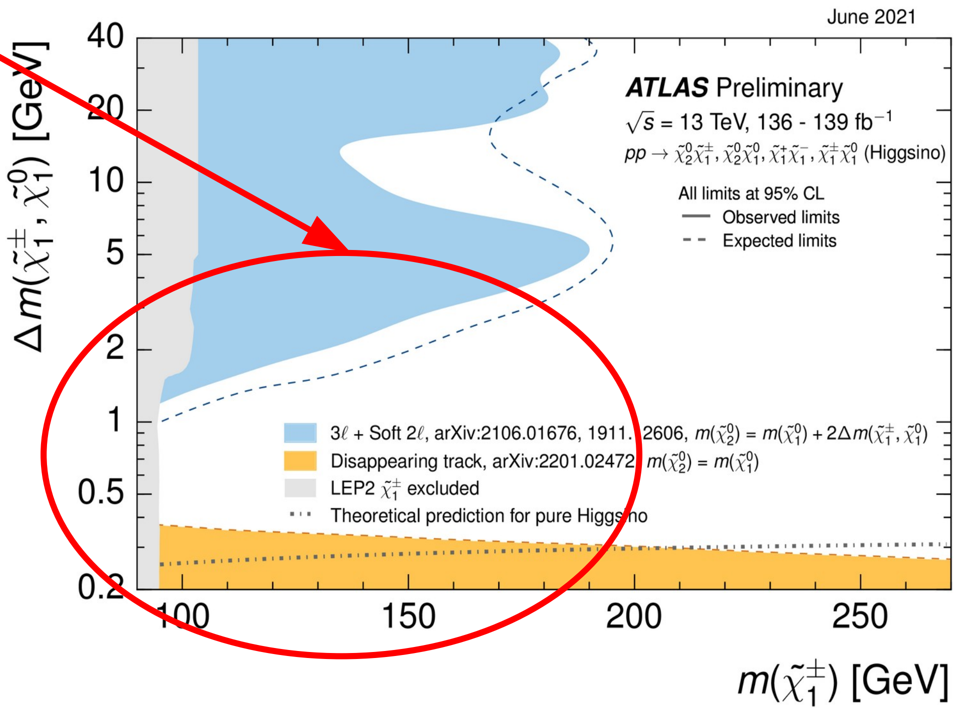
pMSSM scans can show uncovered points in gaugino parameter space

Need explicit benchmarks.

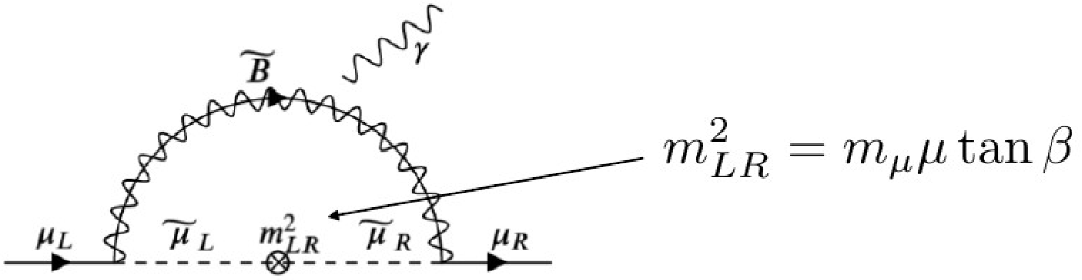
- Input from ATLAS/CMS pMSSM studies
- Input from theory, see e.g. the paper from one of our theory conveners:

  https://arxiv.org/abs/2207.05103





SUSY: g-2



$$m^2_{LR} = m_\mu \mu \tan\beta$$

From a talk by R.Barbieri

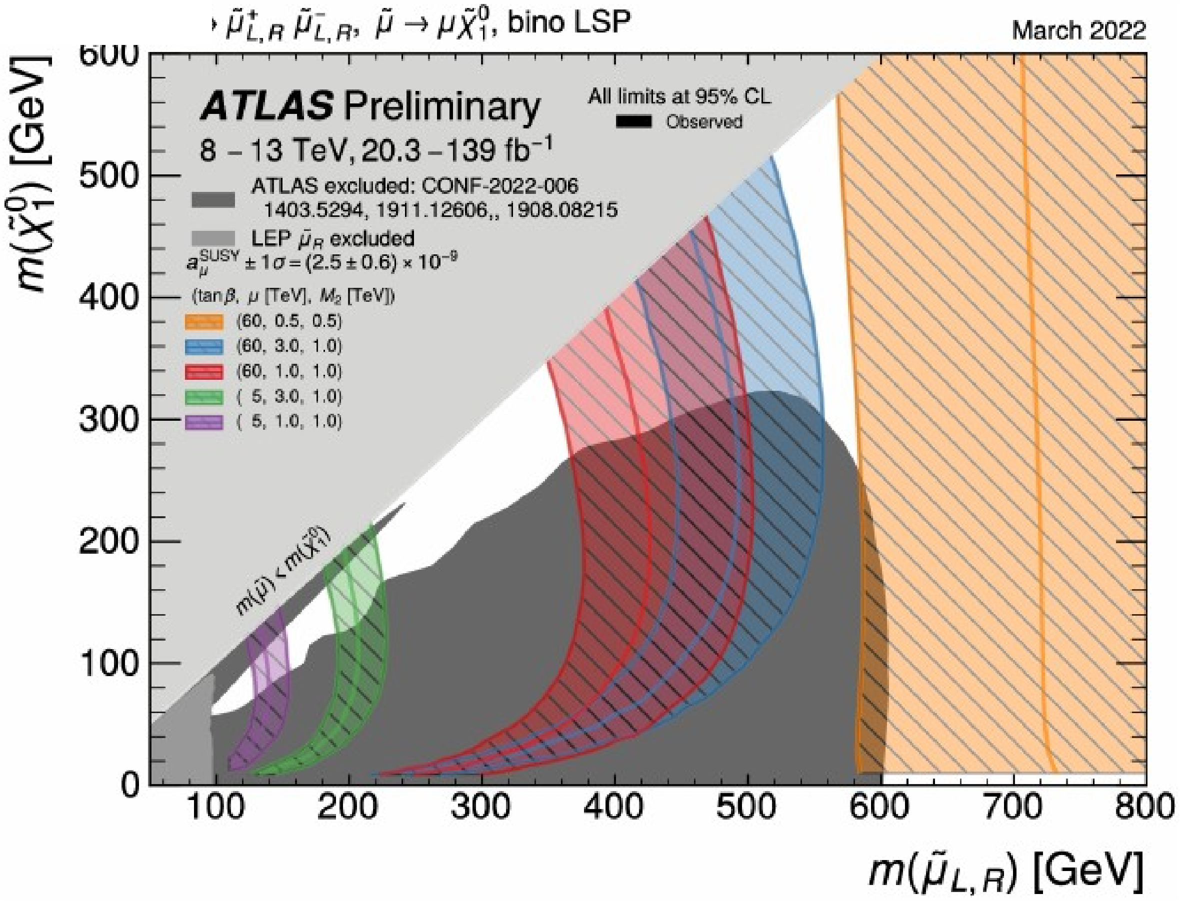
g-2 discrepancy can be explained with light sleptons FCC should be able to cover uncovered area relevant for this explanation

Possible benchmark:

Simplified model: direct slepton production with

m(slep)=150 GeV

m(chi01)=100-140 GeV

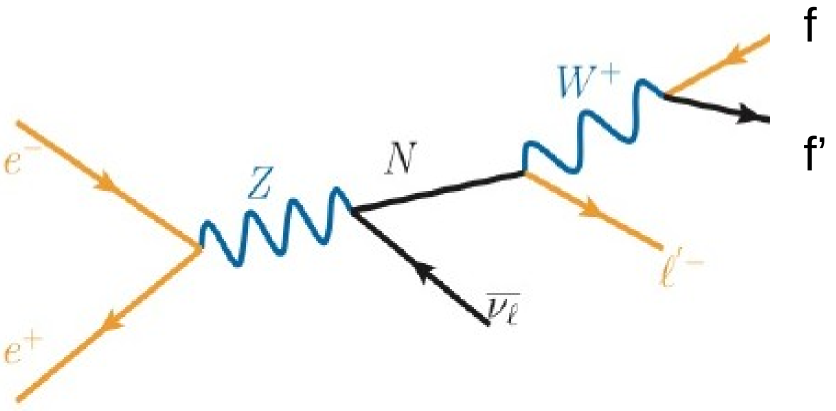


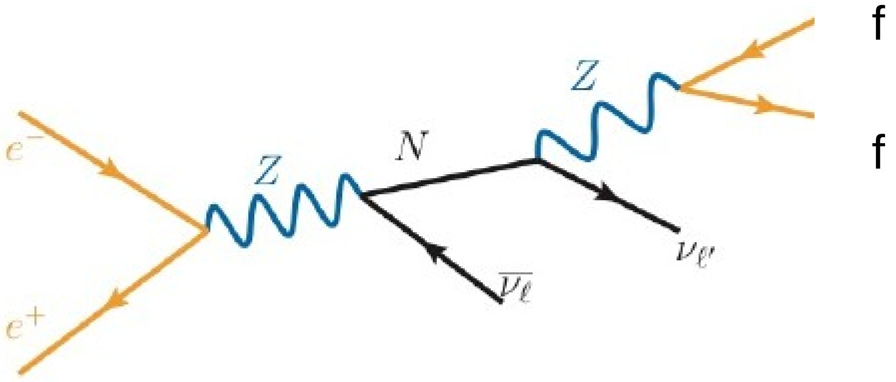
HNL signatures

Rich set of final states and signatures, work in the group performed for both prompt and LLP signatures, in particular

- eenu: LLP in ID

  μμν: LLP in ID
- ejj and μjj prompt (LL in ID)
- Dirac vs. Majorana

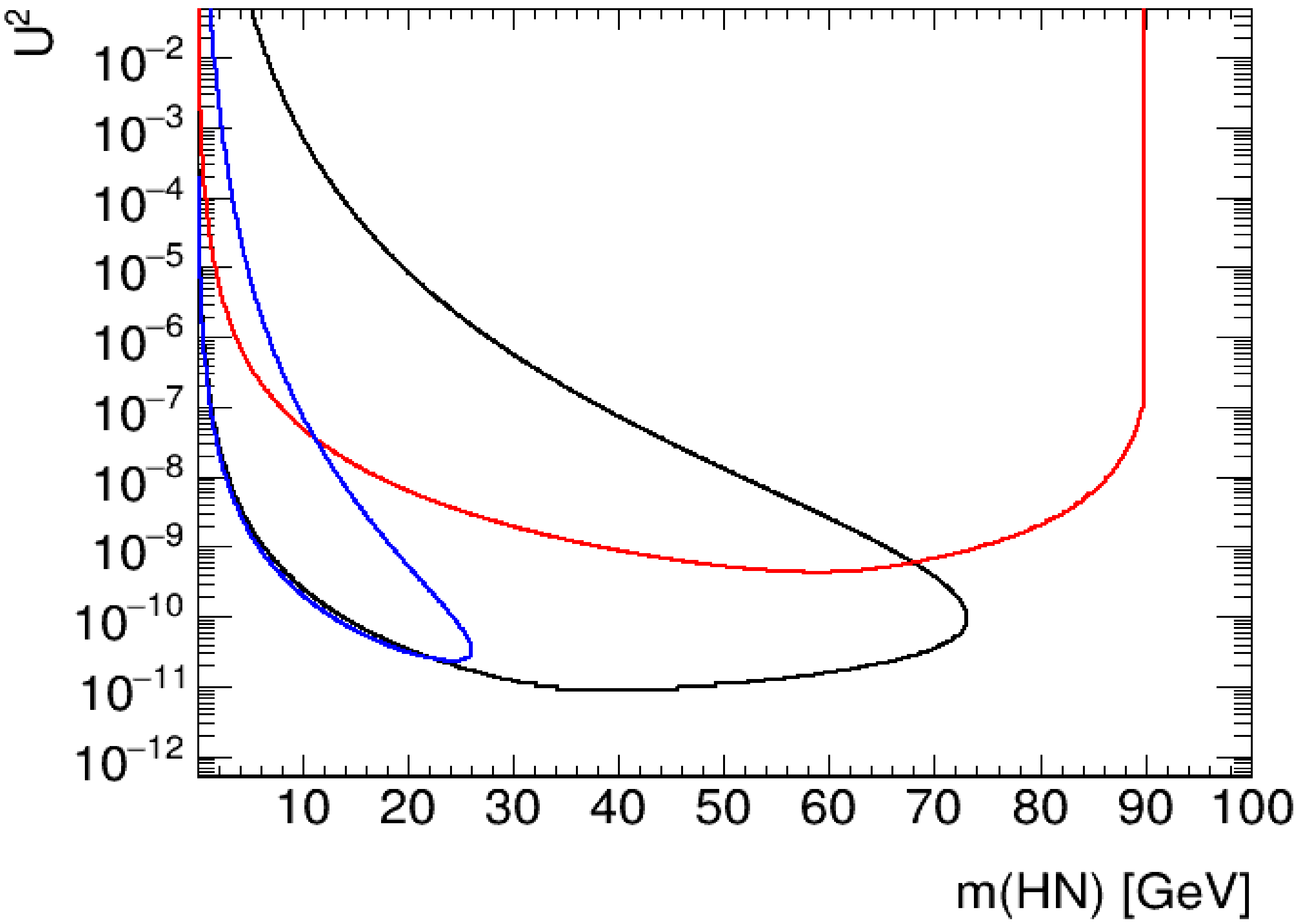




Analysis matrix

- Decay final state:
  - j j l
  - j j nu
  - l l nu
  - j nu nu
- Decay length
  - Prompt
  - LL decay In ID
  - LL decay in Calo

Linear scale



Assume 1 flavour active

5×10^{12}Z at Z peak

Require 100 events for prompt decay and 4 events for long-lived

Red: Prompt:

$0 < \lambda < 1$mm

Black:ID decay

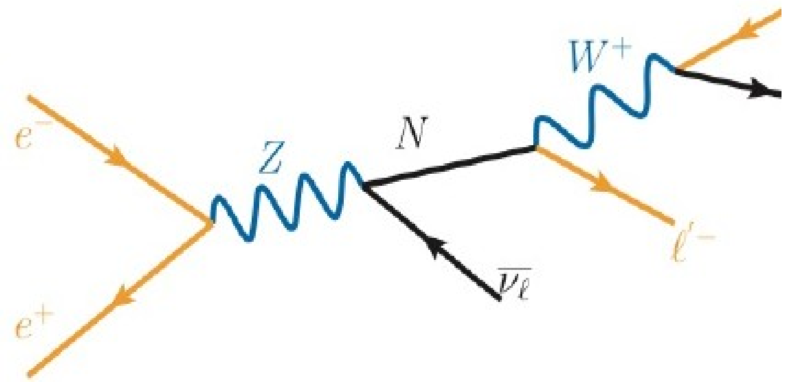
$0.04 < \lambda < 150$ cm

Blue: Calo decay

$200 < \lambda < 450$ cm

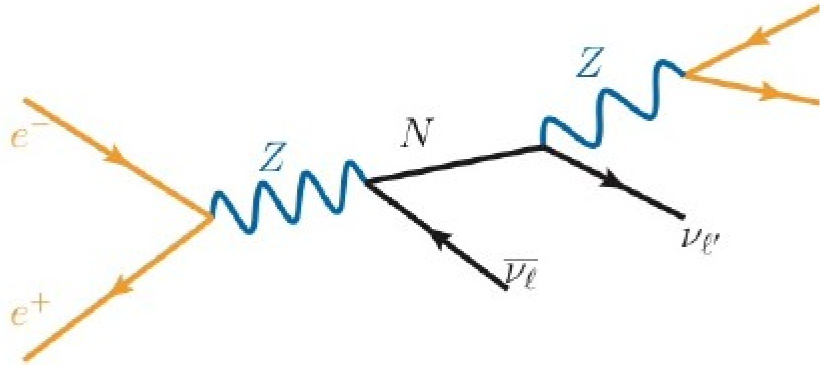
Prompt decays dominate for $m_{HNL} > 70$ GeV

Decay signatures



l^+ q

ν q’



l^+ q

l^- q

Analysis matrix: for HNL

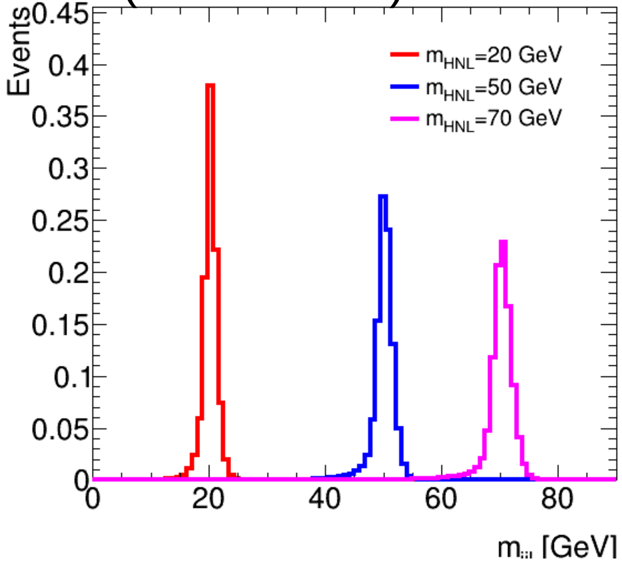
- Decay final state (l=e,μ):
  - j j l ~50%
  - j j nu ~20%
  - l l nu ~5%
  - l l’ nu ~9%
  - l τ nu ~9%

  (BRs for m_{HN}<80 GeV)
- Decay lengths
  - Prompt
  - LL decay In ID
  - LL decay in Calo

Previous experimatal FCC/CEPC studies

FCC: Master thesis by Sissel Bay Nielsen(Copenhagen 2017)

IDEA DELPHES card (GP+N.Valle)

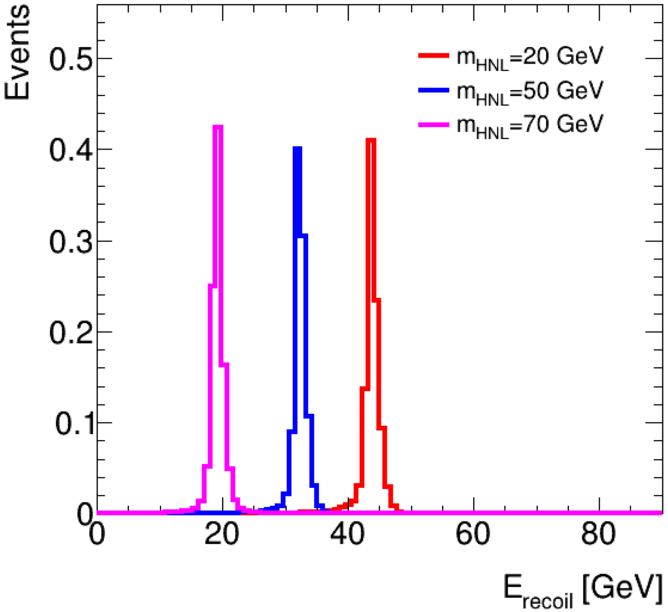


Two CEPC papers

- arXiv:1903.02570:2jet+lep

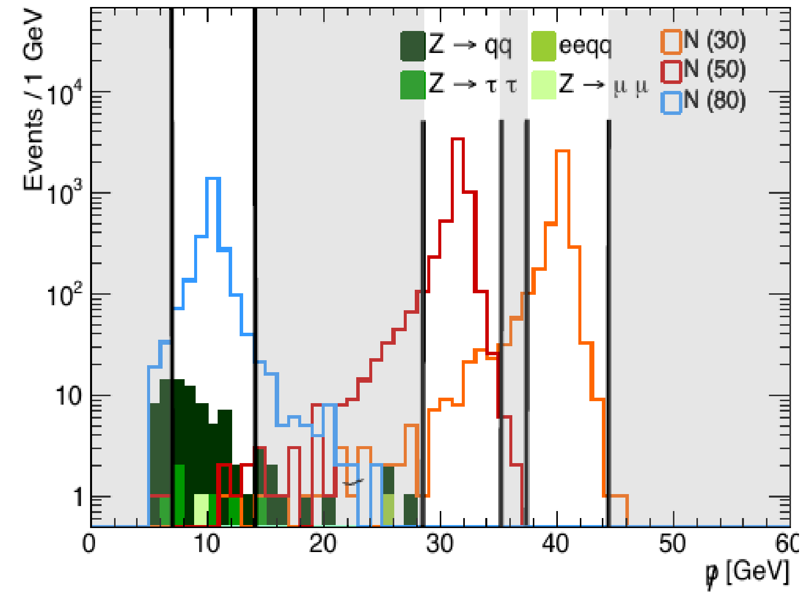
  m_{HNL}:10-90 GeV
- arXiv:2201.05831 Monojet+lep

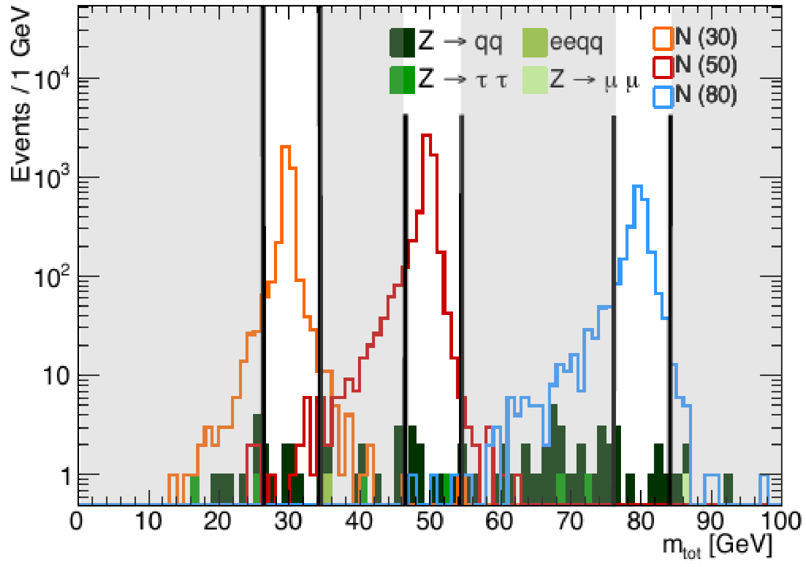
  m_{HNL}: 3-15 GeV

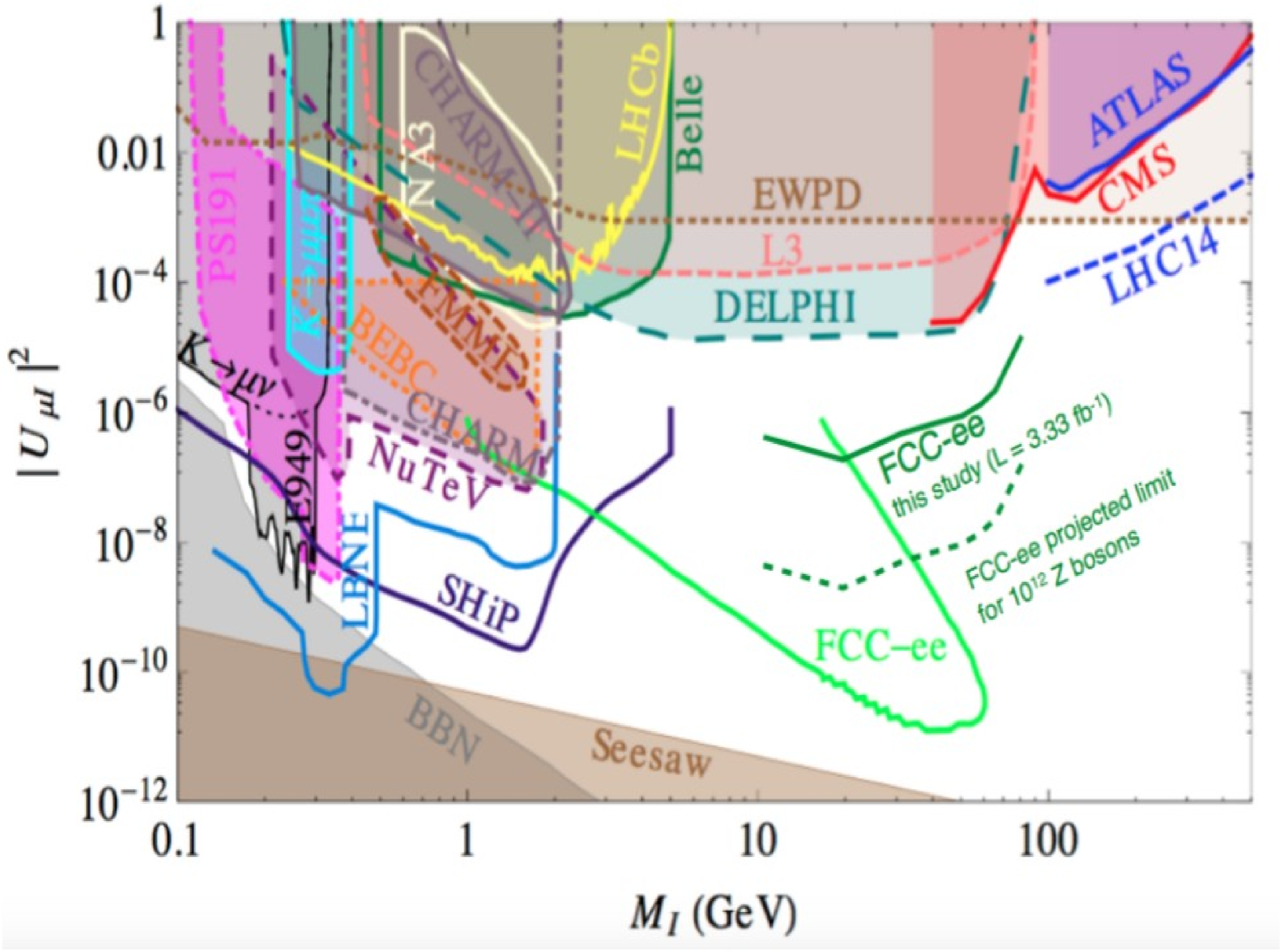


Results (FCC)

Sissel Bay Nielsen's
Master thesis







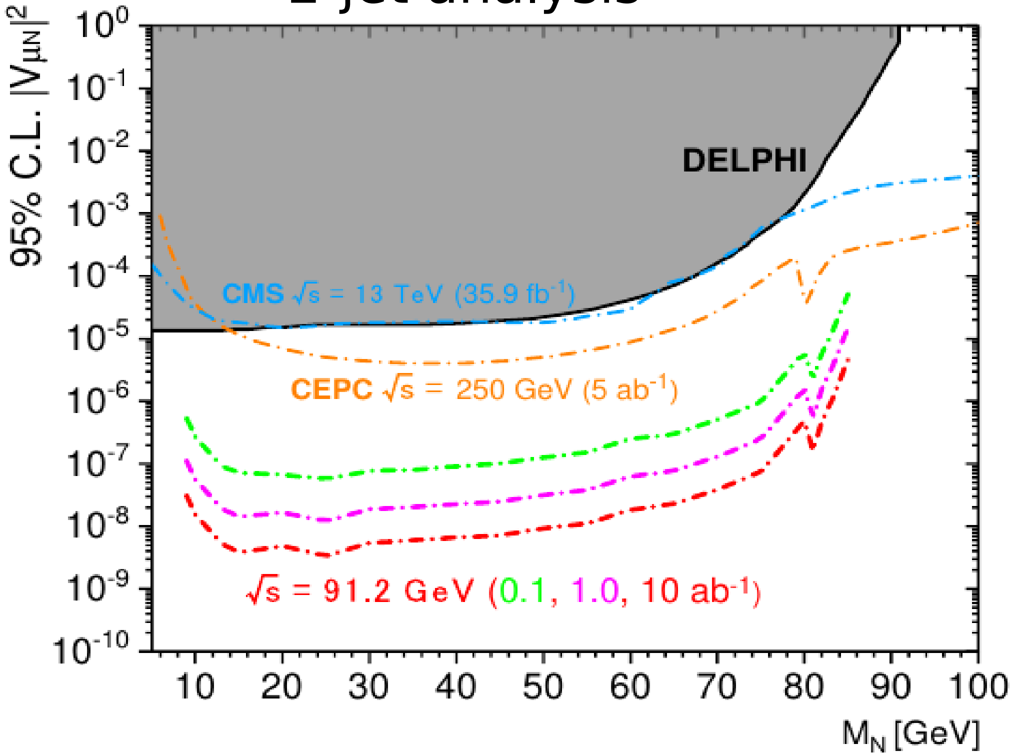
DELPHES for CLIC detector, μjj channel

Study performed for 3.3 fb^{-1} (10^8Z)

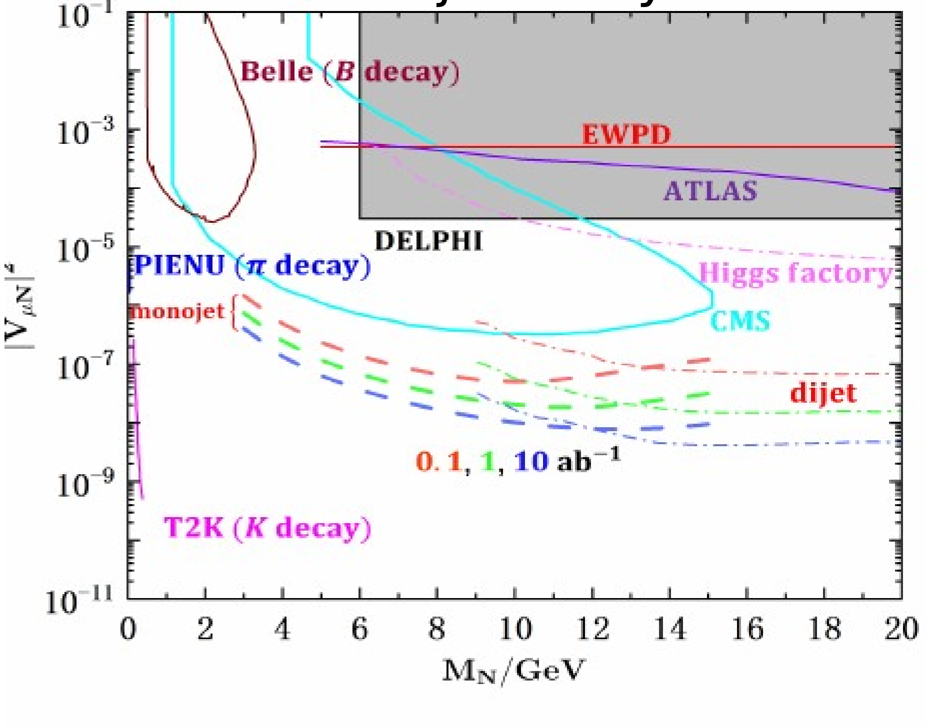
Difficult to extrapolate to 5×10^{12} Z because of MC statistics

Results (CEPC)

2-jet analysis



Monojet analysis



Results both for ejj and μ jj final state.

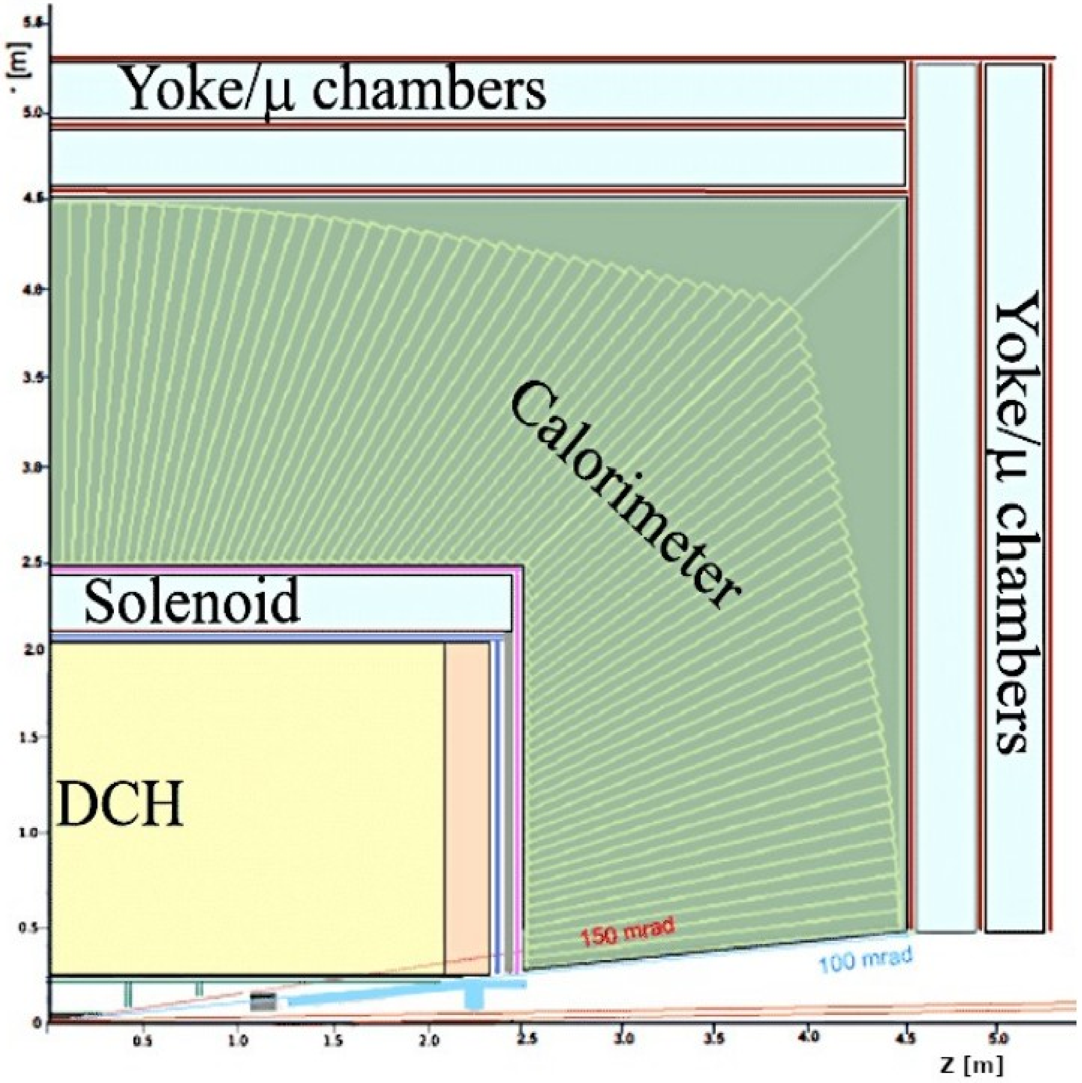
All Z decays and 4-fermion backgrounds considered

Main background for monojet analysis Z → τ τ

Coverage extended down to 3 GeV

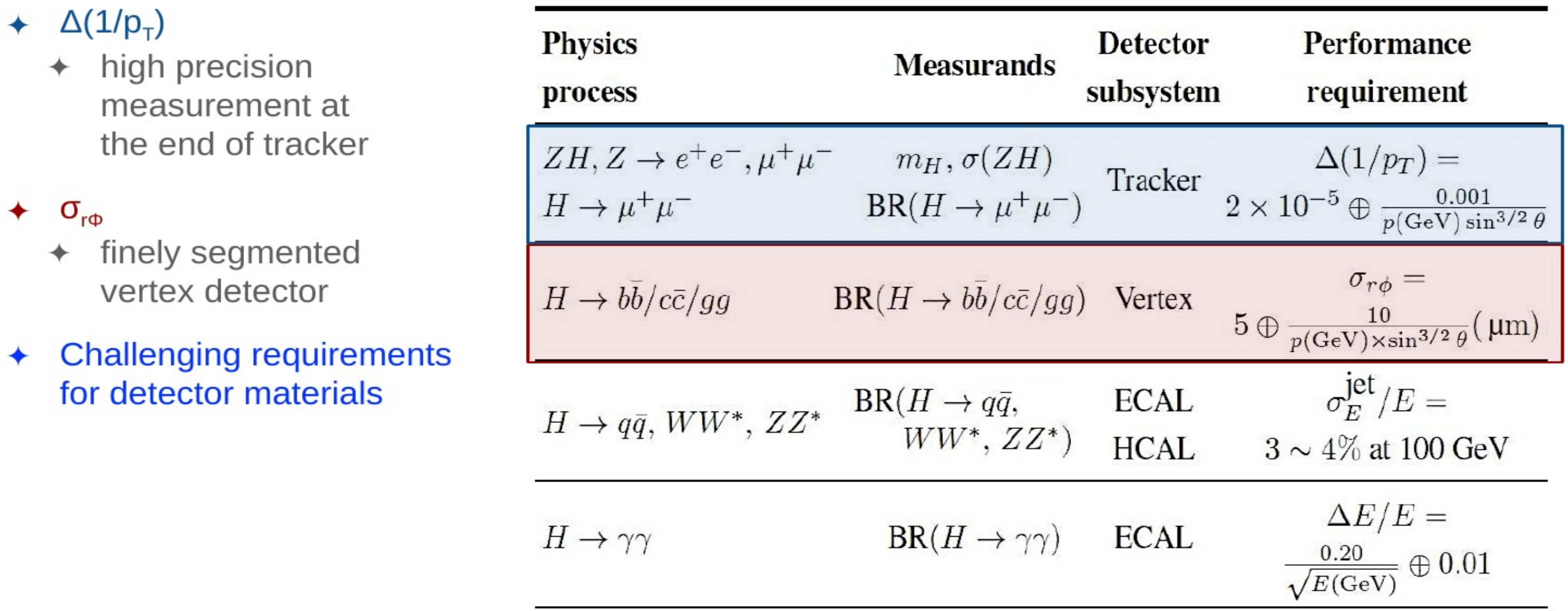
IDEA concept

- Muon chambers
  - µRwell in the return yoke
- Dual-readout calorimetry 2 m / 7 λ_{int}
  - Preshower µRwell
- Thin superconducting solenoid
  - 2 T, 30 cm, ~ 0.7 X_0 , 0.16 λ_{int} @ 90°
- Transparency for tracking
  - Si pixel vertex detector
  - Drift Chamber
  - Si wrappers (strips)
- Beam Pipe: R ~ 1.5 cm



Slide by R.Ferrari

FCC-ee / CepC general requirements



- $\Delta(1/p_T)$
  - high precision measurement at the end of tracker
- $\sigma_{r\Phi}$
  - finely segmented vertex detector
- Challenging requirements for detector materials

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Slide by R.Ferrari

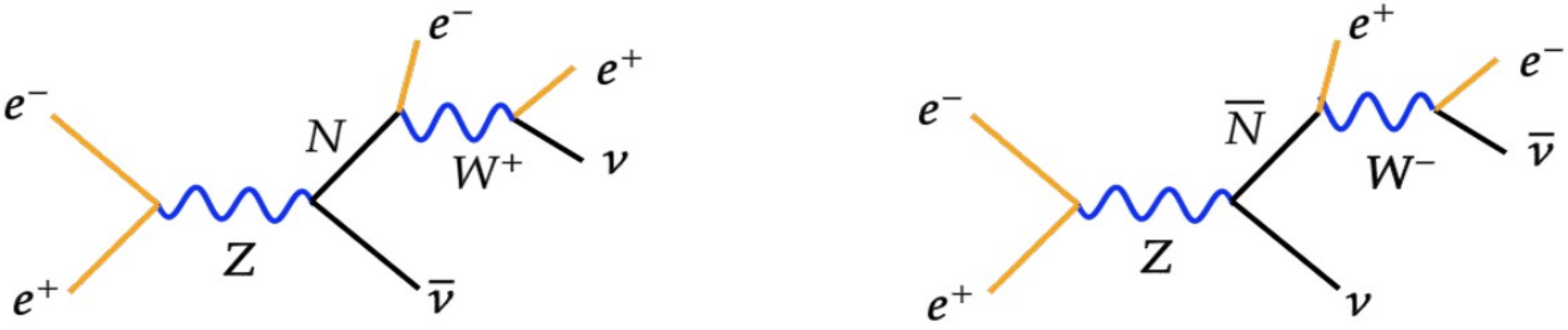
DELPHES setup for Spring 2021:

- Detailed parametrisation of IDEA tracker, including covariance matrices
- Calo resolution: EM 11%/sqrt(E), HAD: 30%/sqrt(E), 1% constant term
- Particle flow approach to jet reconstruction

Dirac versus Majorana

Blondel et al
arXiv:2105.06576

No same-sign lepton signature as for W→ l HNL, rely on final state kinematics



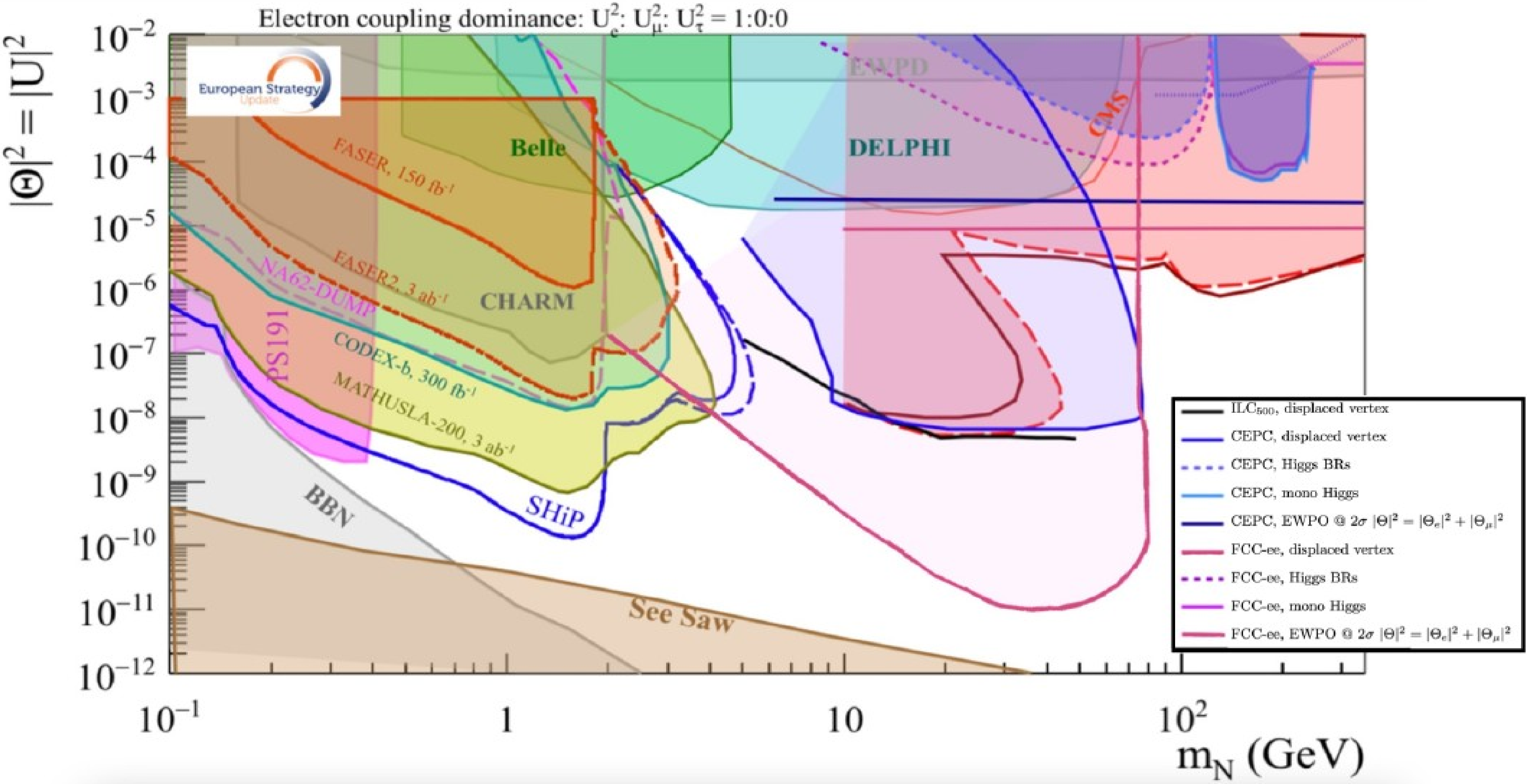
- Dirac neutrinos $(e^+e^- \to Z \to \nu\bar{N};\ e^+e^- \to Z \to \bar{\nu}N)$

$$\frac{1}{\sigma_{N,\bar{N}}}\frac{d\sigma_{N,\bar{N}}}{d\cos\theta} \propto \left(g_R^2\,(1 \mp \cos\theta)^2 + g_L^2\,(1 \pm \cos\theta)^2 + \frac{M_N^2}{m_Z^2}\,(g_L^2 + g_R^2)\ \sin^2\theta \right)$$

- Majorana neutrinos $(e^+e^- \to Z \to \nu N)$

$$\frac{1}{\sigma_N}\frac{d\sigma_N}{d\cos\theta} \propto \left(1 + \cos^2\theta + \frac{M_N^2}{m_Z^2}\sin^2\theta \right)$$

Relevant both for prompt and LLP, LLP has additional handle in lifetime


Electron coupling dominance: U_e^2: U_μ^2: U_τ^2 = 1:0:0
$|\Theta|^2 = |U|^2$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
1
10
10^2
m_N (GeV)
European Strategy Update
EWPD
CMS
Belle
DELPHI
FASER, 150 fb⁻¹
FASER2, 3 ab⁻¹
CHARM
NA62-DUMP
PS191
CODEX-b, 300 fb⁻¹
MATHUSLA-200, 3 ab⁻¹
SHiP
BBN
See Saw
ILC$_{500}$, displaced vertex
CEPC, displaced vertex
CEPC, Higgs BRs
CEPC, mono Higgs
CEPC, EWPO @ 2σ $|\Theta|^2 = |\Theta_e|^2 + |\Theta_\mu|^2$
FCC-ee, displaced vertex
FCC-ee, Higgs BRs
FCC-ee, mono Higgs
FCC-ee, EWPO @ 2σ $|\Theta|^2 = |\Theta_e|^2 + |\Theta_\mu|^2$