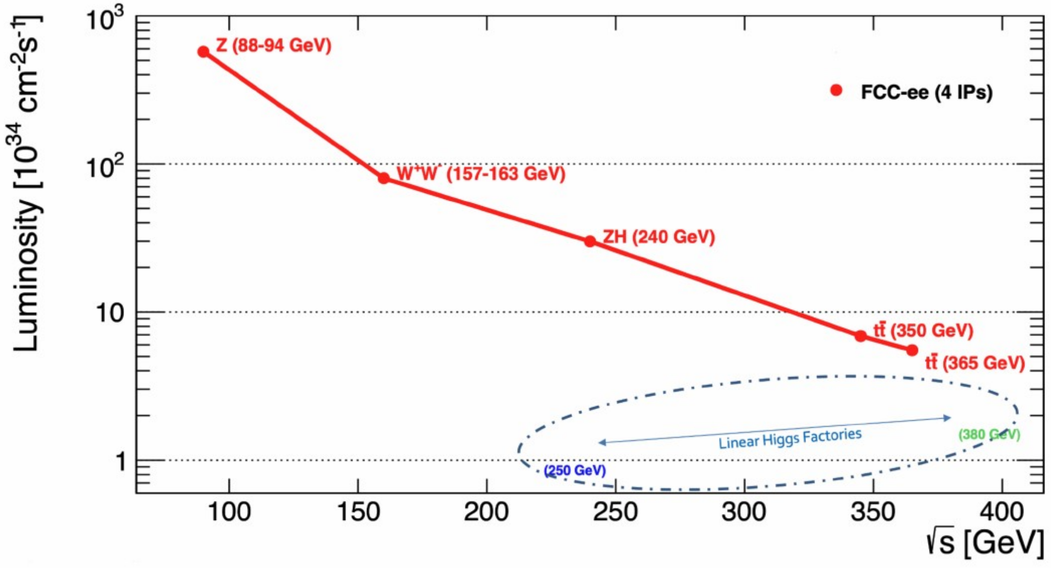
New Physics at FCC-ee

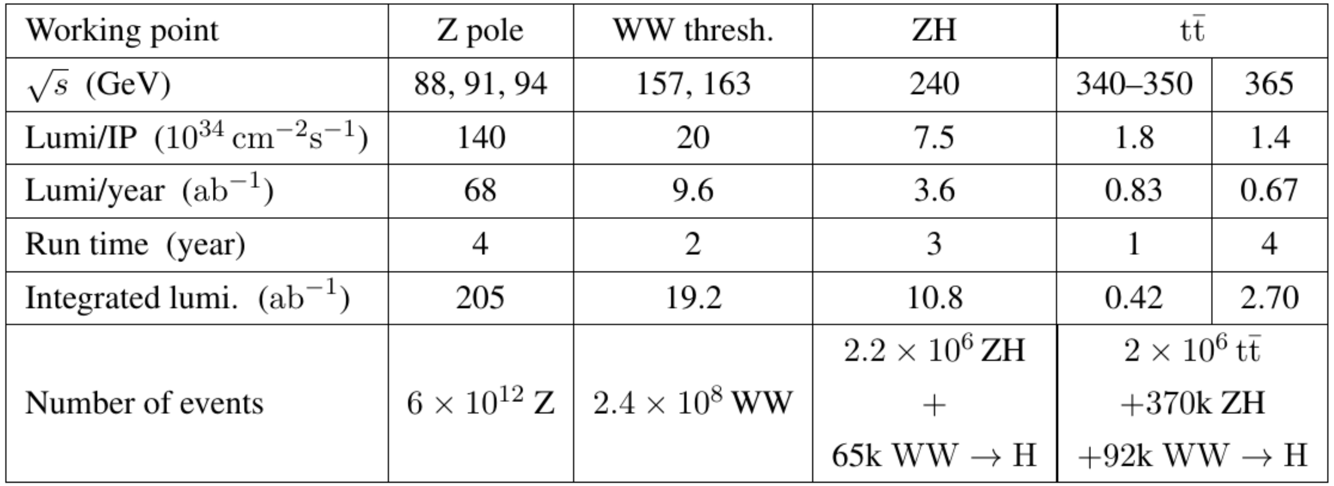
G. Polesello (INFN Pavia)

FCC-ee

- Energy range: Z-pole to ttbar production
- Very high luminosity yielding huge statistics of SM high mass particles, in particular
  - $6\text{x}10^{12}$ Z bosons
  - ~$2.5\text{x}10^{6}$ Higgs bosons
- Very clean (e^+e^-) experimental environment as compared to hadron machines

  → see opportunities for BSM discovery in this environment





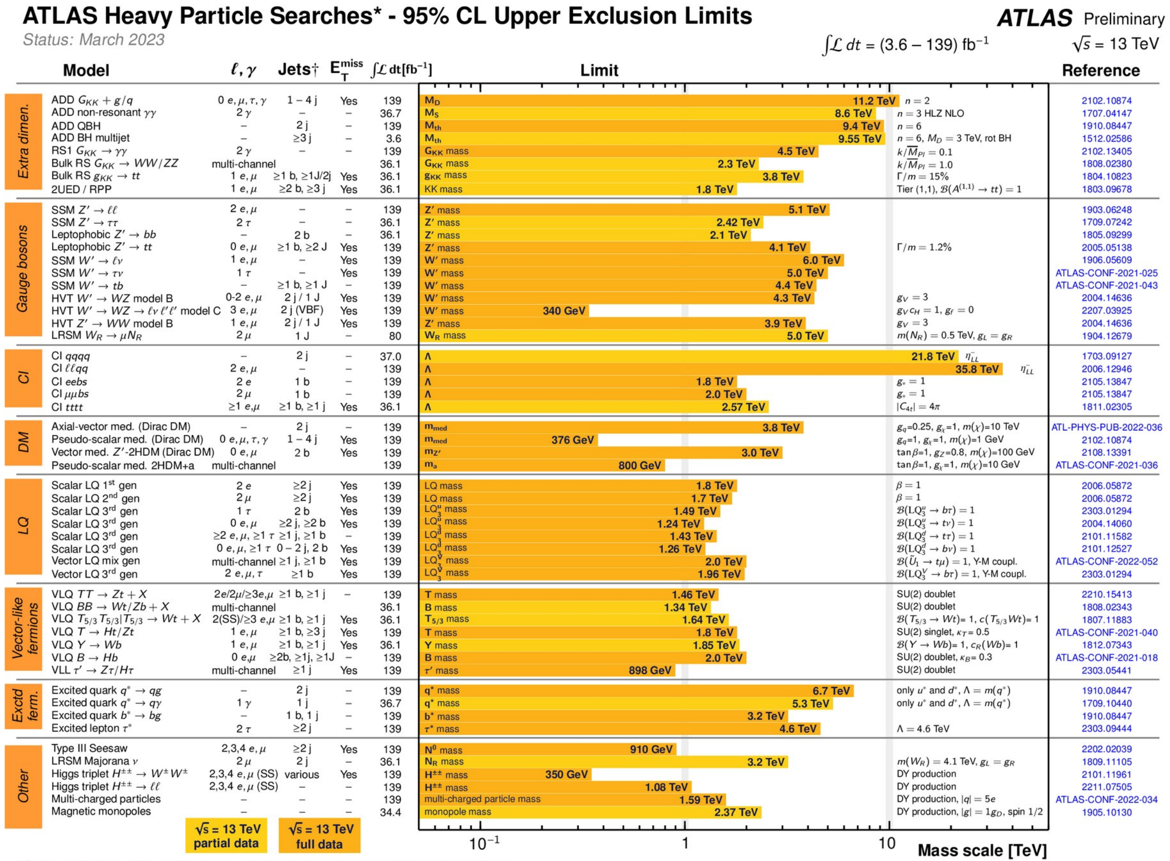
Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW → H	2×10^{6} $t\bar{t}$ +370k ZH +92k WW → H	

BSM

After (HL-)LHC, generic new physics excluded up to scale of few TeV

How to go beyond:

- Loopholes in LHC searches:
  - BSM particles with masses <few GeV
  - Compressed BSM spectra
- High statistics and clean environment to explore higher mass scales:
  - Deviations from SM prediction of precision measurements
  - Direct detection of rare decays of H,Z,top



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

Talk by A. Valenti today

Main thrust of this talk, based on results shown at recent:
ECFA workshop
FCC workshop

LHC loopholes: SUSY

Two obvious examples:

- Compressed slepton
- Higgsino

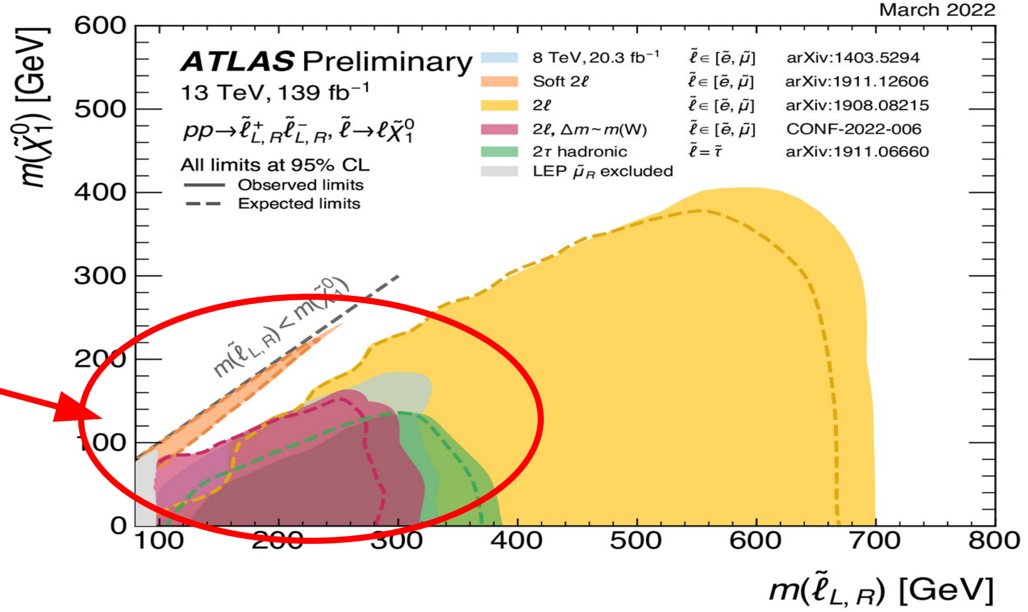
Need to verify what kind of challenges for detector design these signatures provide.

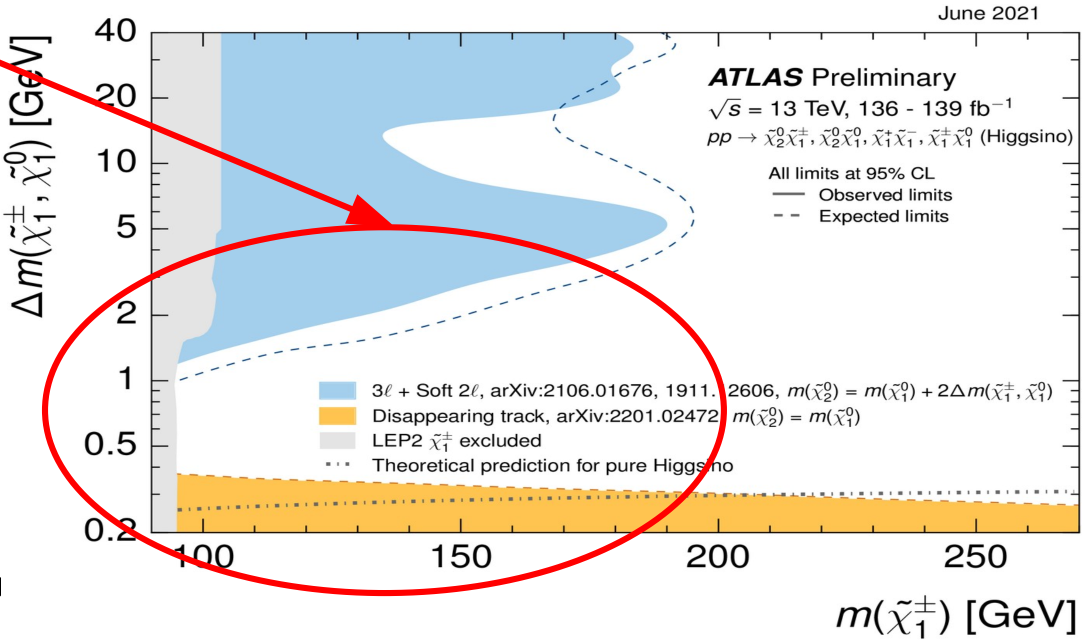
pMSSM scans can show uncovered points in gaugino parameter space

Need explicit benchmarks.

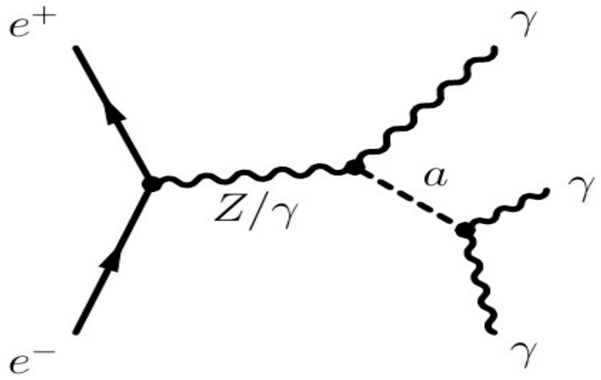
- Input from ATLAS/CMS pMSSM studies
- Input from theory, see e.g.

https://arxiv.org/abs/2207.05103





The role of EFTs



Before LHC clear theory font-runner: SUSY

For FCC no strong theoretical guidance: rely on EFT approach:

- Postulate a new BSM particle a
- Add to SM Lagrangian terms for coupling of a to relevant SM particles suppressed by scale of new physics Λ

Example: axion-like particle coupling to vector bosons

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

Achievable scale with 10^{12} Z:

$BR(Z\to a\gamma)=(C_{\gamma Z}/\Lambda)^2 x8.6e^{-4}$ (Λ in TeV)

→ For $BR(Z\to a\gamma)=1e^{-12}$:

$C_{\gamma Z}/\Lambda \sim 3e^{-5}\ \mathrm{TeV}^{-1}$

With 10^{12} Z, a new physics scale of ~10^4 TeV can be explored by looking for rare decays

Lifetime of new particles

Width of particle a of mass m_a decaying only through vertex (C/Λ):

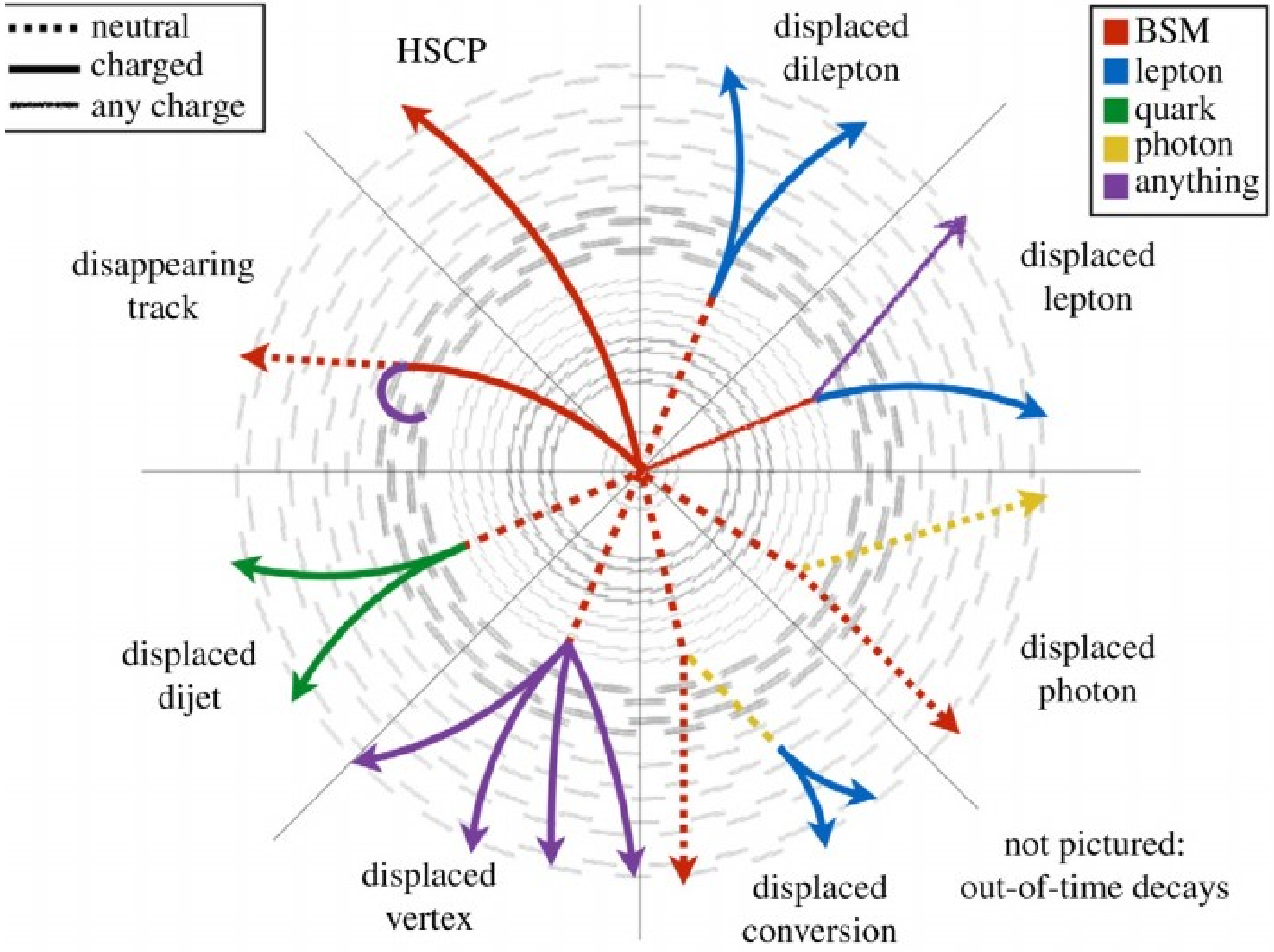
$$\Gamma_a \sim m_a^3 (C/\Lambda)^2$$

For low masses and low couplings small BSM particle width → long lifetimes, LLPs

Wealth of signatures with little/no SM background

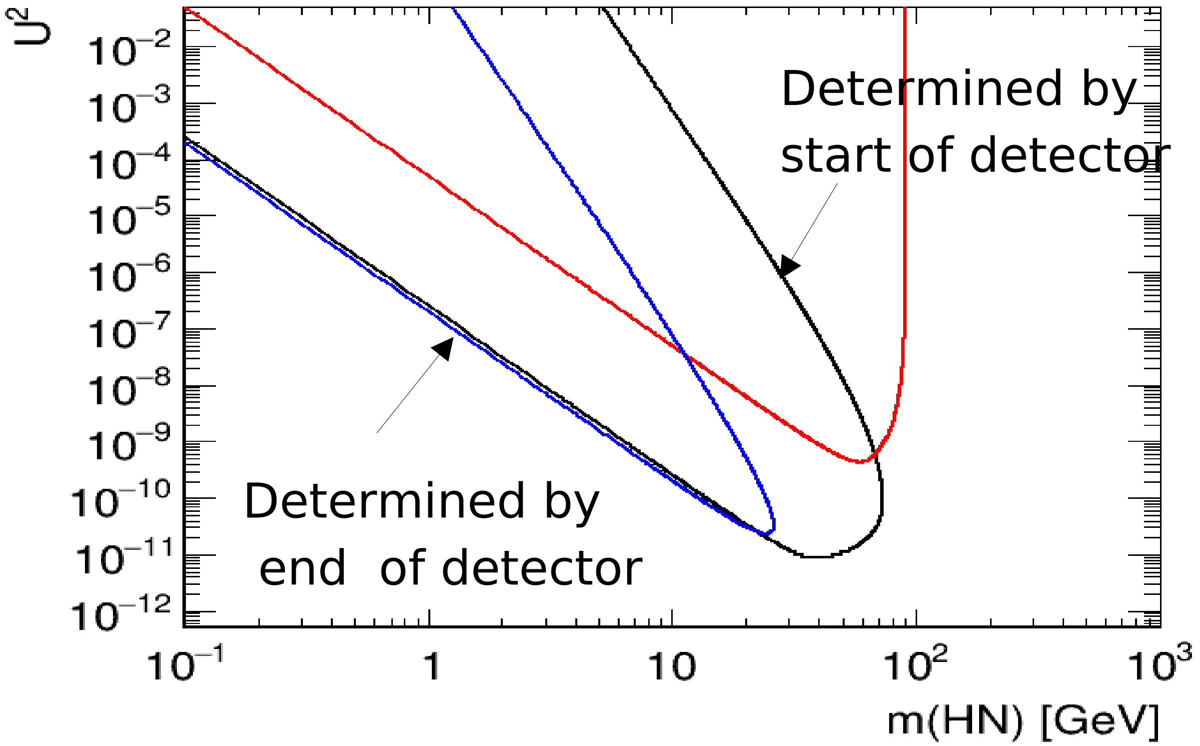
LHC detectors designed without thinking of LLPs (although they are doing pretty well on it!)

Establish requirements for FCC detectors enabling them to fully exploit physics opportunity of LLPs



Prompt vs LLP

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



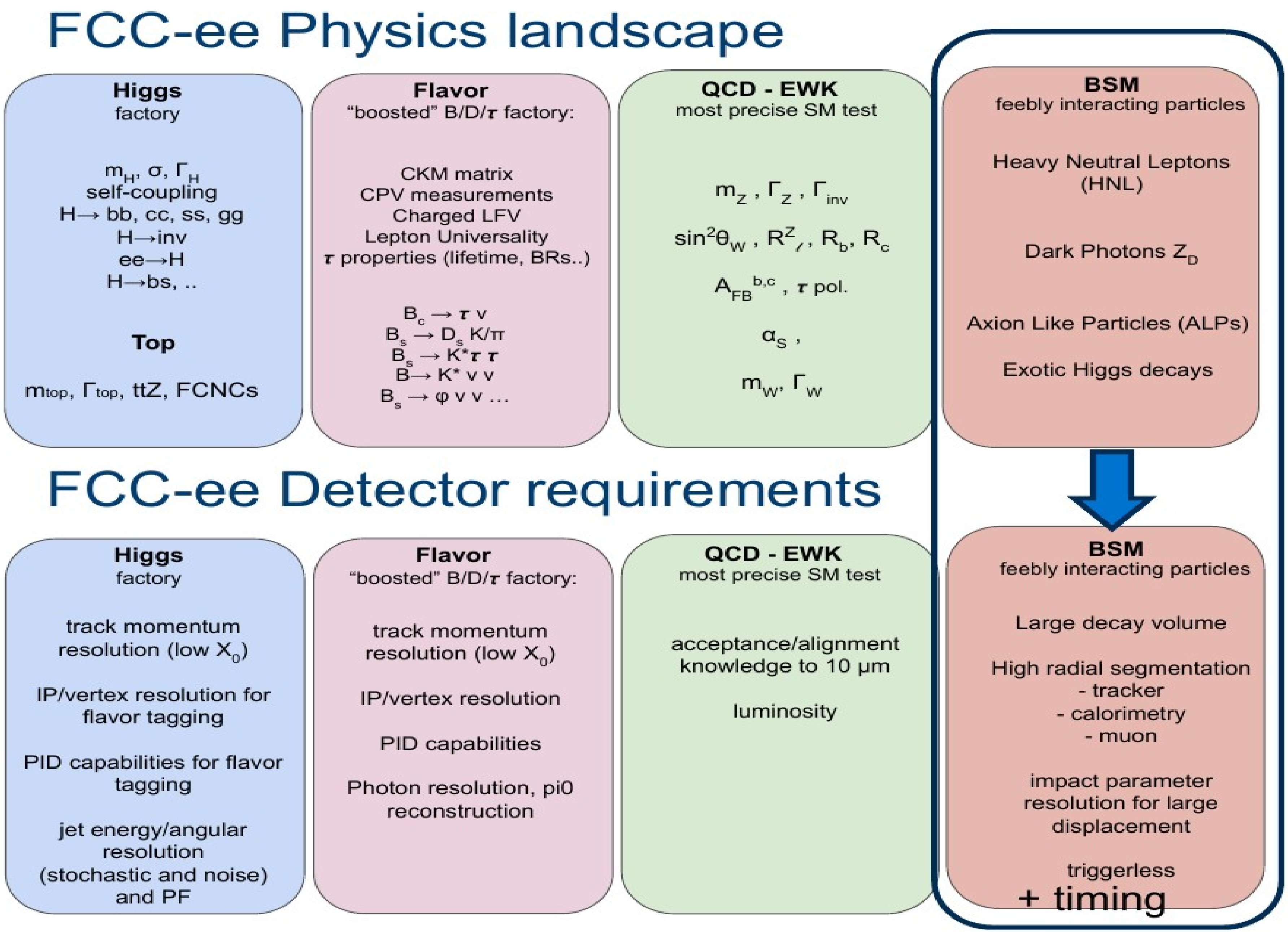
Complementary reach of three different signatures:

- 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

FCC-ee: physics vs detector requirements



FCC-ee Physics landscape

Higgs
factory

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

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

Benchmark studies in FCC-ee PED BSM group

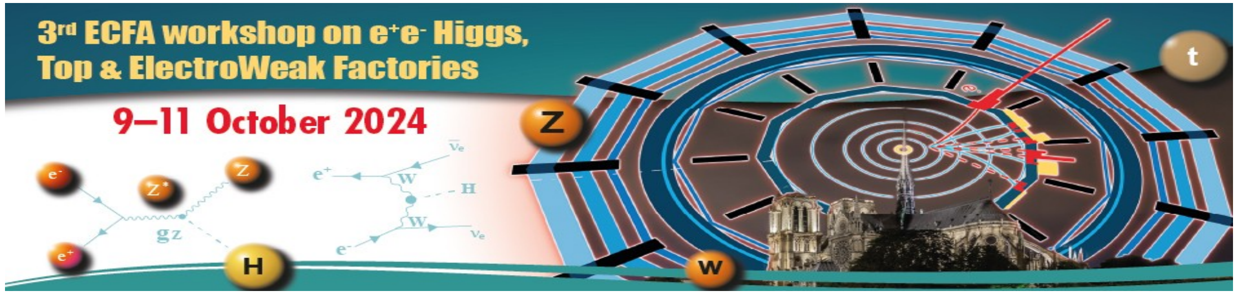
- Z-pole (extendable to all Fcc-ee runs)
  - Axion-like particle searches
  - Heavy Neutral Lepton (HNL) searches
- Higgs sector
  - Higgs decay to long-lived scalars
  - Searches for additional higgses

Reach studies based on parametrised simulation: define requirements on detectors for full exploitation of FCC-ee direct BSM potential.

Next step will be moving to detailed GEANT4 simulation

Recent workshops

Today personal choice out of large material,more info in three recent workshops



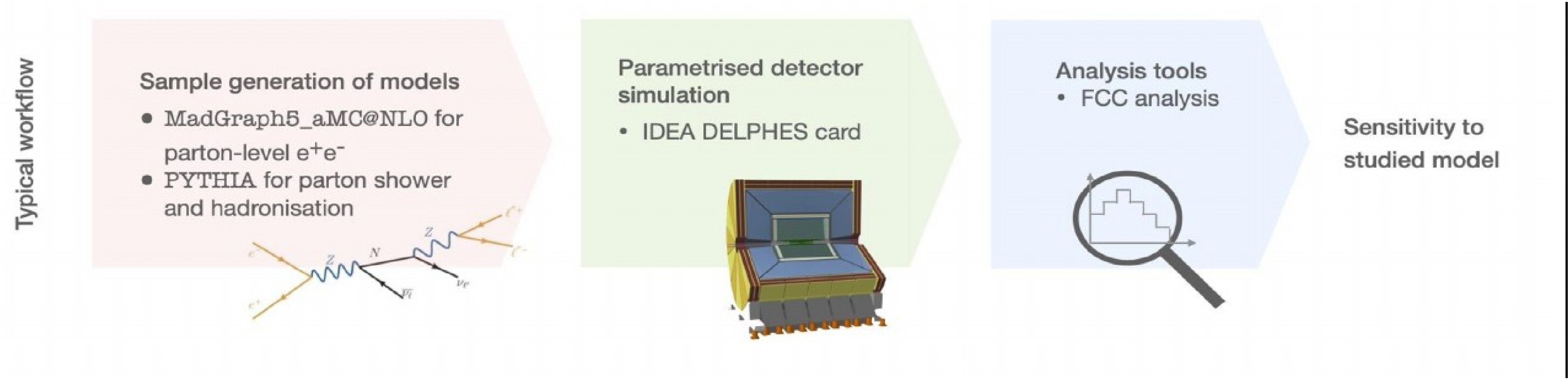
ECFA workshop link

See talk of R. Franceschini there for topics
I will not touch Link

Venice workshop link

CERN workshop link

Workflow of experimental analyses



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

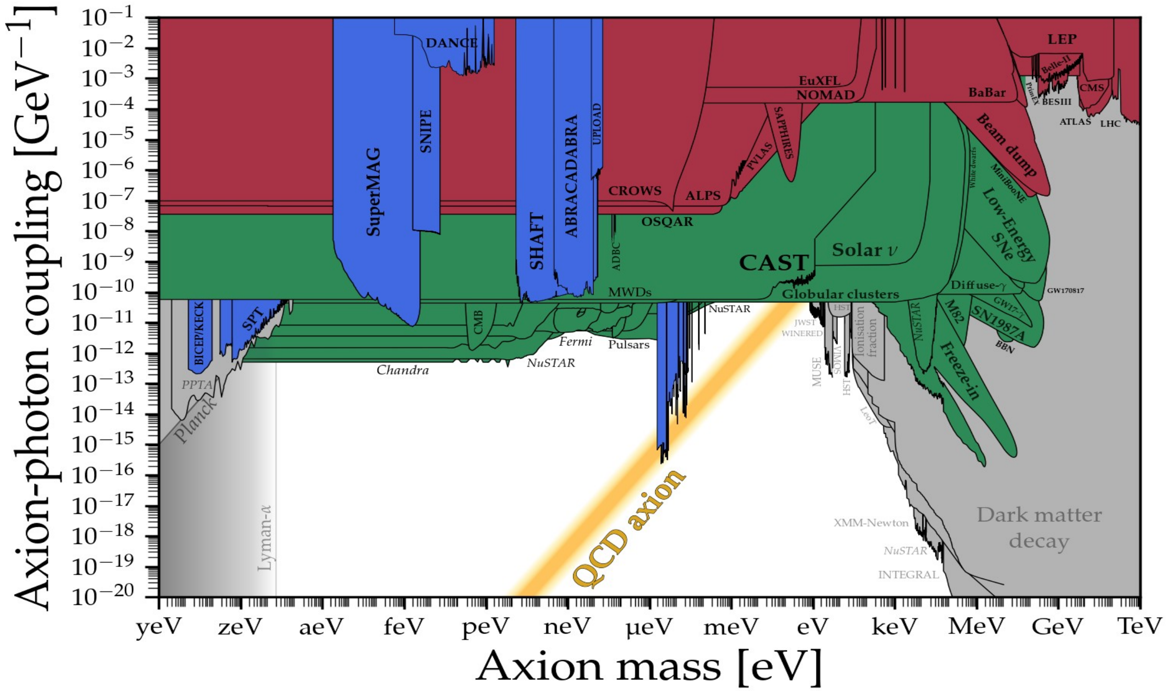
- Background files produced centrally based on FCC software.
- Signal files produced either centrally or by analysis group.
- DELPHES output stored in EDM4HEP format
- Use FCCsoftware to produce ntuples for analysis based on FCCanalysis package
- Two large production campaigns, spring2021 and winter2023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

Z-pole studies

ALPs

Axion Like Particles (ALP): hypothetical pseudoscalar with similar interactions as the QCD axion, appearing naturally in many extensions of the SM

Couples to Z/photon, can be abundantly produced at FCC-ee



High statistics of FCC-ee Z-pole run allows exploration of much lower couplings to photons than tested to date in mass range 0.1-90 GeV

In BSM group ongoing studies for different ALP decay modes:

a→γγ, a→gluon gluon, a→μμ

Typical vector boson part of ALP Lagrangian

Bauer et al:arXv:1808.10323

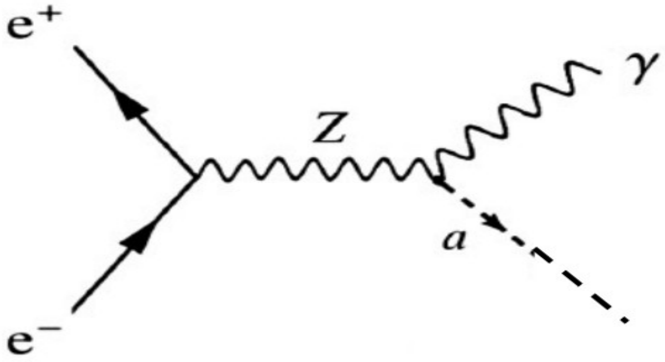
$$\mathcal{L}_{\text{eff}} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

with $C_{\gamma\gamma} = C_{WW} + C_{BB}, \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB}, \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$

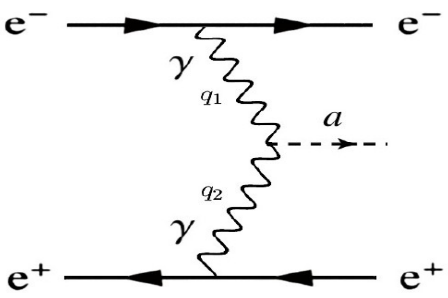
Benchmark:Assume a couples to hypercharge and not to SU2 (C_{WW}=0) $\quad C_{\gamma Z} = -s_w^2\, C_{\gamma\gamma}$

2-d parameter space: (m_a,$C_{\gamma\gamma}$)

Production in FCC-ee Z-pole run



Decay Z→ γa: function of $C_{Z\gamma}$ Coupling. Mode assumed in analyses shown today.



Photon-photon fusion: function of $C_{\gamma\gamma}$ coupling Studied in:

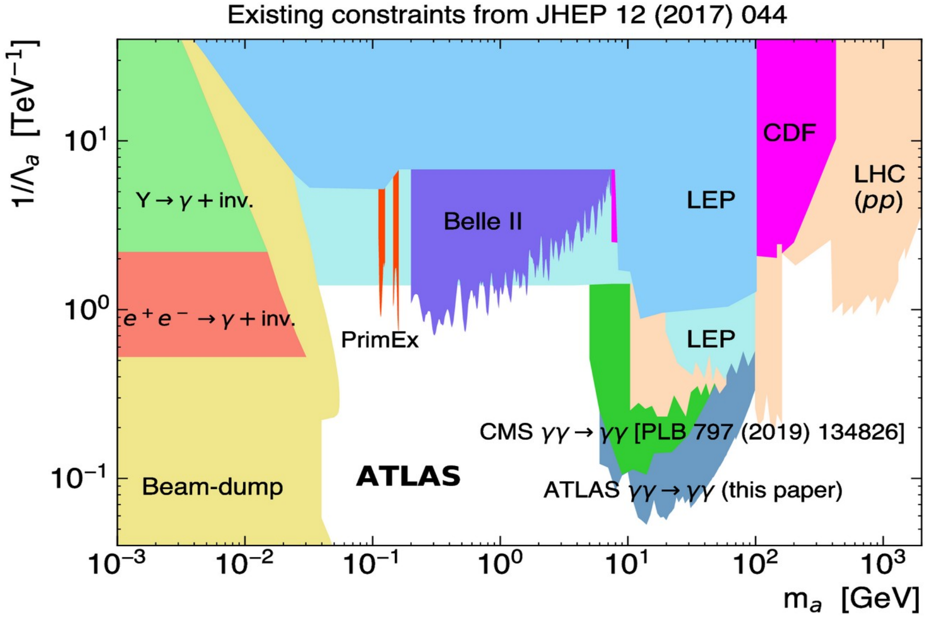
Rebello Teles et al.

$a \to \gamma\gamma$

Regions of interest:

- 0.1< ma < 10 GeV:
  loose limits from previous e+e- searches, out of reach of beam dump
- 10 < m_a < 90 GeV:
  dominated by LHC photon-photon fusion potential for FCC-ee Z pole run

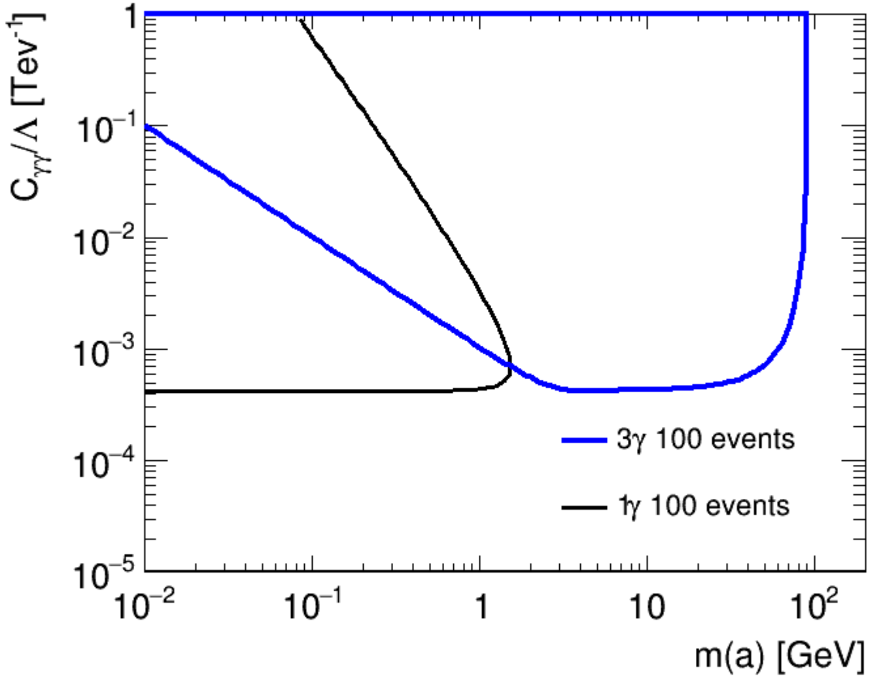
ATLAS:arXiv 200805355



Depending on a lifetime consider two cases

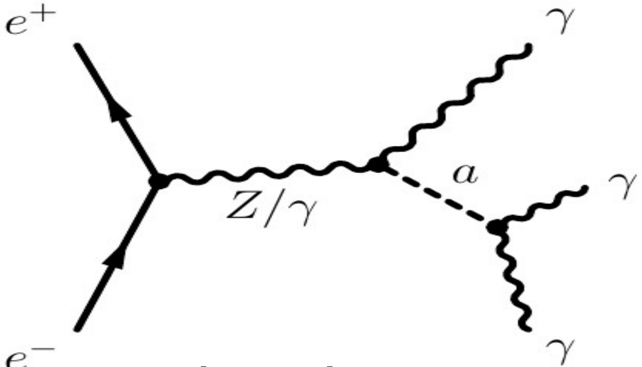
- Three photons are observed in detector
- The ALP decays outside the detector: only a monocromatic photon in the event

Two different regions in parameter space covered.

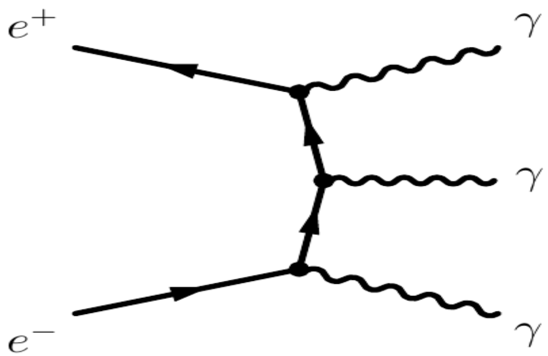


3γ ALP analysis

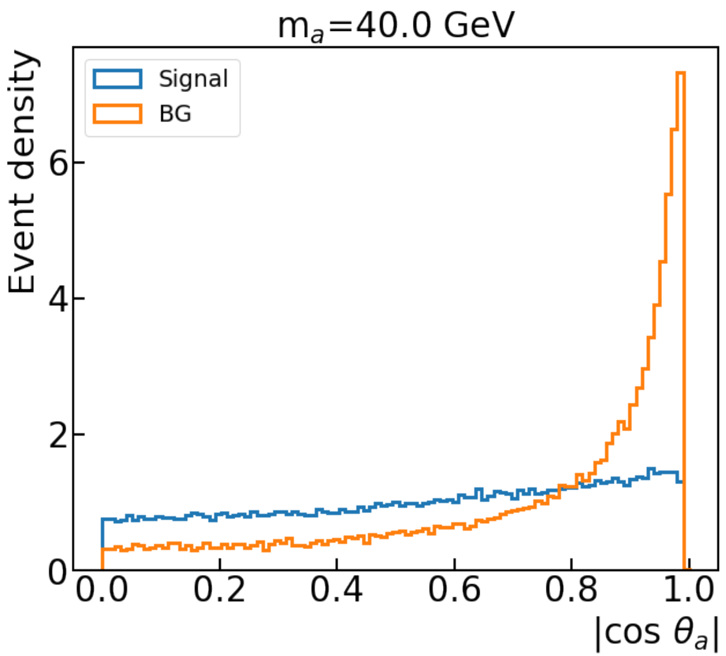
G.P. Talk at CERN

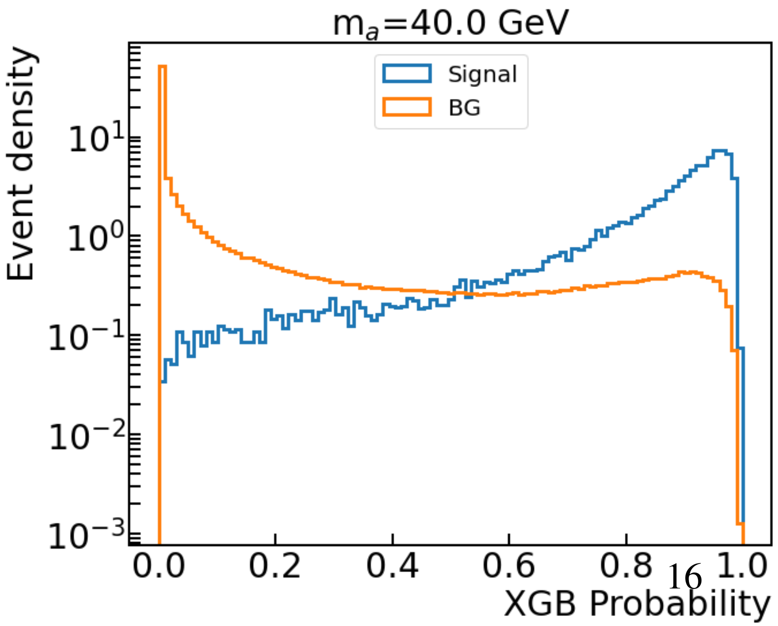


Signal



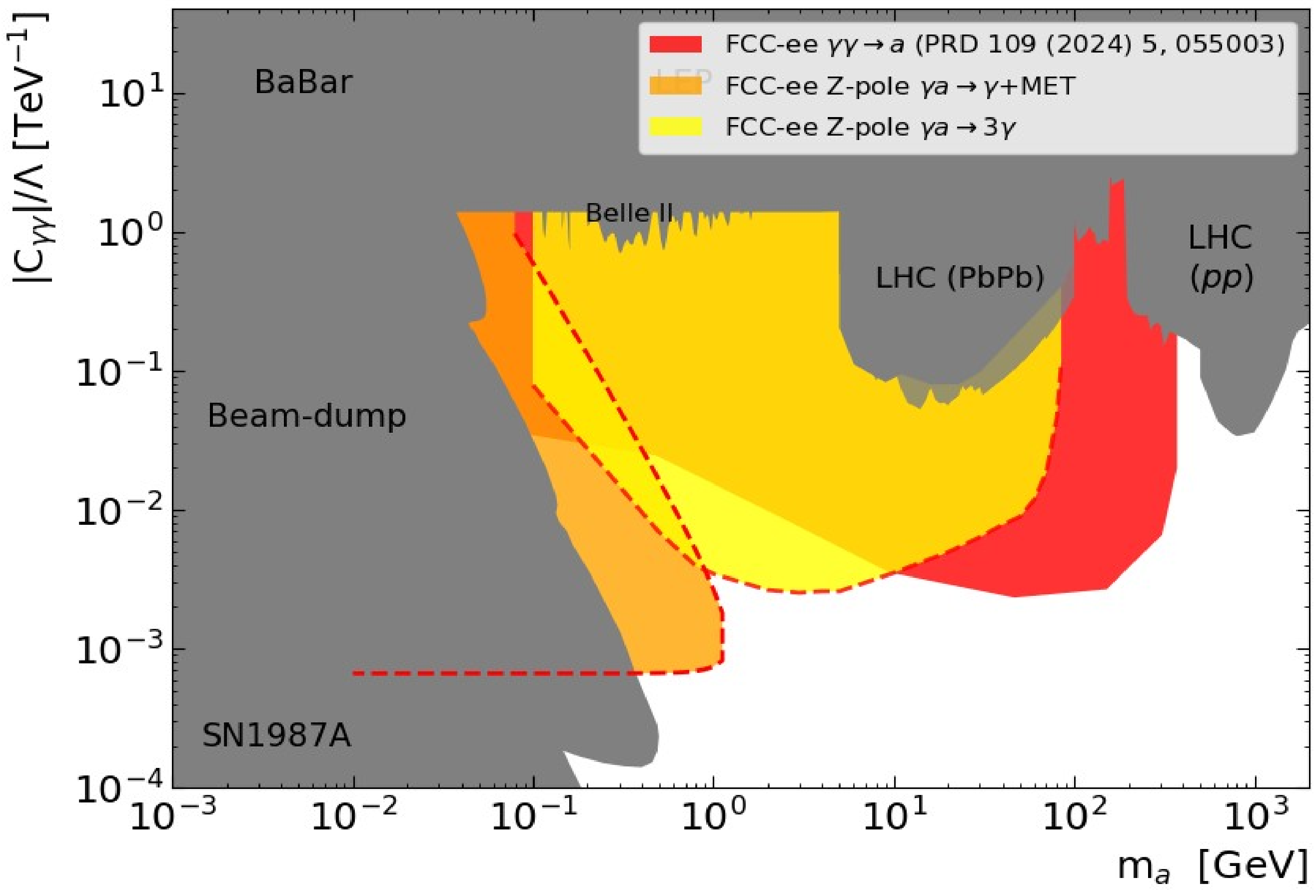
Dominant background





- 3 photons within $|\eta|<2.6$ and energy>1 GeV
- Scan test masses *M* between 0.1 and 85 GeV
- Assign 2 photons to ALP decay based on kinematic compatibility (γ_1,γ_2), third photon to Z decay (γ_3)
- Build BDT probability based on 3 angular variables+ $m(\gamma_1\gamma_2)$, $E_{\gamma3}$, and $E_{\gamma2}/E_{\gamma1}$

Results

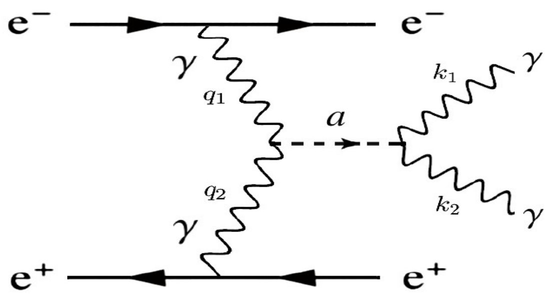


Coverage down to a ~10^{-3} in the mass range 0.1-300 GeV

Grey areas :existing exclusions

Yellow and orange: areas with >2σ significance respectively For the 3-photon and 1-photon analysis

Red area is analysis of Rebello Teles et al. addressing ALP production in photon-photon fusion



HNL Models

Production in Z decay via mixing with light neutrinos

$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2\ \mathrm{BR}(Z \to \mathrm{invisible})\ \left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right)\left(1 - \frac{{m_N}^2}{{m_Z}^2}\right)$$

$$|U_N|^2 \equiv \sum\nolimits_{\ell=e,\mu,\tau} |U_{\ell N}|^2$$

For each HNL, phenomenology determined by 4 parameters: mass, mixing with three lepton flavours

Decay: three-body decay into 3 fermions via virtual W/Z

Decay length:

$$L_{N_i} = \simeq \frac{1.6}{U_i^2}\left(\frac{M_i}{GeV}\right)^{-6}\left(1 - (M_i/M_Z)^2\right)\ cm$$

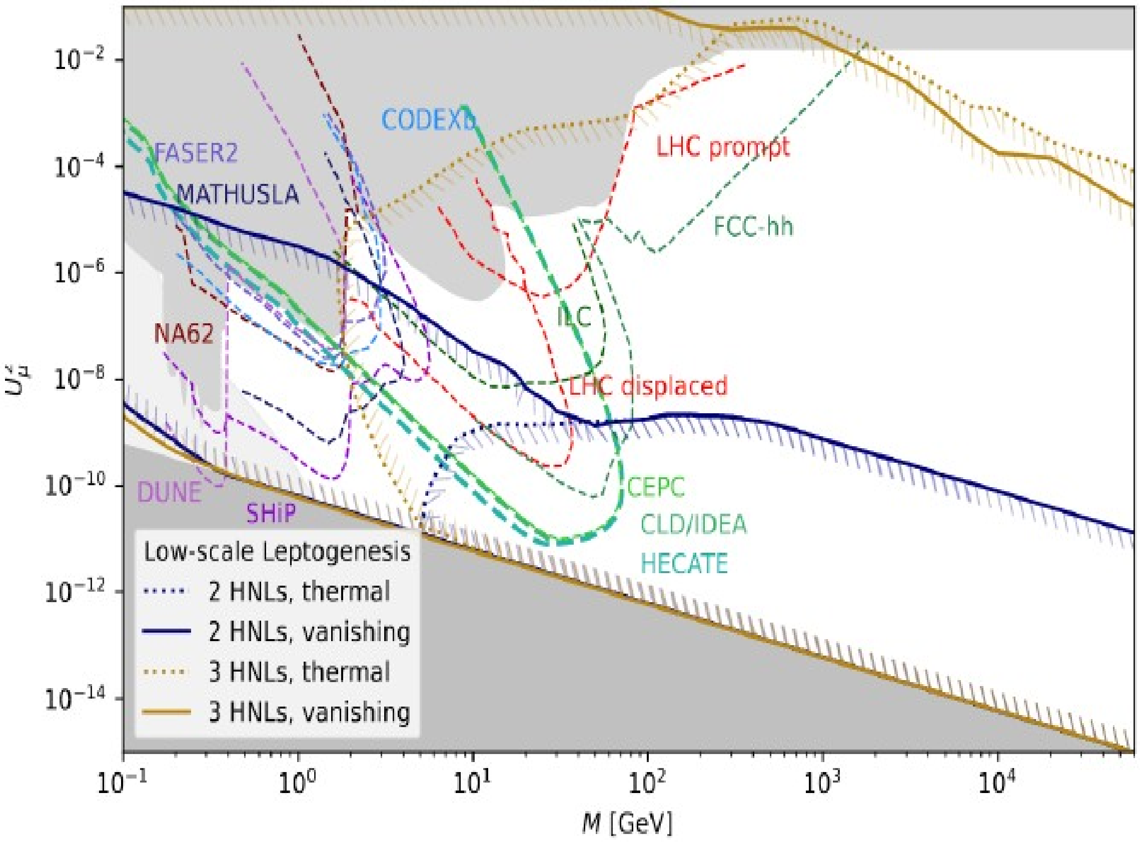
Benchmark models

ArXiv:2203.05502

Two models:

- Minimal realistic seesaw scenario:
  - Pseudo Dirac pair of semi-degenerate Majorana HNLs
  - Coupling to all leptons
  - Parameter choices compatible with leptogenesis and oscillation data
- Single low-mass HNL

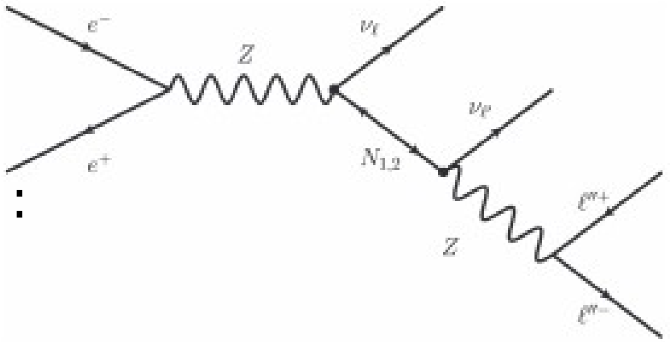
mixing with one lepton flavour l: only 2 parameters m_N and U_l, useful for comparing experiments or accelerators

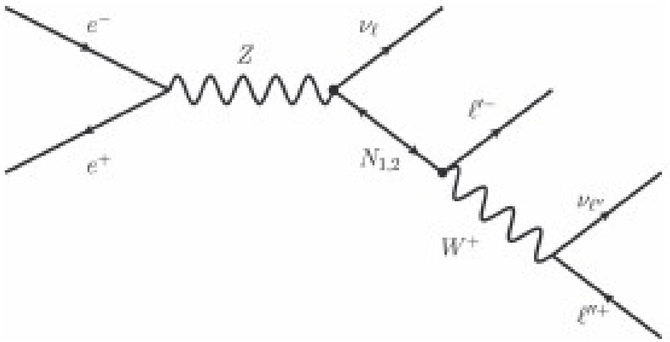


For single HNL several analysis with coupling to both e and μ and considering fully leptonic and semileptonic N decay: show only semileptonic μ case

Two HNLs

S. Giappichini et al. arXiv:2410-03615





Consider only decay of N into 3 leptons :

$e^+e^- \rightarrow N_{1,2}\nu$, $N_{1,2} \rightarrow ll\nu$

For τ consider only leptonic decays

Final state with two leptons and two neutrinos

Backgrounds: Z decays from official production+ 4-fermion irreducible:

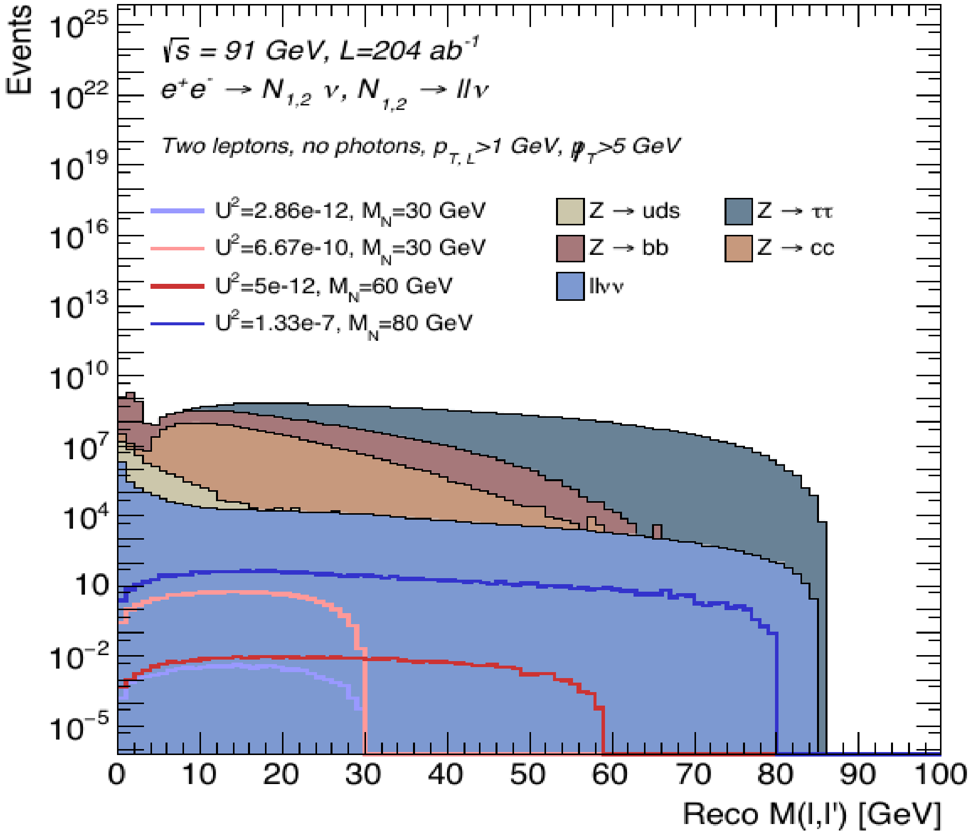
$e^+e^- \rightarrow l^+l^-\nu\nu$

Preselection:

2 reco leptons pT>1 GeV p_T^{miss}>5 GeV

veto photons and additional tracks

+ kinematic selections to suppress background



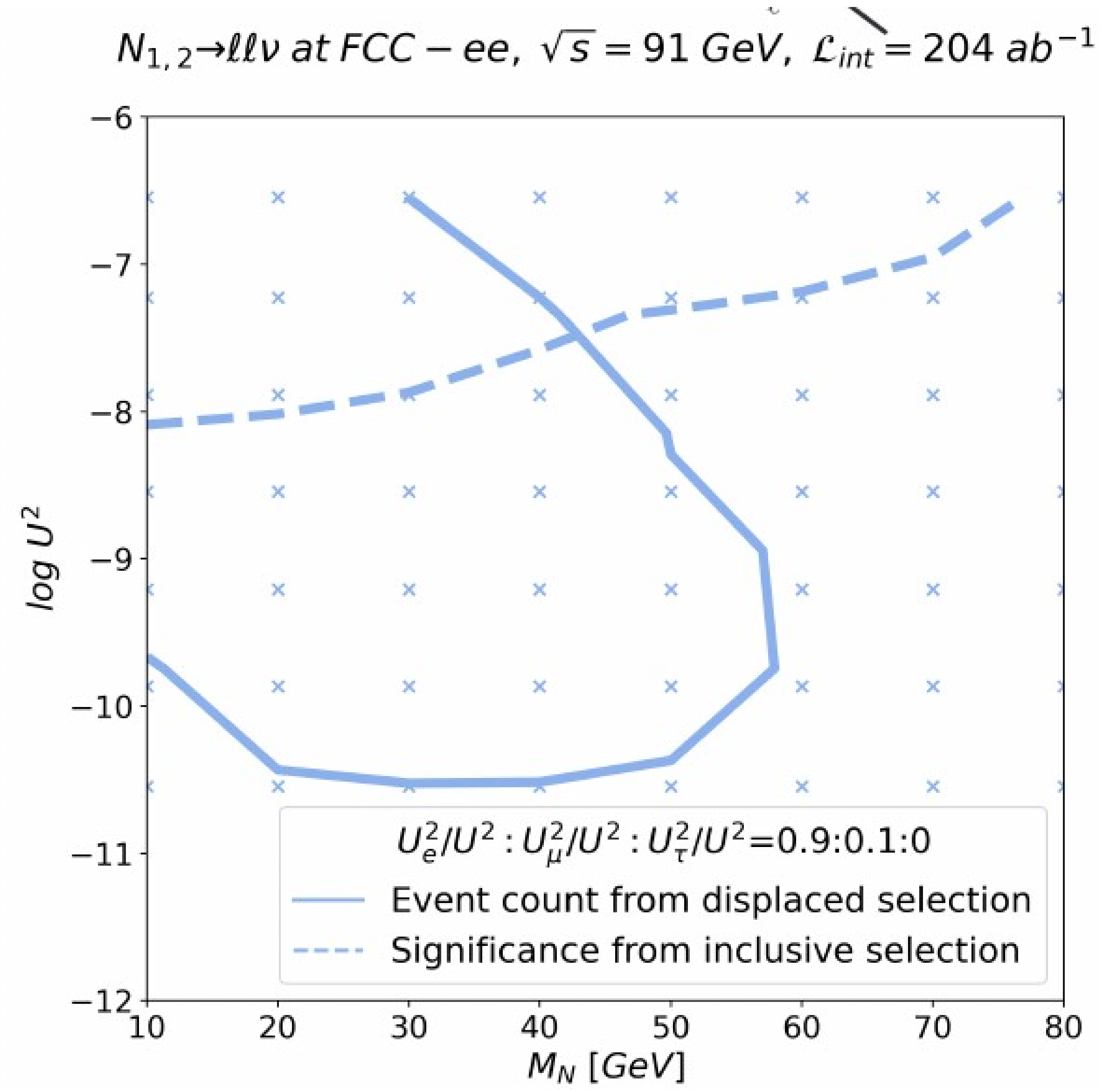
Results

Two different kinematic selections: inclusive and displaced, separated by requirement on impact parameter of leptons

Displaced:

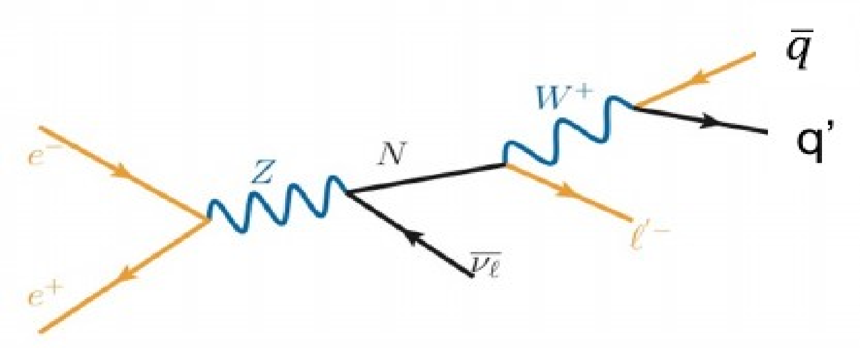
$|d_0^l|>0.64$ mm

For displaced selection achieve zero background, sensitive up to ~60 GeV



Single HNL→ μjj

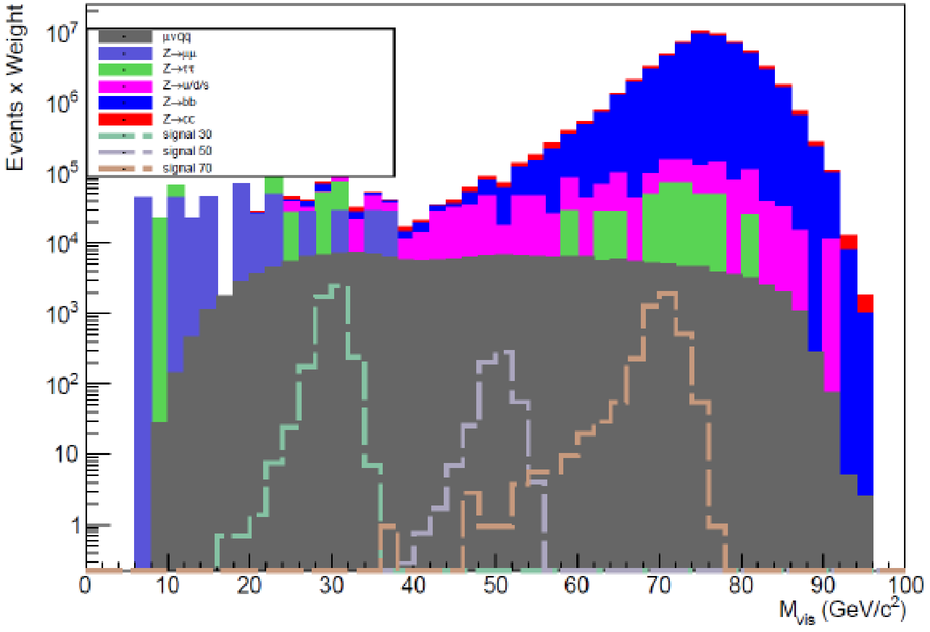
GP, Nicolò Valle



- 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 efficient Background suppression



Prompt analysis at Z peak:

Reducible backgrounds:

Z decays, dominated by Zbb

Irreducible background:

4-body μνqq

Results

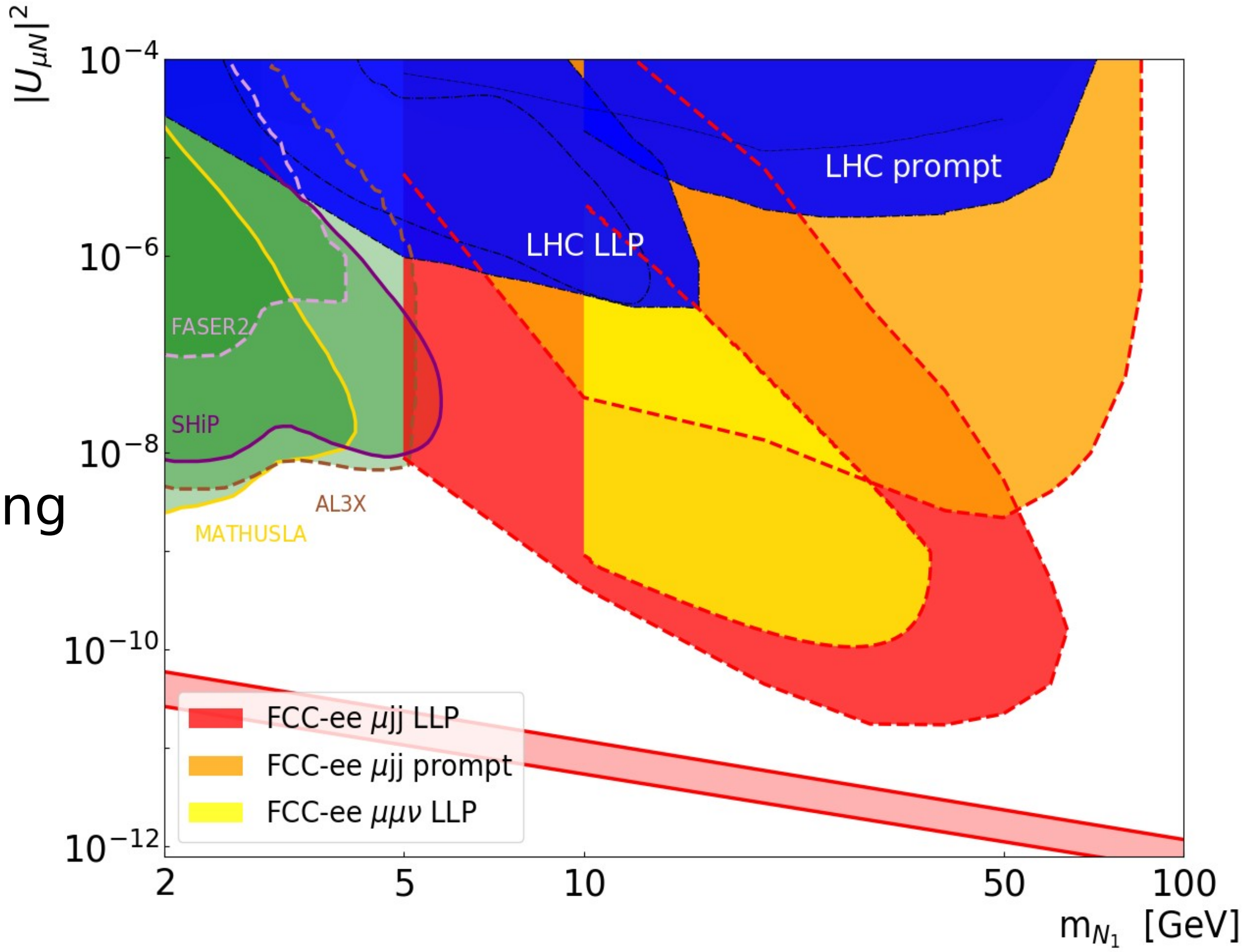
Require 1 or 2 reconstructed jets,
1 lepton and E^{miss}

Reconstruct good vertex from all tracks in event, require most tracks connected to vertex

Two different kinematic selections depending on radial position of vertex $r_{vx:}$

- Prompt (orange) $r_{vx}<0.5$mm
- LLP (red): $r_{vx}>0.5$mm → zero background

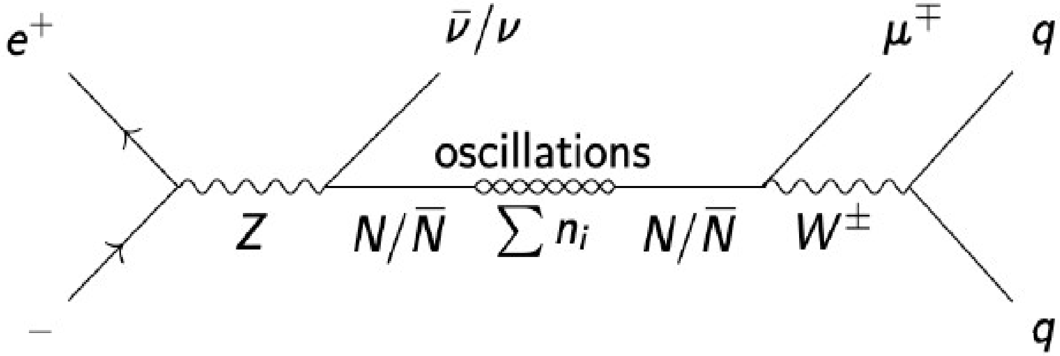
Also shown LLP μμνν final state (yellow)



HNL oscillations

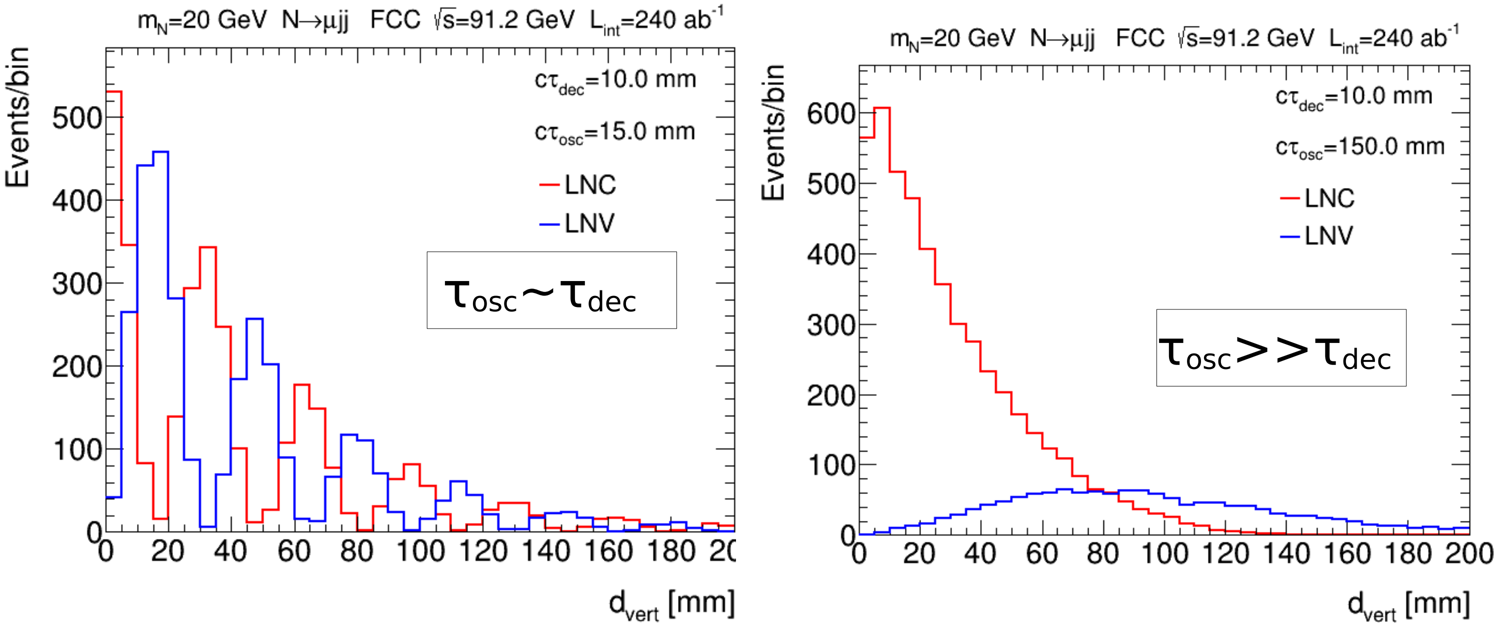
Pseudo-Dirac pair, decay N→μjj
Implemented in pSPSS(phenomenologically symmetry protected seesaw) model
S. Antusch et al. JHEP 10 (2023) 129

Two HNL oscillate into each other as they propagate before decaying



$$P_{\rm osc}^{\rm LNC/LNV}(\tau) = \frac{1 \pm \cos(\Delta m \tau)\exp(-\lambda)}{2}$$

LNC: neutrino at vx, μ^+ from $\bar{N}$ decay
LNV: antineutrino at vx, μ^- from N decay



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Interplay of two times:

- τ_{osc}: oscillation period ~Δm
- τ_{dec}: determined by mass and mixing angle

GP, Nicolò Valle

ECFA Talk

Oscillation variables

Production:

Asymmetry in HNL production angle from EWK Z polarization

$$A_\ell^{\mathrm{FB}}(\tau) := \frac{A_{\ell^-}^{\mathrm{FB}}(\tau) - A_{\ell^+}^{\mathrm{FB}}(\tau)}{2} = A_N^{\mathrm{FB}}\,\Delta P_{\mathrm{osc}}(\tau)$$

Decay:

Opening angle neutrino-lepton in HNL rest frame (α) from HNL polarisation

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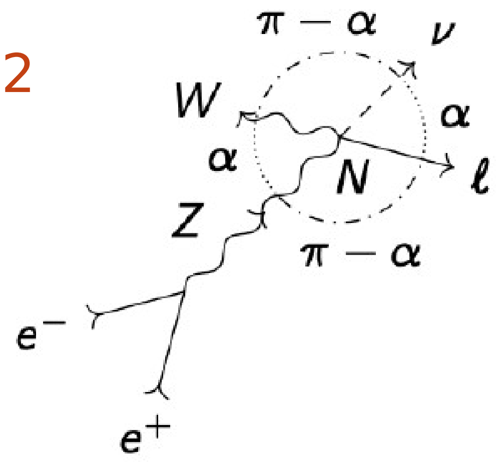
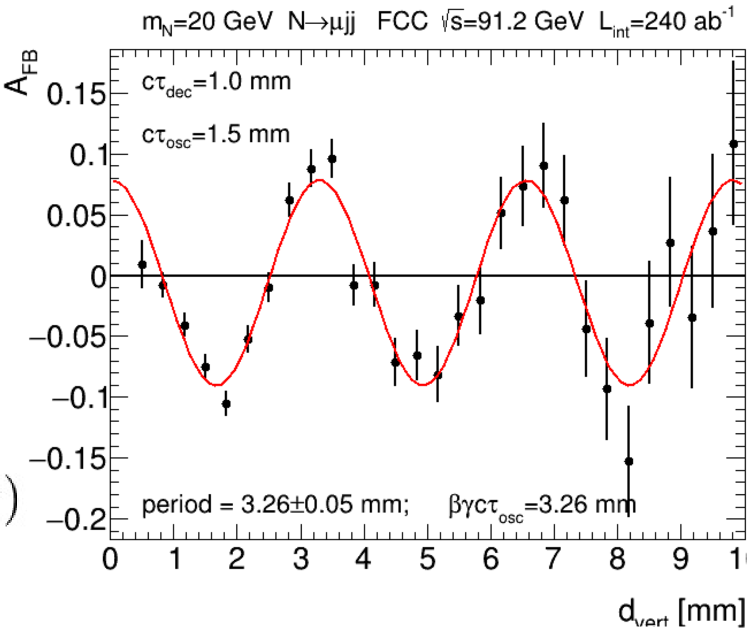
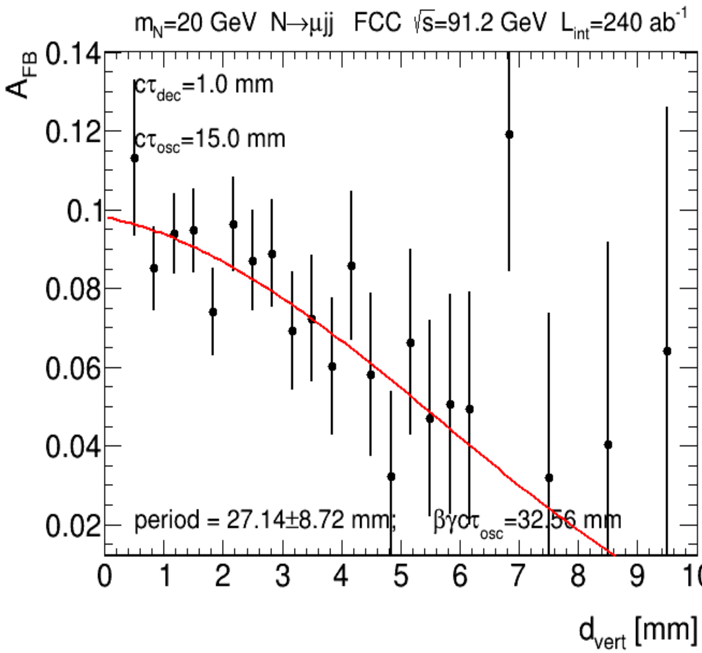



m_N=20 GeV N→μjj FCC $\sqrt{s}$=91.2 GeV L_{int}=240 ab^{-1}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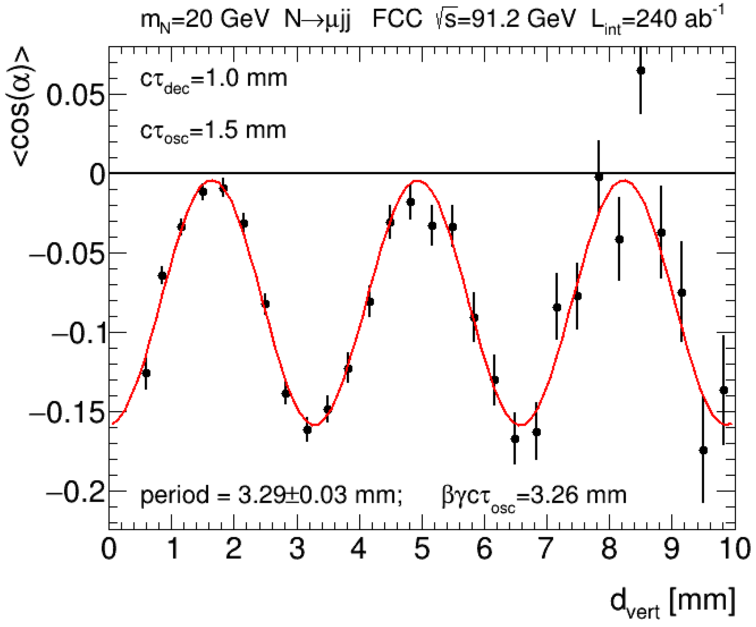
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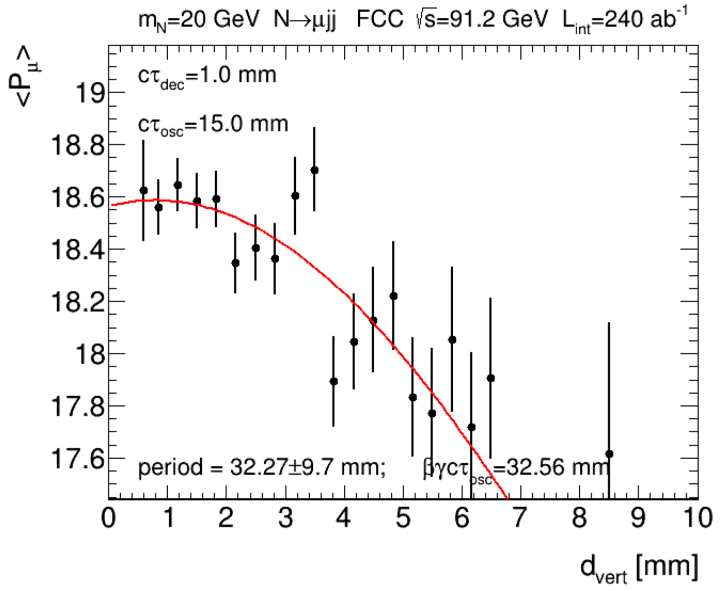
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Dirac-Majorana

Seminal work:Blondel et al
arXiv:2105.06576

Investigate Dirac or Majorana nature of HNL

HNL production:

Dirac HNL:

HNL production angle ϑ_{vis} different for positive and negative μ

Two-state Majorana:

No difference

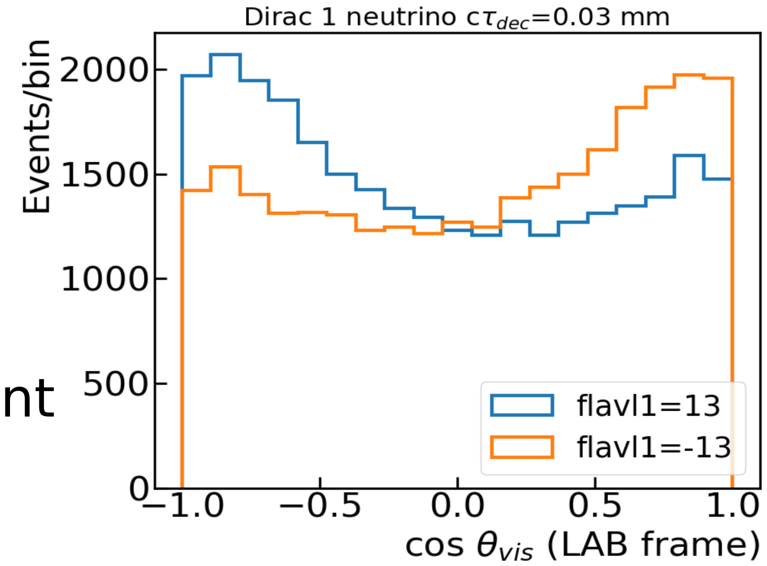
In pSPPS model:

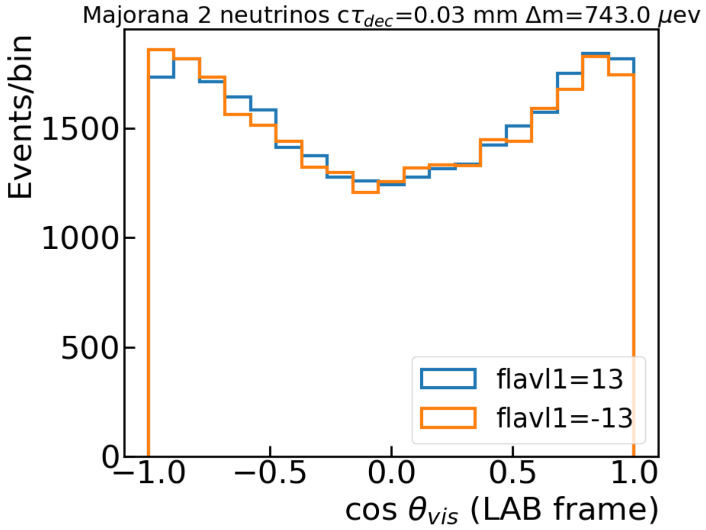
Majorana behaviour for $c\tau_{dec}=c\tau_{osc}$

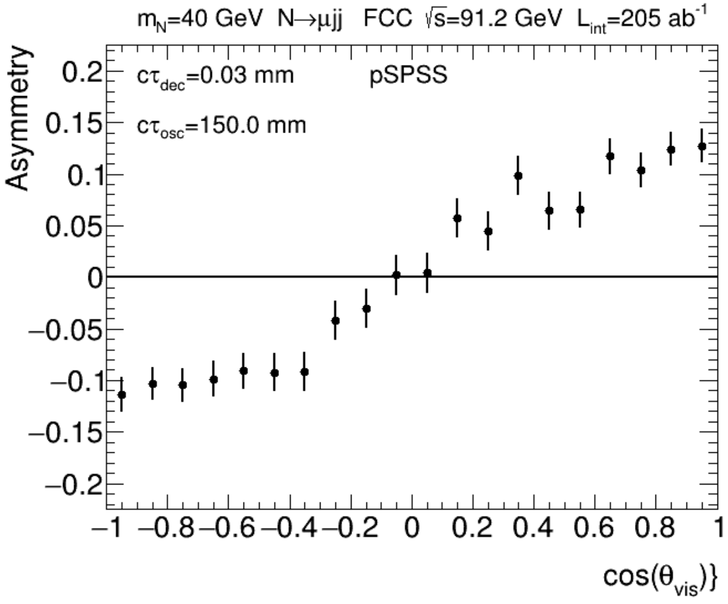
Dirac behaviour for $c\tau_{osc} \gg c\tau_{dec}$

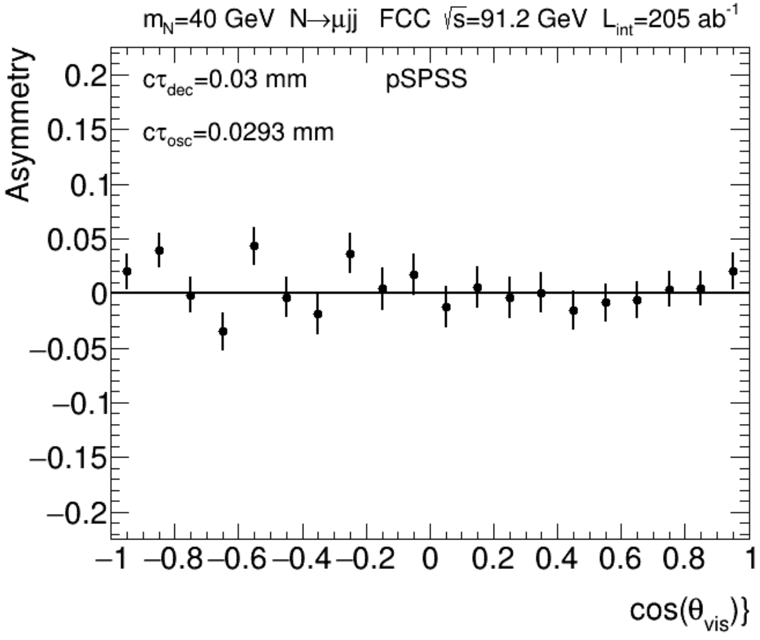
Plot $\mu^+\mu^-$ asymmetry in bins of $\cos\vartheta_{vis}$

$$\frac{\#(\mu^+)-\#(\mu^-)}{\#(\mu^+)+\#(\mu^-)}$$









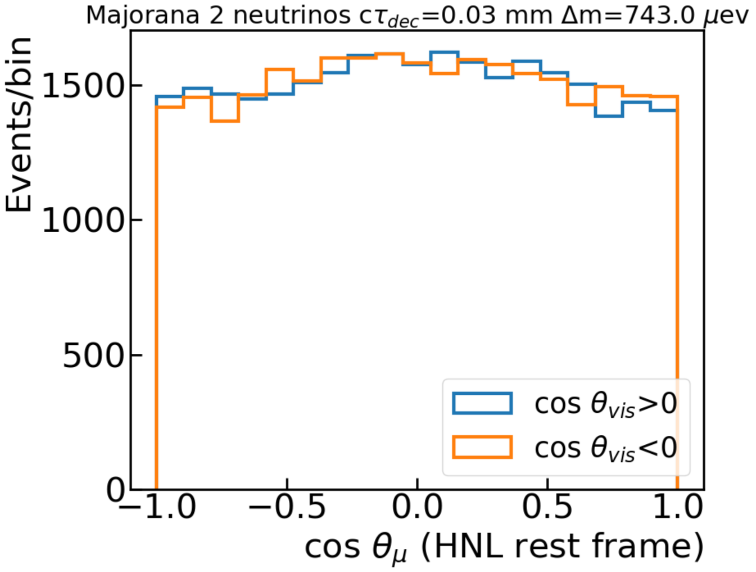
Dirac-Majorana

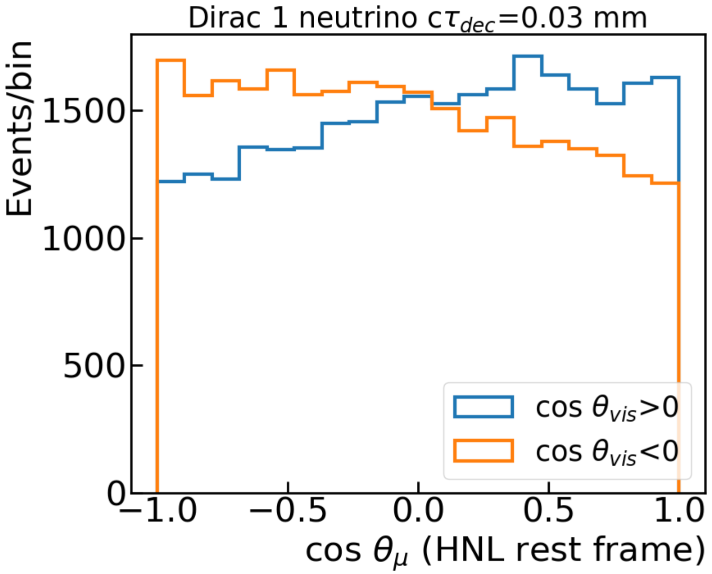
HNL decay:

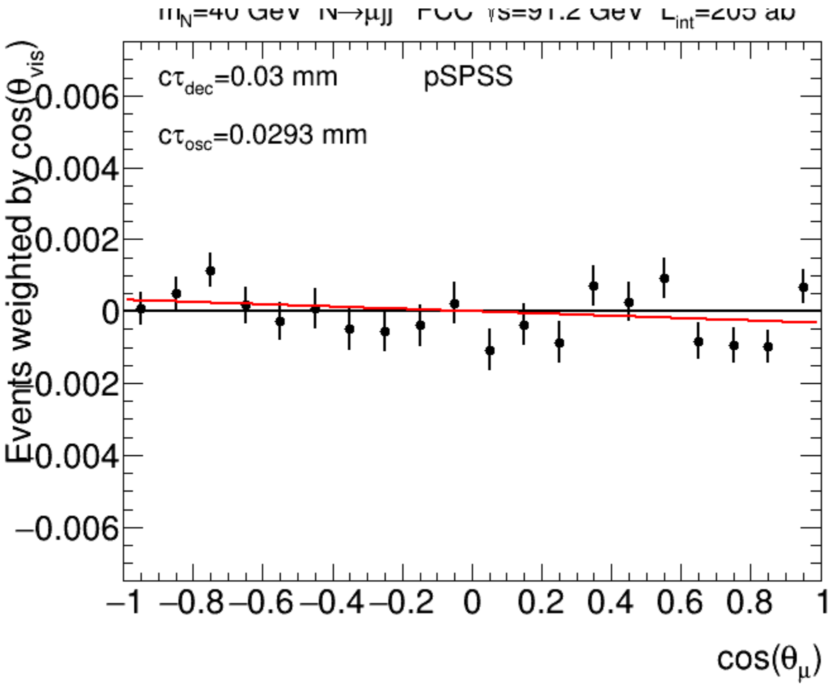
ϑ_μ, angle of μ with respect to HNL direction of flight in HNL rest frame sensitive to Dirac-Majorana nature

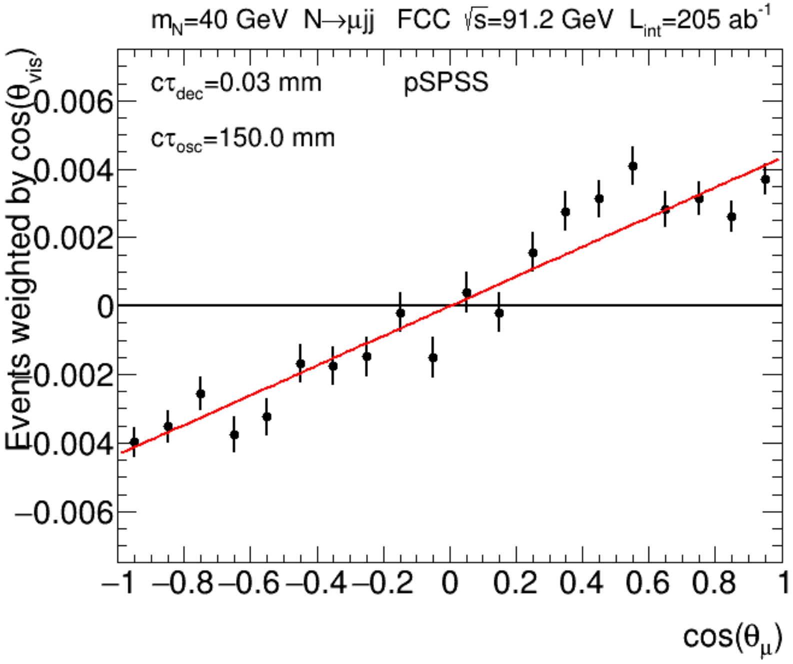
Different distributions for forward and backward produced HNL for Dirac case

Plot number of events in bins of $\cos\vartheta_\mu$ weighted by $\cos\vartheta_{vis}$









Higgs run

Higgs decay into long-lived scalars

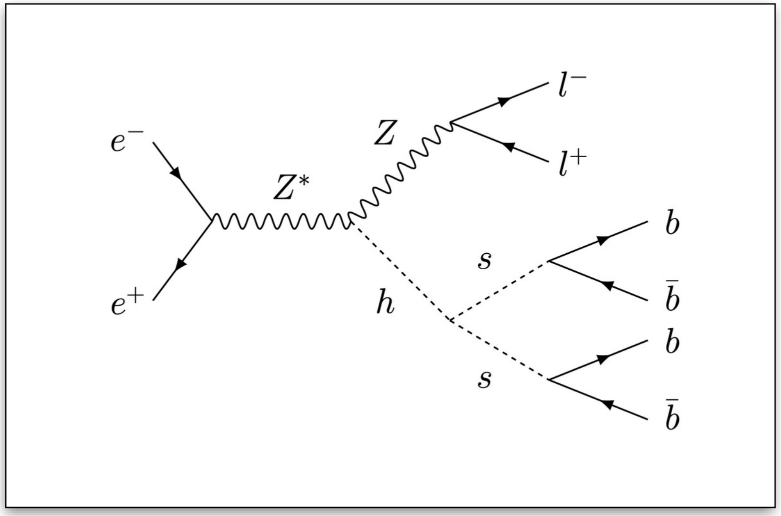
- Hidden sector model with scalar portal
  - New dark scalar mixes with SM Higgs via angle sinϑ
- Exotic decay of SM Higgs, , into new scalar then decays into SM states
- Small mixing angles yields long-lived scalars:
  - LLPs →Displaced Vertex (DV) search
- Targets Zh stage; 240 GeV & 10.8 ab-1
- Signature generated with HAHM model:

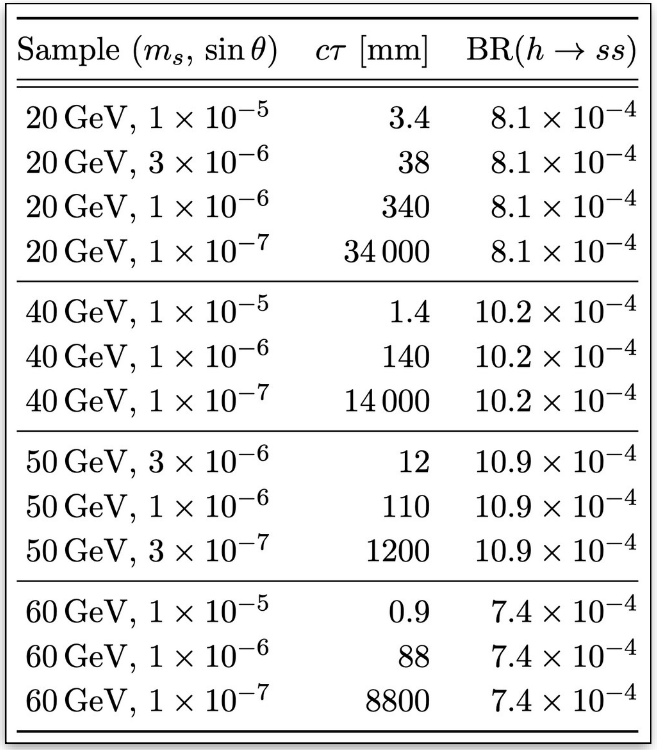
$$e^+e^- \to Z \to Zh,\, Z \to l^+l^-,\, h \to ss,\, s \to b^+b^-$$

- Main backgrounds:WW, ZZ, WZ

G. Ripellino, M. Vande Voorde, A. Gallén, R. Gonzalez Suarez

arXiv:2412.10141



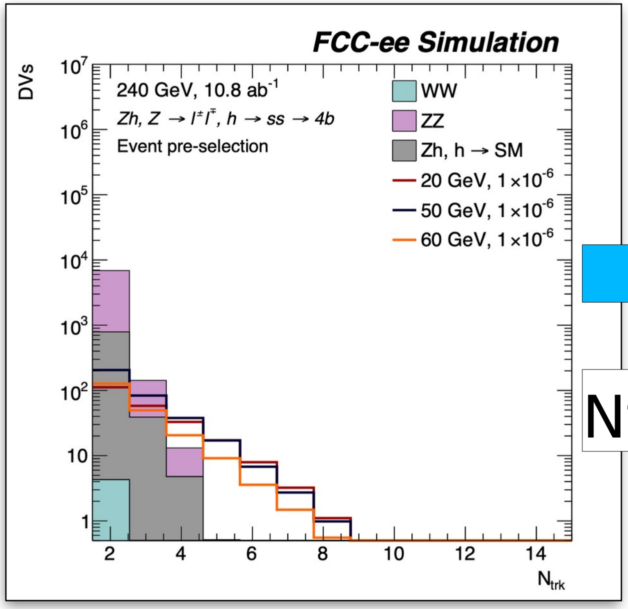


Sample $(m_s, \sin\theta)$	$c\tau$ [mm]	BR$(h \to ss)$
20 GeV, 1×10^{-5}	3.4	8.1×10^{-4}
20 GeV, 3×10^{-6}	38	8.1×10^{-4}
20 GeV, 1×10^{-6}	340	8.1×10^{-4}
20 GeV, 1×10^{-7}	34 000	8.1×10^{-4}
40 GeV, 1×10^{-5}	1.4	10.2×10^{-4}
40 GeV, 1×10^{-6}	140	10.2×10^{-4}
40 GeV, 1×10^{-7}	14 000	10.2×10^{-4}
50 GeV, 3×10^{-6}	12	10.9×10^{-4}
50 GeV, 1×10^{-6}	110	10.9×10^{-4}
50 GeV, 3×10^{-7}	1200	10.9×10^{-4}
60 GeV, 1×10^{-5}	0.9	7.4×10^{-4}
60 GeV, 1×10^{-6}	88	7.4×10^{-4}
60 GeV, 1×10^{-7}	8800	7.4×10^{-4}

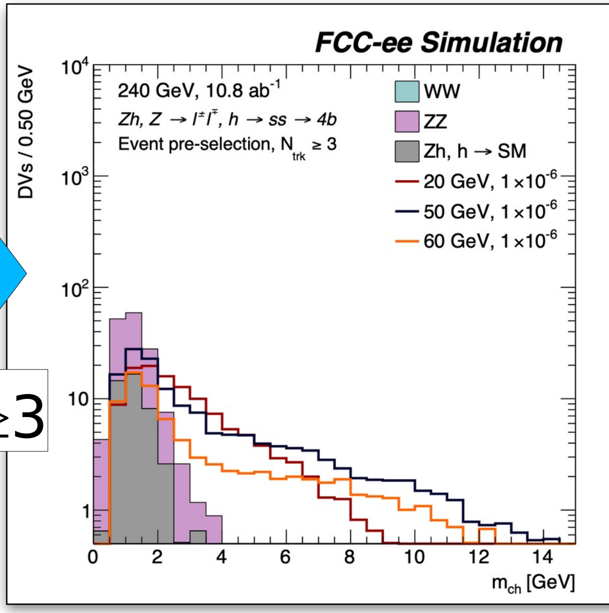
Analysis

- Secondary Vertex finder of LCFIPlus algorithm used
  - Custom track selection: $p_T > 1$ GeV & $|d_0| > 2$ mm

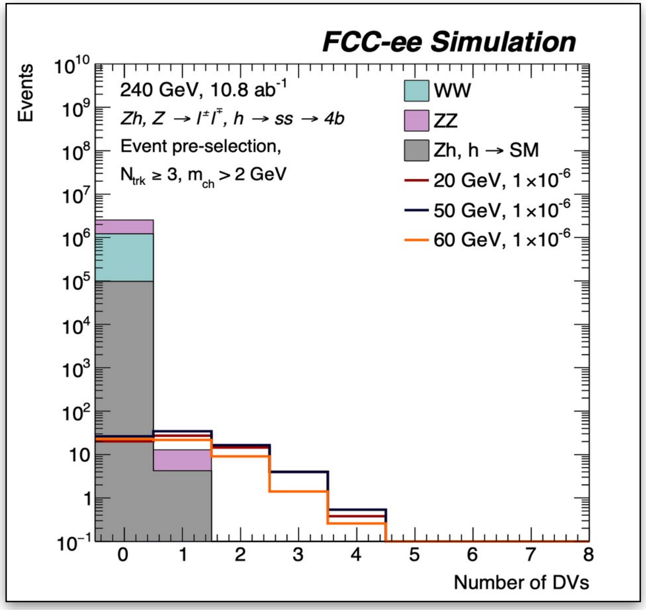
- Selections:
  - Event selection:
    - 2 iso. leptons (μ or e), opposite-sign, same flavour
    - 70 GeV < $m_{ll} <$ 110 GeV
    - At least 2 DVs passing the full DV selection
  - DV selection:
    - $N_{trk} \geq 3$
    - $m_{ch} > 2$ GeV



$N_{trk} \geq 3$



$m_{ch} > 2$

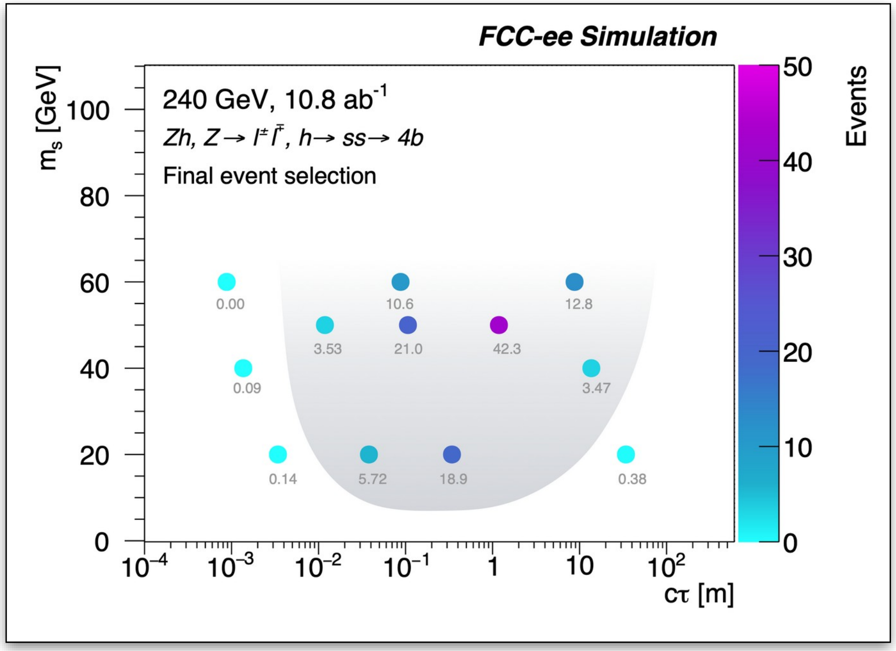


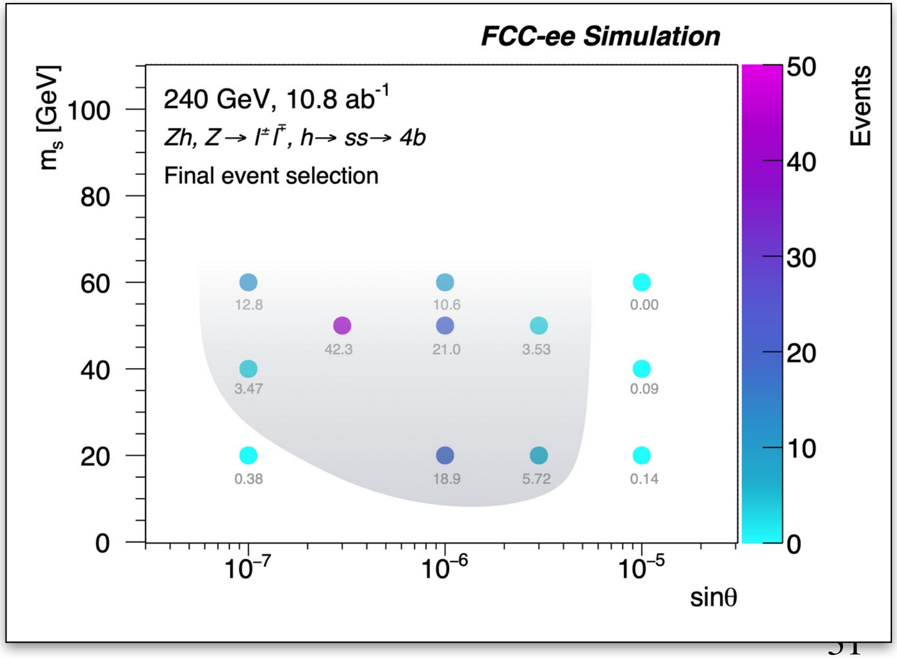
$N_{DV} \geq 2$

Zero background!

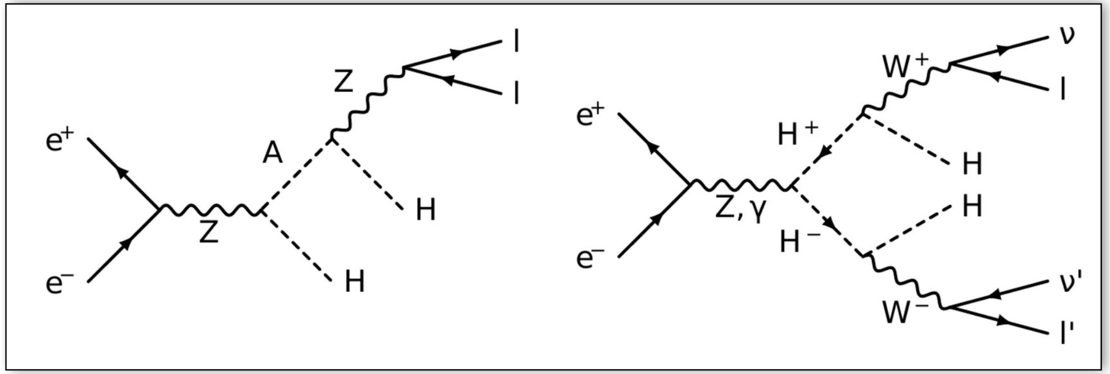
Results

- SM background free search
- Based on generated grid draw contour of signal points with 3 events in two planes
  - ms vs cτ
  - ms vs sinϑ
- Successfully performed sensitivity analysis
  - BR(h→ss) probed to 1e-4 for cτ~1m

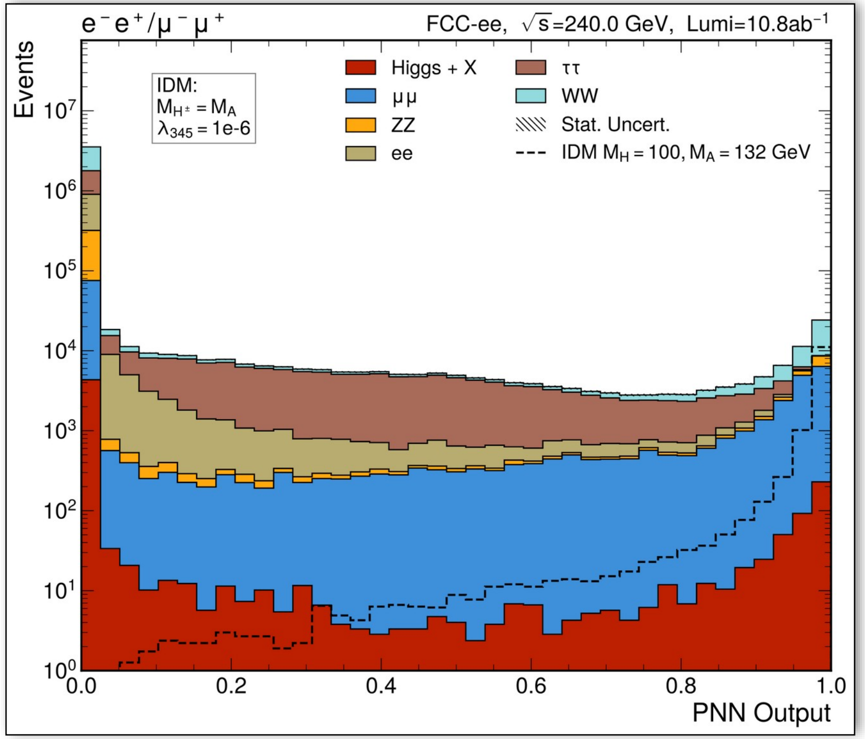




Additional Higgs bosons



- Inert Two-Higgs-Doublet model (IDM)
  - Five Higgs bosons, h is SM Higgs
  - BSM Higgs do not couple to fermions and are pair-produced
  - Five new free parameters: ,m_H,m_A,m_{H+}, quartic couplings λ_2,λ_{345}
- One new Dark matter candidate: H (invisible)
- Final state: l^+l^-HH (signature 2 leptons + missing energy)
- Backgrounds: inclusive $e^+e^-\to l^+l^-$, WW,ZZ,ZH, top when open
- Require 2e (2μ) with p>5 GeV + some E^{miss} and nothing else in event
- Insert kinematic variables for event in parametric neural network (PNN)

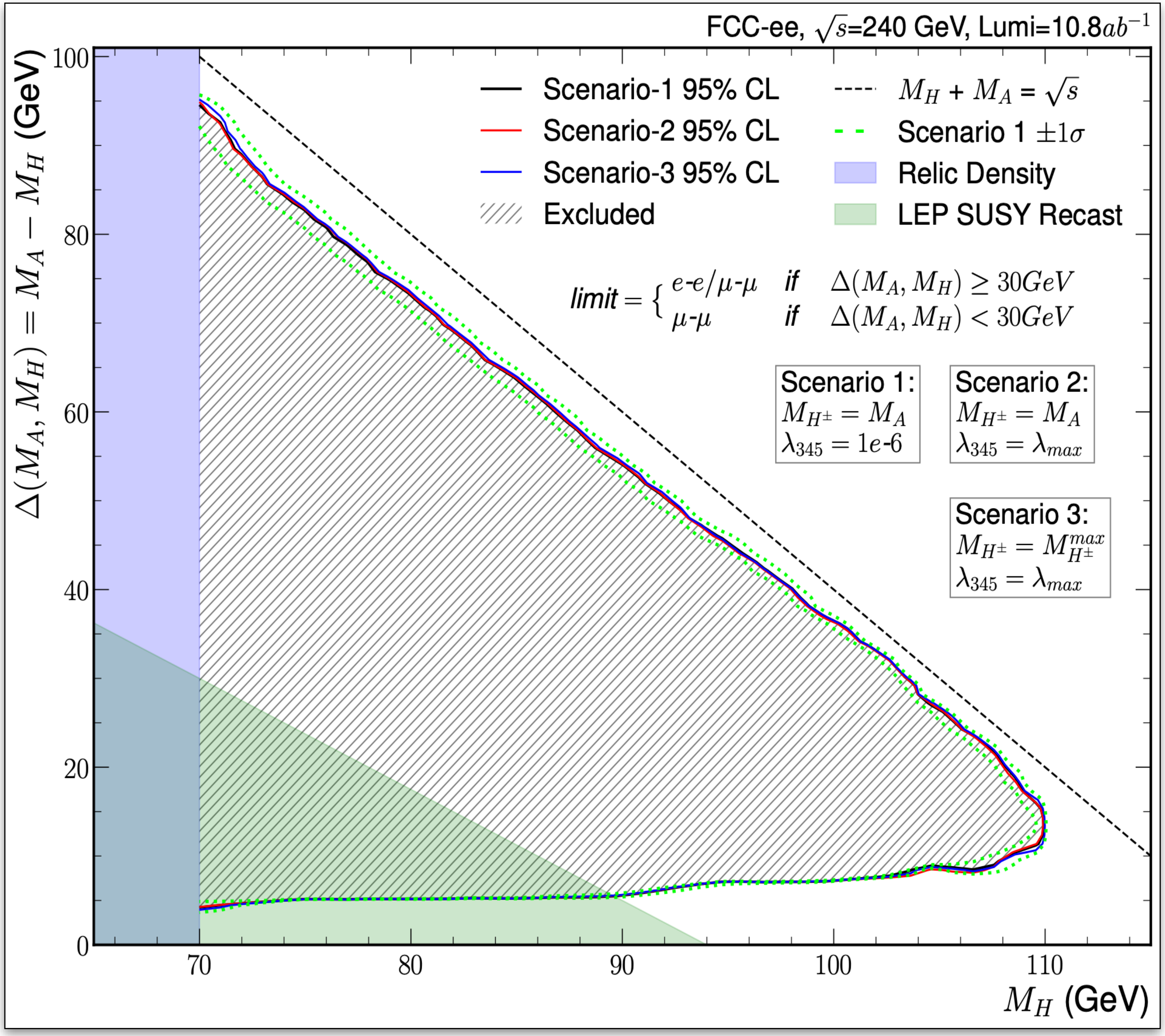


E. Curtis, A.-M. Magnan & Tania Robens

ECFA 2024 presentation, CDS note

Results

- Results plotted in plane defined by DM mass M_H, and mass difference M_A-M_H
- Three different scenarios with different values of M_{H+} and quartic couplings
- Little sensitivity to additional parameters
- Sensitivity dominated by ZA channel
- Most of kinematically accessible parameter space covered



Conclusions

The FCC-ee has a large potential for new physics through direct searches

- High statistics at Z pole gives access to very rare decays: new physics suppressed by high scales
- Exotics Higgs decays open a portal to dark physics

Exploration of low masses and couplings addresses long-lived signatures which have low SM backgrounds

Vigorous effort in FCC PED group to assess reach of FCC-ee data for most relevant benchmark models, and to extract detector requirements as an input to detector design

Backup

List of topics

Cross-check a recently circulated list of ECFA-WRG1-SRCH (Rebeca G-S. 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

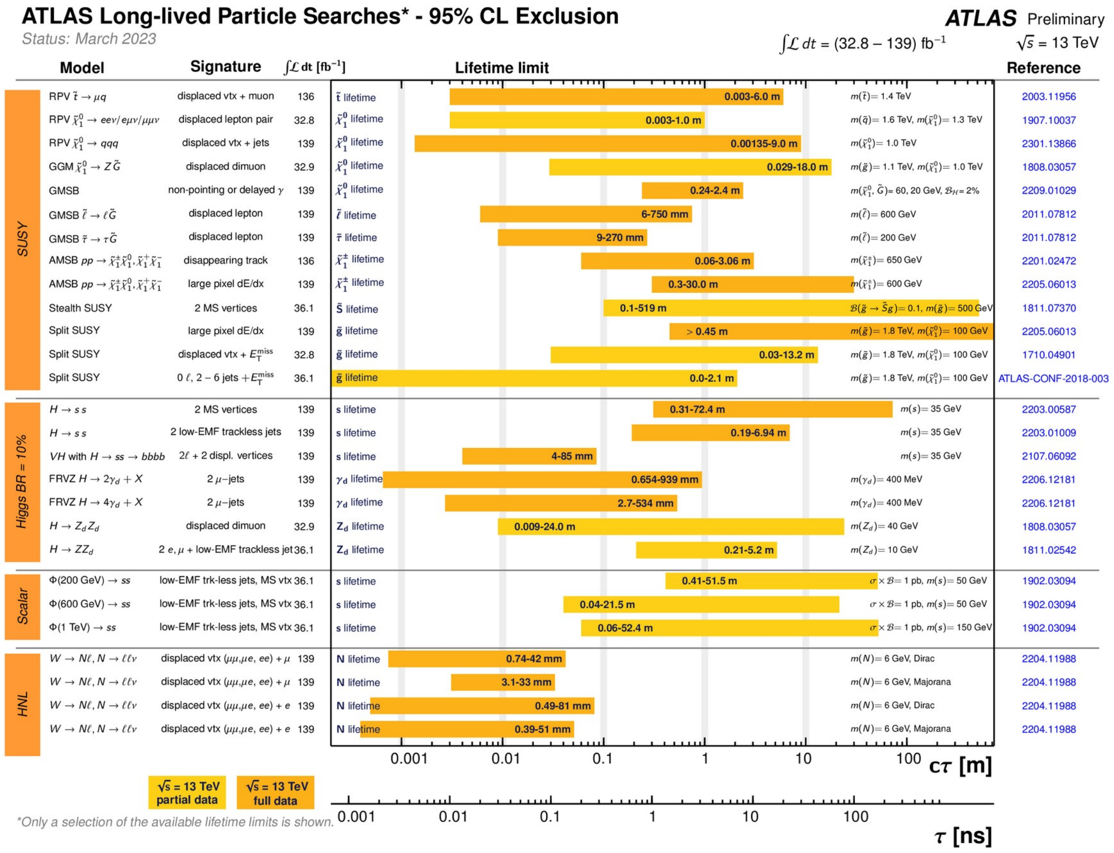
For items with * organised activity in our community, addressed in talks by G. Ripellino and S. Kulkarni

For SUSY I’ll discuss some benchmark possibilities

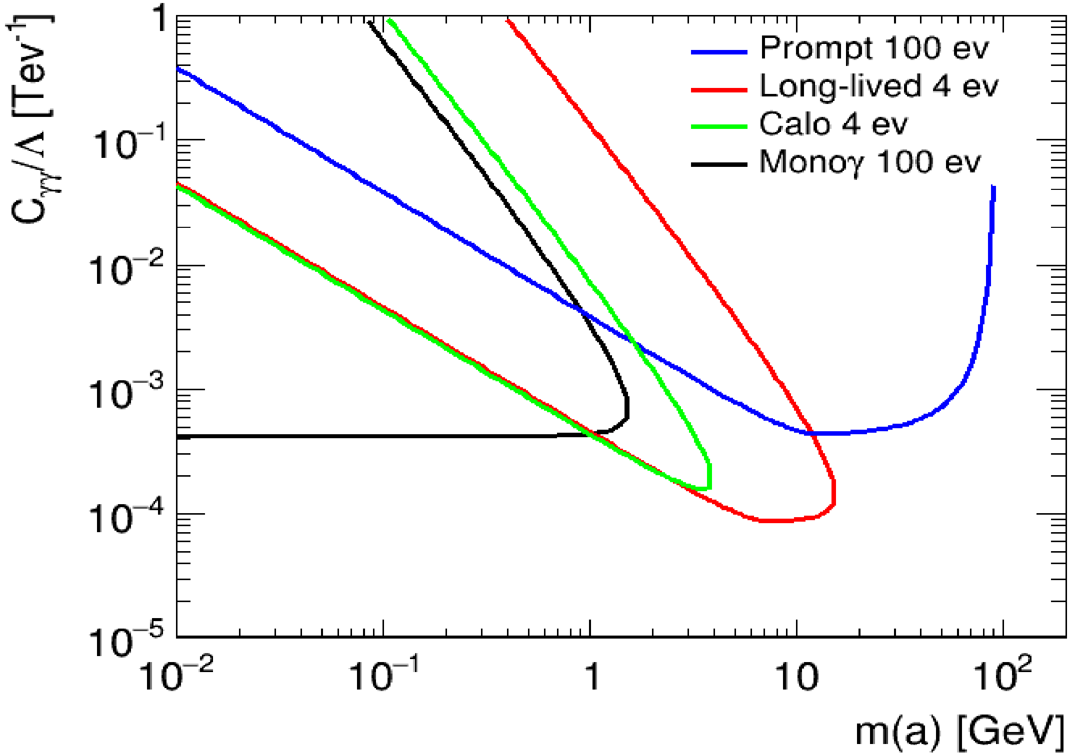
Long Lived searches: History

Rend. Fis. Acc. Lincei
s. 9, v. 12:5-18 (2001)

Fisica. — *SUSY Long-Lived Massive Particles: Detection and Physics at the LHC.* Nota di Sandro Ambrosanio, Barbara Mele, Alessandro Nisati, Silvano Petrarca, Giacomo Polesello, Adele Rimoldi e Giorgio Salvini, presentata (*) dal Socio G. Salvini.



Parameter space coverage for $e^+e^-\rightarrow\gamma a\rightarrow \gamma\gamma\gamma$



4 experimental regions depending on decay length L of ALP

- 100 events for L<10 mm (prompt)
- 4 events for 10<L<2000 mm (Long lived)
  Decay in ID
- 4 events for 2000<L<4500 mm (Calo)
  Decay in calorimeter
- 100 events for L>4500 mm: ALP decays outside the detector, only accompanying photon detected (monophoton)

Experimental distinction of 3γ prompt analysis and LLP analyses depends on how well one can detect a ALP decay away from vertex → today show 3γ analysis making no assumptions on vertex detection.

In addition study very long-lived ALP resulting in a single photon recoiling against MET from undetected ALP

3γ analysis

- 3 photons within detector acceptance (|η|<2.6) and energy>1 GeV
- Scan test masses *M* between 0.1 and 85 GeV

For each *M* and E_{CM} photon produced alongside ALP has energy

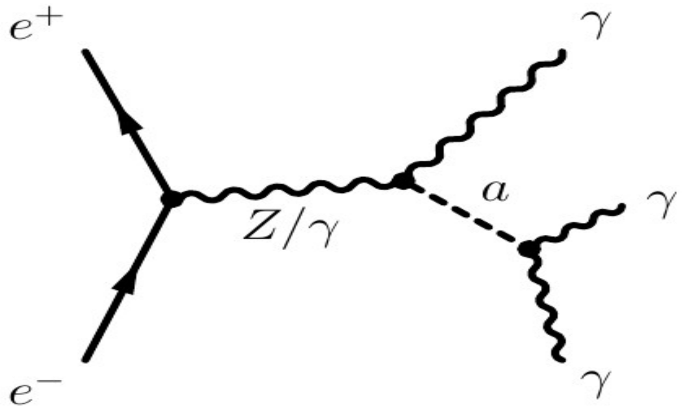
$$E_\gamma = \frac{E_{CM}^2 - M^2}{2E_{CM}}$$

Assign three photons to ALP or to Z decay:

For given test mass and assignment:

Measure compatibility with expected kinematics

$$M_{cut} = \sqrt{(M_a - M)^2/\sigma_{M_a}^2 + (E_{\gamma_3} - E_\gamma)^2/\sigma_{E_{\gamma_3}}^2)}$$



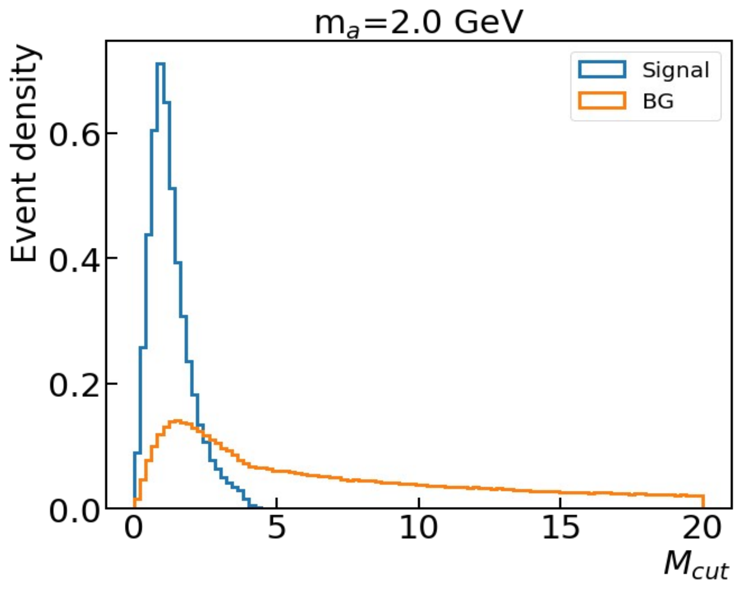
γ_3

γ_1

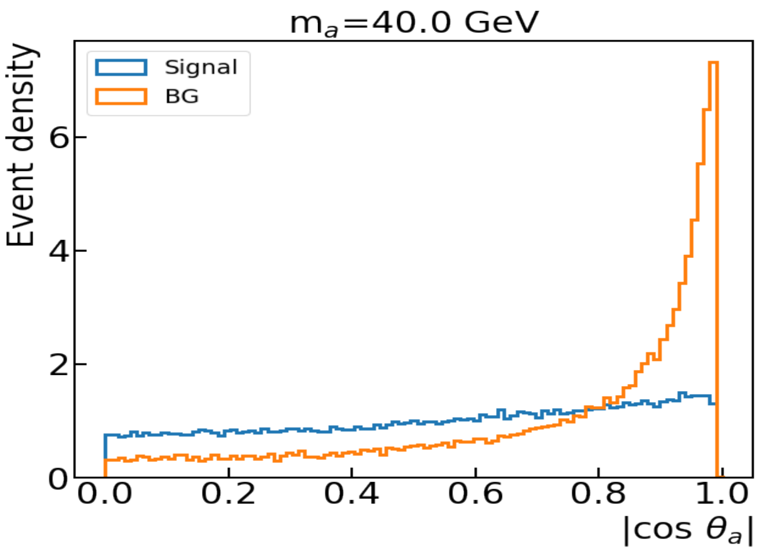
γ_2

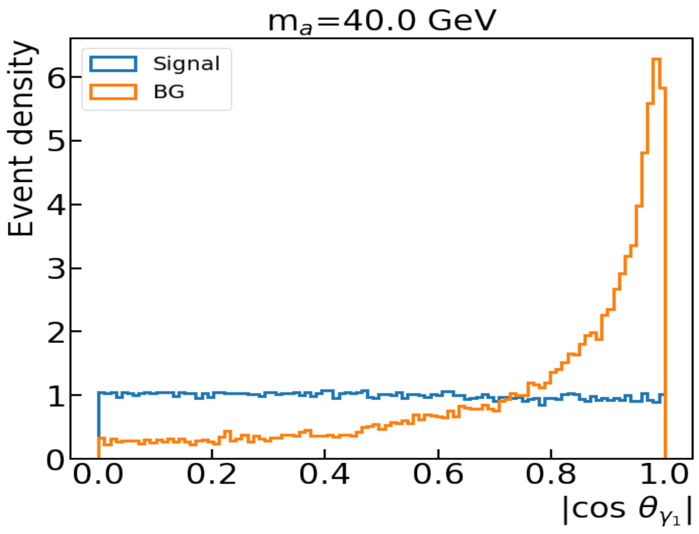
Choose assignment minimising M_{cut}

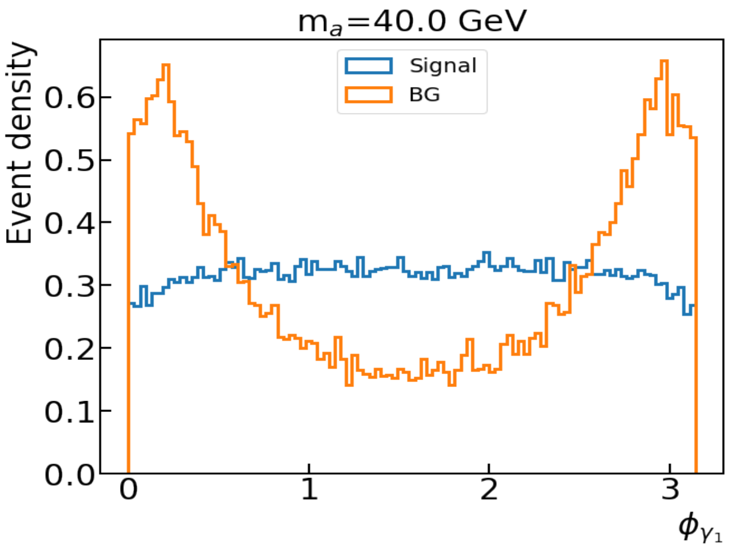
$m(\gamma1, \gamma2) \equiv M_a$



Discriminant variables





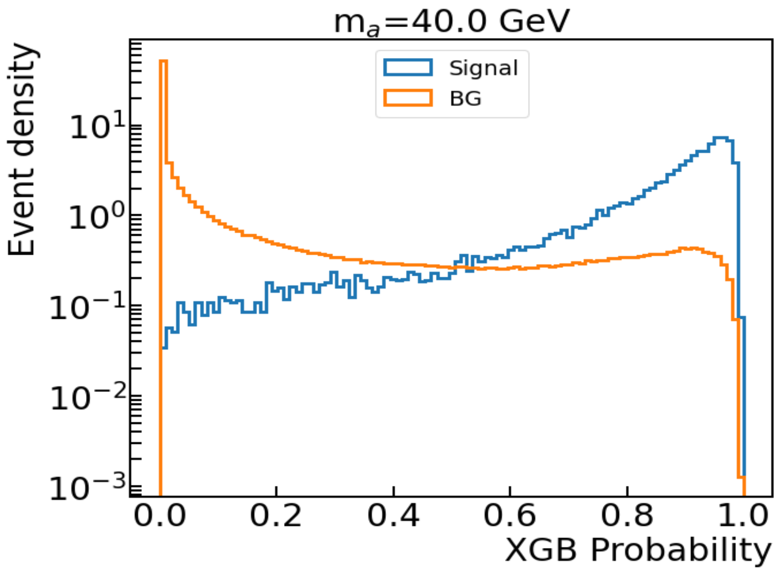


Require that event only contains three photons.

For a fixed mass, signal fully defined by three variables, after rotation such that $\varphi_{\gamma 3}=0$:

- Polar angle of ALP in lab system $|\cos\vartheta_\alpha|$
- Polar angle of γ_1 in ALP rest system $|\cos\vartheta_{\gamma 1}|$
- Azimuthal angle of γ_1 in ALP rest system $\varphi_{\gamma 1}$

Train a boosted decision tree (XGB) on 5 variables, the three above+ $E_{\gamma 2}/E_{\gamma 1}$ and M_{cut}



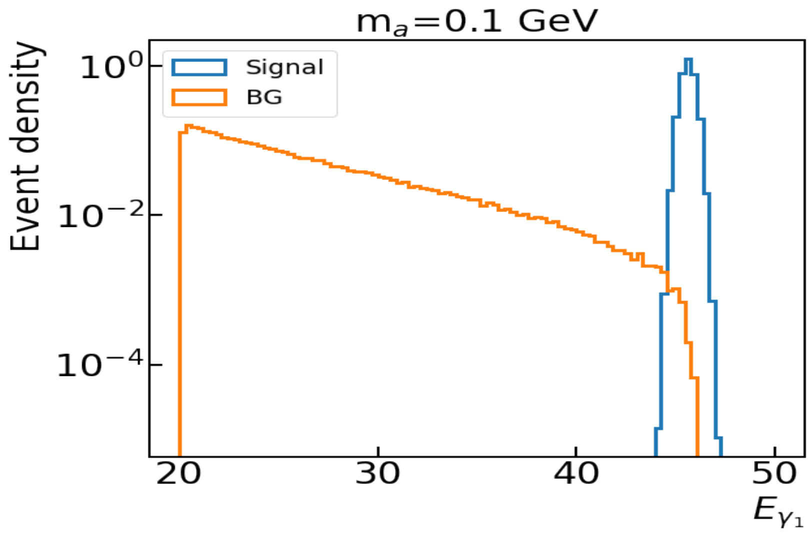
γ+MET analysis

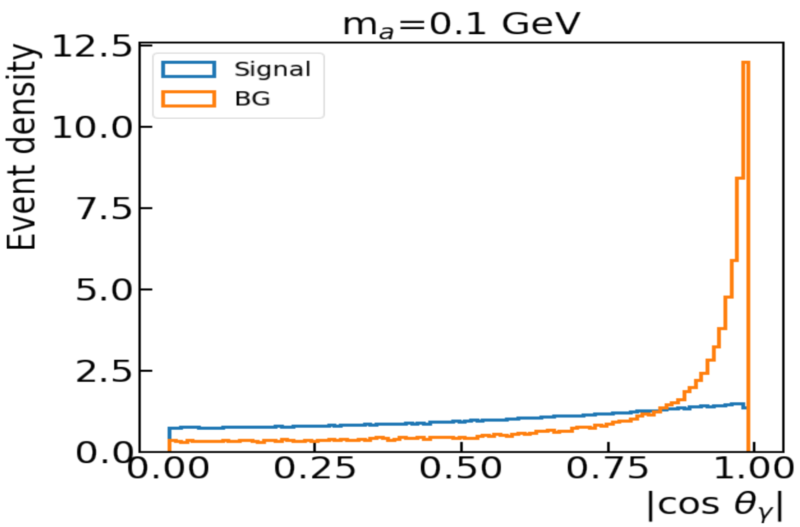
Relevant mass range below ~2~GeV → signature is a monochromatic photon of energy ~45.5 GeV and nothing else in the detector

Consider two backgrounds: irreducible: $e^+e^- \to \gamma\nu\nu$

reducible: e+e-→γe+e- where the electron and positron are outside detector acceptance (|η|>3).

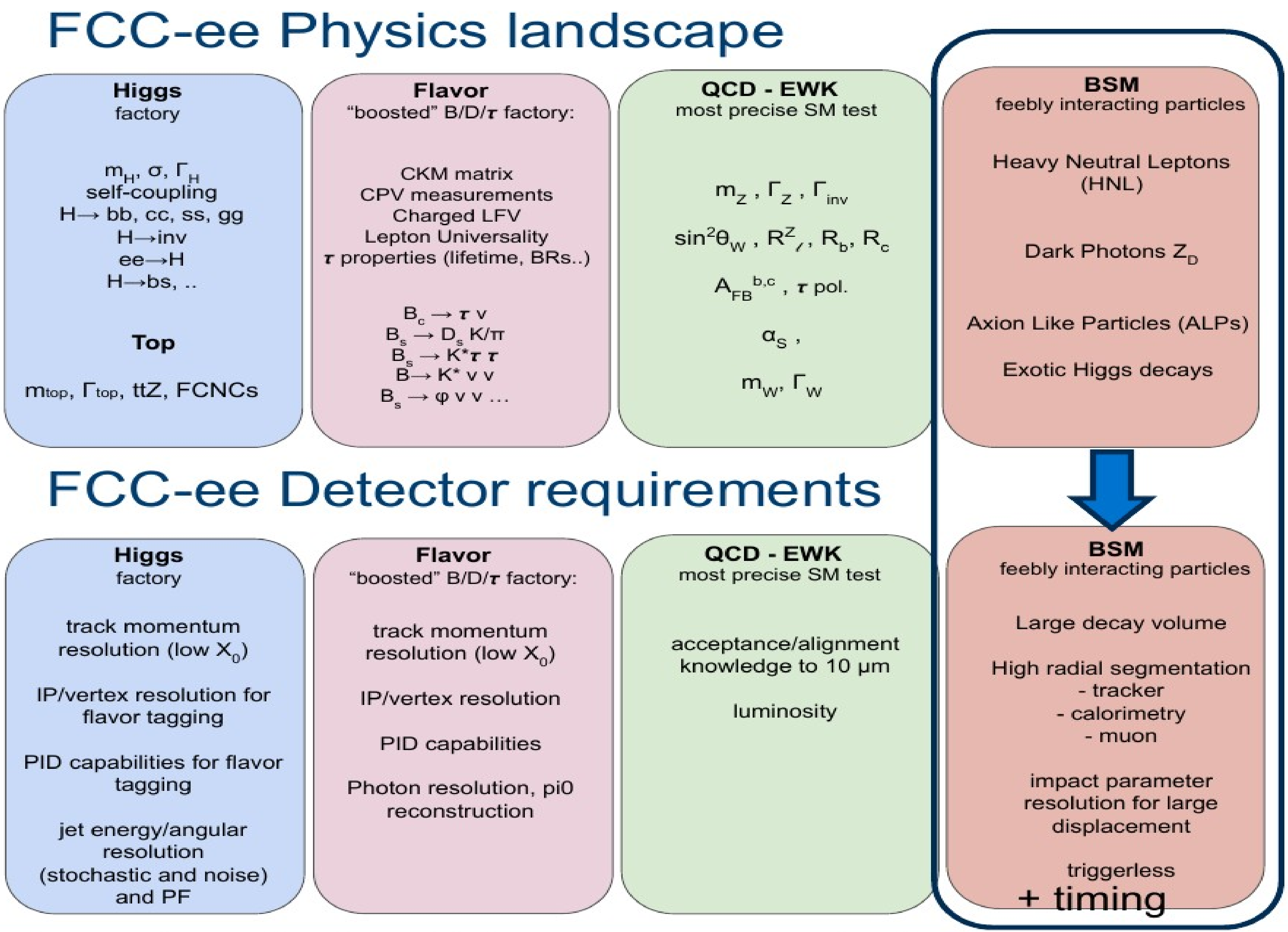
Signal and backgrounds produced with MG5MC@NLO and passed through the usual PYTHIA-DELPHES chain





Two variables characterise event, energy and polar angle of photon.
Combine them through XGB as for prompt analysis

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..)

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

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

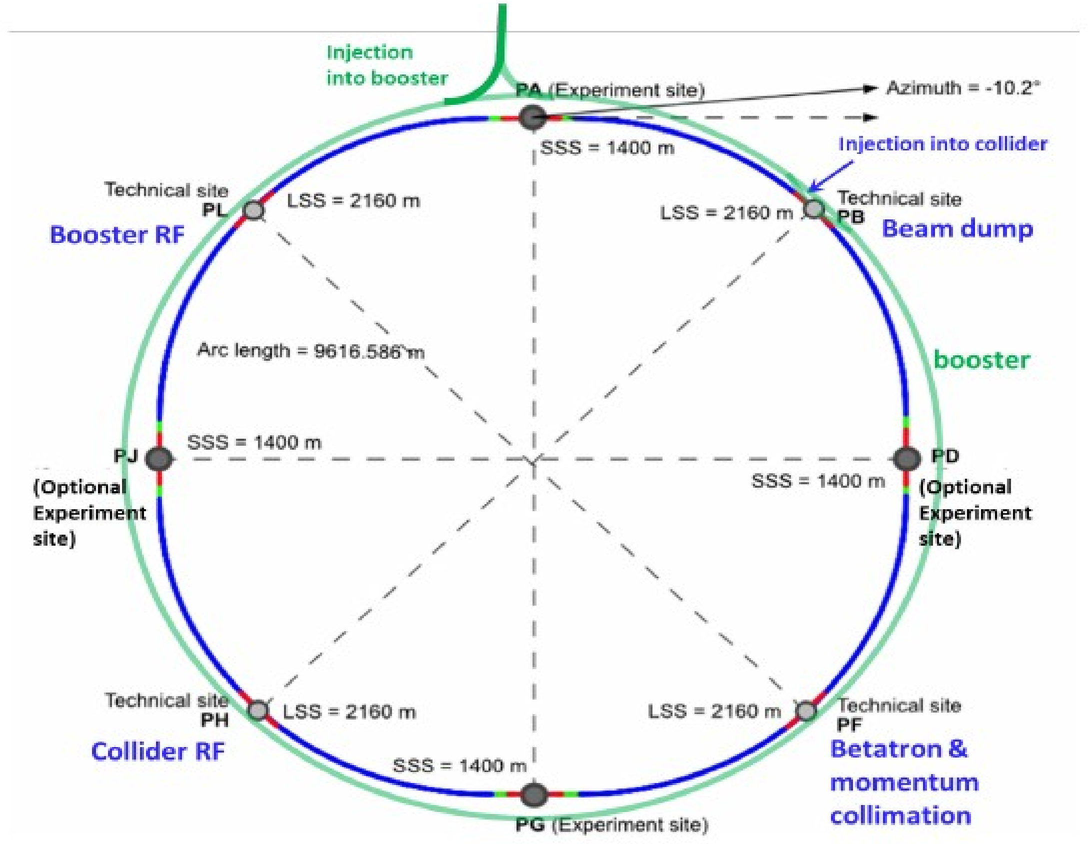
Each of these poses a specific experimental challenge and pushes detector optimisation

Unique challenges from BSM: long-lived particles

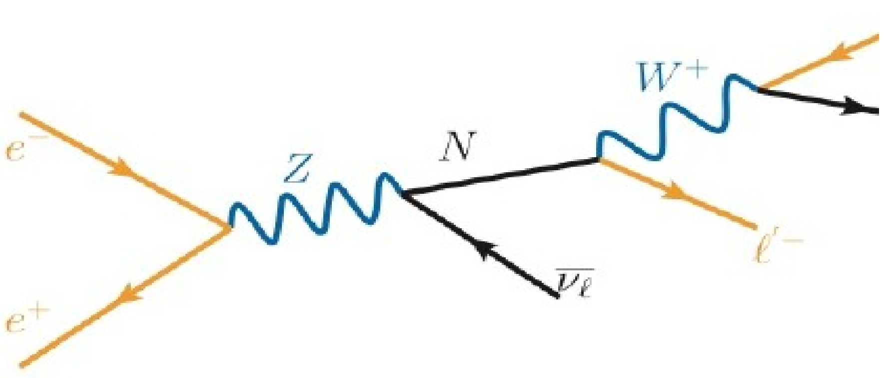
Luminosity scenario

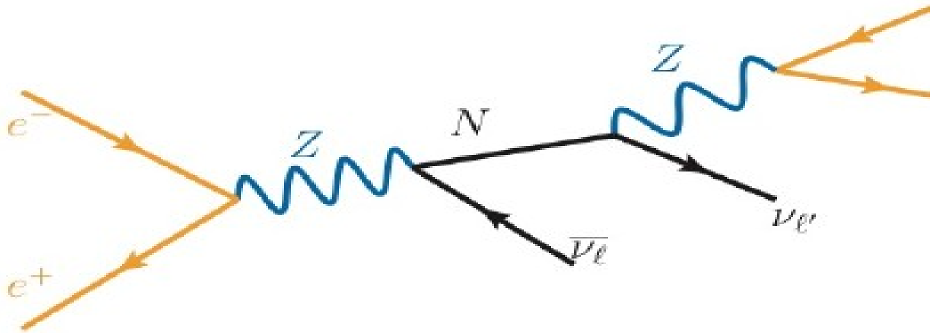
4 Interaction points (IP):
For Z pole run assume an Integrated luminosity of 205 ab-^{1}, corresponding to 6 10^{12} Z

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



Decay signatures





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

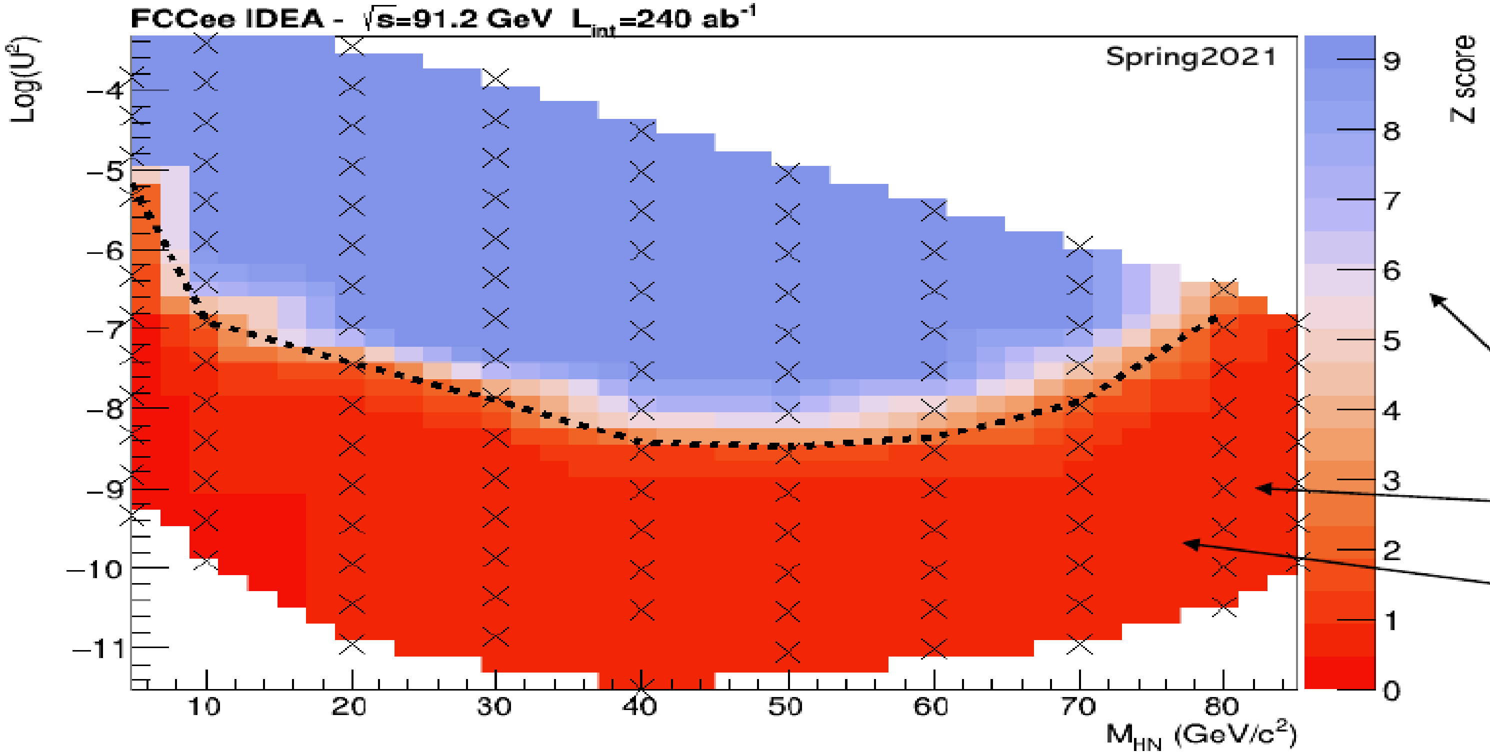
GP, Nicolò Valle

Prompt results

- Baseline: Integrated Lumi = **240 $\mathbf{ab^{-1}}$** ↔ 8×10^{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

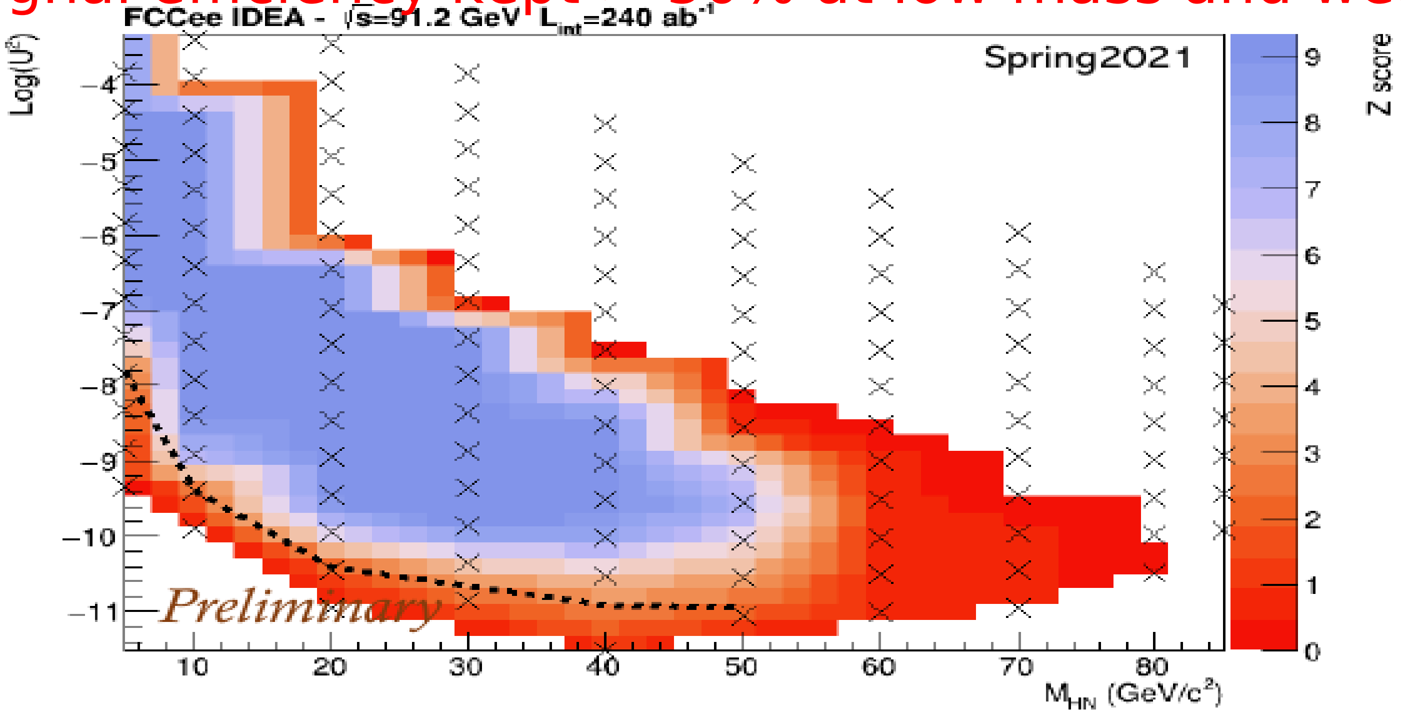
Low mass (≲ 40 GeV/c 2) HNL long-lived for couplings of interest, loss of efficency when requiring muon prompt

Background highly suppressed

Use detailed parameterization of IDEA tracking performance in DELPHES-FCC

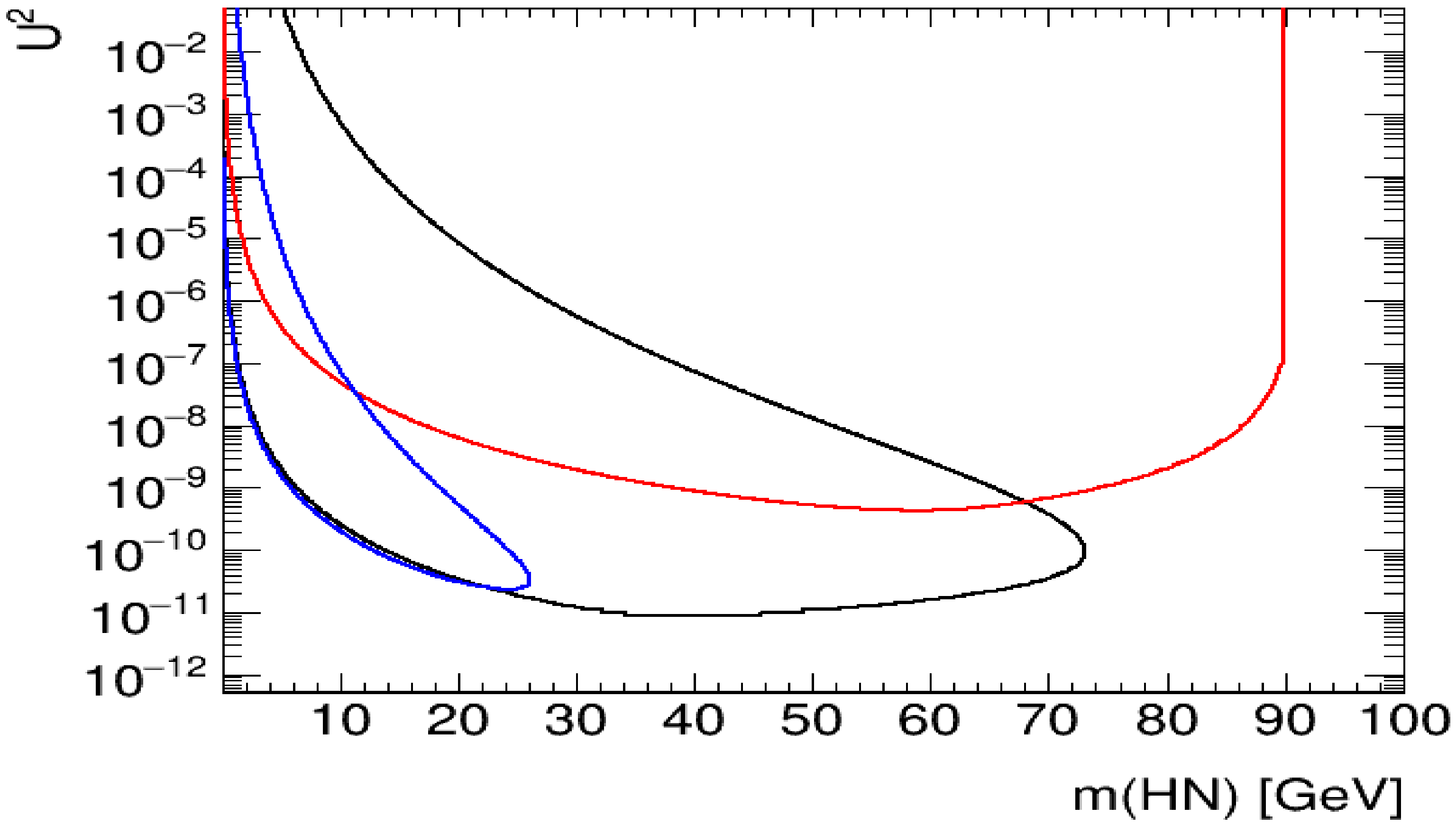
Kinematic selection not modified, prompt background suppressed by D_μ > 1 mm

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



Work in progress on approach exploiting detailed HNL vertex reconstruction

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

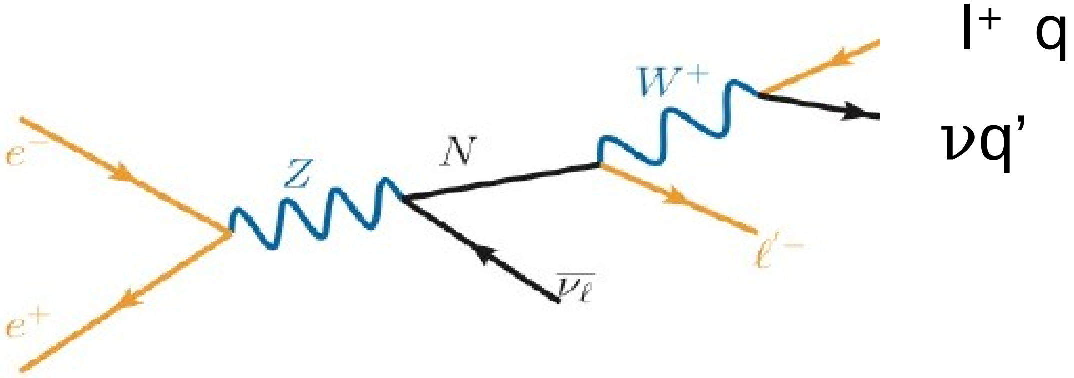
$0.04 < \lambda < 150$ cm

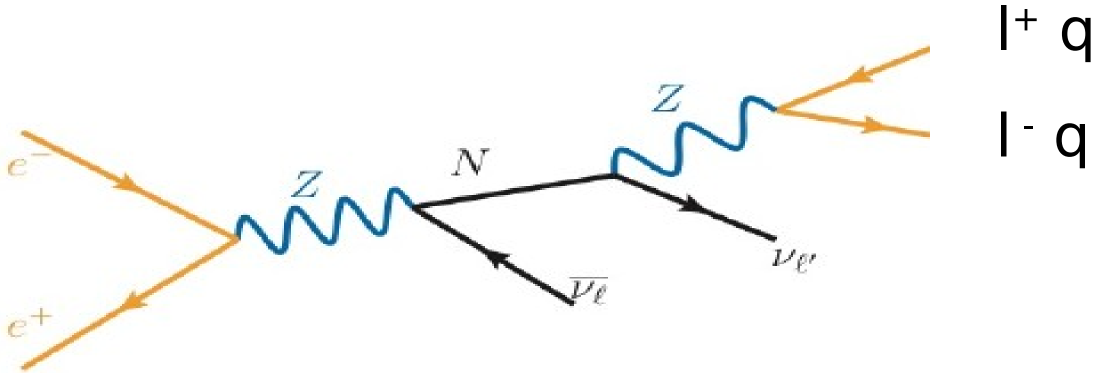
Blue: Calo decay

$200 < \lambda < 450$ cm

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

Decay signatures





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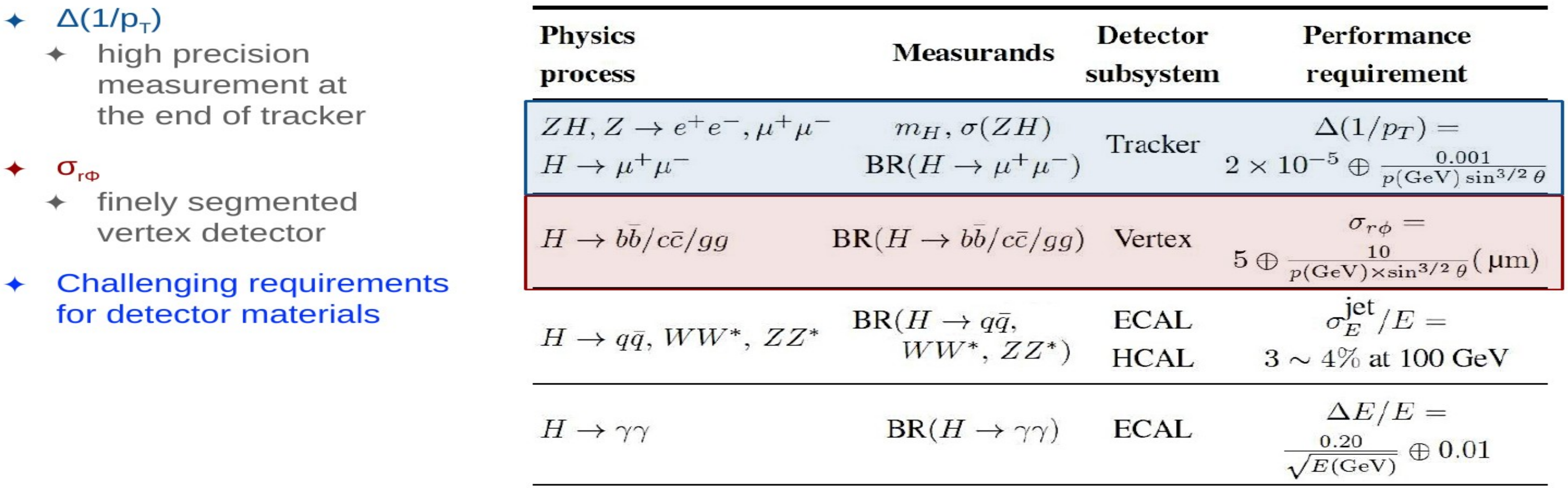
  - l τ nu ~9%

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

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

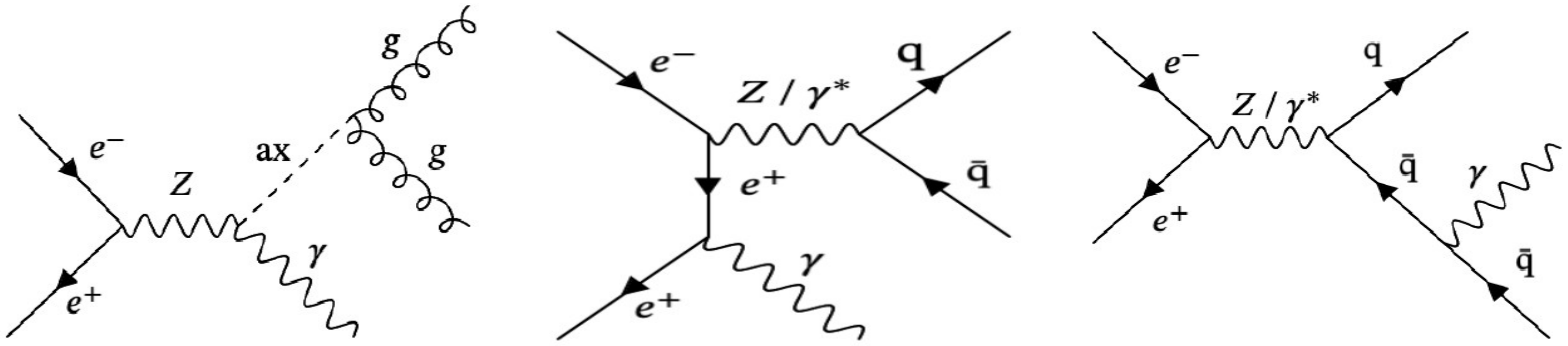
$$\frac{1}{\sigma_{N,\bar{N}}}\frac{d\sigma_{N,\bar{N}}}{d\cos\theta} \propto \left(g_R^2\,(1 \mp \cos\theta)^2 + g_L^2\,(1 \pm \cos\theta)^2 + \frac{M_N^2}{m_Z^2}\,(g_L^2 + g_R^2)\ \sin^2\theta \right)$$

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

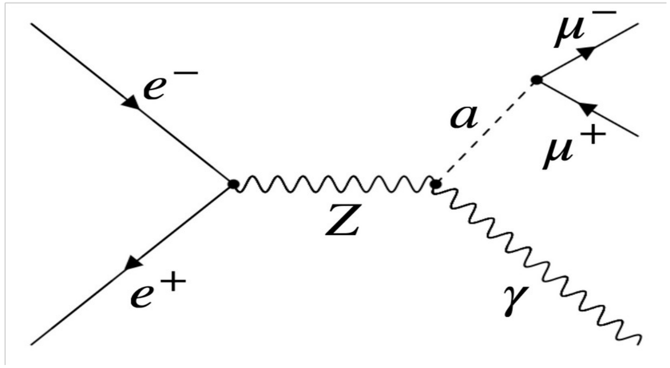
$$\frac{1}{\sigma_N}\frac{d\sigma_N}{d\cos\theta} \propto \left(1 + \cos^2\theta + \frac{M_N^2}{m_Z^2}\sin^2\theta \right)$$

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

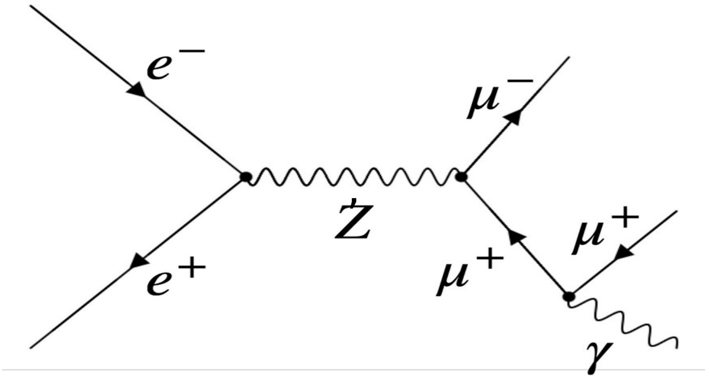
Additional ALP decay modes considered



Signal (left) Backgrounds (middle & right)

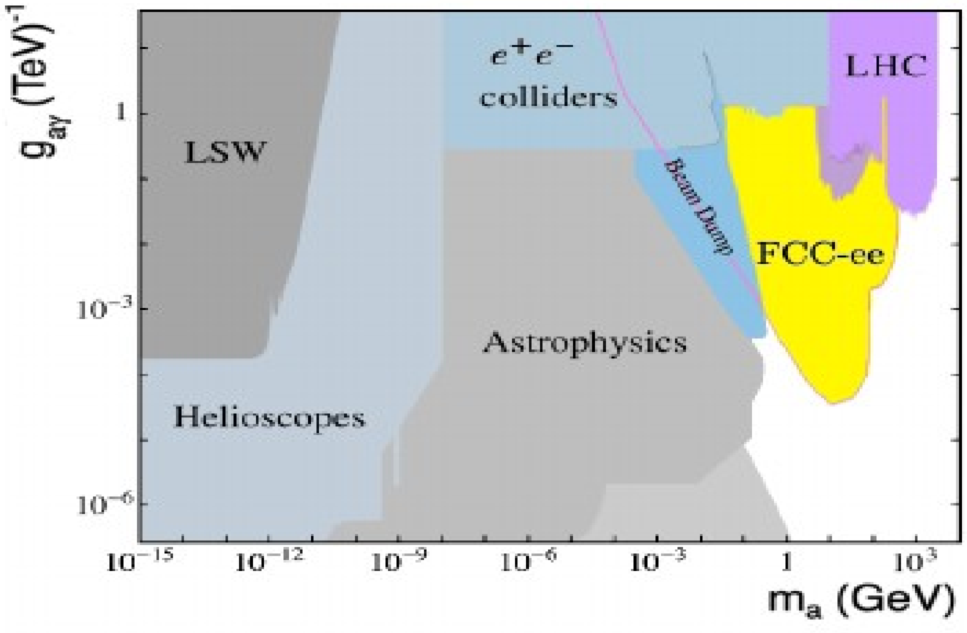


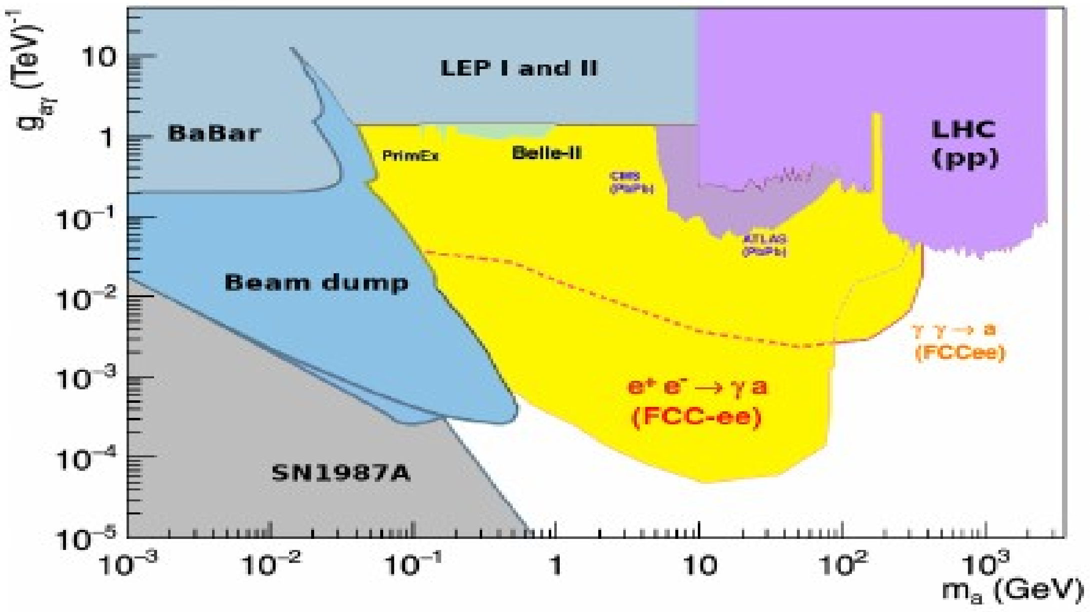
Signal



Background

Parameter space coverage



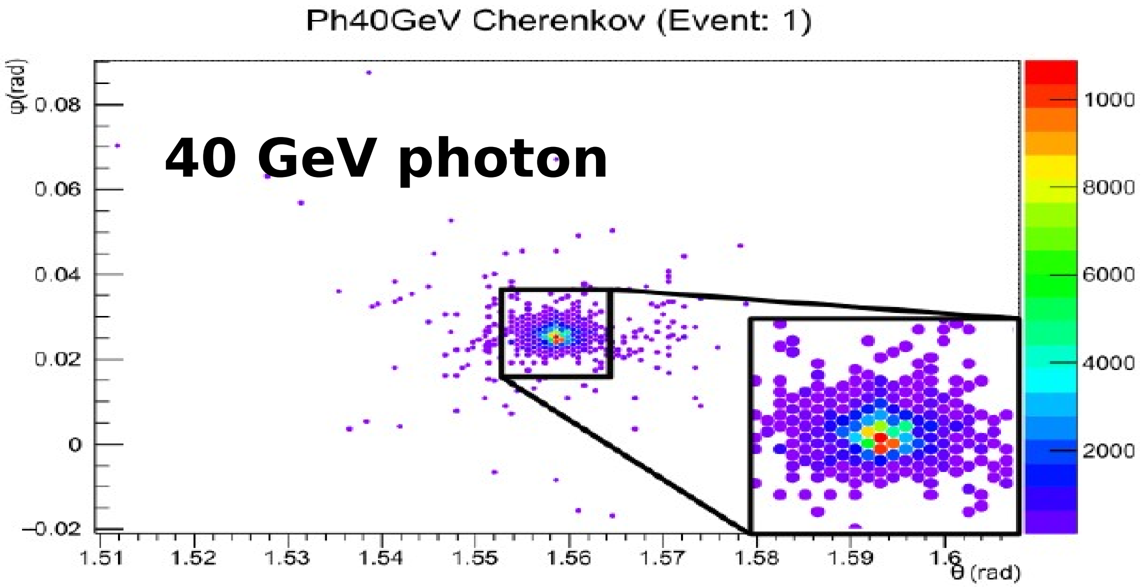


Plot in the MT report: $e^+e^-\to \gamma a$ line is theory calculation requiring 4 ALP decays inside detector. 4 events might work for long-lived but prompt analysis has a huge irreducible background e+e+→ γγγ, requiring detailed background analysis

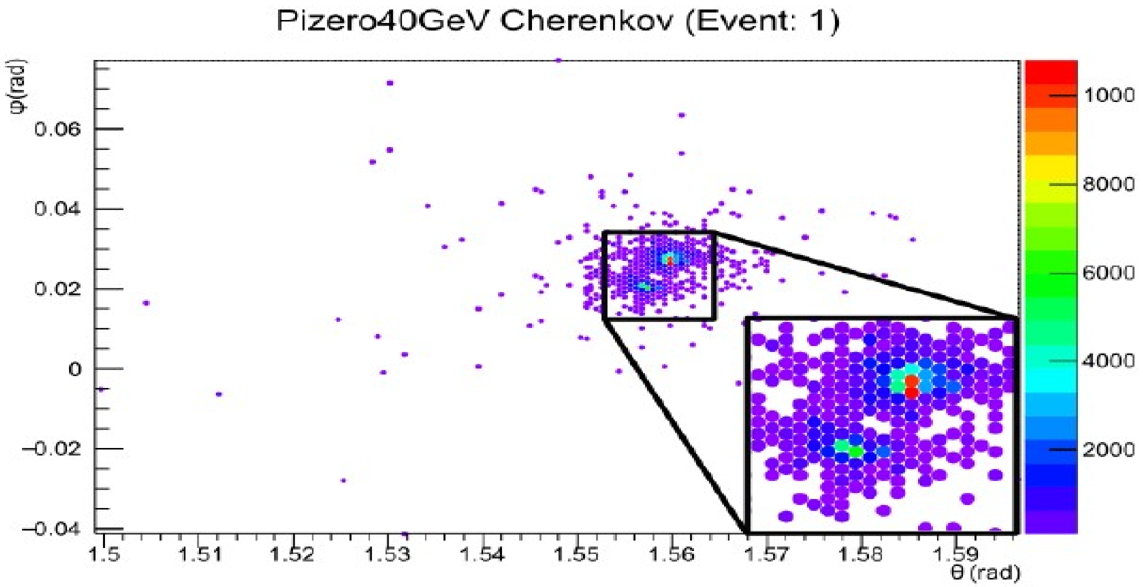
Plots originally from Rebello Teles et al.

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


Ph40GeV Cherenkov (Event: 1)

40 GeV photon


Pizero40GeV Cherenkov (Event: 1)

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

Calorimeter parametrisation

Take truth stable photons from PYTHIA tree in edm4hep, and smear them according to:

For DR fiber: performance figures from full simulation of testbeam prototype. Shown e.g in talk at ICHEP

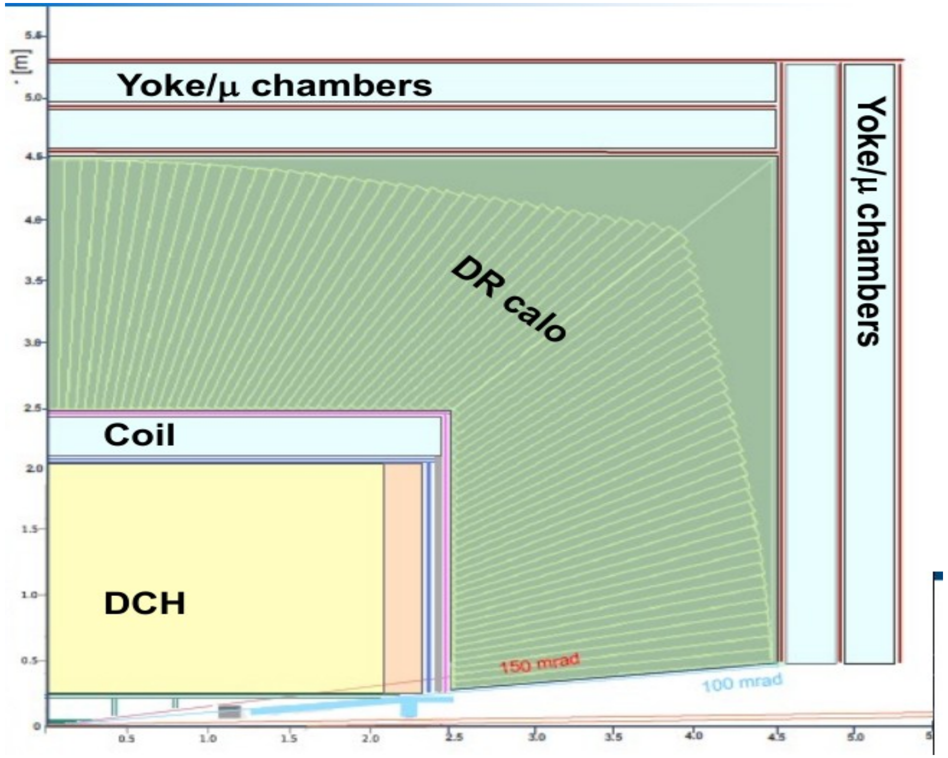
$$\frac{\sigma(E)}{E} = \frac{0.139}{\sqrt{E}} + 0.006$$

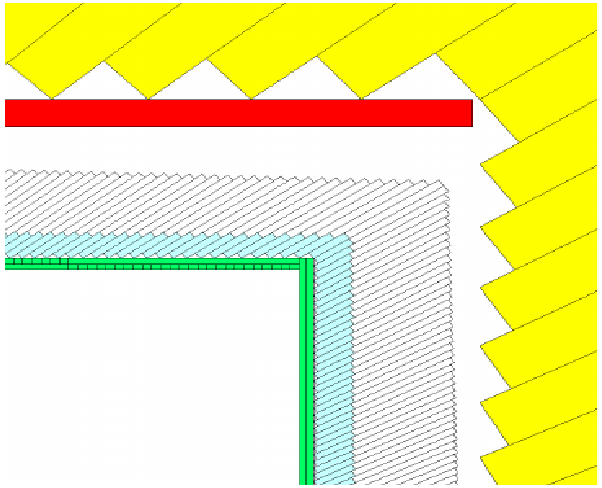
$$\sigma(x) = \frac{4.05}{\sqrt{E}} + 0.0 \qquad \sigma(y) = \frac{3.23}{\sqrt{E}} + 0.0055$$

For crystal: energy resolution as in DELPHES card, Position resolution from Lucchini et al. paper

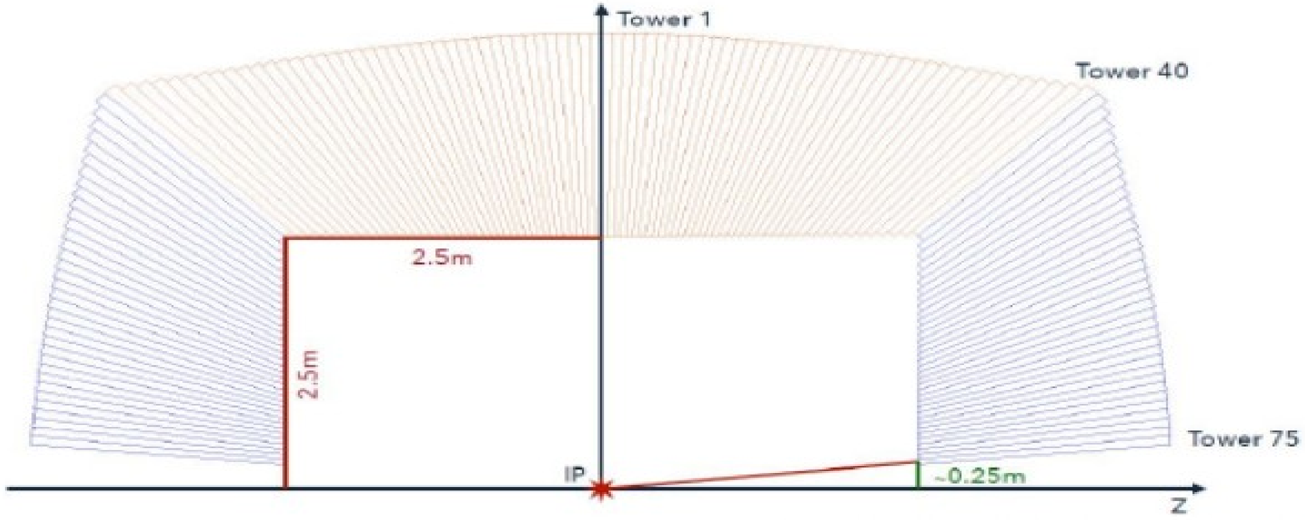
$$\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005 \oplus \frac{0.002}{E}$$

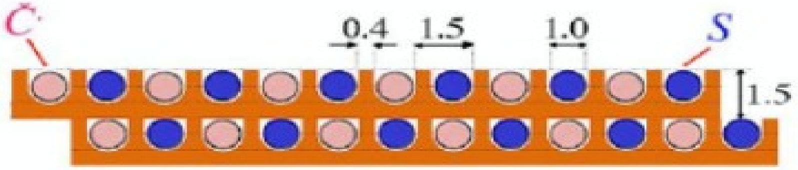
$$\sigma(\theta) = \frac{1.5}{\sqrt{E}} \oplus 0.33$$

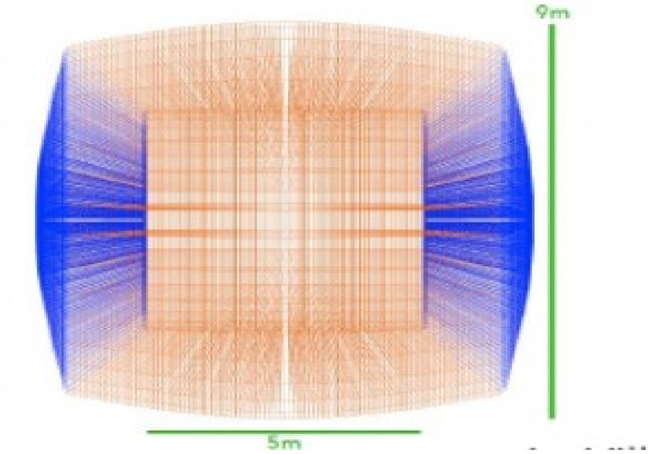




IDEA DR Calorimeter, old version

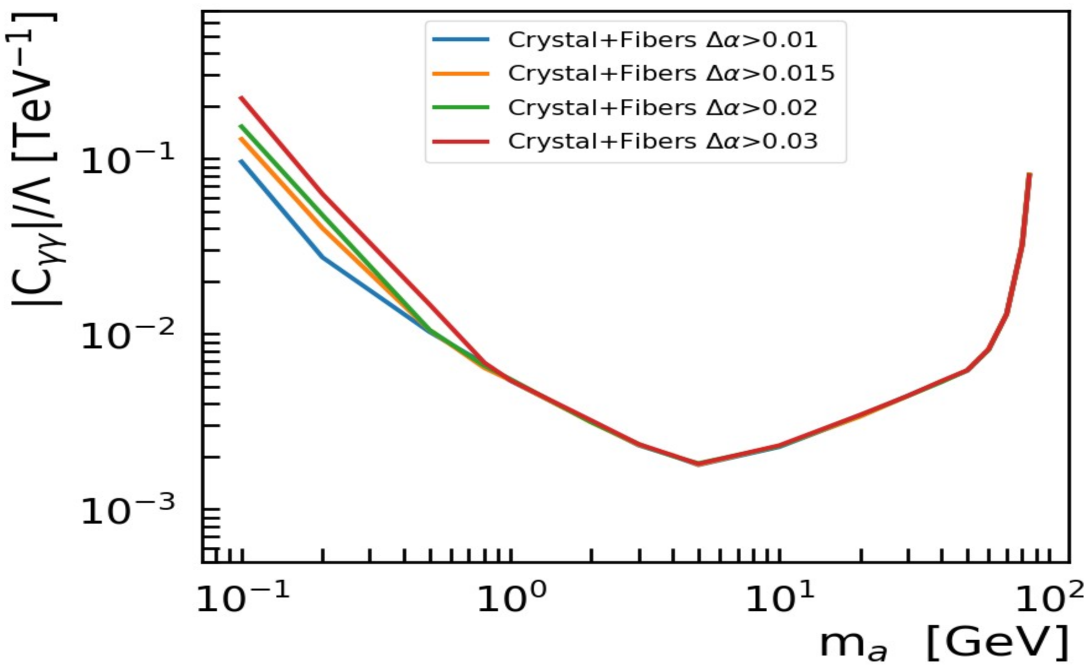




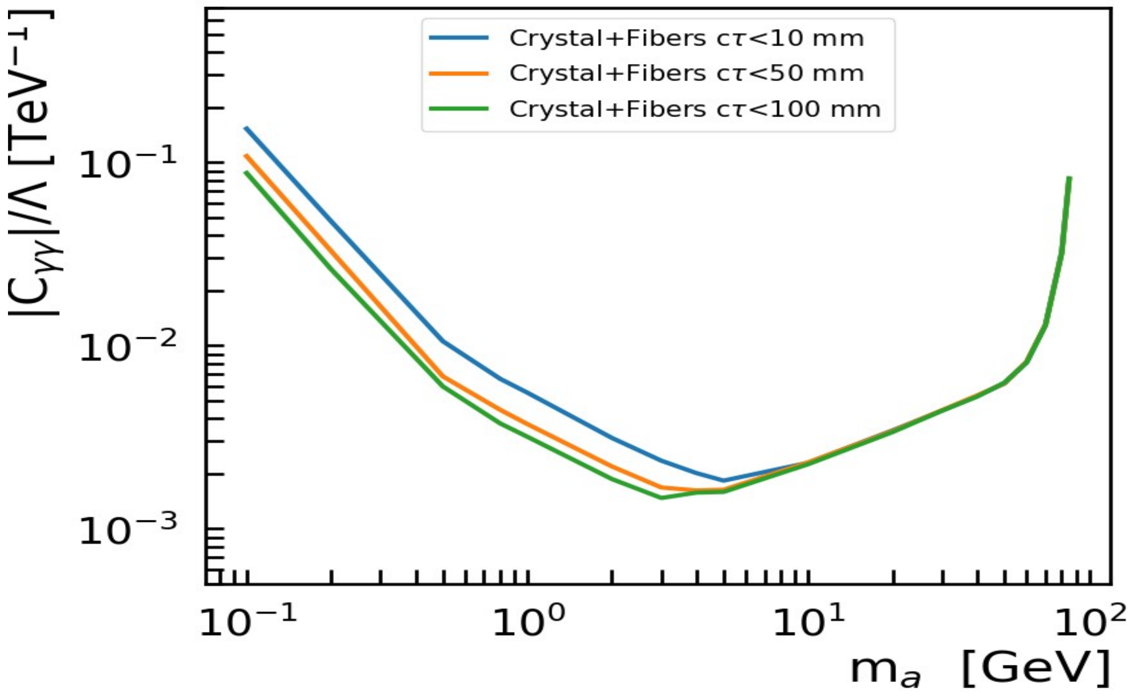


Reach as a function of Δα and of cut on cτ

Cτ<10 mm



Δα>0.02



Plot 2σ reach as function of mass and coupling, assuming 0.1% systematics

Define significance as:

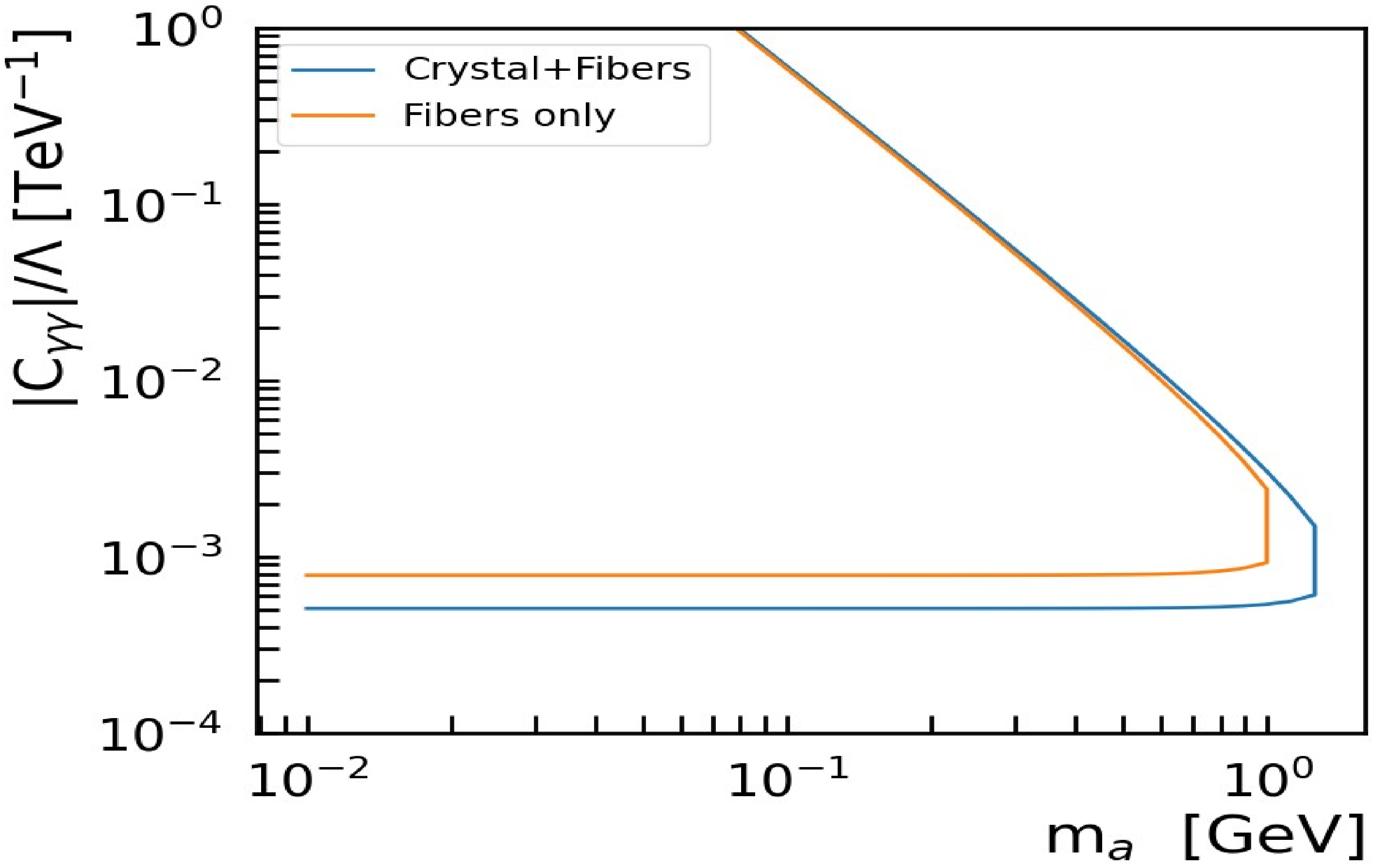
s=number of signal events after cuts

b=background events after cuts

n=s+b, σ = systematic uncertainty on b

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

Results



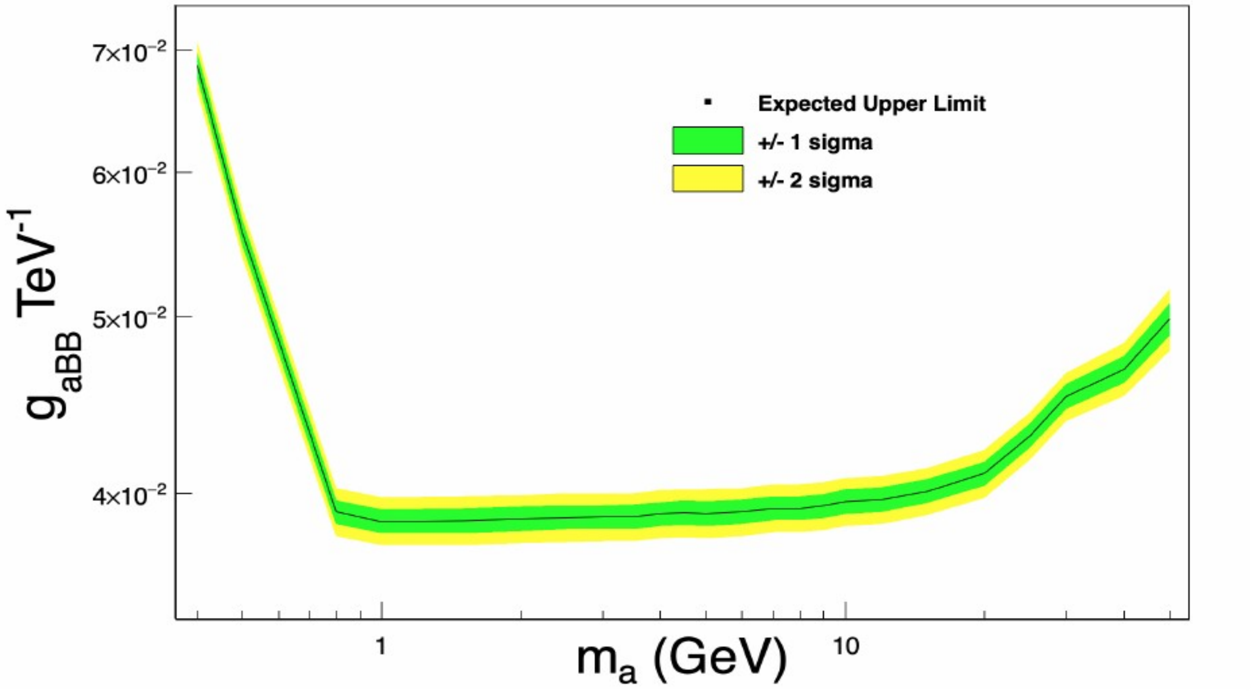
Irreducible background small at 45.6 GeV, but it increases very fast as energy goes down.

Smaller energy window determined by better resolution significantly increases reach

A similar exercise

Recent paper: Steinberg, Wells, arXiv:2101.00520

Addressing the same model in the framework of ILC GigaZ
ILC detector: R(ECal)~1.85 m. GARLIC photon reco: require photons with ΔR>0.035 and with less than 10% of energy in reconstructed cone from nearby photon



Simple analysis, require:

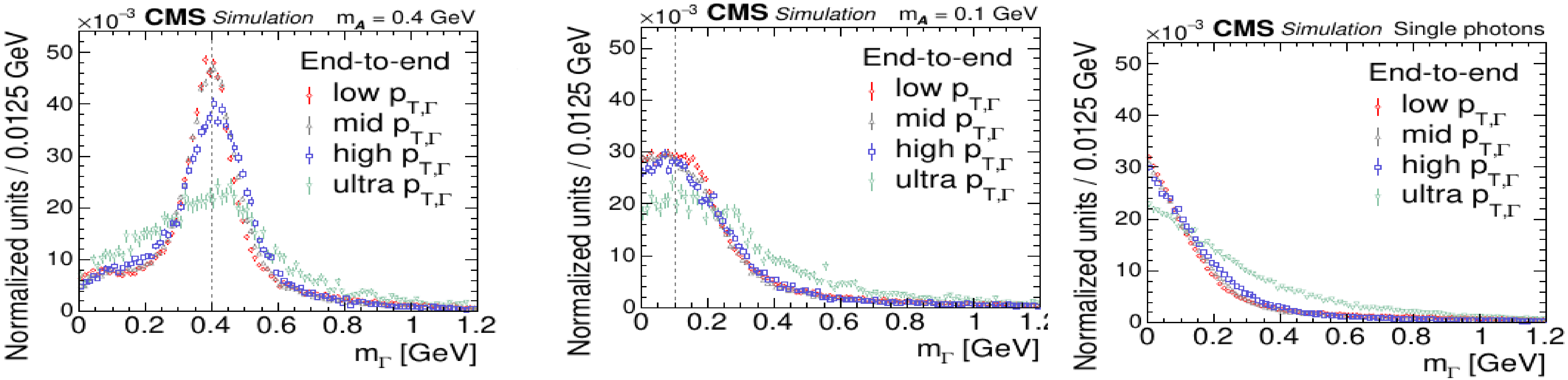
- 3 non-overlapping photons E>2 GeV
- $E\gamma - E\gamma^{\text{recoil}} < 5$ GeV

$$E^{\gamma}_{\text{recoil}}(m_a) = (M_Z^2 - m_a^2)/2M_Z$$

Significant loss in sensitivity, but in this setup search extended down to ALP masses if few hundred MeV

An encouraging example from CMS

PRD 108 (2023) 052002



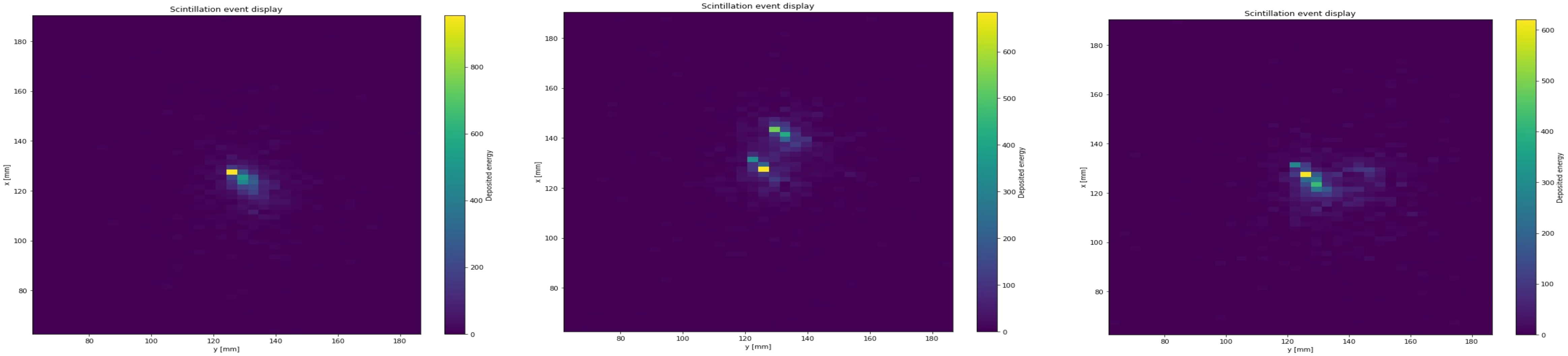
Using a CNN-based algorithm, reconstruct peak of 100 MeV particle.

CMS granularity: 2.3 cm,   IDEA Crystal: 1 cm   IDEA Fiber: 2 mm

Can probably improve on CMS result

Two photons in fiber calorimeter

One fiber every 2 mm read with SiPMs



G4 simulation of energy deposition of a 40 GeV photon (left),

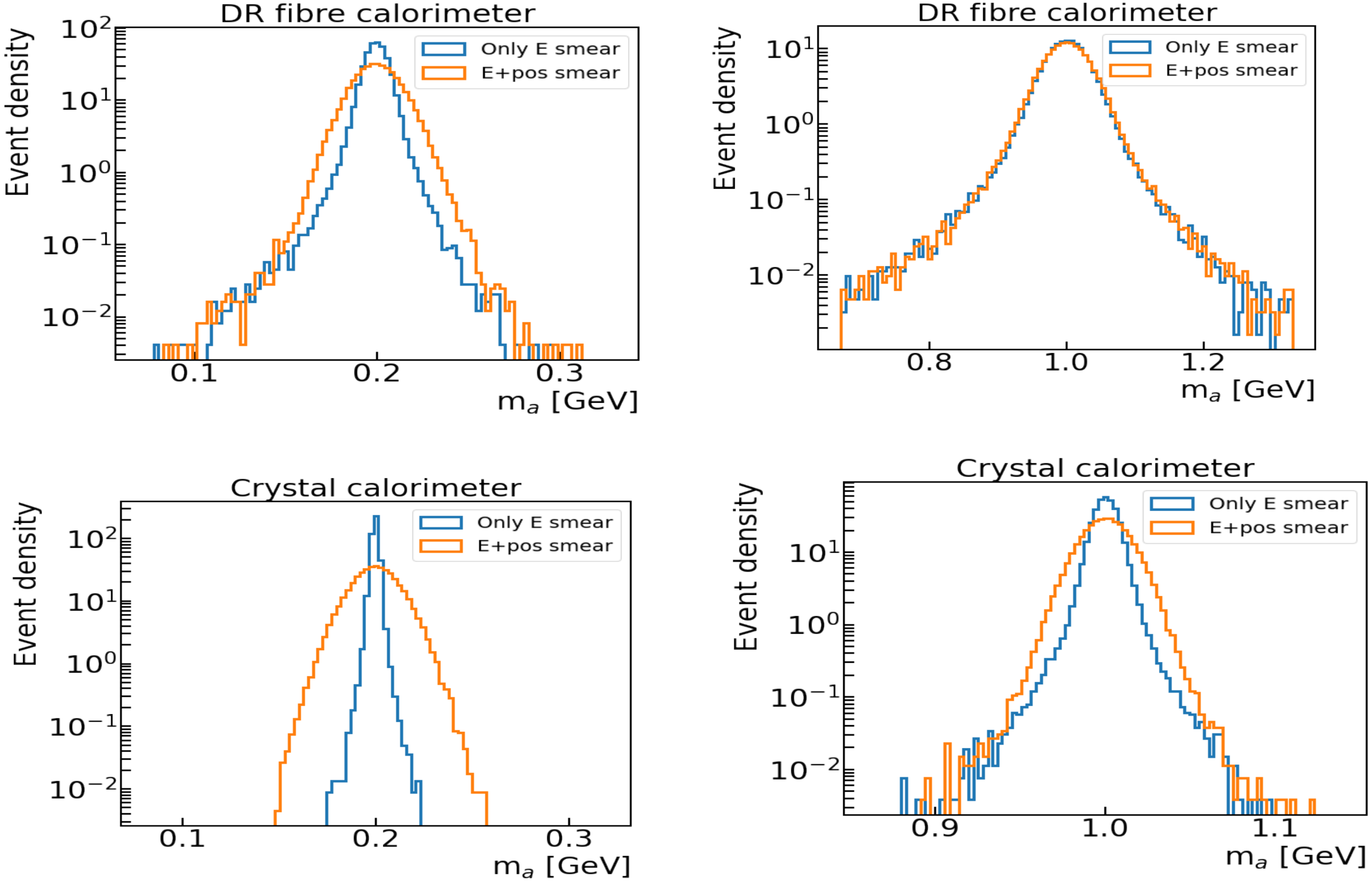
and of two examples 40 π^0 produced at 2m from a fiber calorimeter prototype

(Master thesis G.Salsi)

Very high granularity can be exploited to measure the two clusters using image reconstruction techniques → start work soon on that

Waiting for results becoming available, reject events where Δα between two photons smaller than 0.01, 0.015, 0.02, 0.03, and study reach as a function of cut

Mass resolution



Compare mass resolution for m_a=0.2, 1 GeV for the two calorimeter options, for prompt decays of ALP

Position resolution dominant effect up to ~1 GeV

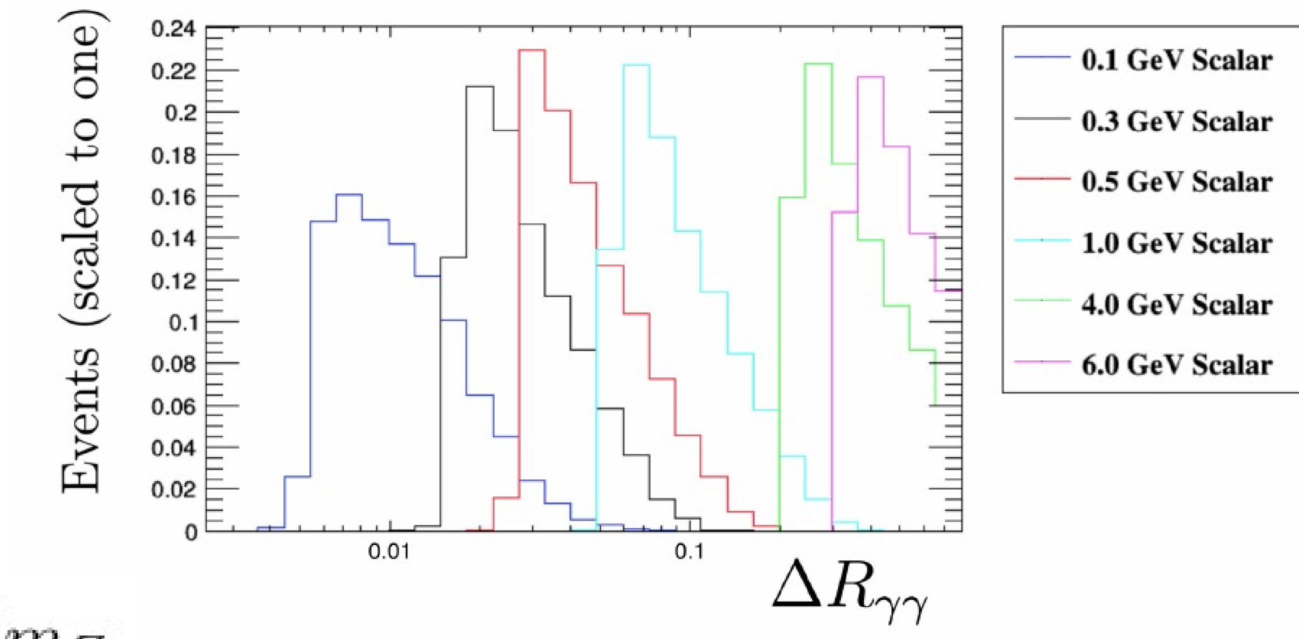
Coalescing Photons

For M_a <~ 5 GeV two photons very collimated: e.g for M_a=0.5 GeV ΔR_{peak} ~ 0.03

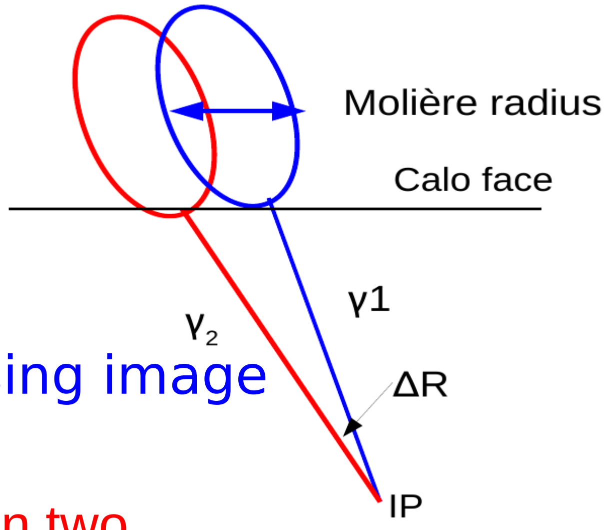
If distance from interaction point to calo face = 2 m (IDEA), two photons from 0.5 GeV ALP have distance of 6 cm.

$$\Delta R_{\rm peak} = 4 m_a / m_Z$$

Steinberg, Wells, arXiv:2101.00520



Size of photon shower in calorimeter: Molière radius, depends on material and geometry, around 2 cm for crystal calorimeter, ~2.4 cm for fibre calorimeter



Very high granularity can be exploited to measure the two clusters using image reconstruction techniques → start work soon on that

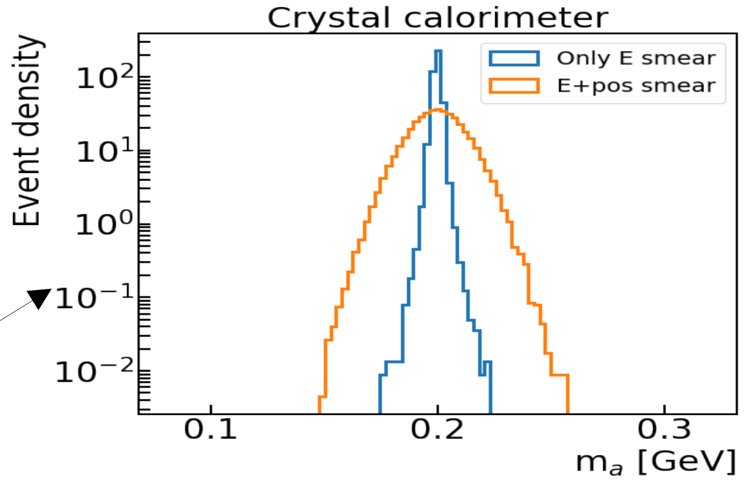
Waiting for results becoming available, reject events where Δα between two photons smaller than 0.01, 0.015, 0.02, 0.03 and study reach as a function of cut

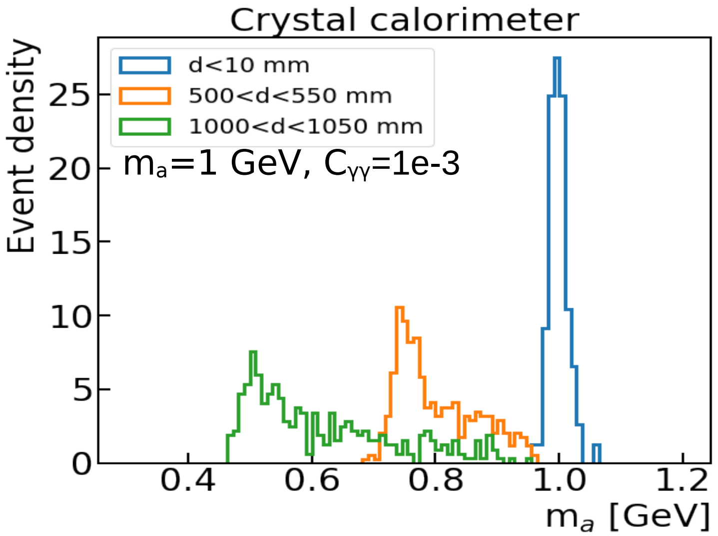
Experimental issues at low masses (~<5 GeV)

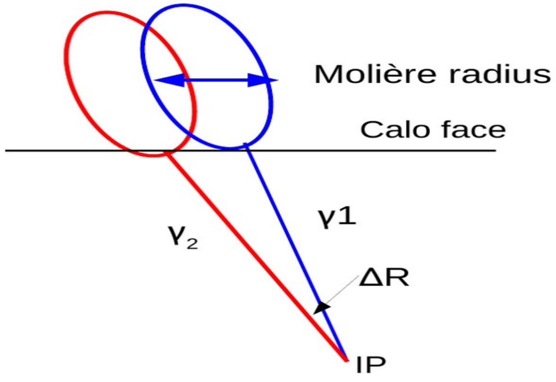
Signal acceptance strongly affected by width of measured ALP mass

At low masses three geometrical effects:

- γγ Mass resolution of dominated by uncertainty on measured photon impact point
- ALP decaying far from interaction point: mass reconstruction assumes photons produced in centre of detector. If long decay path, γγ angle Δα and mass underestimated
- γγ from ALP decay coalesce in calorimeter:







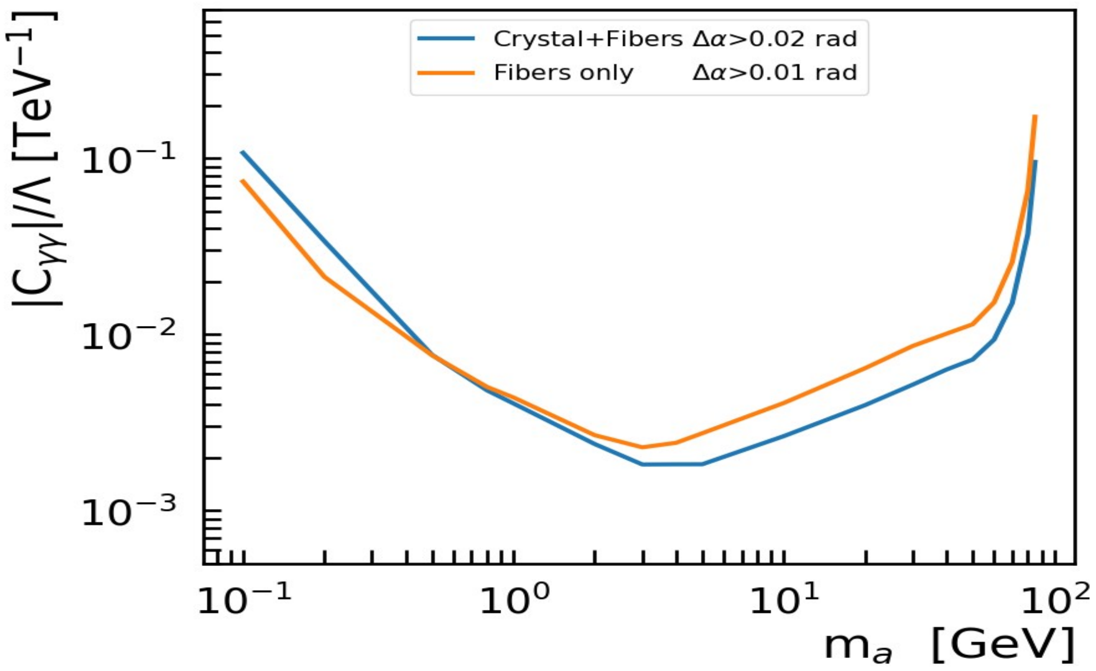
$$\Delta R_{\text{peak}} = 4m_a/m_Z$$

Need full simulation for separation of nearby photons

For this study assume two photons reconstructed as one

If Δα>02 (0.1) for crystal (fibre) EM calo

Results



For each signal and background sample events after cuts normalised to FCC-ee lumi

s=number of signal events after cuts

b=background events after cuts

n=s+b, σ = systematic uncertainty on b

Find cut on XGB output maximising significance calculated as:

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

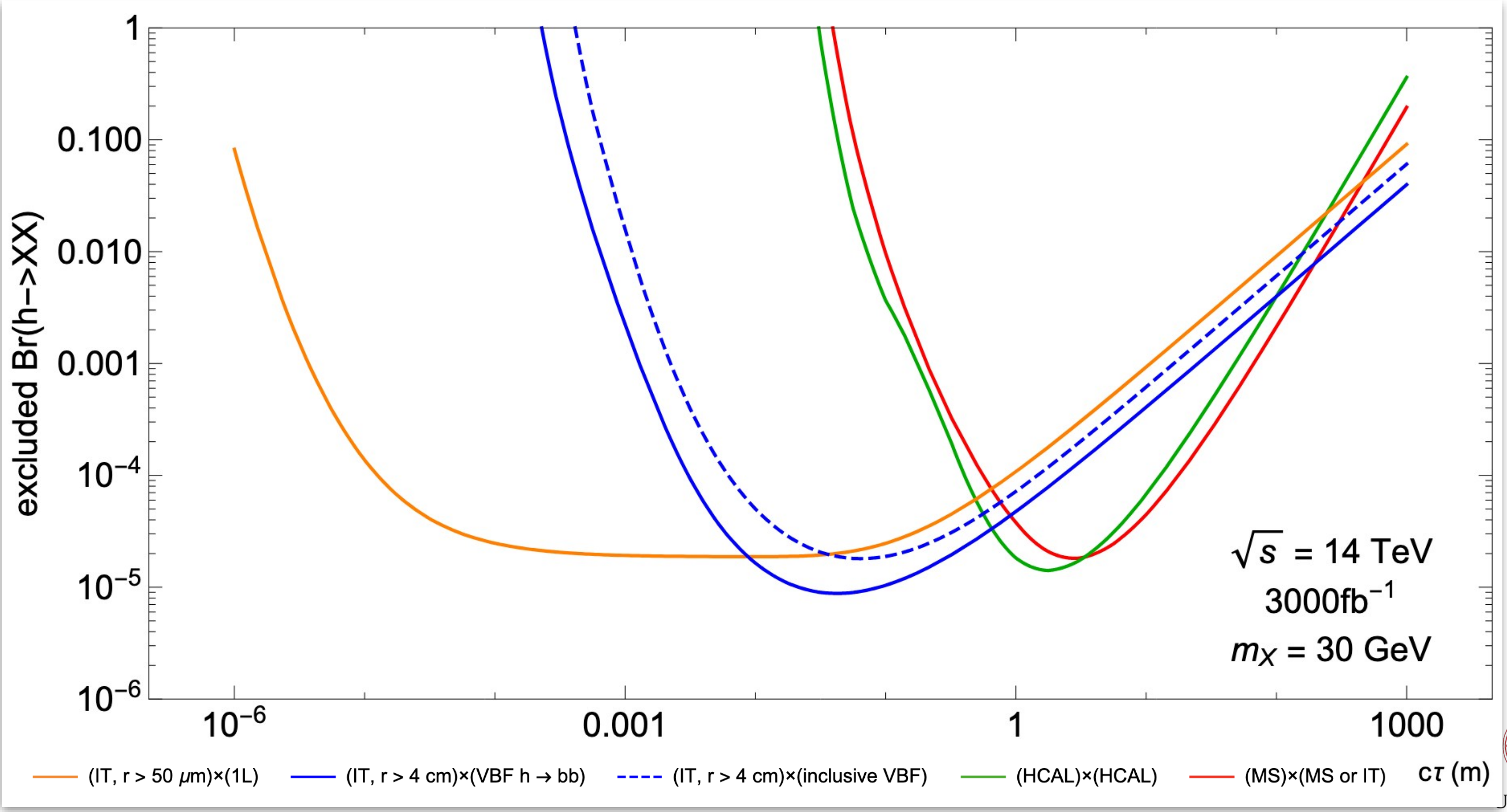
Significant advantage of better energy resolution at high masses

At low masses better granularity should allow better separation of close-by photons

Cross-section proportional to $C_{\gamma\gamma}^2$

For each test mass plot $C_{\gamma\gamma}$ such that Z=2

Projected HL-LHC limits for exotic Higgs decays



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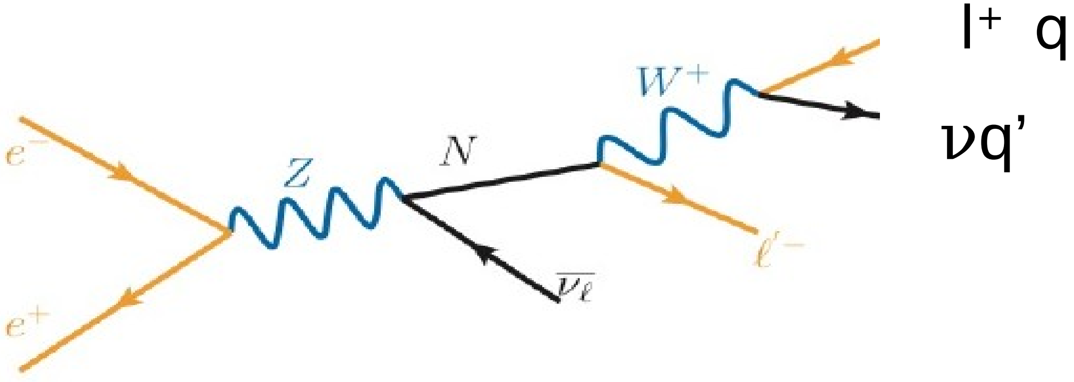
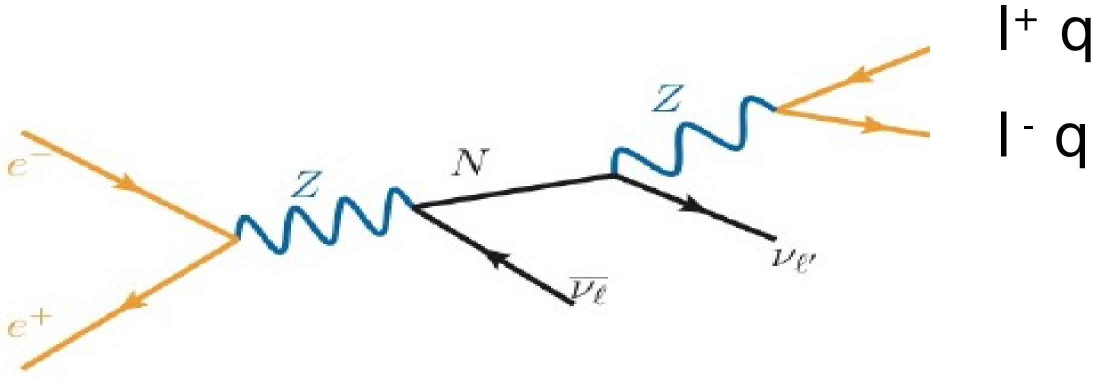
[Curtin & Verhaaren - 1506.06141](#)

Decay signatures





Analysis matrix: for HNL

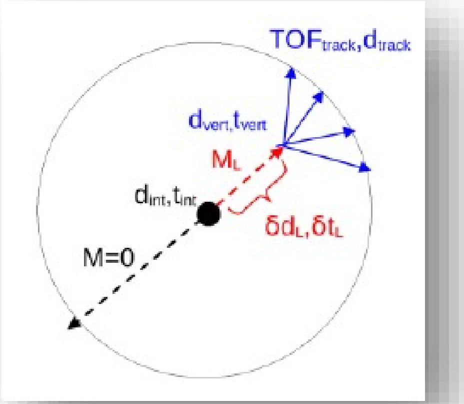
- Decay final state (l=e,μ):
  - j j l ~50% *
  - j j' nu ~20%
  - l l nu ~5% *
  - l l' nu ~9%
  - l τ nu ~9%

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

Signatures with * studied in group

Mass measurement through timing

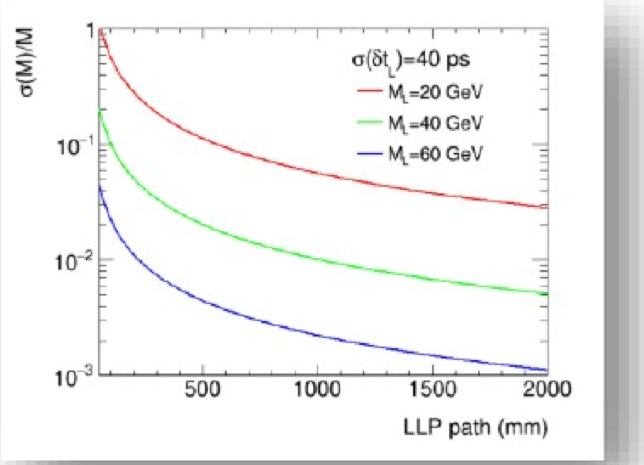
$$m_N = E_{cm}\sqrt{\frac{1-\beta_N}{1+\beta_N}} = E_{cm}\,F(\beta_N) \qquad \sigma(m_N) \sim E_{cm}F'(\beta_N)\,\sigma(\beta_N) \qquad \beta_N = \frac{\delta d_N}{\delta t_N}$$



The **HNL mass** can be constrained by measuring its decay **timing and path**

Resolution controlled by the uncertainty on HNL decay time and on the **undetected interaction point** *

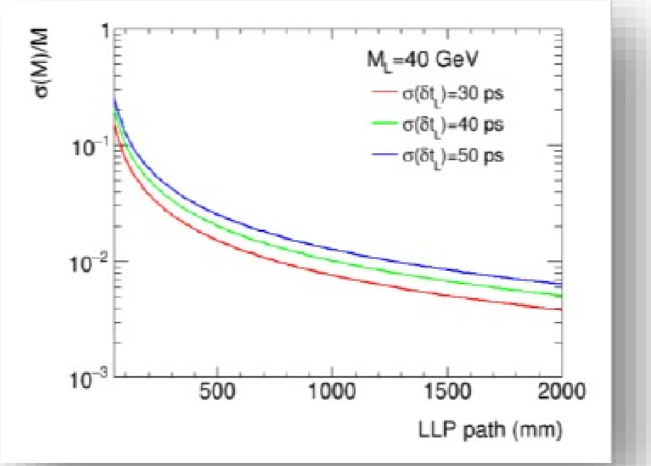
* σ_x = 5.96 μm, σ_y = 23.8 nm, σ_z = 0.397 mm, σ_z = 36.3 ps



Measurement below the percent
level is possible with plausible detector
performance,

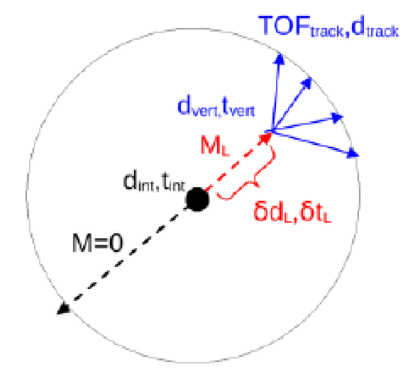
for sufficiently high masses

and long lifetimes



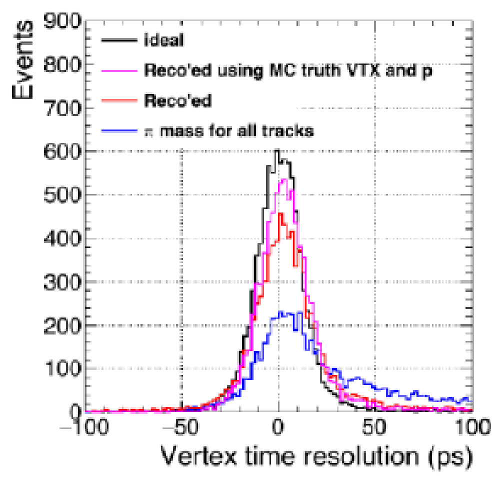
Mass measurement through timing

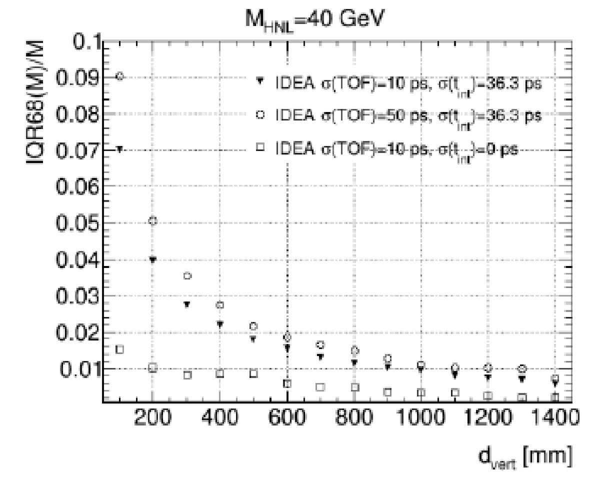
arXiv:2406.05102

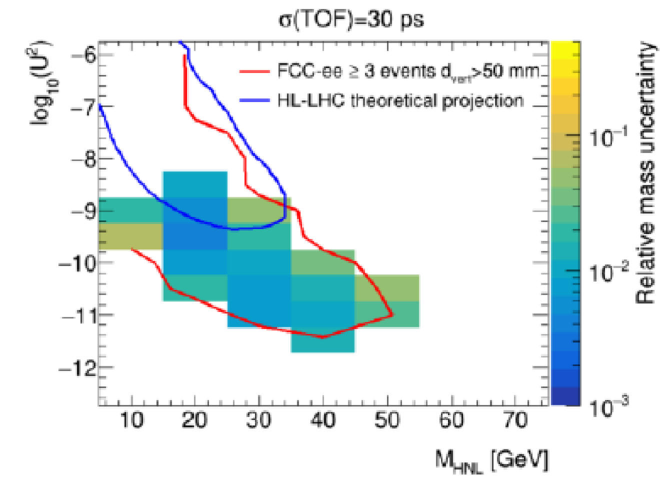


Realistic conditions simulated in IDEA, using the $N \rightarrow \mu jj$ channel

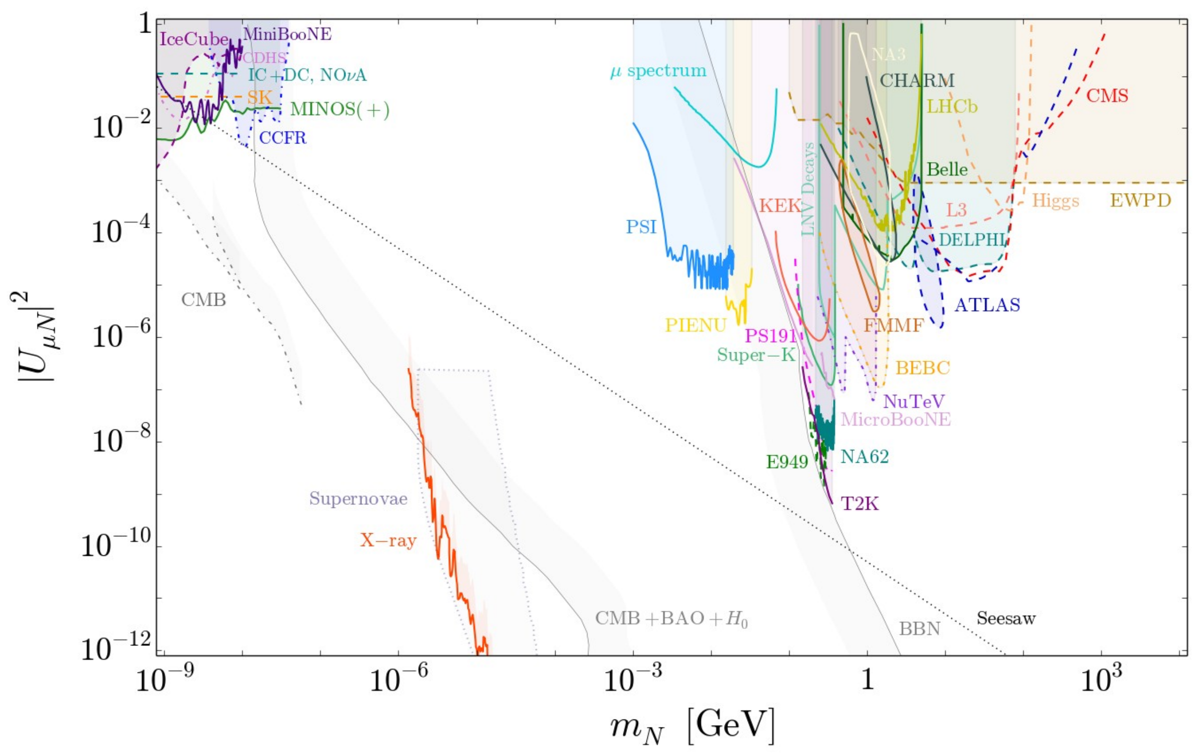
- $\sigma(\mathrm{TOF})$ determined only by detector technology
- The HNL vertex is known and its flight distance is computed
- Iterative procedure set up to optimize the mass hypotheses, possibly spoiled by the long HNL flight distance
- Timing resolution roughly scaling with sqrt of number of tracks
- $200\mu m \simeq \sigma(d_{vert})$ dominated by the uncertainty on the interaction point
- Dependence on HNL yield vs (m_N, U): evaluated with MC for the expected Z-pole run luminosity

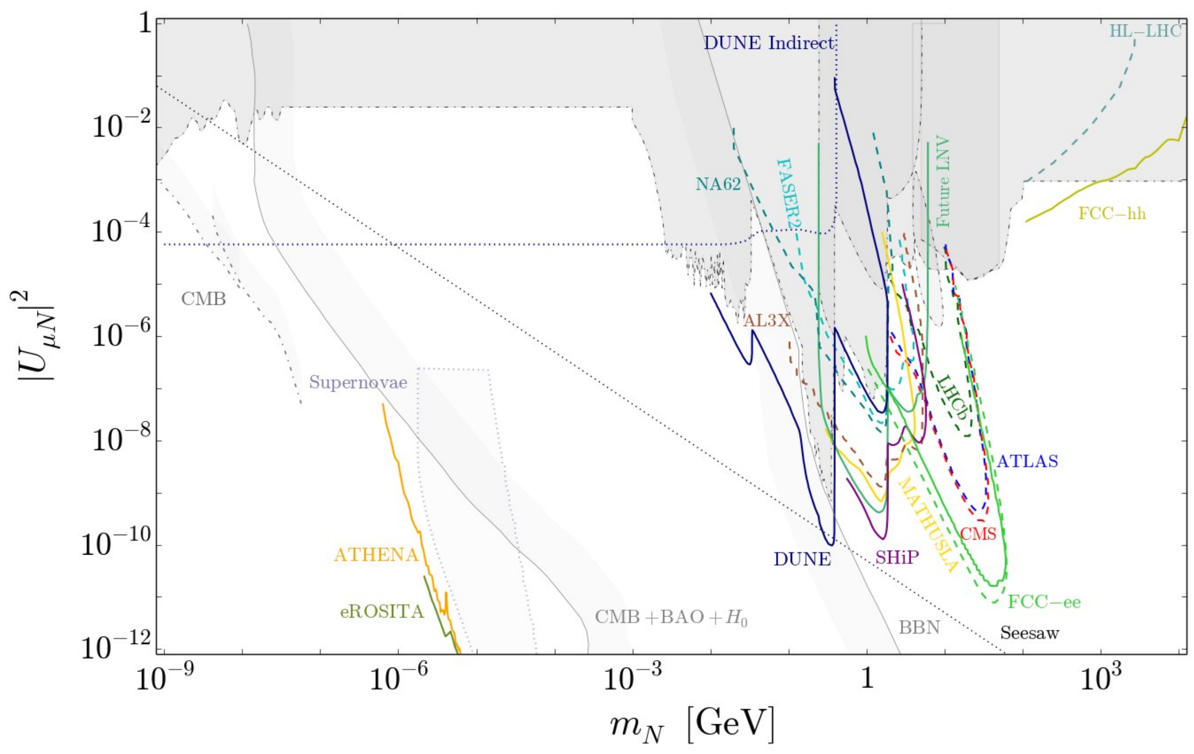






Existing limits and projections





arXiv:1912.03058

Dependence on hadronic resolution

1. Window for baseline study from DELPHES
2. Assume signal efficiency unchanged after enlarging mass window according to resolution
3. Calculate number of background events for enlarged window and calculate significance

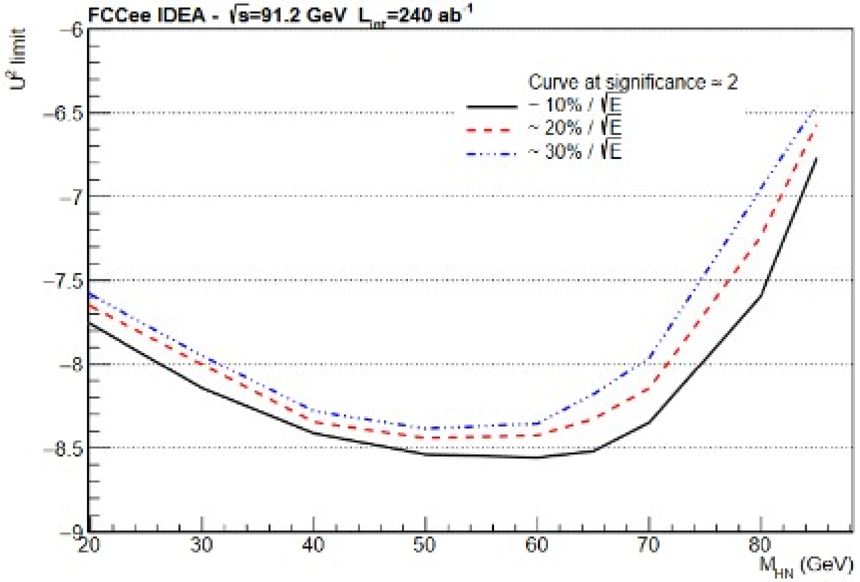


Fig. 24 Curves at Significance = 2 for different values of the assumed hadronic resolution. Each line is a linear interpolation of Z vs. $\log(U)$ at the value $Z = 2$.

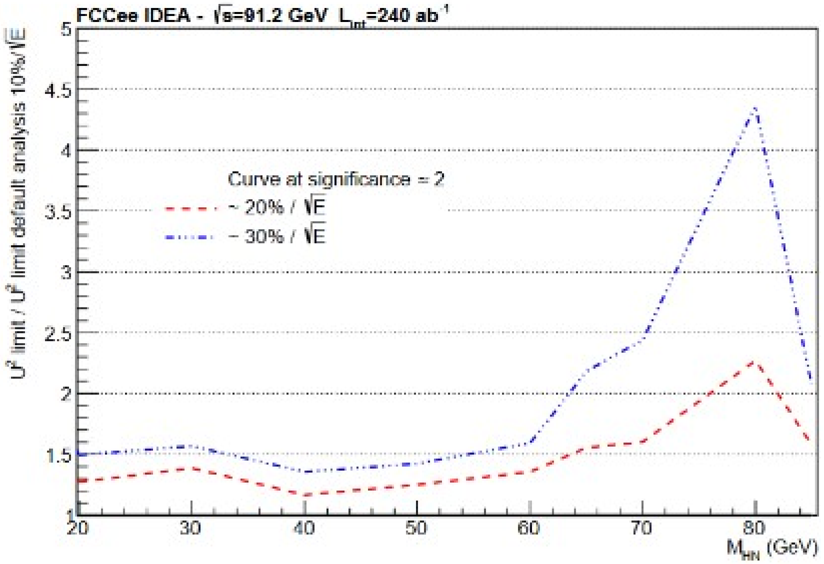


Fig. 25 Ratio of the U^2 limit obtained with 20% and 30% resolutions with respect to the nominal resolution as a function of M_{N_1}.