# BSM Prompt Signatures: case studies for detector requirements

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on behalf of the FCC PED – BSM Physics group





## **BSM at FCC**

- Very different experimental requirements for different signatures
  - Prompt
  - Decay in inner detector
  - Decay in calo/muon detector
- Study of coverage for a given model should address all three signatures
- New particles:
  - Broad range of coupling and masses accessible at FCCee thanks to clean environment and high statistics
    - Axion-Like Particles (ALP)
    - Heavy Neutral Leptons (HNL)
    - Light SUSY and light scalars scenarios
    - Z', dark photons, ...
    - Exotic Higgs decays

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Recent activities in the group, case studies for this talk

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Michele Selvaggi [plenary, Monday] and Sarah Williams [few minutes ago]

See talks by

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Recent activities in the group, case studies for this talk

This talk is focused on IDEA for FCCee

See talks by Michele Selvaggi [plenary, Monday] and Sarah Williams [few minutes ago]

# i. ALP

## **Axion Like Particles**

- Axion-Like Particles: hypothetical pseudoscalar appearing naturally in many extensions of the SM ٠
- Unpredicted masses and couplings ranging over orders of magnitudes ٠
- FCCee: ALP associated • production as a function of  $m_a$  and the coupling to vector bosons ( $C_{\nu\nu}$ )
- Different decays, depending ٠ on which couplings non-zero







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## **Axion Like Particles**

Axion-Like Particles: hypothetical pseudoscalar appearing naturally in many extensions of the SM

 $Z/\gamma$ 

- Unpredicted masses and couplings ranging over orders of magnitudes ٠
- FCCee: ALP associated • production as a function of  $m_a$  and the coupling to vector bosons ( $C_{\gamma\gamma}$ )
- Different decays, depending • on which couplings non-zero
- Final state with three photons specially relevant at FCC-ee
  - Imposes requirements on the performances of EM calorimetry
- $m_a \gtrsim 5$  GeV: sensitivity dominated by EM calo resolution
- $m_a \leq 5$  GeV: large contribution from position resolution and photon-photon separation power (granularity)
- Results from LHC photon-photon collisions



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Investigation from  $m_a$ between 0.2 and 360 GeV, at different  $\sqrt{s}$ 



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

- 3 photons channel. Signal and bkg with MG5 + Pythia8; DELPHES for IDEA fast simulation ٠
- Discrimination based on  $\gamma\gamma$  invariant mass, opening angle and energy of the third photon ٠



N.Valle, on behalf of the BSM Physics Group

L. Pezzotti Thesis

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## ALP - analysis

• Looking for  $C_{\gamma\gamma}$  value such that significance = 2

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

- In the 10-100 GeV region FCC-ee reach is in the same ballpark as projected PbPb LHC results [1]
- Low mass (≤ 5 GeV/c<sup>2</sup>) sensitive to effective separation of collimated photons: low mass ALPs are excellent benchmark for detector optimisation
- Detector-dependent work based on full simulation needed to fully assess potential for nearby photons



# ii. HNL

## Heavy Neutral Leptons

- Dirac or Majorana fermions with sterile neutrino quantum numbers
- One of the most promising new physics channels for FCC-ee at the Z pole
- FCC will probe space not constrained by astrophysics or cosmology, complementary to accelerator and neutrino prospects
- Rich set of final states signatures, both prompt and long-lived



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# $HNL \rightarrow \mu j j$

- High branching fraction  $\sim 50\%$ ٠
- Good background rejection through constraints on • HNL mass and missing energy
- One flavor assumed: model defined in terms of HNL • mass and coupling U with active neutrino

$$e^+$$
  $Z$   $N$   $\overline{\nu_{\ell}}$   $\ell^-$ 

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

$$Lifetime \sim \frac{1}{|\boldsymbol{U}|^2 \, \boldsymbol{m}_N^5}$$

- Discovery is possible over a large range of the parameters space of interest
  - ✓ *High mass*

#### prompt singnals

- Jet energy resolution
- Vertexing performances

#### $\checkmark$ Low mass

- Background mainly supprssed by measurements ۲ of displacement of decay vertex
- Requirements on vertexing and timing performances

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## $HNL \rightarrow \mu j j$ analysis

- MG5aMC@NLO to generate signal samples
  - SM\_HeavyN\_CKM\_AllMasses\_LO model with a single flavour
- Pythia8 for hadronization and DELPHES for IDEA Detector fast simulation.
- Scan over the HNL mass, from 5 to 85 GeV
- Scan over  $U^2$  according to existing excluded limits and to a proper decay length



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## $HNL \rightarrow \mu j j$ analysis

#### • Background:

- A. Z boson hadronic decay: muon in the final state from decay of a meson in one jet (  $"Z \rightarrow bb/cc/uds"$ )
- B. Z boson leptonic decays " $Z \rightarrow \mu\mu$ ,  $Z \rightarrow \tau\tau$ " : muon and jets in the final state
- C. four-fermion process  $e^+e^- \rightarrow \mu \nu q q'$ , which is an irreducible background
- A. and B. from official FCC production
- C. with MG5aMC@NLO, Pythia8 for hadronization and DELPHES for IDEA Detector fast simulation.



### Analysis outline

- Events filtered by requiring  $\geq$  3 tracks;  $E_{miss} > 5$  GeV; at least one muon with p > 3 GeV/c
- Jet reconstruction:
  - Asking for a single reconstructed lepton (muon), excluded from clusterization
  - Detailed study on different algorithms offered by FASTJET. Comparison with 4-momenta of partons

 $\geq e^+e^-k_T$  (Durham) alogorithm, forcing #jets = 2 if more than 2 jets are found



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## Analysis outline

- Sum of visible 4-momenta to select HNL mass and  $\nu$  recoil energy: independent from jet algorithm
- Further background rejection by cutting on jets and muon angular distributions
- Z to hadrons → back-to-back jets with muon flowing close to one jet
  - ▶ Reduced to < 1%, relevant at high masses
- **Z** to  $\mu\mu \rightarrow$  single jet reconstructed, muon-jet back to back
  - ≻ Relevant at low HNL masses
- Z to  $\tau \tau \rightarrow$  single jet reconstructed, multiple neutrinos in the final state,  $p_{miss}$  flowing in the same direction of the muon

 $\triangleright$  Reduced to < 1%

- **4-body**: irreducible (but purely prompt) background
  - ➤ Suppressed ~50%

Signal efficiency from ~80 % (M=20 GeV) to ~50 % (M=70 GeV). ~30 % at M=80GeV



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## Analysis outline

• Z to hadrons

- Sum of visible 4-momenta to select HNL mass and v recoil energy: independent from jet algorithm
- Further background rejection by cutting on jets and muon angular distributions ٠

• Z to hadrons $\rightarrow$ back-to-back lets with muon				
flowing close to one jet	Sample	$\sigma(pb)$	Ngen	Weight
➢ Reduced to < 1%, relevant at high masses	Signal $U^2 = 10^{-7}$ M = 20 GeV	$4.2 \times 10^{-4}$	10 <sup>3</sup>	~ 10
<ul> <li>Z to μμ → single jet reconstructed, muon-jet back to back</li> <li>▶ Belevent at low UNU messes</li> </ul>	Signal $U^2 = 10^{-7}$ M = 50 GeV	$2 \times 10^{-4}$	10 <sup>3</sup>	~ 4.8
Relevant at low HINL masses	$Z \rightarrow bb$	6645	10 <sup>9</sup>	~ 1627
• Z to $\tau\tau \rightarrow$ single jet reconstructed, multiple neutrinos in the final state, $p_{miss}$ flowing in the	$Z \rightarrow cc$	5215	10 <sup>9</sup>	~ 1264
same direction of the muon	$Z \rightarrow u/d/s$	18616	10 <sup>9</sup>	~ 4467
$\blacktriangleright$ Reduced to < 1%	$Z  ightarrow \mu \mu$	1462	107	~ 35090
• <b>4-body</b> : irreducible (but purely prompt)	$Z \to \tau \tau$	1476	107	~ 35437
ackground	μνqq	$3.2 \times 10^{-3}$	$5  imes 10^5$	~ 1.5
► Suppressed ~50%				$L_{int} = 240ab^{-1}$

Signal efficiency from  $\sim 80 \%$  (M=20 GeV) to  $\sim 50 \%$  (M=70 GeV).  $\sim 30 \%$  at M=80GeV

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## Analysis outline





• Invariant maass resolution roughly scaling as 20% /  $\sqrt{E}$ : parameters of IDEA simulation in Spring2021 samples, particle flow jets without confusion term

• Setting 
$$\Sigma = 2 \times 20\% \times \sqrt{M_{HNL}}$$
  
> 20 GeV  $\rightarrow \Sigma = 1.9$  GeV ... 70 GeV  $\rightarrow \Sigma = 3.3$  GeV

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### Analysis outline

- Hadronic channel further suppressed by requiring muon coming from Interaction Point
  - > Only one (secondary) vertex expected
  - > Muon impact parameter close to zero
  - ≻ Muon identified as primary track...

▶ b-tagging

• Prompt analysis implemented on muon impact parameter on the xy plane

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

- $\sigma = O(5 \ \mu m) \rightarrow$  far from a critical region for jet reconstruction
- ✓ Importance of tracker **pointing resolution**
- High impact to signal efficiency in the low HNL mass and weak coupling regime



## **Preliminary results**

G. Polesello, N. Valle

- Baseline: Integrated Lumi = **240**  $ab^{-1} \leftrightarrow 8 \times 10^{12}$  Z boson events
- Looking for  $U^2$  producing 95% CL excess of events

For each HNL mass *M*:  $P[n < b | HNL(M, U^2)] = 1 - CL$ 



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- Looking for  $U^2$  producing 95% CL excess of events

For each HNL mass *M*:  $P[n < b | HNL(M, U^2)] = 1 - CL$ 

b =#background events

• Impact of the impact parameter cut:



## **Preliminary results**

G. Polesello, N. Valle

- Fast simulation with parametric particle energy resolution
  - EM: ~ 11% /  $\sqrt{E}$  ; HAD: ~ 30% /  $\sqrt{E}$  ; 1% constant term
- Impact of calo resolution could be assessed by smearing energy of jets built from stable particles
- Preliminary simplified approach: estimate variation of background when varying mass window as a function of the jet-jet mass resolution



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## Reversed displacement cut: long-lived analysis

- ✓ Low mass (  $\leq 40 \text{ GeV}/c^2$ ) much more discrimated by displacement cuts
  - Background highly suppressed
  - Detailed parameterization of IDEA tracking performance in DELPHES-FCC
- Kinematic selection not modified, prompt background suppresed by  $D_{\mu} > 1 \text{ mm}$
- Signal efficiency kept > 50% at low mass and weak coupling



G. Polesello, N. Valle

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• Jets built at the analysis level with the Durham algorithm in #jet = 2 mode

$$Z = \sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]} = 2$$
  
With 10% syst. uncertainty

Selection:

 $E_{miss} > 12$  GeV, accounts for neutrino fixed energy in 3-body decay

A. Sfyrla, D. Moulin, P. Kontaxakis

- Leading electron energy > 35GeV, to remove most of the electrons from jets
- $\theta(j_1, j_2) < 2.4$  rad, distance electron dijet  $\Delta R(e, jj) < 3$



# Defining the final state variables for which difference Dirac-Majorana can be observed [1] Electron energy, HNL (dijet) energy, Electron-HNL angle: studied both at the

 $HNL \rightarrow ejj: Dirac/Majorana$ 

• Good discrimination coming from electron/positron distributions separately



A. Sfyrla, D. Moulin, P. Kontaxakis

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Excellent FCC-ee potential for direct searches of BSM signatures both in prompt and long-lived channels (**Talk by Sarah** on LL signatures) Full exploitation of this potential poses severe requirements on detector performance

HNL production is a key BSM search for FCC-ee. Analyses prove sensitivity down to small mixing angles
 Complementary role of prompt and LLP signatures in covering the paramters' space
 Promising studies ongoing for discrimination of Dirac and Majorana HNLs

Vigorous activity on benchmark models ongoing, at the moment based on parametrised performance of detectors

Thanks to all those who contributed to the talk and the analyses, Thank you for your attention! **BSM Prom** 

## BACKUP

• Efficiency of each selection on background: (% events passing the cut)

Variable	$N_{jet}$	$\cos(p_n$	niss) co	$s(p_{miss},\mu)$	$E_j, M_j$	COS	s(j,j) of	$\cos(j,\mu)$	$\cos(2$	$j,\mu)$	$M_{tot}$	
Cut	= 2	< 0.	94	< 0.80	$> 3 \mathrm{GeV}$ > 0.2 GeV	> -	-0.80	< 0.80 > -0.98		0.98	> 80	Combined
Background												
$Z \xrightarrow{\bigcirc} bb$	(100)	91	_	18	100		1	7	3	3	89	0
$Z \to cc$	(100)	91		10	100		1	5	1	6	95	0
$Z \rightarrow u/d/s$	(100)	86	5	22	100		2	37	7	0	98	0
$Z \to \mu \mu$	(6)	40	)	93	27		60	40	8	0	93	0
$Z \to \tau \tau$	(3)	93	3	24	13		46	58	5	2	44	0
$\mu u qq$	(73)	94	ł	94	99		61	86	9	6	99	44
Variab	ole <i>I</i>	V <sub>jet</sub> c	$os(p_{miss})$	$\cos(p_{miss})$	$,\mu)$ $E_j,$	$M_j$	$\cos(j,\mu$	cos(j)	$,\mu)$	$M_{tot}$		
Cut	=	= 1	< 0.94	< 0.50	> 3 - 0.2	GeV l GeV	< 0.96	5 >-	0.5	> 80	Comb	bined
Backgro	und											
$Z \rightarrow l$	bb	(0)	_	—	-	_	—	—		—	_	
$Z \to a$	cc	(0)	—	—	-	_	—	_		—	_	
$Z \rightarrow u/$	d/s	(0)	_	_	-	_	_	_		_	_	
$Z \to \mu$	$\iota \mu$ (	(94)	30	99	6	4	88	57		96	5	
$Z \to \tau$	- au (	(97)	93	8	10	00	100	0		35	0	
$\mu u q q$	(	(27)	93	94	10	00	98	63		99	56	5

• Signal efficiency from  $\sim 80 \%$  (M=20 GeV) to  $\sim 50 \%$  (M=70 GeV).  $\sim 30 \%$  at M=80GeV

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## $NHL \rightarrow \mu j j cuts$

- Sum of visible 4-momenta to select HNL mass and  $\nu$  recoil energy: independent from jet algorithm
- Further background rejection by cutting on jets and muon angular distributions
- Event selecton dependent on #jets + mass-dependent  $M_{vis}$  and  $E_{miss}$  cuts
- Discriminating variables:



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- Discriminating variables:



• + technical cuts on missing momentum  $\theta$ , and jet mass

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## ALP projections from pPb and PbPb UPC

#### https://arxiv.org/abs/2010.07855 https://doi.org/10.1016/j.physletb.2020.135512



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