# Detector performance requirements motivated from heavy neutrinos

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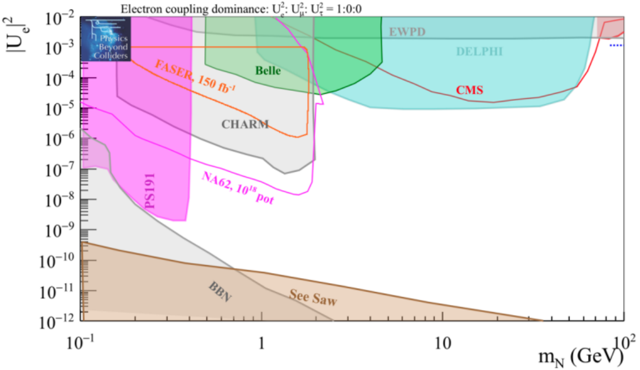
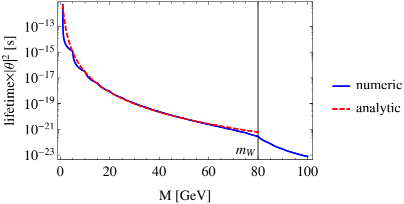
# Motivation for heavy neutrinos

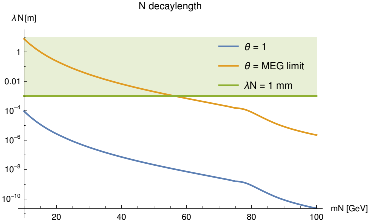



J. Beacham *et al.* J. Phys. G **47** (2020) no.1, 010501

- Well motivated by neutrino oscillations
- Searched for in many different experiments
- Electroweak masses are a collider target.
- Constraints require mixings $\theta^2 <\sim 10^{-5}$

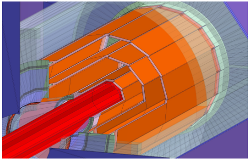
# Long lived heavy neutrinos

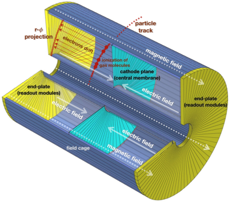


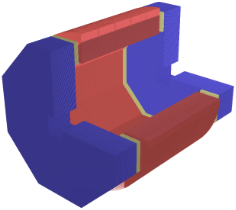




- Their interactions are given by the weak currents times $\theta$.
- Decay rate $\Gamma_N$ similar to muon decay $\propto G_F^2 M_N^5 \theta^2$.
- Exclusion limits for $M = 10$ GeV: $\theta^2 < 10^{-5}$
  $\Rightarrow$ lifetimes $\tau_N = 1/\Gamma_N > 1$ ps.
- 1 ps translates into a displacement of $\sim 0.3$ mm.

# Detector Geometry (baseline)





- Vertex detector: 1.6 to 6.0 cm (six layers)
- Inner tracker: two layers at 15.3 cm and 30. cm
- External tracker: one layer at 181 cm
- TPC (220 radial layers) from 30 cm to 180 cm
- Ecal from 202.8 cm, the Hcal to 314.4 cm.
- Muon system (incl. flux return yoke) from 440 cm to 608 cm

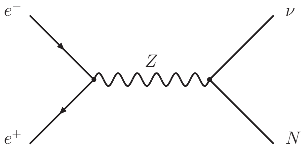
⋆ Impact parameter resolution: 5$\mu$m.

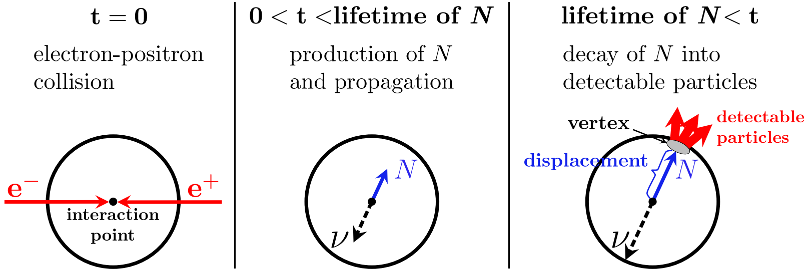
⋆ Photon energy resolution: $20\%/\sqrt{E} \oplus 1\%$.

⋆ Boson Mass Resolution: 4% or better.

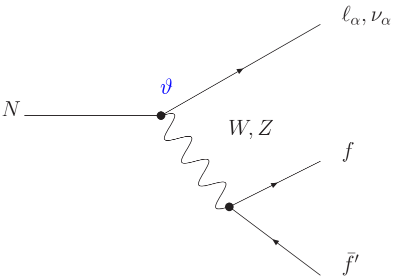
# Displaced vertices from heavy neutrinos

- Here: $Z$ pole (more lumi).
- Production rate $\propto \theta^2$.
- Energy: $M_Z/2$.
- Lifetime $\propto 1/\theta^2$.



# Signature




- $N$ is produced fairly isotropically.
- $N$ decays via weak currents: $N \to \nu Z, \ell_\alpha^\pm W^\mp$.
- For $M_N < M_Z$, three-body decays:
  $\ell_\alpha \ell_\alpha + E_{\rm miss}$, hadrons $+ E_{\rm miss}$, $\ell_\alpha \ell_\beta + E_{\rm miss}$, $\ell$ + hadrons
- For $M_N \geq 10$ GeV, decay products reasonaby well separated.
- Final state particles have energies of $\mathcal{O}(10)$ GeV.
- Conventional searches e.g. in Ding, Qin and Yu, Eur. Phys. J. C **79** (2019) no.9, 766

# Backgrounds

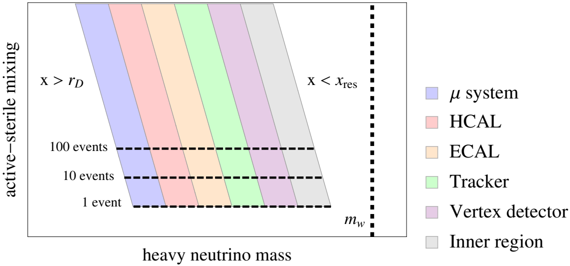
**Standard Model processes:**

- Particles lost in the beam pipe.
- $\tau\tau$ lepton decays.
- $B$ hadron decays.

**Machine related:**

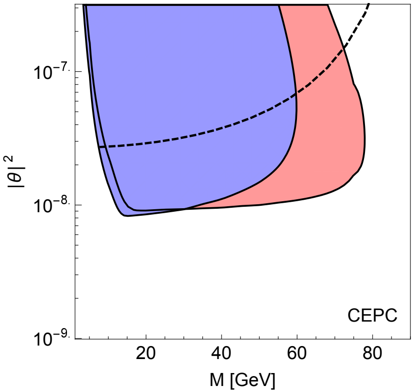
- Particle ID.
- Synchrotron radiation.
- $e^+e^-$ pair production from Beamstrahlung.
  22 hits/cm2 per crossing dominant at $Z$.
- Off energy beam particles, e.g. Bhabha scattering.
  0.22 hits/cm2 per crossing.

# Detection is **not** the problem



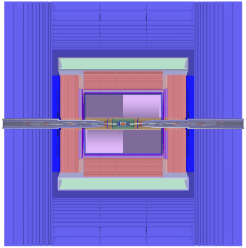

- Most decays will be detected by any detector component.
- Veto by "skipped" components removes backgrounds.
  $\Rightarrow$ Background free.
- Enhanced sensitivity:
  - Larger detector radius $r_D$: smaller masses!
  - Better impact parameter resolution $x_{res}$: larger masses!
  - More luminosity: smaller active-sterile mixing!

# Sensitivity estimate



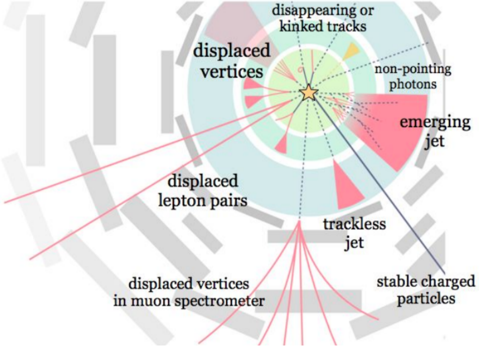

- Assuming zero backgrounds.
- Displacements from 0.1 *mm* (background) to 249 cm (tracker)
- Blue: $Z$ pole with 0.1 $ab^{-1}$.
- Red: Higgs run at 250 GeV with 5 $ab^{-1}$.
  - Larger $E_N$ ($\equiv \sqrt{s}$) $\Rightarrow$ larger masses.
  - Sensitive to $\theta_e$ only.

# The problem is loss of information



- Displacements of $\mathcal{O}(1)$ m are possible.
- Missing information makes standard particle ID for the final state next-to-impossible.
- Consider $N$ decay ...
  ... inside the vertex detector or TPC. Photon conversion?
  ... just before the calorimeters. Neutral hadron?
  ... in the muon system and out-of-time. Cosmic background?
- What final states have been observed?

# Appearing object vs. displaced vertex

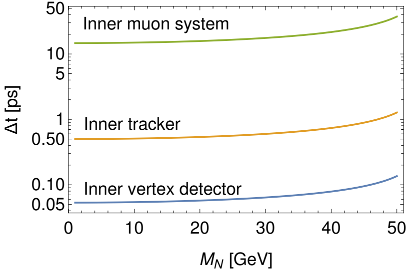



Credits: G. Cottin and H. Russel

- Detection of a vertex requires measurement of several tracks.
- $N$ decays into several charged particles inside the TPC.
- Close to calorimeters separation can be a problem.

  (Detection in calorimeters fine, as $E_{\Delta x} \sim \sqrt{s}/2$.)
- This could be circumvented by *pointing* in the calorimeters.

# Timing measurement

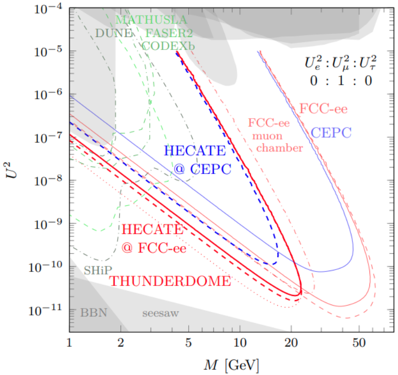



- Final states with mass $\ll$ energy are fast: $\beta\gamma \simeq 1$.
- Heavy particles with mass $\sim$ energy are slow.
- Delay of massive $N$ with respect to "massless" particles:

$$\Delta t(x) = \left(\frac{1}{\beta} - 1\right)\frac{x}{c}, \qquad \beta = \frac{p_N}{E_N}$$

- Measurement of delay $\Delta t$ and $E_N \Rightarrow M_N$.

# External detectors



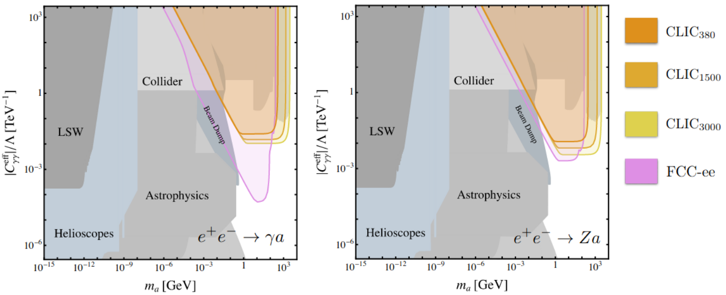

M. Chrzaszcz, M. Drewes and J. Hajer, Eur. Phys. J. C **81** (2021) no.6, 546

see also Z. S. Wang and K. Wang, Phys. Rev. D **101** (2020) no.7, 075046

- HErmetic CAvern TrackEr for $3.5 \cdot 10^{11}$ $Z$ bosons. Cost estimate for $4\pi$ scintillator at 15 m $\sim$ 5 MCHF.
- Faint curves: main detector ($x_{min} = 5$ mm, $x_{max} = 1.22$ m)
- Thick curves: HECATE ($x_{min} = 4$ m, $x_{max} = 15$ m)

Leaving the HNL...

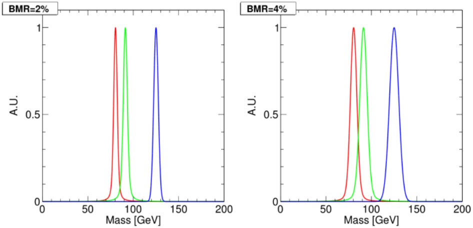
# Axion-like particles




M. Bauer *et al.* Eur. Phys. J. C **79** (2019) no.1, 74

- Pseudoscalar particles ‘motivated’ by the strong CP problem.
- Interact possibly with all SM particles.
- Well constrained from many different experiments.
- Target mass for collider studies: $m_a \geq 0.1$ GeV.
- $a \to \gamma\gamma$ no problem for $\delta E_\gamma = 20\%/\sqrt{E} \oplus 1\%$

# Scalar bosons with "tight" mass spectrum




- New resonances could be close to $M_W, M_Z, M_H$

cf. the 96 GeV excess at LHC, e.g. P. J. Fox and N. Weiner, JHEP **08** (2018), 025

- New resonances with spectrum $\delta m < M_Z - M_W$ possible.
- Difficult example: HEIDI Higgs

$$D_{HH}(q^2) = \left[q^2 + M^2 - \mu(q^2 + m^2)^{\frac{d-6}{2}}\right]$$

$\Rightarrow$ Test if the "Higgs signal" stems from a continuum.

J. J. van der Bij and S. Dilcher, Phys. Lett. B **638** (2006), 234-238

- The Boson Mass Resolution should be as good as possible!

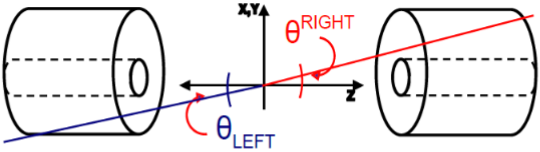
# Forward physics

- Reminder:
  - At the $Z$ pole $N$ are produced isotropically.
  - At higher energies, production is closer to beam direction.
- QED processes occur preferably with small angles.
- New physics example: the dark photon $A'$
  - gauge mixing with the SM photon: $\frac{\epsilon}{2} X_{\mu\nu} F^{\mu\nu}$
  - Interactions with SM fermions: $\bar{f}\,\epsilon\,e\,q_f\,A'\,f$
- Conjecture:
  In $e^- e^+ \to e^- e^+ A'$ with $m_{A'} \to 1$ GeV, $\theta_{A'} \to 0$.

  Proven for $pp \to A' j + X$ in [arXiv:1909.02312 [hep-ph]].

  In particular, $\theta_{A',max}(m_1) \neq \theta_{A',max}(m_2)$ for $m_1 \neq m_2$.
- Instrumentation at small $\theta$ is crucial!

# The Luminometers




- Used to measure low angle Bhabha scattering for luminosity measurement.
- Could measure contributions from dark photons.
- Overall rate similar to Bhabha $\times\epsilon^2$.
- However, most dark photon contribution around specific angle.
- Differential measurement of Bhabha scattering will enhance sensitivity!

# Conclusions

- Lepton colliders are a great environment to study the most elusive signatures.
- The current baseline for the detector 'looks good'.
- In general, the more the better:
  - Resolution.
  - Granularity.
  - Hermiticity.
- In particular:
  - Track reconstruction (pointing) with the calorimeters.
  - Improve the boson mass resolution.
  - Consider instrumenting the detector cavern.
  - Luminometers as displaced vertex detectors.
- Implement LLP signatures into the Particle Flow Algorithm.