Status of heavy neutrino searches at ep colliders

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Contribution to the FCC week 2021

Introduction

1- The measured neutrinos oscillation can only be explained when neutrinos have masses

2- The SM successfully describes an impressive amount of data, but neutrinos are massless in the SM framework

Introduction

1- The measured neutrinos oscillation can only be explained when neutrinos have masses

2- The SM successfully describes an impressive amount of data, but neutrinos are massless in the SM framework

3- The simplest extension is to add right handed neutrinos, N

$$\mathcal{L}_y \supset \mathcal{L}_y^{\rm SM} - y^\nu \, \overline{l_L}\tilde{\phi} \, N_R - M_N \overline{N_R^c} \, N_R + {\rm H.C.}$$

fix the observed neutrino masses

Mass of N is unconstrained !!

Introduction

One can look for sterile neutrinos (for fixed mixing parameters) in different mass ranges as:

- $M_N \sim$ KeV

  sterile neutrino is very long-lived and it skip the detector before it decays.
  In this mass range N can be probed as dark matter

- $M_N \sim$ GeV

  sterile neutrino is long-lived but it decay inside the detector.
  In this mass range N can be probed via its displaced distance

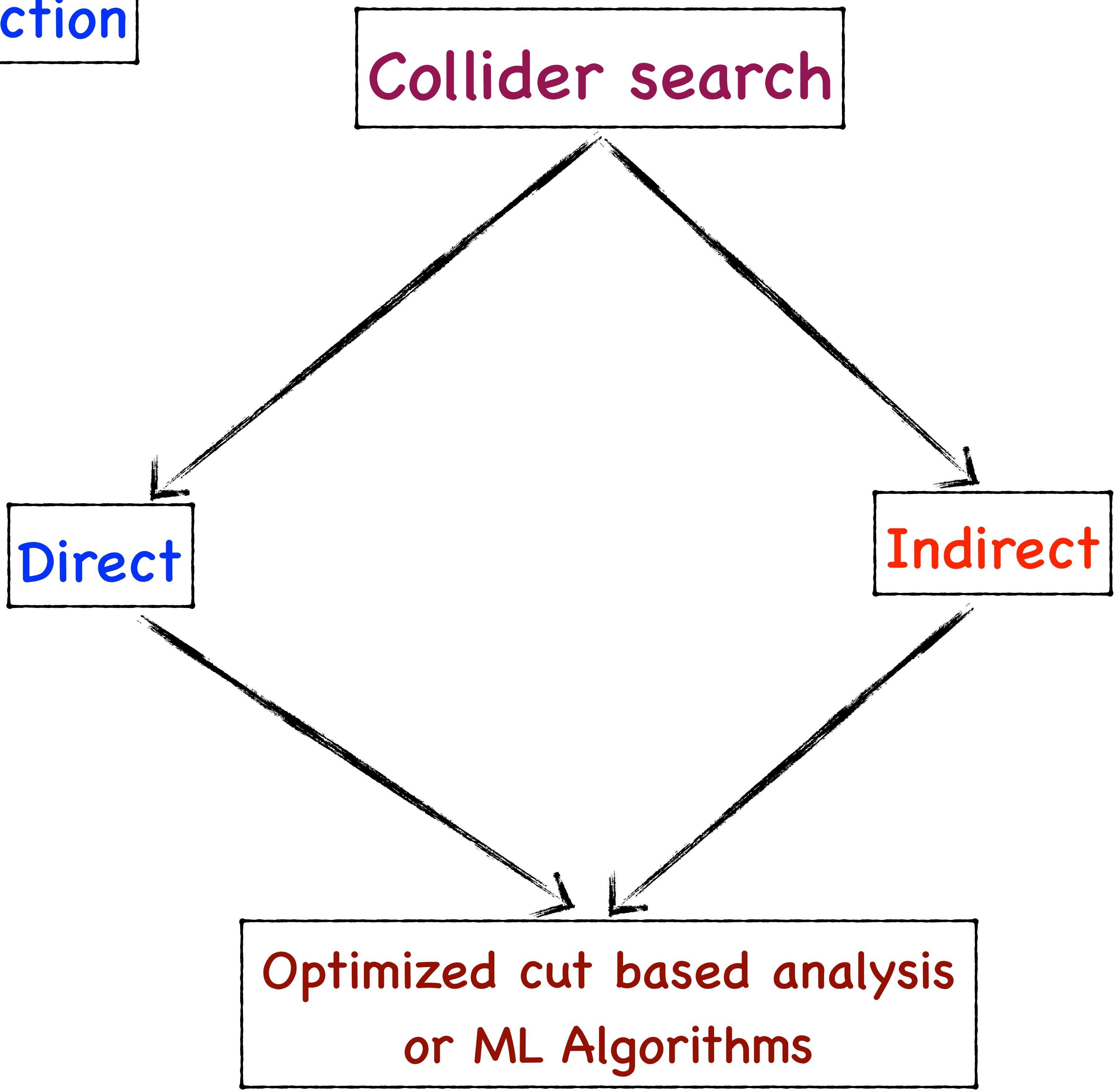
- $M_N \sim$ EW

  sterile neutrino is no longer long-lived and it decays promptly.
  In this mass range N can be probed via its LNV or LFV decays

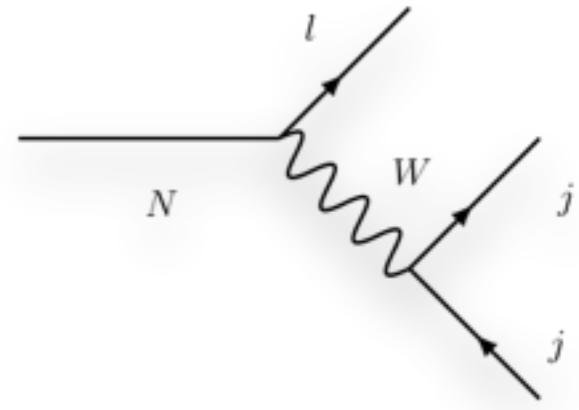
- $M_N > \mathcal{O}(\text{TeV})$

  This mass range is out of reach of the current colliders energy.
  N can be probed indirectly from loop processes, $\mu \to e\gamma, \ \mu \to 3e, \text{etc}$

Introduction



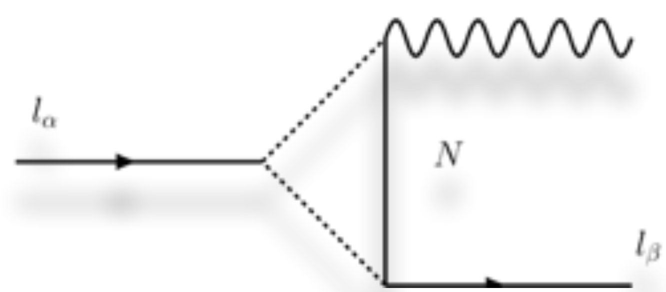
Direct search



1- The heavy neutrino has to be produced on mass shell (mass range is limited to $\sqrt{s}$)

2- possible reconstruction of N from its final state products

Indirect search

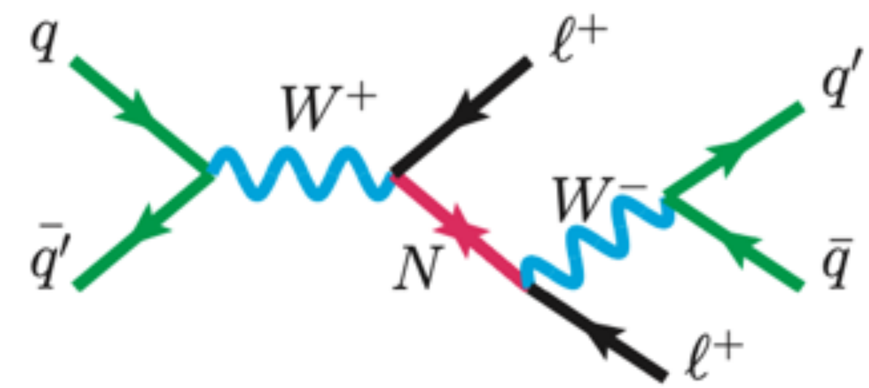


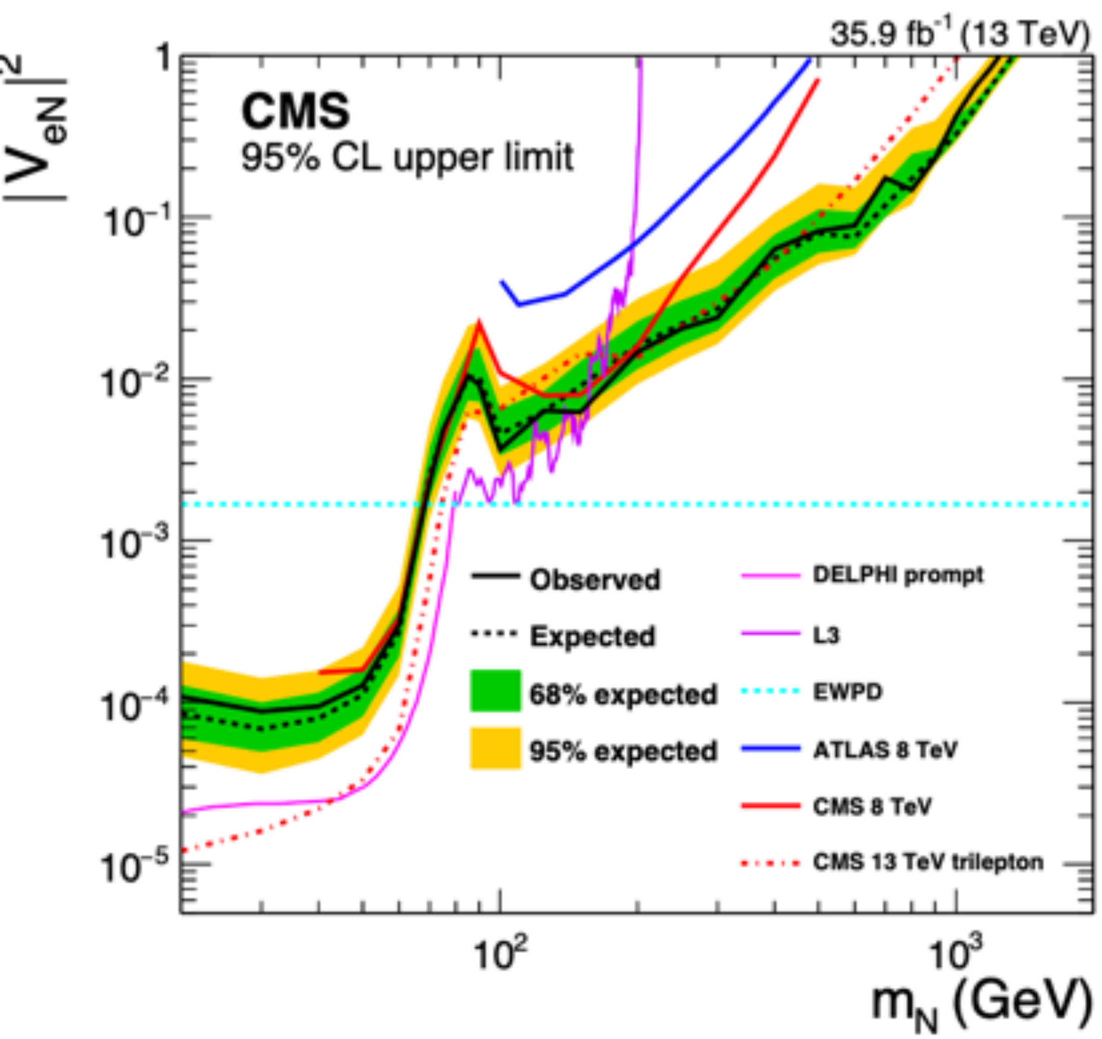
1- N in the loop and not required to be on mass shell (mass range not limited)

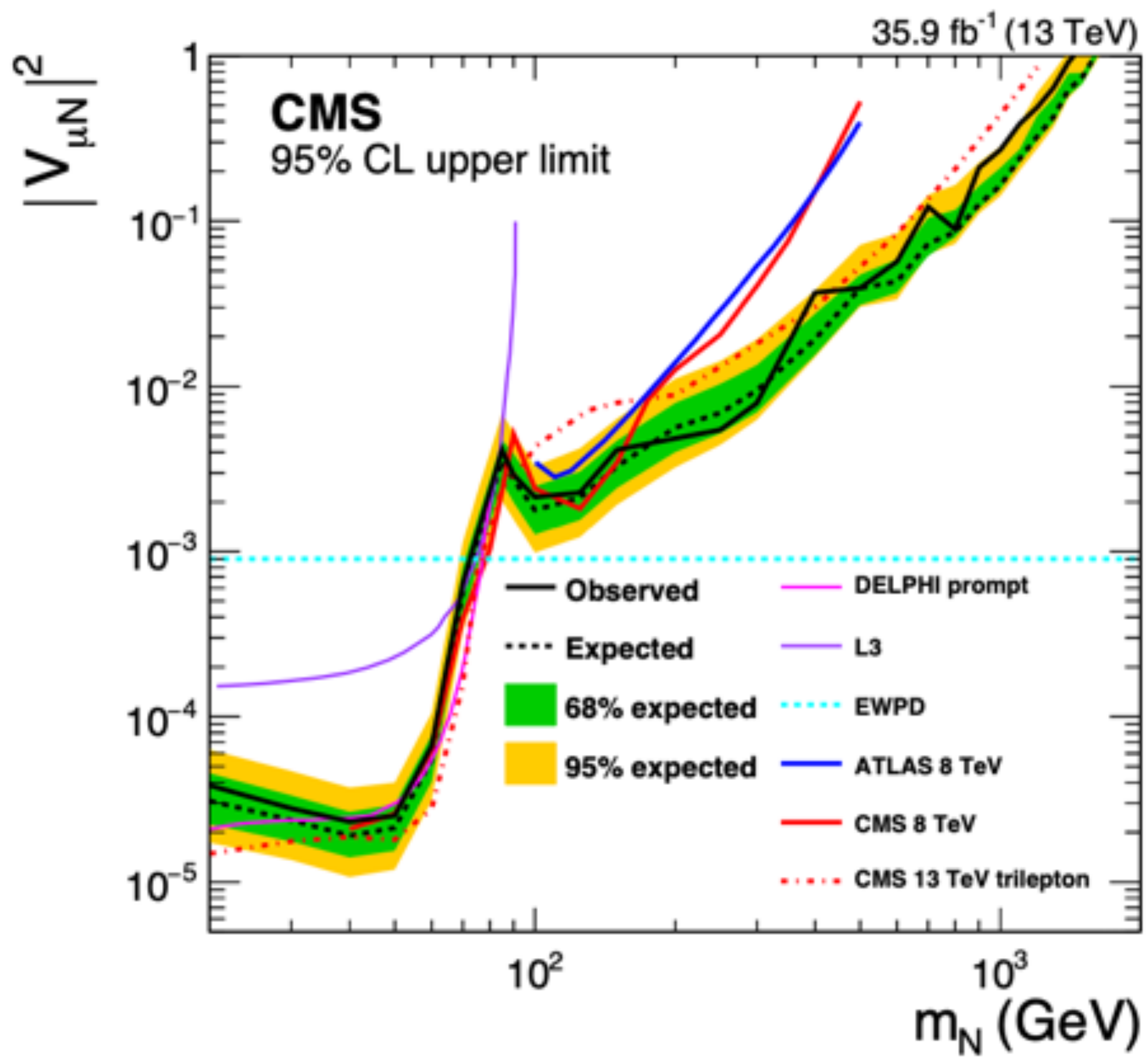
2- The enhanced measurement for LFV is an indication for heavy neutrino contribution

3- We cannot reconstruct the properties of the N!!

At EW scale the LHC is sensitive to LNV but not LFV processes !!

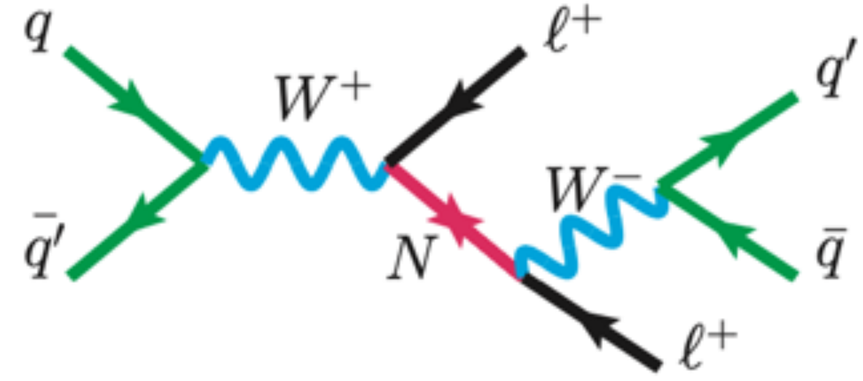




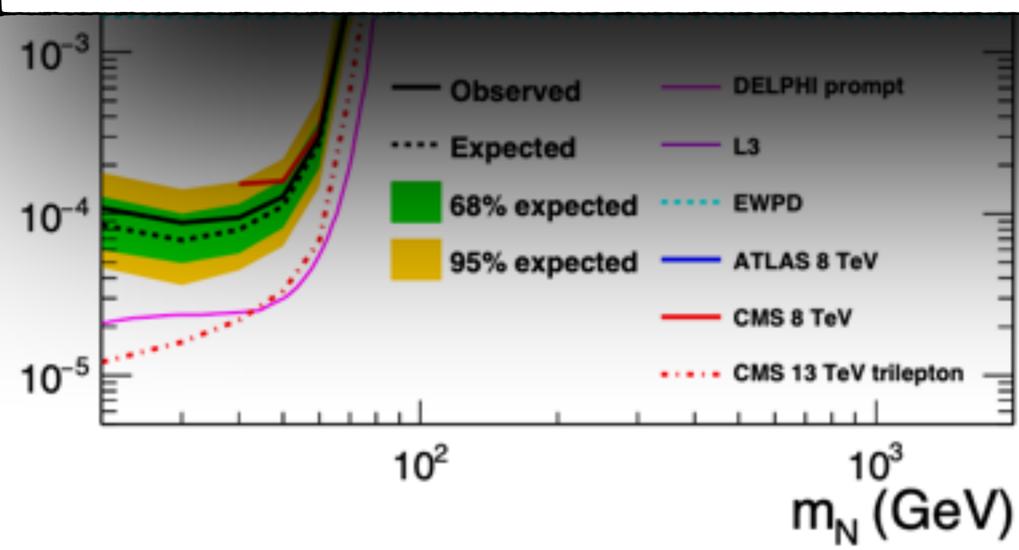


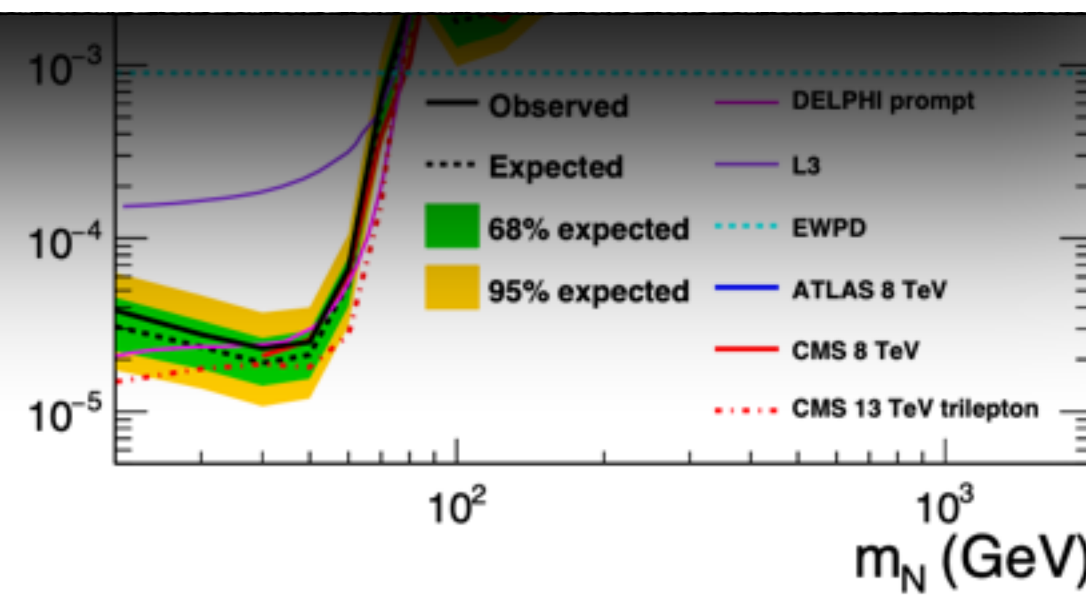
arXiv:1806.10905

At EW scale the LHC is sensitive to LNV but not LFV processes !!



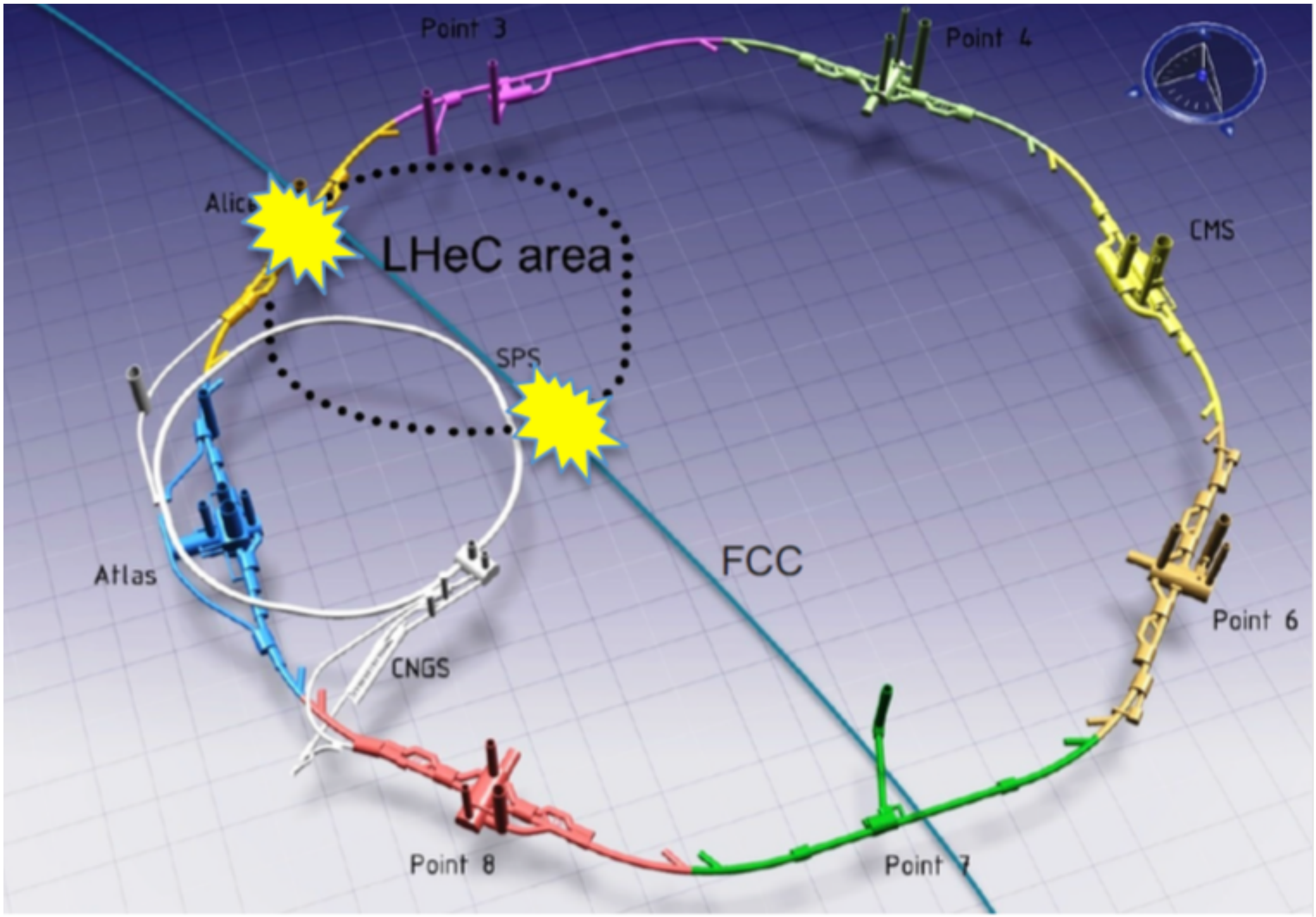
Where to look for LFV heavy neutrino decays ??





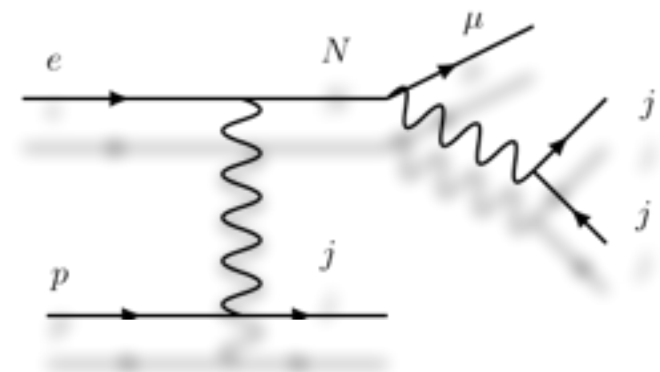
arXiv:1806.10905

The Large Hadron electron Collider (LHeC)

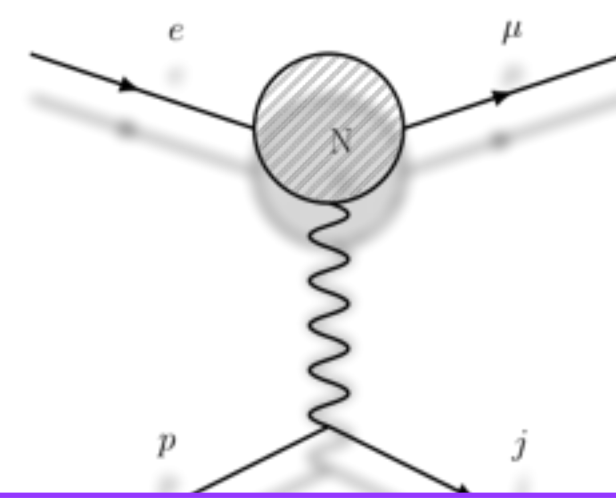


In this talk we discuss two examples

1- Lepton flavor violating heavy neutrino decays at the LHeC and FCChe (prompt & displaced)



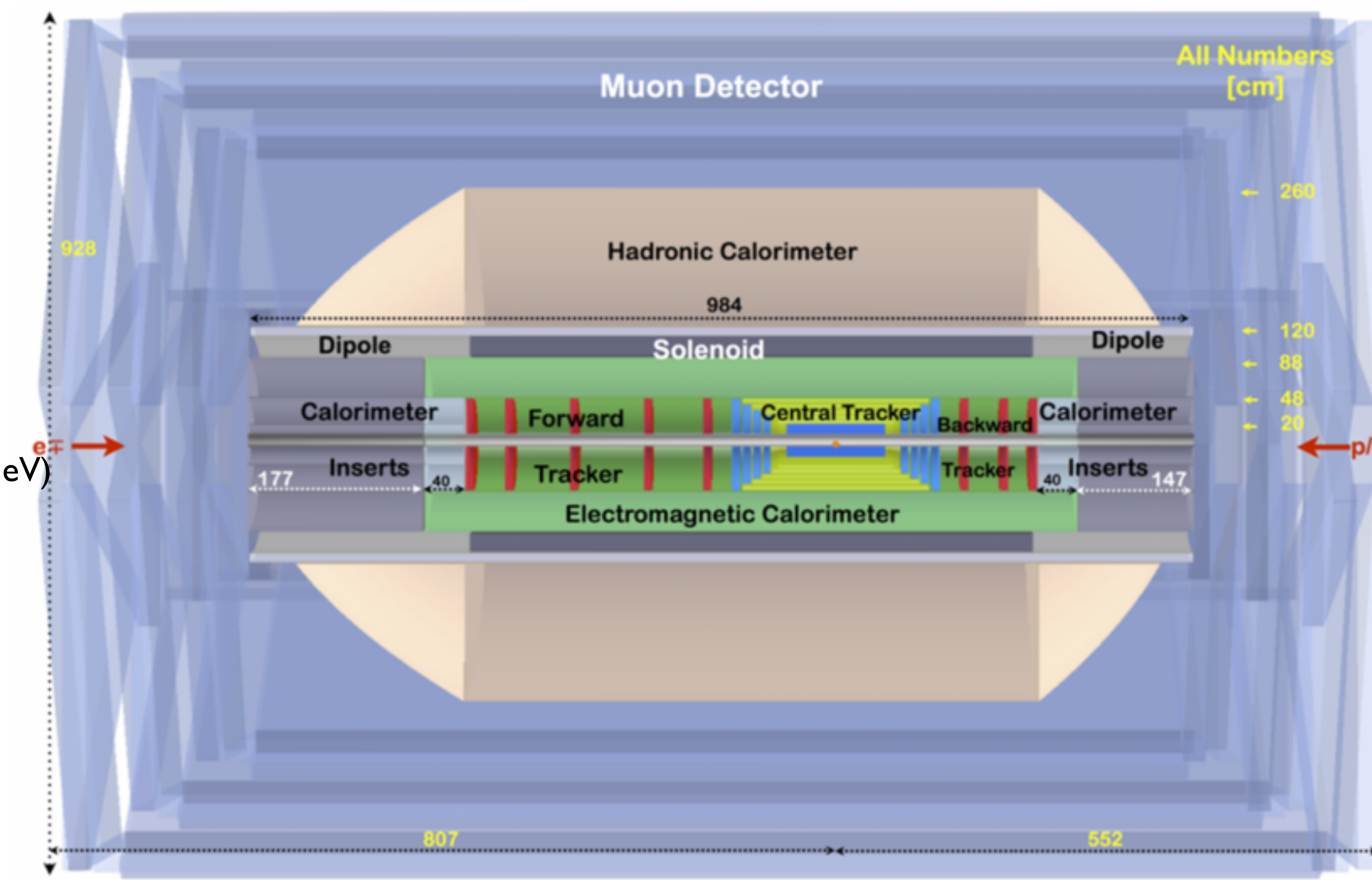
2- Induced Lepton flavor violation by heavy neutrino at the LHeC



So let us first introduce the proposed LHeC

Detector geometry

(60 GeV)

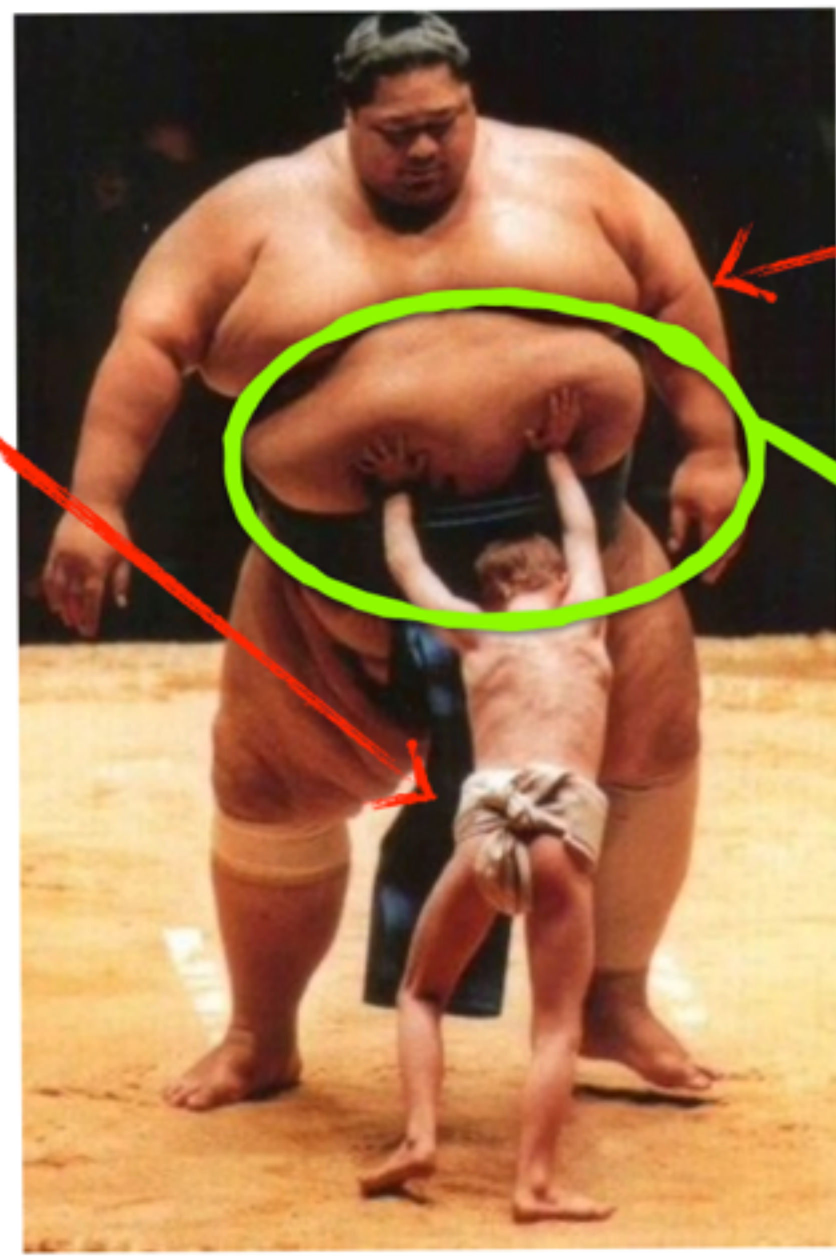


(7 TeV)

arXiv:1305.2090v1

The LHeC is expected to provide a collision of proton beam with energy 7000 GeV and electron beam with energy 60 GeV

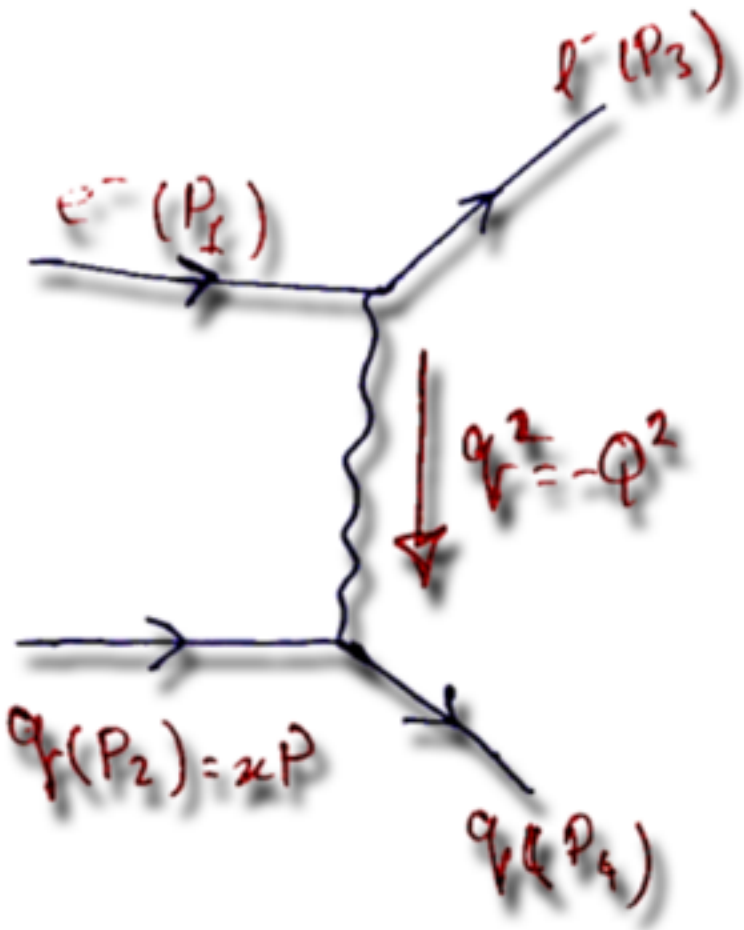
Electron beam

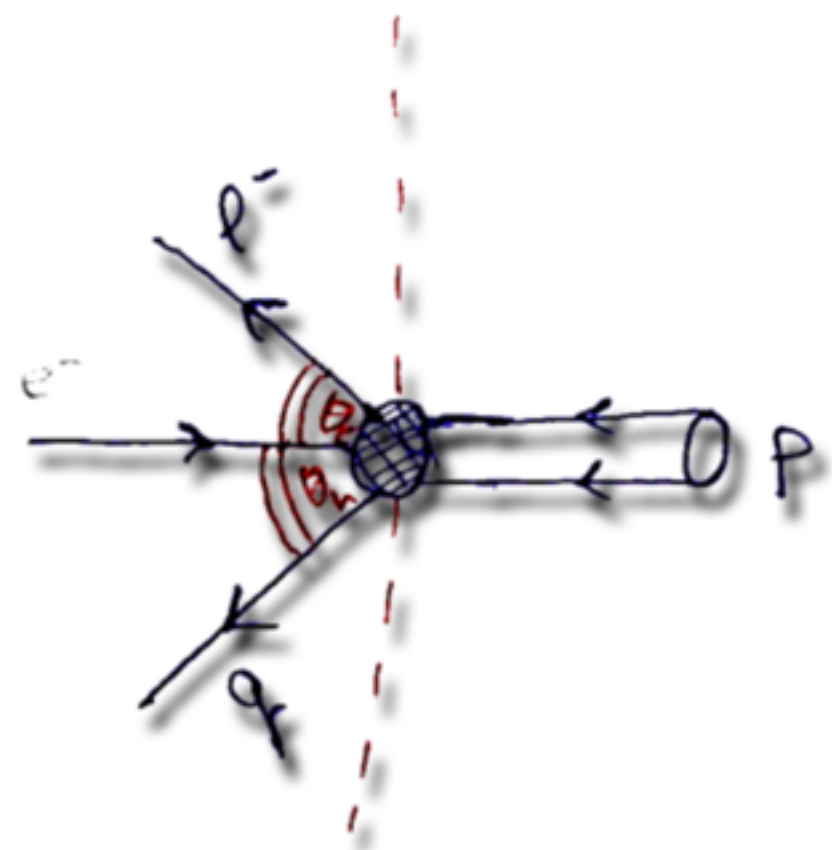


Proton beam

Physics is expected to be boosted in the forward proton beam direction

LHeC Kinematics





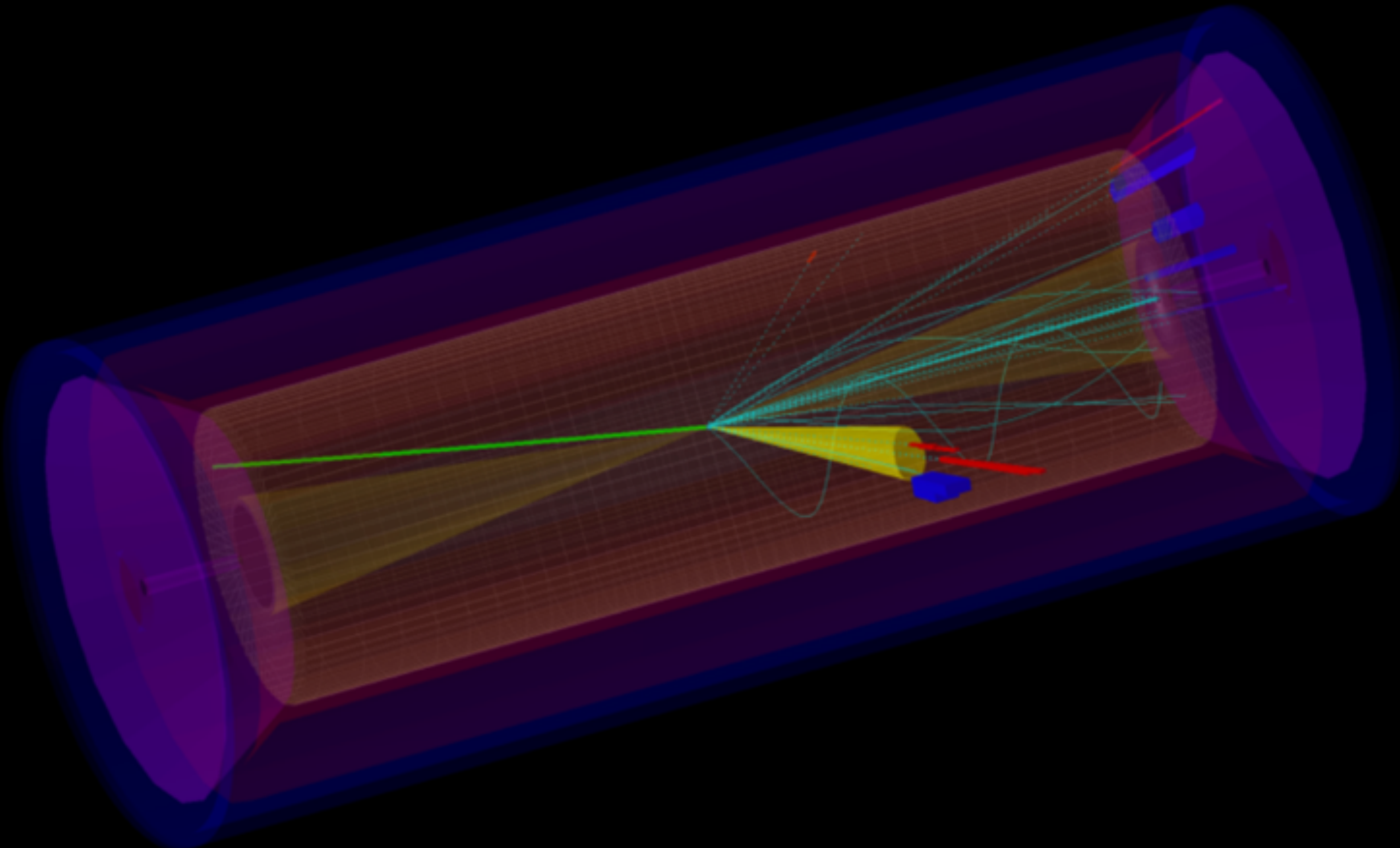
Couple of equations that control the whole kinematics

$$x = \frac{q^2}{s\ y_e}, \quad \text{with} \quad y_e = 1 - \frac{E_l}{2E_e}(1 - \cos\theta_e)$$

LHeC Kinematics

At the LHeC, Bjorken variable controls the incoming quark energy. For most of the parameter space the energy of the incoming electron and quark are similar

For small energy transfer, the final state lepton scatter in the backward direction of the detector: "Lepton back scattering at ep colliders"



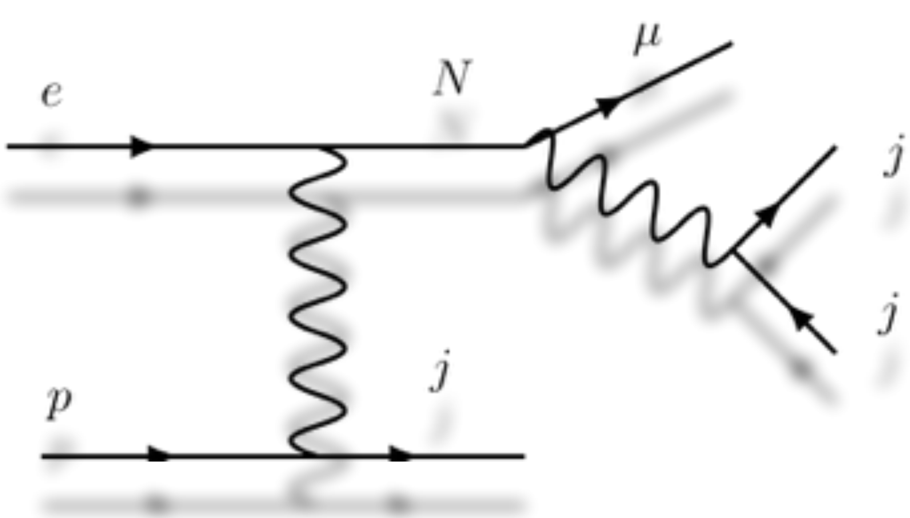
Delphes event display

Part 1

Direct search:

Lepton-Trijet Searches for Heavy Neutrinos

prompt decays



The model

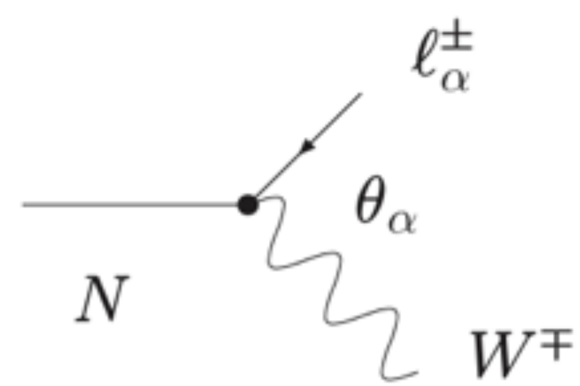
Low scale seesaw model with two right handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} - y_{\nu\alpha}\overline{N_R^1}\widetilde{\phi}^\dagger L^\alpha - \overline{N_R^1} M_N N_R^{2c} + H.C.$$

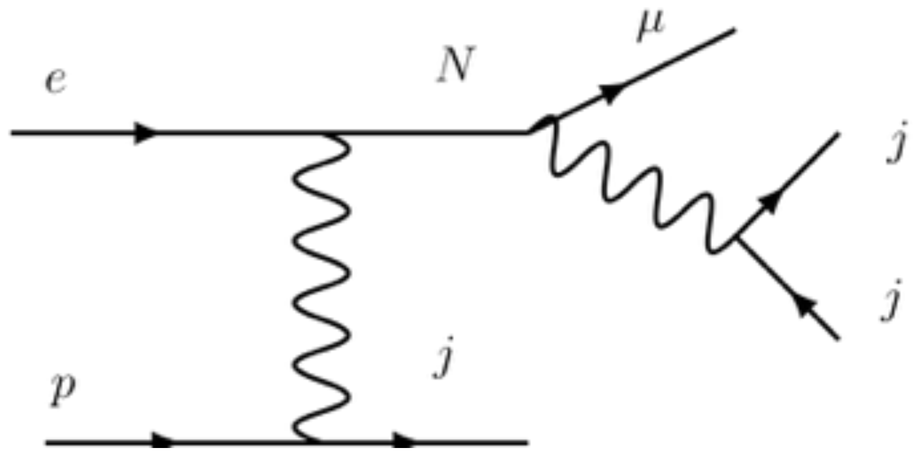
$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{i}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} & -\frac{i}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} & -\frac{i}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-i}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

with active-sterile mixing angels

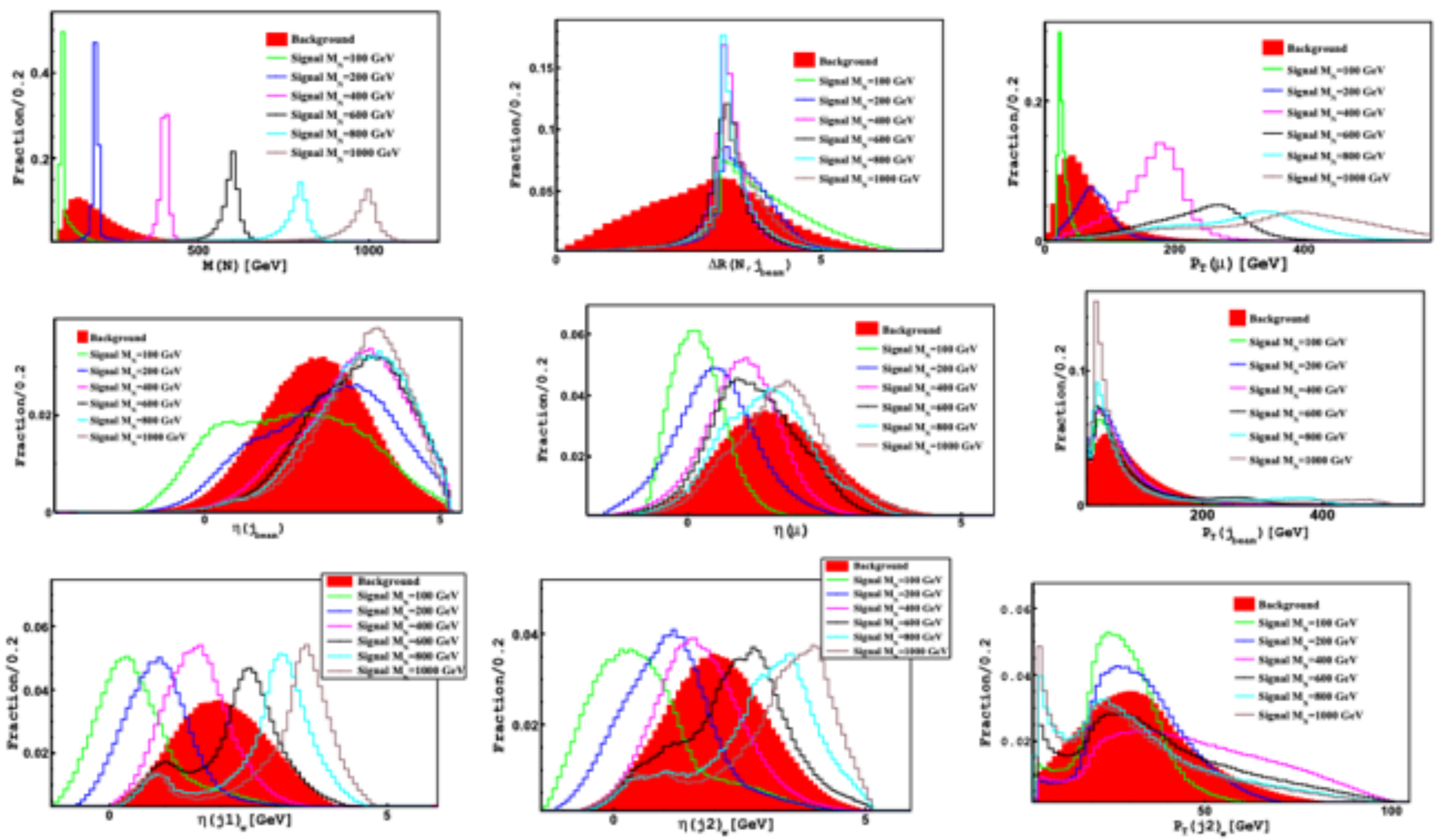
$$\theta_\alpha = \frac{y_{\nu\alpha}^* v_{EW}}{\sqrt{2} M_N}$$



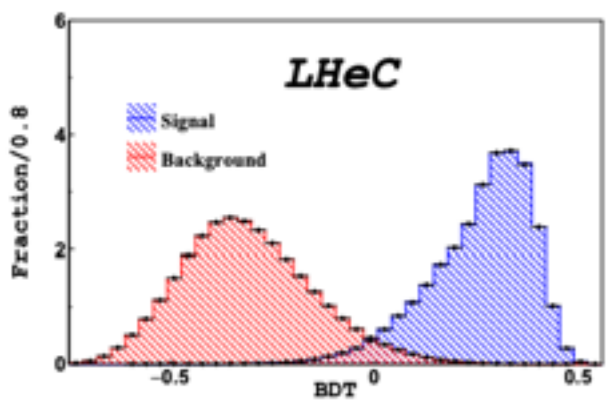
Kinematic variables

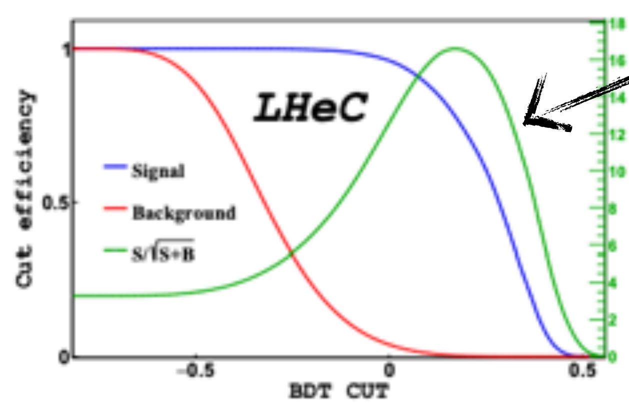


Backgrounds
$pe^- \to je^- VV$, where $VV \to jj\mu^-\mu^+$
$pe^- \to je^- VV$, where $VV \to jj\mu^-\bar{\nu}_\mu$
$pe^- \to j\nu_e VV$, where $VV \to jj\mu^-\mu^+$
$pe^- \to j\nu_e VV$, where $VV \to jj\mu^-\bar{\nu}_\mu$



Kinematic variables

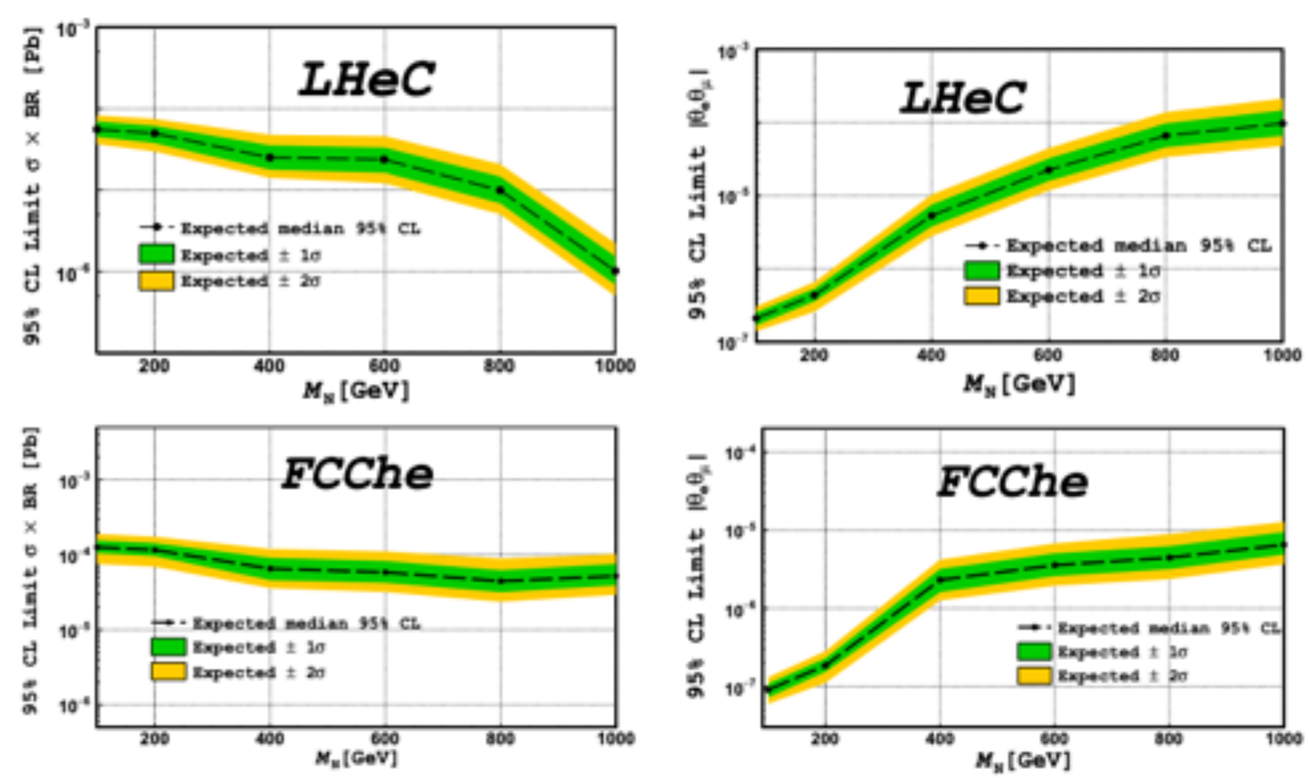




Optimized cut
MN = 500GeV

arXiv:1908.02852

Remaning events

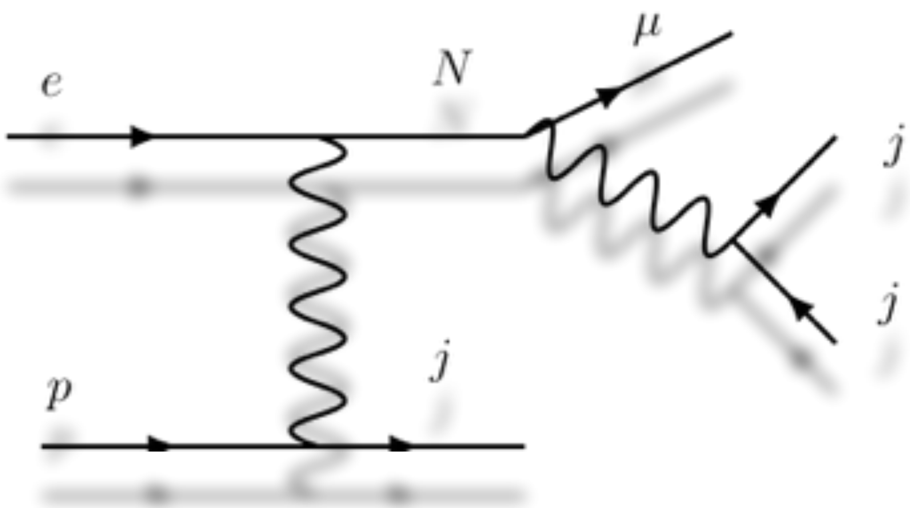


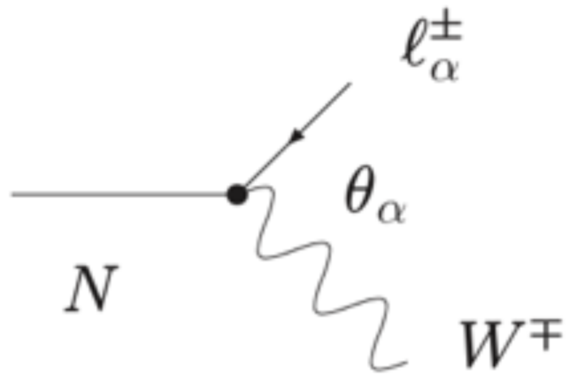
Part 2

Direct search:

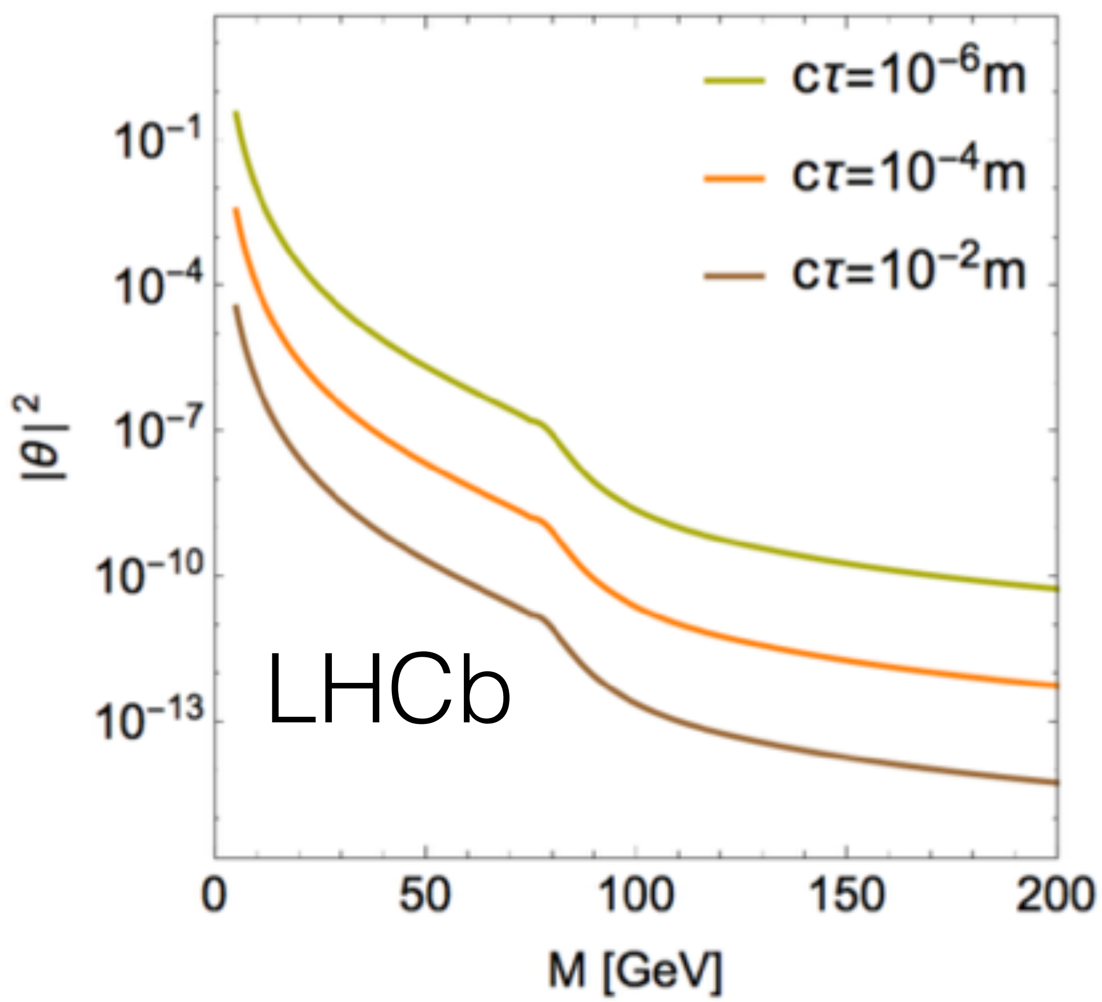
Lepton-Trijet Searches for Heavy Neutrinos

displaced decays





Heavy neutrino can be long-lived by $M_N < M_W$ and/or small θ_α



arXiv:1709.03797

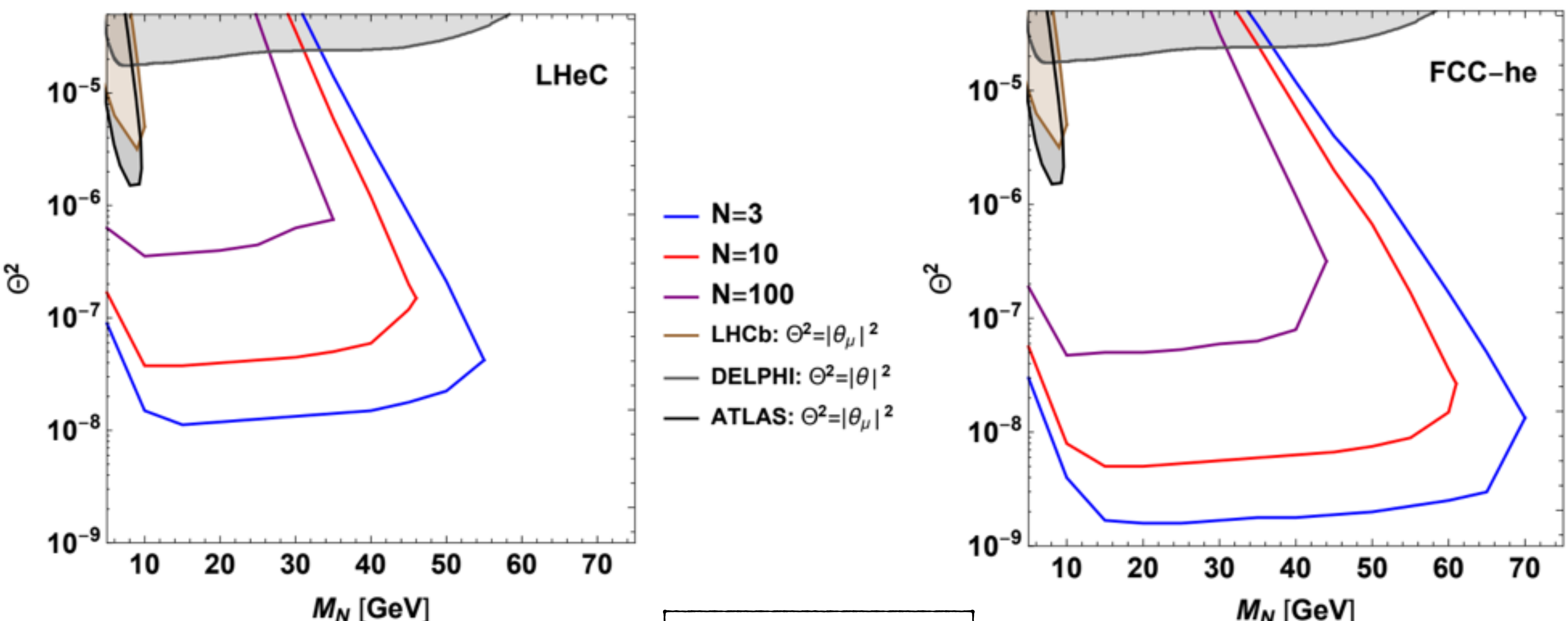
Number of events

$$N_{\rm dv}(\sqrt{s}, \mathcal{L}, m_N, |\theta|) = \overbrace{\sigma_{\rm tot}(\sqrt{s}, m_N, |\theta|)\mathcal{L}}^{\text{Number of events}} \times \int D_N(\Theta, \gamma) P_{\rm dv}(x_{\rm min}(\Theta), x_{\rm max}(\Theta), \Delta x_{\rm lab}(\tau, \gamma)) d\Theta d\gamma$$

Number of signal events from displaced vertices

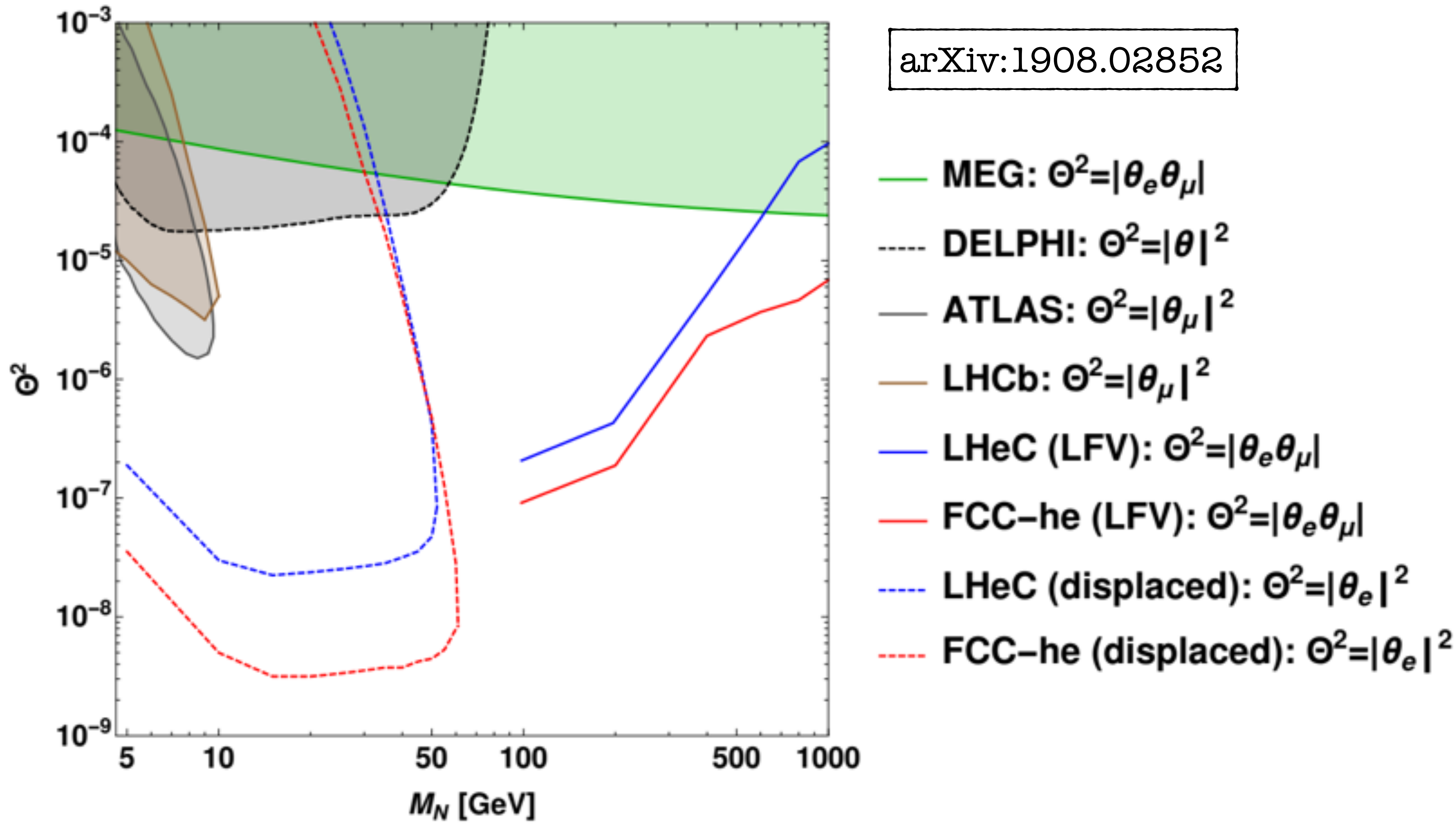
Probability distribution for producing N with certain angle Θ and γ

Probability distribution for N decays with certain parts of the detector



arXiv:1908.02852

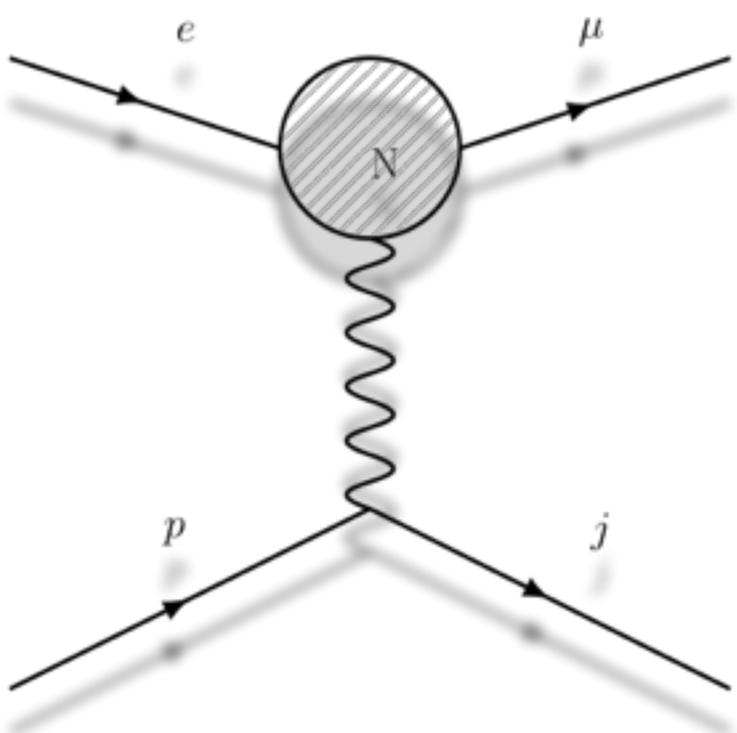
Summary of heavy neutrino direct search



limited sensitivity to heavy neutrino mass around 1 TeV!!

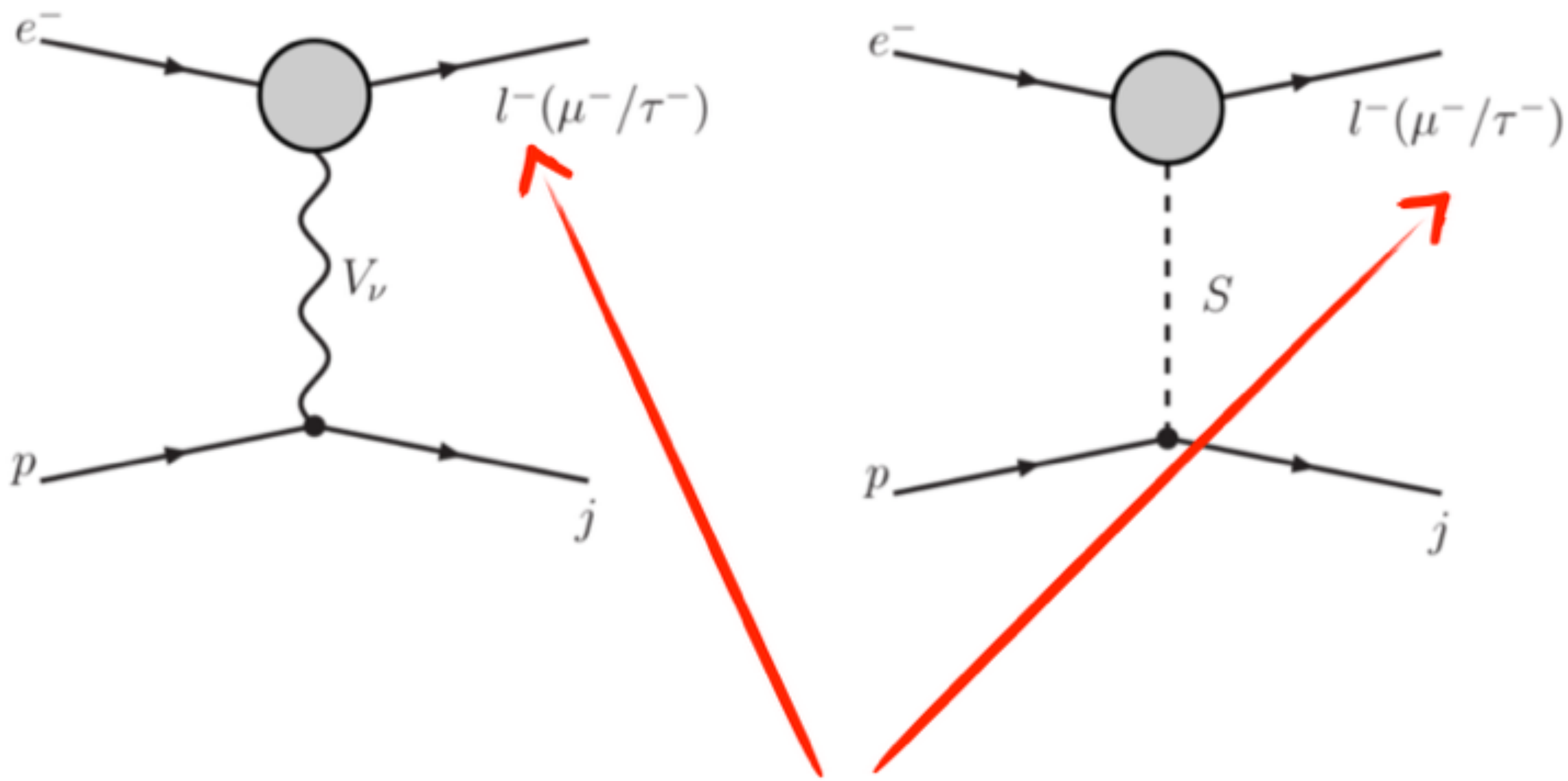
Part 3

Indirect search



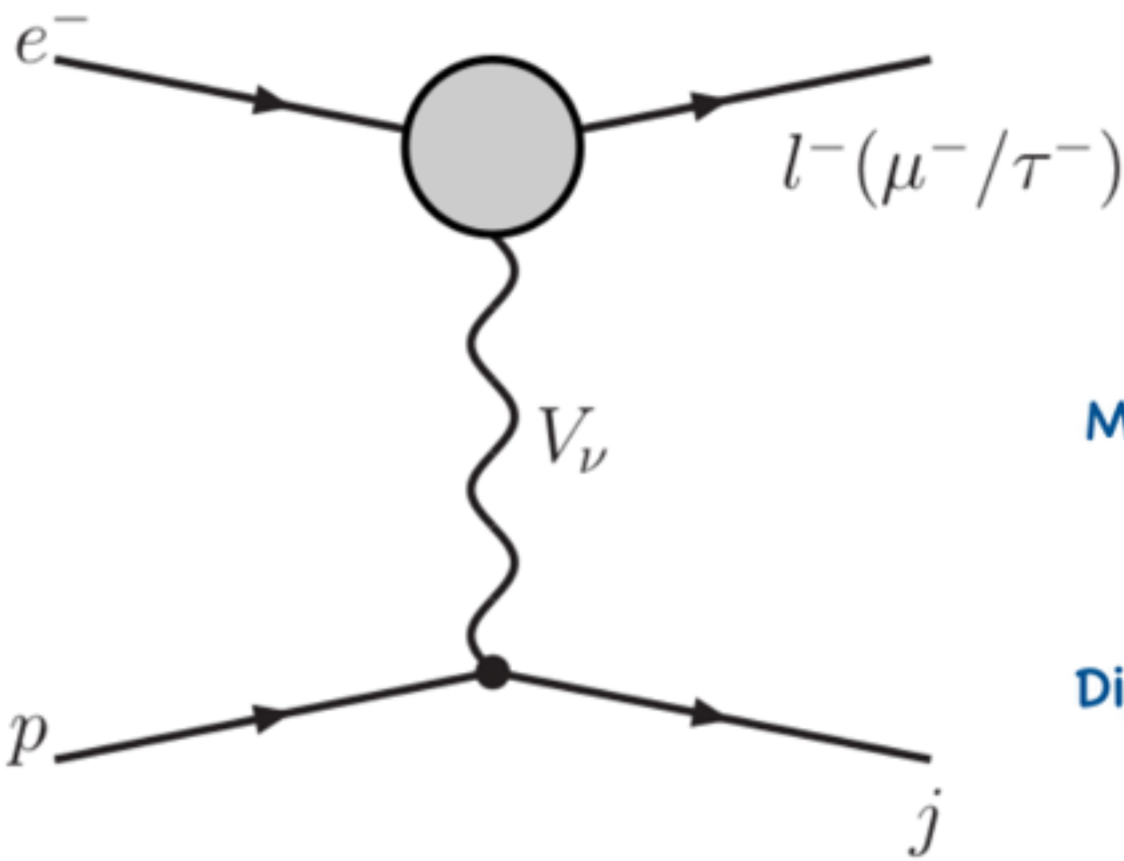
The model

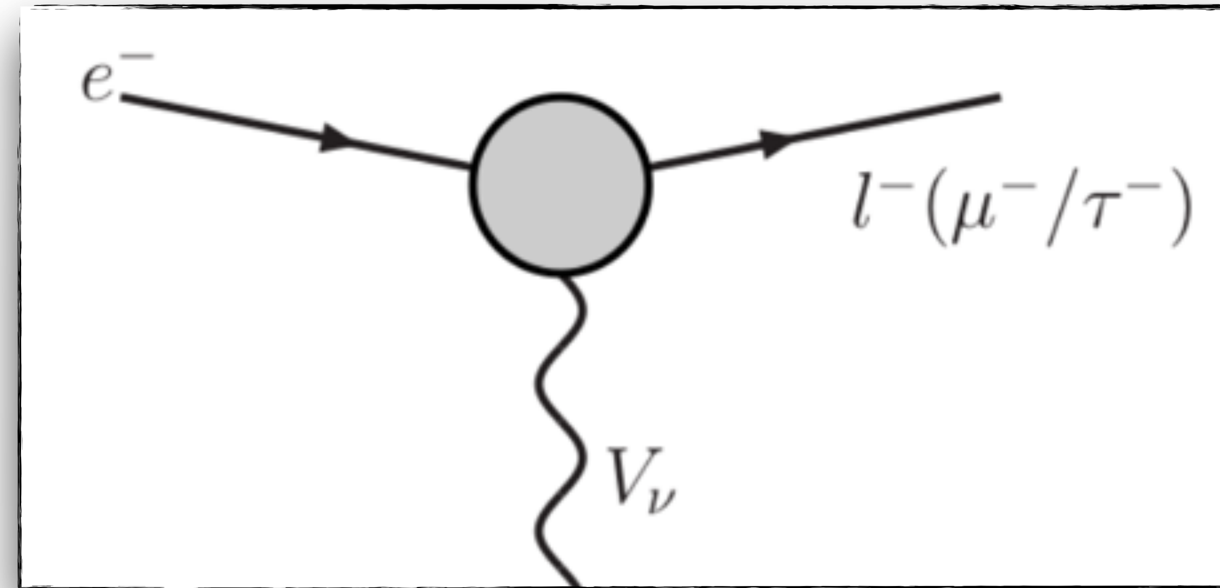
Effective theory is a generic framework that can be fitted to any specific model



Tree level renormalized SM Lagrangian has no source for LFV

The model





Monopole operator

$$\mathcal{L}_{\text{eff}}^{\text{monopole}} = \bar{\ell}_\alpha \gamma_\mu P_{L,R} \ell_\beta \left[A_{L,R}\, g^{\mu\nu} + B_{L,R}(g^{\mu\nu} q^2 - q^\mu q^\nu)\right] V_\nu,$$

Dipole operator

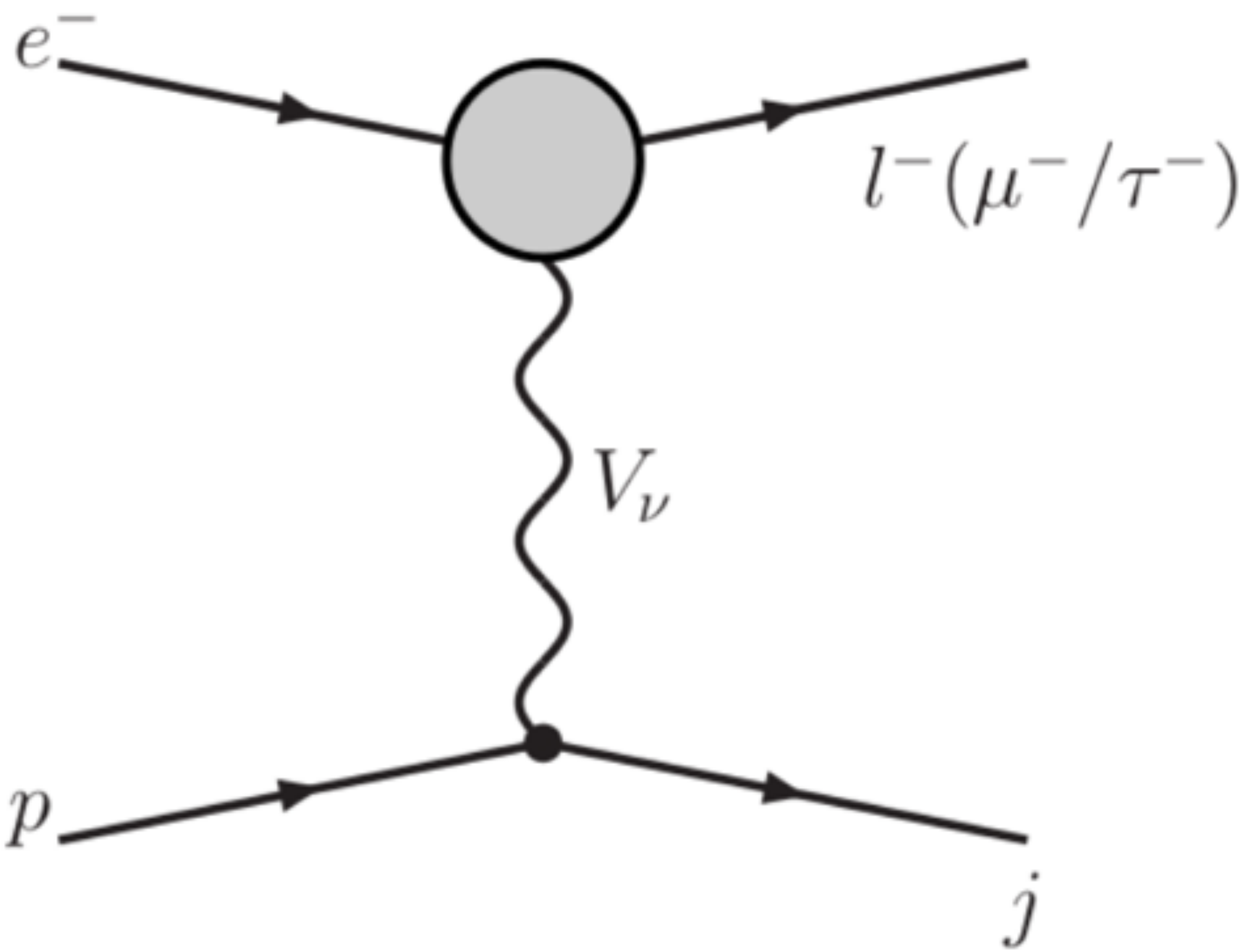
$$\mathcal{L}_{\text{eff}}^{\text{dipole}} = \bar{\ell}_\alpha \sigma^{\mu\nu} P_{L,R} \ell_\beta\, q_\mu V_\nu\, D_{L,R},$$

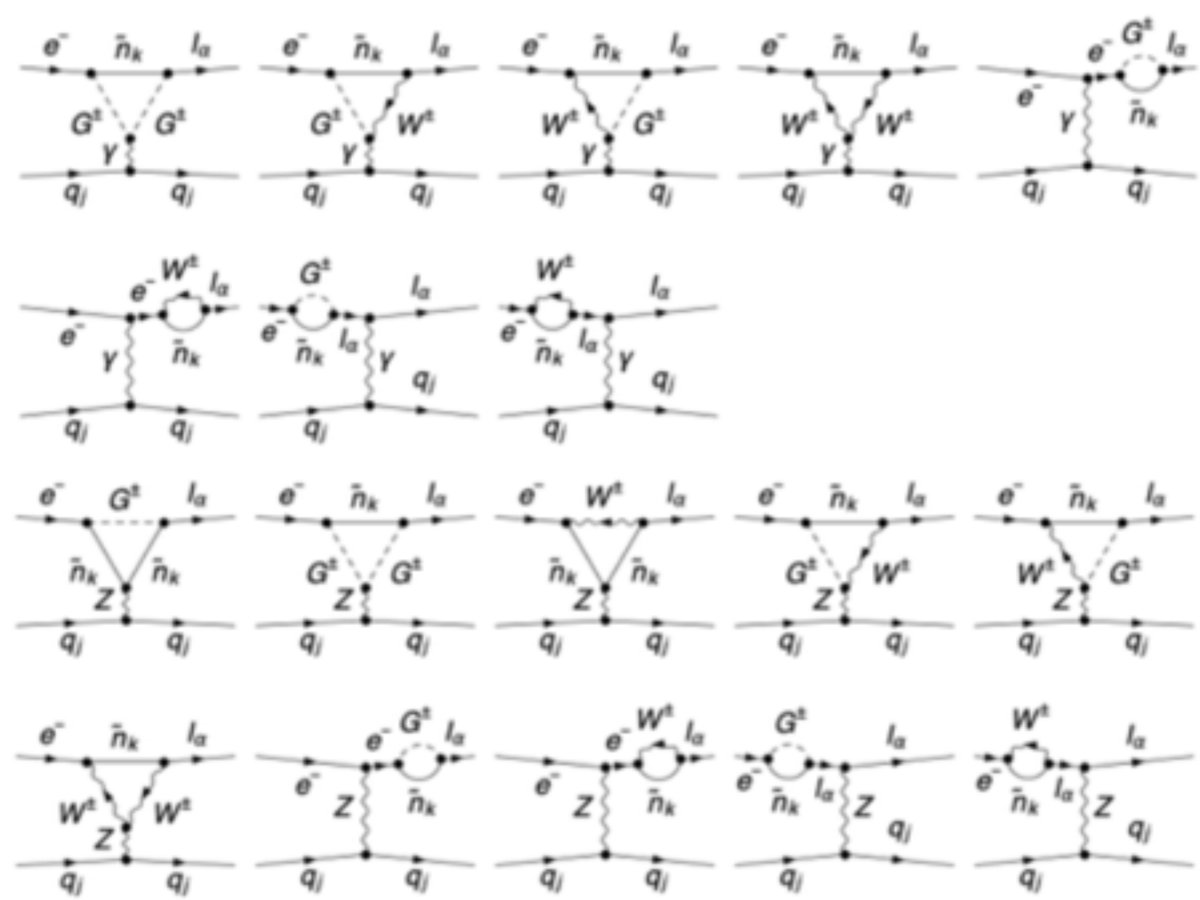
Matrix element for the process

$$\mathcal{M}_{\gamma^*} = \bar{u}_{l_\alpha} \left[B^\gamma_{L,R} P_{L,R}\, q^2\, \gamma^\nu - i\sigma^{\mu\nu} q_\mu\, D^\gamma_{L,R} P_{L,R}\right] u_e \left(\frac{-ie\; g_{\mu\nu}}{q^2}\right) \bar{u}_q(-ieQ_q\gamma^\mu)v_q\ ,$$

$$\mathcal{M}_Z = \bar{u}_{l_\alpha} \left[A^Z_{L,R} P_{L,R} \gamma^\nu + B^Z_{L,R} P_{L,R} q^2 \gamma^\nu - i\sigma^{\mu\nu} q_\mu D^Z_{L,R} P_{L,R}\right] u_e \left(\frac{-ig_{\mu\nu}}{q^2 - M_Z^2}\right) \bar{u}_q(\gamma^\mu\, g_{L,R} P_{L,R})v_q.$$

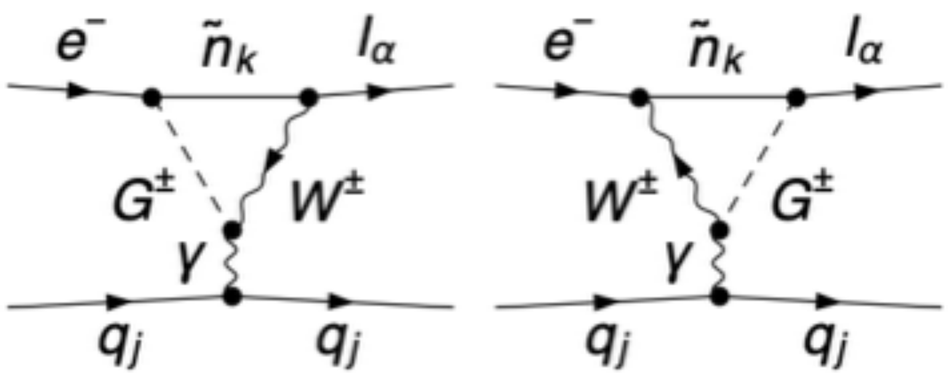
Example model: low scale seesaw



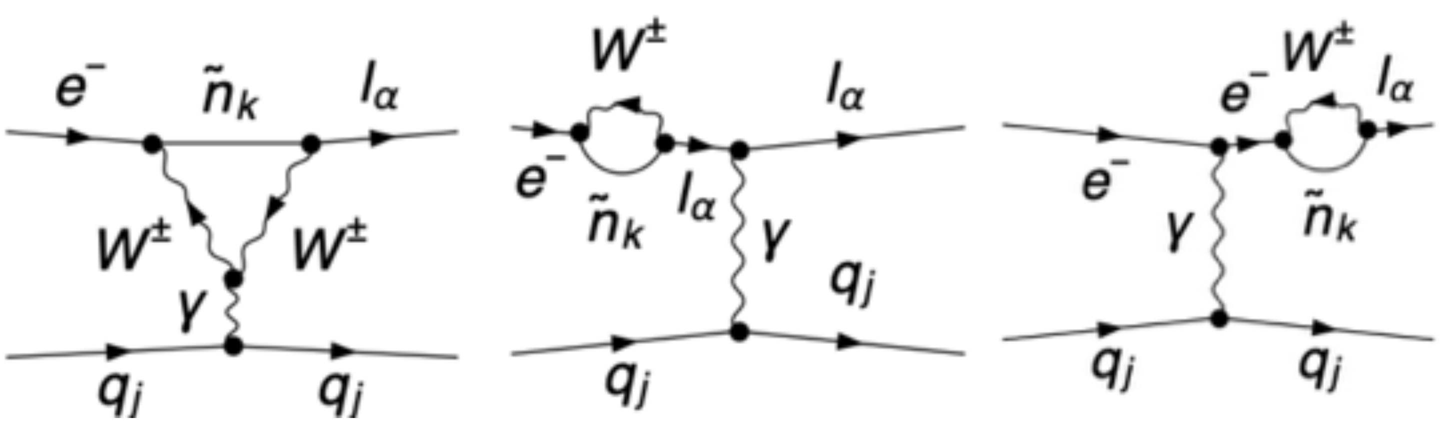


Tree level not exist ⟹ Processes are UV finite

Example model: low scale seesaw

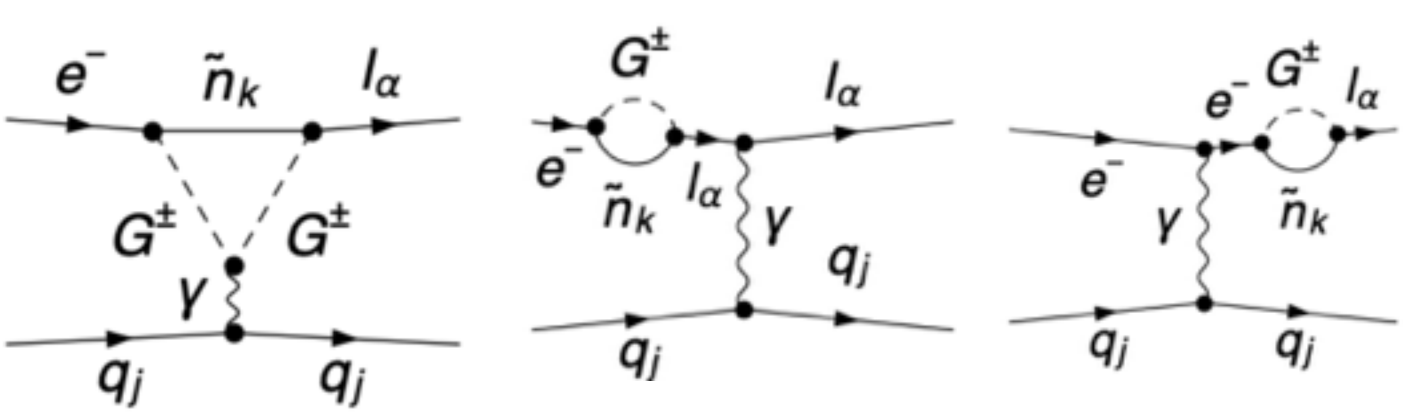


UV finite



UV finite =

Sum Up + unitarity of the mixing matrix



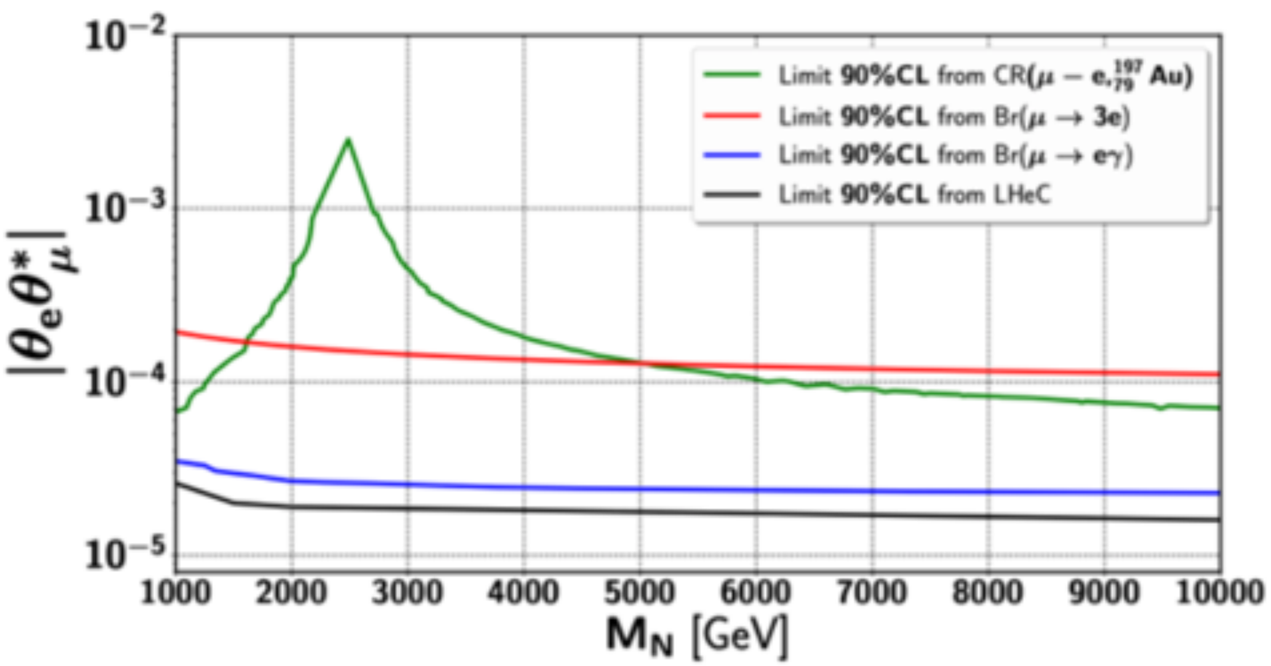
UV finite =

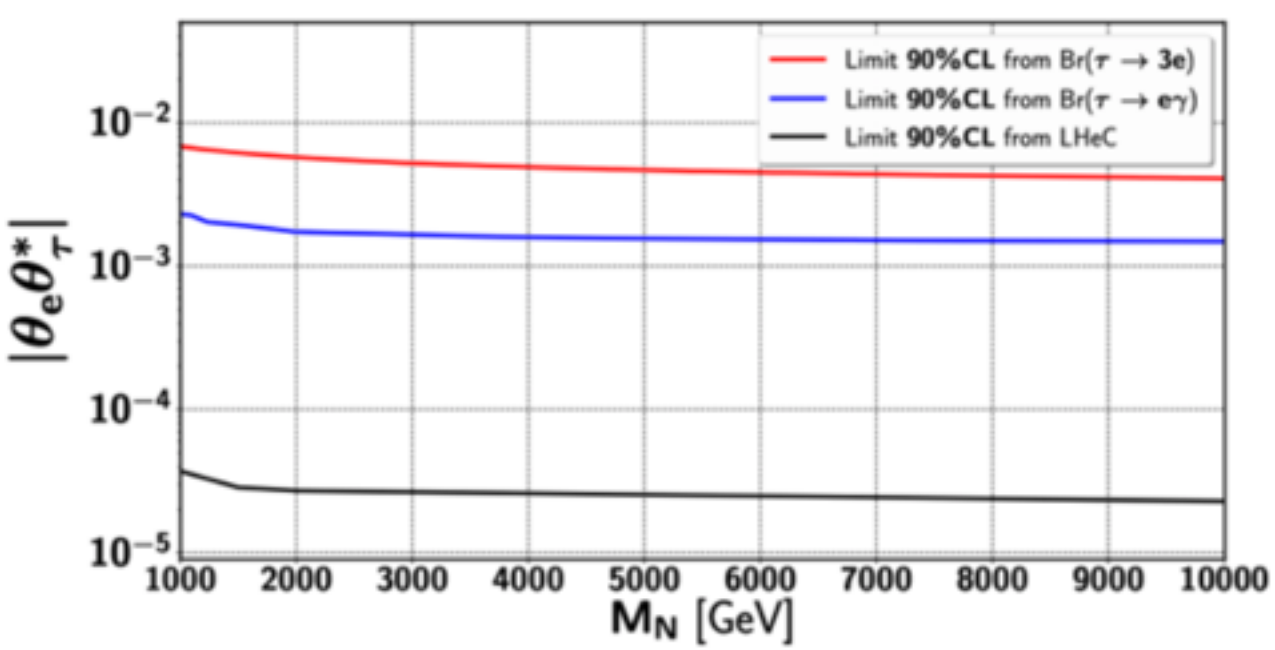
Sum Up + unitarity of the mixing matrix

Example model: low scale seesaw

arXiv:2010.08907

LHeC can provide better sensitivity for LFV search than all the existing searches



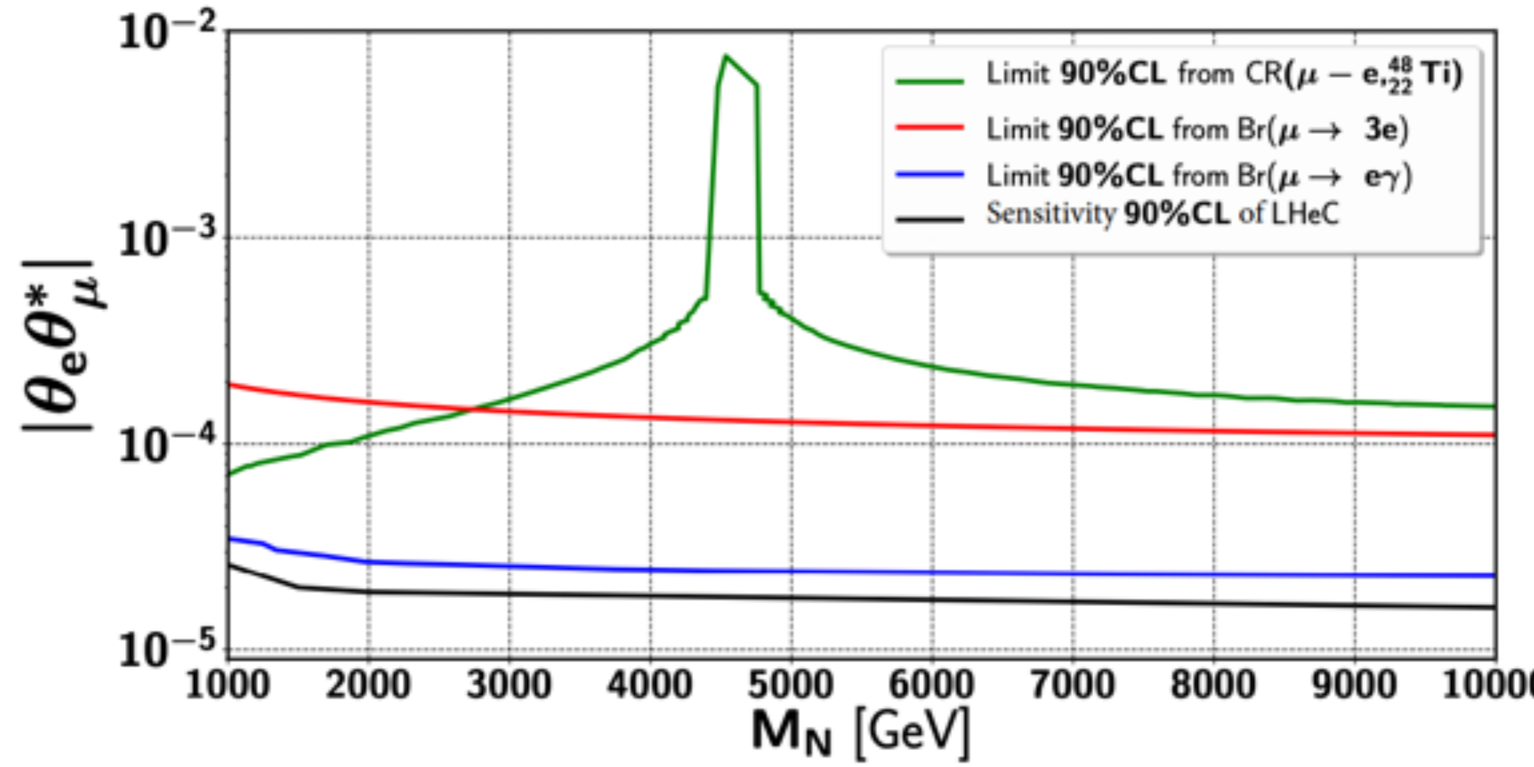


Current limit from different experiments

$$Br(\mu \to e\gamma) \leq 4.2 \times 10^{-13}$$
$$Br(\tau \to e\gamma) \leq 3.3 \times 10^{-8}$$
$$Br(\mu \to e^-e^+e^-) \leq 1. \times 10^{-12}$$
$$Br(\tau \to e^-e^+e^-) \leq 2.7 \times 10^{-8}$$
$$Cr(\mu - e,\ ^{197}_{79}\mathrm{Au}) \leq 7 \times 10^{-13}$$

Remark

Dominant contribution comes from the Z mediator



$$\mathcal{M}_Z = \bar{u}_{l_\alpha}\left[A^Z_{L,R}P_{L,R}\gamma^\nu + B^Z_{L,R}P_{L,R}q^2\gamma^\nu - i\sigma^{\mu\nu}q_\mu D^Z_{L,R}P_{L,R}\right]u_e\left(\frac{-ig_{\mu\nu}}{q^2 - M_Z^2}\right)\bar{u}_q(\gamma^\mu g_{L,R}P_{L,R})v_q.$$

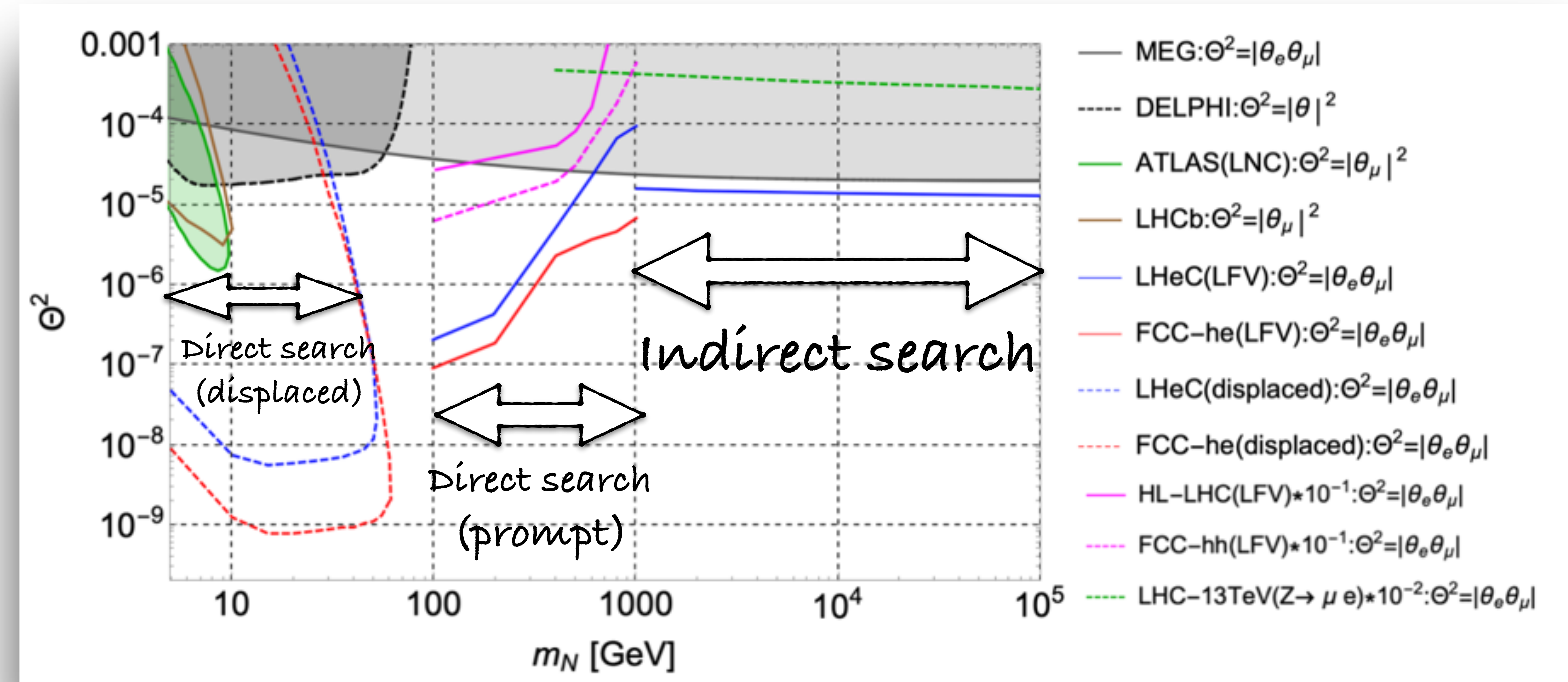
For the processes $\mu \to e\,\gamma$, $\mu \to 3e$ and $CR(\mu \to e)$ the energy $(q^2 \sim M_\mu^2)$

$$\mathcal{M}_Z \propto \frac{-ig_{\mu\nu}}{M_\mu^2 - M_Z^2}$$

The LHeC can provide energy about 1.3 TeV that can always produce on shell Z mediator

Summary

The LHeC provides the best sensitivity for heavy neutrino searches in all mass ranges




THANK YOU
FOR YOUR
ATTENTION

Backup

Start with hand written Lagrangian

Calculate all tree level vertices

Calculate total cross section for the process under consideration

Generate the events at parton level weighted by the cross section

Hadronization is required due to the color confinement

Electroweak and QCD radiation

Initial/Final state radiation, etc

Jet clustering

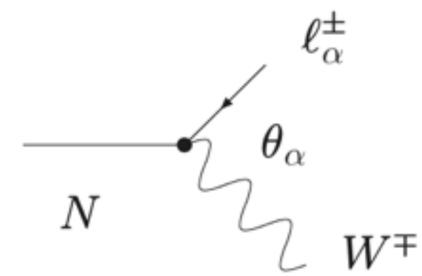
Detector simulation (Fast/full)

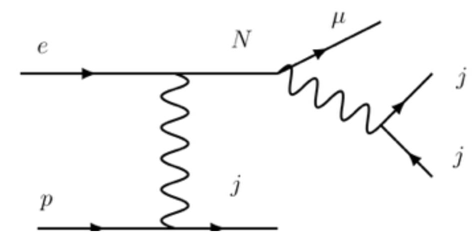
Constructing all kinematic variables

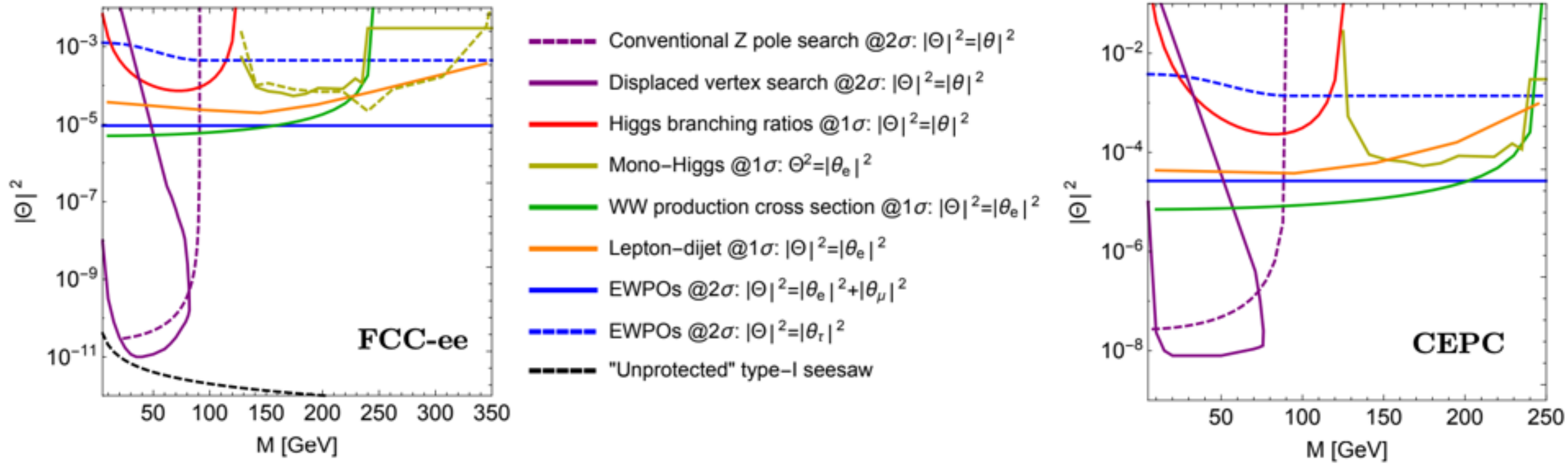
Highest ranked variables are fed to Machine Learning model

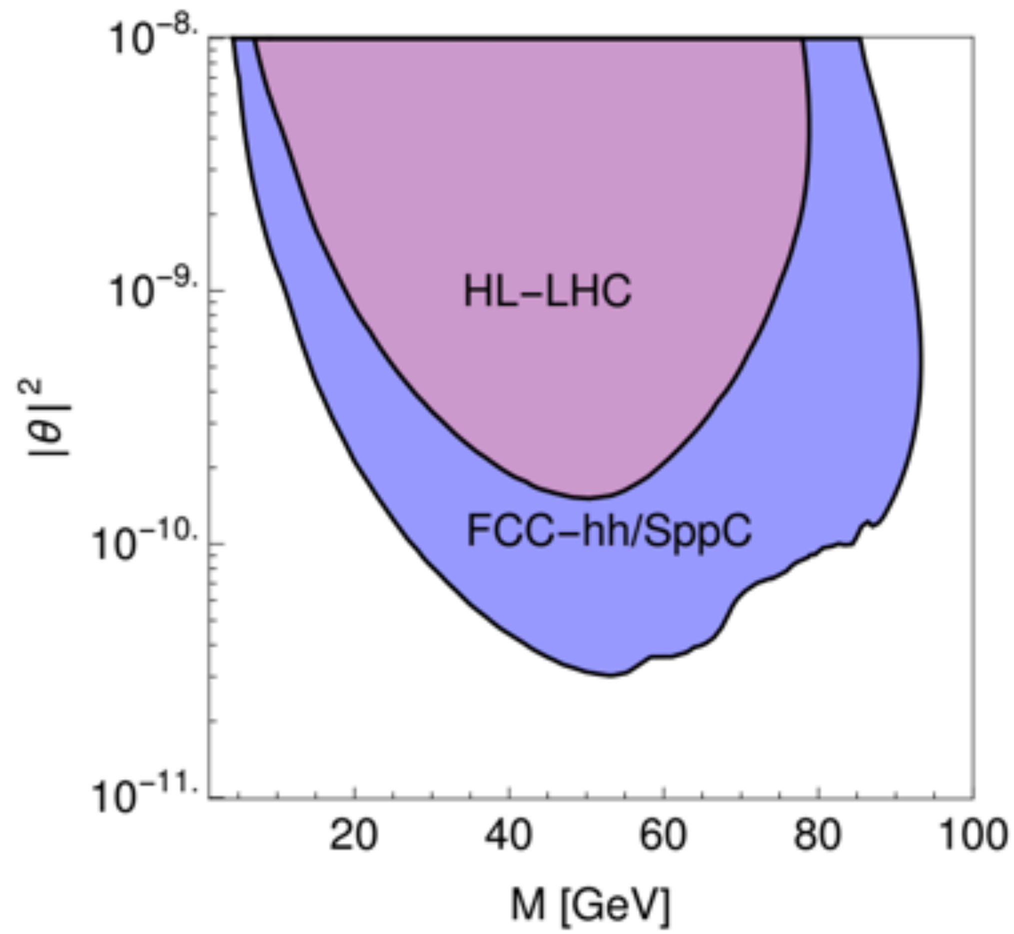
Optimize ML output by maximizing signal to bkg yield

Statistical analysis (Maximum likelihood) to provide the significance level/limit







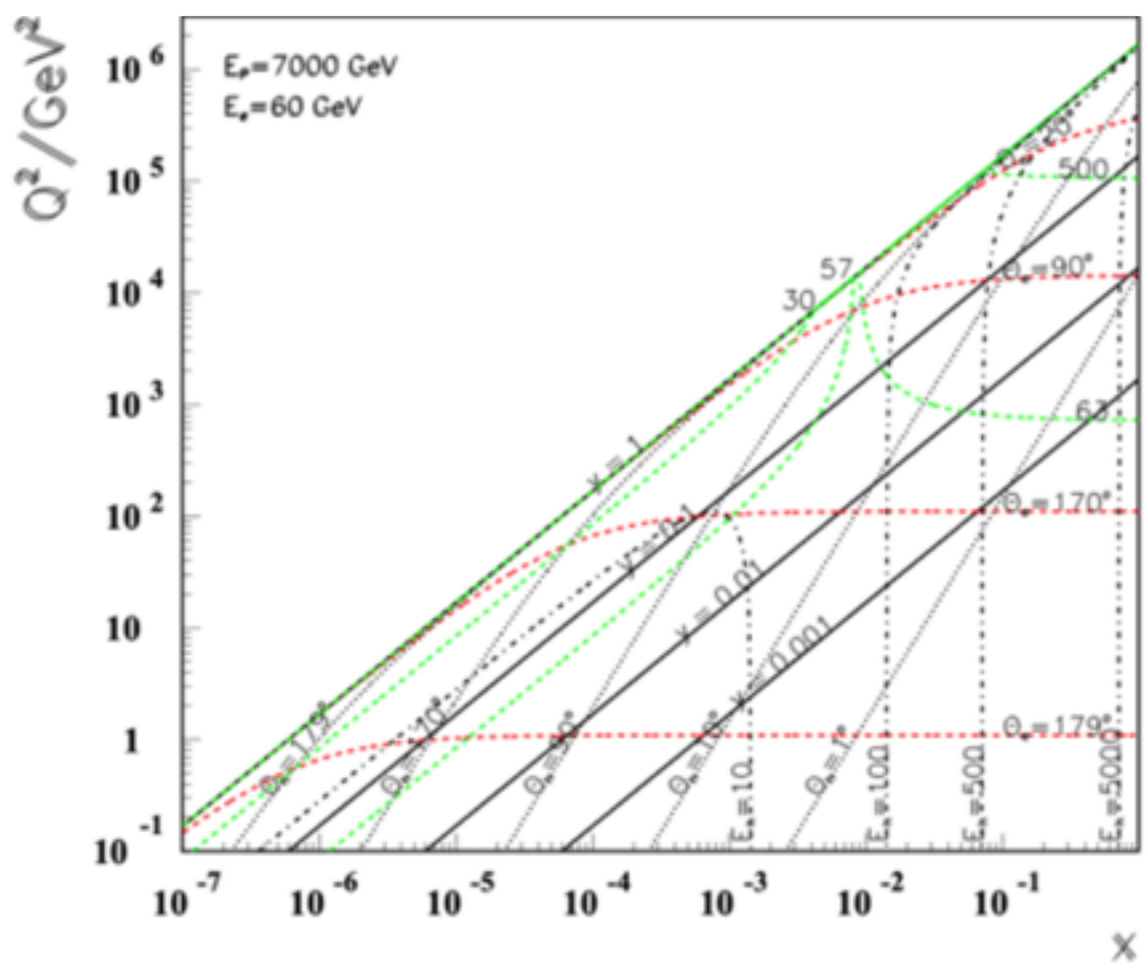


arXiv:1612.02728

LHeC Kinematics

At the LHeC, Bjorken variable controls the incoming quark energy. For most of the parameter space the energy of the incoming electron and quark are similar

For small energy transfer, the final state lepton scatter in the backward direction of the detector: "*Lepton back scattering at ep colliders*"



LHeC and FCC-he Study Group
arXiv:2007.14491

Kinematics of the scattered muon