Hunting for Heavy Neutral Leptons at Future Lepton Colliders

DESY. HELMHOLTZ

NARODOWE CENTRUM NAUKI Opus

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

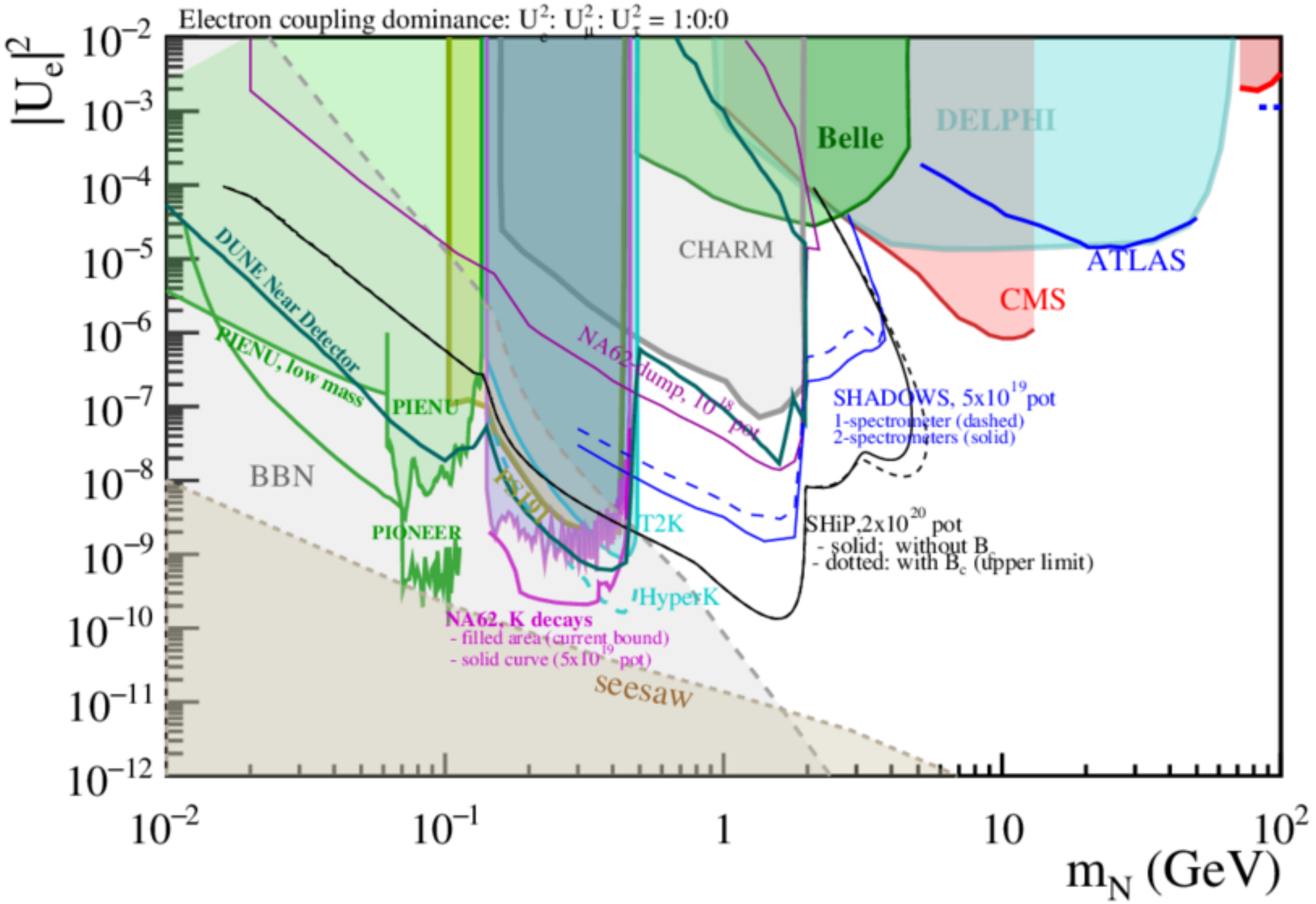
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

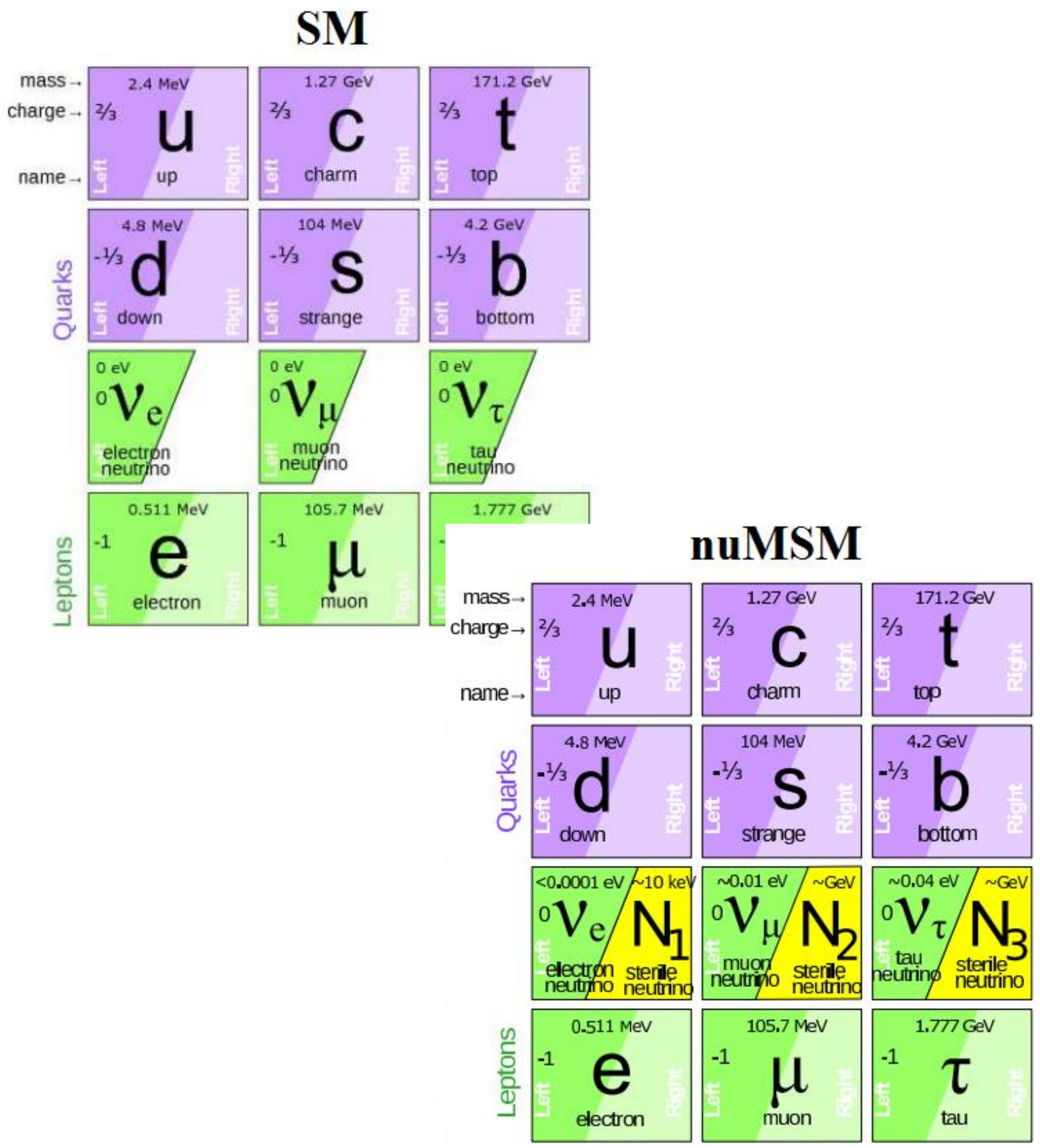
K. Mękała/JRR/A.F. Żarnecki, arXiv: 2202.06793 [JHEP] + 2301.02602 [PLB] + 2310.xxxxx

Jürgen R. Reuter

DESY.

Search for Heavy Neutral Leptons (HNL)

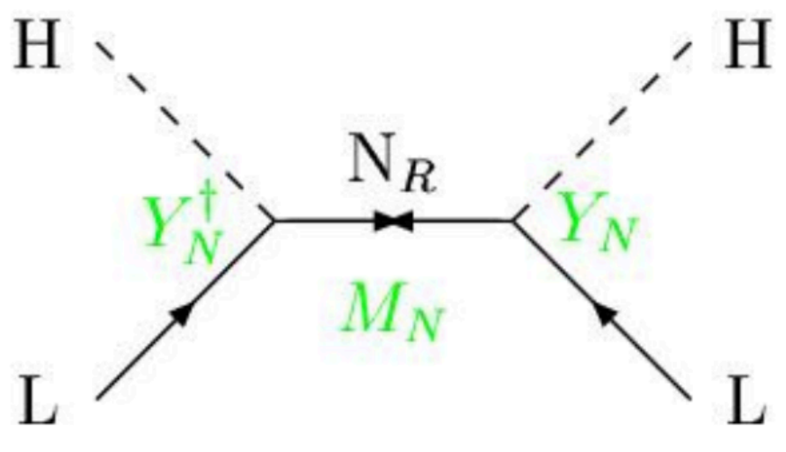




The neutrino mystery

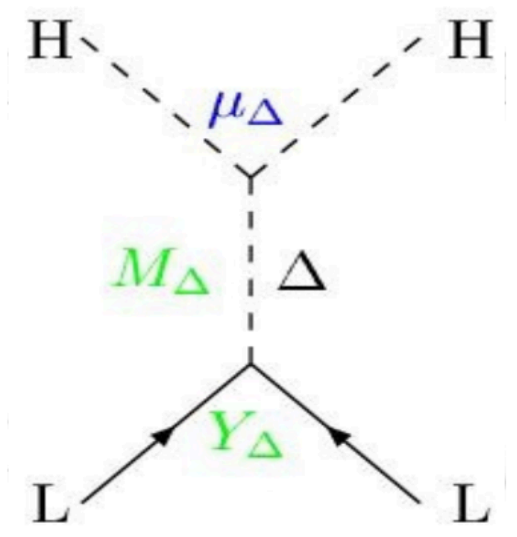
- Neutrinos masses is already physics beyond the standard model
- Simple extension of SM: just add ν_R and Yukawa couplings $\nu_R = (\mathbf{1}, \mathbf{1}, 1)$ $\quad - m_\nu(\overline{\nu}_L \nu_R + h.c.)\left(1 + \frac{h}{v}\right)$
- Singlet allows for a Majorana mass term: $-M_\nu \, \overline{\nu^C} \nu$ [Minkowski, 1977; Mohapatra/Senjanovic, 1980; Yanagida, 1981]
- Dedicated "seesaw" models for neutrino physics: type I (singlet fermion), type II (triplet scalar), type III (triplet fermion)

Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet: (type-II seesaw)



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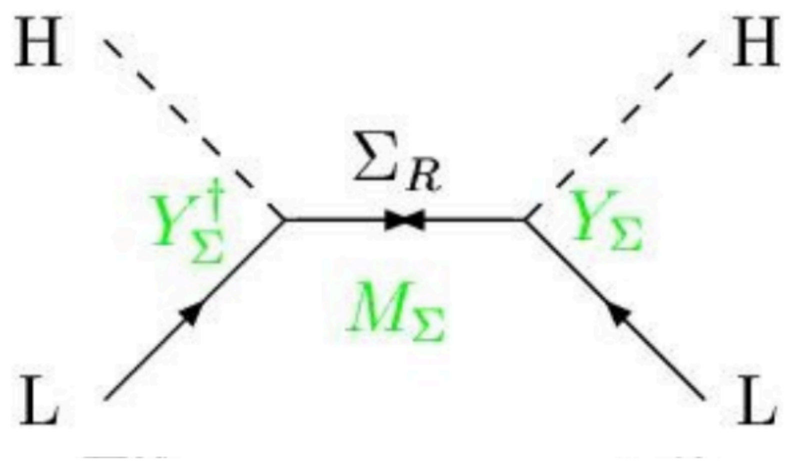
Fermion triplet: (type-III seesaw)



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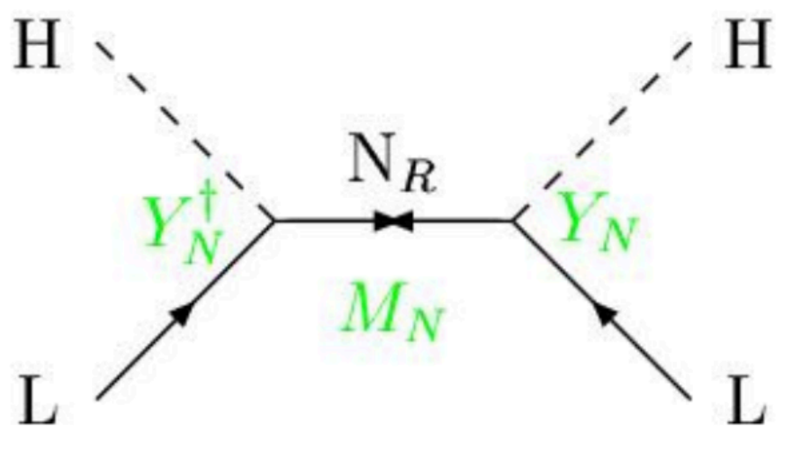

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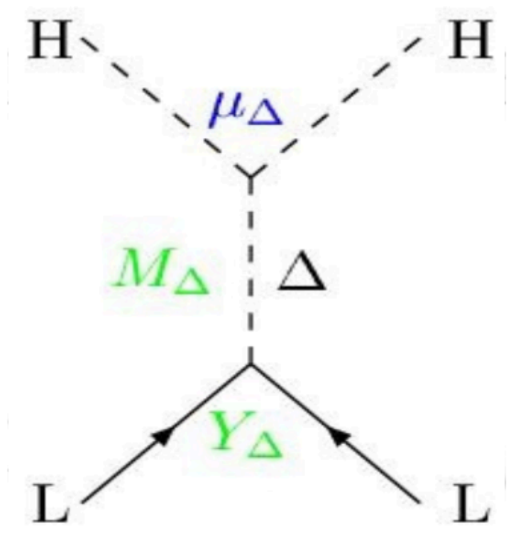

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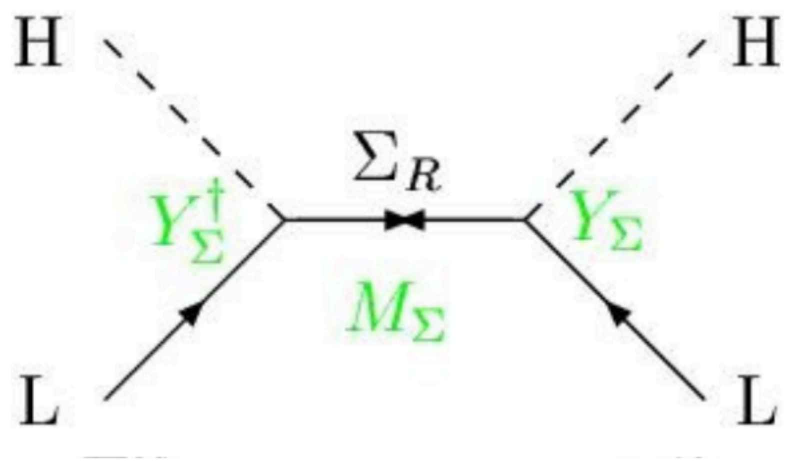

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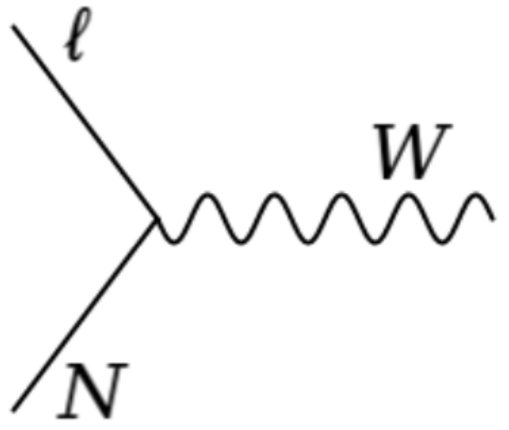
- Pheno of neutrino oscillations, flavor etc.
- Connections to Dark Matter (DM) (?)
- Lepton sector CP violation (?)
- Leptogenesis / Baryogenesis / Baryon Asymmetry of Universe (BAU)
- Lepton Flavor/Number Violation
- Fundamental Majorana Particles (?)

Simplified neutrino model

- Simplified model with right-handed (νSM) and sterile neutrinos
- After EWSB heavy (sterile) neutrinos do mix with νSM neutrinos
- Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WN\ell} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu}$

$$\mathcal{L}_N = \xi_\nu \cdot \left(\bar{N}_k i\partial\!\!\!/ N_k - m_{N_k}\bar{N}_k N_k\right) \qquad \text{for } k = 1,\, 2,\, 3 \qquad \xi_\nu = \frac{1}{2}, 1 \quad \text{[Majorana/Dirac]}$$

$$\mathcal{L}_{WN\ell} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{k=1}^{3} \sum_{l=e}^{\tau} \bar{N}_k V_{lk}^* \gamma^\mu P_L \ell^- + \text{ h.c.,}$$



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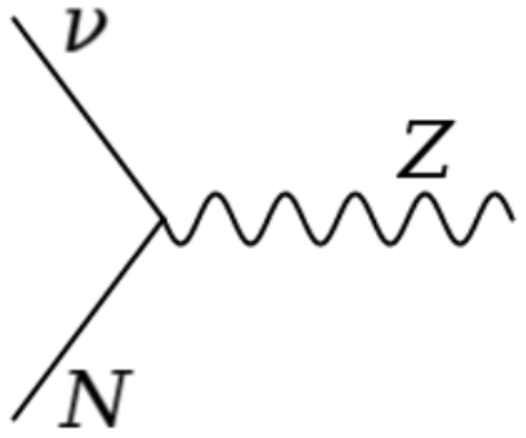

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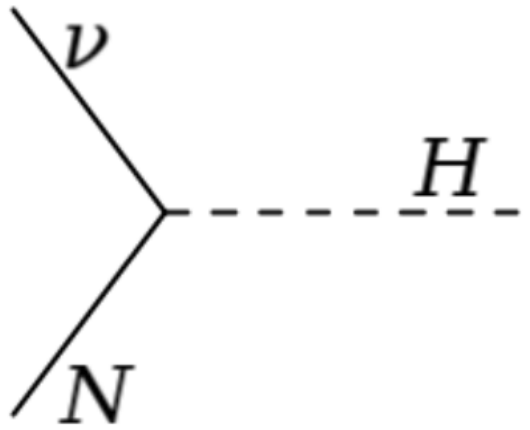

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Vast (incomplete) literature:

Aguilar-Saavedra ea., hep-ph/0502189; hep-ph/0503026; Shaposhnikov, 0804.4542; Das/Okada, 1207.3734; Banerjee ea., 1503.05491; Antusch, Cazzato, Fischer, 1612.0272; Cai, Han, Li, Ruiz, 1711.02180; Pascoli, Ruiz, Weiland, 1812.08750

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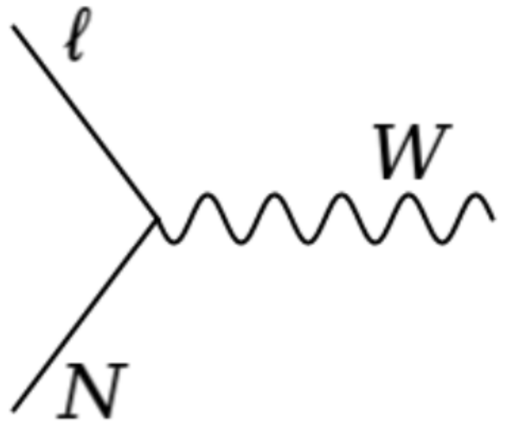

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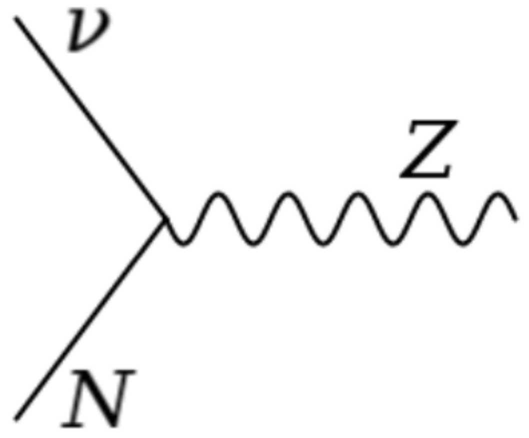

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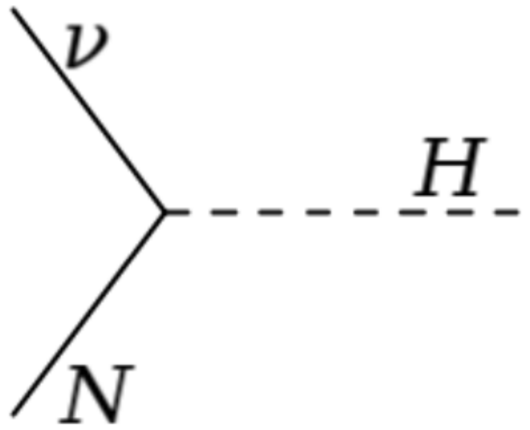

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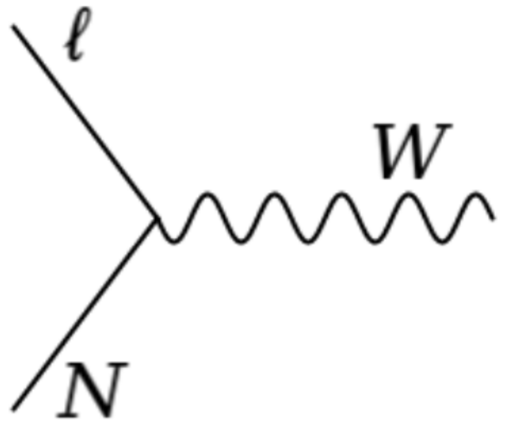

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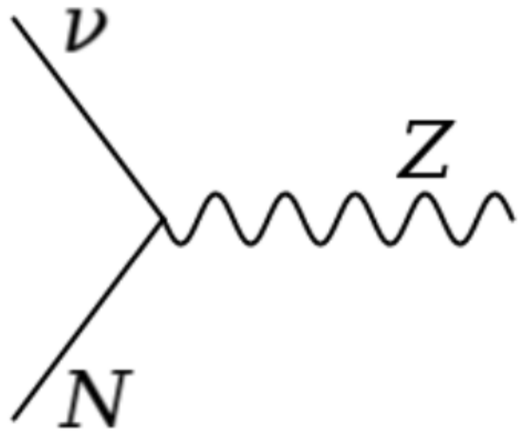

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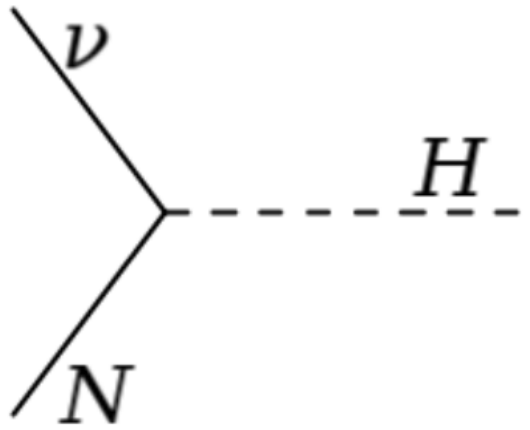
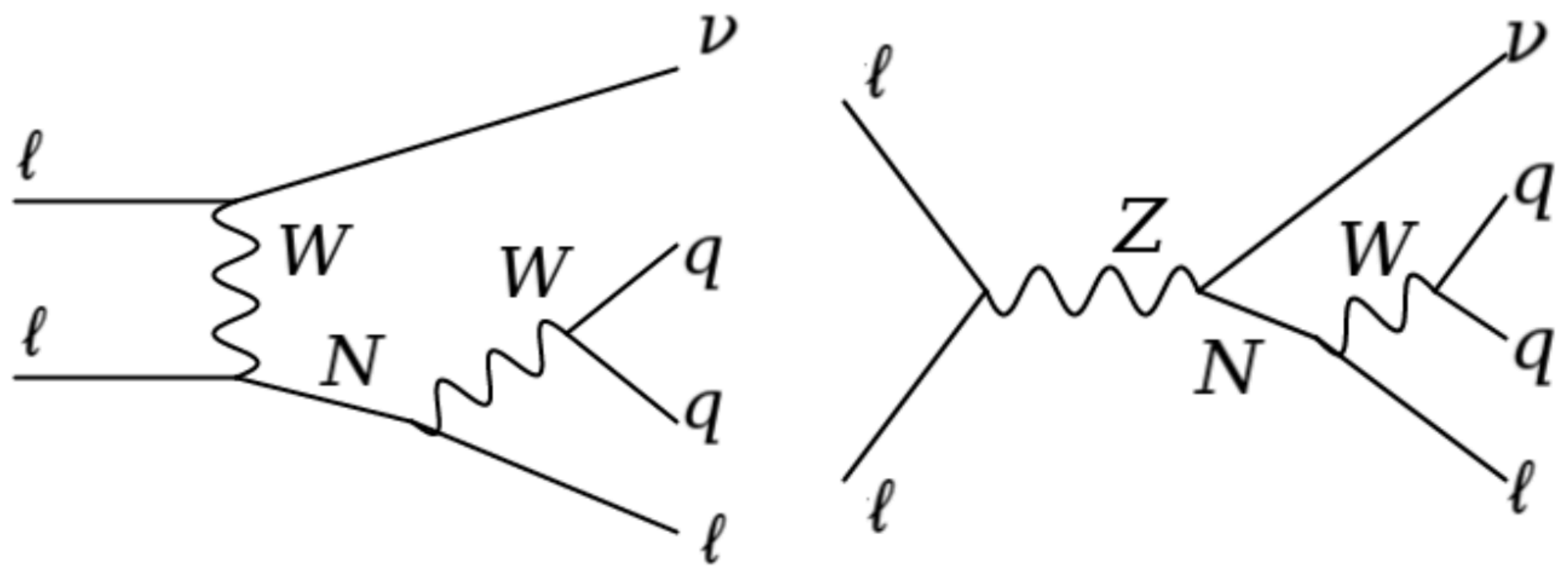


- ☑ At lepton colliders, single production possible
- ☑ Associated production: $\ell^+\ell^- \to \nu N$
- ☑ Vector boson fusion: $\ell^+\ell^- \to \bar{\nu}\nu N + \ell^+\ell^- N$
- ☑ Three neutrino masses: $M_{N_1}, M_{N_2}, M_{N_3}$
- ☑ Nine real mixing parameters: $V_{\ell k}$, $\ell = e, \mu\, \tau, k = N_1, N_2, N_3$
- ☑ Three neutrino widths: $\Gamma_{N_1}, \Gamma_{N_2}, \Gamma_{N_3}$
- ☑ Studied parameter space: neutrino decays prompt
- ☑ No long-lived particles or displaced vertices

Signal, simulation, selection

- At lepton colliders: optimal channel single production with decay to $N \to jj\ell$
- In that case: full reconstruction of *N* (incl. mass peak) possible
- Study for ILC250, ILC500, ILC1000, CLIC 3 TeV, MuC 3+10 TeV
- Simulation with `Whizard 3.0` (first paper!) + `Pythia6 + Delphes`
- Using UFO model `HeavyN`



K. Mękała/JRR/A.F. Żarnecki, 2202.06703; 2301.02602

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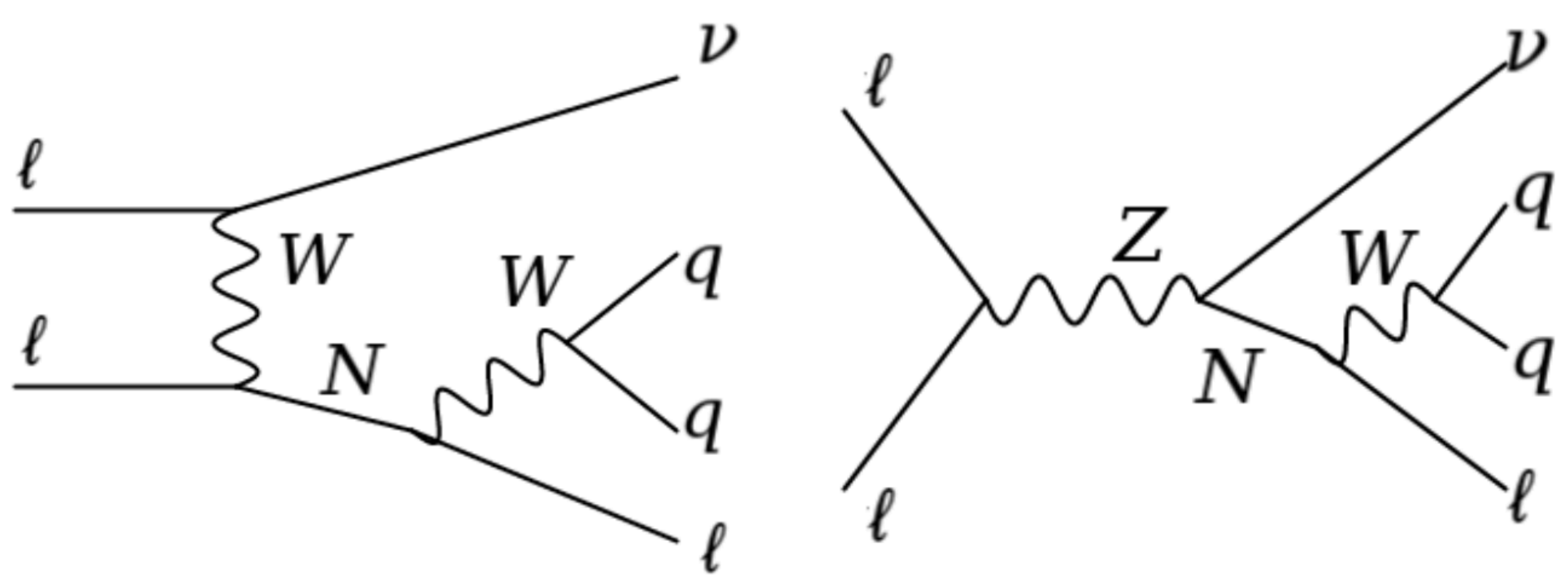

K. Mękała/JRR/A.F. Żarnecki, 2202.06703; 2301.02602

- ☑ Assumption on couplings: $|V_{eN_1}|^2 = |V_{\mu N_1}|^2 = |V_{\tau N_1}|^2 \equiv |V_{\ell N_1}|^2$
- ☑ Reference signal sample with $|V_{\ell N_1}| = 0.0003$, N_2, N_3 couplings set to zero
- ☑ Neutrinos masses: $100\,\text{GeV} \leq M_{M_1} \leq 10.5\,\text{TeV}$, $M_{N_{2,3}} = 10^{10}\,\text{GeV}$
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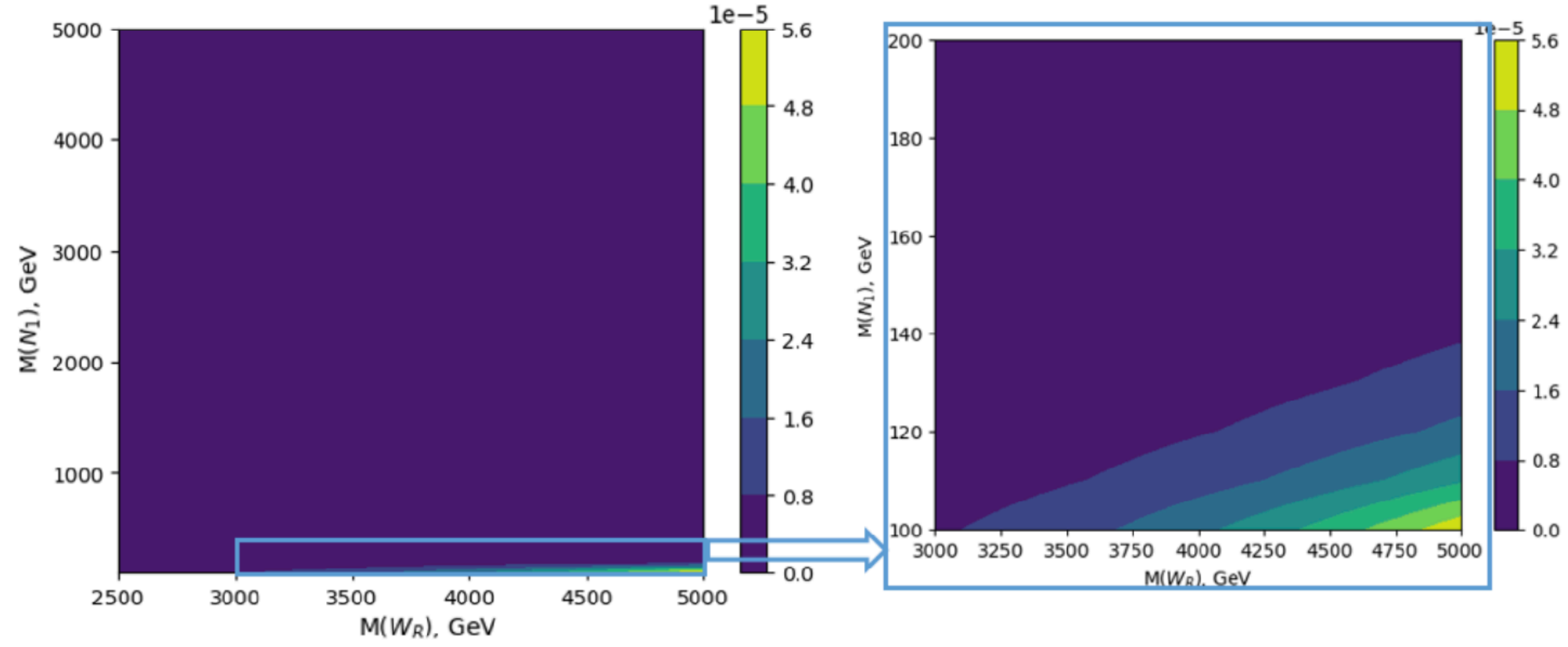

K. Korshynska/M. Löschner/M. Marinichenko/
JRR/K. Mękała, Febr. 2023

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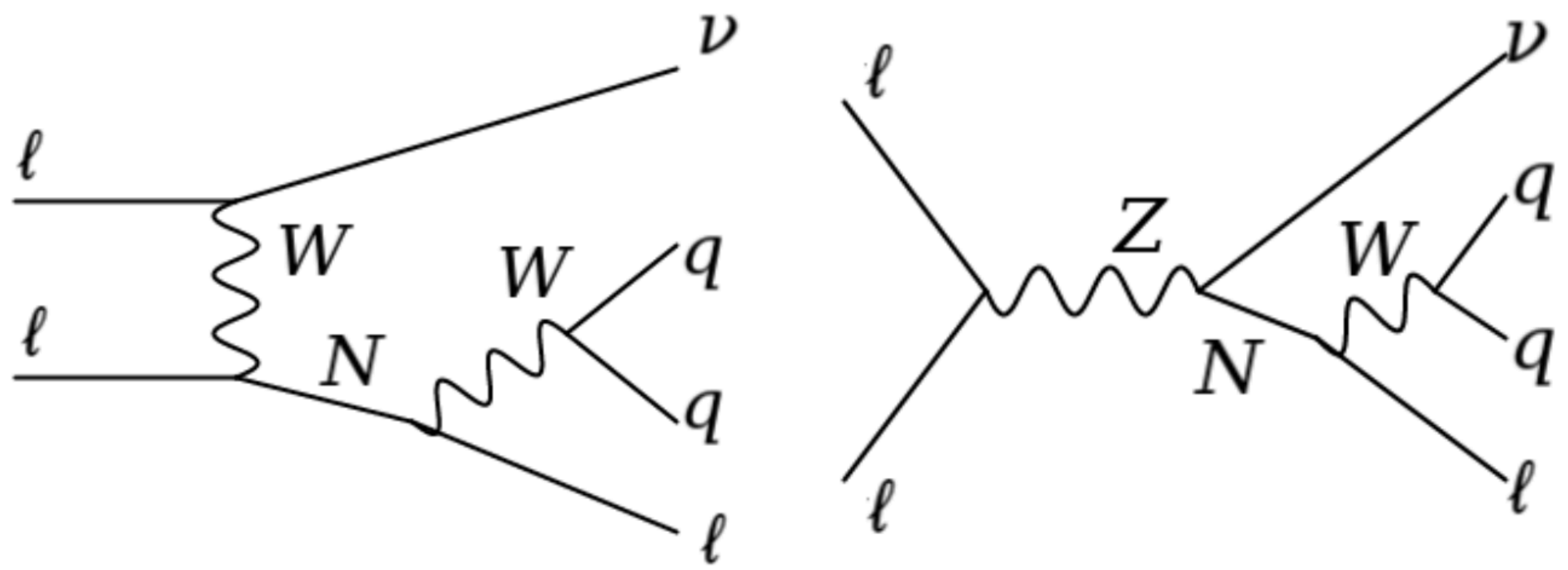

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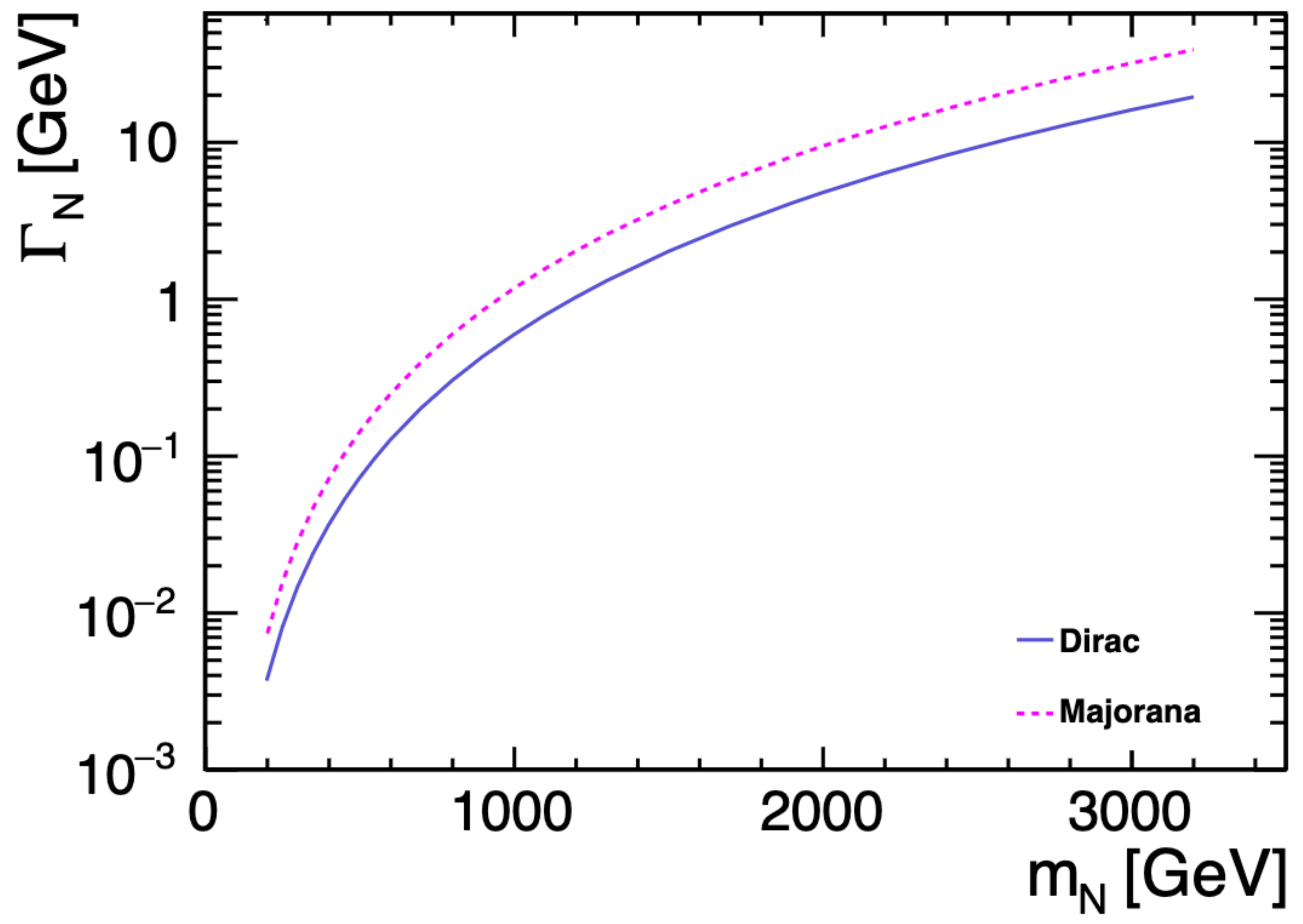

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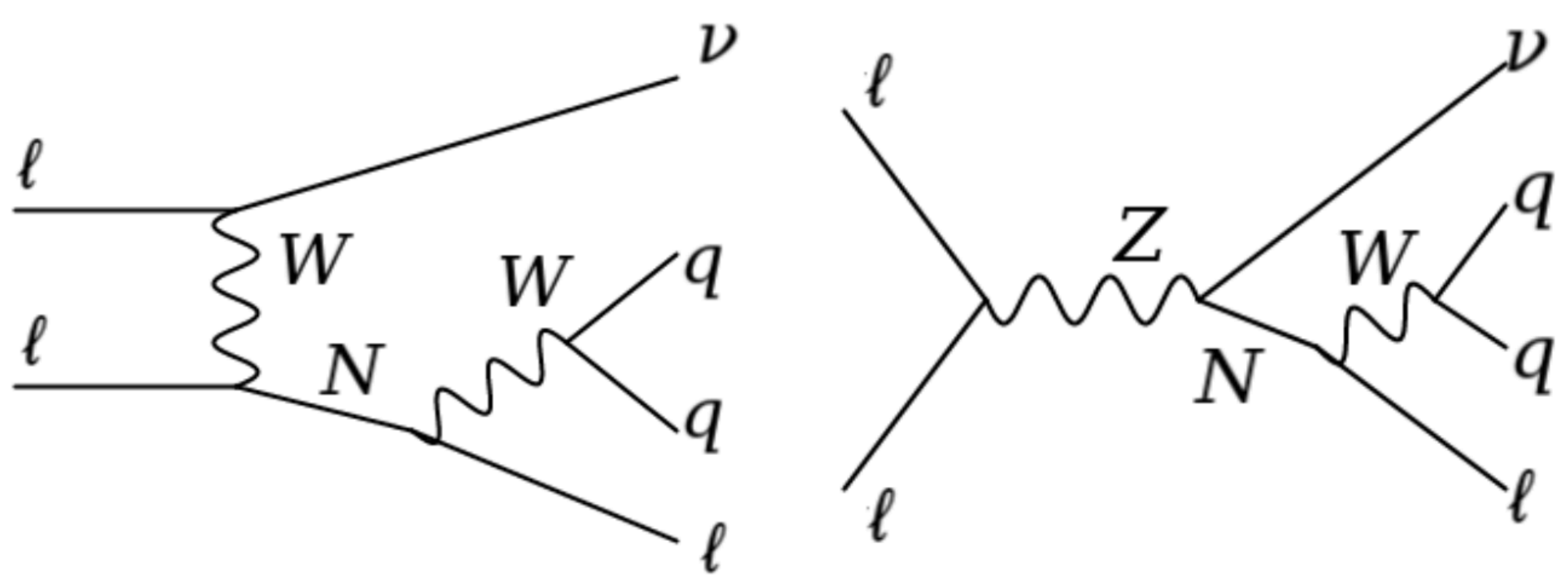

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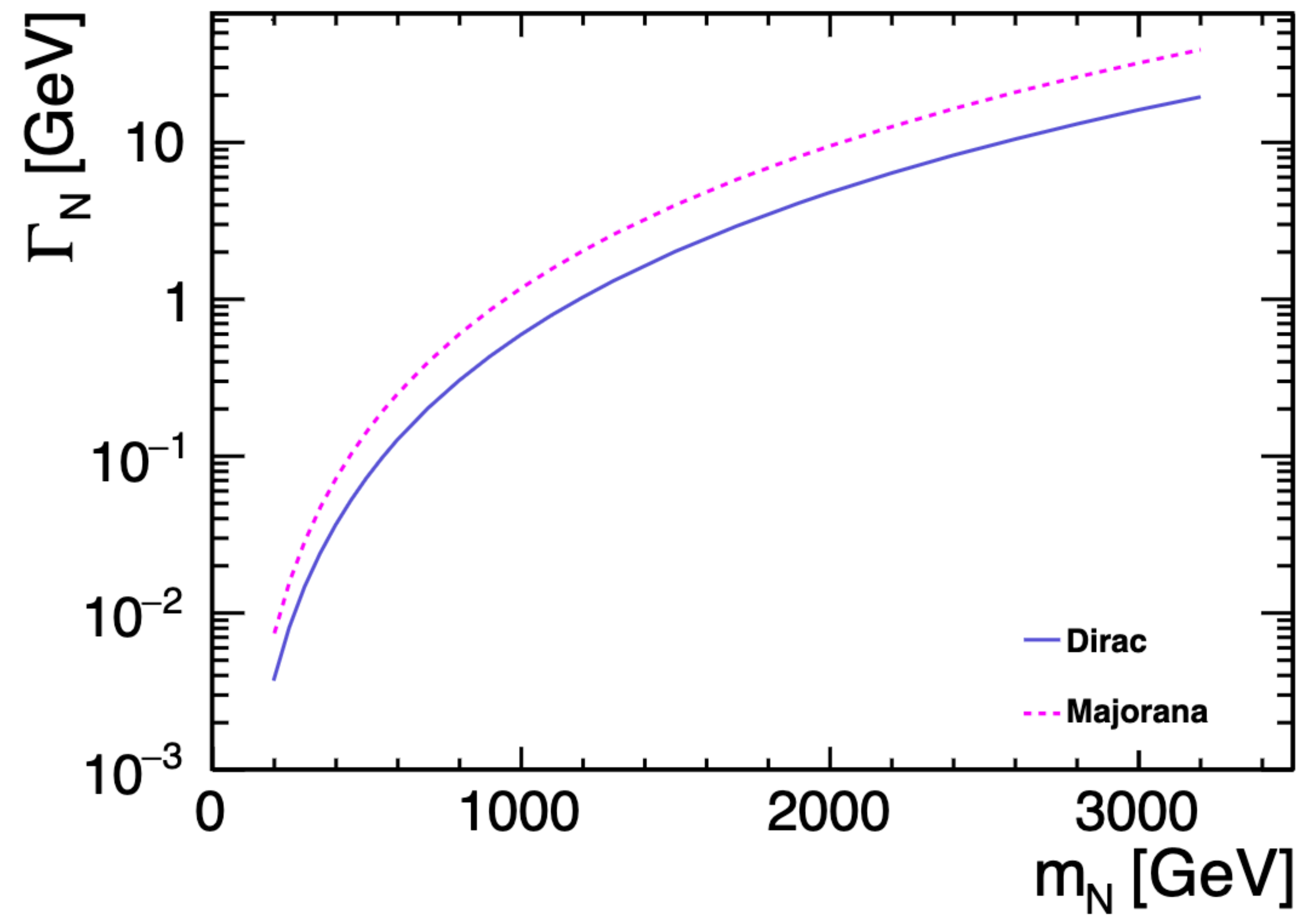

- Background simulation: without N propagators ("background")
- Signal simulation: $\ell\ell \to N\nu \to \ell jj\nu$ ("signal")
- $S/B \sim 10^{-3}$ e.g. ILC500: $jj\ell\nu$ bkgd. ~ 10 pb, signal ~ 10 fb
- Preselection on signal topology: exactly 1 lepton and 2 jets
- BDT training; CLs method to get final results

Analysis at ILC / CLIC

Bkgd processes with at least one lepton

- $e^+e^- \to qq\ell\nu$,
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Initial-state $e^\pm \to \gamma e^\pm$ splitting (EPA)

- $e^+\gamma/\gamma e^- \to qq\ell$ (denoted as $\gamma e^\pm \to qq\ell$),
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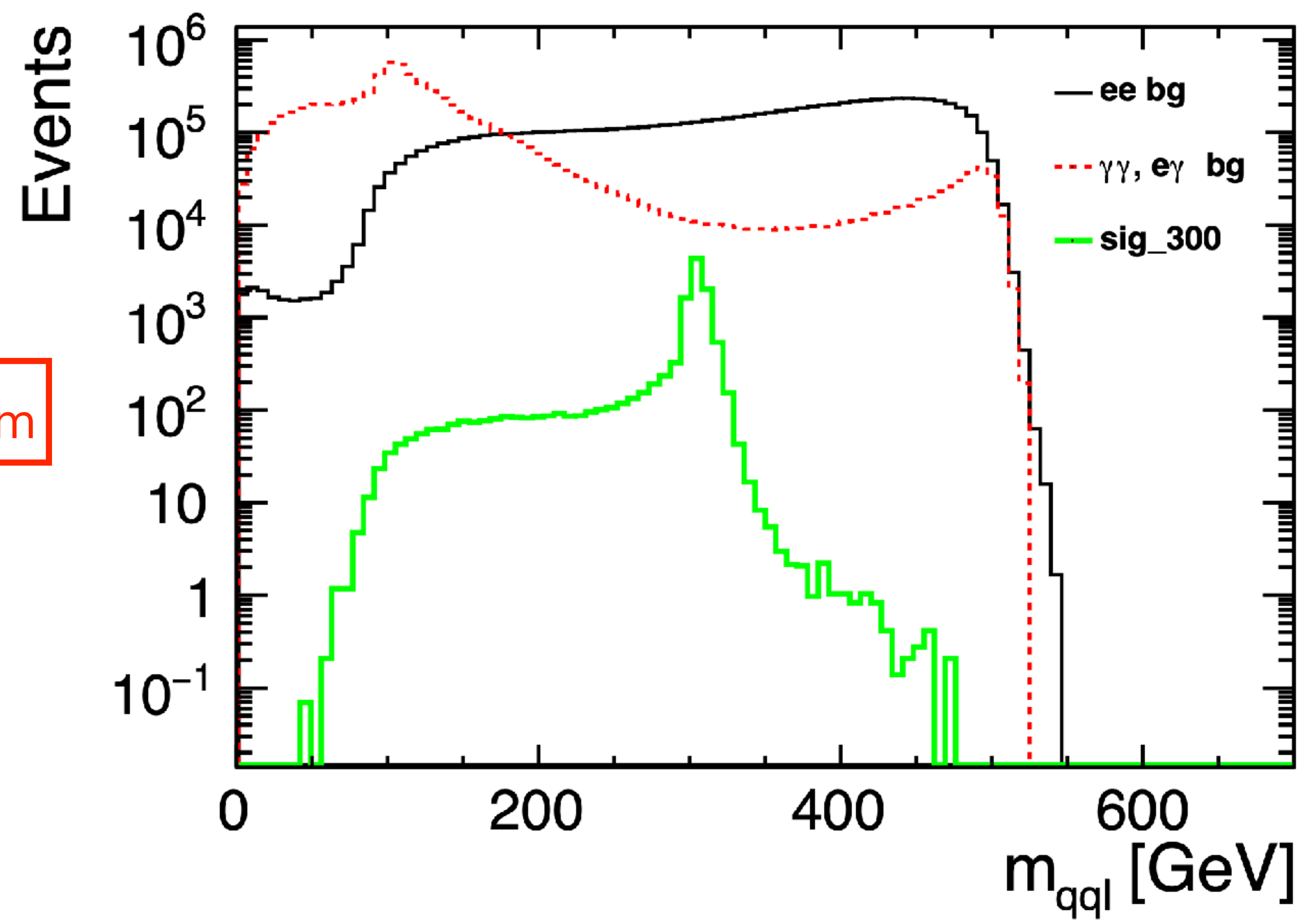
Caveat on ILC1000 γ spectrum

Bkgd. from beamstrahlung

- ILC500: $\gamma^B(e^\pm/\gamma^E)$ – 57%, $\gamma^B\gamma^B$ – 44%;
- ILC1000: $\gamma^B(e^\pm/\gamma^E)$ – 65%, $\gamma^B\gamma^B$ – 54%;
- CLIC3000: $\gamma^B(e^\pm/\gamma^E)$ – 79%, $\gamma^B\gamma^B$ – 69%.



ILC 500 GeV, (-80%, +30%), m_N = 300 GeV

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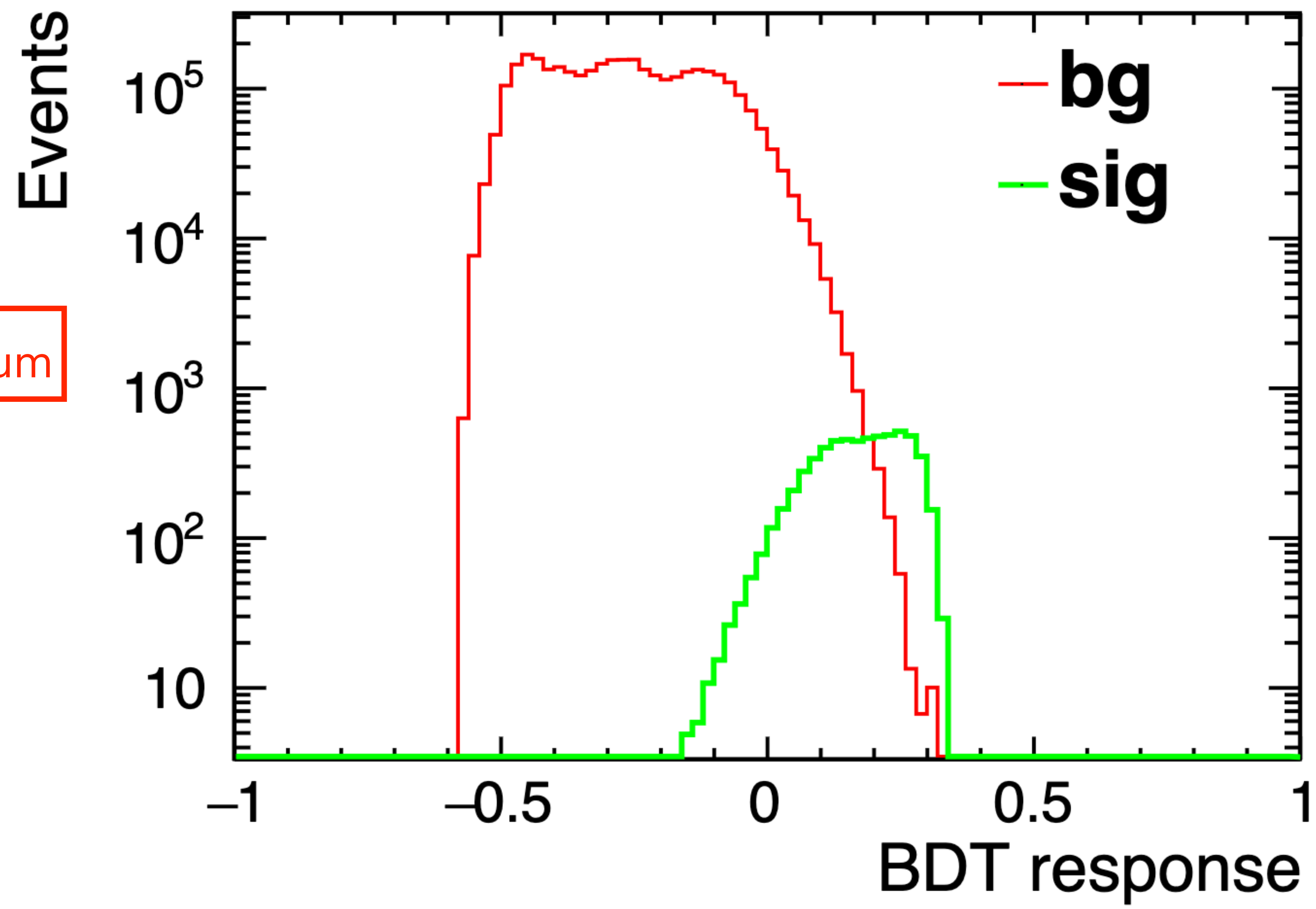


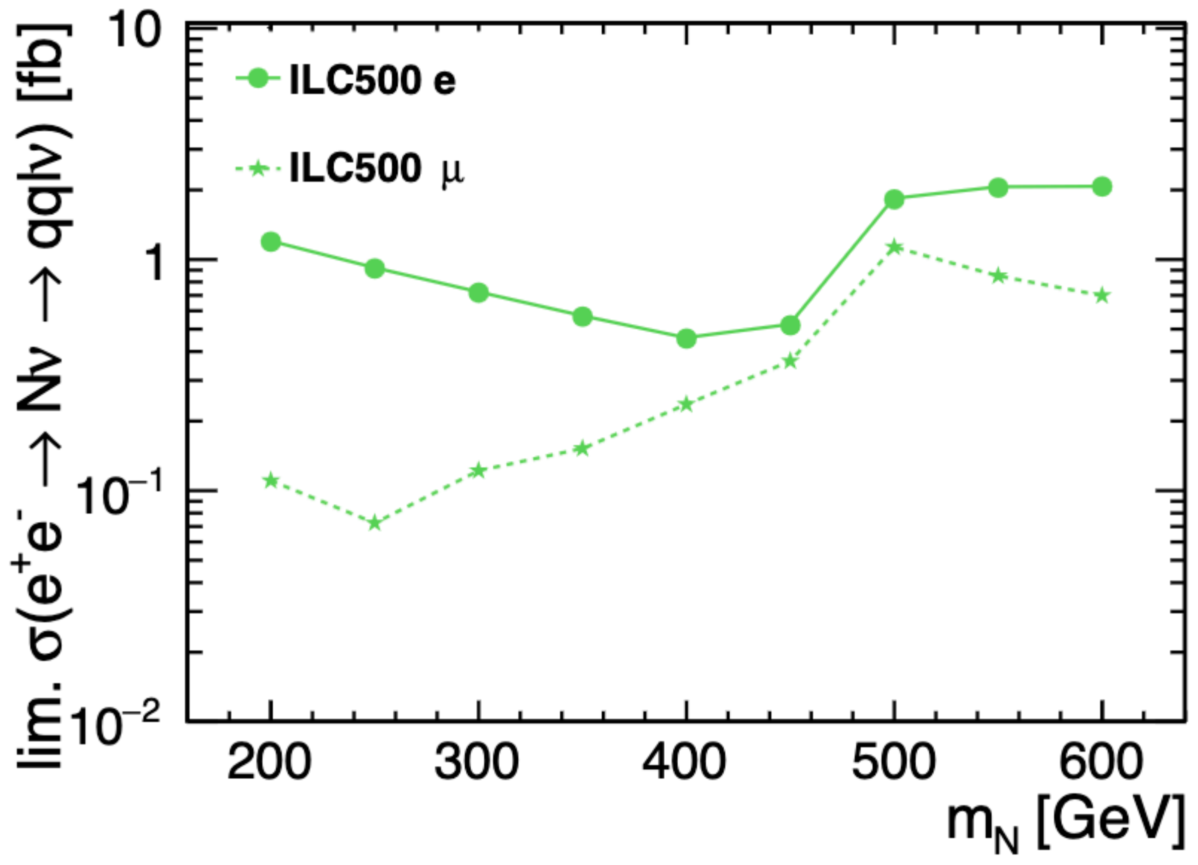
8 variables considered in BDT

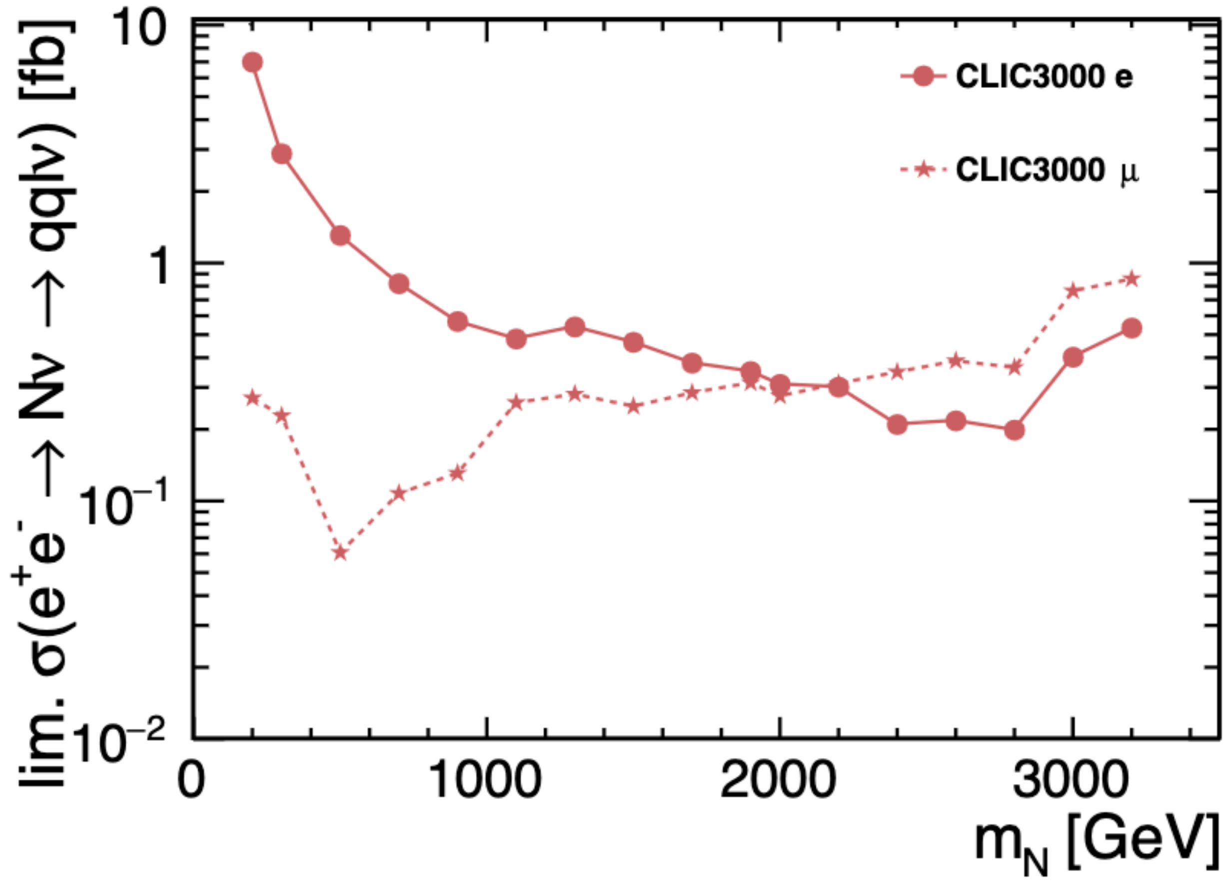
- $m_{qq\ell}$ – invariant mass of the dijet-lepton syster
- α – angle between the dijet-system and the lepton,
- α_{qq} – angle between the two jets,
- E_ℓ – lepton energy,
- $E_{qq\ell}$ – energy of the dijet-lepton system,
- p^T_ℓ – lepton transverse momentum,
- p^T_{qq} – dijet transverse momentum,
- $p^T_{qq\ell}$ – transverse momentum of the dijet-lepton system.

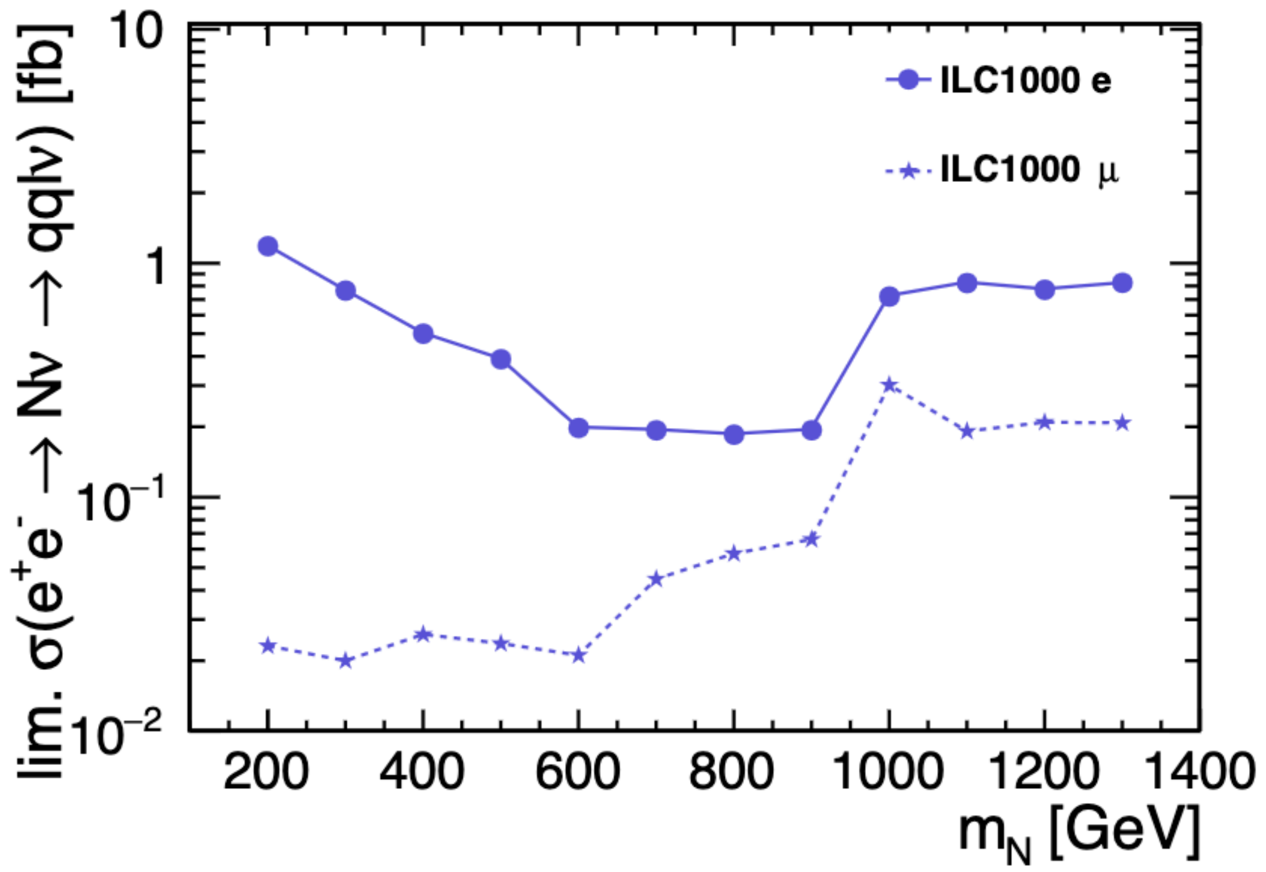
BDT CLs cross section limits

BDT response used to build model in `RooStats` to use CLs method to set limits on cross sections:

Combination of $e^\pm$ and $\mu^\pm$ channels







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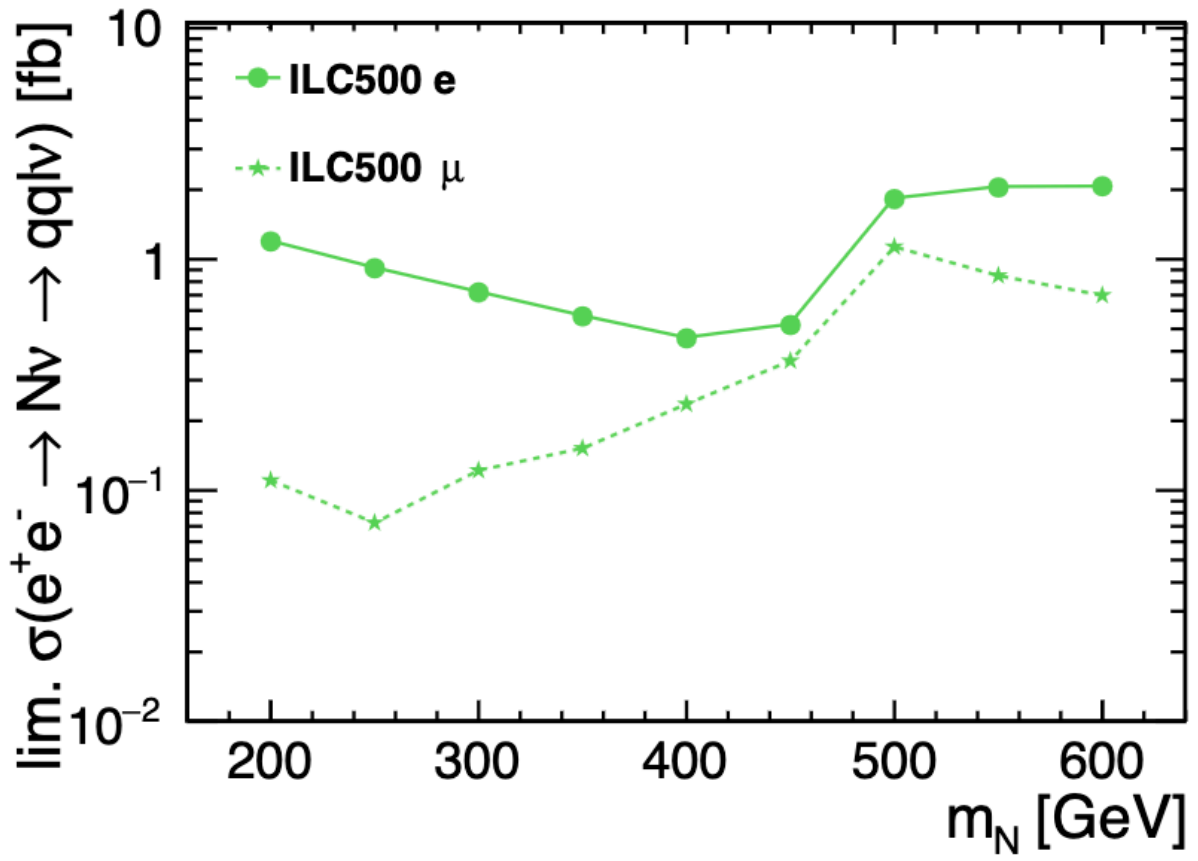
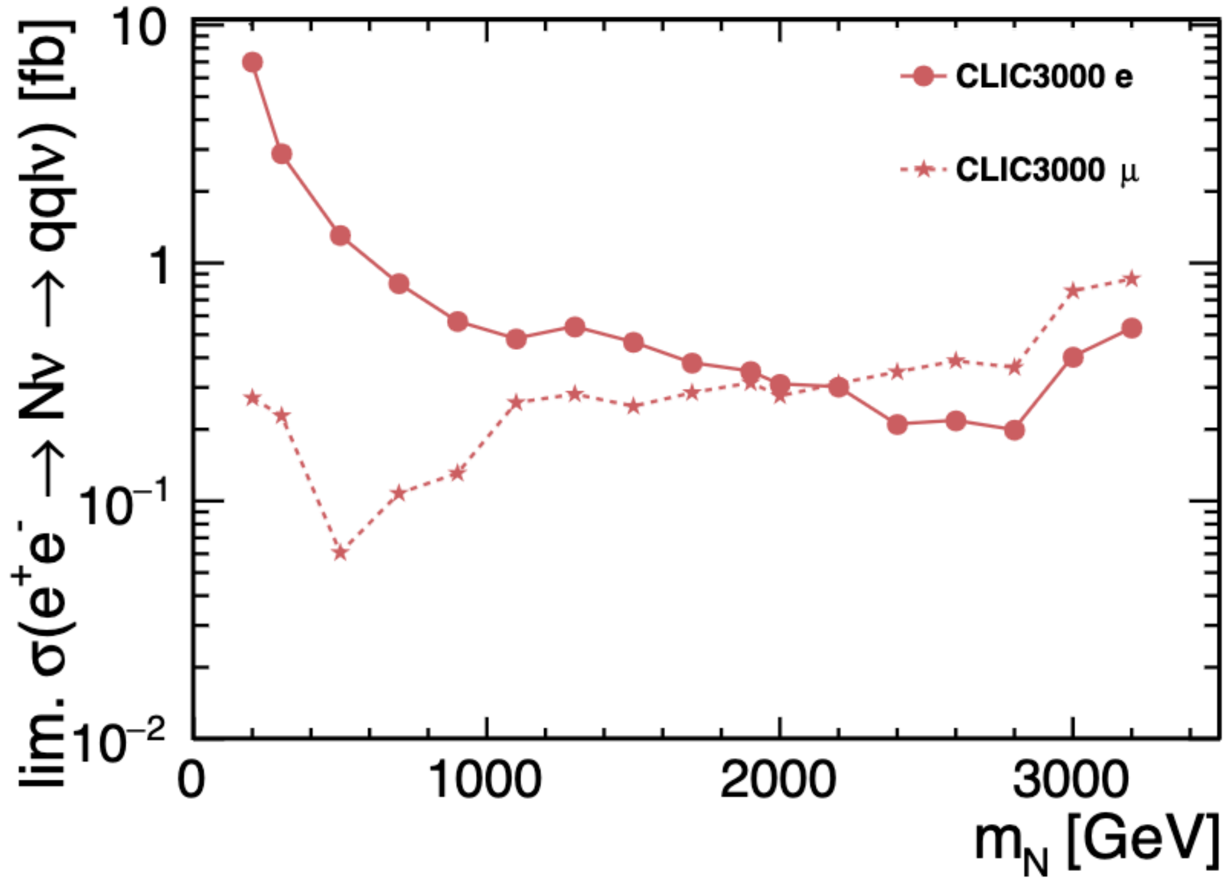
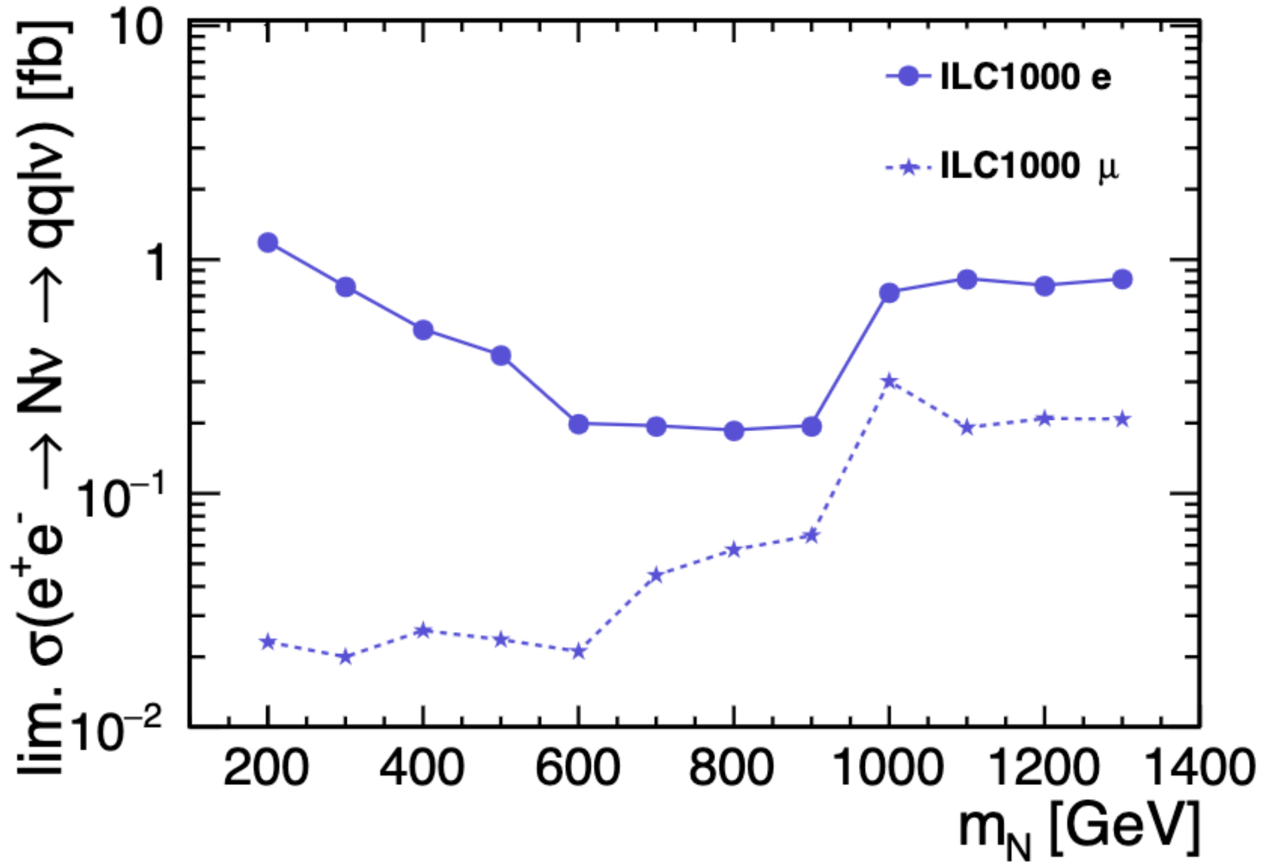
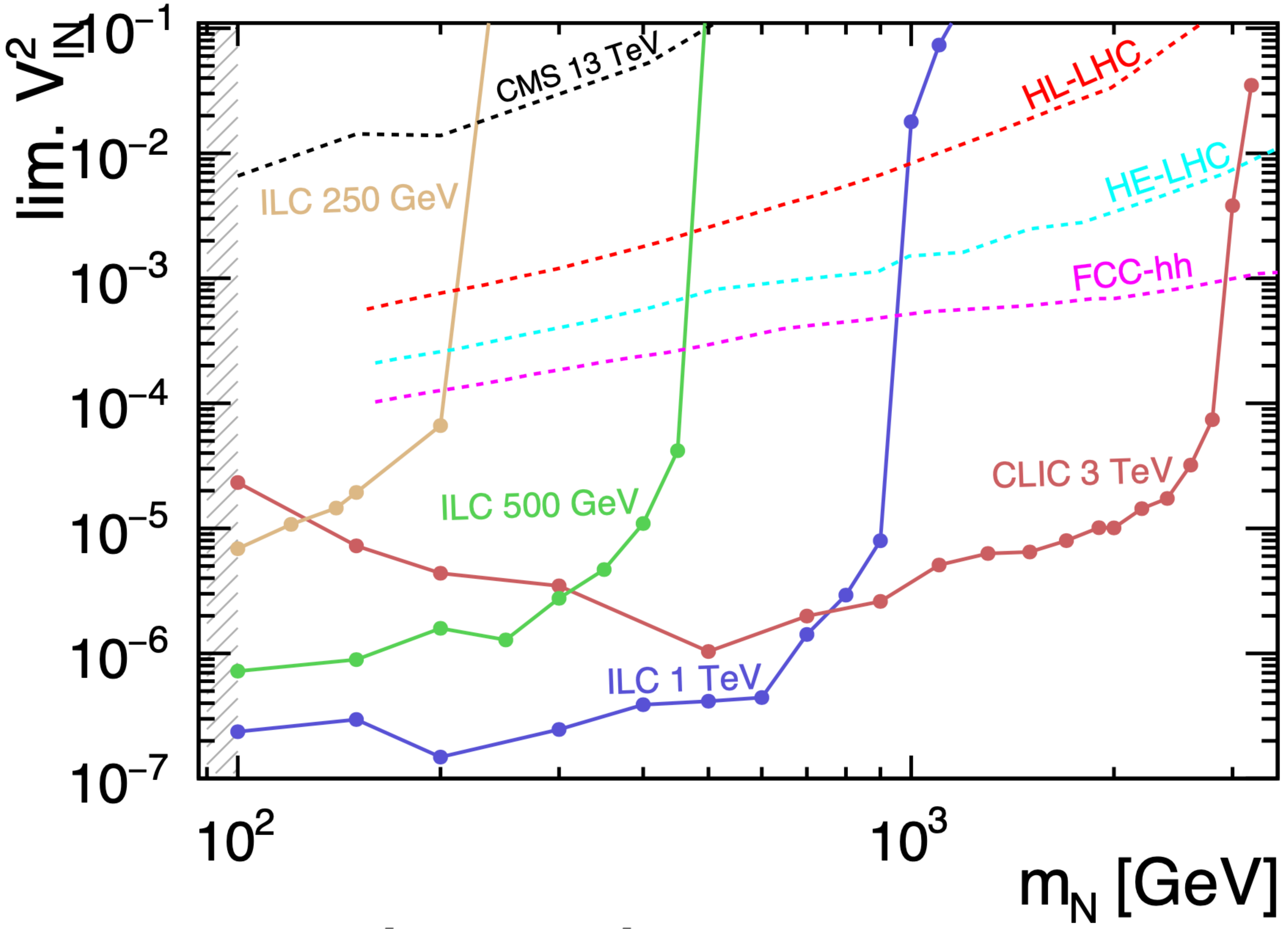






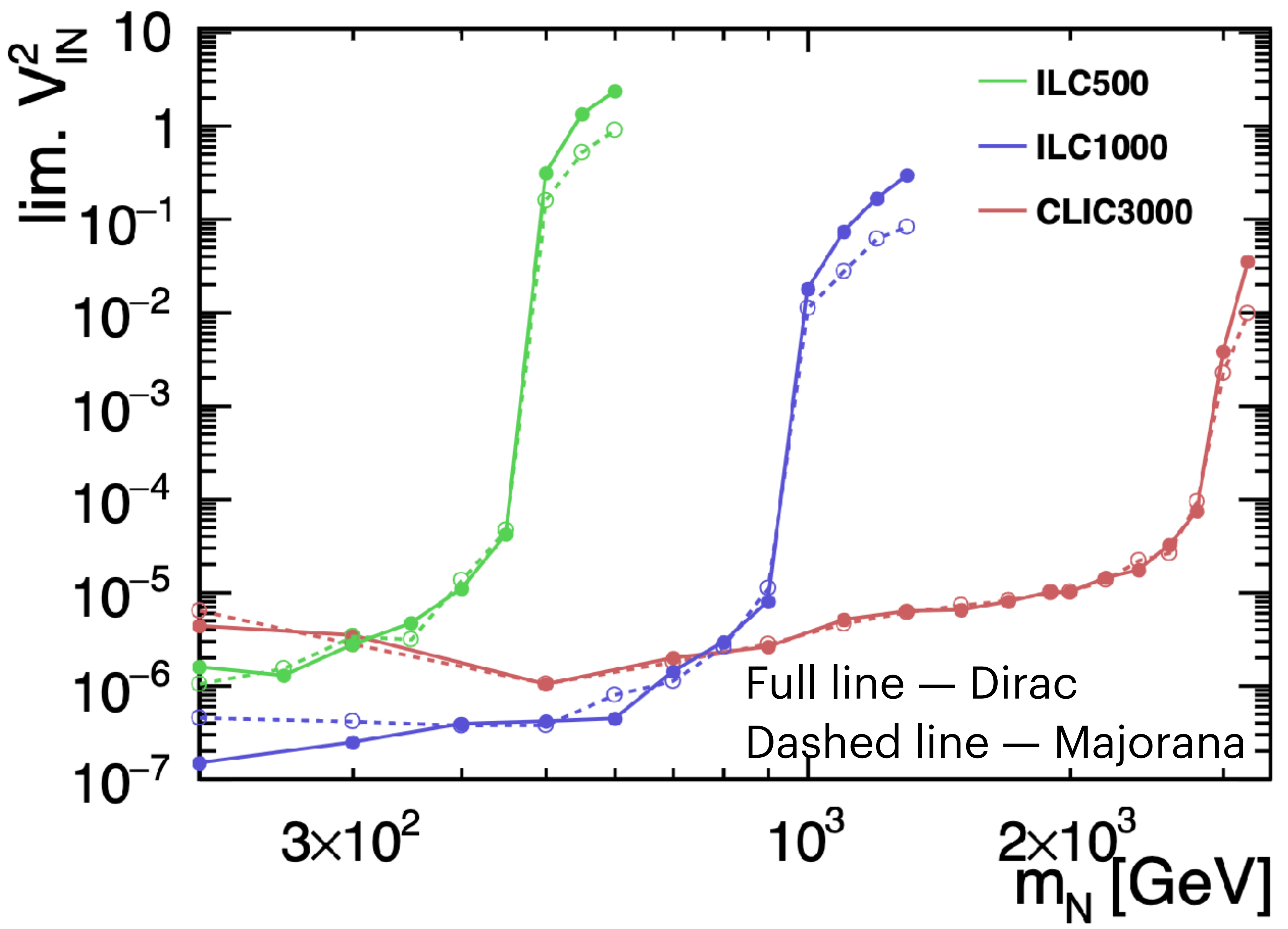
Typical hadron/lepton duality:
masses vs. coupling reach!



LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

Discrimination of Dirac vs. Majorana

- Exclusion limit very similar for Dirac & Majorana neutrino (except: off-shell production)
- Possible discriminant: lepton emission angle in *N* rest frame



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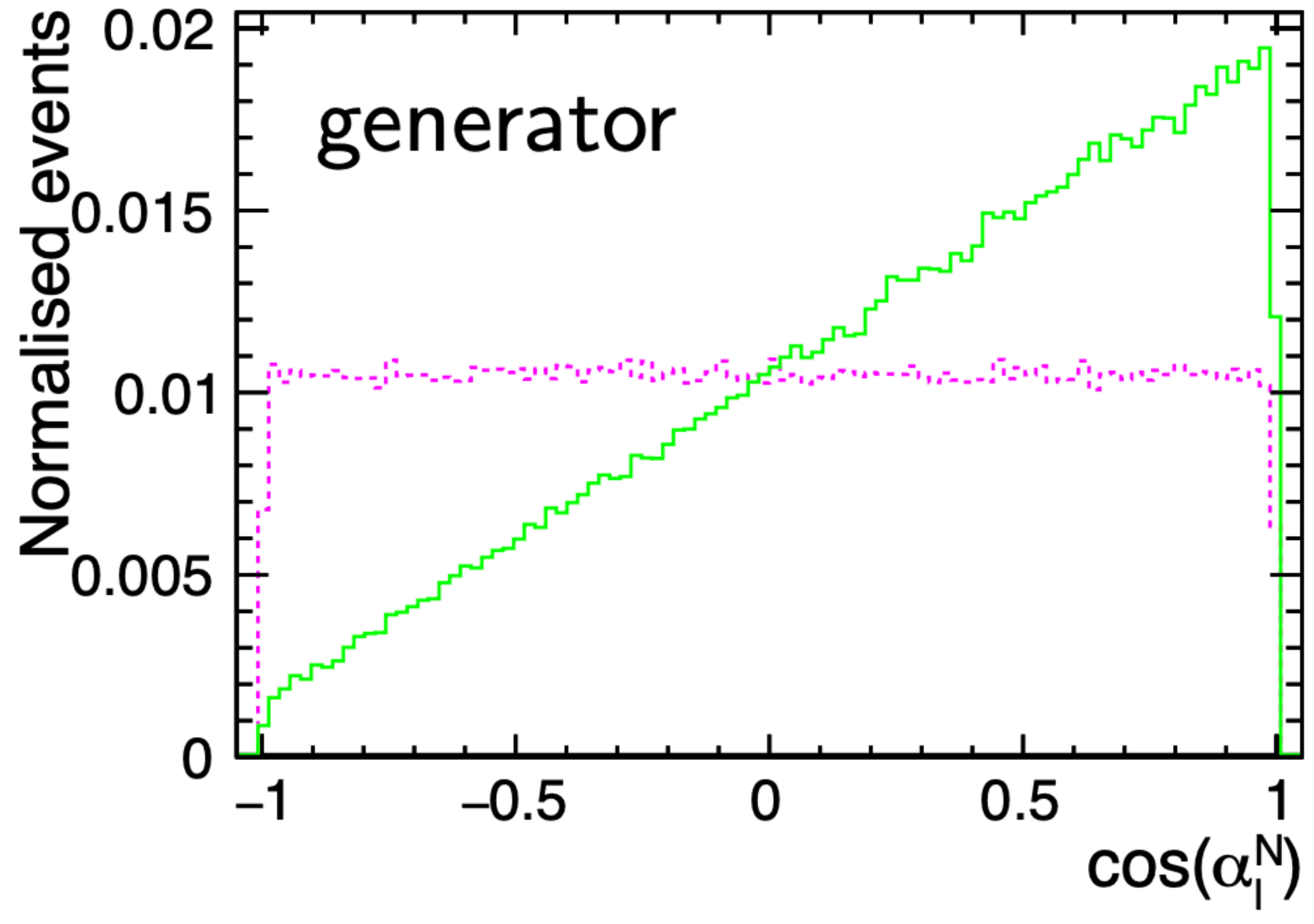

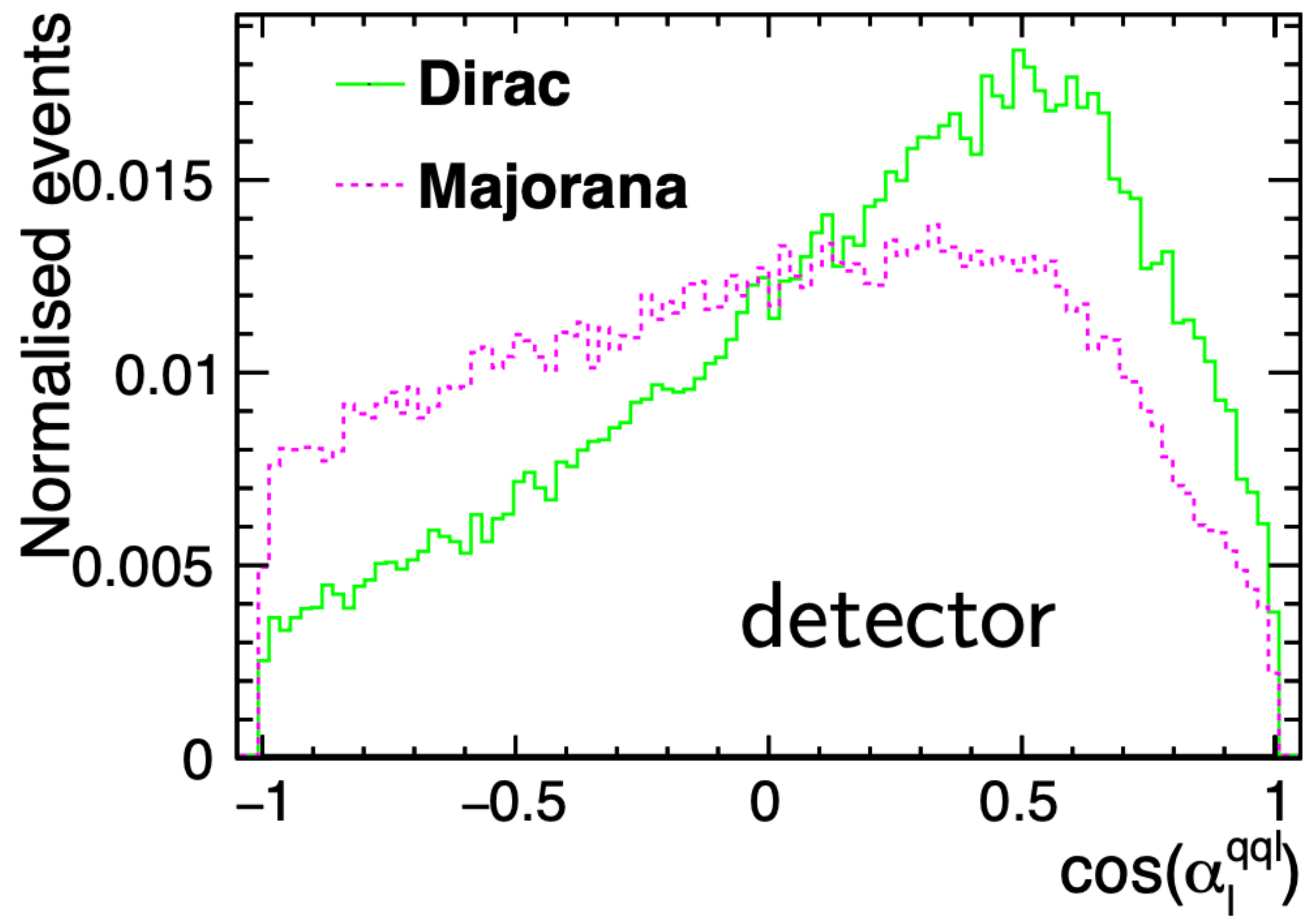

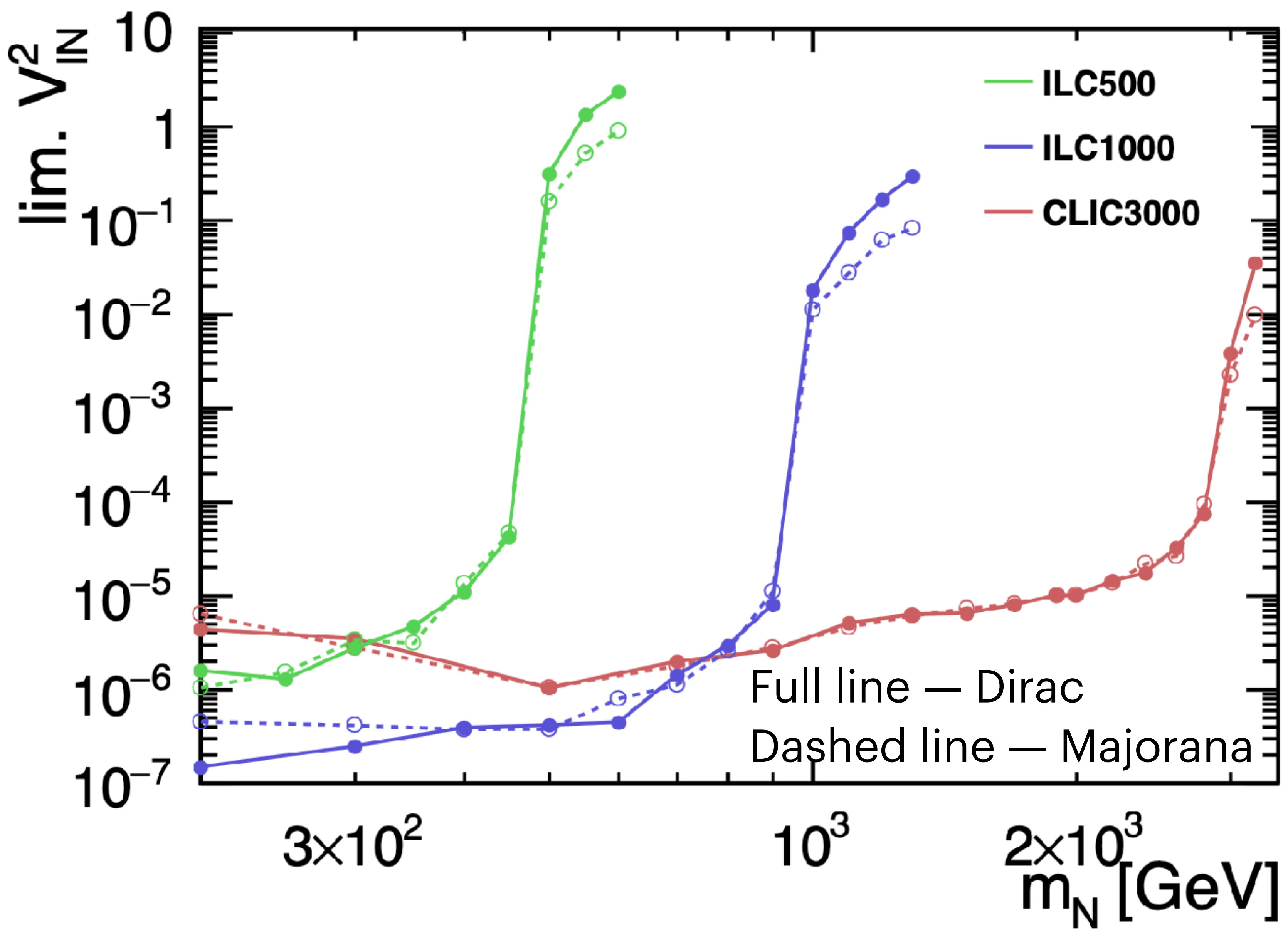

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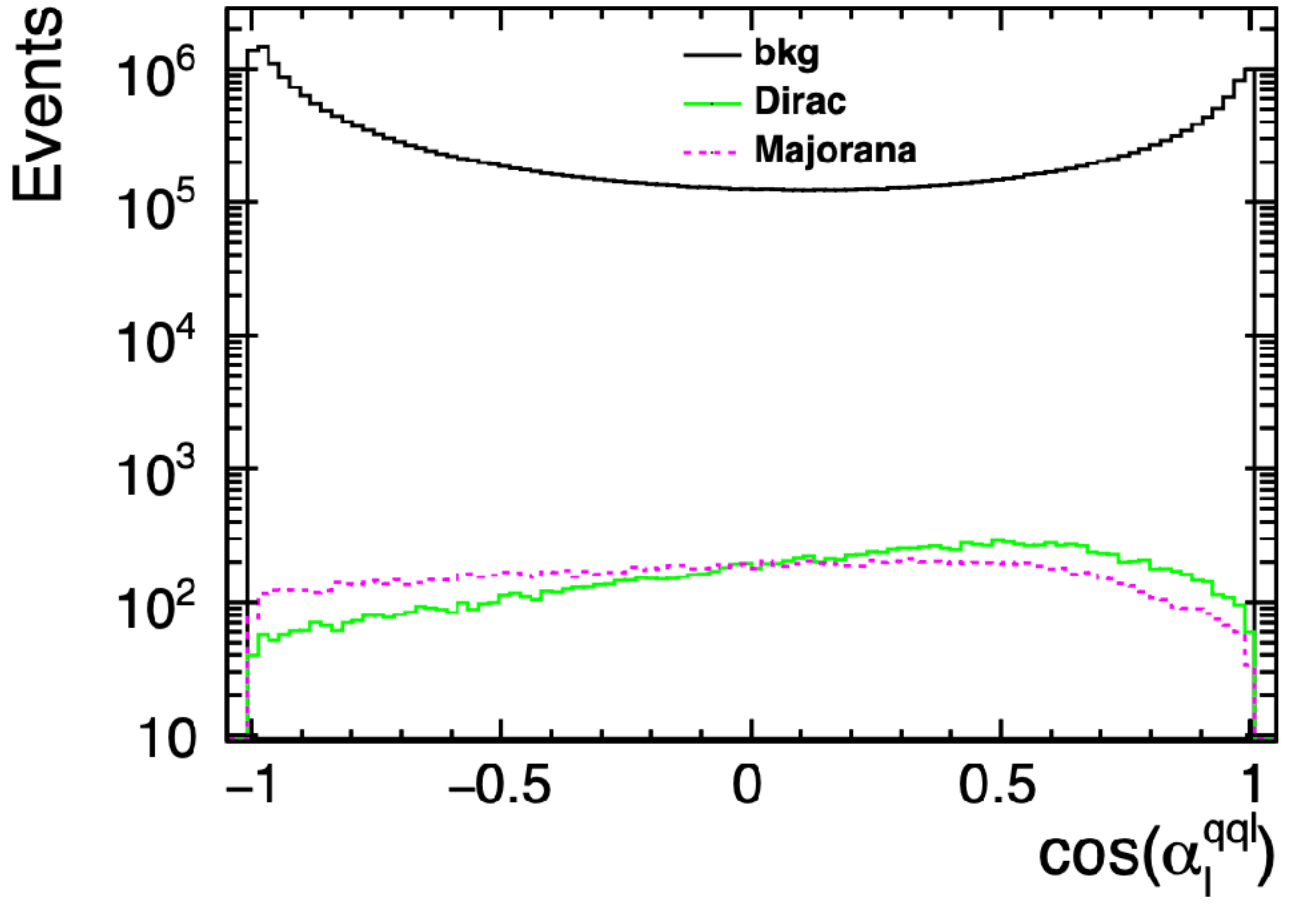

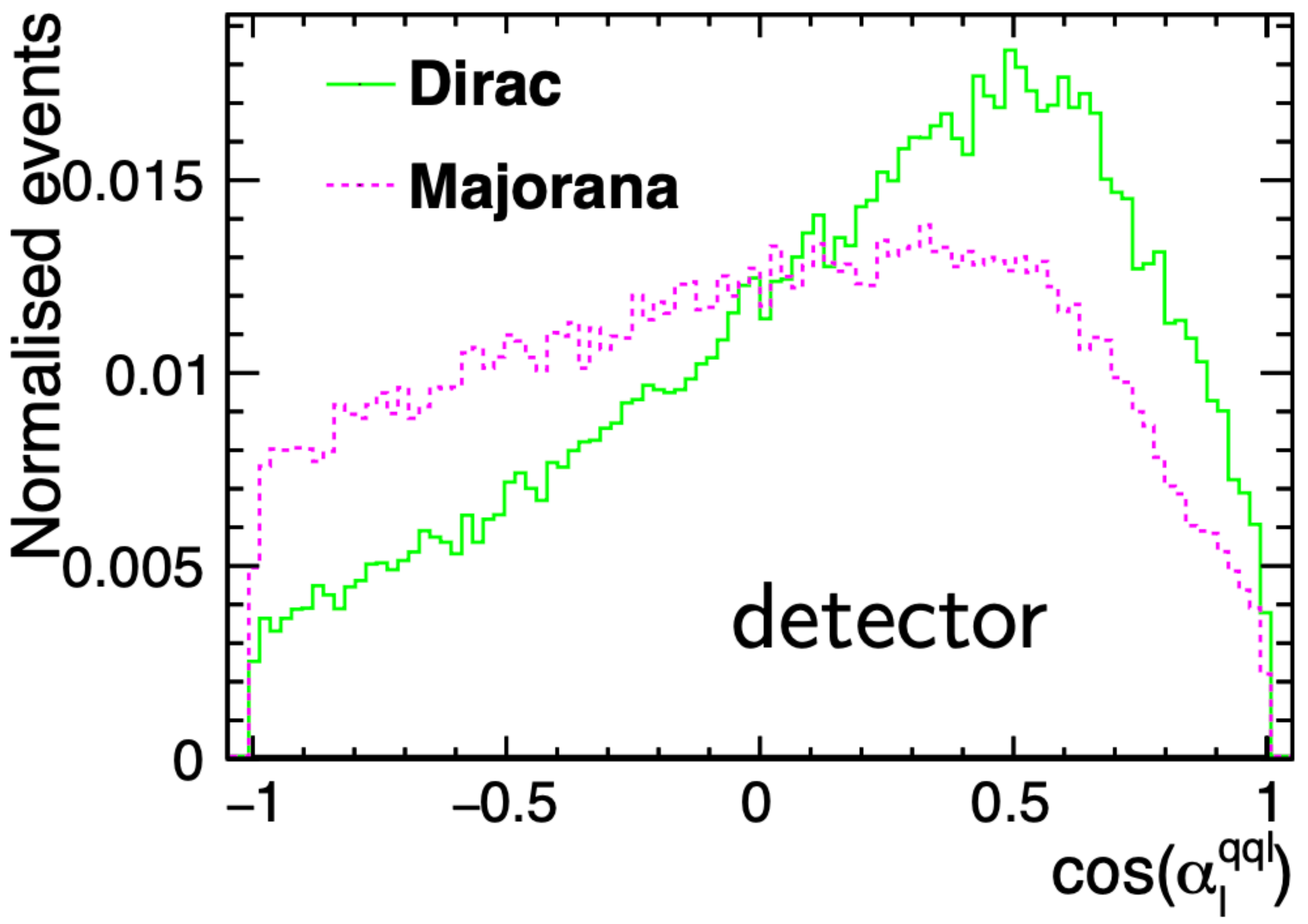

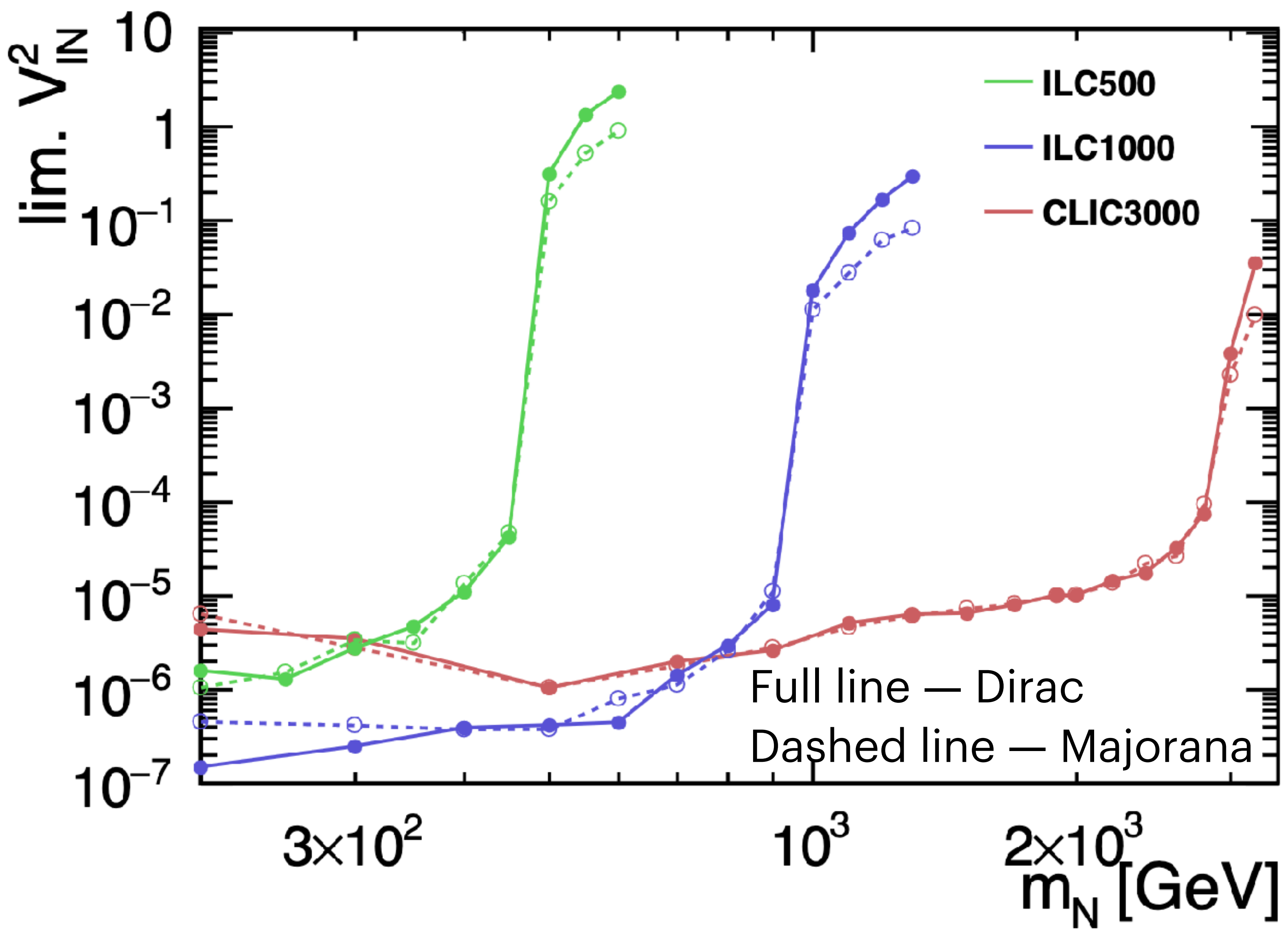

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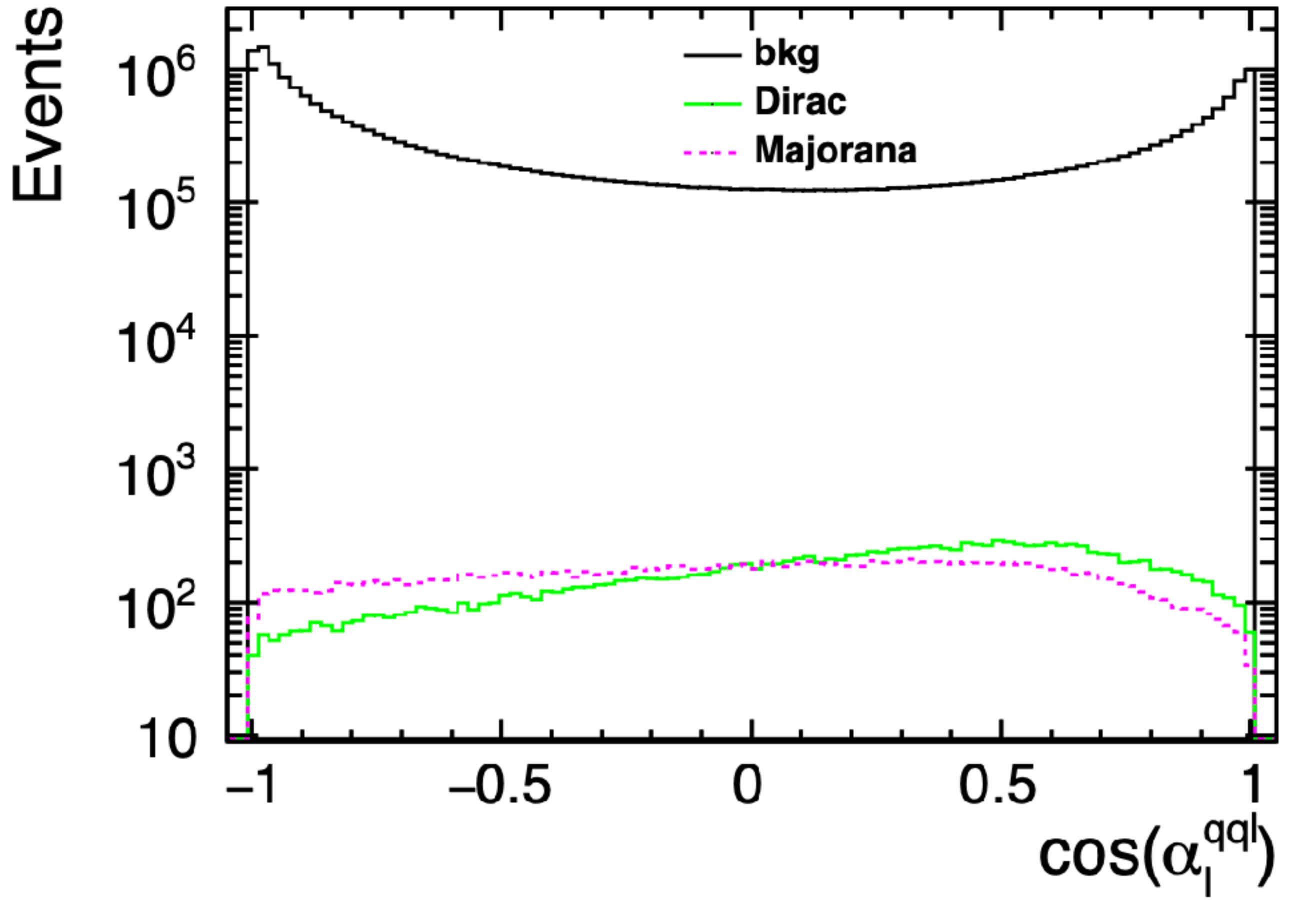
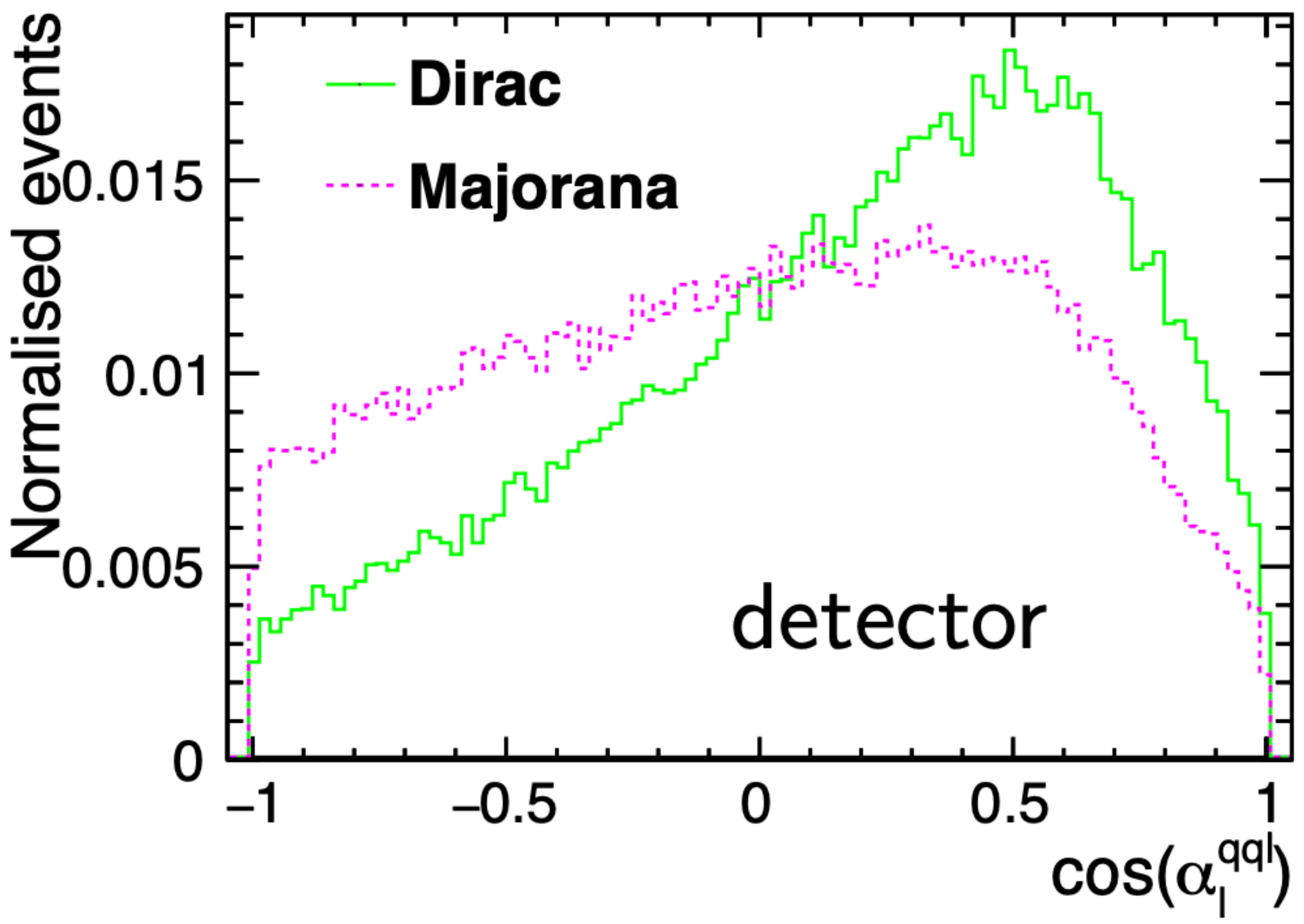
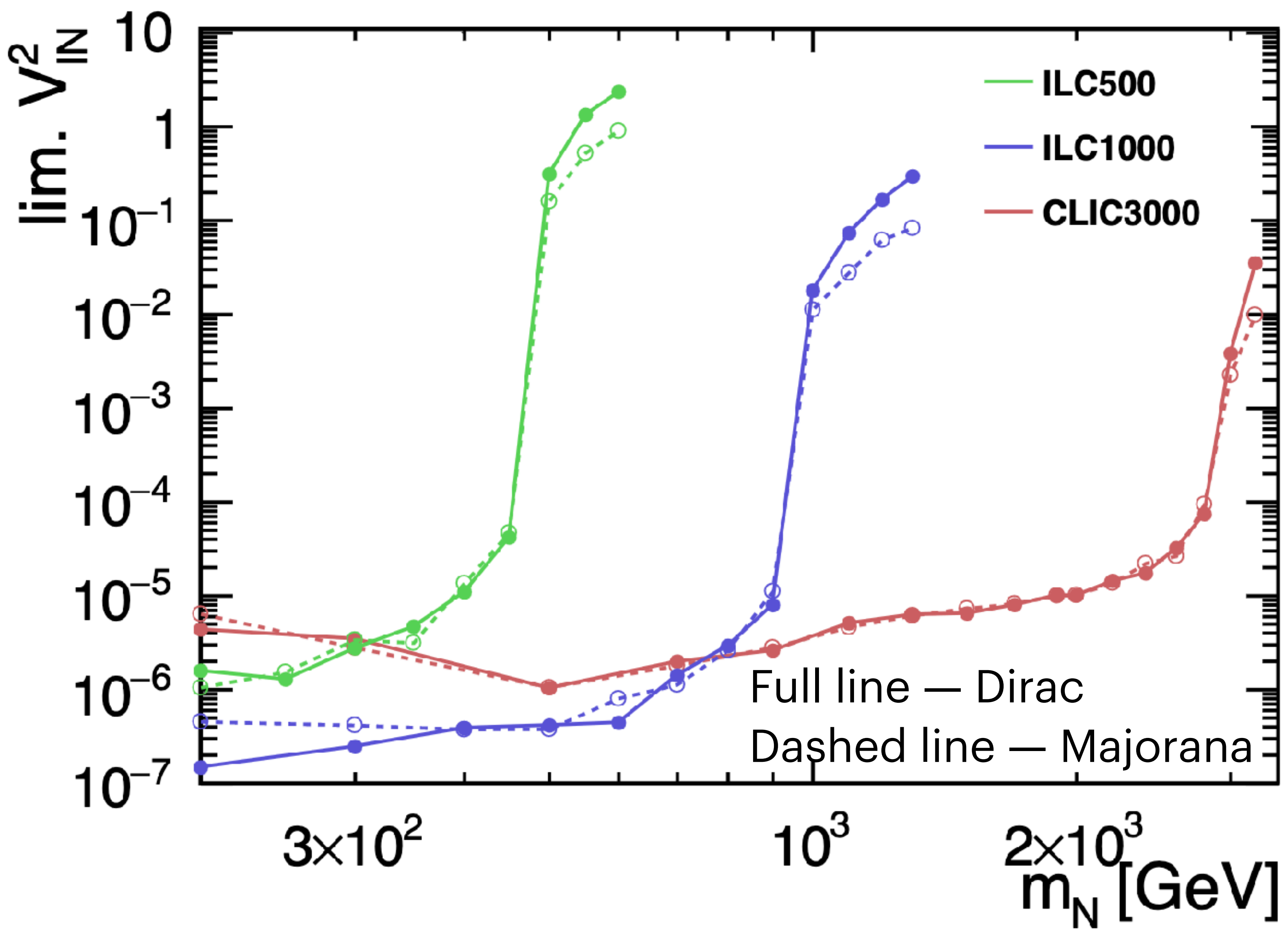
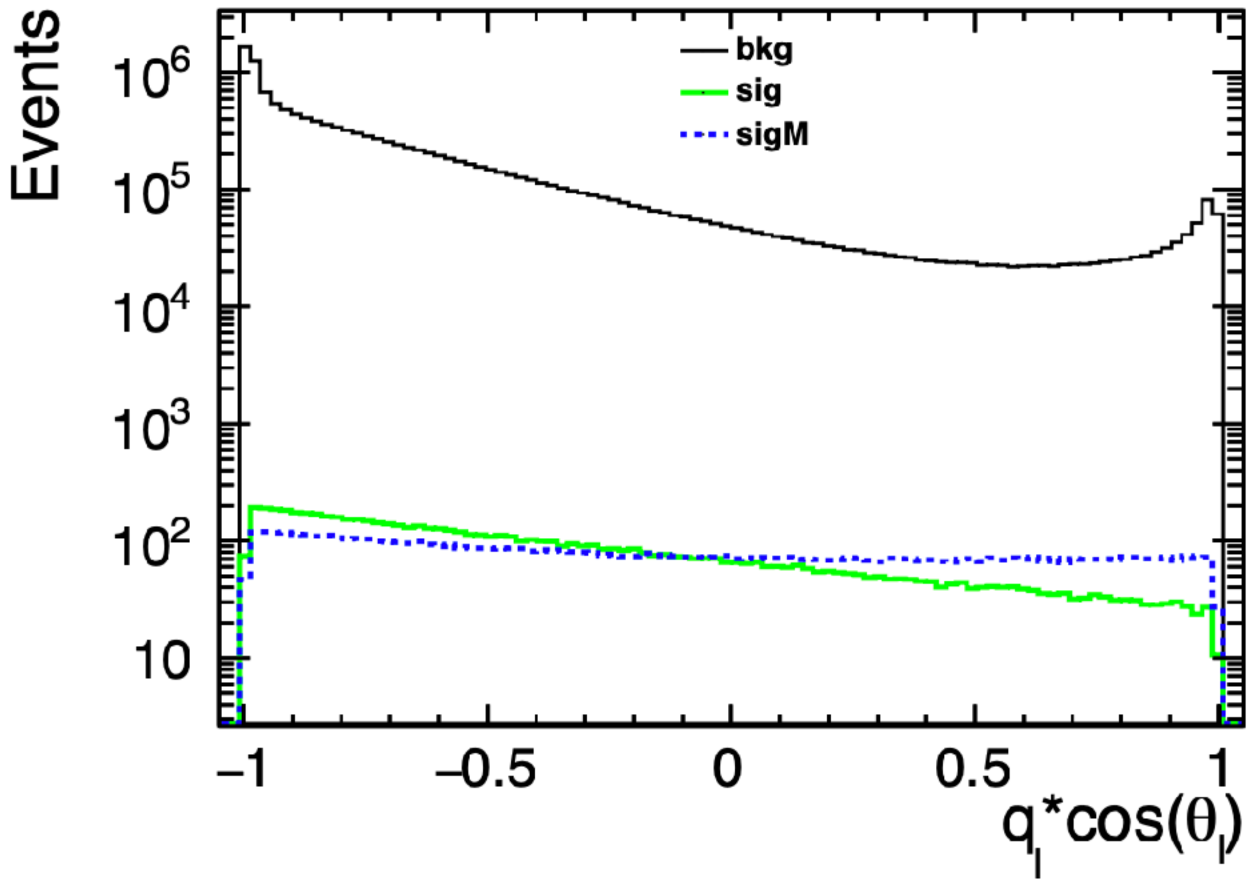


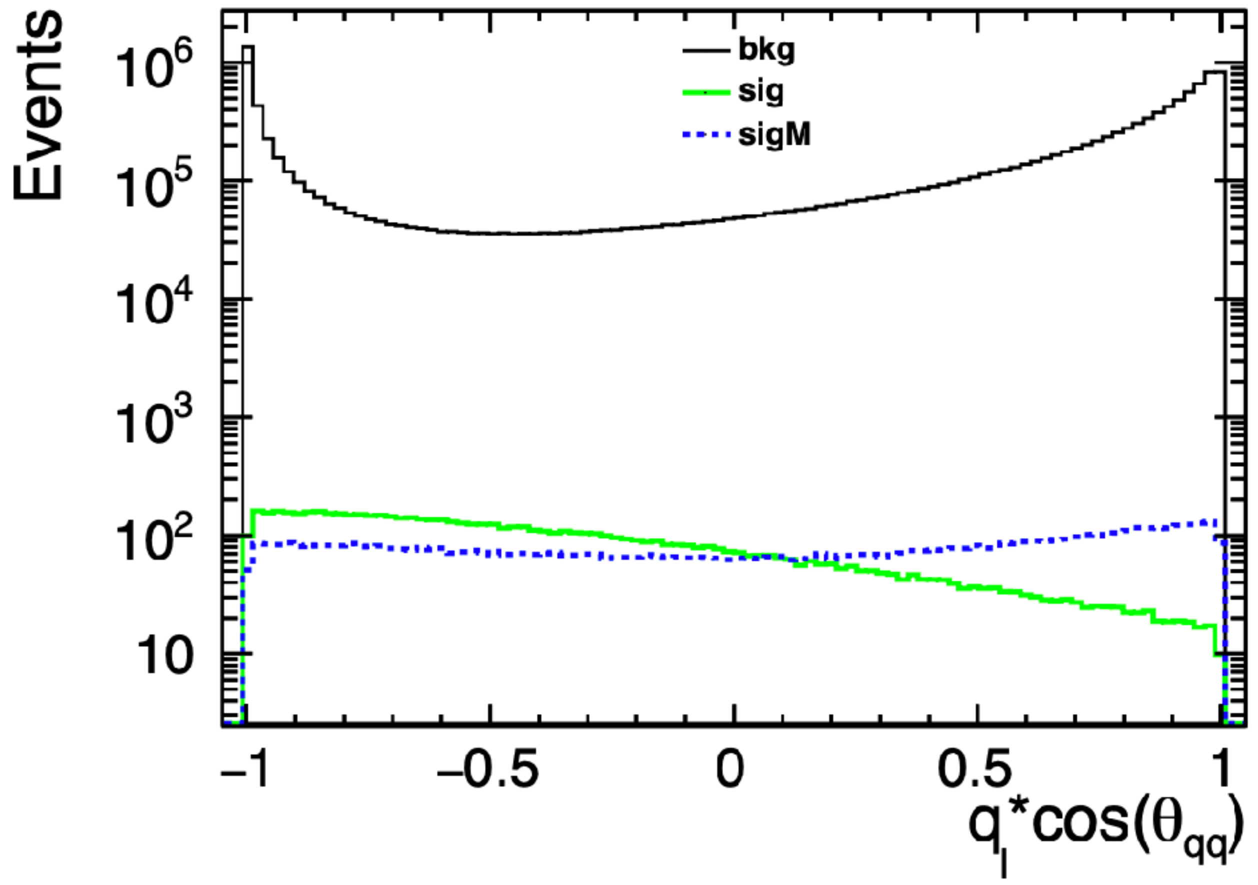




- More sophisticated variable: lepton and dijet angles relative to beam weighted by the lepton charge q_ℓ

ILC 250 GeV, $m_N = 150$ GeV

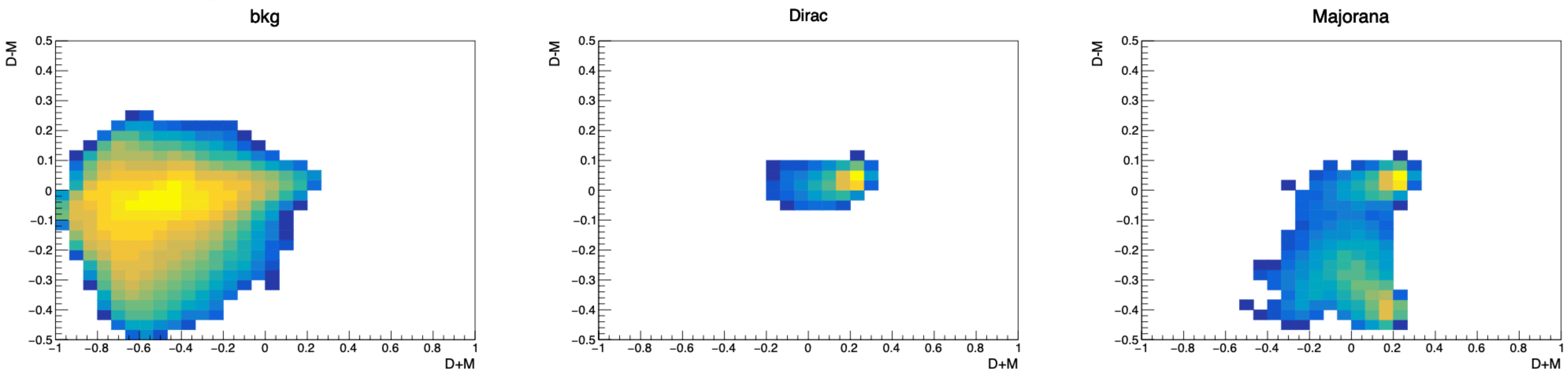




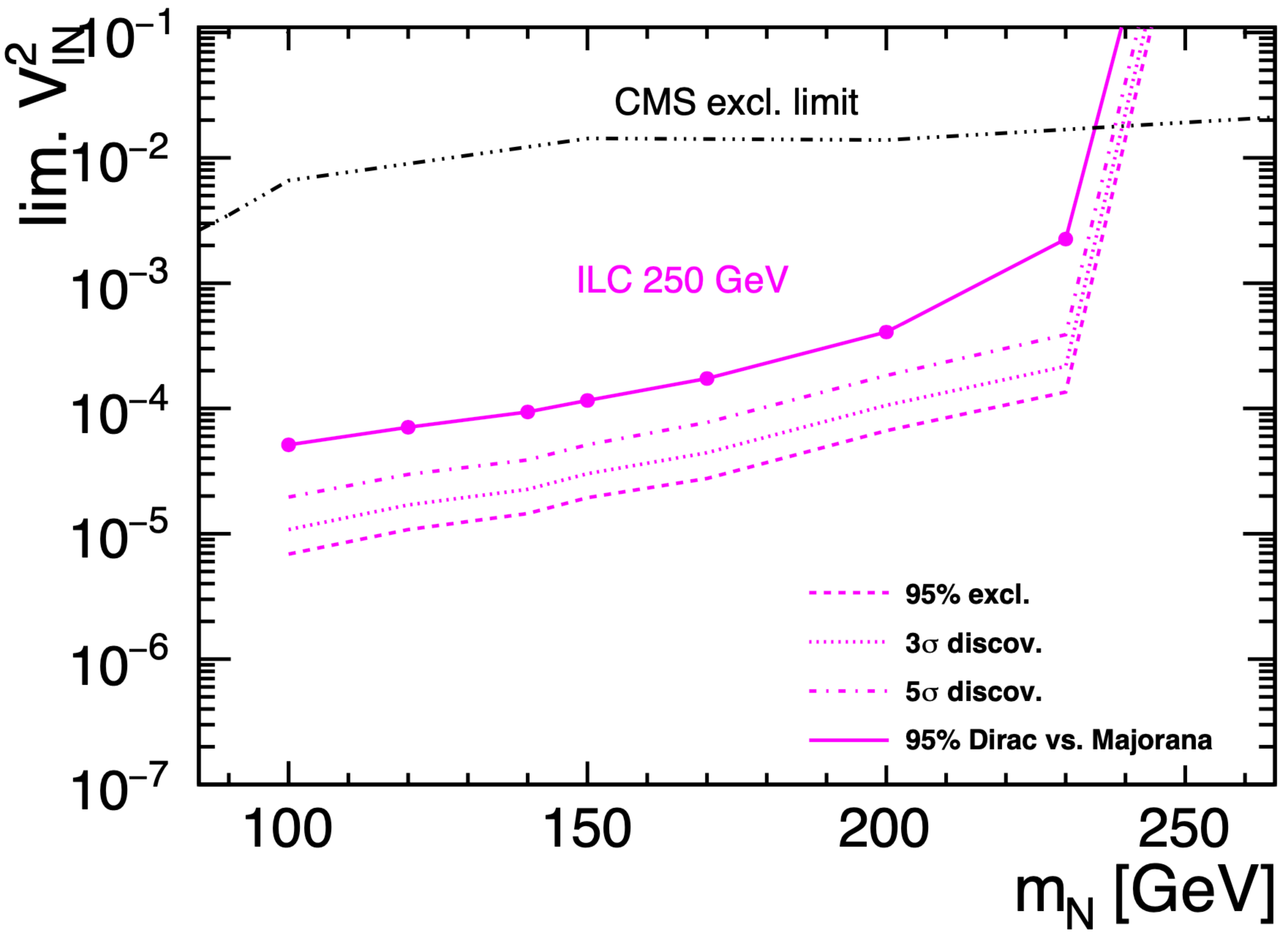
BDT framework for model discrimination

- 2 independent BDT trainins: Dirac vs. ($\alpha_{BDT} \cdot$ Majorana + Bkgd.) & Majorana vs. ($\alpha_{BDT} \cdot$ Dirac + Bkgd.)
- 2D histograms: $\mathrm{BDT}_D + \mathrm{BDT}_M$, $\mathrm{BDT}_D - \mathrm{BDT}_M$
- χ^2-like statistics: $T' = \sum_{bins} \frac{[(B+D)-(B+M)]^2}{\frac{1}{2}[(B+D)+(B+M)]} = \sum_{bins} \frac{(D-M)^2}{B + \frac{D+M}{2}}$ $\quad T' = T + \mathrm{DOF}$ $\quad T' \longrightarrow T'(\alpha_{lim}) = \sum_{bins} \frac{\alpha_{lim}^2 (D-M)^2}{B + \alpha_{lim} \cdot \frac{D+M}{2}}$
- Limit setting procedure: search for α_{lim} such that: $T(\alpha_{lim}) \stackrel{!}{=} \chi^2_{crit}(\mathrm{DOF})$
- Statistical test: $T \geq \chi^2_{crit}(\mathrm{DOF}) \implies$ signal hypotheses distinguishable
- Technical procedure:

1. Train BDT for different values α_{BDT}
2. For each α_{BDT}: calculate 95% CL limit
   α_{lim} such that $T(\alpha_{lim}) = \chi^2_{crit}(\mathrm{DOF})$
3. Select the best limit: $\alpha_{min} = \min\{\alpha_{lim}\}$
4. Set final limit as $V_{\ell N}^{\lim} = \alpha_{min} \cdot V_{\ell N}^{ref}$



Preliminary results



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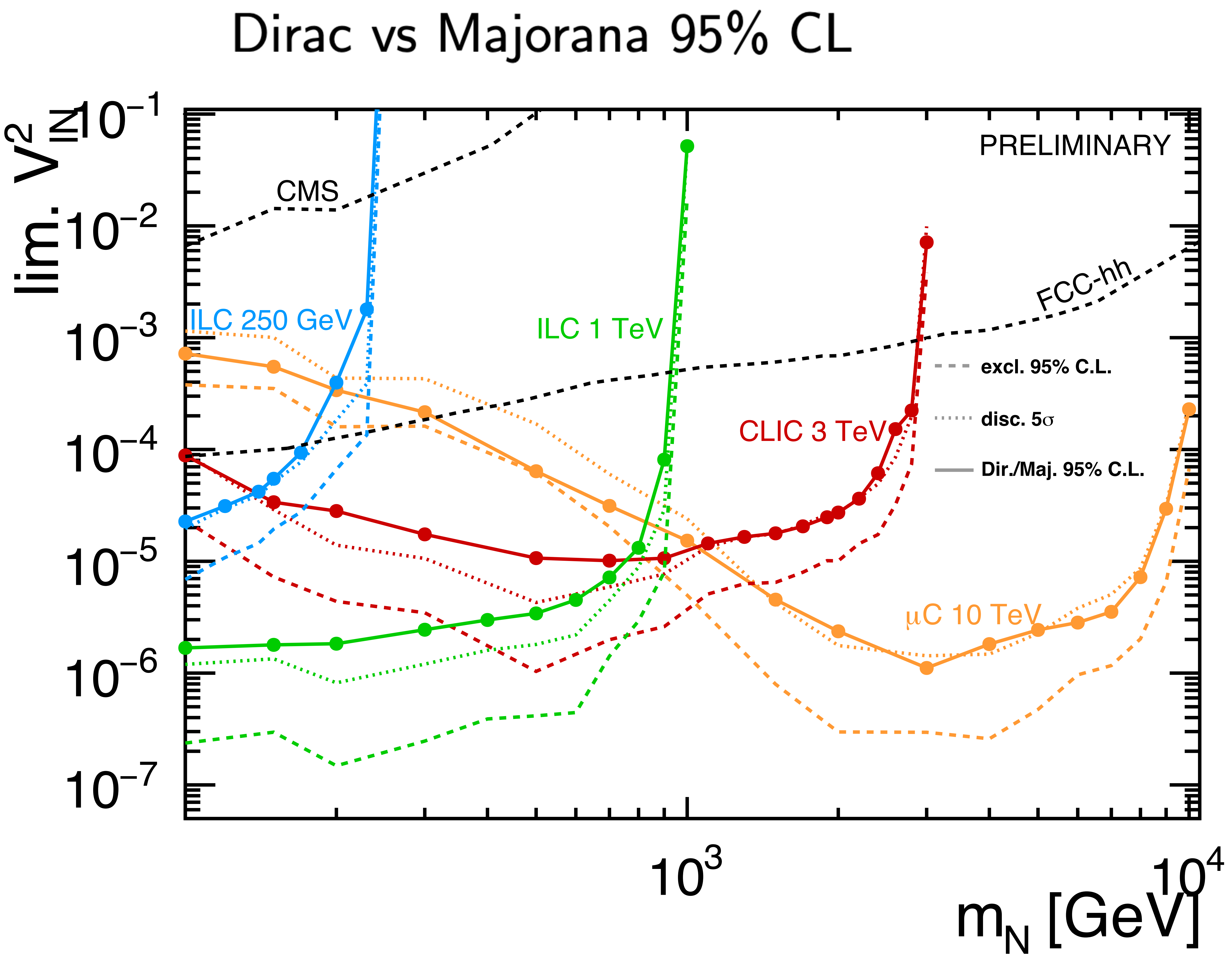


Almost directly with a discovery a Majorana vs. Dirac discrimnation possible!

Conclusions & Outlook

- Neutrinos connected (?) to many BSM roads: CP violation, Dark Matter, Flavor, Structure of the Universe
- Lepton collider with weak production excellent tool for discovery and discrimination
- Studies performed in simplified model resembling type-I seesaw model
- BDT analysis based on WHIZARD+Pythia+Delphes simulation chain: CLs limits
- Discovery reach for ILC-250/500/1000, CLIC-3000 [and MuC-3/10]
- Hadron collider reaches higher masses, lepton collider (much) lower couplings [MuC supersedes FCC-hh]
- Combination of charge & angular information allows access on Dirac vs. Majorana nature
- Discrimination almost always possible after a discovery
- Work in progress: complimentarity of electron- and muon measurements on flavor structure of mixings

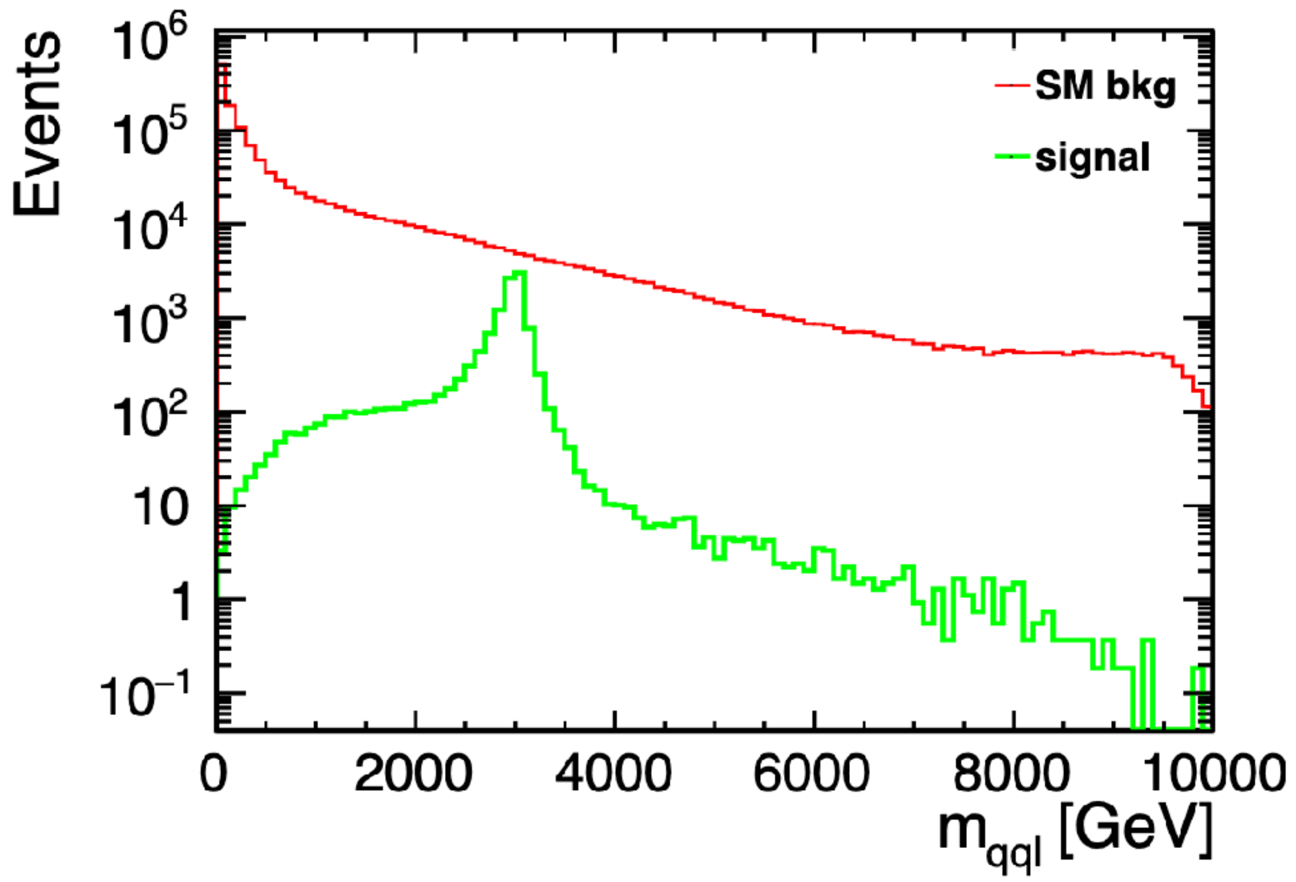
BACKUP

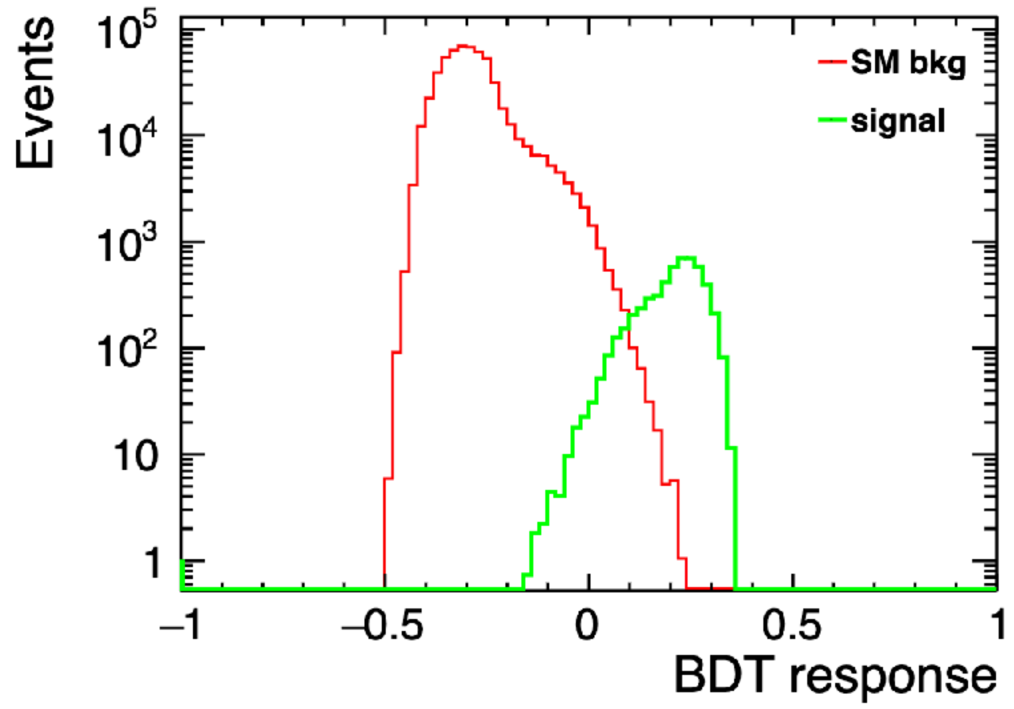
Analysis at MuC

Same analysis at muon collider much easier:

K. Mękała/JRR/A.F. Żarnecki, 2301.02602

- ☑ No beamstrahlung, Gaussian beam spread irrelevant
- ☑ QED initial state radiation is almost negligible
- ☑ QED-ISR/beamstrahlung: CLIC-3 vs. MuC-3
- ☑ Off-shell processes extend sensitivity beyond collider energy!





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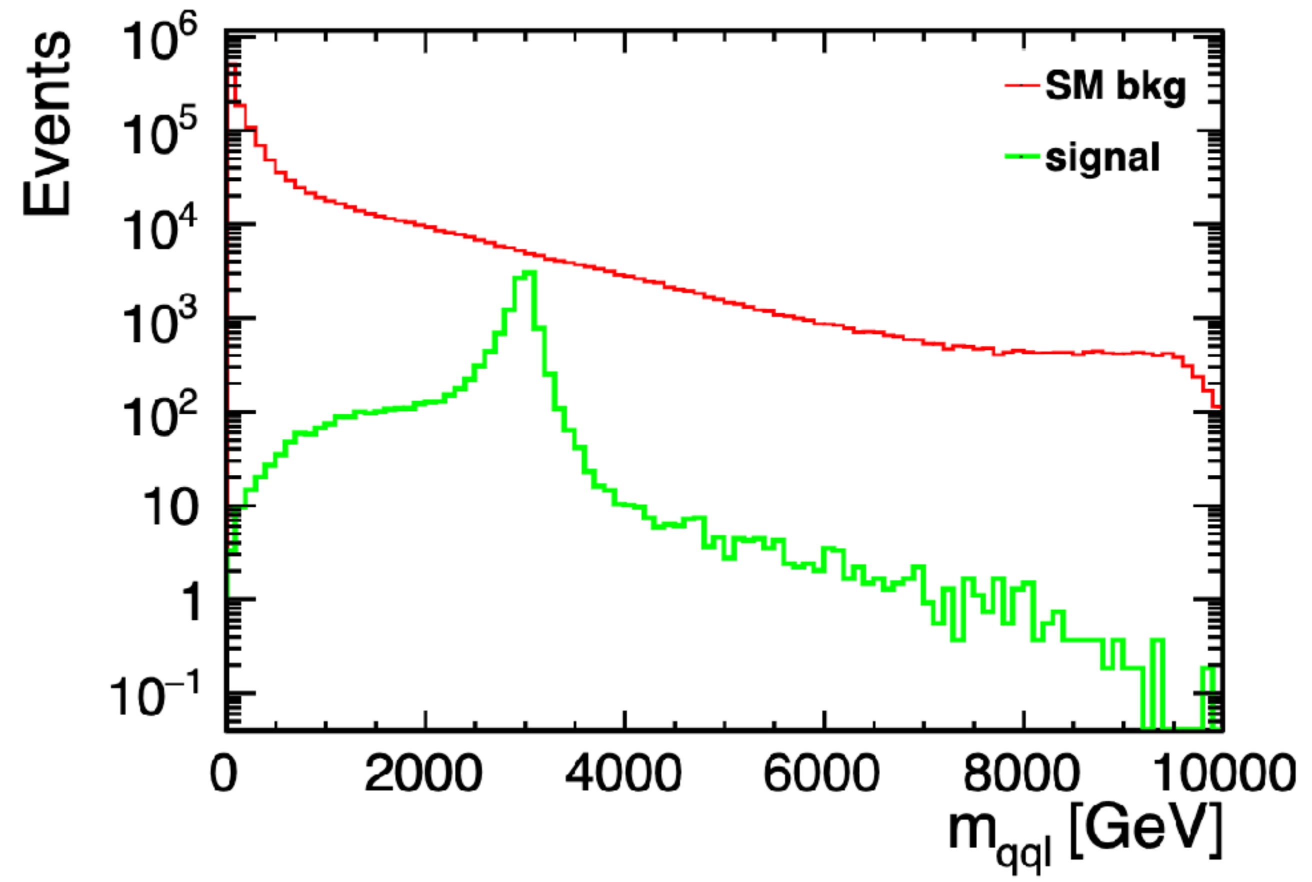

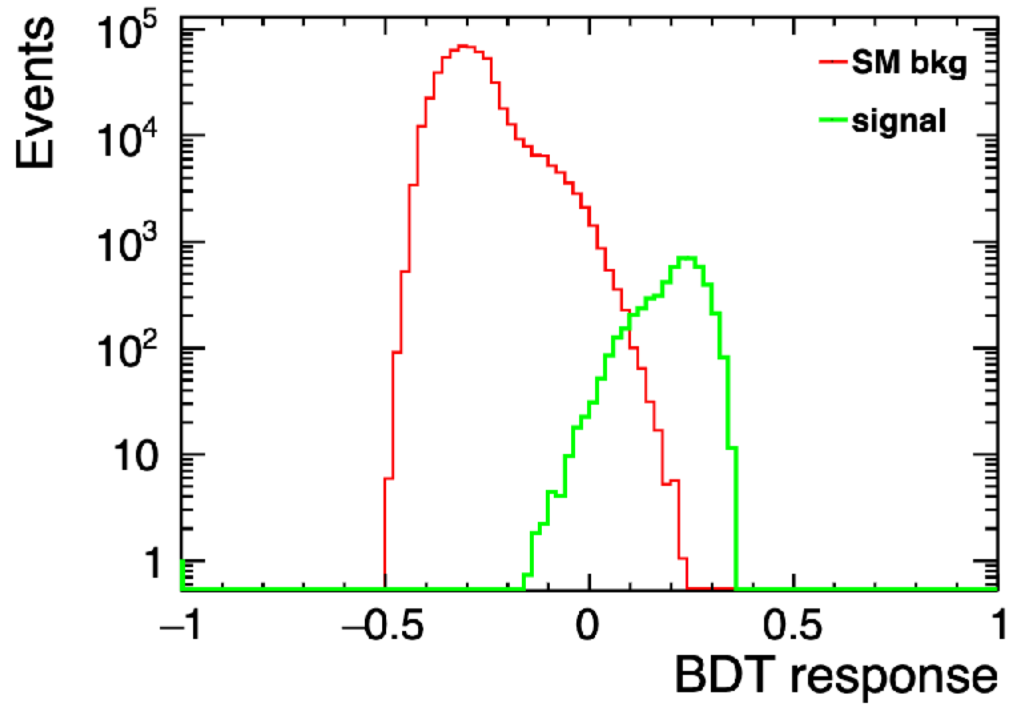

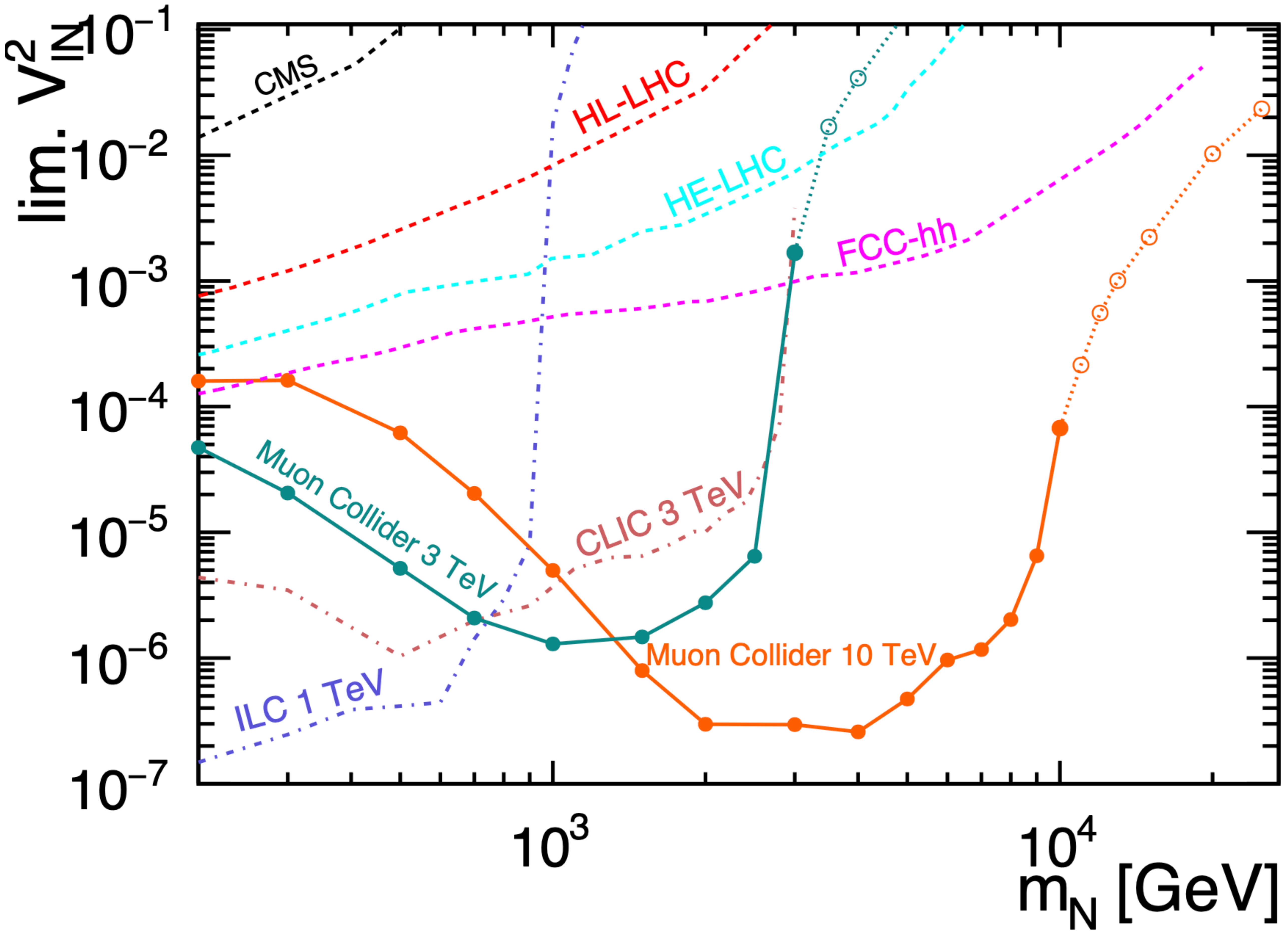

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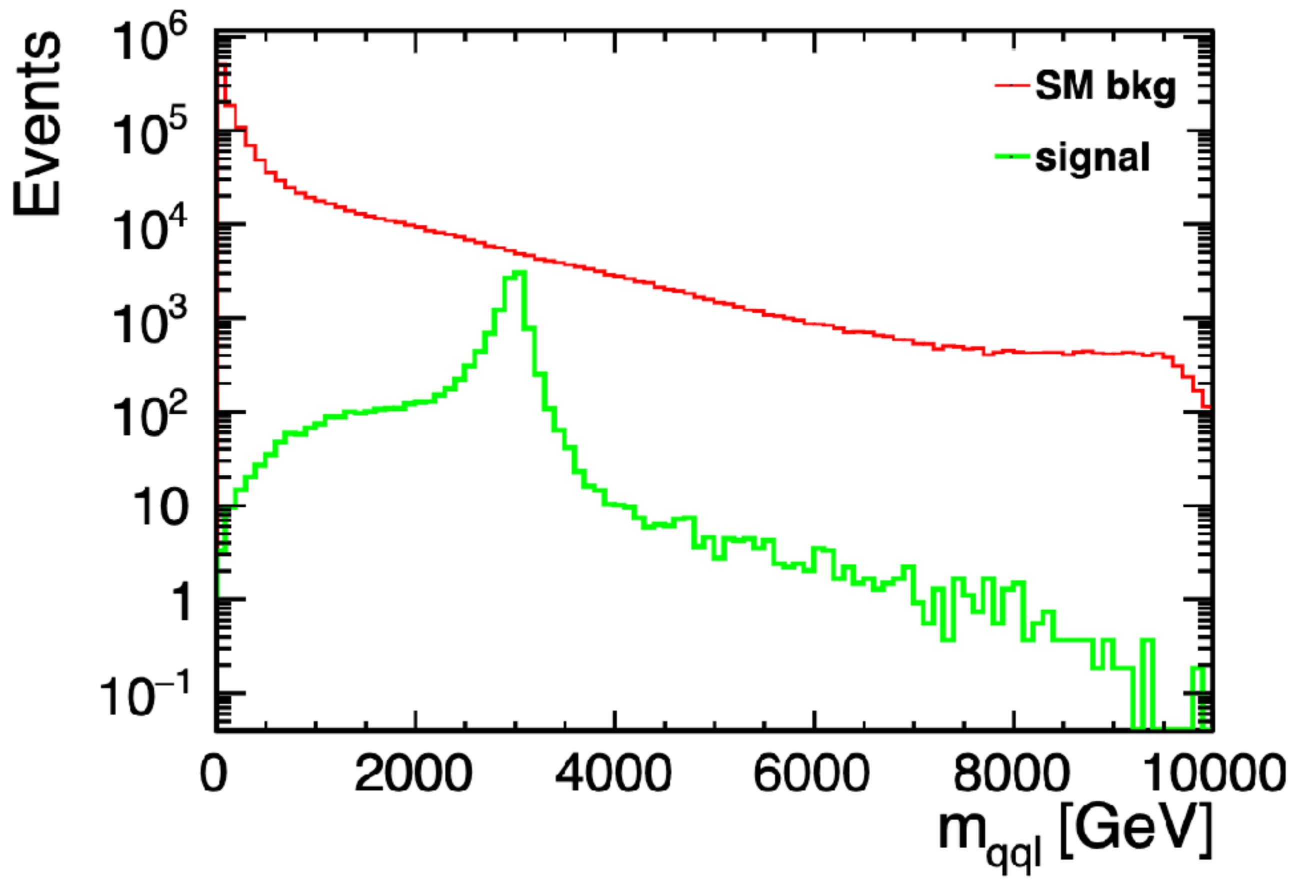

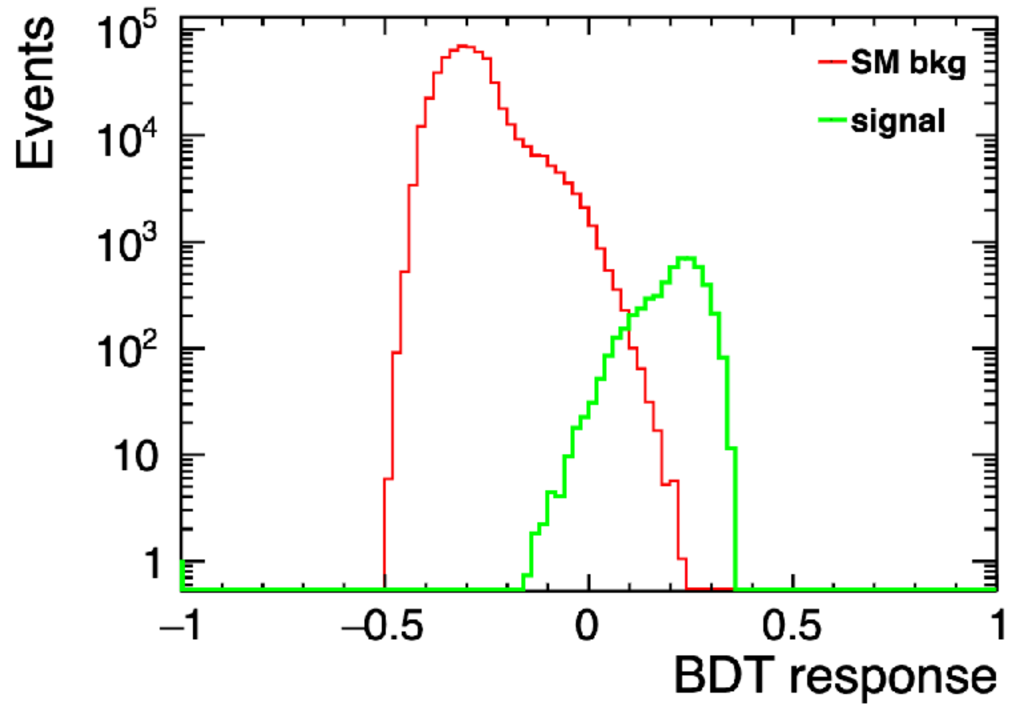

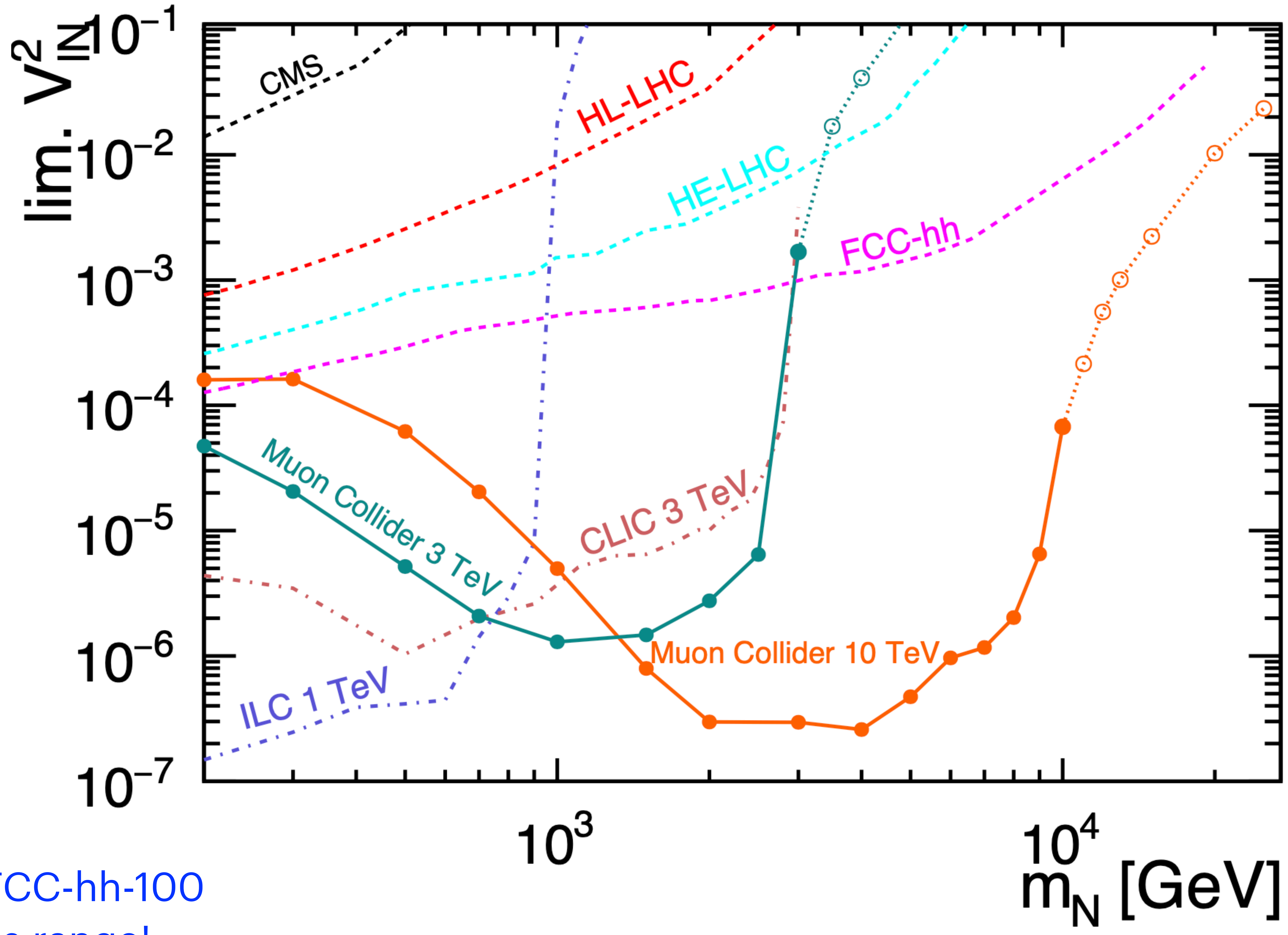

MuC-10 outperforms FCC-hh-100 over the whole mass range!