SIGNATURES FROM HEAVY NEUTRAL LEPTONS AT THE LHC

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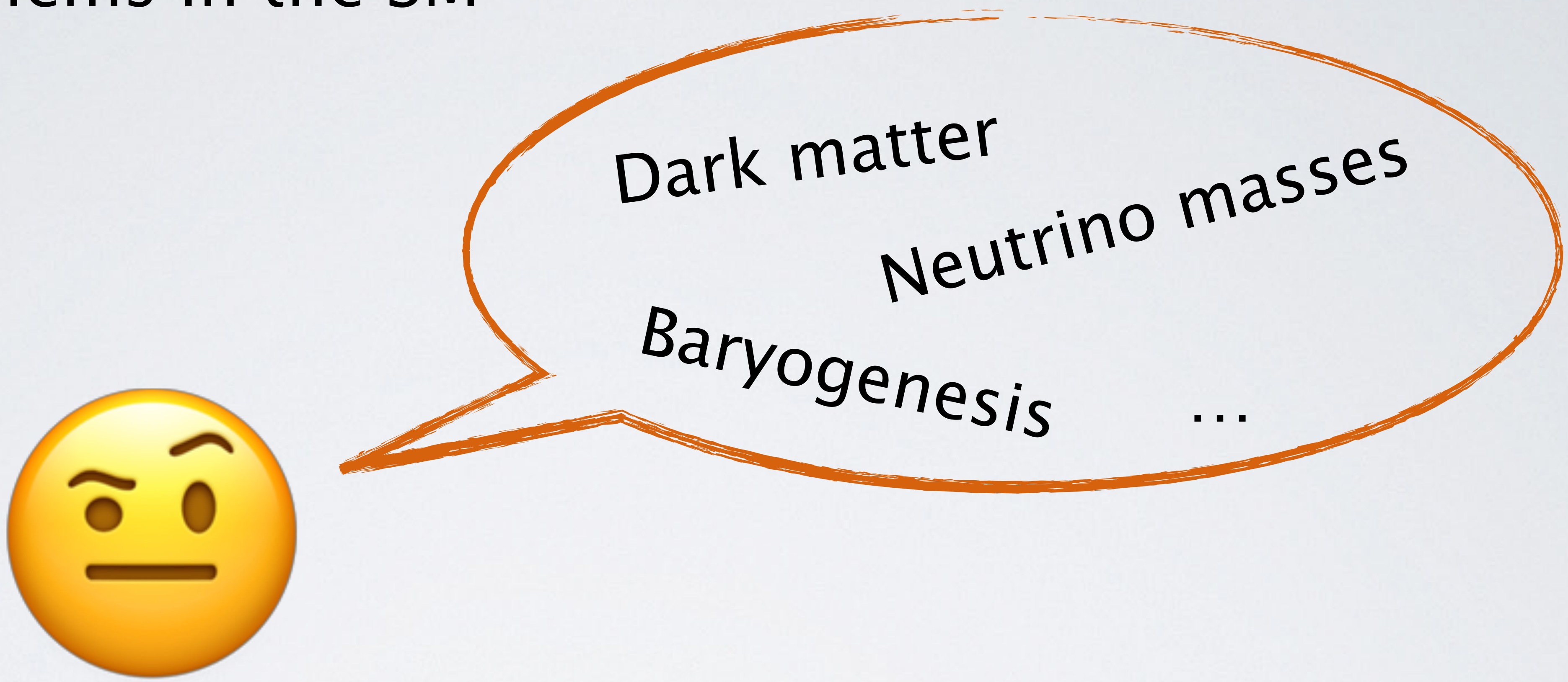
with **Asmaa Abada, Nicolás Bernal** and **Marta Losada**

Rencontre de Physique des Particules 2019

Jan 24th 2019, LPC Clermont

Why study Heavy Neutral Leptons?

- Open problems in the SM

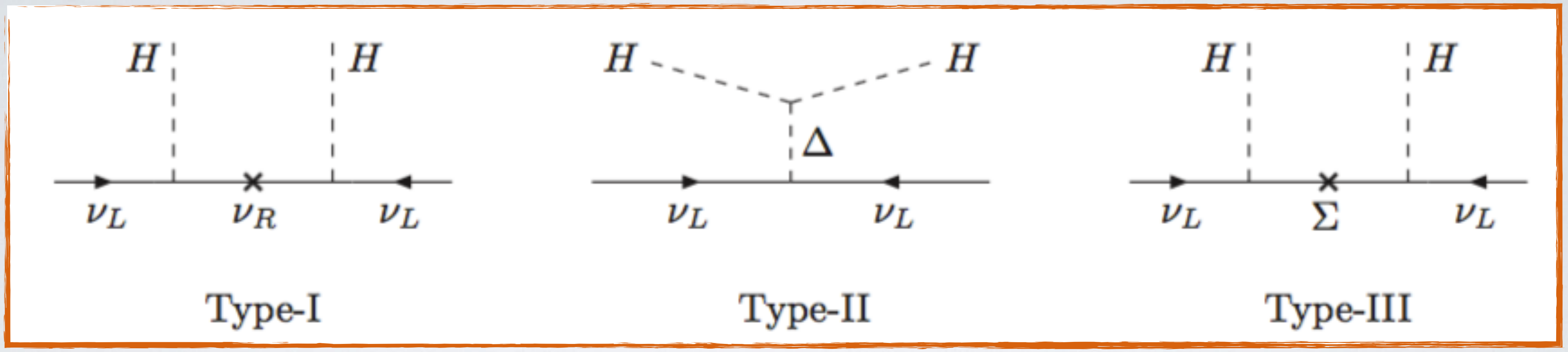


- Many BSM extensions add HNL to address some of these issues

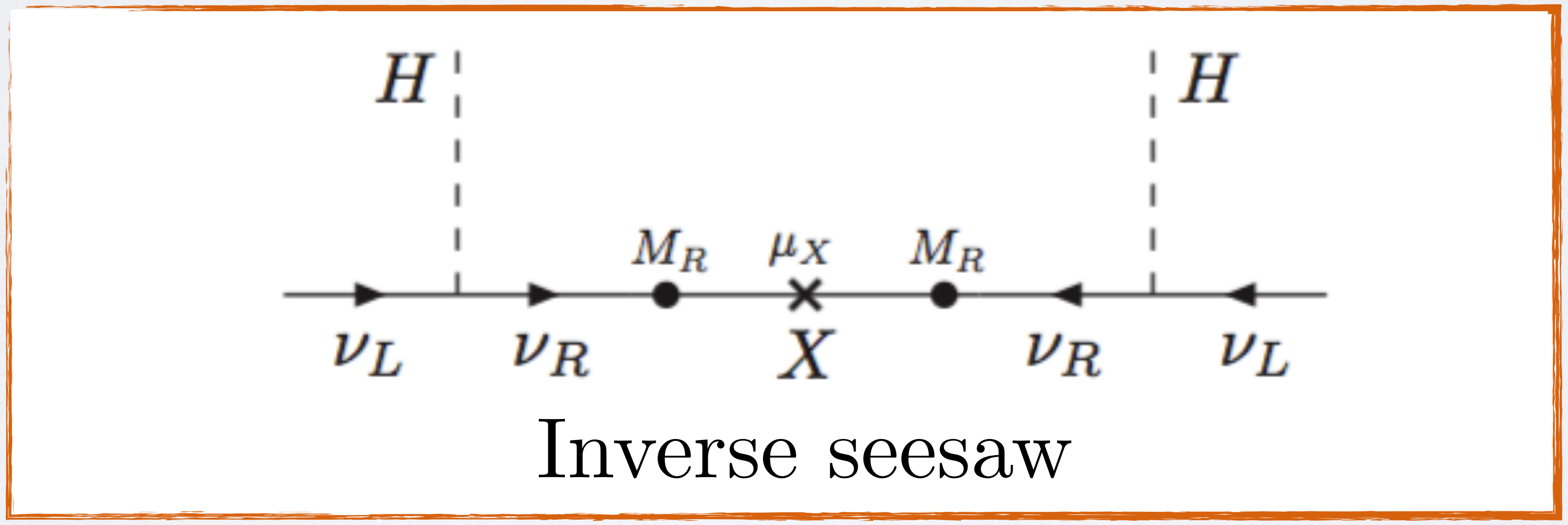
Heavy Neutral Leptons → Massive RH or sterile neutrinos

Seesaw models

- Well-known example:
  Heavy Neutral Leptons are present in seesaw models



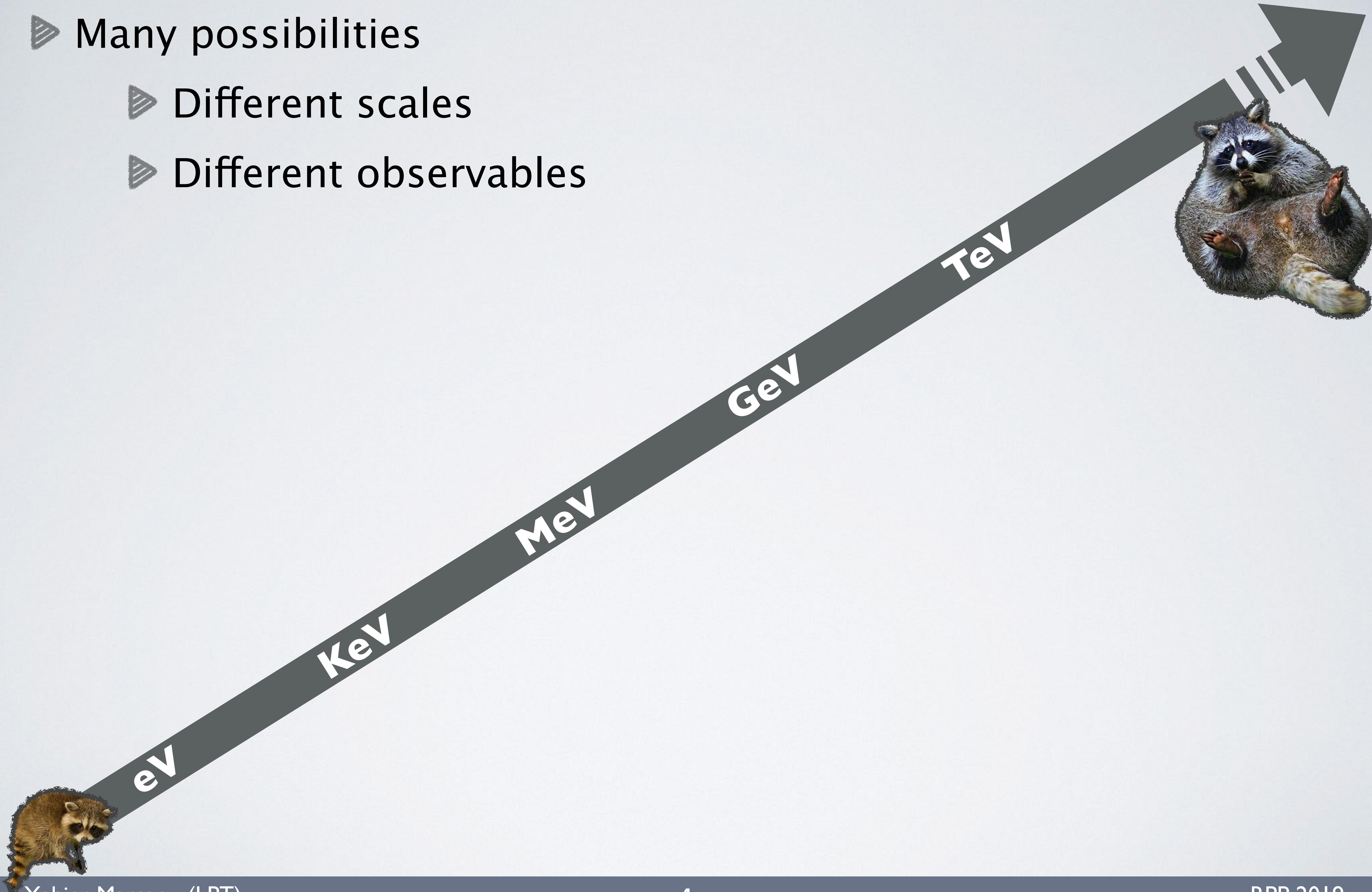
- Low scale seesaw models: νSM, inverse/linear seesaw…
  interesting variants with lower masses and larger couplings



- How heavy are these new HNL?

New (unknown) mass scale

- Many possibilities
  - Different scales
  - Different observables



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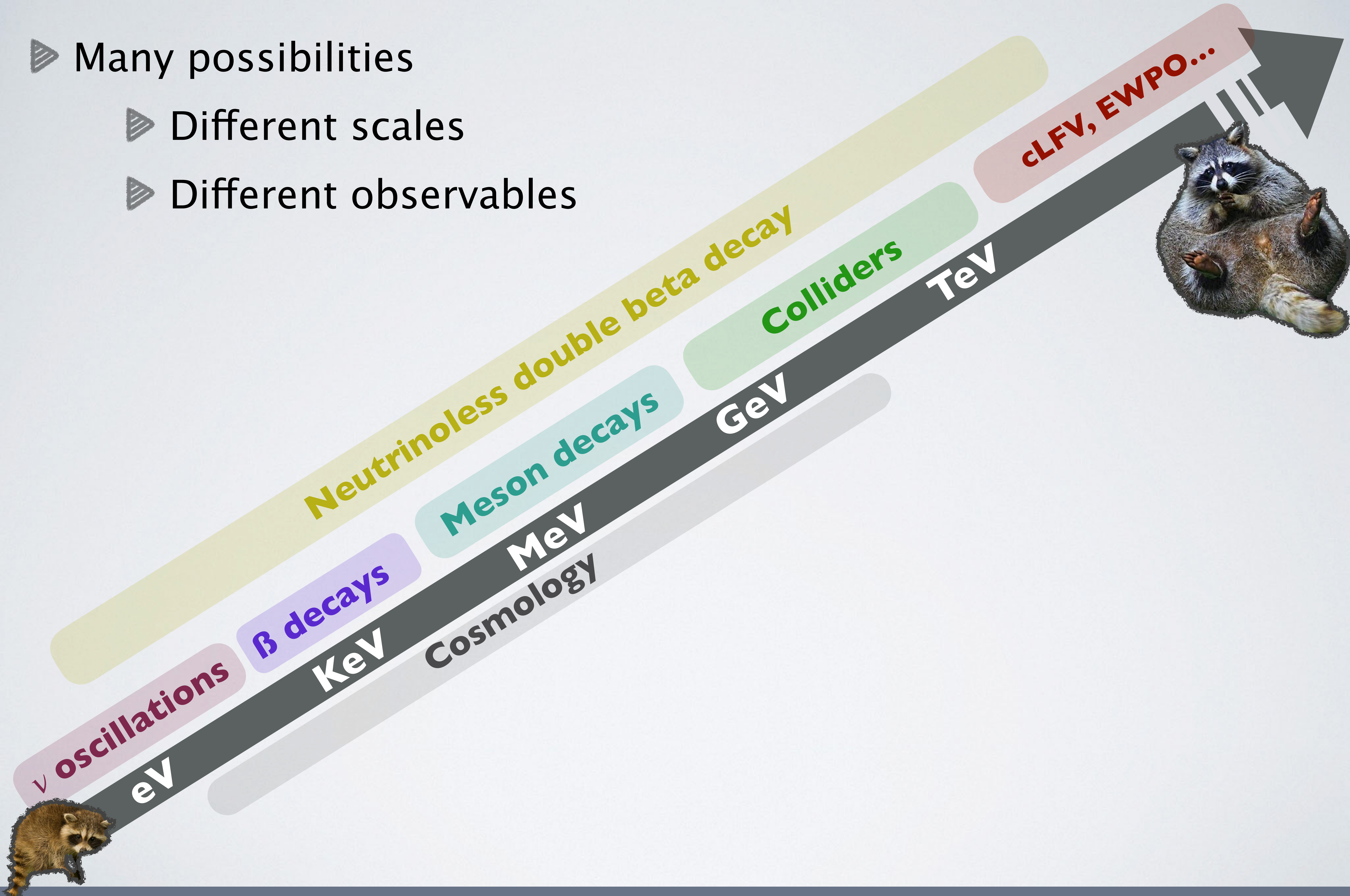

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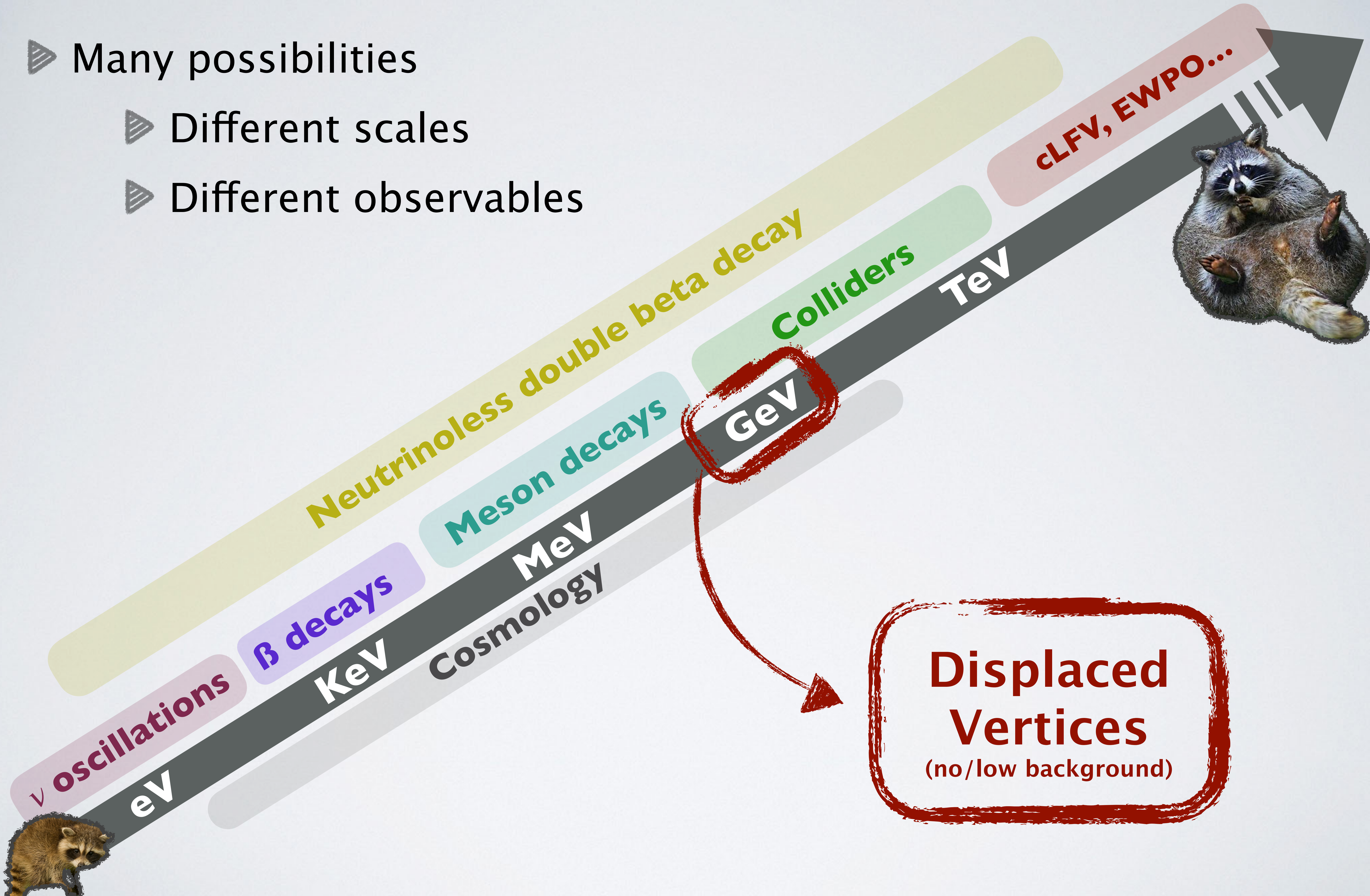
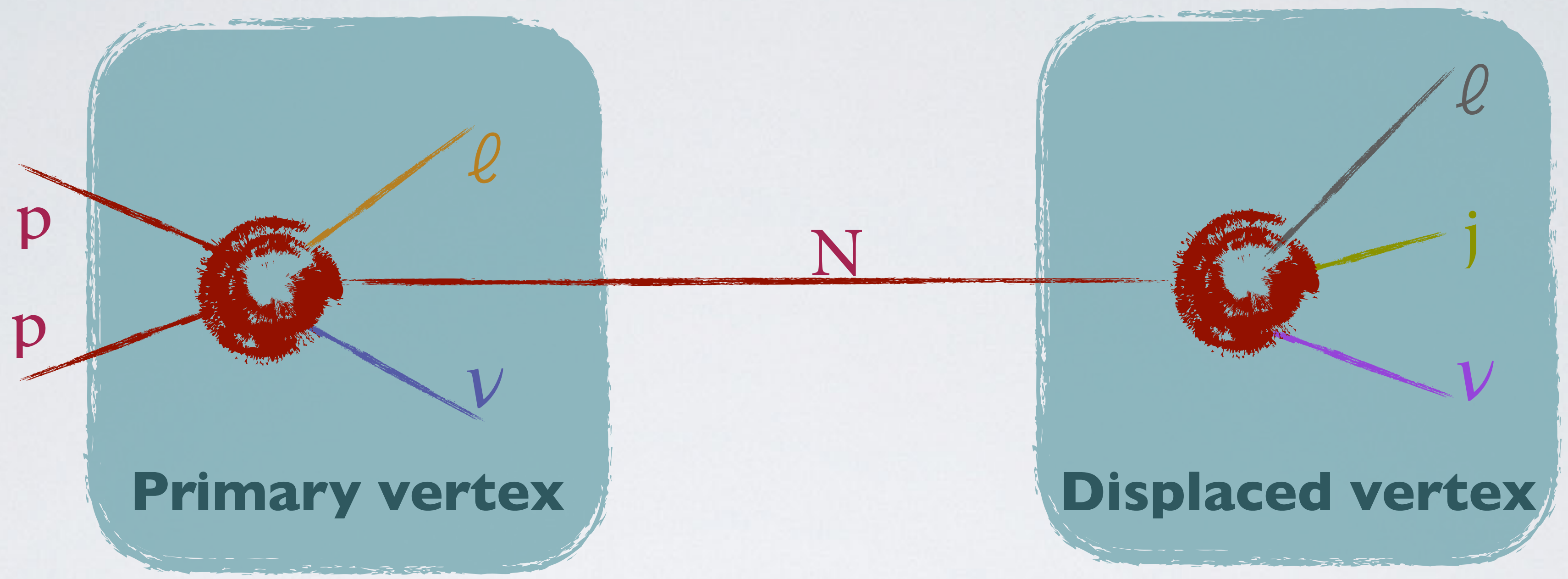


Displaced Vertex signatures @LHC



- Predictions for DV from HNL:

Helo, Hirsch, Kovalenko [PRD89 (2014) 073005]
Izaguirre, Shuve [PRD91 (2015) 093010]
Gago et al [EPJC75 (2015) 470]
Antusch, Cazzato, Fisher [PLB774(2017)114]
Cottin, Helo, Hirsch [PRD97 (2018) 055025]
Kling, Trojanowski [PRD97 (2018) 095016]
Helo, Hirsch, Wang [JHEP1807 (2018) 056]
…

- In this talk*:

The role of HNL flavor

LHC sensitivities

*More in the paper!!! JHEP 01 (2019) 093

Effective 3+1 Neutrino Model

- 4 masses $m_\nu = (m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_N)$

- 4x4 mixing matrix

$$U^{\nu}_{4\times 4} = \left(\begin{array}{c|c} \widetilde{U}_{\rm PMNS} & \begin{array}{c} V_{eN} \\ V_{\mu N} \\ V_{\tau N} \end{array} \\ \hline & \end{array} \right)$$

- FeynRules > MadGraph > Pythia > MadAnalysis

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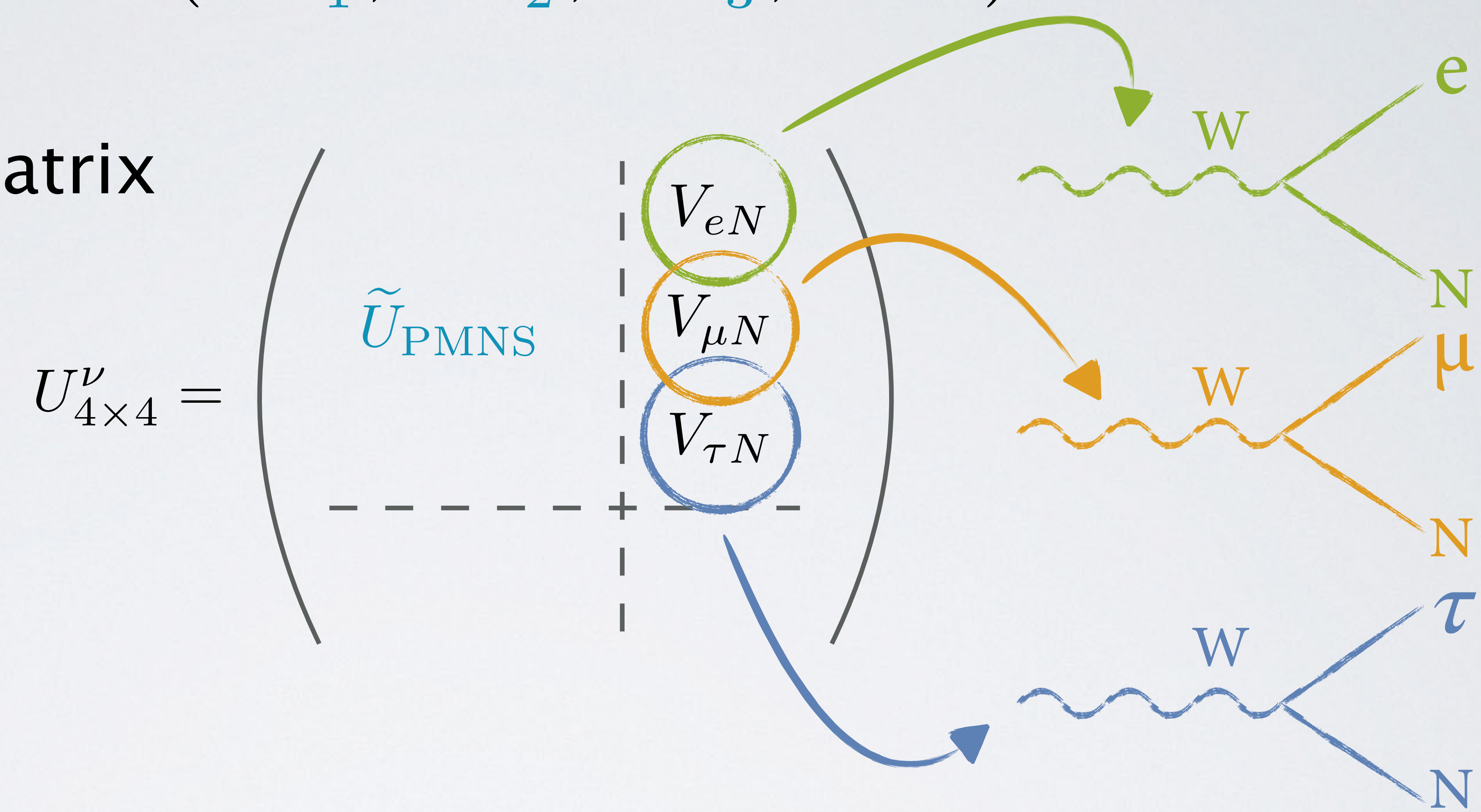

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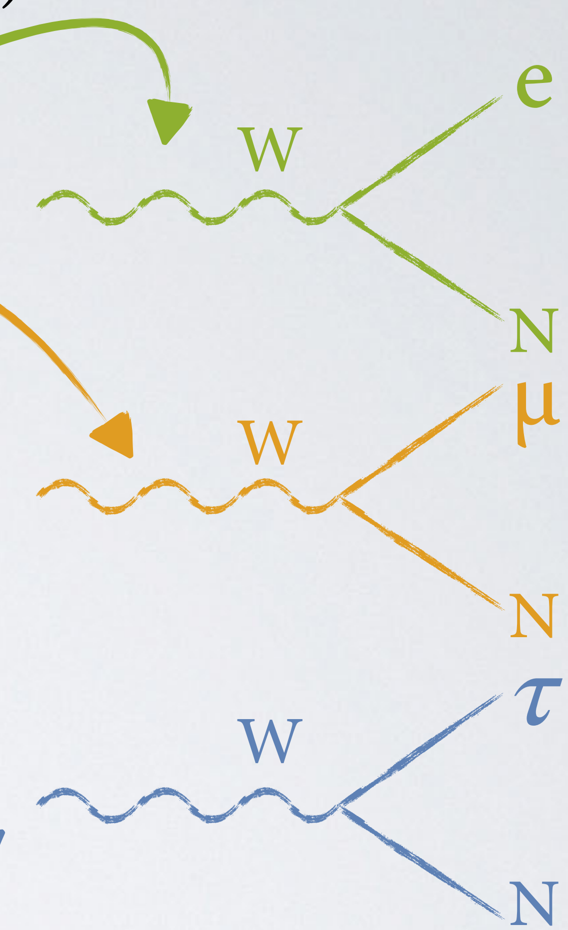


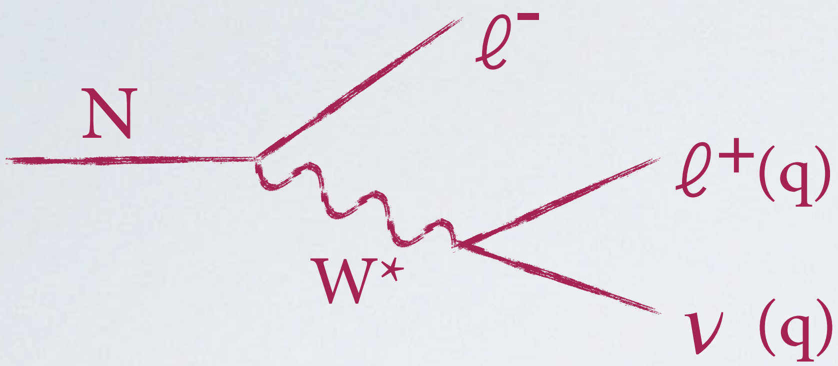
⊕Neutral currents

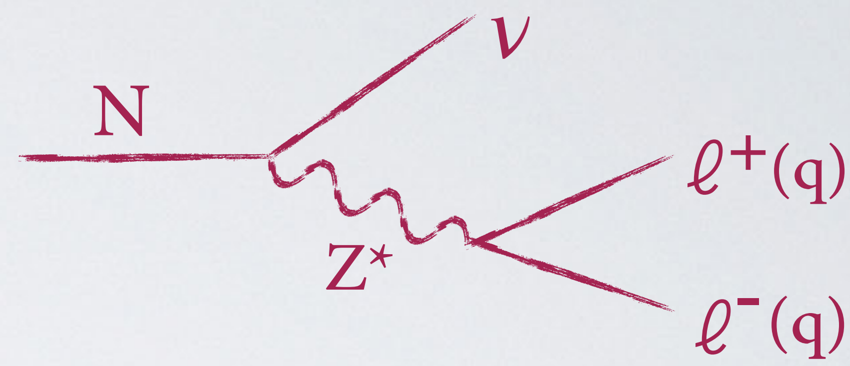
- FeynRules > MadGraph > Pythia > MadAnalysis

Heavy Neutral Lepton decays

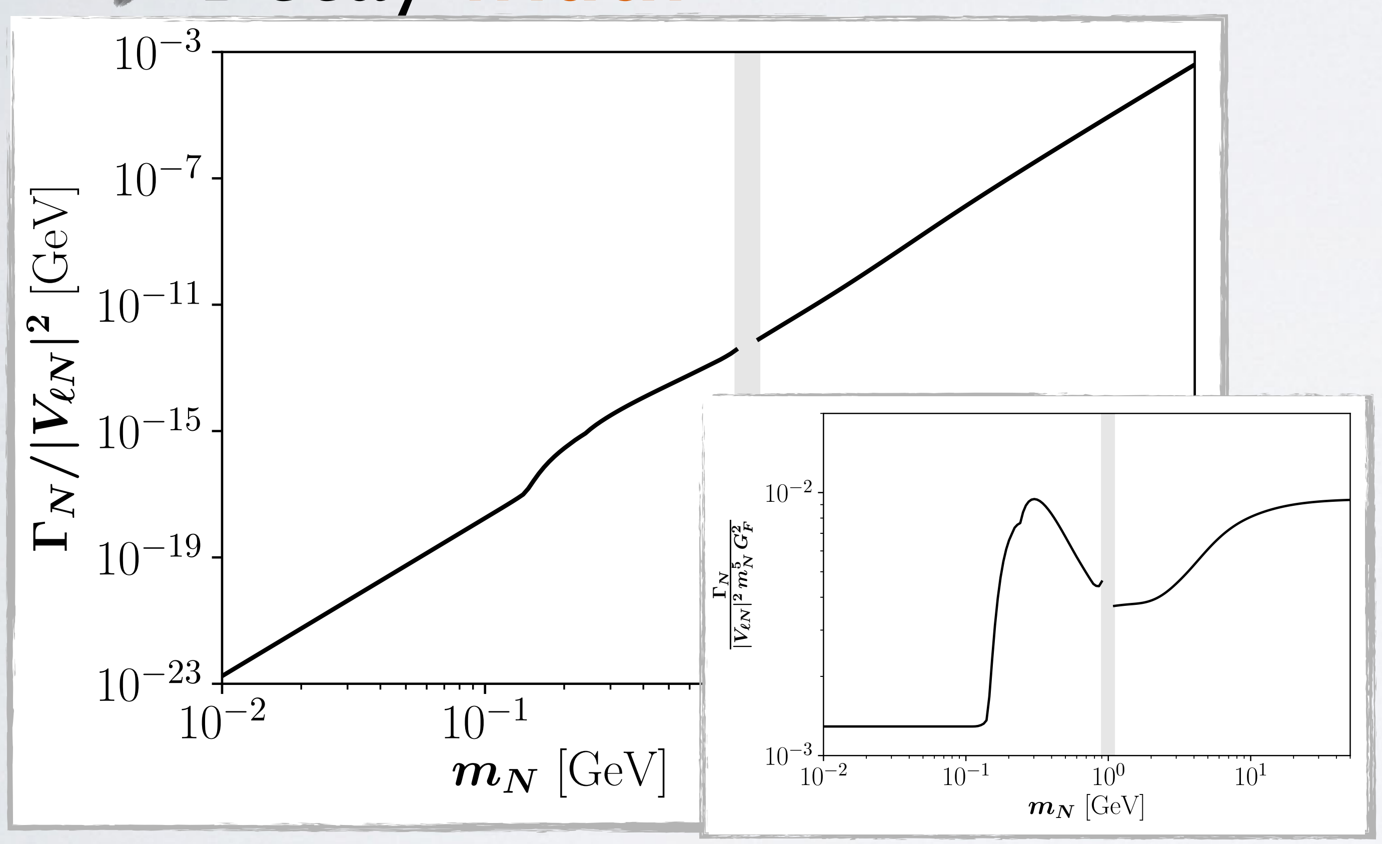
$m_N < m_W$

- Decays via off-shell W and Z

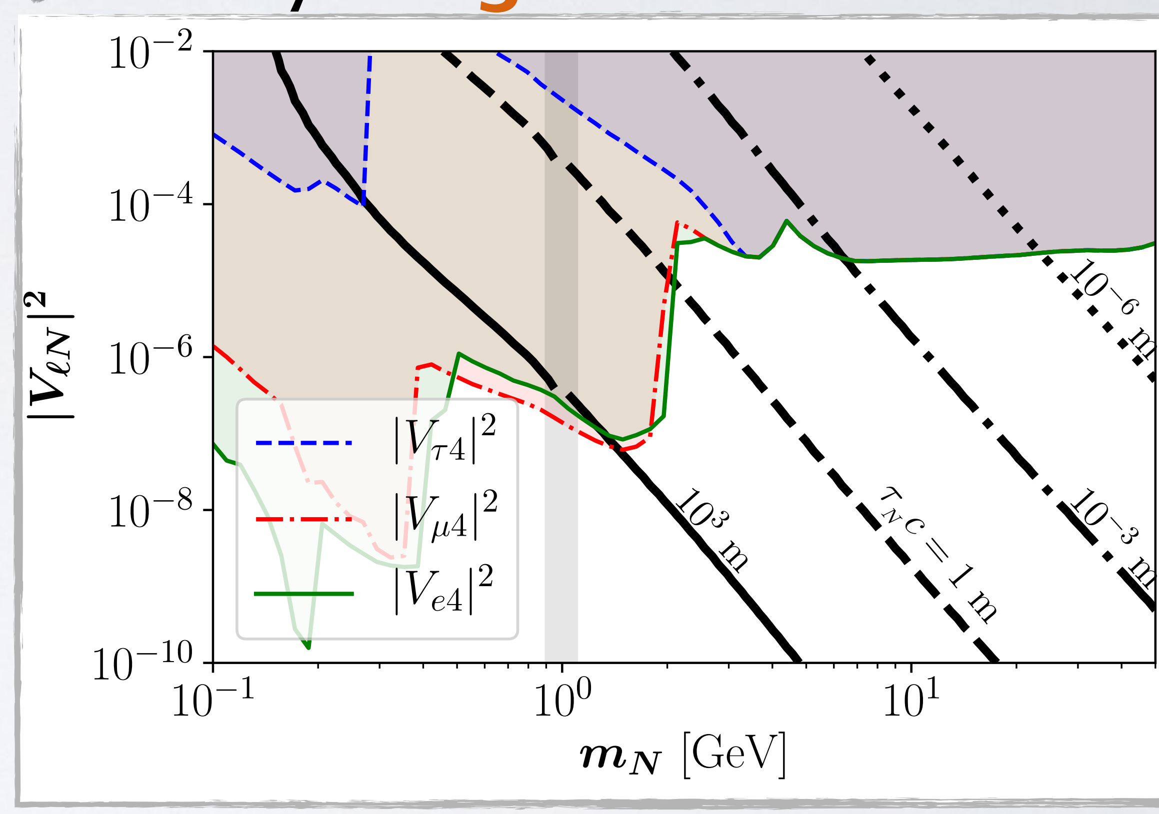




- Decay **width***



- Decay **length**



$$\Gamma_N \propto G_F^2 m_N^5 \sum_\ell |V_{\ell N}|^2$$

*Computed using formulas from:
Atre et al [JHEP 05 (2009) 030]
Abada et al [JHEP 02 (2018) 169]
Bondarenko et al [JHEP 11 (2018) 032]

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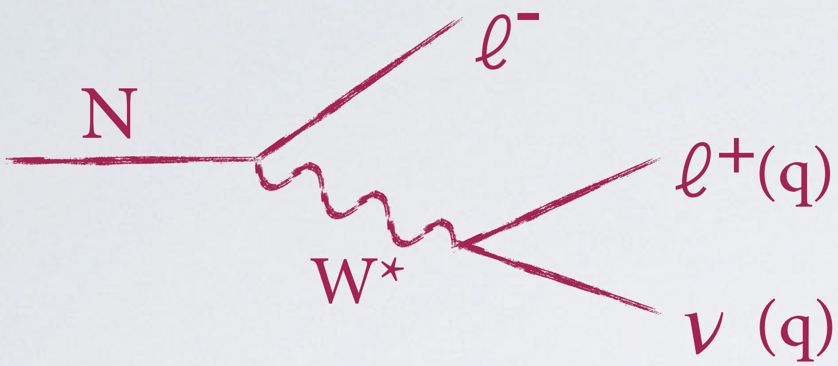

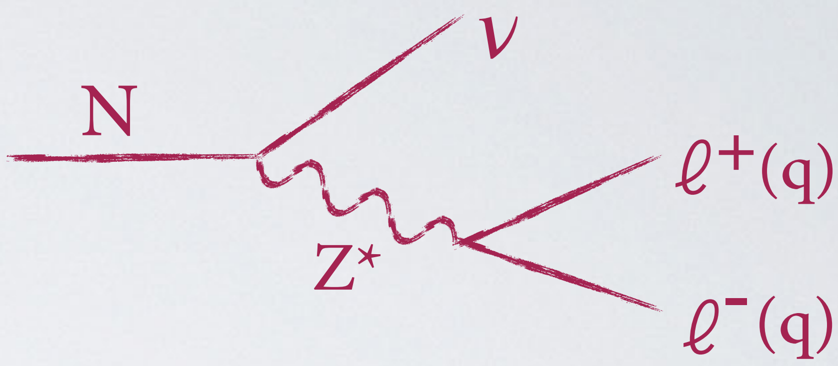

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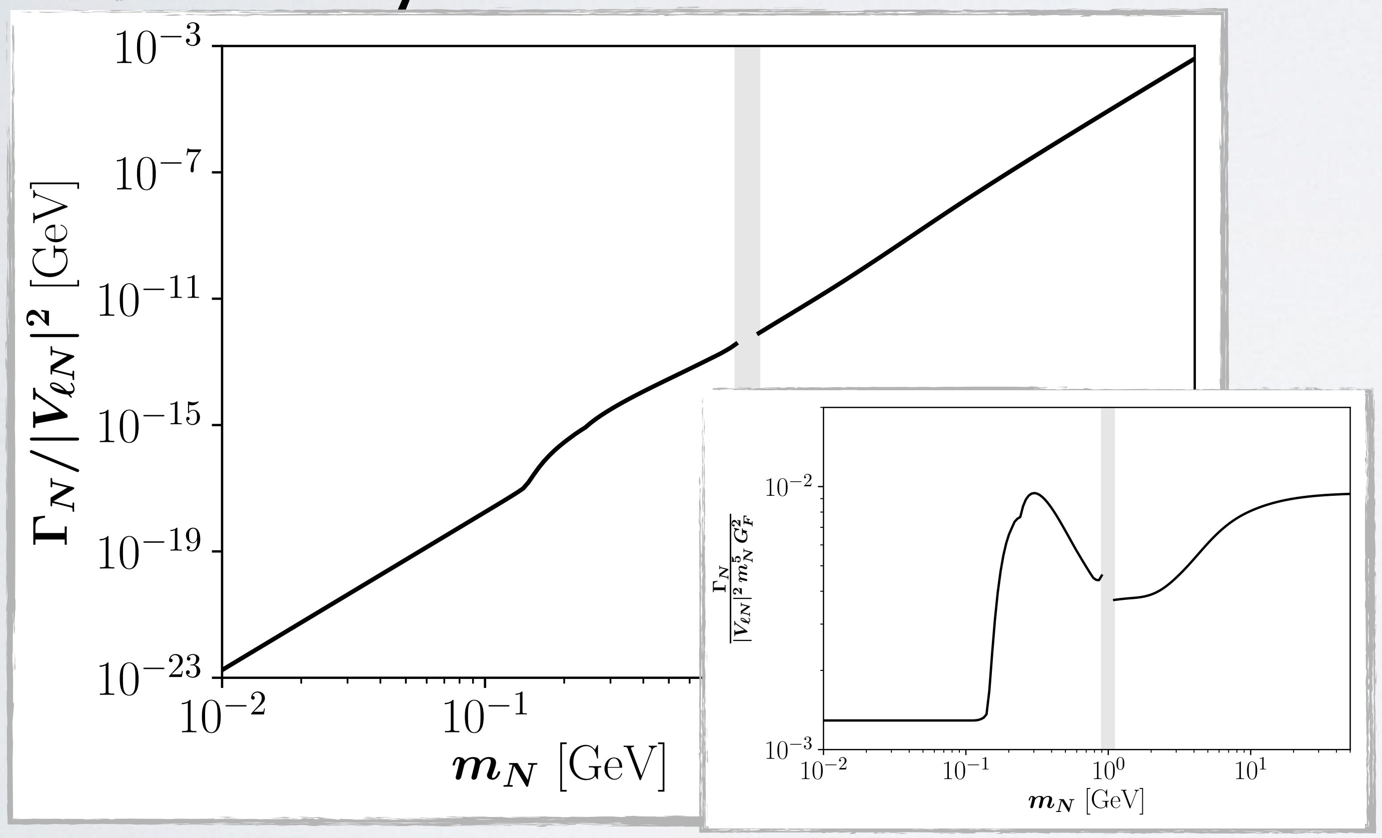

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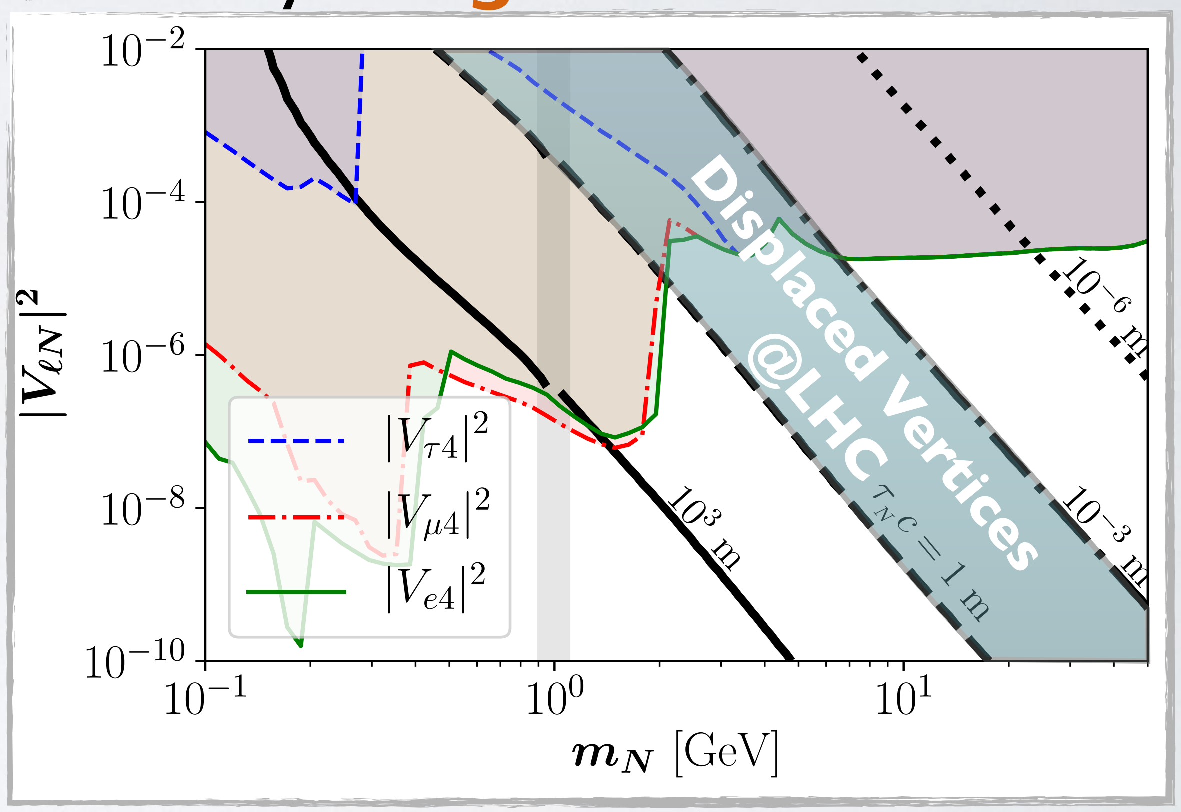

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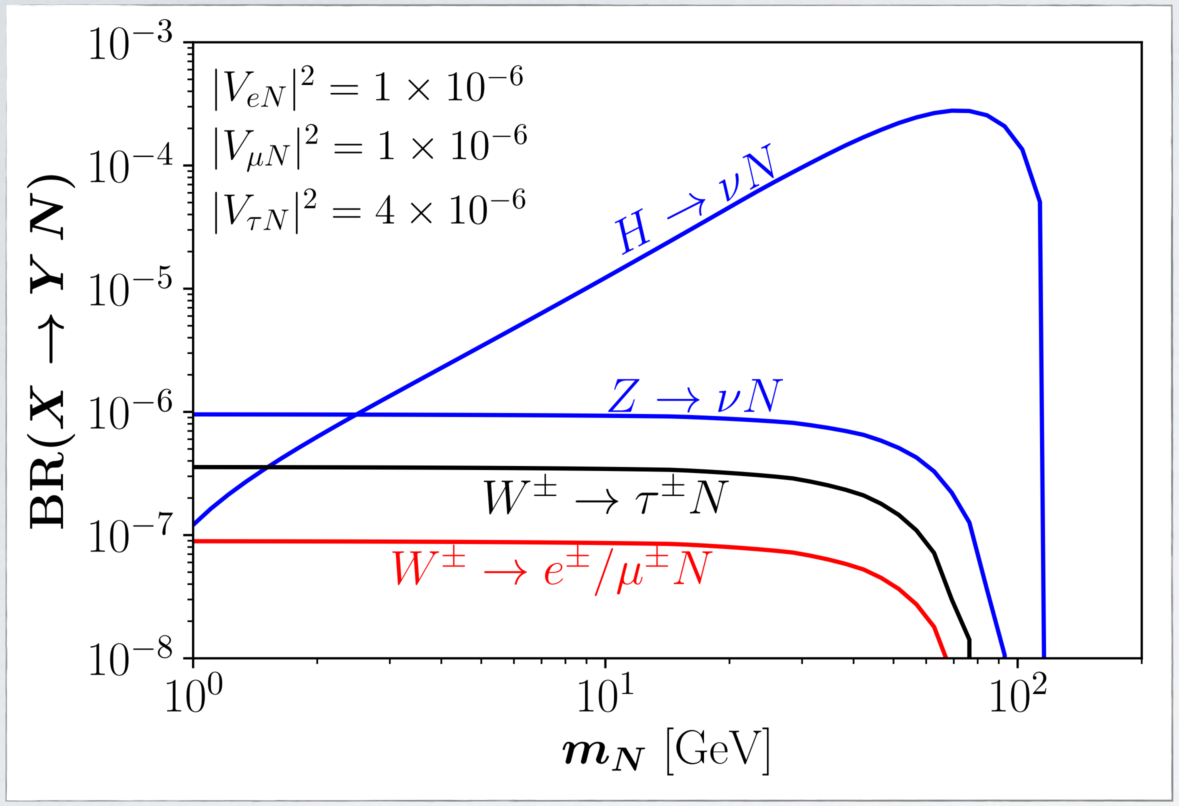
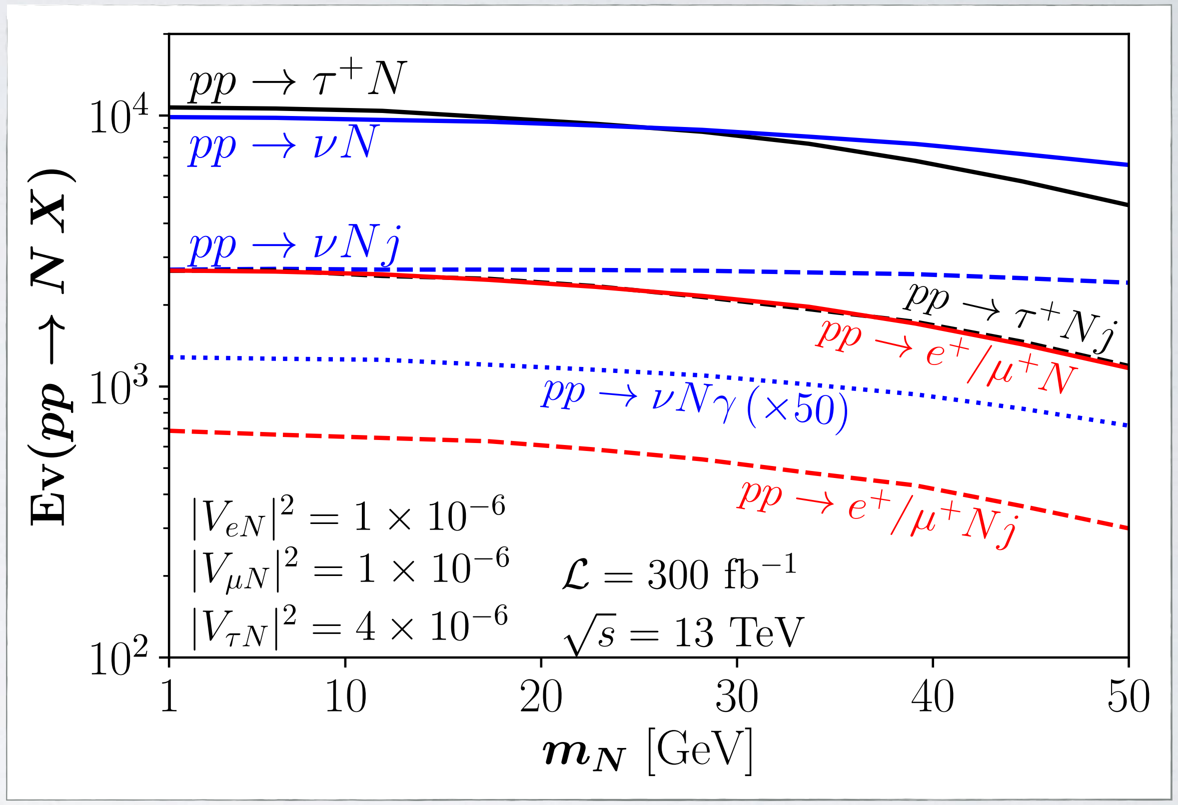
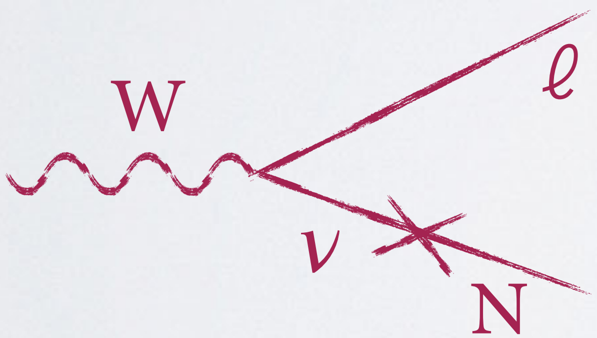
Heavy Neutral Lepton production

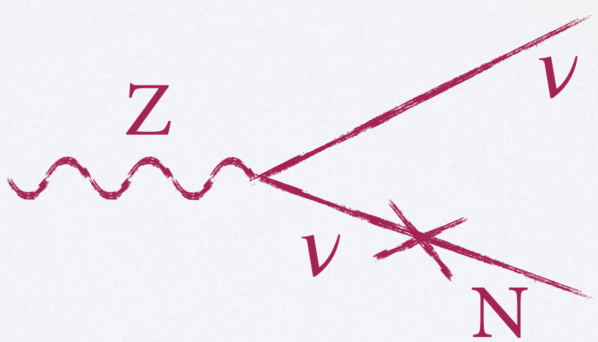
- Main production from **W, Z and H decays**



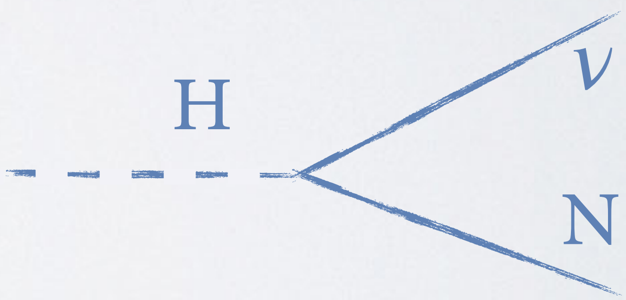




$\mathrm{BR}_{W^\pm \to \ell^\pm N} \propto |V_{\ell N}|^2$



$\mathrm{BR}_{Z \to \nu N} \propto \sum_\ell |V_{\ell N}|^2$

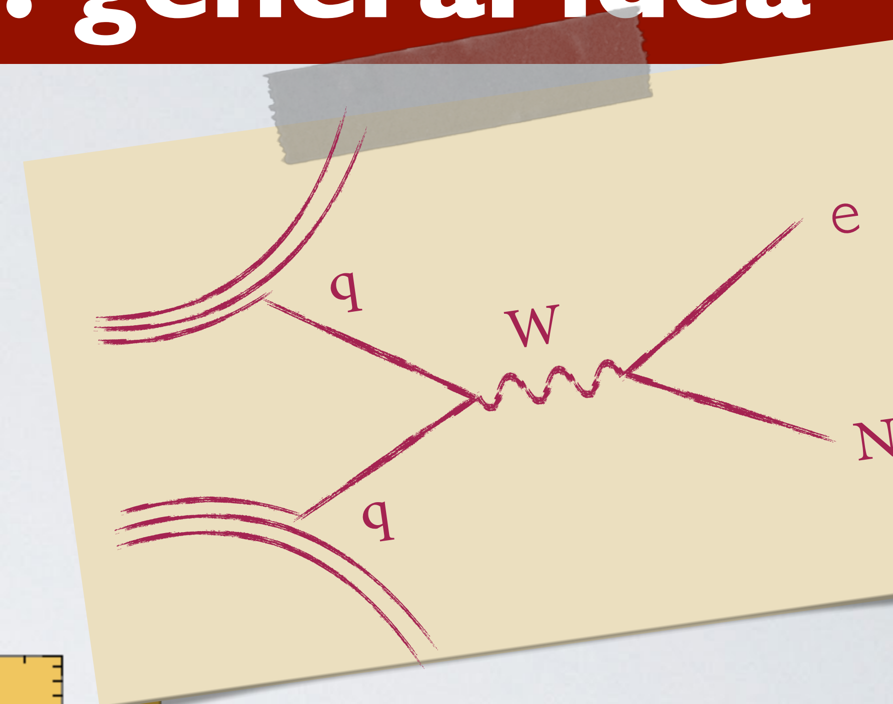


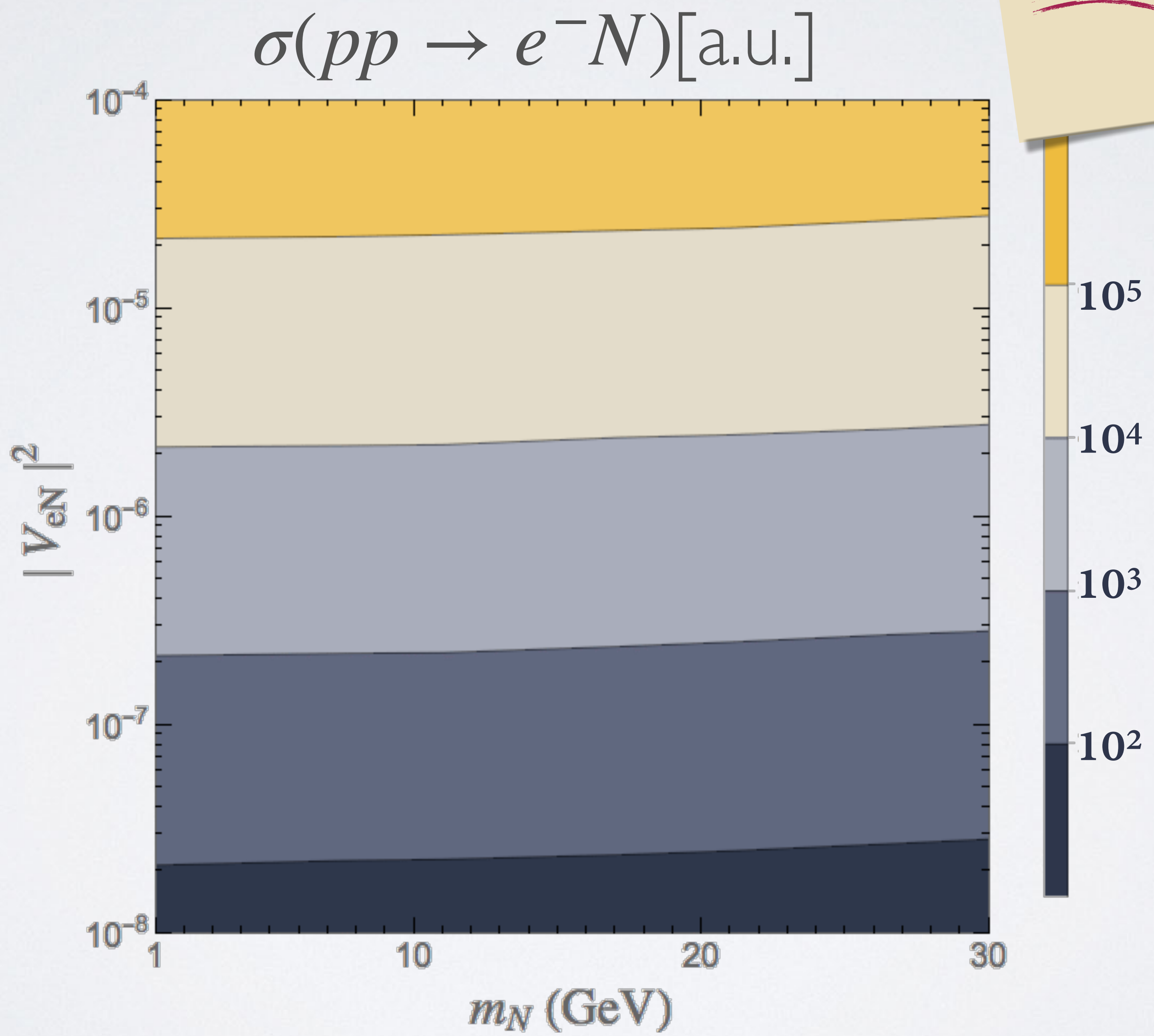
$\mathrm{BR}_{H \to \nu N} \propto \frac{m_N^2}{m_W^2} \sum_\ell |V_{\ell N}|^2$

Displaced vertices from HNL: general idea

- Example: p p > e N

  Dominated by Drell Yan on-shell W





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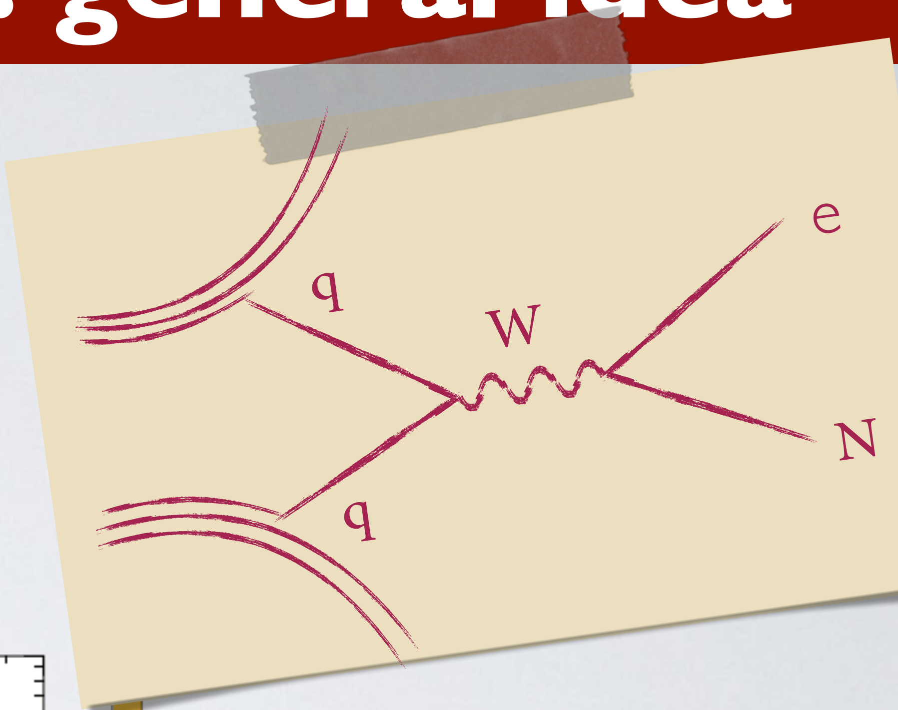

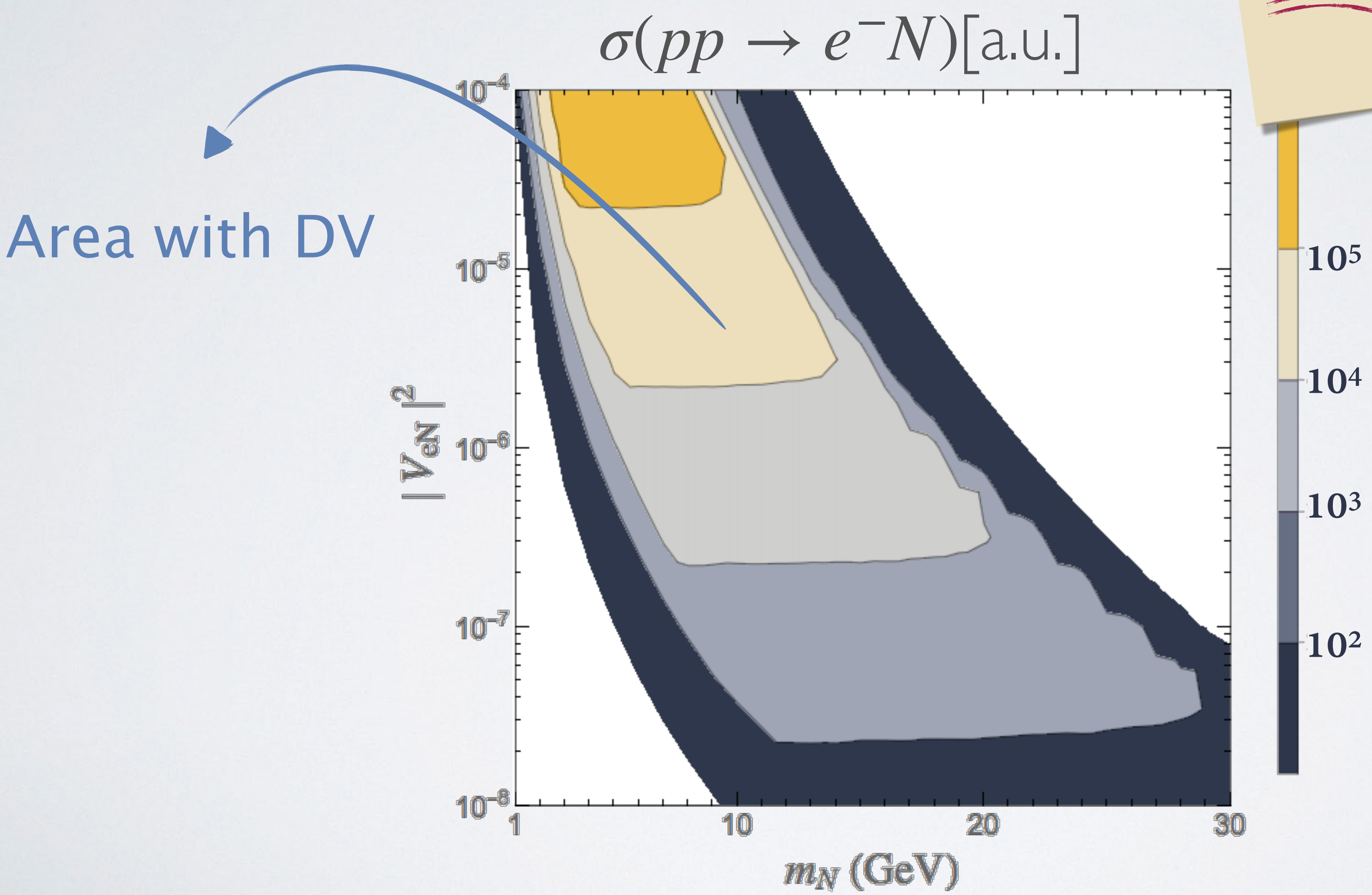

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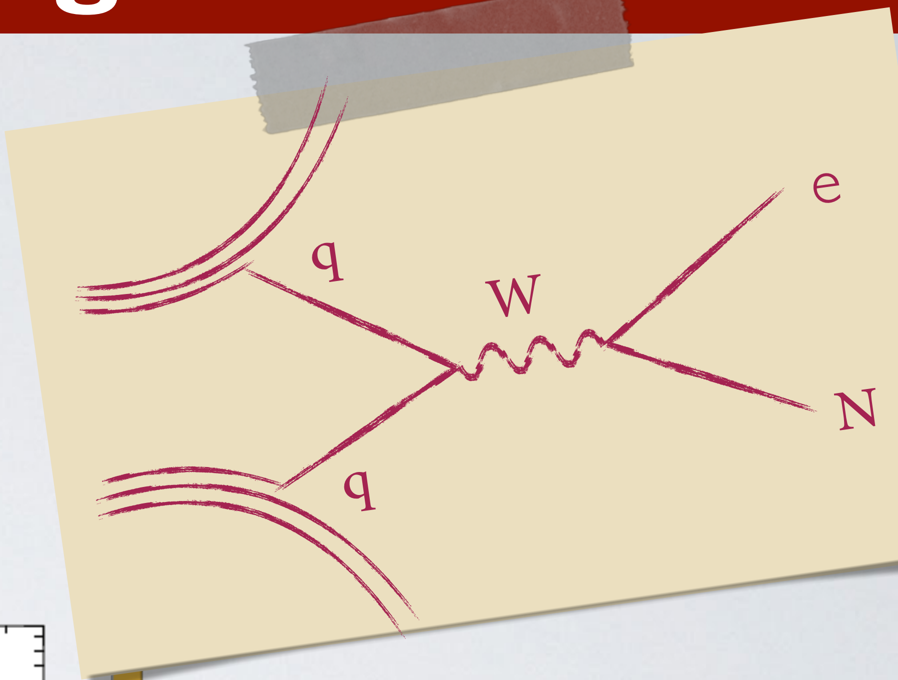

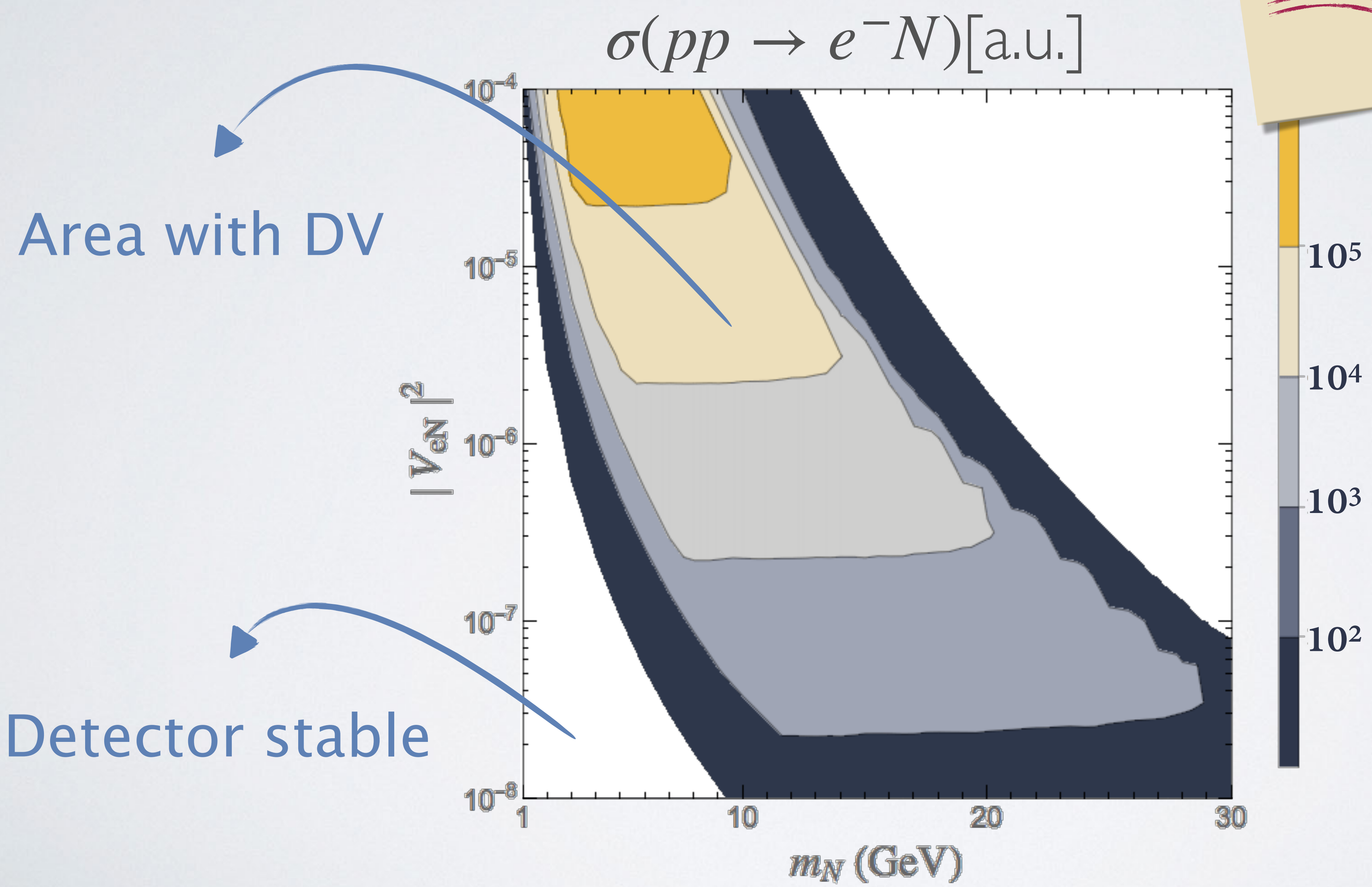

Displaced vertices from HNL: general idea

- Example: p p > e N

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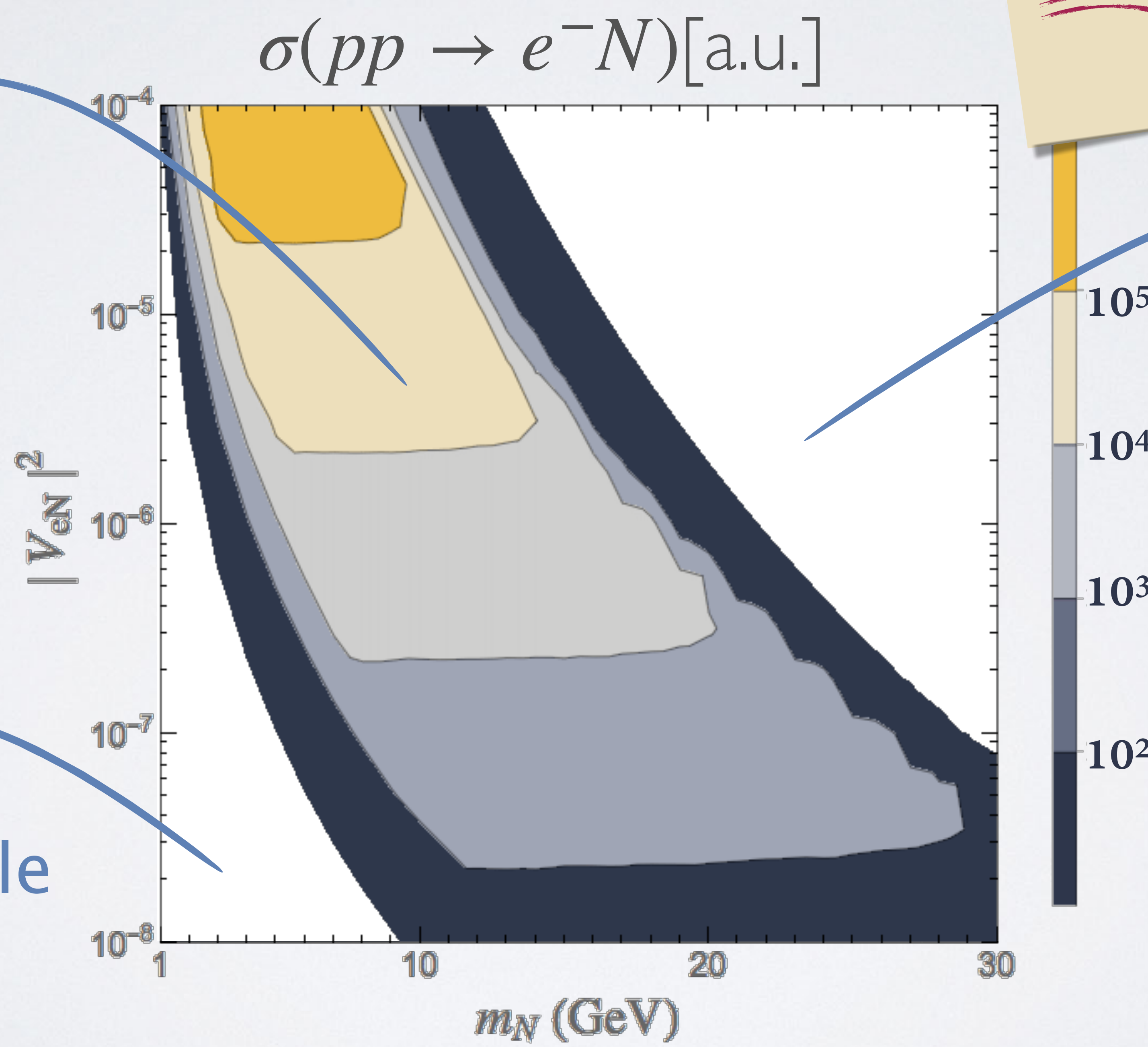
Area with DV

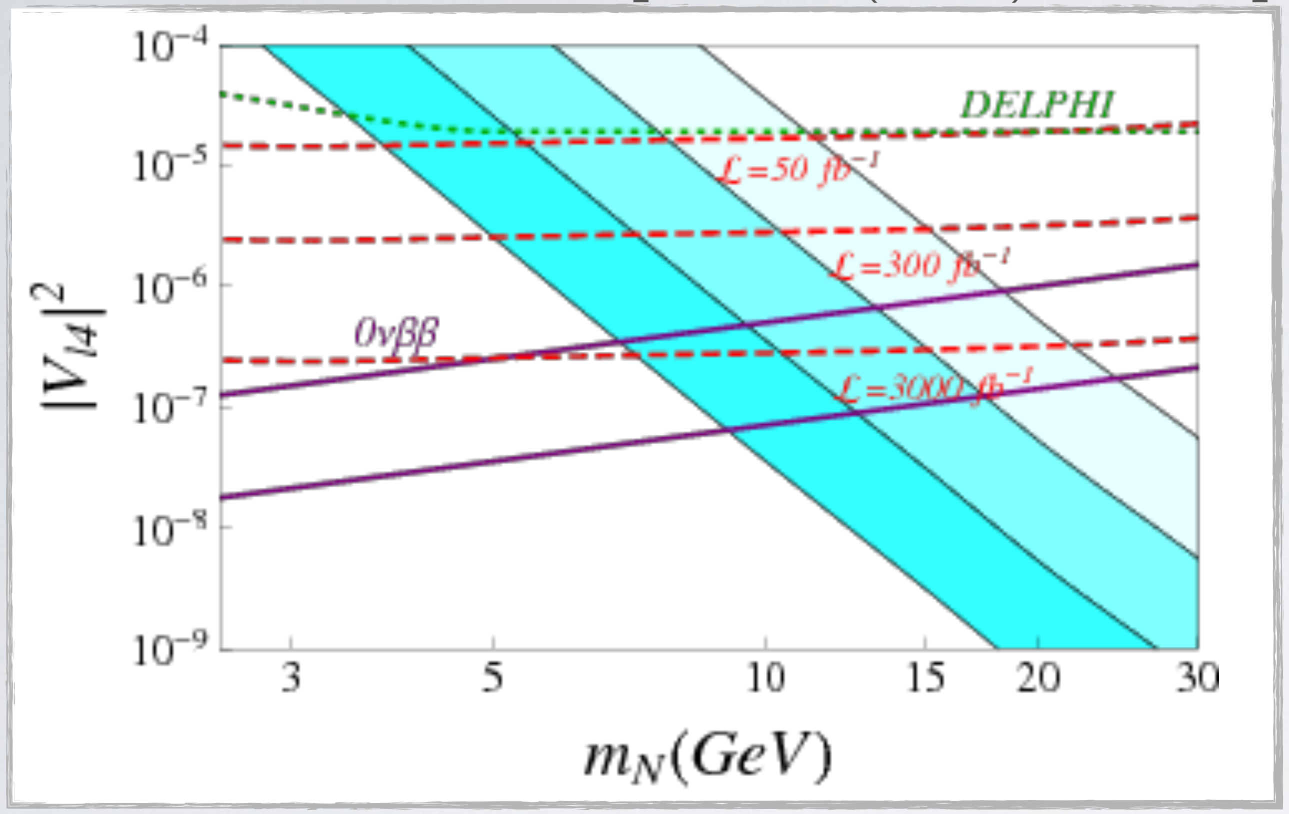


Prompt decay

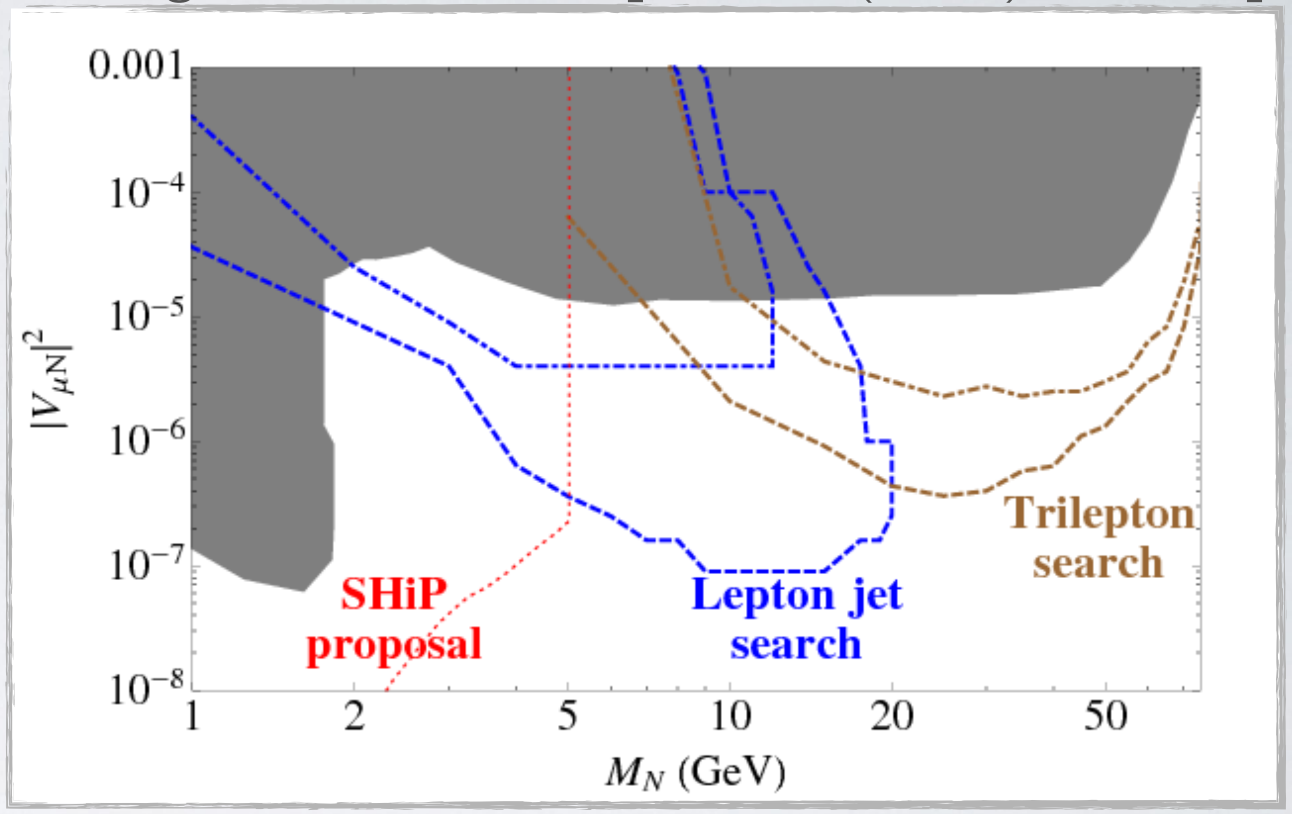
Detector stable

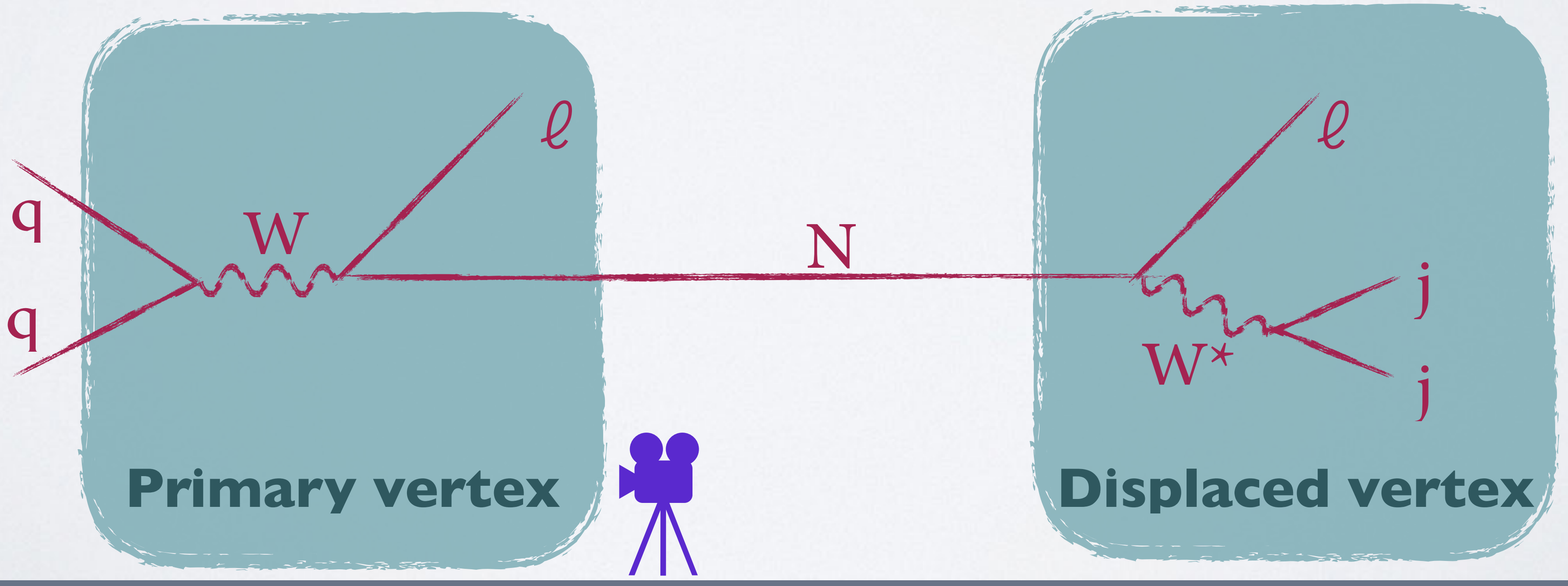
HNL produced with a prompt lepton

Helo, Hirsch, Kovalenko[PRD89 (2014) 073005]



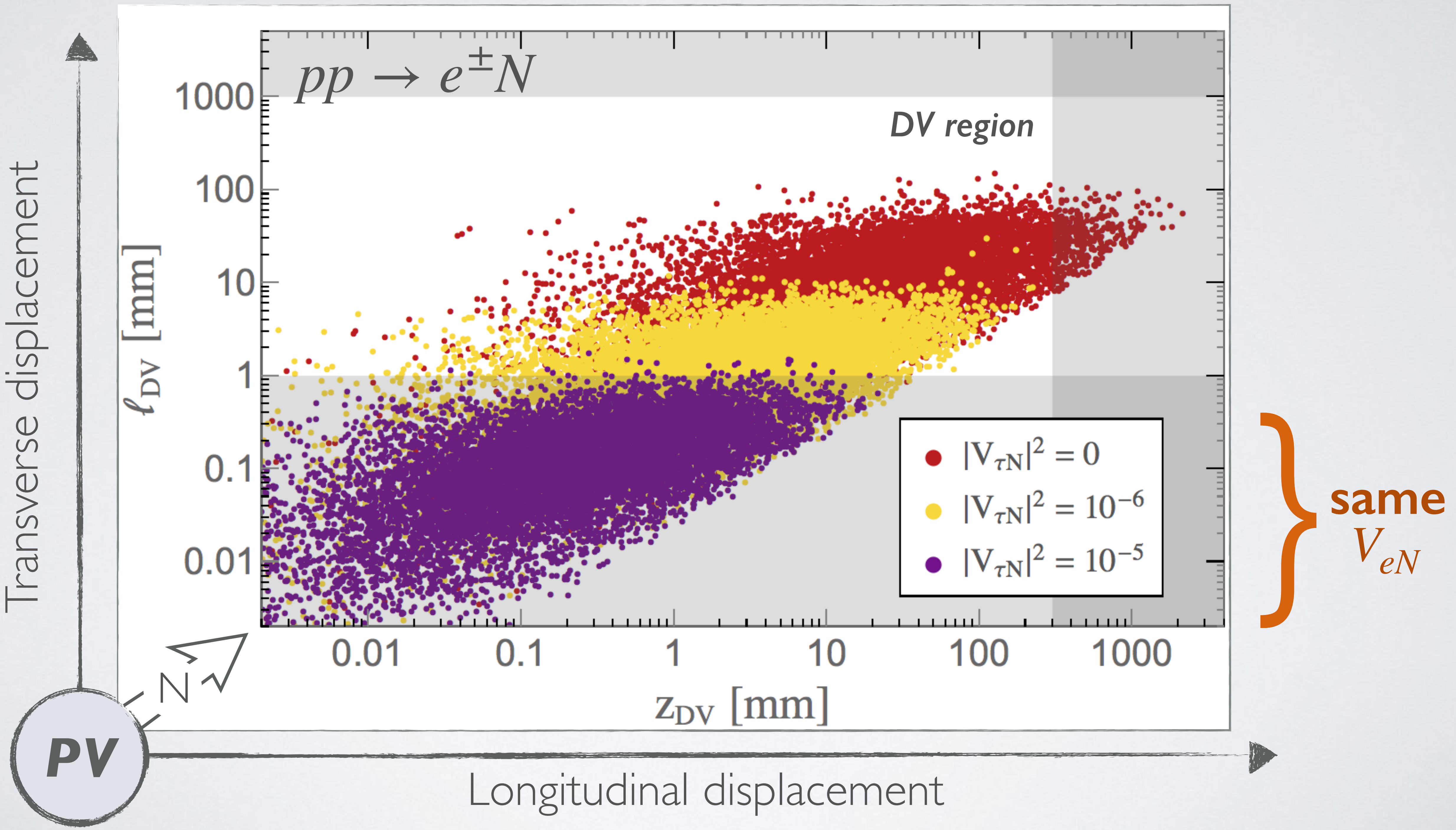
Izaguirre and Shuve [PRD91 (2015) 093010]





The role of HNL flavor

- Standard assumption: only one non-zero mixing at a time
- In DV searches all of them are important



The role of HNL flavor

Displaced vertex searches $\Longleftrightarrow |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$

Flavor dependent HNL production

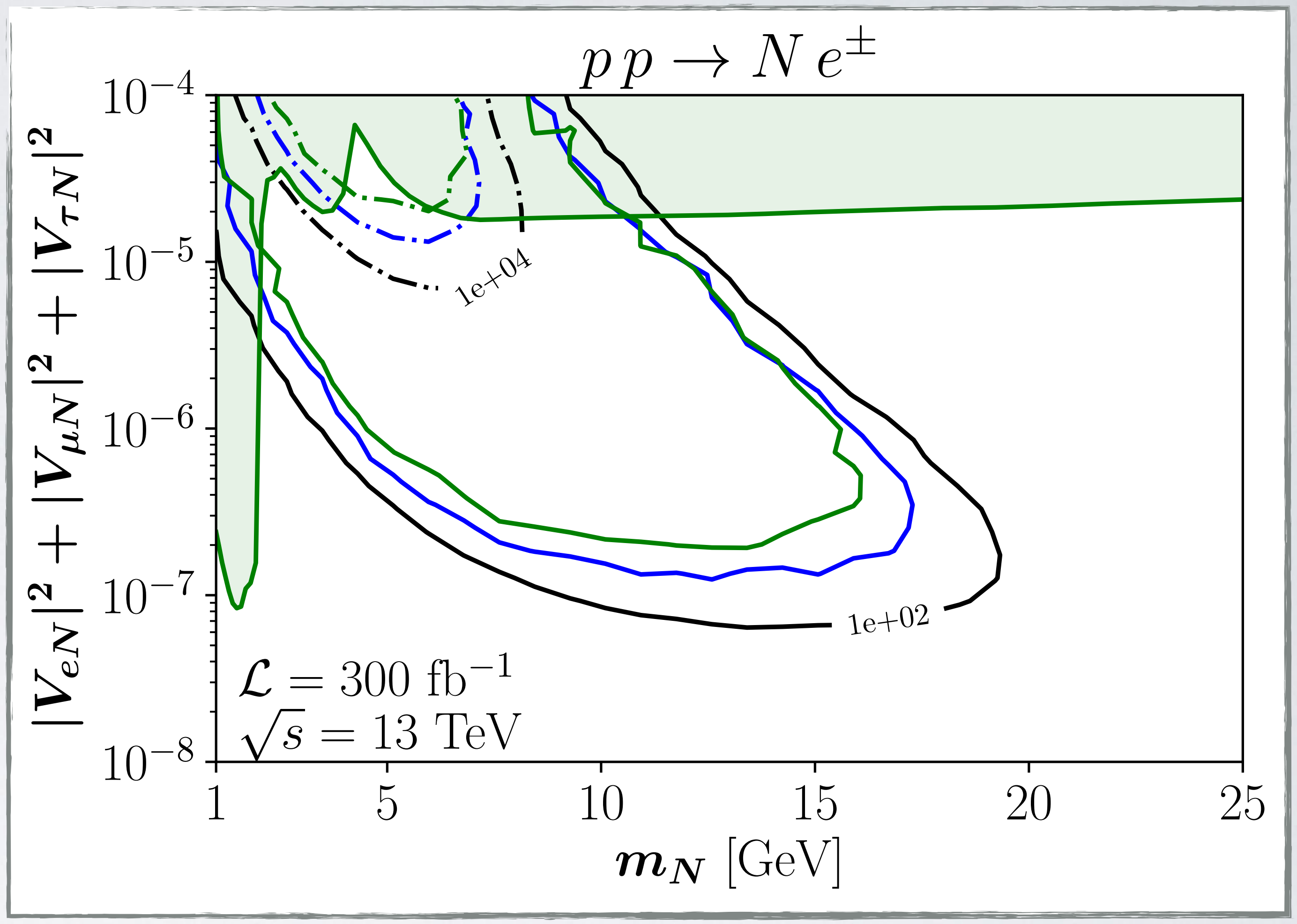
- Simplified scenario

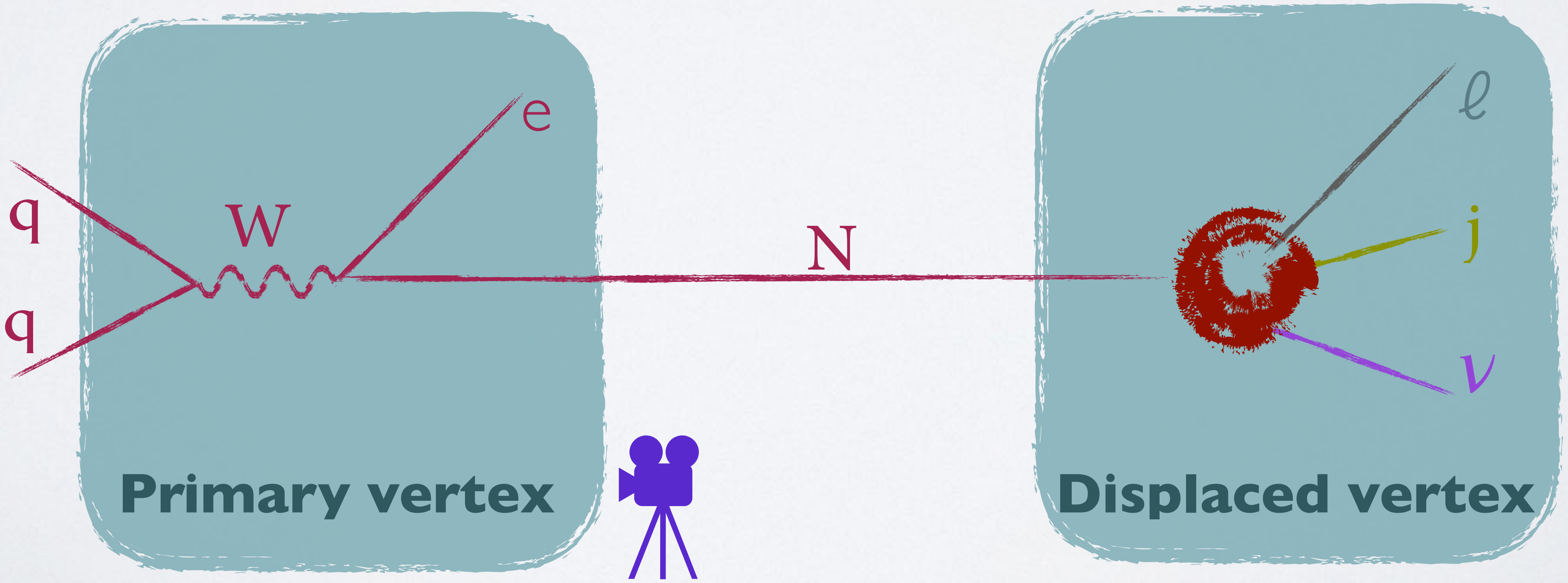
$|V_{eN}| : |V_{\mu N}| : |V_{\tau N}| = 1 : 0 : 0$

- Different flavor scenarios

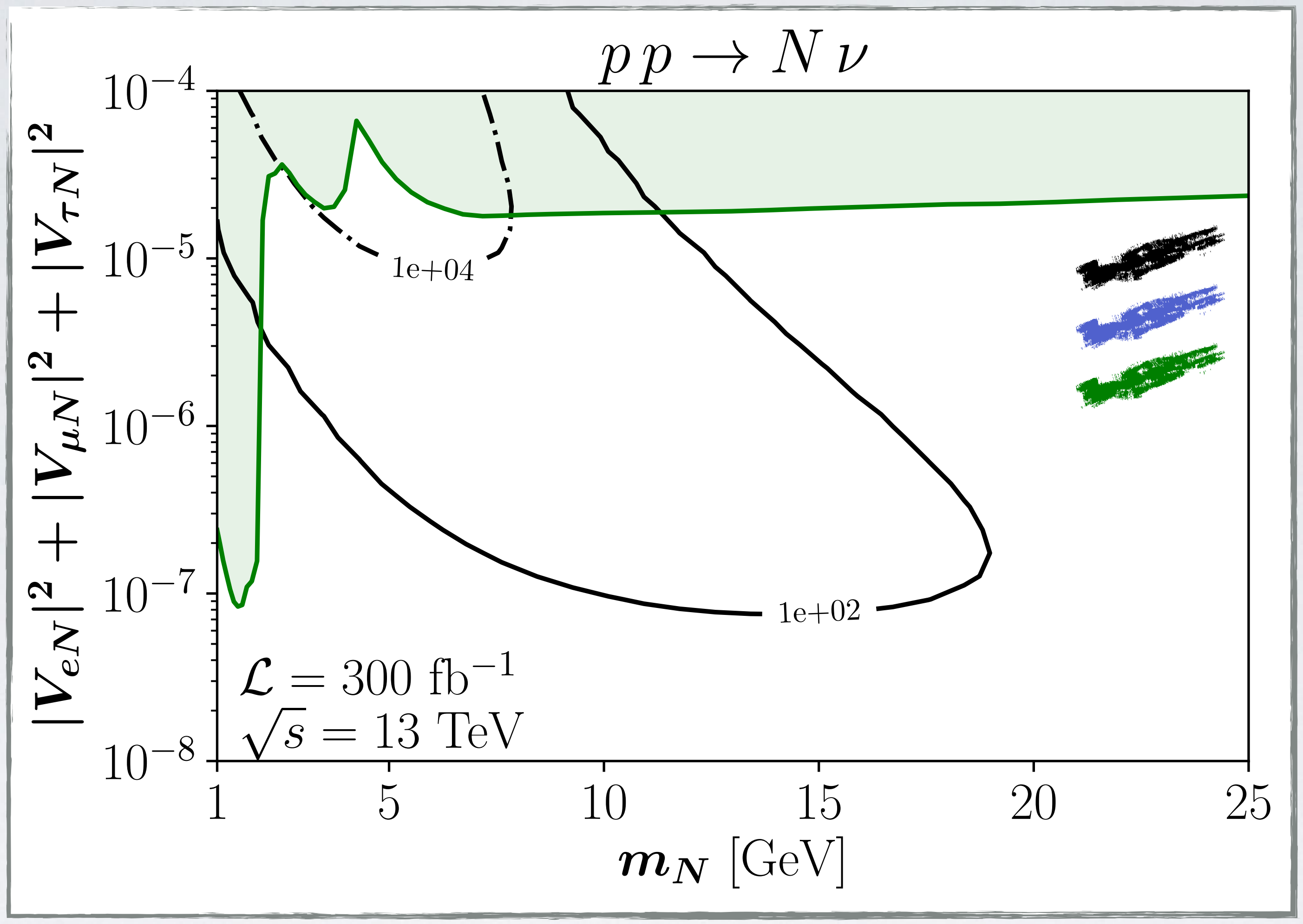
$|V_{eN}| : |V_{\mu N}| : |V_{\tau N}| = 1 : 1 : 0$

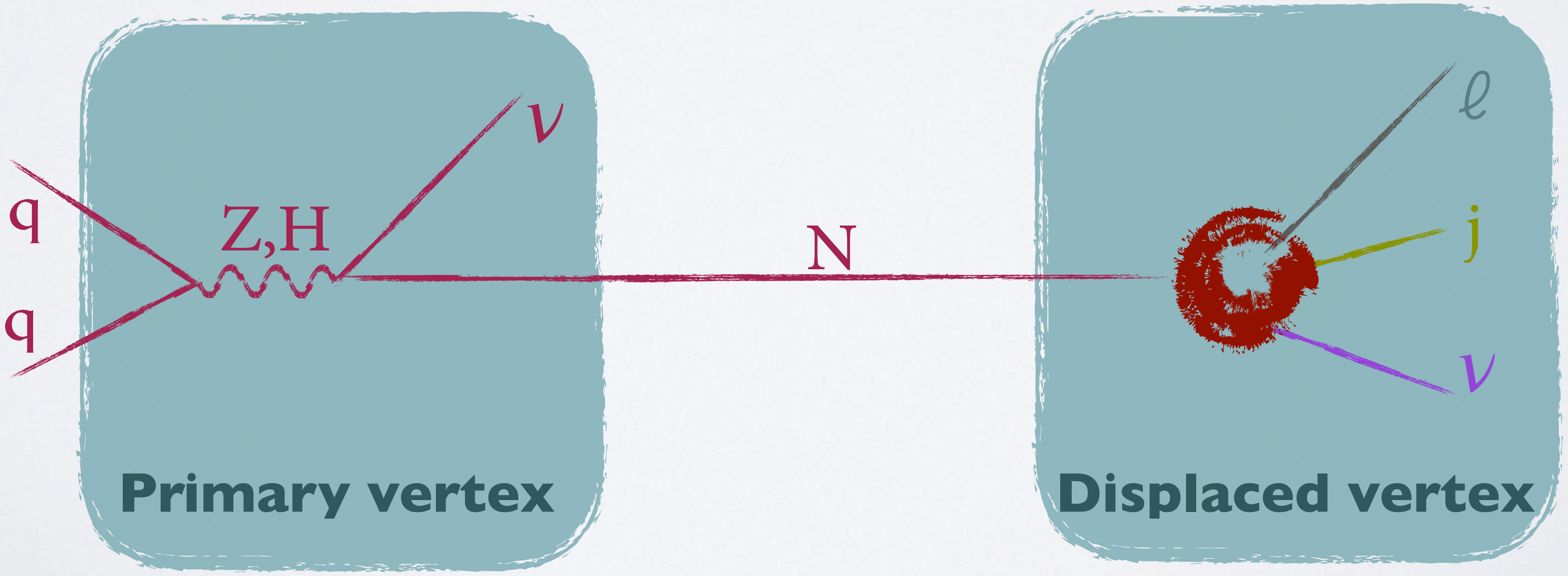
$|V_{eN}| : |V_{\mu N}| : |V_{\tau N}| = 1 : 1 : 1$





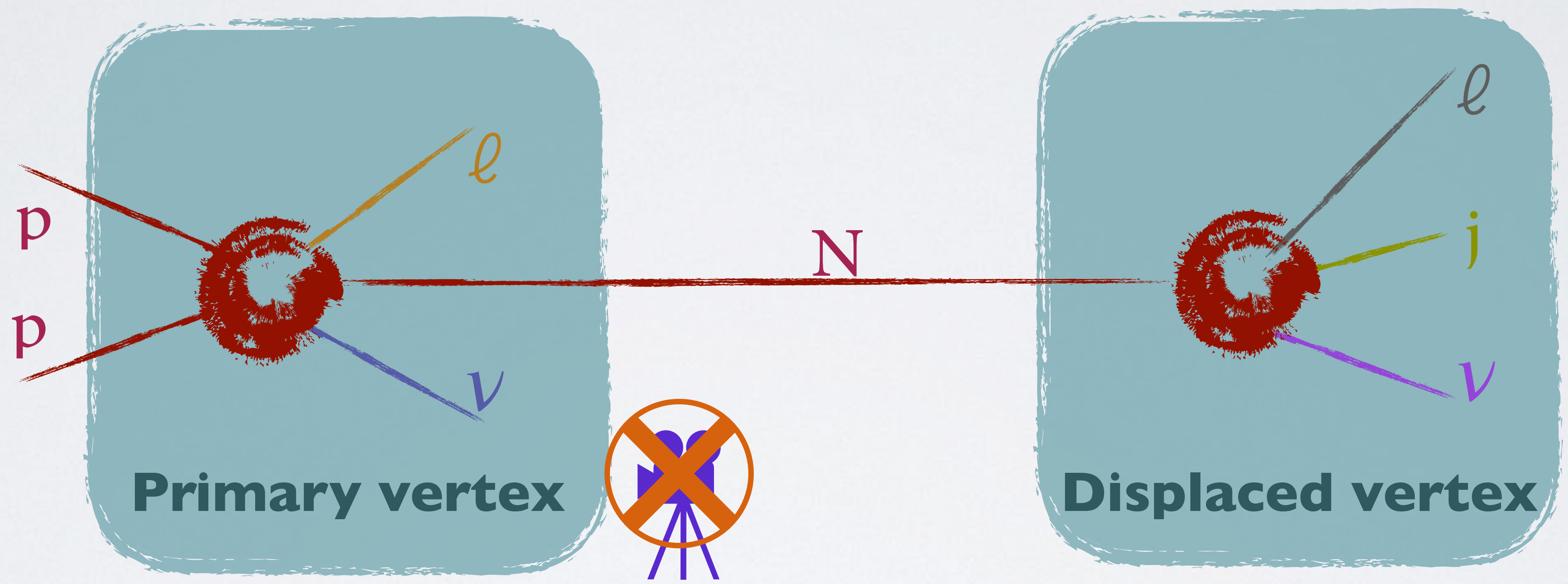
Flavor blind HNL production





It may be better to...

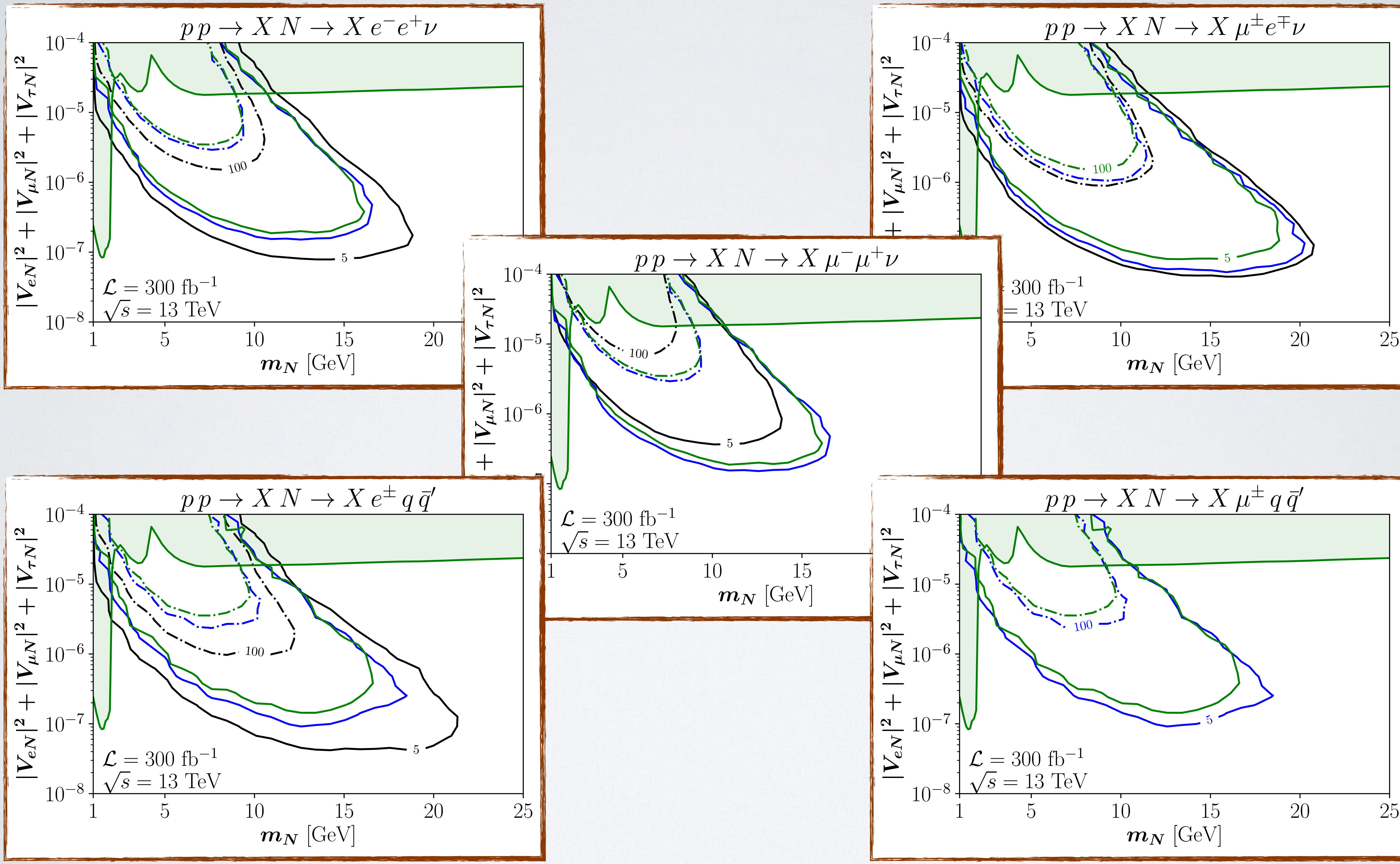
GO INCLUSIVE!!!



Focusing only on the DV

It may be better to...

And explore all final state channels in the DV



A more realistic collider analysis

$$\text{Ex} : pp \to NX \to \mu^+\mu^-\nu X$$

- **Trigger** on displaced collimated muons

ATLAS [1808.03057], CMS [1411.6977]

$$p_T^\mu > 20 \ \& \ 15 \text{ GeV} \qquad \Delta R_{\mu\mu} < 0.5$$

- **Displaced vertex** condition

$$1 \text{ mm} < \ell_{\text{DV}} < 1 \text{ m} \qquad z_{\text{DV}} < 300 \text{ mm}$$

- **Dimuon invariant mass** close to the HNL mass

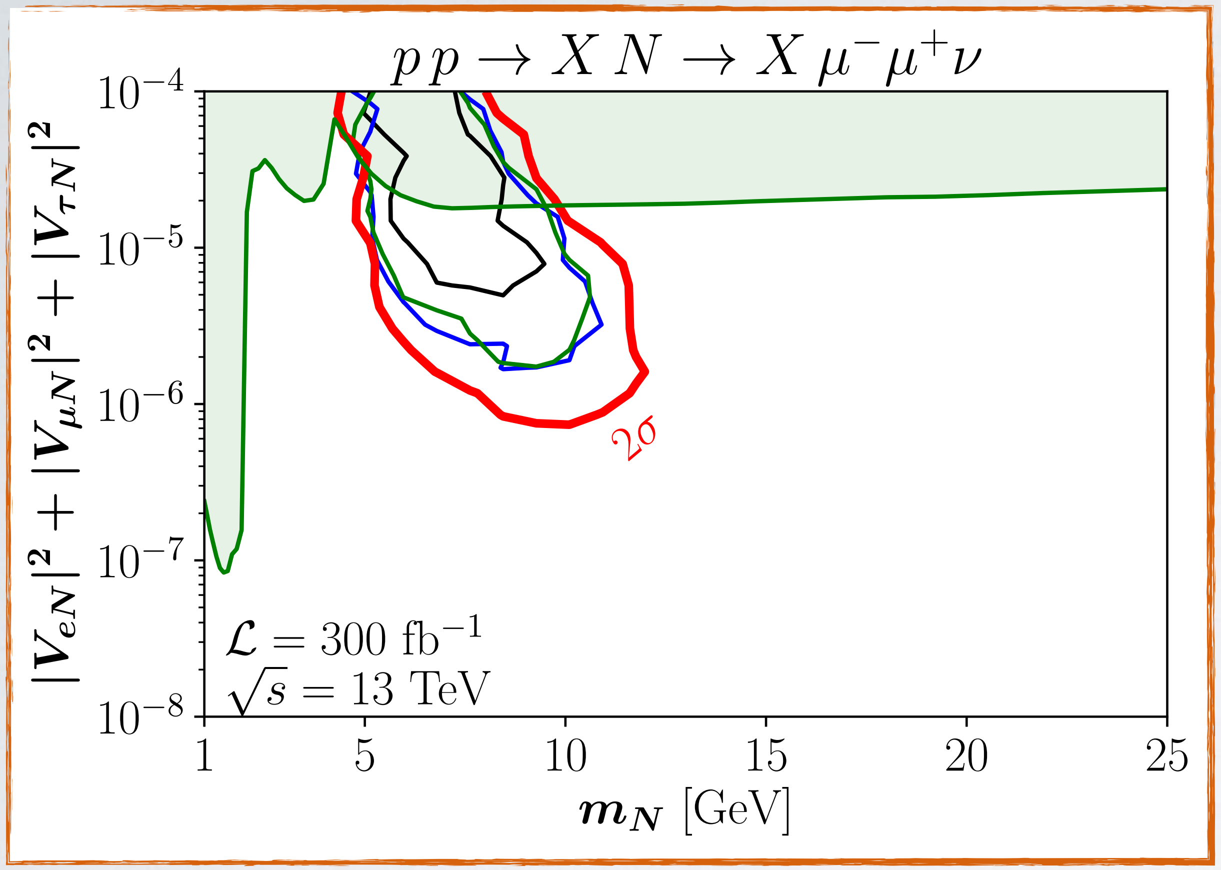
$$5 \text{ GeV} < m_{\mu\mu} < m_N$$

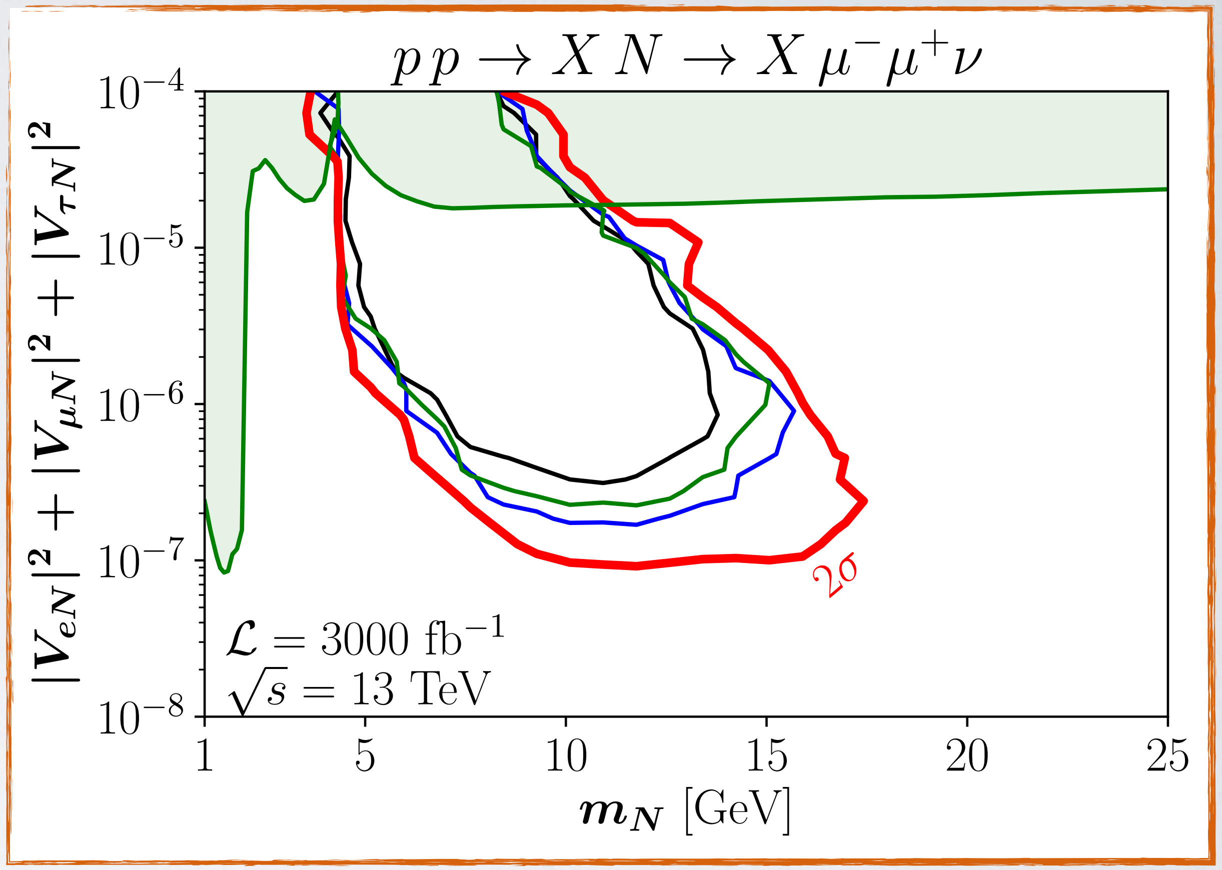
- **Isolation** from hadron activity

- **Cosmic ray** veto

- **Background free** (optimistic) hypothesis

A more realistic collider analysis





- **Challenging** searches due to very **soft leptons**
- **LHC** could **improve present bounds** going for **inclusive** DV searches
- Even better **lowering the triggers** (back up)

Conclusions

- **Heavy Neutral Leptons** present in many BSM theories

- If they are long-lived ⟶ **Displaced Vertices**

- HNL flavor matters

$$|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$$

↙ Inclusive DV searches ↘ Explore all final states

- **LHC could prove new areas** of the parameter space

$m_N \sim \mathcal{O}(10)$ GeV and $|U_{\ell N}|^2 \lesssim \mathcal{O}(10^{-6}\text{–}10^{-7})$

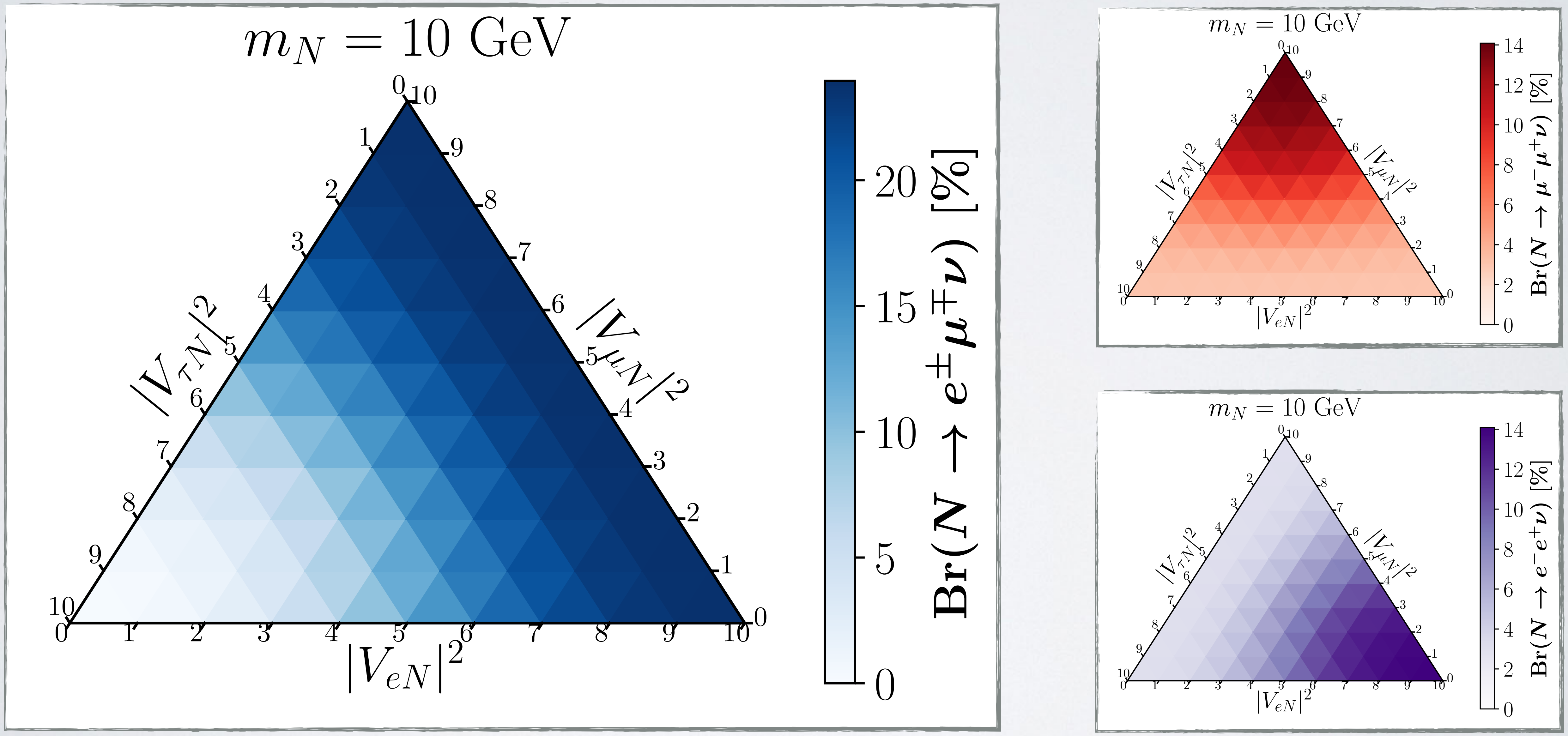
Thank you!

Back up slides

Different decay channels

- For our range of masses what matters is the ratio

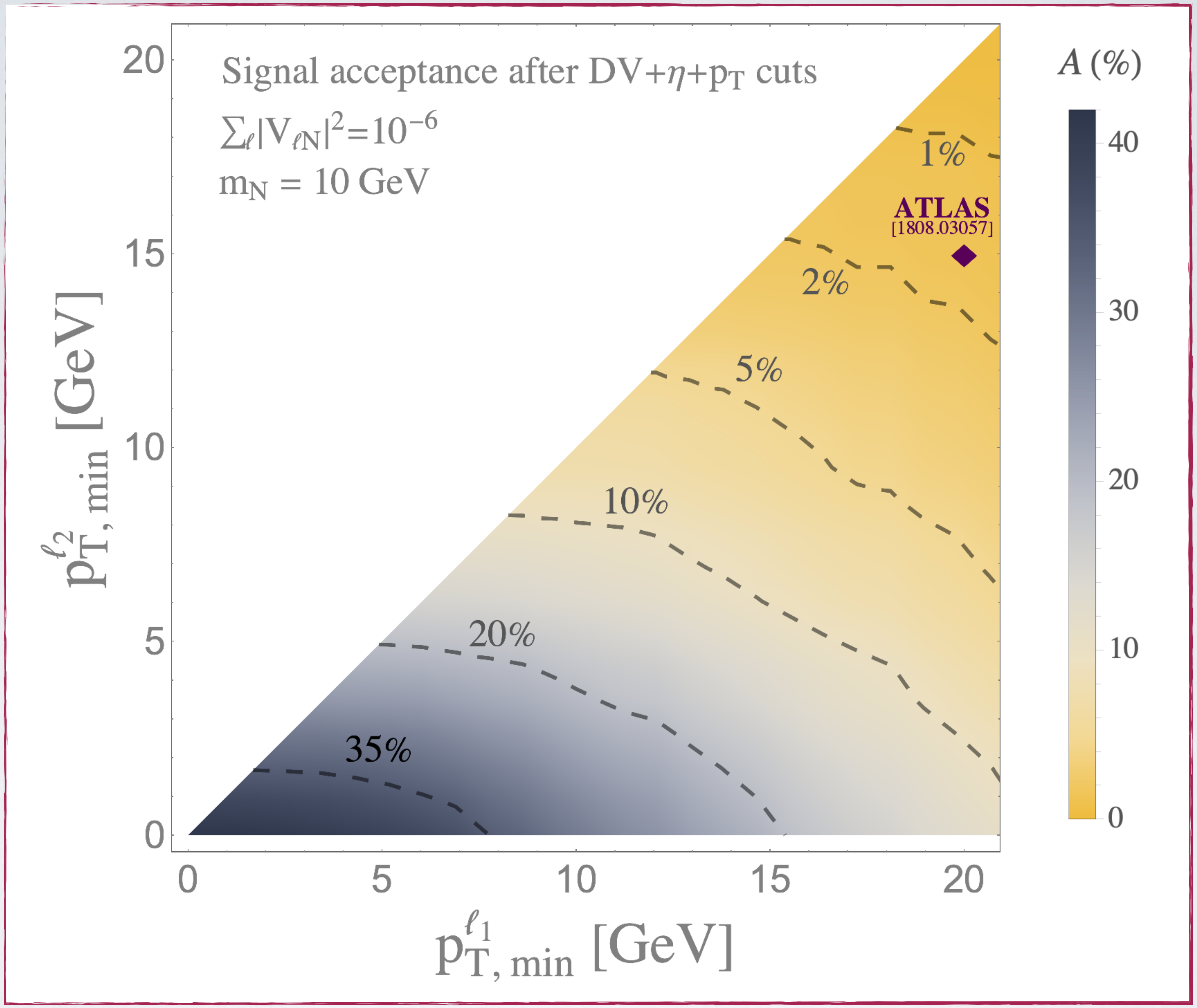
$$|V_{eN}| : |V_{\mu N}| : |V_{\tau N}|$$



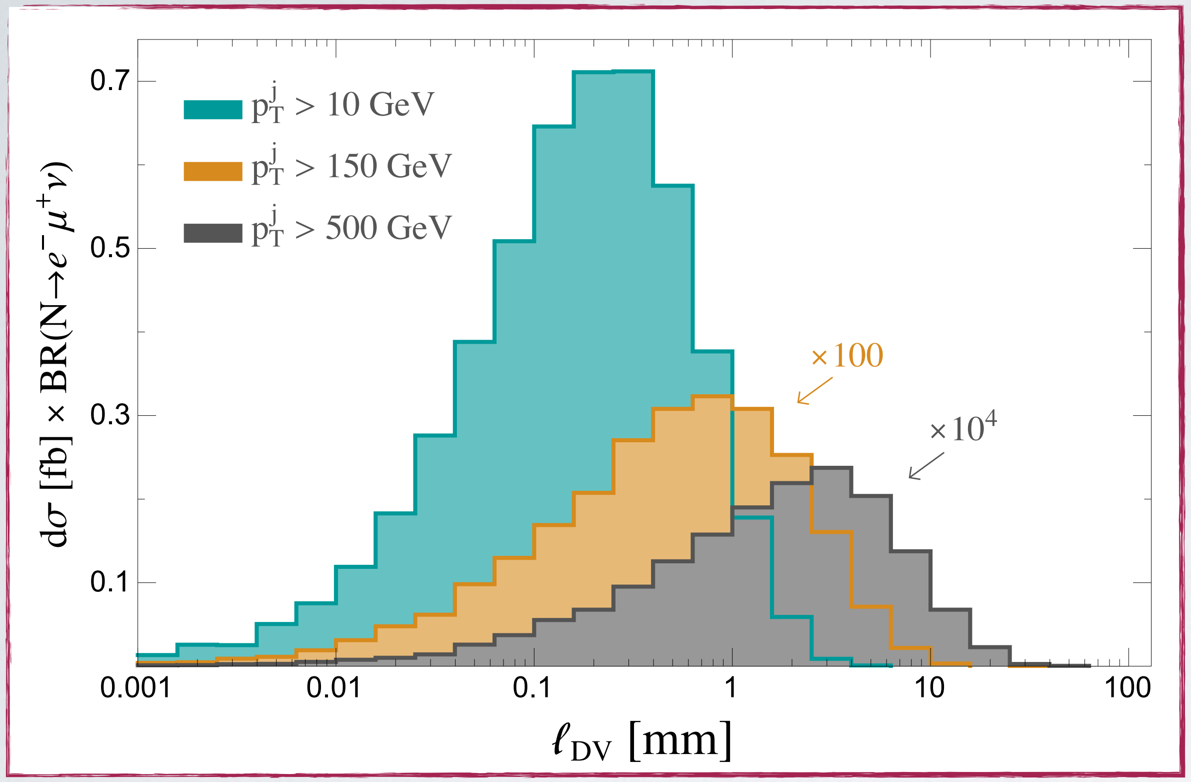
Cutflow

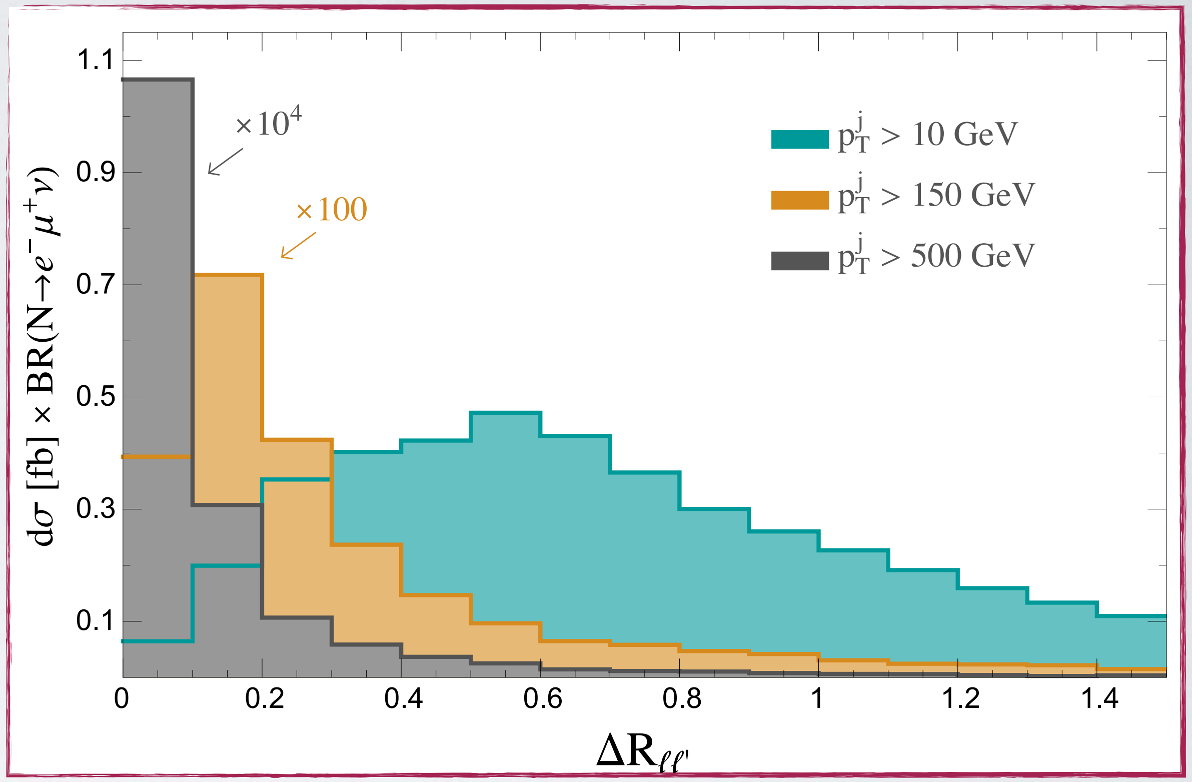
Signal acceptance after cut	$m_N = 10$ GeV $\Sigma_\ell \lvert V_{\ell N}\rvert^2 = 10^{-6}$	$m_N = 15$ GeV $\Sigma_\ell \lvert V_{\ell N}\rvert^2 = 10^{-7}$
$1\ \text{mm} < \ell_{\text{DV}} < 1\ \text{m},\ z_{\text{DV}} < 300\ \text{mm}$	66%	73%
$\lvert\eta_\mu\rvert < 2.5$	43%	46%
$p_T^{\mu_1} > 20\,\text{GeV},\ p_T^{\mu_2} > 15\,\text{GeV}$	1.7%	1.4%
$\Delta R_{\mu\mu} < 0.5$	1.6%	1.0%
$5\,\text{GeV} < m_{\mu\mu} < m_N$	1%	0.9%
jet-isolation eqs. (4.2) and (4.3)	1%	0.9%
$H_T < 60\,\text{GeV}$	0.8%	0.7%
Cosmic veto eq. (4.4)	0.8%	0.7%

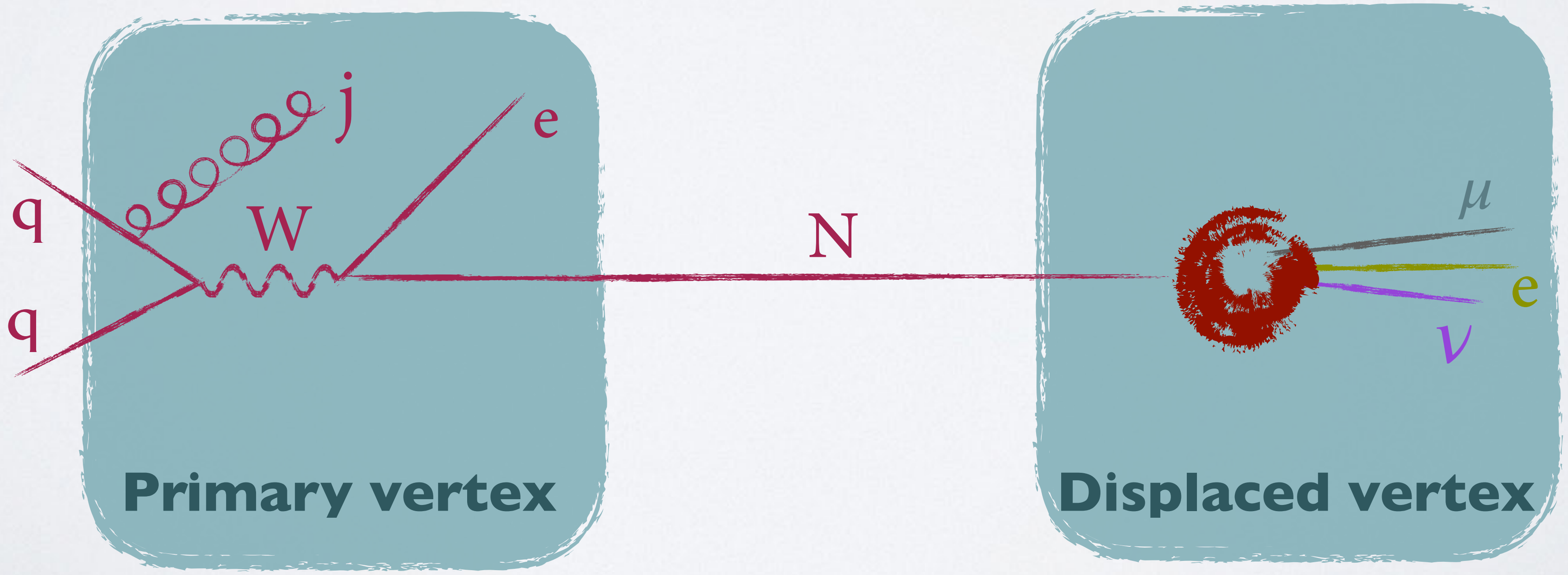
Lowering the triggers



Boosted topologies

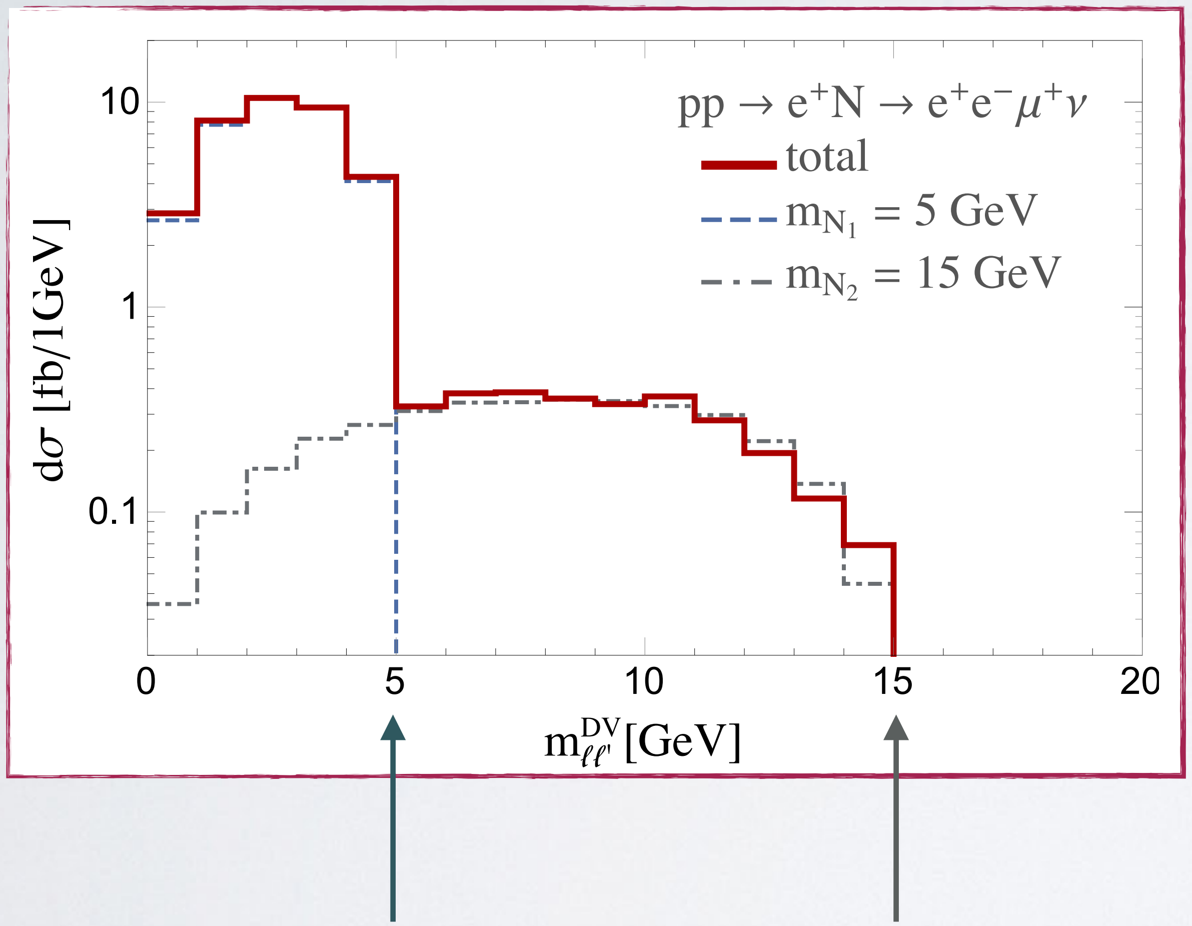




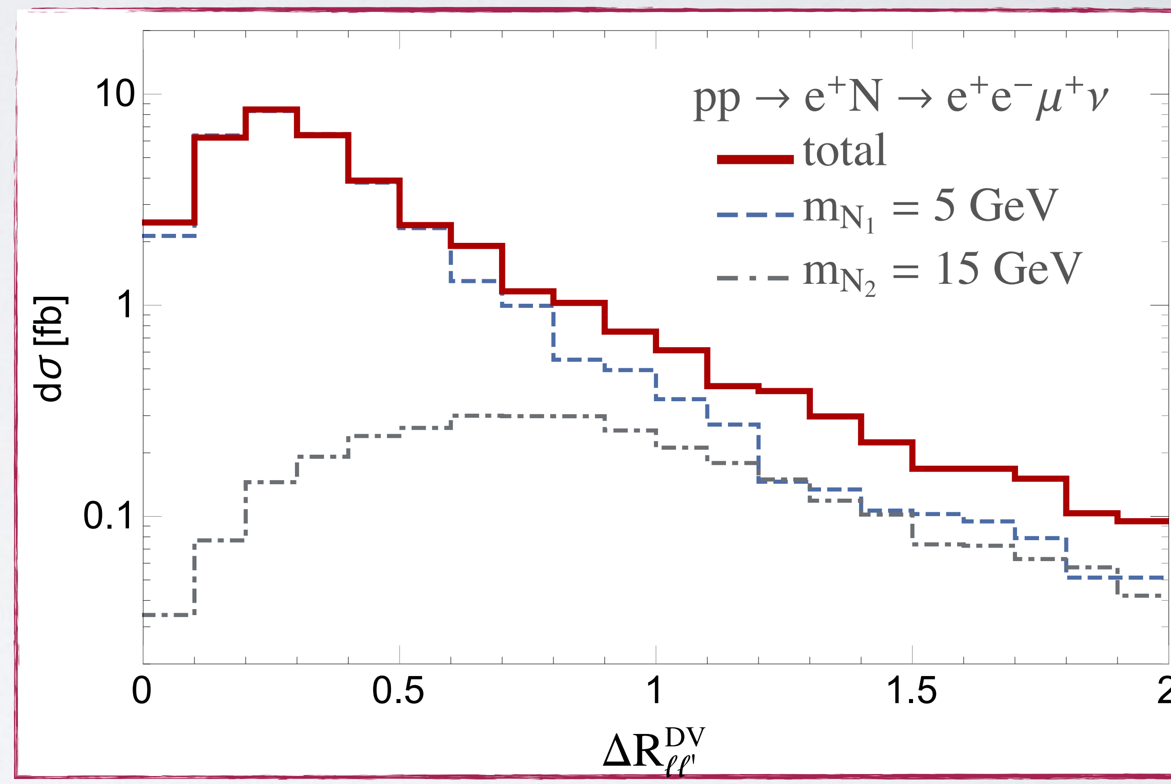


How many HNL?

- Imprints in the distributions?



m_{N_1} m_{N_2}



Future - lepton colliders

Antusch, Carazzo, Fischer [JHEP 1612 (2016) 007]