The Improved Bounds on the Heavy Neutrino Productions at the LHC

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Introduction

- Standard Model (SM) Neutrinos are massless
- Recent experiments on the neutrino oscillation disproves the massless-ness of the SM neutrinos.
- Extend the SM

Right Handed singlet Majorana neutrino (N_R)

- Seesaw mechanism

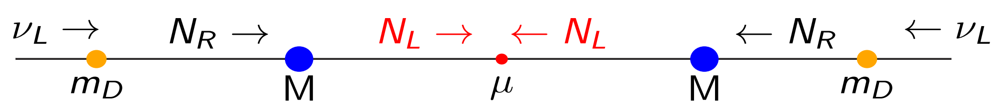
$$\bullet \mathcal{L}_{Seesaw} \supset -m_D \bar{\nu}_L N_R - \frac{1}{2} M \bar{N}_R^C N_R + h.c : m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \quad \bullet\ m_\nu = m_D \boxed{\frac{m_D}{M}}$$

- Inverse Seesaw Mechanism

Mohapatra, PRL 56, 561 (1986), Mohapatra and Valle, PRD 34, 1642 (1986)

	SU(2)	U(1)$_Y$
ℓ_L	**2**	$-1/2$
H	**2**	$-1/2$
N_R^j	**1**	0
N_L^j	**1**	0

$$\mathcal{L}_{mass} \supset -\mu_{ij} \overline{((N_L)^c)^i} N_L^j - m_{ij} \overline{N_R^i} N_L^j - Y_{D_{ij}} \overline{\ell_L^i} H N_R^j + H.c.$$



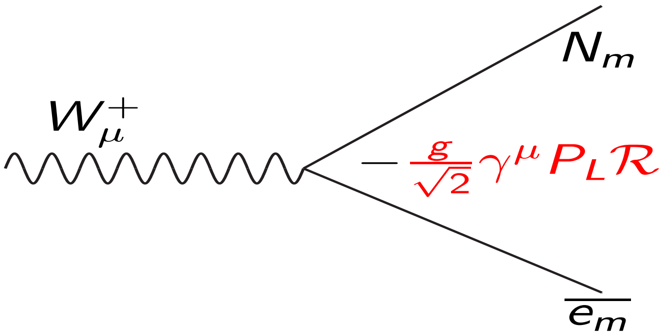
$$m_D M^{-1} \ll 1,\ m_\nu = (m_D \mathbf{M}^{-1}) \mu (m_D \mathbf{M}^{-1})^T$$

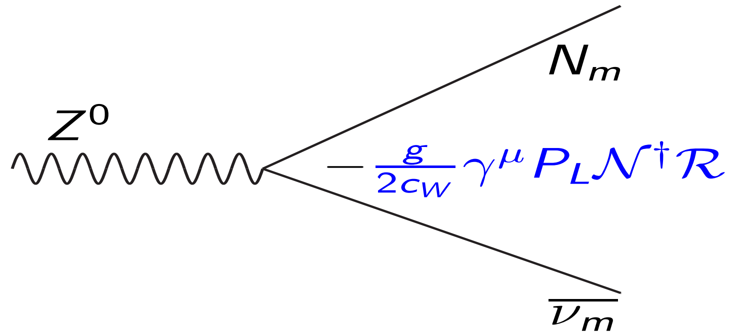
Heavy (Pseudo-Dirac) neutrino can be produced at high energy colliders

Charged and the neutral current interactions

The flavour eigenstate (ν) in terms of the mass eigenstates

$$\nu \simeq \mathcal{N}\nu_m + \mathcal{R}N_m, \quad \mathcal{N} = (1 - \frac{1}{2}\mathcal{R}^*\mathcal{R}^T)U_{MNS}$$





$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu \overline{e_m}\gamma^\mu P_L \left(\mathcal{N}\nu_m + \mathcal{R}N_m\right) + h.c.,$$

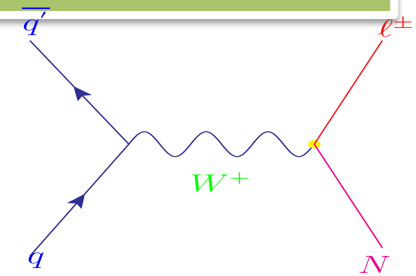
$$\begin{aligned}\mathcal{L}_{NC} \quad &= \quad -\frac{g}{2c_w} Z_\mu \left[\overline{\nu_m}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{N})\nu_m + \overline{N_m}\gamma^\mu P_L(\mathcal{R}^\dagger\mathcal{R})N_m\right] \\ &- \quad \frac{g}{2c_w} Z_\mu \left[\overline{\nu_m}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{R})N_m + h.c.\right]\end{aligned}$$

e_m, ν_m, N_m are the three generations of the leptons in the vector form.

AD and Okada PRD 88 (2013) 113001

Various N production processes at LHC

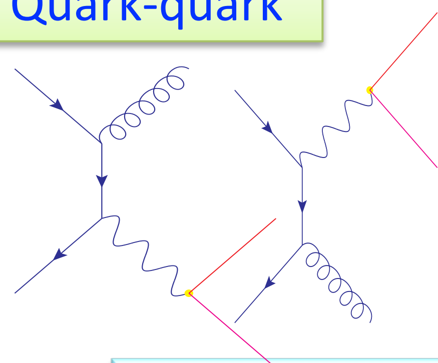
0-jet Process $pp \to N\ell^{\pm}$



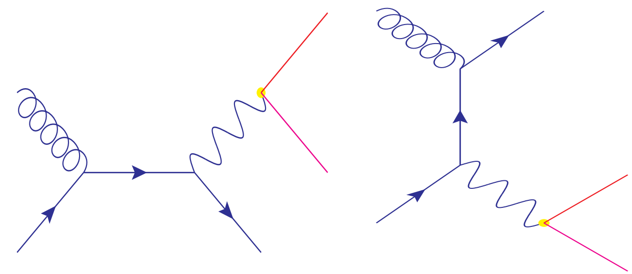
1-jet processes $pp \to N\ell^{\pm}j$

(AD, Dev and Okada PLB 735 (2014) 364–370)

a) Quark-quark

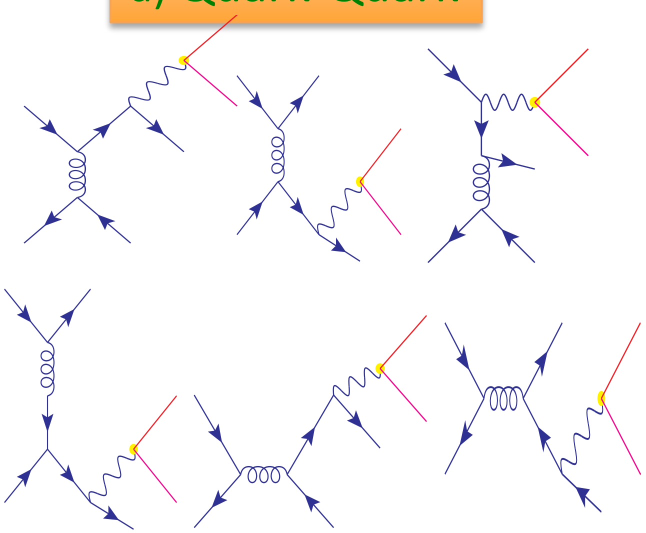


b) Quark-gluon

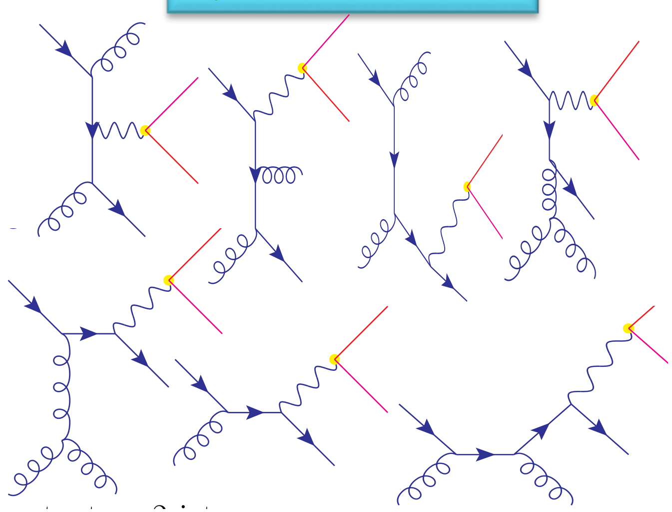


2 – jet processes $pp \to N\ell^{\pm}jj$

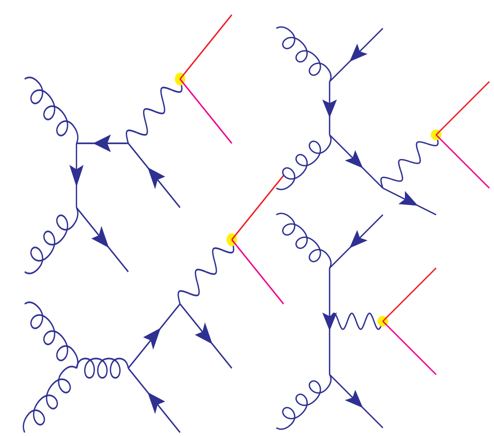
a) Quark-Quark



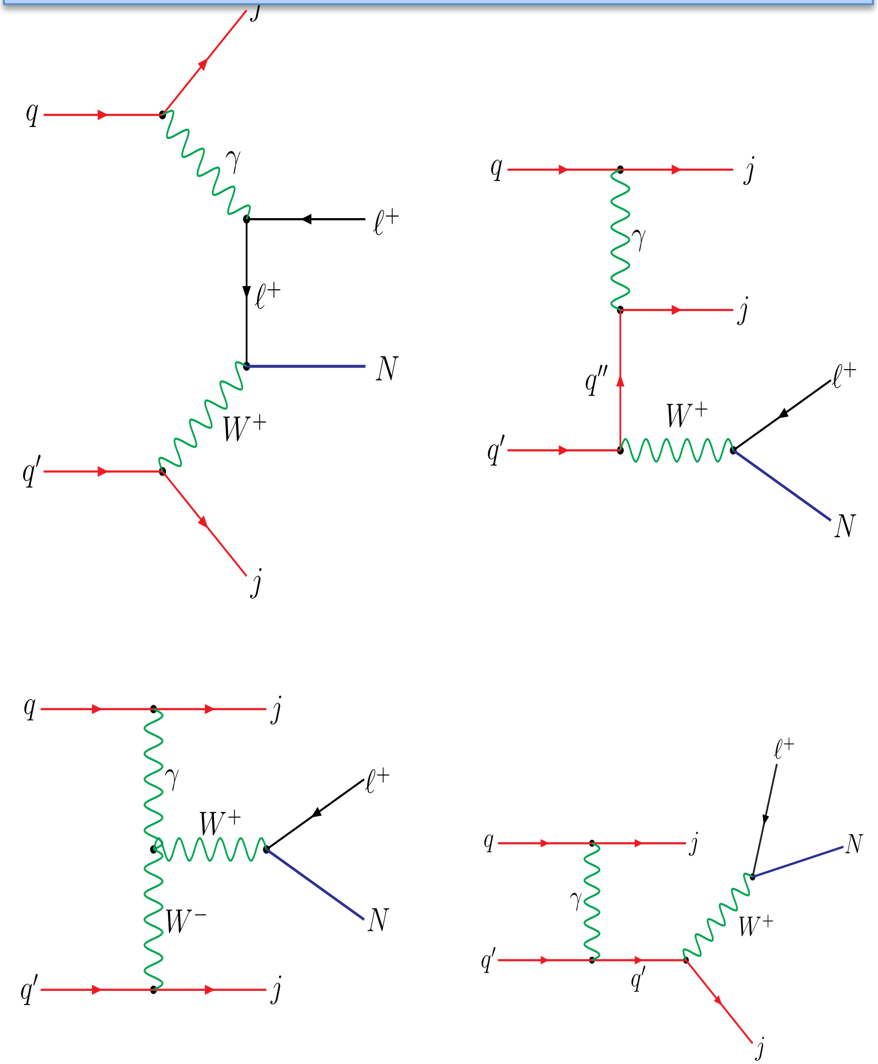
b) Quark-Gluon



c) Gluon-Gluon

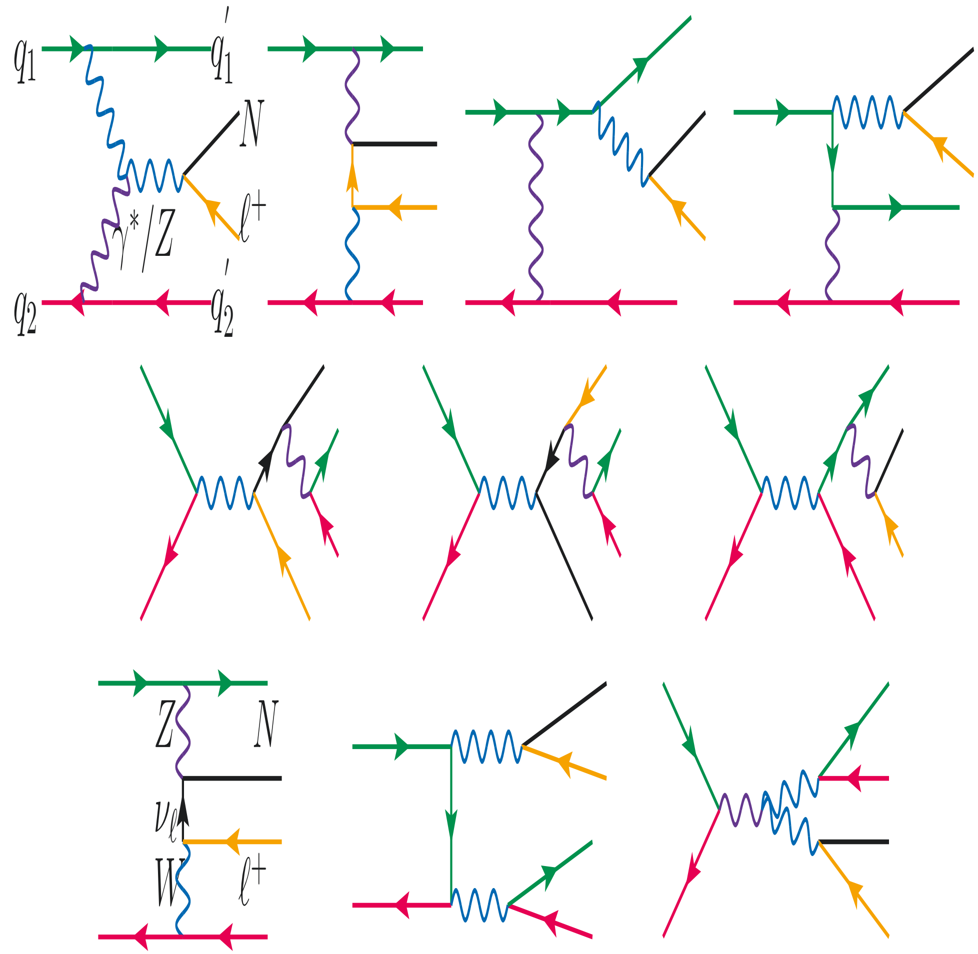


Proton-photon interaction $pa \to N\ell^{\pm}j$



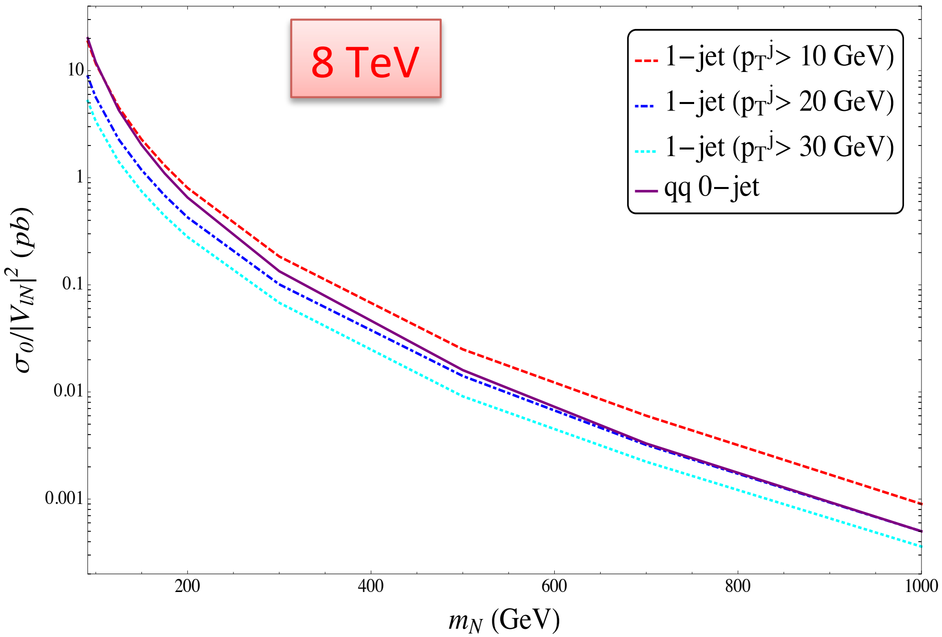
Dev, Pilaftsis and Yang PRL 112 (2014)8, 081801

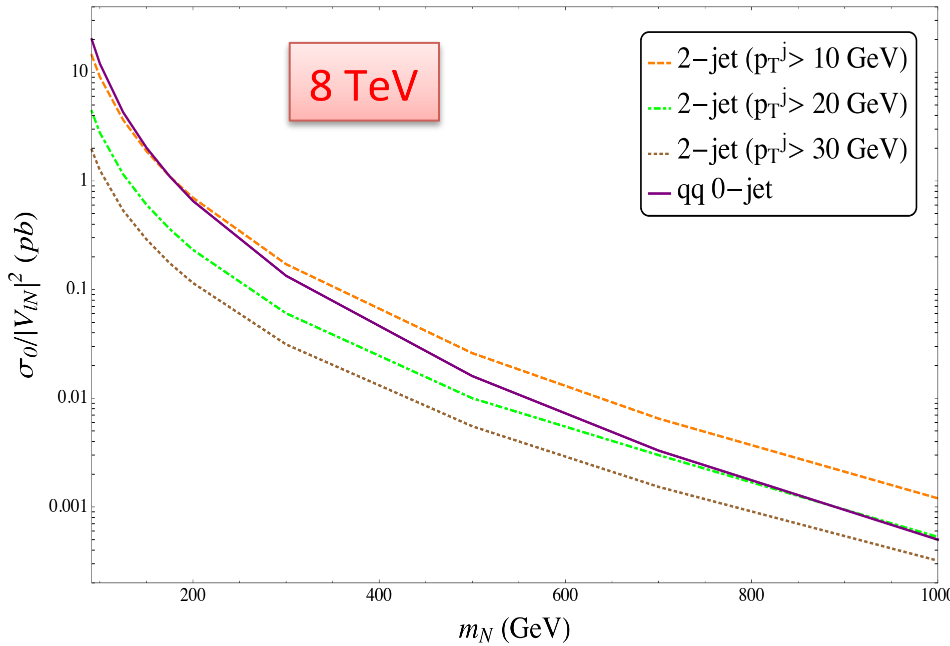
Proton-proton QED Processes $pp \to N\ell^{\pm}jj$ (QED)

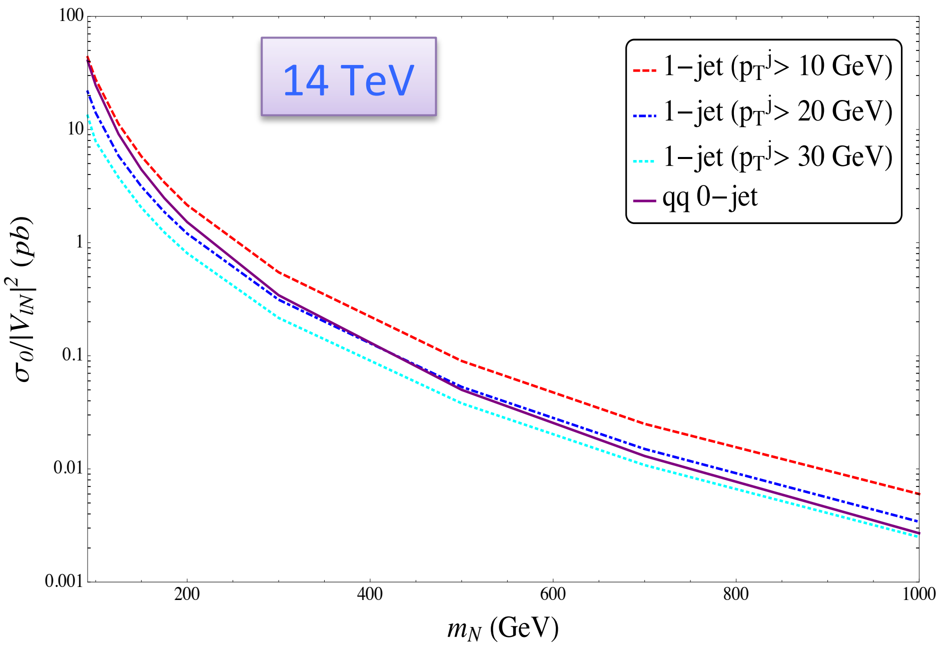


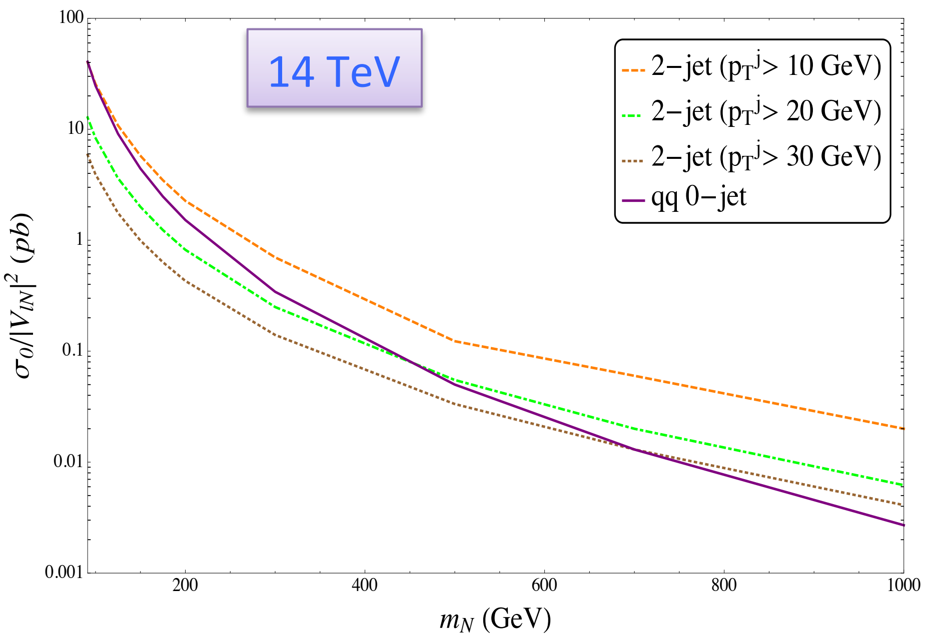
Alva, Han, Ruiz JHEP 1502 (2015) 072

Production cross section normalized by the square of the mixing

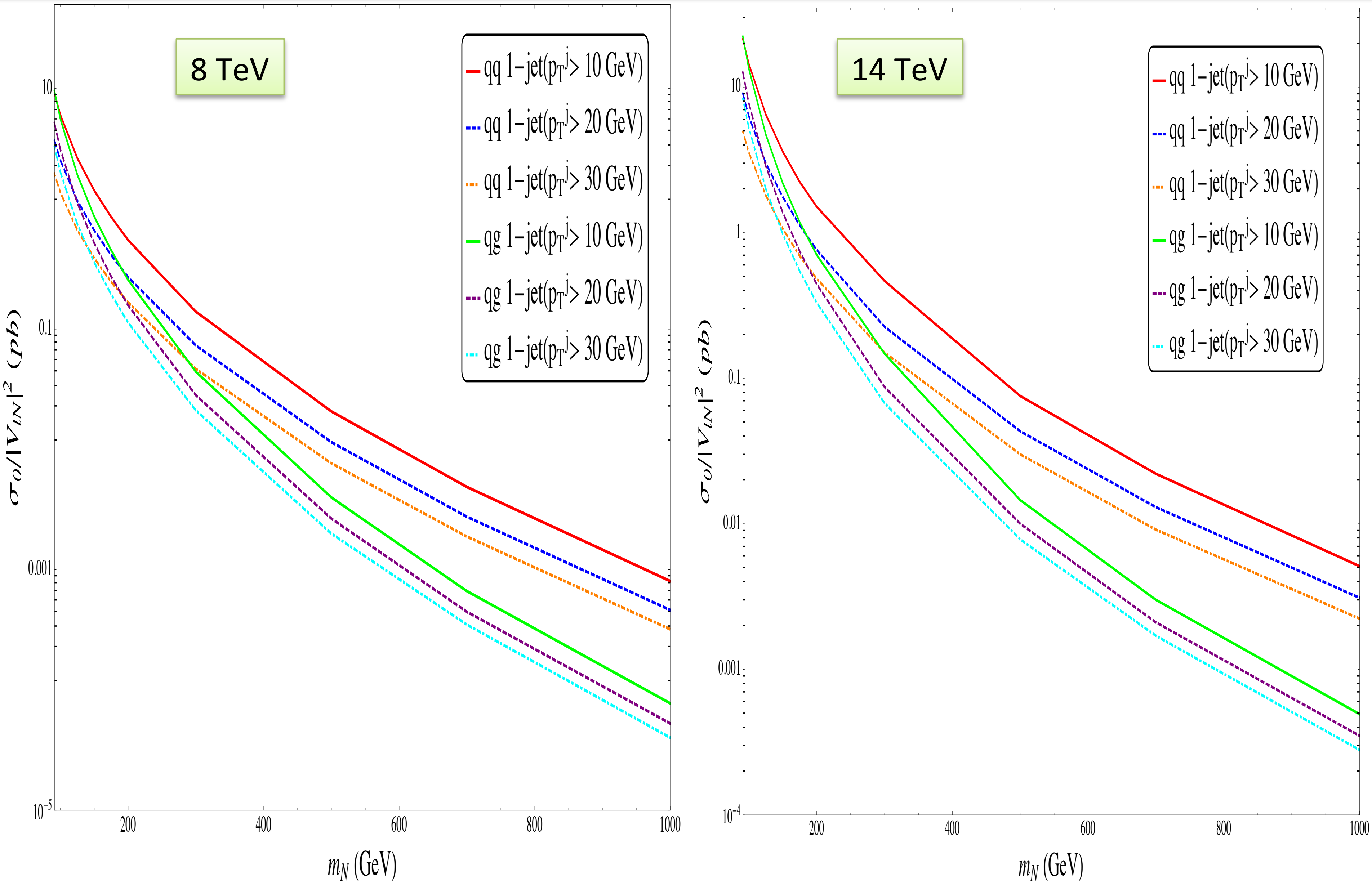




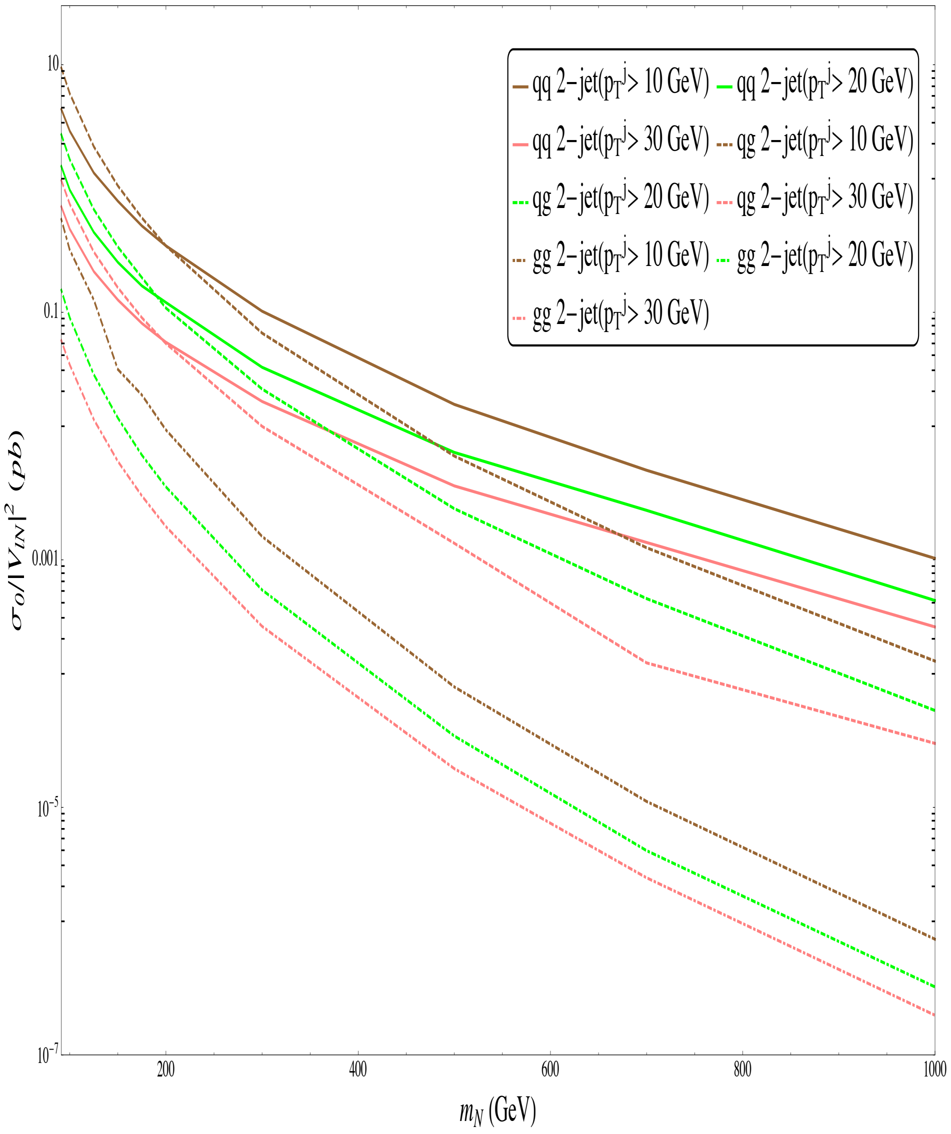


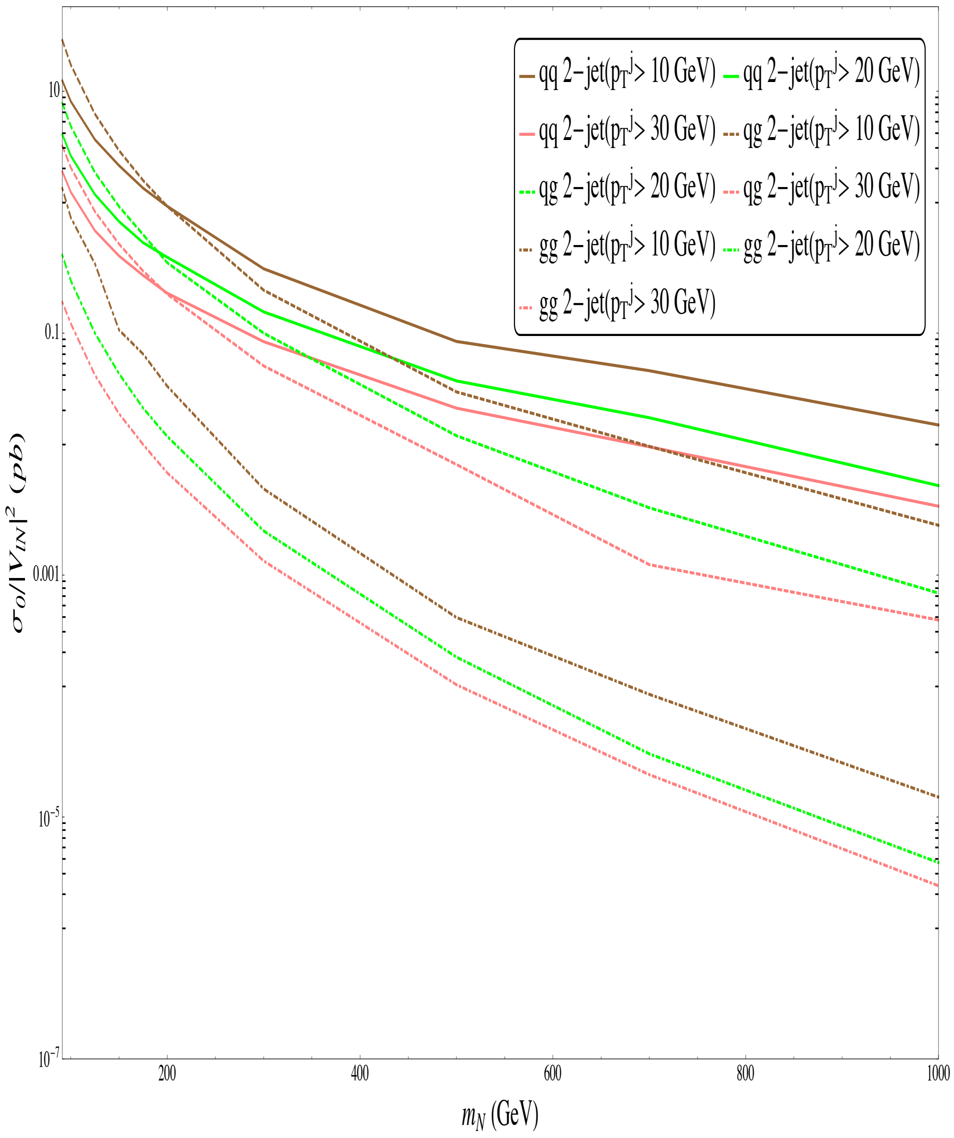


Contributions from the quark-quark and the quark-gluon interaction from the 1-jet processes normalized by the square of the mixing

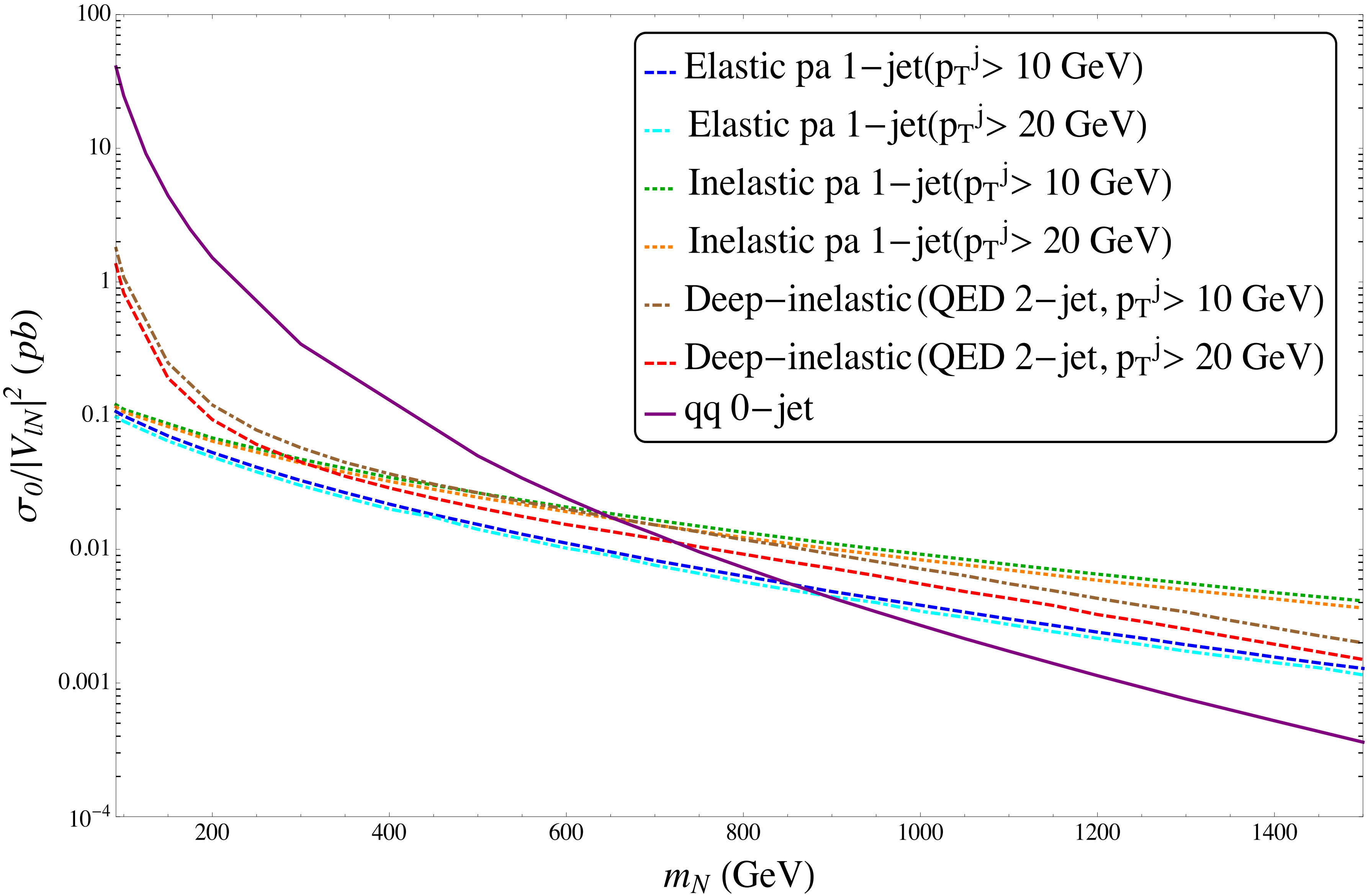


Contributions from the quark-quark, quark-gluon and the gluon-gluon interactions from the 2-jet processes normalized by the square of the mixing



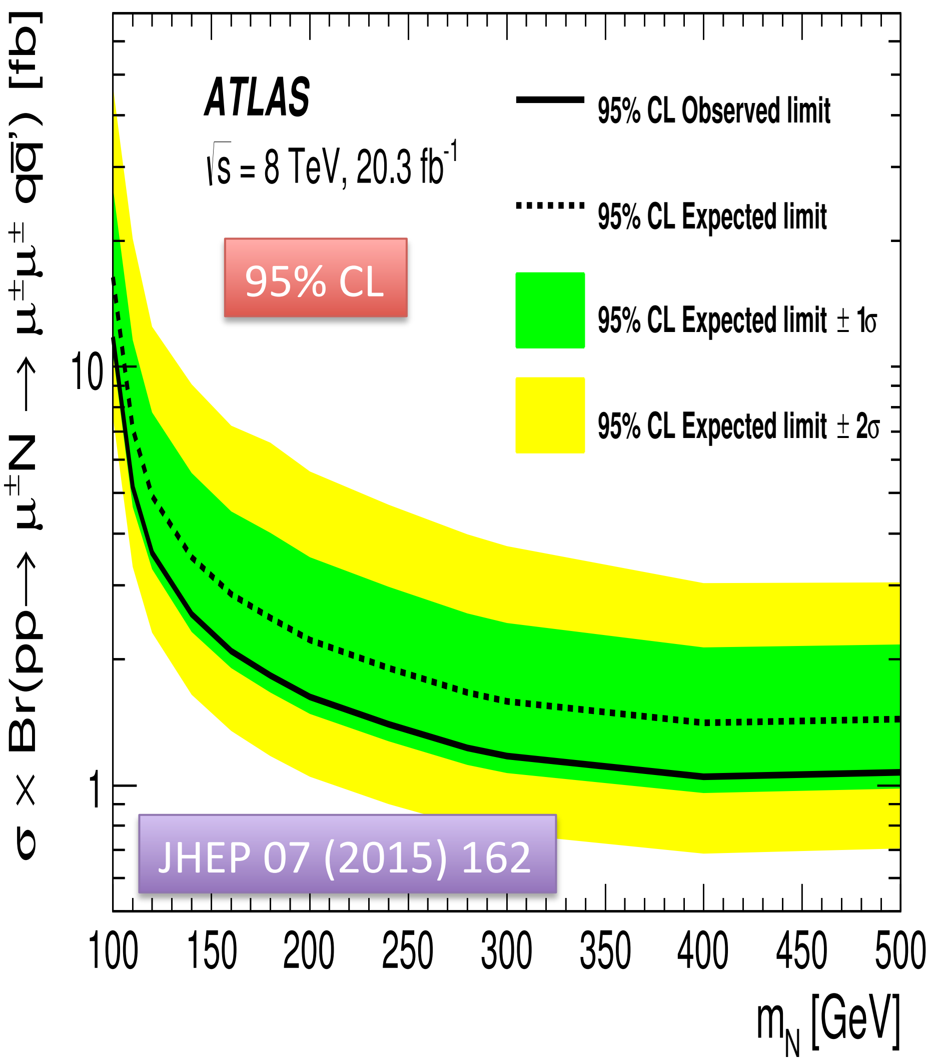


Cross sections of the 1-jet (proton- photon from proton) and 2-jet QED processes normalized by the square of the mixing

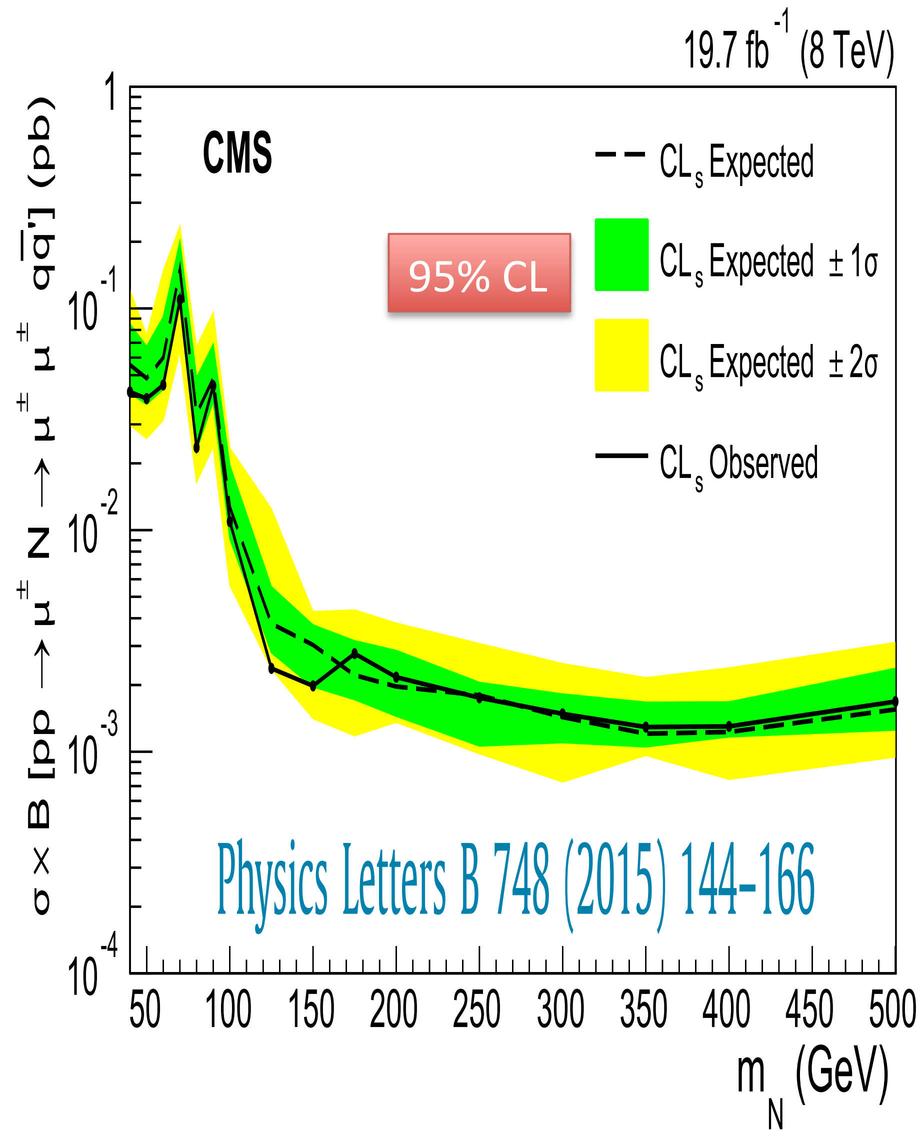


Signal Process at the 8 TeV LHC

ATLAS Results, $p_T^j > 20$ GeV @ 20.3 fb^{-1} 8 TeV , same-sign di- μ



CMS Results, $p_T^j > 20$ GeV @ 19.7 fb^{-1} 8 TeV same-sign di- μ



CMS Criteria for Anomalous multi-lepton Search @ 8 TeV, 19.7 fb^{-1}

(Table-III , Phys. Rev. D 90, 032006)

(i) The transverse momentum of each lepton: $p_T^\ell > 10$ GeV.

(ii) The transverse momentum of at least one lepton: $p_T^{\ell,\text{leading}} > 20$ GeV.

(iii) The jet transverse momentum: $p_T^j > 30$ GeV.

(iv) The pseudo-rapidity of leptons: $|\eta^\ell| < 2.4$ and of jets: $|\eta^j| < 2.5$.

(v) The lepton-lepton separation: $\Delta R_{\ell\ell} > 0.1$ and the lepton-jet separation: $\Delta R_{\ell j} > 0.3$.

(vi) The invariant mass of each OSSF lepton pair: a) $m_{\ell^+\ell^-} < 75$ GeV and b) $m_{\ell^+\ell^-} > 105$ GeV.

(vii) The scalar sum of the jet transverse momenta: $H_T < 200$ GeV.

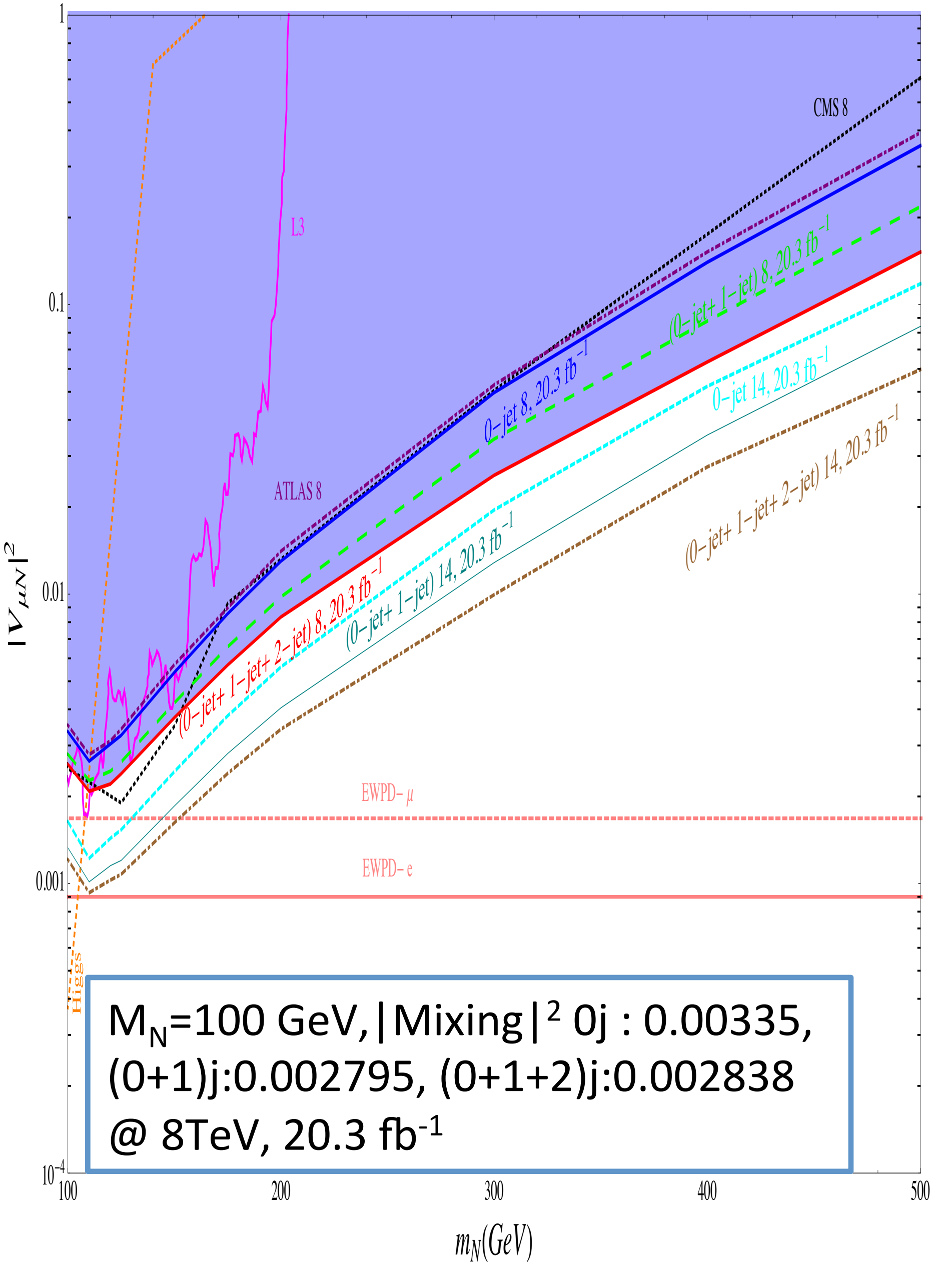
(viii) The missing transverse energy: $\not{E}_T < 50$ GeV.

•Case I : $m_{\ell^+\ell^-} < 75$: CMS has observed 510 events with the SM background expectation 560±87 events . Upper limit of 510 − (560 − 87) =37 events.

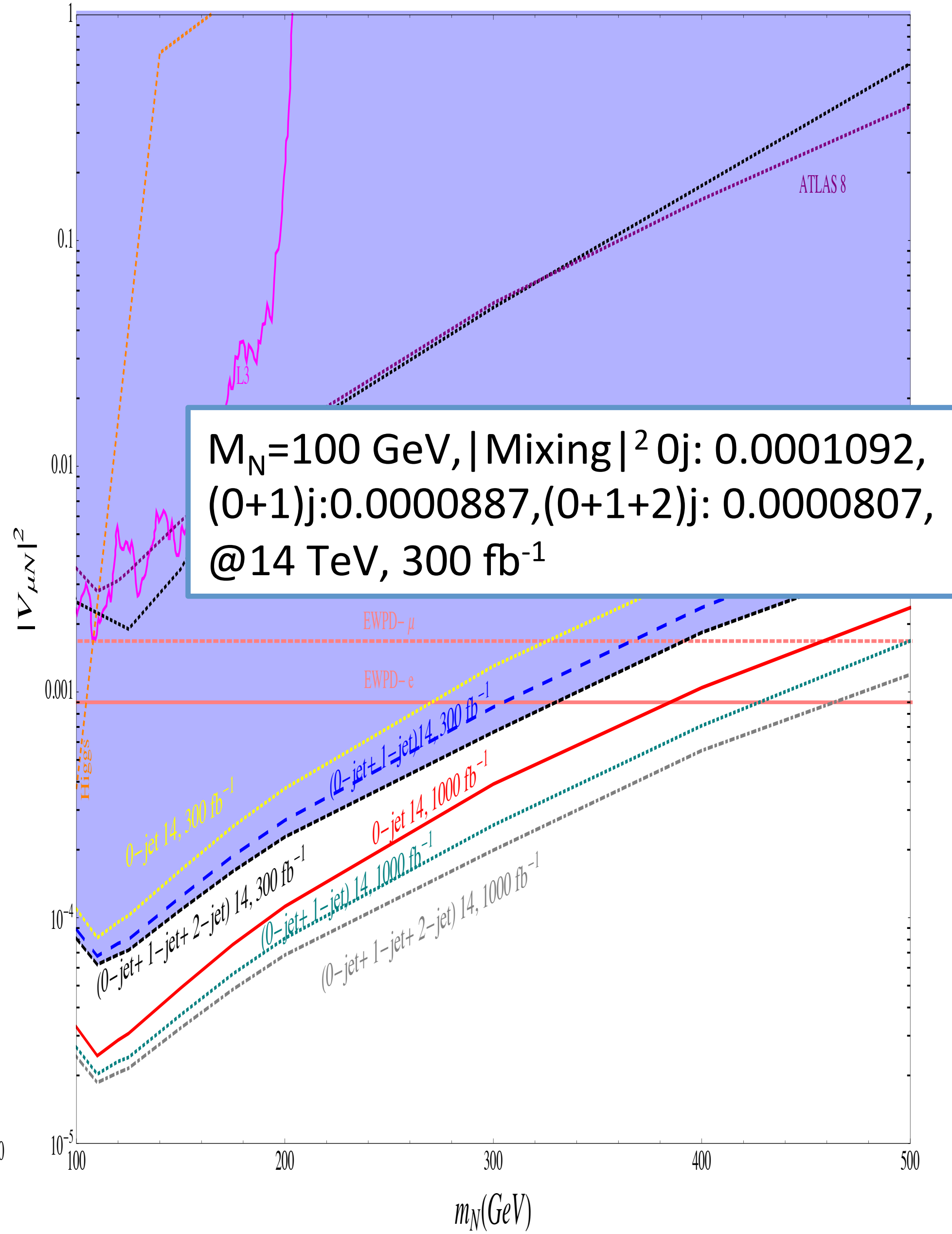
•Case II: $m_{\ell^+\ell^-} > 105$: CMS has observed 178 events with the SM background expectation 200±35 events. Upper limit of 178 − (200 − 35) =13 events.

• These set a 95 % CL on the mixing parameter as a function of the heavy neutrino mass.

Upper bound on the Mixing Square from ATLAS same-sign di-lepton @ 8 TeV

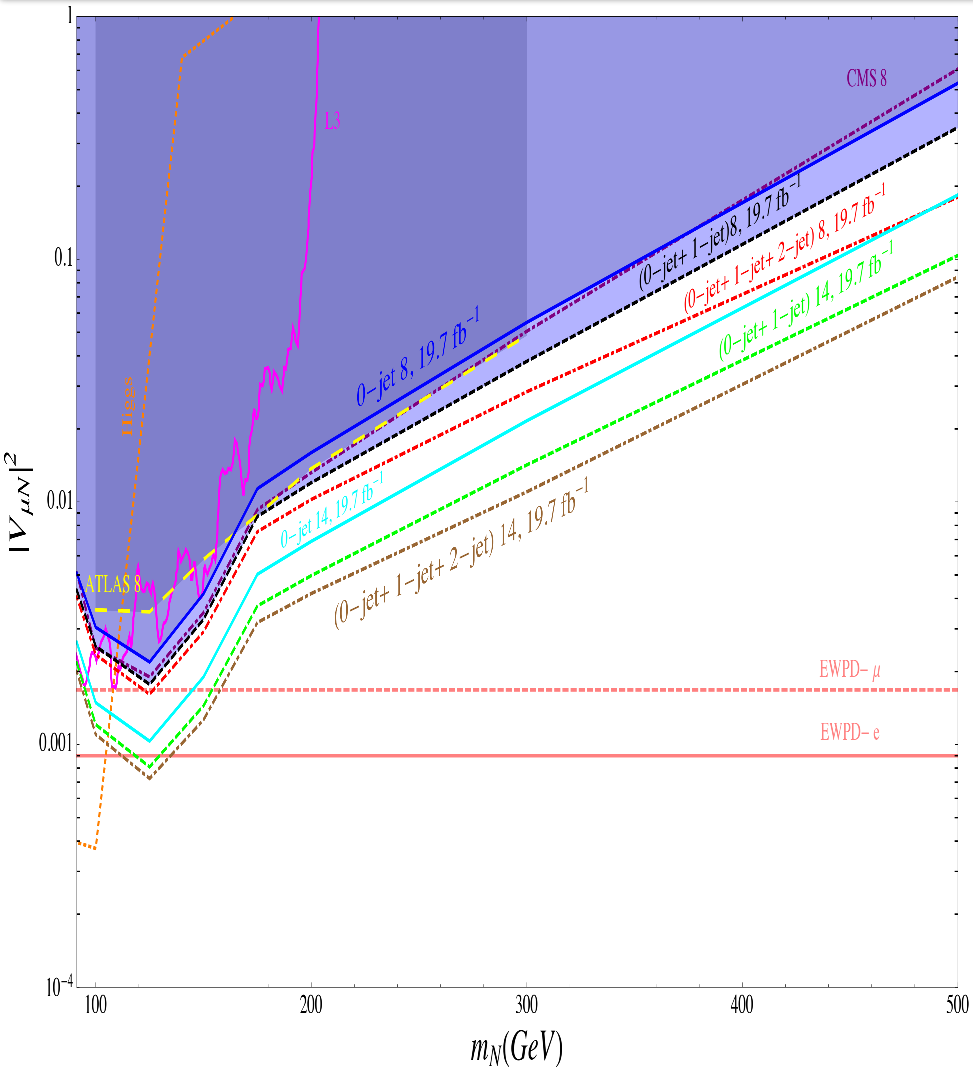


M$_N$=100 GeV, |Mixing|^2 0j : 0.00335, (0+1)j:0.002795, (0+1+2)j:0.002838 @ 8TeV, 20.3 fb^{-1}

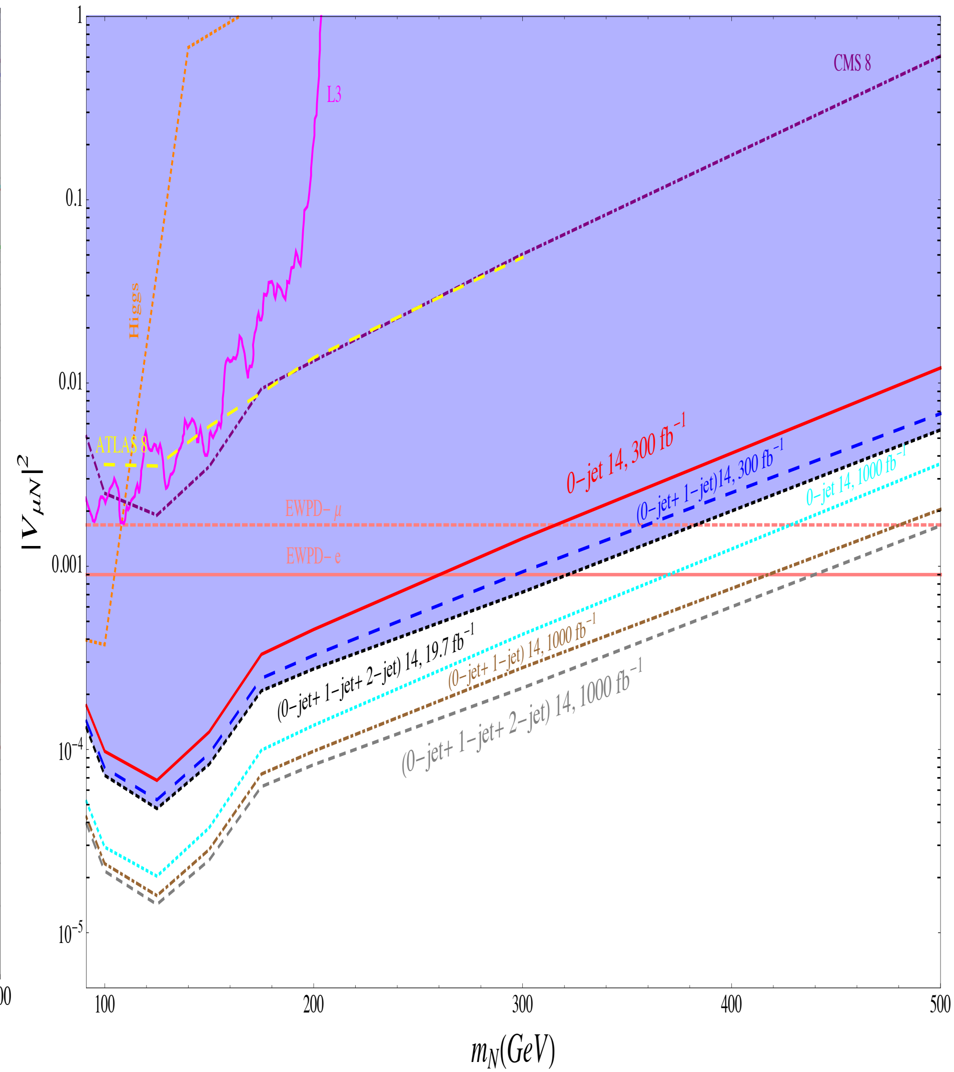


M$_N$=100 GeV, |Mixing|^2 0j: 0.0001092, (0+1)j:0.0000887,(0+1+2)j: 0.0000807, @14 TeV, 300 fb^{-1}

Upper bound on the Mixing Square from CMS same-sign di-lepton @ 8 TeV

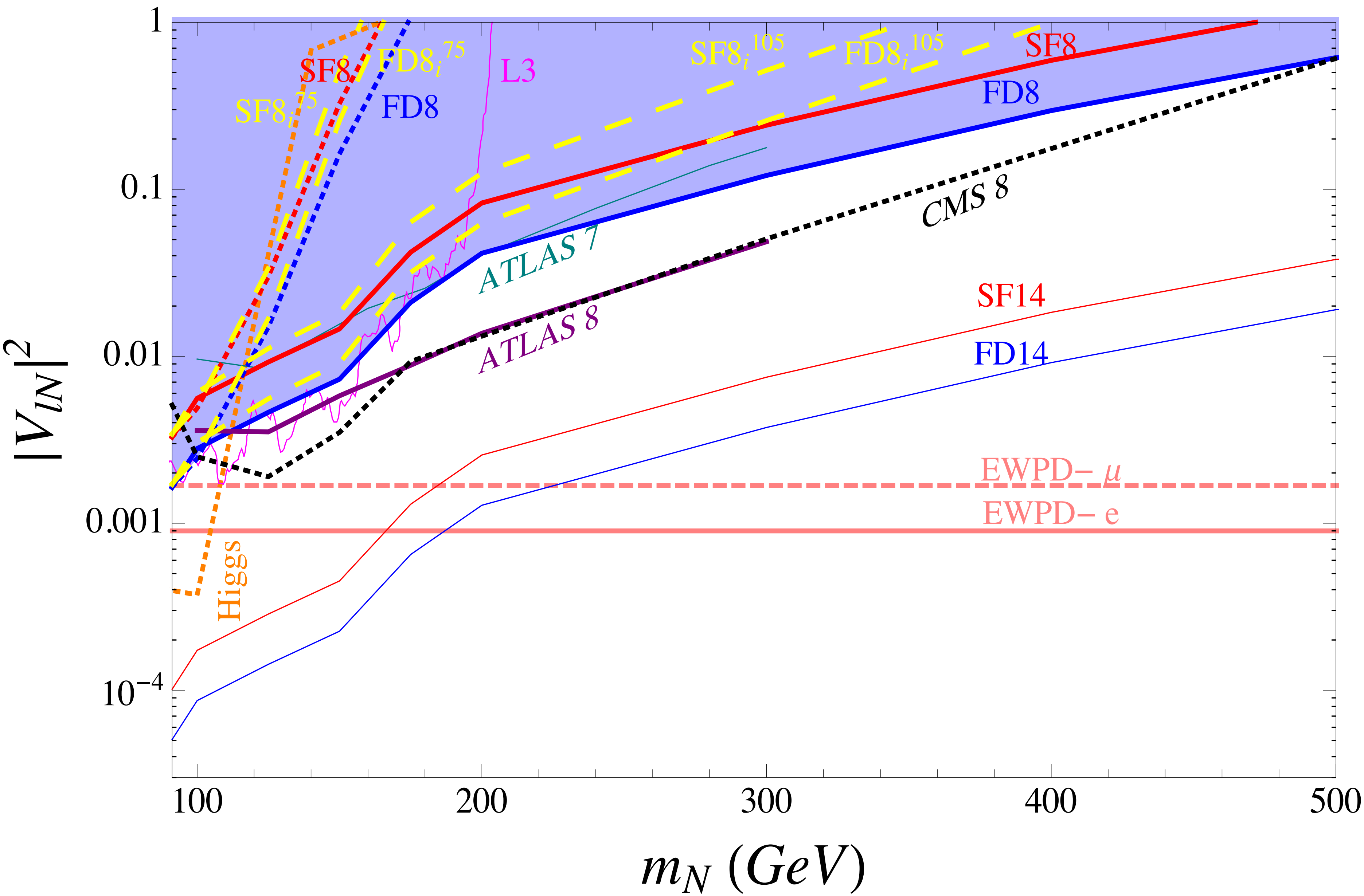


M_N=100 GeV, 0j: 0.005085, 1j:0.00433, 2j: 0.00405 @ 8 TeV, 19.7 fb^{-1}



M_N=100 GeV, 0j: 0.000173, 1j:0.000143, 2j: 0.0001315 @ 14 TeV, 300 fb^{-1}

Upper bound on the Mixing Square from Anomalous multi-lepton search @ 8 TeV



CONCLUSIONS

We studied the seesaw mechanism through Majorana heavy neutrinos and inverse seesaw mechanism through the pseudo-Dirac heavy neutrinos.

The production mechanisms of the Heavy Neutrino at the LHC.

Seesaw:

We studied a variety of initial states such as quark-quark, quark-gluon and the gluon-gluon fusions.

We used the same sign di-lepton signal for the heavy neutrino production in seesaw mechanism.

Inverse Seesaw

Using the recent ATLAS and CMS analyses @ 8 TeV for the same sign di-lepton data we improve the upper limit on $|V_{IN}|^2$ for all the QED and QCD processes.

We used the CMS results @ 8 TeV to improve the upper bound on $|V_{IN}|^2$ from the tri-lepton signal including all the QED and QCD processes.

We also put tentative bounds @ 14 TeV LHC for the above signals.