NNLO QCD corrections to resonant sneutrino/slepton production at LHC

Swapan Majhi
Saha Institute of Nuclear Physics

Collaboration with: V. Ravindran
P. Mathews.

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Outline

- **Introduction & Motivation**
- **Procedure & Discussion**
- **Summary**

SUSY R_p violating model

The possible *R*-parity violating ($\not{R}_p$) terms in the superpotential is given by

$$\mathcal{W}_{\not{R}_p} = \mu_i L_i H_2 + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c$$

SUSY R_p violating model

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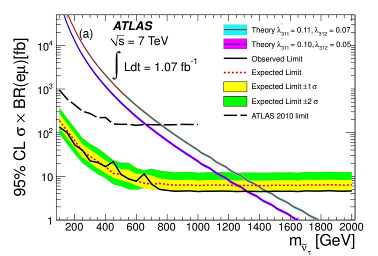
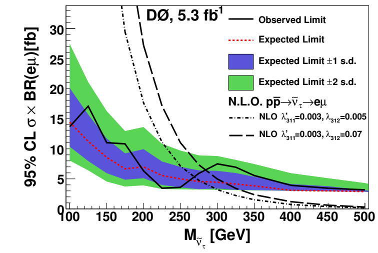
In terms of the component fields

$$\mathcal{L}_{\lambda'} = \lambda'_{ijk} \Big[\overline{d_{kR}} \nu_{iL} \tilde{d}_{jL} + \overline{d_{kR}} d_{jL} \tilde{\nu}_{iL} + \overline{(\nu_{iL})^c} d_{jL} \tilde{d}^*_{kR} - \overline{d_{kR}} \ell_{iL} \tilde{u}_{jL} - \overline{d_{kR}} u_{jL} \tilde{\ell}_{iL} - \overline{(\ell_{iL})^c} u_{jL} \tilde{d}^*_{kR} \Big] + \text{h.c.}$$

ATLAS Plot

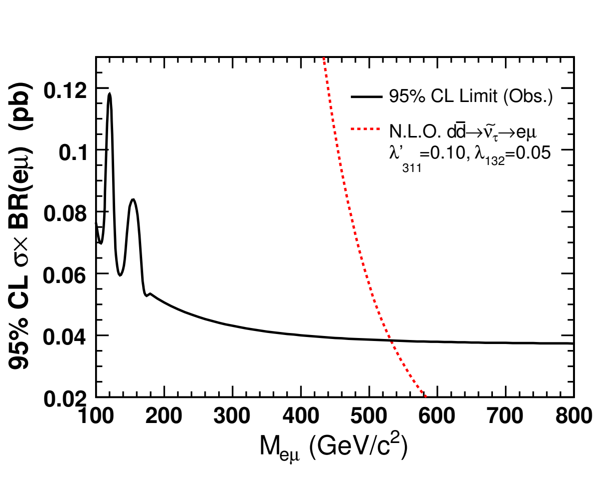


(a)
ATLAS
√s = 7 TeV
∫ Ldt = 1.07 fb-1
Theory λ'311 = 0.11, λ312 = 0.07
Theory λ'311 = 0.10, λ312 = 0.05
Observed Limit
Expected Limit
Expected Limit ±1σ
Expected Limit ±2σ
ATLAS 2010 limit
95% CL σ × BR(eμ)[fb]
m_ν̃τ [GeV]



DØ, 5.3 fb-1
Observed Limit
Expected Limit
Expected Limit ±1 s.d.
Expected Limit ±2 s.d.
N.L.O. pp̄→ν̃τ→eμ
NLO λ'311=0.003, λ312=0.005
NLO λ'311=0.003, λ312=0.07
95% CL σ × BR(eμ)[fb]
M_ν̃τ [GeV]

D0 Plot


95% CL σ× BR(eμ) (pb)
0.12
0.1
0.08
0.06
0.04
0.02
100
200
300
400
500
600
700
800
Meμ (GeV/c2)
95% CL Limit (Obs.)
N.L.O. dd̄→ν̃τ→eμ
λ'311=0.10, λ132=0.05

Theoretical Uncertainties

- Theoretical uncertainties can be reduced by doing the higher order radiative corrections

- The dominant source of theoretical uncertainties are from the strong interaction physics (QCD)
- Doing the QCD corrections one can reduce the theoretical uncertainties coming from strong interaction physics
- Also the scale uncertainties reduced

Inclusive Hadronic Cross section

The inclusive hadronic cross section for the reaction

$$H_1(P_1) + H_2(P_2) \to \phi(p_5) + X$$

is given by

$$\sigma_{\rm tot}^{\phi} = \frac{\pi \lambda'^2(\mu_R^2)}{12S} \sum_{a,b=q,\bar{q},g} \int_{\tau}^{1} \frac{dx_1}{x_1} \int_{\tau/x_1}^{1} \frac{dx_2}{x_2}\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)$$

$$\times \Delta_{ab} \left(\frac{\tau}{x_1\, x_2}, m_\phi^2, \mu_F^2, \mu_R^2 \right)$$

with $\tau = \dfrac{m_\phi^2}{S}$, $S = (P_1 + P_2)^2$, $p_5^2 = m_\phi^2$,

RG evolution

The renormalisation group (RG) invariant with respect to both the scales implies

$$\mu^2 \frac{d\sigma_{\text{tot}}^{\phi}}{d\mu^2} = 0, \qquad \mu = \mu_F, \mu_R\,,$$

$$\mu_R^2 \frac{d}{d\mu_R^2}\left[\lambda'^2(\mu_R^2)\Delta_{ab}\left(x, m_\phi^2, \mu_F^2, \mu_R^2\right)\right] = 0\,.$$

$$\Delta_{ab}\left(x, m_\phi^2, \mu_F^2, \mu_R^2\right) = \sum_{i=0}^{\infty} a_s^i(\mu_R^2)\Delta_{ab}^{(i)}\left(x, m_\phi^2, \mu_F^2, \mu_R^2\right)$$

$$a_s = \frac{\alpha_s}{4\pi}$$

RG evolution equation

Two coupling constant a_s, λ' are the renormalisation constants to obtain the UV finite partonic coefficient functions, Δ_{ab}.

RG evolution equation

The bare coupling constant $\hat{a}_s$ is related to the renormalised one, $a_s(\mu_R^2)$ by the following relation

$$S_\epsilon \hat{a}_s = Z(\hat{a}_s, \mu^2, \mu_R^2, \epsilon) a_s(\mu_R^2) \left(\frac{\mu^2}{\mu_R^2}\right)^{\frac{\epsilon}{2}} .$$

where $S_\epsilon = exp\Big(\epsilon/2(\gamma_E - \ln 4\pi)\Big)$.

RG evolution equation

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where

$$Z(\hat{a}_s, \mu^2, \mu_R^2, \epsilon) = 1 \quad + \quad \hat{a}_s \left(\frac{\mu_R^2}{\mu^2}\right)^{\frac{1}{2}\epsilon} S_\epsilon \left[\frac{2\beta_0}{\epsilon}\right] + \hat{a}_s^2 \left(\frac{\mu_R^2}{\mu^2}\right)^{\epsilon} S_\epsilon^2 \left[\frac{\beta_1}{\epsilon}\right]$$

RG evolution equation

For the Yukawa coupling, λ'

$$S_\epsilon \hat{\lambda}' = Z_{\lambda'}(\hat{a}_s, \mu^2, \mu_R^2, \epsilon)\lambda'(\mu_R^2)\left(\frac{\mu^2}{\mu_R^2}\right)^{\frac{\epsilon}{2}},$$

where

$$Z_{\lambda'}(\hat{a}_s, \mu^2, \mu_R^2, \epsilon) = 1 + \hat{a}_s\left(\frac{\mu_R^2}{\mu^2}\right)^{\frac{\epsilon}{2}} S_\epsilon\left[\frac{1}{\epsilon}\Big(2\,\gamma_0\Big)\right] + \hat{a}_s^2\left(\frac{\mu_R^2}{\mu^2}\right)^{\epsilon} S_\epsilon^2\left[\frac{1}{\epsilon^2}\Big(2\Big(\gamma_0\Big)^2 - 2\beta_0\gamma_0\Big) + \frac{1}{\epsilon}\Big(\gamma_1\Big)\right]$$

The anomalous dimensions γ_i for $i = 1, ..., 4$ can be obtained from the quark mass anomalous dimensions.

RG evolution equation

$$\mu_R^2 \frac{d}{d\mu_R^2} \ln a_s(\mu_R^2) = -\sum_{i=1}^{\infty} a_s^i(\mu_R^2)\, \beta_{i-1}\,,$$

$$\mu_R^2 \frac{d}{d\mu_R^2} \ln \lambda'(\mu_R^2) = -\sum_{i=1}^{\infty} a_s^i(\mu_R^2)\, \gamma_{i-1}\,.$$

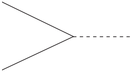


Figure 1: Subprocess $q_i + \bar{q}_j \to \phi$.

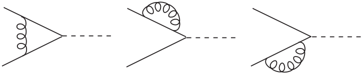


Figure 2: Subprocess $q_i + \bar{q}_j \to \phi$.

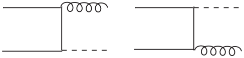


Figure 1: Subprocess $q_i + \bar{q}_j \to \phi + g$.

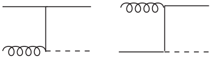


Figure 2: Subprocess $q_i + g \to \phi + q_j$.

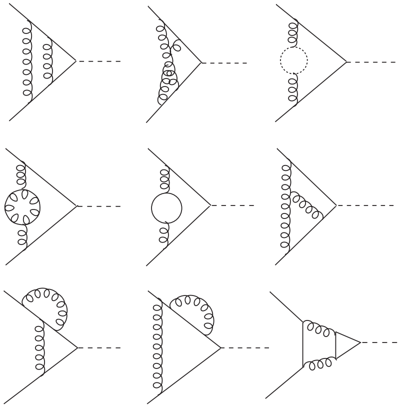


Figure 1: Subprocess $q_i + \bar{q}_j \to \phi$.

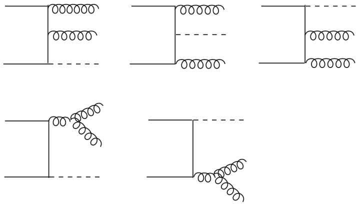


Figure 1: Subprocess $q_i + \bar{q}_j \to \phi + g + g$.

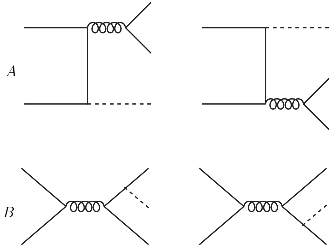


Figure 2: s channel annihilation graphs contributing to the subprocess $q_i + \bar{q}_j \to \phi + q_k + \bar{q}_l$.

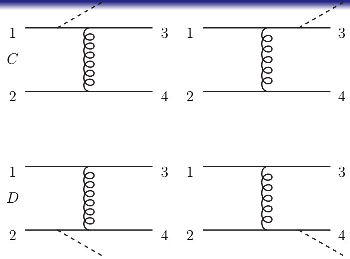
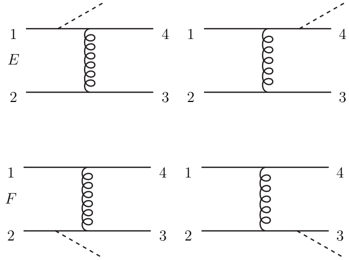


Figure 1: t channel gluon exchange graphs contributing to the subprocesses $q_i + \bar{q}_j \to \phi + q_k + \bar{q}_l$, $q_i + q_j \to \phi + q_k + q_l$ and $\overline{q}_i + \overline{q}_j \to \phi + \overline{q}_k + \overline{q}_l$.



Divergences present in any higher order corrections:

- UV-divergence $(k -> \infty)$
- IR-divergence $(k -> 0)$

IR-divergence

soft

($\lambda \to 0, \lambda$ is the mass of the gauge field)

collinear

(Bothλ, $m \to 0$, m is the mass of the of the matter field)

Divergences present in any higher order corrections and calculational technique

UV + IR (soft + collinear)-divergences

- The form factor (two-loop) are evaluated using dispersion technique
- All the one loop tensorial integrals reduced to scalar integrals using Passarino-Veltman method in $4 + \epsilon$ dimension.
- Two and three body phase space integrals are done by choosing appropriate Lorentz frame
- For algebraic manipulation, we use FORM.
- We use the dimensional regularisation and MS-bar scheme. We also assume all partons are massless.

How to remove Singularities

- The UV singularities go away after performing renormalisation through the constants Z and $Z_{\lambda'}$.
- The soft singularities cancel among virtual and real emission processes at every order in perturbation theory - Bloch-Nordseick theorem
- The remaining collinear singularities are renormalised systematically using mass factorisation.

Calculational technique

The resulting UV and soft finite partonic cross sections as

$$\hat{\Delta}_{ab}\left(x, m_\phi^2, \mu_R^2\right) = \frac{s}{\lambda'^2(\mu_R^2)}\, \hat{\sigma}_{ab,\phi}\left(x, m_\phi^2, \mu_R^2\right) .$$

Calculational technique

The collinear singular partonic cross section $\hat{\Delta}_{ab}$ can be written in terms of pair of singular transition functions $\Gamma_{cd}(x, \mu_F^2, \epsilon)$, and finite partonic coefficient function Δ_{ab}:

$$\hat{\Delta}_{ab}\left(x, m_\phi^2, \mu_R^2\right) = \sum_{c,d=q,\bar{q},g} \int_x^1 \frac{dx_1}{x_1} \int_{x/x_1}^1 \frac{dx_2}{x_2} \times \Gamma_{ca}(x_1, \mu_F^2, \epsilon)\, \Gamma_{db}(x_2, \mu_F^2, \epsilon) \times \Delta_{cd}\left(\frac{x}{x_1\, x_2}, m_\phi^2, \mu_F^2, \mu_R^2\right) .$$

Calculational technique

$$\hat{\Delta}_{ab}\left(x, m_\phi^2, \mu_R^2\right) = \sum_{c,d=q,\bar{q},g} \int_x^1 \frac{dx_1}{x_1} \int_{x/x_1}^1 \frac{dx_2}{x_2} \times \Gamma_{ca}(x_1, \mu_F^2, \epsilon)\, \Gamma_{db}(x_2, \mu_F^2, \epsilon) \times \Delta_{cd}\left(\frac{x}{x_1\, x_2}, m_\phi^2, \mu_F^2, \mu_R^2\right).$$

$$\Gamma_{ab}(x, \mu_F^2, \epsilon) = \sum_{i=0}^{\infty} a_s^i(\mu_F^2)\Gamma_{ab}^{(i)}(x, \epsilon)\,.$$

Calculational technique

In $\overline{MS}$ mass factorisation scheme, they are found to be (suppressing the arguments x and ϵ)

$$\begin{aligned} \Gamma_{ab}^{(0)} &= \delta_{ab}\delta(1-x)\,, \\ \Gamma_{ab}^{(1)} &= -\frac{1}{\epsilon}P_{ab}^{(0)}\,, \end{aligned}$$

and

$$\Gamma_{ab}^{(2)} = \frac{1}{2\epsilon^2}\sum_c \left(P_{ac}^{(0)} \otimes P_{cb}^{(0)} + 2\beta_0 P_{ab}^{(0)}\right) + \frac{1}{2\epsilon}P_{ab}^{(1)}\,.$$

How to remove the singularities

UV + IR (soft + collinear)-divergences

Renormalisation

$\Downarrow$

IR (soft + collinear)-divergences

Virtual + real

$\Downarrow$

IR (collinear)-divergence

KLN-theorem or Mass Factorisation

$\Downarrow$

Finite

Various checks

We checked our calculations in both analytic as well as numerics.

- Analytically, all the singularities (UV, IR and collinear) cancel properly.
- We have also checked our calculation with Harlander's (*et. al.*) paper NNLO calculation of Higgs bosons production ($b\bar{b} \rightarrow H$, Phys.Rev.D68,013001).
- We have also reproduced the numarical result of Harlander's paper.

Discussion

The solution to RGE for $\lambda'(\mu_R^2)$ is given by ,

$$\lambda'(\mu_R^2) = \lambda'(\mu_0^2)\frac{C(a_s(\mu_R^2))}{C(a_s(\mu_0^2))}$$

with

$$C(a_s) \quad = \quad a_s^{A_0} \sum_{i=0}^{\infty} a_s^i \, C_i \, .$$

Discussion

The C_i are given by

$$C_0 = 1, \qquad C_1 = A_1,$$
$$C_2 = \frac{1}{2}(A_1^2 + A_2), \qquad C_3 = \frac{1}{6}(A_1^3 + 3A_1A_2 + 2A_3),$$

with

$$A_0 = c_0, \qquad A_1 = c_1 - b_1c_0, \qquad A_2 = c_2 - b_1c_1 + c_0(b_1^2 - b_2),$$
$$A_3 = c_3 - b_1c_2 + c_1(b_1^2 - b_2) + c_0(b_1b_2 - b_1(b_1^2 - b_2) - b_3),$$

and

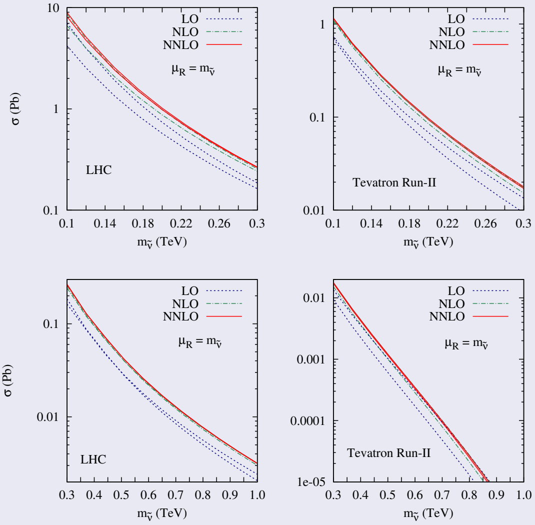
$$c_i = \frac{\gamma_i}{\beta_0}, \qquad b_i = \frac{\gamma_i}{\beta_0},$$

Discussion

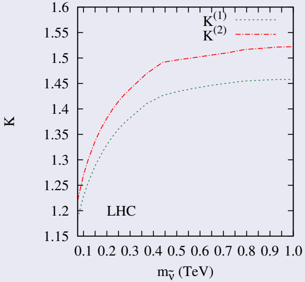
The reference scale $\mu_0 = M_Z$

- $\lambda'(M_Z^2) = 0.01$
- We have used MSTW2008 PDFs set.
- $\alpha_s(M_Z^2)$ for LO,NLO,NNLO provided with the MSTW2008 PDFs set.

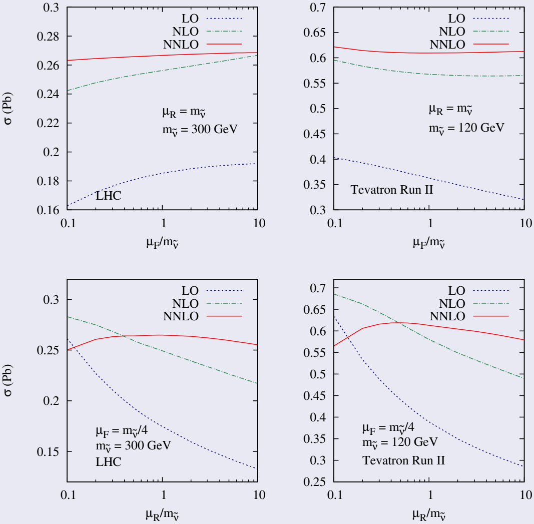
sneutrino cross section



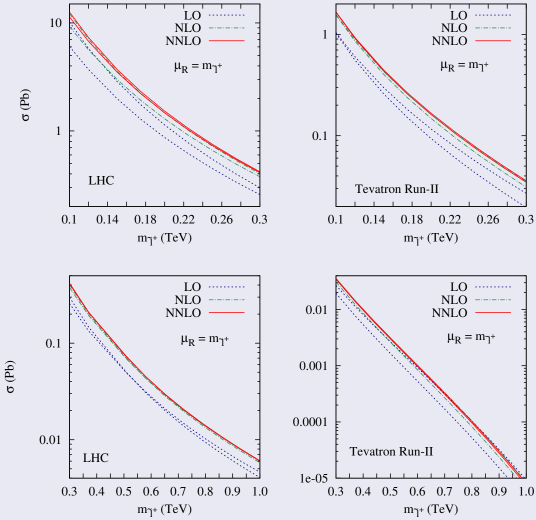
sneutrino K-factor



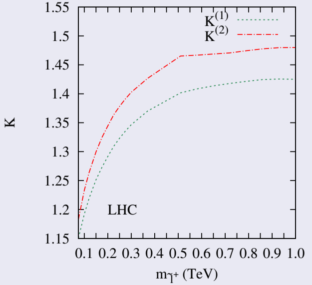
sneutrino μ_R, μ_F variation



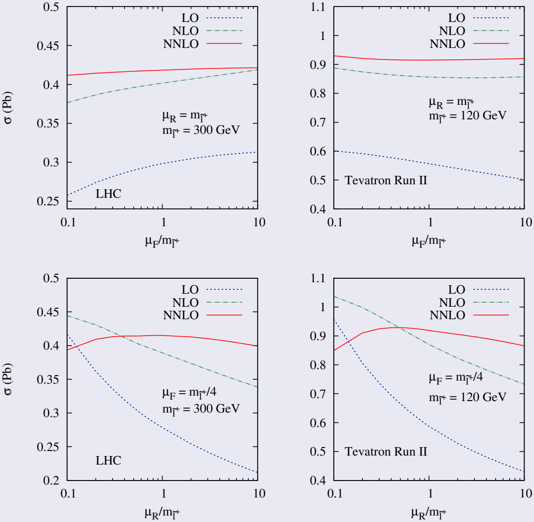
charged slepton cross section



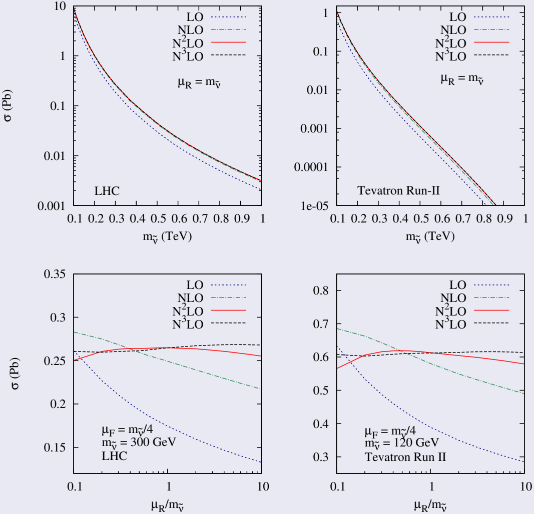
charged slepton K-factor



charged slepton μ_R, μ_F variation



N^3LO approximation



Summary and Conclusion

- Discuss the procedure to do the QCD radiative corrections to various machines

- We have shown that the scale uncertainties reduced significantly
- Theoretical uncertainties coming from QCD reduced by the radiative corrections
- Many more radiative corrections we need specially for LHC!

Thank You!