Probing Radiative Neutrino Mass Generation through Monotop Production

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PHENO 2014 Symposium
University of Pittsburgh
May 5th, 2014

Based on arXiv:1307.2606 and arXiv:1404.1415 in collaboration with John Ng.

Outline

- Motivation
- Model
  - Dark Matter
  - Neutrinos masses
- Constraints
- Monotop Probe
- Summary

Motivation

- Two important questions in the field of High Energy physics:
- Neutrino mass generation.

- Nature of Dark Matter.

- Cosmological results based on Planck's measurements of the CMB:
- $\Omega_c h^2 = 0.1199 \pm 0.0027$

- $N_{eff} = 3.30 \pm 0.27$ Planck Collaboration arXiv:1303.5076

- Introduce a model of physics beyond the Standard Model which can naturally generate small neutrino masses while providing a viable candidate for the dark matter present in our universe.

Model

- **Use the top quark as a dark portal and for neutrino mass generation:**

Dark Matter:

- **Extension of the Standard Model:**
  - **Z_2 yields a viable dark matter candidate.**

$$\mathcal{L}_{BSM} = \sum_{i=u,c,t} y_{\psi}^{u_i} \bar{u}_i P_L N^c \psi + \text{ h.c.}$$

$N : (\mathbf{1}, \mathbf{1}, \mathbf{0})$

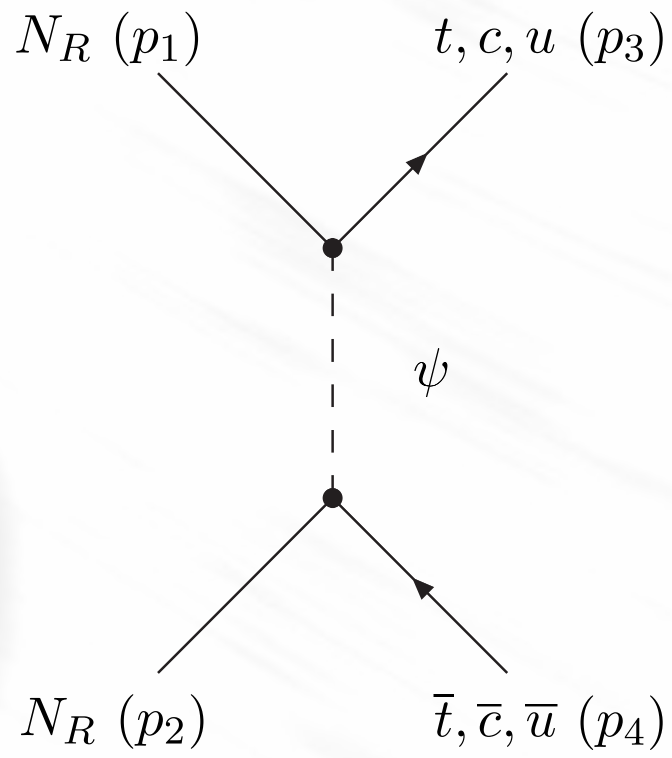
$\psi : (\mathbf{3}, \mathbf{1}, \mathbf{2/3})$

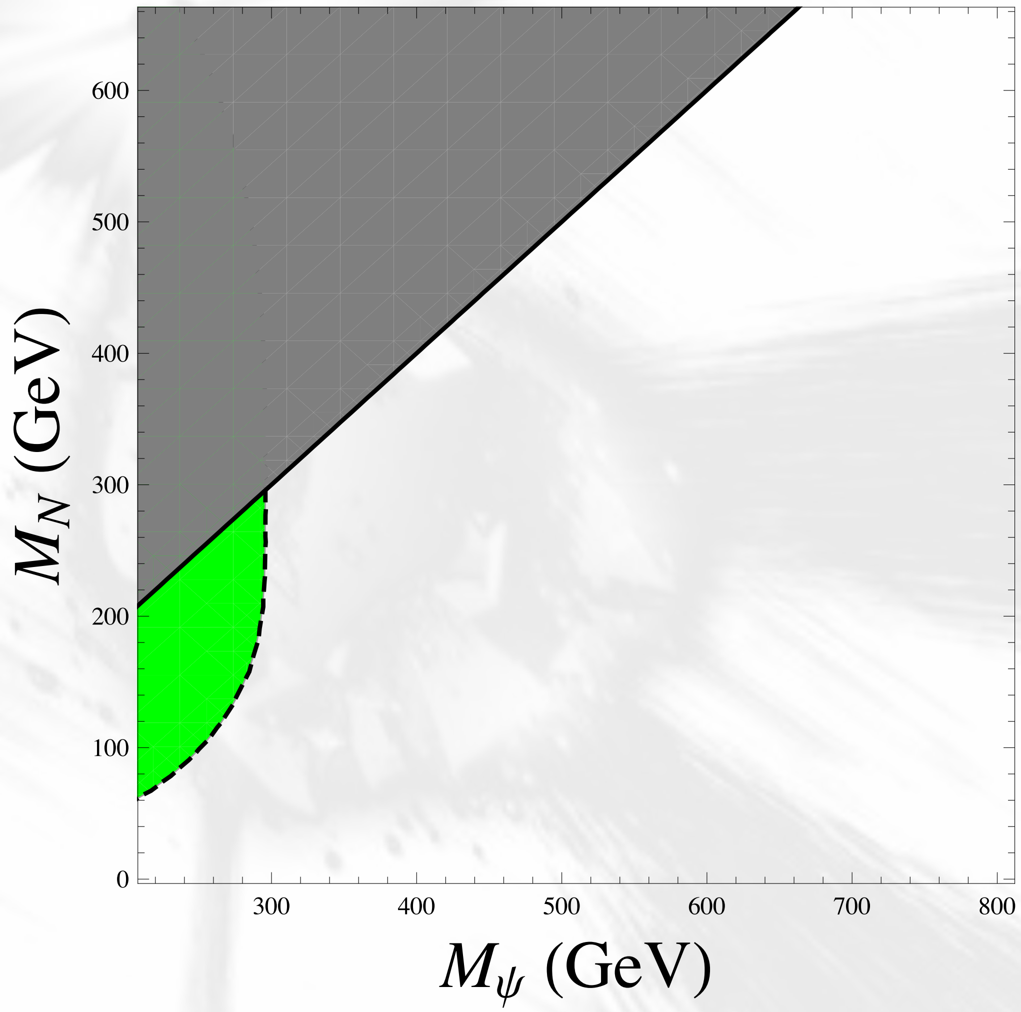
Y. Bai and J. Berger
S. Chang, R. Edezhath, J. Hutchinson, and M. Luty
H. An, L. -T. Wang and H. Zhang
A. DiFranzo, K. I. Nagao, A. Rajaraman, and T. M. P. Tait
M. Garny, A. Ibarra, S. Rydbeck, and S. Vogl

Dark Matter:

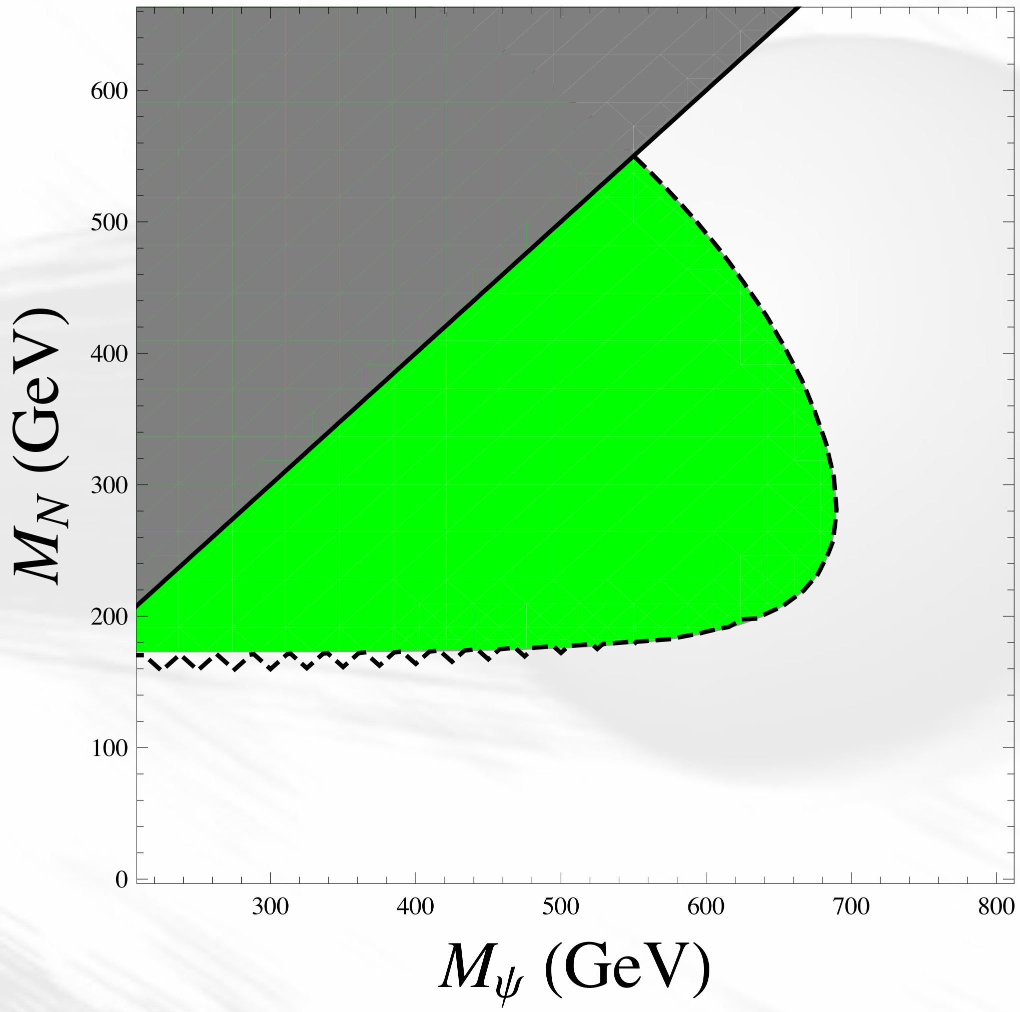
- Extension of the Standard Model:
  - Z_2 yields a viable dark matter candidate: $M_{N_R} < m_\psi$

- Annihilation only into lights quarks is p-wave suppressed.
- Non-zero coupling to the top quark leads to an s-wave contribution.





c-quark



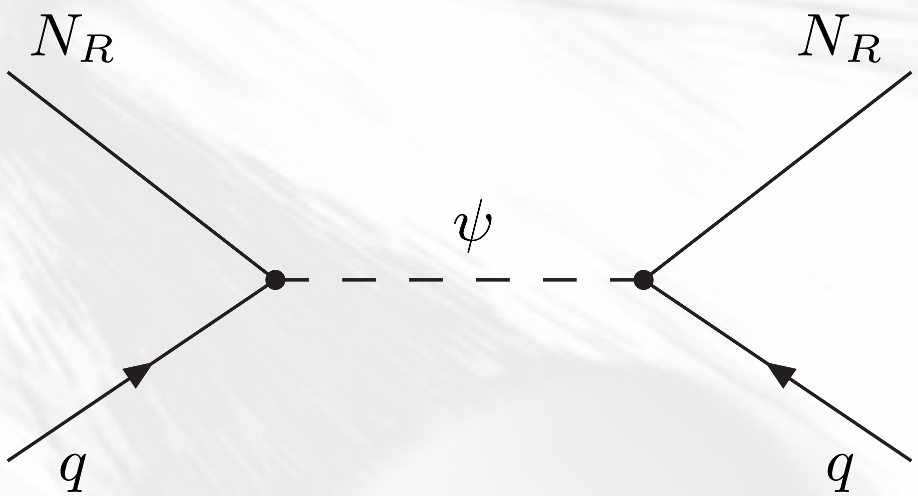
t-quark

- **Co-annihilation effects can be safely neglected:**

$$N_R\psi^\dagger \to u/c/t\ g,\ \ \psi\psi^\dagger$$

Direct Detection:

- Majorana fermion has chiral symmetric interactions:
- Scattering is dominated by spin dependent interactions.



$$\mathcal{M} = \frac{(y_\psi^u)^2}{4(m_\psi^2 - M_{N_R}^2)} \bar{N}_R \gamma^\mu \gamma^5 N_R \left\langle \bar{u} \gamma_\mu \gamma^5 u \right\rangle$$

Neutrino mass generation:

- Conserved Z_2 prevents Dirac neutrino mass terms for the active neutrinos.
  - Incorporate two coloured electroweak-triplet scalars.

$$\chi = \begin{pmatrix} \chi_2/\sqrt{2} & \chi_1 \\ \chi_3 & -\chi_2/\sqrt{2} \end{pmatrix} : (\mathbf{3}, \mathbf{3}, -\mathbf{1}/\mathbf{3})$$

$$\omega = \begin{pmatrix} \omega_2/\sqrt{2} & \omega_1 \\ \omega_3 & -\omega_2/\sqrt{2} \end{pmatrix} : (\mathbf{3}, \mathbf{3}, \mathbf{2}/\mathbf{3})$$

Neutrino mass generation:

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$$\mathcal{L}_{BSM} = \sum_{i=u,c,t} y_\psi^{u_i} \bar{u}_i P_L N^c \psi + \sum_{\ell=e,\mu,\tau} \left\{ \lambda_\ell \left[\bar{t} P_R \left(\chi_1 \nu_\ell^c + \chi_2 \ell^c \right) + \bar{b} P_R \left(\chi_3 \ell^c - \chi_2 \nu_\ell^c \right) \right] \right\} + \frac{1}{2} M_{N_R} \bar{N}^c N + \text{ h.c.}$$

$$\begin{aligned} V(H,\psi,\chi,\omega) &= -\mu^2 H^\dagger H + \frac{\lambda}{4!}(H^\dagger H)^2 + m_\chi^2 Tr\left(\chi^\dagger \chi\right) + m_\omega^2 Tr\left(\omega^\dagger \omega\right) + m_\psi^2 \psi^\dagger \psi + \lambda_\chi \left(Tr \chi^\dagger \chi\right)^2 \\ &+ \lambda_\omega (Tr\omega^\dagger \omega)^2 + \lambda_\psi \left(\psi^\dagger \psi\right)^2 + \kappa_1 H^\dagger H \left(Tr \chi^\dagger \chi\right) + \kappa_2 H^\dagger \chi^\dagger \chi H \\ &+ \kappa_3 H^\dagger H \psi^\dagger \psi + \kappa_4 H^\dagger H Tr \omega^\dagger \omega + \kappa_5 H^\dagger \omega^\dagger \omega H + \rho_1 \left(Tr \chi^\dagger \chi\right) \psi^\dagger \psi \\ &+ \rho_2 \left(Tr \omega^\dagger \omega\right) \psi^\dagger \psi + \rho_3 Tr\left(\omega^\dagger \psi \omega^\dagger \psi\right) + \alpha Tr H^T \sigma_2 \chi \omega^\dagger H + \tilde{V}(\chi,\omega) + \text{h.c} \end{aligned}$$

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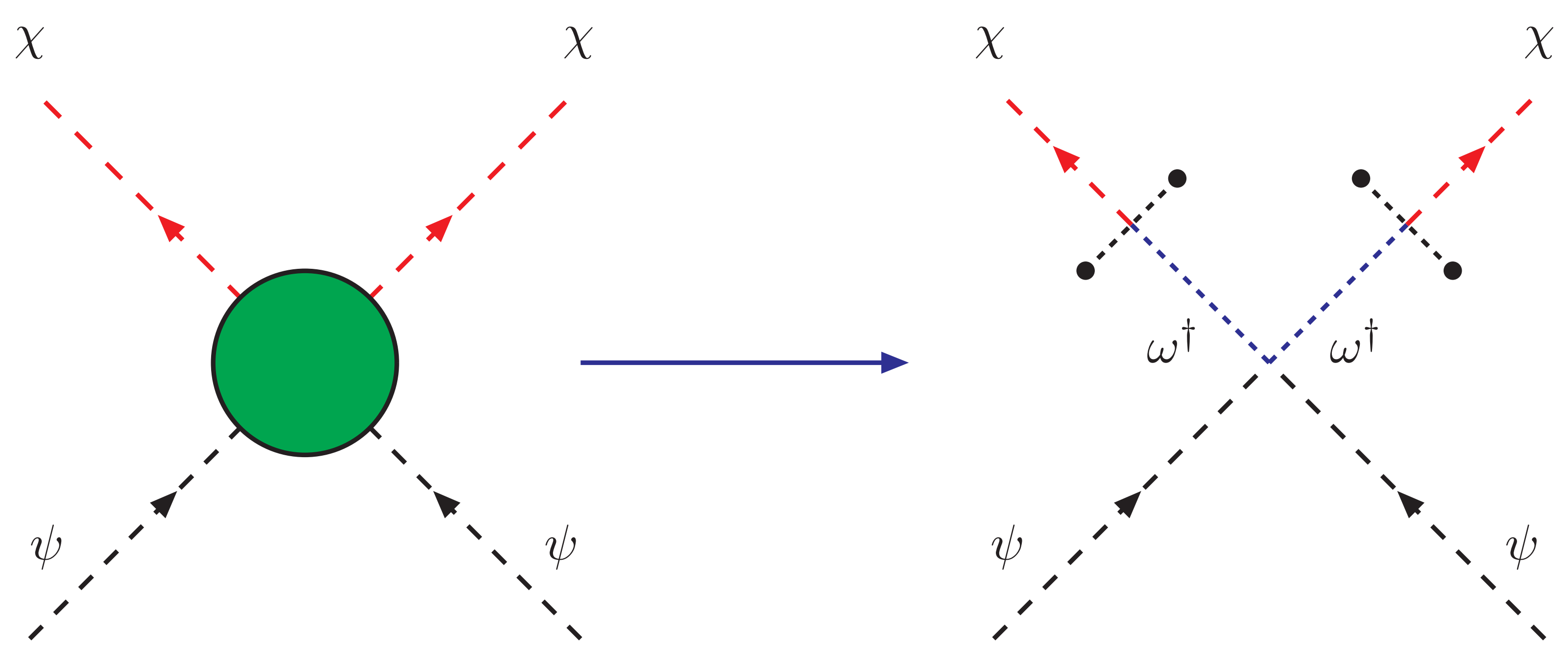

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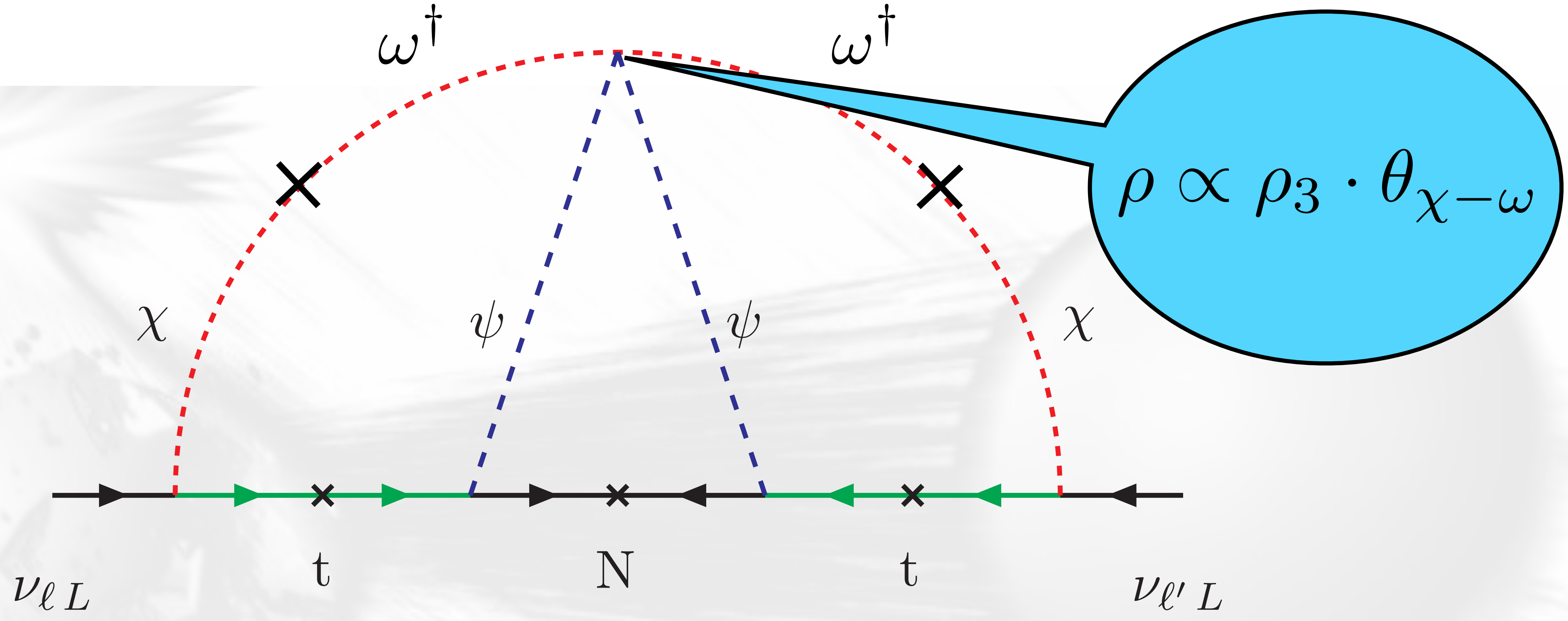


$$(M_\nu)_{\ell\ell'} = \sum_{i,j} K^{ij} \lambda^i_\ell \lambda^j_{\ell'}$$

$$K^{ij} = \frac{y^i_\psi y^j_\psi \rho}{(16\pi^2)^3} \frac{m_i m_j M_{N_R}}{(m^2_\chi - m^2_i)(m^2_\chi - m^2_j)} I(m^2_\chi, m^2_\psi, m^2_i, m^2_j),$$

$$(M^\nu)_{ll'} = \sum_{i,j} K^{i,j} \lambda^i_l \lambda^j_{l'}$$

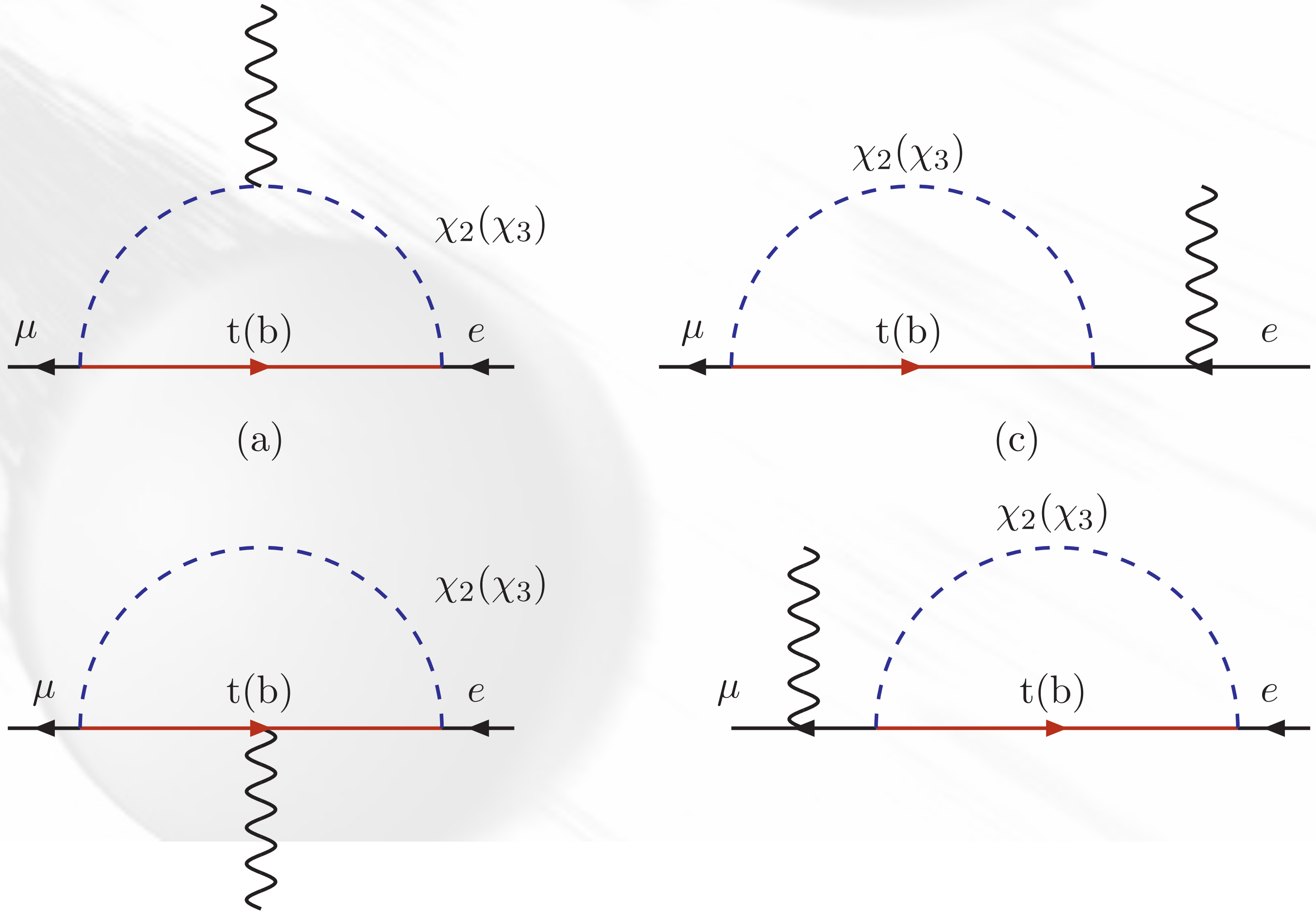
Constraints

- **Rare muon and b decays:** Sensitive to coloured electroweak-triplets.

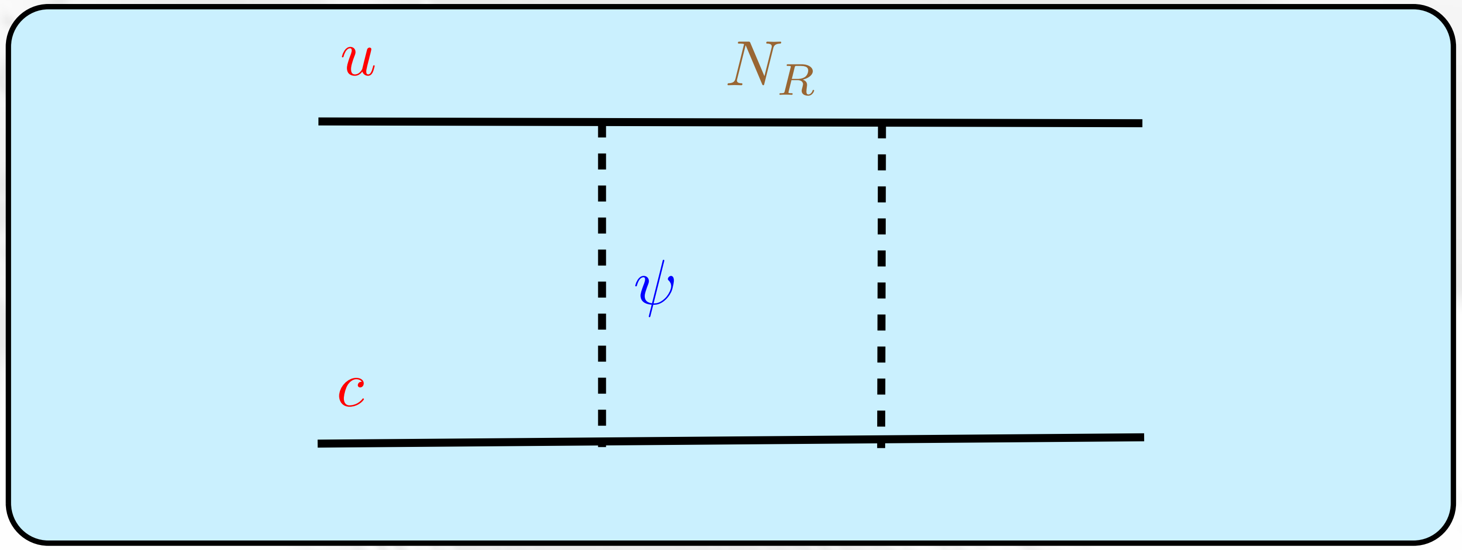
$$\mathcal{L}_{BSM} = \sum_{i=u,c,t} y_{\psi}^{u_i} \bar{u}_i P_L N^c \psi + \sum_{\ell=e,\mu,\tau} \left\{ \lambda_\ell \left[\bar{t} P_R \left(\chi_1 \nu_\ell^c + \chi_2 \ell^c \right) + \bar{b} P_R \left(\chi_3 \ell^c - \chi_2 \nu_\ell^c \right) \right] \right\} + \text{ h.c.}$$

$$Br(\mu \to e\gamma) = 7.2 \times 10^{-6} \left(\frac{m_{e\mu}}{K^{t,t}} \right)$$
$$m_{e\mu} = 1.5 - 8.8 \text{ meV}$$

arXiv:1107.5547



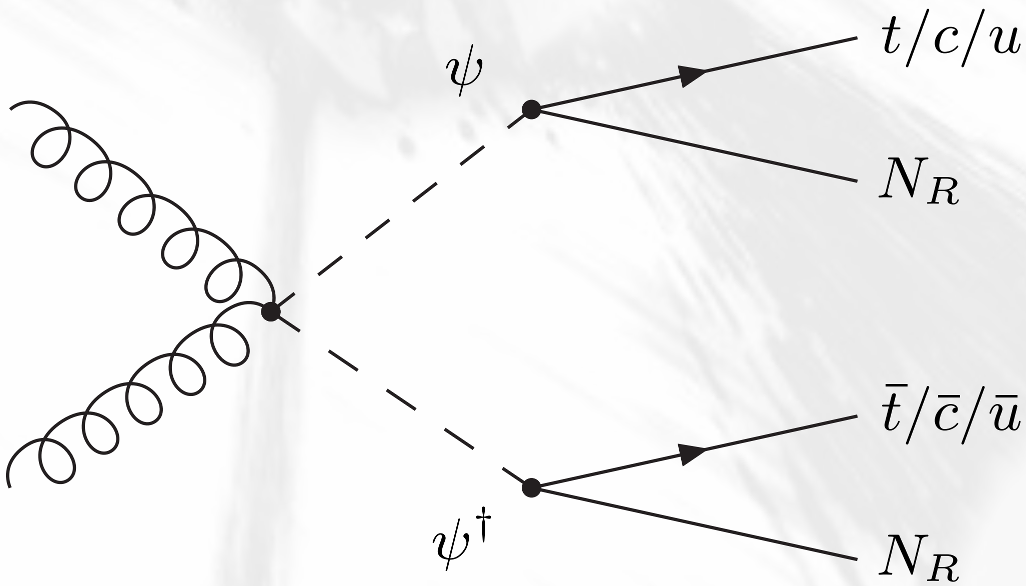
• D meson oscillations:

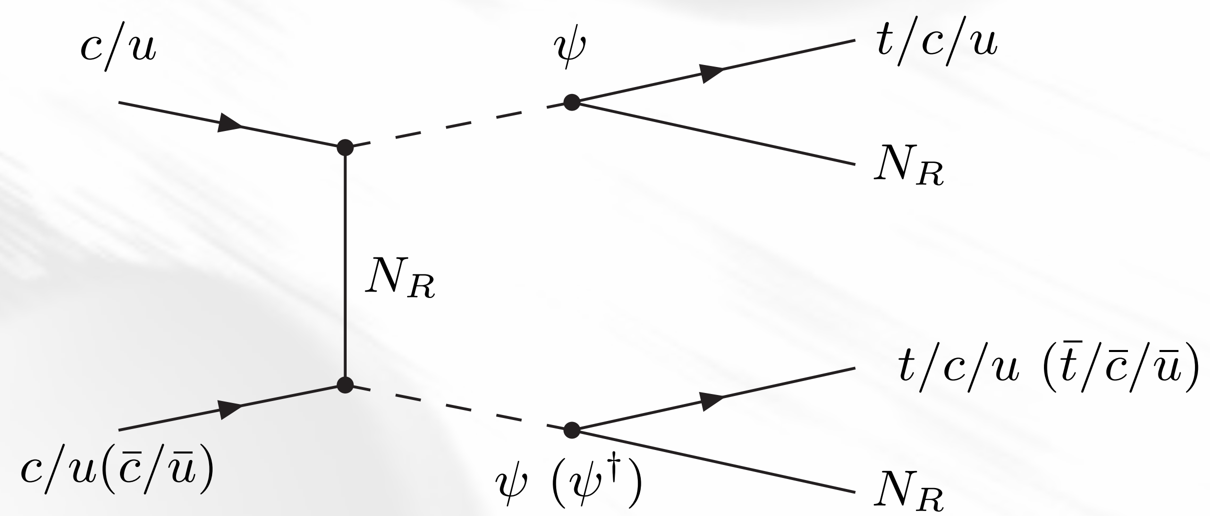


$$\Delta M_D = \frac{\left(y_\psi^u y_\psi^c\right)^2 f_D M_D}{64\pi^2 m_\psi} \frac{2}{3} B_D \beta(m_c, m_{m_\psi}) |L(\eta)|$$

- $x_D = \frac{\Delta M_D}{\Gamma_D} = 0.43^{+0.15}_{-0.16}\%$. arXiv:1207.1158

- **<u>Collider constraints:</u>** **SUSY searches (stop pair-production), monojet+MET and jets+MET**





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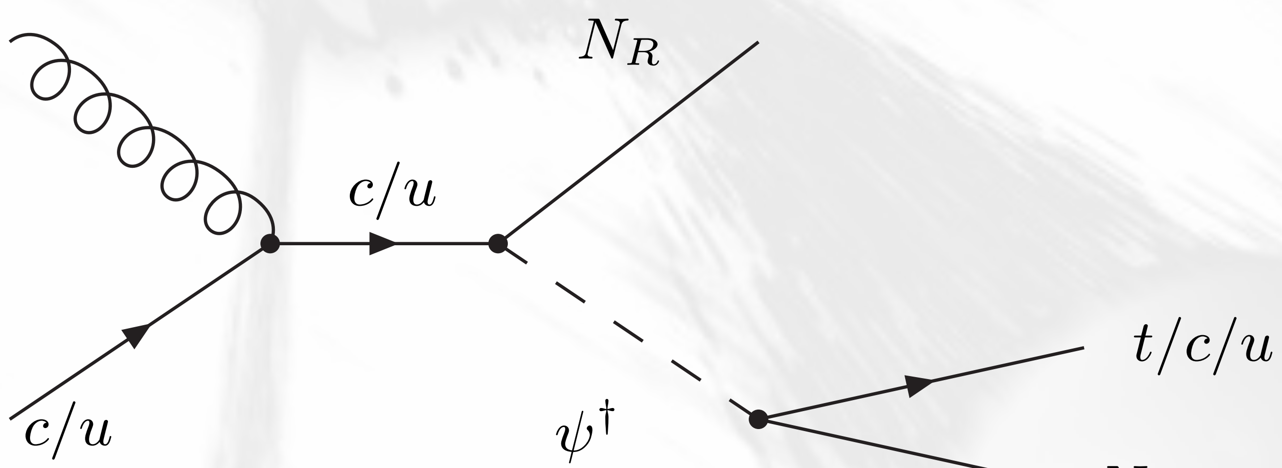
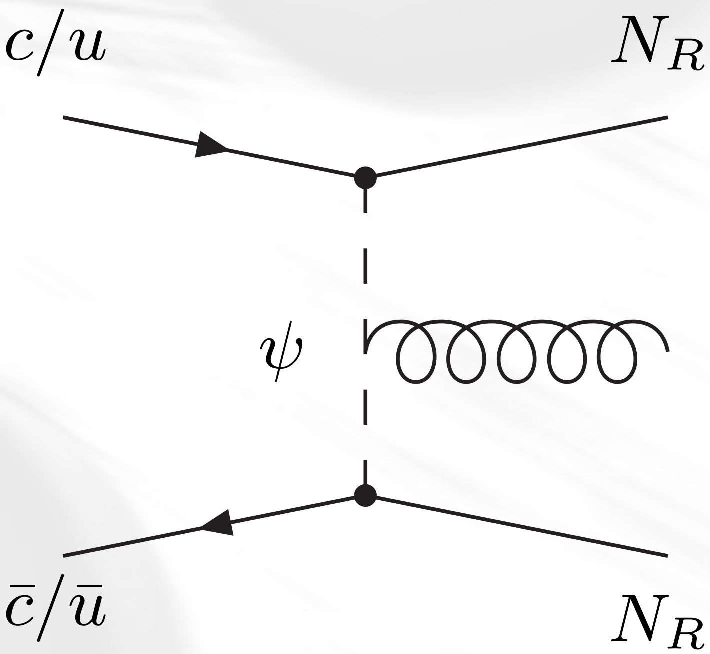
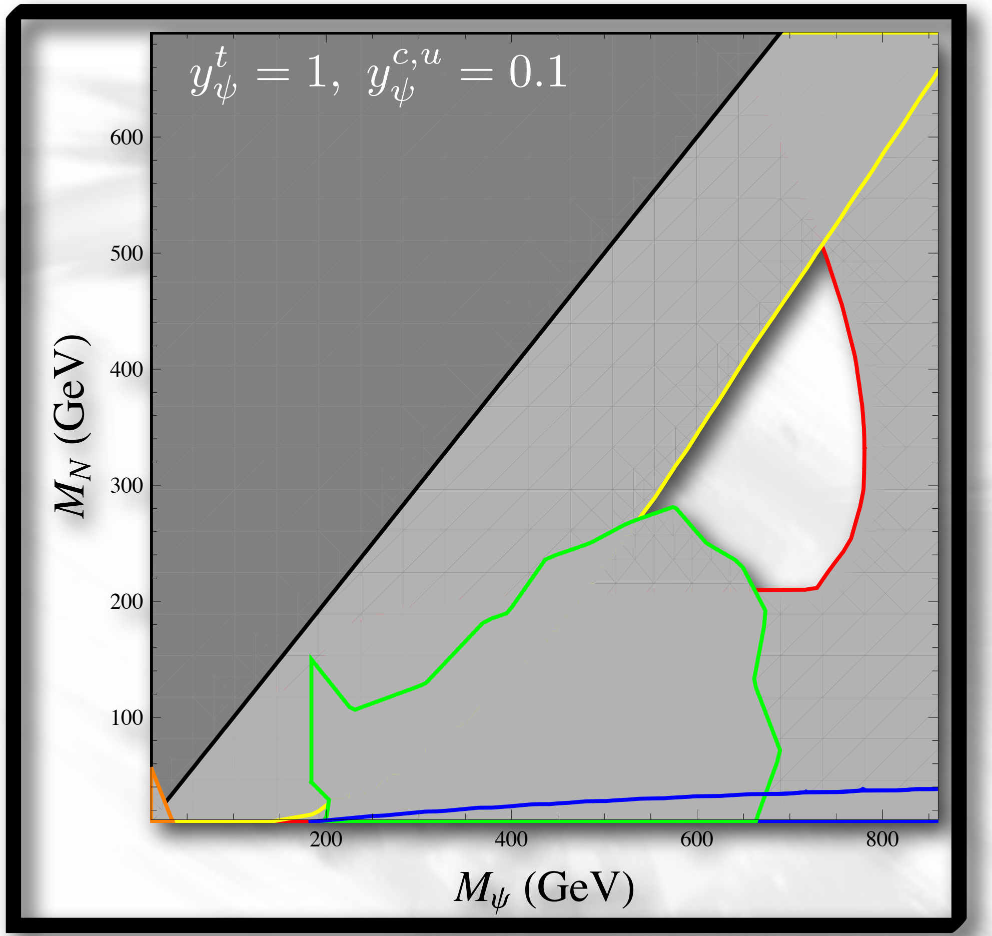
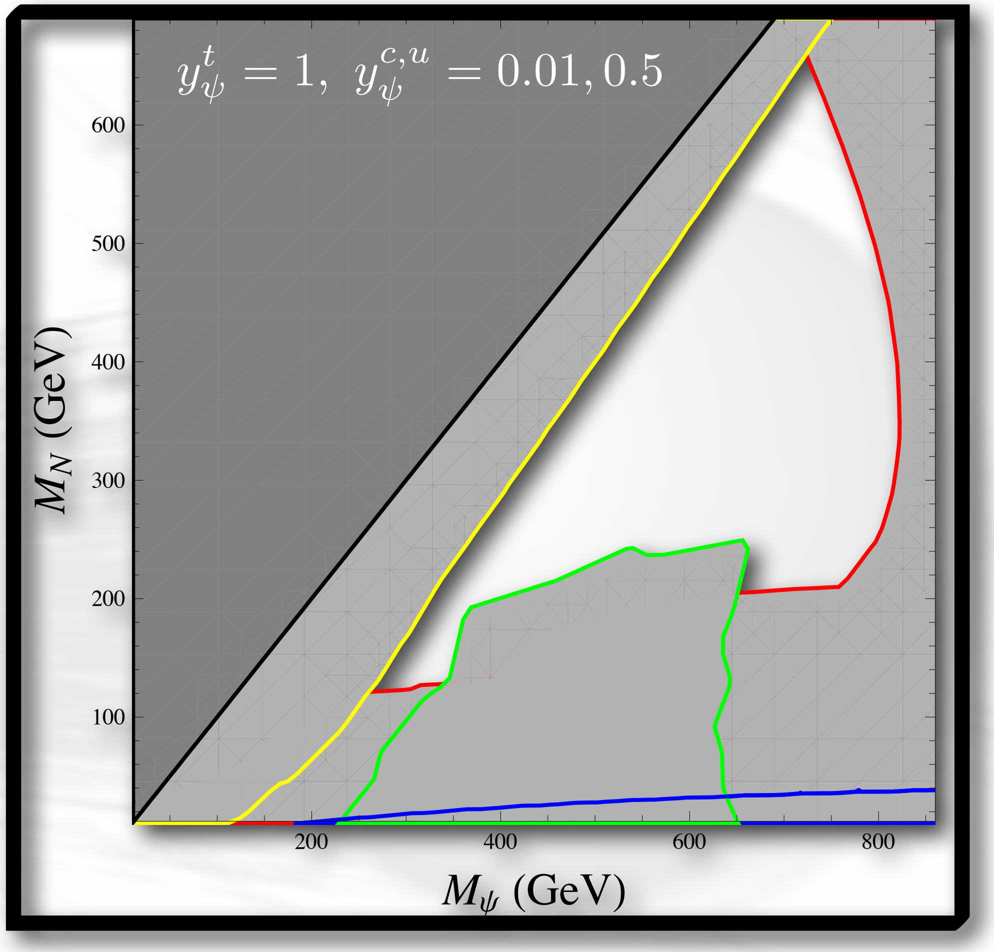


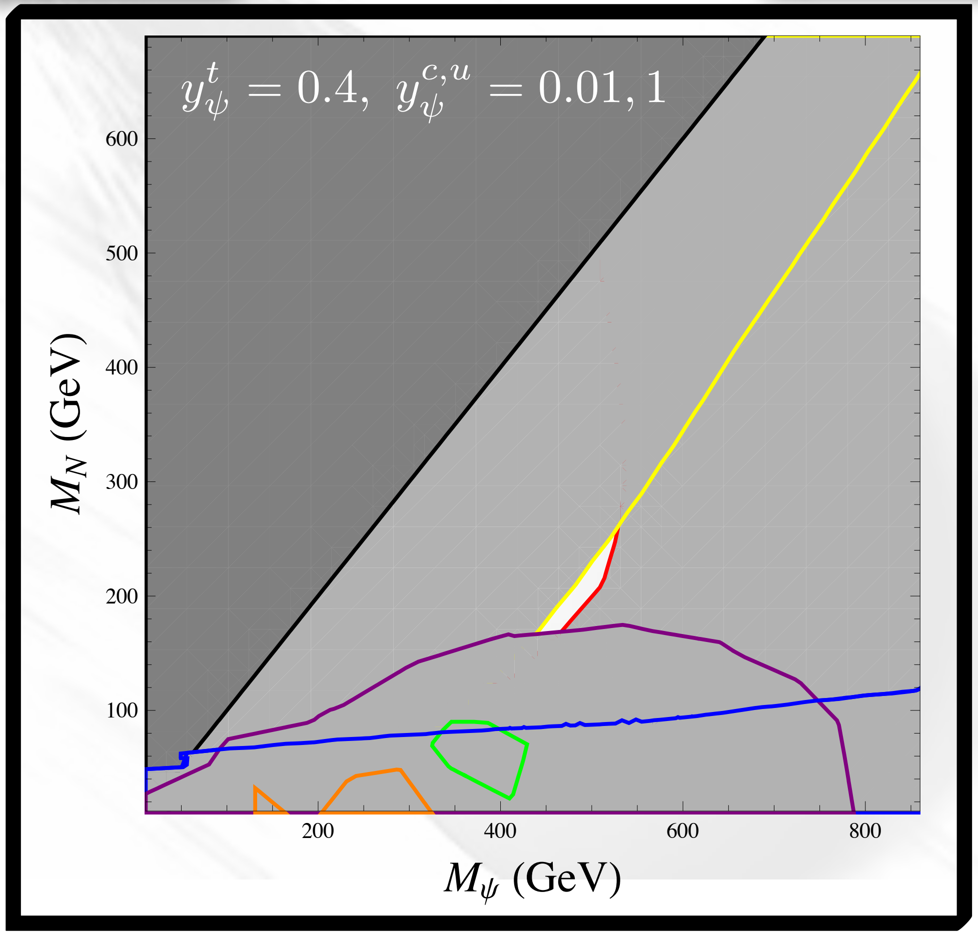




$y_\psi^t = 1,\ y_\psi^{c,u} = 0.1$
600
500
400
300
200
100
M_N (GeV)
200
400
600
800
M_ψ (GeV)



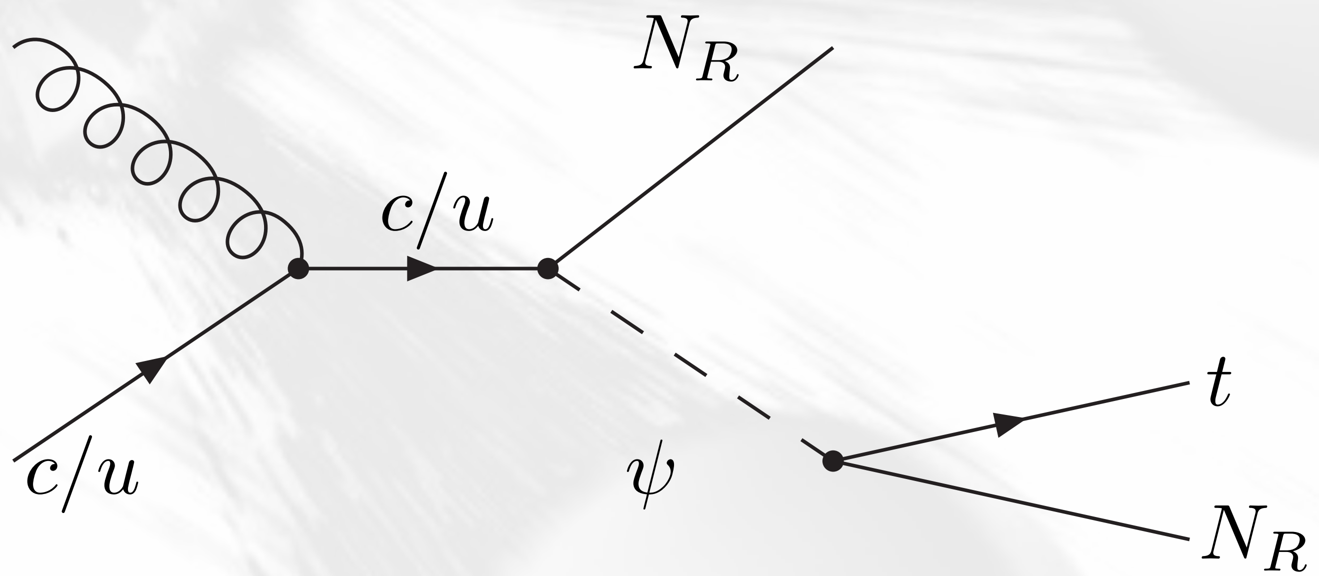
$y_\psi^t = 1,\ y_\psi^{c,u} = 0.01, 0.5$
600
500
400
300
200
100
M_N (GeV)
200
400
600
800
M_ψ (GeV)



$y_\psi^t = 0.4,\ y_\psi^{c,u} = 0.01, 1$
600
500
400
300
200
100
M_N (GeV)
200
400
600
800
M_ψ (GeV)

Monotop probe

- Single top quark production in association with missing energy (MET) at the LHC.



- Apply search strategy for the semi-leptonic decay modes of the top quark at 8 and 14 TeV.

Semi-leptonic mode signal 8 TeV:

$$t + N_R N_R \to bl\nu + N_R N_R$$

- **Main Backgrounds:**
  - $t\bar{t}$
  - $tj + tW$
  - Wj **and** Zj
  - **Di-boson**
  - **Less likely to be contaminated by QCD multijet background. Little contamination from mis-reconstructed jet (p_T cut) .**

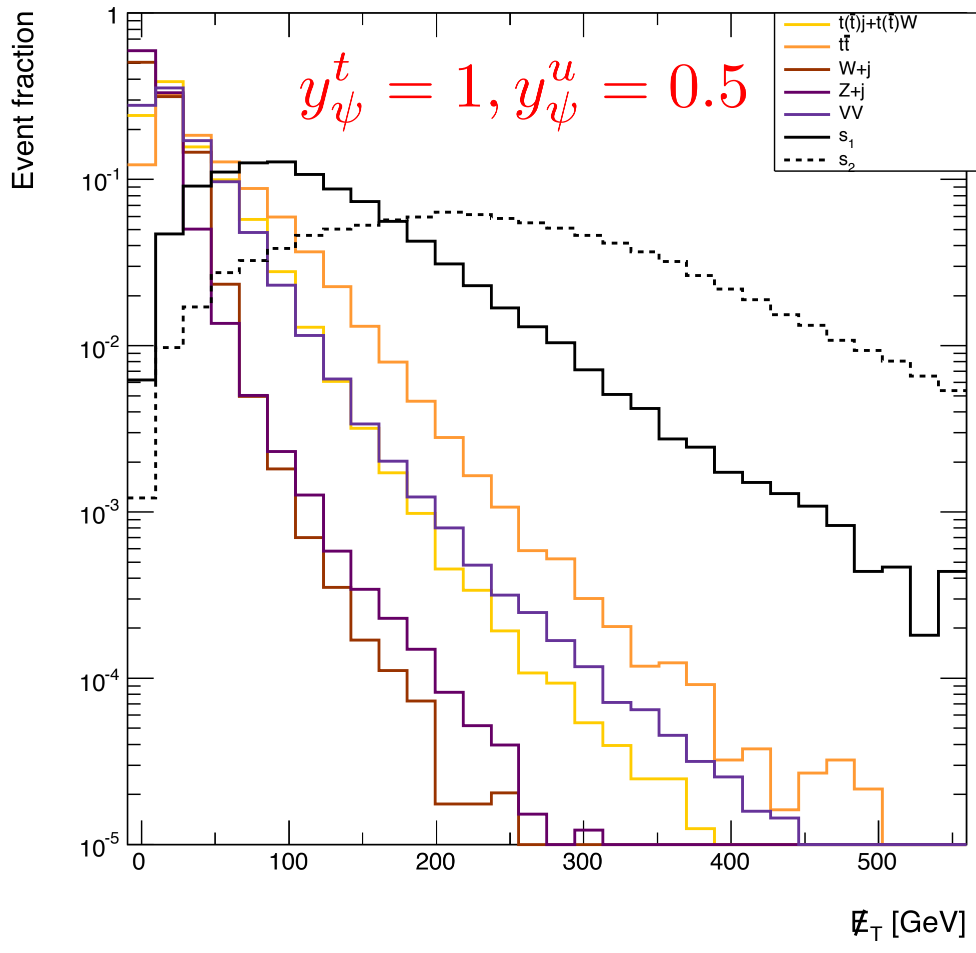
Semi-leptonic mode signal 8 TeV:

$$t + N_R N_R \to bl\nu + N_R N_R$$

- **Pre-selection:**
  - **Require events with a lepton:** $p_T > 20$ GeV, $|\eta| < 2.5$
  - **Require one b-jet to with** $p_T > 20$ GeV, $|\eta| < 2.5$.
  - **At most one light jet.** .

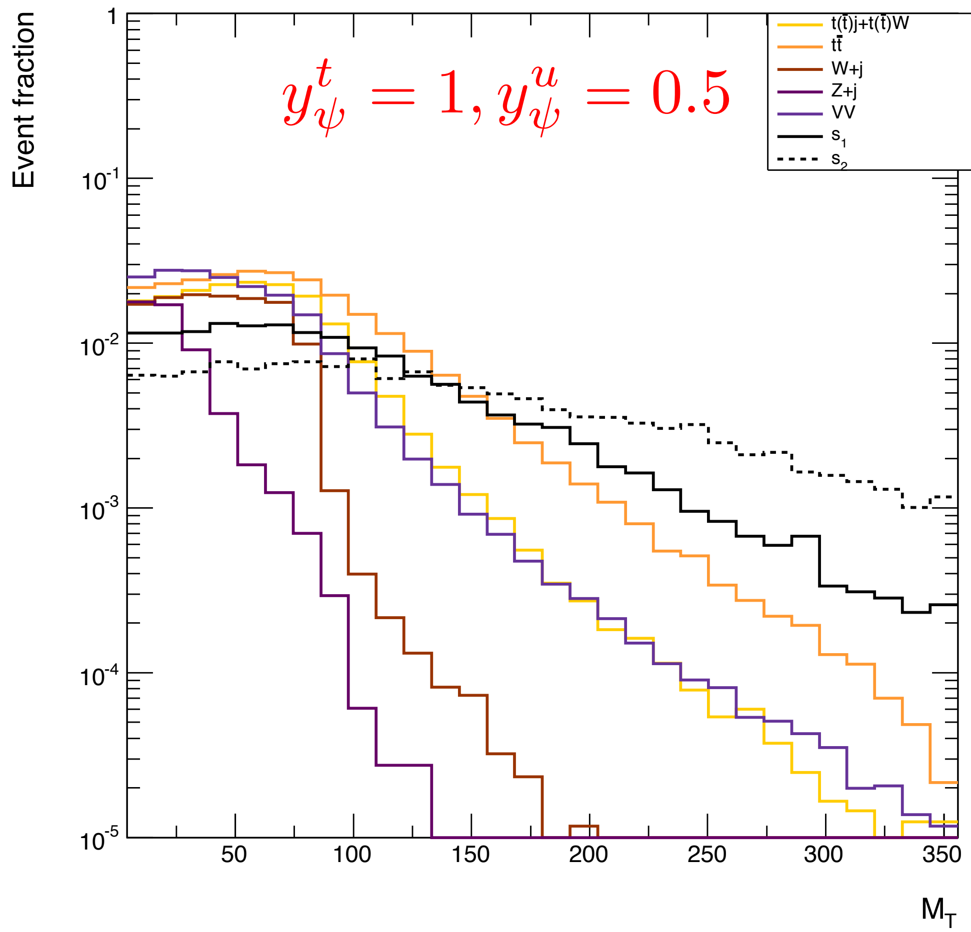
arXiv:1310.7600

Semi-leptonic mode signal 8 TeV:



• Two signal regions defined by the amount of missing energy and the transverse mass of the charged lepton, **M_T**, to probe the small and large m_ψ regions.

$$s_1 : m_\psi = 150 \text{ GeV}, M_{N_R} = 80 \text{ GeV}$$
$$s_2 : m_\psi = 700 \text{ GeV}, M_{N_R} = 210 \text{ GeV}$$



Semi-leptonic mode signal 8 TeV (20 fb^{-1}):

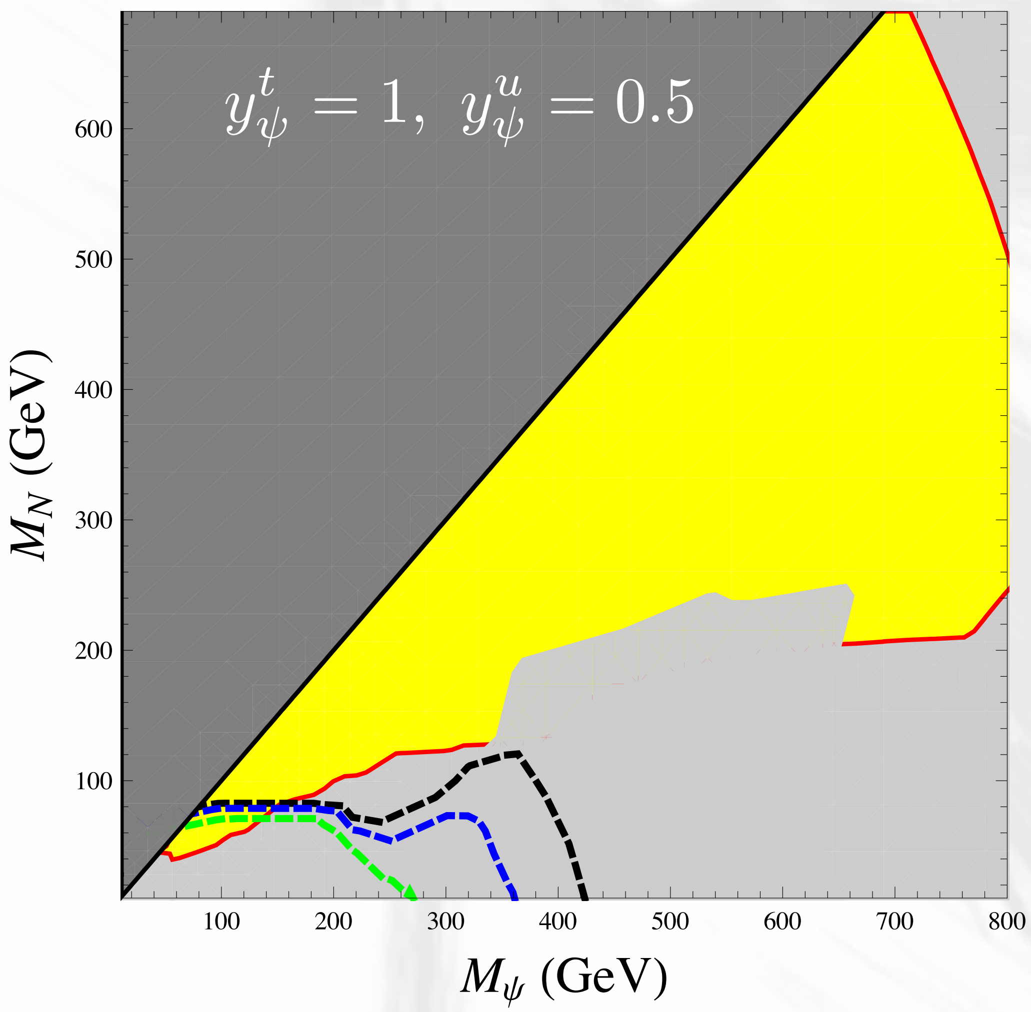
SM background	$N^{\not{E}>90\ \text{GeV}, M_T>110\ \text{GeV}}$ (σ [pb])	$N^{\not{E}>200\ \text{GeV}, M_T>120\ \text{GeV}}$ (σ [pb])
$W\ (\to l\nu) +$ jets	212 (0.011)	< 7 ($< 3.41 \times 10^{-4}$)
$Z+$ jets	< 3 ($< 1.54 \times 10^{-4}$)	< 3 ($< 1.54 \times 10^{-4}$)
$t\bar{t}+$ jets	1327 (0.066)	49 (2.46×10^{-3})
$t\ j + t\ W$	242 (0.012)	< 2 ($< 1.15 \times 10^{-4}$)
WW	2 (1.15×10^{-4})	
WZ	1 (6.86×10^{-5})	
ZZ	*** ($< 7.94 \times 10^{-6}$)	

- **Missing energy from mis-reconstructed jets.**

- **1 b-jet**
- **0-1 light jets with $p_{T,j} < 70, 120$ GeV.**

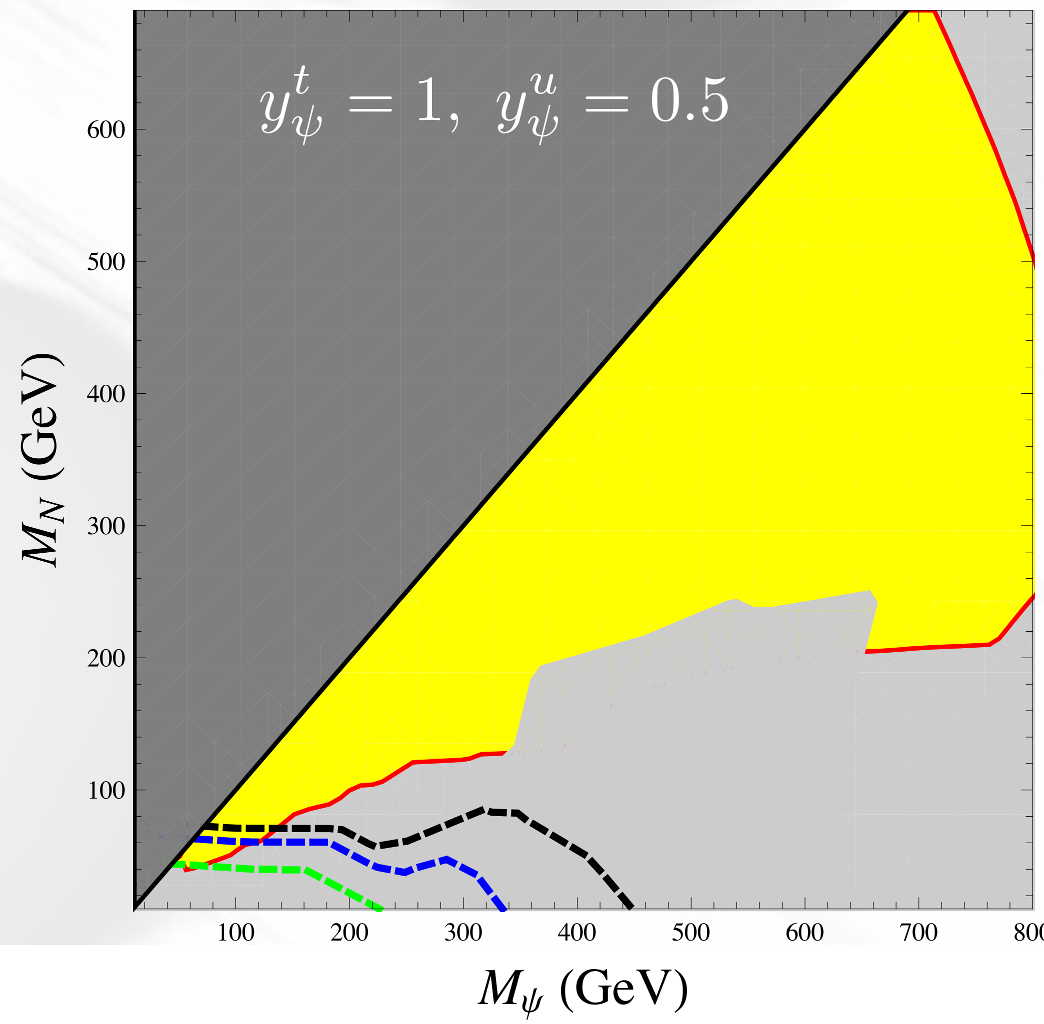
arXiv:1310.7600

Semi-leptonic mode signal 8 TeV (20 fb^{-1}):



MET > 90 GeV, M_T > 110 GeV

MET > 200 GeV, M_T > 120 GeV



Semi-leptonic mode signal 14 TeV:

- SM backgrounds using *k-factors* from 8 TeV cross sections.
- Wj and Zj backgrounds suppressed by a combination of lepton isolation, b-tagging and M_T cuts.
- However, for large collider energies, a large MET cut is necessary.

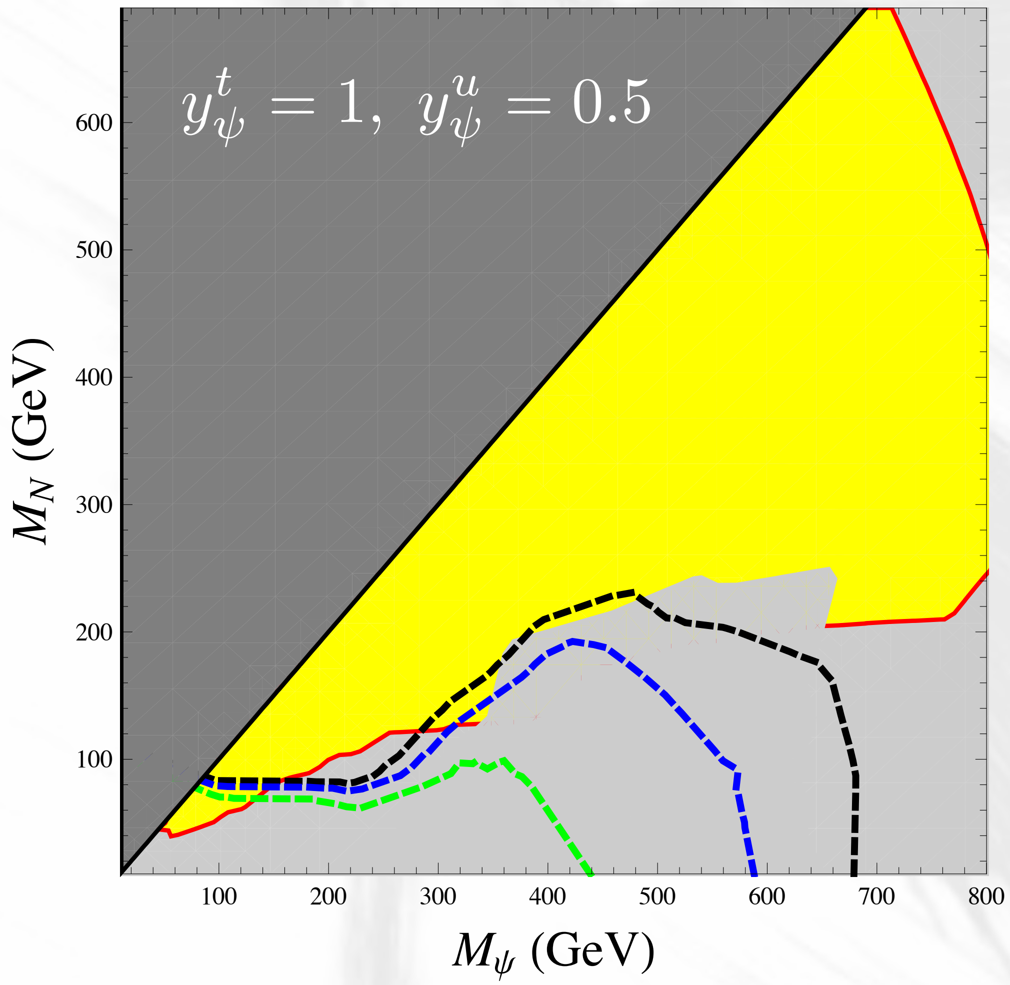
Process	σ [pb]
$W+$ jets	2.19×10^5
$Z+$ jets	6.66×10^4
$t\bar{t}+$ jets	1052.93
$tj+tW$	347.42
WW	119.84
WZ	48.87
ZZ	17.09

$y_\psi^t = 1,\ y_\psi^u = 0.5,\ m_\psi = 700\ \text{GeV},\ M_{N_R} = 210\ \text{GeV}$

$\mathcal{L}$ [fb^{-1}]	$\sigma\,(t\bar{t} + \text{jets})$ [pb], N	$\sigma\,(tj + tW)$ [pb], N	σ_{signal}[pb], N
30	6.31×10^{-3}, 189	1.39×10^{-3}, 42	6.85×10^{-4}, 21
300	1892	417	205

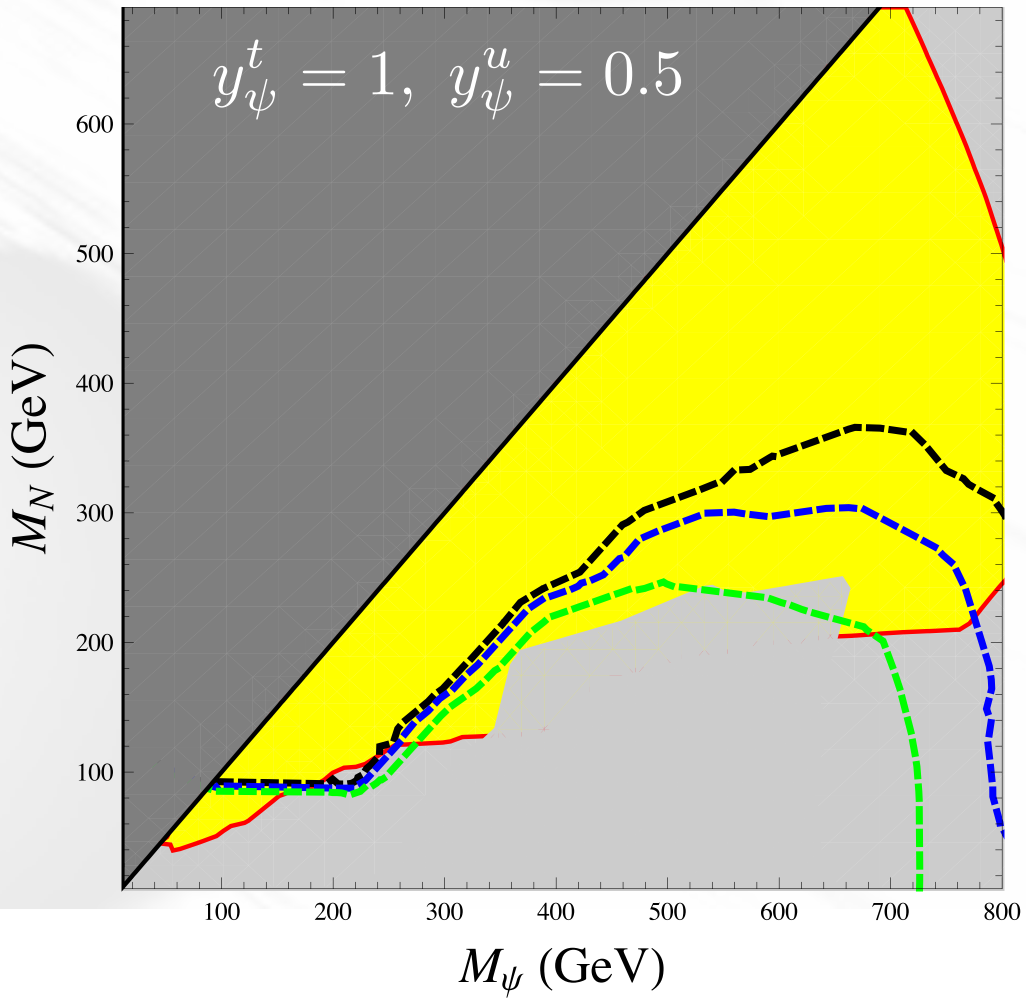
- **MET > 200 GeV, M_T > 120 GeV and $p_{T,j}$ < 120 GeV**

Semi-leptonic mode signal 14 TeV:



L = 30 fb^{-1}

L = 300 fb^{-1}



Summary

• A weakly interacting massive particle is still a very attractive candidate to address the nature of dark matter.

• We must use not only astrophysical resources to address the nature of dark matter but the power of hadron colliders.

• The existence of dark matter may be inferred through exotic processes as well as properties of SM particles.

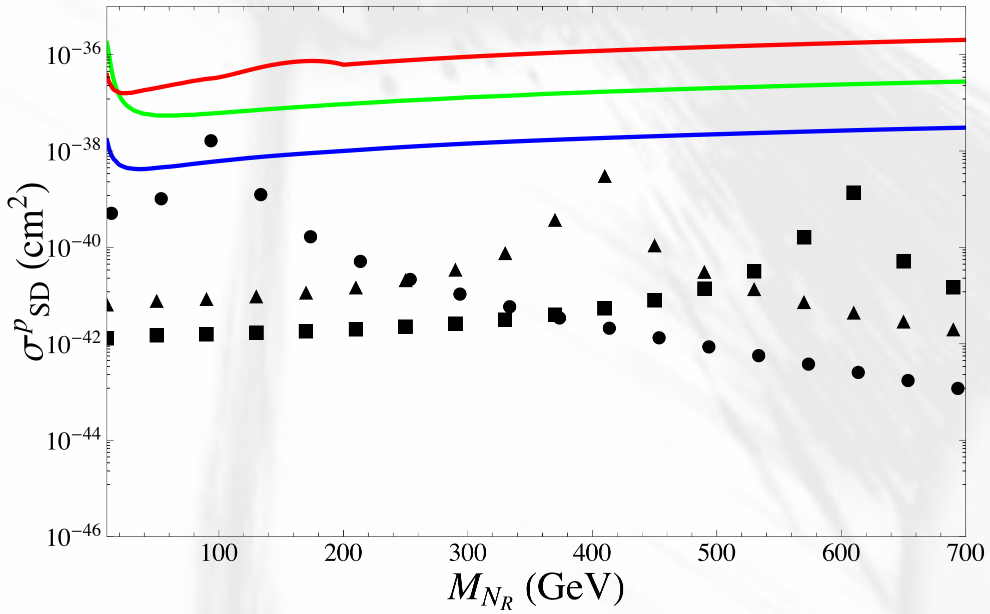
• Next run at the LHC may begin to probe monotop production.

• It may lead to evidence of the underlying mechanism the bestows neutrinos with mass.

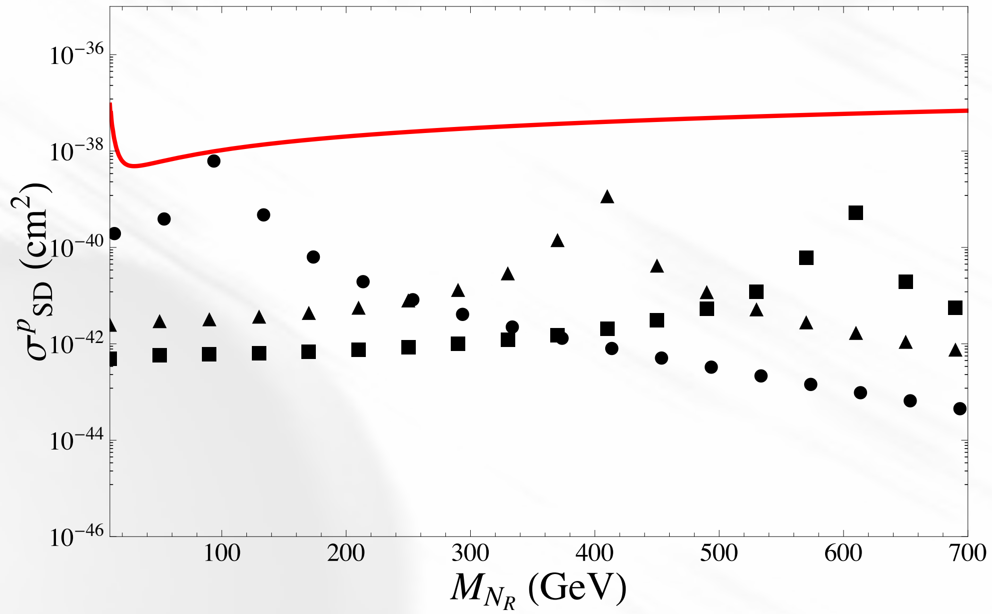
Back-up Slides

Dark matter - nucleon scattering: $y_\psi^u = 0.5$

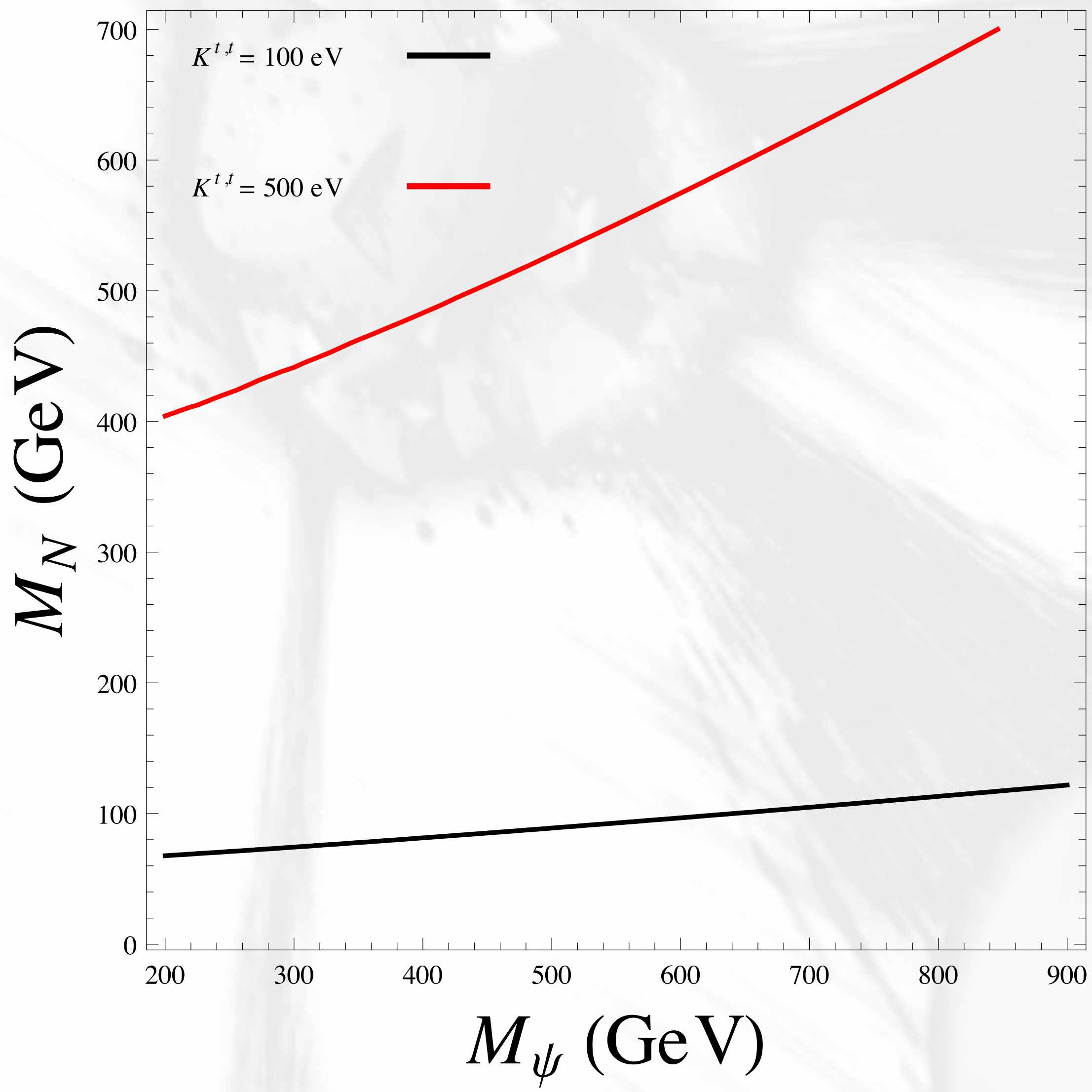
protons



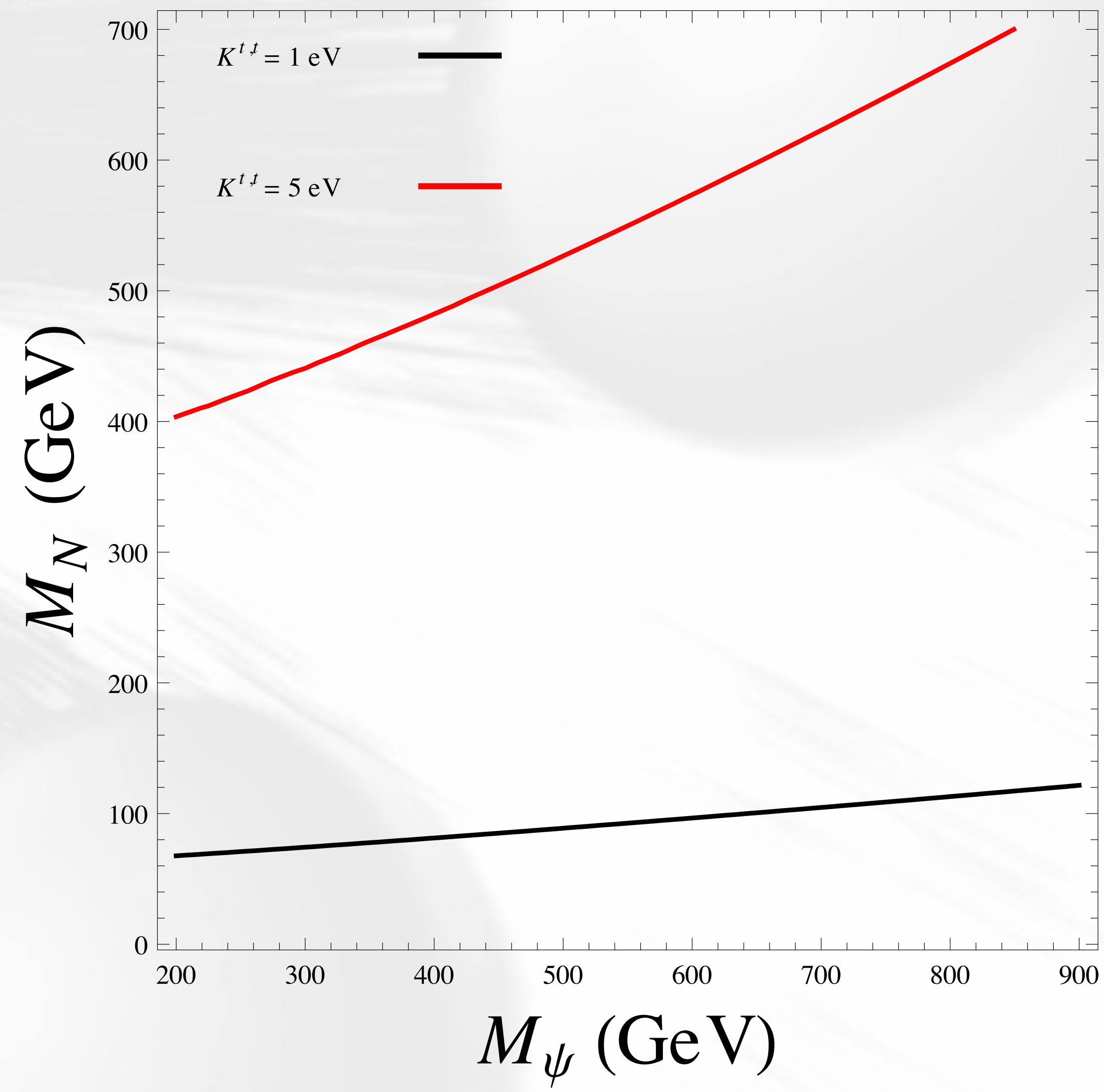
neutrons



$$\rho = 0.1,\ m_\chi = 1\ \text{TeV}$$



$y_\psi^t \approx 1$



$y_\psi^t \approx 0$