Constraints and collider signatures of bulk right-handed neutrinos

Qing-hong Cao, Shrihari Gopalakrishna and C.-P. Yuan

Michigan State University, East Lansing.

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Introduction

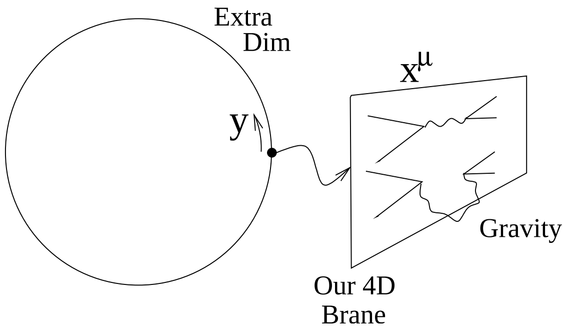
- Hierarchy problem in Standard Model (SM)
  - $M_{EW} \sim 10^3$ GeV $\quad M_{pl} \sim 10^{19}$ GeV
- Tiny neutrino masses
  - $\Delta m^2_{\rm solar} = 7 \times 10^{-5}\ {\rm eV}^2\ , \quad \tan^2\theta_{solar} = 0.4$
  - $\Delta m^2_{\rm atm} = 2.5 \times 10^{-3}\ {\rm eV}^2\ , \quad \tan^2\theta_{atm} = 1$
- Large Extra Dimensions (ADD) + ν_R
  - “Solves” hierarchy problem
  - Small neutrino masses natural
- What are the constraints?
- Are there any collider signatures?

Introduction

- If there are collider signatures
  - can we distinguish neutrino mass hierarchy?
    (Long baseline experiments might also be able to do this)
  - can we find absolute value of neutrino mass?

Large Extra Dimensions (LED)

- Usual picture
  - 3 space + 1 time   Gravity scale $M_{pl} \sim 10^{19}$ GeV
- Arkani-Hamed, Dimopoulos, Dvali (ADD)
  - n (compact) space extra dims   Radius R
  - Only fundamental scale $M_* \sim 10^3$ GeV
  - $M_{pl}^2 = M_*^{2+n} V_n \qquad V_n \sim R^n$
  - Gravity in bulk, SM on brane
  - $\mathcal{S} = \int d^4x \; d^ny \; \left[\mathcal{L}_{\text{Bulk}} \; + \; \delta(\underline{y}) \, \mathcal{L}_{Brane}\right]$



LED + Bulk ν_R

[Dienes, Dudas, Gherghetta]
[Davoudiasl, Langacker, Perelstein]

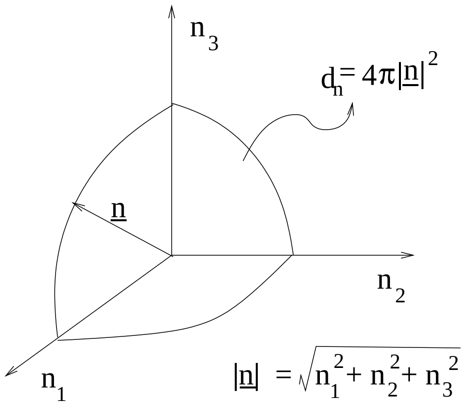
- Introduce Bulk ν_R propagating in δ dimensions
- $\Psi^\alpha(x^\mu, y) = \begin{pmatrix} \psi_L^\alpha(x^\mu, y) \\ \psi_R^\alpha(x^\mu, y) \end{pmatrix} \qquad (\delta = 1) \qquad \alpha \rightarrow$ Generation
- $\mathcal{L}_{\rm Bulk} \supset \bar{\Psi}^\alpha \, i\Gamma^M D_M \Psi^\alpha$

  $\mathcal{L}_{\rm Brane} \supset \mathcal{L}_{\rm SM} - \left(\frac{\Lambda^\nu_{\alpha\beta}}{\sqrt{M_*^\delta}} \, h \, \psi_R^\beta \, \nu_L^\alpha + h.c. \right)$
  - $\nu_L \rightarrow$ Usual SM left-handed neutrino
  - $\psi_R \rightarrow$ Bulk right-handed neutrino $\equiv \nu_R$
  - $\psi_L \rightarrow$ No direct coupling to SM

Kaluza-Klein (KK) 4D theory

- KK expansion
  - $\psi_R(x^\mu, \underline{y}) = \sum_{\underline{n}} \; \psi_R{}^{(\underline{n})}(x^\mu)\; f_{\underline{n}}(\underline{y})$

    $\int_0^{2\pi R} d^\delta y \;\; f_n^*(y) f_m(y) = \delta^{nm} \qquad f_n(y) = \frac{e^{i\frac{n.y}{R}}}{\sqrt{V_\delta}}$



- MNS rotation Go to “mass” basis
  - $\nu_L^\alpha = l^{\alpha i} \nu_L^{\prime i} \qquad e_L^\alpha = l_e^{\alpha i} e_L^{\prime i} \qquad \nu_R^\alpha = (r^{\alpha i})^* \nu_R^{\prime i}$

    $V_{MNS} \equiv l_e^\dagger \, l$ [α, β (flavor) basis $\to$ i, j (mass) basis]

- $\nu \equiv \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}, \quad \nu^{(1)} \equiv \begin{pmatrix} \nu_L^{(1)} \\ \nu_R^{(1)} \end{pmatrix} \; \ldots \; \nu^{(n)} \equiv \begin{pmatrix} \nu_L^{(n)} \\ \nu_R^{(n)} \end{pmatrix}$ (suppress i and $'$)

  sterile ν_s

- $\mathcal{L}^{(4)} = \mathcal{L}_{SM} - \frac{|\hat{n}|}{R} \overline{\nu}^{(\hat{n})} \nu^{(\hat{n})} - \frac{m_\nu}{v} \left[h\bar{\nu}\nu + \sqrt{2} h \left(\sum_{\hat{n}} \bar{\nu}^{(\hat{n})} P_L \nu + h.c. \right) \right]$

  $m_\nu \equiv \frac{\Lambda^\nu \;\; v}{\sqrt{V_\delta M_*^\delta}} \sim 10^{-2}$ eV $\qquad (v = 246 \text{ GeV}) \qquad \Lambda^\nu \sim \mathcal{O}(1)$

  $n \to \; 0, 1, 2 \ldots \qquad \hat{n} \to \; 1, 2, \ldots$

Aside: Magnitude of Λ

δ	$\frac{1}{R}\ (eV)$	$\Lambda^{\nu}_{\alpha\beta}$
1	1	10^{-6}
2	1	0.1
3	10^{3}	1

(Keeping in mind constraints that we will show later)

- Usually $\delta = 1$ considered in the literature
- We will consider $\delta = 1, 2, 3$

Neutrino mass matrix

- $\mathcal{L}^{(4)}_{\text{mass}} = \bar{\nu}_D \, \mathcal{M}_D \, \nu_D \qquad (\nu_D)^T = (\nu \; \nu^{(1)} \; ... \; \nu^{(\hat{n})} \; ...)$

$$\mathcal{M}_D = \begin{pmatrix} m_\nu & \sqrt{2} m_\nu P_R & . & . & . & \sqrt{2} m_\nu P_R & . & . & . \\ \sqrt{2} m_\nu P_L & \frac{1}{R} & & & & & & & \\ . & & . & & & & & & \\ . & & & . & & & & & \\ . & & & & . & & & & \\ \sqrt{2} m_\nu P_L & & & & & (\frac{|\hat{n}|}{R})_{d_{\hat{n}} \times d_{\hat{n}}} & & & \\ . & & & & & & . & & \\ . & & & & & & & . & \\ . & & & & & & & & \frac{|N|}{R} \end{pmatrix}$$

$\frac{N}{R} = M_* \qquad d^{\delta=3}_{\hat{n}} \sim 4\pi \hat{n}^2$

- $m^{(0)} \approx m_\nu \qquad m^{(\hat{n})} \approx \frac{|\hat{n}|}{R} \qquad$ if $\xi \equiv \frac{m_\nu}{\frac{1}{R}} \ll 1$

- L and R diagonalize $\mathcal{M}_D$
  - $L^{00} = 1 - \sum_{\hat{n}} \frac{\xi^2}{\hat{n}^2} d_{\hat{n}} \qquad L^{0\hat{n}} = \sqrt{2} \frac{\xi}{\hat{n}}$

Experimental constraints

- LED constraints
  - Table-top gravity experiments
  - Supernova
  - Collider
- Bulk ν_R constraints
  - Supernova: $\delta = 1$ (literature)
  - ν oscillation
  - $hh \to hh$ unitarity

Neutrino Oscillation

- $P_{\nu_\alpha \to \nu_\beta} = \left| \left\langle \nu_L^\beta | e^{-iHt} | \nu_L^\alpha \right\rangle \right|^2$
- SM
  - $\nu_{\rm active} \to \nu_{\rm active}$

    $$P_{\nu_\alpha \to \nu_\beta} = \left| l^{\beta i *} l^{\alpha i} \left(e^{-i \frac{L}{2E_\nu} m_i^2} \right) \right|^2 = \sin^2(2\theta) \sin^2(\Delta m^2 \tfrac{L}{4E_\nu})$$
- Bulk ν_R
  - $\nu_{\rm active} \to \nu_{\rm active}$

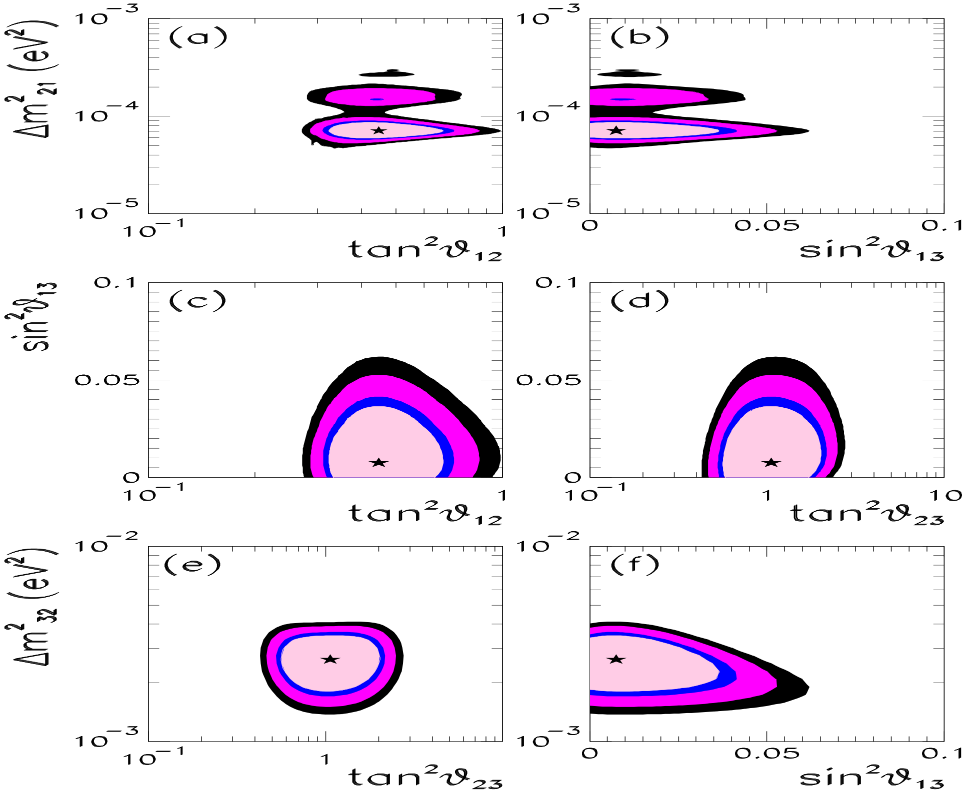
    $$P_{\nu_\alpha \to \nu_\beta} = \left| l^{\beta i *} l^{\alpha i} \left(|L_i^{00}|^2 e^{-i \frac{L}{2E_\nu} m_i^2} + |L_i^{0\hat{n}}|^2 d_{\hat{n}} e^{-i \frac{L}{2E_\nu} m_i^{(\hat{n})\,2}} \right) \right|^2$$
  - $\nu_{\rm active} \to \nu_{\rm sterile}$

    $$P_{\nu_\alpha \to \nu_s} = 1 - \textstyle\sum_\beta P_{\nu_\alpha \to \nu_\beta} = 8|l^{\alpha i}|^2 \xi_i^2 \sum_{\hat{n}} \frac{d_{\hat{n}}}{\hat{n}^2} \sin^2\left(\frac{L\hat{n}^2}{4E_\nu R^2} \right)$$

    $$\approx 4|l^{\alpha i}|^2 \xi_i^2 \textstyle\sum_{\hat{n}} \frac{d_{\hat{n}}}{\hat{n}^2} \qquad \text{using } \left\langle \sin^2\left(\frac{L\hat{n}^2}{4ER^2} \right) \right\rangle = 1/2$$

Oscillation Data

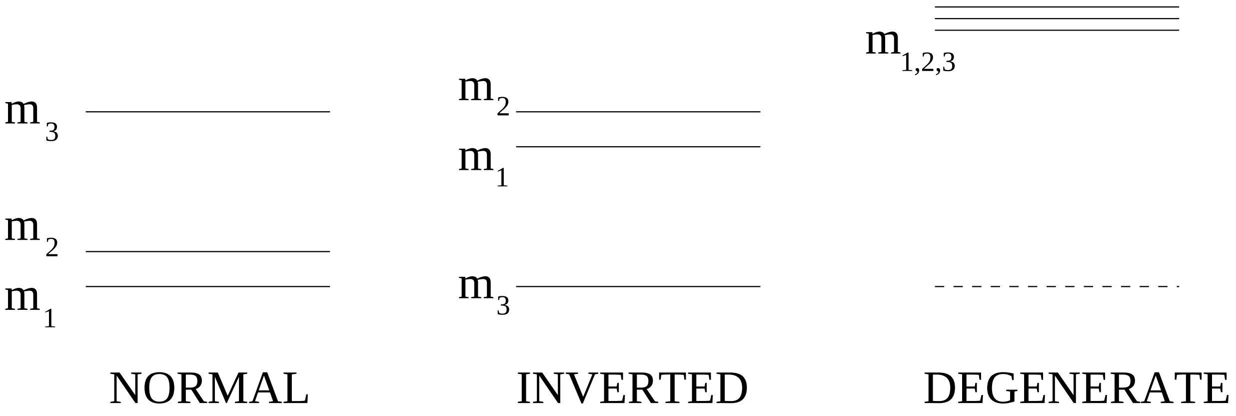
- $3\,\nu$ best fit $(90, 95, 99\%, 3\,\sigma$ C.L. contours) [Gonzalez-Garcia, Pena-Garay]



- Limits on $\nu_{\rm active} \to \nu_{\rm sterile}$ (90% C.L.) [Davoudiasl,Langacker,Perelstein]
  - CHOOZ: $P_{\nu_e\to\nu_s} < 0.058$
  - Atmospheric ν: $\begin{cases} P_{\nu_\mu\to\nu_s} - P_{\nu_e\to\nu_s} < 0.17\ , \\ \frac{1}{2}\left[P_{\nu_\mu\to\nu_s} + P_{\nu_e\to\nu_s}\right] < 0.39\ . \end{cases}$

Neutrino mass schemes

- $\Delta m^2_{\rm solar} = 7 \times 10^{-5}\ {\rm eV}^2\ , \quad \tan^2\theta_{solar} = 0.4$
- $\Delta m^2_{\rm atm} = 2.5 \times 10^{-3}\ {\rm eV}^2\ , \quad \tan^2\theta_{atm} = 1$
- Which pattern of masses is realized?



- We will not address LSND data

Oscillation constraints

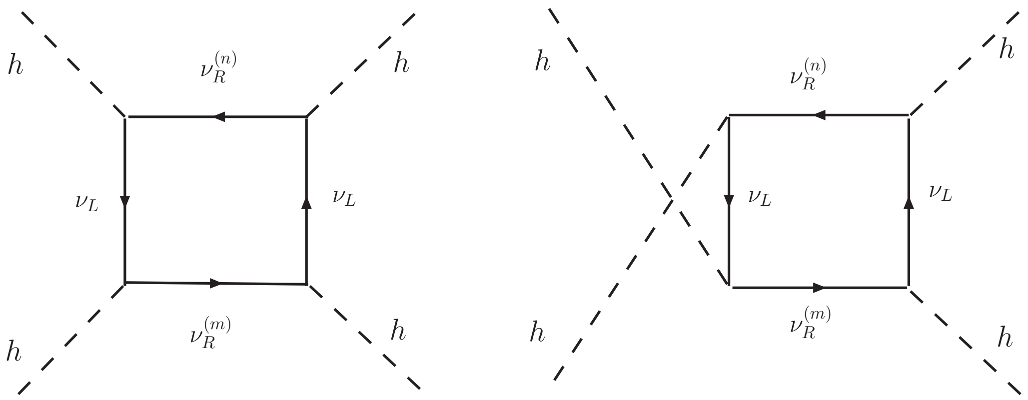
- Lower bound on $\frac{1}{R}$ (eV)

	Normal		Inverted		Degenerate ($m \approx 1$ eV)	
	CHOOZ	Atm	CHOOZ	Atm	CHOOZ	Atm
$\delta = 1$	0.03	0.15	0.5	0.13	10.6	4.1
$\delta = 2$	0.32	1.5	5.3	1.3	100	41.7
$\delta = 3$	2.4×10^3	5.6×10^3	1.2×10^4	4.9×10^3	10^5	5×10^4

- Cut-off dependence (from $\sum_{\hat{n}} \frac{d_{\hat{n}}}{\hat{n}^2}$)
  - No dependence for $\delta = 1$
  - Logarithmic dependence for $\delta = 2$
  - Linear dependence for $\delta = 3$

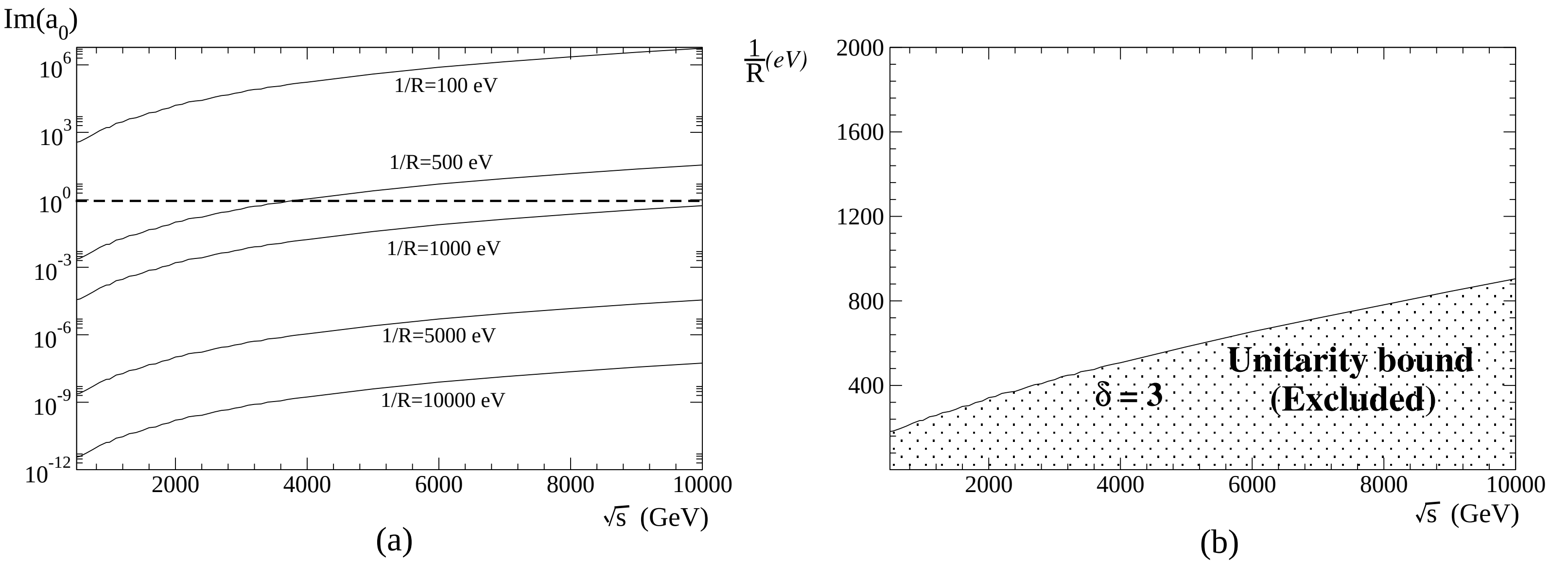
(Perturbative) Unitarity constraints

- Higgs Higgs $\rightarrow$ Higgs Higgs scattering
  - $\mathcal{A}(hh \rightarrow hh) = (32\pi) \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta)\, a_l$
  - $\mathrm{Im}(a_0) < 1$



(Perturbative) Unitarity constraints

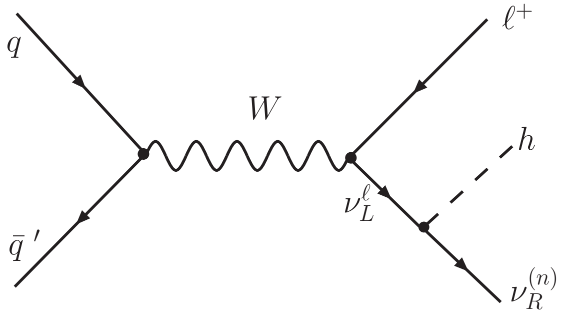
- Constraints weak for $\delta = 1, 2$
- Constraints strong for $\delta = 3$



Collider signatures

- ν_R couples only to ν_L and h (Yukawa)
  - $\mathcal{L}^{(4)} \supset -\left[\frac{\bar{m}_\nu^{i\beta}}{v}\left(h\nu_R'^{i}\nu_L^\beta + \sum_{\hat{n}} \sqrt{2} h \nu_R'^{i(\hat{n})}\nu_L^\beta\right) + h.c.\right] \qquad \bar{m}_\nu \equiv m_0 l^\dagger$
- New Higgs production mechanism (Signal)

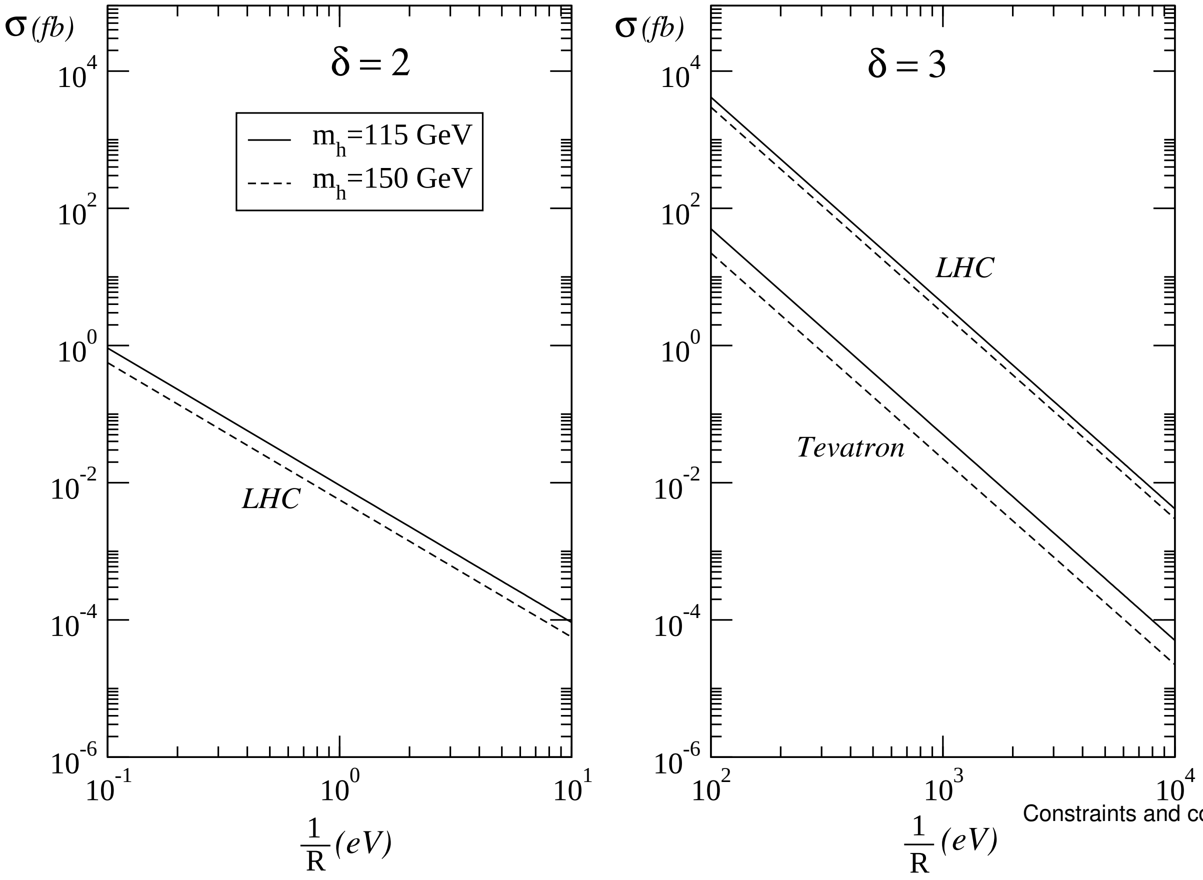
$$q\bar{q}' \to W^* \to \ell^+ \, h \, \nu_R^{(n)} \qquad (\ell = e, \mu, \tau)$$



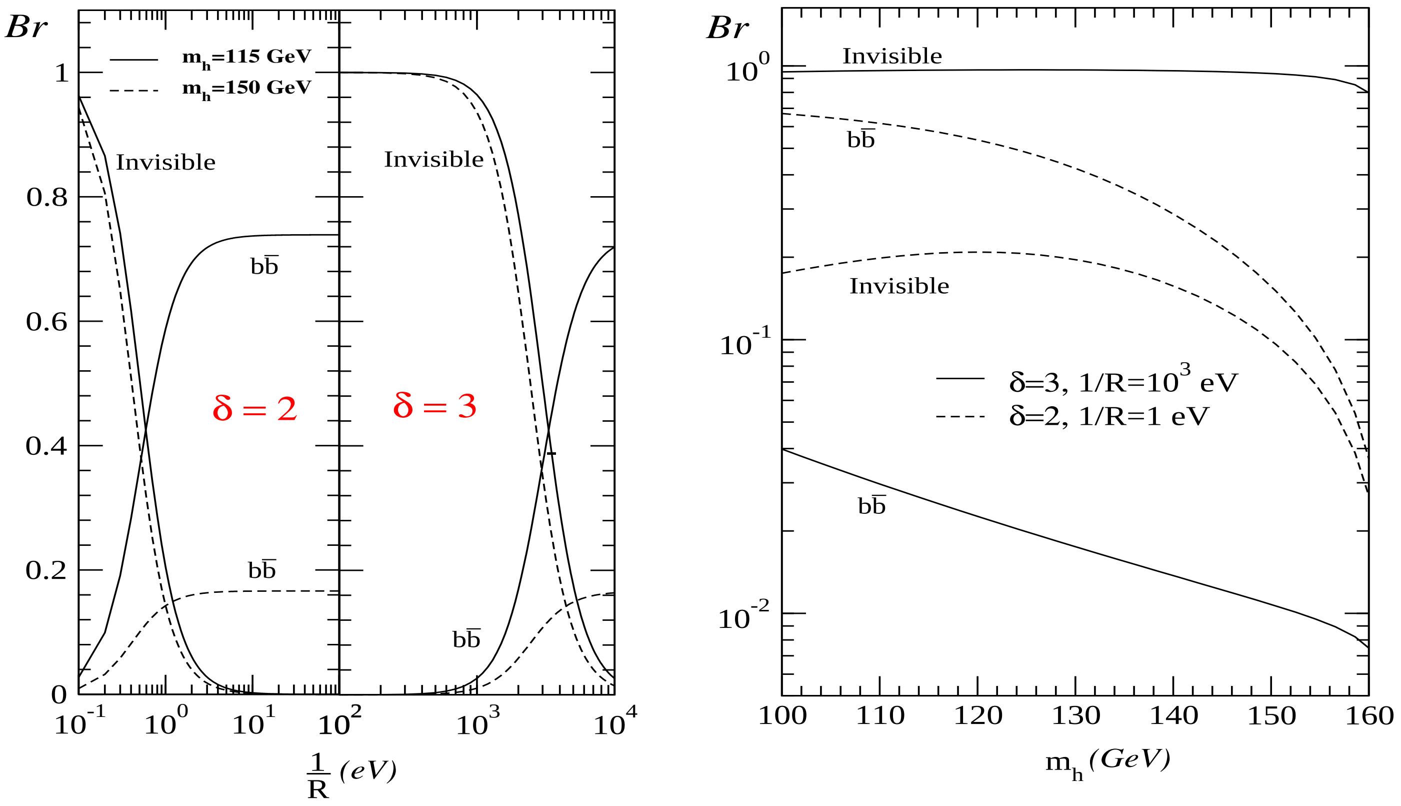
  - Signal can be enhanced due to large number of final state $\nu_R^{(n)}$
- New Higgs decay mode
  - Invisible mode: $(h \to \nu_L \nu_R^{(n)})$
  - (SM: $h \to b\bar{b}$)

Signal cross section

- Monte Carlo for Tevatron and LHC
  (cross section small for $\delta = 1$)



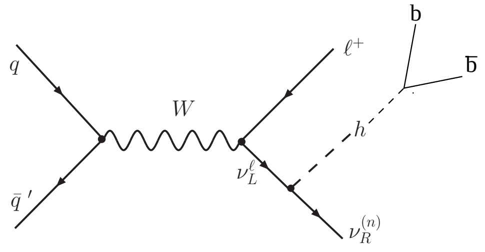
Higgs decay branching ratio



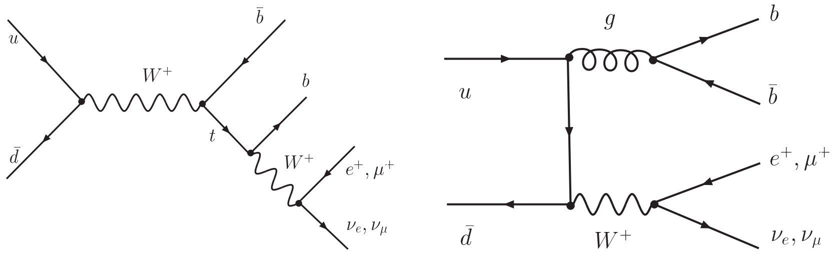
- For 1/R small, invisible decay dominates

h production and $h \to b\bar{b}$

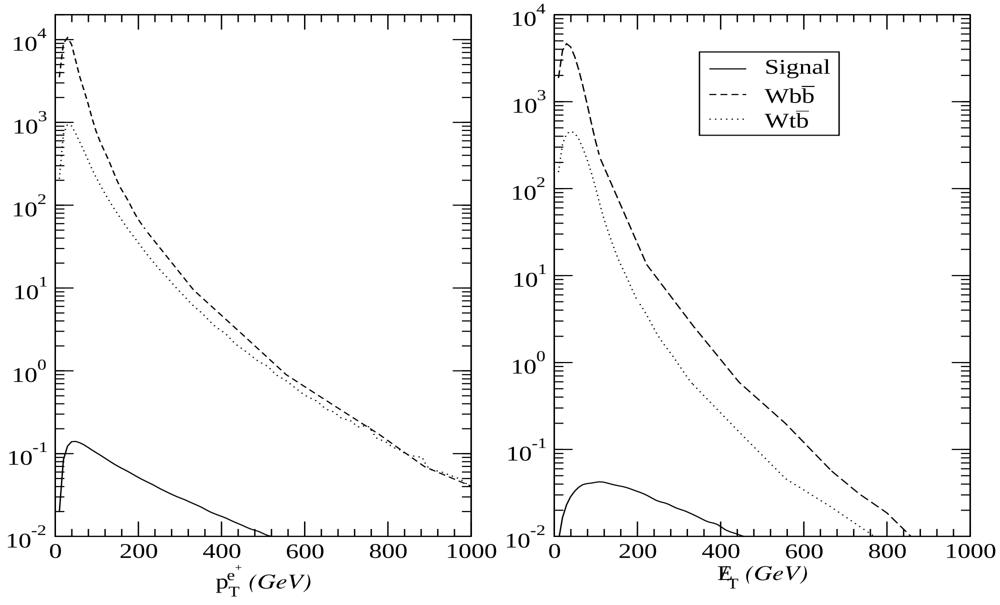
- Signature: $b\,\bar{b}\,\ell^+\,\not{E}_T \quad (\ell = e, \mu)$
- Signal



SM Background



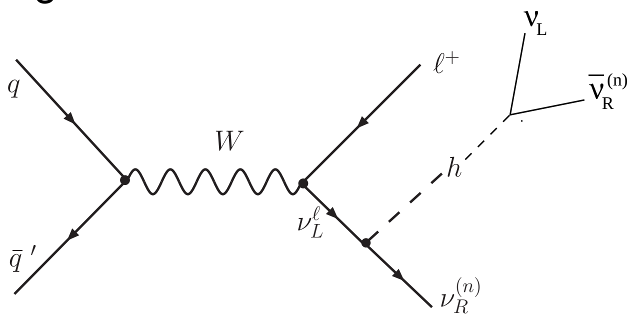
- Cuts:
  $p_T^q > 15\,GeV, \quad |\eta^q| < 3.0$
  $p_T^\ell > 15\,GeV, \quad |\eta^\ell| < 2.5$
  $\not{E}_T > 15\,GeV, \quad \Delta R > 0.4$



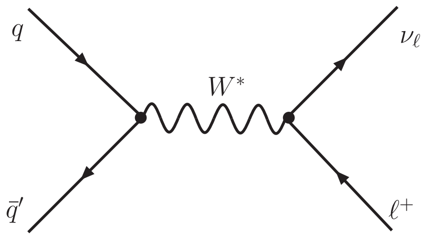
- $h \to b\bar{b}$ difficult to detect

h production and $(h \to \nu_L \nu_R^{(n)})$

- Signature: $\ell^+ \not{E}_T$ $(\ell = e, \mu)$ or $\pi^+ \not{E}_T$ (from τ^+ decay)
- Signal



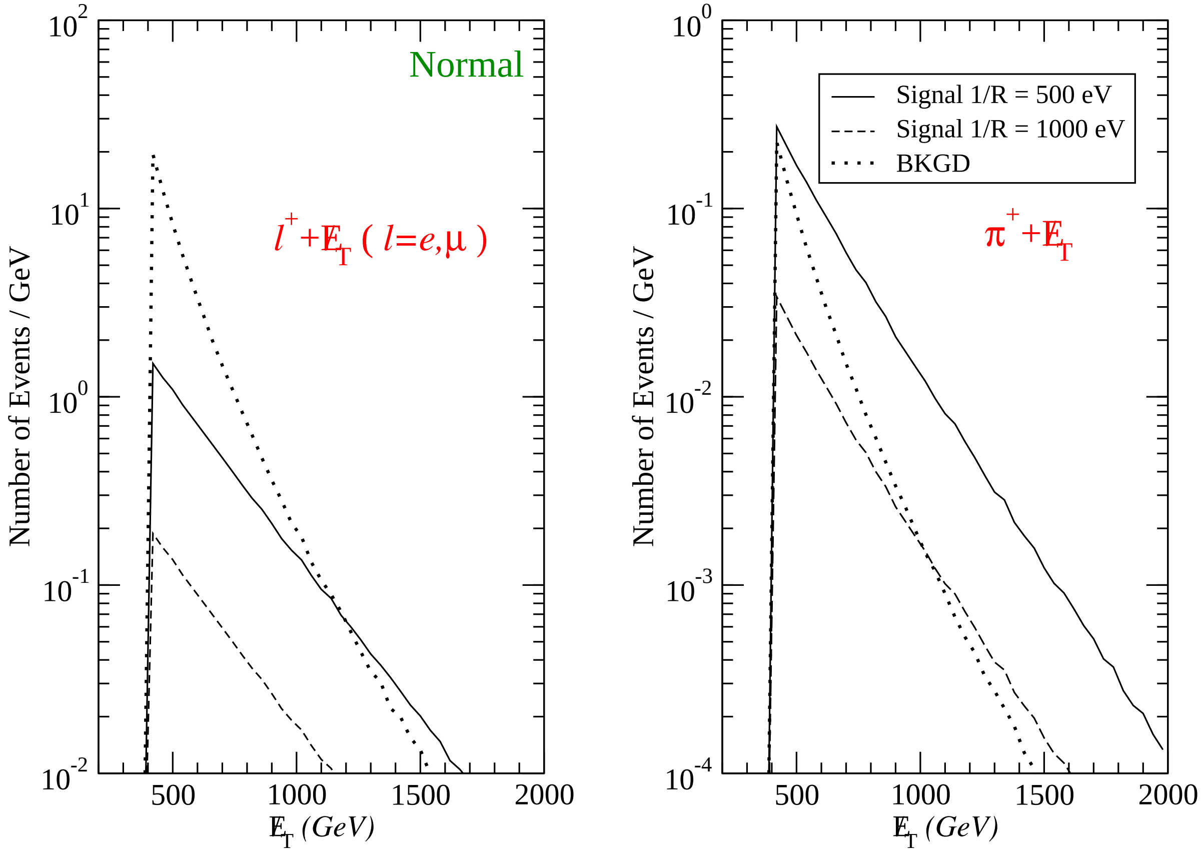
SM Background



- SM Higgs production process $q\bar{q} \to W^* \to W(\to \ell\nu)h$ is small
- Cuts:

	$\ell^+(\ell = e,\ \mu) + \not{E}_T$	$\pi^+ + \not{E}_T$
Basic cuts	$p_T^\ell > 15\,\mathrm{GeV}$	$p_T^\pi > 15\,\mathrm{GeV}$
	$\not{E}_T > 15\,\mathrm{GeV}$	$\not{E}_T > 15\,\mathrm{GeV}$
	$\lvert\eta^\ell\rvert < 2.5$	$\lvert\eta^\pi\rvert < 3.0$
Second cuts	$\not{E}_T > 400\,\mathrm{GeV}$	$\not{E}_T > 400\,\mathrm{GeV}$

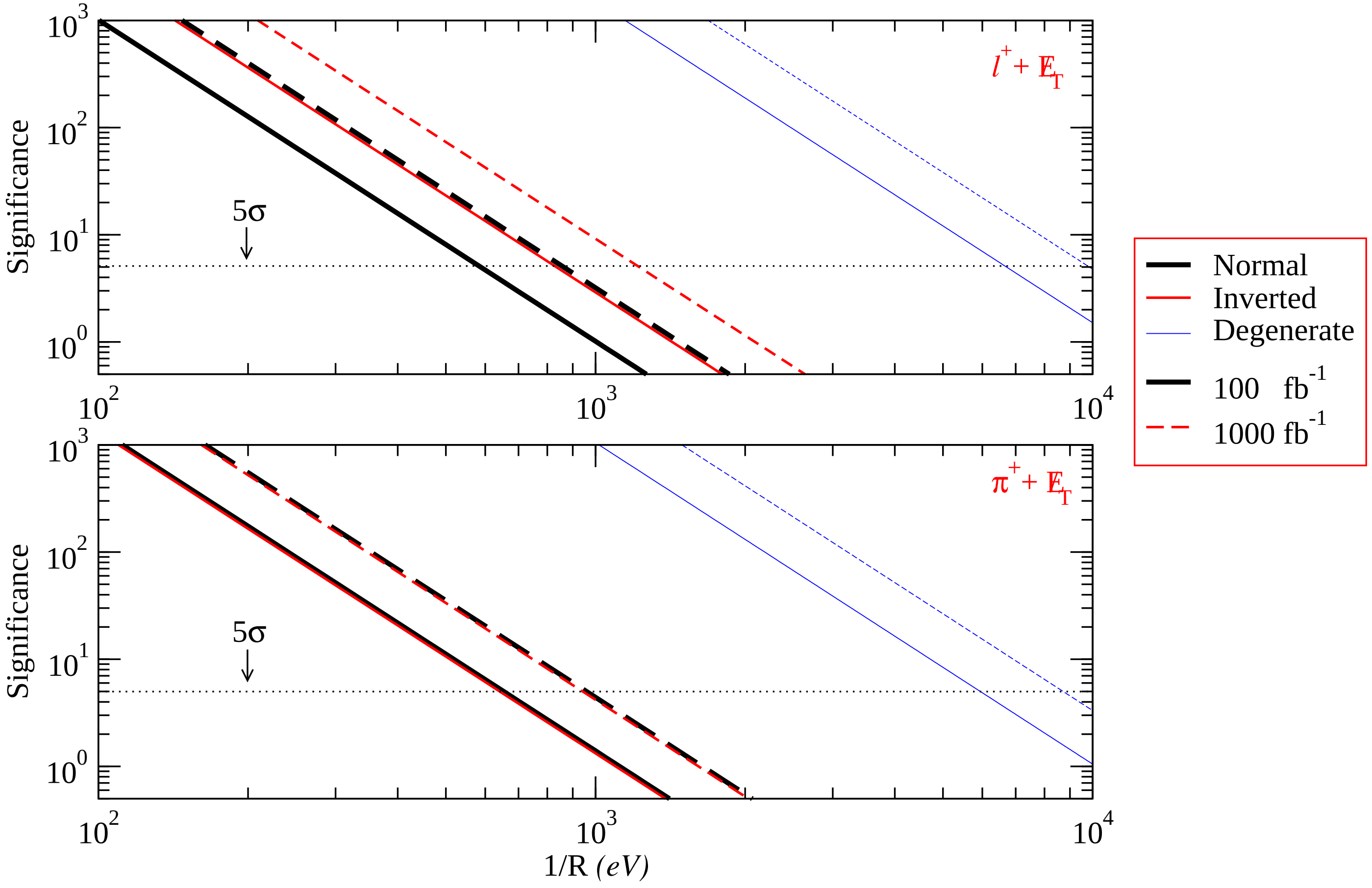
h production and $(h \to \nu_L \nu_R^{(n)})$



- $(h \to \nu_L \nu_R^{(n)})$ looks promising

LHC Discovery potential

- Significance $S_B = \frac{S}{\sqrt{B}} = \frac{\sigma_{signal}\mathcal{L}}{\sqrt{\sigma_{bkgd}\mathcal{L}}}$ $\qquad \sqrt{S} = 14\ \mathrm{TeV},\ \mathcal{L} = 100, 1000\ \mathrm{fb}^{-1}$

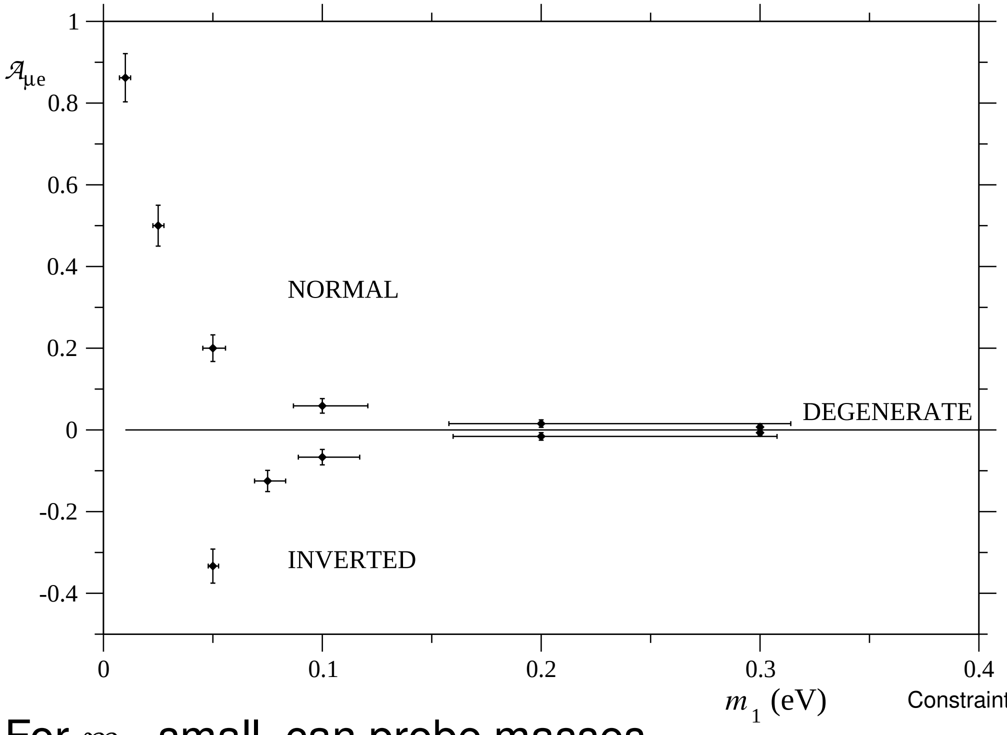


$(\delta = 3)$

Probing neutrino masses

- Normal, Inverted or Degenerate?
- What is the absolute mass scale?
  - Asymmetry

$$\mathcal{A}_{\mu e} \equiv \frac{\mathcal{N}(\mu+\not{E}_T) - \mathcal{N}(e+\not{E}_T)}{\mathcal{N}(\mu+\not{E}_T) + \mathcal{N}(e+\not{E}_T)} \approx \frac{\pm 0.5\,\Delta m^2_{atm}}{2m_1^2 \pm 0.5\,\Delta m^2_{atm}} \rightarrow \begin{cases} > 0 & \text{(normal)} \\ < 0 & \text{(inverted)} \\ \approx 0 & \text{(degenerate)} \end{cases}$$



- For m_1 small, can probe masses

Conclusions

- Bulk ν_R explains the smallness of ν mass
- Oscillation constraints can be strong, esp. for $\delta \geq 3$
- Unitarity constraints also quite strong
- LHC can probe bulk ν_R physics in $\ell^+ \not{E}_T$ channel
  - $q\bar{q}' \to W^* \to \ell^+ \, h \, \nu_R^{(n)} \qquad (h \to \nu_L \nu_R^{(n)})$
  - Backgrounds can be suppressed by cuts discussed
  - $2 - 5\,\sigma$ if $\delta = 3,\ 1/R \sim 900$ eV
- $\mathcal{A}_{\mu e}$ can probe ν mass scheme and m_1