Resonant mono Higgs at the LHC and at future lepton colliders

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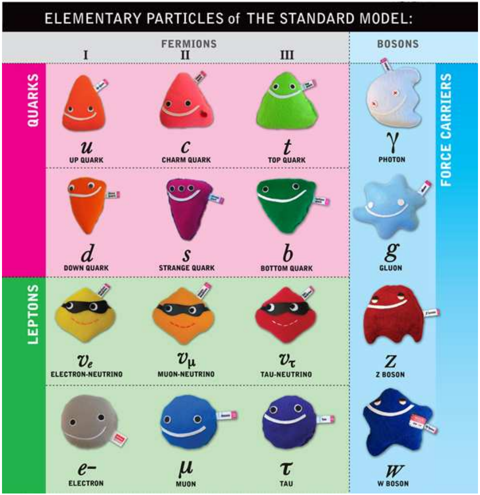
To be released soon

Outline

- Status of the Higgs boson
- Mono Higgs
  - Dark matter
  - Resonant via sterile neutrinos (SPSM)
- Analysis at the LHC
  - Bounds
  - Reinterpretation in SPSM
- Glimpses of FCC-ee
- Conclusions

Introduction

The Standard Model of particle physics: $SU(3)_C \times SU(2)_L \times U(1)_Y$

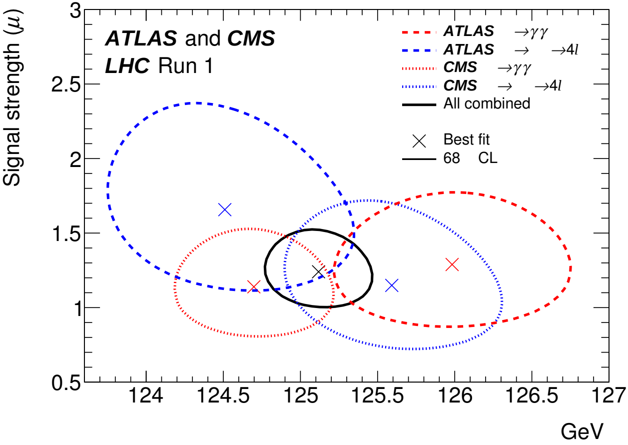


Problems:

- dark matter
- dark energy
- neutrino masses
- baryon-antibaryon asymmetry
- gravity
- ...

Introduction

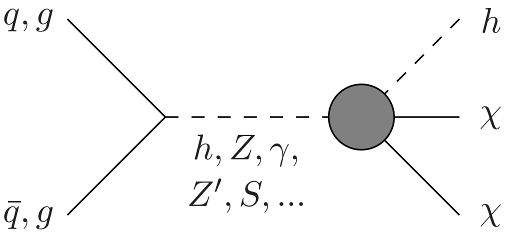
LHC run-I at $\sqrt{s} = 7/8$ TeV: found the Higgs boson



LHC run-II at $\sqrt{s} = 13(14)$ TeV: (among others) study Higgs boson properties, clarify if SM boson, search for New Physics

Mono-X, X = Higgs boson

Mono-X signatures: production of X in association with missing momentum



Vaste literature, $X =$ any SM particle: t/b, W/Z, γ, j, and h

"Missing momentum" $\longleftrightarrow$ (pair) dark matter candidates

For $X = h$, any type of mediator: scalar or vector, SM or BSM

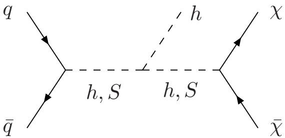
Mono-higgs present also in SM: higgs-strahlung

Mono-X, X = Higgs boson

Simplified models and/or effective Lagrangians

L. Carpenter et al., 1312.2592

(a)



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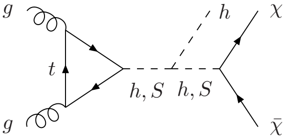

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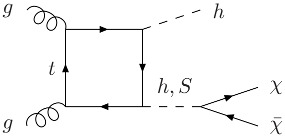

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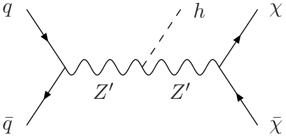

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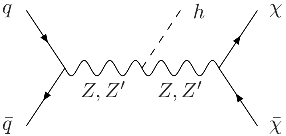
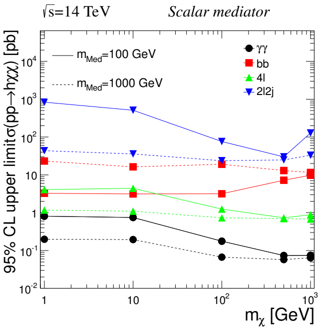
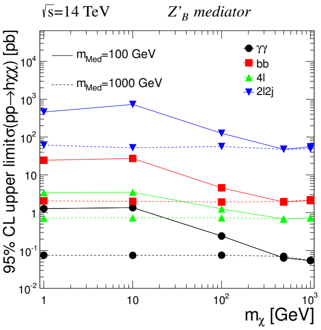


Mono-X, X = Higgs boson

Typical limits differentiating h decay mode

L. Carpenter et al., 1312.2592





Diphoton is the most powerful in costraining $h+$ MET final state

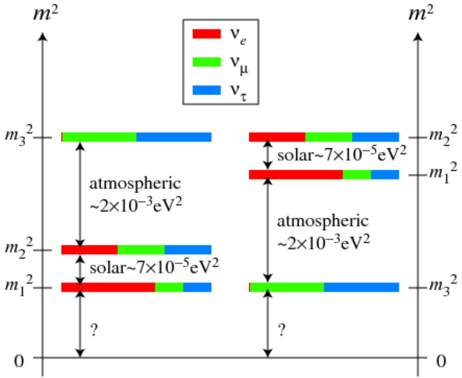
What's missing?

Fermions!

What's missing?

Fermions!

Status of neutrino masses



S.F. King,C. Luhn, Rept.Prog.Phys. 76 (2013) 056201

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{U}_{PMNS}^{-1} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\mathcal{U}_{PMNS} = U_{23} U_{13} U_{12} \, (P_{12})$$

with

$$\begin{aligned} \sin^2\theta_{12} &= 0.31 \pm 0.02, \\ \sin^2\theta_{23} &= 0.41 \pm 0.05, \\ \sin^2\theta_{13} &= 0.024 \pm 0.003. \end{aligned}$$

The previous summary is the result of global fits (assumption: $\mathcal{U}_{PMNS}$ is a *unitary* matrix).

However, most common models that explain neutrino masses predict extra neutrinos that mix with the SM ones: $\nu_i,\ i=1,...,3+n$ mass eigenstates

New unitary diagonalisation matrix is $\mathcal{U}$:

$$\begin{pmatrix} \nu_1 \\ \vdots \\ \nu_{3+n} \end{pmatrix} = \begin{pmatrix} \mathcal{U}_{PMNS} & \mathcal{W} \\ \mathcal{W}^\dagger & \mathcal{V} \end{pmatrix} \begin{pmatrix} \nu_{L_e} \\ \vdots \\ N_n \end{pmatrix}$$

As a submatrix, $\mathcal{U}_{PMNS}$ non unitary (for $n \neq 0$)

Seesaw mechanisms

Neutrino masses where discussed well before the discovery of neutrino oscillations, adding right-handed (sterile) neutrinos

- type-I/III, $N \sim (1,1,0)/(1,3,0)$: $\mathscr{L}_N = -y_D \overline{L}\widetilde{\phi}N - M\overline{N^c}N + \text{H.c.}$,

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \quad \Rightarrow \quad \begin{cases} m_\nu \sim \frac{m_D^2}{M} \\ m_N \sim M \end{cases}$$

  Drawback is as usual, $M \sim M_{GUT}$ or $y_D \sim 10^{-12}$

- linear/inverse, pairs of $N \sim (1,1,0)$, $\mathscr{L}_N = -y_D \overline{L}\widetilde{\phi}N_1 - M\overline{N_1^c}N_2 + \ldots$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & \mu \\ m_D & 0 & M \\ \mu & M & \varepsilon \end{pmatrix} \quad \Rightarrow \quad \begin{cases} m_\nu \sim \overbrace{\mu \frac{m_D}{M}}^{linear} \text{ or } \overbrace{\varepsilon \frac{m_D^2}{M^2}}^{inverse} \\ m_{N_1} \sim m_{N_2} \sim M \end{cases}$$

  SM neutrino masses come from soft breaking of (protective) symmetry, $\mu/\varepsilon \ll 1$, hence simultaneously $M \sim \mathcal{O}(1)$ TeV and $y_D \sim \mathcal{O}(1)$

- type-II, with a Higgs triplet and no extra neutrinos

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- type-II, with a Higgs triplet and no extra neutrinos

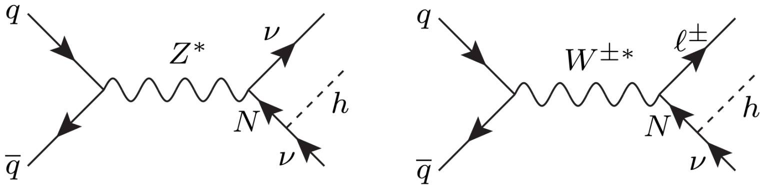
Seesaw mechanisms and mono-Higgs

To explain neutrino masses with sterile states, this interaction term arises

$$\mathscr{L}_N = -\, y_D\, \overline{L}\, \widetilde{\phi}\, N$$

that couples the SM neutrinos to the heavy neutrinos and the Higgs field (h and goldstones)

- $BR(N \to \ell^\pm W^\mp) : BR(N \to \nu Z) : BR(N \to \nu H) \sim 2:1:1$
- Resonant mono-Higgs if N produced on-shell (and $M_N > M_h$)!



Simplified model: low scale inverse seesaw scenario

Neutrino oscillations require 2 neutrinos to be massive

- Assumption: collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry (SPSM), such that

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1}M(N_R^2)^c - y_{\nu_\alpha}\overline{N_R^1}\widetilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

- 3+2 neutrinos, with mass matrix

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix} \overline{\nu^c_{e_L}} \\ \overline{\nu^c_{\mu_L}} \\ \overline{\nu^c_{\tau_L}} \\ \overline{N_R^1} \\ \overline{N_R^2} \end{pmatrix}^T \begin{pmatrix} 0 & 0 & 0 & m_e & 0 \\ 0 & 0 & 0 & m_\mu & 0 \\ 0 & 0 & 0 & m_\tau & 0 \\ m_e & m_\mu & m_\tau & 0 & M \\ 0 & 0 & 0 & M & \epsilon \end{pmatrix} \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \\ (N_R^1)^c \\ (N_R^2)^c \end{pmatrix} + \text{H.c.}$$

- The leptonic mixing matrix to leading order in the active-sterile mixing parameters:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

- Mixing parameters and PMNS (sub-)matrix

$$\theta_\alpha = \frac{y^*_{\nu_\alpha}}{\sqrt{2}}\frac{v_{\mathrm{EW}}}{M}\,, \qquad \mathcal{N}_{\alpha i} = \left(\delta_{\alpha\beta} - \tfrac{1}{2}\theta_\alpha\theta^*_\beta\right)(U_\ell)_{\beta i}$$

Non-unitarity of the PMNS matrix

- Input parameters affected: Fermi constant $G_F = G_\mu(1-\epsilon_\mu)(1-\epsilon_e)$, $\sin\theta_W$
- Weak currents with active neutrinos:

$$\left(J^{\mu,\pm}\right)_{\alpha i} = \ell_\alpha \gamma^\mu \nu_i \mathcal{N}_{\alpha i}\,, \qquad \left(J^{\mu,0}\right)_{ij} = \nu_i \gamma^\mu \nu_j \left(\mathcal{N}^\dagger \mathcal{N}\right)_{ij}$$

$\Rightarrow$ Allows for indirect tests of leptonic mixing (electroweak precision observables)

! $> 3\sigma$ when neglecting $\sin^{\ell,\mathrm{had}}_{eff}$. LB, Fischer, v.d. Bij arXiv:1310.2057 (2013)

! Indication for non-zero mixing with the electron neutrino.

Antusch and Fischer arXiv:1407.6607 (2014)

Present bounds

$$y_{\nu_e} \leq 0.042 \cdot \frac{M_N/GeV}{175} \qquad y_{\nu_\mu} \leq 0.065 \cdot \frac{M_N/GeV}{175} \qquad y_{\nu_\tau} \leq 0.015 \cdot \frac{M_N/GeV}{175}$$

Analysis

- Inspired by the neutrino simplified model, study of resonant mono-Higgs via fermionic resonance
- Free parameters: M_N (and later $y_{\nu_\alpha} \equiv y_\nu \quad \forall \alpha = e,\, \mu,\, \tau$)
- two final states: $h \to b\bar{b}$ and $h \to \gamma\gamma$

Monte Carlo simulation details

LO samples simulation with

- parton level: MG5_aMC@NLO (CTEQ6L1)
- Hadronisation/showering: Pythia6 Tune Z2
- FastSim: Delphes3 ma5Tune
- Analysis: MadAnalysis5

Signal:
5 benchmark points of $M \in [200, 350, 500, 750, 1000]$ GeV. No k-factors

Backgrounds (plus up to 2 jets):

- $b\bar{b}$: ggH, Wh/Zh, $W(Z)b\bar{b}$, $t\bar{t}W$, $t\bar{t}$ and single-t
- $\gamma\gamma$: ggH, Wh/Zh, $\gamma\gamma$, and $\gamma\gamma Z/W$

Samples normalised to NLO cross sections where available

CMS detector emulation
Anti$-k_T$ algorithm with $R = 0.5$
b-tagging CSV medium working point: $b-$tag $= 70\%$, mistag $= 1\%$

Objects selection

Objects identification

$$p_T(\gamma) > 30 \text{ GeV}, \qquad |\eta(\gamma)| < 2.5\,, \tag{1}$$

$$p_T(j) > 40 \text{ GeV}, \qquad |\eta(j)| < 3\,, \tag{2}$$

$$\Delta R(\gamma, j) > 0.4, \tag{3}$$

isolated “loose” charged leptons, with $p_T^\ell > 10$ GeV, $|\eta^\ell| < 2.5(2.4)$ for $\ell = e(\mu)$, are selected for vetoing

$h \to b\bar{b}$

- exactly 2 b-tagged jet
- no other jet
- no loose leptons (e or μ)

$h \to \gamma\gamma$

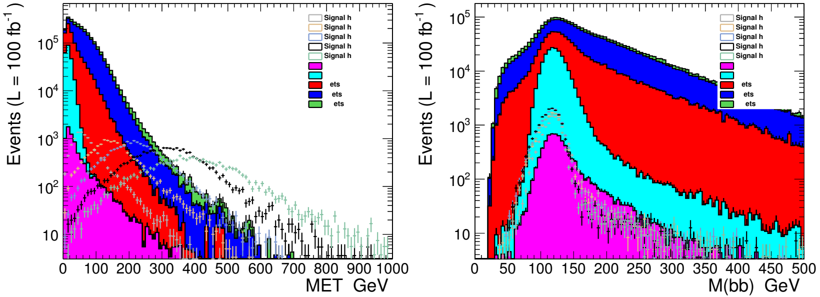
- exactly 2 photons
- no jet
- no loose leptons (e or μ)

$h \to b\bar{b}$

Problem: how do you select (trigger) these events, $b\bar{b}+$ MET?

Di-jet trigger? too high thresholds

MET trigger! fully functional for MET ≥ 200 GeV



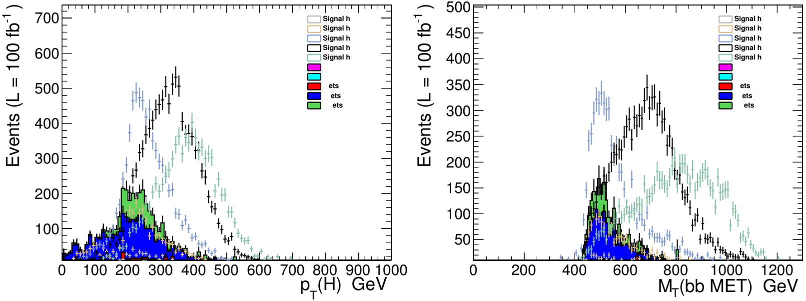
Removes completely $pp \to b\bar{b}$. Suppresses low M_N points.

Then, select Higgs mass window: $100 \leq M(b\bar{b})/\text{GeV} \leq 150$

$h \to b\bar{b}$

Large MET means also large higgs boson boosts (momentum conservation)

$p_T(b\bar{b}) \geq 200$ GeV



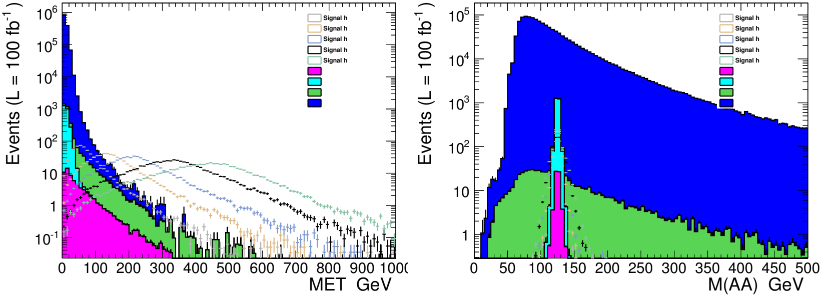
Finally, optimise cut on transverse mass of the whole final state ($b\bar{b}$+ MET) (sort of resonant)

$h \to \gamma\gamma$

Here trigger is not a problem, but signal has still large MET

Enhance signal by cutting MET ≥ 120 GeV

Then, select Higgs mass window: $110 \leq M(b\bar{b})/\text{GeV} \leq 140$

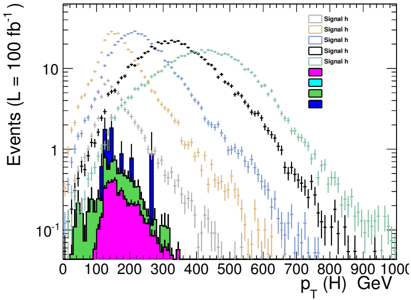


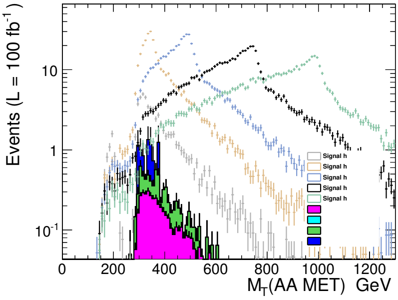
Removes completely $pp \to \gamma\gamma$.

$h \to \gamma\gamma$

Again, large higgs boson boosts (momentum conservation)

$p_T(b\bar{b}) \geq 120$ GeV





Finally, optimise cut on transverse mass of the whole final state ($\gamma\gamma +$ MET) (sort of resonant)

Excluded cross sections for benchmark points

$h \to b\bar{b}$	$M = 200$ GeV	$M = 350$ GeV	$M = 500$ GeV	$M = 750$ GeV	$M = 1000$ GeV
σ (fb), $\mathcal{L} = 100$ fb^{-1}	704.7 ± 44.4	135.2 ± 3.9	35.69 ± 0.57	14.37 ± 0.21	9.65 ± 0.17
σ (fb), $\mathcal{L} = 3$ ab^{-1}	126.5 ± 8.0	24.3 ± 0.7	6.41 ± 0.10	2.53 ± 0.04	1.61 ± 0.03

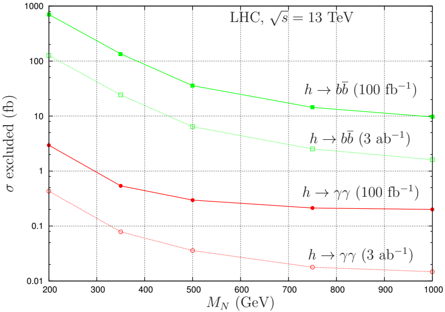
$h \to \gamma\gamma$	$M = 200$ GeV	$M = 350$ GeV	$M = 500$ GeV	$M = 750$ GeV	$M = 1000$ GeV
σ (fb), $\mathcal{L} = 100$ fb^{-1}	2.949 ± 0.010	0.538 ± 0.005	0.297 ± 0.002	0.213 ± 0.002	0.201 ± 0.002
σ (fb), $\mathcal{L} = 3$ ab^{-1}	0.4306 ± 0.0020	0.0488 ± 0.0004	0.0358 ± 0.0003	0.0179 ± 0.0001	0.0148 ± 0.0001

Significance:

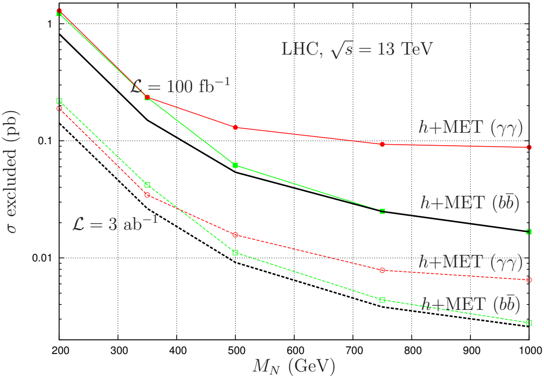
$$\mathbb{S} = \frac{S}{\sqrt{S+B}}$$

Exclusion:

$$\sigma \mid \mathbb{S}(\sigma) \equiv 2$$



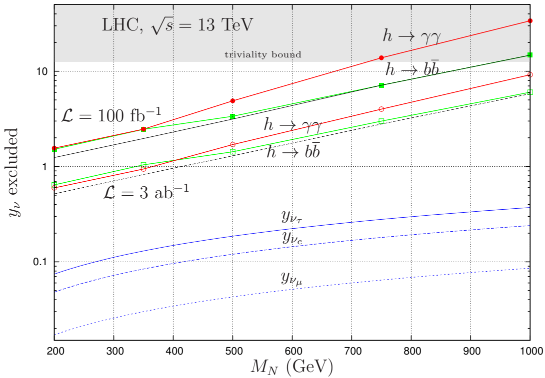
Excluded cross sections for Higgs production



Black line is combination of the two decay modes

$b\bar{b}$ has a larger exclusion power for Higgs boson + MET

Reinterpretation in SPSM

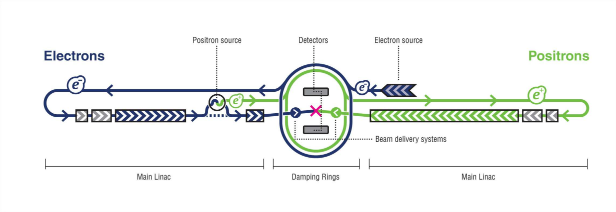


For 100 fb^{-1} of data only neutrino masses below 900 GeV are in the naive non-perturbative regime $y_\nu < 4\pi$

Large gain at the ultimate 3 ab^{-1}

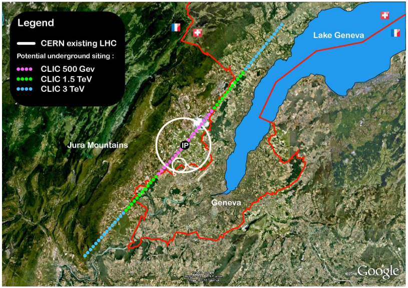
However, still at least one order of magnitude above the current constraints

Future lepton colliders

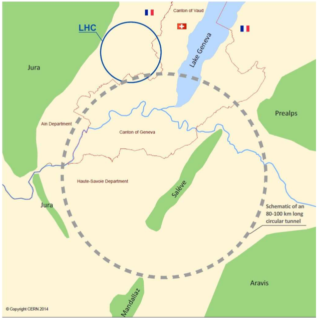


ILC

CLiC

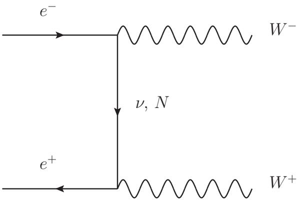


FCC

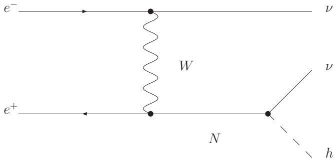


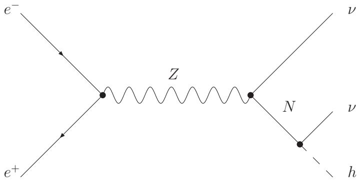
Future lepton colliders

Sterile neutrinos are leptons and mix with LH degrees of freedom
Indirect probe: enhancement of $e^+e^- \to W^+W^-$



Direct probe: mono-Higgs (among others)

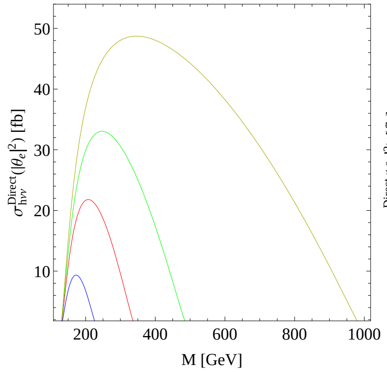




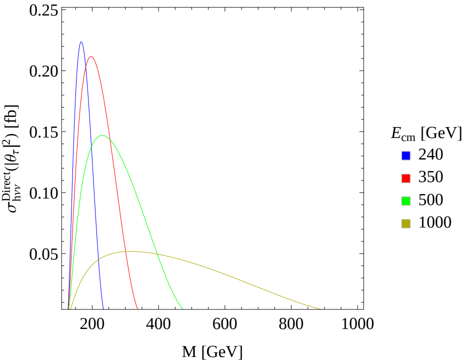
Future lepton colliders

Lepton colliders are sensitive to neutrino flavour

$y_e \neq 0,\, y_{\mu,\tau} = 0$



$y_\tau \neq 0,\, y_{e,\mu} = 0$

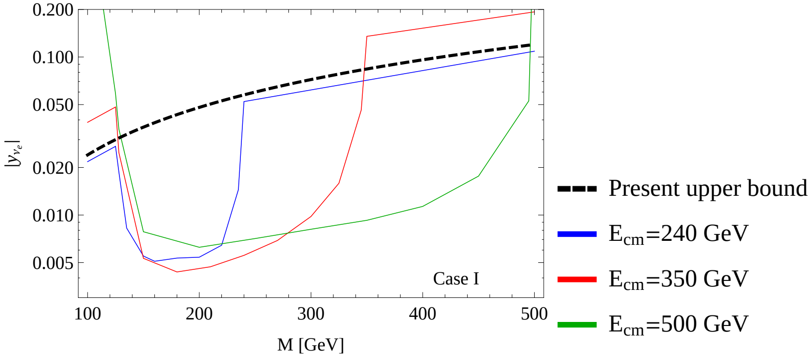


In both cases, s-channel Z production is present, flavour blind

Only if $y_e \neq 0$, also W t-channel contributes

Future lepton colliders

Mono-Higgs, $h \to b\bar{b}$ at parton level, $y_e \neq 0$, $y_{\mu,\tau} = 0$



Potential to improve on existing limits or to observe it.

Still $N \to \ell^{\pm} W^{\mp}$ best search channel.

Conclusions

Higgs boson properties are going to be scrutinised soon

Mono-X signatures promising to look for new physics

- Dark matter

Models neutrino masses predict mono-Higgs, resonant

- studied at LHC in benchmark model (SPSM) to set kinematics
- $h \to b\bar{b}$ and $h \to \gamma\gamma$
- sensitivity of signatures
- combination of decay modes

Reinterpretation to SPSM (original motivation to look at signature)

- LHC cannot improve on existing limits
- Further scope of lepton colliders

Backup slides

Interactions between heavy neutrinos and the SM

- **Charged current** (CC):

$$j^{\pm}_{\mu} = \frac{g}{2}\,\theta_{\alpha}\,\bar{\ell}_{\alpha}\,\gamma_{\mu}\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

$$j^{0}_{\mu} = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_{\mu}\,N_2\; + (\bar{\nu}_i\,\gamma_{\mu}\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_{\mu}\,\xi_{\alpha 2}\,N_2\; + \;\text{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{i=1}^{3}\xi_{\alpha 2}\frac{\sqrt{2}\,M}{v_{\mathrm{EW}}}\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters: $\xi_{\alpha 1} = (-\mathrm{i})\,\mathcal{N}^{*}_{\alpha\beta}\frac{\theta_{\beta}}{\sqrt{2}}$, $\xi_{\alpha 2} = \mathrm{i}\,\xi_{\alpha 1}$

The setup

Courtesy of Eric Conte

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

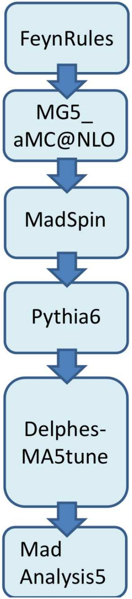
GRPHE UHA

Massive Monte Carlo generation for background

- V + jets
- H + jets
- VV + jets
- VH + jets
- T + jets
- TV + jets
- TH + jets
- TT + jets
- TTV + jets
- TTH + jets
- TTVV + jets

with V=W,Z,γ

- K-factor for background are mainly computed with MG_aMC@NLO
- K-factor for signal are (now) available in the literature …



SM & BSM model description

- Only LO generation + ME/PS merging (MLM kt-cone scheme)
- Frixione isolation for photon

Top-quark & V decay

- Public TuneZ2
- Higgs decay

- **Delphes limitation:** no trigger, no fake lepton
- **MadAnalysis5 tune:**
  - Isolation @ analysis level
  - 8 TeV b-tagging benchmarks (CSV L,M,T)
- **Private improvement:**
  - Basic implementation of fake electron
  - Misidentification of electron electric charge

slide 9

More simulation details

Massive background event generation to gather enough statistics:

Process	# Files	# Events	Process	# Files	# Events
SingleTop_W_madspin	189	18898481	SingleTop_s_madspin	188	18771372
SingleTop_t_5FS_madspin	83	8299246	TTdilep_WToLNu_madspin	1	64191
TTdilep_WWToLLNuNu_madspin	1	99999	TTdilep_WZToLLLNu_madspin	1	99991
TTdilep_ZToLL_madspin	1	99989	TTdilep_ZZToLLLL_madspin	1	99993
TTdilep_madspin	200	9427953	TTsemilep_WToLNu_madspin_1	1	59694
TTsemilep_WToLNu_madspin_2	1	59771	TTsemilep_WWToLLNuNu_madspin_1	1	99989
TTsemilep_WWToLLNuNu_madspin_2	1	99997	TTsemilep_WZToLLLNu_madspin_1	2	199988
TTsemilep_ZToLL_madspin_1	1	99995	TTsemilep_ZToLL_madspin_2	1	99987
TTsemilep_ZZToLLLL_madspin_1	1	99993	TTsemilep_ZZToLLLL_madspin_2	1	99990
TTsemilep_madspin_1	172	8105465	TTsemilep_madspin_2	173	8156688
TZq2_W_trilep1	100	9999157	TZq2_W_trilep2	97	9672987
TZq2_s_trilep	94	9393276	TZq2_t5FS_trilep	97	9699081
WToLNu-0Jet_sm-no_masses	592	52785449	WToLNu-0Jet_sm-no_masses-run2	482	42972689
WToLNu-1Jet_sm-no_masses	586	32827404	WToLNu-2Jets_sm-no_masses	396	15769022
WToLNu-3Jets_sm-no_masses	488	12931463	WWToLLNuNu	194	11221071
WZToLLJJ	5	306339	WZToLLLNu	120	7666801
WZToLNuNuNu	1	59147	WZToNuNuJJ	1	59420
ZToLL10-50-0Jet_sm-no_masses	1	97701	ZToLL10-50-1Jet_sm-no_masses	1	45361
ZToLL10-50-2Jets_sm-no_masses	1	38998	ZToLL10-50-3Jets_sm-no_masses	1	5690
ZToLL50-0Jet_sm-no_masses	9	784399	ZToLL50-1Jet_sm-no_masses	10	549567
ZToLL50-2Jets_sm-no_masses	9	350088	ZToLL50-3Jets_sm-no_masses_split	8	115396
ZToLL50-4Jets_sm-no_masses_split	1	2884	ZZTo4Nu	1	35808
ZZToLLLL	92	6222800	ZZToLLNuNu	1	64305

Monte Carlo errors below permil: neglected