Title: Minimal Electroweak Scale Cosmology at the LHC

Date: May 08, 2009 01:00 PM

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Abstract: It is well known that new physics at the electroweak scale could solve important puzzles in cosmology, such as the nature of dark matter and the origin of the cosmic baryon asymmetry. In this talk, I discuss some of the simplest, non-supersymmetric possibilities, their collider signatures, and the prospects for their discovery and identification at the LHC.

Minimal Electroweak Scale Cosmology and the LHC

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Wisconsin-Madison

NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

http://www.physics.wisc.edu/groups/particle-theory/

Perimeter Institute, May 2009

Outline

Minimal TeV-scale SM extensions

- ***Can help explain the origin of matter (visible and dark)***
- ***Can be discovered at the LHC***
- ***Can be probed in cosmologically relevant parameter space at colliders***

Outline

I. Intro & Motivation

II. Baryogenesis & EWPT

III. Three minimal models & their LHC phenomenology

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- Real Singlet xSM
- Complex Singlet cxSM
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Cosmology at the HEP & NP Interface

Two puzzles:

- **Nature of DM & its interactions**
- **Origin of the BAU**

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  - EDM: CPV

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  - Collider: EWPT & spectrum

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- **Origin of the BAU**
  - → EDM: CPV
  - → Collider: EWPT & spectrum

Additional problems:

- **Gauge hierarchy**
- **EWPO & m_H (little hierarchy)**
- **Origin of m_ν**

Non-minimal Solutions (SUSY)

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✖	Nature of DM & its interactions	✔
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Additional complications:

- Why is $\mu \sim M_{weak}$?
- Why little flavor & CPV ?
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- M_{SUSY} < TeV (hierarchy)
- Bino-Higgsino-like LSP (DM)
- Light RH stop (m < 125 GeV)
- $M_1 \sim \mu$
- $\phi_1 \neq \phi_2$

Minimal Solutions (non-SUSY)

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Extra Scalars

Extra Fermions

Minimal Solutions (non-SUSY)

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- Set aside hierarchy problem (for now)
- To what extent can minimal scenarios for new electroweak scale physics help explain the abundance of matter (visible & dark) ?
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Focus: *Key parameters for cosmo & LHC pheno*

Baryogenesis: Ingredients

Sakharov Criteria

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

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EDMs

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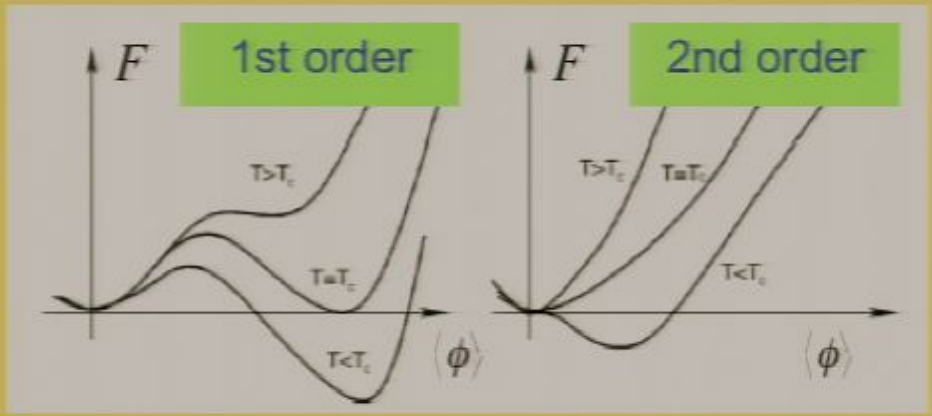
Prevent washout by inverse processes

LHC: Scalars

SM EWPT: ✖

Electroweak Phase Transition & Higgs



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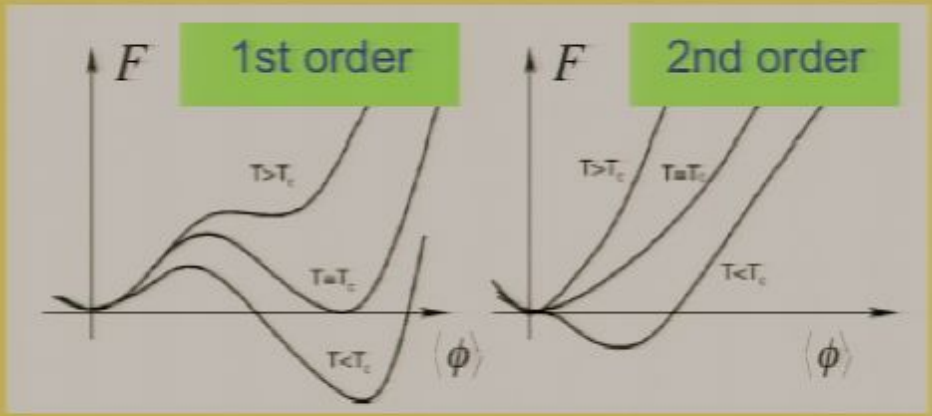
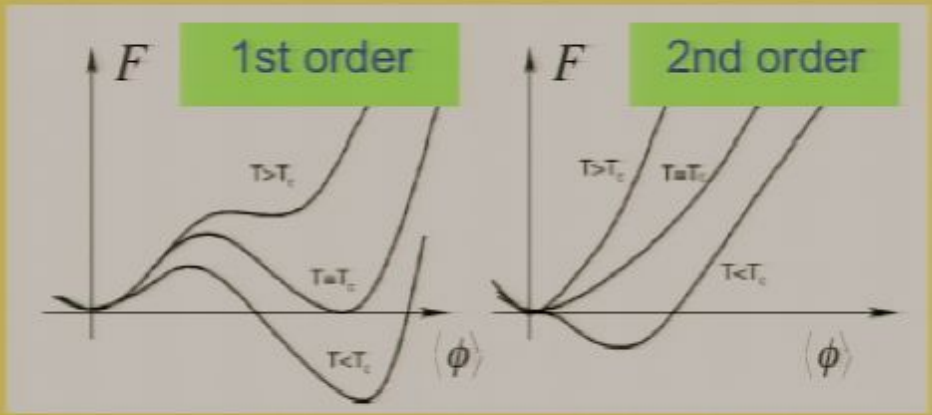


Increasing m_h ⟶

$$V_{EFF}(\varphi,T) = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda}{4}\varphi^4$$

Electroweak Phase Transition & Higgs



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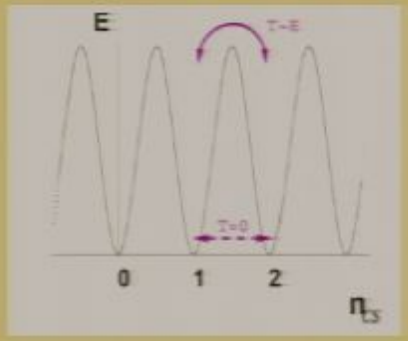
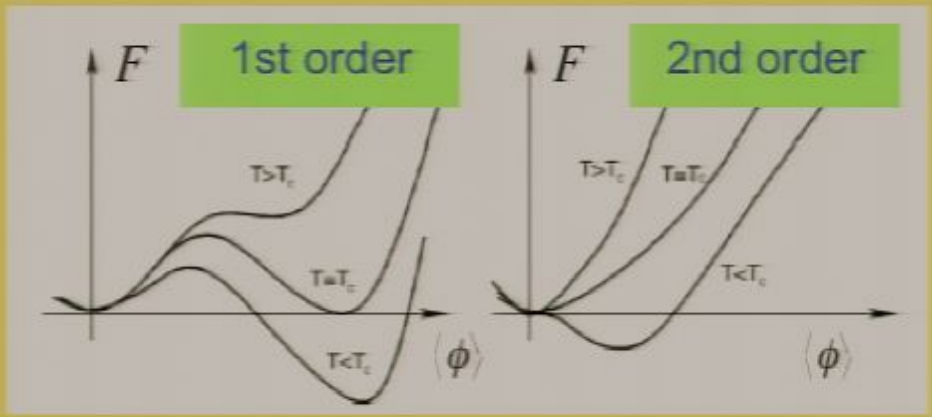


So that $\Gamma_{sphaleron}$ is not too fast

Electroweak Phase Transition & Higgs



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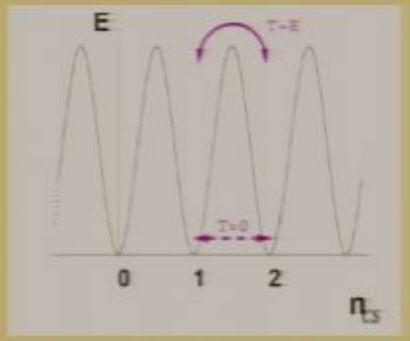

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Computed E_{SM} : m_H < 70 GeV

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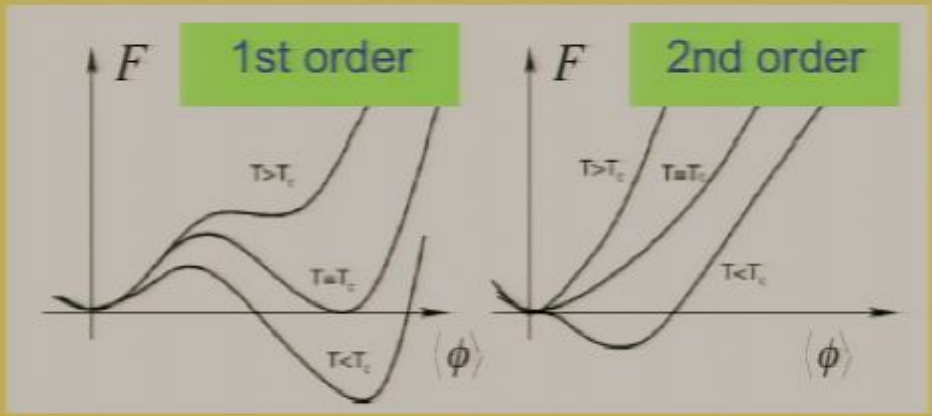
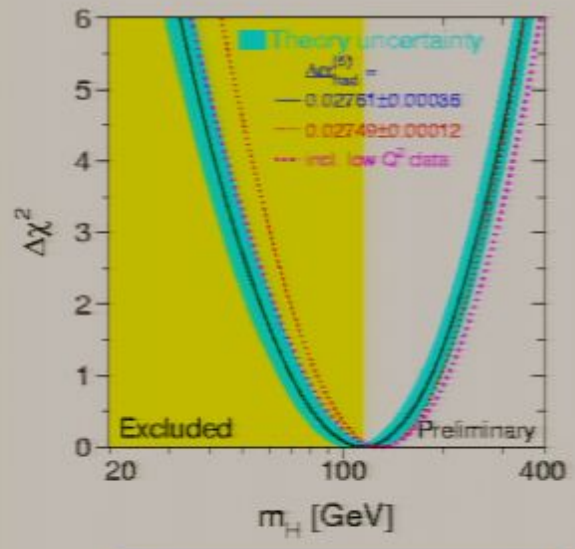


Increasing m_h →

LEP EWWG



m_h>114.4 GeV

or ~ 90 GeV (SUSY)

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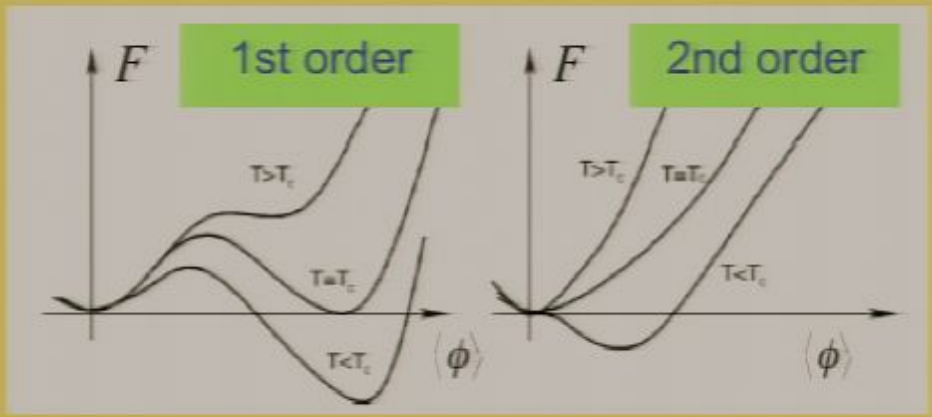

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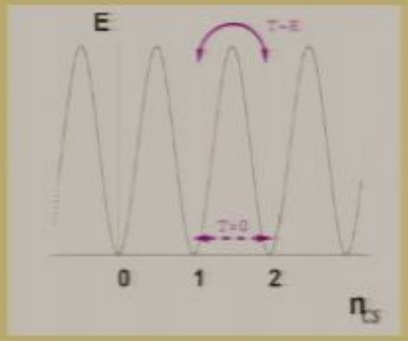

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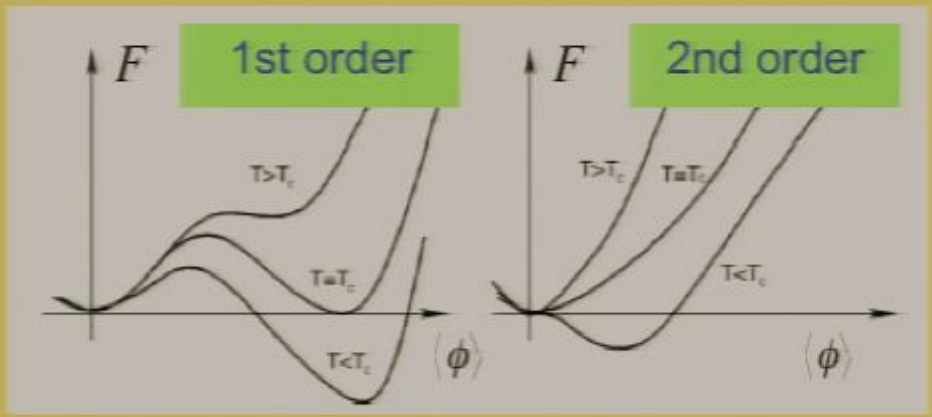
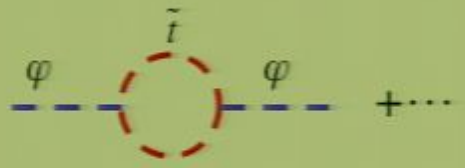


Increasing m_h →

Stop loops in V_{Eff}



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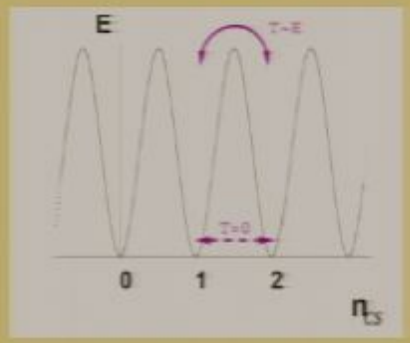

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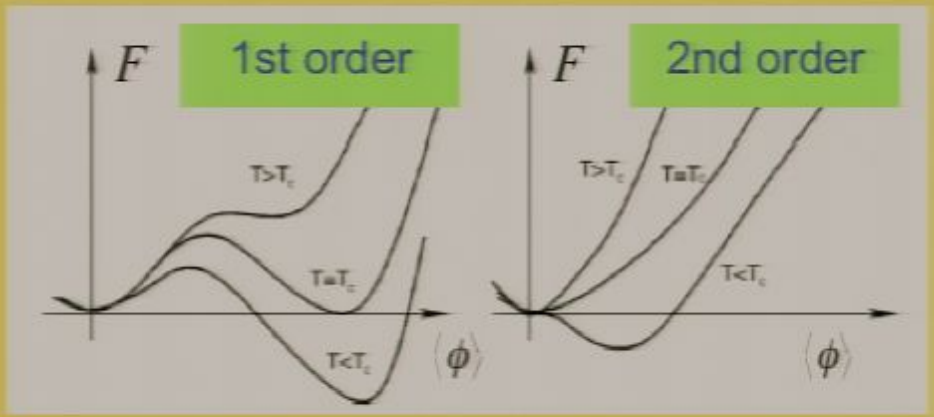

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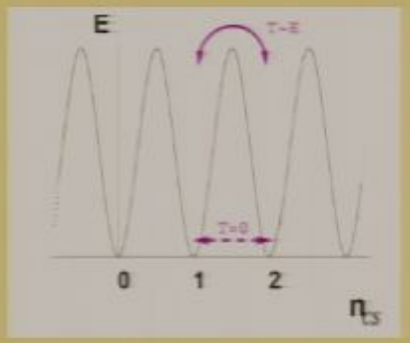

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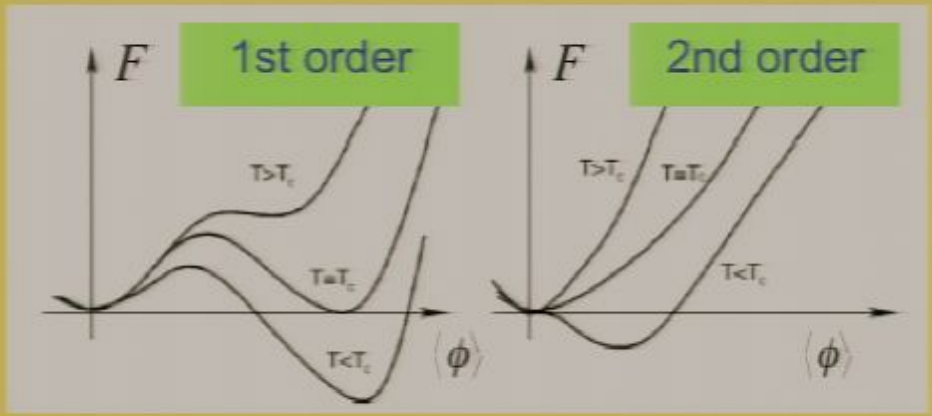

Increasing m_h ⟶

$$\Delta V_{\text{eff}}(\phi, T) \sim T M_s(\phi, T)^3$$

$$M_{\tilde{t}}^2 \sim \tilde{m}^2 + y\phi^2 + \Pi(T)$$

Light RH stop w/ special $M_{\tilde{t}_R}^2$

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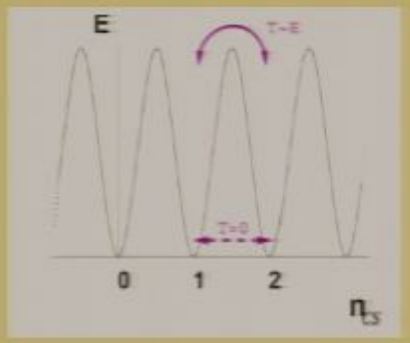

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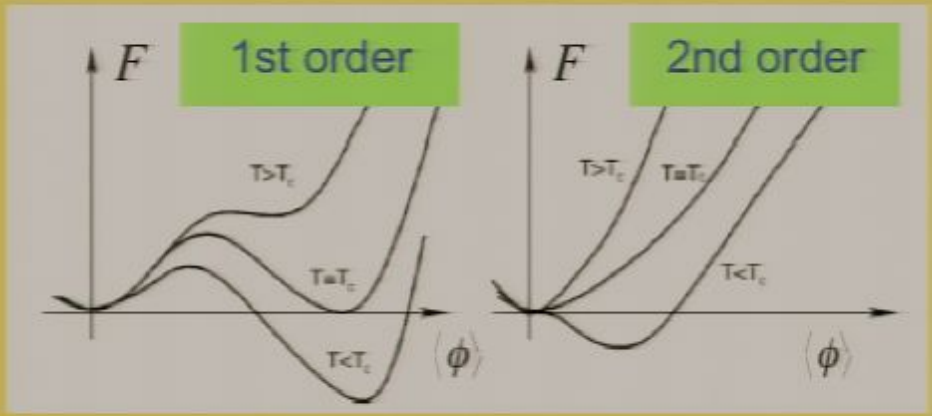

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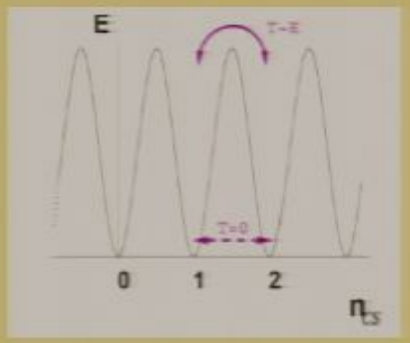

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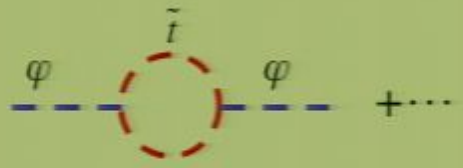

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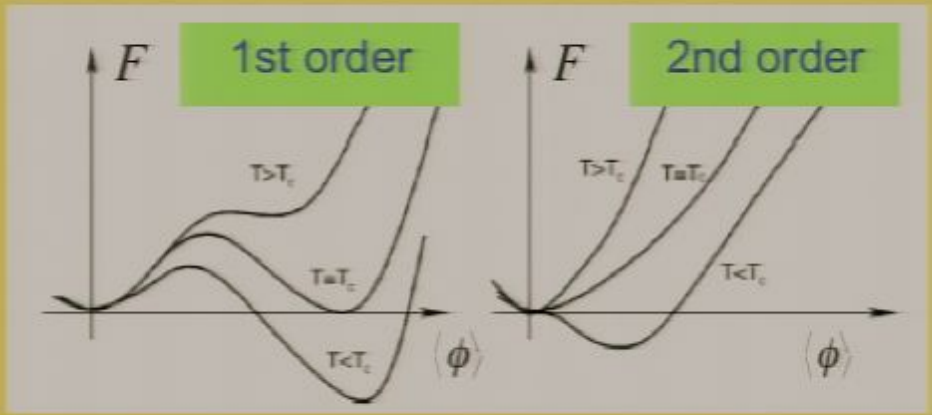

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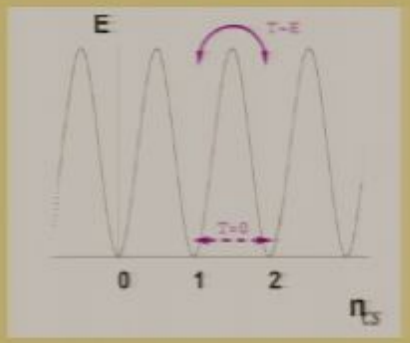

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Non-doublet Higgs (w / wo SUSY)

Decay *Mixing*

Computed E_{SM} : m_H < 70 GeV

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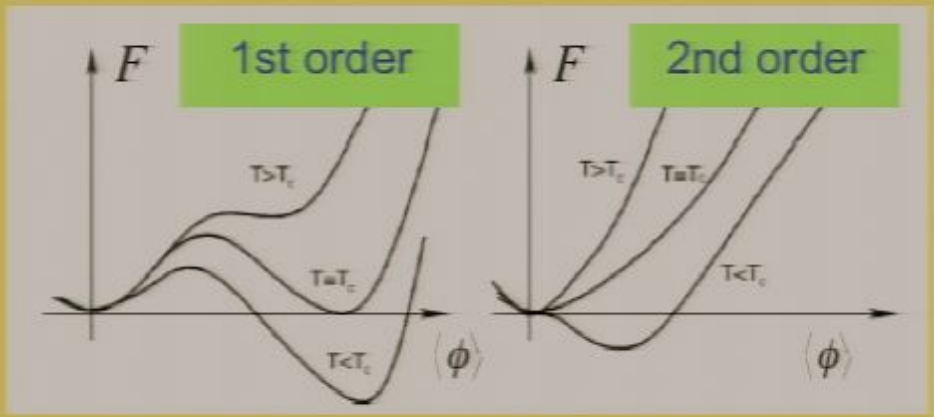
The Simplest Extension

Simplest extension of the SM scalar sector: add one real scalar S

- *Goal: identify generic features of minimal models with new scalars having a strong, 1st order EWPT and/or DM*
- *Determine low-energy phenomenology (Higgs studies, precision ewk)*
- *Address CPV with a different mechanism*

Electroweak Phase Transition & Higgs



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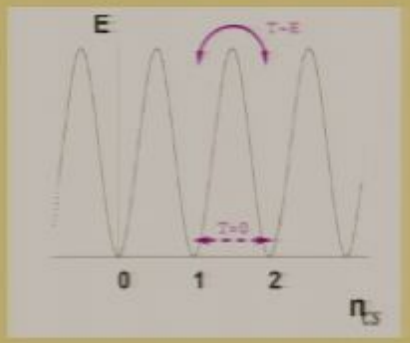

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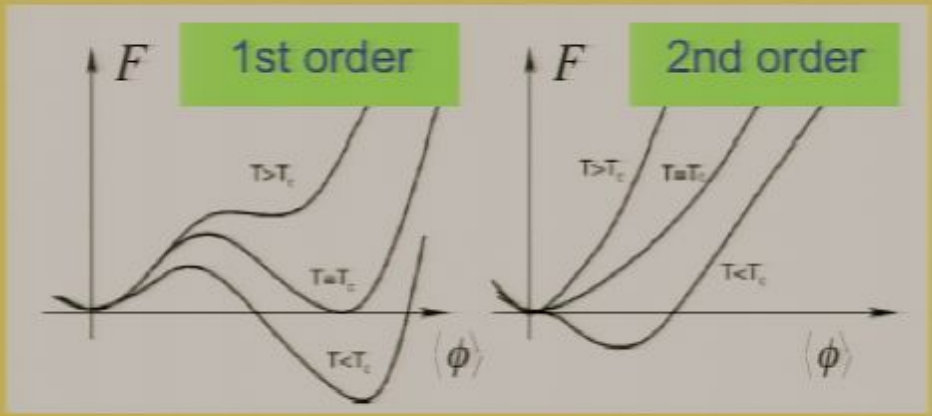
Electroweak Phase Transition & Higgs

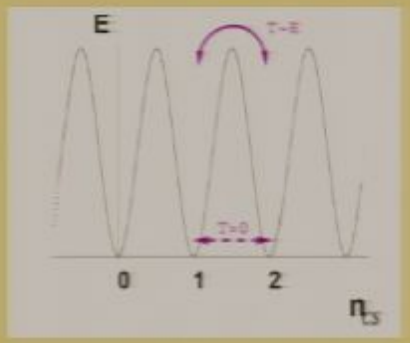


Increasing m_h →

$$V_{EFF}(\varphi,T) = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda}{4}\varphi^4$$

Need

$$\frac{\varphi(T_C)}{T_C} = E\left(\frac{M_{WK}^2}{m_H^2}\right) > 1$$



So that $\Gamma_{sphaleron}$ is not too fast

Computed E_{SM} : $m_H < 70$ GeV

Non-doublet Higgs (w / wo SUSY)

Decay Mixing

Light RH stop w/ special $M_{\tilde{t}_R}^2$

The Simplest Extension

Simplest extension of the SM scalar sector: add one real scalar S

- *Goal: identify generic features of minimal models with new scalars having a strong, 1st order EWPT and/or DM*
- *Determine low-energy phenomenology (Higgs studies, precision ewk)*
- *Address CPV with a different mechanism*

The Simplest Extension

Model

$$V = V_{SM} + V_{HS} + V_S$$

The Simplest Extension

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$$V_{HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

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H-S Mixing

$H_1 \to H_2 H_2$

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$$\left.\frac{\partial V}{\partial H}\right|_{\langle H^0\rangle_{T=0}=v_0/\sqrt{2}} = \left.\frac{\partial V}{\partial S}\right|_{\langle S\rangle_{T=0}=x_0} = 0$$

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Independent Parameters:

v_0, x_0, λ_0, a_1, a_2, b_3, b_4

The Simplest Extension

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$H_1 \to H_2 H_2$

$$V_{HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

Mass matrix

$$M^2 = \begin{pmatrix} \mu_h^2 & \mu_{hs}^2/2 \\ \mu_{hs}^2/2 & \mu_s^2 \end{pmatrix} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\mu_{hs}^2 = \left(a_1 + 2a_2 x_0\right) v_0 \qquad \mu_s^2 = -\frac{a_1 v_0^2}{4x_0} + \cdots$$

The Simplest Extension

Stable S (dark matter?)

- *Tree-level Z_2 symmetry: $a_1=b_3=0$ to prevent s-h mixing and one-loop $s \to hh$*
- *$x_0=0$ to prevent h-s mixing*

- $H_1 \to H_2 H_2$

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The Simplest Extension

Model

H-S Mixi

Signal Reduction Factor

$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

Production

Decay

$H_1 \to H_2 H_2$

Mass matrix

$$M^2 = \begin{pmatrix} \mu_h^2 & \mu_{hs}^2/2 \\ \mu_{hs}^2/2 & \mu_s^2 \end{pmatrix} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

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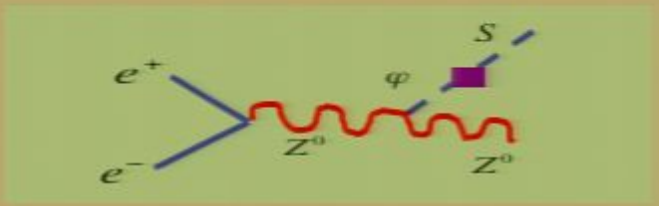

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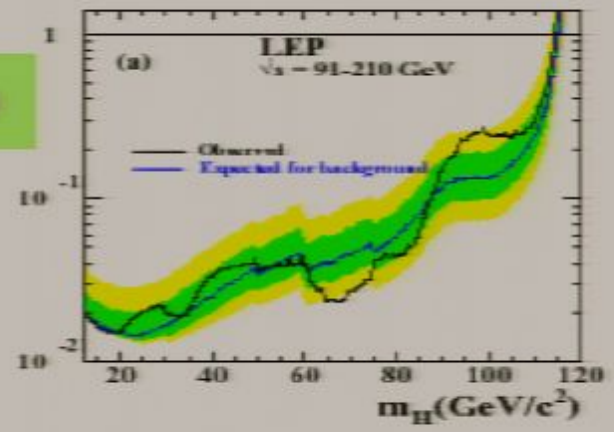
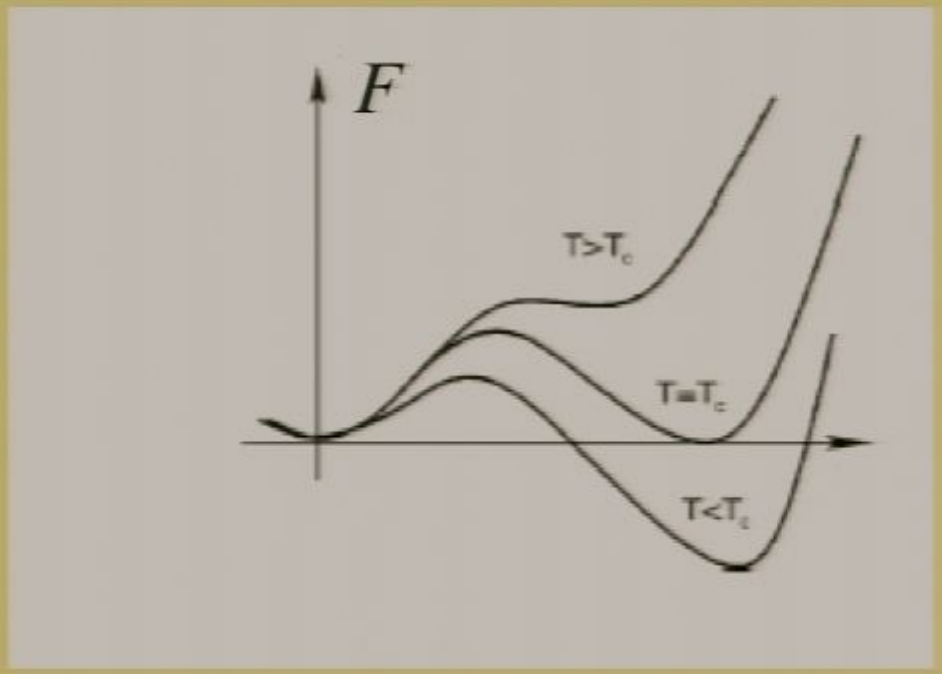
$\sin^2\theta$



Finite Temperature Potential



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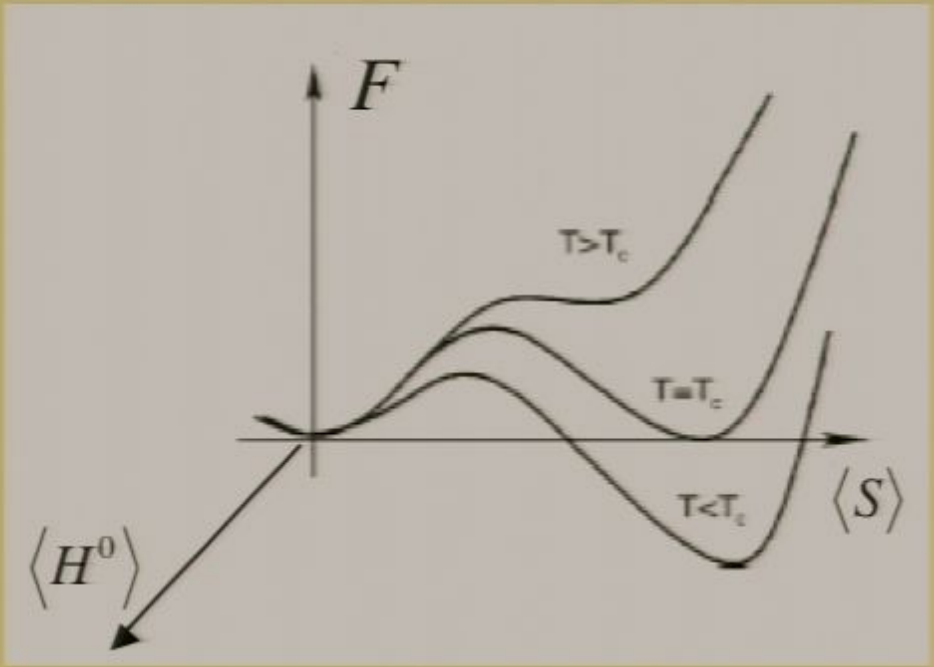
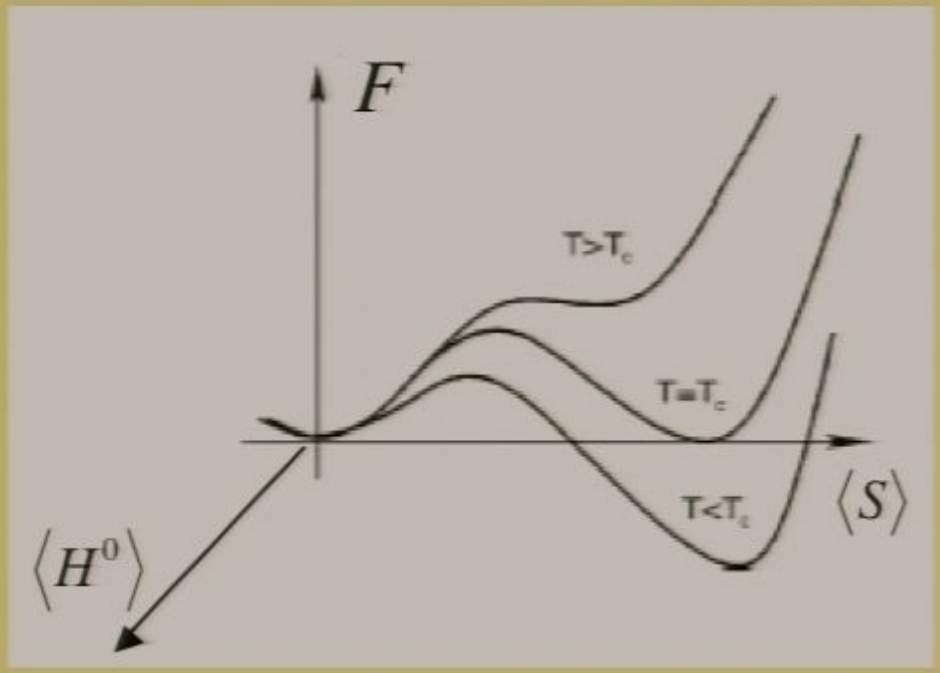


- *What is the pattern of symmetry breaking ?*
- *What are conditions on the couplings in V(H,S) so that $\langle H^0 \rangle / T > 1$ at T_C ?*

Finite Temperature Potential



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$$\langle H^0 \rangle = v/\sqrt{2} \equiv \varphi \cos\alpha$$

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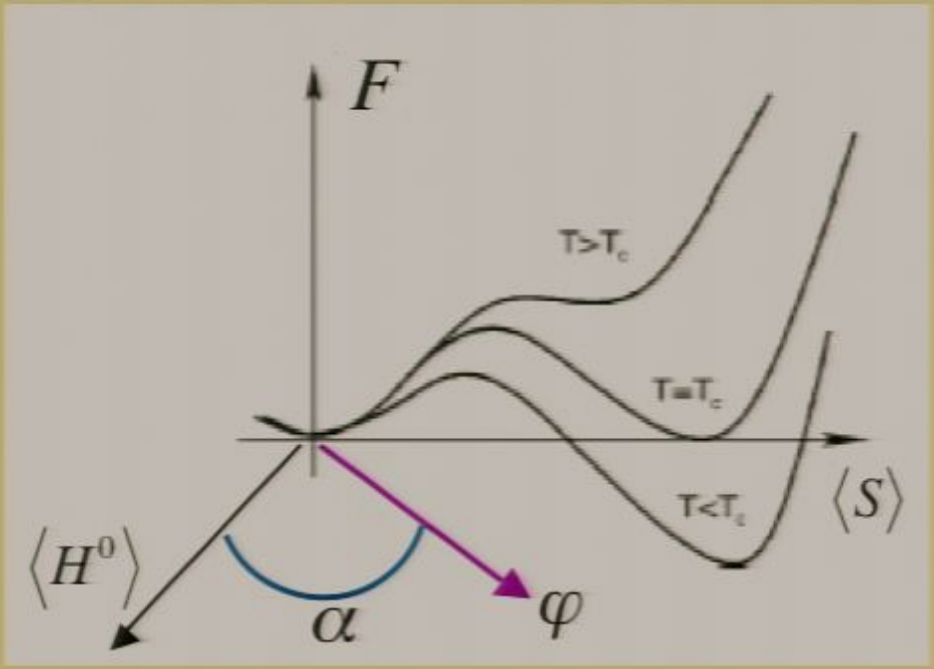

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$$\langle H^0 \rangle = v/\sqrt{2} \equiv \varphi \cos\alpha$$
$$\langle S \rangle = x \equiv \varphi \sin\alpha$$

- *Compute $V_{eff}(\phi, \alpha, T)$*
- *Minimize w.r.t ϕ , α*
- *Find T_C*
- *Evaluate $v(T_C)/T_C \sim \cos\alpha(T_C)\ \phi(T_C)/T_C$*

$V_{EFF}(T)$ & EWSB

Potential

$$V_{eff}(\varphi,\alpha,T) = \bar{\lambda}\varphi^4 + (e-\varepsilon T)\varphi^3$$
$$+\left[2\bar{D}(T^2-T_0^2)+(b_2\sin^2\alpha)/2\right]\varphi^2 + BT^2\varphi + \cdots$$

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$V_{EFF}(T)$ & EWSB

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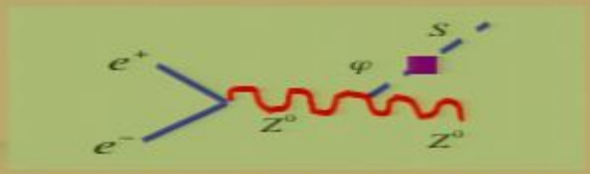

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$V_{EFF}(T)$ & EWSB

Strong first order EWPT: SM

$$\frac{\varepsilon}{2\bar{\lambda}} > 1$$

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$V_{EFF}(T)$ & EWSB

Strong first order EWPT

$$\sqrt{2}\cos\alpha_c \left(\frac{\varepsilon - e/T_c}{2\bar{\lambda}}\right)\left[1+\gamma\frac{|V_0|}{T_c^4}\right]+\cdots \gtrsim 1$$

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Increase ε

Large $e < 0$

Reduce λ

Nonzero V_0

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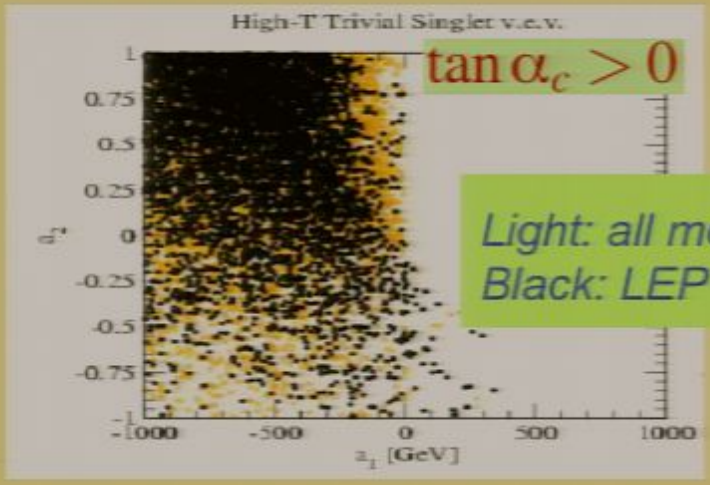

Light: all models
Black: LEP allowed

$a_1<0$, a_2 either sign

$V_{EFF}(T)$ & EWSB

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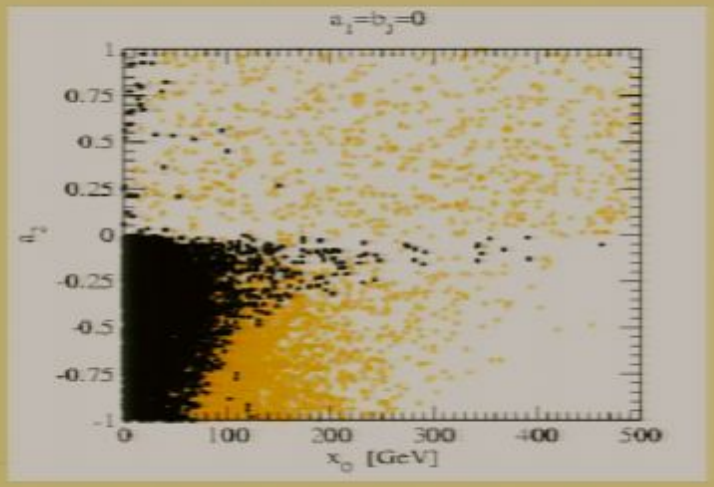

$a_1 = b_3 = 0,\ a_2 < 0$

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LHC Phenomenology

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LHC Phenomenology

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Signatures

Scan: EWPT-viable model parameters

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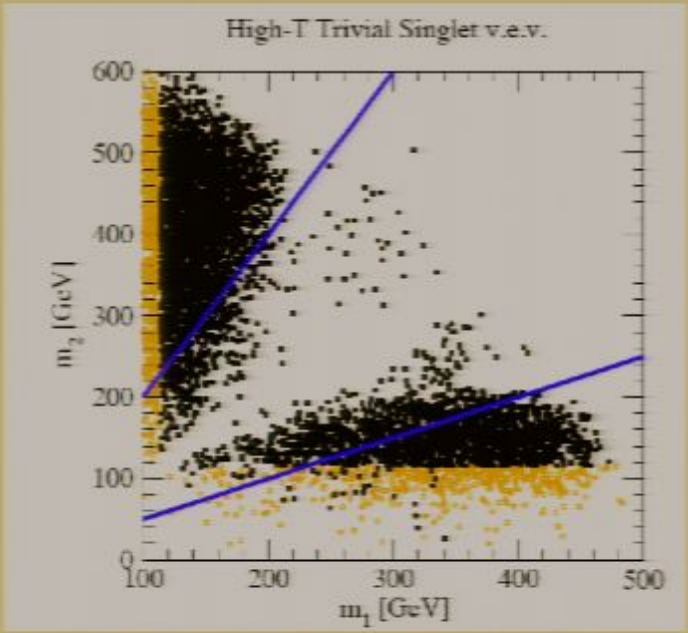

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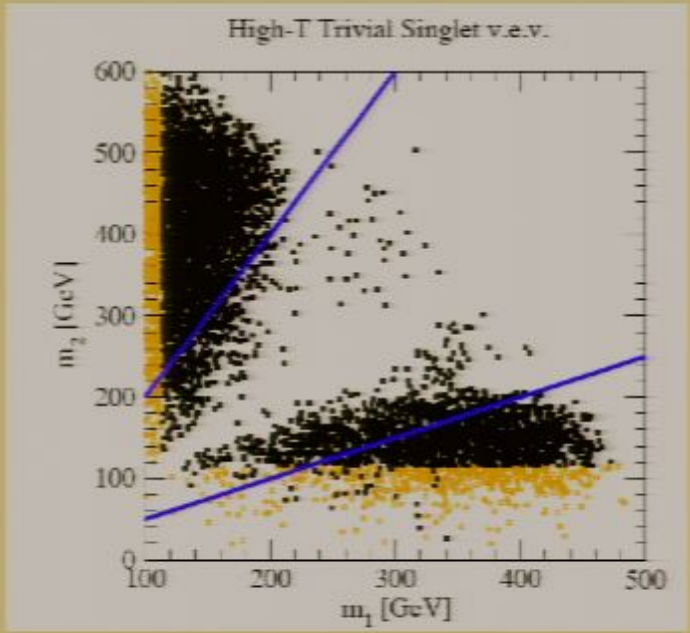

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LHC Phenomenology

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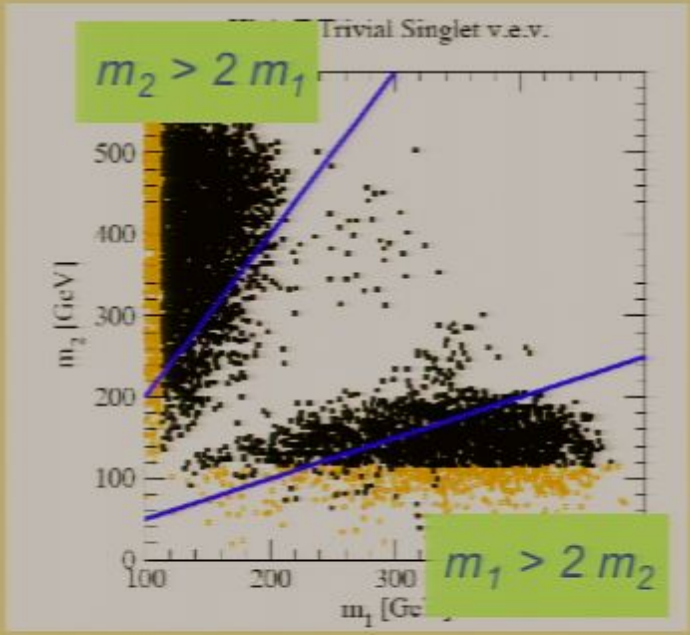

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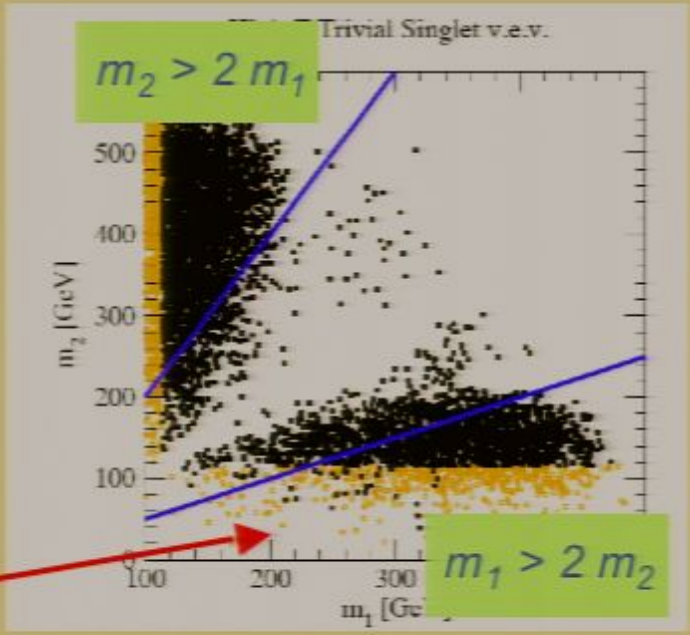
LHC Phenomenology

Signatures

Scan: EWPT-viable model parameters

LHC: reduced BR(h → SM)



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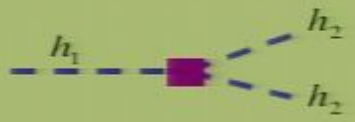
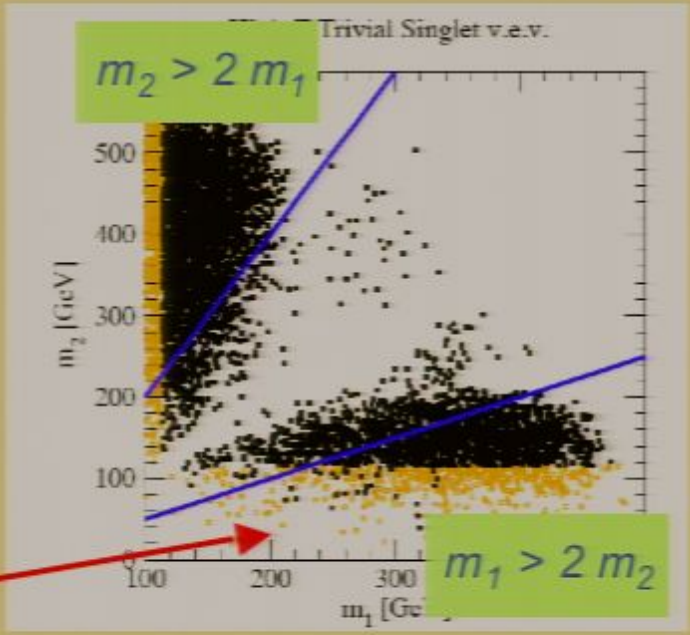
LHC Phenomenology

Signatures



LHC: reduced BR($h \rightarrow$ SM)



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LHC Phenomenology

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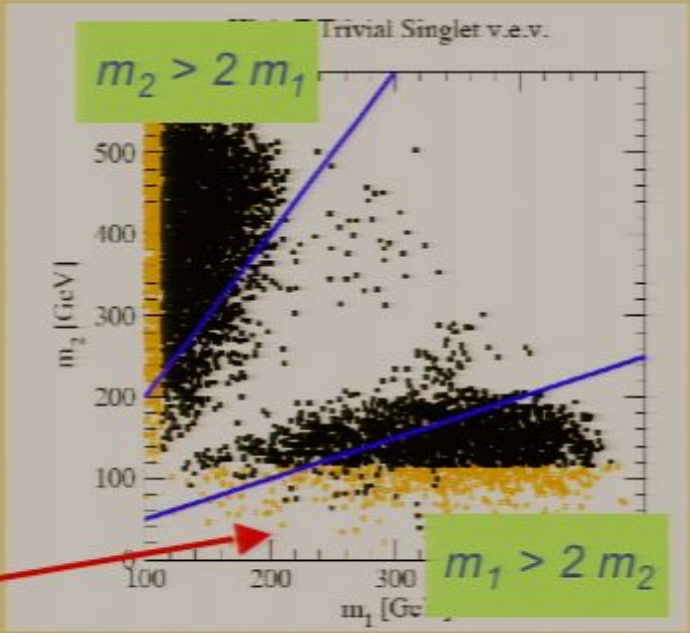

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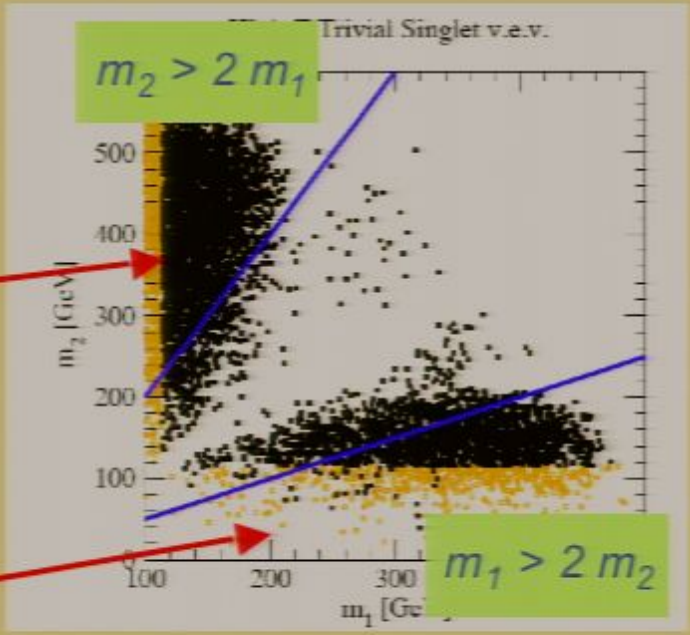
LHC Phenomenology

Signatures

LHC exotic final states: 4b-jets, γ γ + 2 b-jets…

LHC: reduced BR(h → SM)



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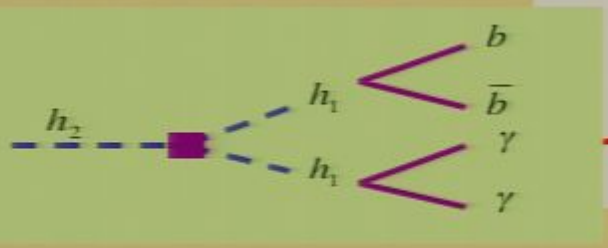

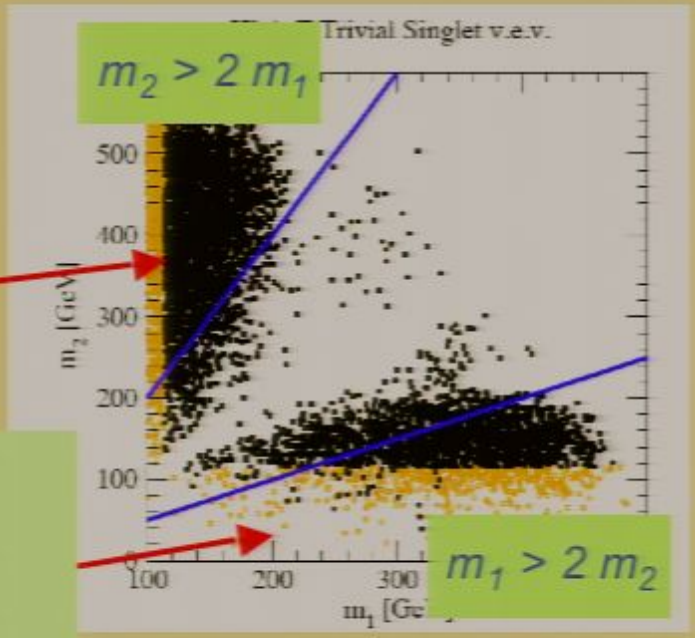

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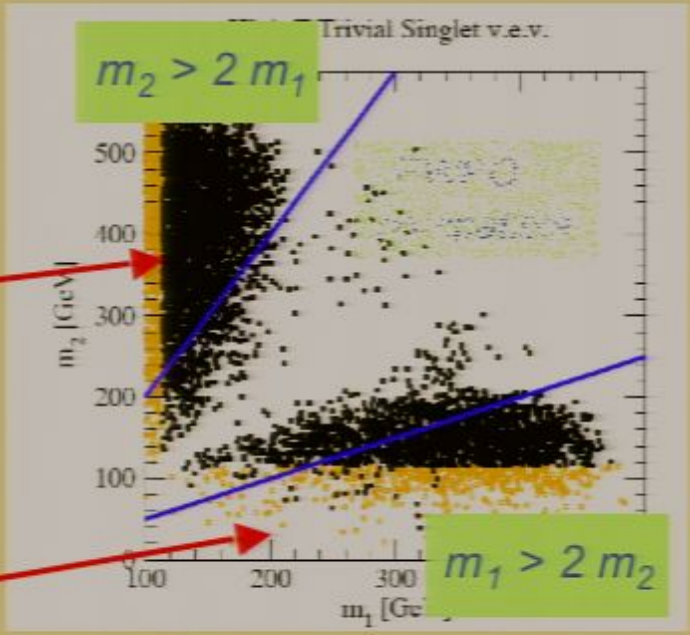

Light: all models
Black: LEP allowed

LHC Phenomenology

Signatures

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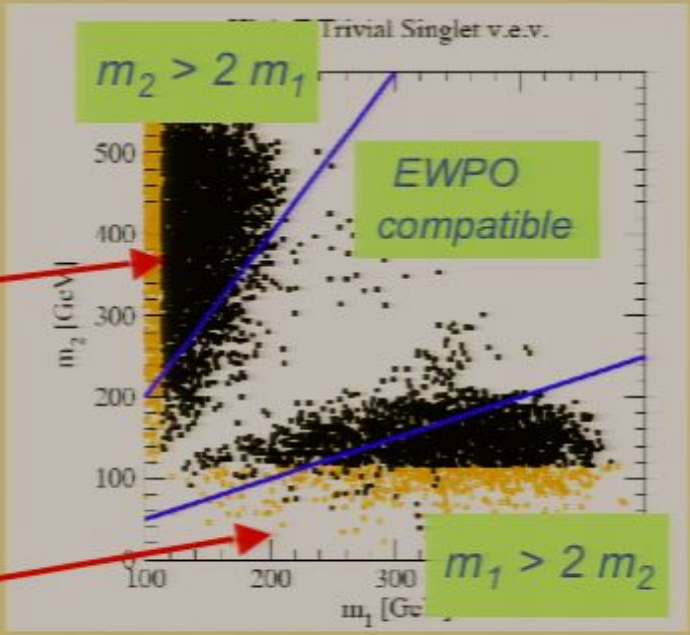

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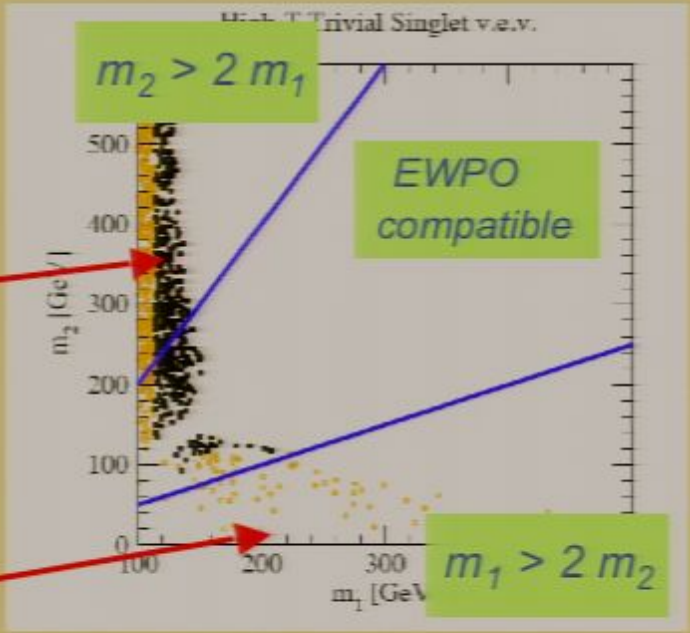

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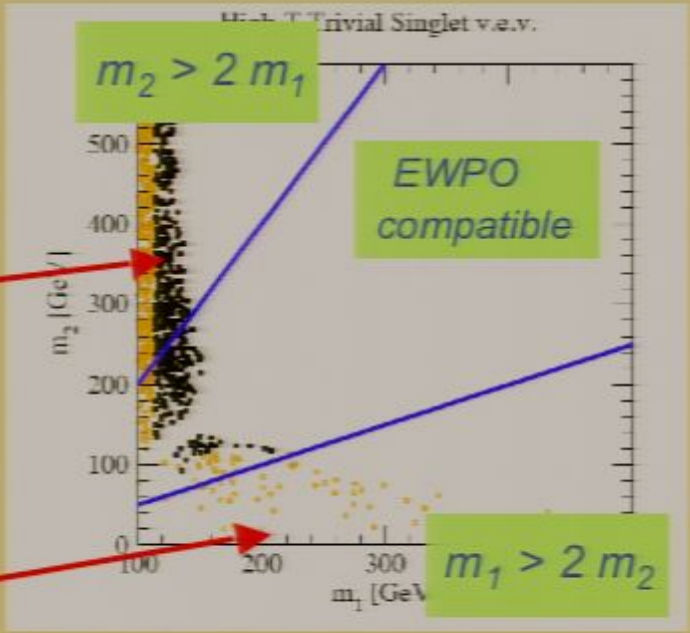

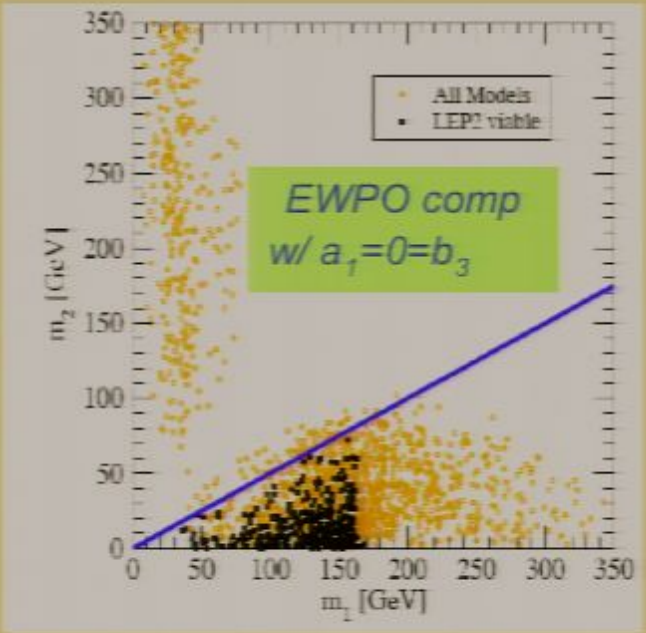

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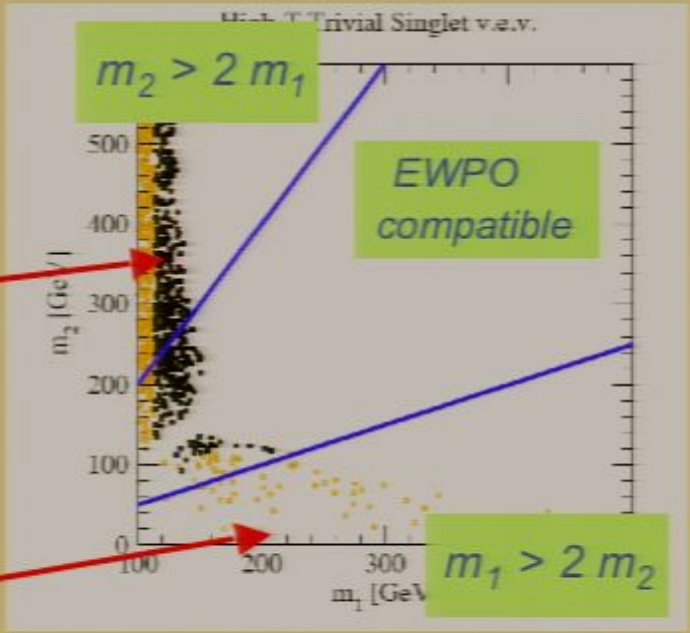

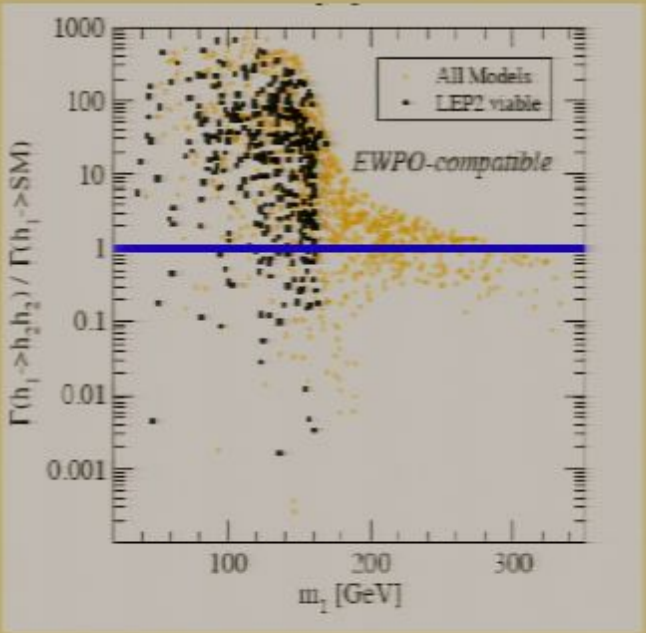

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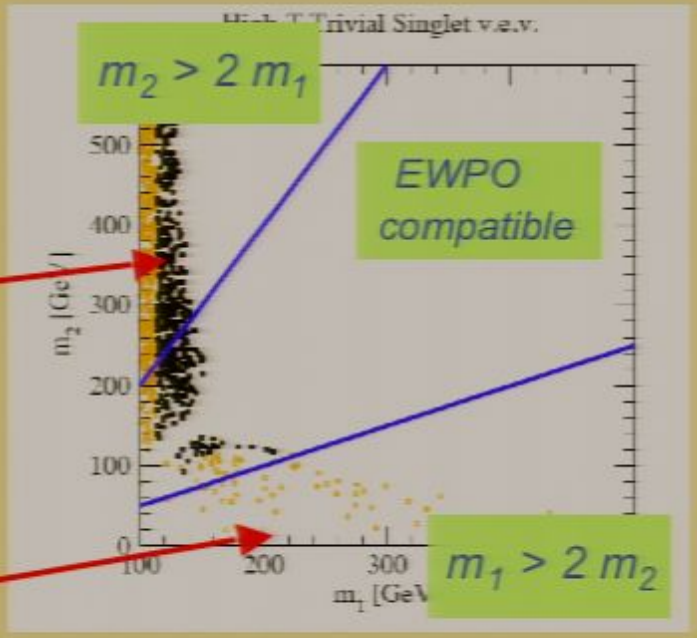

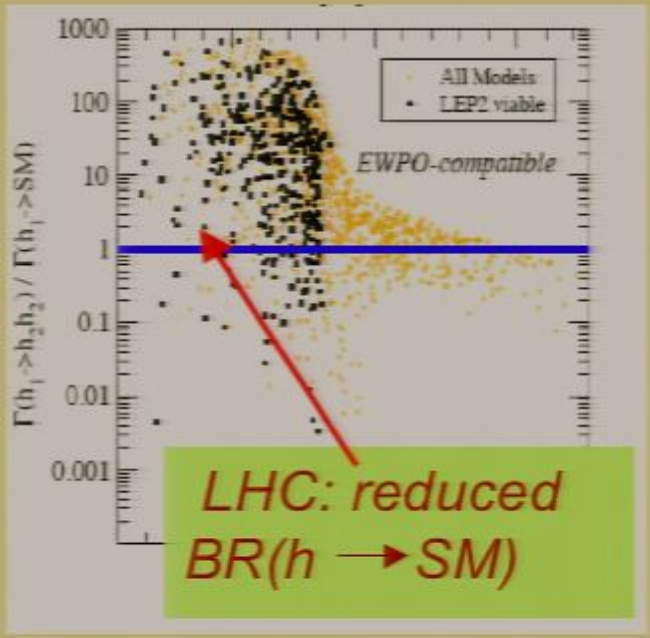

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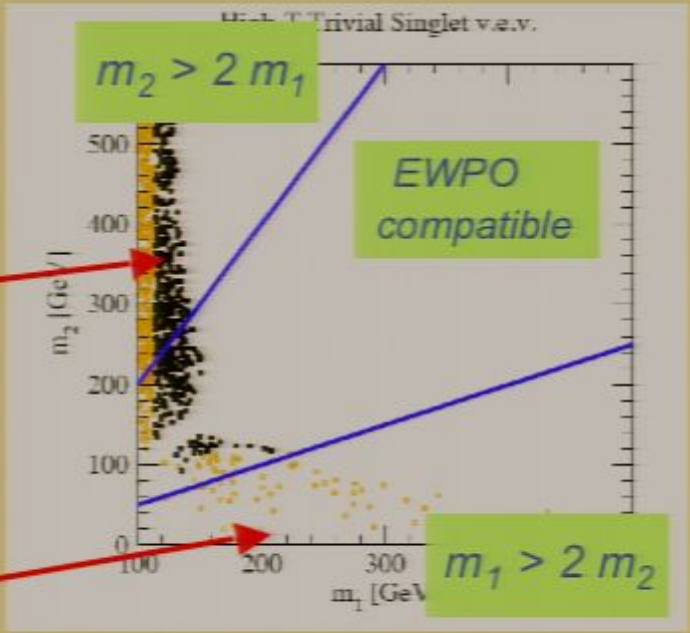

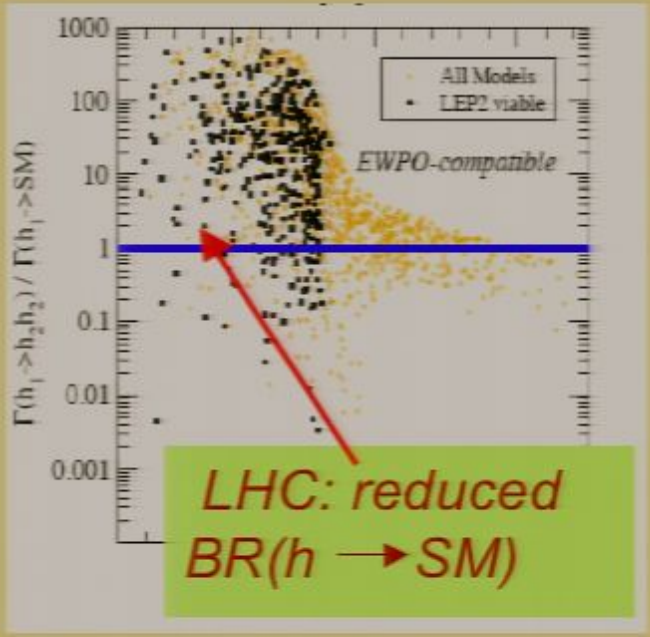

Signal Reduction Factor

$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

Production

Decay

LHC Phenomenology

Signatures

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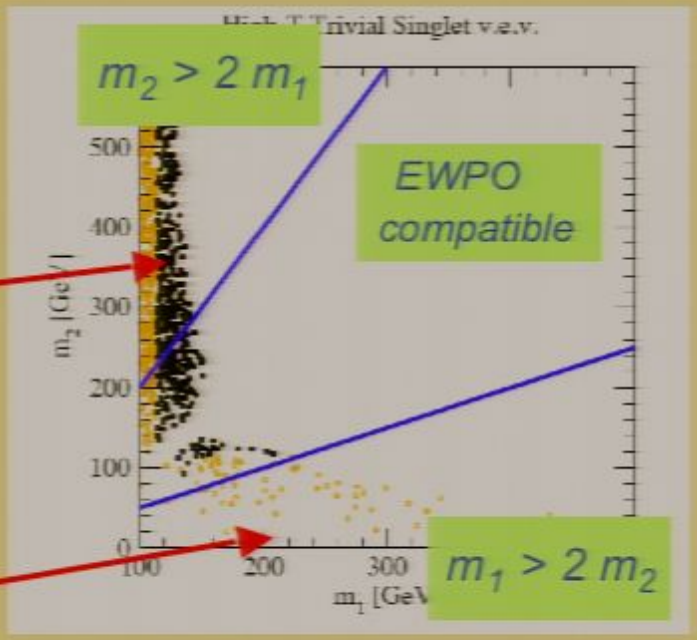

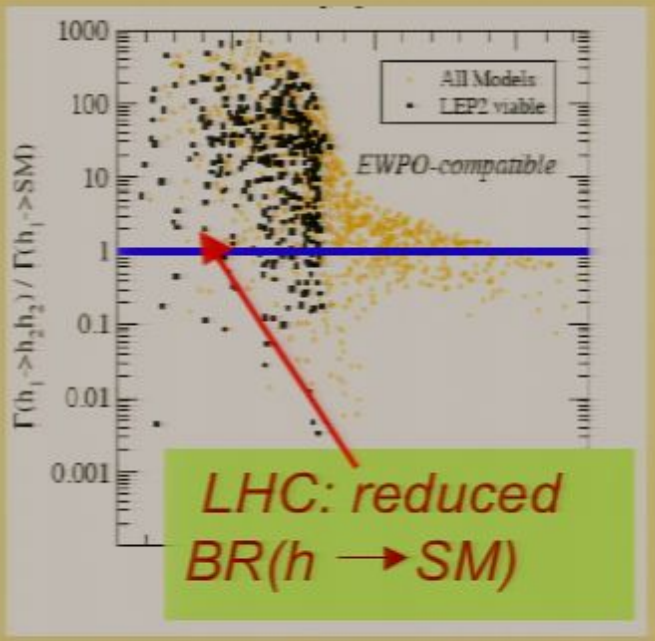

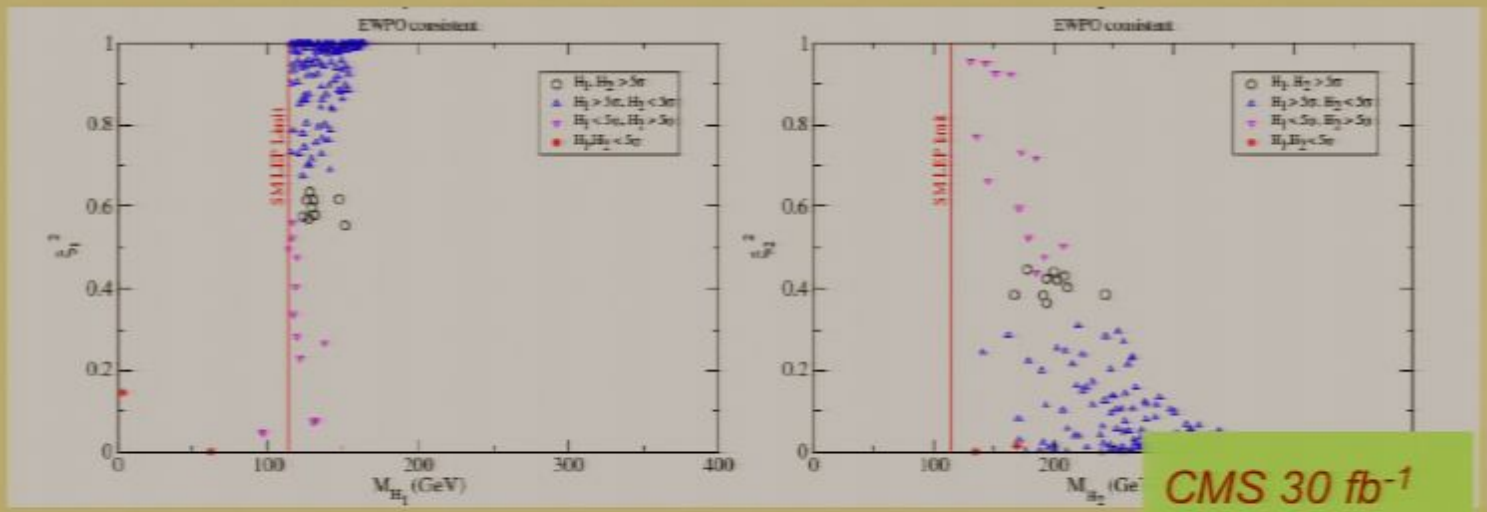

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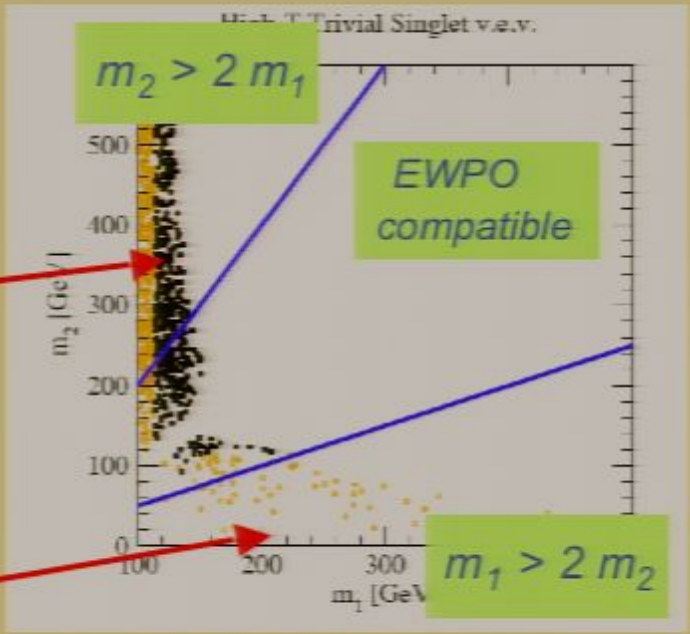
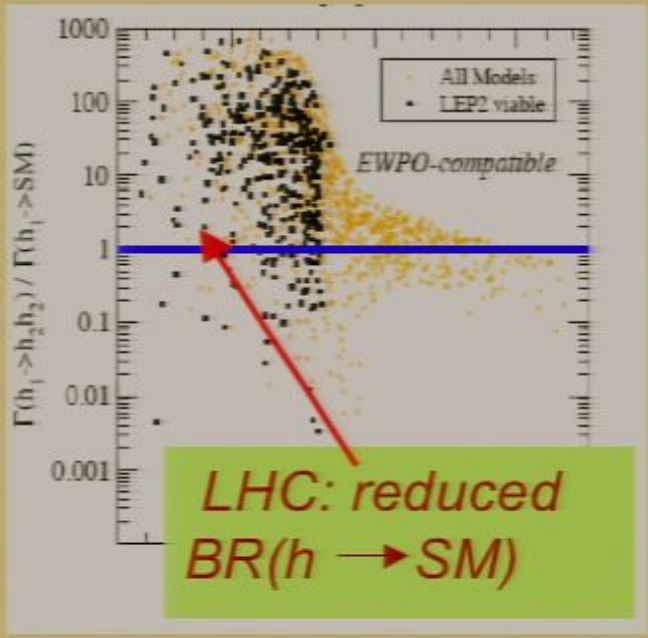
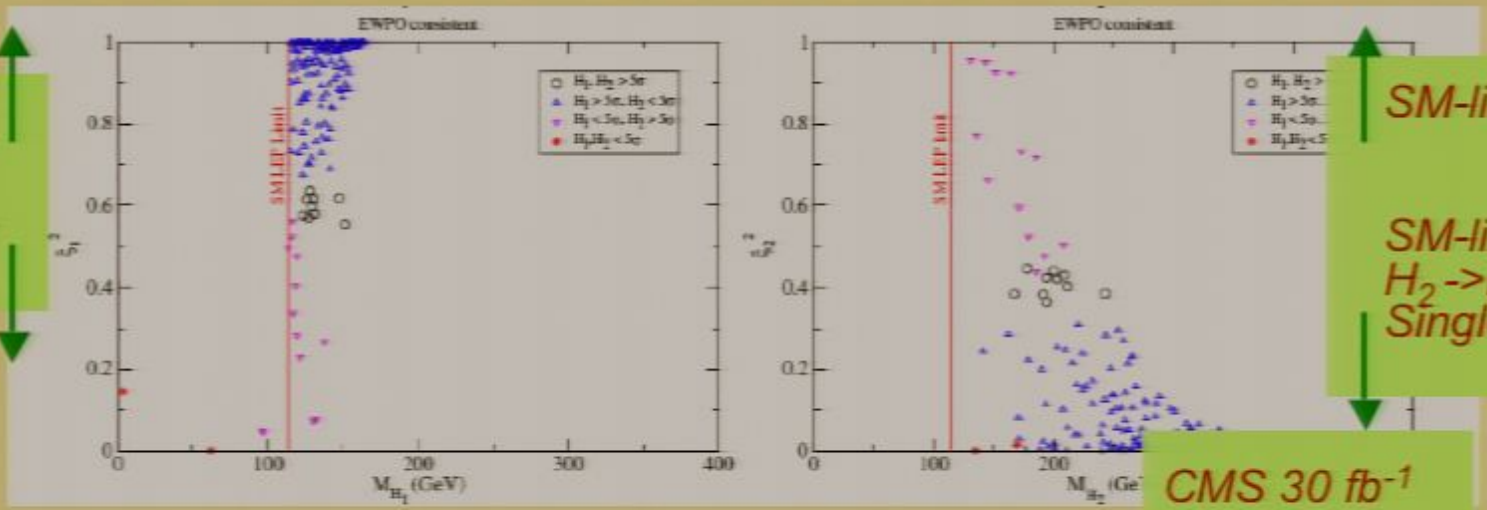




SM-like

Singlet-like



SM-like

SM-like w/ $H_2 \to H_1 H_1$ or Singlet-like

CMS 30 fb^{-1}

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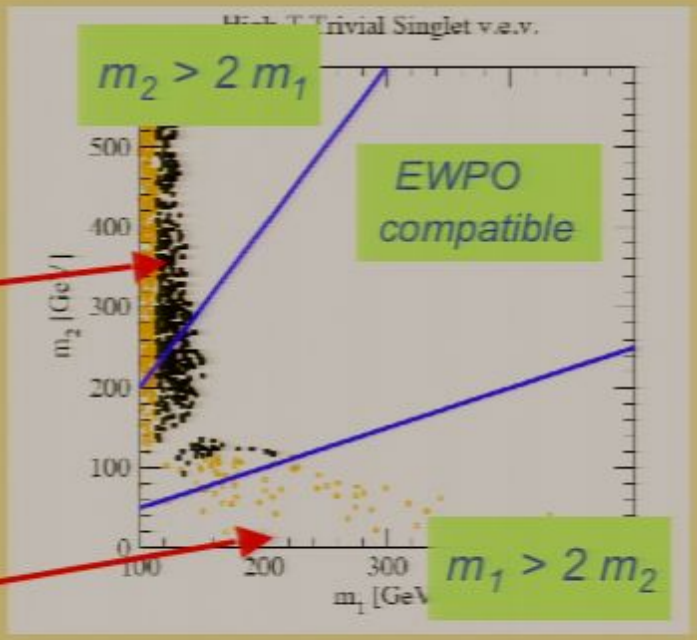
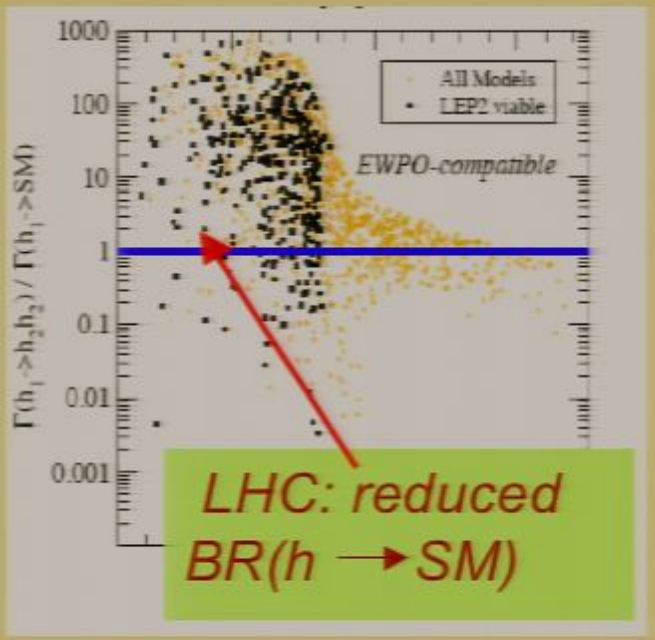
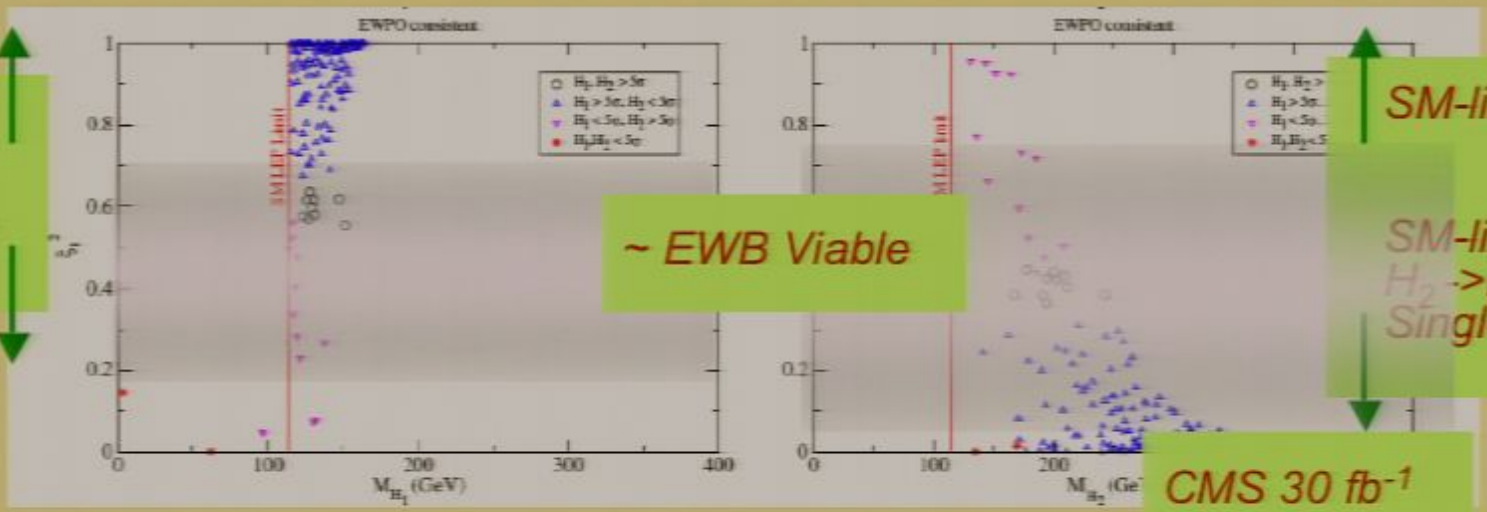




SM-like

Singlet-like



LHC Phenomenology

Signat

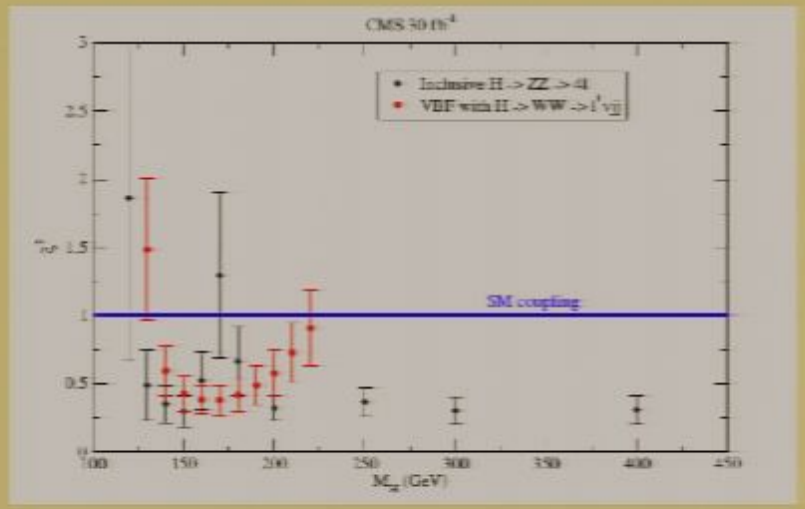
Probing ξ^2 : WBF

LHC ex
states: 4
γ + 2 b-j

$H \rightarrow ZZ \rightarrow 4 l$

$H \rightarrow WW \rightarrow 2j / \nu$

LHC: re
BR(h →



reduced
→ SM)

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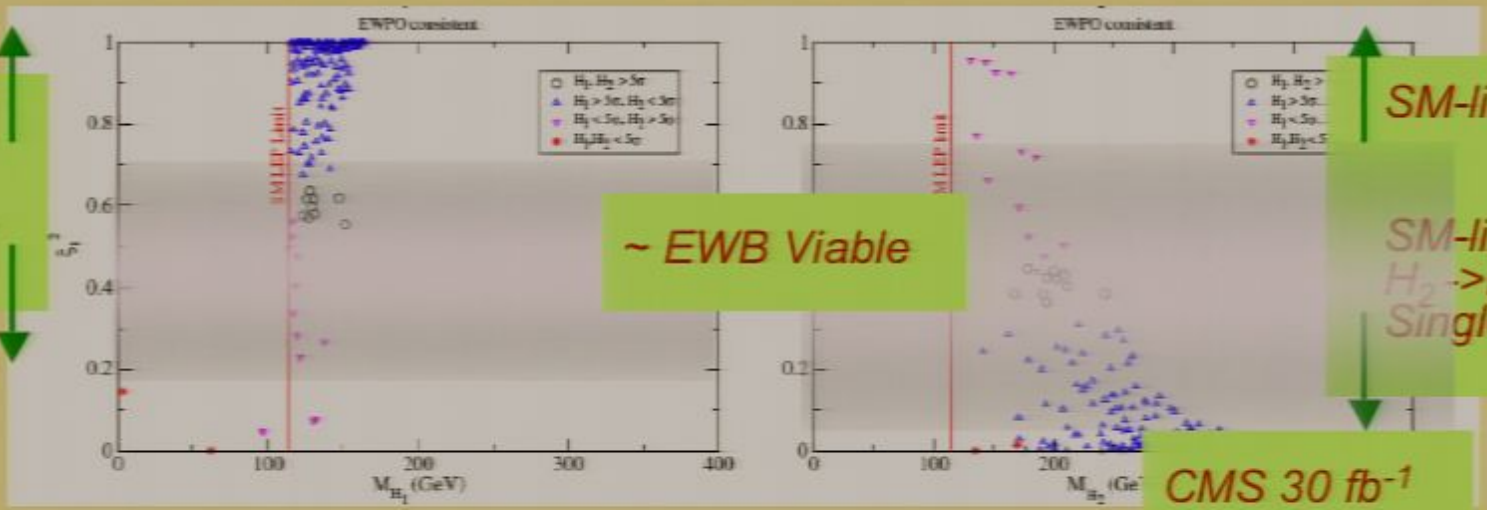

~ EWB Viable

SM-like

SM-like w/
$H_2 \rightarrow H_1 H_1$ or
Singlet-like

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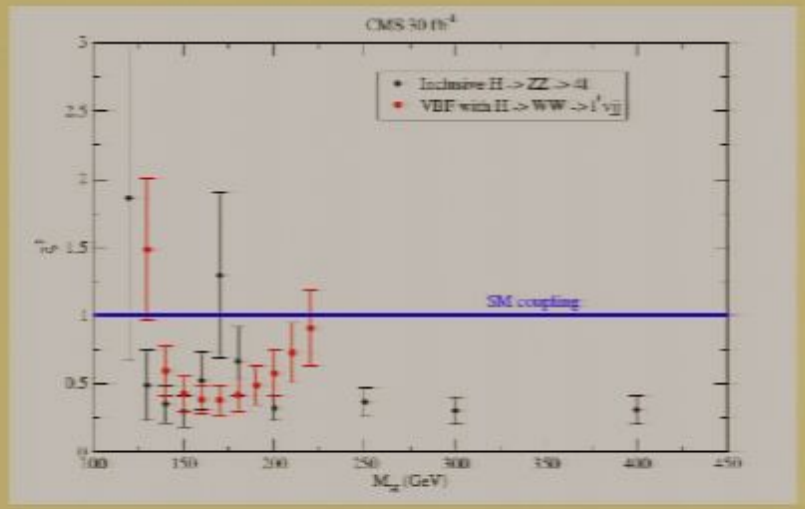
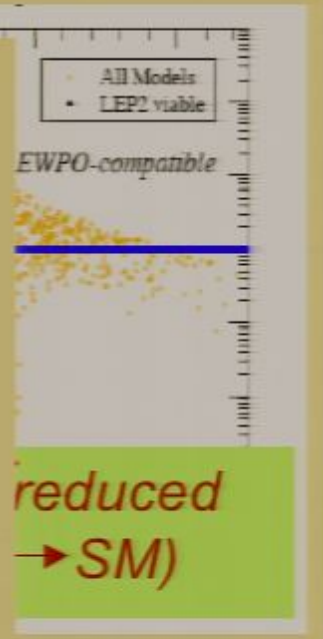


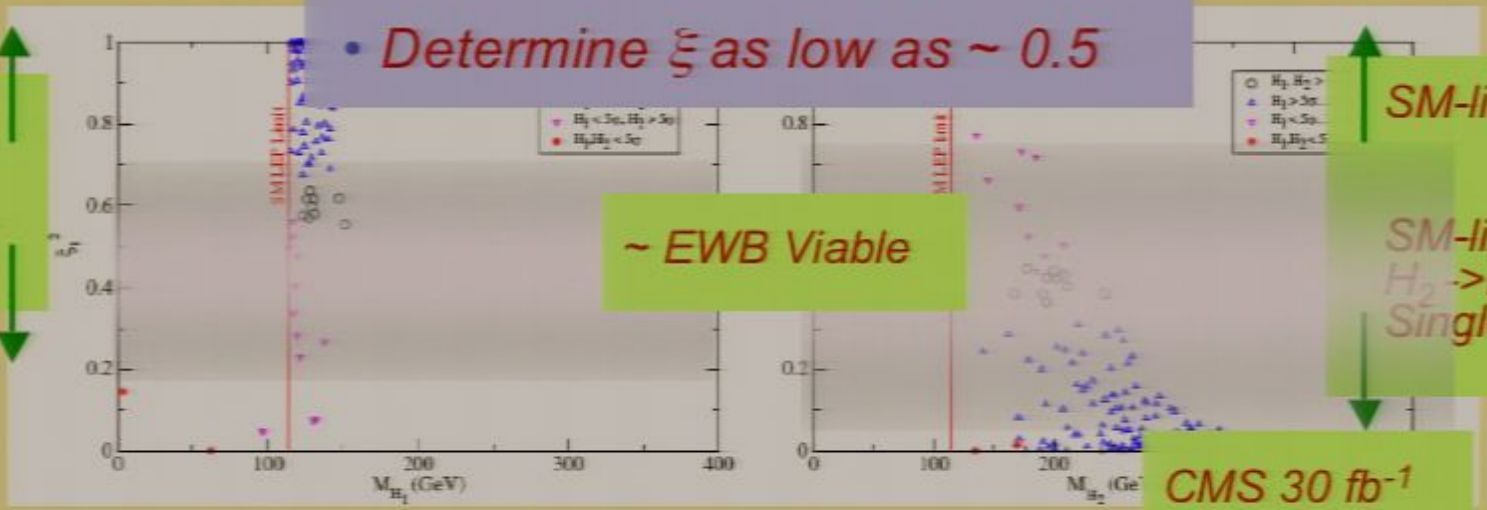


reduced
→ SM)

- Early LHC discovery possible
- Determine ξ as low as ~ 0.5

SM-like

Singlet-like



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CMS 30 fb^{-1}

Complex Singlet: EWB & DM

Barger, Langacker, McCaskey, R-M, Shaugnessy: 0811.0393 [hep-ph]

$$
\begin{aligned}
V = & \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \left(\frac{|\delta_1| e^{i\phi_{\delta_1}}}{4} H^\dagger H \mathbb{S} + c.c.\right) + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 \\
& + \left(\frac{|\delta_3| e^{i\phi_{\delta_3}}}{4} H^\dagger H \mathbb{S}^2 + h.c\right) + \left(|a_1| e^{i\phi_{a_1}} \mathbb{S} + c.c.\right) + \left(\frac{|b_1| e^{i\phi_{b_1}}}{4} \mathbb{S}^2 + c.c.\right) \\
& + \frac{b_2}{2} |\mathbb{S}|^2 + \left(\frac{|c_1| e^{i\phi_{c_1}}}{6} \mathbb{S}^3 + c.c.\right) + \left(\frac{|c_2| e^{i\phi_{c_2}}}{6} \mathbb{S} |\mathbb{S}|^2 + c.c.\right) \\
& + \left(\frac{|d_1| e^{i\phi_{d_1}}}{8} \mathbb{S}^4 + c.c.\right) + \left(\frac{|d_2| e^{i\phi_{d_2}}}{8} \mathbb{S}^2 |\mathbb{S}|^2 + c.c.\right) + \frac{d_2}{4} |\mathbb{S}|^4
\end{aligned}
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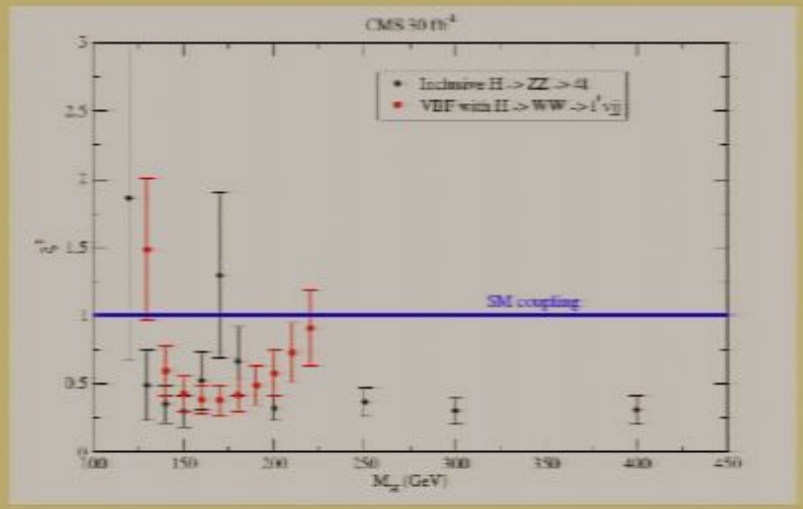

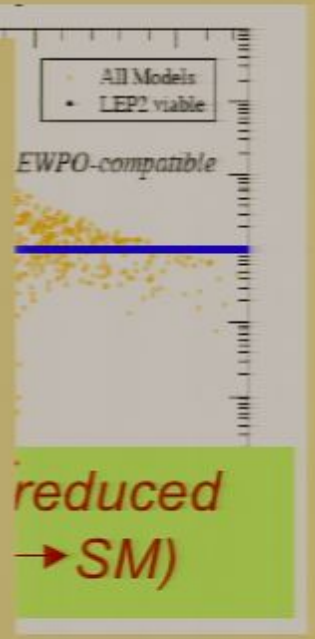

reduced
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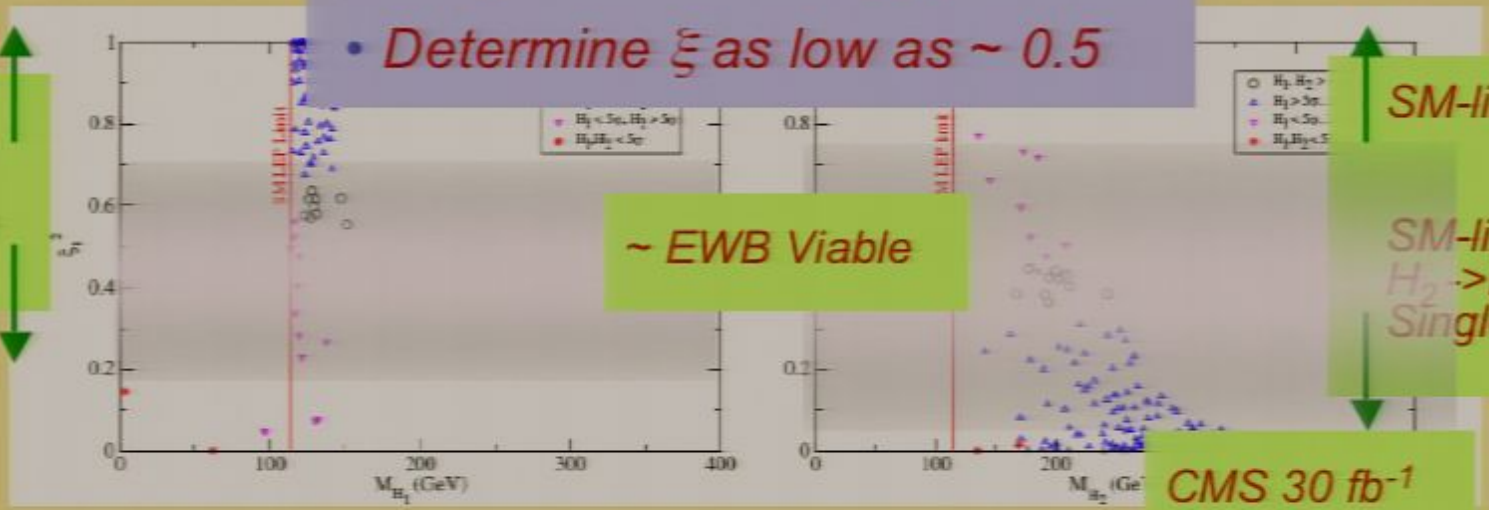
SM-like

Singlet-like



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Complex Singlet: EWB & DM

Barger, Langacker, McCaskey, R-M, Shaugnessy: 0811.0393 [hep-ph]

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\end{aligned}
$$

Key features for EWPT & DM:

(1) Softly broken global U(1)

(2) Closes under renormalization

(3) SSB leading to two fields: S that mixes w/ h and A is stable (DM)

Complex Singlet: EWB & DM

Barger, Langacker, McCaskey, R-M, Shaugnessy: 0811.0393 [hep-ph]

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DM mass

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No domain walls

DM mass

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Barger, Langacker, McCaskey, R-M, Shaugnessy: 0811.0393 [hep-ph]

Controls Ω_{CDM} & EWPT

$$M^2_{\text{scalar}} = \begin{pmatrix} \lambda v^2/2 & \delta_2 v v_S/2 & 0 \\ \delta_2 v v_S/2 & d_2 v_S^2/2 + \sqrt{2}|a_1|/v_S & 0 \\ 0 & 0 & |b_1| + \sqrt{2}|a_1|/v_S \end{pmatrix}$$

Key features for EWPT & DM:

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Complex Singlet: EWB & DM

Barger, Langacker, McCaskey, R-M, Shaugnessy: 0811.0393 [hep-ph]

Controls Ω_{CDM} & EWPT

No CPV for $T < T_{EW}$: Stable A

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Barger, Langacker, McCaskey, R-M, Shaugnessy: 0811.0393 [hep-ph]

Controls Ω_{CDM} & EWPT

$$V = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|\mathbb{S}|^2 + \left(|a_1|e^{i\varphi_{a_1}}\mathbb{S} + c.c.\right) + \left(\frac{|b_1|e^{i\varphi_{b_1}}}{4}\mathbb{S}^2 + c.c.\right) + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4$$

No domain walls

DM mass

Key features for EWPT & DM:

(1) Softly broken global U(1)

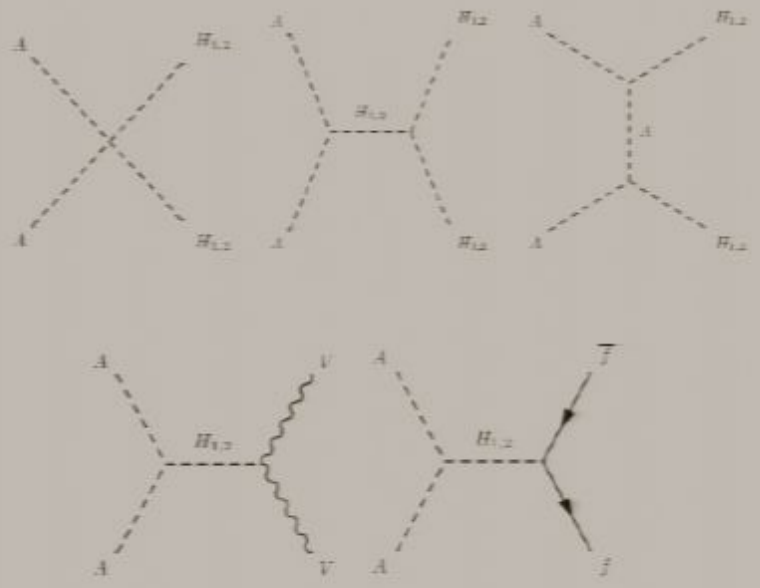
(2) Closes under renormalization

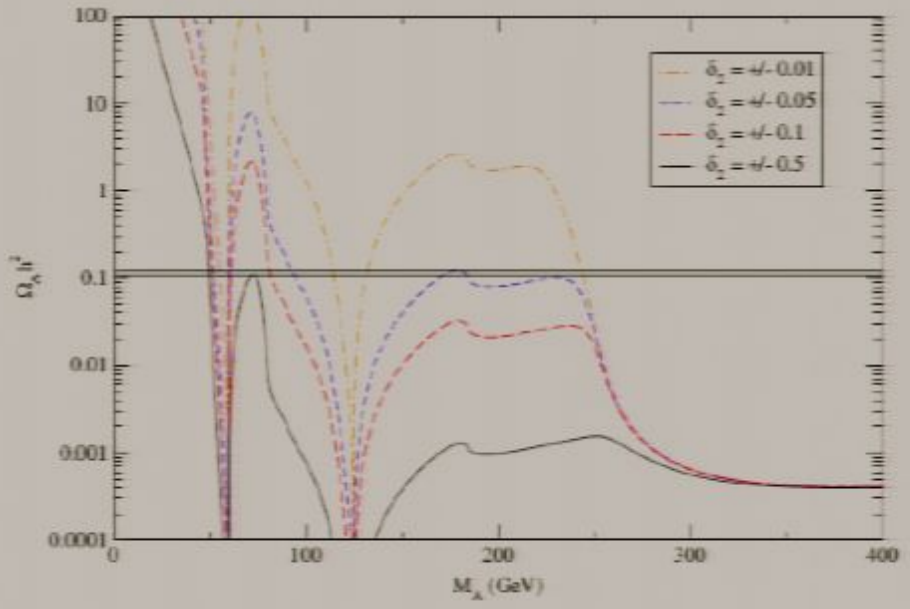
(3) SSB leading to two fields: S that mixes w/ h and A is stable (DM)

Complex Singlet: EWB & DM

Barger, Langacker, McCaskey, R-M, Shaugnessy

δ_2 controls Ω_{CDM} & EWPT



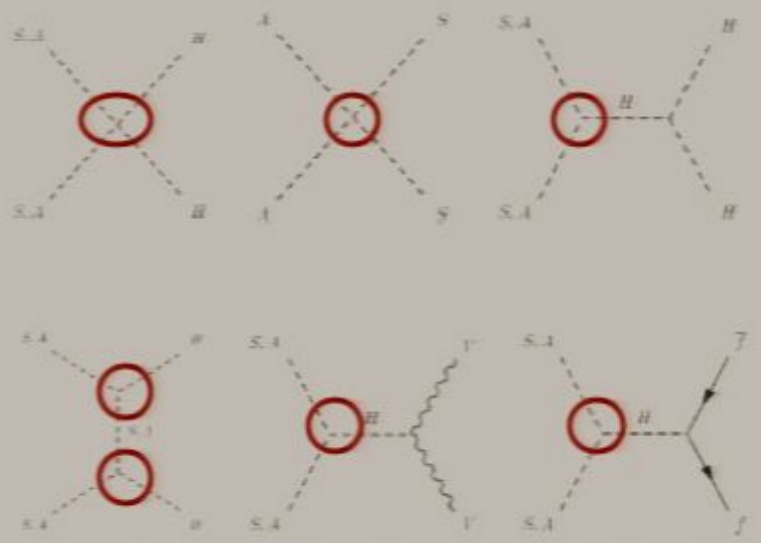


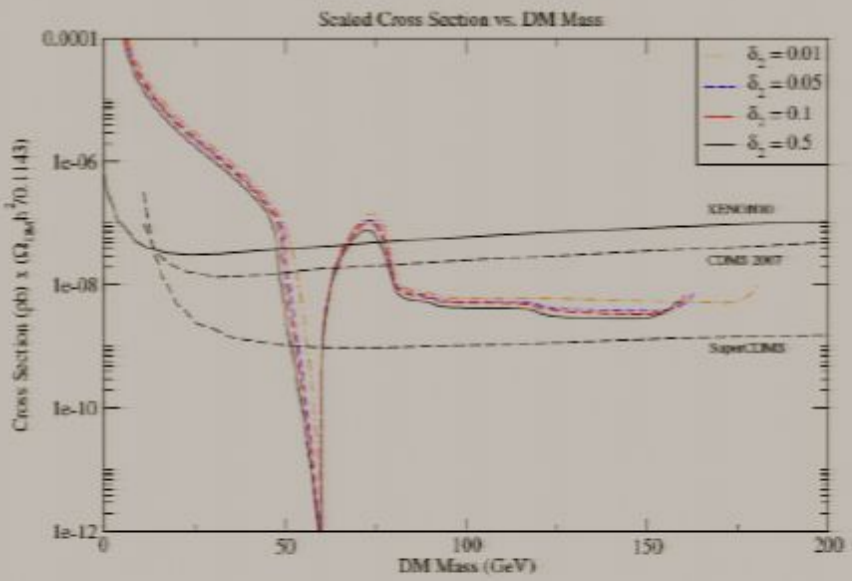
M_{H1} = 120 GeV, M_{H2}=250 GeV, x_0=100 GeV

Complex Singlet: Direct Detection

Barger, Langacker, McCaskey, R-M, Shaugnessy

Two component case (x_0=0)





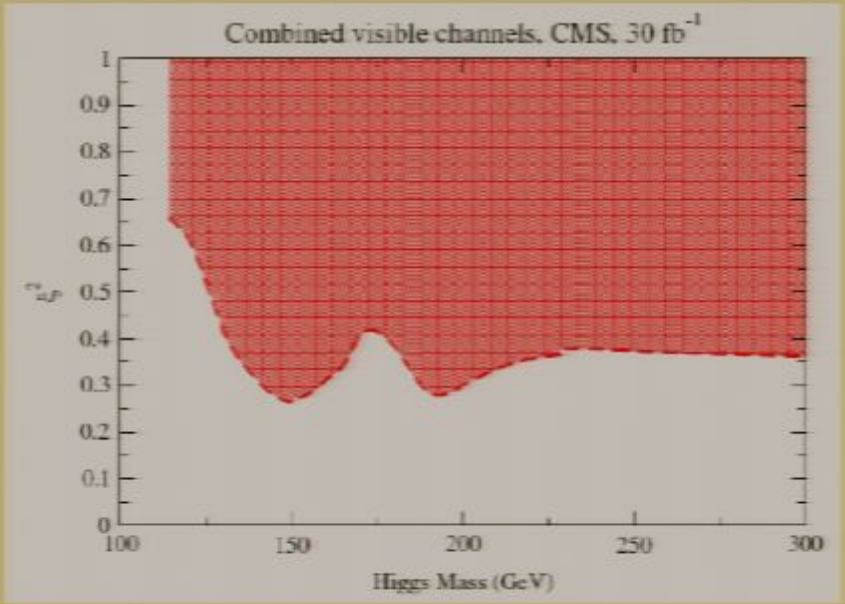
Little sensitivity of scaled σ_{SI} to δ_2

Complex Singlet: LHC Discovery

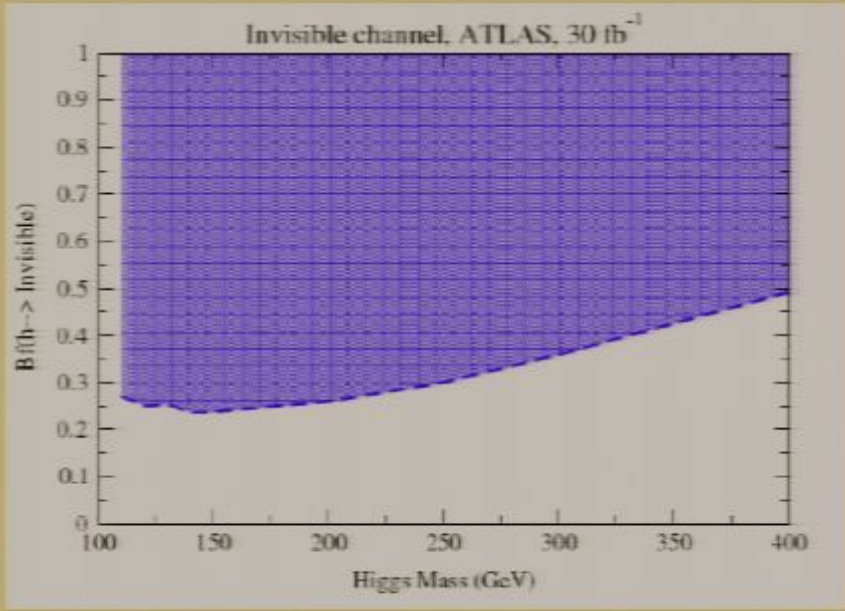
Barger, Langacker, McCaskey, R-M, Shaugnessy

Single component case ($x_0 \neq 0$)

Traditional search: CMS



Invisible search: ATLAS



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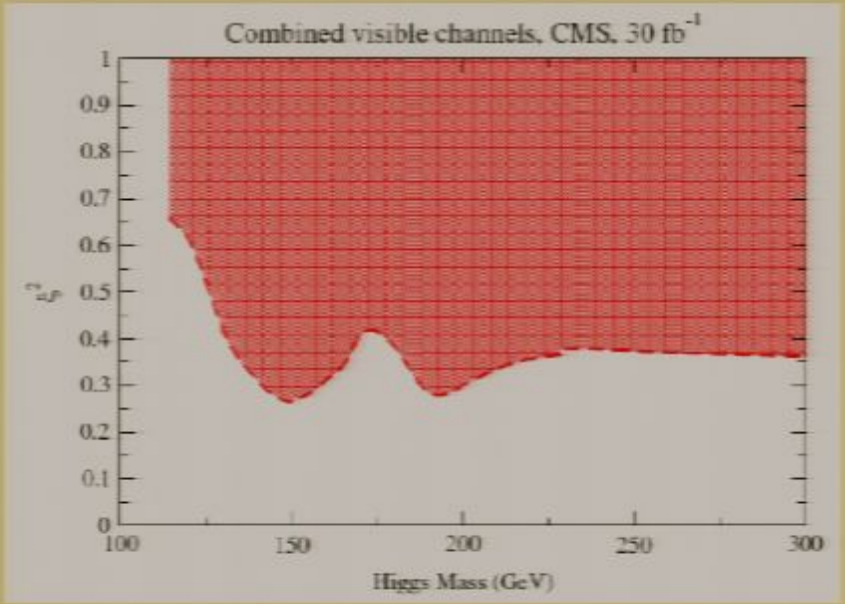
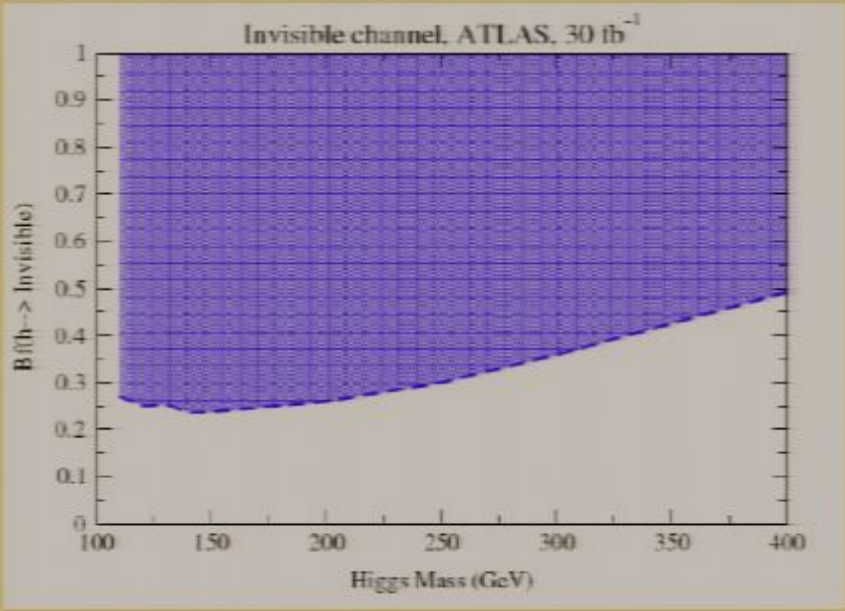
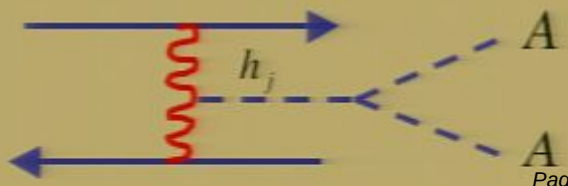


Invisible search: ATLAS

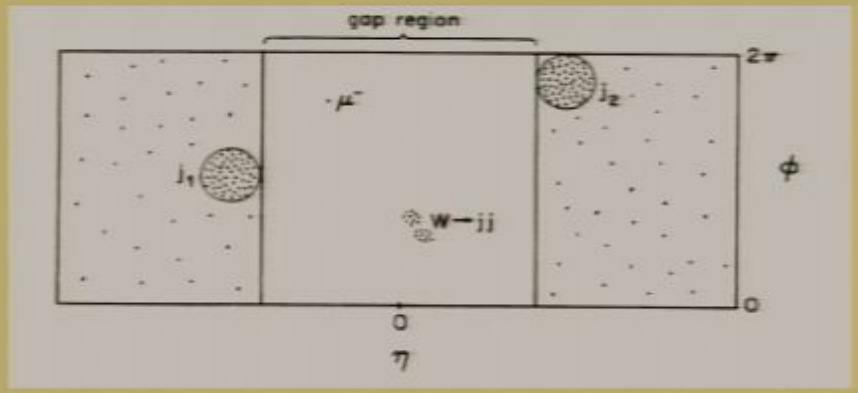


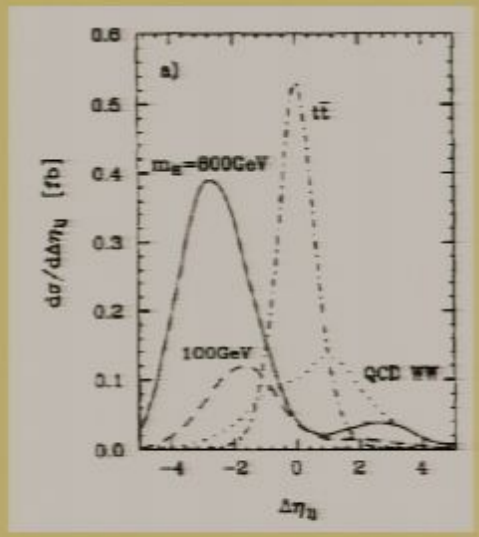


VBF: Invisible Search I

$$\eta = \ln \cot \frac{\theta}{2}$$

Central Jet Veto





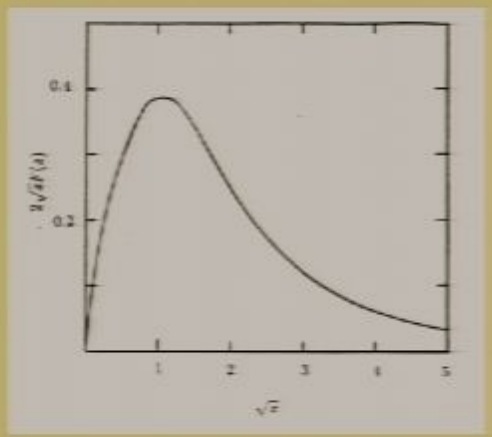
$H \to W^+W^- \to \mu\nu jj$: ideally only W decay products in central region (Chehime & Zeppenfeld '93)

$H \to W^+W^- \to \ell^+\ell^-\nu\nu$: central region minijet from SM bcknd, η separation from dilepton pair (Barger, Phillips, Zeppenfeld '94)

VBF: Invisible Search II

$$\eta = \ln \cot \frac{\theta}{2}$$

$p_T(H)$ distribution

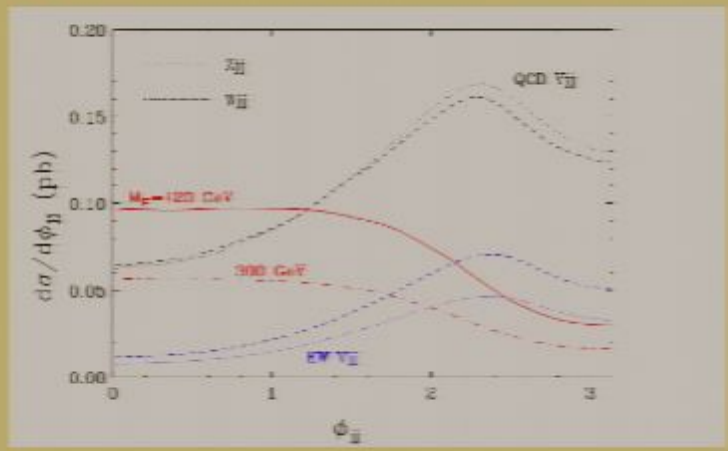


Cahn et al '87

$$z = \frac{p_T^2}{\langle x \rangle M_W^2}$$

Large $\not{p}_T$ (invisible decay)

Dijet azimuthal distribution



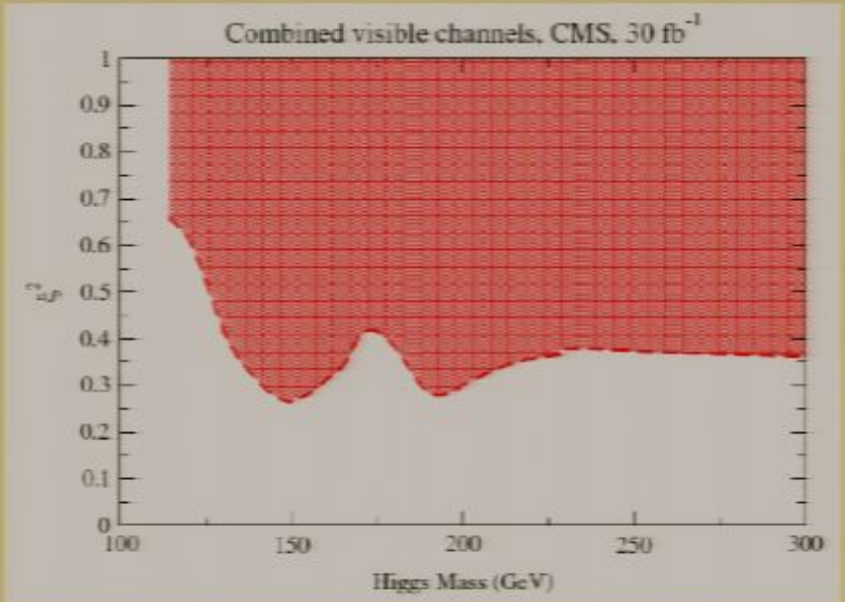
Look for azimuthal shape change of primary jets (Eboli & Zeppenfeld '00)

Complex Singlet: LHC Discovery

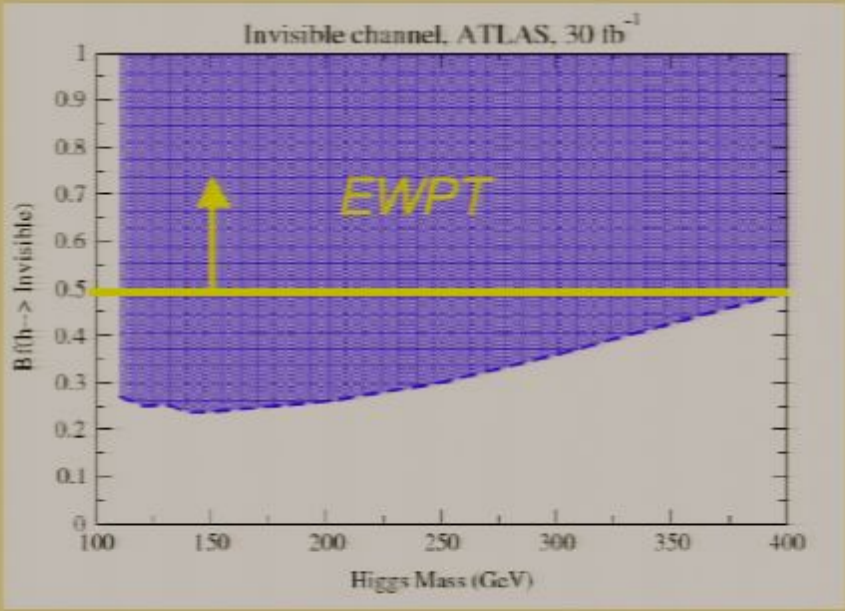
Barger, Langacker, McCaskey, R-M, Shaugnessy

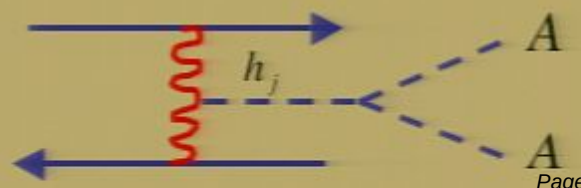
Single component case ($x_0 \neq 0$)

Traditional search: CMS



Invisible search: ATLAS





Real Triplet

$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

Fileviez-Perez, Patel, Wang,
R-M: 0811.3957 [hep-ph]

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$$V(H,\Sigma) = -\mu^2\, H^\dagger H + \lambda_0 \left(H^\dagger H\right)^2 - \frac{1}{2} M^2 F + \frac{b_4}{4} F^2 - a_1\, H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H F$$

$$F \equiv \left(\Sigma^0\right)^2 + 2\Sigma^+\Sigma^-$$

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H-Σ Mixing

$H_1 \rightarrow H_2 H_2$

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$$\langle \Sigma^0 \rangle = x_0$$

Independent Parameters:

$v_0, x_0, \lambda_0, a_1, a_2, b_4$

Real Triplet : Key Features

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Small $x_0(T=0)$: Small mixing & EWPO impact

"Fermiophobic"

1st order EWPT ?

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Four scalars : H_1 ~ SM-like; H_2 ~ triplet-like; H^+, H^-

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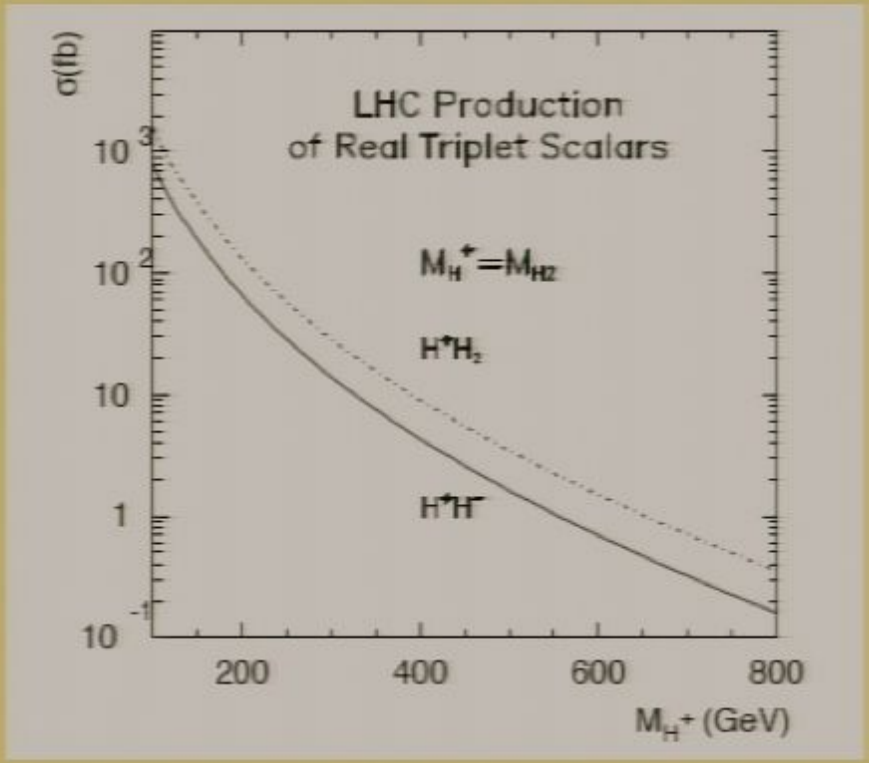
Couplings & 2γ BRs

$H_1H^+H^-$ & $H_2W^+W^-$: Strong a_2-dependence $\to$
Sensitivity of BR($H_j \to \gamma\gamma$)

Real Triplet : Production

Pair production dominant $q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \quad q\bar{q} \to Z^*, \gamma^* \to H^+ H^-$

Assoc production θ_0, θ_+ suppressed



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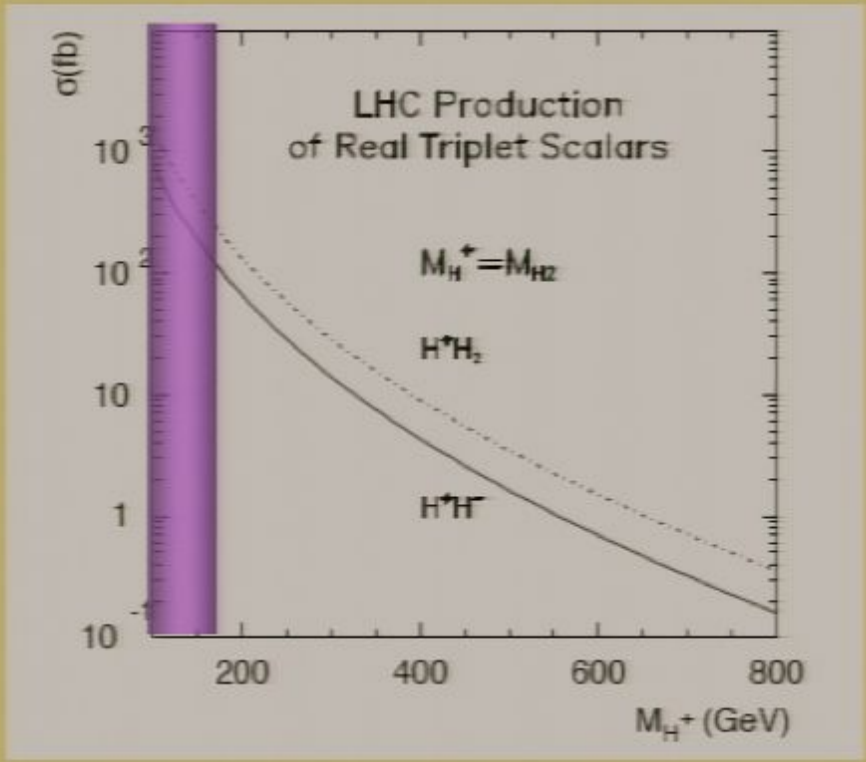

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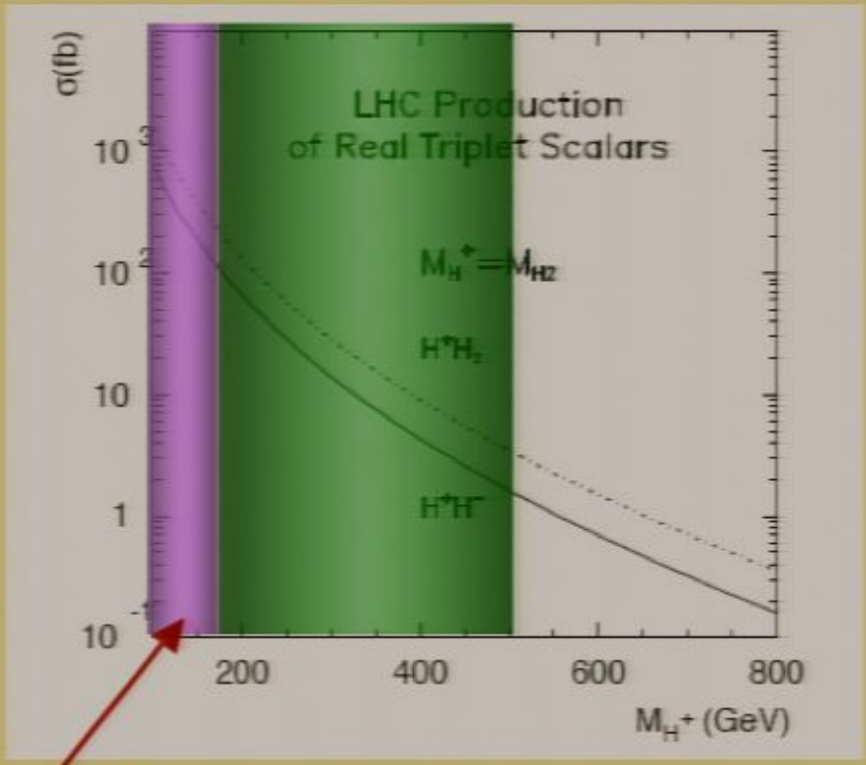

Below WZ Threshold

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Assoc production θ_0, θ_+ suppressed

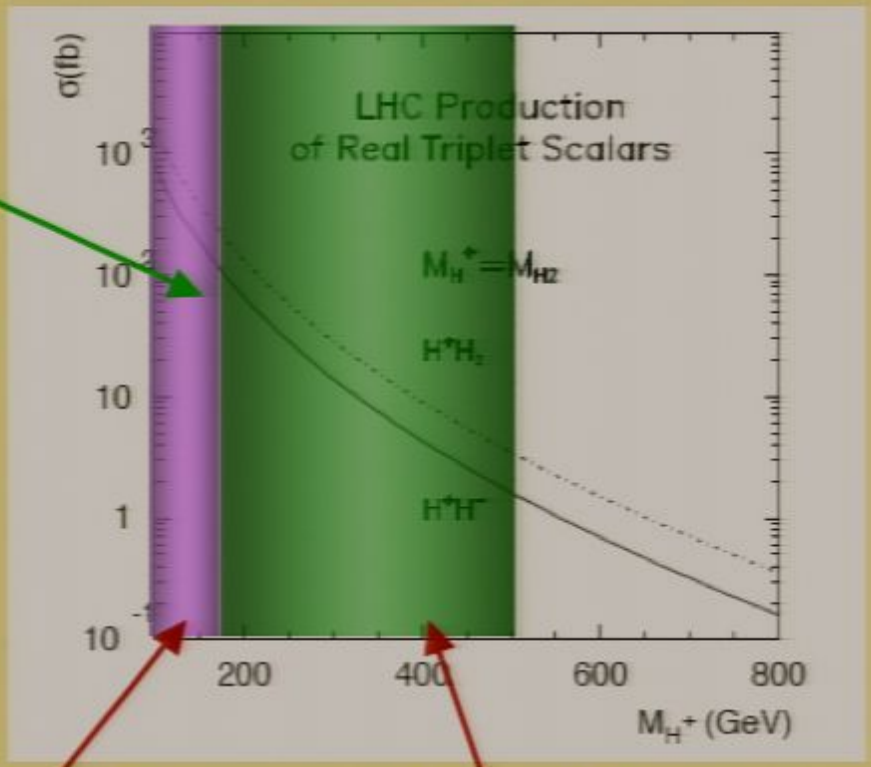
Promising for LHC

$b\bar{b}\gamma\gamma$

$\tau\nu\gamma\gamma$

$\tau\nu b\bar{b}$

$\tau \to \ell\nu, \pi\nu$



Below WZ Threshold

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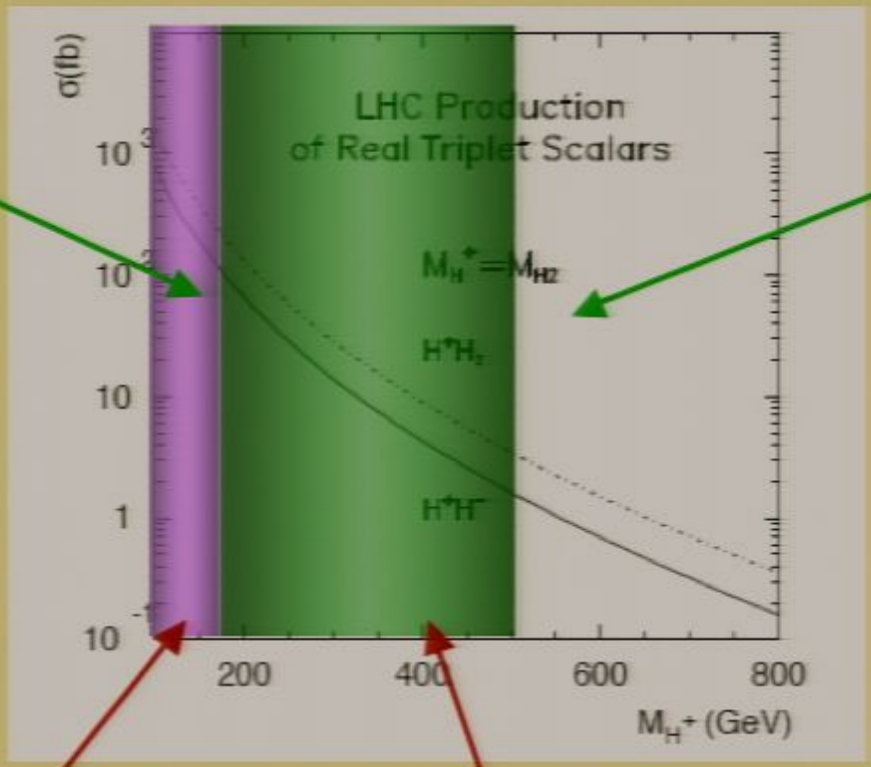


Promising for ILC

W^+W^-ZZ

$W^+Z\,\bar{t}b$

$H_2\pi^+\,\bar{t}b$

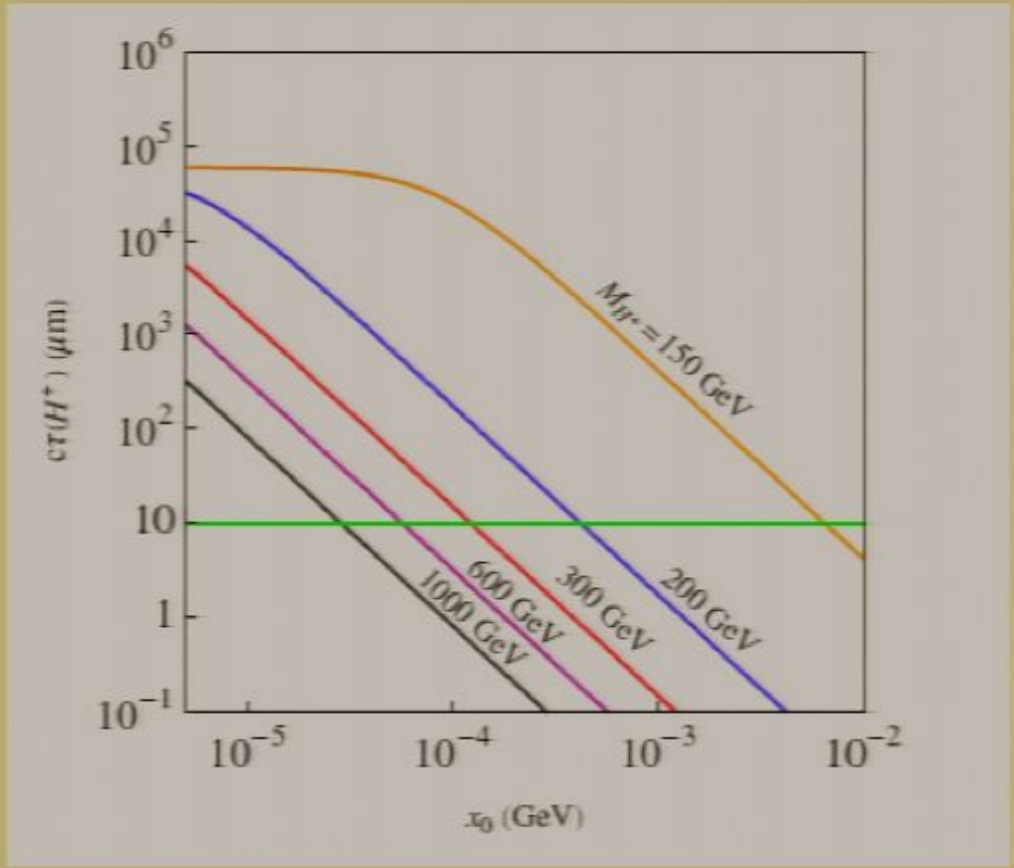
$H_2\pi^+\,W^-Z$

Below WZ Threshold

Above WZ Threshold

Real Triplet : H^+ Decays

Charged: decay length



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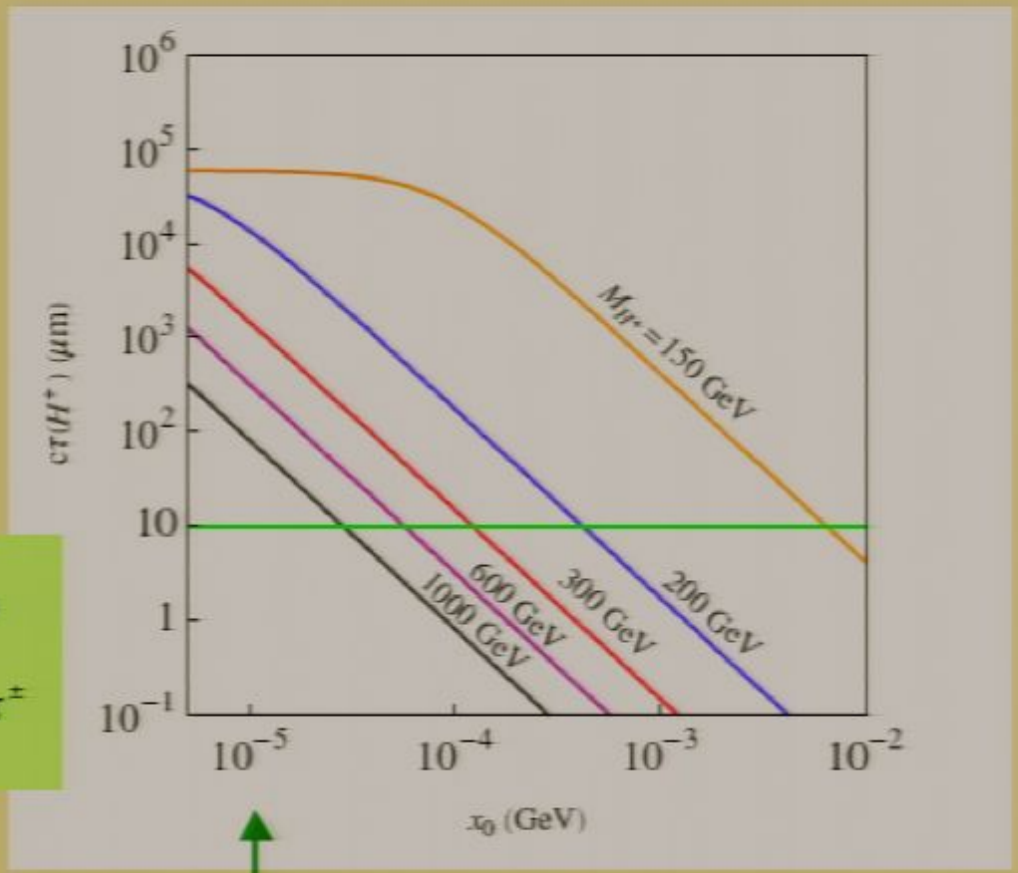


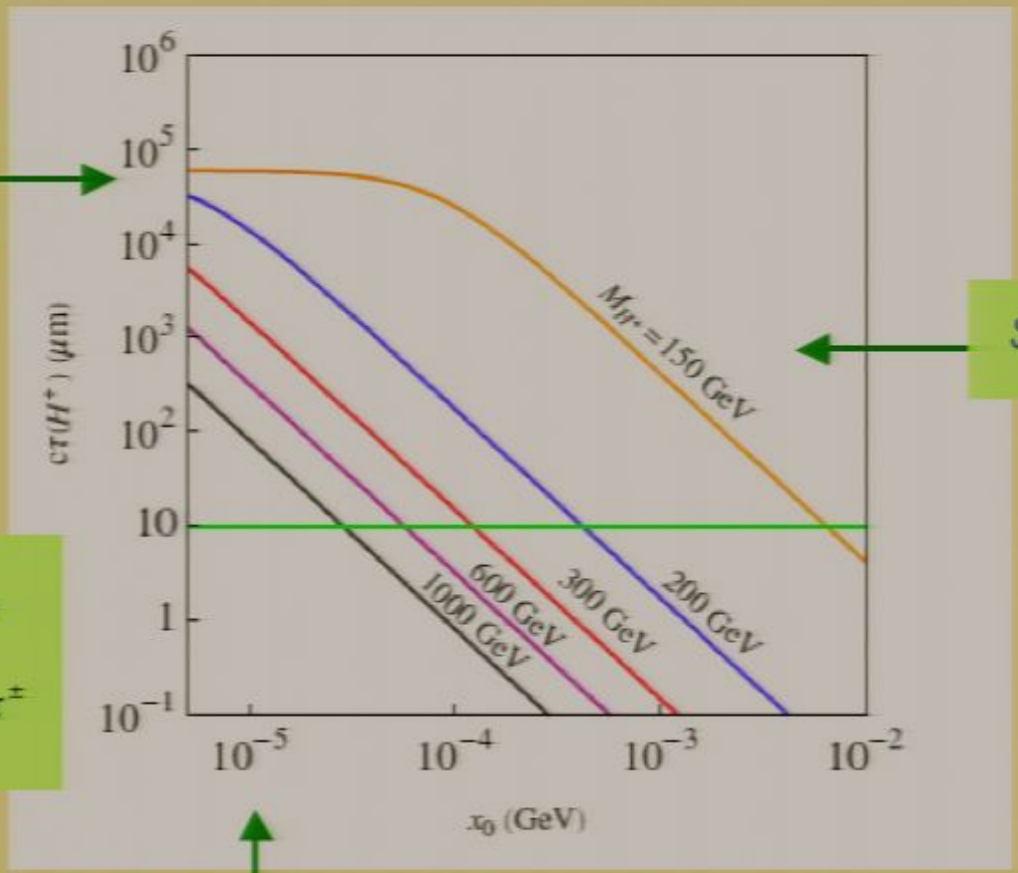
Tiny x_0 : pure gauge

$$H^{\pm} \to H_2 W^{\pm *} \to H_2 \pi^{\pm}$$

Real Triplet : H^+ Decays

Charged: decay length

DM Limit: x_0=0 & $c\tau$ = 5.06 cm



Secondary vertex

Tiny x_0 : pure gauge

$H^{\pm} \rightarrow H_2 W^{\pm *} \rightarrow H_2 \pi^{\pm}$

Real Triplet : DM Search

Basic signature:

$x_0 = 0 : H^{\pm} \to H_2 \pi^{\pm}$

Charged track disappearing after ~ 5 cm

$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \quad q\bar{q} \to Z^*, \gamma^* \to H^+ H^-$

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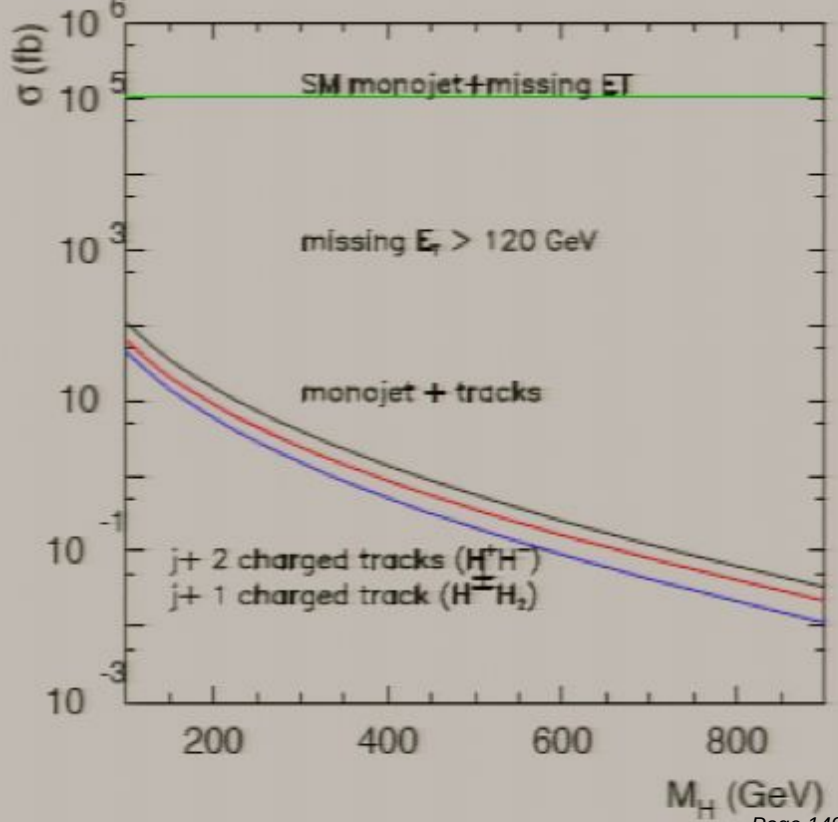
Trigger: Monojet (ISR) + large $\not{E}_T$



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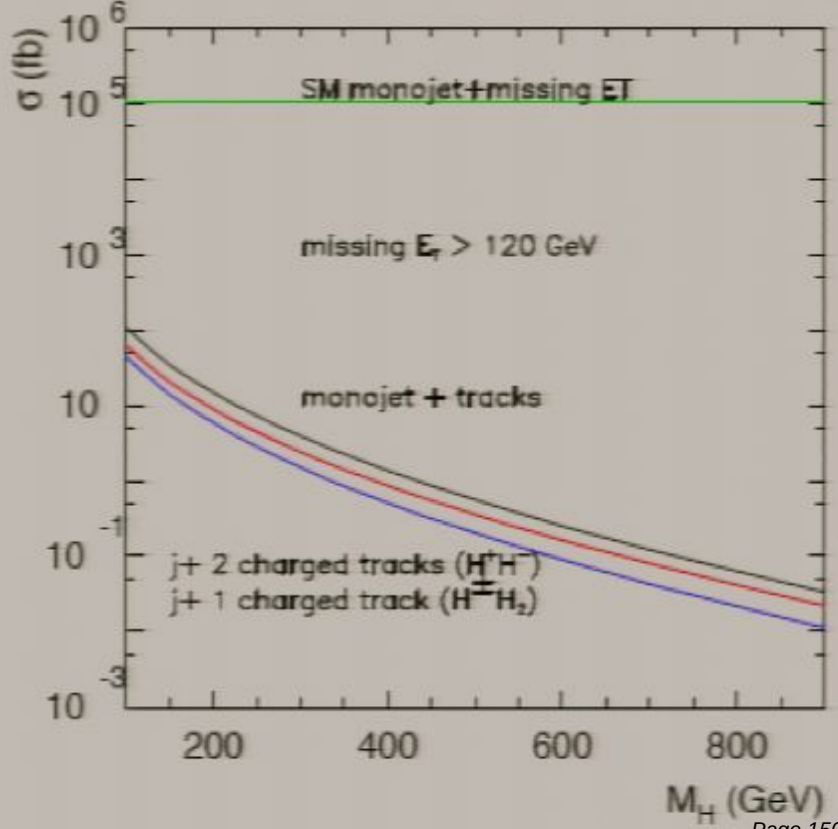
SM Background: QCD jZ and jW w/ $Z \to \nu\nu$ & $W \to l\nu$



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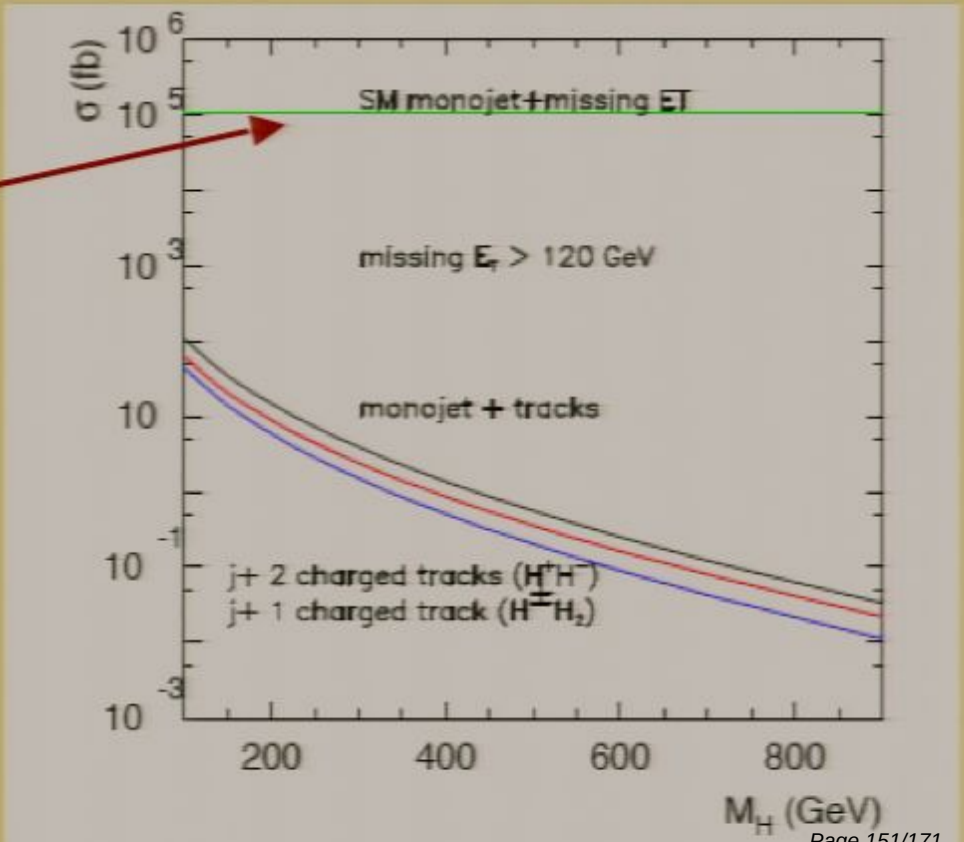
Cuts: ***large $\not{E}_T$***
hard jet
One 5cm track



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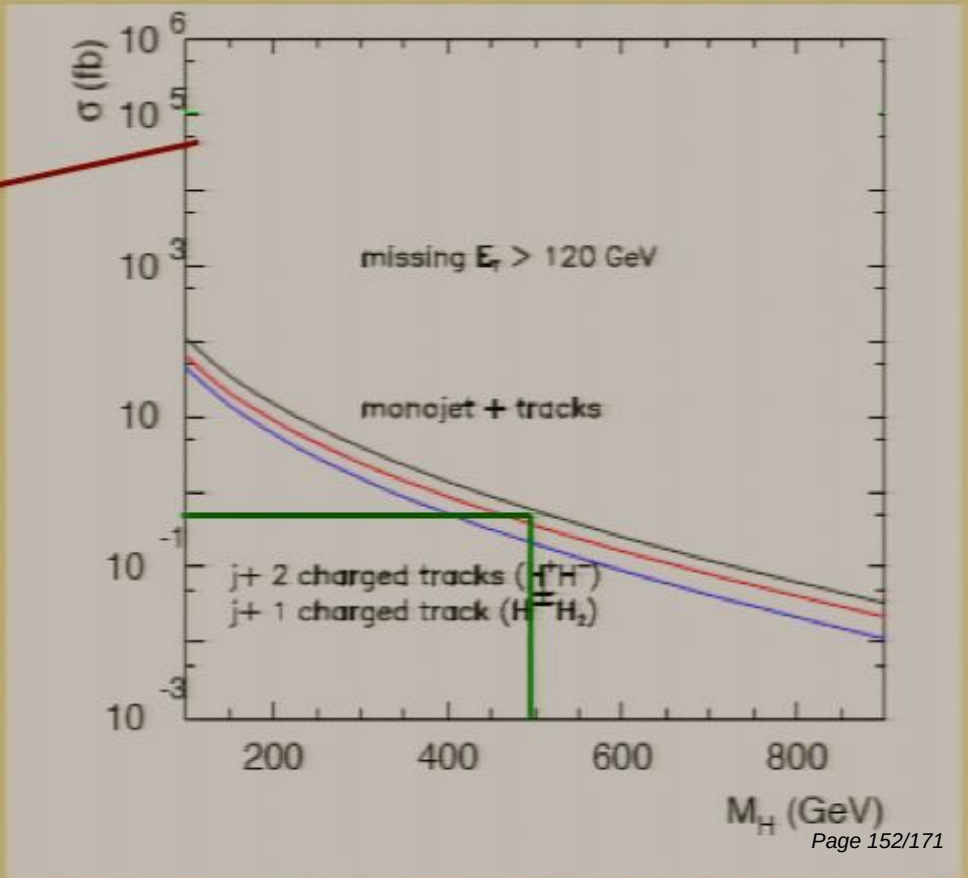

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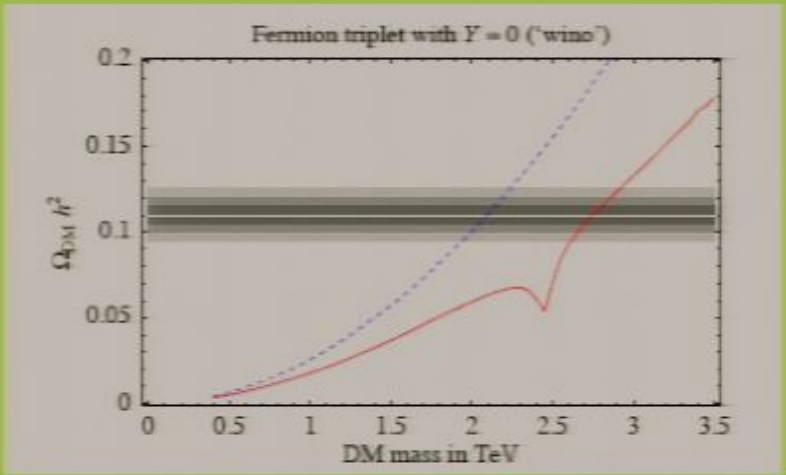
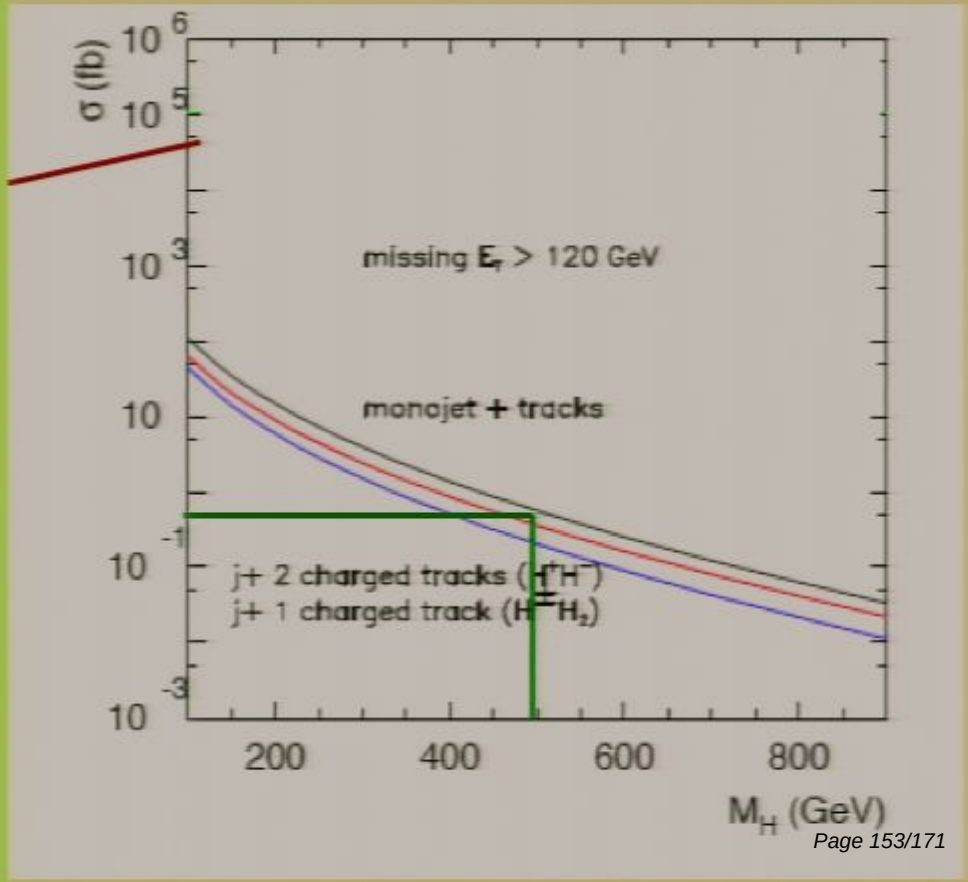
Cirelli et al:



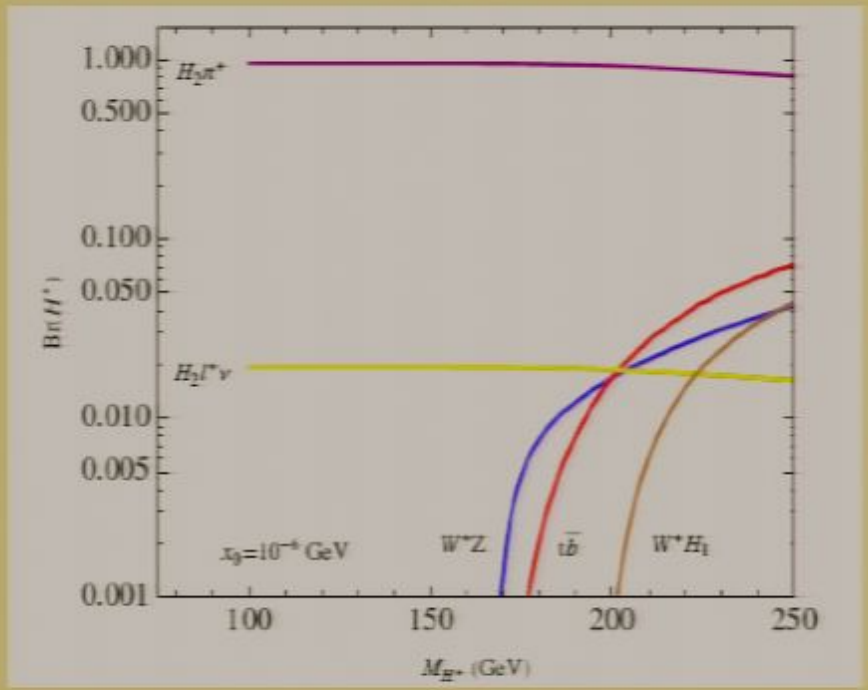
M_Σ = 500 GeV:

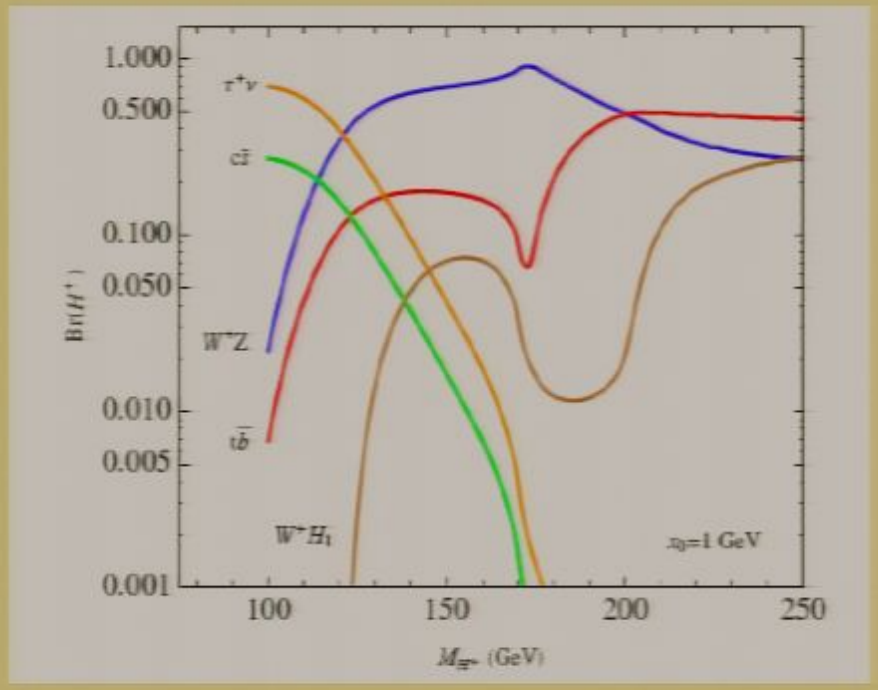
$\Omega_\Sigma / \Omega_{CDM}$ ~ 0.1



Real Triplet : Charged BRs I

Charged: x_0 dependence





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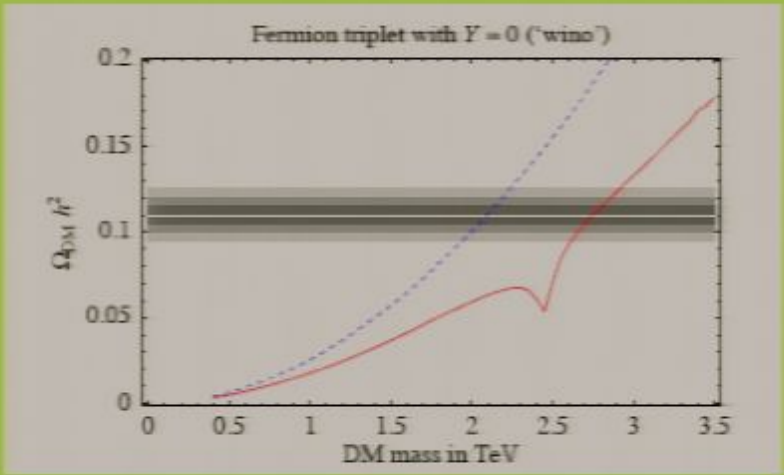
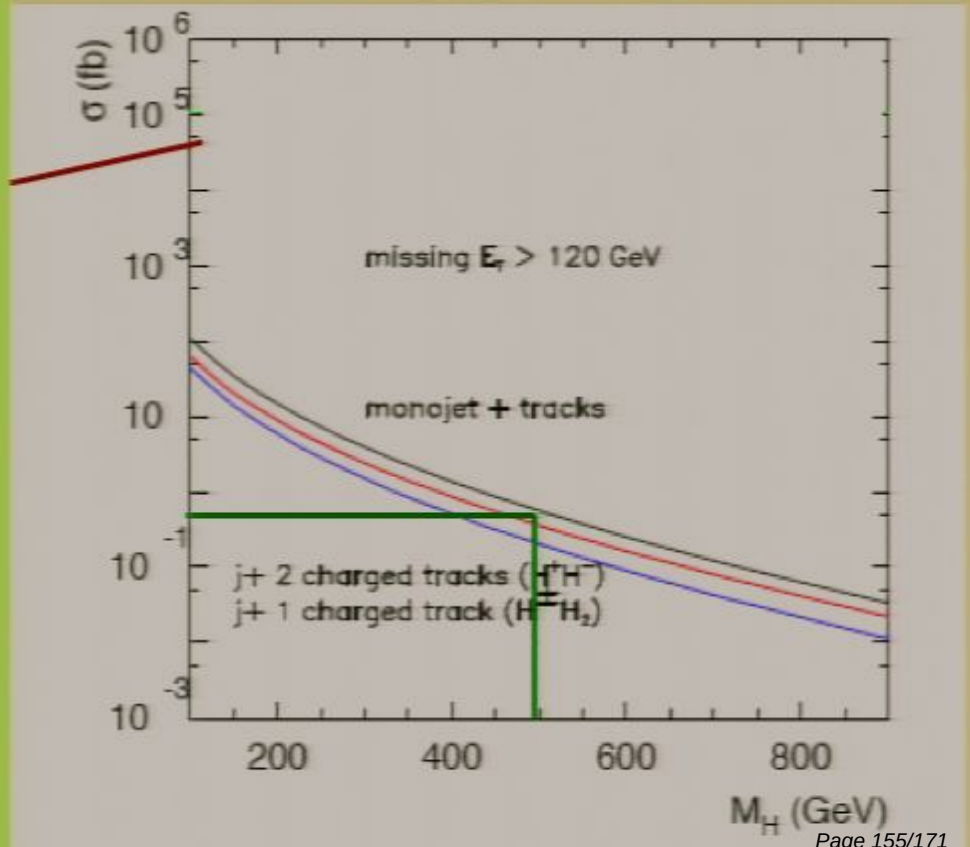
$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \quad q\bar{q} \to Z^*, \gamma^* \to H^+ H^-$

Cirelli et al:



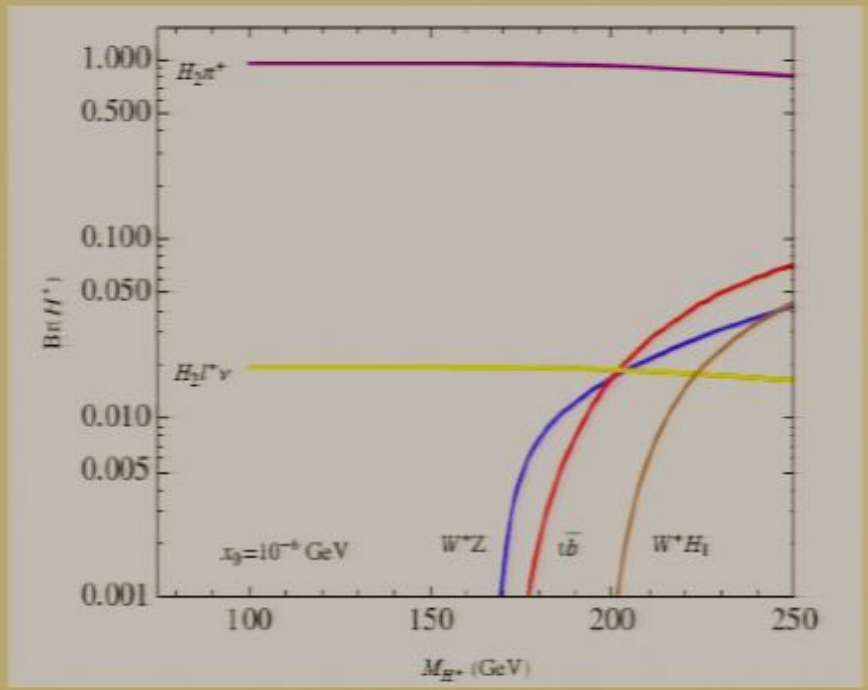
M_Σ = 500 GeV:

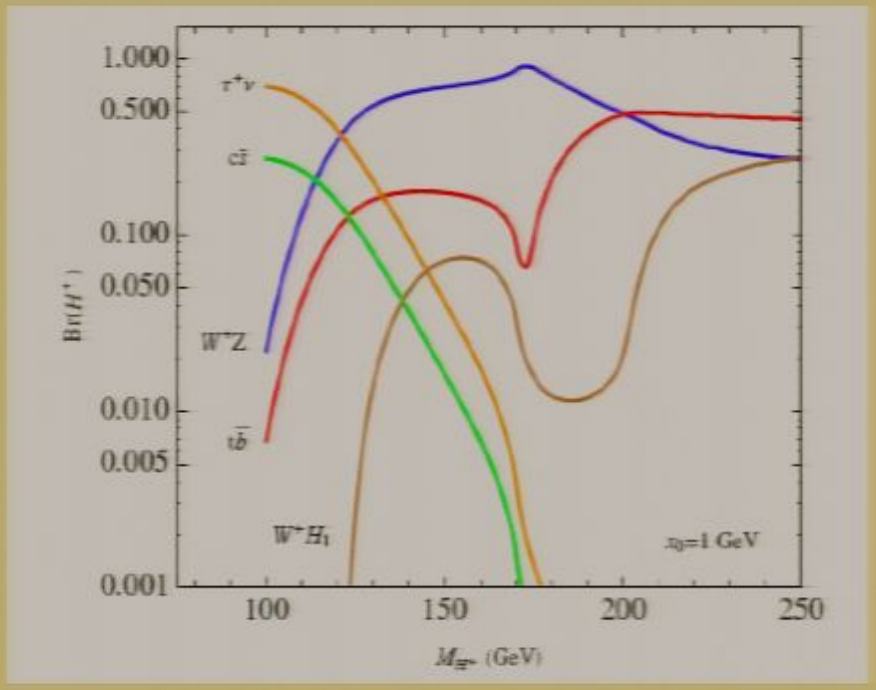
$\Omega_\Sigma / \Omega_{CDM}$ ~ 0.1



Real Triplet : Charged BRs I

Charged: x_0 dependence

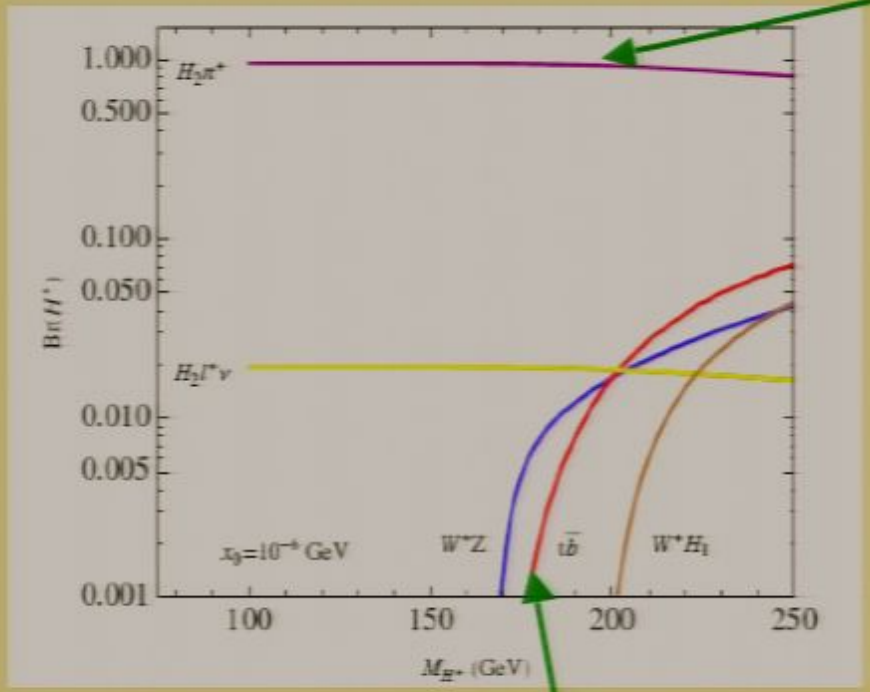


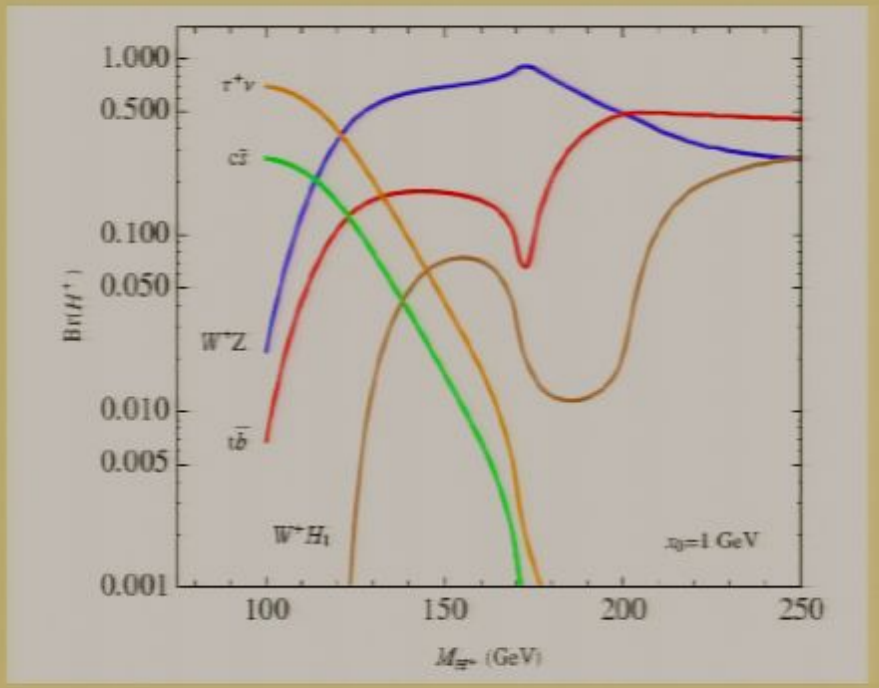


Real Triplet : Charged BRs I

Charged: x_0 dependence

$H^{\pm} \to H_2 W^{\pm *} \to H_2 \pi^{\pm}$ Pure gauge



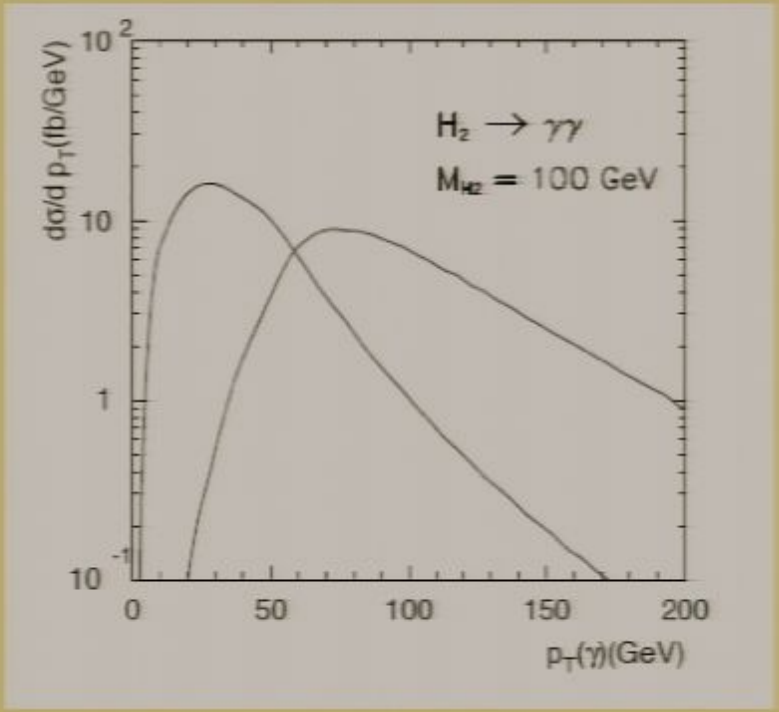


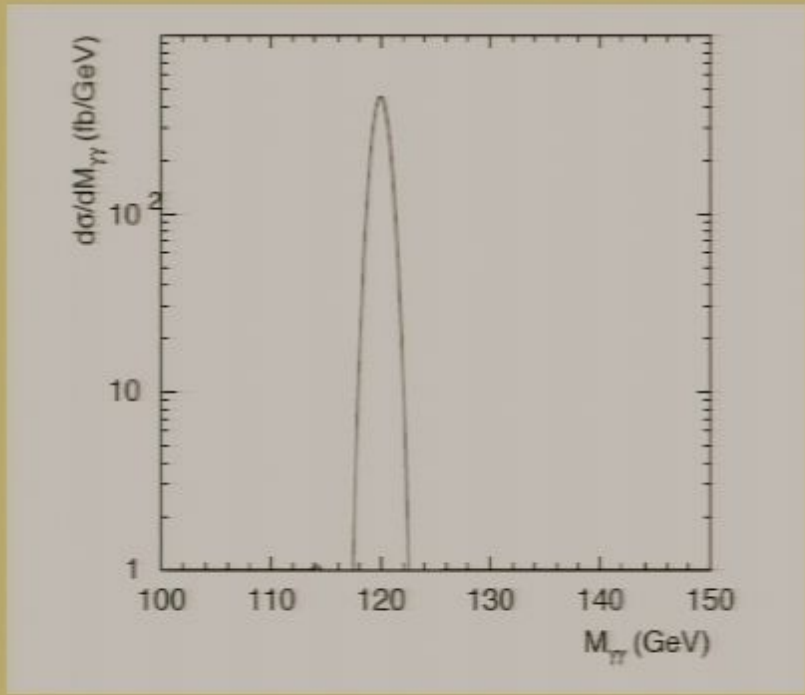
$H^{\pm} \to W^{\pm} Z, f_1 \bar{f}_2$ x_0 suppressed

Real Triplet : General Search I

Basic signature: $\gamma\gamma\,\tau\nu$ (large x_0) or $\gamma\gamma\, b\bar{b}$ (small x_0)

$$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \qquad q\bar{q} \to Z^*, \gamma^* \to H^+ H^-$$





Cuts: min $p_T(\gamma)$> 25 GeV
max $p_T(\gamma)$> 50 GeV
$|\ \eta(\gamma)\ | < 2.8$ $\Delta R > 0.4$

$|\ M_{\gamma\gamma} - M_{H2}\ | < 5$ GeV

Real Triplet : General Search I

Basic signature: $\gamma\gamma\,\tau\nu$ (large x_0) or $\gamma\gamma\,b\bar{b}$ (small x_0)

$$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \qquad q\bar{q} \to Z^*, \gamma^* \to H^+ H^-$$

Identification:

For $b\bar{b}$: b-tagging, $p_T(b) > 15$ GeV, $|\eta(b)| < 3.0$

For $\tau\nu$: soft π from hadronic decay $\to$ Leptonic decay w/ $5\ \text{GeV} < p_T(l) < 40$ GeV, $|\eta(l)| < 2.8$, $\not{E}_T > 20$ GeV, edge of M_T

σ (fb)	Basic cuts	$M_{\gamma\gamma}$ cut	$p_T(l)$ cut
$b\bar{b}(b)\gamma\gamma$	11.59	0.78	N/A
$W\gamma\gamma \to l\nu\gamma\gamma$	3.98	0.27	0.17
$W\gamma\gamma \to \tau\nu\gamma\gamma \to l\gamma\gamma + E_T$	0.70	0.05	0.05

Real Triplet : General Search II

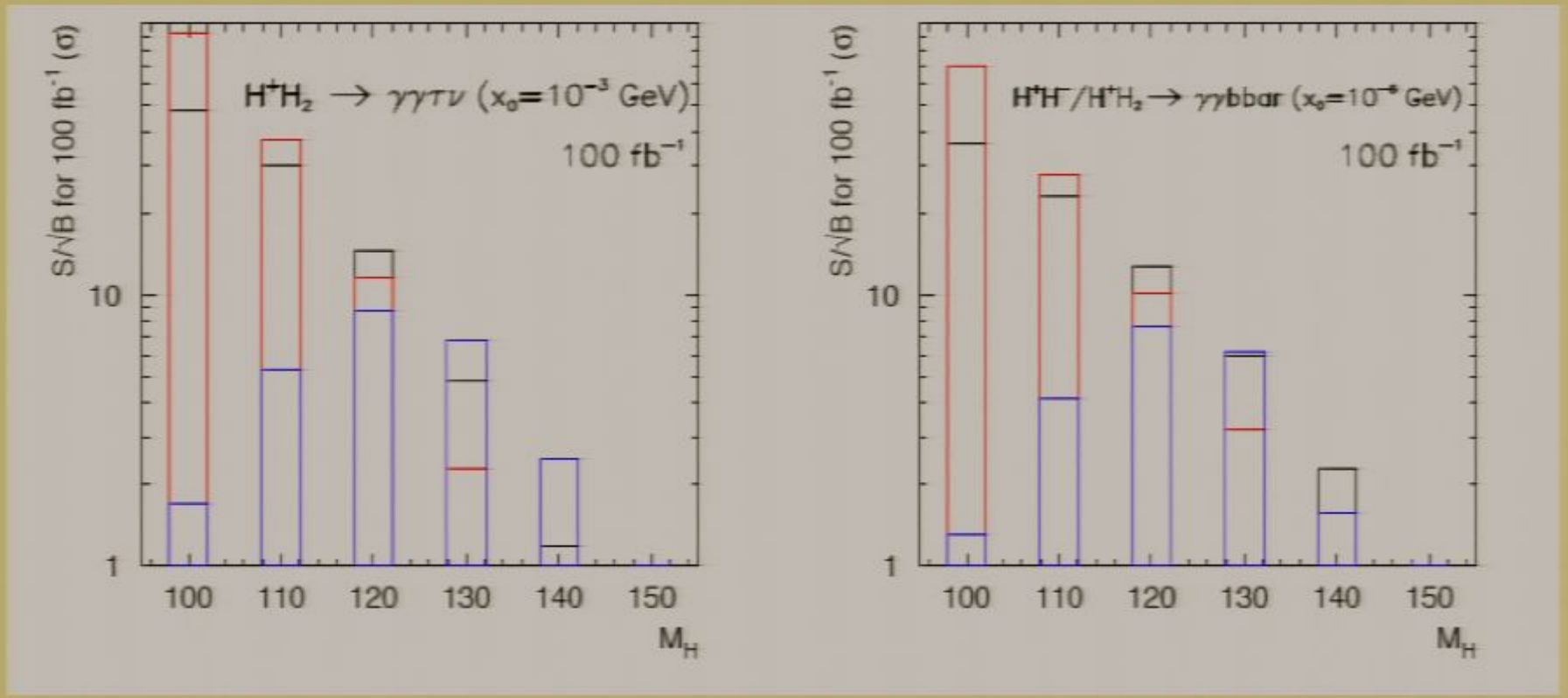
Basic signature: $\gamma\gamma\,\tau\nu$ or $\gamma\gamma\, b\,\bar{b}$

$$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \qquad q\bar{q} \to Z^{*}, \gamma^{*} \to H^{+} H^{-}$$

Real Triplet : General Search II

Basic signature: $\gamma\gamma\,\tau\nu$ or $\gamma\gamma\, b\,\bar{b}$

$$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \qquad q\bar{q} \to Z^{*}, \gamma^{*} \to H^{+} H^{-}$$



Real Triplet : General Search II

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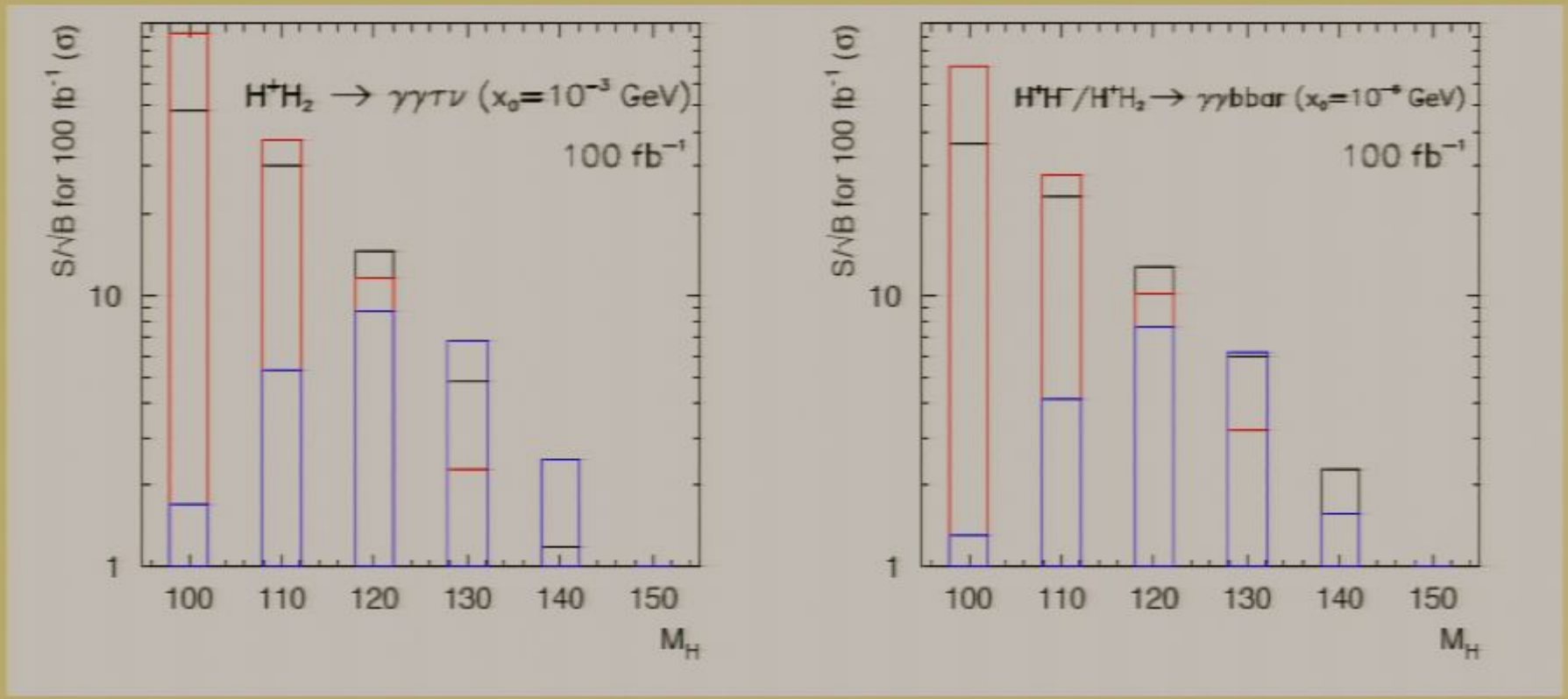

$a_2 = 1, 0, -1$: a_2-dependence of $H_2 W^{+} W^{-}$ coupling

Real Triplet : Couplings

H_2 WW Coupling

$$H_2 W^+ W^- \quad : \qquad i g^2 (2 - r) x_0 \, g^{\mu\nu}$$

$$\sin\theta_0 \approx 2r(x_0/v_0) \qquad r = \frac{M_{H^+}^2 - a_2 v_0^2/2}{2M_{H^+}^2 - M_{H_1}^2 - M_{H_2}^2} \approx \frac{M_{H^+}^2 - a_2 v_0^2/2}{M_{H^+}^2 - M_{H_2}^2}$$

Real Triplet : Couplings

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$\Gamma(H_2 \to \gamma\gamma)$ depends on a_2 via W^+W^- loops

Real Triplet : Couplings

H_2 WW Coupling

$$H_2 W^+ W^- \quad : \qquad i g^2 (2 - r) x_0 \, g^{\mu\nu}$$

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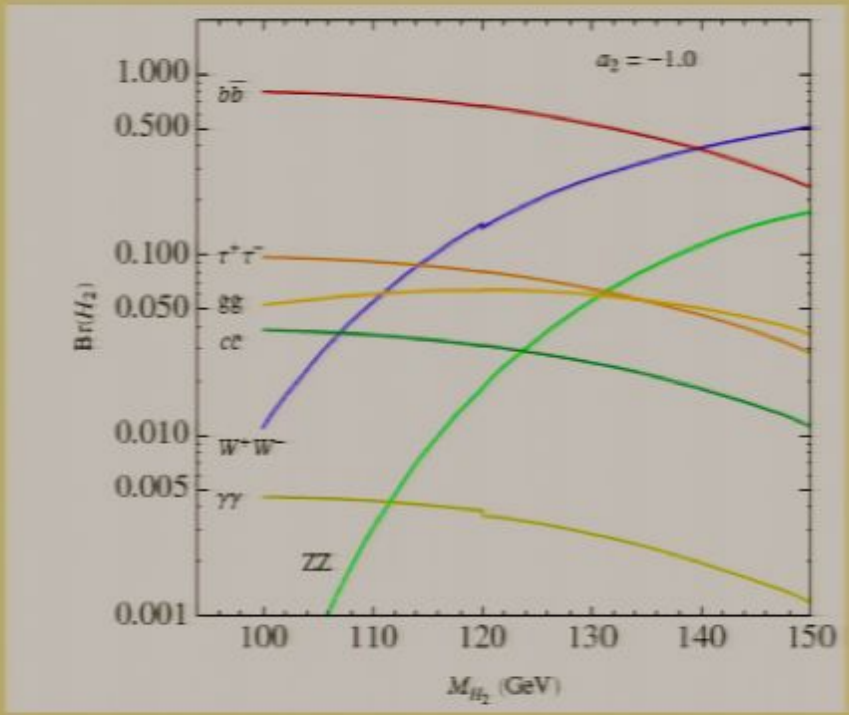
$\Gamma(H_2 \to \gamma\gamma)$ depends on a_2 via W^+W^- loops

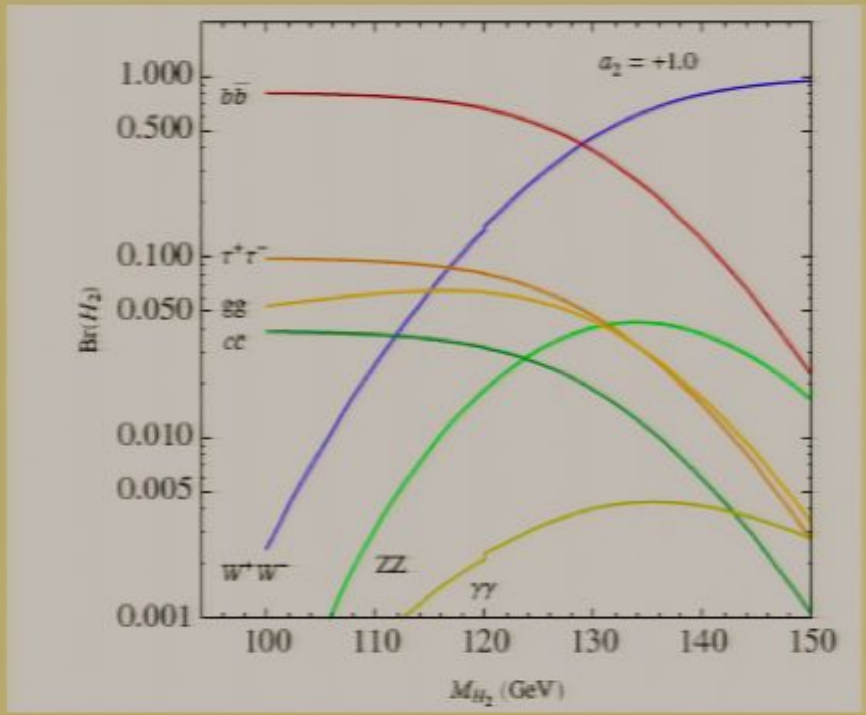
H_1 H^+ H^- Coupling:

$$-i\left(a_1 c_+ s_+ c_0 - \tfrac{1}{2} a_1 s_+^2 s_0 + a_2 v_0 c_+^2 c_0 + a_2 x_0 s_+^2 s_0 + 2 b_4 x_0 c_+^2 s_0 + 2\lambda_0 v_0 s_+^2 c_0\right)$$

Real Triplet : Neutral BRs

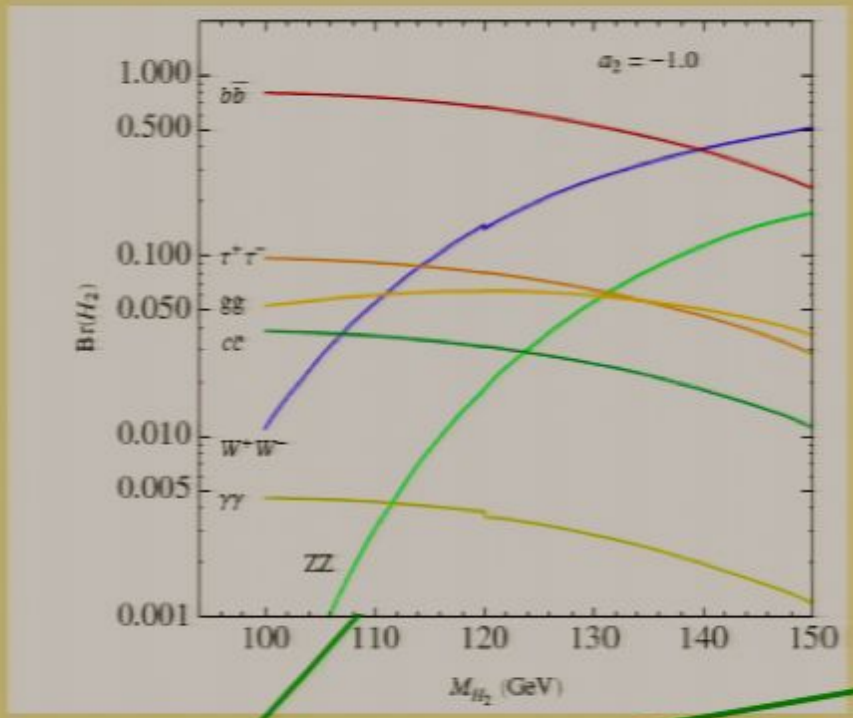
Neutral: differences with SM Higgs & a_2 dependence

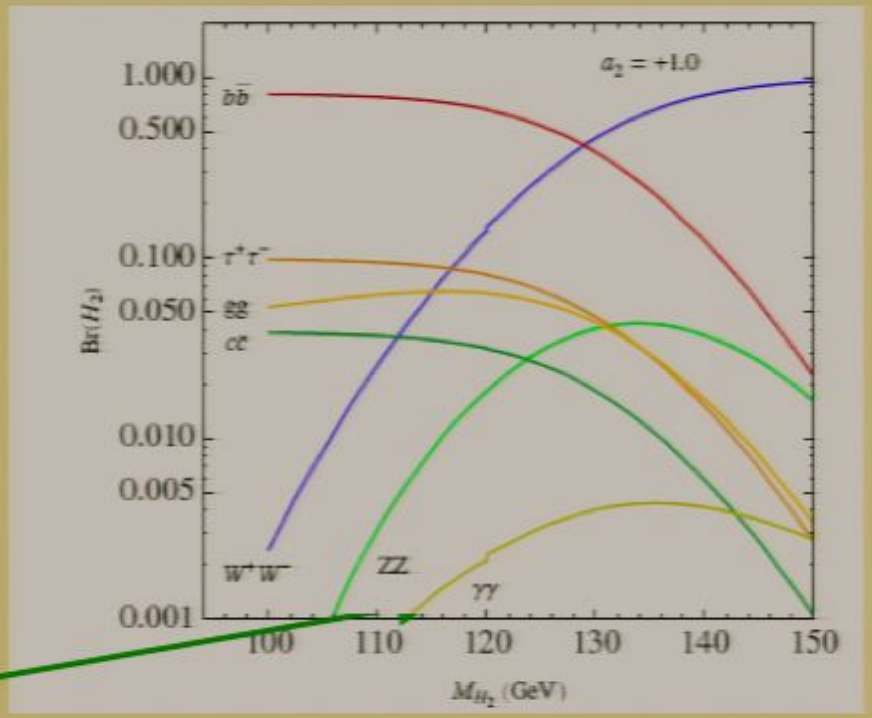




Real Triplet : Neutral BRs

Neutral: differences with SM Higgs & a_2 dependence



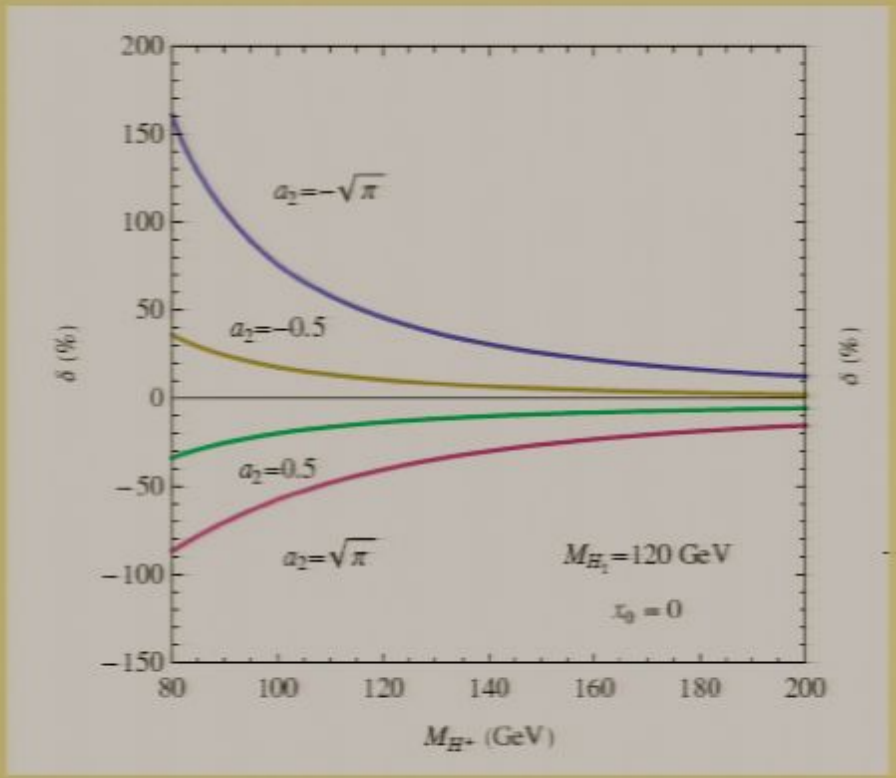


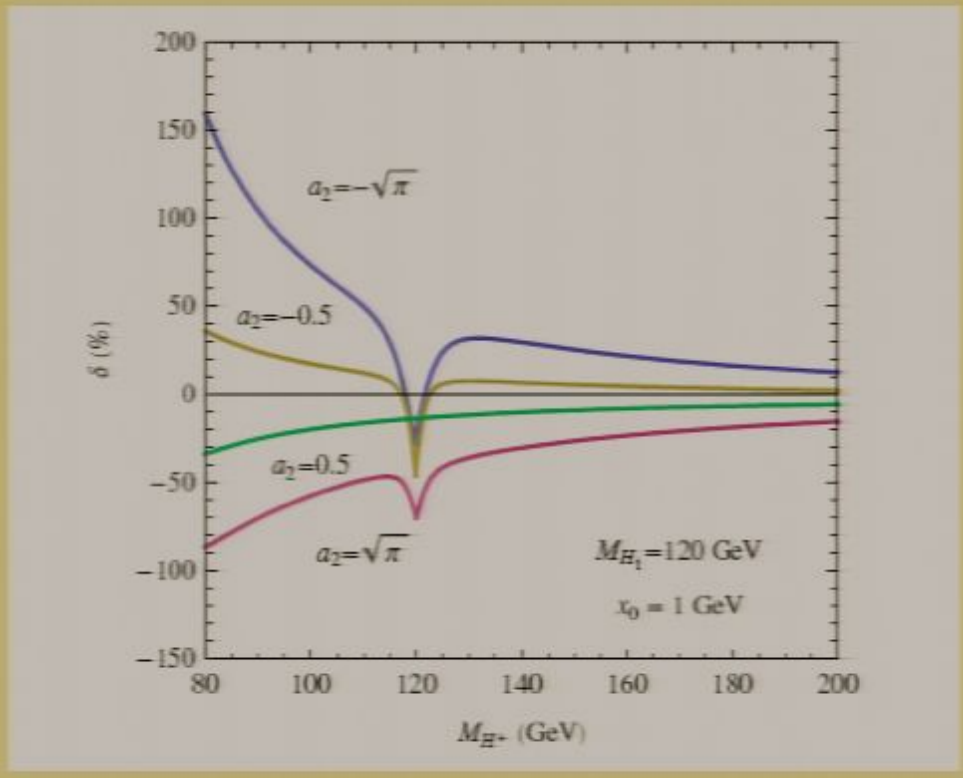
Different ratio of WW and ZZ, γγ BRs

$$\frac{\Gamma(H_2 \to WW)}{\Gamma(H_2 \to f\bar{f})} \propto \left(\frac{2-r}{r}\right)^2$$

Real Triplet : H_1 Decays

Neutral SM-like Higgs: H^+ loops and BR ($H_1 \to \gamma\gamma$)





X_0=0: DM case

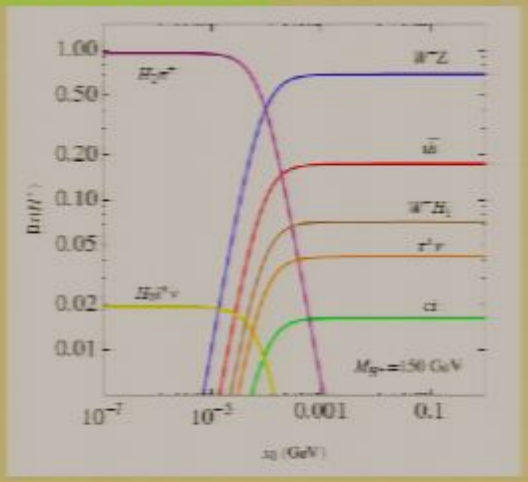
X_0>0: EWPT case

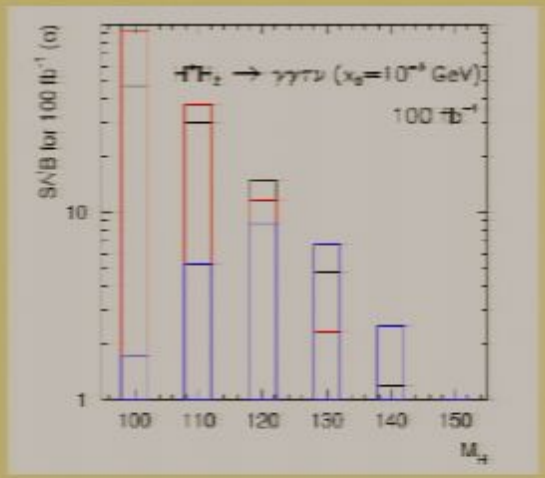
Real Triplet : Summary

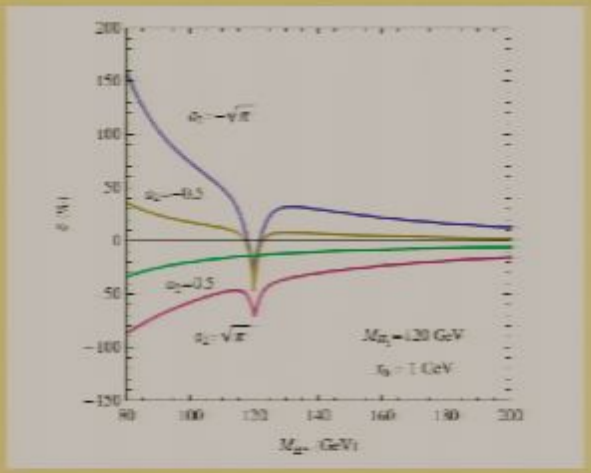
Parameters relevant for EWPT: x_0 , a_1 , a_2

H^+ mass & decays: x_0 , a_1 $H_{1,2}WW$ coupling via $\gamma\gamma$: a_2

$M^2_{H^\pm} \approx a_1 v_0^2/4x_0^2$







DM Search: ~ 50 events for $\Omega_\Sigma / \Omega_{CDM}$ ~ 0.1
(M_Σ ~ 500 GeV); study BR($H_1 \rightarrow \gamma\gamma$)

Summary

Minimal TeV-scale SM extensions

- ***Can help explain the origin of matter (visible and dark)***
- ***Can be discovered at the LHC***
- ***Can be probed in cosmologically relevant parameter space at colliders***

Summary

No Gauge Interactions

Simplest: 1 new dof

Real Singlet (xSM):

DM or BAU-m_H/ EWPO

BAU: H-S Mixing & Reduced BRs

DM: Reduced BRs & σ_{SI}

Next Simplest: 2 new dof

Complex Singlet (cxSM):

DM, BAU, and m_H/ EWPO

H-S Mixing, Reduced BRs, & σ_{SI}

Gauge Interactions

Simplest: 3 new dof
(2HDM: 4 new dof)

Real Triplet (ΣSM):

DM or BAU (EWPT)

DM: Charged track & σ_{SI}

BAU: $\tau\nu\gamma\gamma$ or $bb\gamma\gamma$; $\Delta Br(H\rightarrow\gamma\gamma)$