Scalar Dark Matter and the Higgs Portal

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Goals

- *Motivate Higgs portal DM*
- *Introduce generic models*
- *Outline signatures & constraints:*
  modified Higgs properties, new states,
  EWPO, vacuum stability
- *Discuss future directions*

Outline

1. *Dark Matter Portals*
2. *Why the Higgs portal?*
3. *Why scalar dark matter ?*
4. *General considerations*
5. *Simplest examples: scalar DM & LHC*
6. *Discussion*

I. Dark Matter Portals

Standard Model ↔ Hidden Sector (DM)

Portals

Two approaches to particle dark matter :

- *Specific model (MSSM….)*
- *“Model independent”*

Model Independent Portals

- *Vector portal ("dark photons"…)*
- *Neutrino portal*
- *Axion portal*
- *Higgs portal*
- *Higher dimensional op's portal*

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$$\mathcal{L}_4 = \Lambda^4 + \mu^2 \mathcal{O}_2 + \mathcal{O}_4 + \frac{1}{\Lambda_{\rm BSM}} \mathcal{O}_5 + \cdots$$

Model Independent Portals

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- *Higher dimensional op's portal*

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Higgs Portal

$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger \phi\ H^\dagger H$$

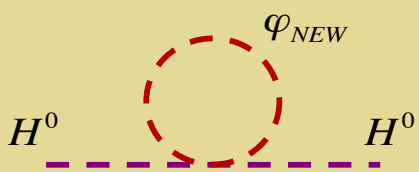
- *Renormalizable*
- *Z_2 symmetric*
- *Dimensionless coupling*
- *ϕ (DM): singlet or charged under $SU(2)_L \times U(1)_Y$*

II. Why the Higgs Portal ?

Scalar Fields in Particle Physics

Scalar fields are a simple

Scalar fields are theoretically problematic

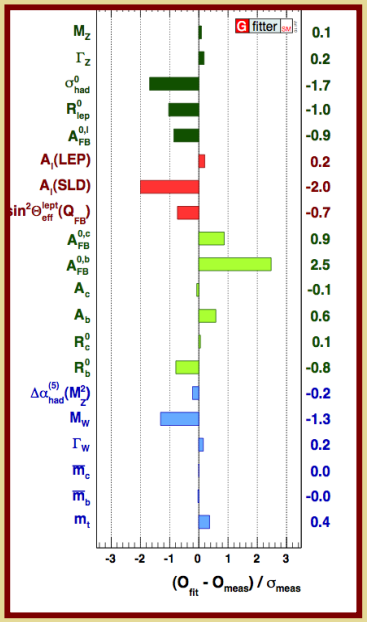


$\Delta m^2 \sim \lambda \Lambda^2$

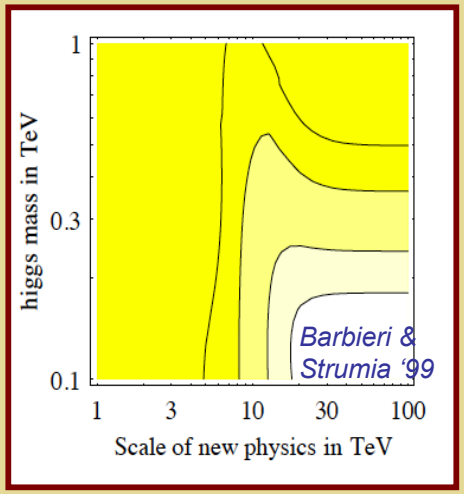
Has a fundamental scalar finally been discovered ?

If so, is it telling us anything about Λ ?

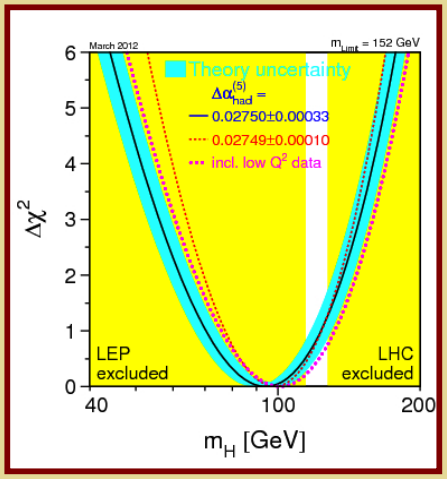
What is the BSM Energy Scale Λ ?



~ 10^{-3} agreement with EWPO



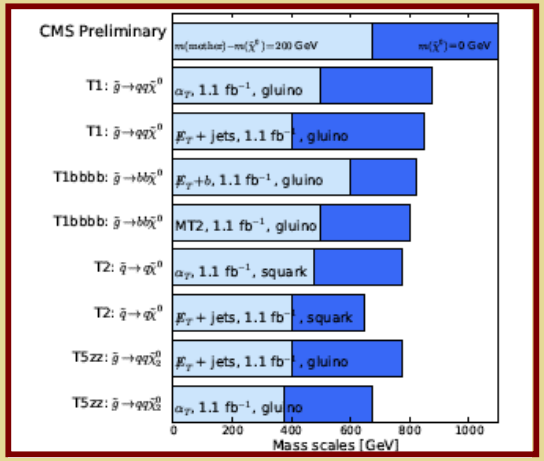
BSM: $O_{BSM} = c / \Lambda^2 \rightarrow$ $\Lambda \sim 10$ TeV generically

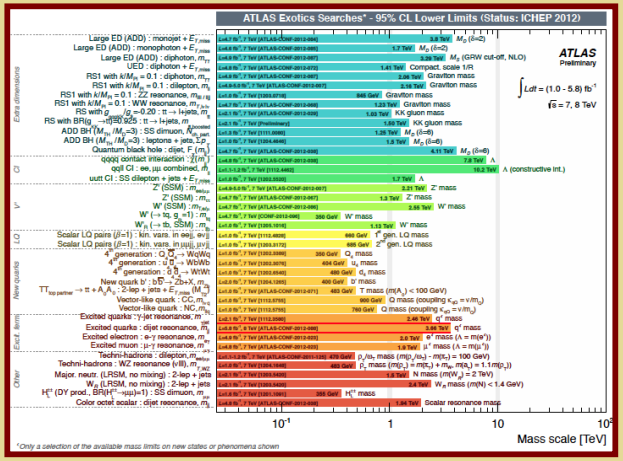


EWPO: data favor a "light" SM-like Higgs scalar

LHC: so far no sub-TeV BSM physics

Hierarchy problem(s) ?





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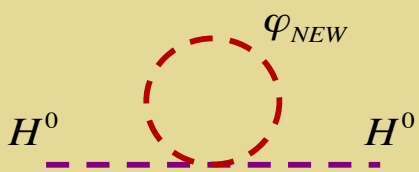


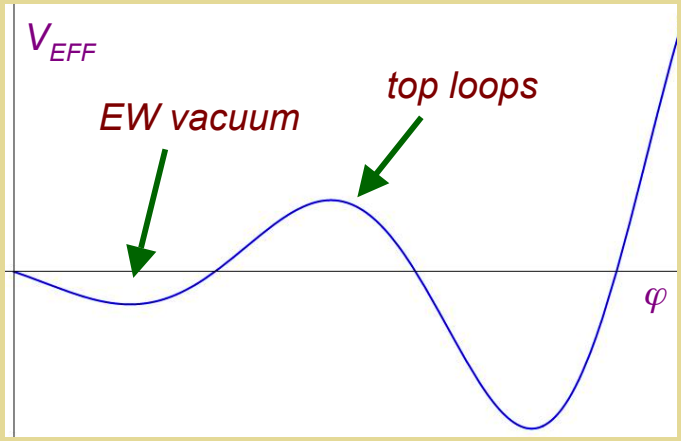
$\Delta m^2 \sim \lambda \Lambda^2$

Must Λ_{BSM} ~ TeV to maintain a weak scale scalar ?

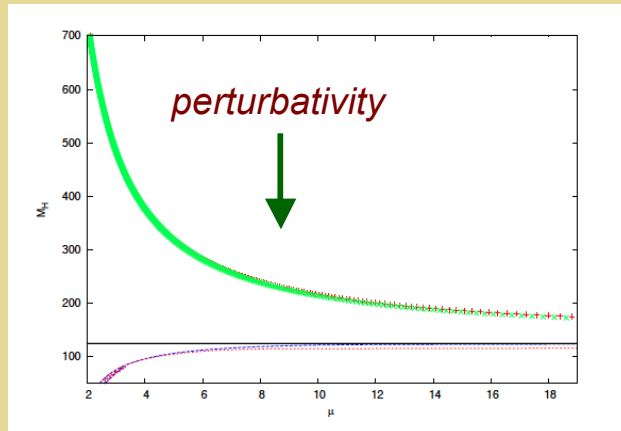
Perhaps new weak scale physics couples only to scalar sector: "Higgs portal"

Stable EW Vacuum ?

Preserving EW Min



"Funnel plot"



$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 \qquad - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4\right)$$

sets m_H

top loops

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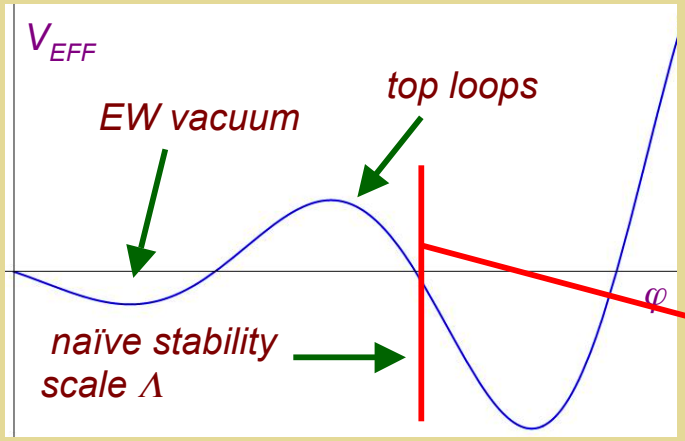

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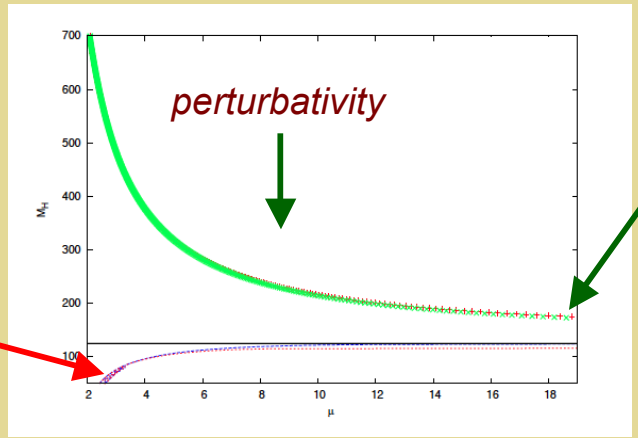

SM stability & pert'vity

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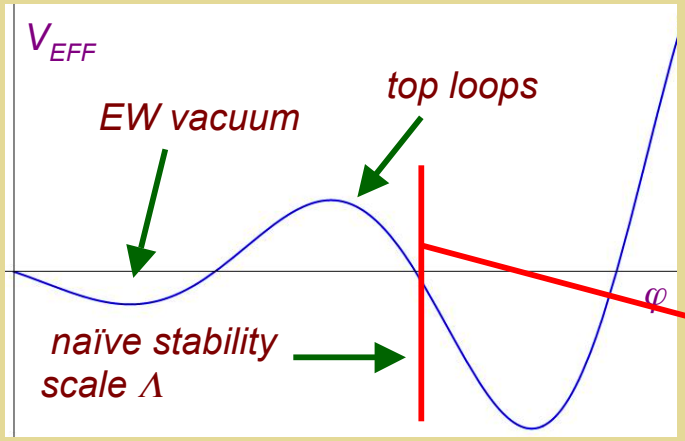

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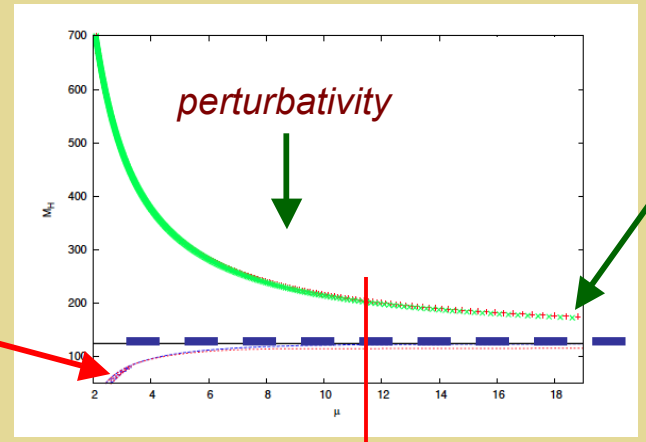

SM stability & pert'vity

m_H

SM unstable above ~ 10^8 - 10^{13} TeV

$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4\right)$$

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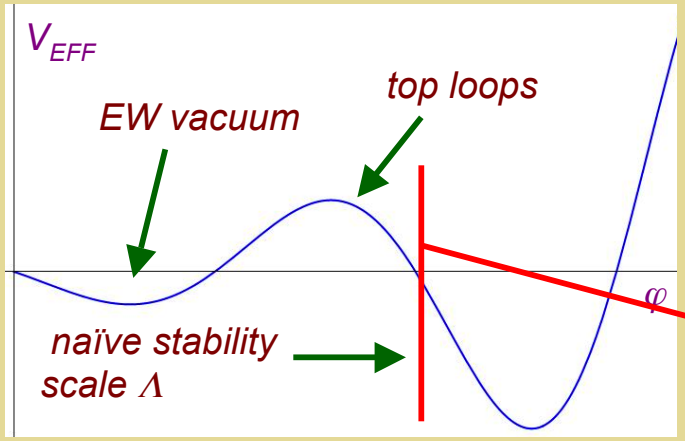

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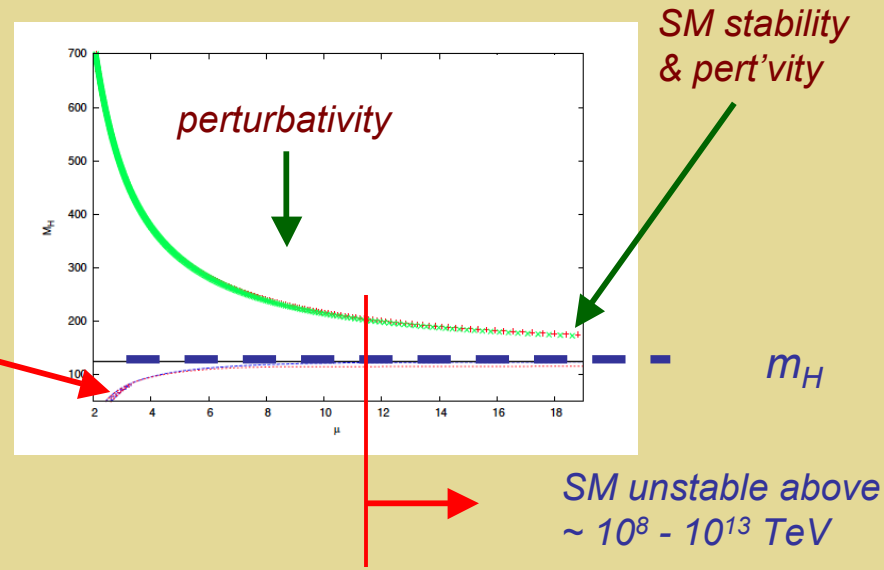

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sets m_H

top loops

Higgs portal interactions → more robust stability

III. Why scalar dark matter ?

φ ?

Scalar Fields in Cosmology

What role do scalar fields play (if any)
in the physics of the early universe ?

Scalar Fields in Cosmology

Problem	*Theory*	*Exp't*
• *Inflation* • *Dark Energy* • *Dark Matter* • *Phase transitions*		

Scalar Fields in Cosmology

Problem	*Theory*	*Exp't*
• *Inflation*	✔	
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Scalar Fields in Cosmology

Problem	*Theory*	*Exp't*
• *Inflation*	✔	?
• *Dark Energy*	✔	?
• *Dark Matter*	✔	?
• *Phase transitions*	✔	?

• *Could experimental discovery of a fundamental scalar point to early universe scalar field dynamics?*

• *Are there signatures in modified Higgs properties, new states, or EW precision tests ?*

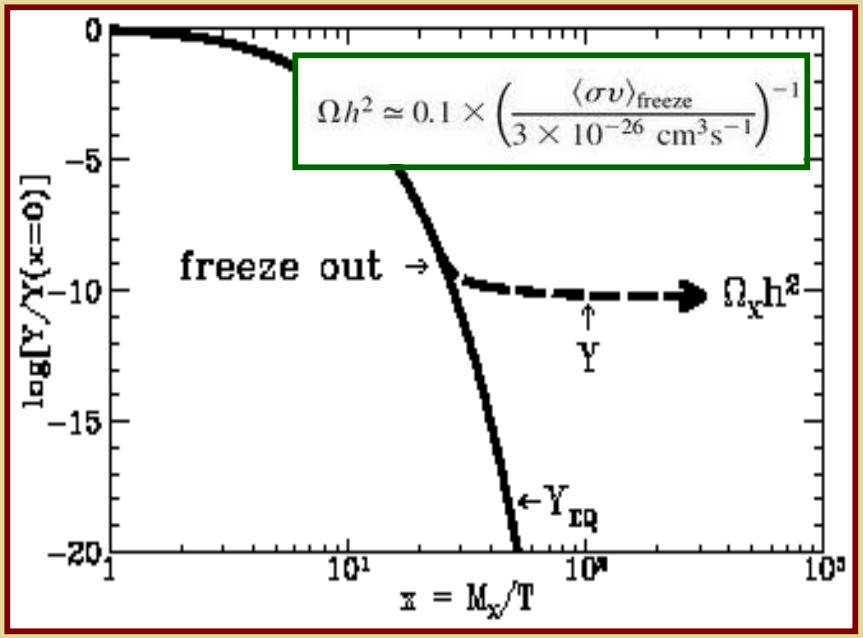
Scalar Fields in Cosmology

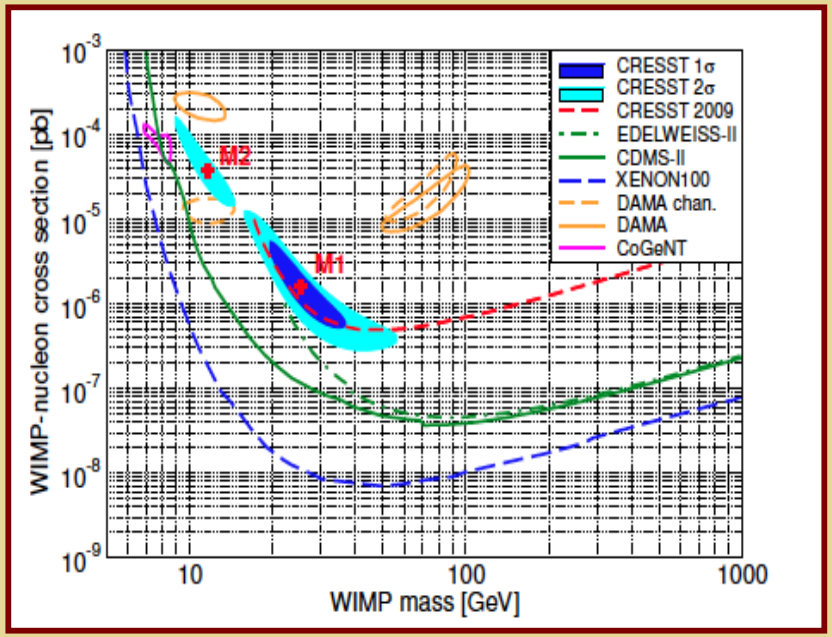
Problem	*Theory*	*Exp't*
• *Inflation*	✔	?
• *Dark Energy*	✔	?
• *Dark Matter*	✔	?
• *Phase transitions*	✔	?

Focus of this talk, but perhaps part of larger role of scalar fields in early universe

IV. General Considerations

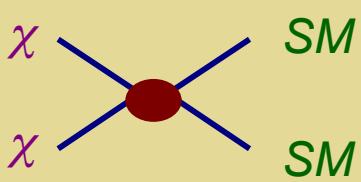
Thermal DM: Ω_{CDM} & σ_{SI}

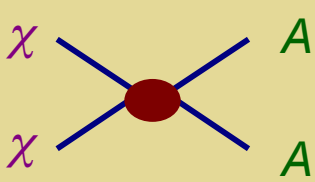




Thermal DM: WIMP

Direct detection: Spin-indep DM-nucleus scattering





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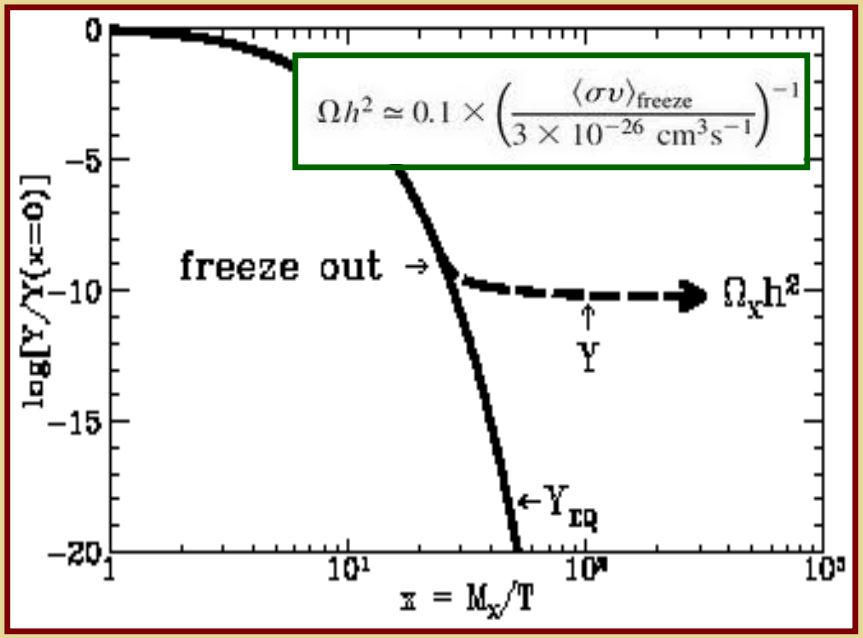

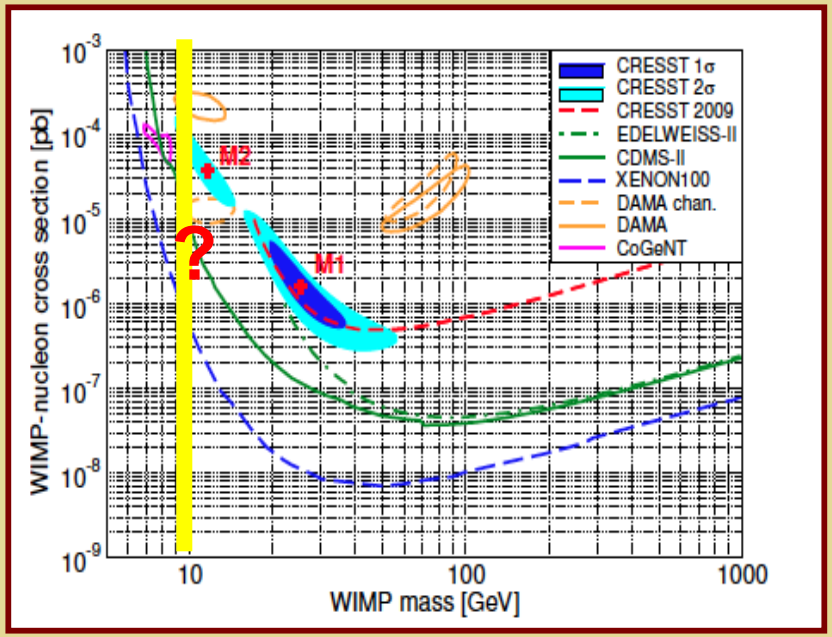

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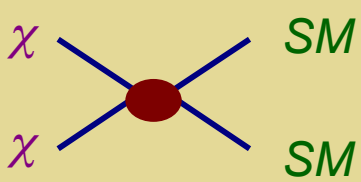
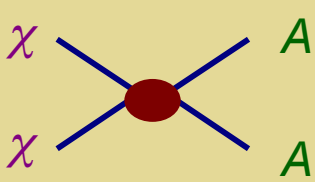
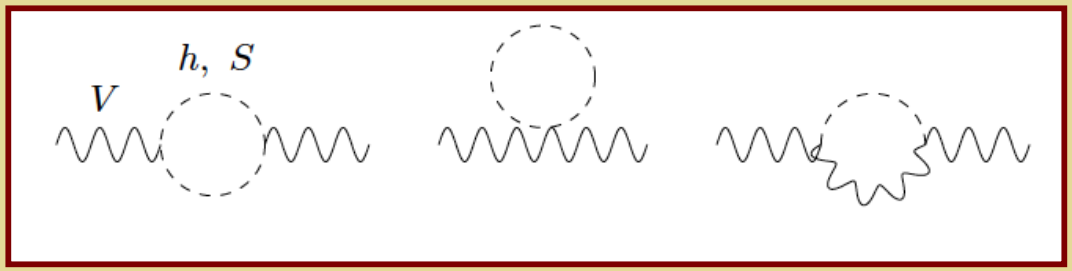




EWPO



$$\hat{\alpha}S = \frac{4\hat{s}^2\hat{c}^2}{M_Z^2}\mathrm{Re}\left\{\hat{\Pi}_{ZZ}(0) - \hat{\Pi}_{ZZ}(M_Z^2) + \frac{\hat{c}^2-\hat{s}^2}{\hat{c}\hat{s}}\left[\hat{\Pi}_{Z\gamma}(M_Z^2) - \hat{\Pi}_{Z\gamma}(0)\right] + \hat{\Pi}_{\gamma\gamma}(M_Z^2)\right\}^{\mathrm{New}},$$

$$\hat{\alpha}T = \frac{1}{M_W^2}\left\{\hat{c}^2\left(\hat{\Pi}_{ZZ}(0) + \frac{2\hat{s}}{\hat{c}}\hat{\Pi}_{Z\gamma}(0)\right) - \hat{\Pi}_{WW}(0)\right\}^{\mathrm{New}},$$

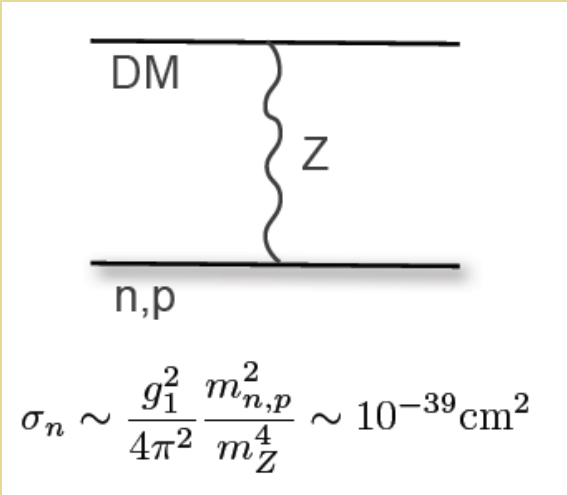
- *New states: h-S mixing*
- *$SU(2)_L$ x $U(1)_Y$ multiplets: direct contributions*

$$\alpha S \sim \Pi_{3Y}$$

EWPO & σ_{SI}

- *New states: h-S mixing*
- *Gauge interactions: direct contributions*

$$\alpha S \sim \Pi_{3Y}$$



$g_{\chi\chi Z} \propto 2\, I_3 - 4\, Q \sin^2\theta_W$

$Y = 2\,(Q - I_3)$

→ *Want $Y = 0$*

EW corrections break custodial SU(2): $T \neq 0$ (but small)

V. Simple examples

Higgs Portal: Simple Scalar Extensions

Extension	*DOF*	*EWPT*	*DM*
Real singlet	*1*	✔	✖
Real singlet	*1*	✖	✔
Complex Singlet	*2*	✔	✔
Real Triplet	*3*	✔	✔

May be low-energy remnants of UV complete theory & illustrative of generic features

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May be low-energy remnants of UV complete theory & illustrative of generic features

The Simplest Extension

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

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

EWPT: $a_{1,2} \neq 0$ & $\langle S \rangle \neq 0$

DM: $a_1 = 0$ & $\langle S \rangle = 0$

O'Connel, R-M, Wise; Profumo, R-M, Shaugnessy; Barger, Langacker, McCaskey, R-M Shaugnessy; He, Li, Li, Tandean, Tsai; Petraki & Kusenko; Gonderinger, Li, Patel, R-M; Cline, Laporte, Yamashita; Ham, Jeong, Oh; Espinosa, Quiros; Konstandin & Ashoorioon…

The Simplest Extension, Cont'd

Mass matrix

$$M^2 = \begin{pmatrix} \mu_h^2 & \mu_{hs}^2/2 \\ \mu_{hs}^2/2 & \mu_s^2 \end{pmatrix}$$

$$\mu_h^2 \equiv \frac{\partial^2 V}{\partial h^2} = 2\bar{\lambda}_0 v_0^2$$

$$\mu_s^2 \equiv \frac{\partial^2 V}{\partial s^2} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$

$$\mu_{hs}^2 \equiv \frac{\partial^2 V}{\partial h \partial s} = (a_1 + 2a_2 x_0)\, v_0$$

x_0 = <S>

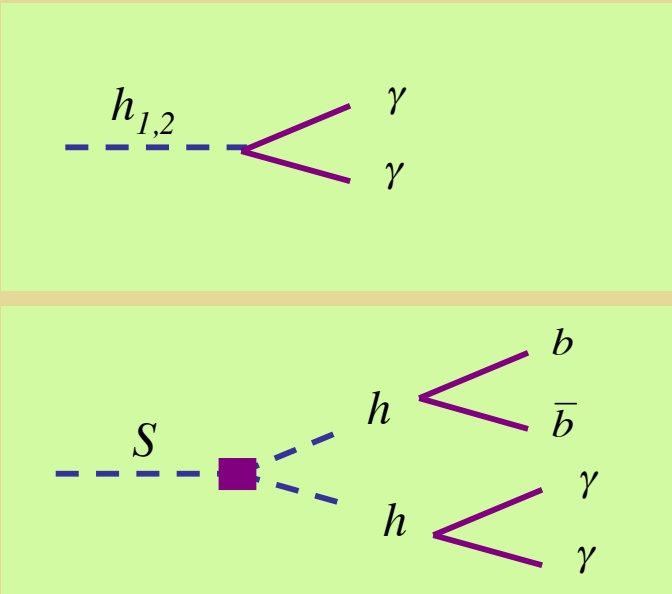
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\tan\theta = \frac{y}{1+\sqrt{1+y^2}}, \qquad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2}$$

$$m_{1,2}^2 = \frac{\mu_h^2 + \mu_s^2}{2} \pm \frac{\mu_h^2 - \mu_s^2}{2}\sqrt{1+y^2}$$

The Simplest Extension, Cont'd

Mass matrix



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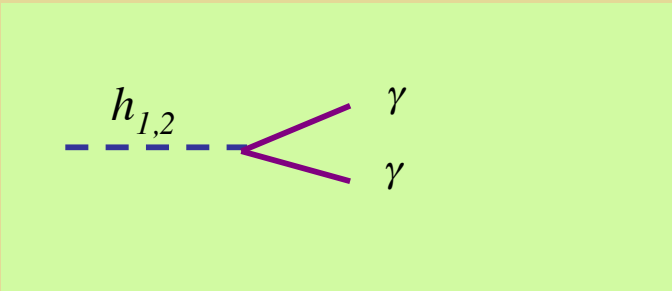
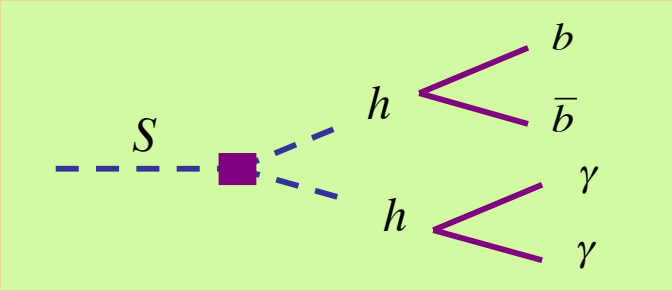
New topologies

The Simplest Extension, Cont'd

Mass matrix





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Stable S (dark matter)

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

The Simplest Extension

DM Scenario

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

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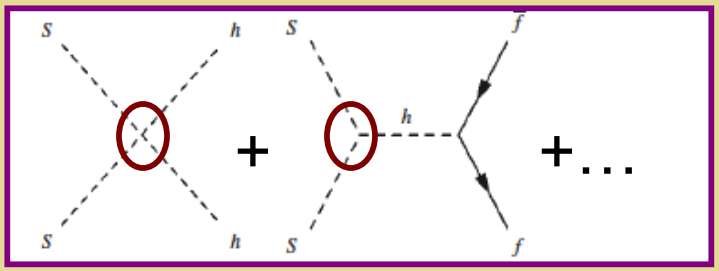
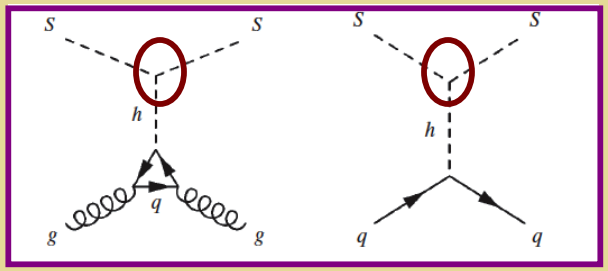
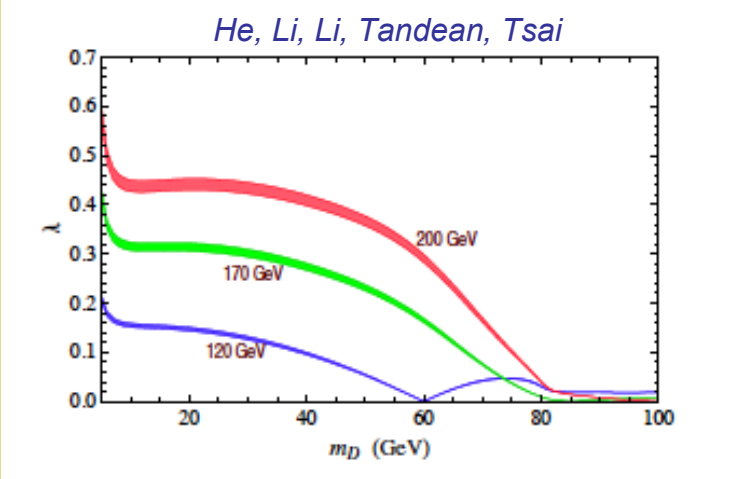
Ω_{DM} & σ_{SI}





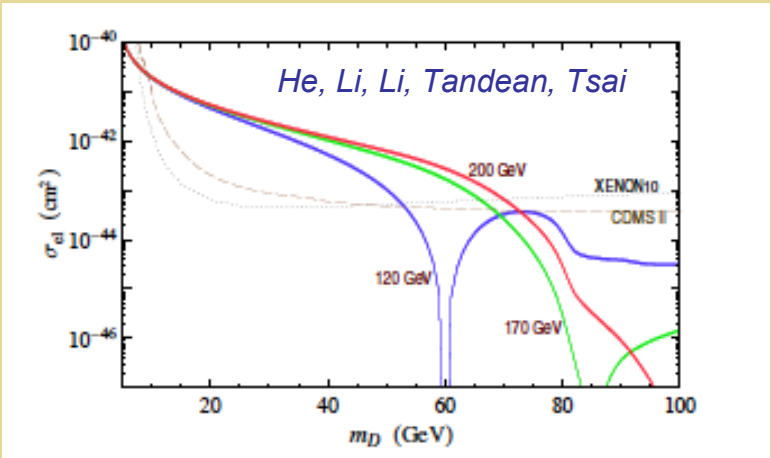
DM Phenomenology

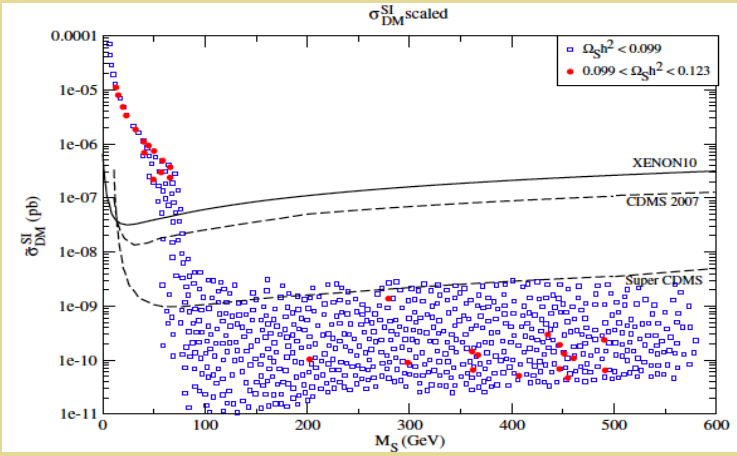
Relic Density



Direct Detection

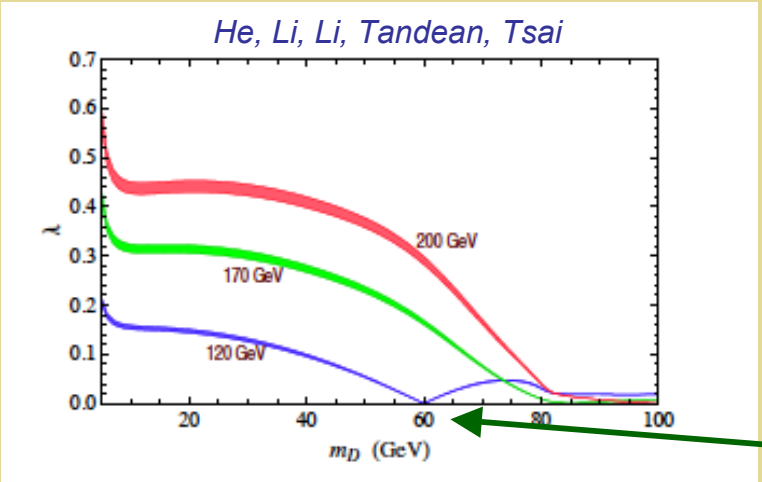
Barger, Langacker, McCaskey, R-M, Shaugnessy

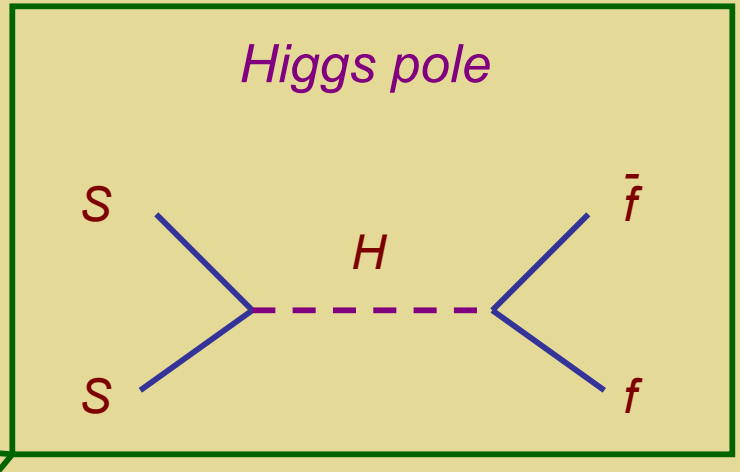




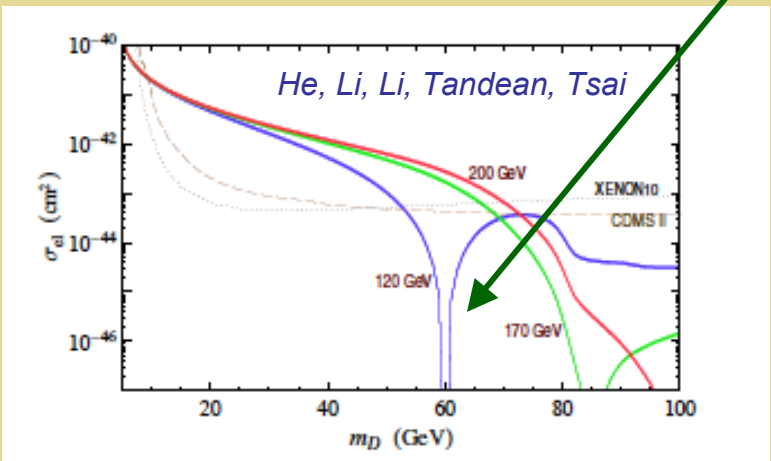
DM Phenomenology

Relic Density

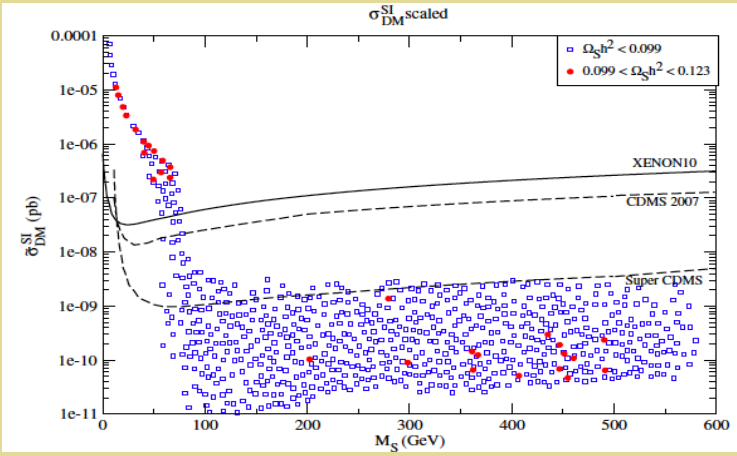




Direct Detection

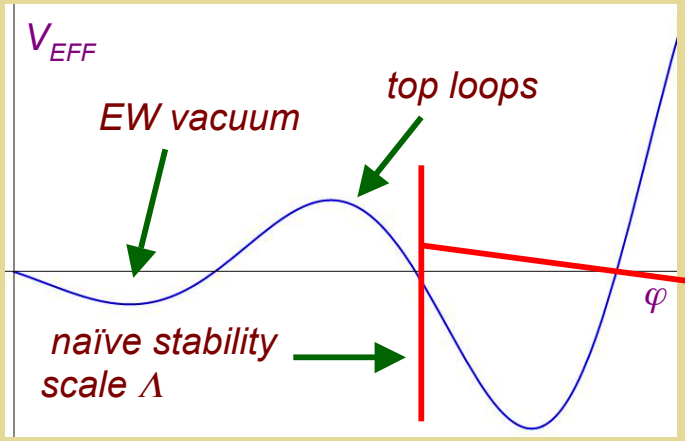


Barger, Langacker, McCaskey, R-M, Shaugnessy

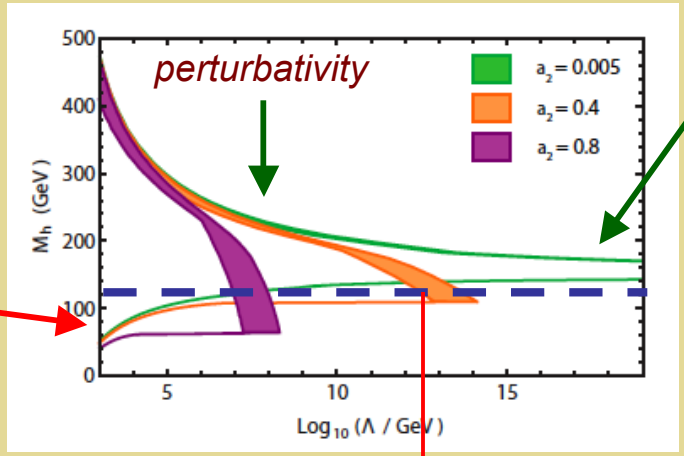


New Scalars EW Vacuum Stability

Preserving EW Min



"Funnel plot"



SM stability & pert'vity

m_H

SM + singlet: stable but non-pertur'tive

$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4\right)$$

DM-H coupling *top loops*

Gonderinger, Li, Patel, R-M

LHC & Higgs Phenomenology

LHC discovery potential

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 → V_{1j}

Decay → $\mathrm{BF}(H_j \to X_{SM})$

V_{1j} < 1: mixed states h_j

New decays: $h_2 \to h_1\, h_1$

Dark matter: no mixing → states are h,S

New decays $h \to SS$ (invisible!) possible

LHC & Higgs Phenomenology

LHC discovery potential

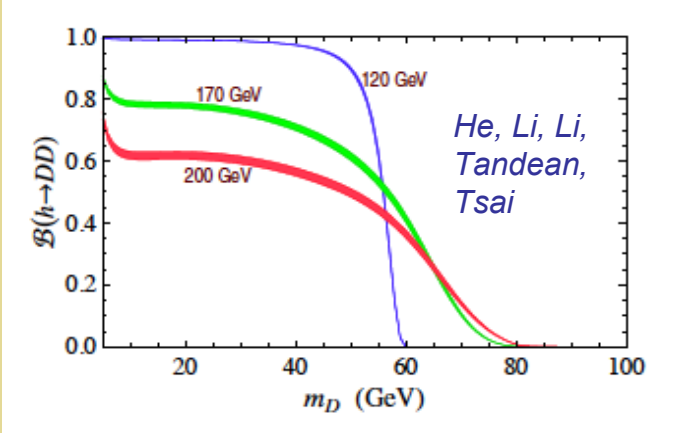
Signal Reduction Factor

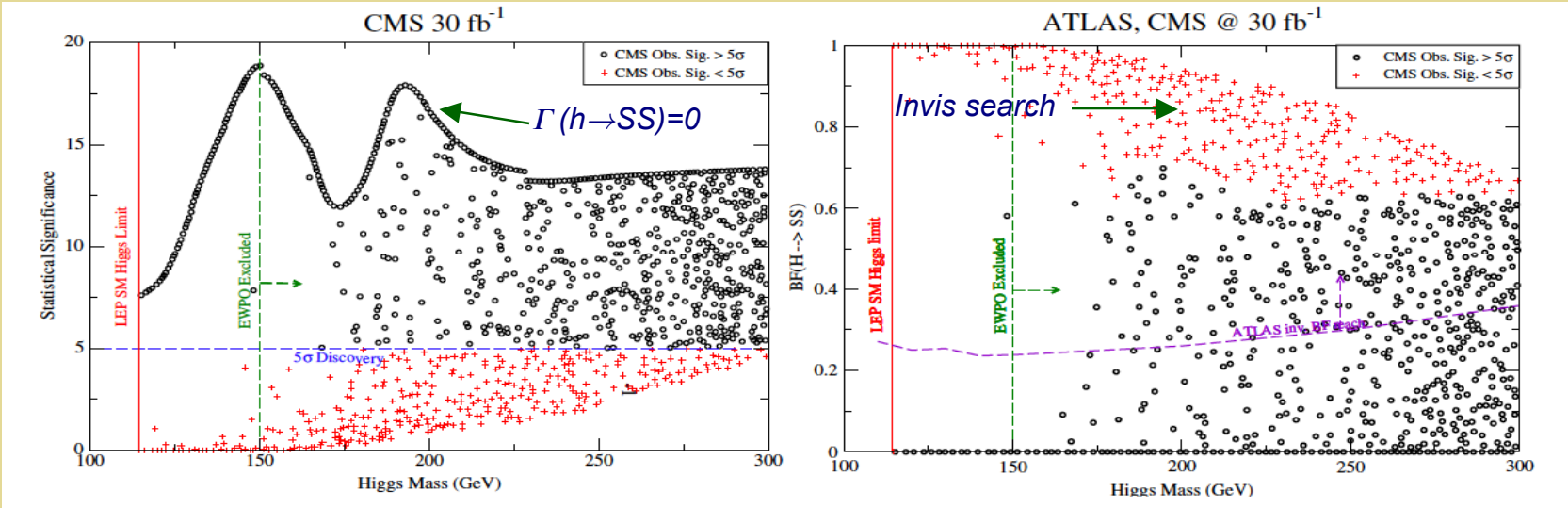
$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

Production

Decay

Invisible decays





LHC & Higgs Phenomenology

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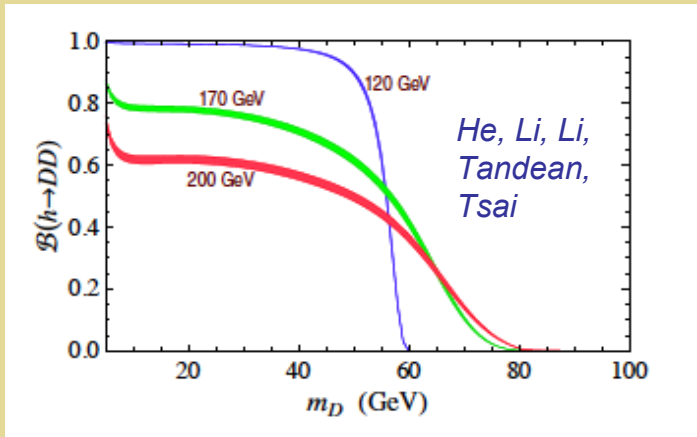
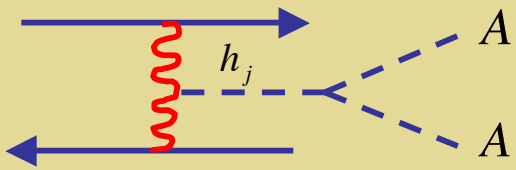
Production *Decay*

Invisible decays



Dijet azimuthal distribution

Jets + $\not{E}_T$



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

LHC & Higgs Phenomenology

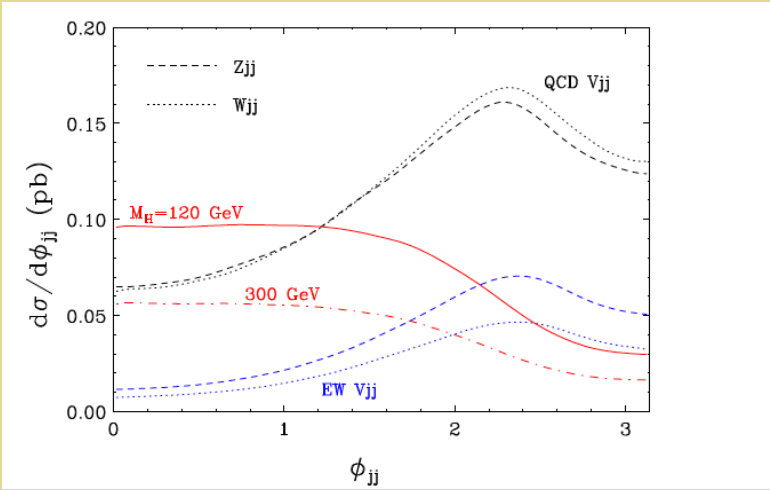
LHC discovery potential

Signal Reduction Factor

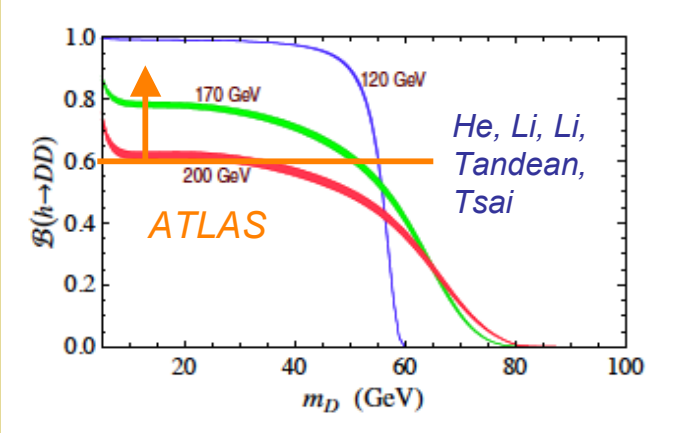
$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

Production

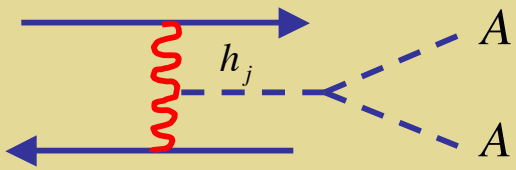
Decay



Invisible decays



Dijet azimuthal distribution



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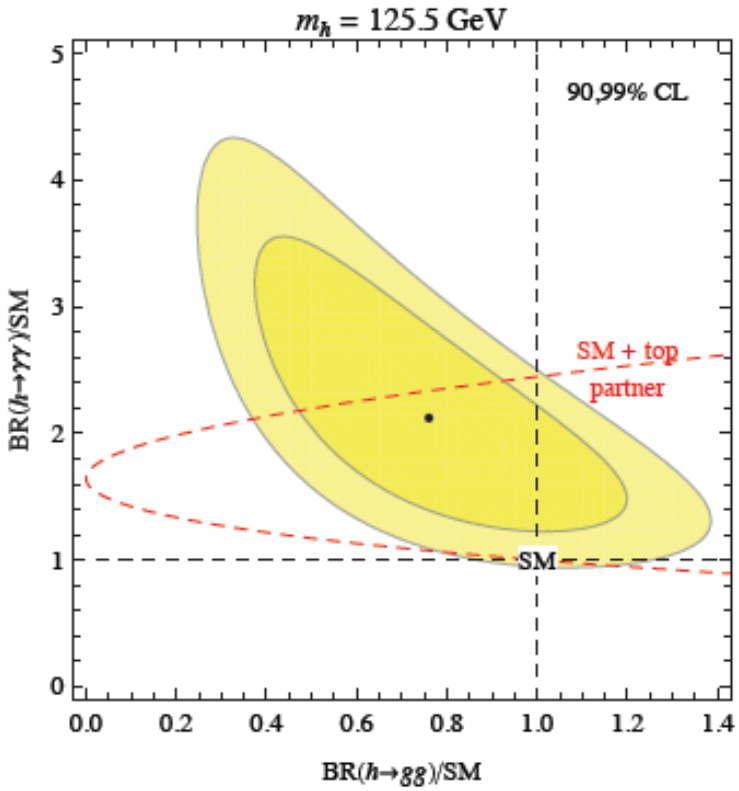
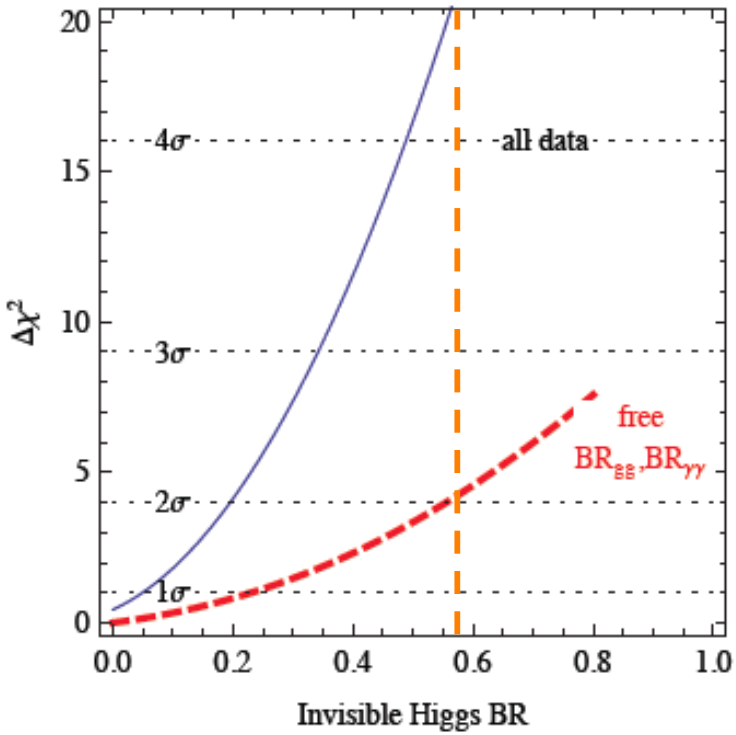
LHC & Higgs Phenomenology





Giardino et al:
arXiv 1207:1347

Higgs Portal: Simple Scalar Extensions

Extension	*DOF*	*EWPT*	*DM*
Real singlet	*1*	✔	✖
Real singlet	*1*	✖	✔
Complex Singlet	*2*	✔	✔
Real Triplet	*3*	✔	✔

May be low-energy remnants of UV complete theory & illustrative of generic features

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Spontaneously & softly broken global U(1) $\langle S \rangle \neq 0$

$$V_{HS} = \frac{\delta_2}{2} H^\dagger H |\tilde{S}|^2 = \frac{\delta_2}{2} H^\dagger H (S^2 + A^2)$$

↓

Controls Ω_{CDM}, T_C, & H-S mixing

$$V_{\tilde{S}} = \frac{b_2}{2} |\tilde{S}|^2 + \frac{b_1}{2} \tilde{S}^2 + \text{c.c.} + \cdots$$

↓

Gives non-zero M_A

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Consequences:

Three scalars: h_1 , h_2 : *mixtures of h & S*

A : dark matter

Phenomenology:

- *Produce* h_1 , h_2 *w/ reduced* σ
- *Reduce BR* ($h_j \rightarrow$ *SM)*
- *Observation of BR (invis)*
- *Possible obs of* σ^{SI}

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Consequences:

Impact EWPO

Three scalars:

h_1 , h_2 : mixtures of h & S

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Phenomenology:

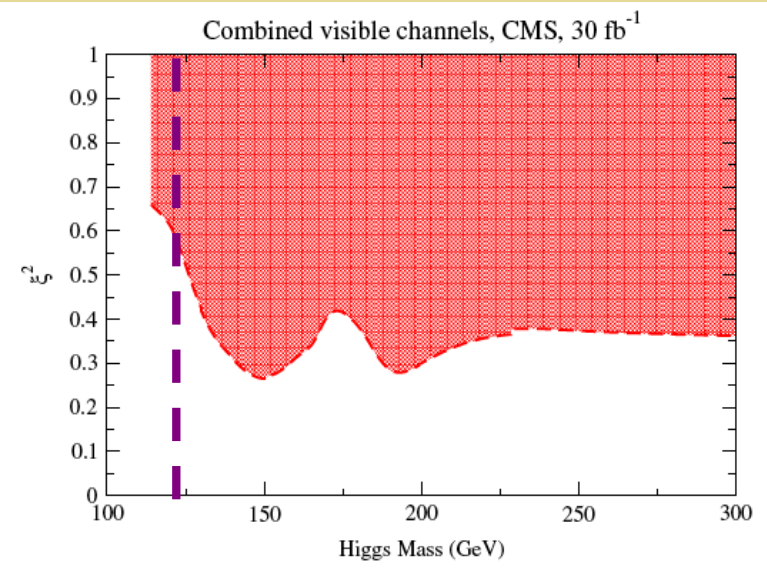
- Produce h_1 , h_2 w/ reduced σ
- Reduce BR ($h_j \rightarrow$ SM)
- Observation of BR (invis)
- Possible obs of σ^{SI}

Complex Singlet: LHC Discovery

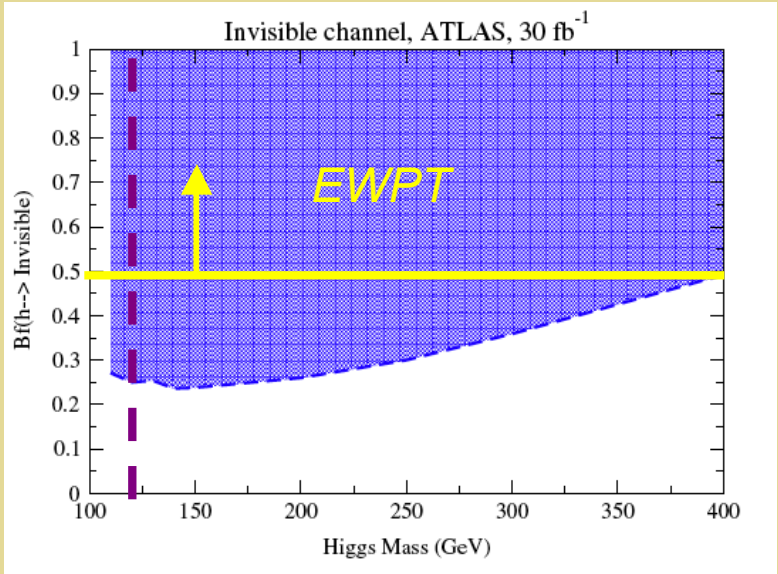
Barger, Langacker, McCaskey, R-M, Shaugnessy

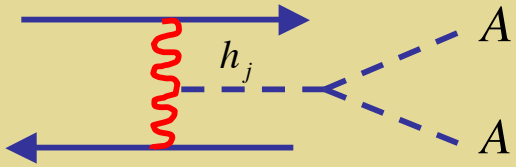
Single component case ($x_0 \neq 0$)

Traditional search: CMS



Invisible search: ATLAS

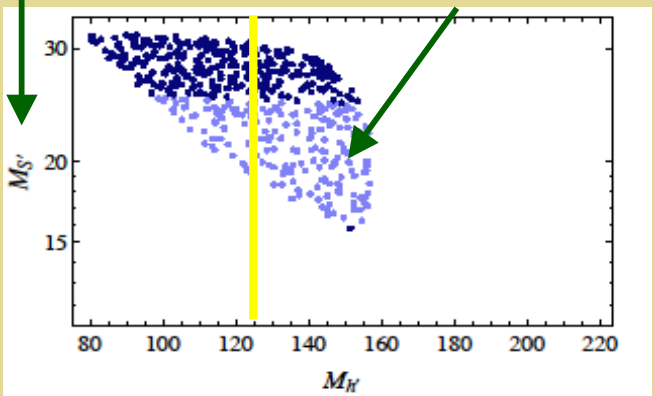




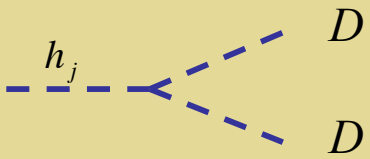
Complex Singlet: New Light State ?

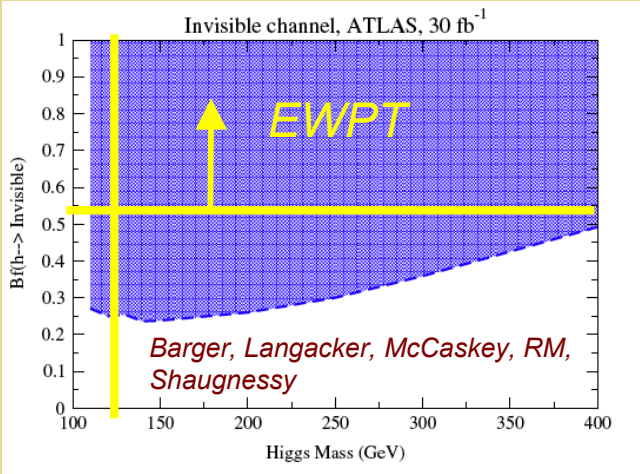
2nd light state

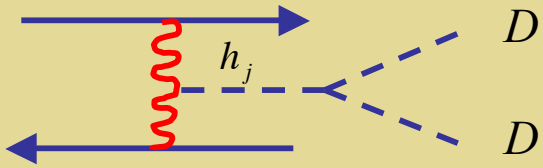
- $\Omega_{TH} < \Omega_{WMAP}$
- $\sigma < \sigma_{Xenon}$
- Br(inv) > 0.6



Gonderinger, Lim, R-M







Three scalars: $h_{1,2}$ (Higgs-like)
D (dark matter)

LHC: WBF "Invisible decay" search

Higgs Portal: Simple Scalar Extensions

Extension	*DOF*	*EWPT*	*DM*
Real singlet	*1*	✔	✖
Real singlet	*1*	✖	✔
Complex Singlet	*2*	✔	✔
Real Triplet	*3*	✔	✔

Simplest non-trivial EW multiplet

Real Triplet

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

Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]

$$V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

EWPT: $a_{1,2} \neq 0$ & $\langle \Sigma^0 \rangle \neq 0$

DM & EWPT: $a_1 = 0$ & $\langle \Sigma^0 \rangle = 0$

Real Triplet

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Small: ρ-param

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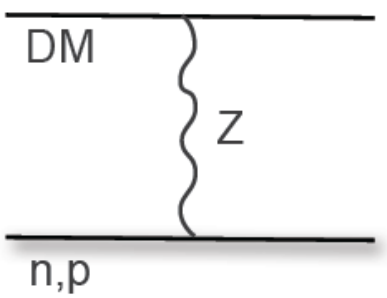
$$V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

New feature: gauge interactions & direct detection



$$\sigma_n \sim \frac{g_1^2}{4\pi^2} \frac{m_{n,p}^2}{m_Z^4} \sim 10^{-39}\mathrm{cm}^2$$

$g_{\chi\chi Z} \propto 2\, I_3 - 4\, Q \sin^2 \theta_W$

$Y = 2\,(\,Q - I_3\,)$

→ *Want Y = 0*

Real Triplet

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

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

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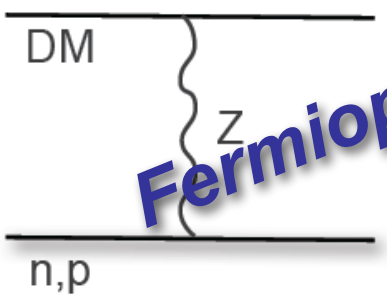

Fermiophobic

$$\sigma_n \sim \frac{g_1^2}{4\pi^2} \frac{m_{n,p}^2}{m_Z^4} \sim 10^{-39}\mathrm{cm}^2$$

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→ Want $Y = 0$

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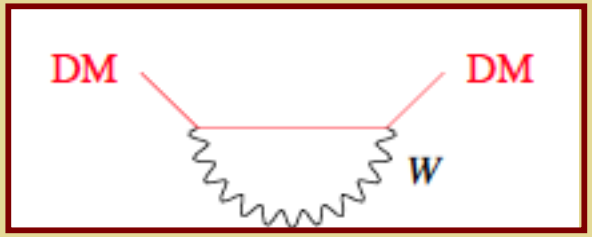
Fileviez-Perez, Patel, Wang,
R-M: 0811.3957 [hep-ph]

$$V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

EWPO

$$T_\Sigma \approx -\frac{1}{6\pi\hat{s}^2}\frac{(\Delta M)^2}{M_W^2}.$$

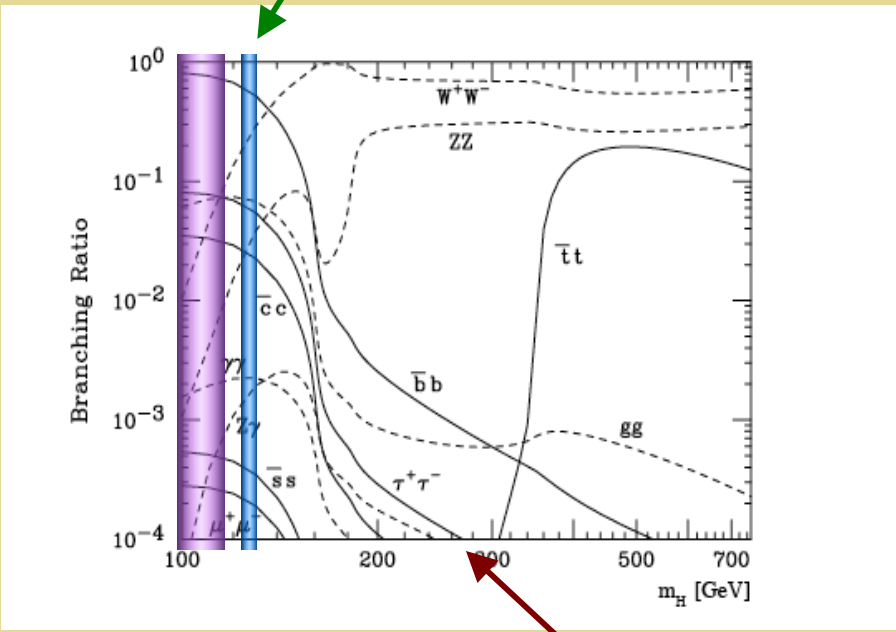


$\alpha S \sim \Pi_{3Y} = 0$

ΔM = 166 MeV

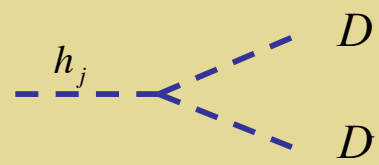
LHC Phenomenology

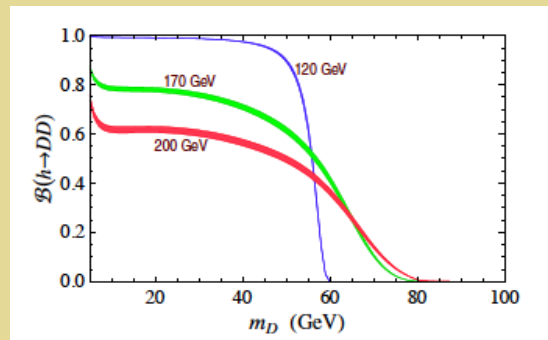
SM Branching Ratios ?

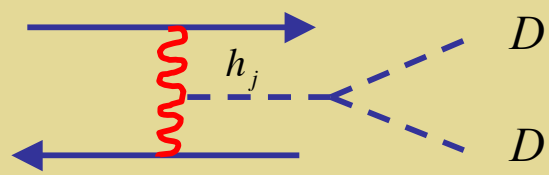


Four scalars: h_1 (Higgs-like)
Σ^0 (dark matter)
Σ^+ , Σ^- (new states)

Fileviez-Perez, Patel, R-M, Wang







LEP: M_Σ > 100 GeV $\rightarrow$
BR(invis) = 0

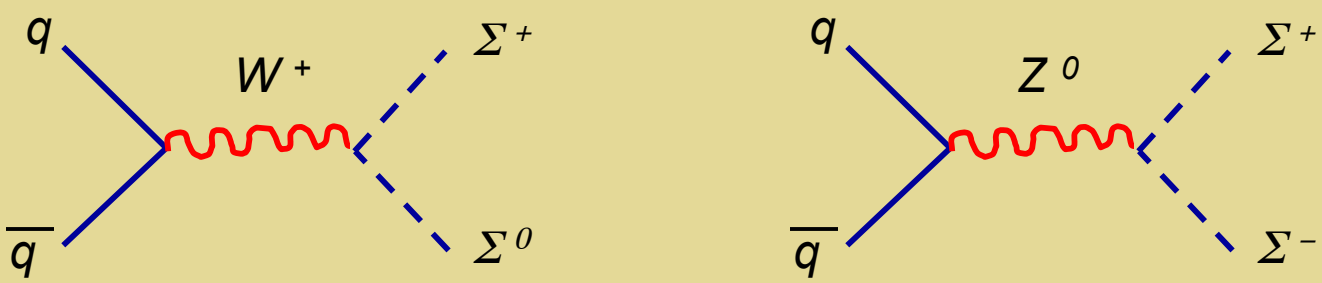
Production

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

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

$$V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

New feature: gauge interactions & LHC production

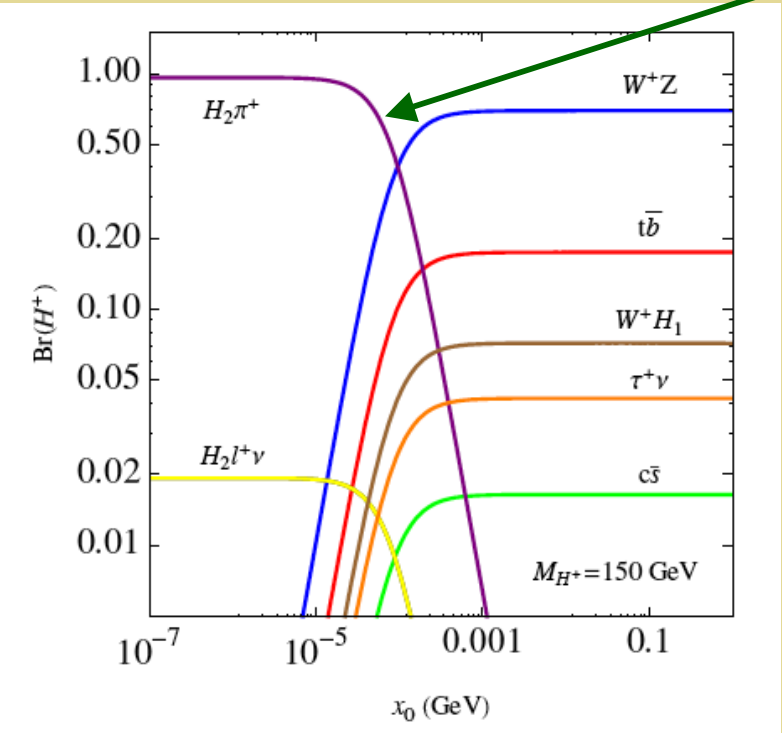


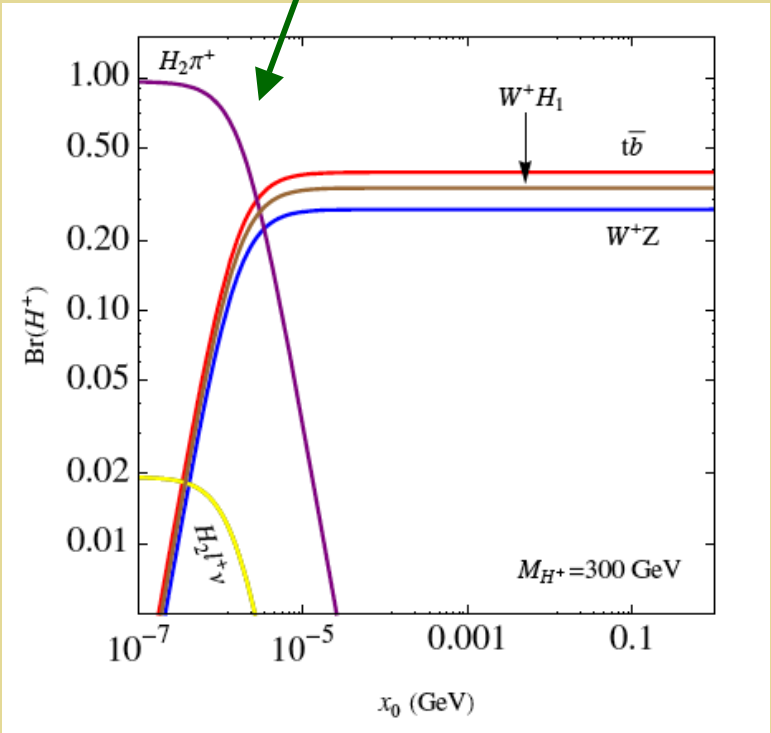
EW cross sections w/ charged states + $\not{E}_T$

Decays : Charged BRs

Charged: x_0 dependence

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





Below WZ Threshold

DM: $x_0 = 0$

Above WZ Threshold

Decays : Charged BRs

Charged: x_0 dependence

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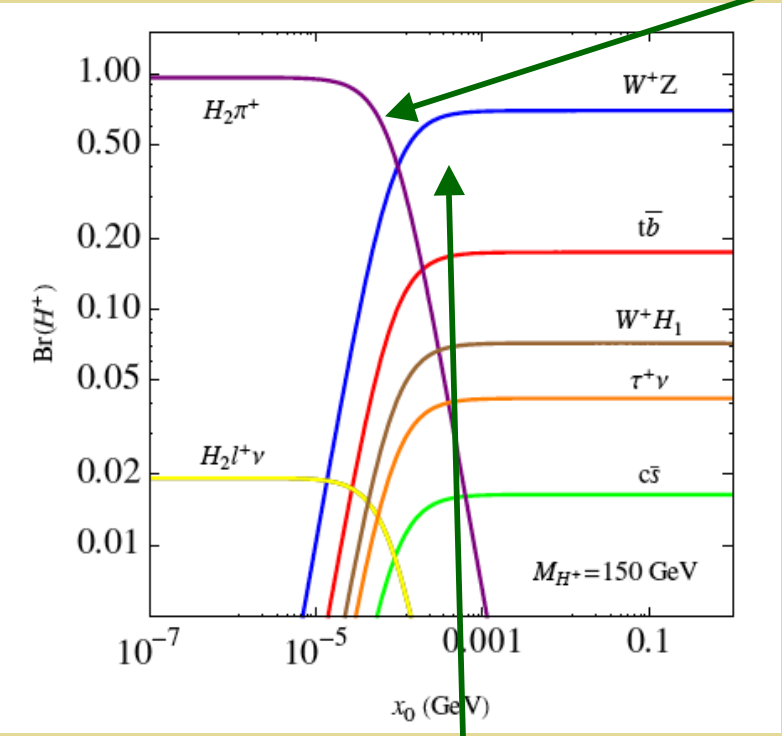
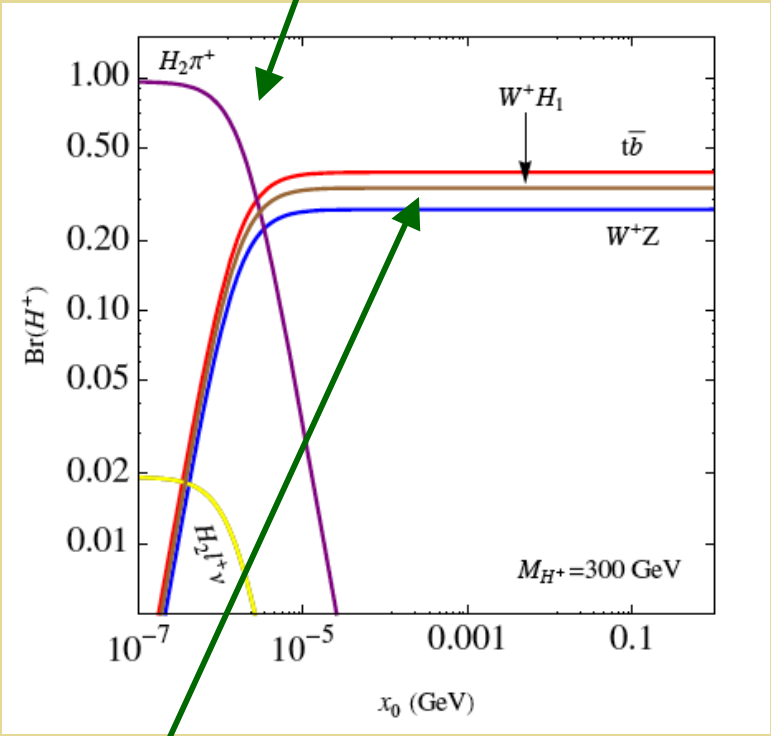




Below WZ Threshold

$H^{\pm} \rightarrow W^{\pm} Z, f_1 \bar{f}_2$ *x_0 dependent*

Above WZ Threshold

Real Triplet : DM Search

Basic signature:

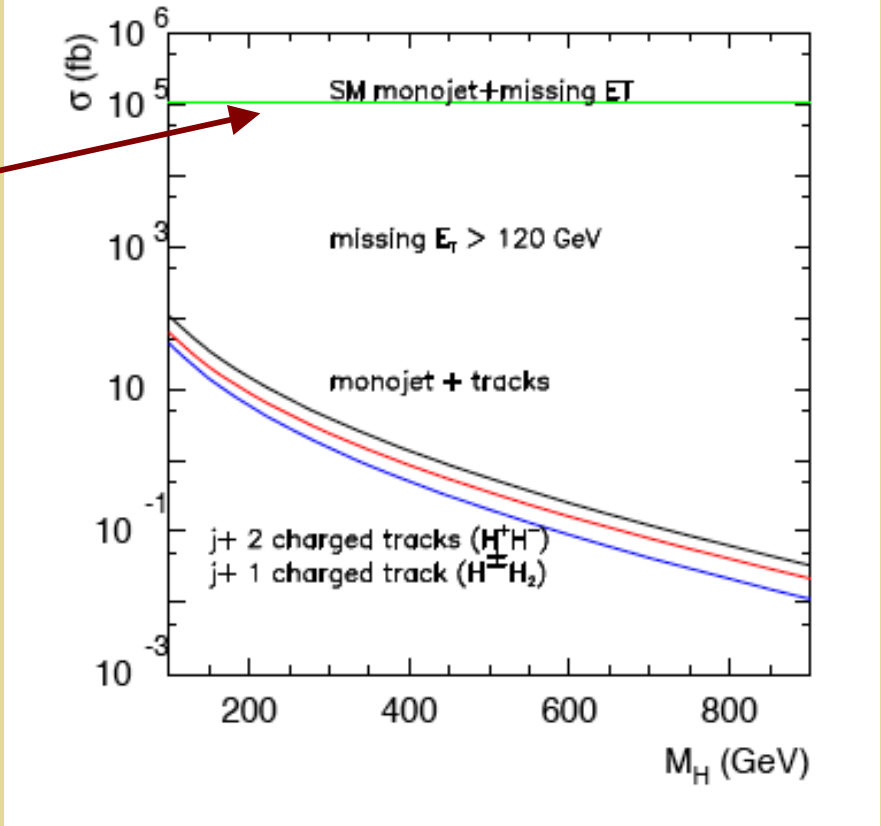
$x_0 = 0 : H^{\pm} \to H_2 \pi^{\pm}$

Charged track disappearing after ~ 5 cm

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

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

SM Background: QCD jZ and jW w/ Z →νν & W→lν



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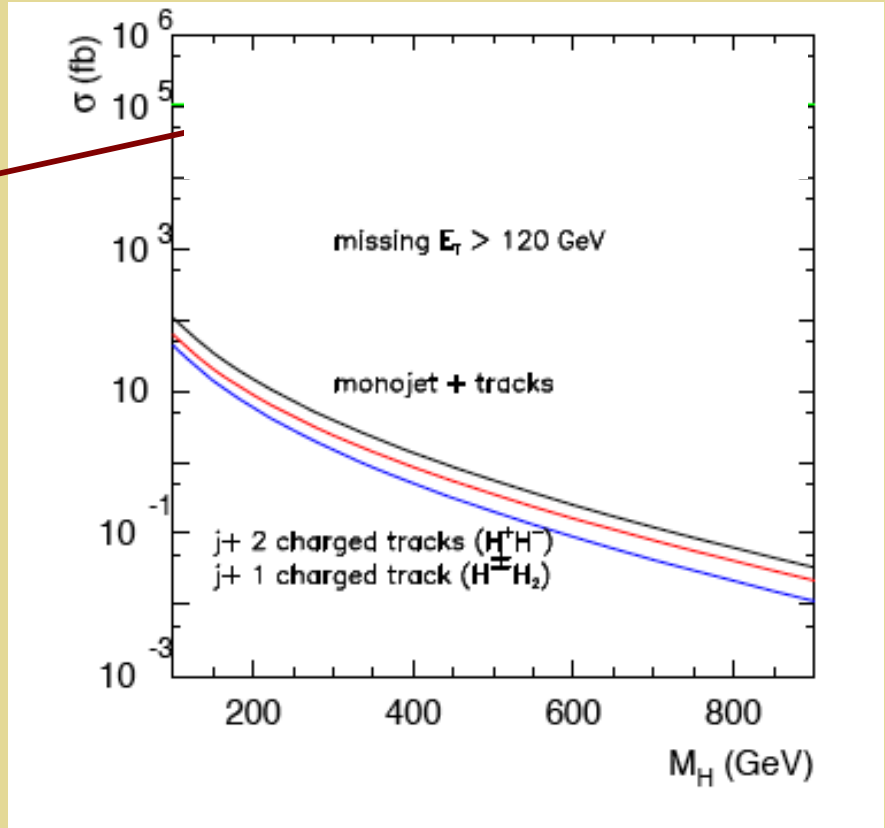
Trigger: Monojet (ISR) + large $\not{E}_T$

SM Background:
QCD jZ and jW w/
Z →νν & W→lν

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



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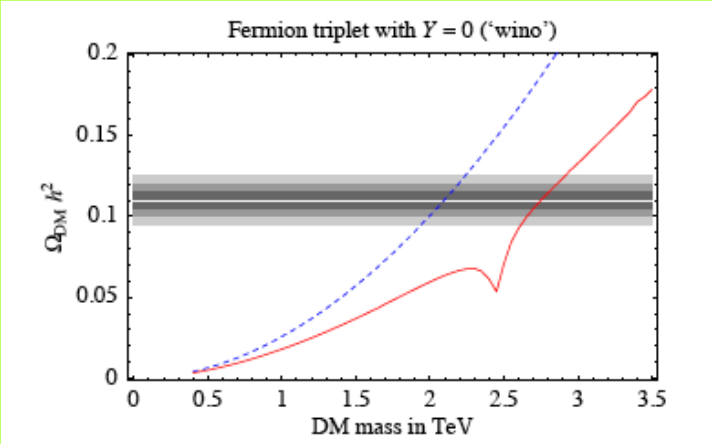
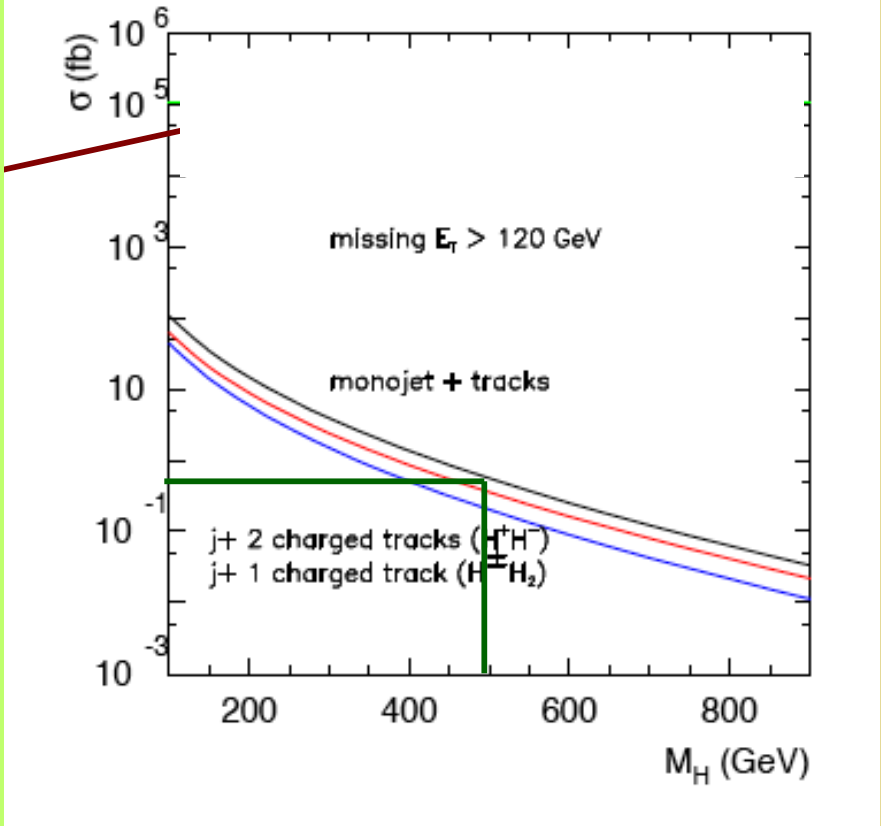
Cirelli et al:



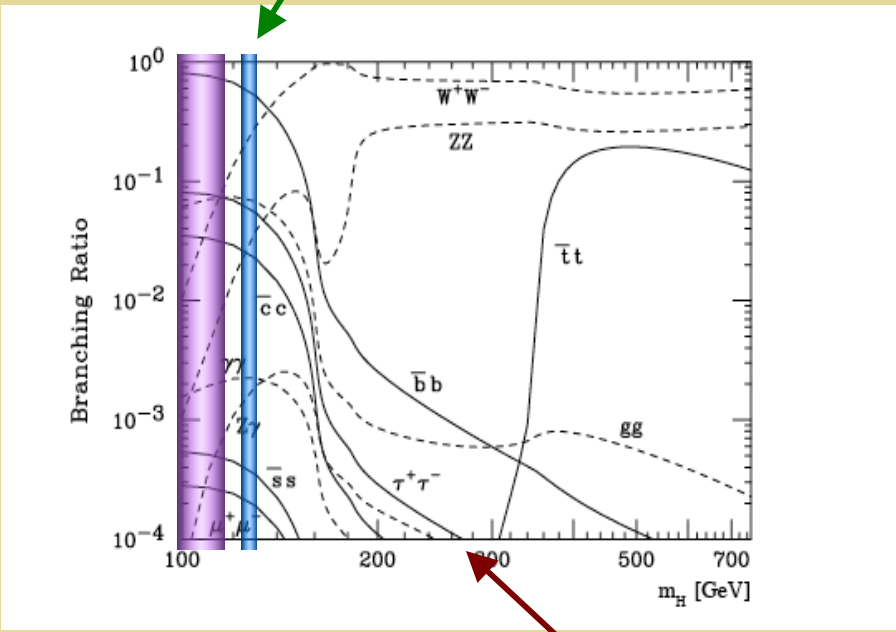


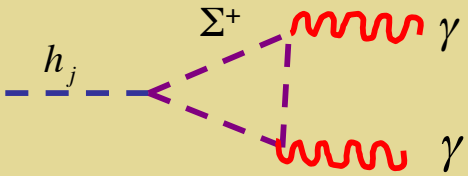
M_Σ = 500 GeV:

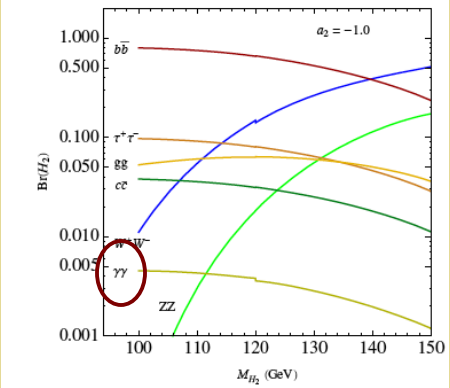
$\Omega_\Sigma / \Omega_{CDM}$ ~ 0.1

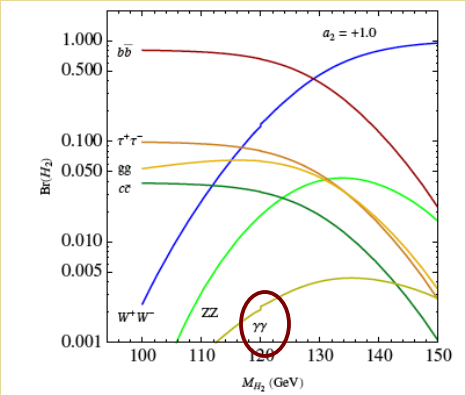
Higgs Diphoton Decay

SM Branching Ratios ?







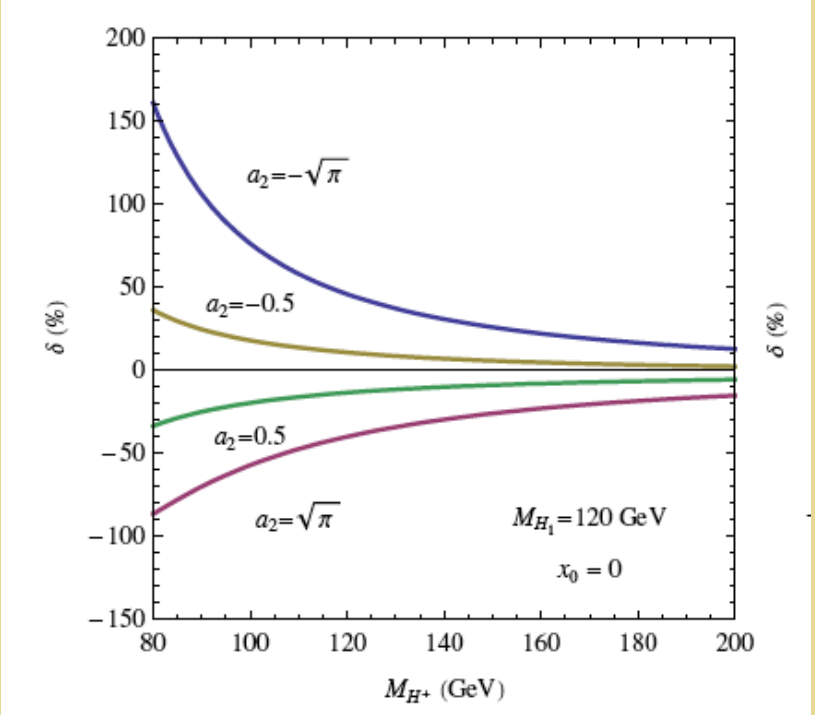


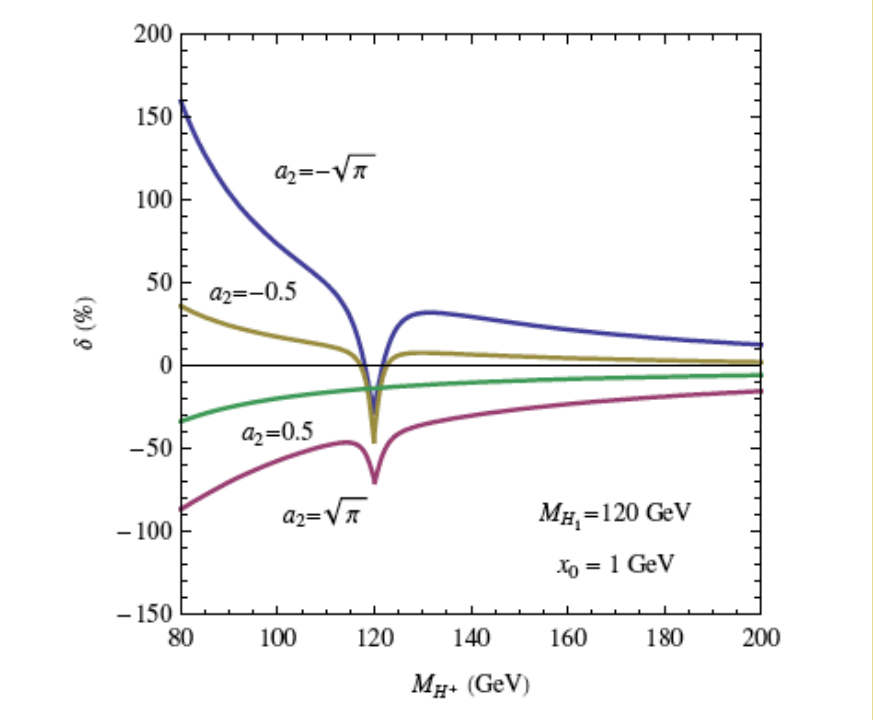
Four scalars: h_1 (Higgs-like)
Σ^0 (dark matter)
Σ^+ , Σ^- (new states)

Fileviez-Perez, Patel, R-M, Wang

Real Triplet : H_1 Diphoton Decays

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



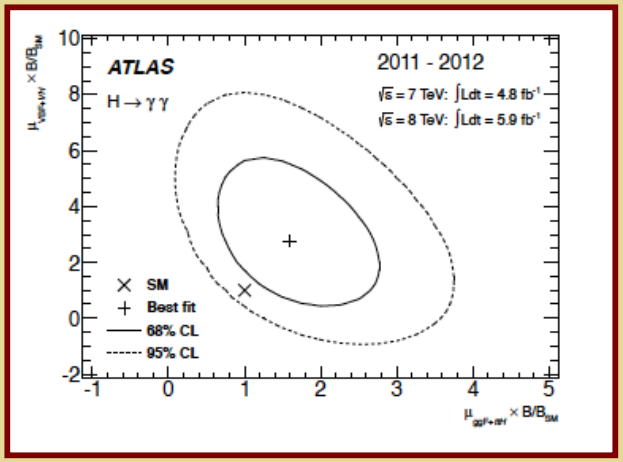


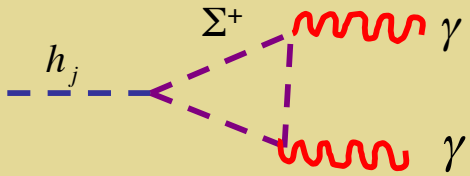
X_0=0: DM & EWPT case

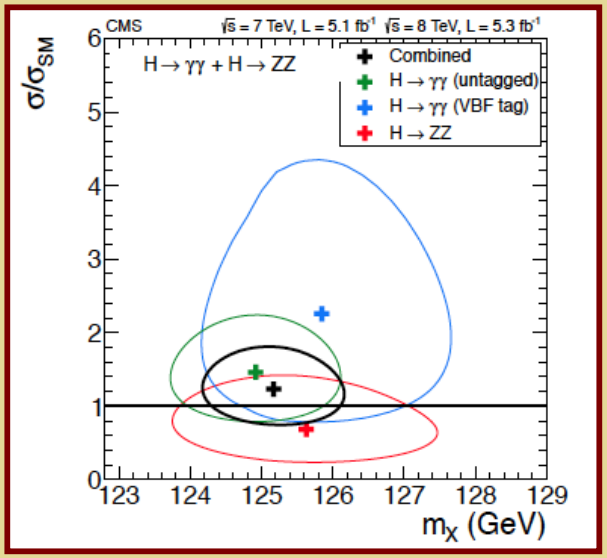
X_0>0: EWPT case

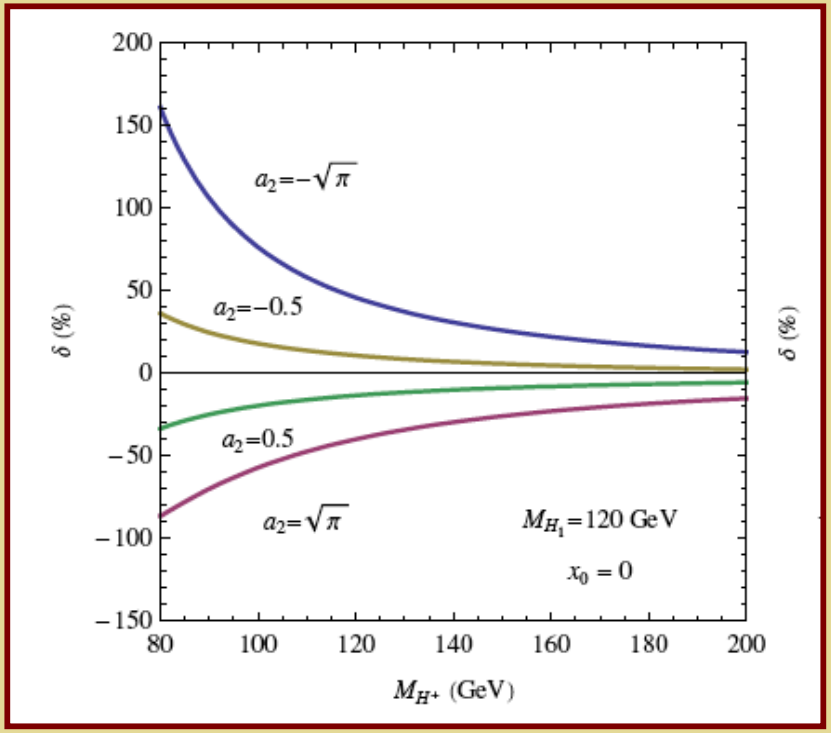
Higgs Diphoton Decays

LHC: H $\rightarrow \gamma\gamma$

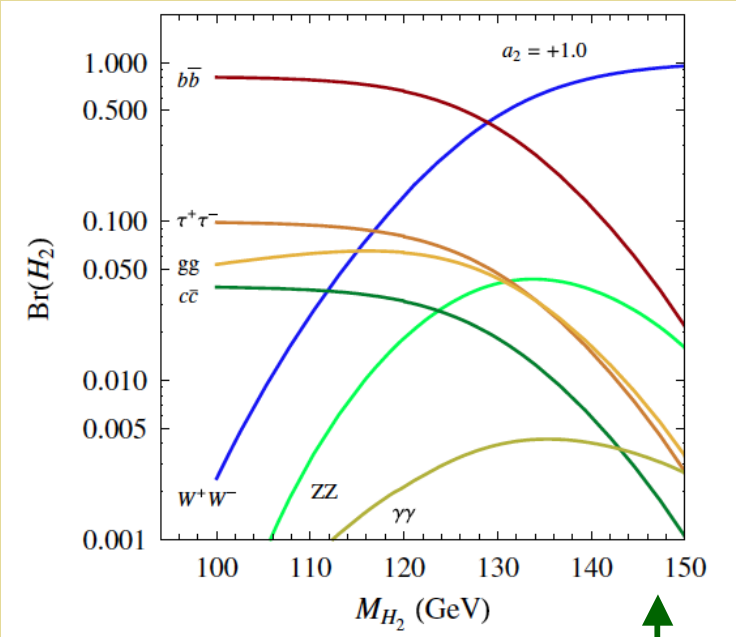


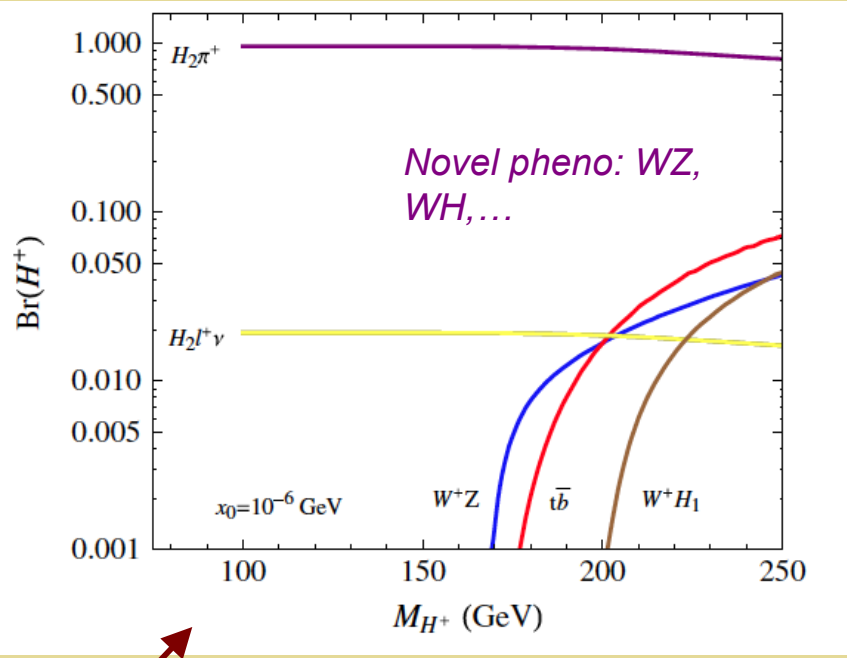






EWPT: Heavier States ?





Four scalars: h_1 (Higgs-like)

$h_2 \sim \Sigma^0$ (unstable)

Σ^+ , Σ^- (new states)

Topologies:

bb $\tau\,\nu$

$\gamma\gamma$ $\tau\nu$ ...

Fileviez-Perez, Patel, R-M, Wang

VI. Discussion

Higher Dim Multiplets

Cirelli, Forengeno, Strumia '05

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

See also Cai, He, R-M, Tsai '11; Kumericki et al '12:

Neutrino portal w/ $\phi \sim (1,6,-1/2)$

→ *Rich collider pheno w/ σ_{EW}*

Is it a Scalar ?

Extension	*DOF*	*EWPT*	*DM*
Real singlet	*1*	✔	✖
Real singlet	*1*	✖	✔
Complex Singlet	*2*	✔	✔
Real Triplet	*3*	✔	✔

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Extension	*DOF*	*EWPT*	*DM*
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Complex Singlet	*2*	✔	✔
Real Triplet	*3*	✔	✔

Mixed Higgs-like states and/or modified BRs: signal reduction ξ , invisible search…

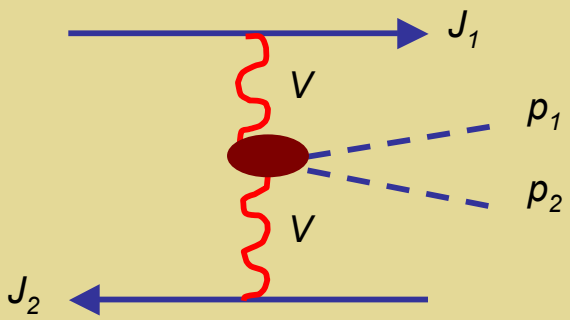
Is it a Scalar ?

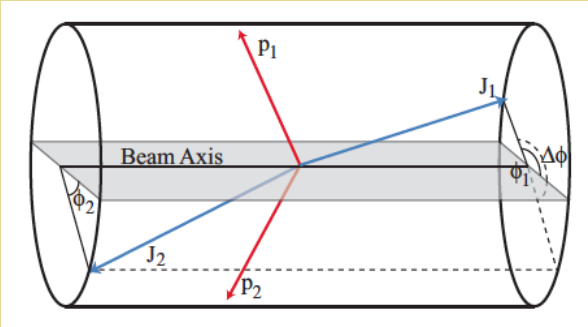
Extension	*DOF*	*EWPT*	*DM*
Real singlet	*1*	✔	✖
Real singlet	*1*	✖	✔
Complex Singlet	*2*	✔	✔
Real Triplet	*3*	✔	✔

Could be fermionic triplet [e.g., Buckley, Randall, Shuve, JHEP 1105 (2011) 97]. How to distinguish?

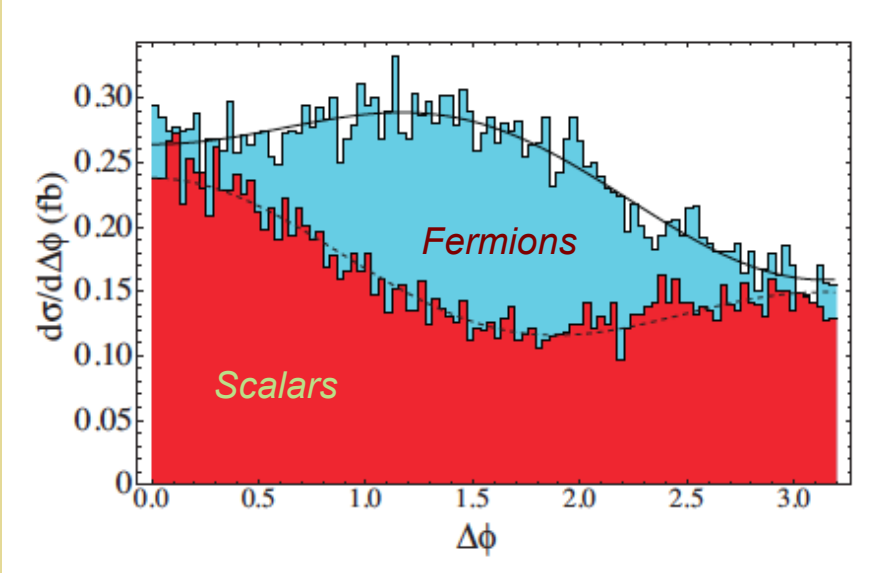
Di-Jet Correlations

Buckley, R-M JHEP 1109 (2011) 094





R-hadrons from gg fusion



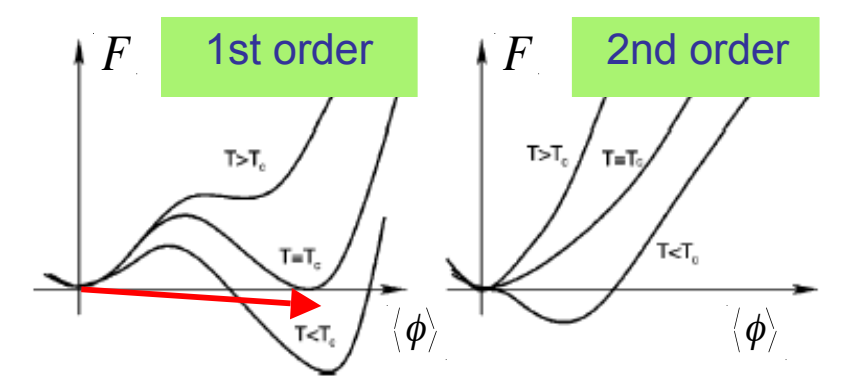
Summary

- *Observation of ~125 GeV Higgs-like scalar makes Higgs portal particularly interesting window on a number of questions: EW vacuum stability, gauge hierarchy, dark matter, EW phase transition…*
- *Higgs portal presents a rich array of possible signatures: modified Higgs properties, new (heavy) states, new event topologies associated w/ mixing and/or EW cross sections*

Back Up Slides

Electroweak Phase Transition

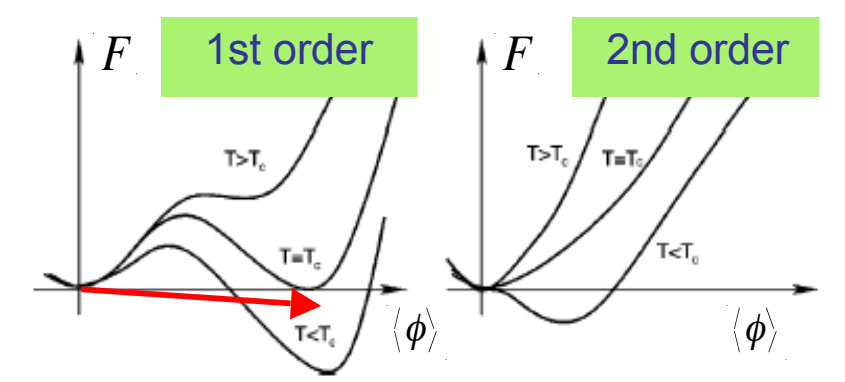
EW Phase Transition: New Scalars



Increasing m_h →

← *New scalars*

EW Phase Transition: New Scalars

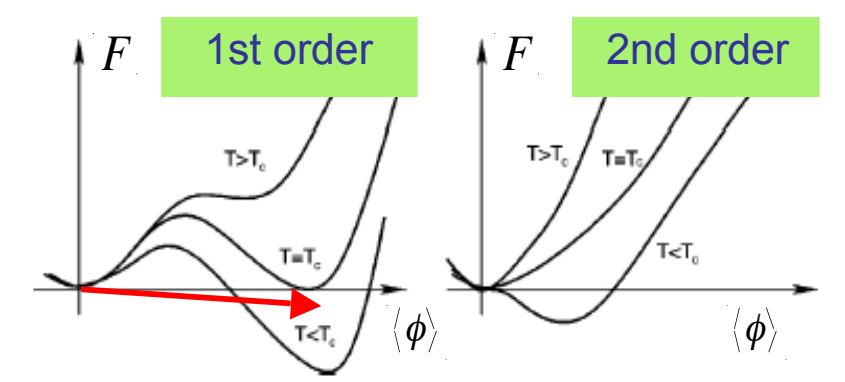


Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

EW Phase Transition: New Scalars



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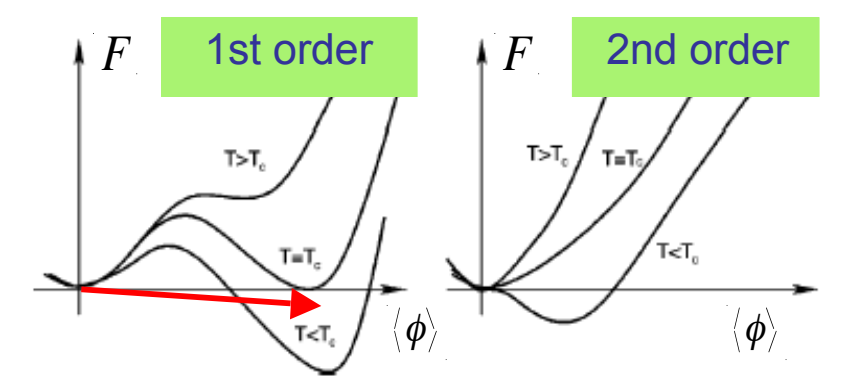
"Strong" 1st order EWPT

EW Phase Transition: New Scalars



Increasing m_h →

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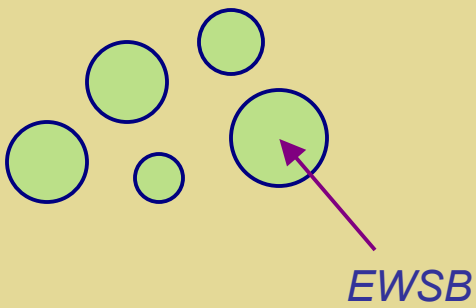
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

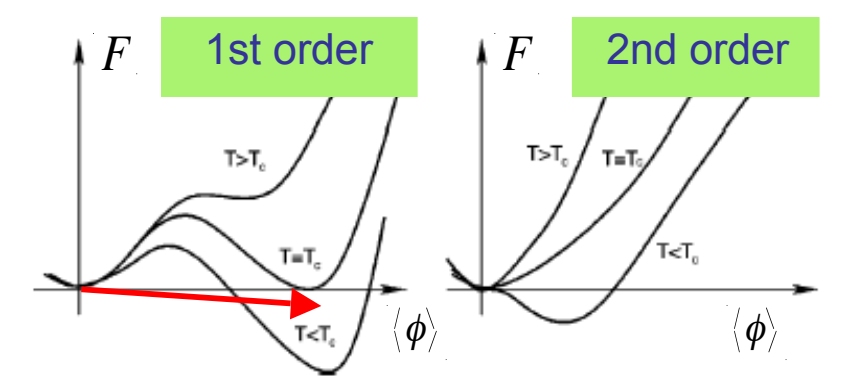
"Strong" *1st order EWPT*

↓

Bubble nucleation



EW Phase Transition: New Scalars



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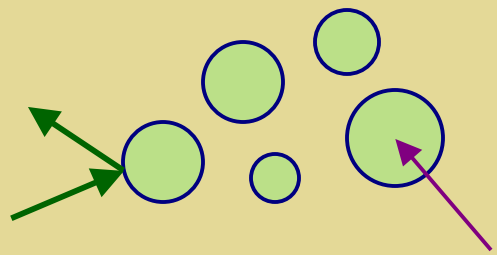
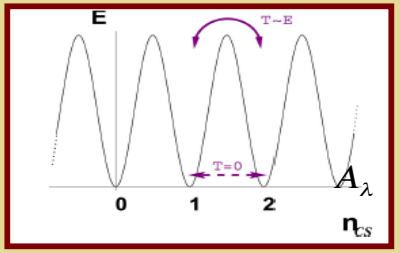
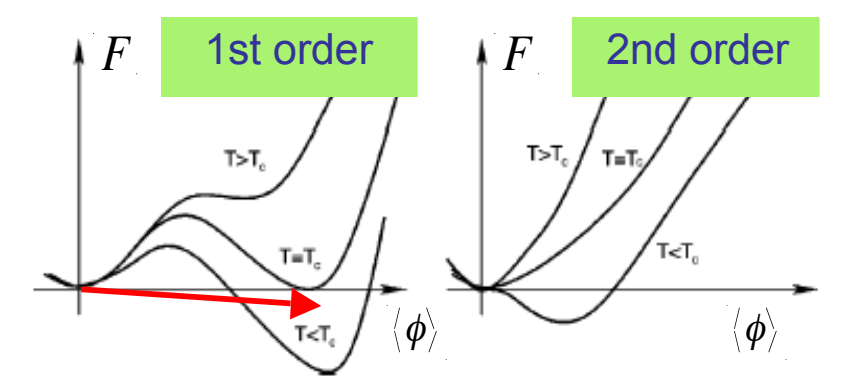


Y_B : CPV & EW sphalerons

EWSB



EW Phase Transition: New Scalars



Increasing m_h →

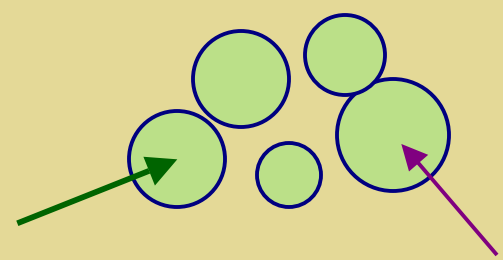
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1st order EWPT*

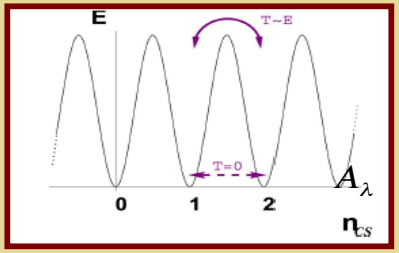
↓

Bubble nucleation

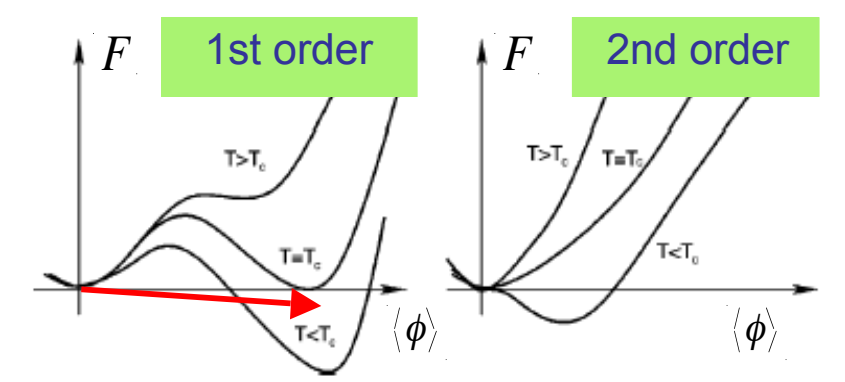


Y_B : diffuses into interiors

EWSB



EW Phase Transition: New Scalars



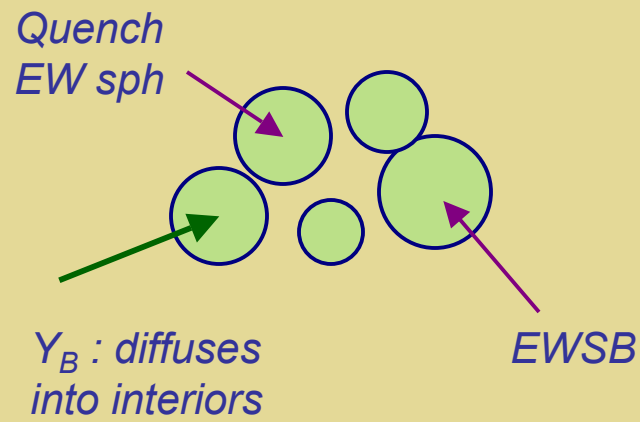
Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

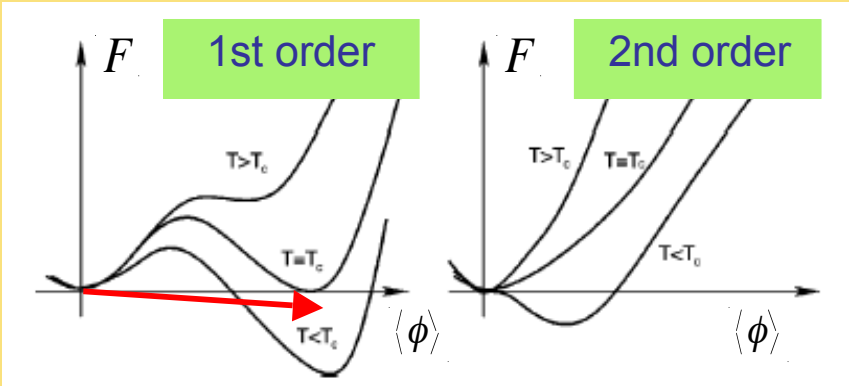
"Strong" | *1st order EWPT*

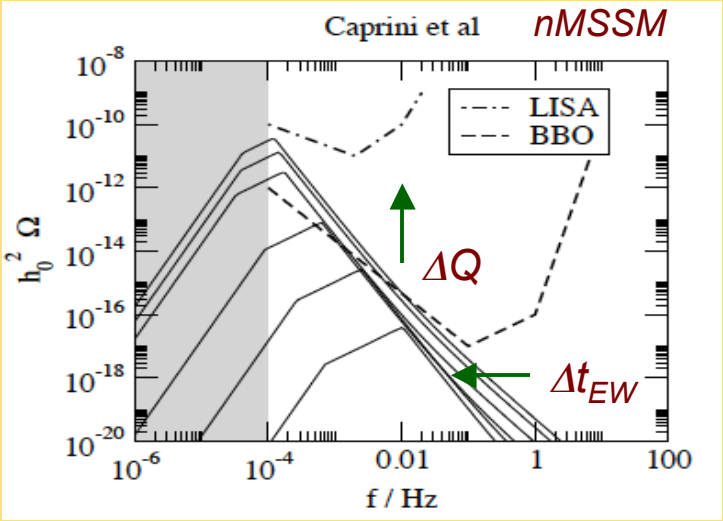
Preserve $Y_B^{initial}$ | *Bubble nucleation*



T_C , E_{sph}, S_{tunnel} ↔ $F(\phi)$

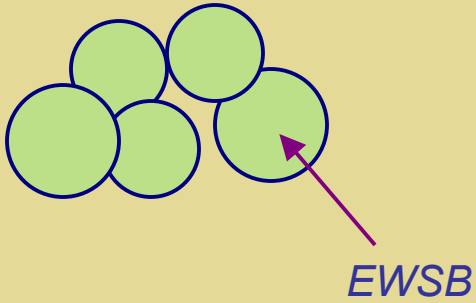
EW Phase Transition: New Scalars





"Strong" → Detonation & turbulence

1st order EWPT → Bubble nucleation



GW Spectra: ΔQ & Δt_{EW} ⟷ $F(\phi)$