Inert Higgs Doublet Model:

Dark Matter Implication and Collider Phenomenology

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In collaboration with E. Dolle, X. Miao and B. Thomas

Outline

- Introduction
- Inert Higgs Doublet Model
- Experimental and Theoretical Constraints
- Dark Matter Relic Density
- Collider Phenomenology

Dark matter candidate

WMAP: Ωh^2=0.112 ± 0.009

WIMP: natural candidate for dark matter

- **Spin 1/2 DM: neutralino LSP in MSSM**
- **Spin 1 DM: LKP photon in UED** G. Servant and I.M.P.Tait, NPB 650, 391 (2003)
- **Spin 0 DM**
  - **SM + extra scalar S**

    V. Silveira and A. Zee, PLB 161, 136 (1985)
    J. McDonald, PRD 50, 3637 (1994)
    C.P. Burgess, M. Pospelov and T. ter Veldhuis, NPB 619, 709 (2001)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S\,\partial^\mu S - \frac{m_0^2}{2}\,S^2 - \frac{\lambda_S}{4}\,S^4 - \lambda\,S^2\,H^\dagger H$$

Viable DM region: 100 GeV ≤ m_h ≤ 200 GeV, 10 ≤ m_S ≤ 100 GeV

fine tuned !

- **SM + extra $SU(2)_L$ scalar doublet: WIMP**

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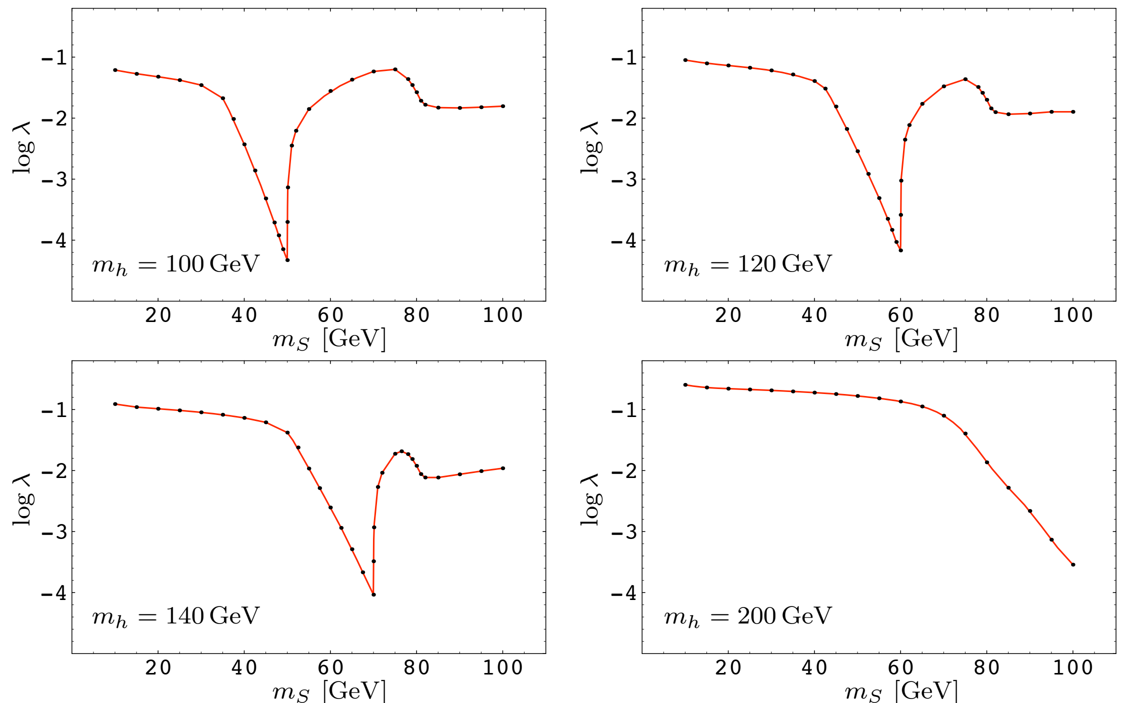

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Inert Higgs Doublet Model

➡ Introduce another Higgs field that only couples to gauge sector

impose Z_2 parity: SM particles + , extra Higgs: -

$$H_1 = H_{\rm SM} \qquad H_2 = \begin{pmatrix} H^+ \\ (S+iA)/\sqrt{2} \end{pmatrix}$$

→ lightest one: DM candicate

"Inert" Higgs Doublet Model (IHDM)

- first proposed in late 70's, neutrino mass

  N.G.Deshpande and E. Ma, PRD 18, 2574 (1978)
- naturalness problem in SM R. Barbieri, L.J. Hall and V.S. Rychkov, PRD 74, 015007 (2006)
- appears in left-right Twin Higgs models

  Z. Chacko, H.S. Goh and R. Harnik, JHEP 0601, 108 (2006)
- majorana neutrino mass E. Ma, PRD 73, 077301 (2006)
- electroweak symmetry breaking T. Hambye and M.H.G. Tytgat, PLB 659, 651 (2008)
- grand unification M. Lisanti and J.G. Wacker, 0704.2816
- leptogenesis E. Ma, MPLA 21, 1777 (2006),
  T. Hambye, K. Kannike, E. Ma and M. Raidal, PRD75, 095003 (2007)

Dark matter studies

- **relic density** L. Honorez, E. Nezri, J. Oliver, M. Tytgat, JCAP 0702, 028 (2007)
- **direct detection**
  R. Barbieri, L.J. Hall and V.S. Rychkov, PRD 74, 015007 (2006)
  L. Honorez, E. Nezri, J. Oliver, M. Tytgat, JCAP 0702, 028 (2007)
  D. Majumdar and A. Ghosal, MPLA23, 2011 (2008)
- **neutrino signature**
  P. Agrawall, E.M. Dolle and C.A. Krenke, PRD 79, 015015 (2009)
  S. Andreas, M.H.G. Tygat and Q. Swillens, 0901.1750
- **gamma ray spectrum**
  L. Honorez, E. Nezri, J. Oliver, M. Tytgat, JCAP 0702, 028 (2007)
  M. Gustafsson, E. Lundstrom, L. Bergstrom and J. Edsjo, PRL99, 041301 (2007)
- **positron and antiproton** E. Nezri, M.H.G. Tytgat and G. Vertongen, 0901.2556
- **LEP II limit** E. Lundstrom, M. Gustafsson and J. Edsjo, 0810.3924
- **collider SA with $A \to SII$**
  Q.H. Cao, E. Ma and G. Rajasekaran, PRD 76, 095011 (2007)

S. Su

IHDM: parameters

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

$$\begin{aligned} m_h^2 &= -2\mu_1^2 = 2\lambda_1 v^2 \\ m_{H^\pm}^2 &= \mu_2^2 + \lambda_3 v^2/2, \\ m_S^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2/2, \\ m_A^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2/2. \end{aligned}$$

$$\delta_1 = m_{H^\pm} - m_S = -\frac{(\lambda_4 + \lambda_5)v^2}{2(m_{H^\pm} + m_S)}, \quad \delta_2 = m_A - m_S = -\frac{\lambda_5 v^2}{(m_A + m_S)}.$$

$$(\mu_1^2, \mu_2^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5) \rightarrow (v, m_h, m_S, \delta_1, \delta_2, \lambda_2, \lambda_L)$$

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SSh coupling $\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$

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SAH$^\pm$ couplings not important for DM analysis

SSh coupling $\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$

Constraints

✦ W and Z decay width

W→S/A + H$^\pm$, Z→S+A, H$^+$H$^-$

$$2m_S + \delta_1 > m_W, \quad 2m_S + \delta_1 + \delta_2 > m_W,$$
$$2m_S + \delta_2 > m_Z, \quad 2m_S + 2\delta_1 > m_Z.$$

✦ LEP II constraints

Neutral and charged Higgs searches at LEP and Tevatron: does not apply

rely on VVh coupling and the couplings of Higgses to fermions

Charged Higgs searches: $m_{H\pm}$ > 74 −79 GeV at 95% C.L.

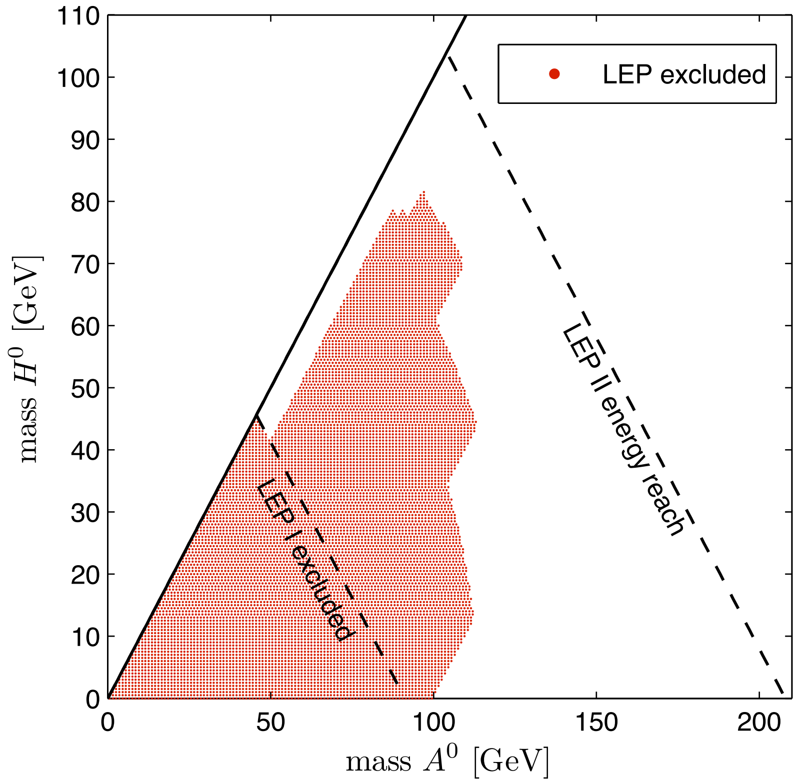
LEP: $H^+ \to c\bar{s}$, $H^+ \to \tau^+\nu$

CDF: t→H$^+$b, with H$^+$ decays to qq', lv, W$^+\phi$

Constraints

- LEP II constraints

MSSM searches: $e^+e^- \to \chi_1^0\, \chi_2^0$ with $\chi_2^0 \to \chi_1^0$ qq/μμ/ee
similar to $e^+e^- \to SA$ with $A \to S$qq/μμ/ee



E. Lundstrom, M. Gustafsson and J. Edsjo, 0810.3924

MSSM searches: $e^+e^- \to \chi_1^+\, \chi_1^-$ similar to $e^+e^- \to H^+H^-$
➡ $m_{H\pm} \geq 70$ GeV

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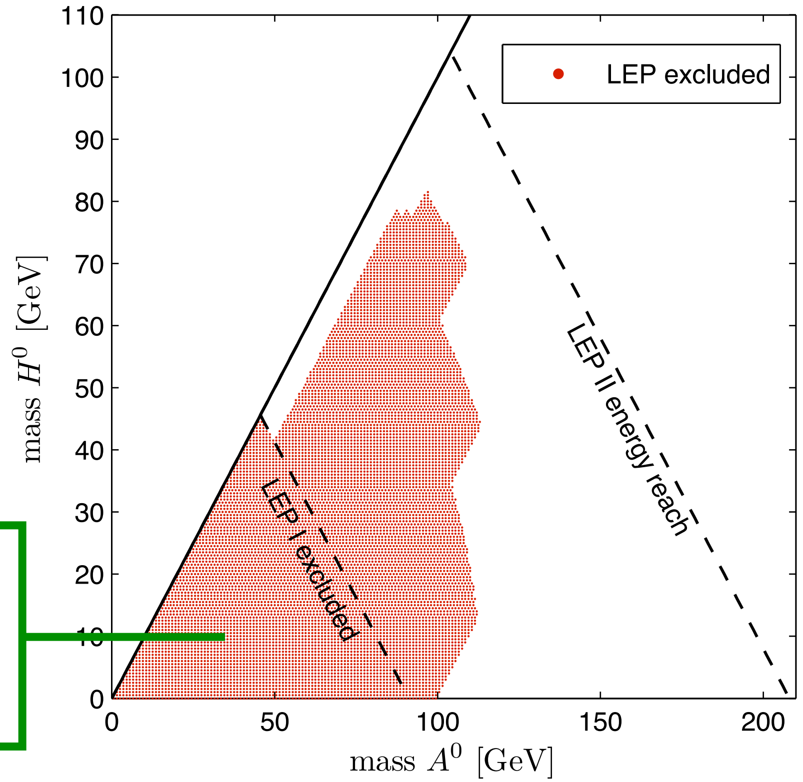

LEP I
$m_S + m_A < m_Z$
excluded

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✦ **LEP II constraints**

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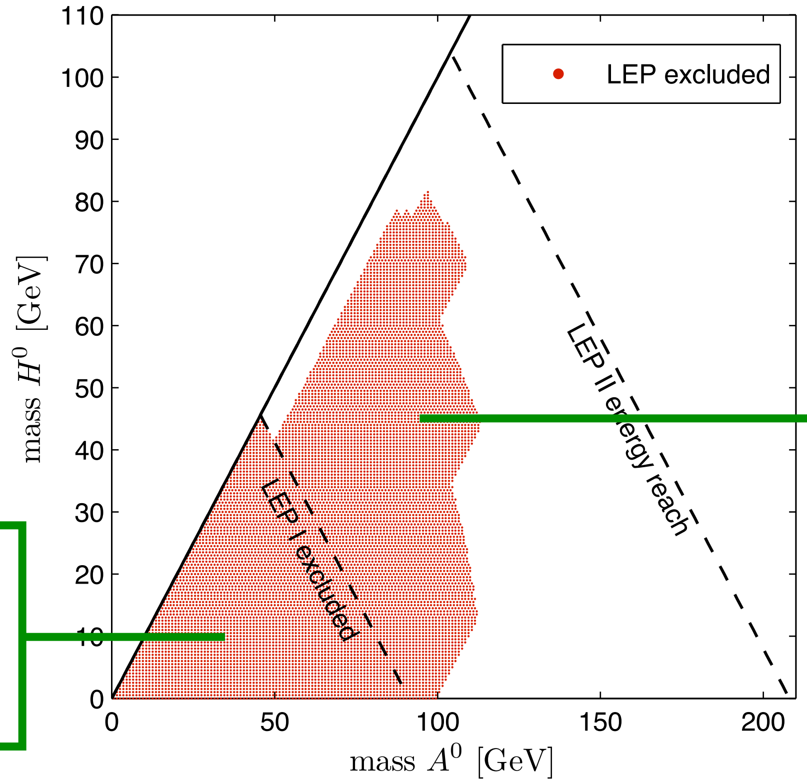

LEP II
δ_2 > 8 GeV
m_S < 80 GeV
m_A < 100 GeV
excluded

LEP I
$m_S + m_A < m_Z$
excluded

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- LEP II constraints

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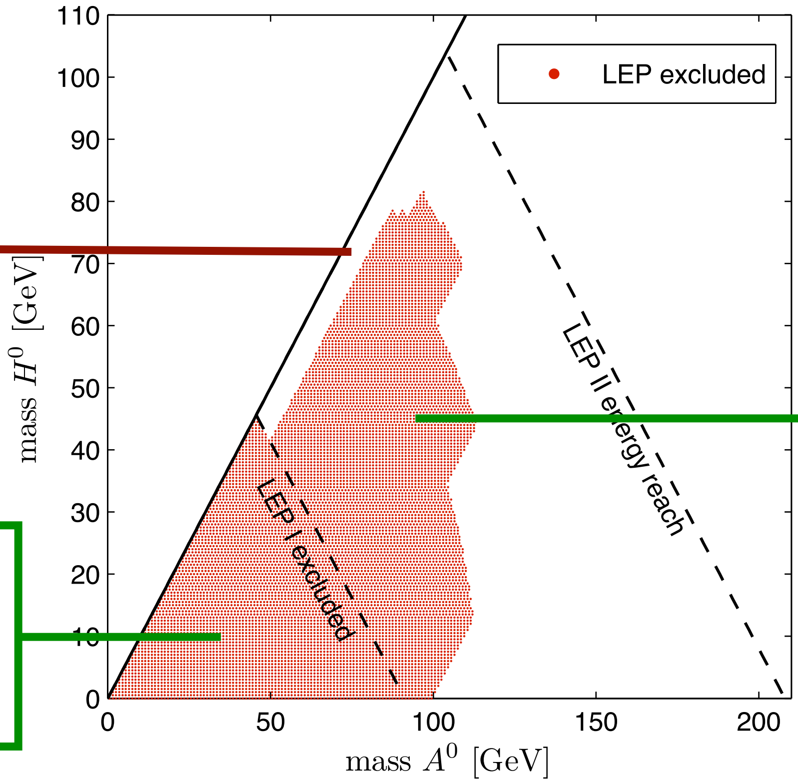
$\delta_2 < 8$ GeV
$m_S + m_A > m_Z$
allowed



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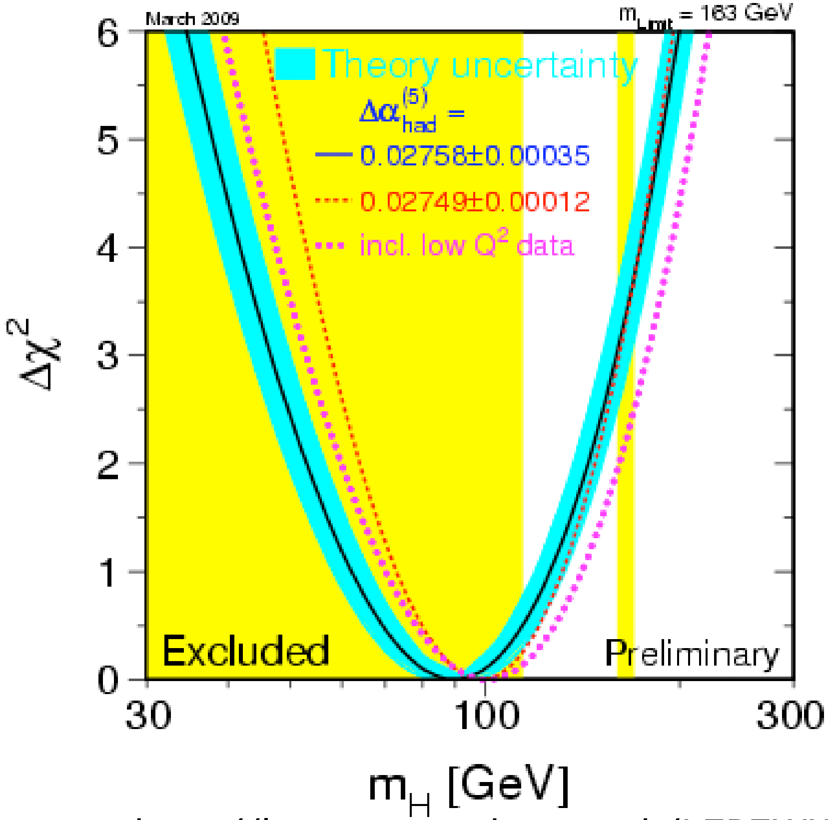
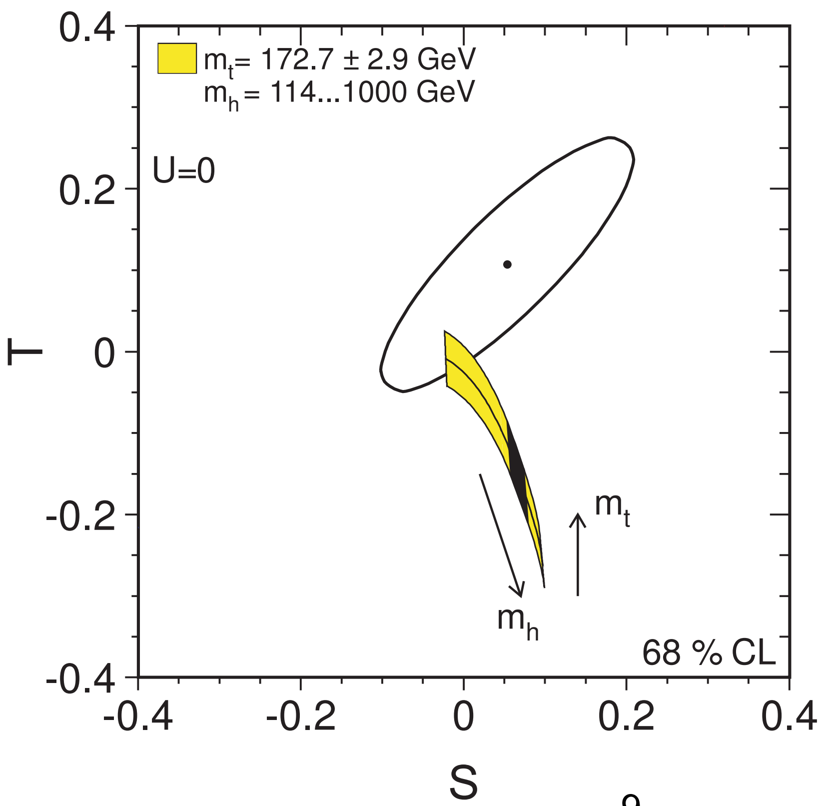
Electroweak Precision Test

- Electroweak precision test

$m_h = 90^{+36}_{-27}$ GeV

$m_h < 163$ GeV @ 95% C.L.



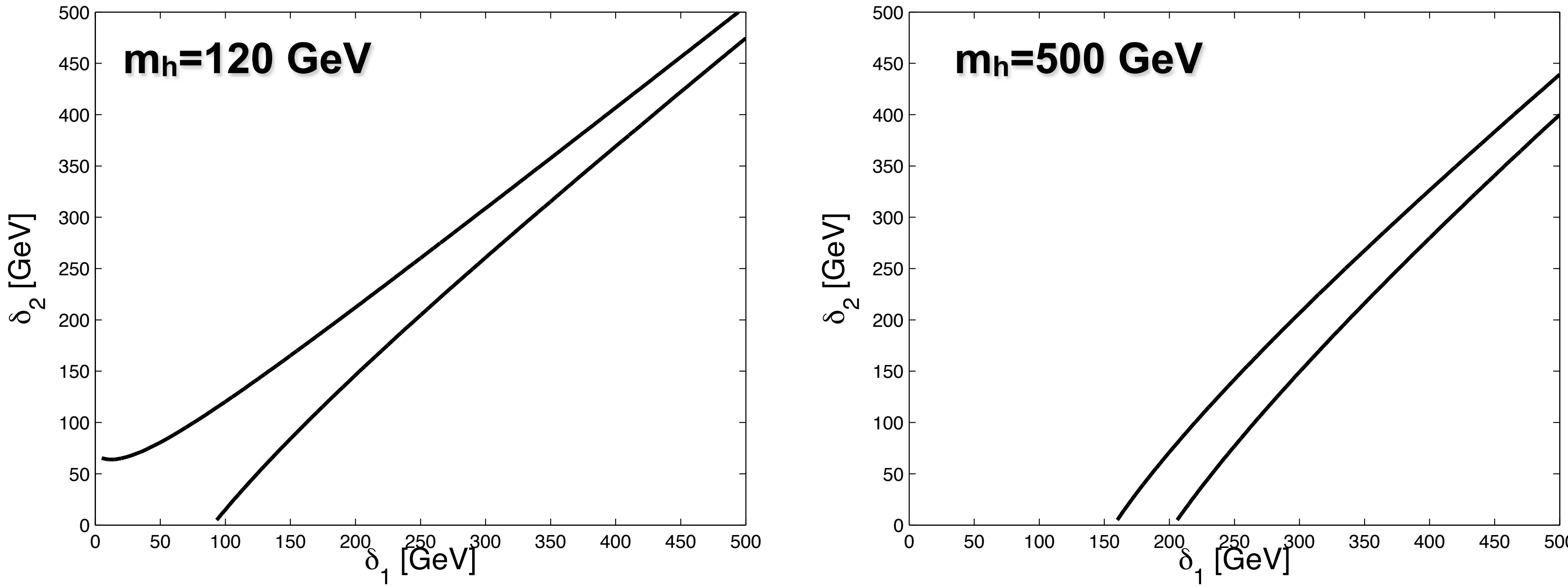


http://lepewwg.web.cern.ch/LEPEWWG/

Electroweak Precision Test

✦ **Electroweak precision test**

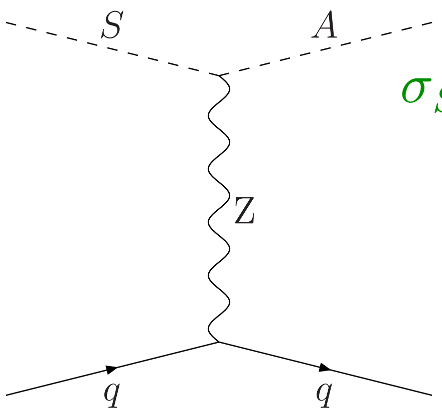
$$H_2 = \begin{pmatrix} H^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$$



m_S=75 GeV

Dark matter direct detection

✦ Dark matter direct detection



$$\sigma_{SI(Z)} = \frac{G_F^2 m_N^2}{2\pi}(N-(1-s_W^2)Z)^2 \sim 10^{-31}\mathrm{cm}^2$$

Current CDMS limit: 10^{-42} cm^2

Avoid such constraints if $|m_S - m_A| > 0.1$ GeV

Theoretical constraints

- Vacuum stability

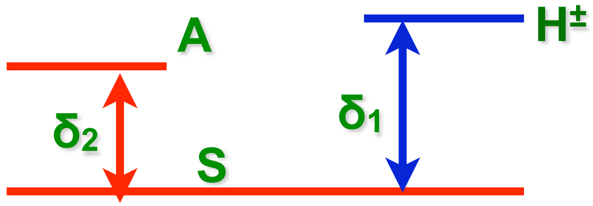
$$\lambda_{1,2} > 0$$
$$\lambda_3, \lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1 \lambda_2}.$$

- Perturbativity: RG running of λ_1 from non-SM terms < 50% of SM term

$$\lambda_3^2 + (\lambda_3 + \lambda_4)^2 + \lambda_5^2 < 12\lambda_1^2$$
$$\lambda_2 < 1$$

Dark matter relic density

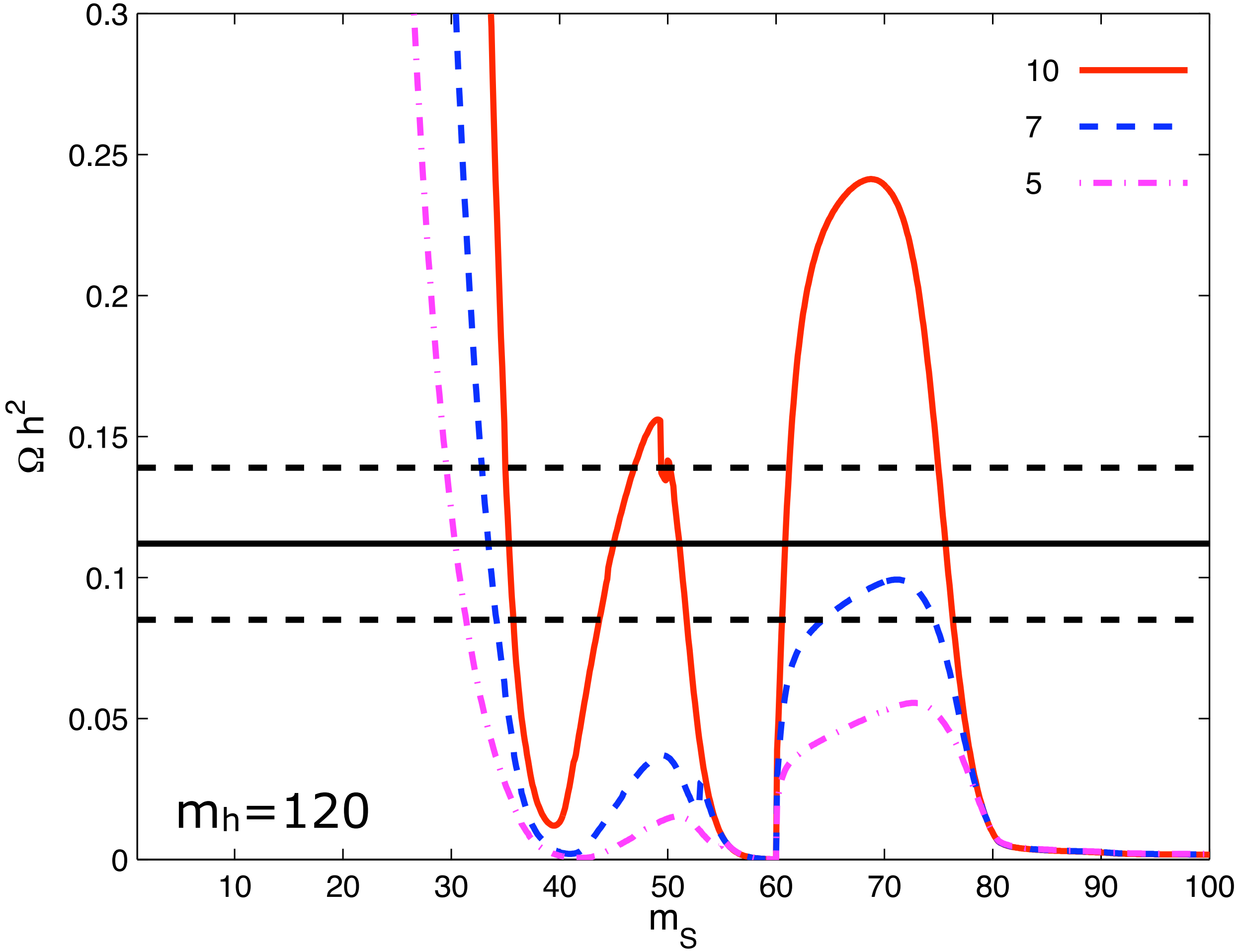
- coannihilation of S, A $\delta_2 = m_A - m_S$
- coannihilation of S, $H^\pm$ $\delta_1 = m_{H\pm} - m_S$



- Use MicrOMEGA /CalCHEP to calculate the relic density
  - ➡ low mass region: $m_S < 100$ GeV
  - ➡ high mass region: $m_S > 400$ GeV

Low mass region: vary δ_2

$\delta_1 = m_{H\pm} - m_S$ = 50 GeV, λ_L=0.01



- $\delta_2 = m_A - m_S$ = 10 GeV
- $\delta_2 = m_A - m_S$ = 7 GeV
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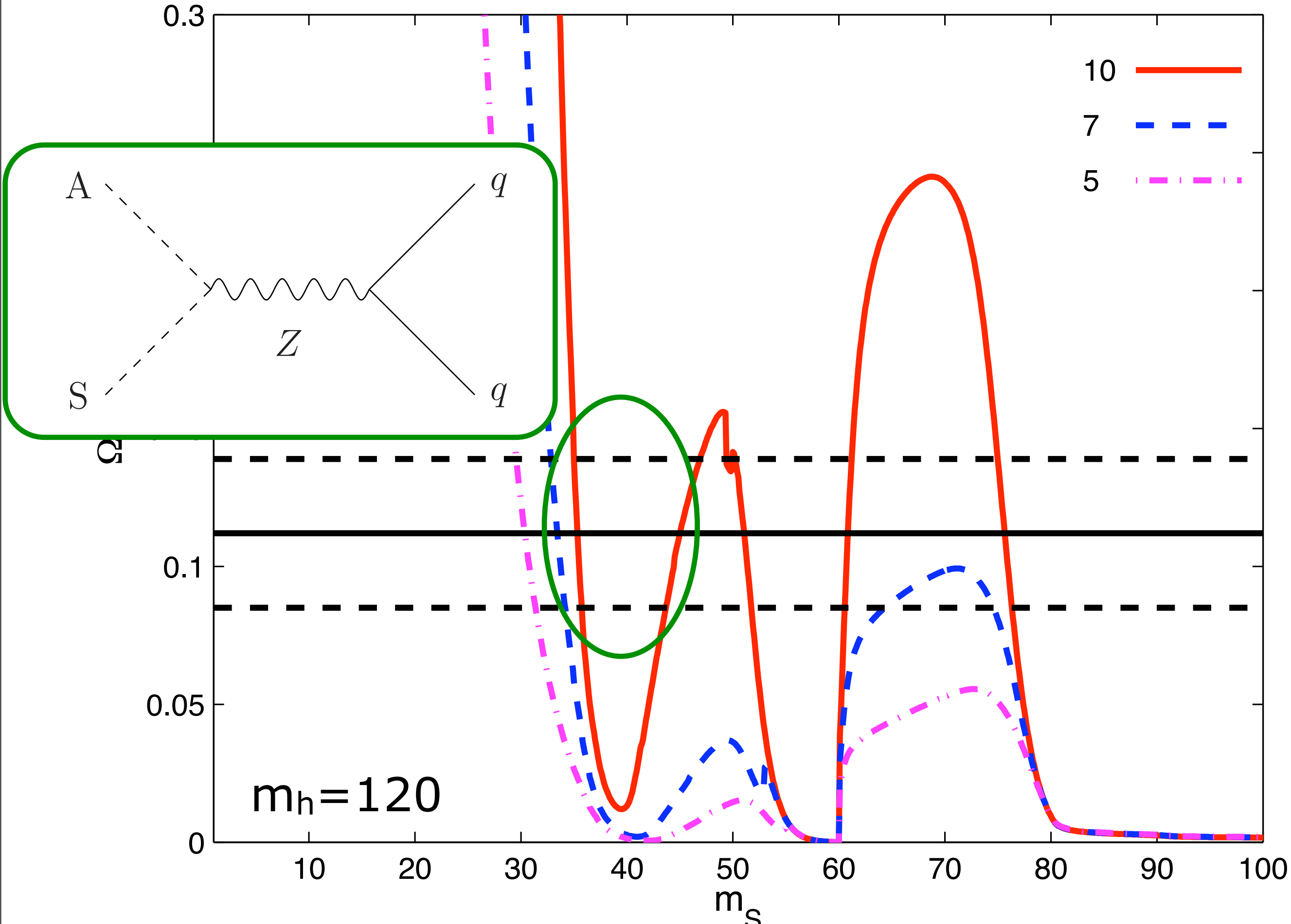

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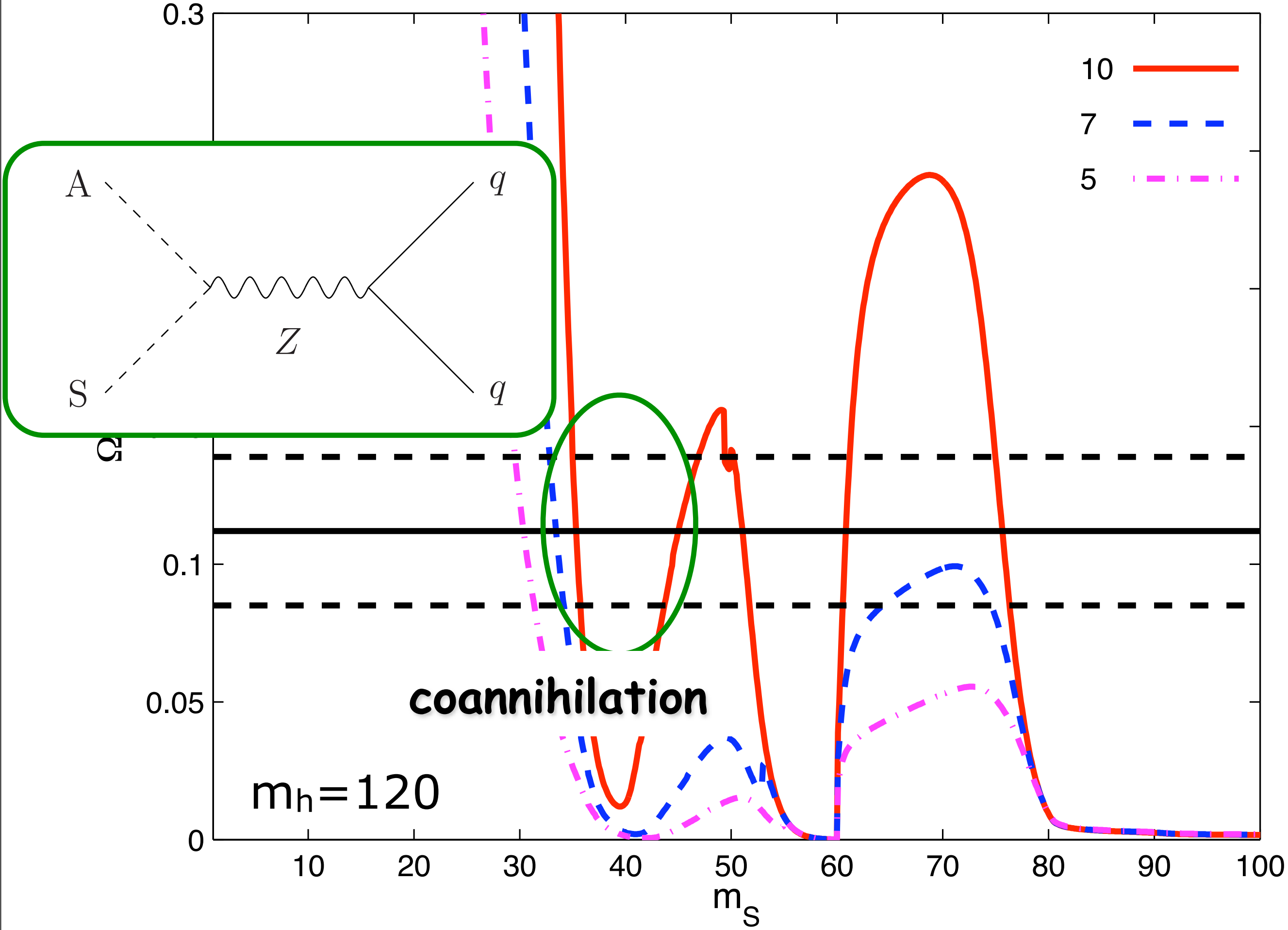

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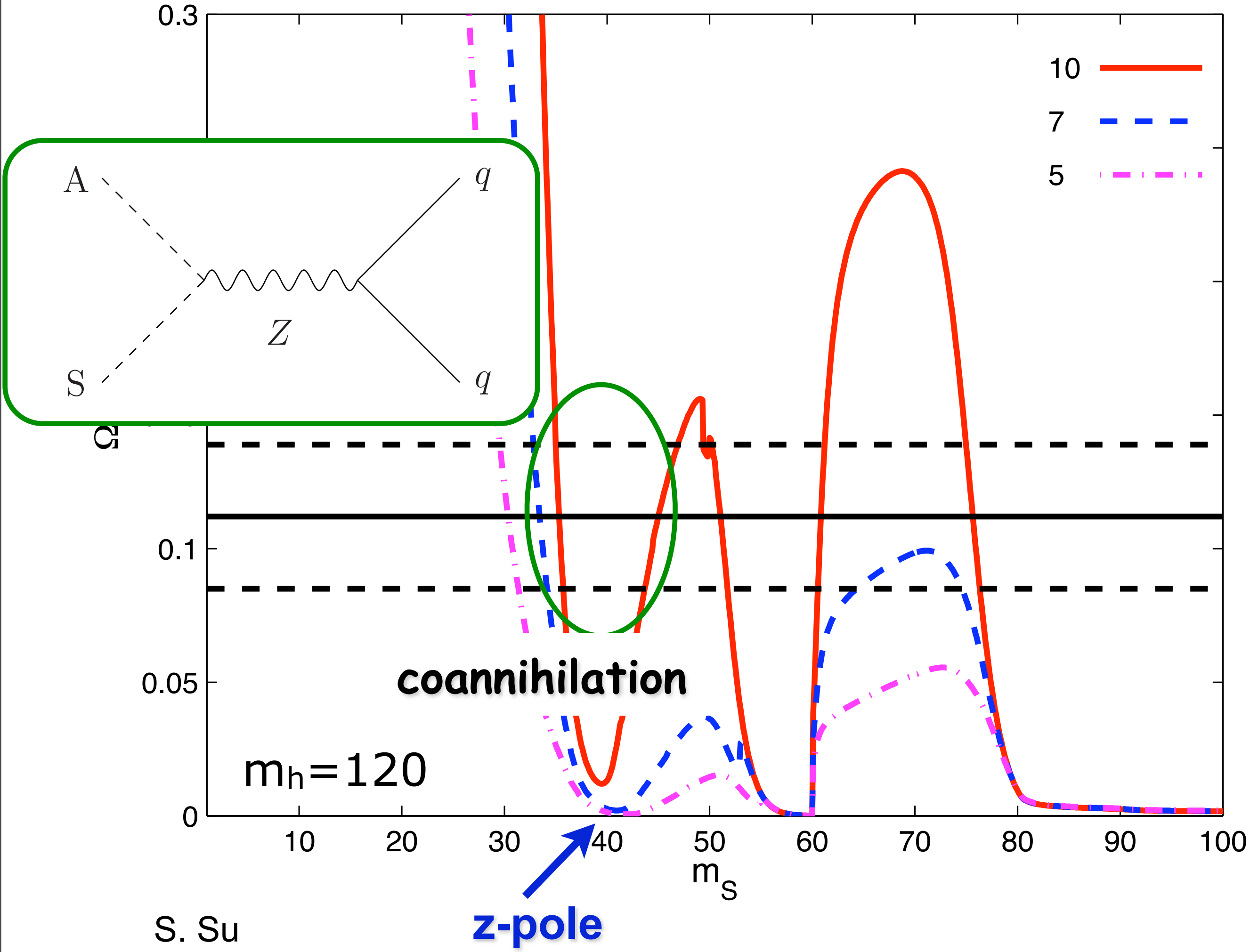

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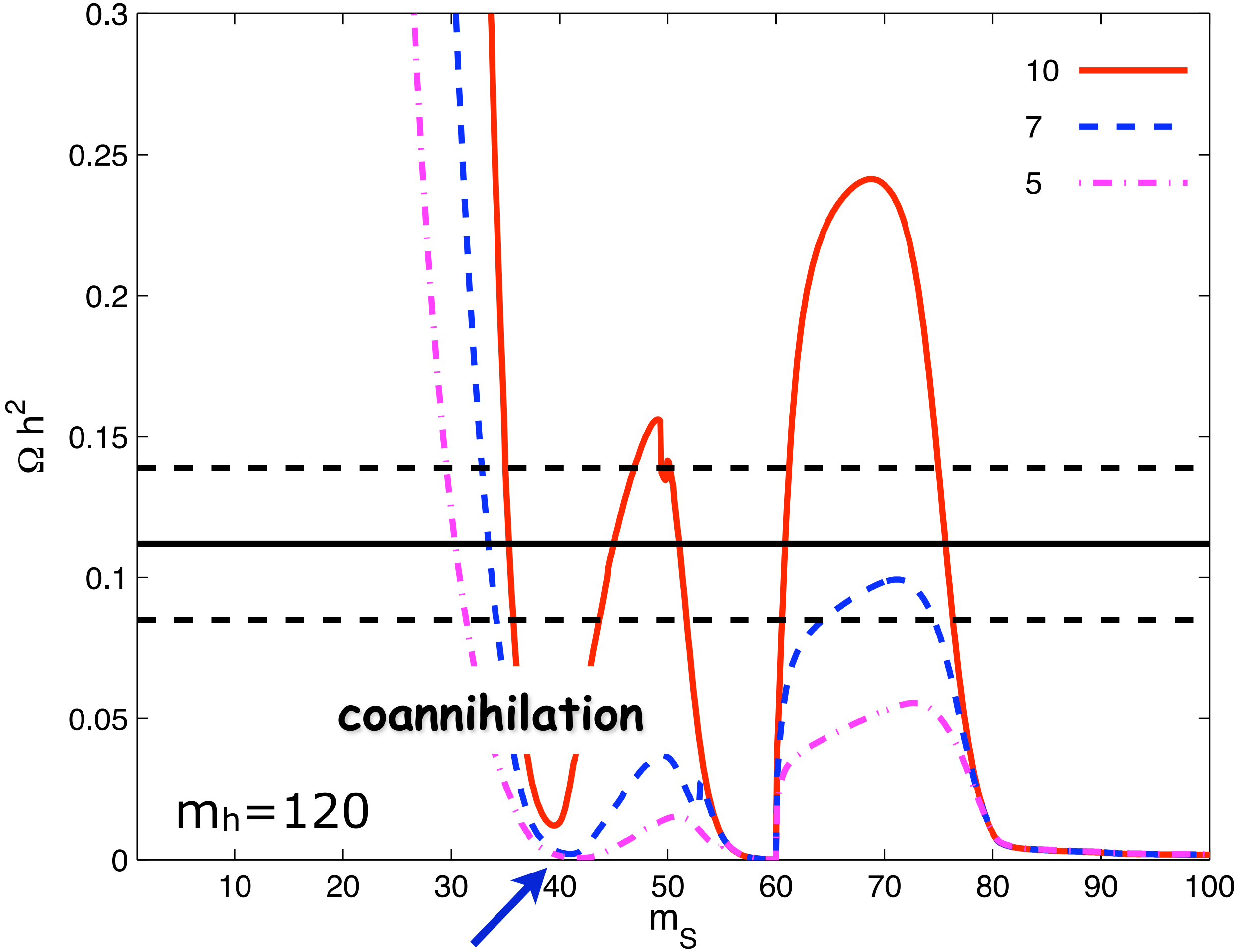

z-pole

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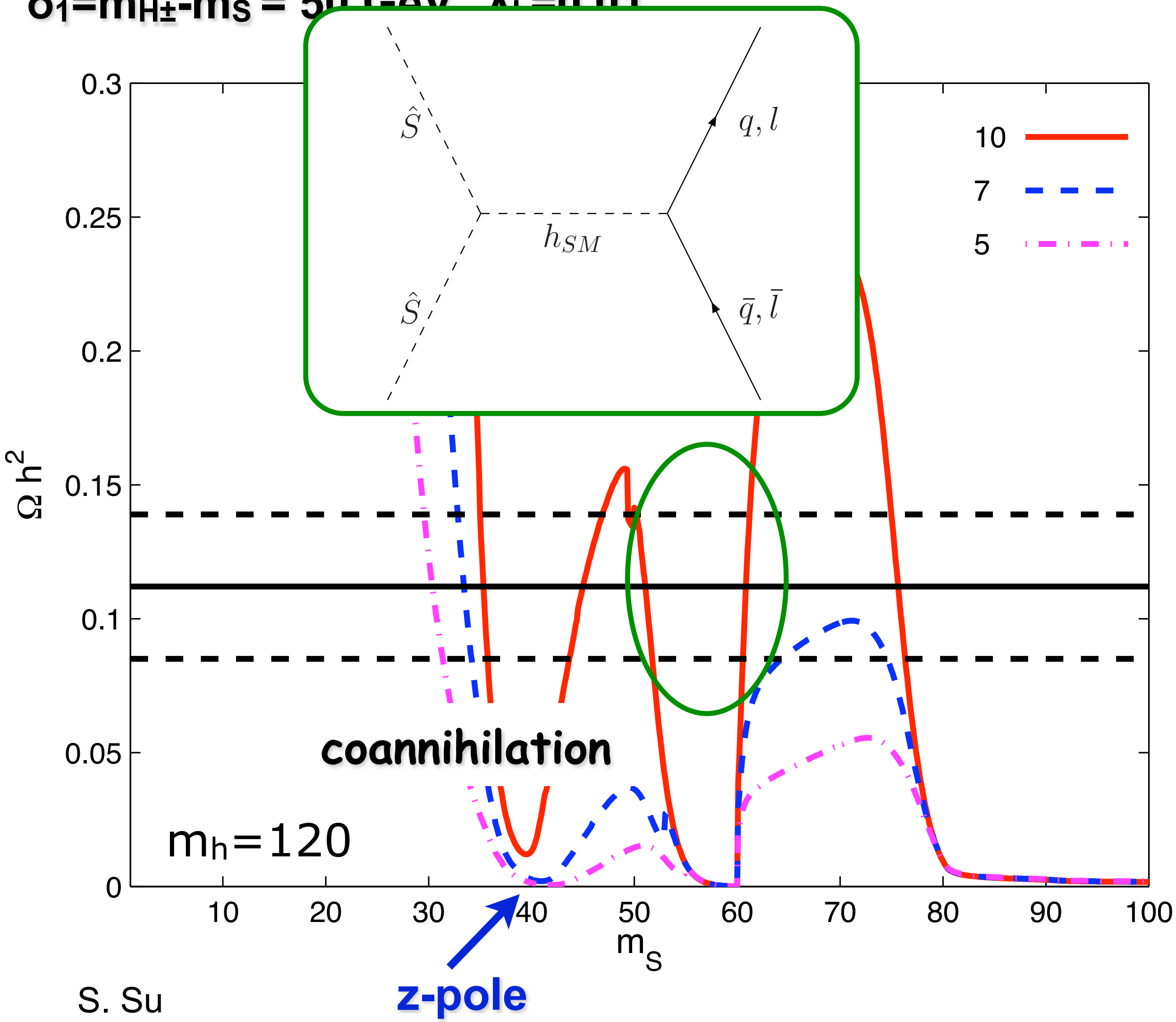

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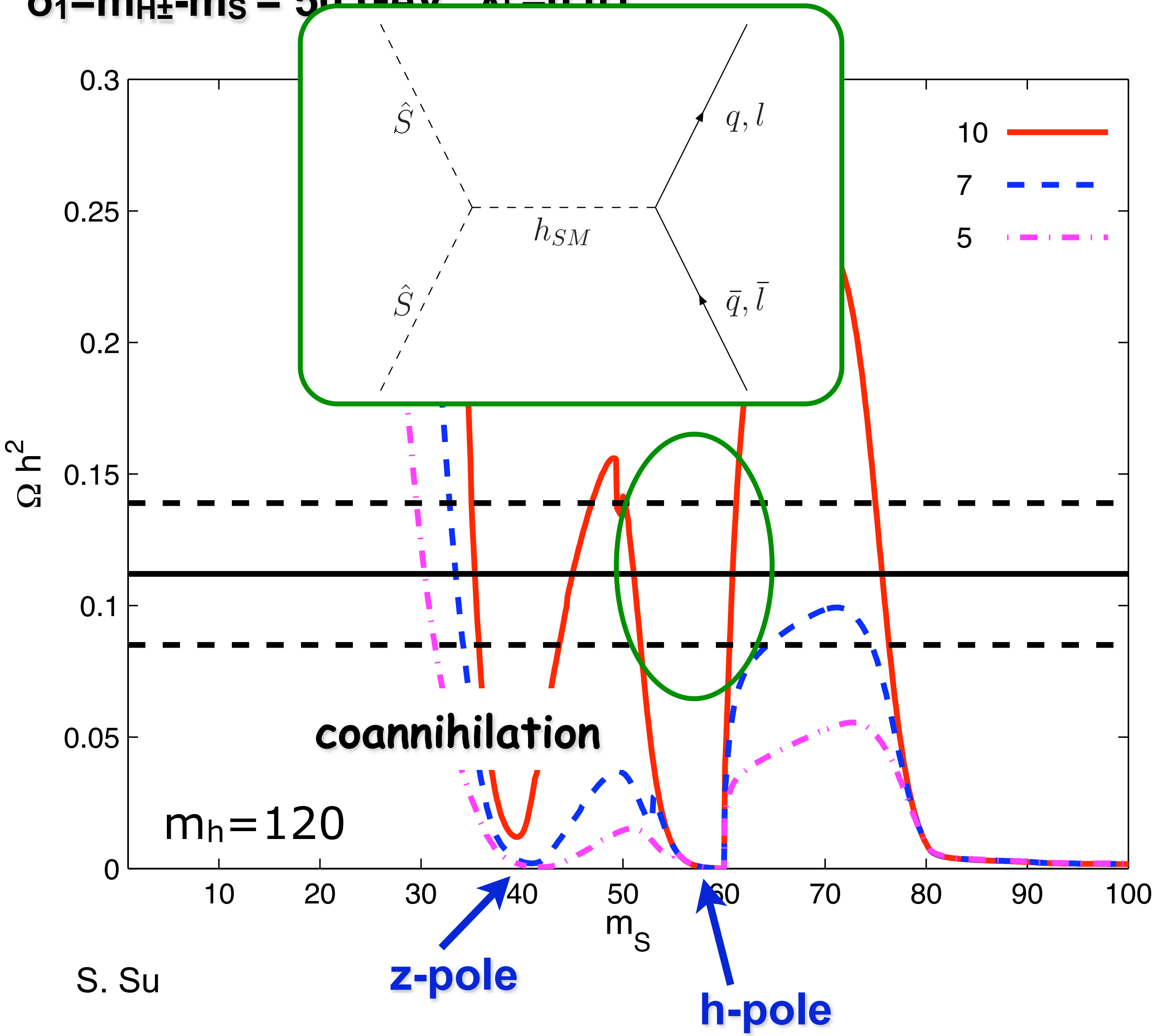

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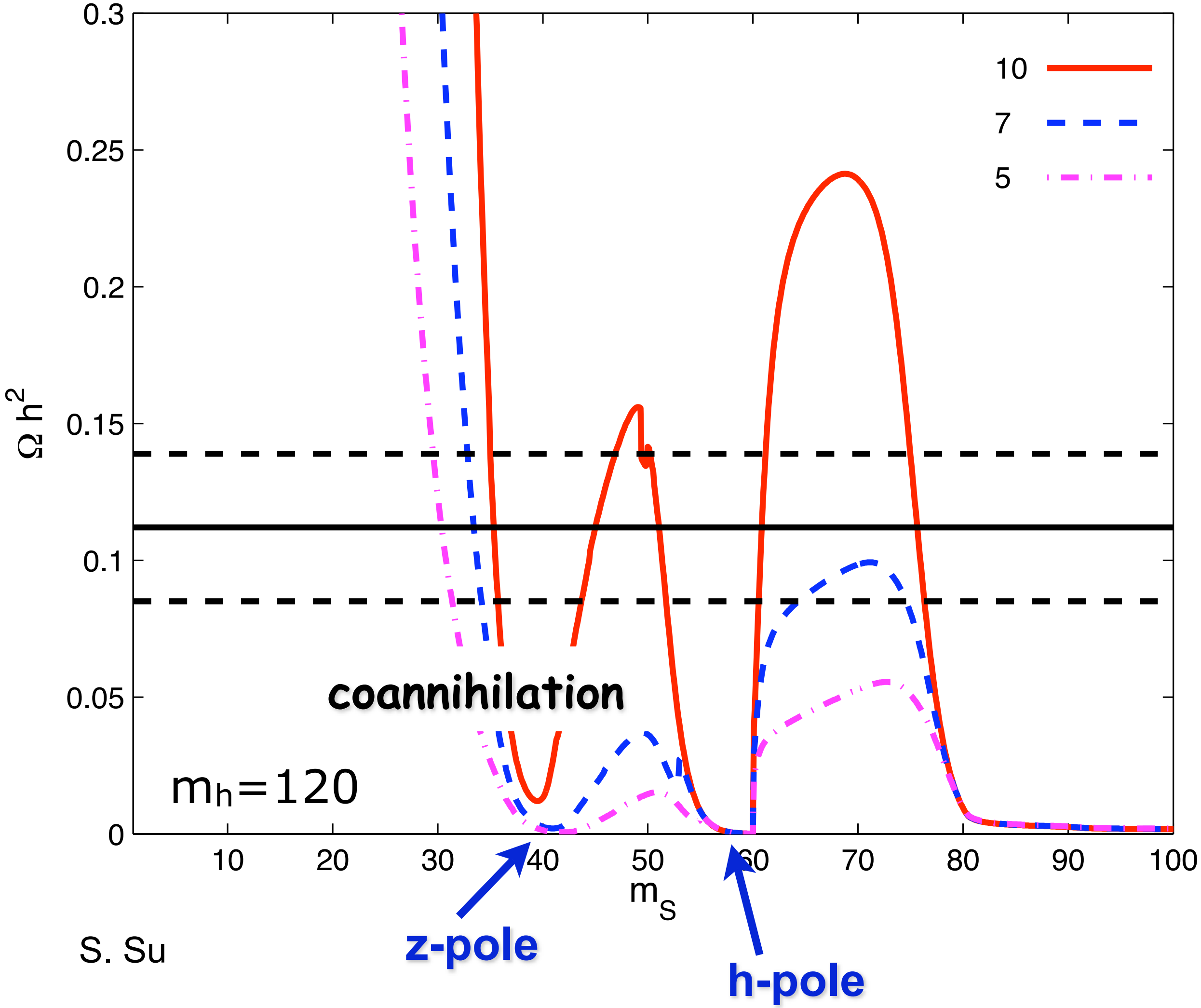

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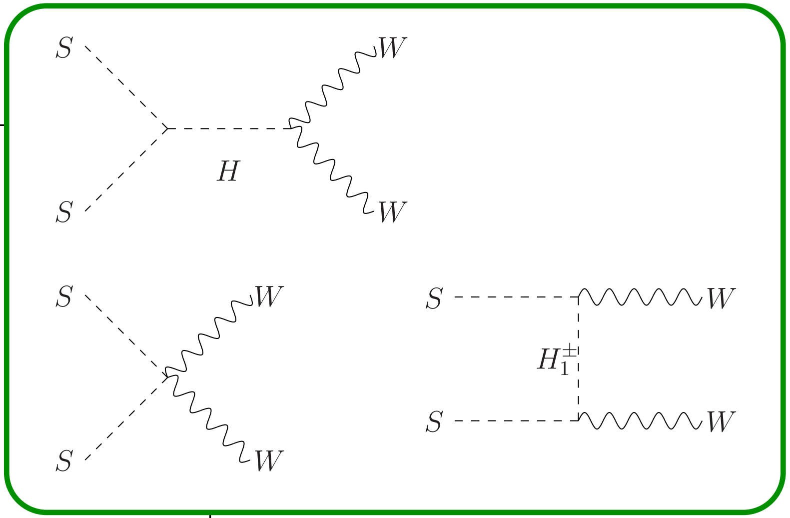

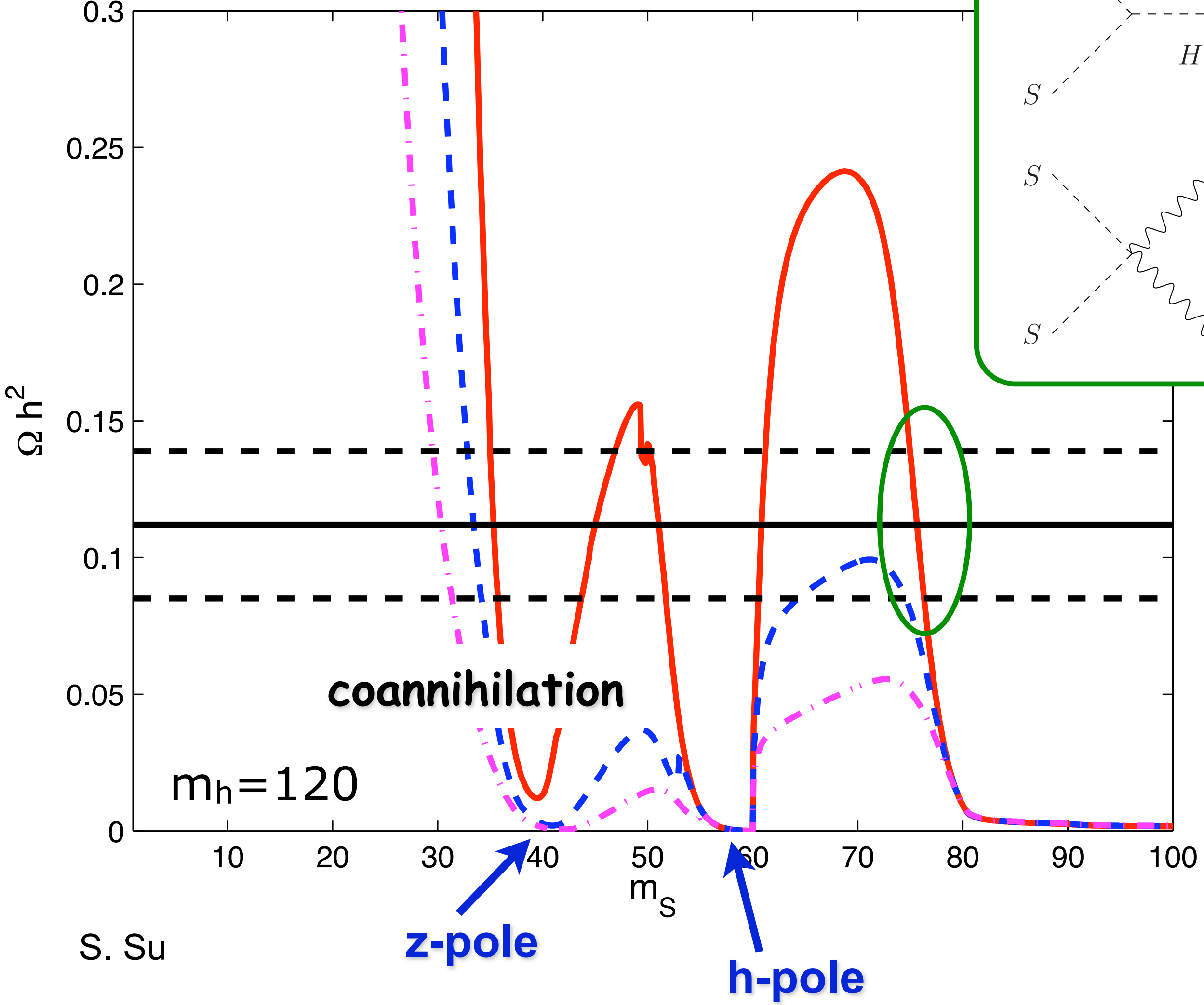

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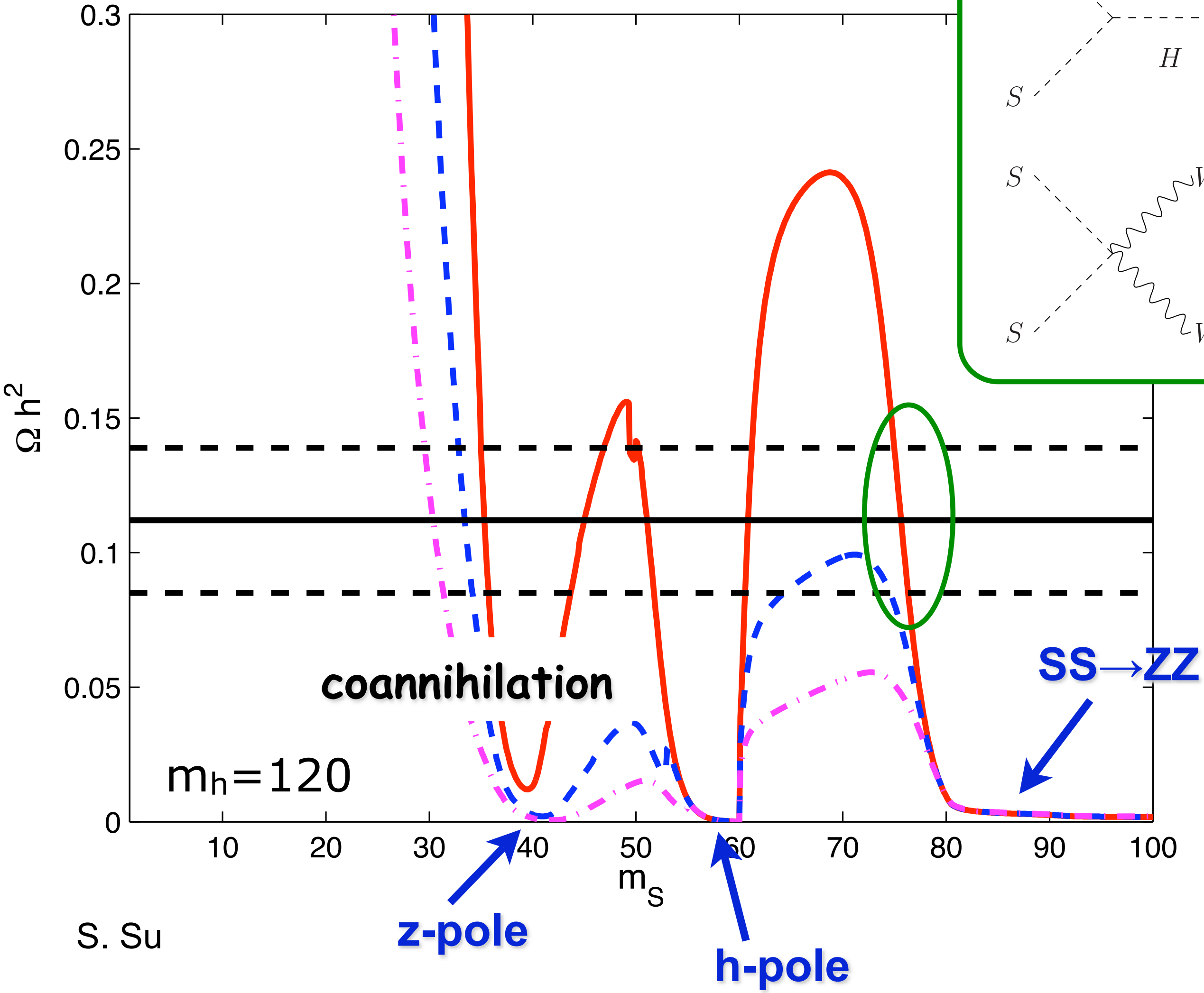

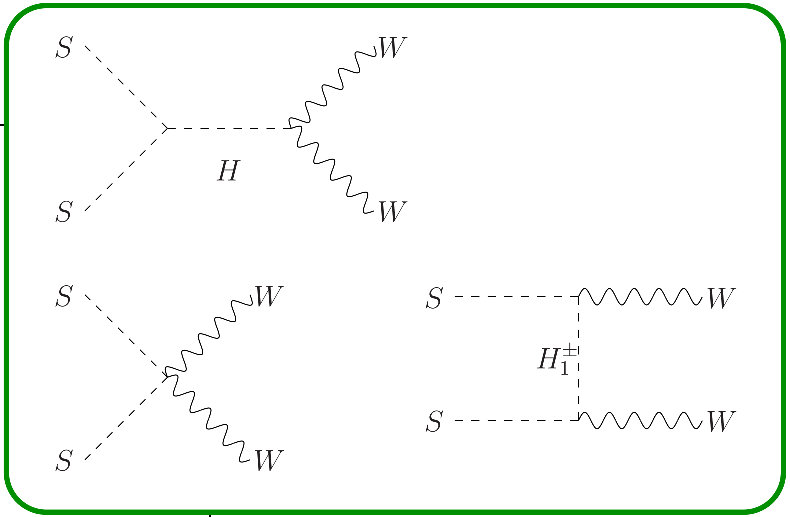

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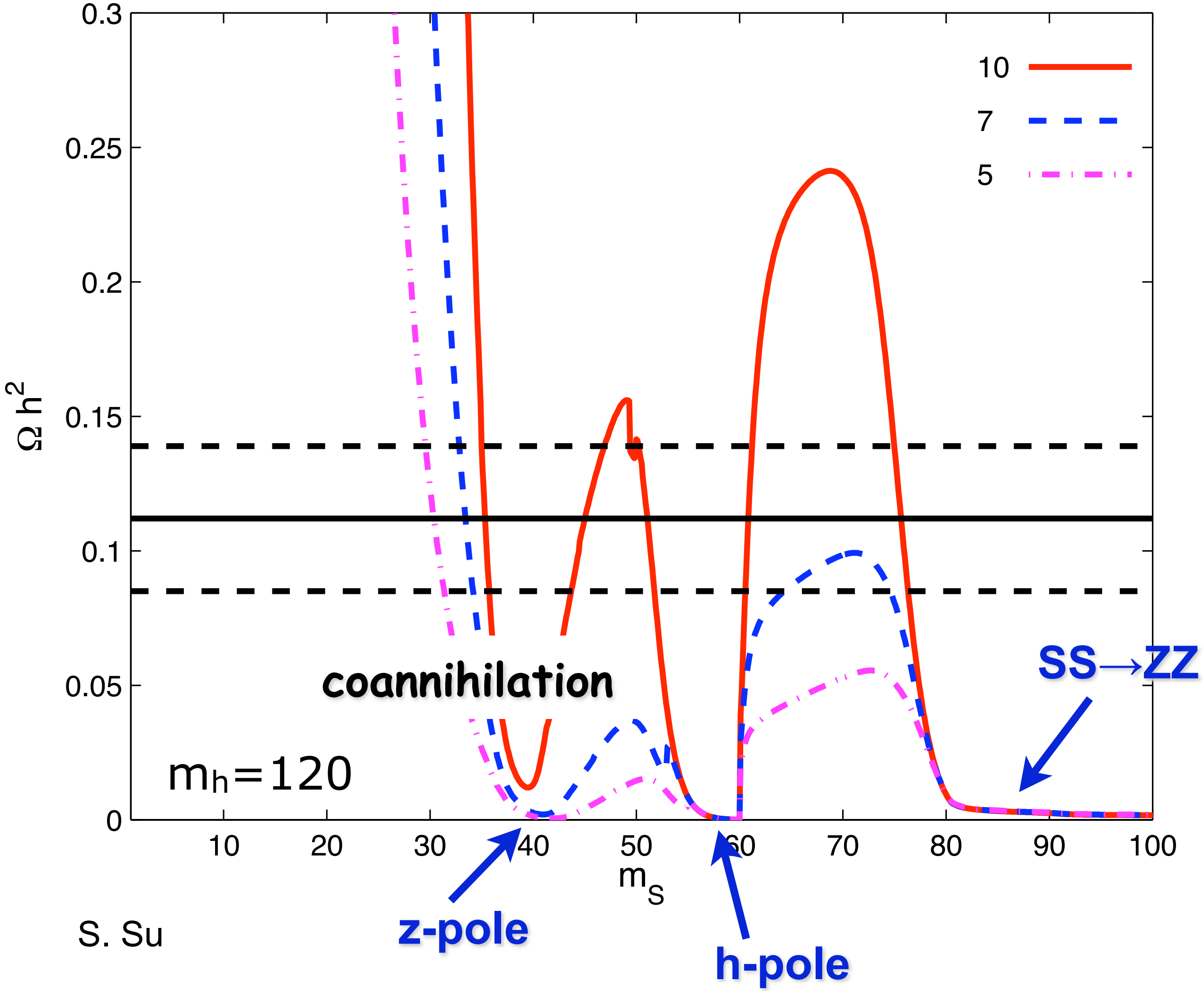

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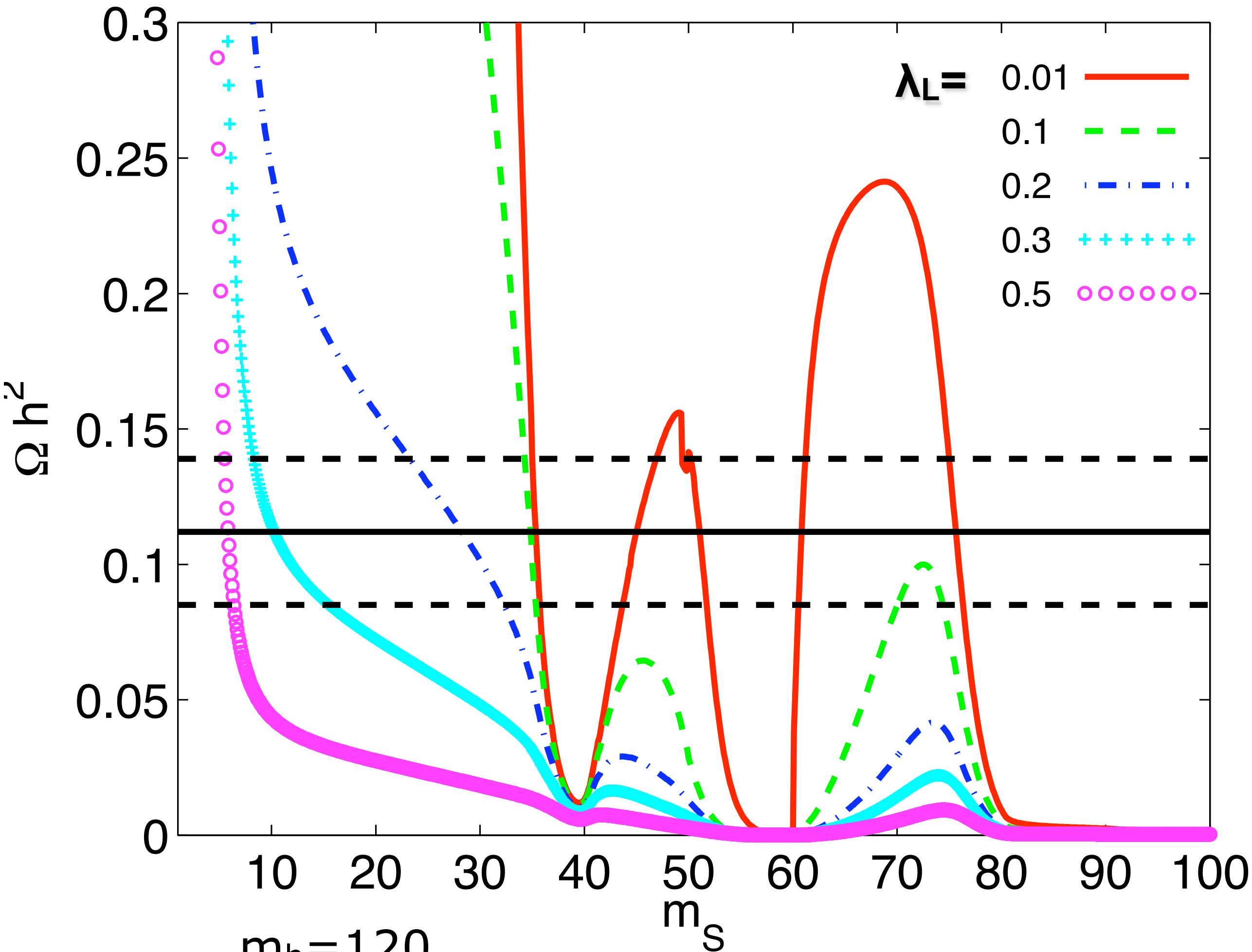
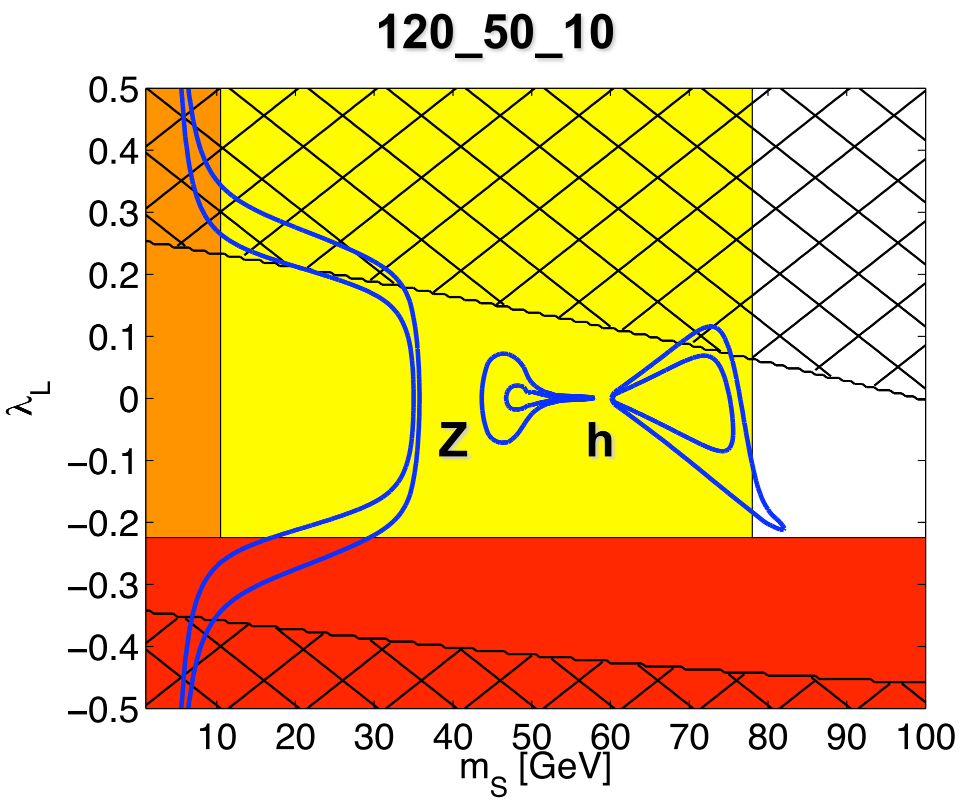
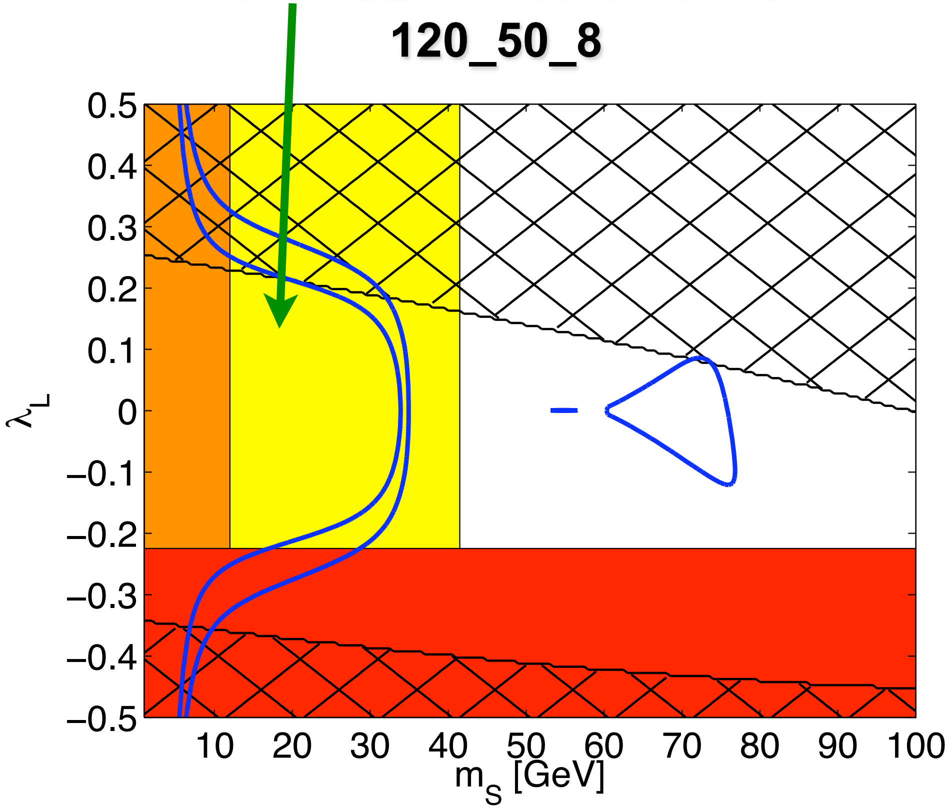


m_h=120

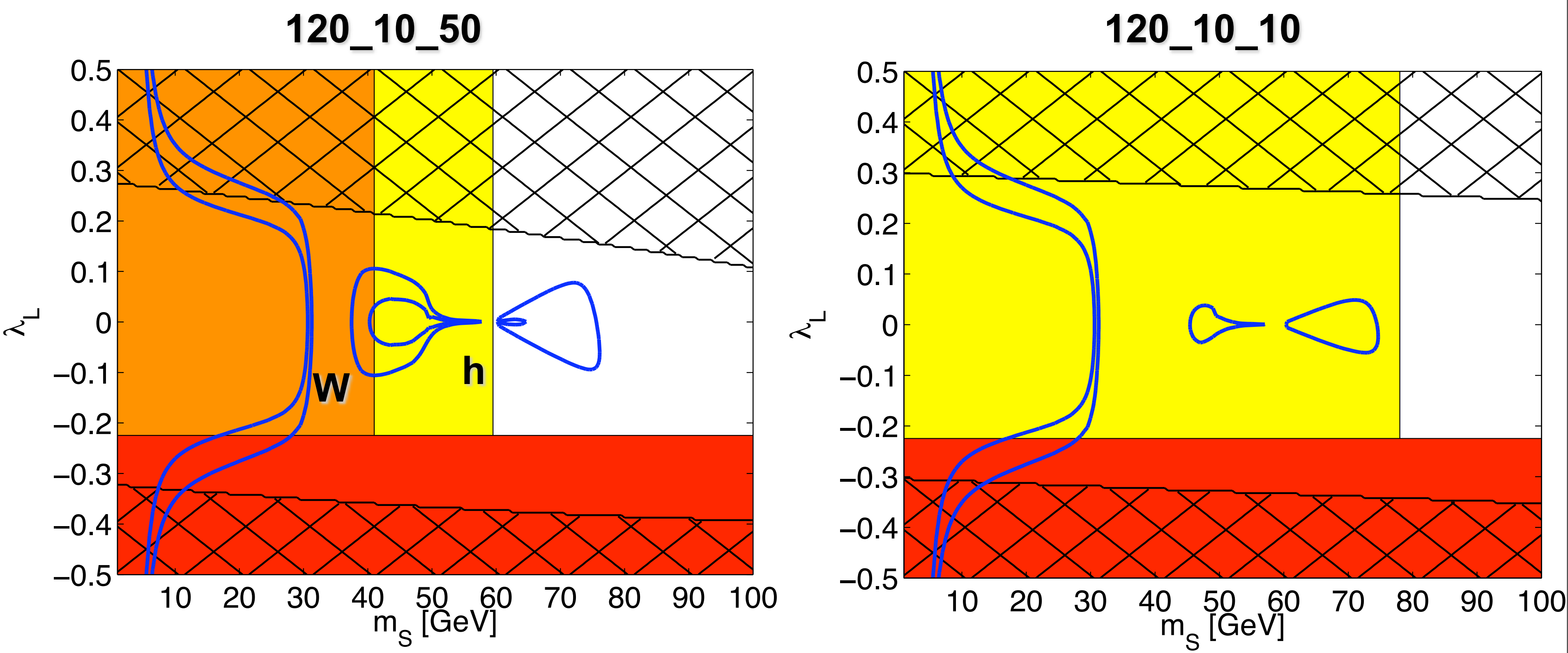
Low mass region: low m_h



weak LEP II constraints

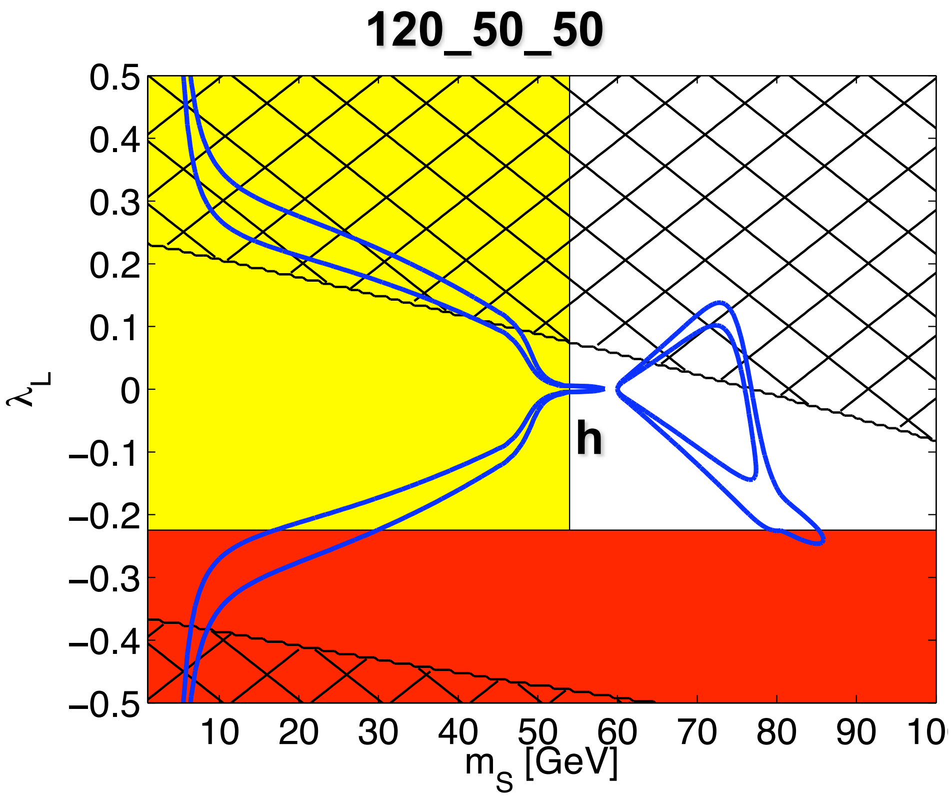


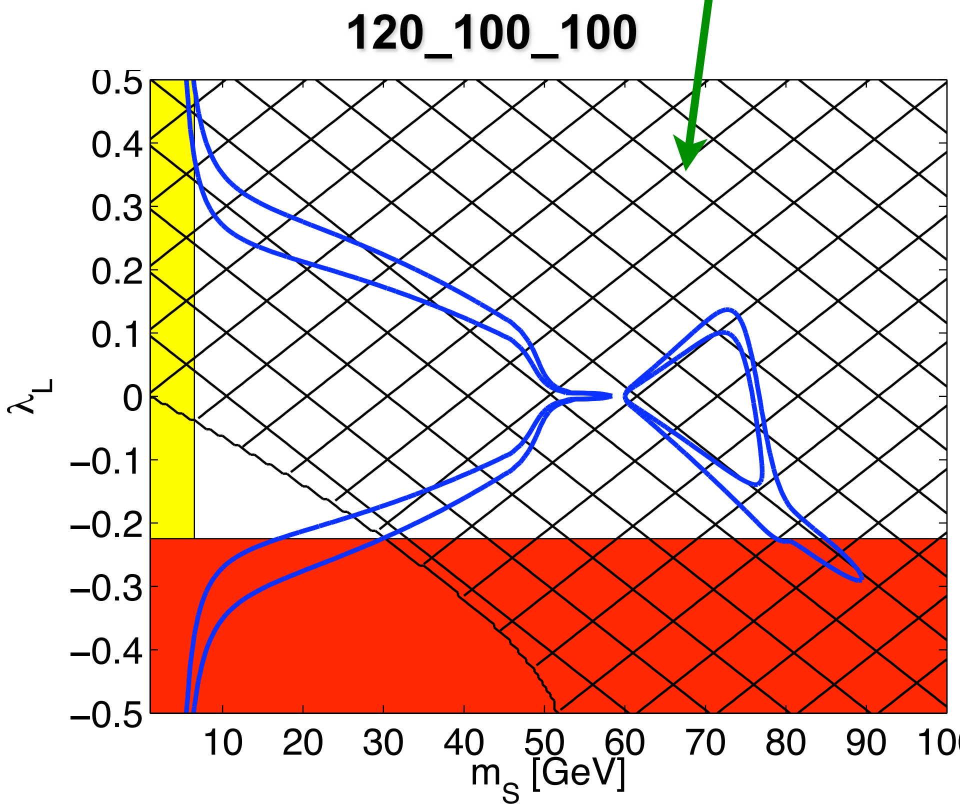
Low mass region: low m_h



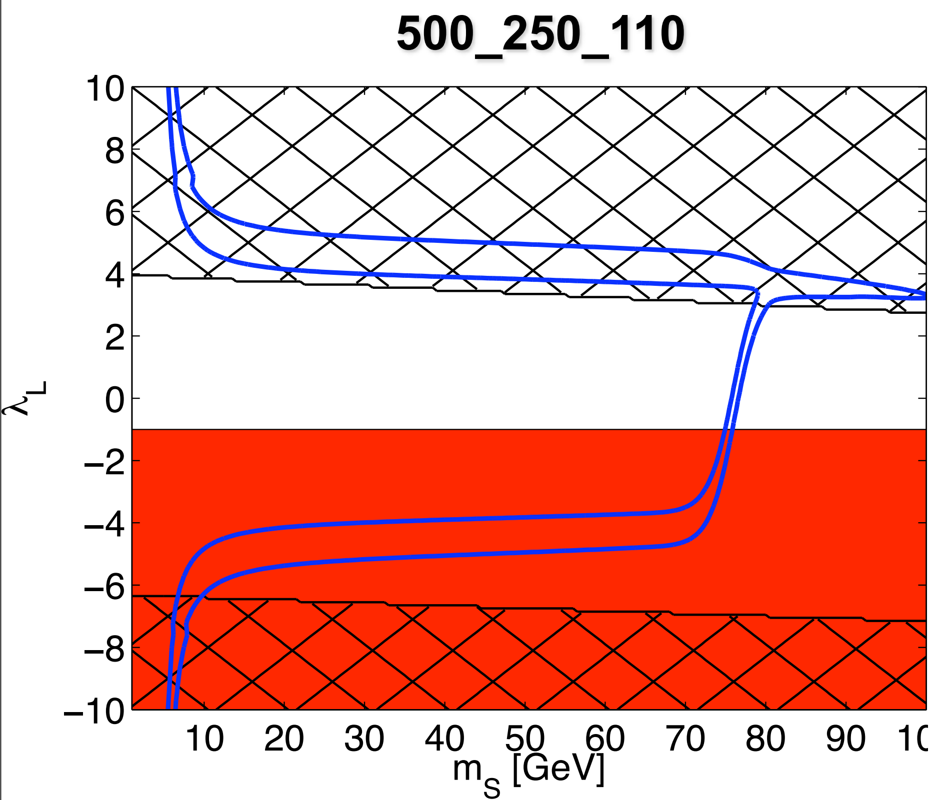
Low mass region: low m_h

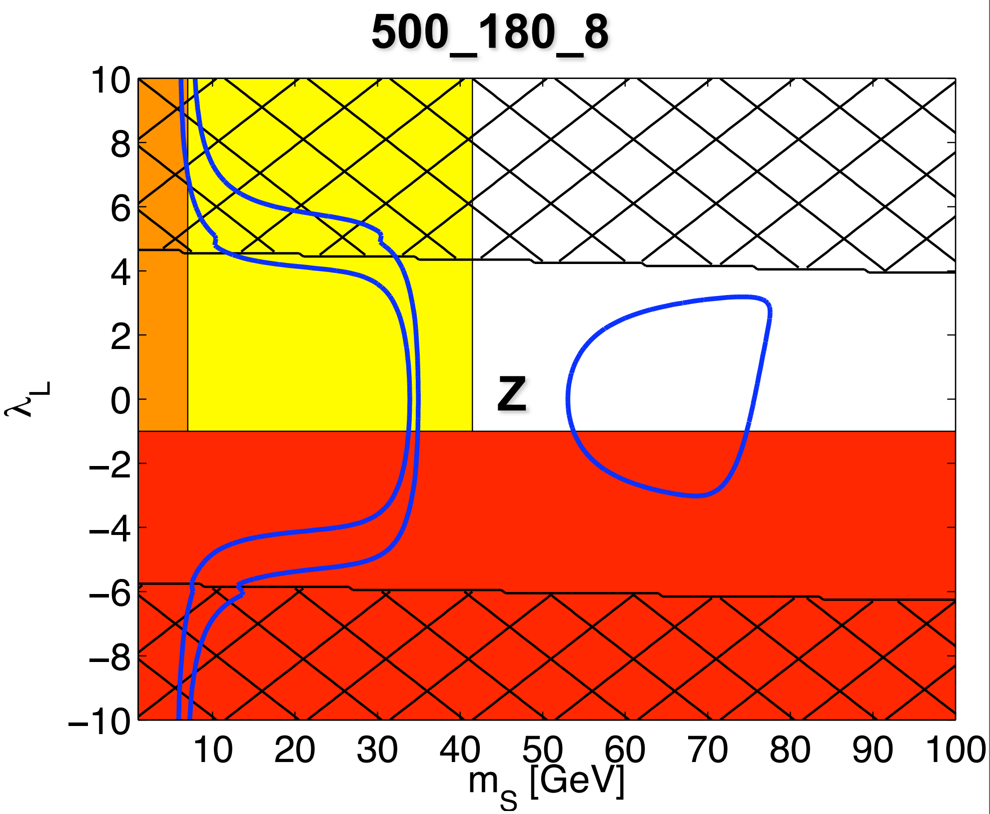
strong pert. constraints





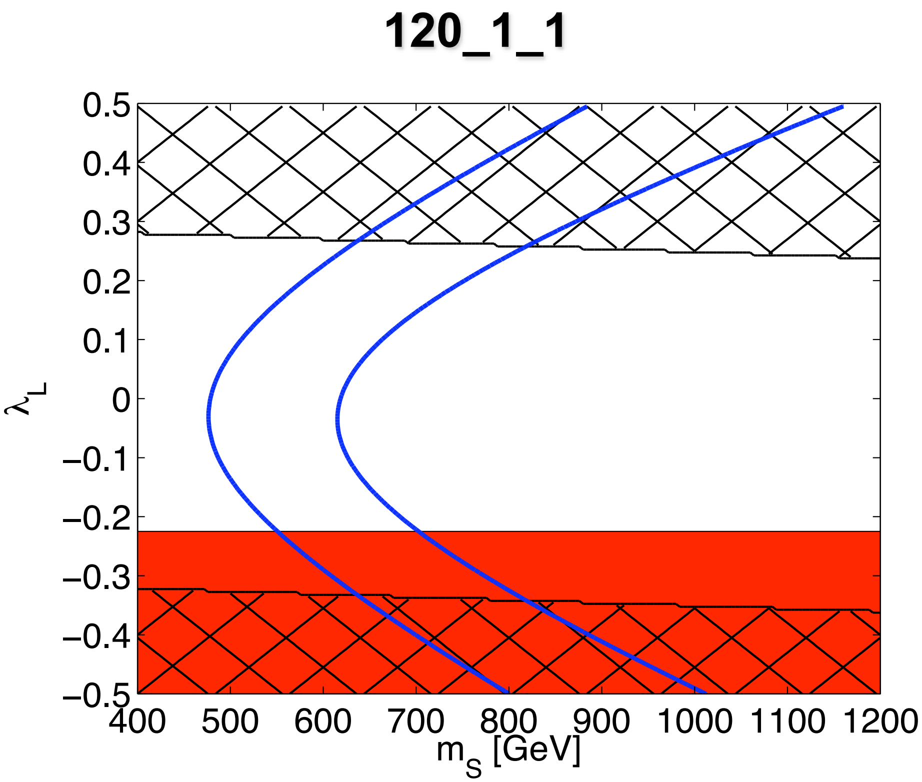
Low mass region: high m_h

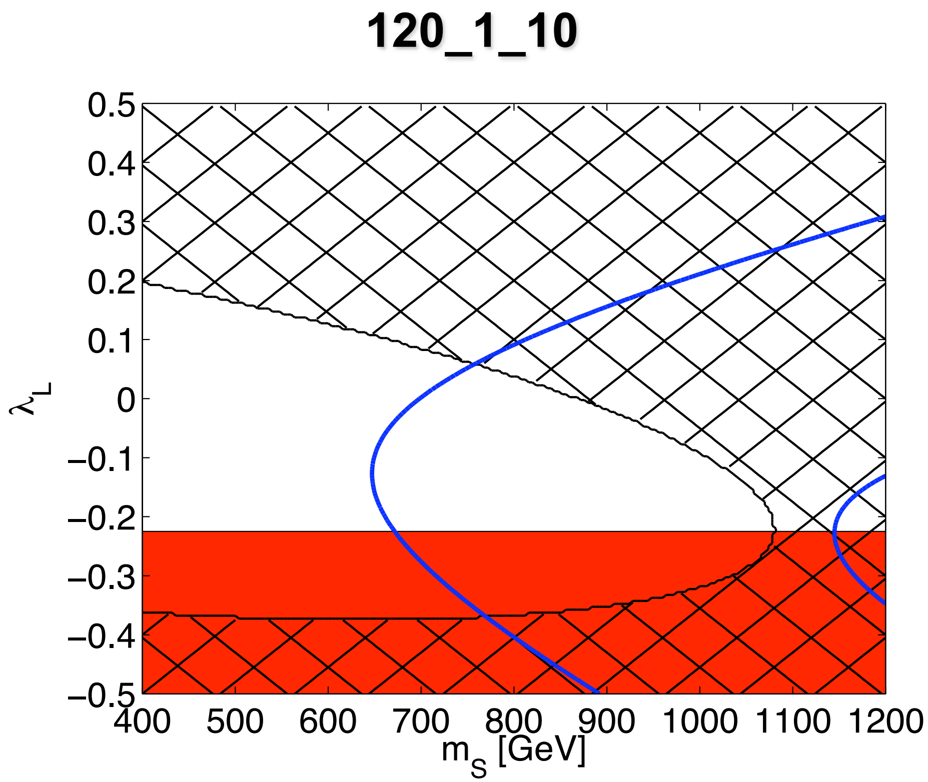




High mass region: low m_h

- small m_h



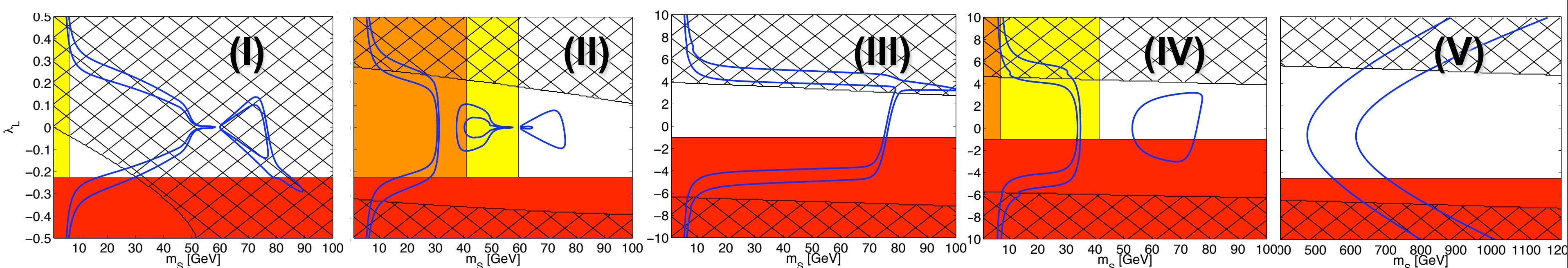


- large $m_h \sim 500$ GeV, large δ_1, δ_2 is needed

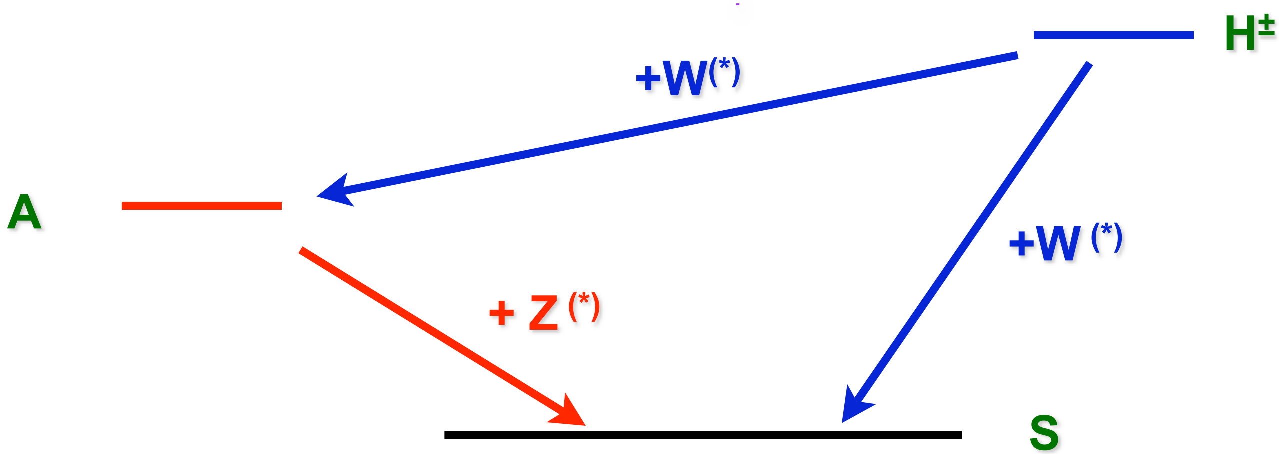
annihilation cross section is too large, relic density is too small.

Viable region for relic density

	DM	SM h	m_S	δ_1, δ_2	λ_L
(I)	low m_S	low m_h	~20 GeV	both large	~ -0.2
(II)			60 – 80 GeV	at least one is large	-0.2 – 0.2
(III)		high m_h	50 – 75 GeV	large δ_1 $\delta_2 < 8$ GeV	-1 – 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 – 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 – 0.2



Collider signatures



$$pp \to SA \to SSZ^{(*)}, SSW^{(*)}W^{(*)}$$

$$pp \to SH^{\pm} \to SSW^{(*)}, SSZ^{(*)}W^{(*)}$$

$$pp \to AH^{\pm} \to SSZ^{(*)}W^{(*)}, SSZ^{(*)}Z^{(*)}W^{(*)}, SSW^{(*)}W^{(*)}W^{(*)}$$

$$pp \to H^{+}H^{-} \to SSW^{(*)}W^{(*)}, SSW^{(*)}W^{(*)}Z^{(*)}, SSW^{(*)}W^{(*)}Z^{(*)}Z^{(*)}.$$

Signatures: jets + leptons + missing E_T

jets and leptons could be soft for small splittings

Leptonic signals

Focus on purely leptonic signals

- single lepton: $SH^{\pm}$
- dilepton: SA, $H^{+}H^{-}$
- trilepton: $AH^{\pm}$
- ...

Dominant background

- WW, ZZ, WZ

Benchmark points

	m_S (GeV)	(δ_1, δ_2) (GeV)	λ_L
(I)	25	(100,100)	− 0.2
(II)	79	(50,10)	− 0.18
(III)	73	(10,50)	0
(IV)	82	(50,50)	− 0.2

Sig. vs. Bg. cross sections

	σ	(I)	(II)	(III)	(IV)
S (pb)	pp→SA	0.543	0.475	0.251	0.181
	pp→H^+H^-	0.103	0.093	0.438	0.0852
	pp→$SH^\pm$	0.920	0.356	1.076	0.319
	pp→$AH^\pm$	0.189	0.303	0.372	0.157
B (pb)	pp→WW	71.8			
	pp→ZZ	10.0			
	pp→WZ	27			

Dilepton signal from Z*

Dilepton signals:

- $pp \to SA \to SSZ^{(*)} \to SSl^+l^-$
- $pp \to H^+H^- \to SSW^{(*)}W^{(*)} \to SSl^+l^-\nu\nu$

Signal: $pp \to SA \to SSZ^{(*)} \to SSl^+l^-$

Two isolated opposite charge e or μ with missing E_T, no hard jets.

Background:

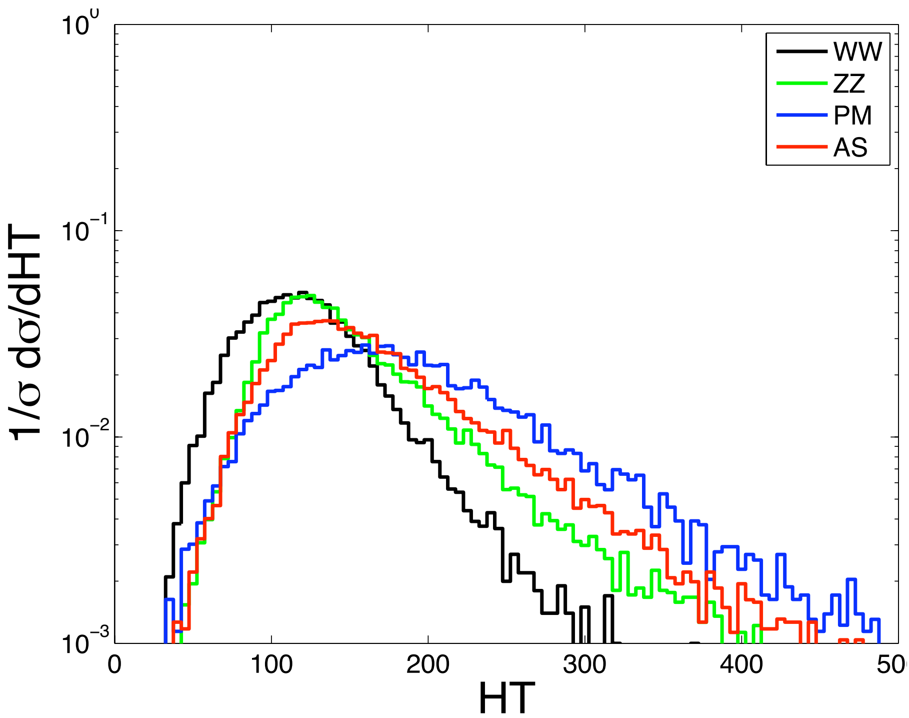
- from IHDM $pp \to H^+H^- \to SSW^{(*)}W^{(*)} \to SSl^+l^-\nu\nu$
- from SM
  - $pp \to WW \to l^+l^-\nu\nu$
  - $pp \to ZZ \to l^+l^-\nu\nu$

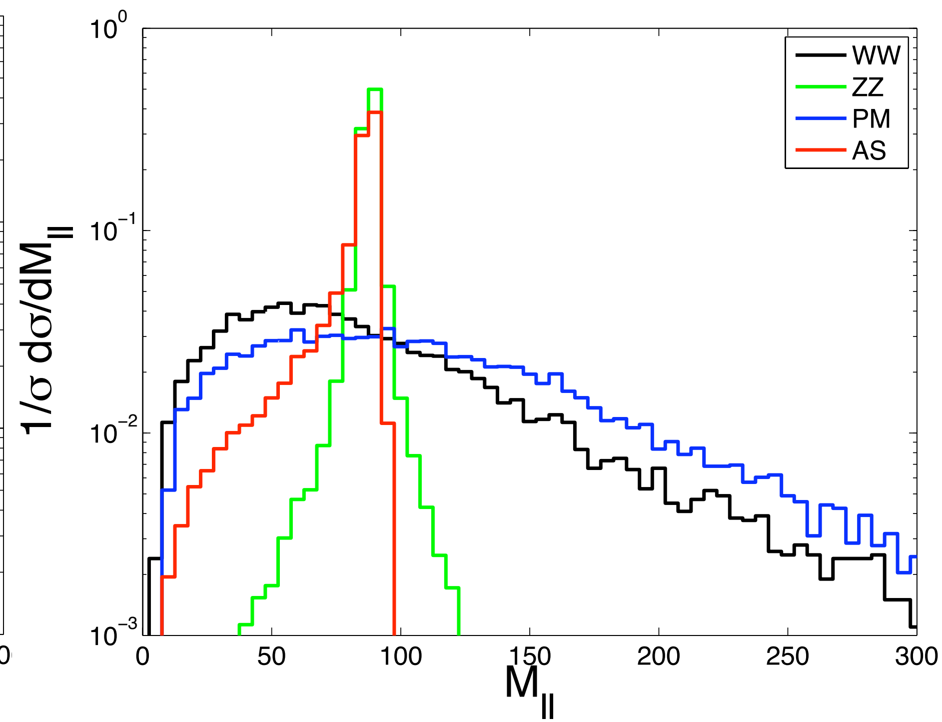
Dilepton signal: point I

• **Benchmark I: m_S = 25 GeV, (δ_1, δ_2)=(100,100) GeV**

Signal: $pp \to SA \to SSZ \to SSl^+l^-$, l=e,μ

Two isolated opposite charge e or μ with missing E_T, no hard jets.



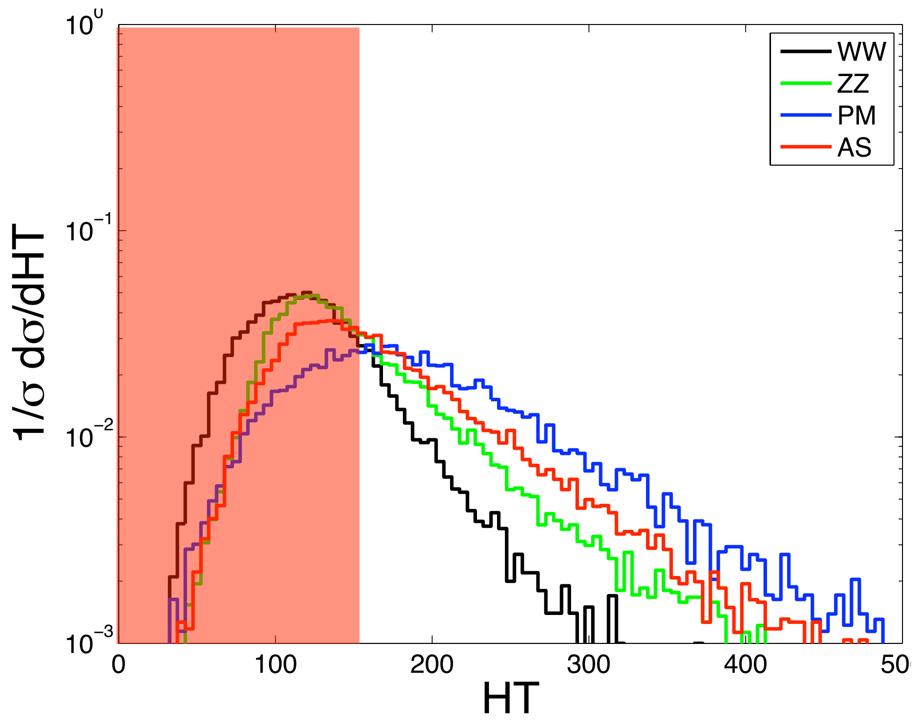


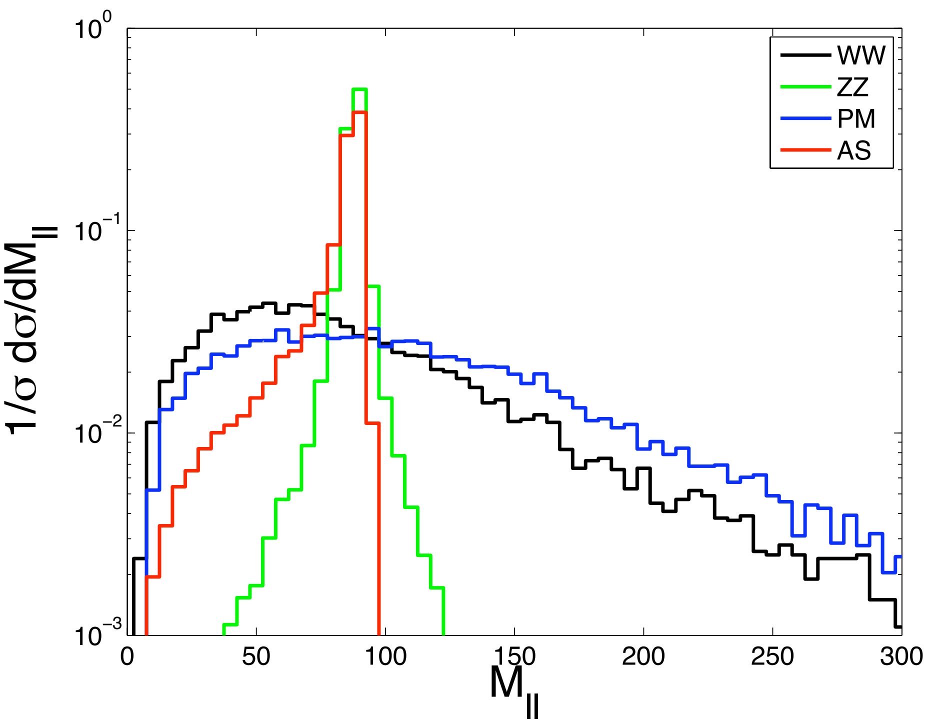
Dilepton signal: point I

- **Benchmark I: m_S = 25 GeV, (δ_1, δ_2)=(100,100) GeV**

Signal: $pp \to SA \to SSZ \to SSl^+l^-$, l=e,μ

Two isolated opposite charge e or μ with missing E_T, no hard jets.



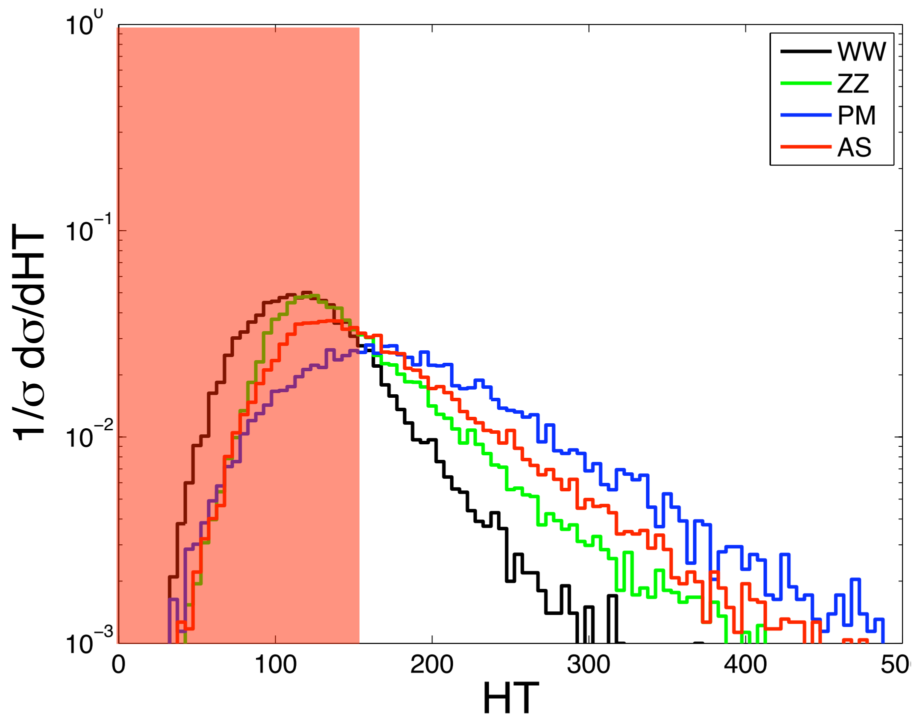


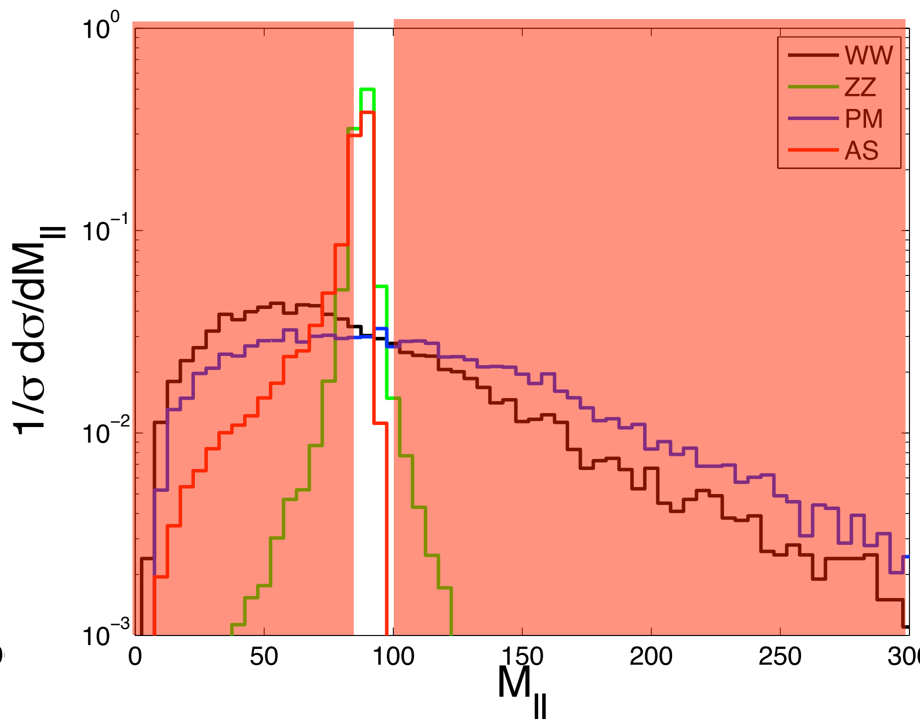
Dilepton signal: point I

- **Benchmark I: m_S = 25 GeV, (δ_1, δ_2)=(100,100) GeV**

Signal: $pp \to SA \to SSZ \to SSl^+l^-$, l=e,μ

Two isolated opposite charge e or μ with missing E_T, no hard jets.





Dilepton signal: point I

- **Benchmark I: m_S = 25 GeV, (δ_1, δ_2)=(100,100) GeV**

Cuts

- H_T >150 GeV
- ME_T >15 GeV
- P_T^l >15 GeV, $|\eta_l|$<2.5
- $\Delta R(ll)$>0.4
- P_T^Z >50 GeV
- 80 GeV < M_{ll} < 100 GeV
- no jets with P_T^j>20 GeV, $|\eta_j|$<2.5

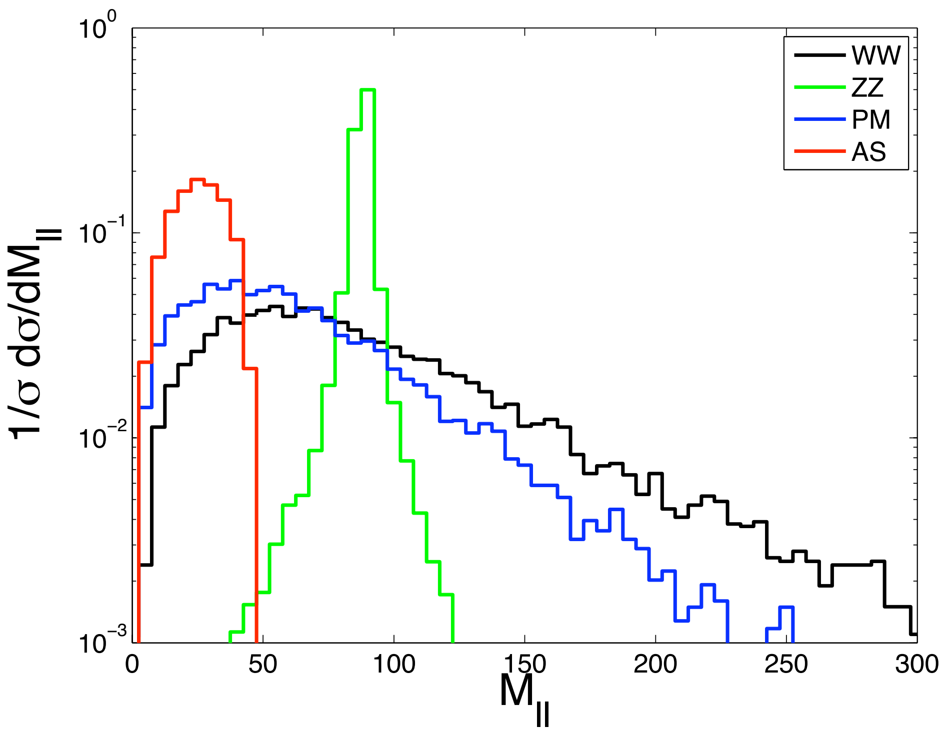
Prelimenary		before cuts	after cuts
S (fb)	SA	41.27	5.83
B (fb)	H^+H^-	5	0.048
	WW	3404.6	1.21
	ZZ	280.8	3.86
L=100 fb^{-1}		S/B	0.115
		$s/\sqrt{(B)}$	8.18

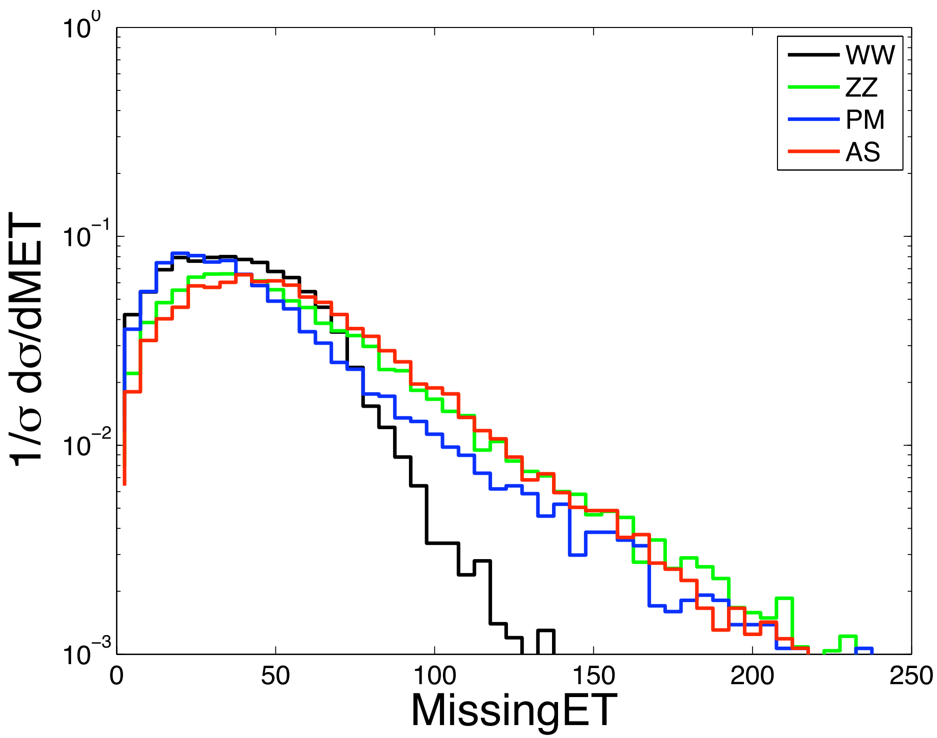
Low mass region: point IV

- **Benchmark IV: m_S = 82 GeV, (δ_1, δ_2)=(50,50) GeV**

Signal: $pp \to SA \to SSZ^* \to SSl^+l^-$, l=e,μ

Two isolated opposite charge e or μ with large missing E_T, no hard jets.



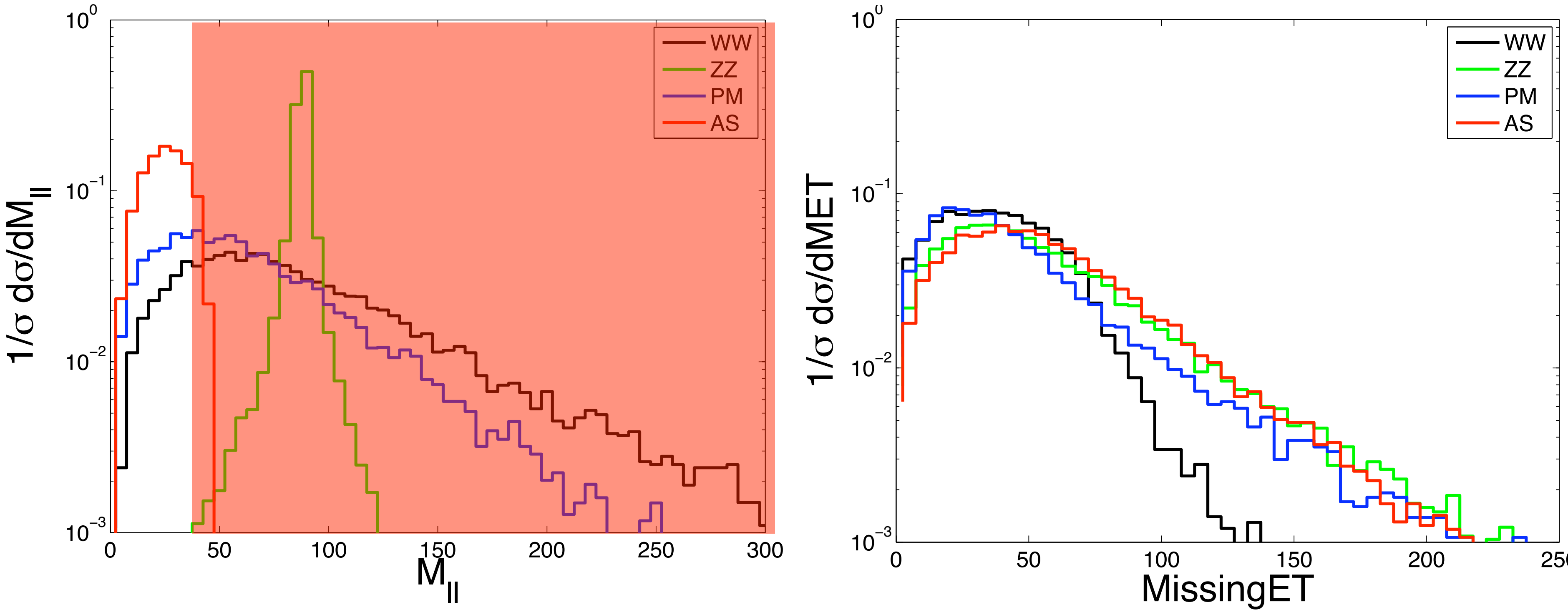


Low mass region: point IV

- **Benchmark IV: m_S = 82 GeV, (δ_1, δ_2)=(50,50) GeV**

Signal: pp→SA→SSZ*→SSl^+l^-, l=e,μ

Two isolated opposite charge e or μ with large missing E_T, no hard jets.

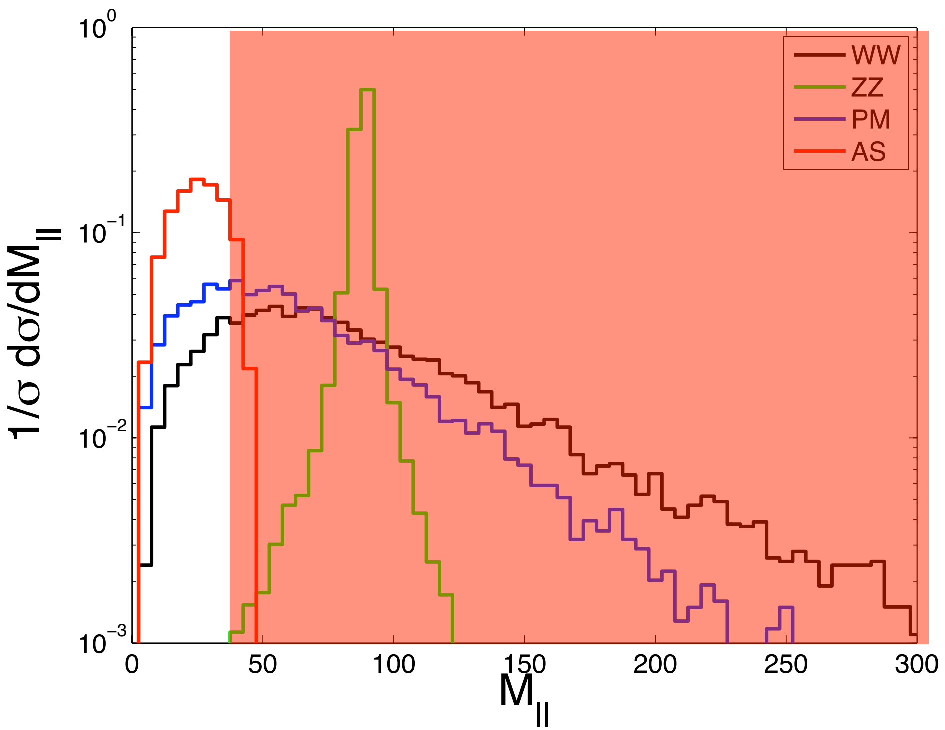


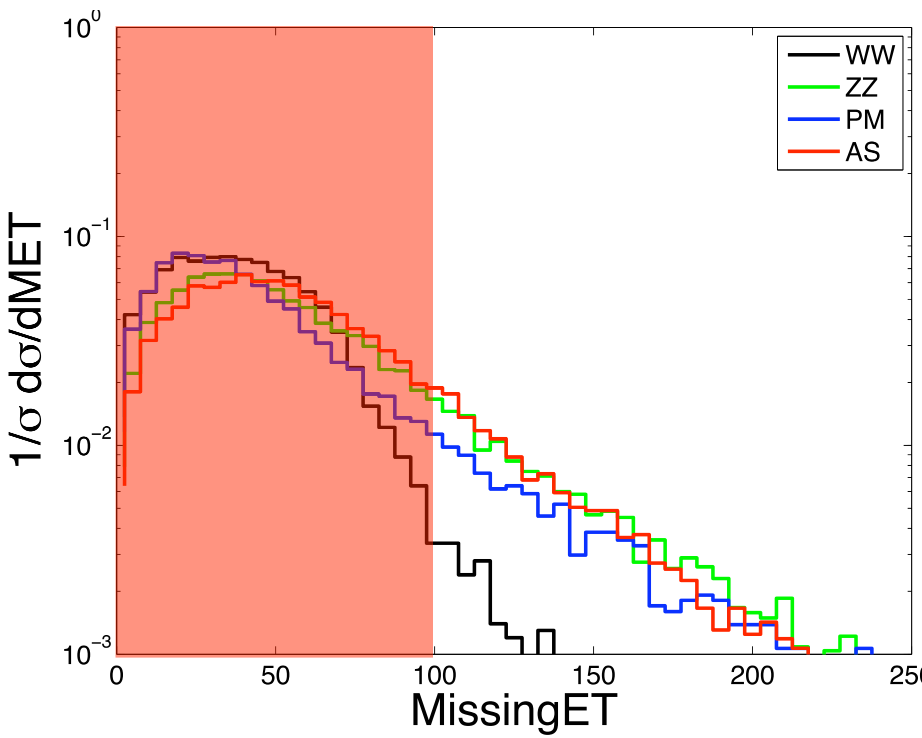
Low mass region: point IV

- **Benchmark IV: m_S = 82 GeV, (δ_1, δ_2)=(50,50) GeV**

Signal: pp→SA→SSZ*→SSl⁺l⁻, l=e,μ

Two isolated opposite charge e or μ with large missing E_T, no hard jets.





Low mass region: point IV

- **Benchmark IV: m_S = 82 GeV, (δ_1, δ_2)=(50,50) GeV**

Cuts

- H_T >200 GeV
- ME_T >100 GeV
- P_T^l >15 GeV, $|\eta_l|$<2.5
- $\cos(\phi_{ll})$>0.8
- $\Delta R(ll)$>0.4
- P_T^Z >100 GeV
- M_{ll} < 40 GeV
- no jets with P_T^j>20 GeV, $|\eta_j|$<2.5

Prelimenary		before cuts	after cuts
S (fb)	SA	11.42	0.130
B (fb)	H^+H^-	3.56	0
	WW	3404.6	0.025
	ZZ	280.8	0.0025
L=100 fb^{-1}		S/B	4.70
		s/√(B)	7.81

Dilepton signal: point II

- **Benchmark II:** m_S = 79 GeV, (δ_1, δ_2)=(50,10) GeV

Signal: $pp \to SA \to SSZ^* \to SSl^+l^-$, $l=e,\mu$

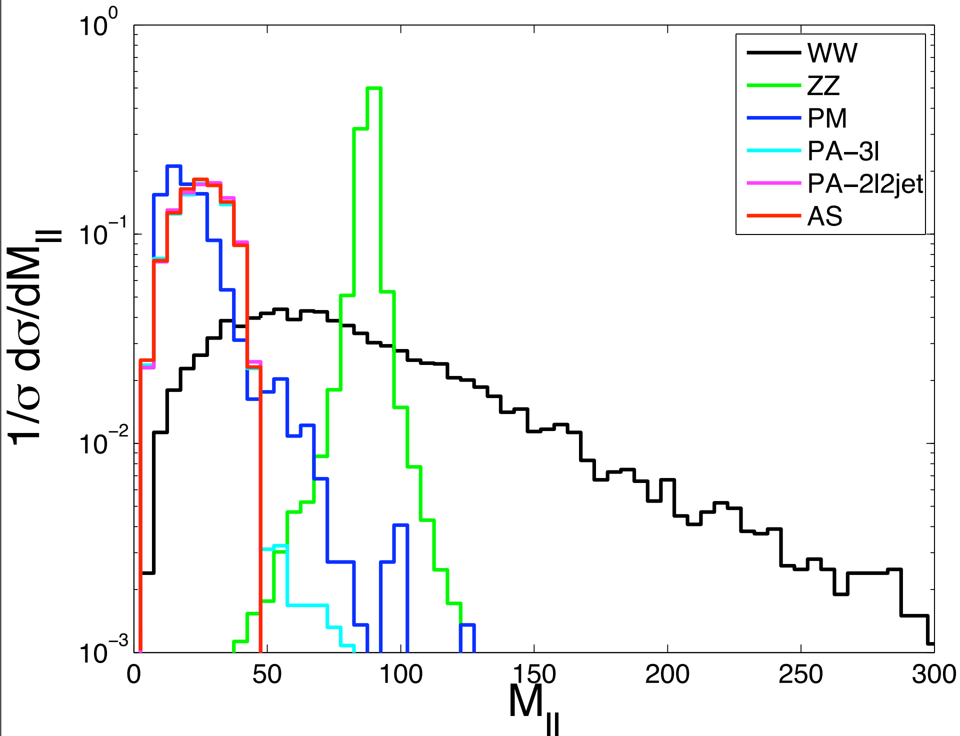
Soft leptons. Difficult.

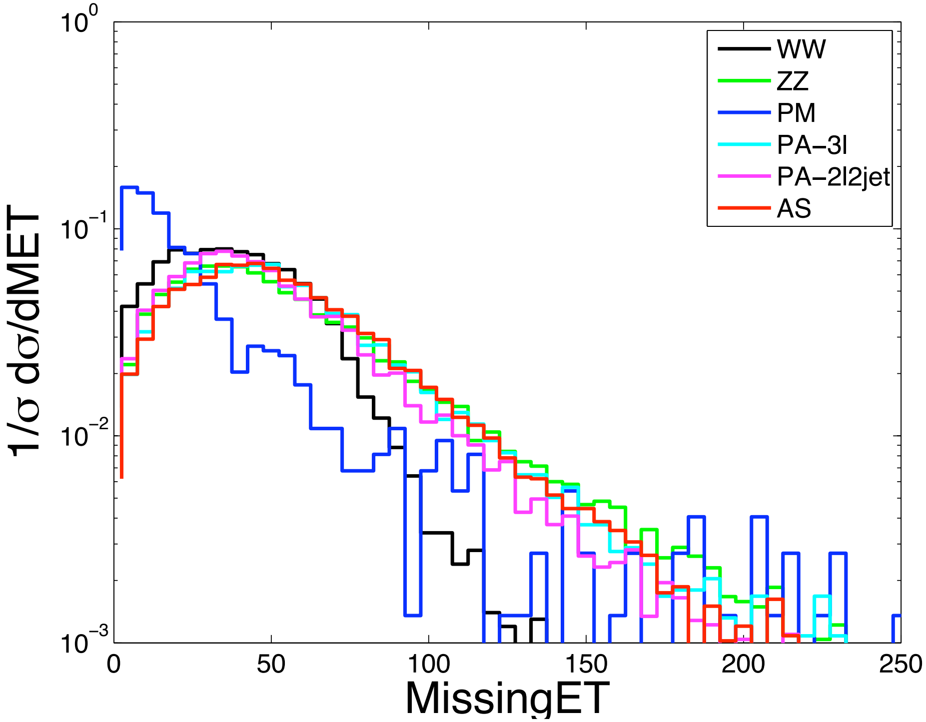
Low mass region: point III

- **Benchmark III**: m_S = 73 GeV, (δ_1, δ_2)=(10,50) GeV

Signal: pp→SA→SSZ*→SSl⁺l⁻, l=e,μ; also including AH±

Two isolated opposite charge e or μ with large missing E_T, no hard jets.



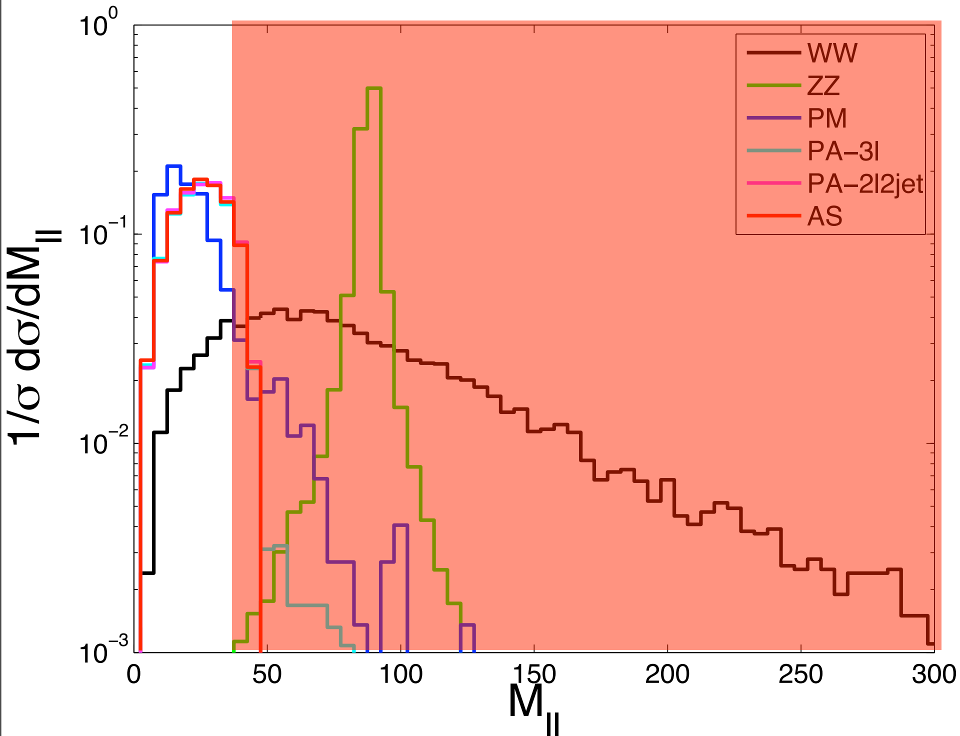


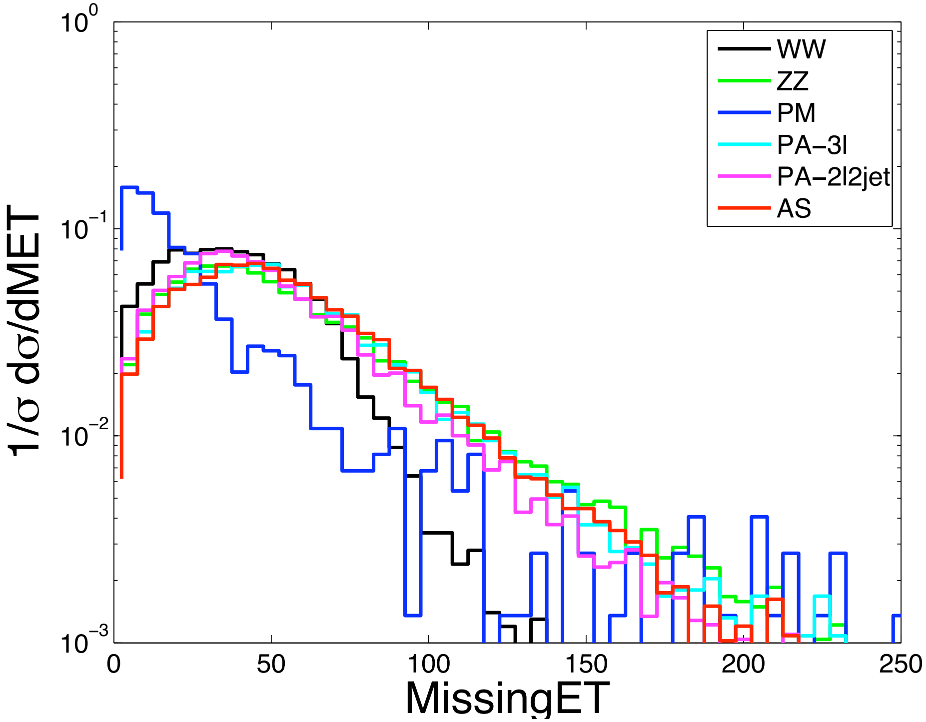
Low mass region: point III

- **Benchmark III: m_S = 73 GeV, (δ_1, δ_2)=(10,50) GeV**

Signal: pp→SA→SSZ*→SSl⁺l⁻, l=e,μ; also including AH±

Two isolated opposite charge e or μ with large missing E_T, no hard jets.



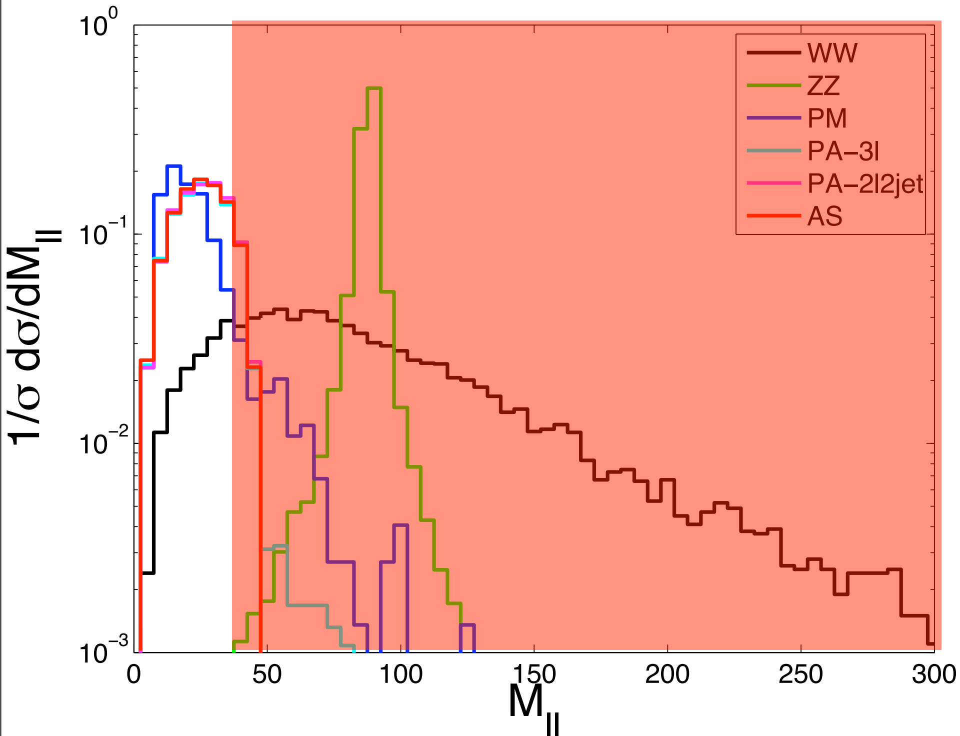


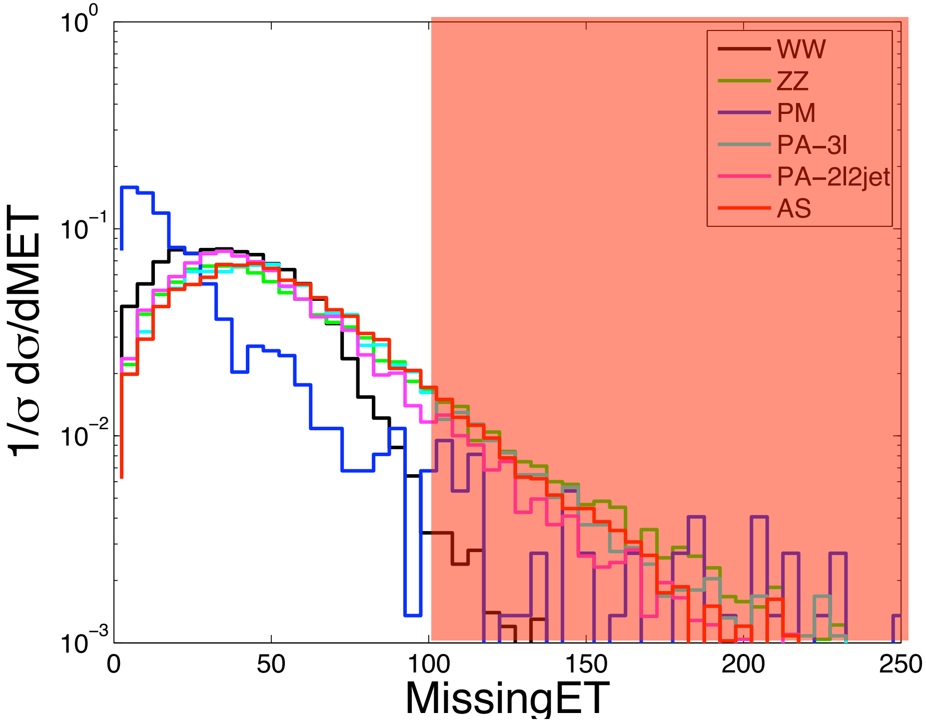
Low mass region: point III

- **Benchmark III: m_S = 73 GeV, (δ_1, δ_2)=(10,50) GeV**

Signal: pp→SA→SSZ*→SSl^+l^-, l=e,μ; also including $AH^\pm$

Two isolated opposite charge e or μ with large missing E_T, no hard jets.





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Low mass region: point III

- **Benchmark III: m_S = 73 GeV, (δ_1, δ_2)=(10,50) GeV**

Cuts

- H_T >200 GeV
- ME_T >100 GeV
- P_T^l >15 GeV, $|\eta_l|$<2.5
- $\cos(\phi_{ll})$>0.8
- $\Delta R(ll)$>0.4
- P_T^Z >100 GeV
- M_{ll} < 40 GeV
- no jets with P_T^j>20 GeV, $|\eta_j|$<2.5

Prelimenary		before cuts	after cuts
S (fb)	SA	19.51	0.146
B (fb)	H^+H^-	17.84	0
	WW	3404.6	0.025
	ZZ	280.8	0.0025
L=100 fb^{-1}		S/B	5.31
		s/√(B)	8.81

Collider reach @ LHC

$pp \to SA \to SSZ^{(*)} \to SSl^+l^-$

Prelimenary

	m_S	(δ_1, δ_2)	S	B	S/B	S/√(B)
	GeV	GeV	fb	fb	L=100 fb^{-1}	
(I)	25	(100,100)	5.826	5.068	0.115	8.18
(II)	75	(50,10)	difficult			
(III)	75	(10,50)	0.146	0.0276	5.31	8.81
(IV)	75	(50,50)	0.130	0.028	4.70	7.81

Conclusions

- IHDM: provide a scalar WIMP dark matter candidate
- Viable regions of parameter spaces provide correct relic density

	DM	SM h	m_S	δ_1, δ_2	λ_L
(I)	low m_S	low m_h	~20 GeV	both large	~ -0.2
(II)			60 – 80 GeV	at least one is large	-0.2 – 0.2
(III)		high m_h	50 – 75 GeV	large δ_1 $\delta_2 < 8$ GeV	-1 – 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 – 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 – 0.2

- Rich collider phenomenology

  * dilepton signal from SA production observable for large δ_2