Inert Doublet Model:

Dark Matter Implication and Collider Phenomenology

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

Inert 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" Doublet Model (IDM)

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

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

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$\delta_1 = m_{H\pm} - m_S$

$\delta_2 = m_A - m_S$

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

Constraints

- Vacuum stability
- Perturbativity
- Dark matter direct detection
- W and Z decay width $W \to S/A + H^{\pm}$, $Z \to S+A$, H^+H^-
- LEP II constraints

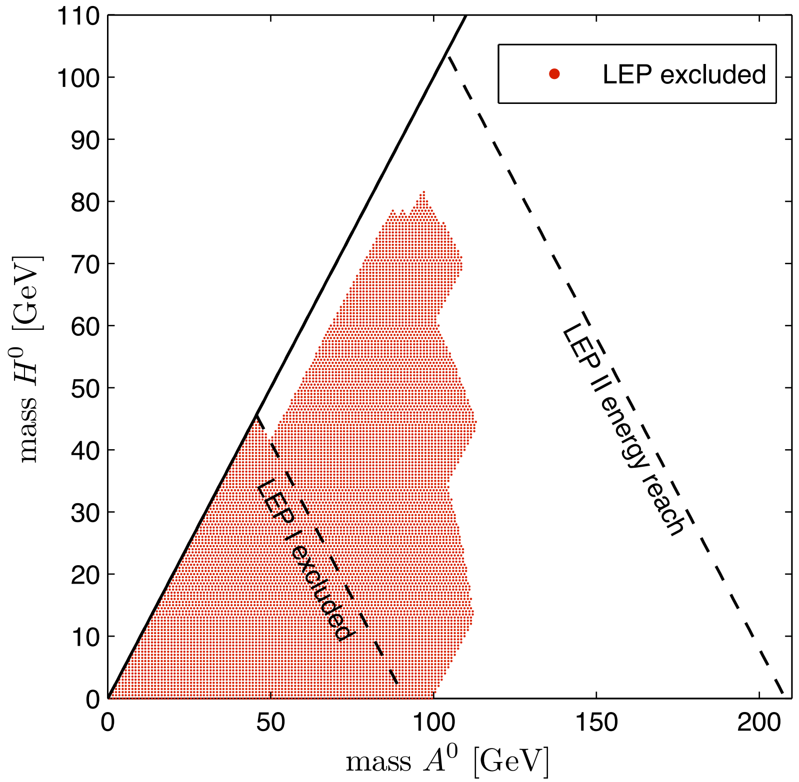
Neutral and charged Higgs searches at LEP and Tevatron: does not apply

rely on VVh coupling and the couplings of Higgses to fermions

Constraints

✦ **LEP II constraints**

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



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

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➡ $m_{H\pm} \geq 70$ GeV

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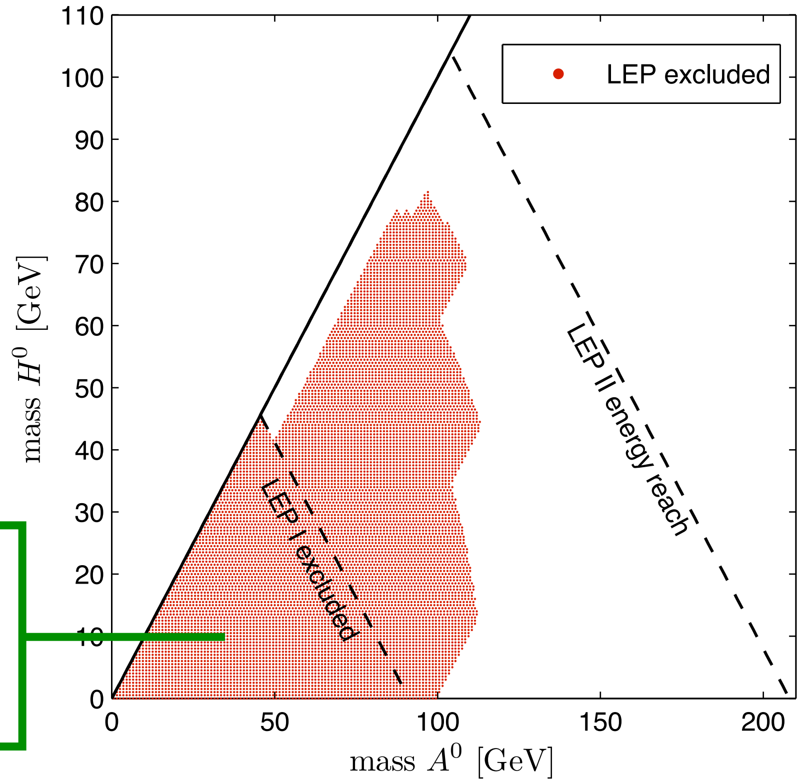

LEP I
$m_S + m_A < m_Z$
excluded

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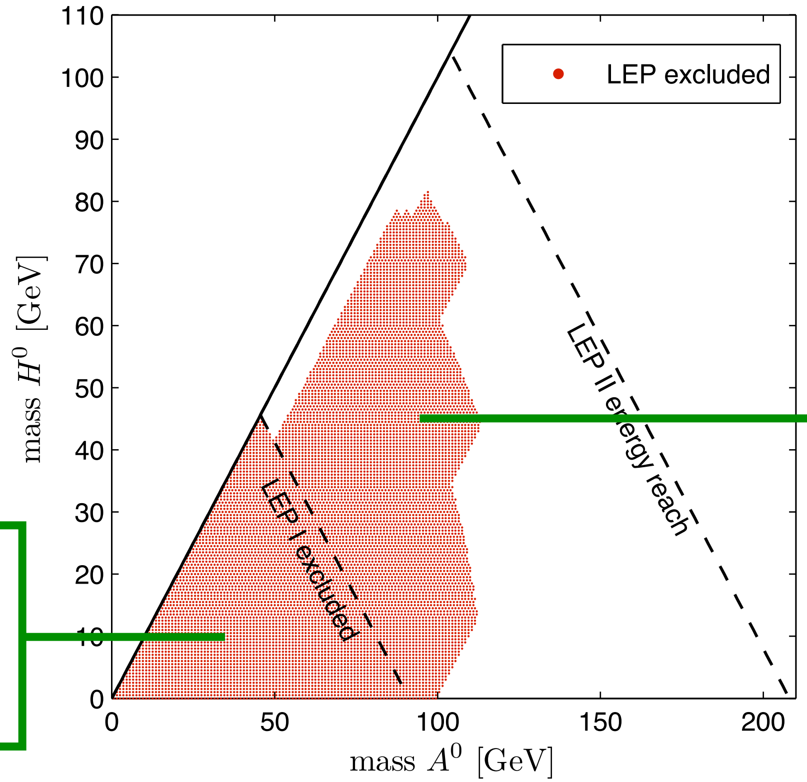

LEP II
δ_2 > 8 GeV
m_S < 80 GeV
m_A < 100 GeV
excluded

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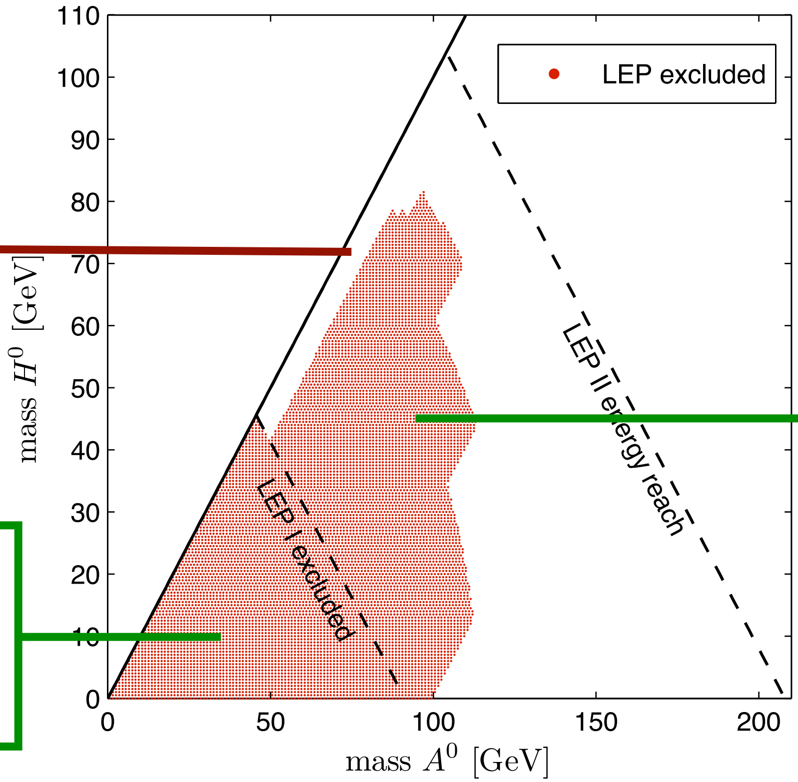
δ_2 < 8 GeV
$m_S + m_A > m_Z$
allowed



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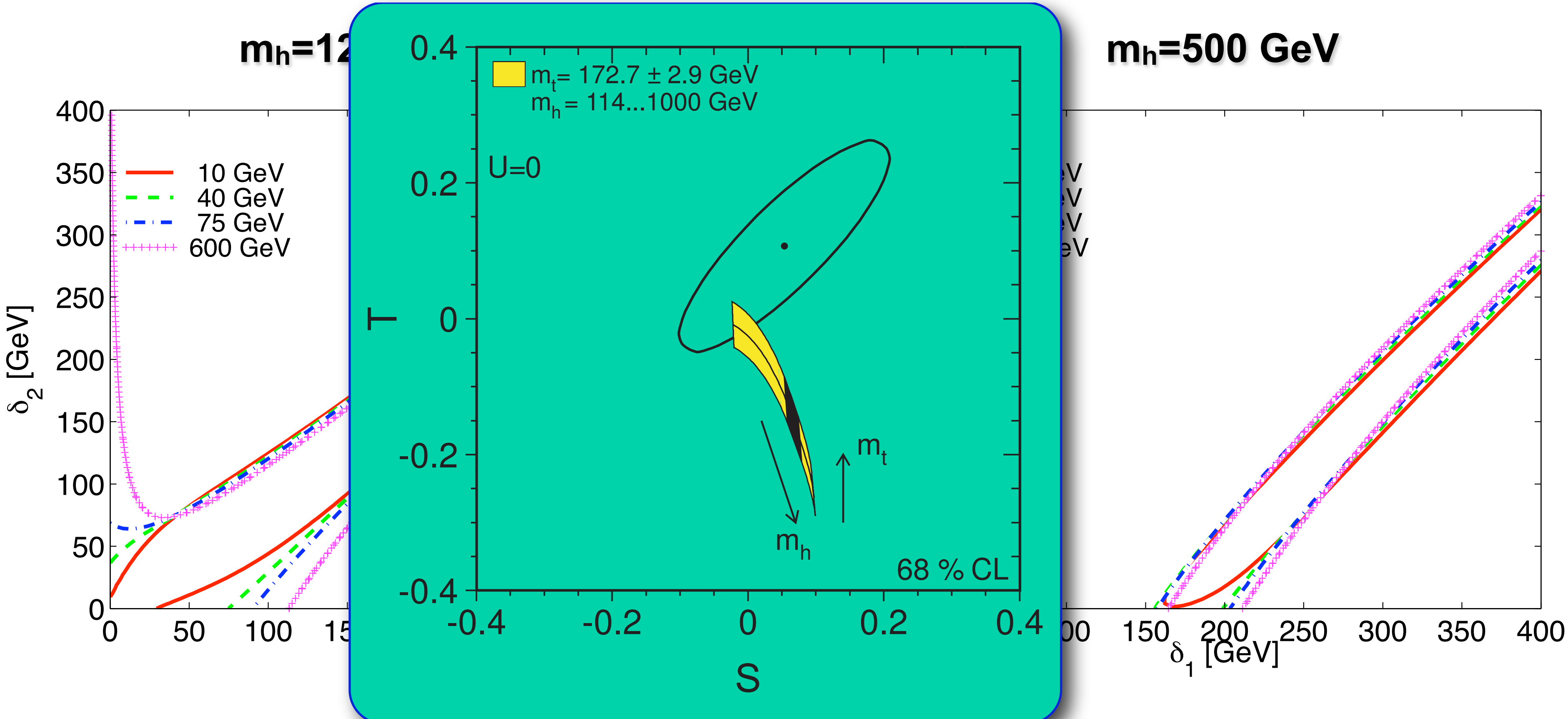
➡ $m_{H\pm} \geq 70$ GeV

Electroweak Precision Test

- ✦ **Electroweak precision test**

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

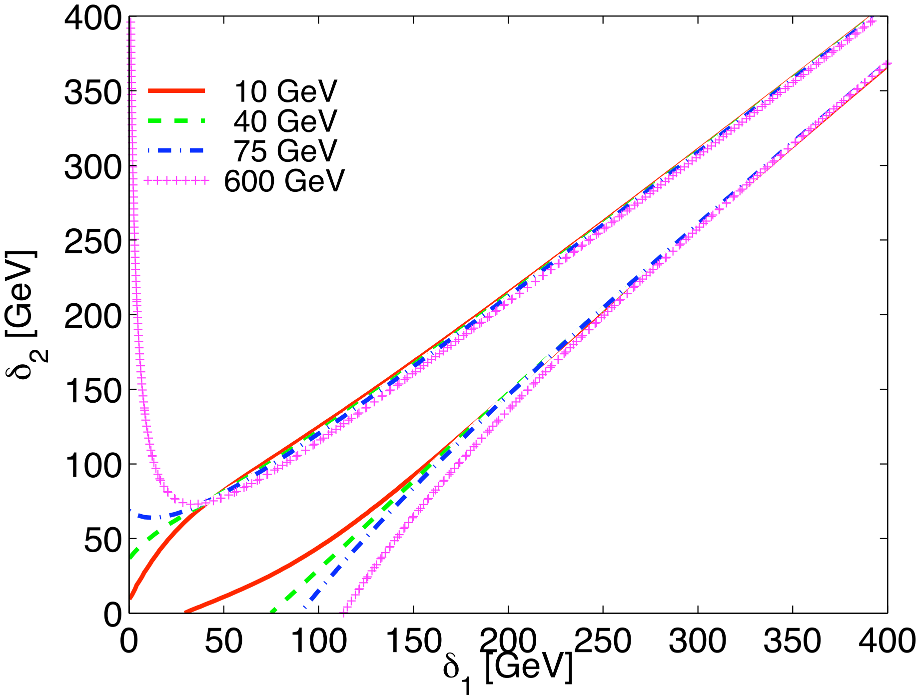


Electroweak Precision Test

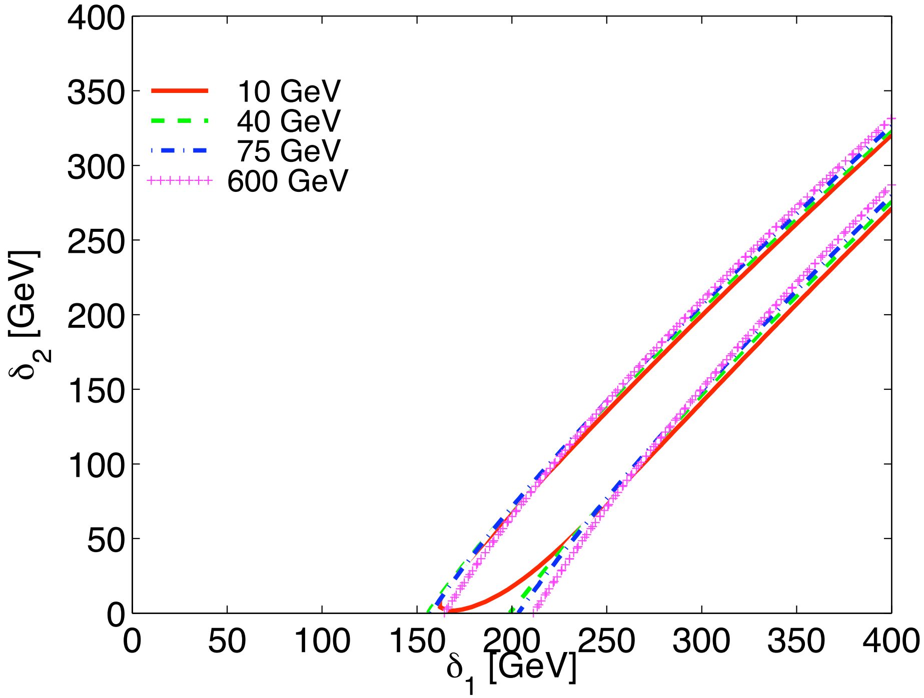
- Electroweak precision test

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

m_h=120 GeV

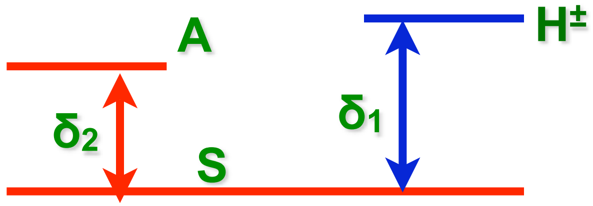


m_h=500 GeV



Dark matter relic density

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



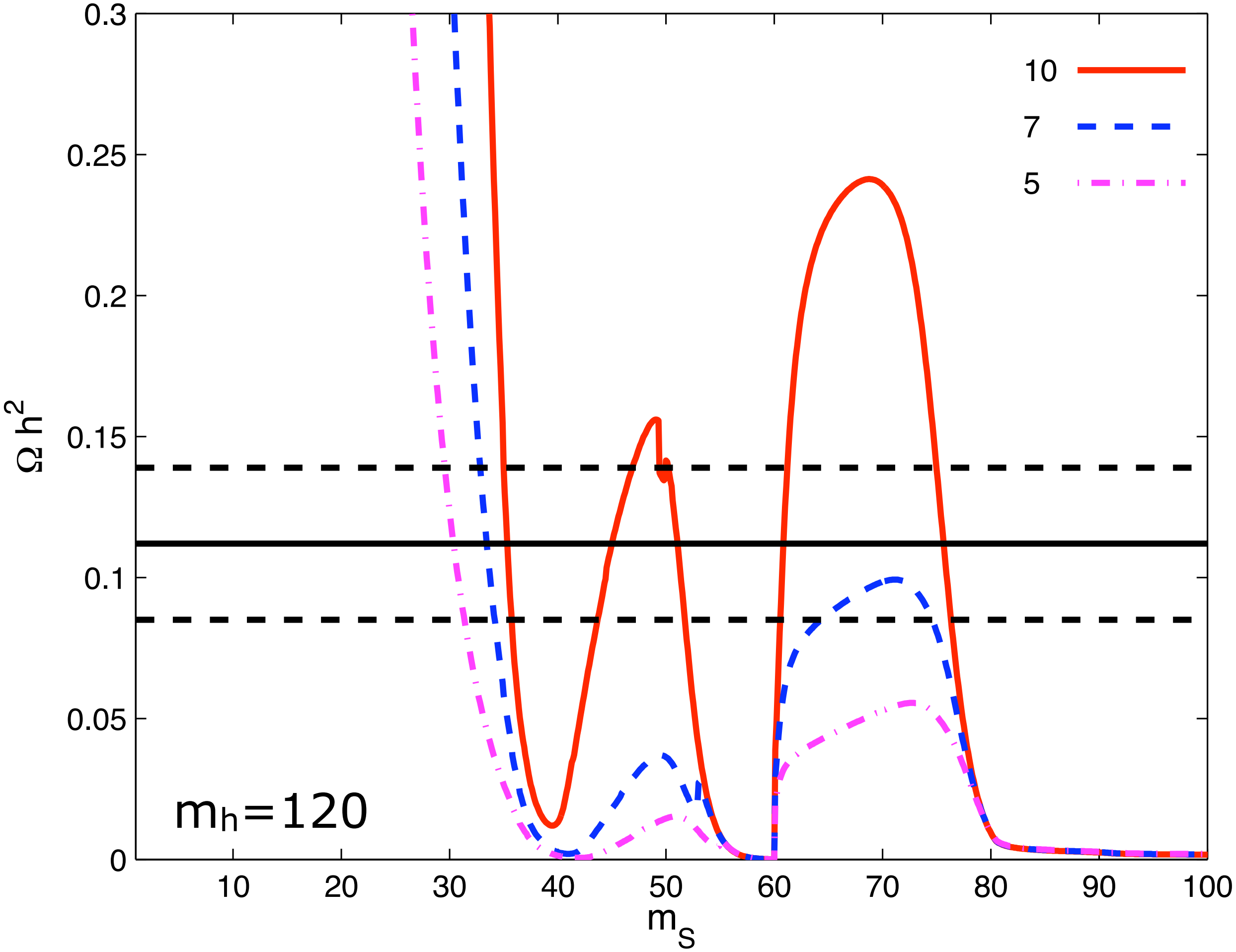
- Use MicrOMEGA /CalCHEP to calculate the relic density

➡ 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, $\lambda_L = 0.01$



- $\delta_2 = m_A - m_S$ = 10 GeV
- $\delta_2 = m_A - m_S$ = 7 GeV
- $\delta_2 = m_A - m_S$ = 5 GeV

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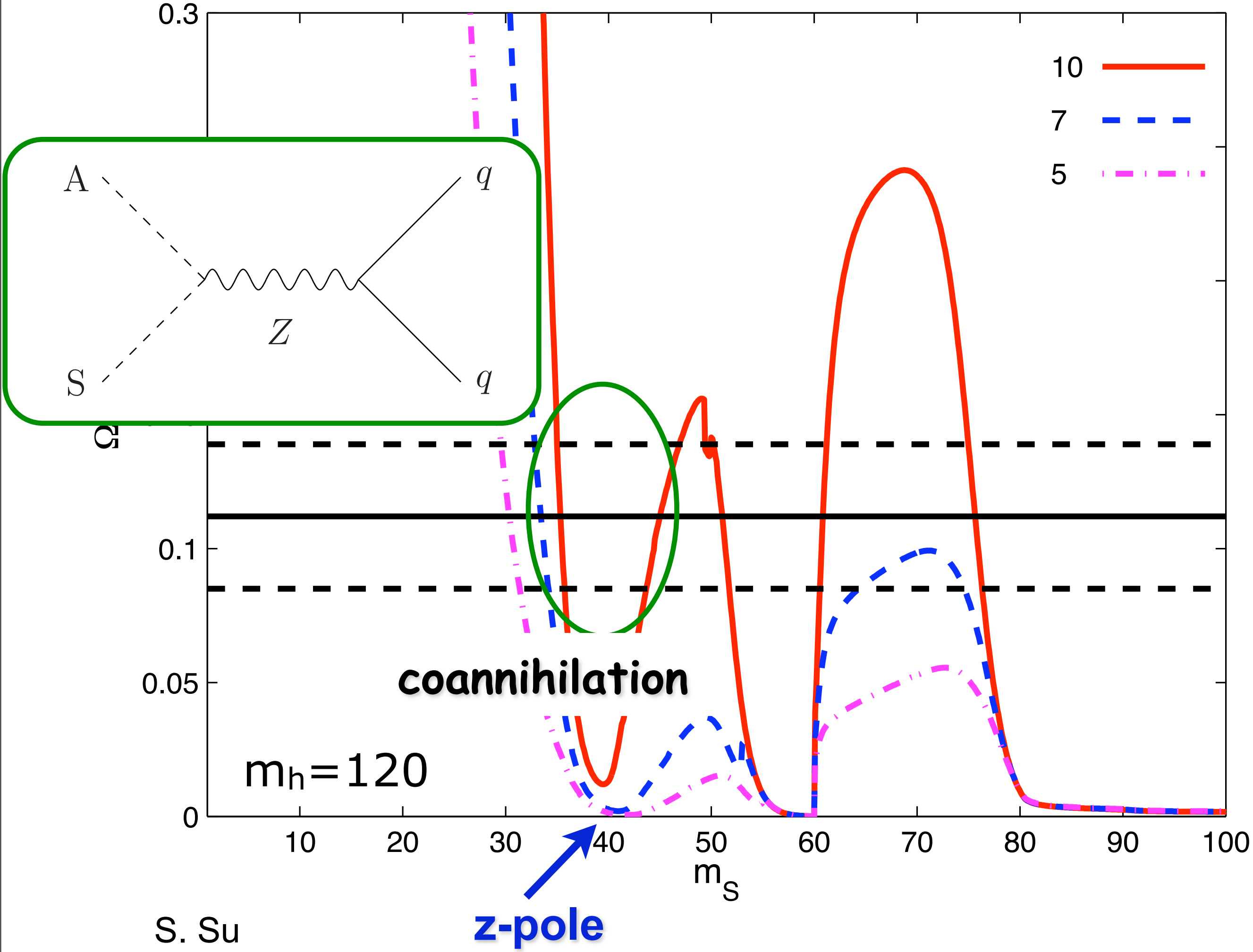

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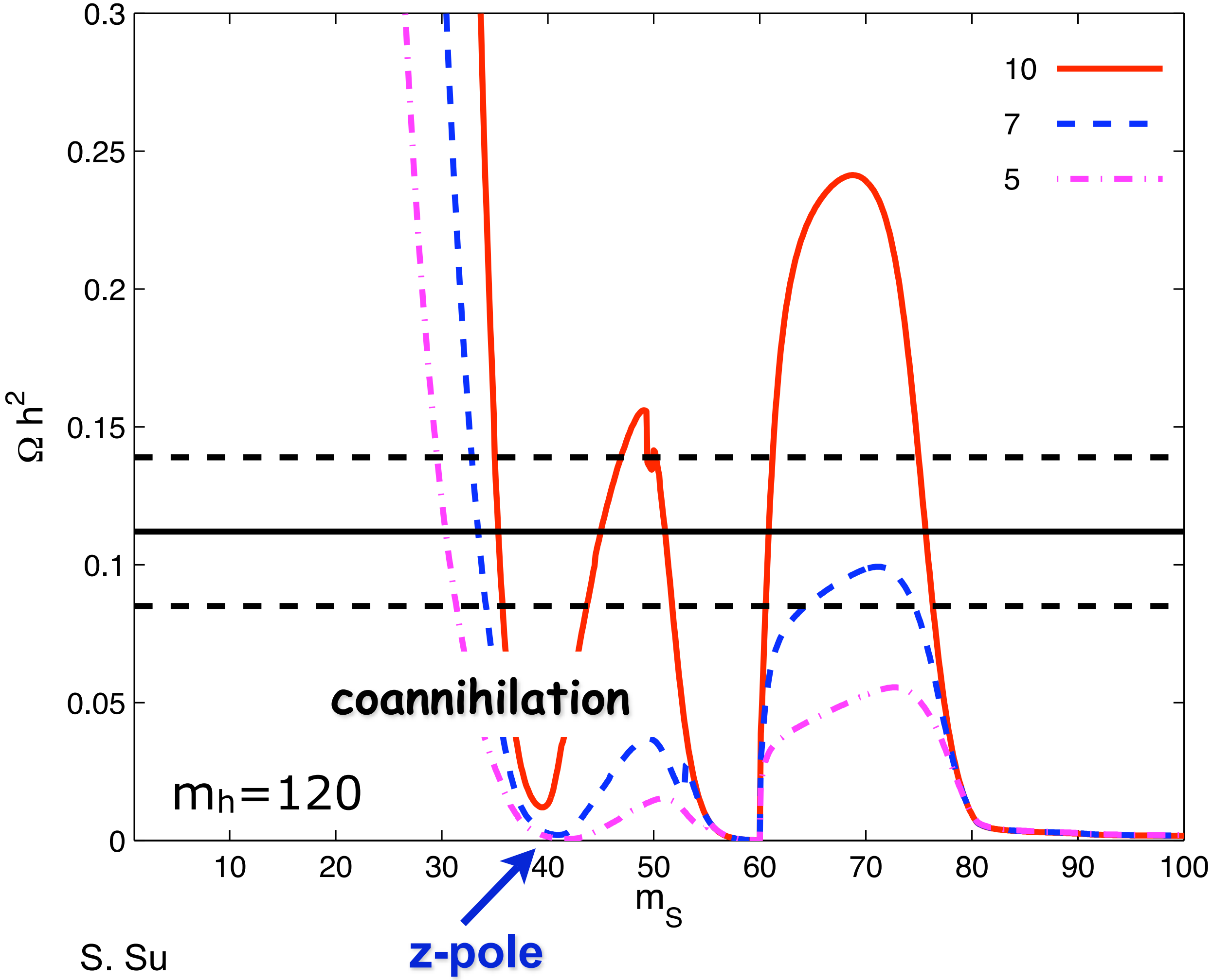

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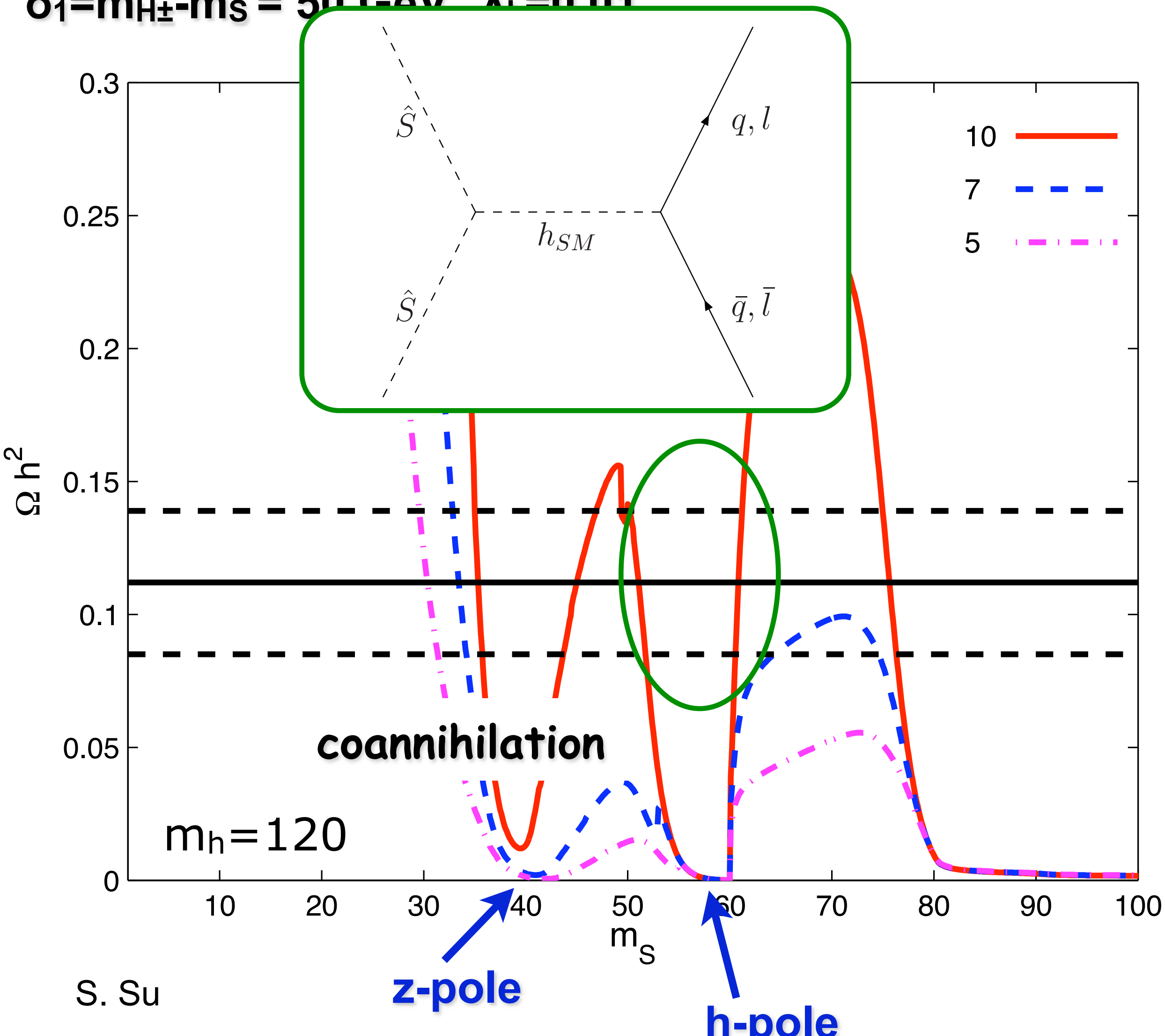

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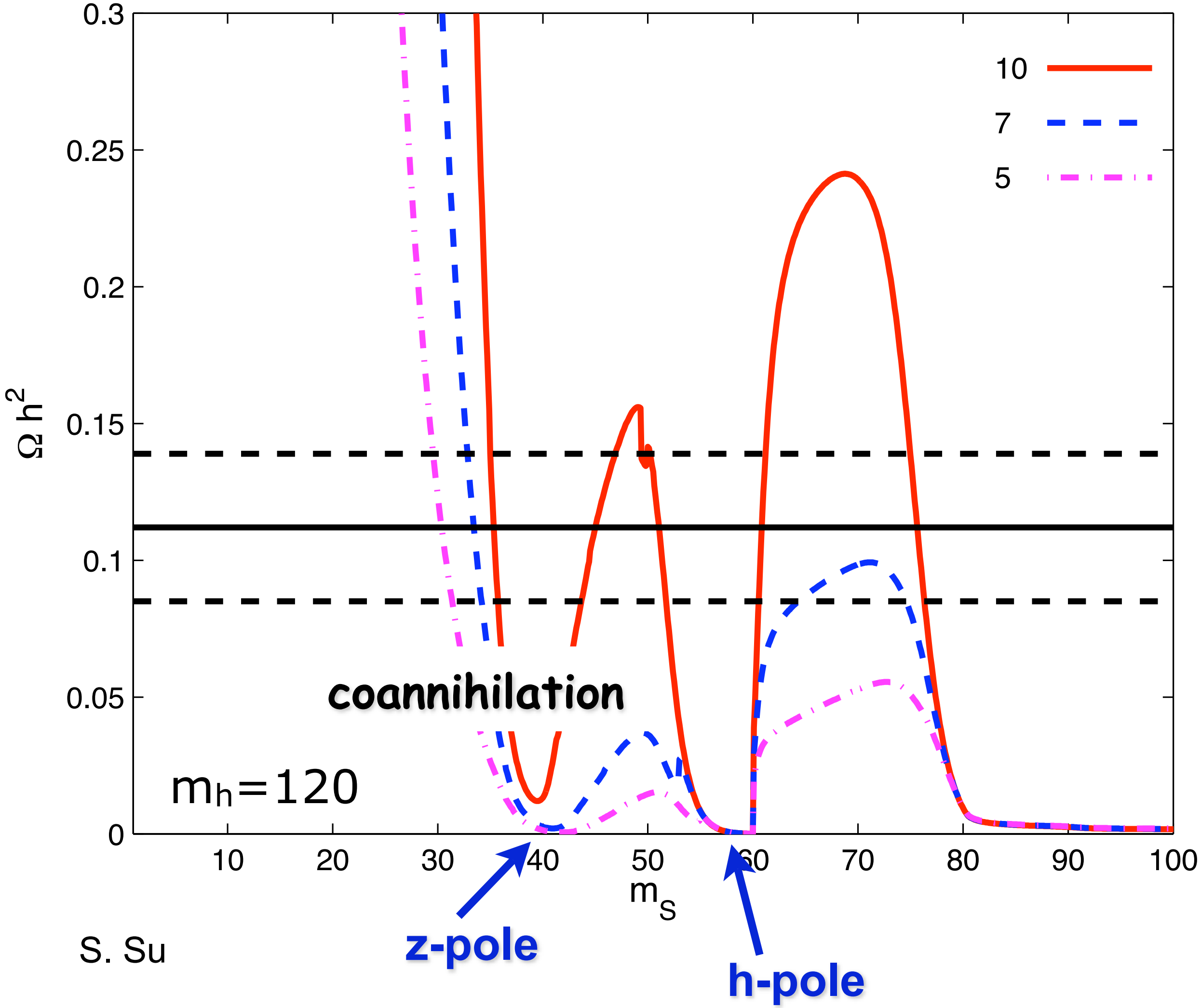

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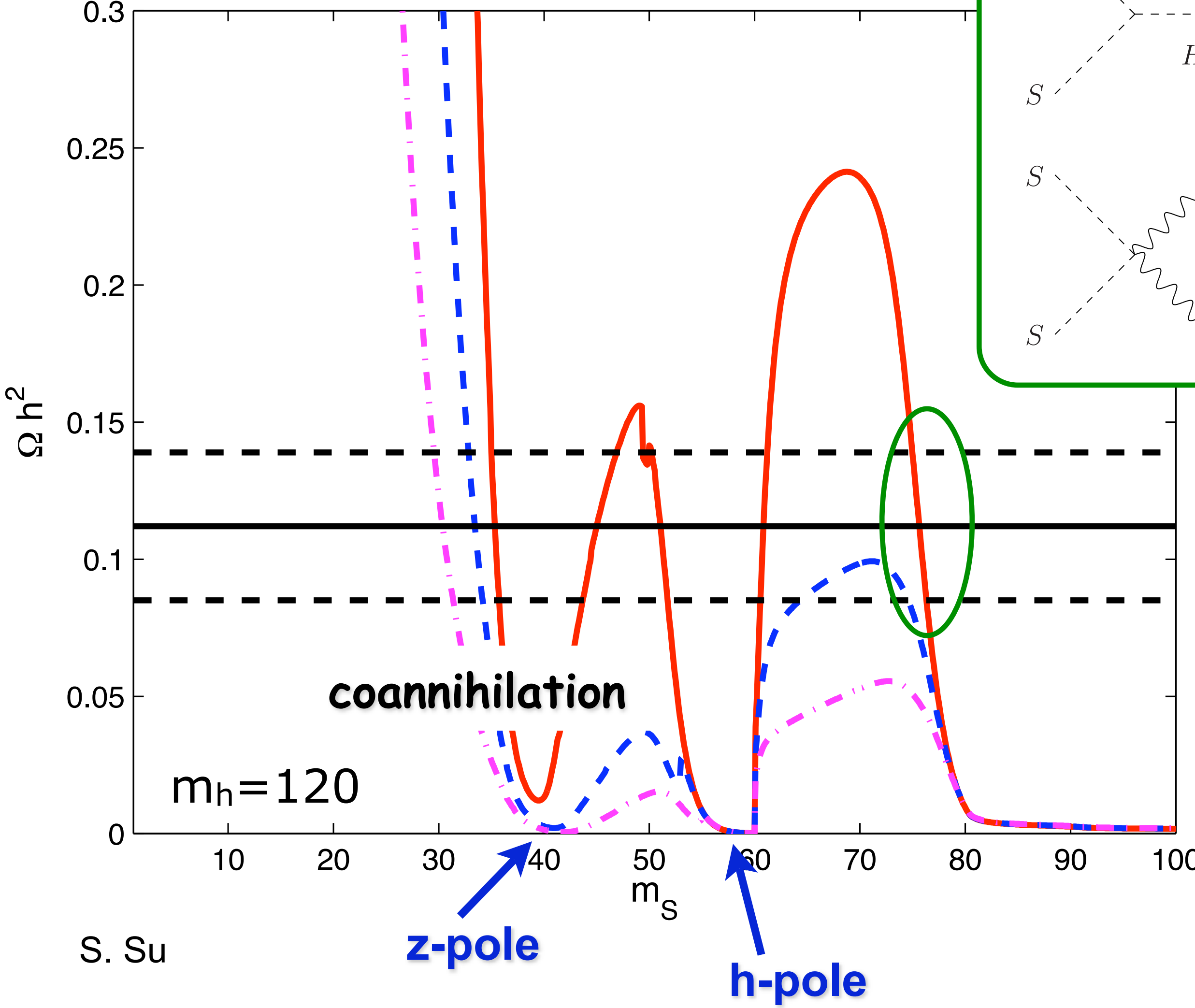

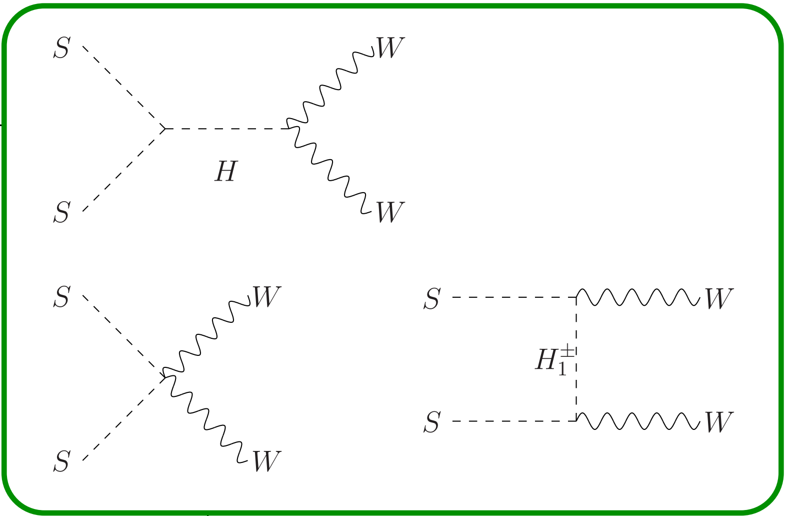

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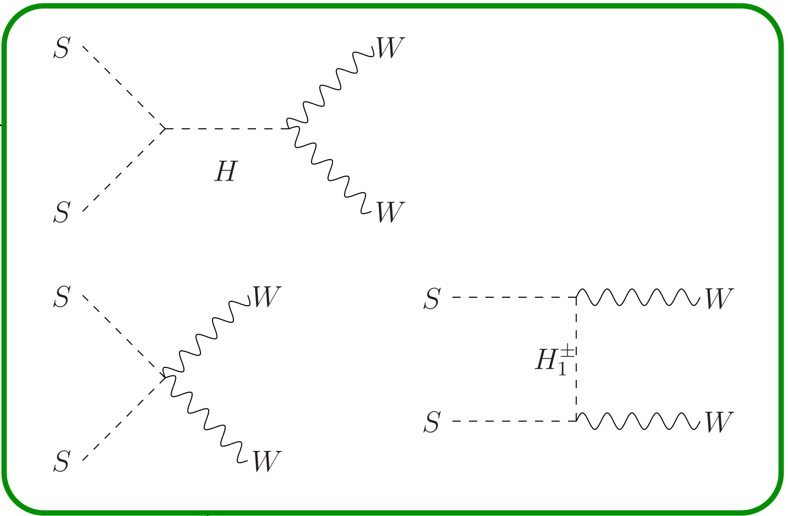

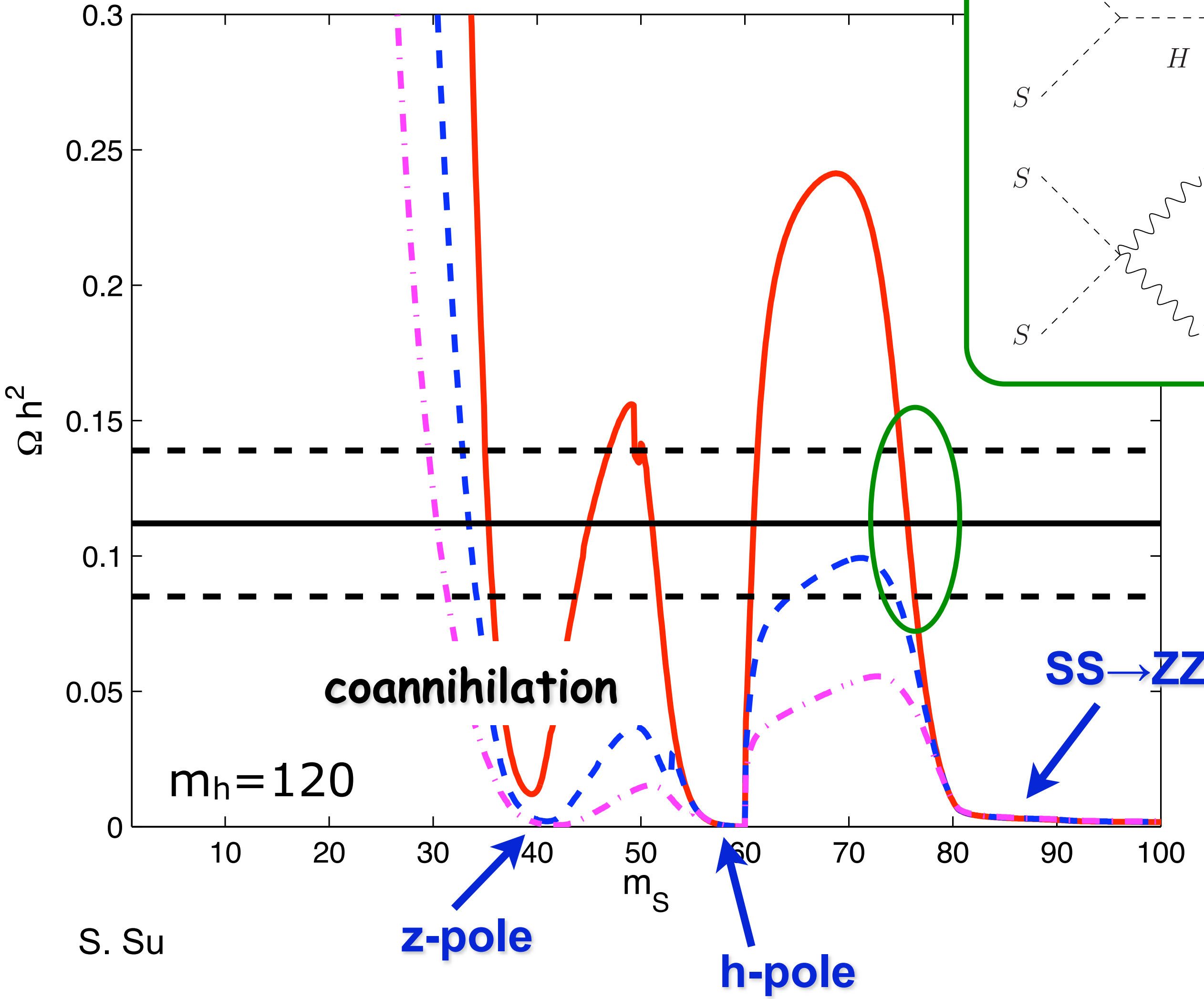

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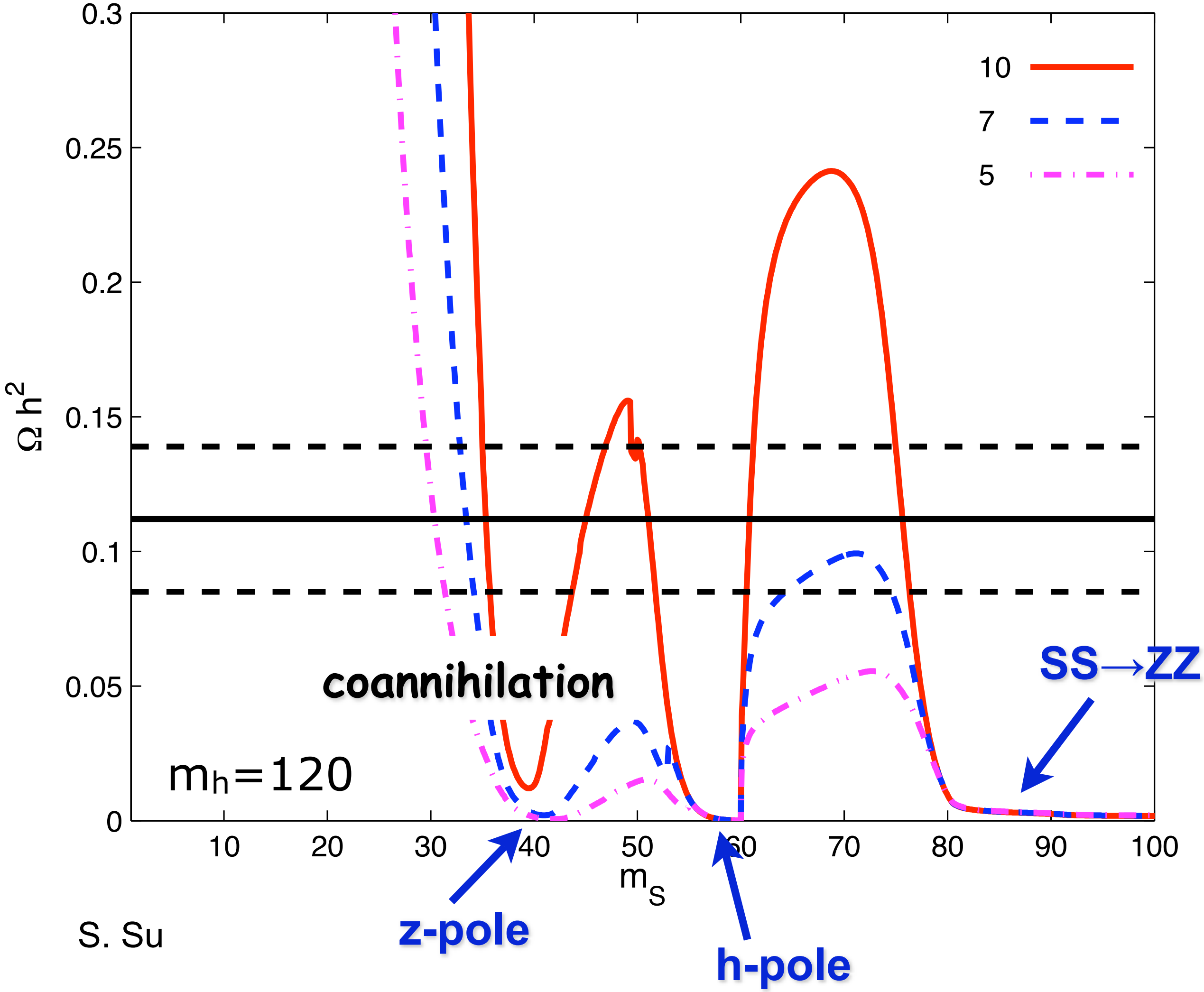

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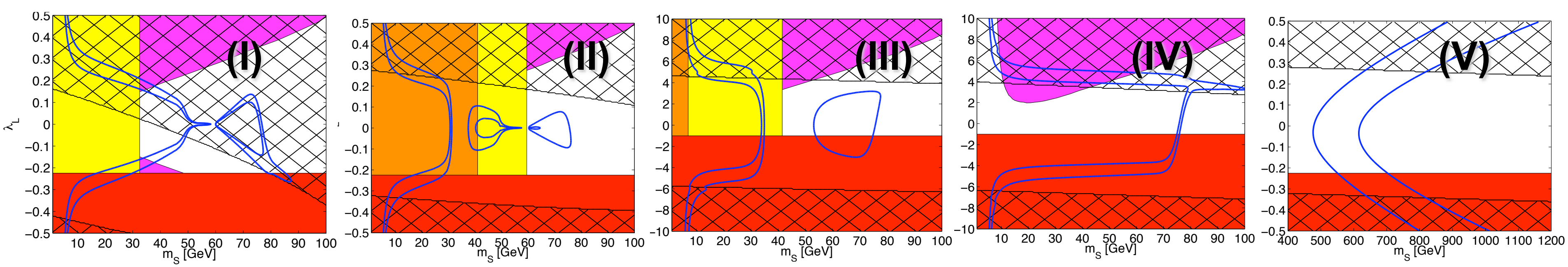
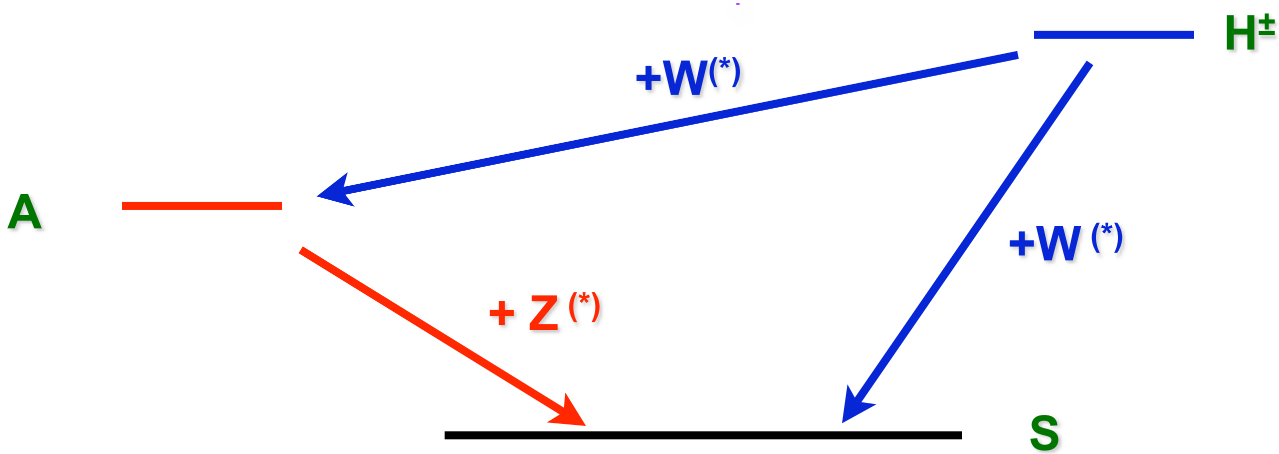
Viable region for relic density

	DM	SM h	m_S	δ_1, δ_2	λ_L
(I)	low m_S	low m_h	30 – 60 GeV	50 - 90 GeV	-0.2 to 0
(II)			60 – 80 GeV	at least one is large	-0.2 to 0.2
(III)		high m_h	50 – 75 GeV	large δ_1 $\delta_2 < 8$ GeV	-1 to 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 to 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 to 0.3



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/γ, WZ/γ, tt, ...

Benchmark points

	m_h (GeV)	m_S (GeV)	(δ_1, δ_2) (GeV)	λ_L
LH1	150	40	(100,100)	− 0.275
LH2	120	40	(70,70)	− 0.15
LH3	120	82	(50,50)	− 0.2
LH4	120	73	(10,50)	0
LH5	120	79	(50,10)	− 0.18
HH1	500	76	(250,100)	0
HH2	500	76	(200,30)	0

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 IDM $pp \to H^+H^- \to SSW^{(*)}W^{(*)} \to SSl^+l^-\nu\nu$
- from SM
  - $pp \to WW \to l^+l^-\nu\nu$
  - $pp \to ZZ/\gamma \to l^+l^-\nu\nu$
  - tt, WZ, Wt, Zt ... with missing lepton or jets

Dilepton signal: LH1

•LH1: m_S = 40 GeV, (δ_1, δ_2)=(100,100) GeV

Signal: pp→SA→SSZ→SSl^+l^-, l=e,μ

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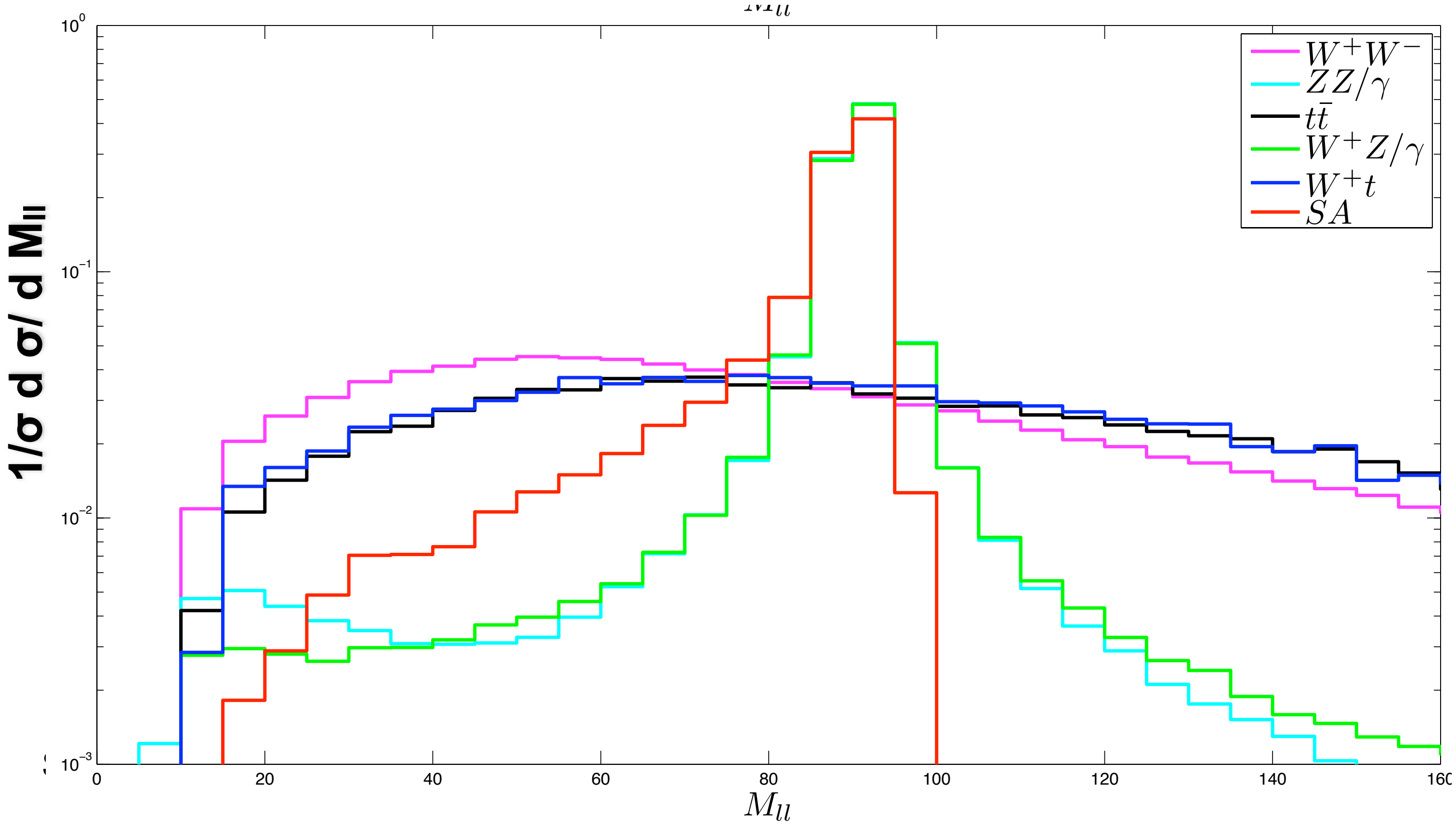

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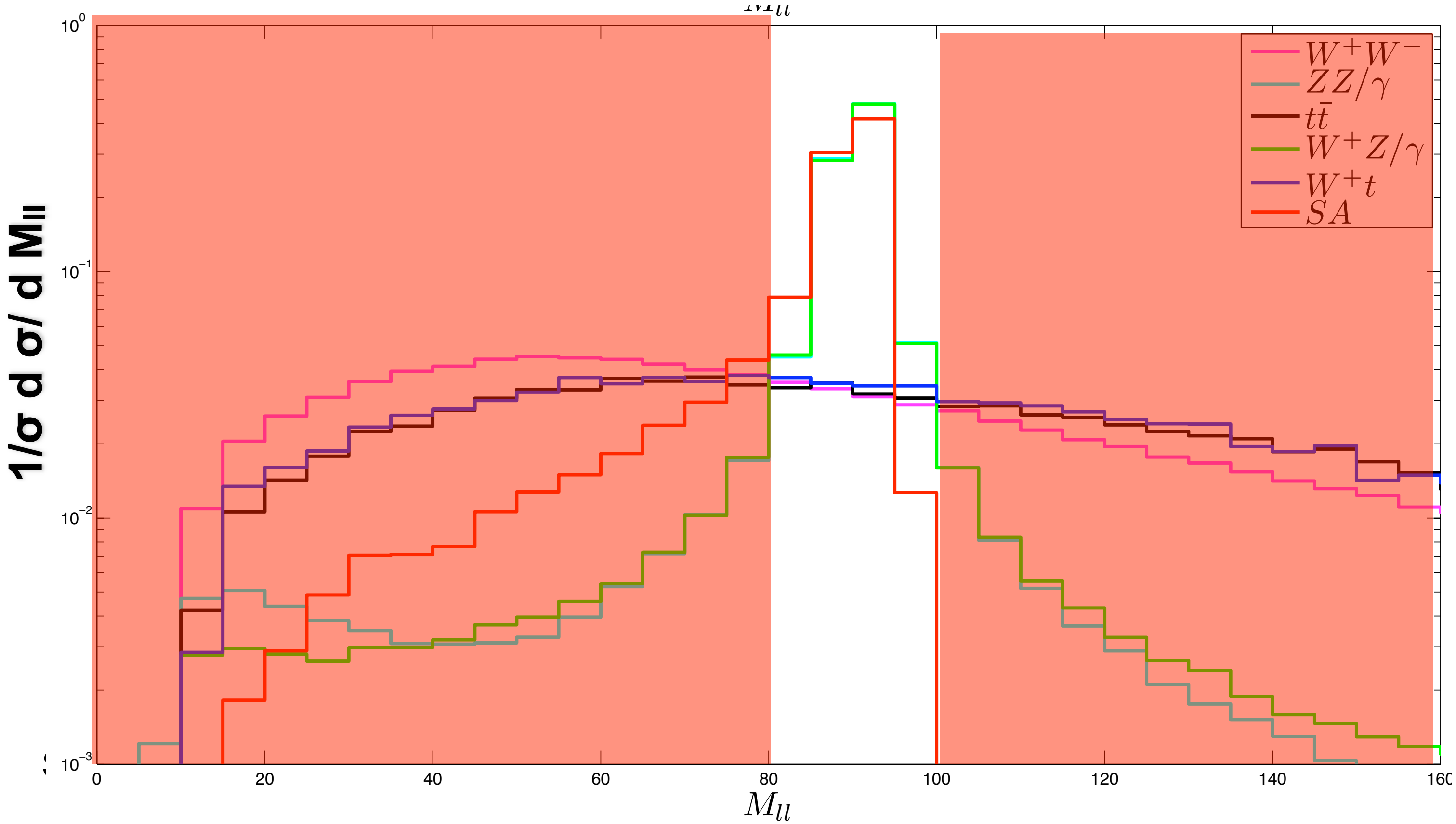

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Cuts
- P_T^l >15 GeV, $|\eta_l|$<2.5
- $\Delta R(ll)$>0.4
- no jets with P_T^j>20 GeV, $|\eta_j|$<3
- ME_T >100 GeV
- H_T >200 GeV
- 80 GeV < M_{ll} < 100 GeV

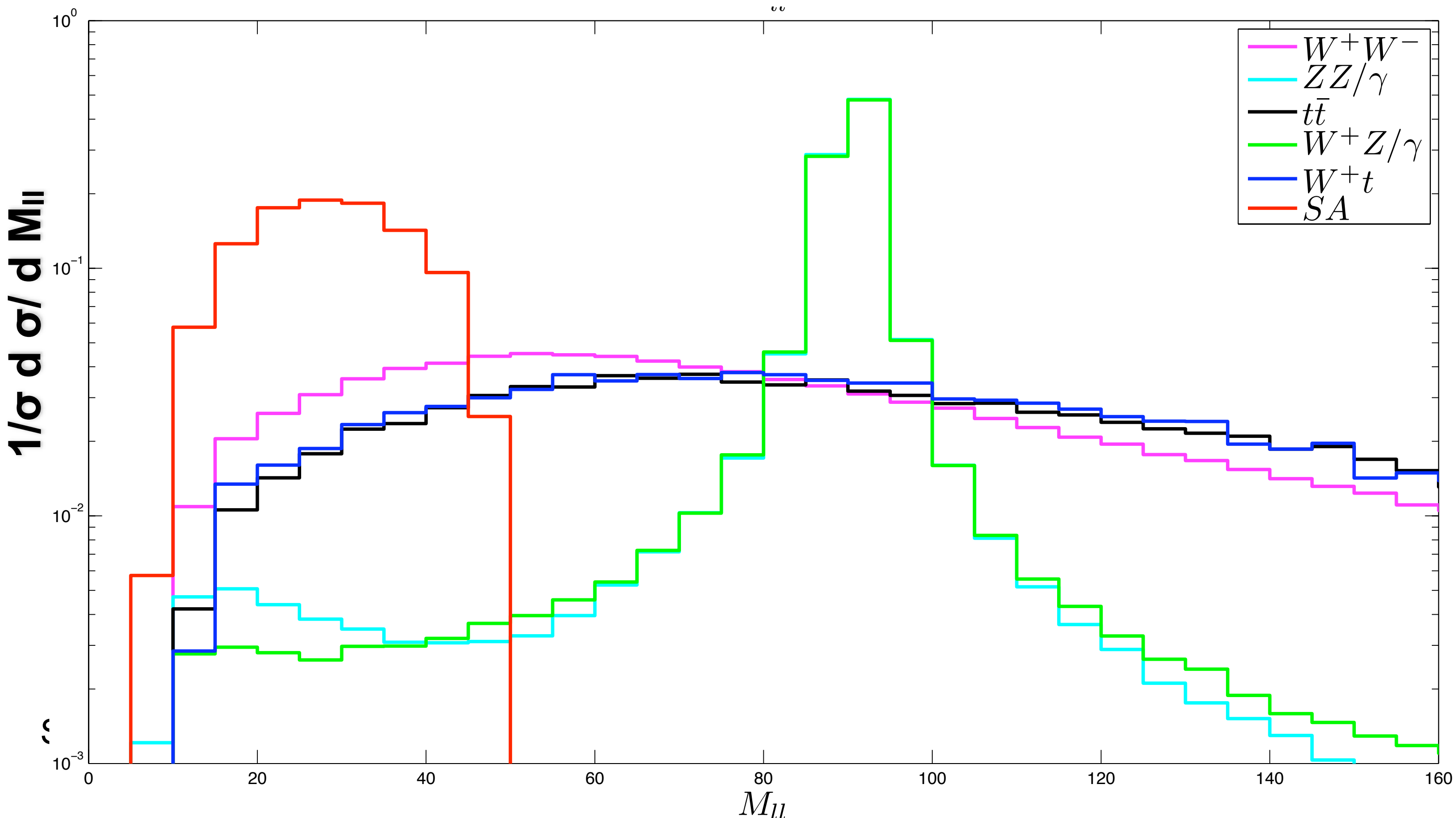
		I+II	I+II+III
S (fb)	SA	6.550	3.68
B (fb)	H^+H^-	0.496	0.040
	WW	345.1	12.41
	ZZ /γ	82.69	39.86
	tt	91.20	7.37
	WZ	104.35	37.55
	Wt	68.68	15.00
	total		102.18
L=100 fb^{-1}		S/B	0.04
		s/√(B)	3.64

Low mass region: LH4

•LH4: m_S = 73 GeV, (δ_1, δ_2)=(10,50) 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.



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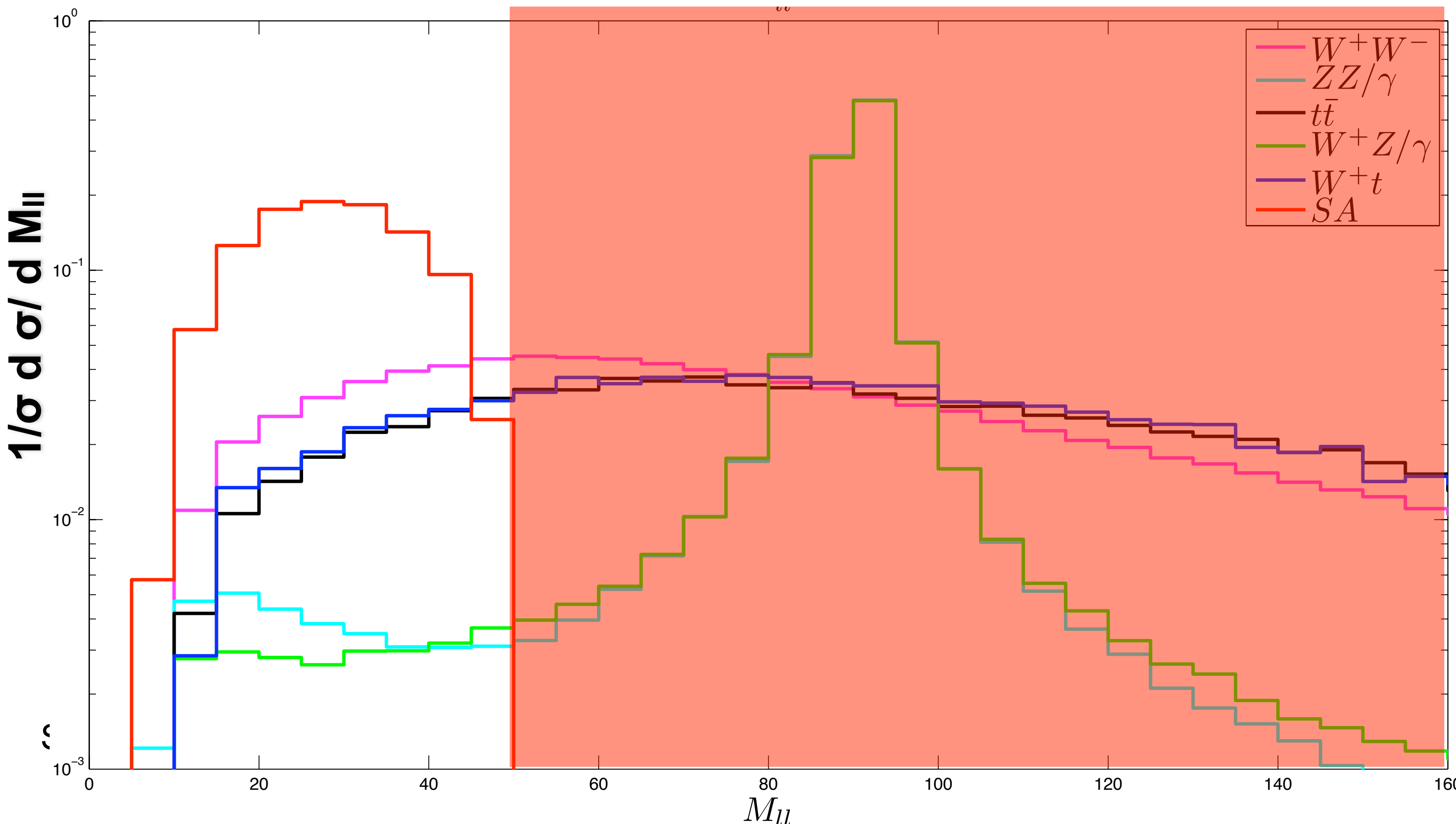

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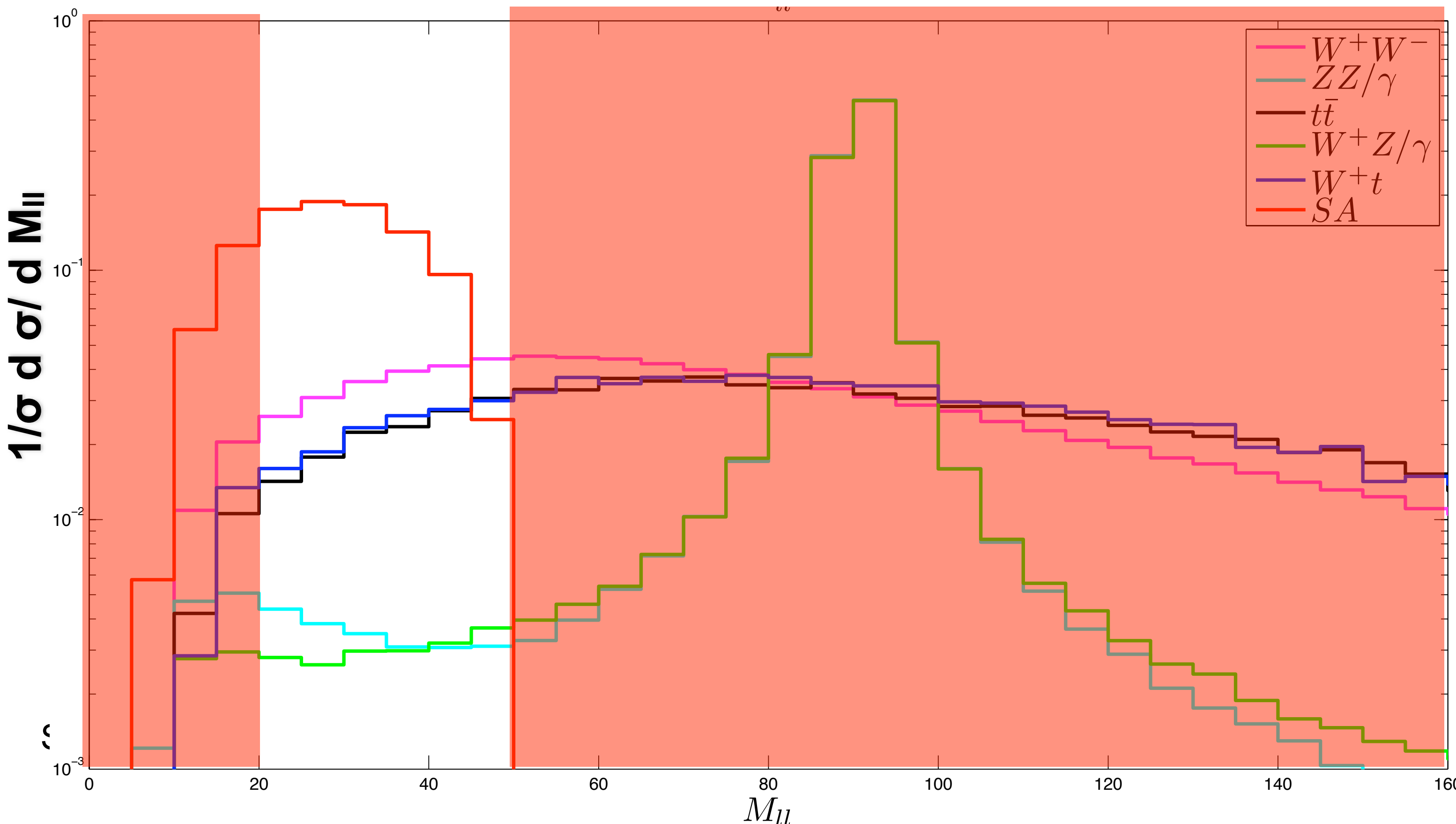

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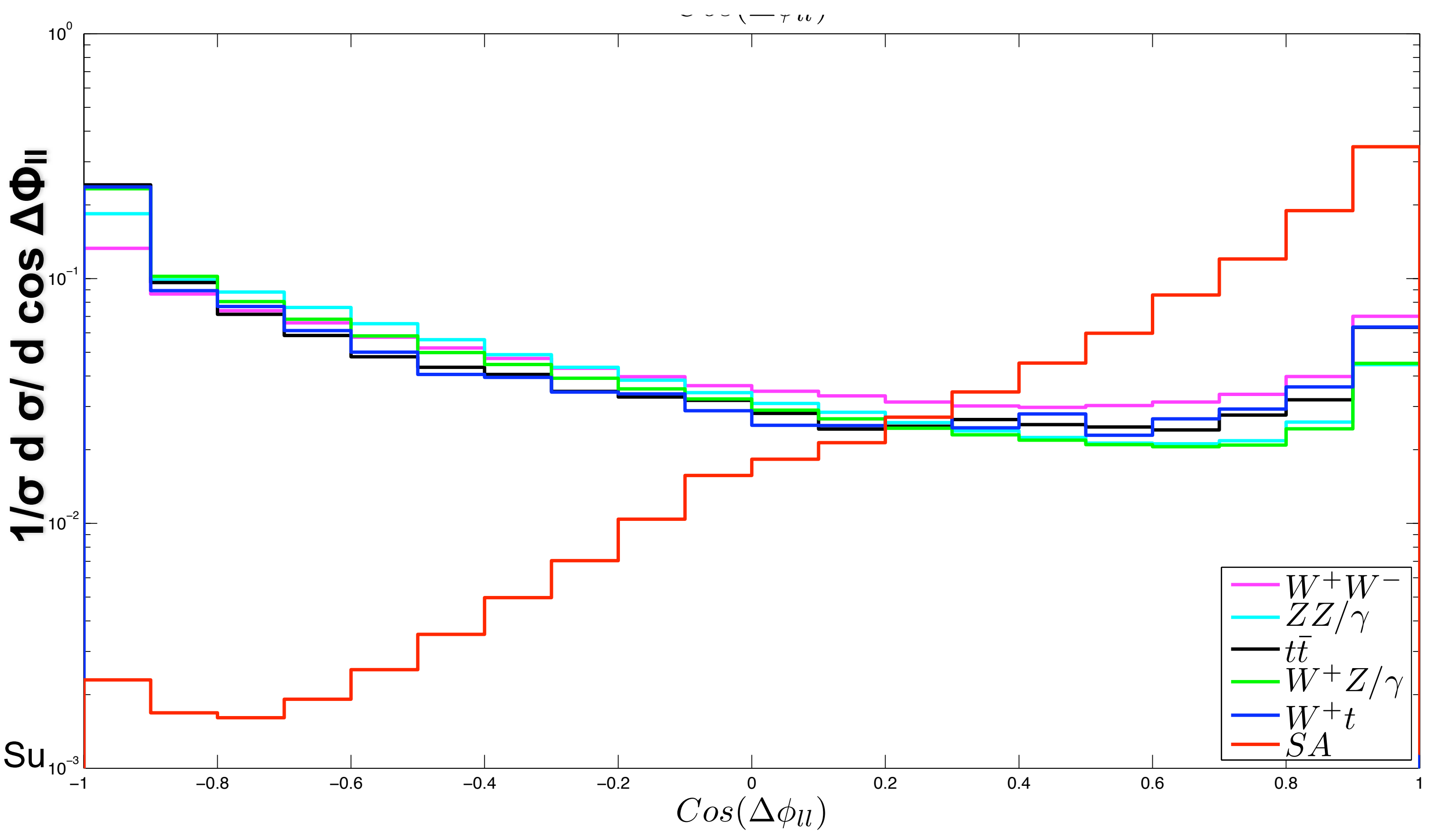

S. Su

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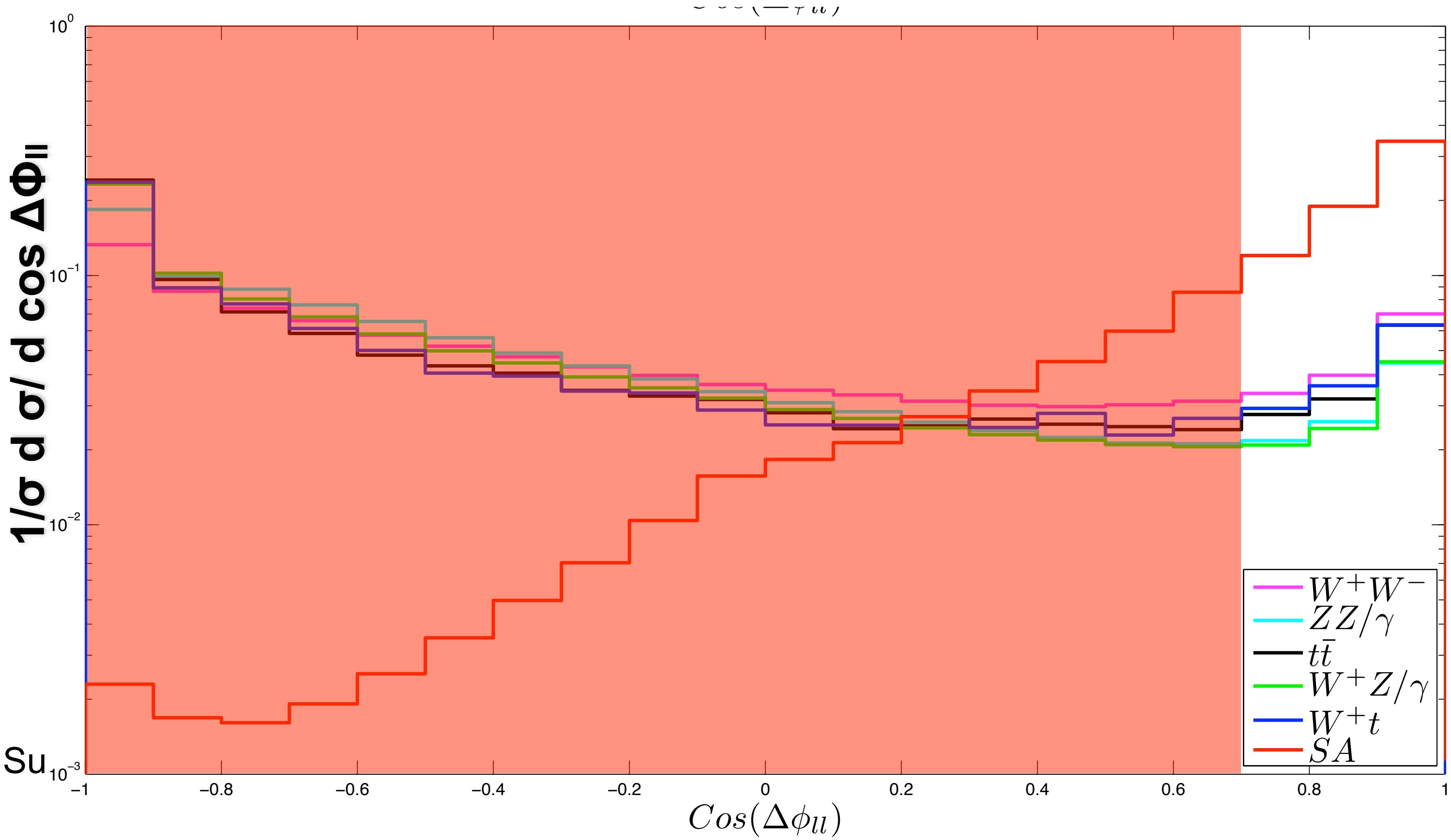

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- $\Delta R(ll)$>0.4
- no jets with P_T^j>20 GeV, $|\eta_j|$<3
- ME_T >90 GeV
- H_T >200 GeV
- 20 GeV< M_{ll} < 50 GeV
- $\cos(\phi_{ll})$>0.7
- $\Delta R(ll)$<0.8

		I+II	I+II+III
S (fb)	SA	2.48	0.22
B (fb)	H^+H^-	<0.0001	<0.001
	WW	345.14	0.04
	ZZ /γ	82.69	0.16
	tt	91.20	0.09
	WZ	104.35	0.07
	Wt	68.68	0.09
	total		0.47
L=100 fb^{-1}		S/B	0.47
		$s/\sqrt{(B)}$	3.23

Low mass region: LH2

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- $\Delta R(ll)$>0.4
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- ME_T >50 GeV
- H_T >150 GeV
- M_{ll} < 70 GeV
- $\cos(\phi_{ll})$>0.7
- $\Delta R(ll)$<1.2

		I+II	I+II+III
S (fb)	SA	7.392	0.97
B (fb)	H^+H^-	0.568	<0.001
	WW	345.1	0.09
	ZZ /γ	82.69	0.28
	tt	91.20	0.23
	WZ	104.35	0.14
	Wt	68.68	0.13
	total		0.88
L=100 fb^{-1}		S/B	1.11
		s/√(B)	10.37

Dilepton signal: LH5

- **LH5: m_S = 79 GeV, (δ_1, δ_2)=(50,10) GeV**

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

Soft leptons. Difficult.

Collider reach @ LHC

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

	m_S	(δ_1, δ_2)	S	B	S/B	S/√(B)
	GeV	GeV	fb	fb	L=100 fb^{-1}	
LH1	40	(100,100)	3.68	102.18	0.04	3.64
LH2	40	(70,70)	0.97	0.88	1.11	10.37
LH3	82	(50,50)	0.19	0.47	0.40	2.75
LH4	73	(10,50)	0.22	0.47	0.47	3.23
LH5	79	(50,10)	0.33	0.30	0.09	0.52
HH1	76	(250,100)	0.69	27.17	0.03	1.33
HH2	76	(200,30)	1.22	27.65	0.04	2.32

Collider reach @ LHC

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Conclusions

- IDM: 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	30 – 60 GeV	50 - 90 GeV	-0.2 to 0
(II)			60 – 80 GeV	at least one is large	-0.2 to 0.2
(III)		high m_h	50 – 75 GeV	large δ_1 $\delta_2 < 8$ GeV	-1 to 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 to 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 to 0.3

- Rich collider phenomenology
  - * dilepton signal (from SA) observable for not too small δ_2 .