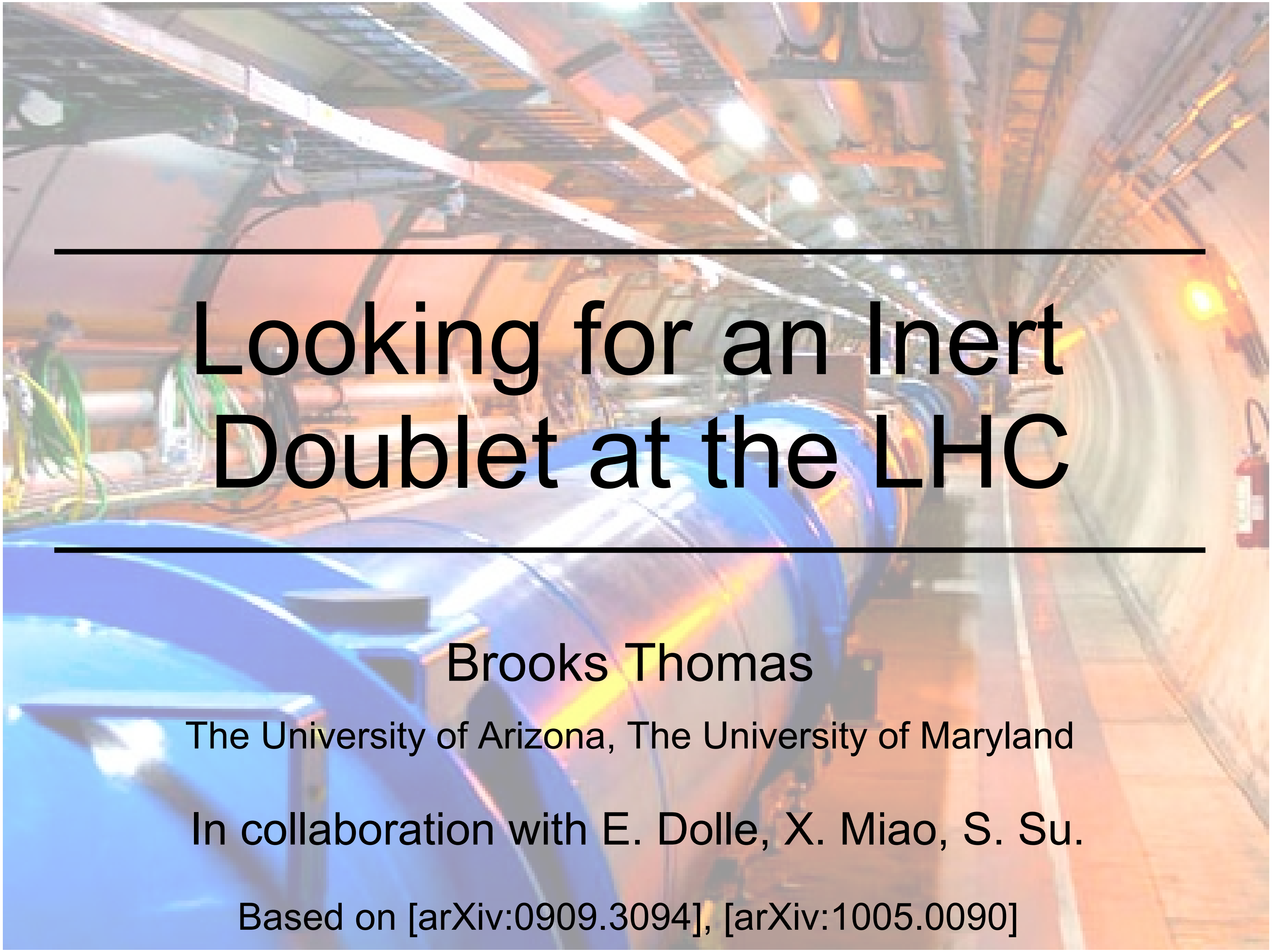

Looking for an Inert Doublet at the LHC

Brooks Thomas

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In collaboration with E. Dolle, X. Miao, S. Su.

Based on [arXiv:0909.3094], [arXiv:1005.0090]

Since this is the last talk in this session, many of you are now thinking about warm dark matter...

...so if you're interested in more details, please don't hesitate to ask me during the coffee break.

What is an Inert Doublet?

(Deshpande, Ma 1978; Ma 2006; Barbieri, Hall, Rychkov 2006; and others)

It's a scalar SU(2) doublet that receives no VEV and has no Yukawa couplings with SM fermions.

- ϕ_1 : SM Higgs doublet ($\langle\phi_1\rangle = v/\sqrt{2} = 174$ GeV).
- ϕ_2 : The inert doublet ($\langle\phi_2\rangle = 0$)
- There exists an **unbroken** $\mathbb{Z}_2$ parity under which:

Even

$\phi_1 \rightarrow \phi_1$ $\quad f_{SM} \rightarrow f_{SM}$ $\quad V^\mu_{SM} \rightarrow V^\mu_{SM}$

Odd

$\phi_2 \rightarrow -\phi_2$

(Note that this is not your typical 2HDM.)

Why would one want an Inert Doublet?

Such doublets have a host of phenomenological applications:

- **A promising dark matter candidate: the "LIP"**

  (Barbieri, Hall, Rychkov 2006; Honorez, Nezri, Oliver, Tytgat 2007; Gustafsson, Lindström, Bergström, Edsjö 2007; Dolle, Su, 2009; et al.)

- **Oblique S and T Contributions from an inert doublet allow for a heavy (400-600 GeV) Higgs.**

  (Barbieri, Hall, Rychkov 2006)

- **A connection to neutrino physics**

  (Deshpande, Ma, 1978; Ma 2006; Agrawal, Dolle, Krenke 2008)

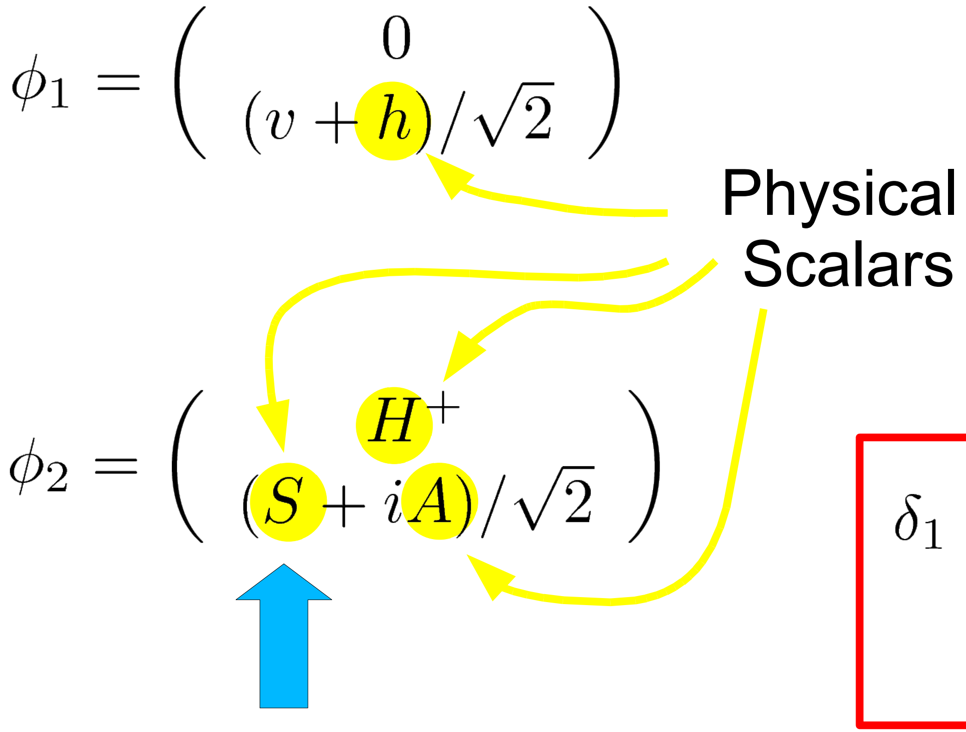
- **Triggering Electroweak symmetry-breaking**

  (Hambye, Tytgat 2007)

Plus a wide variety of theoretically-motivated models include inert doublets, or reduce to the SM + Extra Scalar doublets at low energies (e.g. LR Twin Higgs).

Parameter Space of the Model

$$
\begin{aligned}
V \quad = \quad & \mu_1^2|\phi_1|^2 + \mu_2^2|\phi_2|^2 + \lambda_1|\phi_1|^4 + \lambda_2|\phi_2|^4 + \\
& \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \lambda_5[(\phi_1^\dagger\phi_2)^2 + h.c.]
\end{aligned}
$$



$$\phi_1 = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

Physical Scalars

$$\phi_2 = \begin{pmatrix} H^+ \\ (S+iA)/\sqrt{2} \end{pmatrix}$$

Take S to be the LIP:

$$\boxed{m_s < m_A, m_{H^\pm}}$$

Mass Splittings:

$$\boxed{\begin{aligned} \delta_1 &\equiv m_{H^\pm} - m_S = -\tfrac{1}{2}(\lambda_4+\lambda_5)v^2 \\ \delta_2 &\equiv m_A - m_S = -\lambda_5 v^2 \end{aligned}}$$

Also useful to define: $\boxed{\lambda_L \equiv \lambda_3 + \lambda_4 + \lambda_5}$

(Represents physical hSS coupling)

Constraints on the IDM

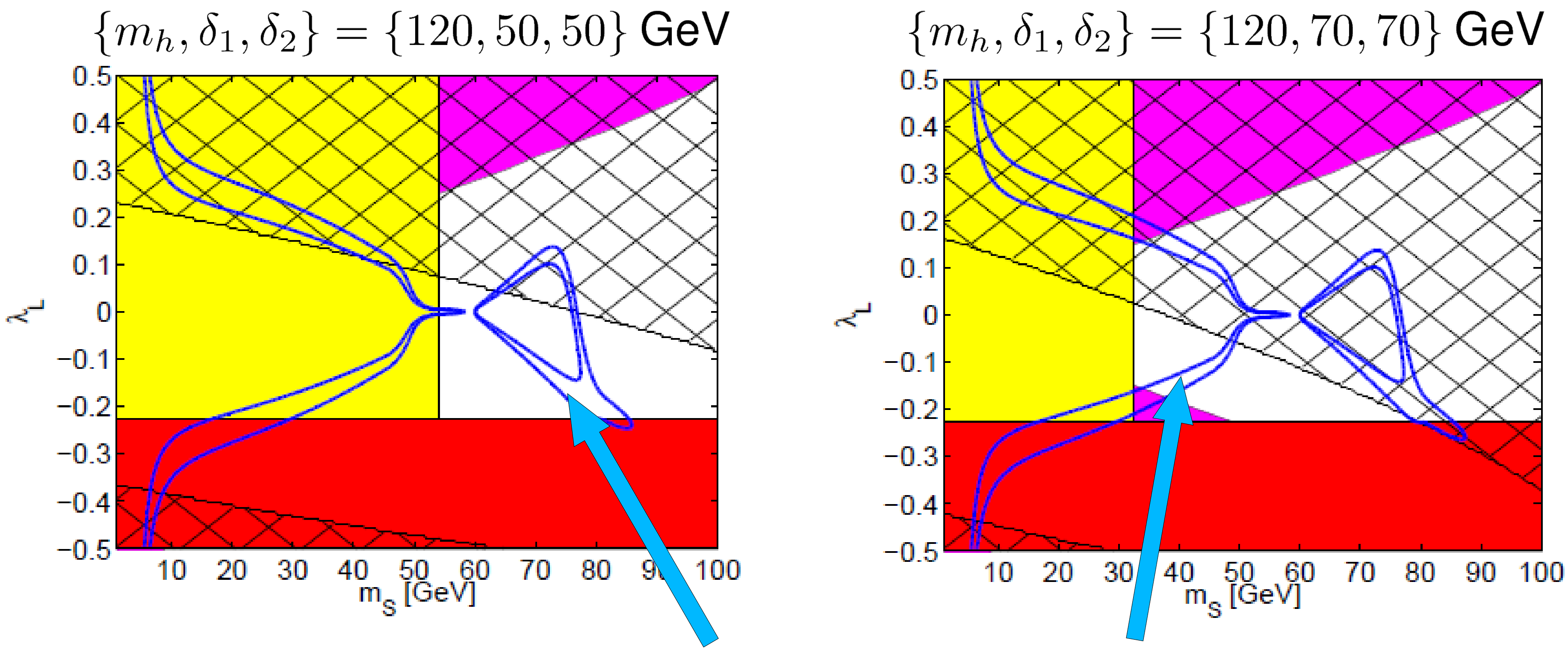
Consistency Conditions

- Vacuum Stablility
- Perturbativity

Experimental Constraints

- Dark matter relic abundance (WMAP)
- Precision electroweak constraints (LEP)
- BSM Searches (LEP)
- Direct detection bounds (CDMS, etc.)

Combined Constraints: Light Higgs



$\{m_h, \delta_1, \delta_2\} = \{120, 50, 50\}$ GeV

$\{m_h, \delta_1, \delta_2\} = \{120, 70, 70\}$ GeV

🟪 Direct detection limits

🟨 LEP direct searches

🟥 Vacuum stability

▨ Perturbativity

▨ DM relic density

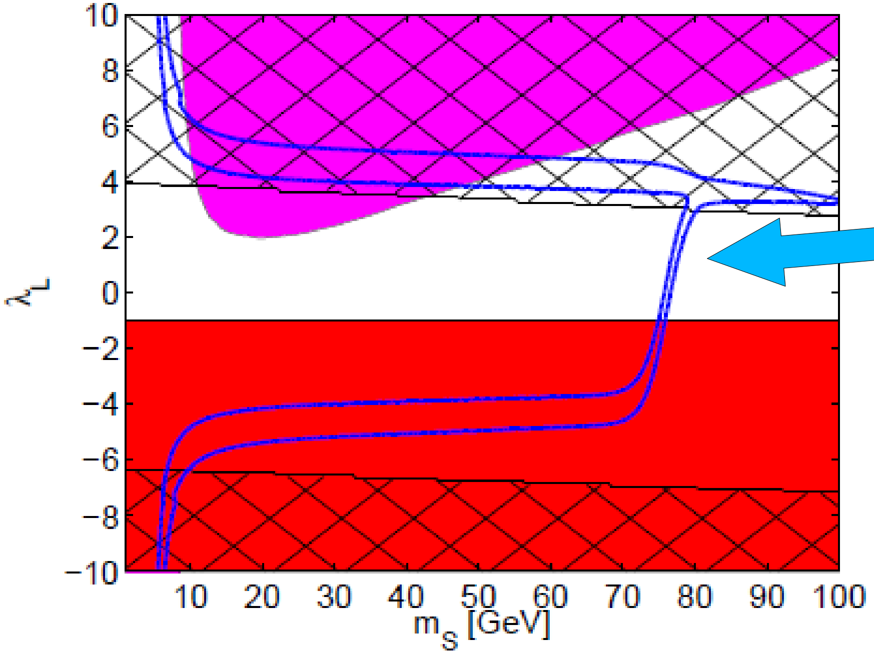
Light LIP:
m_s ~ 60 - 80 GeV

Very light LIP:
m_s ~ 40 GeV

- Applying the combined constraints, we find a set of consistent scenarios in which the LIP accounts for the observed DM abundance.

Combined Constraints: Heavy Higgs

$\{m_h, \delta_1, \delta_2\} = \{500, 250, 110\}$ GeV



PEW constraints imply heavy charged scalars

LIP Mass ~ 75 - 80 GeV

- For heavy-Higgs scenarios, with $m_h = 500$ GeV, it is also possible to obtain an appropriate LIP relic density.
- Other viable regions of parameter space exist, but don't lead to interesting collider phenomenology.

🟪 Direct detection limits
🟨 LEP direct searches
🟥 Vacuum stability
▩ Perturbativity
▨ DM relic density

Detection Prospects at LHC

There are many ways in which one may detect the presence of an additional, inert doublet at the LHC. These include:

- The modification of the total width Γ_h of the Higgs boson.
  (Barbieri, Hall, Rychkov 2006; Cao, Ma, Rajasekaran, 2007)
- Direct signals of the inert scalars $A, H^\pm$ via their decays to SM particles + S.

The cleanest signatures come from final states including multiple high-p_T charged leptons and substantial missing transverse energy:

① Dilepton Channel: $pp \longrightarrow \ell^+\ell^- + \not{E}_T$

(Initial discovery process at LHC)

② Trilepton Channel: $pp \longrightarrow \ell^+\ell^-\ell^\pm + \not{E}_T$

(Additional evidence for IDM, further information about the scalar mass spectrum)

Benchmark Scenarios for Collider Phenomenology

Satisfy all applicable constraints and reproduce the WMAP DM abundance within 3σ range.

	Benchmark	m_h (GeV)	m_S (GeV)	δ_1 (GeV)	δ_2 (GeV)	λ_L
Light Higgs	LH1	150	40	100	100	-0.275
	LH2	120	40	70	70	-0.15
	LH3	120	82	50	50	-0.20
	LH4	120	73	10	50	0.0
	LH5	120	79	50	10	-0.18
Heavy Higgs	HH1	500	76	250	100	0.0
	HH2	500	76	225	70	0.0
	HH3	500	76	200	30	0.0

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- **LH1, HH1:** $\delta_2 > M_Z$ (on-shell $A \to SZ$ decay).

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- **LH2-3, HH2:** $M_Z > \delta_2 \gtrsim 40$ GeV; off-shell $A \rightarrow S\ell^+\ell^-$ decay via virtual Z^*.

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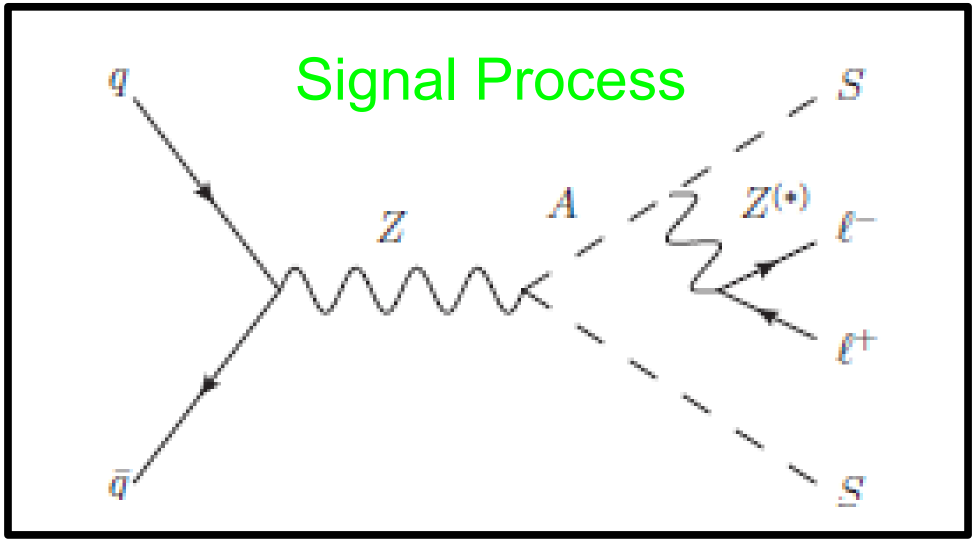
- **LH5, HH3:** $\delta_2 \lesssim 40$ GeV; off-shell A decay, very soft leptons.
- **LH4** small δ_1; $H^\pm A \to \ell^+\ell^-\ell^\pm + \not{E}_T$ with soft $\ell^\pm$ contributes.

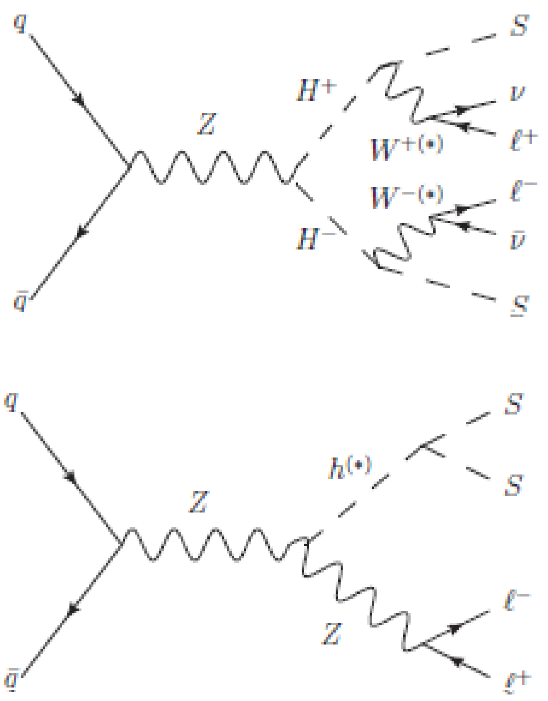
Dilepton Channel: Signals

A number of processes contribute to $pp \to \ell^+\ell^- + \not\!\!E_T$ in the IDM:



Signal Process

SA Pair-Production

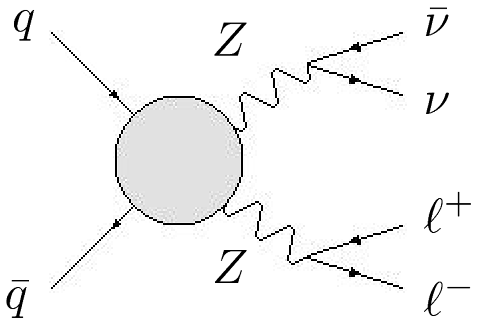


Model-Dependent Backgrounds

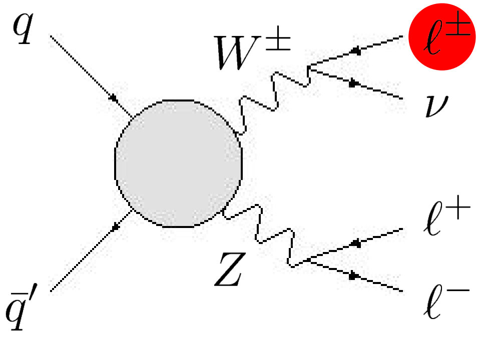
Standard-Model Backgrounds

“Z-Type”

($M_{\ell\ell}$ peaked around Z-pole)



(irreducible)

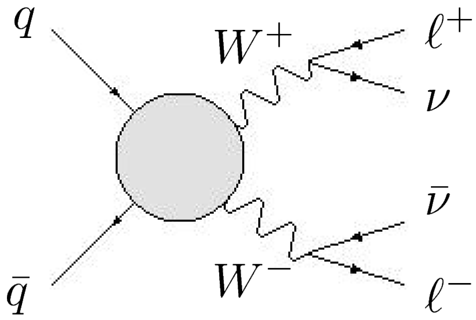


$Zb\ +$ jets

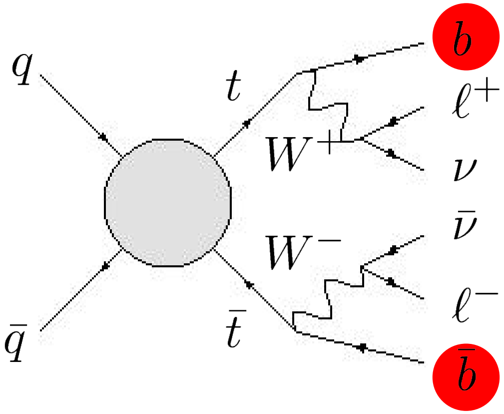
etc.

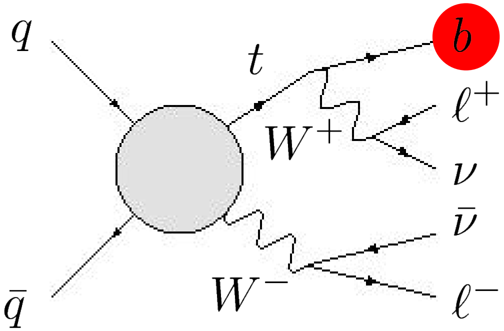
“W-Type”

(broad $M_{\ell\ell}$ distribution)

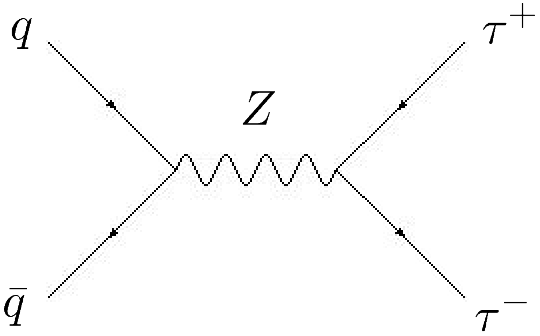


(irreducible)





$W^\pm b\ +$ jets



etc.

Event Selection

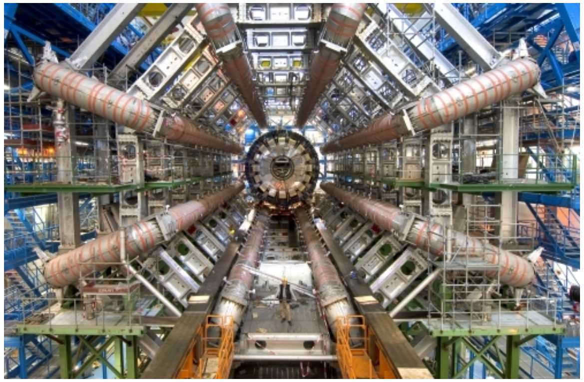
Level I: Detector Acceptance Cuts

- Exactly two SFOS leptons (e or μ).
- $p_{T\ell} \geq 15$ GeV, $|\eta_\ell| < 2.5$ for each lepton.
- Lepton isolation: $\Delta R_{\ell\ell} \geq 0.4$ for lepton pair, $\Delta R_{\ell j} \geq 0.4$ for each possible jet-lepton pairing.

$\Delta R_{\ell\ell}$ resolution limit crucial for small δ_2!

Level II: Universal Background Suppression Cuts

- $\not\!\!E_T \geq 30$ GeV.
- Jet veto: no jet with both $p_{Tj} > 20$ GeV and $|\eta_j| < 3.0$.



- Basic cuts designed to mimic realistic LHC detector acceptance.

~~Hard Jets~~

- Substantial reduction in Wt, $t\bar{t}$, $W +$ jets.
- Effective elimination of Drell-Yan $\tau\tau$ BG.

Event Selection

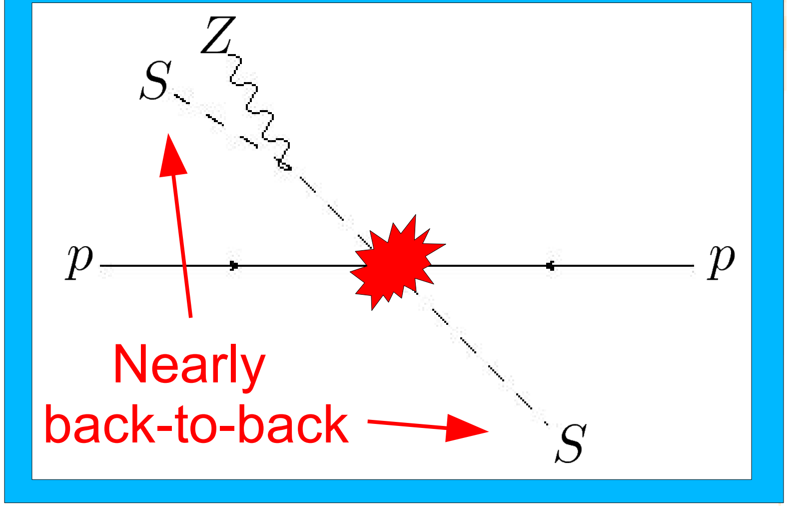
Level III: Optimization Cuts

- Angular-separation cuts:
  - $\cos\phi_{\ell\ell} \geq \cos\phi_{\ell\ell}^{\min}$
  - $\Delta R_{\ell\ell} \leq \Delta R_{\ell\ell}^{\max}$
- Invariant mass cut: $M_{\ell\ell}^{\min} \leq M_{\ell\ell} \leq M_{\ell\ell}^{\max}$.
- Minimum total transverse momentum H_T for each event: $H_T \geq H_T^{\min}$.
- Elevated thresholds for missing transverse energy: $\not{E}_T \geq \not{E}_T^{\min} > 30$ GeV.
- Maximum lepton p_T: $p_{T\ell} \leq p_T^{\max}$.

Useful for $\delta_2 < M_Z$

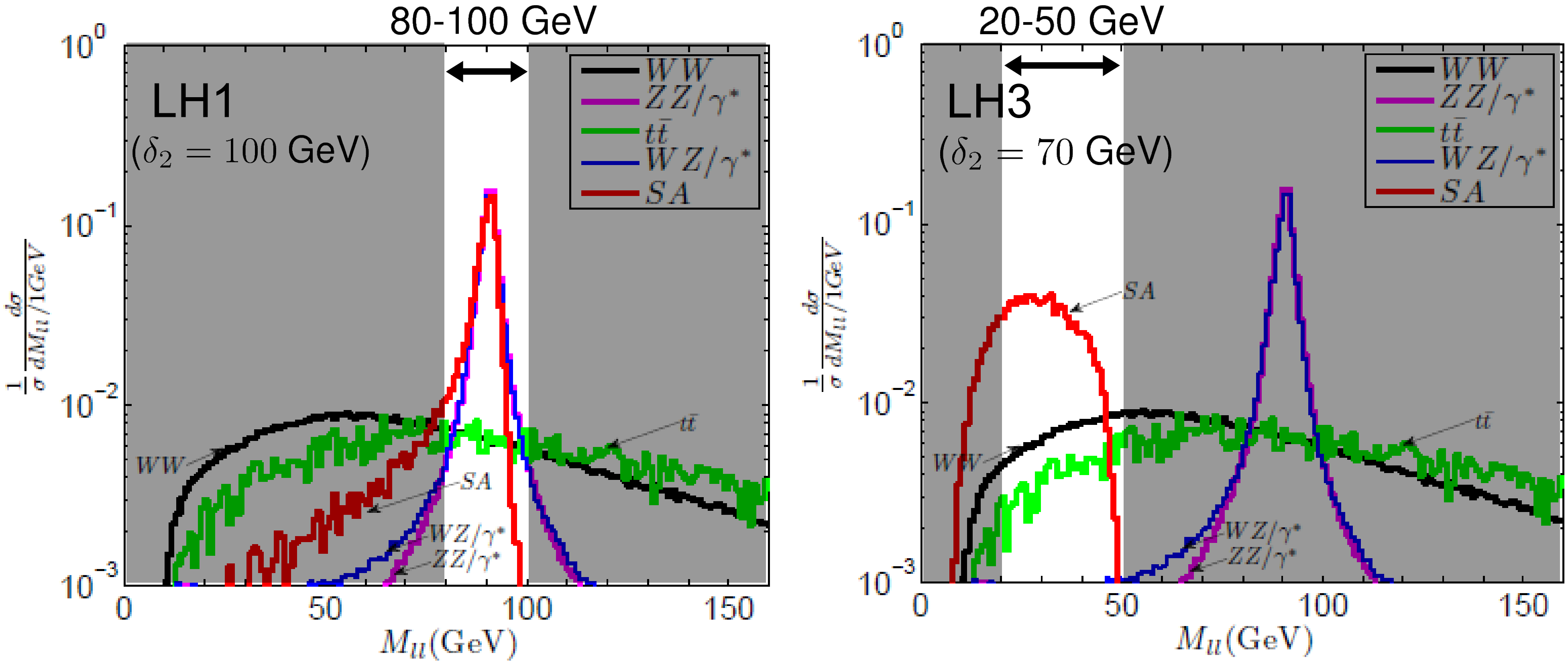
$$H_T \equiv \sum_{i=1}^{2} p_{T\ell}^i + \not{E}_T$$

Not a terribly powerful discriminant: $\not{E}_T$ contributions from the LIPs largely cancel.



Useful when δ_2 is small and $\ell^{\pm}$ quite soft.

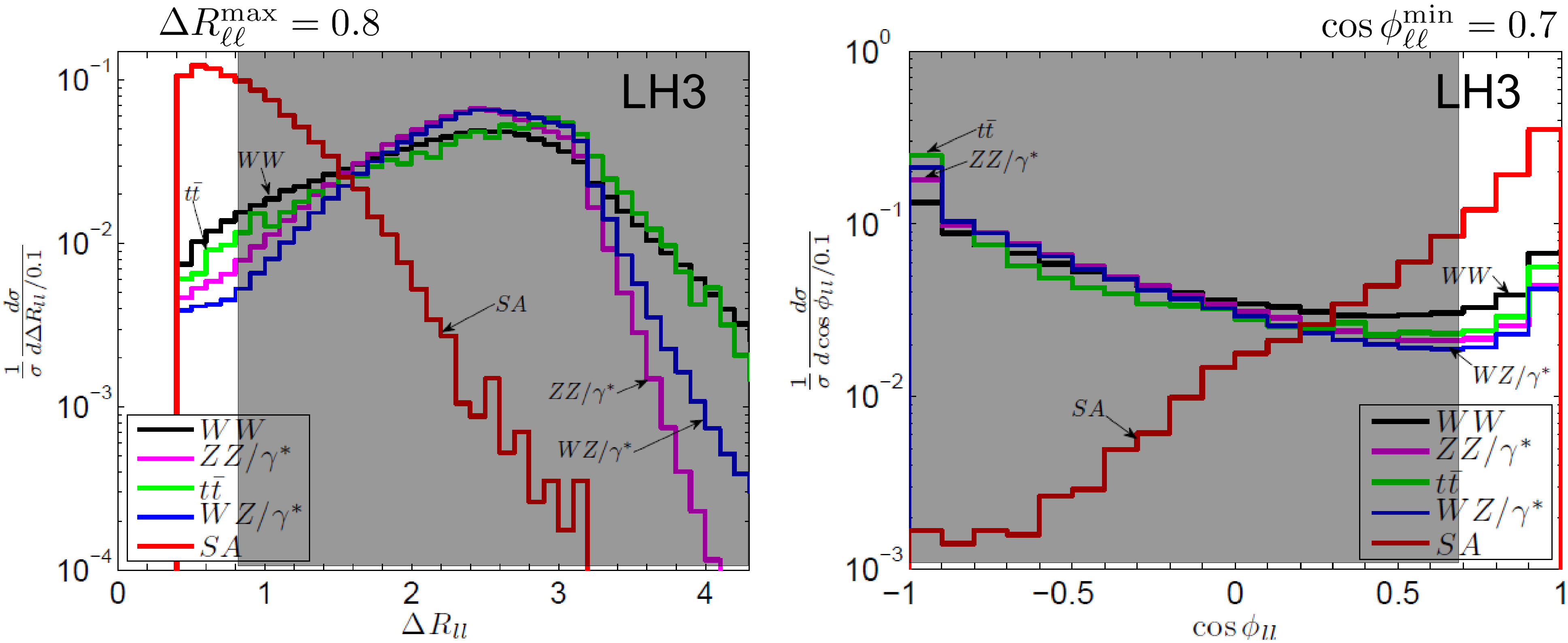
Invariant Mass Distributions



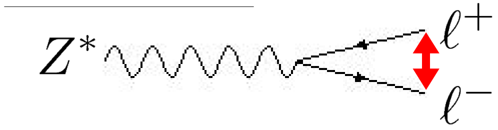
- When $\delta_2 > M_Z$ and A decays are on shell, $t\bar{t}$, WW backgrounds can be substantially reduced by a cut on $M_{\ell\ell}$.
- When $\delta_2 < M_Z$ and A decays are off shell, WZ/γ^* and ZZ/γ^* can be effectively eliminated by a Z veto.

Note: all distributions
Normalized to one!

Charged-Lepton Separation



Off shell:



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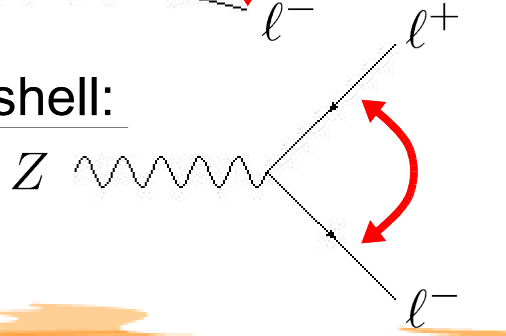

- When $\delta_2 < M_Z$, the charged leptons from A decay are more collinear and less energetic than those from on-shell Z-decays.
- This allows us to further reduce SM BGs via cuts on angular variables: e.g. $\cos\phi_{\ell\ell}$ and $\Delta R_{\ell\ell}$.

Results

Benchmark	S/B	$S/\sqrt{B}$
LH1	0.04	3.87
LH2	1.53	11.66
LH3	0.52	3.04
LH4	0.57	3.29
LH5	0.02	0.02
HH1	0.03	1.42
HH2	0.56	4.55
HH3	0.04	2.12

($\sqrt{s} = 14$ TeV, $\mathcal{L} = 100$ fb^{-1})

Best Discovery Prospects:

Light Higgs

(LIP accounts for DM relic abundance)

- **LH2** ($\delta_2 = 70$ GeV, $m_S = 40$ GeV): Large σ_{SA} due to light scalars. A decays off-shell, making angular cuts efficient.

Dramatic signal!

Heavy Higgs

(DM relic abundance and improved naturalness!)

- **HH2** ($\delta_2 = 70$ GeV, $m_S = 76$ GeV): Similar to LH2. σ_{SA} lower due to heavier scalars, but angular cuts still effective.

Results

Light Scalars, On-Shell Decay:

Benchmark	S/B	$S/\sqrt{B}$
LH1	0.04	3.87
LH2	1.53	11.66
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($\sqrt{s} = 14$ TeV, $\mathcal{L} = 100$ fb^{-1})

Light Higgs

(LIP accounts for DM relic abundance)

- **LH1** ($\delta_2 = 100$ GeV, $m_S = 40$ GeV): Large σ_{SA}, but A decays off-shell and ZZ/γ^*, WZ BGs hard to eliminate. Good discovery prospects nevertheless.

Heavy Higgs

(DM relic abundance and improved naturalness!)

- **HH1** ($\delta_2 = 100$ GeV, $m_S = 76$ GeV): Similar to LH1: A decays off-shell ZZ/γ^*, WZ BGs again hard to eliminate. Signal difficult to resolve at $\mathcal{L} = 100$ fb^{-1}.

Results

Heavier Scalars, Off-Shell Decay:

Benchmark	S/B	$S/\sqrt{B}$
LH1	0.04	3.87
LH2	1.53	11.66
LH3	0.52	3.04
LH4	0.57	3.29
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HH3	0.04	2.12

($\sqrt{s} = 14$ TeV, $\mathcal{L} = 100$ fb^{-1})

Light Higgs

(LIP accounts for DM relic abundance)

- **LH3, LH4** ($\delta_2 = 50$ GeV, $m_S \sim 80$ GeV): σ_{SA} smaller due to heavier LIP. LH4 significance augmented by $pp \to H^\pm A$ contribution where $\ell^\pm$ from $H^\pm$ decay is soft.
- **LH5** ($\delta_2 = 10$ GeV, $m_S \sim 80$ GeV): Leptons too soft to detect, due to small δ_2.

Heavy Higgs

(DM relic abundance and improved naturalness!)

- **HH3** ($\delta_2 = 30$ GeV, $m_S = 76$ GeV): $M_{\ell\ell}$ cut effective, but surviving BGs have similar $\cos\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$ to signal.

… and from this, we learn:

The best prospects for detection in the dilepton channel are obtained for a light Higgs boson (m_h ~ 114 – 180 GeV) and:

$$40\ \mathrm{GeV} \lesssim \delta_2 \lesssim 80\ \mathrm{GeV} \qquad m_S \sim 40\ \mathrm{GeV}$$

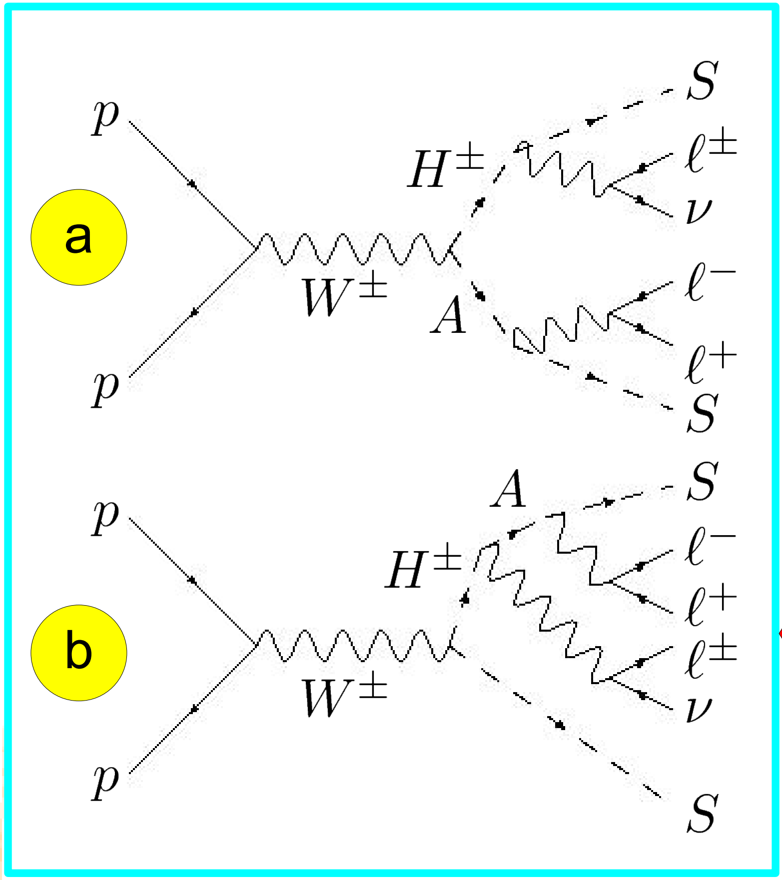
with a statistical significance as high as ~ 10σ.

… but also (and perhaps even more importantly):

It is possible for the IDM to explain the observed dark-matter abundance, provide the necessary *S* and *T* contributions to correct for a heavy Higgs, and at the same time yield visible signals in the dilepton channel at the LHC!

Analysis: Trilepton Channel

The Most Relevant Processes:



- One can also look for signatures of the inert doublet model in the trilepton channel.
- Analysis similar to SUSY trilepton searches.

Principal signal process

Occurs only when $\delta_1 > \delta_2$ (significant for $\delta_1 > \delta_2 + M_W$).

- To examine this effect, three new benchmark points added:

Benchmark	m_h (GeV)	m_S (GeV)	δ_1 (GeV)	δ_2 (GeV)	λ_L
LH6	130	40	100	70	-0.18
LH7	117	37	70	100	-0.14
LH8	120	78	70	35	-0.18

Event Selection

Level I + II

- Exactly three charged leptons (e or μ), including at least one SFOS pair.
- $\not{E}_T \geq 50$ GeV in order to reduce backgrounds from heavy-flavor processes, etc.
- Otherwise, same as for dilepton channel.

Level III

- Also include a cut on the transverse mass variable $M_{T_W} \equiv (E_{\ell_W} + \not{E}_T)^2 - (\vec{p}_{\ell_W} + \vec{\not{p}}_T)^2$.

Dominant Backgrounds After Level I+II Cuts:

$$WZ \to \ell^+\ell^-\ell^\pm + \not{E}_T$$

$$t\bar{t} \to \boxed{\text{jets}} + \ell^+\ell^-\ell^\pm + \not{E}_T$$

(Soft)

Trilepton Channel Results

[arXiv:1005.0090]

Benchmark	$\sigma_{H^\pm A}$ (fb)	$\sigma_{\mathrm{BG}}^{\mathrm{comb}}$ (fb)	S/B	$S/\sqrt{B}$ (300 fb^{-1})
LH1	0.038	0.191	0.20	2.15
LH2	0.078	0.114	0.68	5.64
LH3	0.035	0.131	0.27	2.36
LH6	0.101	0.221	0.46	5.27
LH7	0.270	7.259	0.04	2.45
LH8	0.031	0.591	0.05	1.00

5σ discovery in both dilepton & trilepton channels!

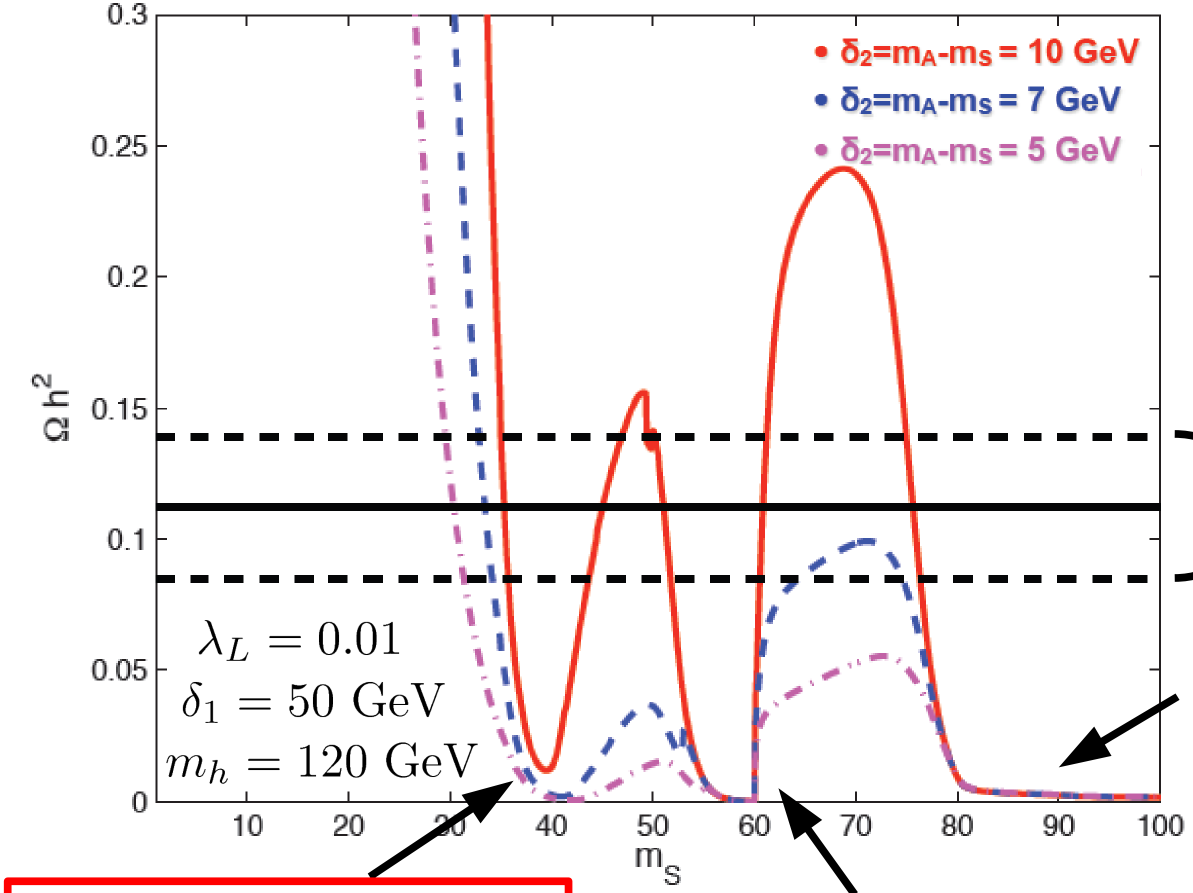
- The discovery prospects in the trilepton channel aren't as good as in the dilepton channel, and higher integrated luminosity is generally required.
- Nevertheless, 5σ evidence can be obtained when $m_s \sim 40$ GeV and 65 GeV $\lesssim \delta_{1,2} \lesssim 80$ GeV.
- For smaller $\delta_{1,2}$, leptons tend to be soft, and often escape detection.

Summary and Conclusions

- The IDM is a simple and versatile model, capable of...
  - explaining the composition and observed relic density of dark matter in the universe.
  - Rendering a heavy Higgs boson with $m_h \sim 400$ - 600 GeV consistent with PEW constraints.
  - much more.
- There are **several** parameter-space regimes in which the model reproduces the WMAP DM density. Most feature a light LIP, with $m_S \lesssim 80$ GeV.
- In many of these scenarios, a **striking signal** should be observable at the LHC in the dilepton channel. Corroborating evidence may also be obtainable in the trilepton channel for models with a light LIP and 65 GeV $\lesssim \delta_2 < M_Z$.

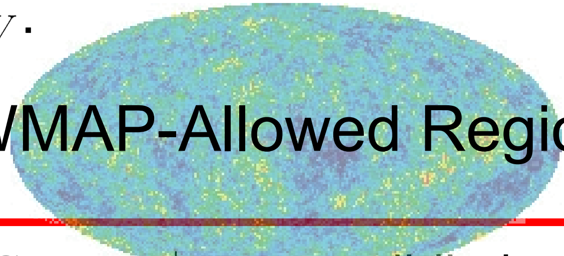
Extra Slides

LIP Dark Matter

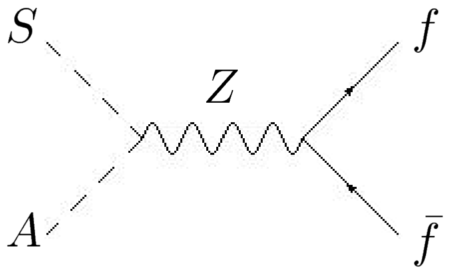


- The stable LIP is a good WIMP dark matter candidate. It annihilates primarily through an h or Z resonance when light, and into W^+W^- when $m_S > M_W$.

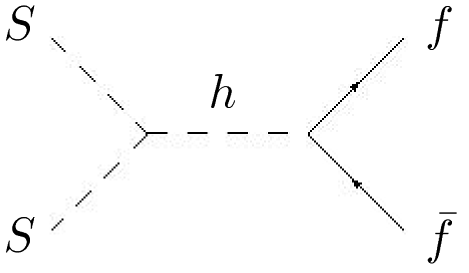
WMAP-Allowed Region



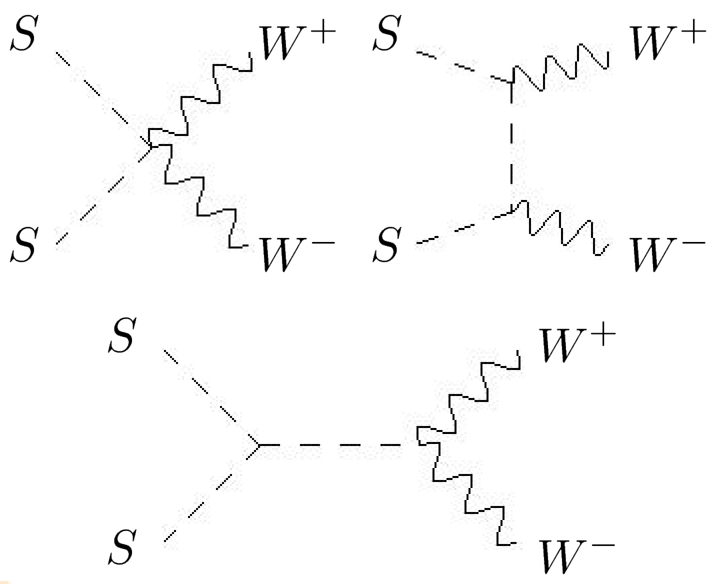
Z-pole annihilation:



h-pole annihilation:

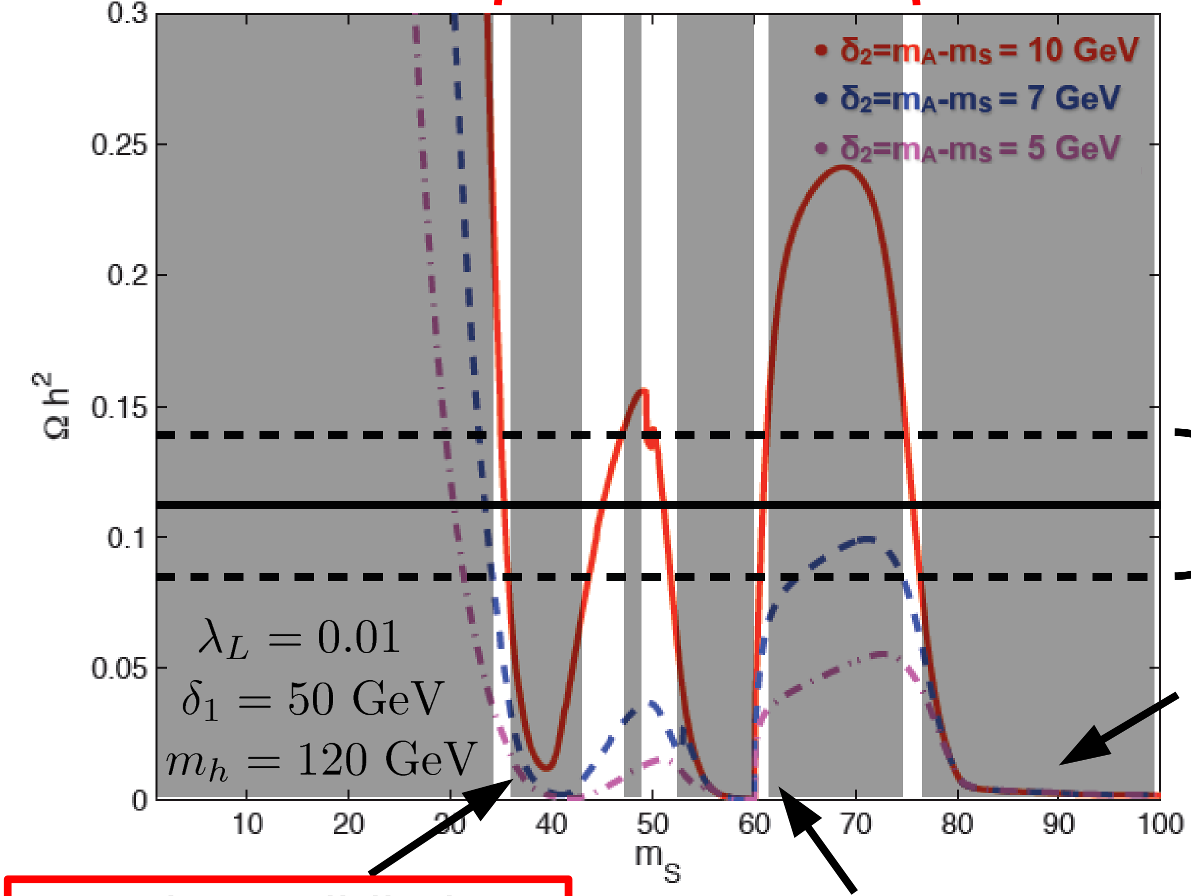


$SS \to W^+W^-$ annihilation:

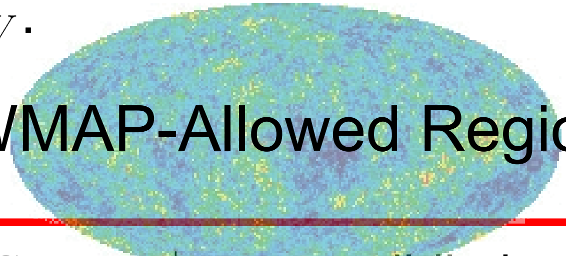


LIP Dark Matter

Bands: $\Omega_{\rm DM}$ within WMAP 3σ range

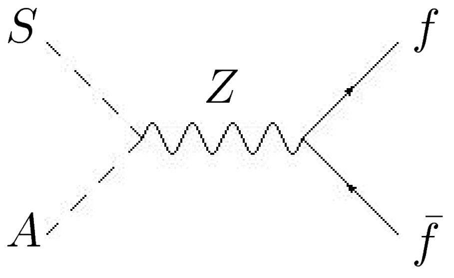


- The stable LIP is a good WIMP dark matter candidate. It annihilates primarily through an h or Z resonance when light, and into W^+W^- when $m_S > M_W$.

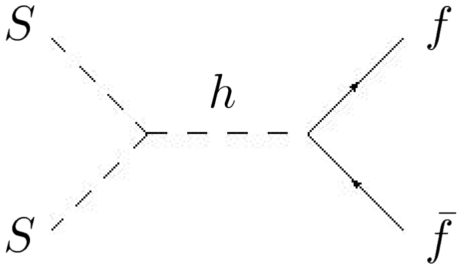


WMAP-Allowed Region

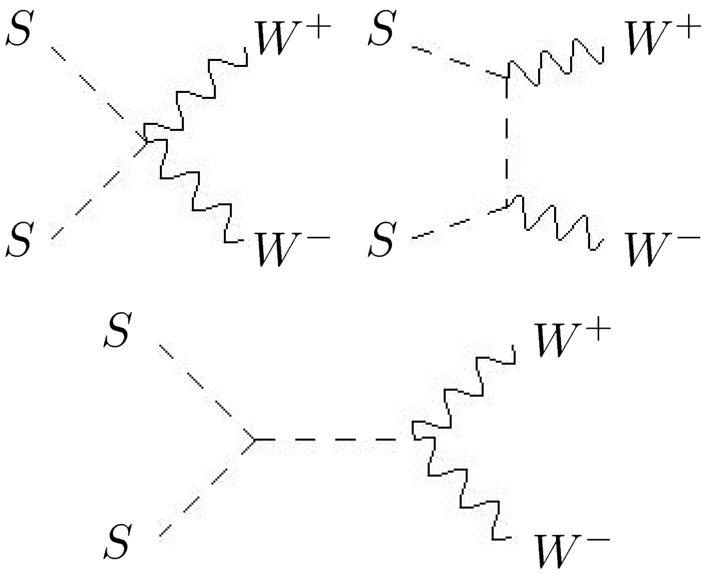
Z-pole annihilation:



h-pole annihilation:



$SS \to W^+W^-$ annihilation:



LIP Dark Matter

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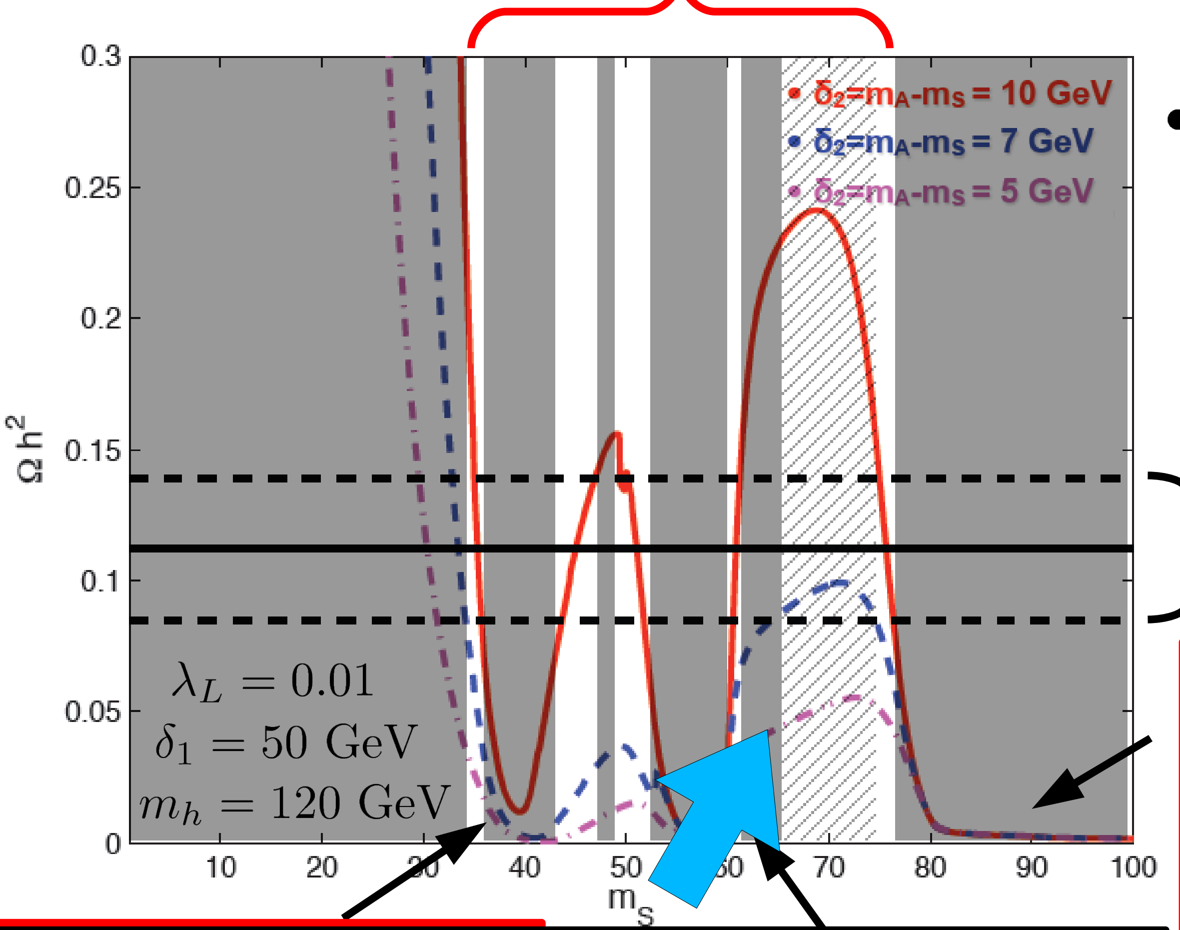
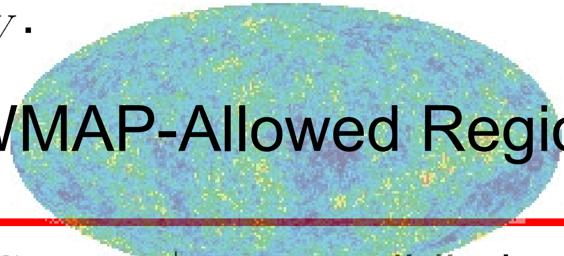
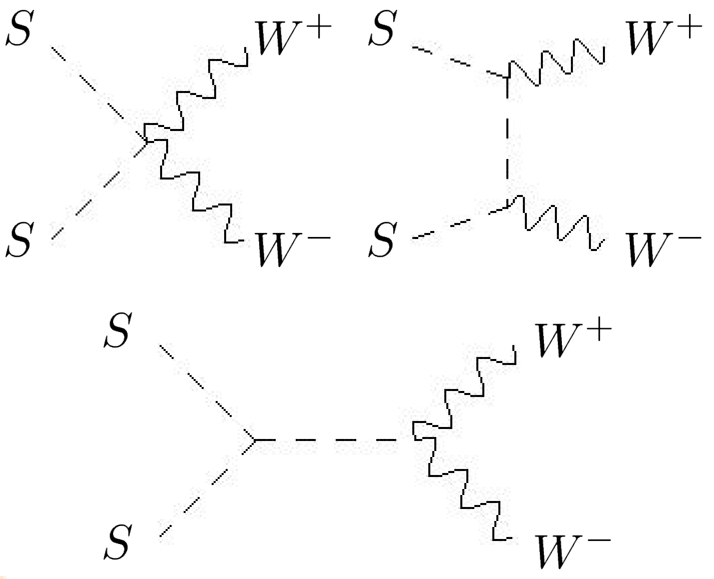
Bands: $\Omega_{\rm DM}$ within WMAP 3σ range





WMAP-Allowed Region

$SS \to W^+W^-$ annihilation:



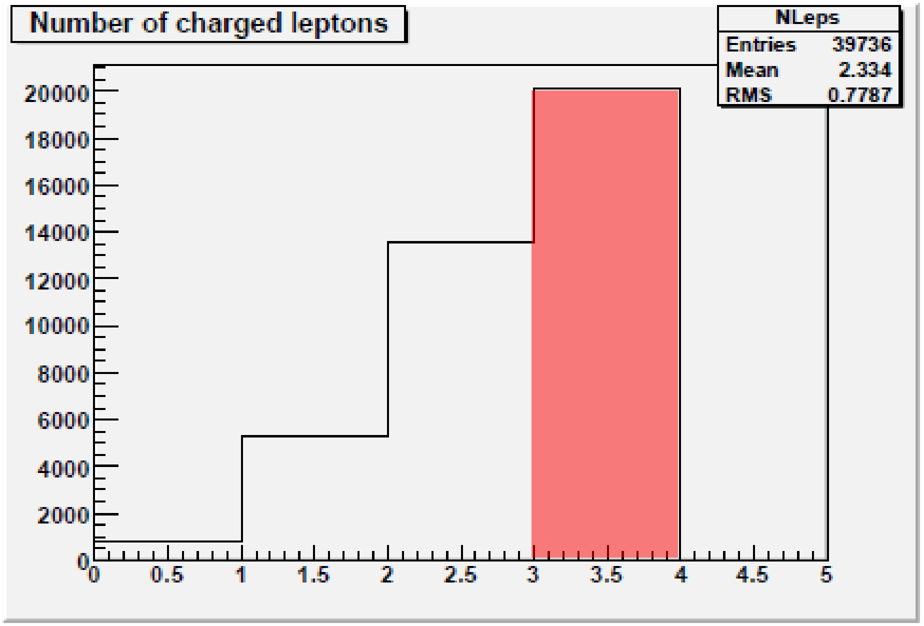
And things may even be a little bit better...

Including three-body contibutions from $SS \to WW^*$ decay can increase annihilation efficiency in cases where $m_S \sim m_W$ (Lopez Honorez, Yaguna 2010).

Problems with Soft Leptons

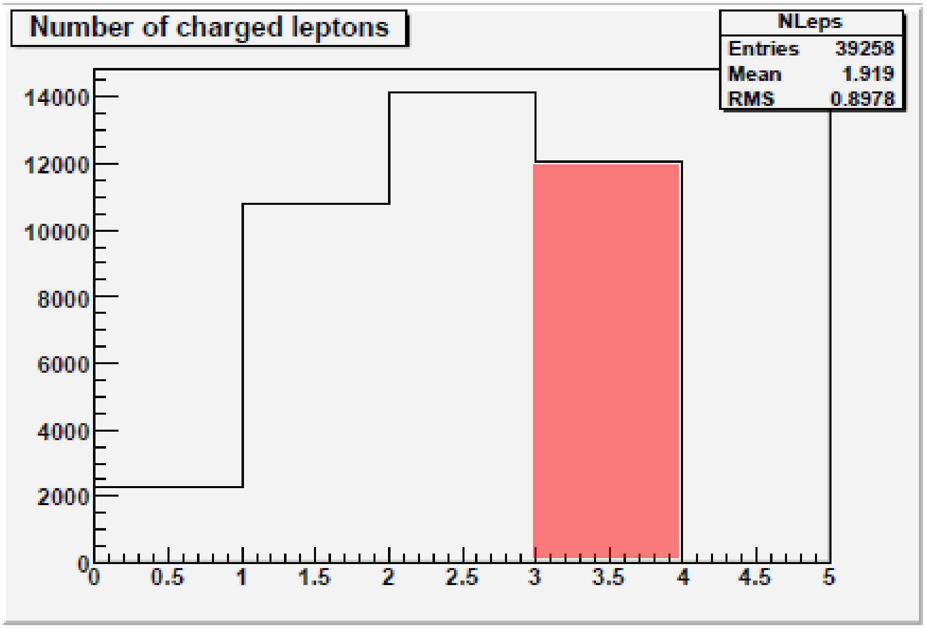
LH1

($\delta_1 = \delta_2 = 100$ GeV)



LH3

($\delta_1 = \delta_2 = 50$ GeV)



- When $\delta_{1,2}$ drop below ~ 65 GeV, one or more of the leptons often has extremely low p_T and escapes detection.