PRECISION CALCULATIONS FOR DARK MATTER SELF-ANNIHILATION IN SUPERSYMMETRIC THEORIES

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LPSC Seminar

Based on work in Collaboration with F. Boudjema, N. Baro, C. McCabe, M. J. Dolan, A. Semenov, Sun Hao.

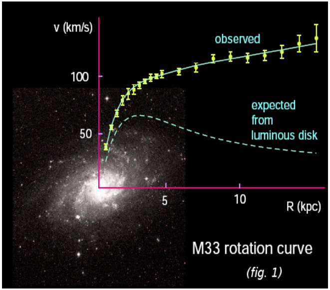
OUTLINE

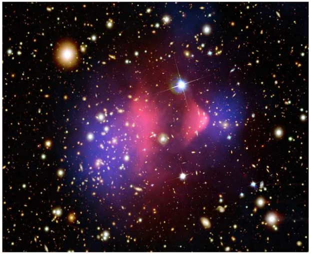
OUTLINE

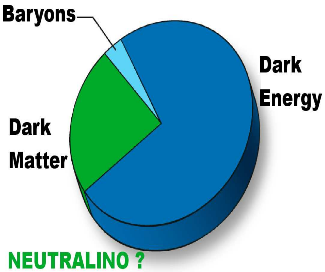
- We know that it exists and it is present in galaxies.

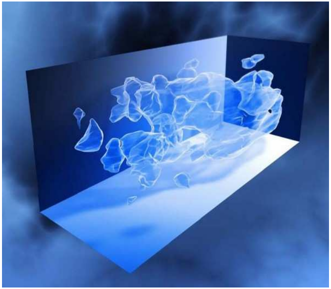
- It is cold (non-relativistic at decoupling)

- It represents 85% of the matter content (22% of the Universe)
- $\Omega_\chi h^2 = 0.1199 \pm 0.0027$ at 1σ





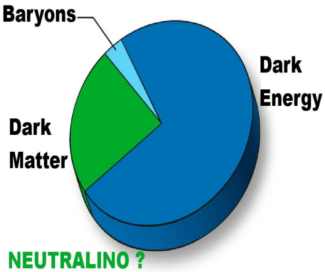


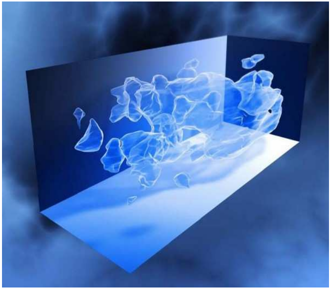


- No informations on exact distribution or local density
- No informations on what is it made of (mass, cross section, spin)

Moreover :

- No existing candidate in SM
- EWSB seems to be related to DM problem





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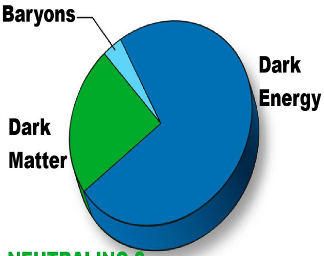
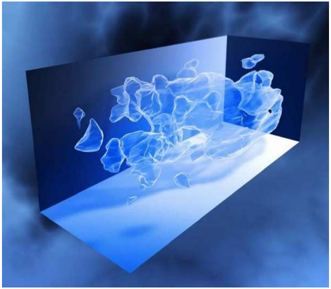
NEW PARADIGM : DM IS
NEW PHYSICS

SUMMARY OF WHAT WE DON'T KNOW ABOUT DM (A LOT)



NEUTRALINO ?



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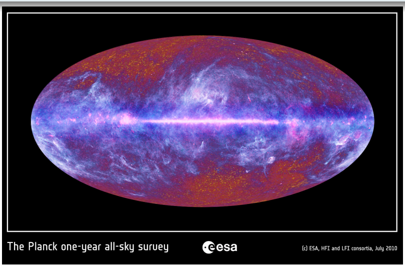
ANY BSM "SHOULD" HAVE A DM CANDIDATE

RELIC DENSITY OF DARK MATTER

- PLANCK+WMAP: $0.1145 < \Omega_{DM} h^2 < 0.1253$



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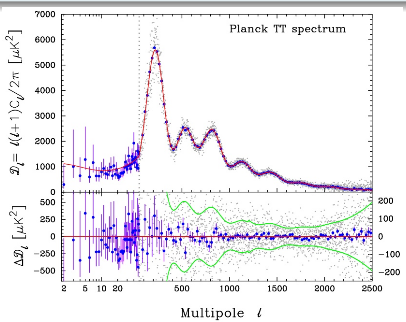

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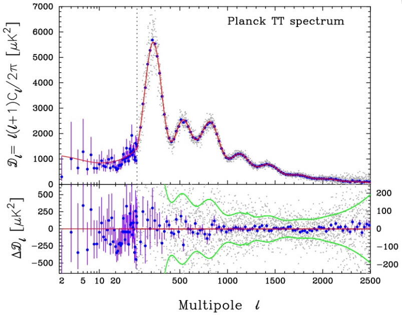


PRECISION MEASUREMENTS

Must be matched by th. calculations $\Rightarrow$ One-loop

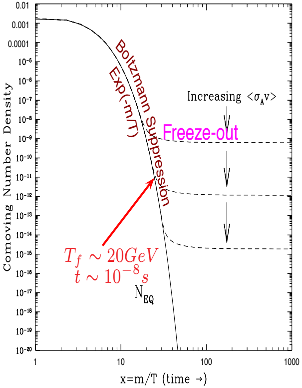
Can be used to constrain cosmological/BSM

STANDARD SCENARIO

THERMAL RELIC DENSITY

- Solve the Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)$$



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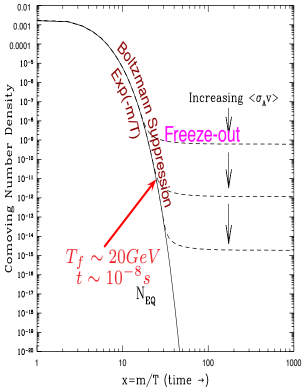
$$\begin{array}{ccc} -3Hn & \Longleftrightarrow & \text{dilution} \\ n^2 & \Longleftrightarrow & \chi\chi \to X_{SM} Y_{SM} \\ n_{eq}^2 & \Longleftrightarrow & X_{SM} Y_{SM} \to \chi\chi \end{array}$$

- If $m_{\chi'}(NLSP) \simeq m_{\chi}(LSP) \Rightarrow$ Coannihilation

$$\begin{array}{ccc} \chi\chi' & \to & X_{SM} Y_{SM} \\ \chi'\chi' & \to & X_{SM} Y_{SM} \end{array}$$



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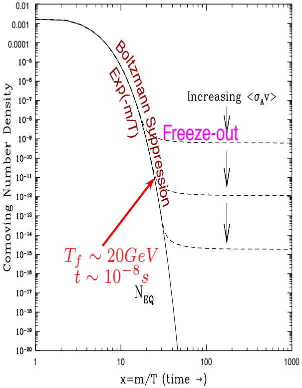
- Thermal average

$$\langle \sigma v \rangle = \frac{\sum_{ij} g_i g_j \int_{(m_1+m_2)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T \left(\sum_i g_i m_i^2 K_2(m_i/T) \right)^2}$$



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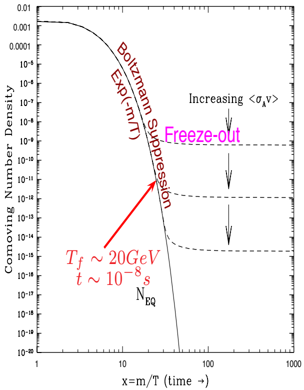
- Thermal average (Maxwell-Boltzmann approx. $x = m/T$ $x \gtrsim 1$)

$$\langle \sigma v \rangle \propto \int_0^\infty (\sigma v) v^2 e^{-xv^2/4}\, dv$$



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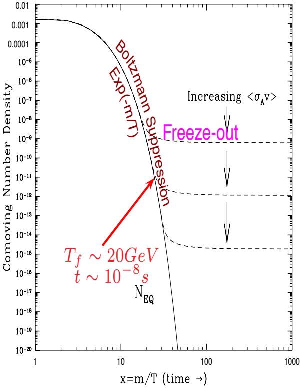

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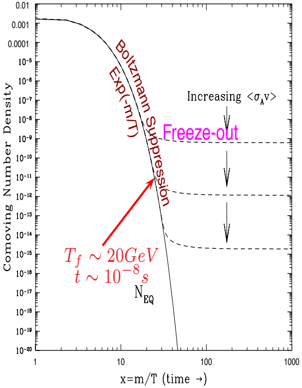

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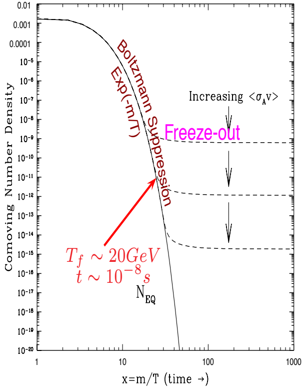

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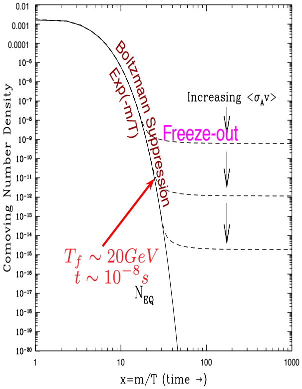

WIMP "MIRACLE" : $\langle\sigma v\rangle \sim \frac{\alpha^2}{M_{EW}^2} \sim 10^{-9}\mathrm{GeV}^{-2} \Longrightarrow \boxed{\Omega_\chi h^2 \sim 0.1}$

- The Standard Model seems to be an "incomplete" theory.
- Mechanism for generating mass to particles ($\equiv$ Electroweak symmetry breaking) yet unknown.
- Does not explain the instability of the Higgs mass w.r.t higher orders.

$$\boxed{\delta m_H^2 \supset -\frac{\lambda_f^2}{8\pi^2}\left(\Lambda^2 - 3m_f^2 \ln\left(\frac{\Lambda}{m_f}\right) + \ldots\right)}$$

- Other masses are protected w.r.t higher orders thanks to a symmetry (chiral for fermions, gauge for vector bosons).
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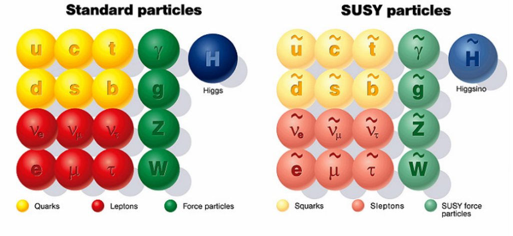
NEED FOR NEW PHYSICS

OUTLINE

Supersymmetry (SUSY): a solution for physics beyond the SM

- Symmetry linking Bosons to Fermions.
- Transfer the symmetry properties of fermions to scalar bosons to stabilise the scalar sector.
- Not yet observed in nature $\Rightarrow$ Broken symmetry.
- MSSM: Minimal Supersymmetric Standard Model $= \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$.
- 2 Higgs doublet $\Rightarrow$ Five Higgs bosons : $h, H, H^{\pm}, A^0$



NEW PARTICLES

NEW INTERACTIONS

NEW PHENOMENOLOGY

- Hint : Dark Matter cross section resembles the one of a weakly interacting massive particle (WIMP).

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle \sigma v \rangle}$$

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YES if R-parity is conserved (or at least if $\tau_\chi > \tau_{\mathrm{Univ.}}$)

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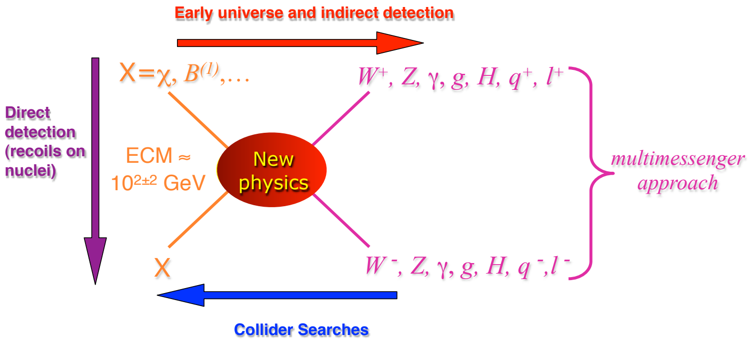

NEUTRALINO/CHARGINO SECTOR

- Mass matrices in the $(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_1^0, \widetilde{H}_2^0)$ basis

$$\underbrace{Y = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix},}_{\xrightarrow{N} (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)}$$

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- Diagonalisation + Decomposition $\Rightarrow$ 6 eigenstates/eigenvalues : 4 neutralinos $\tilde{\chi}_i^0$ and 2 charginos $\tilde{\chi}_i^\pm$.

$$\hookrightarrow \boxed{\tilde{\chi}_1^0 = N_{11} \widetilde{B} + N_{12} \widetilde{W}^0 + N_{13} \widetilde{H}_1^0 + N_{14} \widetilde{H}_2^0} \text{ with} \sum_{j=1}^{4} N_{1j}^2 = 1$$

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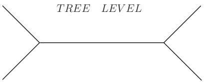
- The value of each N_{1j} determine the nature of $\tilde{\chi}_1^0$ and its couplings to other particles.
- The LSP $\tilde{\chi}_1^0$ can couple to ANY sector of the MSSM
- $\longrightarrow$ COMPLETE renormalisation needed.

OUTLINE

DIVERGENCES

- Due to perturbative development in the coupling constant.



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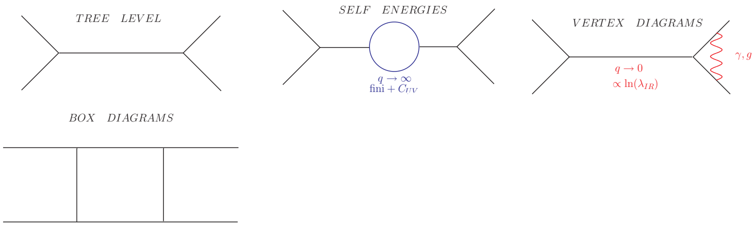

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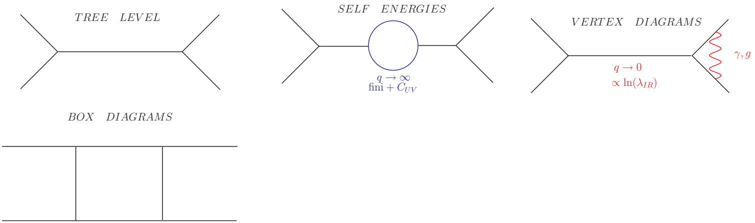

REGULARISATION

Isolate infinite parts in loops

- UV: $\ln \Lambda_{UV}$ with cut-off, $1/\epsilon_{UV}$ poles in DR.
- IR: $\ln \lambda_{IR}$ with cut-off, $1/\epsilon_{IR}$ poles in DR.

RADIATIVE CORRECTIONS-RENORMALISATION

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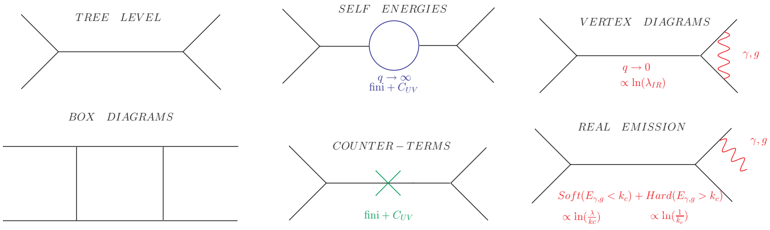

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RENORMALISATION

$$\mathcal{L}^0 = \mathcal{L}^0(g_i^0, M_{ij}^0, \phi_i^0)$$

SHIFTS

- $\Phi_i^0 \longrightarrow (\delta_{ij} + \frac{1}{2}\delta Z_{ij})\Phi_j$
- $g_i^0 \longrightarrow g_i + \delta g_i$
- $M_{ij}^{0\,2} \longrightarrow M_{ij}^2 + \delta M_{ij}^2$

ON-SHELL SCHEME

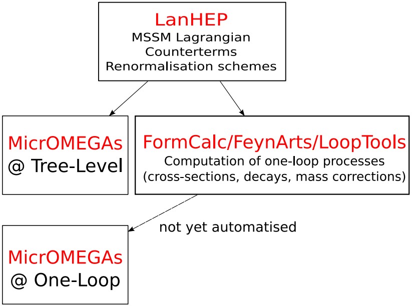
- $\widetilde{\mathcal{R}e}\hat{\Sigma}_{ii}(M_i^2) = 0 \longrightarrow \delta M^2$
- $\widetilde{\mathcal{R}e}\hat{\Sigma}'_{ii}(M_i^2) = 0 \longrightarrow \delta Z_{ii}$
- $\widetilde{\mathcal{R}e}\hat{\Sigma}_{ij}(M_i^2) = 0 \longrightarrow \delta Z_{ij}$

$$\mathcal{L}^0 = \mathcal{L}(g_i, M_{ij}, \phi_i) + \delta\mathcal{L}(g_i, M_{ij}, \phi_i, \delta g_i, \delta M_{ij}, \delta Z_{ij})$$

SECTORS

- Fermion
- Gauge
- Higgs
- Chargino/Neutralino
- Sfermion

OUTLINE



SLOOPS

A code for calculation of loops diagrams in the MSSM with application to colliders, astrophysics and cosmology.

- Evaluation of one-loop diagrams including a complete and coherent renormalisation of each sector of the MSSM with an OS scheme.
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Checks: results UV,IR finite and gauge independent.

`http://code.sloops.free.fr/`

ANNIHILATION INTO GAUGE BOSONS : WINO

Baro, Boudjema, GC, Sun Hao, Phys. Rev **D81** *(2008) 015005*

- Neutralino is wino-like when $M_2 \ll M_1, |\mu| \Rightarrow N_{12} \simeq 1, N_{1i} = 0 \; i \neq 2$.
- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm}$

NEUTRALINO/CHARGINO SECTOR

- Mass matrices in the $(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_1^0, \widetilde{H}_2^0)$ basis and $(\widetilde{W}^\pm, \widetilde{H}_{1,2}^\pm)$ one

$$\underbrace{Y = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix}}_{\xrightarrow{N} (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)}, \; \underbrace{X = \begin{pmatrix} M_2 & \sqrt{2} s_\beta M_W \\ \sqrt{2} c_\beta M_W & \mu \end{pmatrix}}_{\xrightarrow{U,V} (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)}$$

- Diagonalisation + Decomposition $\Rightarrow$ 6 eigenstates/eigenvalues : 4 neutralinos $\tilde{\chi}_i^0$ and 2 charginos $\tilde{\chi}_i^\pm$.

$$\hookrightarrow \boxed{\tilde{\chi}_1^0 = N_{11} \widetilde{B} + N_{12} \widetilde{W}^0 + N_{13} \widetilde{H}_1^0 + N_{14} \widetilde{H}_2^0} \text{ with } \sum_{j=1}^{4} N_{1j}^2 = 1$$

Baro,Boudjema,GC,Sun Hao, Phys. Rev **D81** *(2008) 015005*

- Neutralino is wino-like when $M_2 \ll M_1, |\mu| \Rightarrow N_{12} \simeq 1, N_{1i} = 0 \; i \neq 2$.
- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm}$

In the pure wino limit :

$$\mathcal{L}_{\rm int} \quad = \quad -\frac{e}{s_W}\left(\overline{\tilde{\chi}_1^0} \not{W}^\dagger \tilde{\chi}_1^- + \mathrm{c.c.}\right) + e\frac{c_W}{s_W}\overline{\tilde{\chi}_1^-} \not{Z} \tilde{\chi}_1^- + e\overline{\tilde{\chi}_1^+} \not{A} \tilde{\chi}_1^+$$

DOMINANT ANNIHILATION CHANNELS FOR RELIC DENSITY

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ (EW corrections)
- $\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to Z^0W^\pm$ (EW corrections)
- $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \to W^\pm W^\pm$ (EW corrections)
- $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to W^\pm W^\mp, Z^0Z^0$ (EW corrections)
- $\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to q\bar{q}'$ (EW+QCD corrections)

We corrected channels contributing more than 5% to $\Omega_\chi h^2$

HEAVY-WINO NEUTRALINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000

$$\tilde{\chi}_1^0 = 0.000\tilde{B} - 0.999\tilde{W} + 0.004\tilde{H}_1^0 + 0.032\tilde{H}_2^0$$

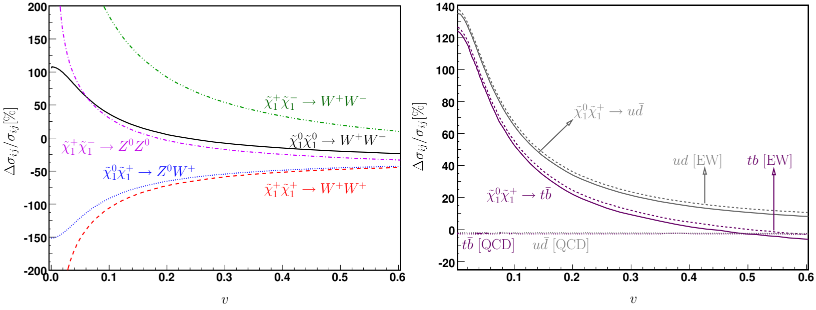
		Tree
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ [10%]	a	$+2.43$
	b	$+0.52$
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \to W^\pm W^\pm$ [10%]	a	$+2.44$
	b	$+0.52$
$\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to Z^0 W^\pm$ [9%]	a	$+1.02$
	b	$+0.24$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to t\bar{b}$ [9%]	a	$+1.08$
	b	-0.46
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}$ [9%]	a	$+1.08$
	b	-0.46
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to Z^0 Z^0$ [6%]	a	$+0.73$
	b	$+0.16$
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-$ [6%]	a	$+0.65$
	b	$+0.17$
$\Omega_\chi h^2$		0.0997

- $m_{\tilde{\chi}_1^0} = 1799.1$ GeV
- $\delta(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) = 0.0003$ GeV

- $\sigma_0 v = a + bv^2$
- $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$ almost degenerate
- Coannihilation very important
- Degeneracy between processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ and $\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+$
- A lot of processes contribute

HEAVY-WINO NEUTRALINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000



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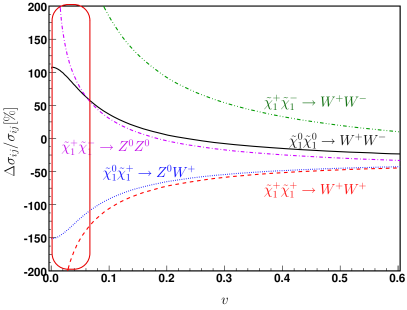
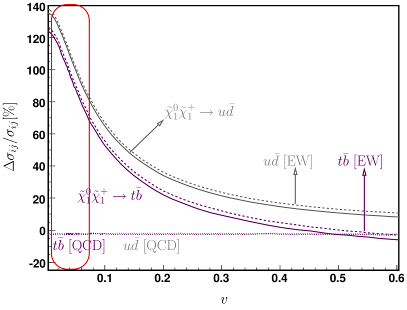
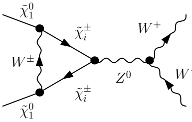
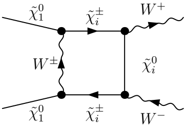


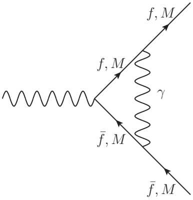


- $M_W/m_{\tilde{\chi}_1^0} = 0.045 \Rightarrow W^\pm, Z^0$ bosons almost considered as massless.
- $v \to 0$: Large Sommerfeld (QED+EW) enhancement.





- Singularities arise in scalar triangle C_0 and box D_0 loop integrals when $\beta \longrightarrow 0$.

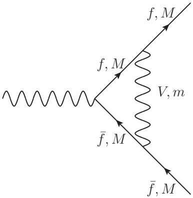


$$\boxed{C_0 \xrightarrow{\beta \to 0} -\frac{\pi^2}{Q^2 \beta}}$$

$$\beta = v/2 = \sqrt{1 - 4M^2/Q^2}$$

- D_0 has the same infrared behavior because for $\beta \longrightarrow 0$ it can be split into a sum of triangle integrals.
- This effect can be resummed to all orders.
- $S_{1L} = \frac{\pi\alpha}{v} \times \sigma_0 Q_i Q_j$
- $S_{nr} = X_{nr}/(1 - e^{-X_{nr}}) \times \sigma_0 \quad X_{nr} = 2\pi\alpha Q_i Q_j / v$

Drees, Jie Gu, PRD87 063524



- Let us pose $x = |\vec{q}|/|\vec{p}|$ and $\mu = m^2/|\vec{p}|^2$ then

$$C_0^{\text{Som.}} = -\frac{1}{M \cdot m}\frac{\sqrt{\mu}}{2} I_S(\mu) \qquad \text{with}$$

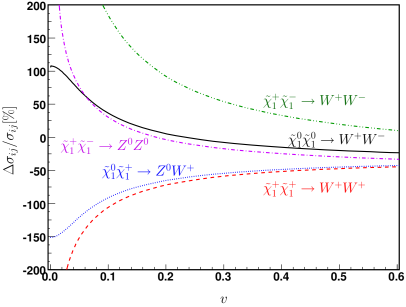
$$I_S(\mu) = \int_0^{\infty} dx \frac{x}{x^2-1} \ln\left[\frac{(x+1)^2+\mu}{(x-1)^2+\mu}\right]$$

- In the limit of vanishing velocity we have

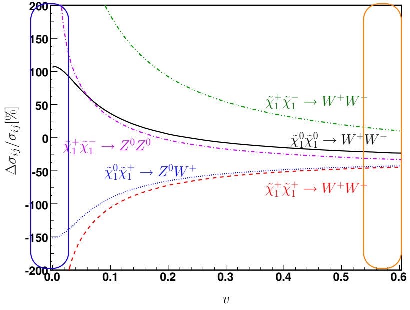
$$\boxed{\lim_{\beta \to 0} \mathcal{R}e(C_0^{\text{Som.}}) = -\frac{\pi}{M \cdot m}}$$

CHANNELS WITH GAUGE BOSONS IN THE FINAL STATE

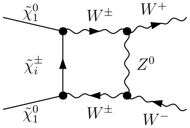
Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000



Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000

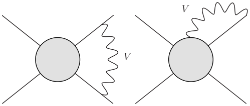


- $v \longrightarrow 1$: Large negative corrections of Sudakov type.



- Originate from vertex and box diagrams involving virtual bosons.
- General form of one-loop Sudakov corrections

$$\alpha\left[C_2 \underbrace{\ln^2\left(\frac{s}{M_V^2}\right)}_{\text{LL}} + C_1 \underbrace{\ln^1\left(\frac{s}{M_V^2}\right)}_{\text{NLL}} + C_0\right] + \mathcal{O}\left(\frac{M_V^2}{s}\right) \quad V = \gamma, W^\pm, Z^0$$

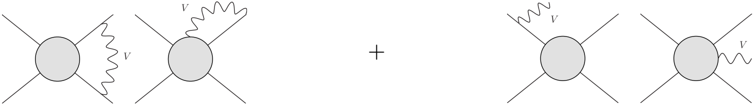


- The $\ln(s/M_V^2)$ represent mass singularities and originate from soft and collinear regions.
- For QED corrections always present ($M_\gamma \to 0$), for EW ones when $s \gg M_{W,Z}^2$.

SUDAKOV VIRTUAL CORRECTIONS

- Originate from vertex and box diagrams involving virtual bosons.
- General form of one-loop Sudakov corrections

$$\alpha\left[C_2 \underbrace{\ln^2\left(\frac{s}{M_V^2}\right)}_{\text{LL}} + C_1 \underbrace{\ln^1\left(\frac{s}{M_V^2}\right)}_{\text{NLL}} + C_0\right] + \mathcal{O}\left(\frac{M_V^2}{s}\right) \quad V = \gamma, W^{\pm}, Z^0$$



- The $\ln(s/M_V^2)$ represent mass singularities and originate from soft and collinear regions.
- For QED corrections always present ($M_\gamma \to 0$), for EW ones when $s \gg M_{W,Z}^2$.
- Dependency on M_γ unphysical $\Rightarrow$ removed by adding real emission as stated by the Bloch-Nordsieck theorem [Bloch,Nordsieck(1937)].
- For EW corrections, $M_{W,Z}$ physical and retained in the calculation.

SUDAKOV VIRTUAL+REAL CORRECTIONS: ABELIAN EXAMPLE

- Adding real emission of EW gauge boson can counterbalance virtual effects.
- Abelian $Z' \to \bar{\nu}\nu + Z^0$ (of mass $\sqrt{s}$) as an example (in the limit $s \gg M_Z^2$):

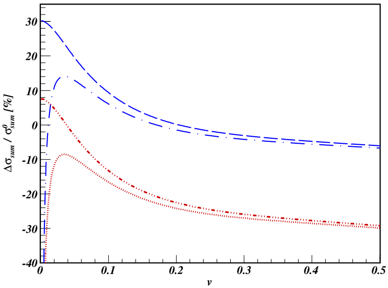
$$\Gamma^{V}{}_{\nu\bar{\nu}} = - \quad \Gamma^0_{\nu\bar{\nu}} \frac{\alpha_Z}{4\pi}\left[2\left(\ln^2\left(\frac{m_Z^2}{s}\right) + 3\ln\left(\frac{m_Z^2}{s}\right)\right) - \frac{2\pi^2}{3} + 7\right]$$

$$\Gamma^{R}{}_{\nu\bar{\nu}} = + \quad \Gamma^0_{\nu\nu} \frac{\alpha_Z}{4\pi}\left[2\left(\ln^2\left(\frac{m_Z^2}{s}\right) + 3\ln\left(\frac{m_Z^2}{s}\right)\right) - \frac{2\pi^2}{3} + 10\right]$$

- Complete compensation between virtual and real logarithmic corrections.

- For our heavy-wino case Sudakov corrections important ($M_W^2/m^2_{\tilde{\chi}_1^0} = 2.10^{-3}$).
- $2 \to 3$ to be taken into account for relic density.
- Real emission of Z^0 boson added.
- virtual $W^\pm$ emission changes isospin $\to$ one state of a mutliplet turned into another state of the same multiplet.
- By summing/averaging over all members of the same multiplet, the cancellation should take place $\Rightarrow$ Summing over all channels and processes (KLN Theorem).
- $W^\pm$ real emission must also be added to form an isospin singlet.

Virtual + real $2 \to 2 + \gamma, Z^0, W^\pm$.



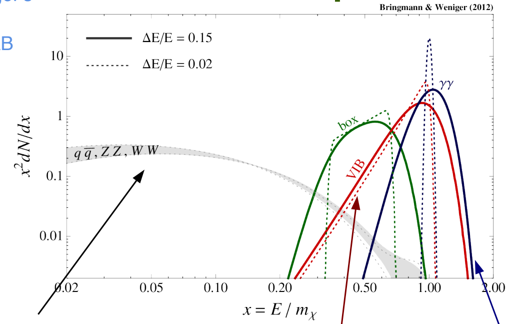
- Large corrections for individual processes $\Rightarrow$ important effect for Indirect Detection
- For relic density calculation, in the thermal bath sum over all members of the isospin multiplet automatically done
- However due to coannihilation weight ($\simeq$ Boltzmann Suppression) violation of KLN in the Early Universe possible (*see e.g [Ciafaloni et. al '13]*)

OUTLINE

GAMMA-RAY LINES

From Weniger's TALK at FERMILAB

Annihilation spectra



Continuum emission/ secondary photons

- often largest component
- featureless spectrum
- difficult to distinguish from astrophysical background

$$\chi\chi \to \bar{q}q \to \pi^0 \ldots$$

$$\pi^0 \to \gamma\gamma$$

Internal Bremsstrahlung (IB)

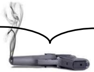
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

$$\chi\chi \to \bar{f} f \gamma$$

Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

$$\chi\chi \to \gamma\gamma$$



(smoking guns)

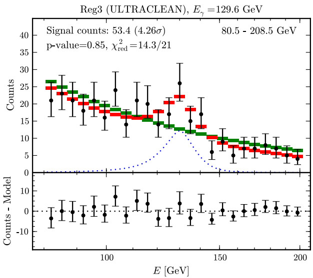
Theoretically favoured :

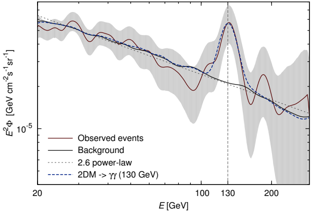
- DM particle annihilation or decay into primary $\gamma + X$ can produce monochromatic gamma rays
- "Smoking gun" signature
- No known astrophysical source can mimic this signal
- γ's point directly to the source → no propagation uncertainties.
- Give direct information on m_χ :

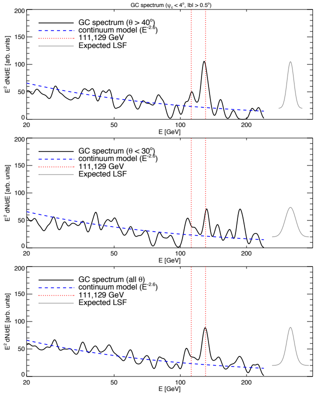
$$\chi\chi \to \gamma\gamma \quad : \quad E_{\gamma\gamma} \simeq m_\chi$$
$$\chi\chi \to \gamma X \quad : \quad E_{\gamma X} \simeq m_\chi \left(1 - \frac{M_X^2}{4{m_\chi}^2}\right)$$

Experimentally challenging :

- DM is a neutral particle → suppressed process
- Very small branching ratio (if loop-induced $\mathcal{O}(\alpha^2)$)
- Difficult to detect from the overwhelming astrophysical background
- Optimal energy resolution (≈ 10% at 100 GeV) and calibration very important







Weniger JCAP 1208 007

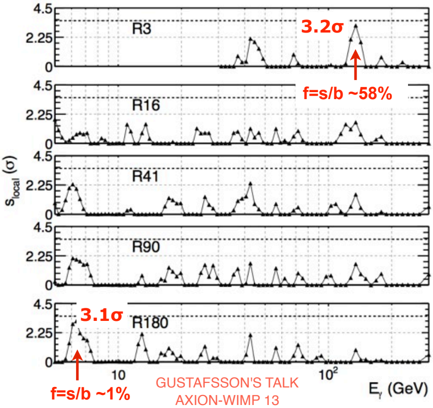
Tempel et. al JCAP 1209 032

Finkbeiner & Su arXiv:1206.1616

γX	m_χ [GeV]	$\langle\sigma v\rangle_{\gamma X}$ $[10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}]$	$\frac{\langle\sigma v\rangle_{\gamma\gamma}}{\langle\sigma v\rangle_{\gamma X}}$	$\frac{\langle\sigma v\rangle_{\gamma Z}}{\langle\sigma v\rangle_{\gamma X}}$	$\frac{\langle\sigma v\rangle_{\gamma H}}{\langle\sigma v\rangle_{\gamma X}}$
$\gamma\gamma$	$129.8 \pm 2.4^{+7}_{-14}$	$1.27 \pm 0.32^{+0.18}_{-0.28}$	1	$0.66^{+0.71}_{-0.48}$	< 0.83
γZ	$144.2 \pm 2.2^{+6}_{-12}$	$3.14 \pm 0.79^{+0.40}_{-0.60}$	< 0.28	1	< 1.08
γH	$155.1 \pm 2.1^{+6}_{-11}$	$3.63 \pm 0.91^{+0.45}_{-0.63}$	< 0.17	< 0.79	1

- FERMI-LAT has searched for spectral line from 5-300 GeV : no globally significant lines
- A line-like feature at 133 GeV present with a global significance below 1σ (2.9σ local).

Local significances in # of sigma
(2σ global sigma dashed line)



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– All fits have global significance < 1.6σ

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- Instrumental effects (Earth limb, 2D fit)
- rare stat. fluctuation
- genuine signal of DM ?

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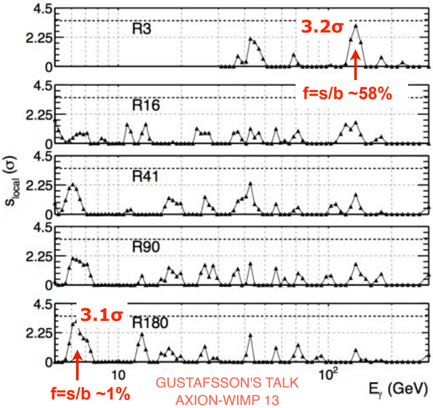

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FERMI OWN DEDICATED REANALYSIS

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IF DM HUGE IMPACT ON PP

- DM ann. at rest $\longrightarrow E_\gamma = m_\chi$
- m_χ sets $\not{E}_T$ for Colliders
- target mass for Direct Detection

Local significances in # of sigma
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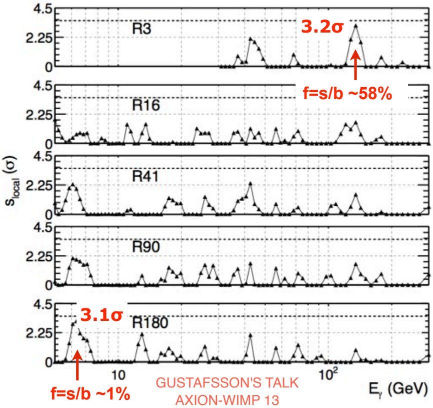

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ACCOUNTING FOR THE GAMMA LINES IN SUSY

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SINGLET EXTENSION OF THE MSSM : NMSSM

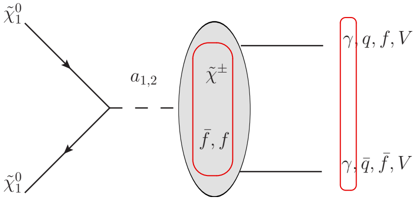
- MSSM content extended by 1 singlet superfield S
- More neutralinos (5), more Higgs bosons (6)

$$\tilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W}^0 + N_{13}\widetilde{H}_1^0 + N_{14}\widetilde{H}_2^0 + N_{15}\tilde{S}$$

- Possible to have $2m_{\tilde{\chi}_1^0} \approx m_{a_1^0}$ and evade all existing constraints

G.C, M.J. Dolan,C. McCabe JCAP 1302 016

- Main mechanism



- $\langle \sigma v \rangle_{\gamma\gamma/Z^0}$ computed with `SloopS` extended to deal with the NMSSM
- GI checked thanks to an extended NLG GF for the NMSSM GC,Semenov '11
- Modified version of `LOOPTOOLS` to handle vanishing Gram determinants at $v = 0$ Boudjema,Semenov,Temes '05

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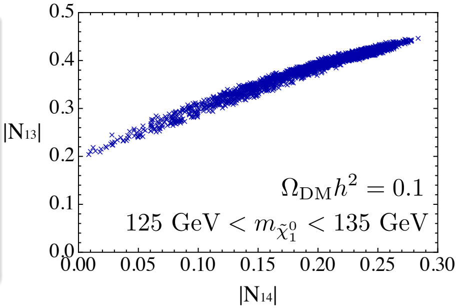
- a_1^0 dominantly singlet $\longrightarrow$ no coupling to SM
- We can (almost) boost independently $\langle \sigma v \rangle_{\gamma\gamma}$ while leaving $\langle \sigma v \rangle_{\chi\chi} = 3 \times 10^{-26}\,\mathrm{cm^2 s^{-1}}$
- DD evaded using parametric cancellations in $g_{h_i\chi\chi}$ coupling $\longrightarrow$ requires $\mu_{\rm eff} \leq 0$.
- Sizeable Higgsino fraction needed for $\Omega_\chi h^2$ (as large as 25%)
- Bino is the dominant component.



Kozaczuk, Profumo,Wainwright PRD87 075011

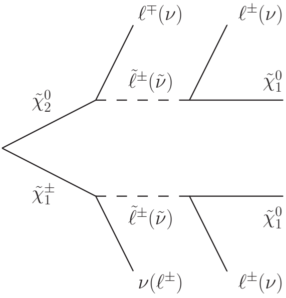
- Successful EW Baryogenesis
- Strongly first order EWPT

- Generation of right BAU ($\cancel{CP}$ phase for M_2)
- OK with EDM

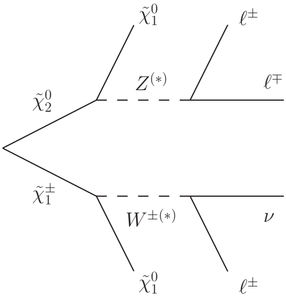
- We looked at three benchmark points

Parameter	Well-Tempered	Intermediate-Slepton	λ-SUSY
λ	-0.7	-0.7	-1.5
κ	-0.863	-0.77	-2.19
$\tan\beta$	4.0	4.0	5.45
A_λ [GeV]	-369.9	-378.0	-478.3
A_κ [GeV]	75.5	74.95	-55.9
$\mu_{\rm eff}$ [GeV]	-150.0	-190.0	-168.0
M_1 [GeV]	135.0	135.5	128.4
$m_{\tilde\chi_1^0}$ [GeV]	130.0	133.7	129.9
N_{11}, N_{15}	-0.89, 0.1	0.96, -0.06	0.975, -0.083
N_{13}, N_{14}	0.39, 0.19	-0.26, -0.09	-0.21, 0.012
m_A [GeV]	259.45	267.27	259.33
$\langle\sigma v\rangle_{\gamma\gamma} \times 10^{-27}$ cm^{3}s^{-1}	1.2	1.1	0.9
$\Omega_{\rm DM} h^2$	0.10	0.12	0.11
$\sigma^p_{\rm SI} \times 10^{-45}$ cm^2	1.4	0.23	3.1
$\sigma^p_{\rm SD} \times 10^{-4}$ pb	5.4	1.4	0.7
$\sigma^n_{\rm SD} \times 10^{-4}$ pb	4.2	1.1	0.5
$\langle\sigma v\rangle_{\gamma Z}/\langle\sigma v\rangle_{\gamma\gamma}$	0.64	0.52	0.67
$\Delta a_\mu \times 10^{10}$	-1.0 ± 2.9	0.8 ± 2.8	-1.4 ± 2.8

- Singlet-like a_1^0 does not give interesting collider signature
- Our benchmarks have large Higgsino fraction $\rightarrow$ light $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ and $\tilde{\chi}_1^\pm$.
- Best prospects for neutralino and chargino production
- Most promising signatures are dileptons/trileptons + $\not{E}_T$ and intermediate slepton scenario



(a) via sleptons



(b) via gauge bosons

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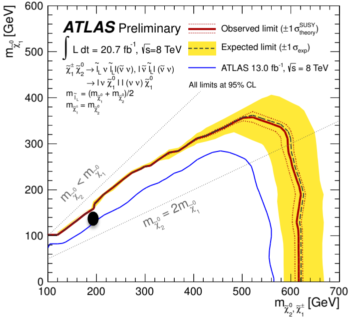
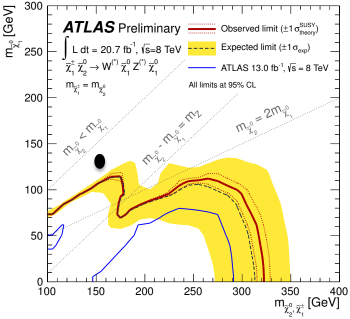


(a) Decay via sleptons



(b) Decay via gauge bosons

CONCLUSION

- Importance of radiative corrections DM self-annihilation can be very large.
- Need to control them to be able to extract informations from it and to constrain the underlying cosmological scenario.
- Complete renormalisation of the MSSM achieved and an automatic tool has been developped
- Including $2 \to 3$ processes is needed in specific scenarios where the real emission is important.
- One should consider the complete set of corrections (virtual + real) to give a precise result for $\Omega_\chi h^2$.
- Tentative gamma-ray line investigated in the NMSSM
- Possible to evade all constraints (except $(g-2)_\mu$) at the expense of significant amount of fine-tuning
- Benchmarks point could be quickly excluded (thanks to complementarity between LHC and DD next run of LUX)
- Gamma-line signal observation still not confirmed, PASS8 should clarify, HESS-II, CTA, GAMMA400 should tell.

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