Interplay of the LHC and DM search experiments in unravelling Natural Supersymmetry

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

SMU, Dallas, April 25, 2016

Collaborators

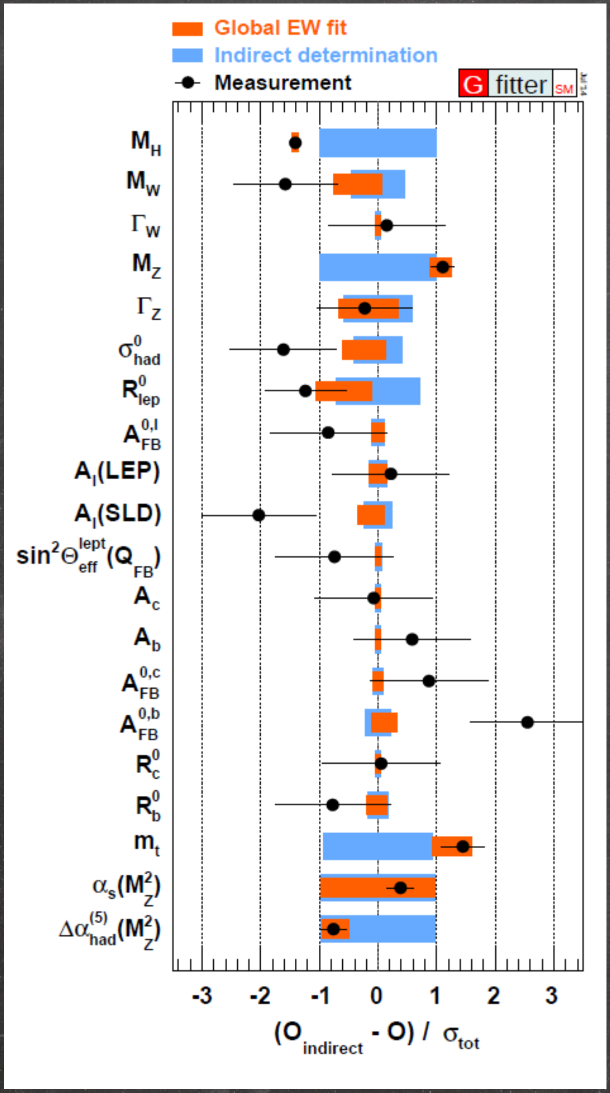
- D. Barducci, AB, A.Bharucha, W. Porod, V. Sanz, arXiv:1504.02472

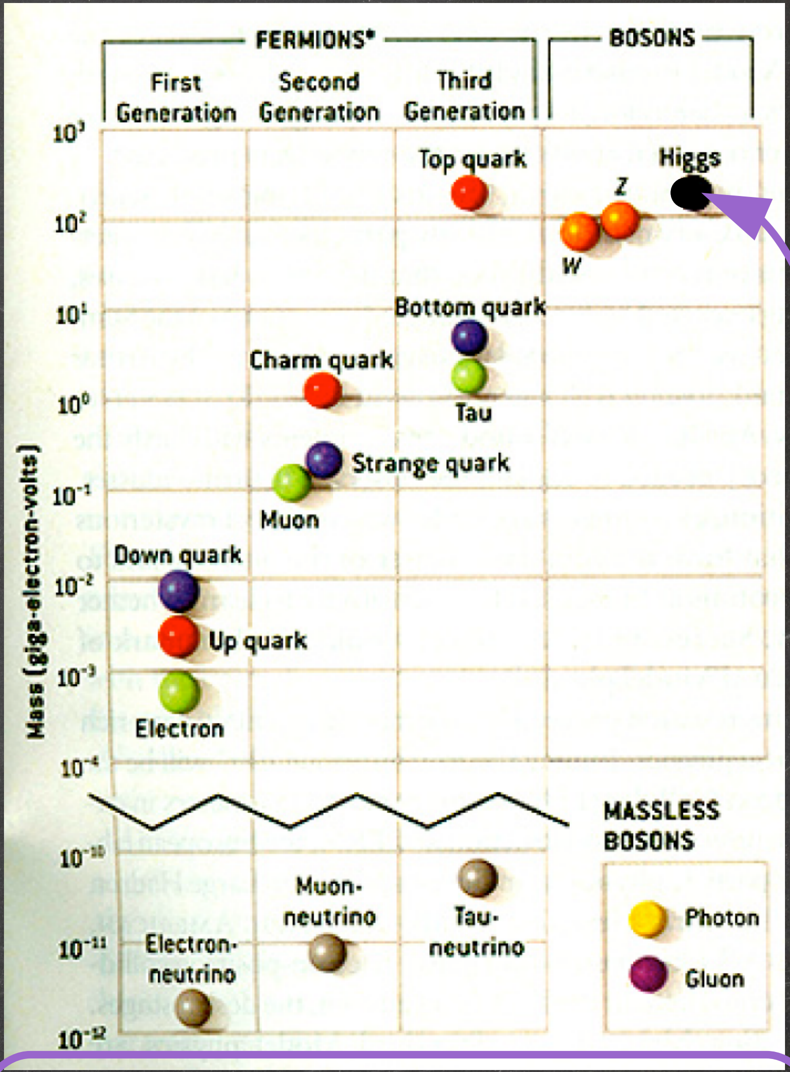
- D. Barducci, AB, S. Pokorski, K. Sakurai work in progress

OUTLINE

- Motivation for BSM
- General approach for SUSY hunt
- DM search interplay
- Natural SUSY probe at the LHC and DD of DM
- Conclusions

The the Standard Model is very successful !





Confirmed to better than 1% precision by 100's of precision measurements

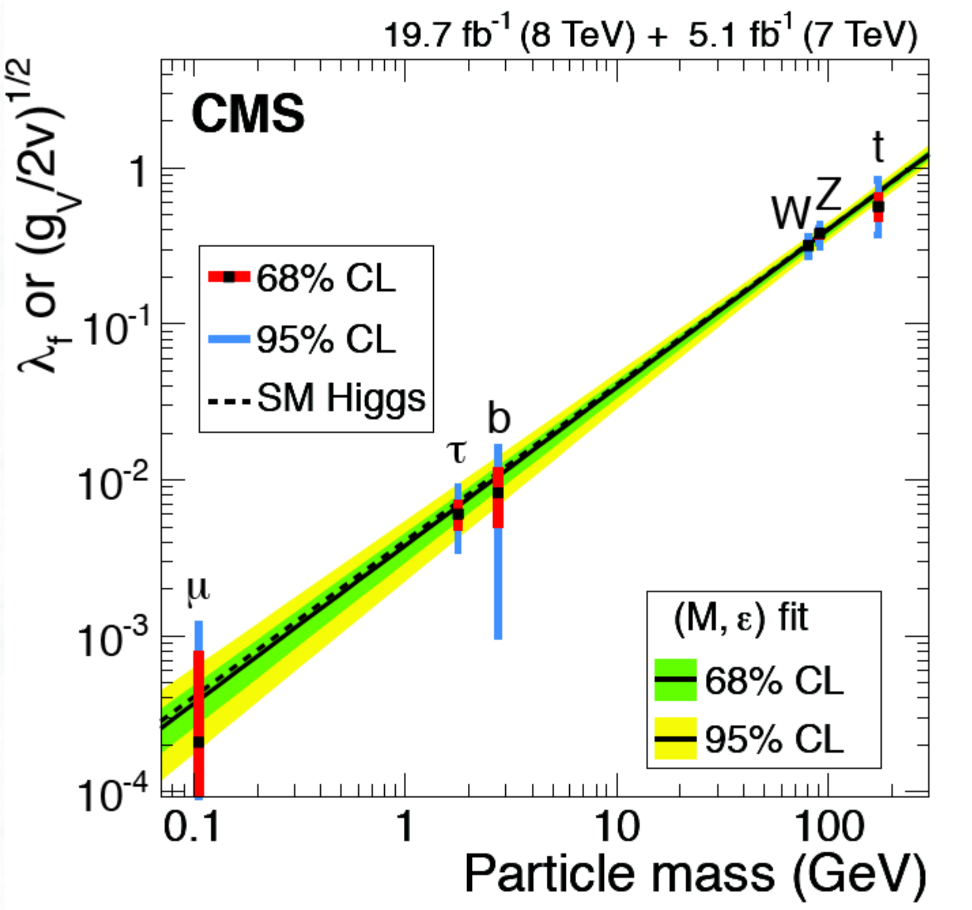
The last missing particle – Higgs boson with ~125 GeV mass is discovered on the 4th of July 2012

Higgs Boson Status

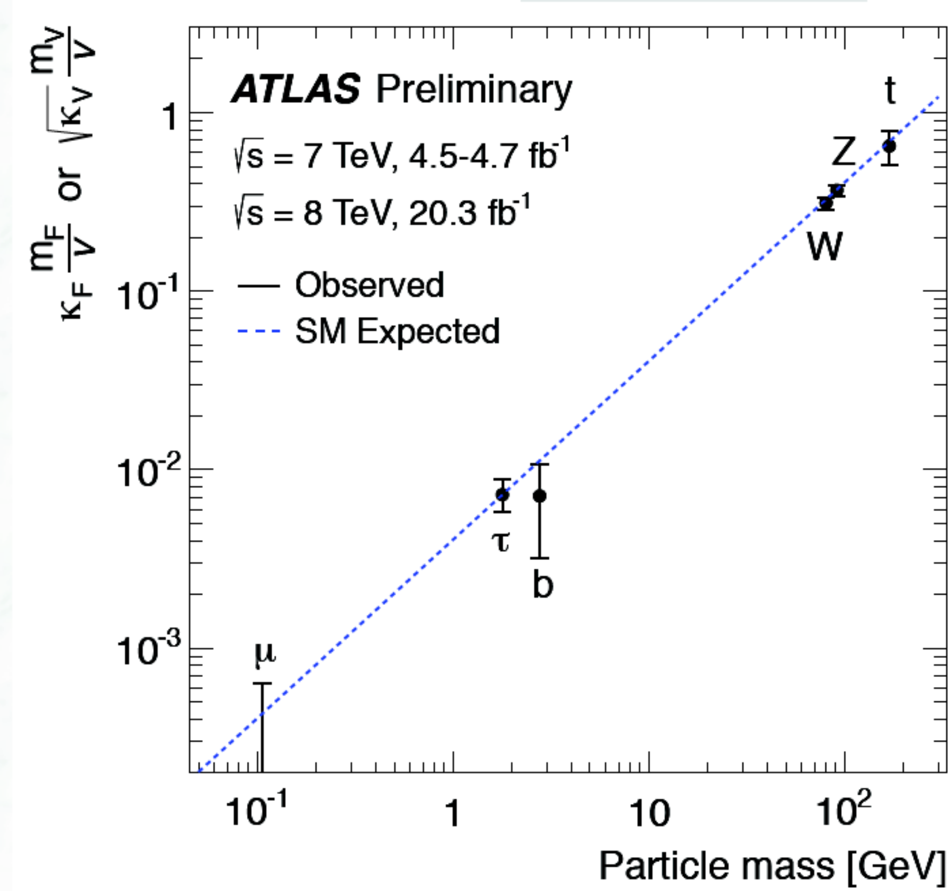
λ = Yukawa coupling for fermions
√g/2v = couplings for W/Z bosons

For the first time, non-universal, mass-dependent couplings observed

EPJ C75 (2015) 5, 212



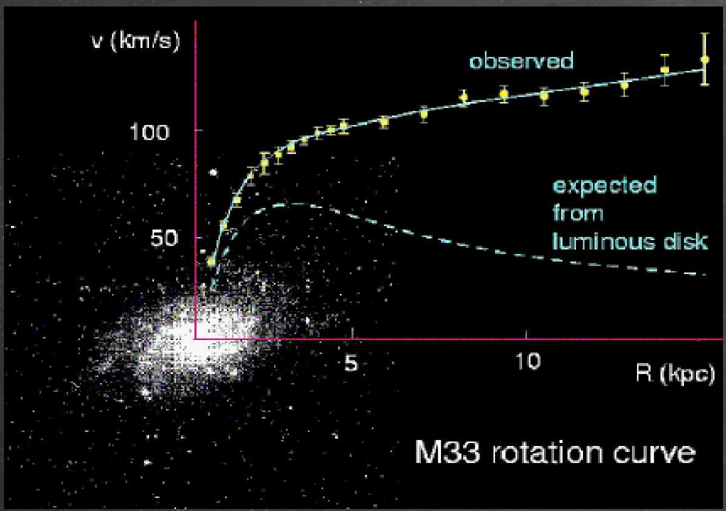
ATLAS-CONF-2015-007



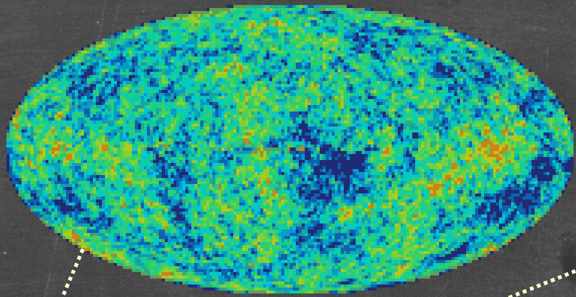
SM is empirically incomplete

- the presence of non-baryonic, cold dark matter: DM is neutral, stable, colourless, non-baryonic and massive (cold or warm). Neutrinos are too light, make instead hot DM

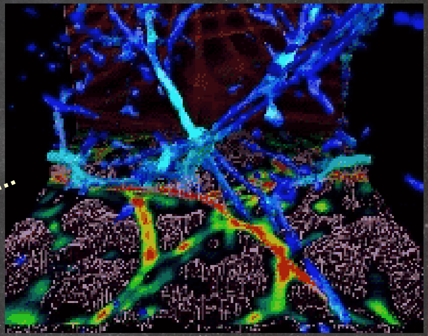
Galactic rotation curves



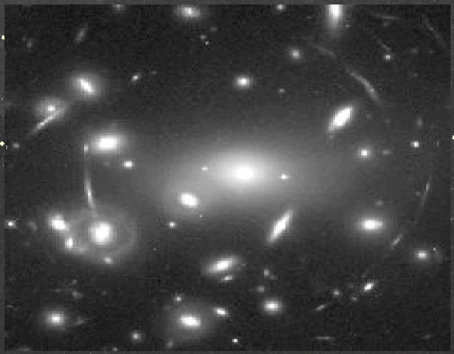
CMB: WMAP and PLANCK



Large Scale Structures



Gravitational lensing



Bullet cluster

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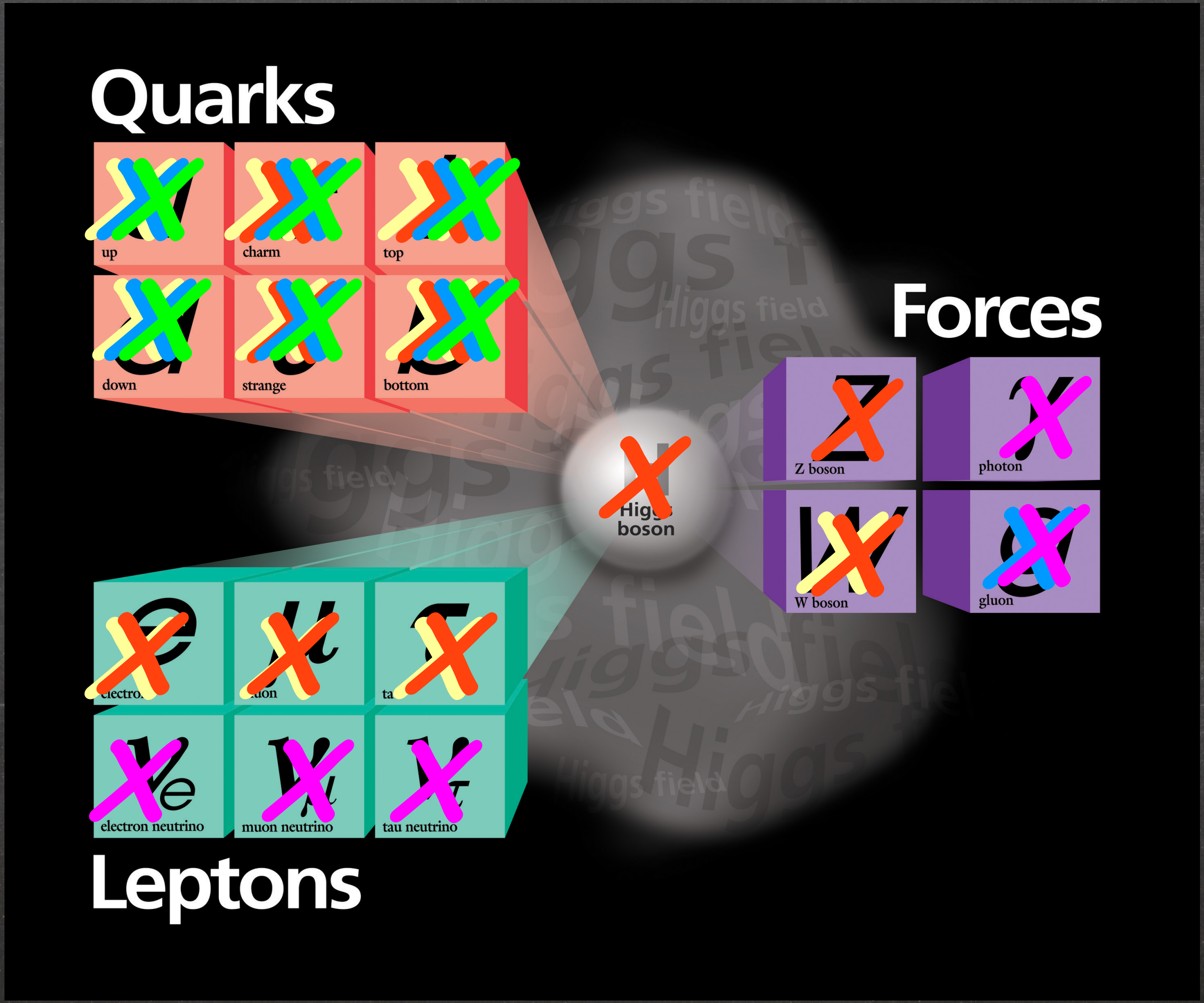
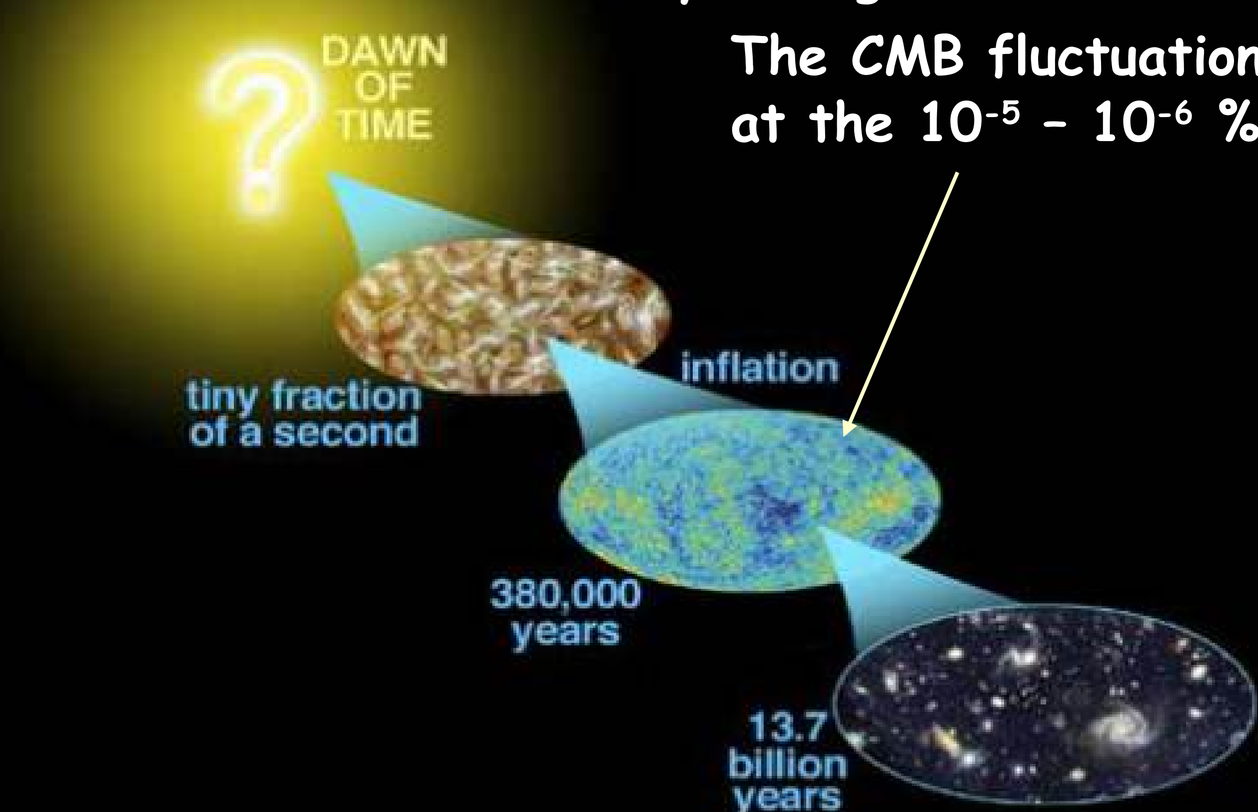


SM is empirically incomplete

- the presence of scale-invariant, Gaussian, and apparently acausal density perturbations: consistent with a period of inflation at early times

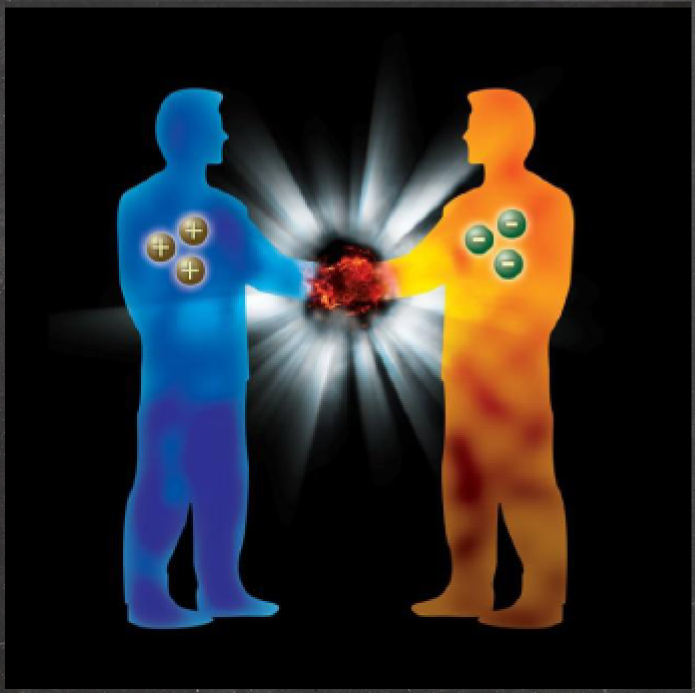
the universe, on large scales, is extremely homogeneous and isotropic

The CMB fluctuations are at the 10^{-5} - 10^{-6} % level



SM is empirically incomplete

- **the observed abundance of matter over anti-matter**: note, moreover, that inflation would destroy any asymmetry imposed as an initial condition.



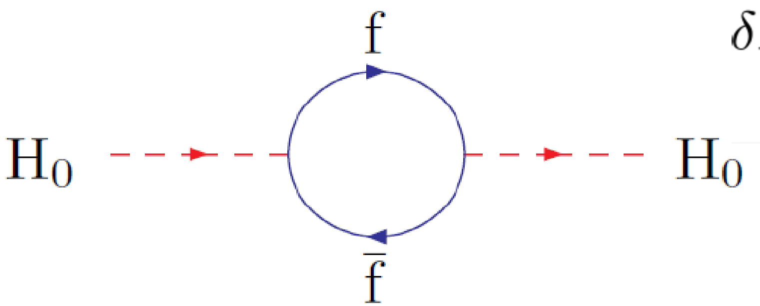
The amount of CP violation in the SM which could lead to baryon-antibaryon asymmetry is too small (would provide BAU orders of magnitude below the observed one)

$$\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

Empirical problems of the SM stated above have been established beyond reasonable doubt.

SM is aesthetically unacceptable

- **inability to describe physics at planckian scales:** General relativity makes perfect sense as a theory of quantum gravity up to planckian scales (as an effective field theory) but beyond that we need a theory of quantum gravity, such as string theory
- **hierarchy between the observed cosmological constant and other scales:** the measured energy density associated with the accelerated expansion of the Universe is $(10^{-3}\ \mathrm{eV})^4$, but receives contributions of size GeV^4 and TeV^4 from QCD and weak scale physics respectively. How is it achieved?
- **the hierarchy between the weak and other presumed scales:** as above, but now the question is how to get a TeV from the Planck scale.



$$\delta M_{H\,f}^2 = i\frac{|g_f|^2}{4}\int \frac{d^4k}{(2\pi)^4}\frac{\mathrm{tr}\left[(k+p+m_f)(k+m_f)\right]}{\left[(k+p)^2-m_f^2\right]\left[k^2-m_f^2\right]}$$

$$= \frac{|g_f|^2}{16\pi^2}\left[-2\Lambda^2+6m_f^2\ln\left(\Lambda/m_f\right)\right]$$

$$M_H^2 = M_{H\,\mathrm{bare}}^2 + \delta M_H^2$$

there is a cancellation of over 30 orders of magnitude to have 125 GeV Higgs

Higgs Boson Discovery has completed the puzzle of the Standard model ...

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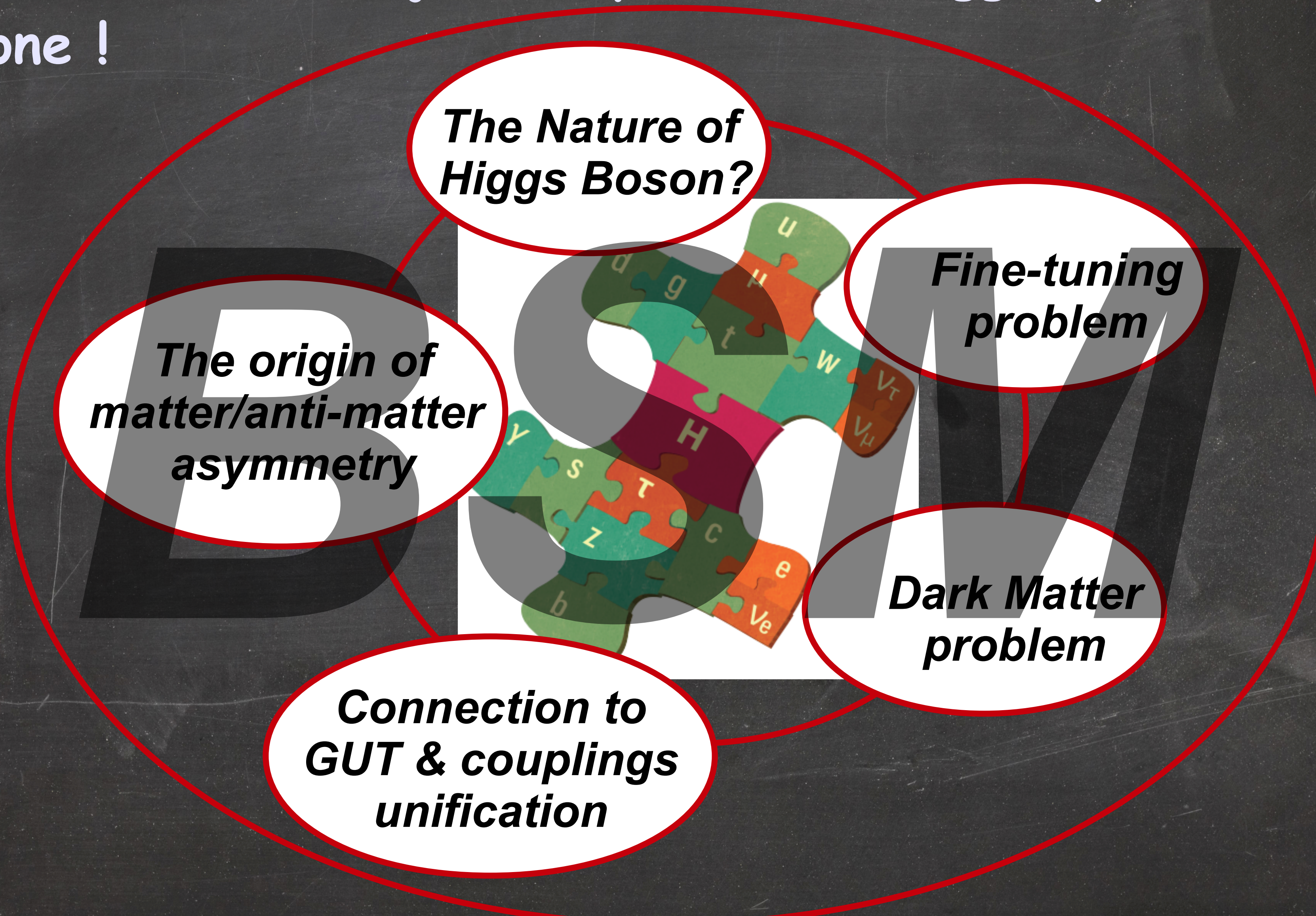
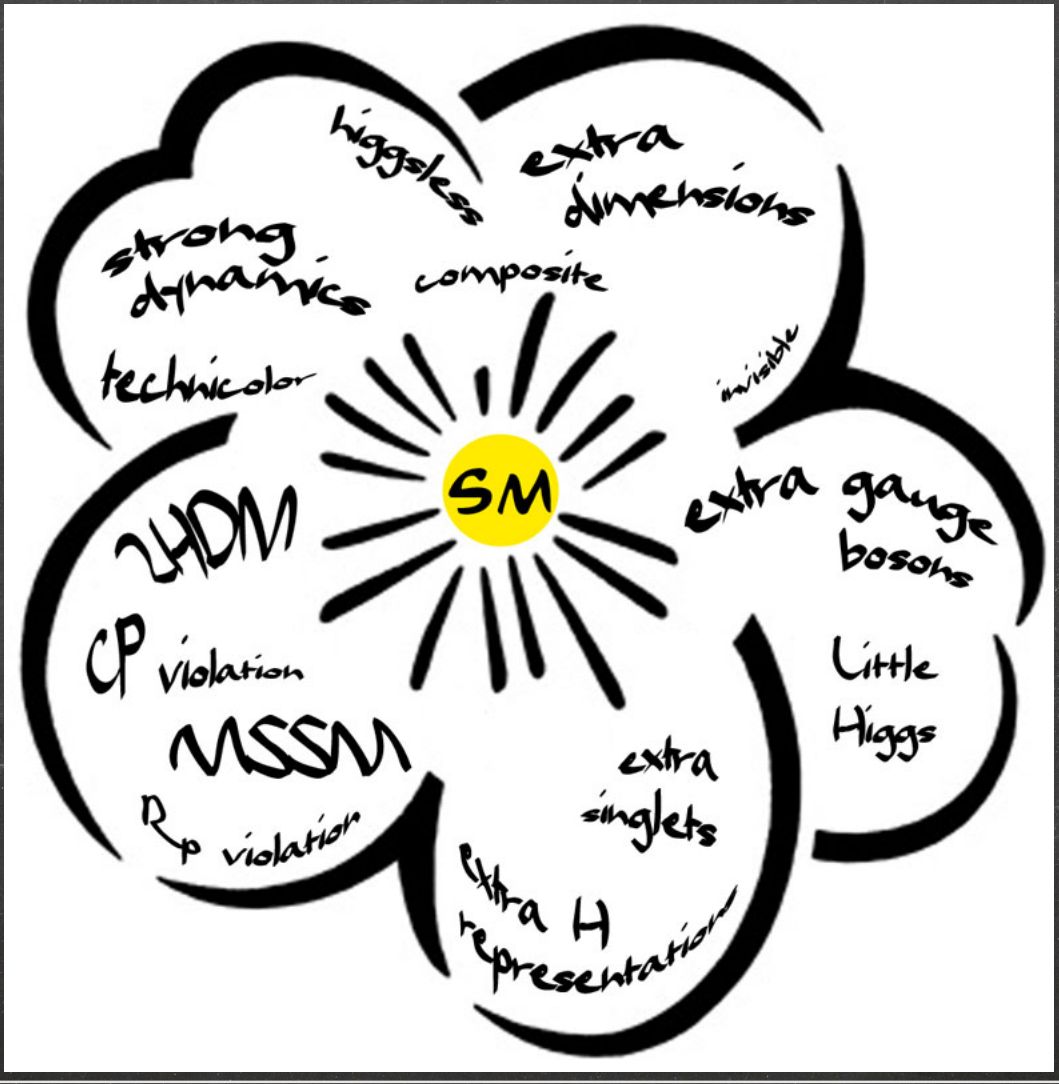
But the SM itself is just a piece of a bigger puzzle - BSM one !



Beyond the Higgs discovery

- Higgs properties are amazingly consistent with all main compelling underlying theories (except higgsless ones!) Some parameter space of BSM theories was eventually excluded.



CPNSH workshop
CERN 2006-009

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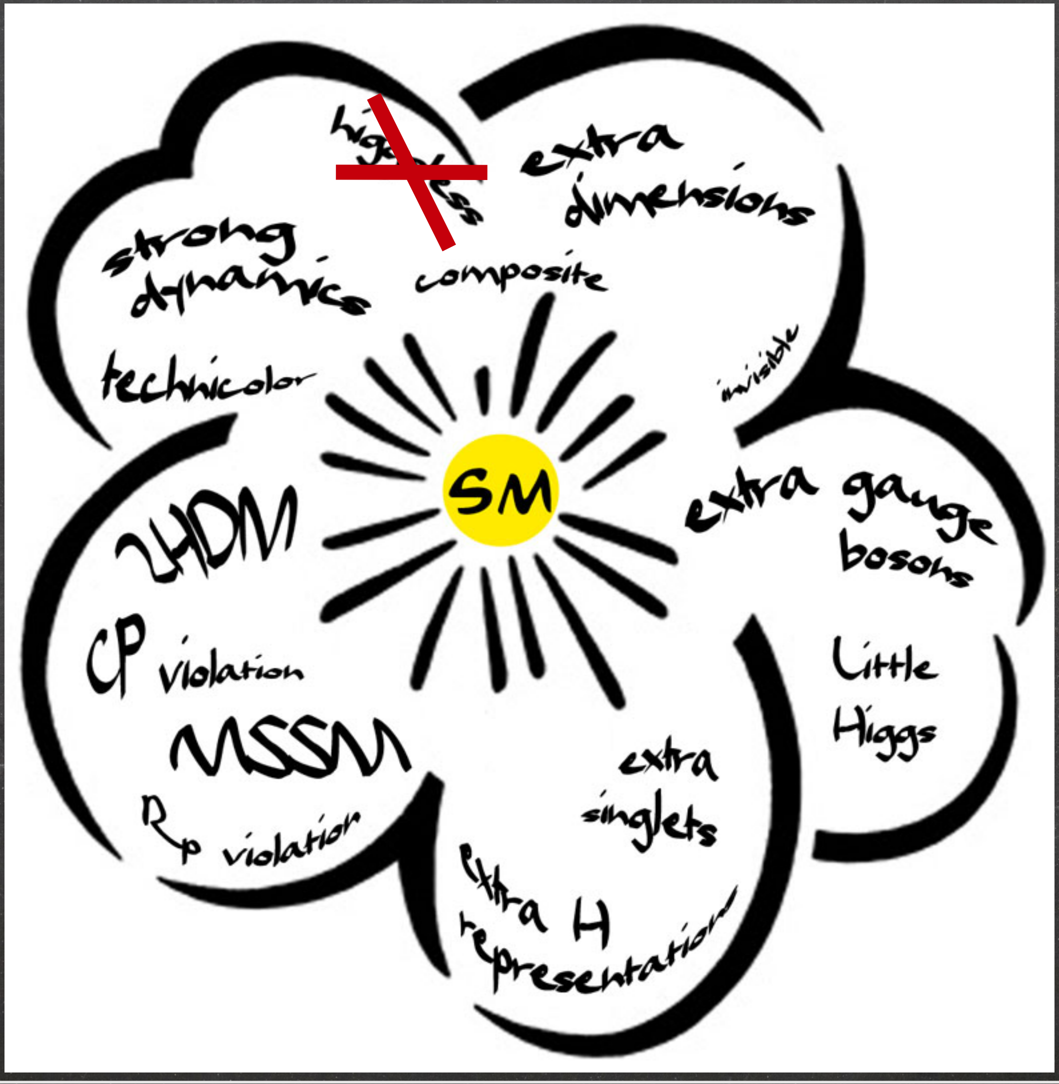

Present Status

What do we know about Dark Matter?

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Spin $\boxed{?}$

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Mass $\boxed{?}$

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behind stability $\boxed{?}$

Couplings

gravity $\boxed{V}$

Weak $\boxed{?}$

Higgs $\boxed{?}$

Quarks/gluons $\boxed{?}$

Leptons $\boxed{?}$

New sector $\boxed{?}$

Thermal relic

Yes $\boxed{?}$ No $\boxed{?}$

SUSY

Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

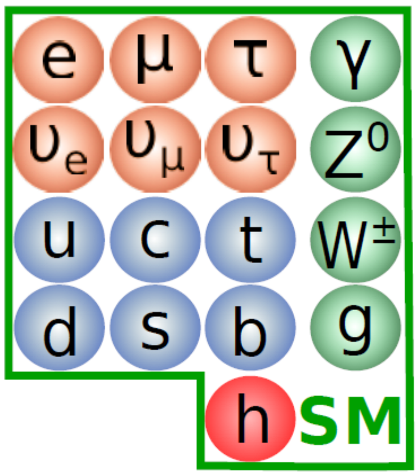
$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

extends Poincare algebra to Super-Poincare Algebra:

the most general set of space-time symmetries! (1971-74)

$$\{f,f\} = 0, \quad [B,B] = 0, \quad \{Q_\alpha, \bar{Q}_\beta\} = 2\gamma^\mu_{\alpha\beta} P_\mu$$

Golfand and Likhtman'71; Ramond'71; Neveu,Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74



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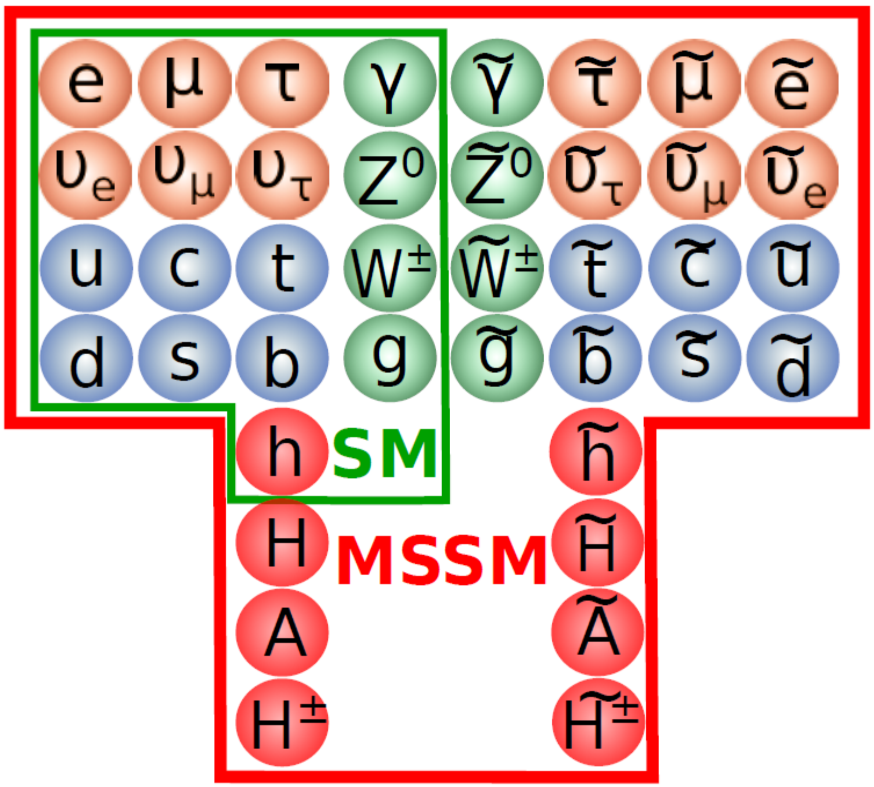

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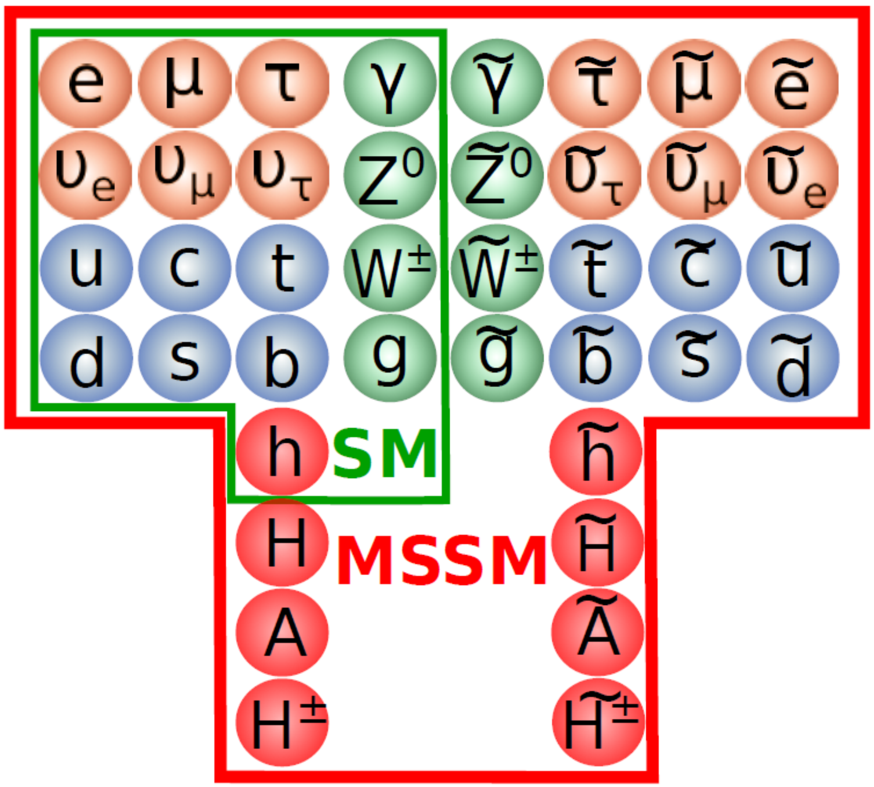

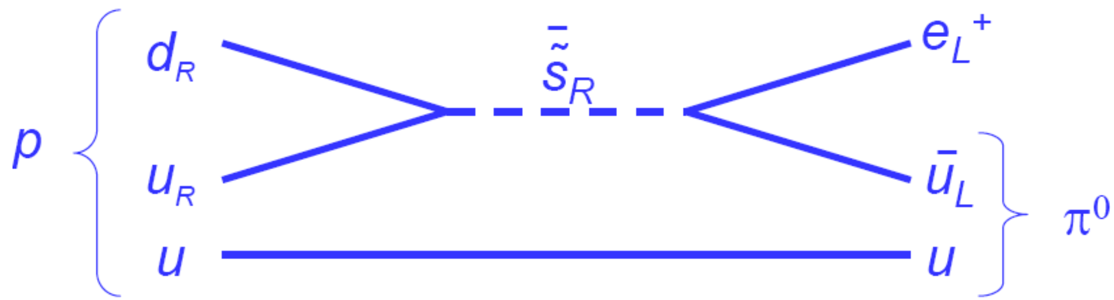

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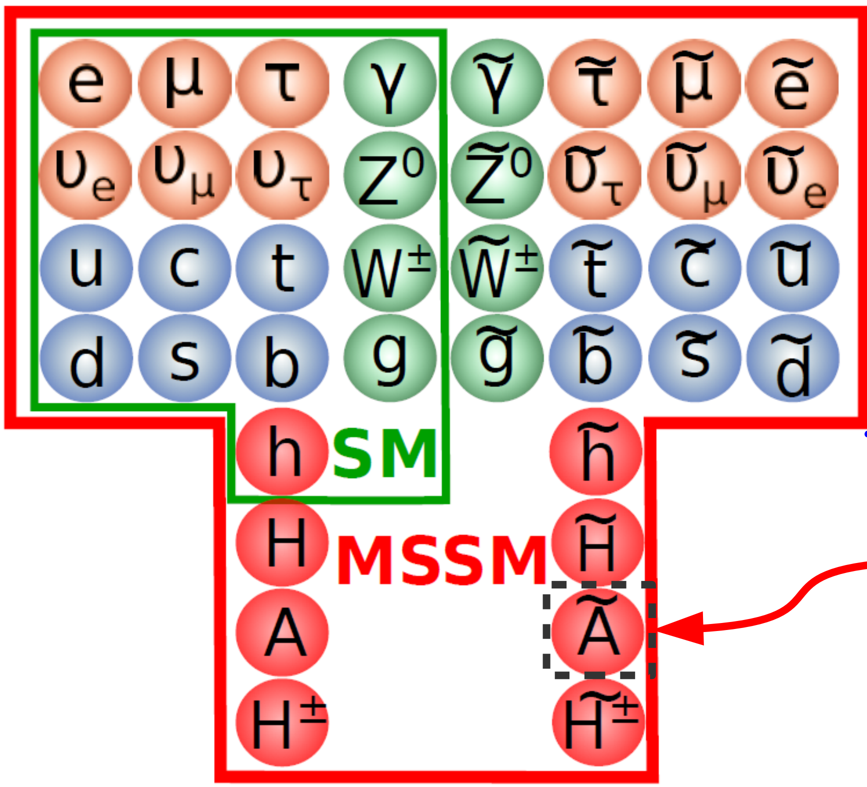

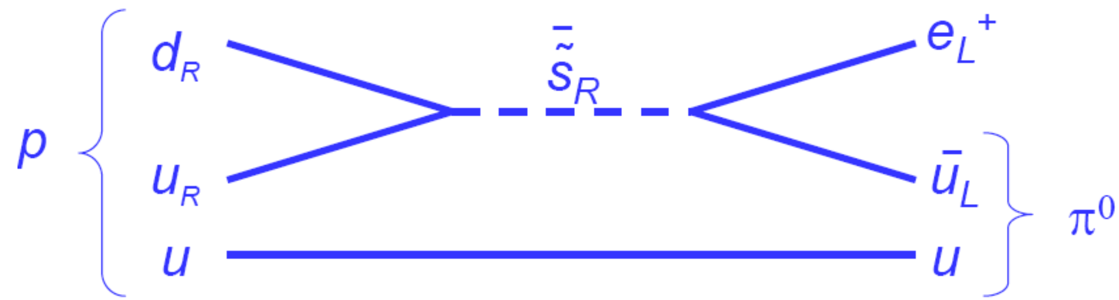

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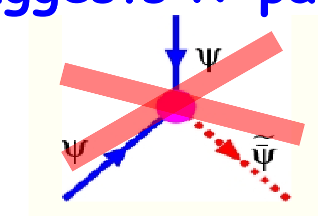
the absence of proton decay suggests R-parity

$$\boxed{R=(-1)^{3(B-L)+2S}}$$



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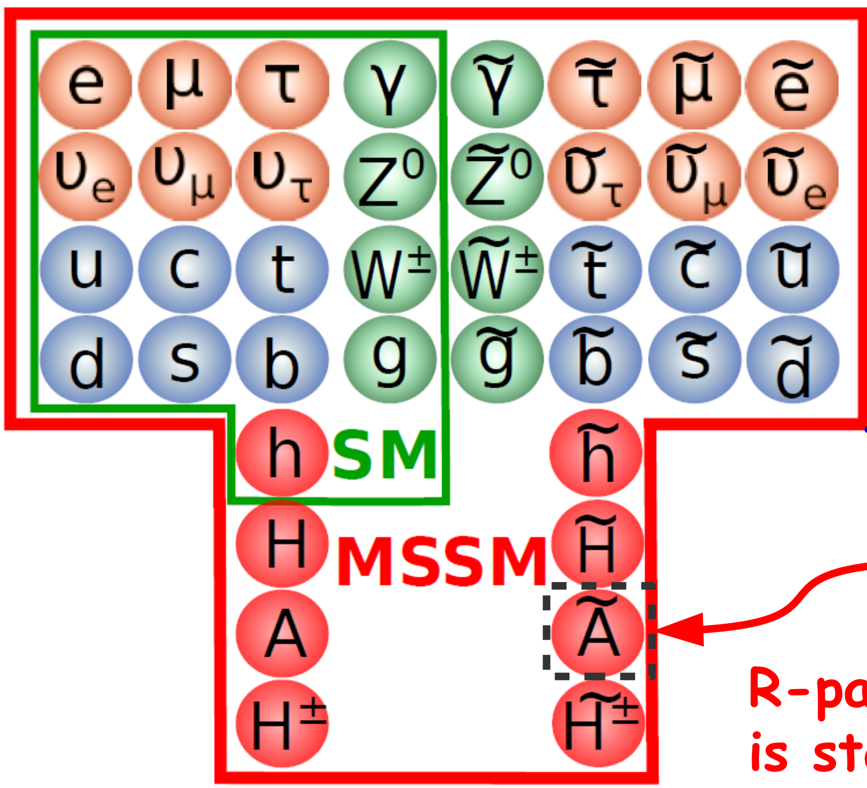

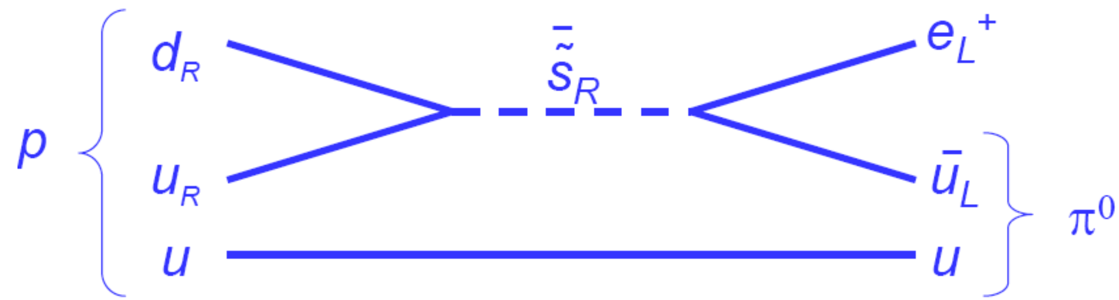

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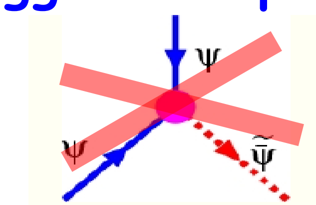
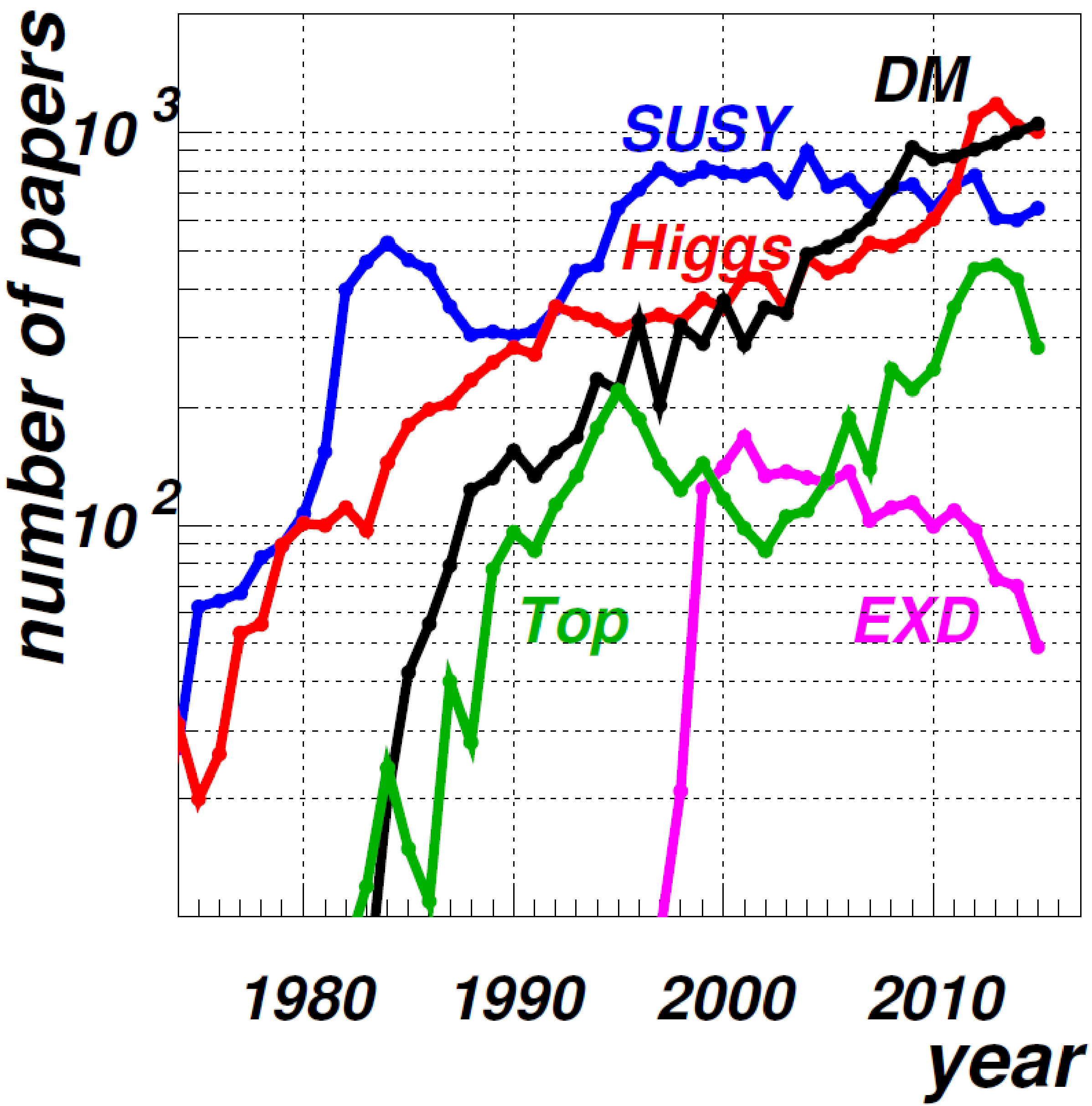


R-parity guarantees Lightest SUSY particle (LSP) is stable - DM candidate!

We are still inspired by this beauty ...



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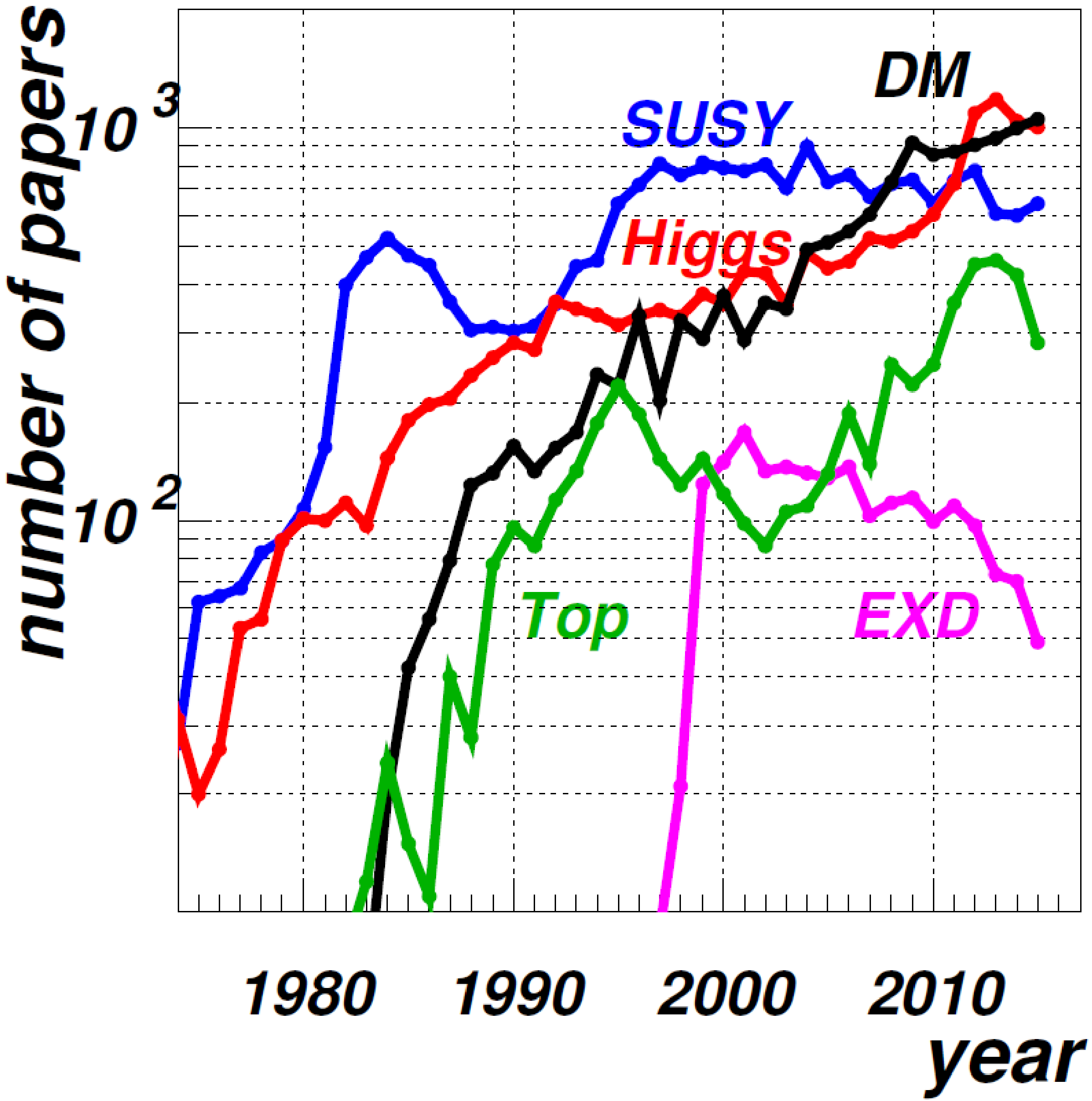
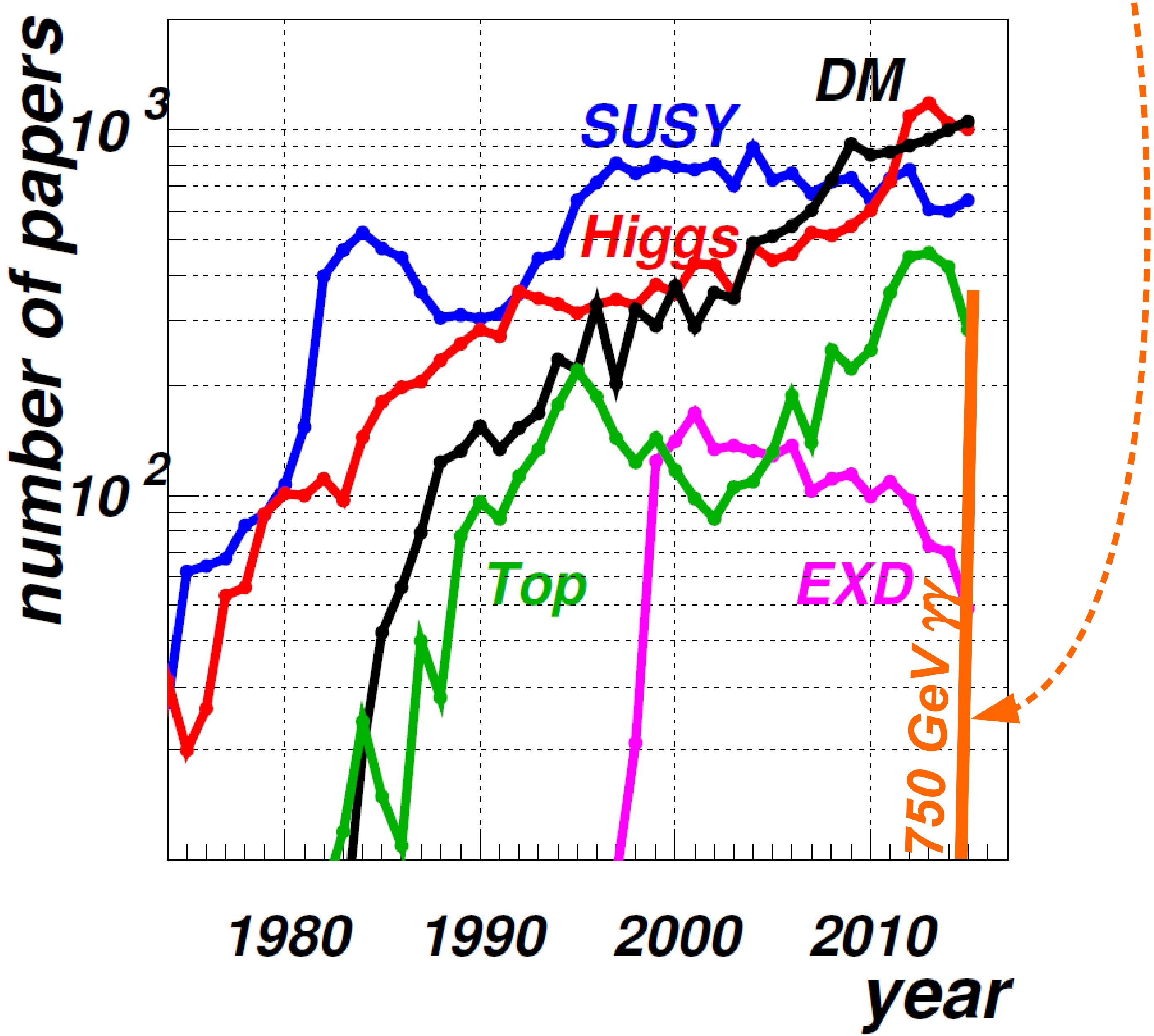
even after more than 30 year unsuccessful searches ...

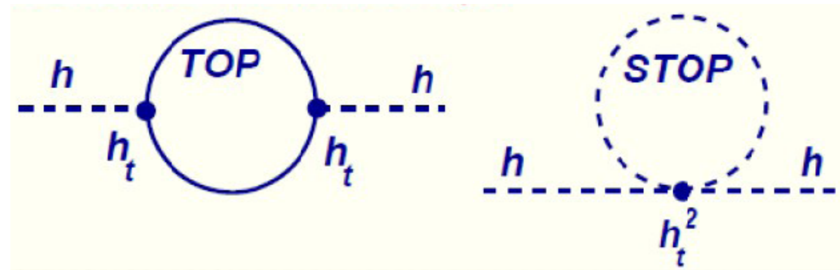


Another source of inspiration?!

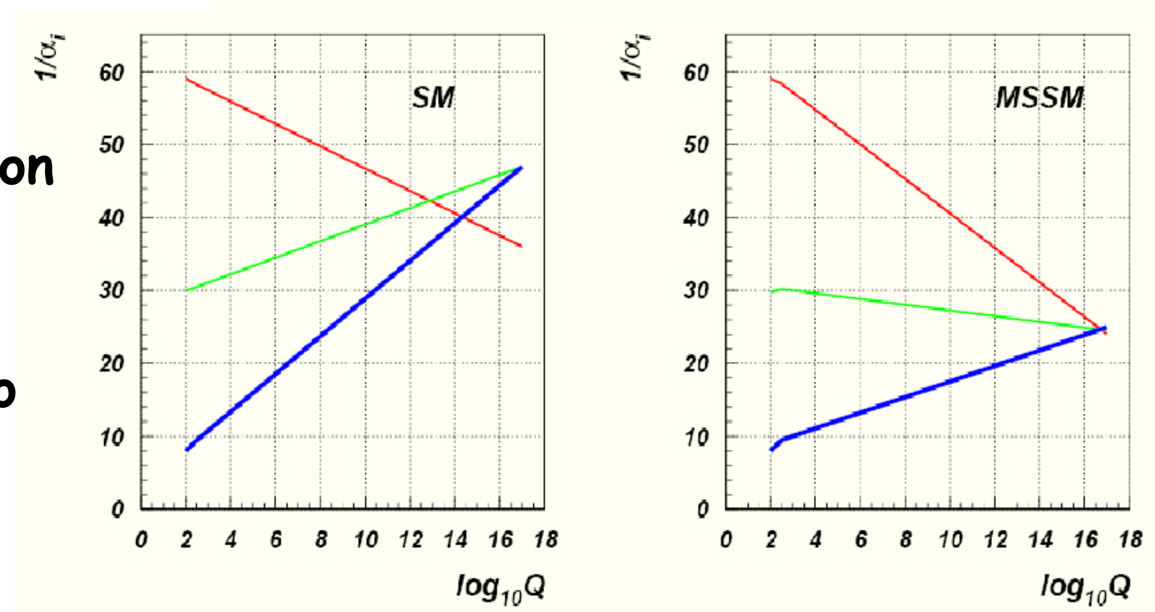


Beauty of SUSY

- Provides good DM candidate – LSP
- CP violation can be incorporated - baryogenesis via leptogenesis
- Radiative EWSB
- Solves fine-tuning problem
- Provides gauge coupling unification
- local supersymmetry requires spin 2 boson – graviton!
- allows to introduce fermions into string theories



$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$

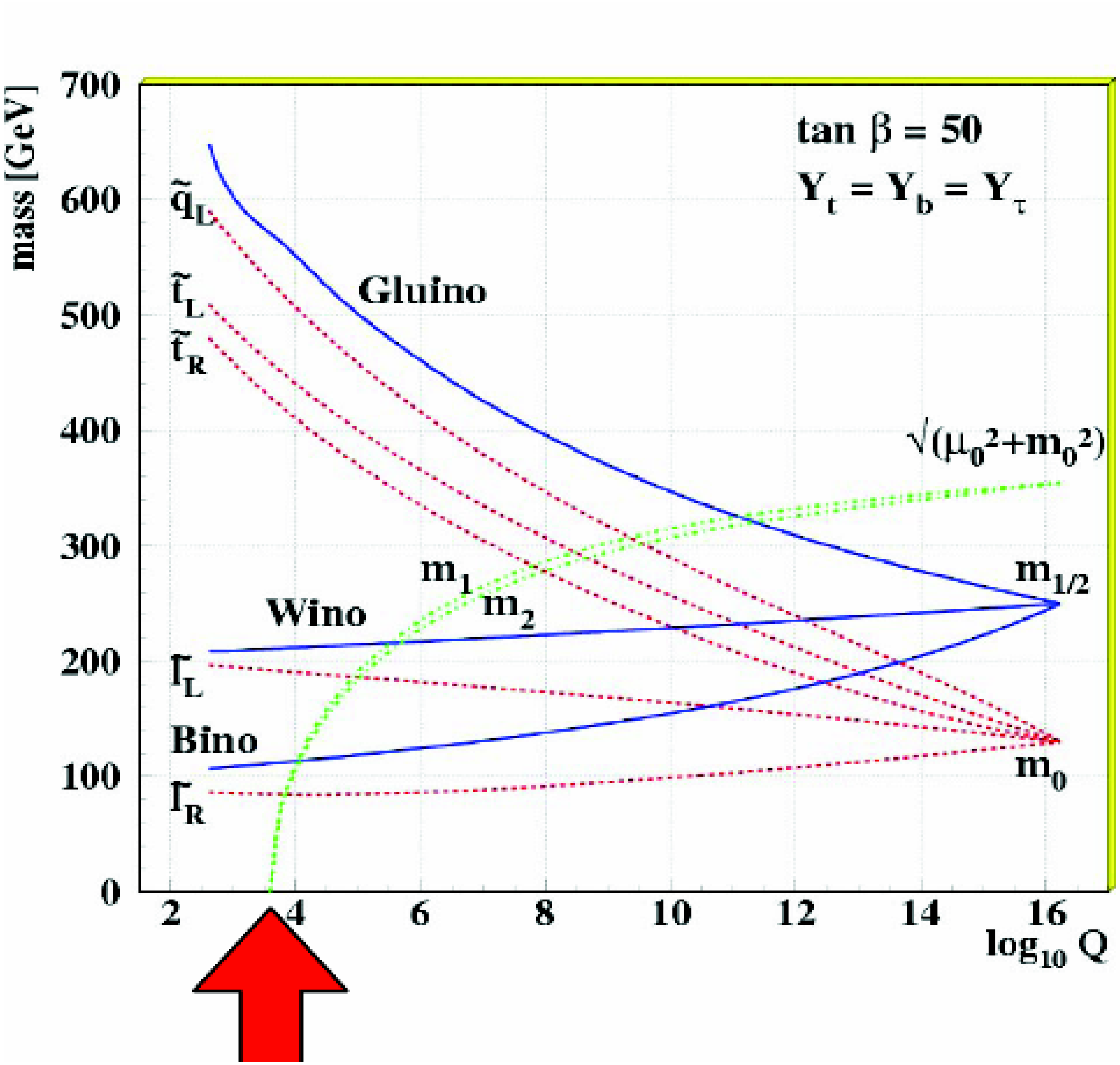


It was not deliberately designed to solve the SM problems!

How do we search/constrain SUSY?

- Collider search
  - strong SUSY particles production, cascade decay: missing PT + jets/leptons
  - EW DM pair production: mono-jet signature
- Direct/Indirect DM detection experiments
- Constraints from Relic Density
- Constraints from EW precision measurements and rare decays

Mass spectrum for mSUGRA scenario



independent parameters:

m0
universal scalar mass

m1/2
universal gaugino masses

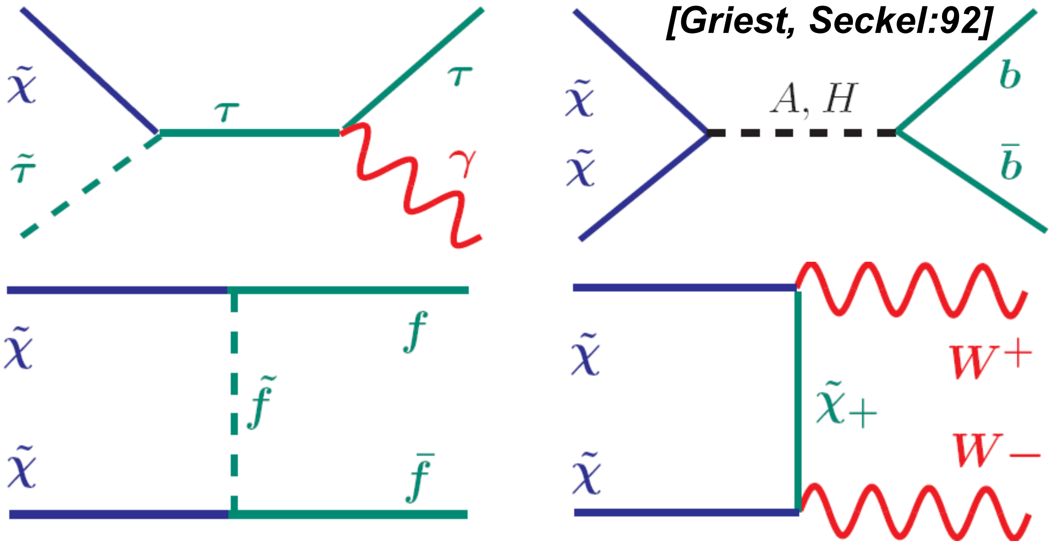
A
trilinear soft parameter

tan(beta) = v1/v2

ISASUGRA, SPHENO,SUSPECT,SOFTSUSY

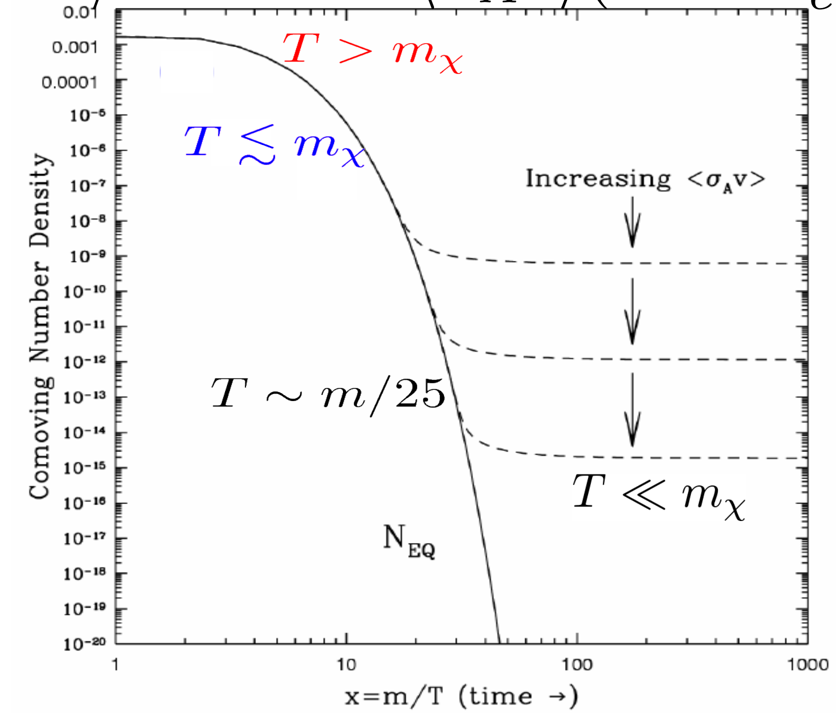
Evolution of neutralino relic density

Challenge is to evaluate thousands annihilation/co-annihilation diagrams



time evolution of number density is given by Boltzmann equation

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



Evolution of neutralino relic density

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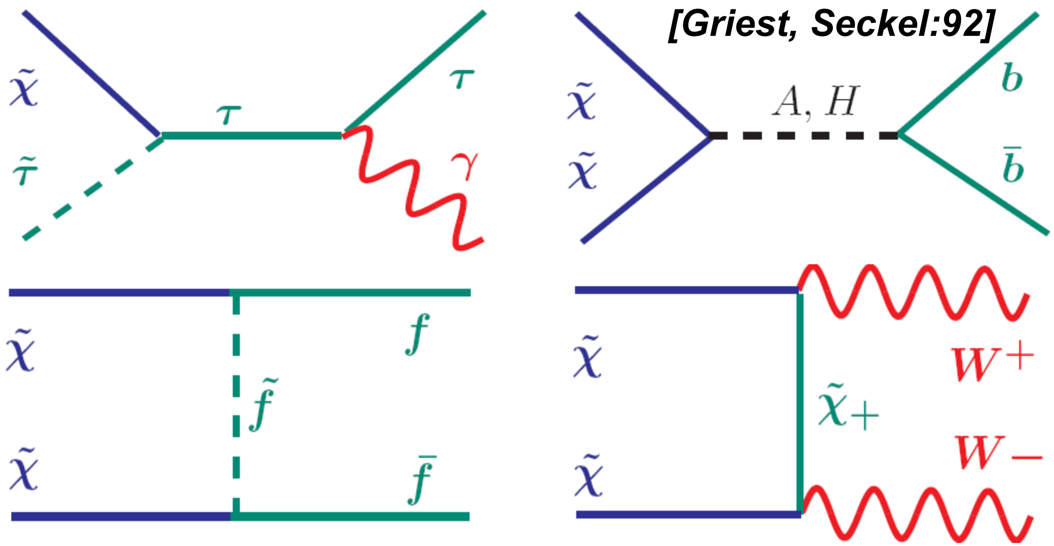
[Griest, Seckel:92]



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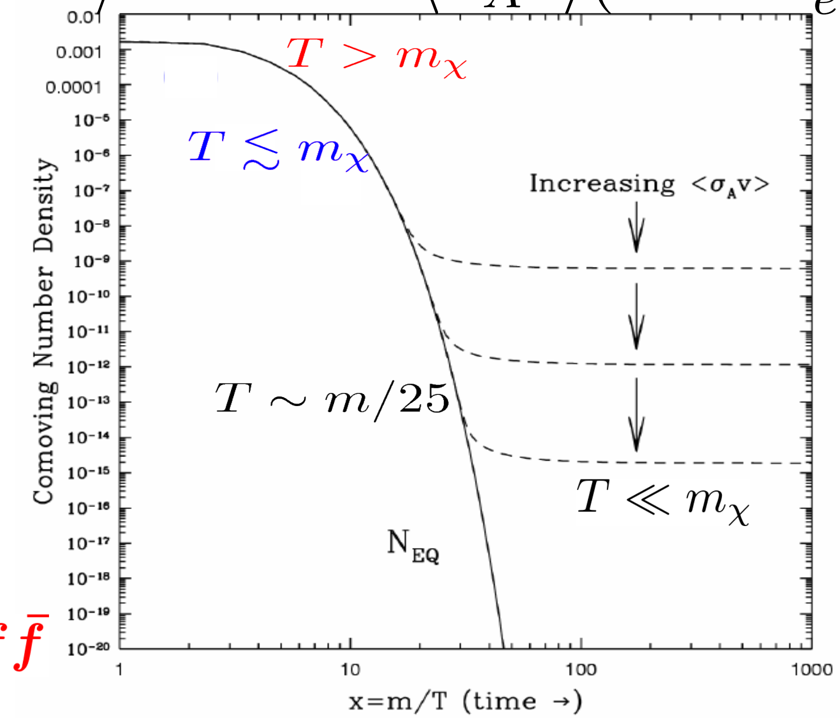
$$\mathrm{dn/dt}=-3\mathrm{Hn}-\langle\sigma_A v\rangle(n^2-n_{eq}^2)$$



relic density depends crucially on thermal equilibrium stage: $\langle\sigma_A v\rangle$ $T > m_\chi, \;\; \chi\chi \leftrightarrow f\bar{f}$

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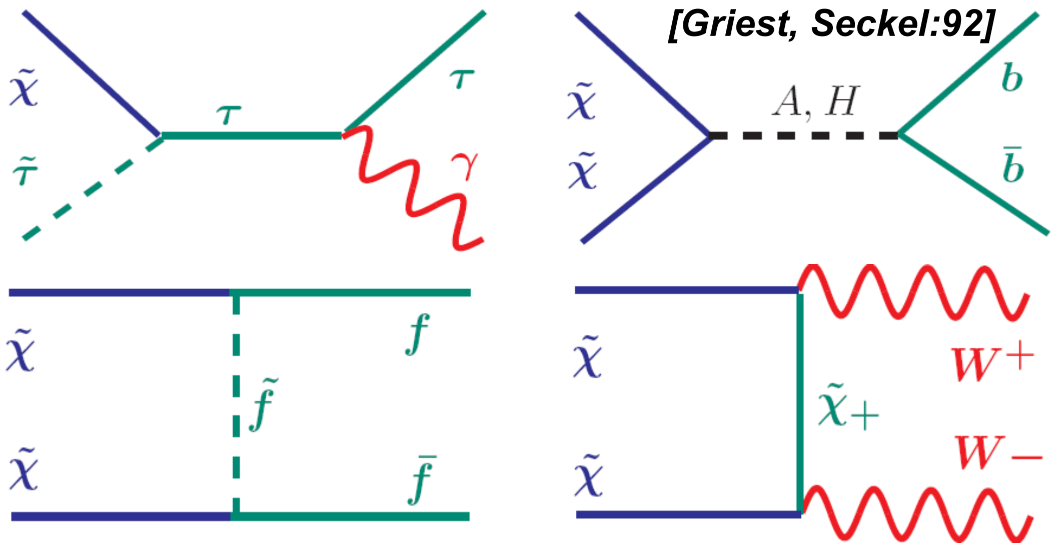

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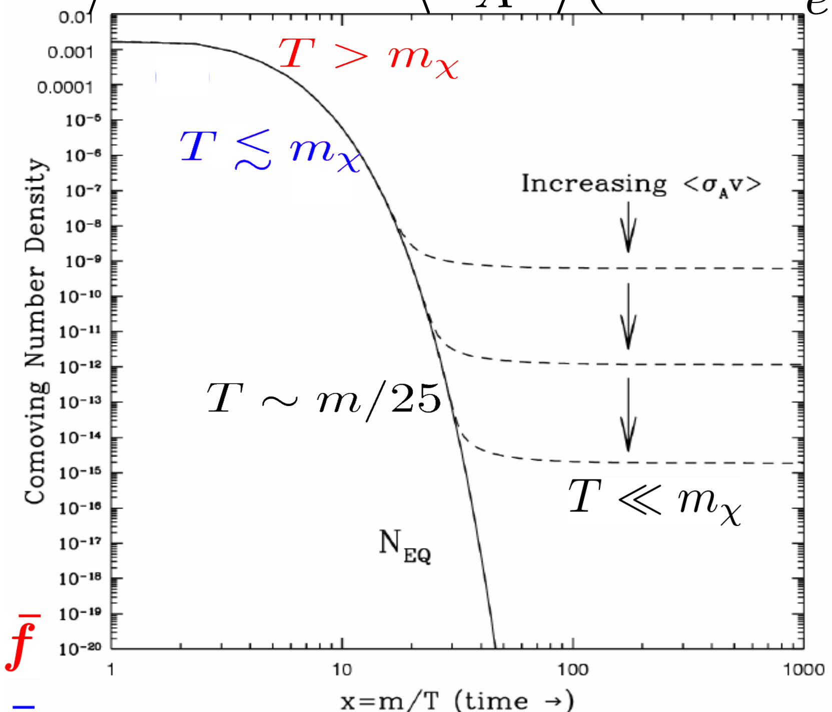

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universe cools: $T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$

n = n_{eq}~ $e^{-m/T}$

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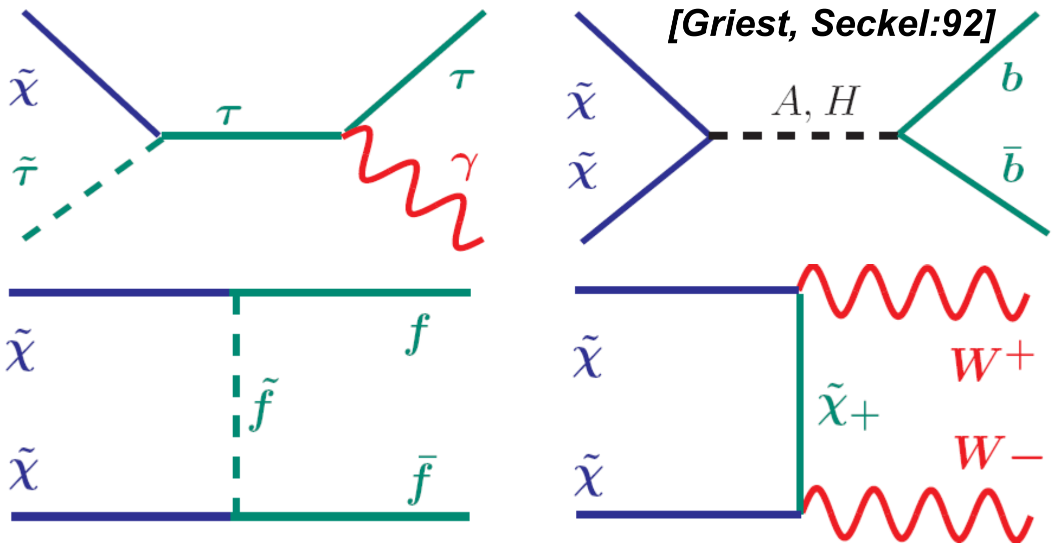

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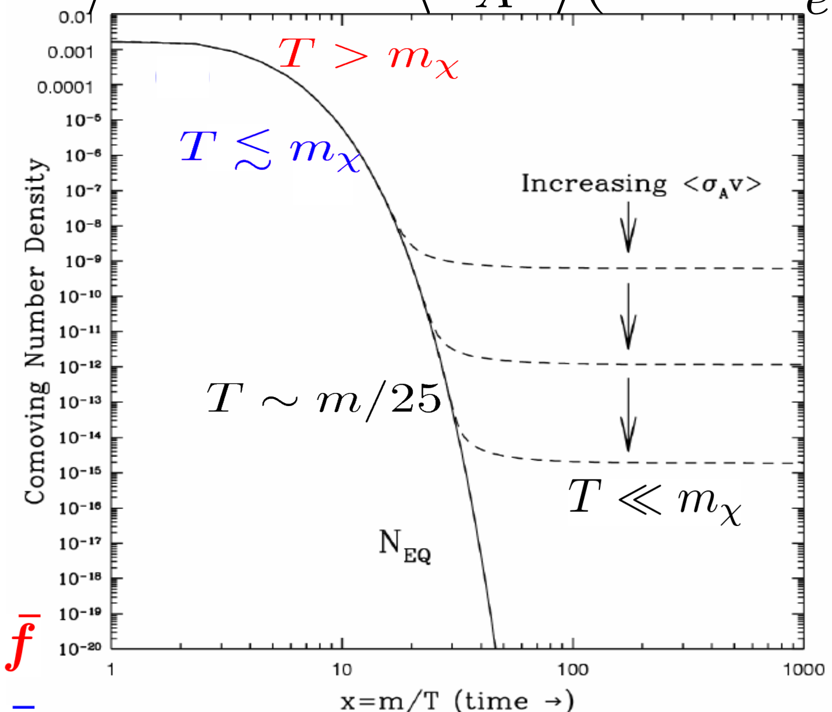

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neutralinos "freeze-out" at $T_F \sim m/25$

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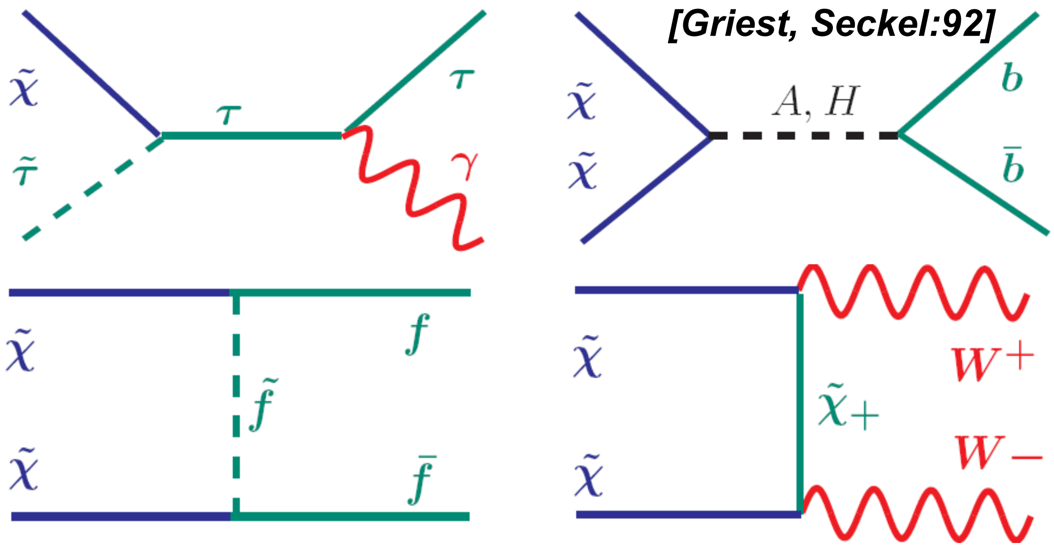
[Griest, Seckel:92]



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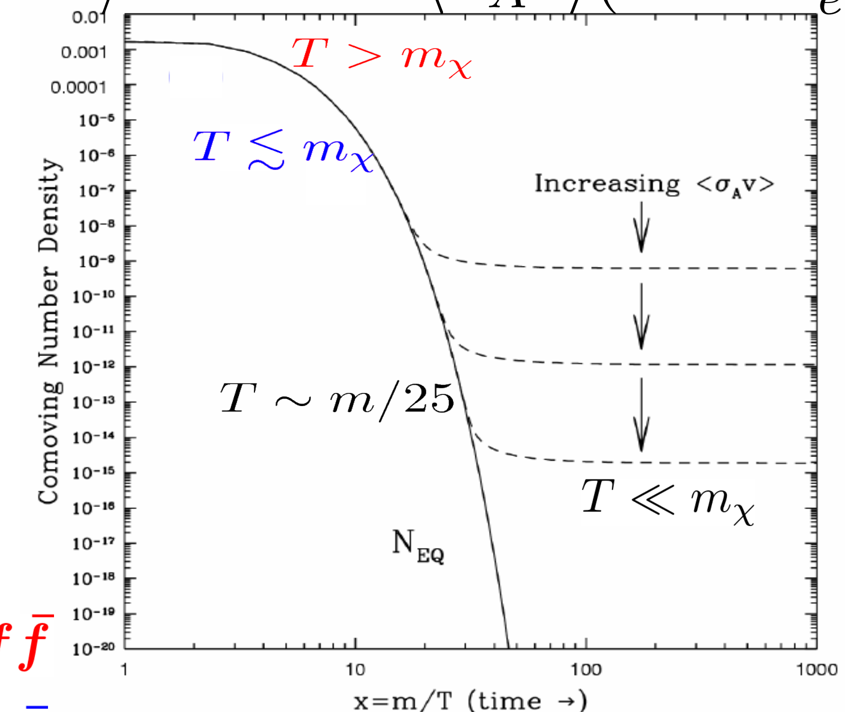

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Packages:

MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

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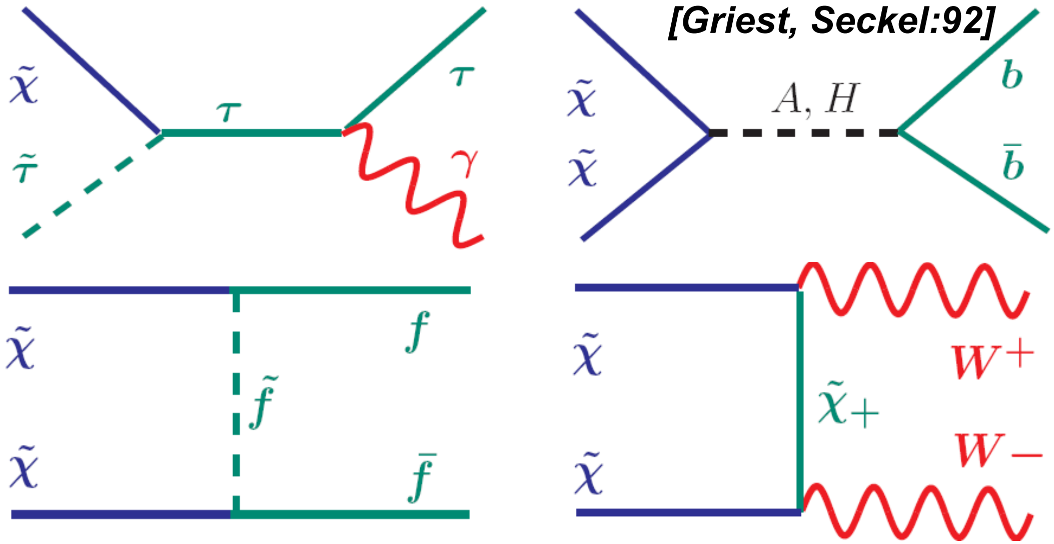

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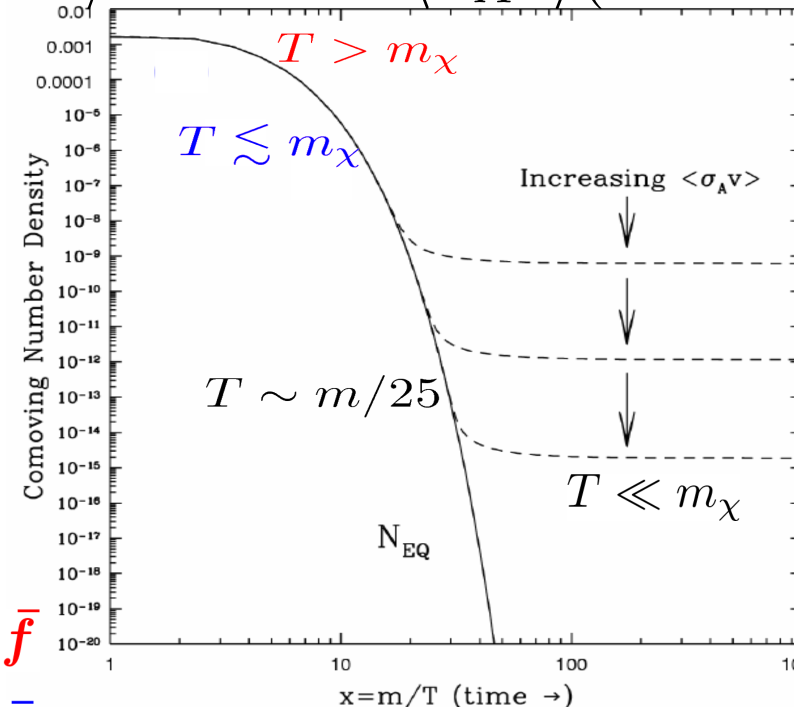


relic density depends crucially on $\langle\sigma_A v\rangle$

thermal equilibrium stage: $T > m_\chi, \quad \chi\chi \leftrightarrow f\bar{f}$

universe cools: $T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$

$n = n_{eq} \sim e^{-m/T}$

neutralinos "freeze-out" at $T_F \sim m/25$

$$\Omega_\chi = \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

$$\Omega_\chi = 0.112 \rightarrow \langle\sigma_A v\rangle = 1\mathrm{pb}$$

$$\langle\sigma_A v\rangle = \frac{\pi\alpha^2}{8m^2}$$

$$m = 100\mathrm{GeV}$$

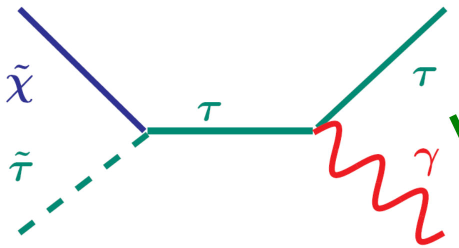
mass of the mediator

Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

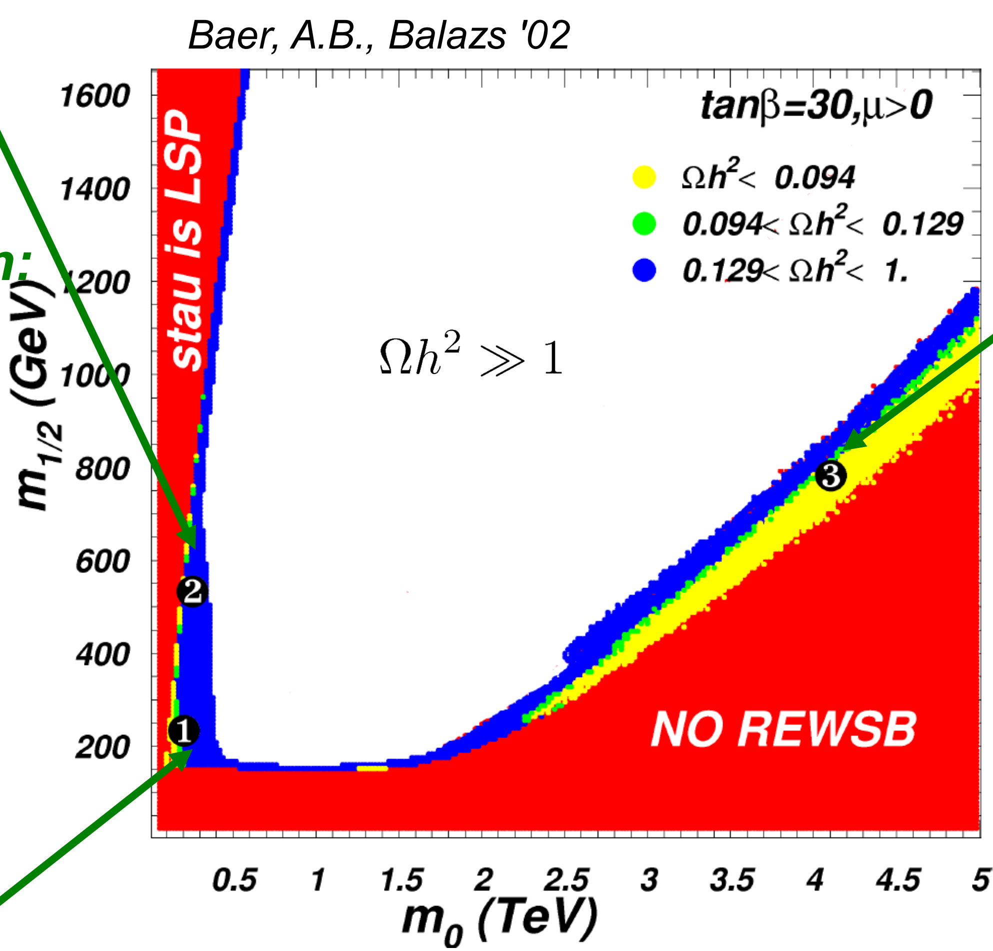
Neutralino relic density in mSUGRA

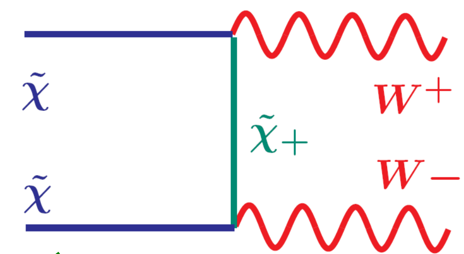
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$



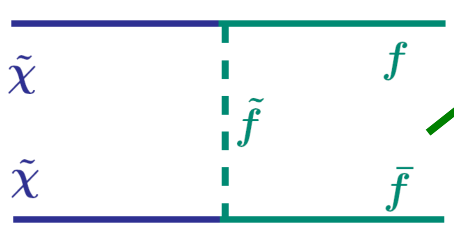
2. stau coannihilation:
degenerate χ and stau





3. focus point:
mixed neutralino, low μ, importance of higgsino-wino component

$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$



1. bulk region: ***light sfermions***

Neutralino relic density in mSUGRA

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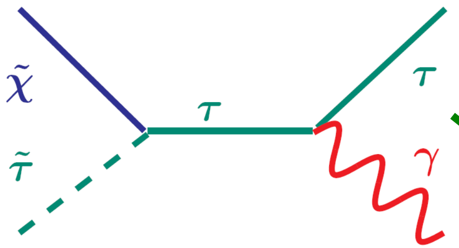

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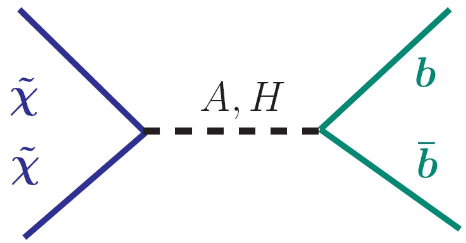
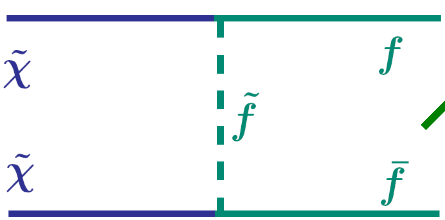
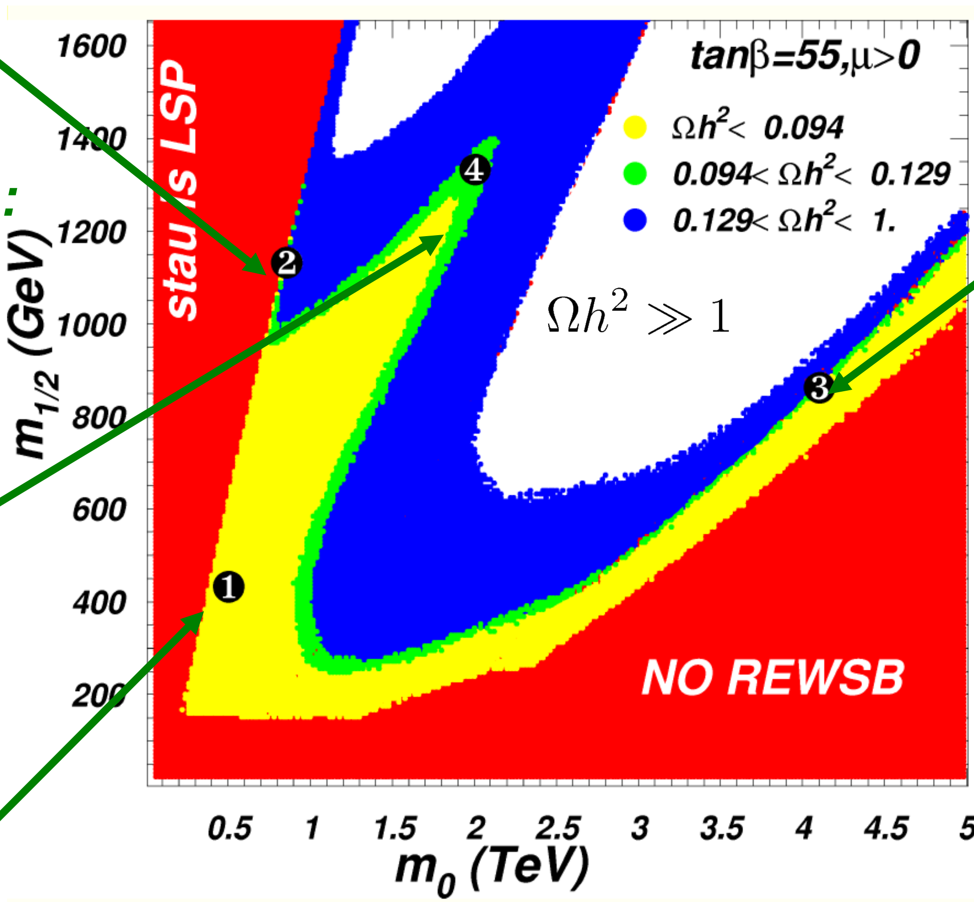


4. funnel: (large $\tan\beta$)
annihilation via A, H



Baer, A.B., Balazs '02



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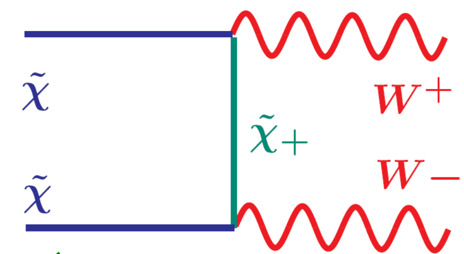


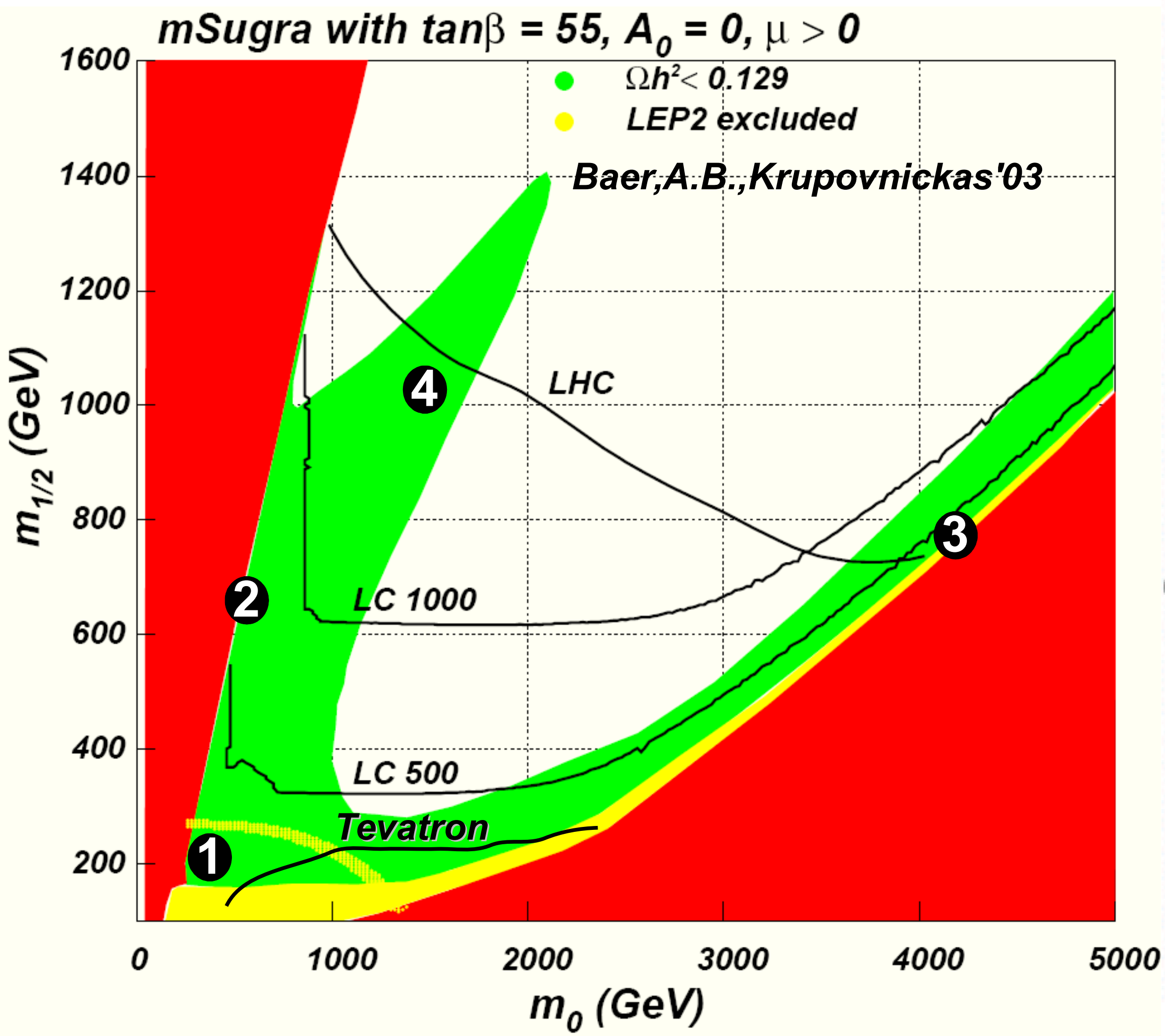
3. focus point:
mixed neutralino, low μ, importance of higgsino-wino component

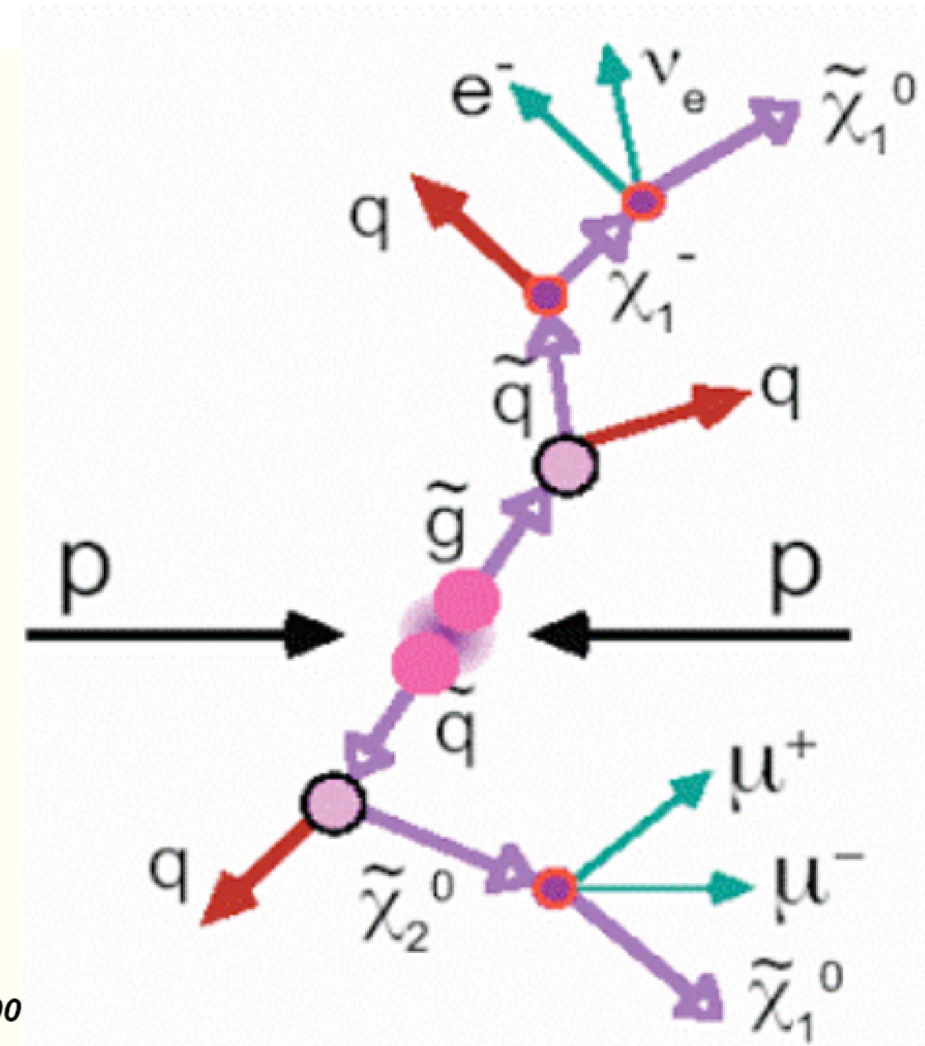
$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$

additional regions:
Z/h annihilation
stop coannihilation

Collider signatures in DM allowed regions

- DM allowed regions are difficult for the observation at the colliders: stau(stop) co-annihilation , FP region: small visible energy release





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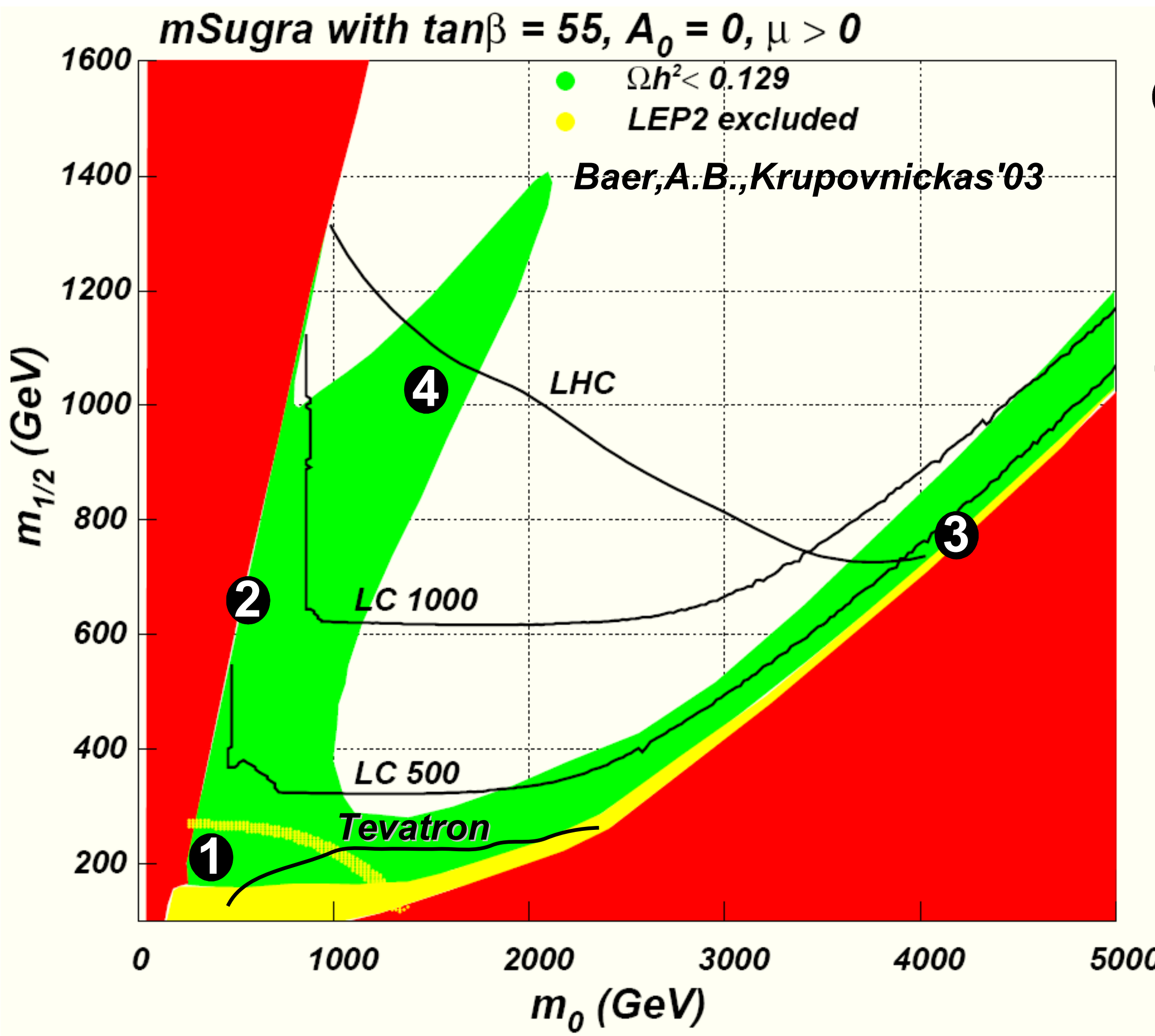
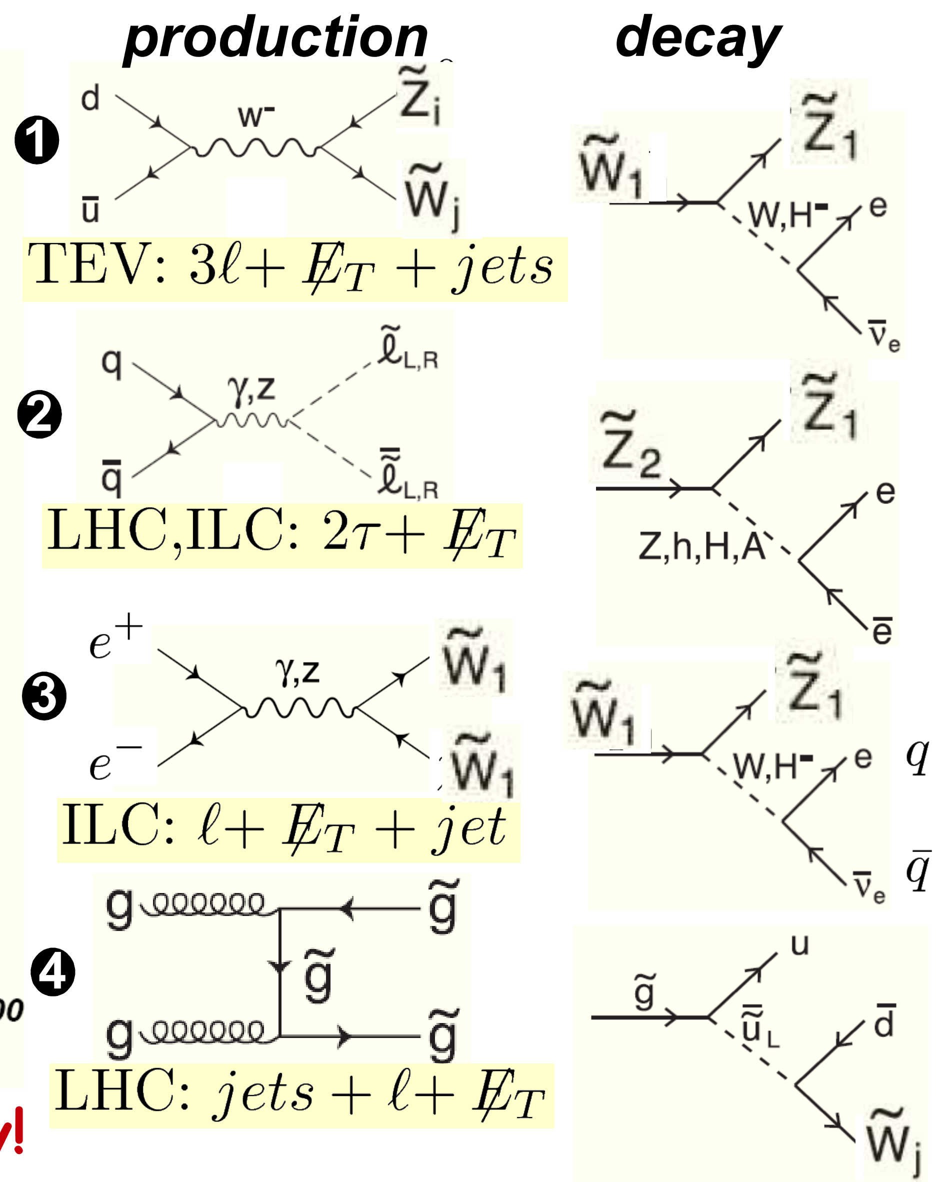
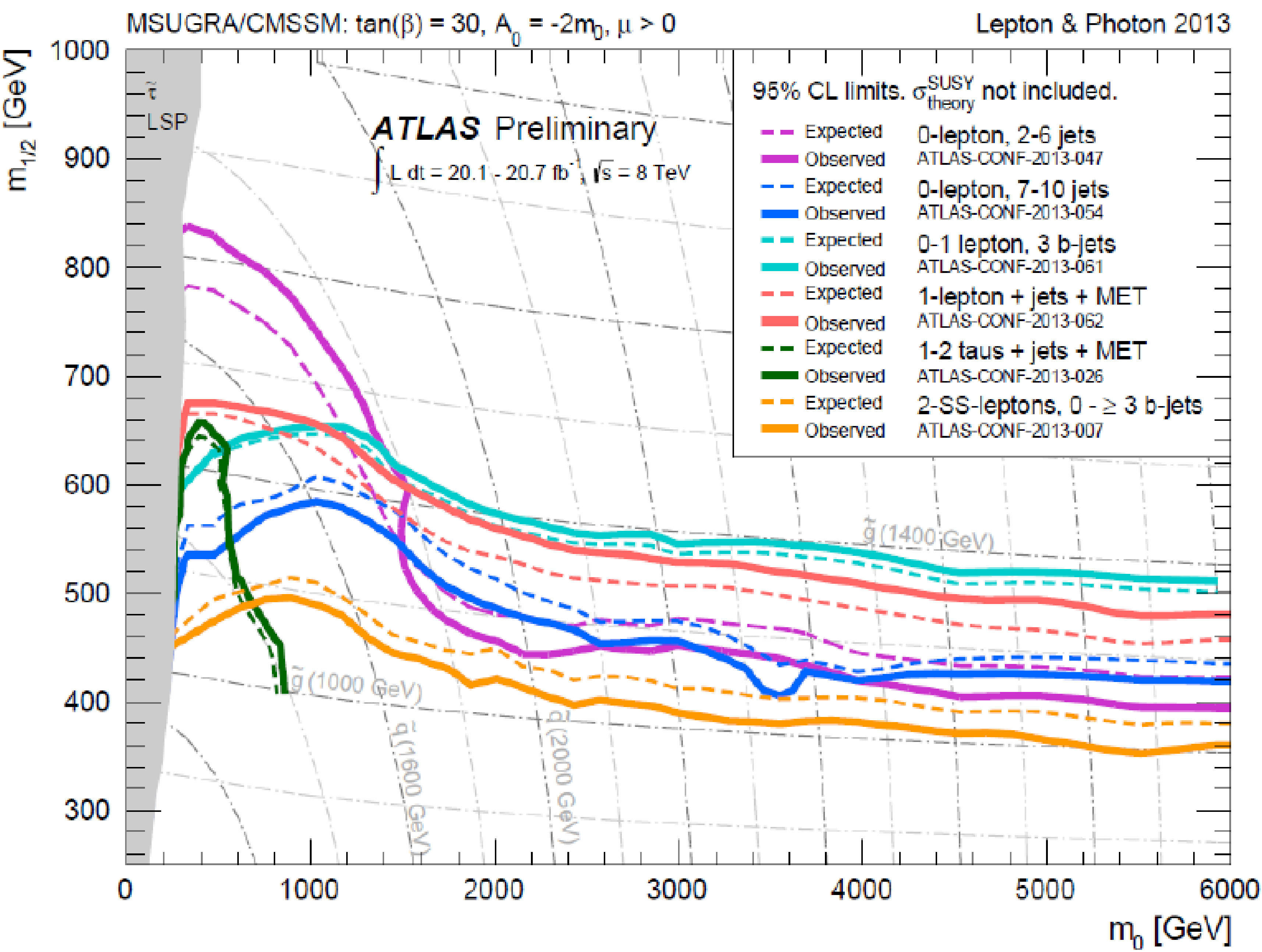


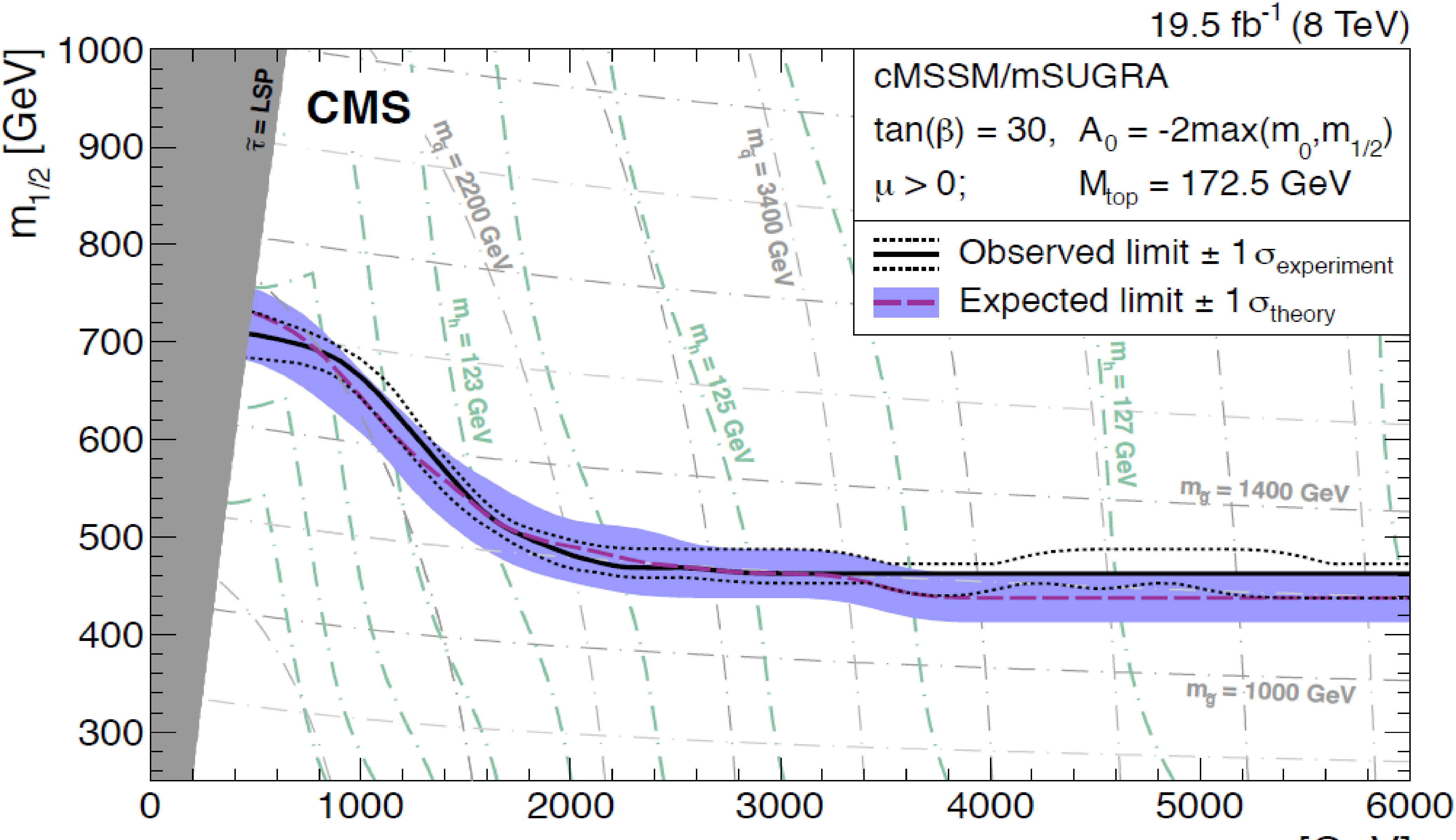


LHC and ILC are highly complementary!

Limits from LHC8 for mSUGRA scenario

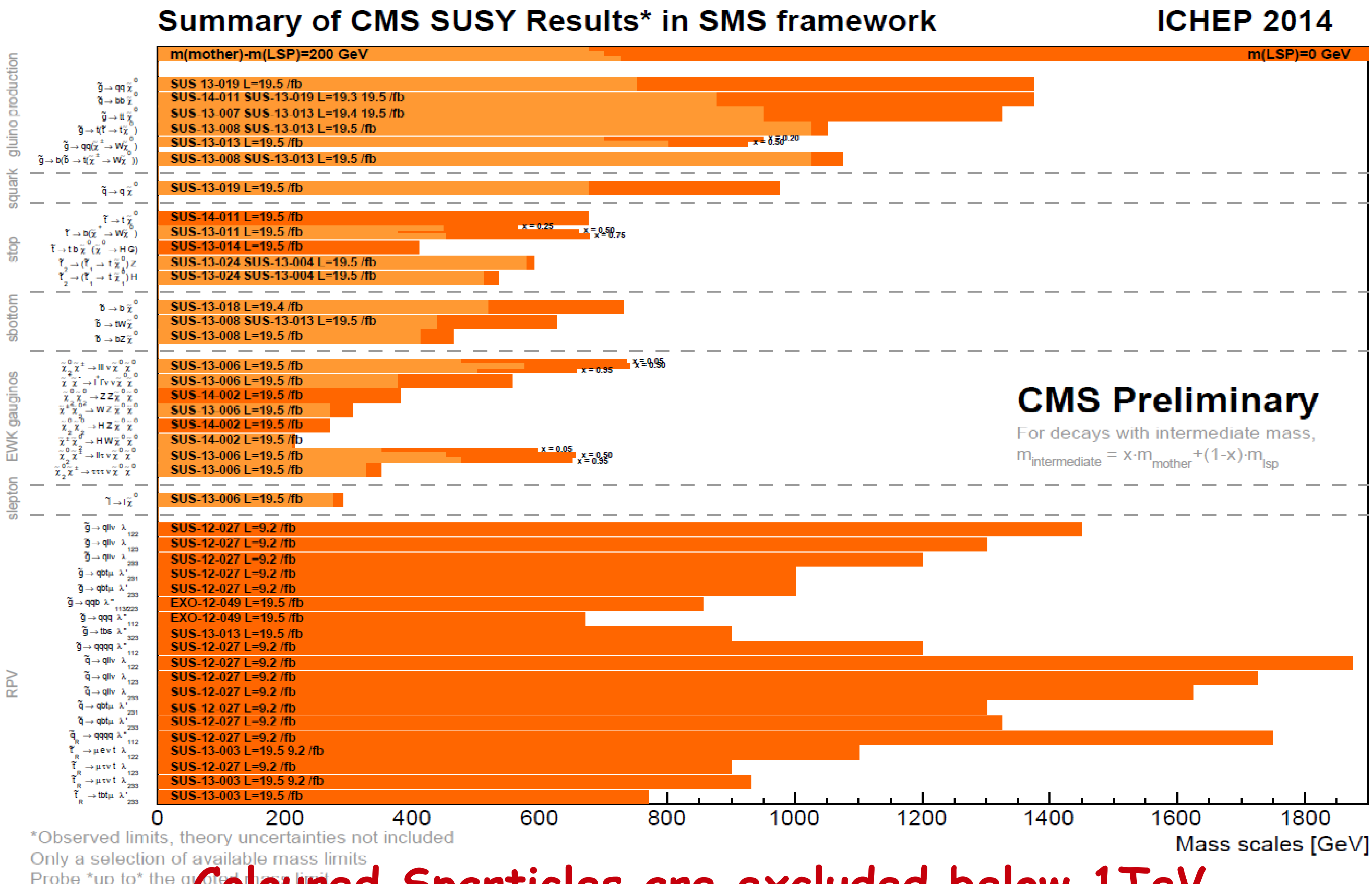


Limits from LHC8 for mSUGRA scenario



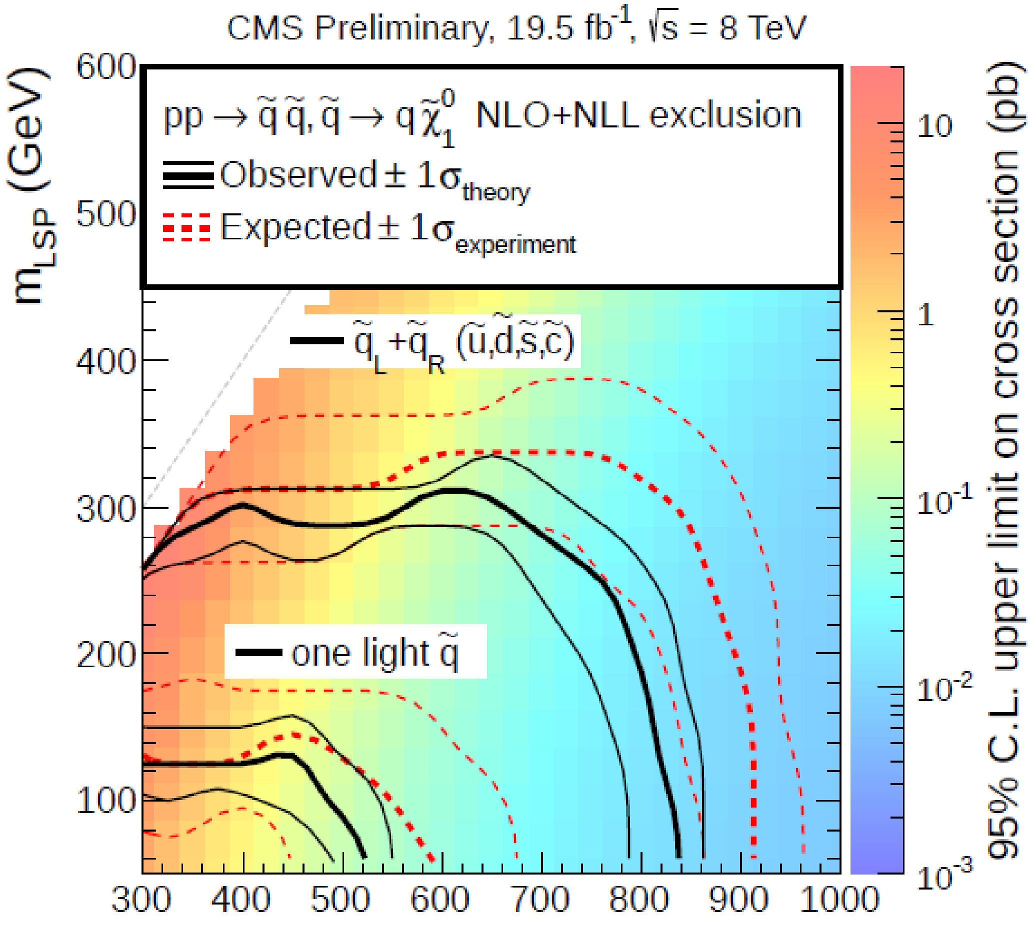
CMS-SUS-13-019

No SUSY hint from the experimental searches ...

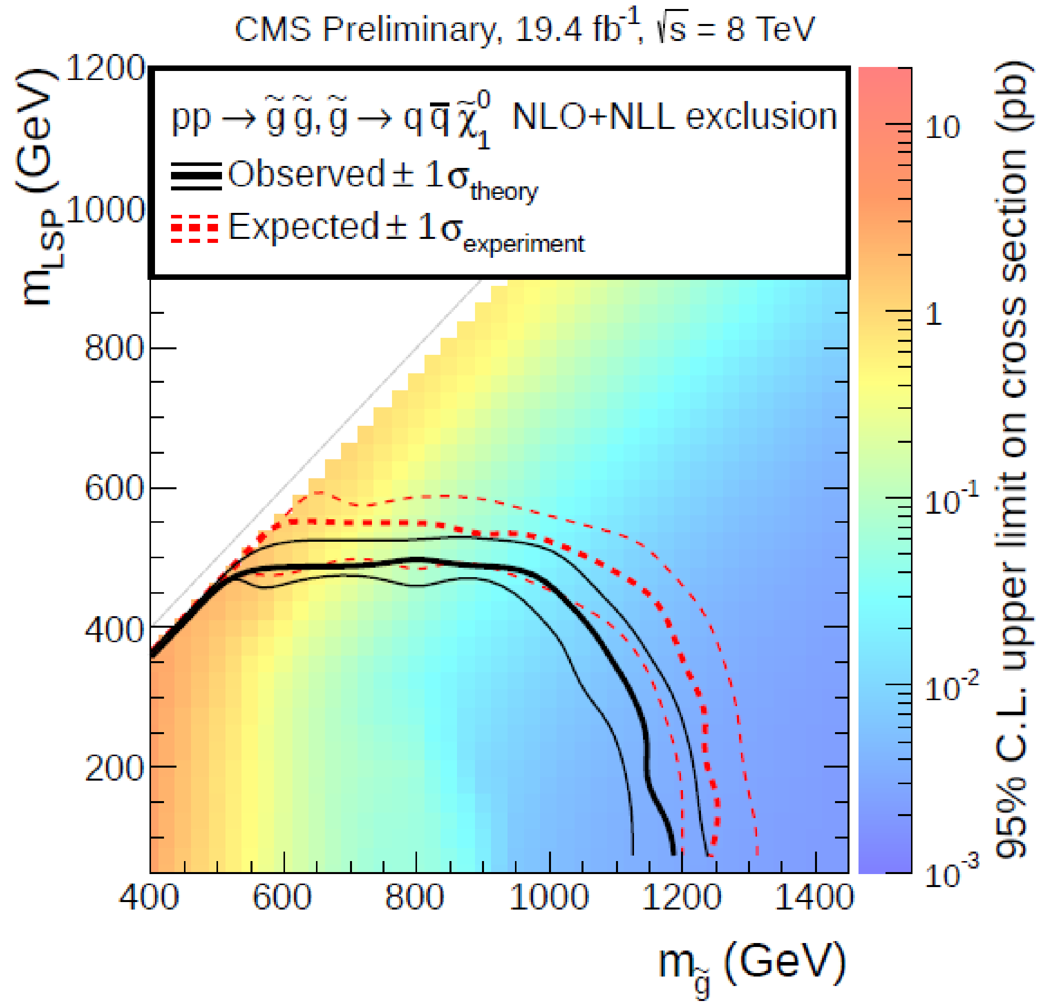


Coloured Sparticles are excluded below 1TeV if their mass gap with LSP is large enough

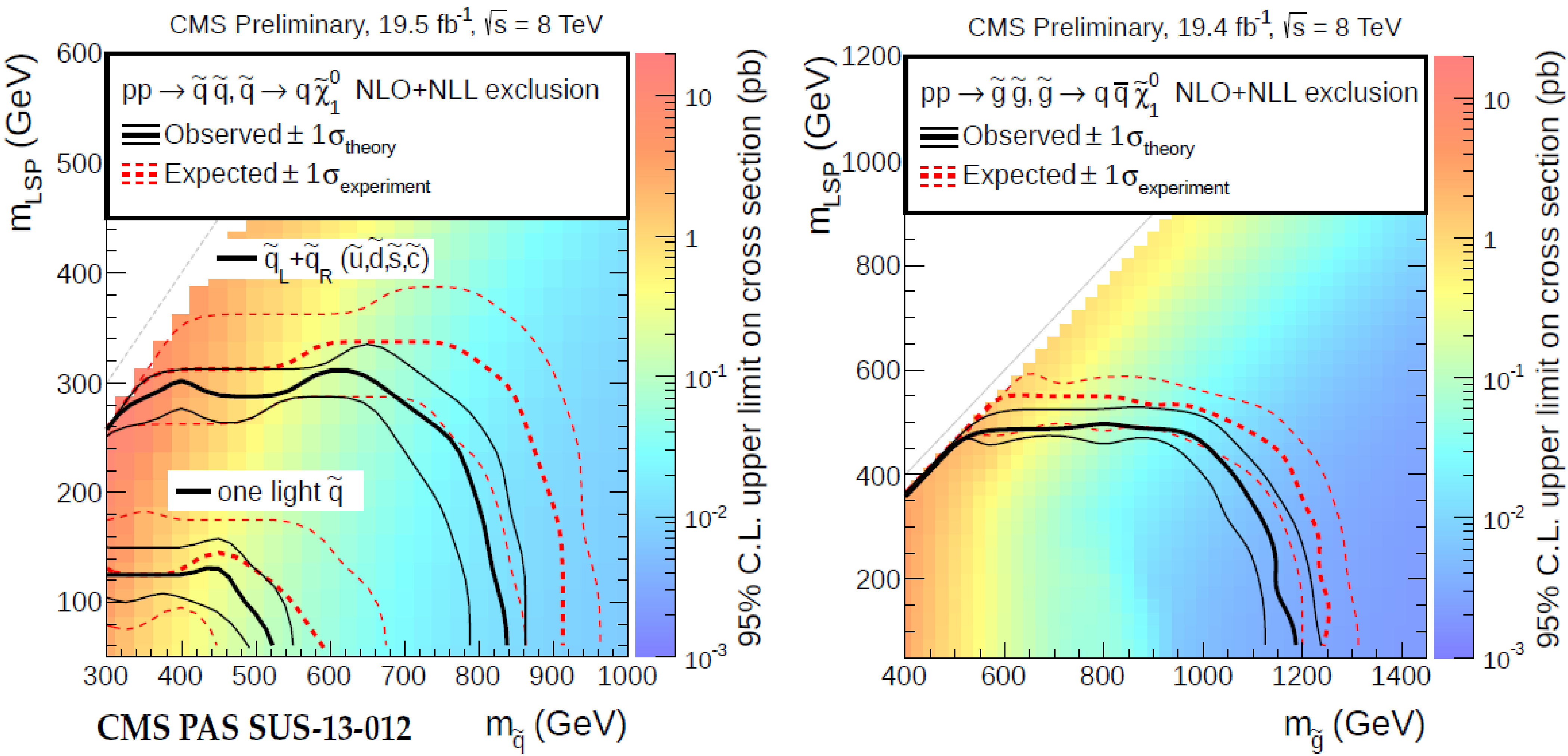
What is about DM mass?



CMS PAS SUS-13-012

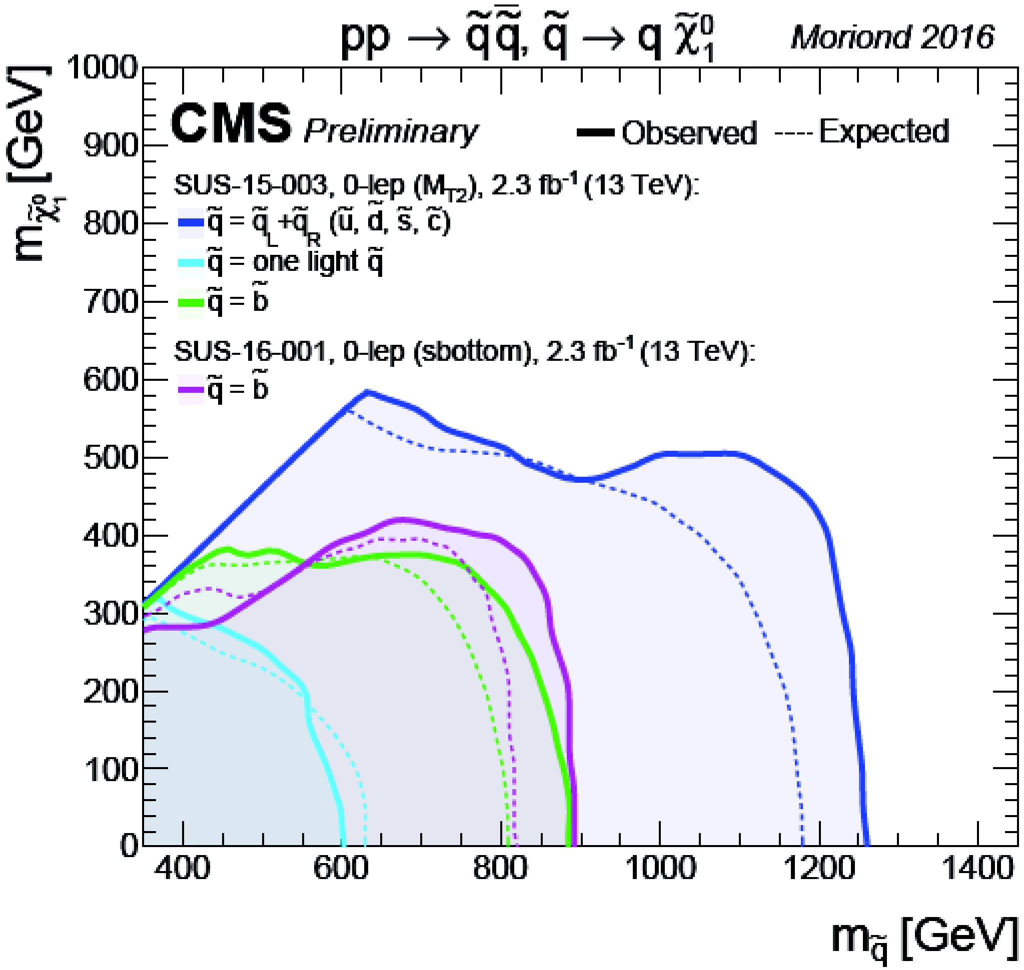


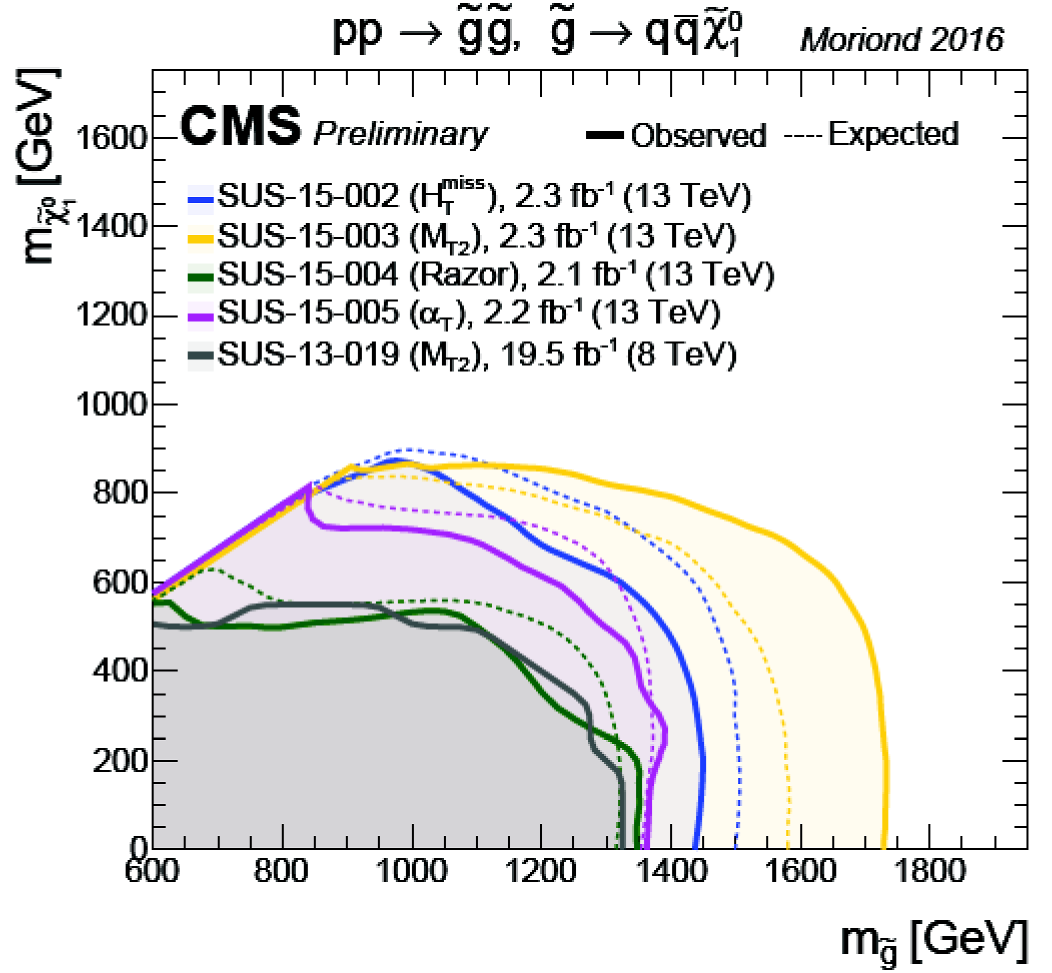
What is about DM mass?



There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.2 TeV

What is about DM mass?





There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.7 TeV

Complementarity of DM searches

Correct relic density → Efficient annihilation

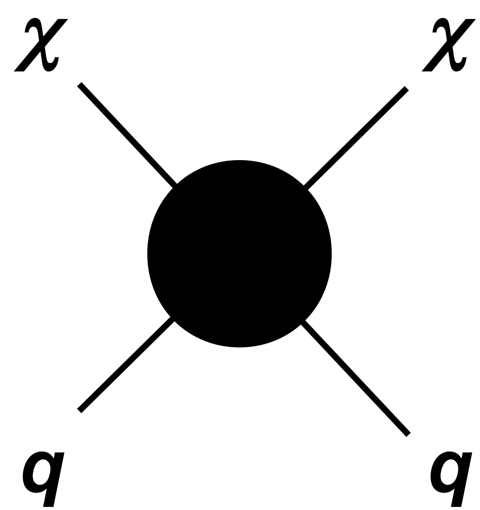
DM indirect detection:

signatures from neutralino annihilation in halo, core of the Earth and Sun

photons,
anti-protons, positrons,
neutrinos

Neutrino telescopes:
Amanda,
Icecube,
Antares

Efficient annihilation now
(Indirect detection)



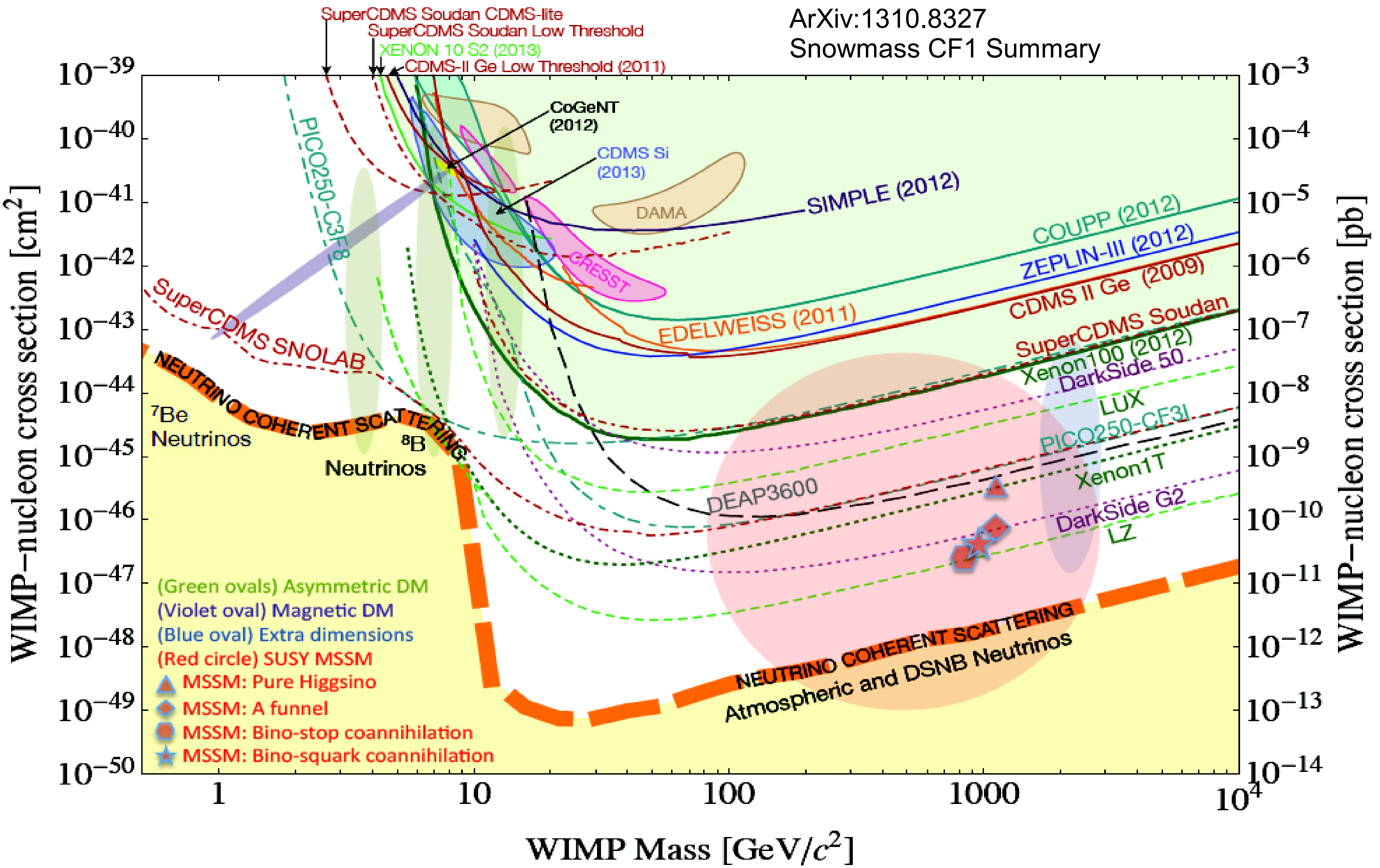
Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

DM direct detection: neutralino scattering off nuclei

Stage 1: CDMS1(2), Edelweiss, Zeplin(2)
Stage 2: LUX, XENON 100, ...
Stage 3: XENON 1 ton, WARP

Summary of DM search potential



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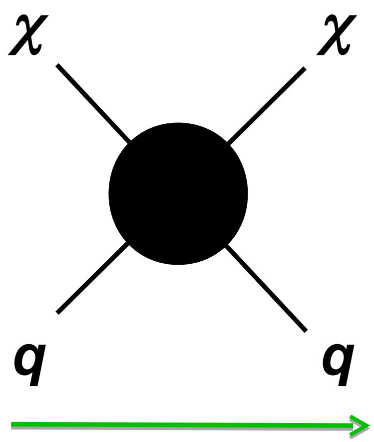
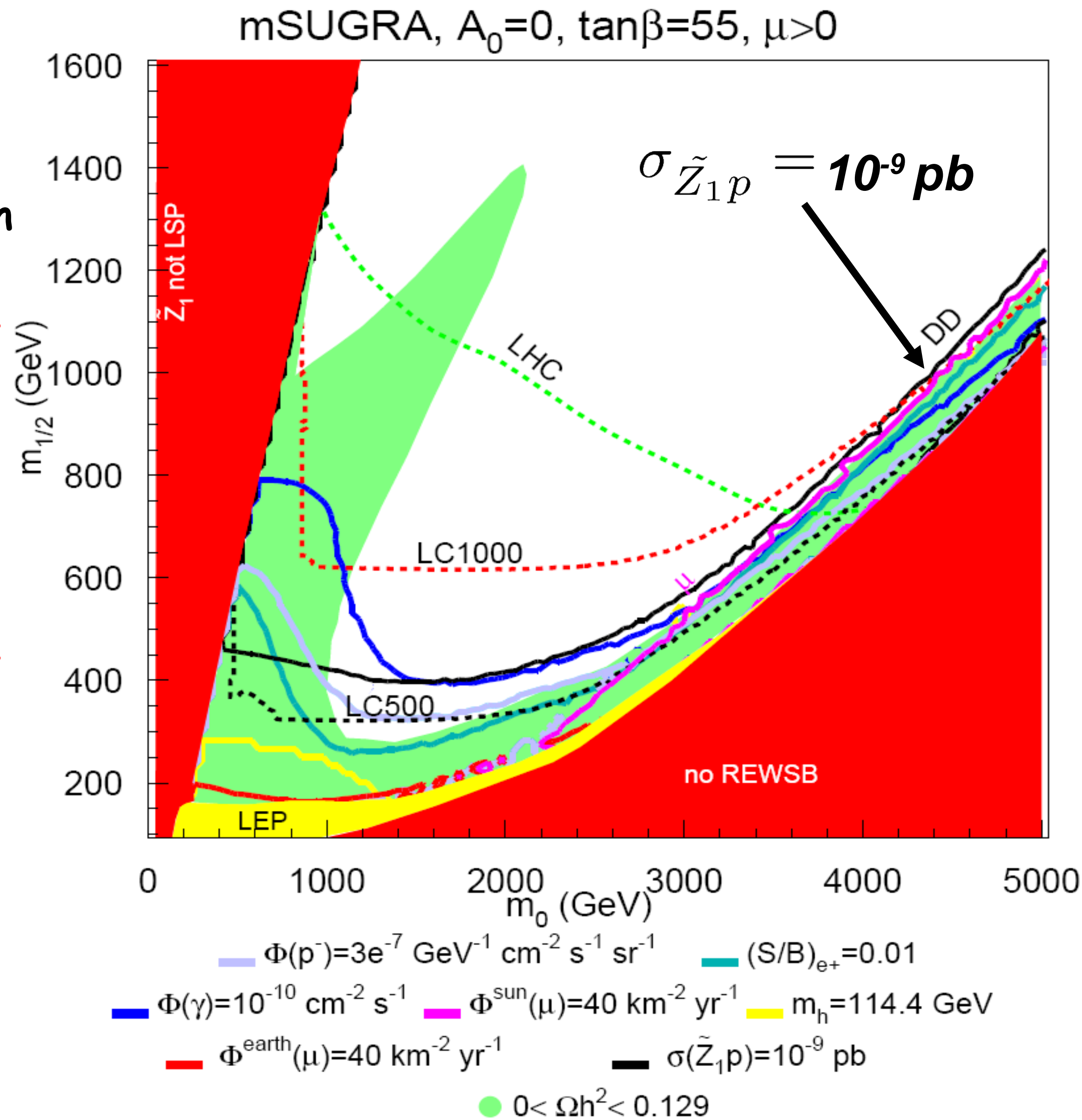
Efficient annihilation now (Indirect detection)



Efficient production now (Particle colliders)

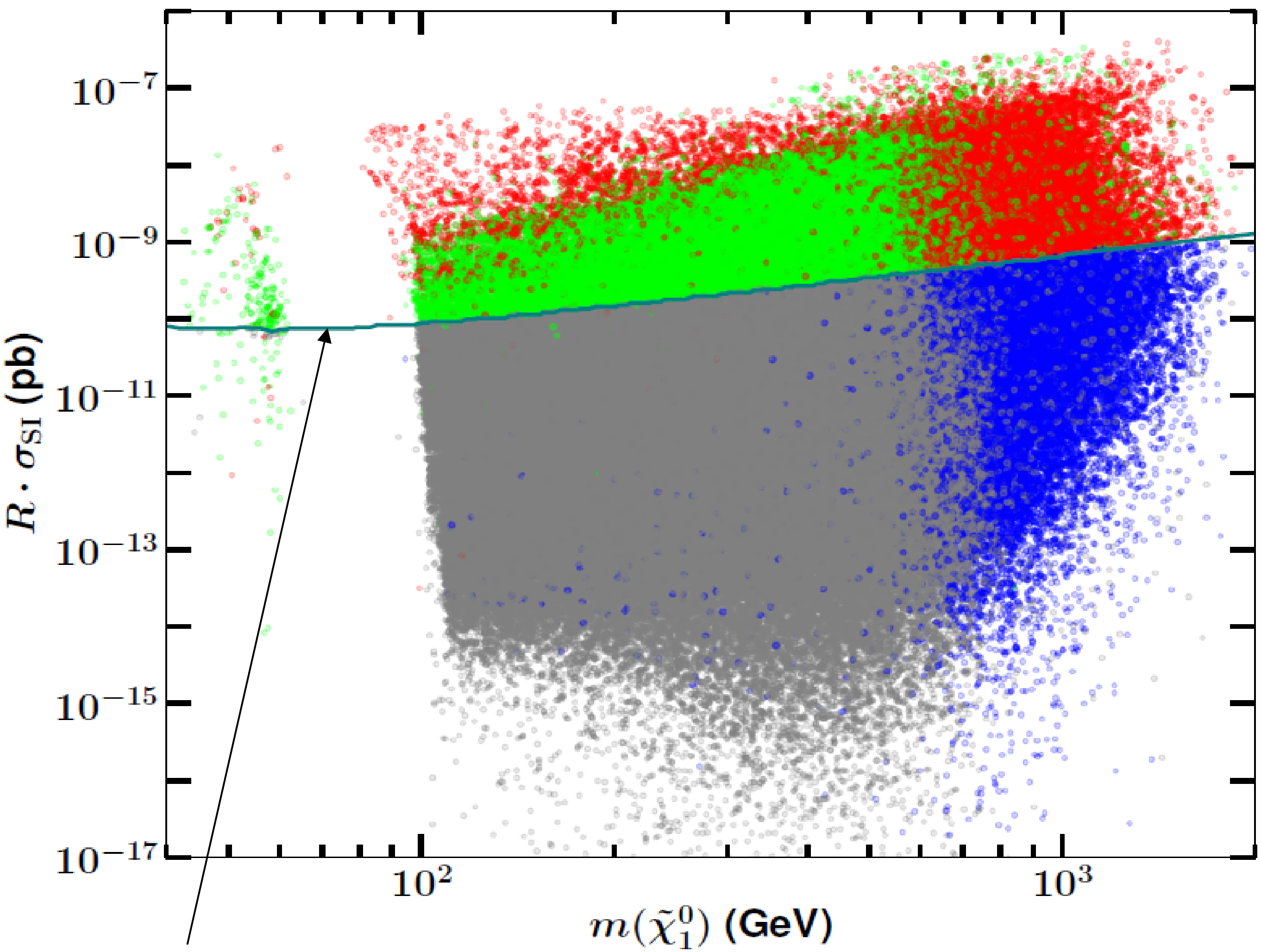
Efficient scattering now (Direct detection)

Baer, A.B., Krupovnikas, O'Farrill '04



pMSSM combined results

ArXiv:1305.6921: Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett



XENON 1T

dark matter can be discovered

- ***in DD experiments***
- ***in ID experiments***
- ***in both, DD and ID***
- ***may be discovered at the upgraded LHC, but escape detection in future DD or ID detection experiments***

The EW measure of Fine Tuning

$$\mathcal{L}_{\mathrm{MSSM}} = \mu \tilde{H}_u \tilde{H}_d + \text{h.c.} + (m_{H_u}^2 + |\mu|^2)\ |H_u|^2 + (m_{H_d}^2 + |\mu|^2)\ |H_d|^2 + \ldots$$

Low EW FT ↔ no large/unnatural cancellations in deriving m_Z from the weak scale scalar potential:

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

using fine-tuning definition which became standard

Ellis, Enqvist, Nanopoulos, Zwirner '86; Barbieri, Giudice '88

$$\Delta_{FT} = max[c_i], \qquad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$$

one finds $\Delta_{FT} \simeq \Delta_{EW}$ which requires as well as

$$\boxed{\begin{array}{l} |\mu^2| \simeq M_Z^2 \\ |m_{H_u}^2| \simeq M_Z^2 \end{array}}$$

The last one is GUT model-dependent, so we consider the value $|\mu^2|$ as a measure of the minimal fine-tuning

“Compressed Higgsino” Scenario (CHS)

chargino-neutralino mass matrices

in $(\tilde{W}^-, \tilde{H}^-)$ basis

$$\begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix}$$

charginos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

neutralinos

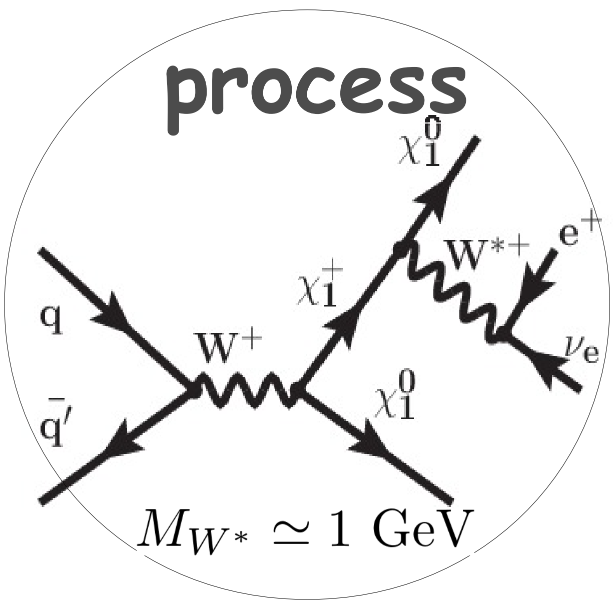
M_2 real, $\quad M_1 = |M_1| e^{-\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$

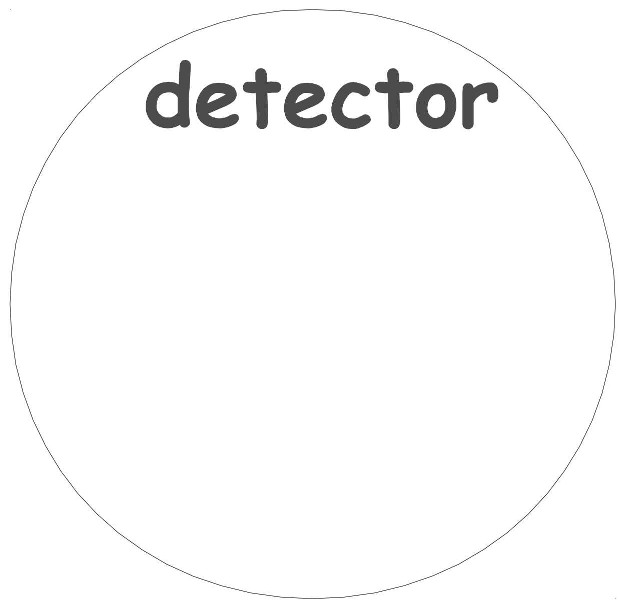
- Case of $\mu \ll M1, M2$: $\chi^0_{1,2}$ and $\chi^\pm$ become quasi-degenerate and acquire large higgsino component. This provides a naturally low DM relic density via gaugino annihilation and co-annihilation processes into SM V's and H
- This is the case of relatively light higgsinos-electroweakinos compared to the other SUSY particles.
- This scenario is not just motivated by its simplicity, but also by the lack of evidence for SUSY to date

CHS Mass Spectrum and Challenge for the LHC

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature

- The only way to probe CHS is a mono-jet signature
  ["Where the Sidewalk Ends? ..." Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, *e.g.*
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14





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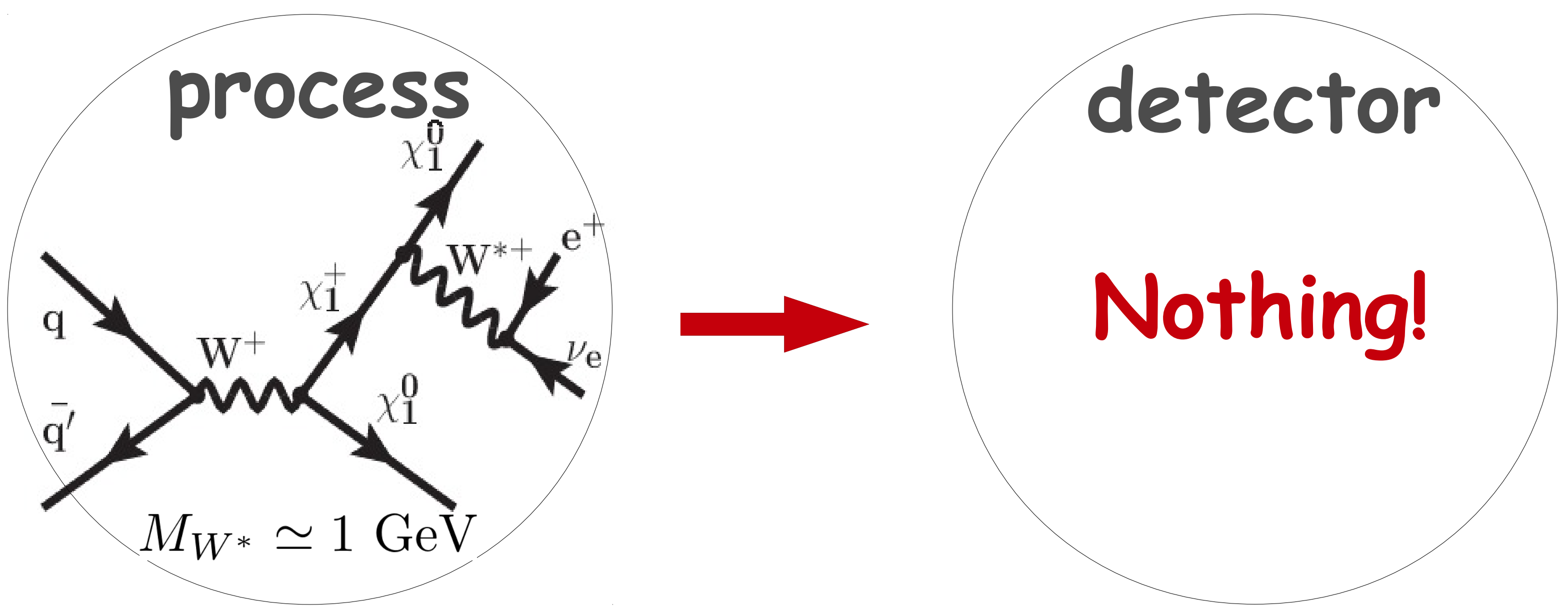

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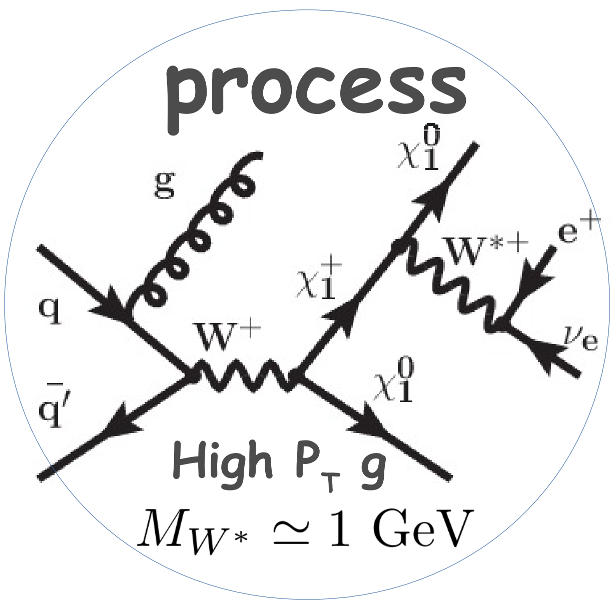

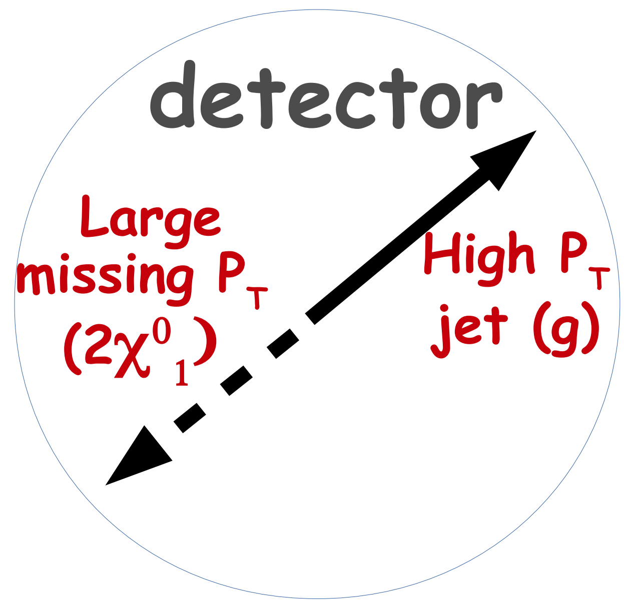

CHS Mass Spectrum and Challenge for the LHC

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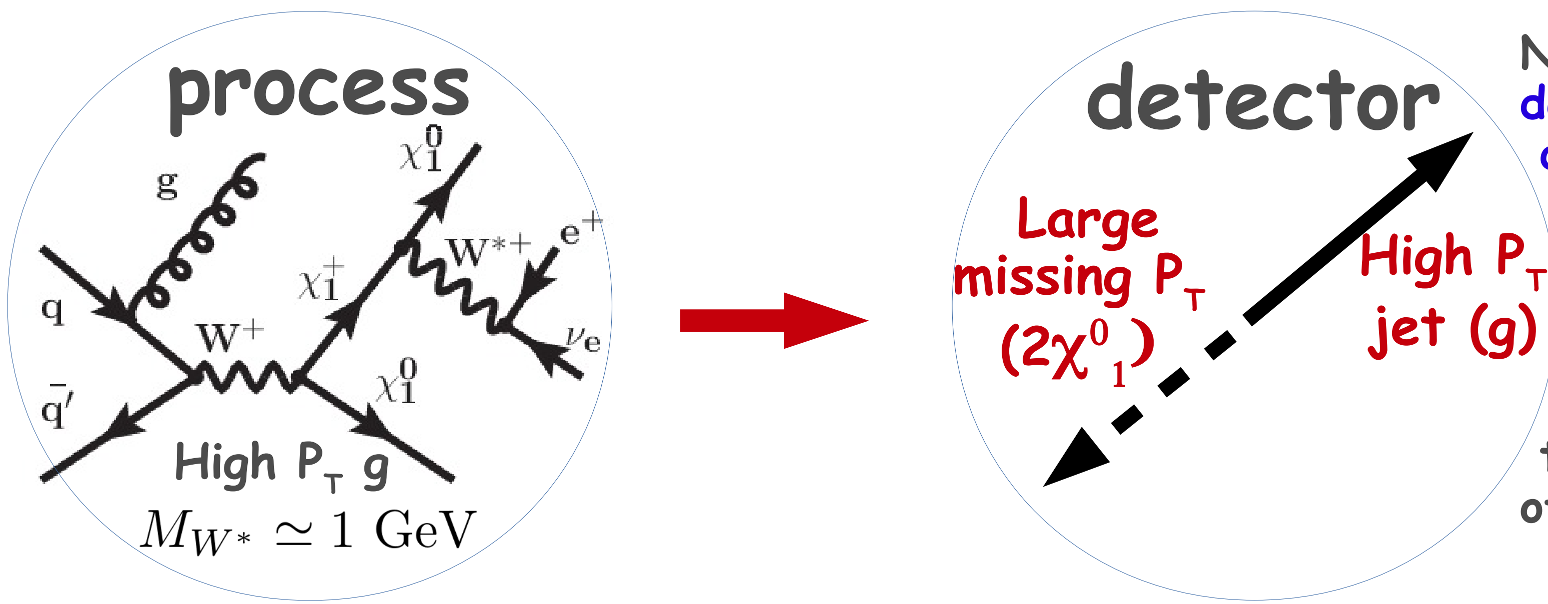


Note that **W* decay products do not get large boost** – it is proportional to the mass of W* which is much smaller than the mass of the LSP

Analysis Setup

MSSM

- SPHENO for mass spectrum, cross checked with ISAJET
- micrOMEGAs for DM relic density, DM DD and ID
- MadGraph for parton level simulations, cross checked with CalcHEP
- PYTHIA6 for hadronization and parton-showering
- Delphes3 for fast detector simulation
- CTEQ6L1 PDF

Main backgrounds for p_T jet + high MET signature

- Irreducible Z +jet → νν +jet (Zj)
- Reducible W +jet → ℓν + jet (Wj) when ℓ is missed

Spectrum and Decays in CHS

For $|\mu| \ll |M1|, |M2|$ one has

$$m_{\tilde\chi^0_{1,2}} \simeq \mp\left[|\mu| \mp \frac{m_Z^2}{2}(1\pm s_{2\beta})\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)\right]$$

$$m_{\tilde\chi_1^\pm} \simeq |\mu|\left(1+\frac{\alpha(m_Z)}{\pi}\left(2+\ln\frac{m_Z^2}{\mu^2}\right)\right) - s_{2\beta}\frac{m_W^2}{M_2}$$

$$\Delta m_o = m_{\tilde\chi^0_2} - m_{\tilde\chi^0_1} \simeq m_Z^2\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)$$

$$\Delta m_\pm = m_{\tilde\chi^\pm_1} - m_{\tilde\chi^0_1} \simeq \frac{\Delta m_0}{2} + \mu\frac{\alpha(m_Z)}{\pi}\left(2+\ln\frac{m_Z^2}{\mu^2}\right)$$

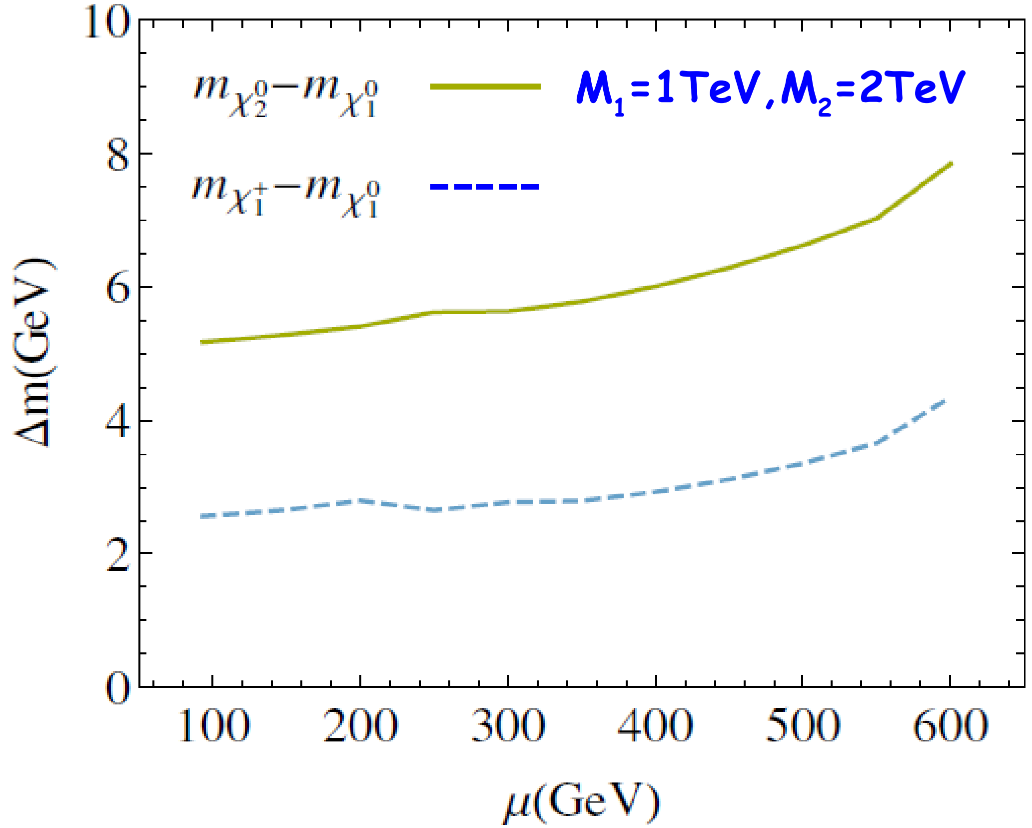
$$\boxed{\Gamma(\tilde\chi_1^\pm, \tilde\chi_2^0 \to f\, f'\, \tilde\chi_1^0) = \frac{C^4}{120\pi^3}\frac{\Delta m^5}{\Lambda^4}}$$

$$C^4 \simeq \frac{1}{4}\frac{g^4}{c_W^4}(s_w^2 - 1/2)^2$$

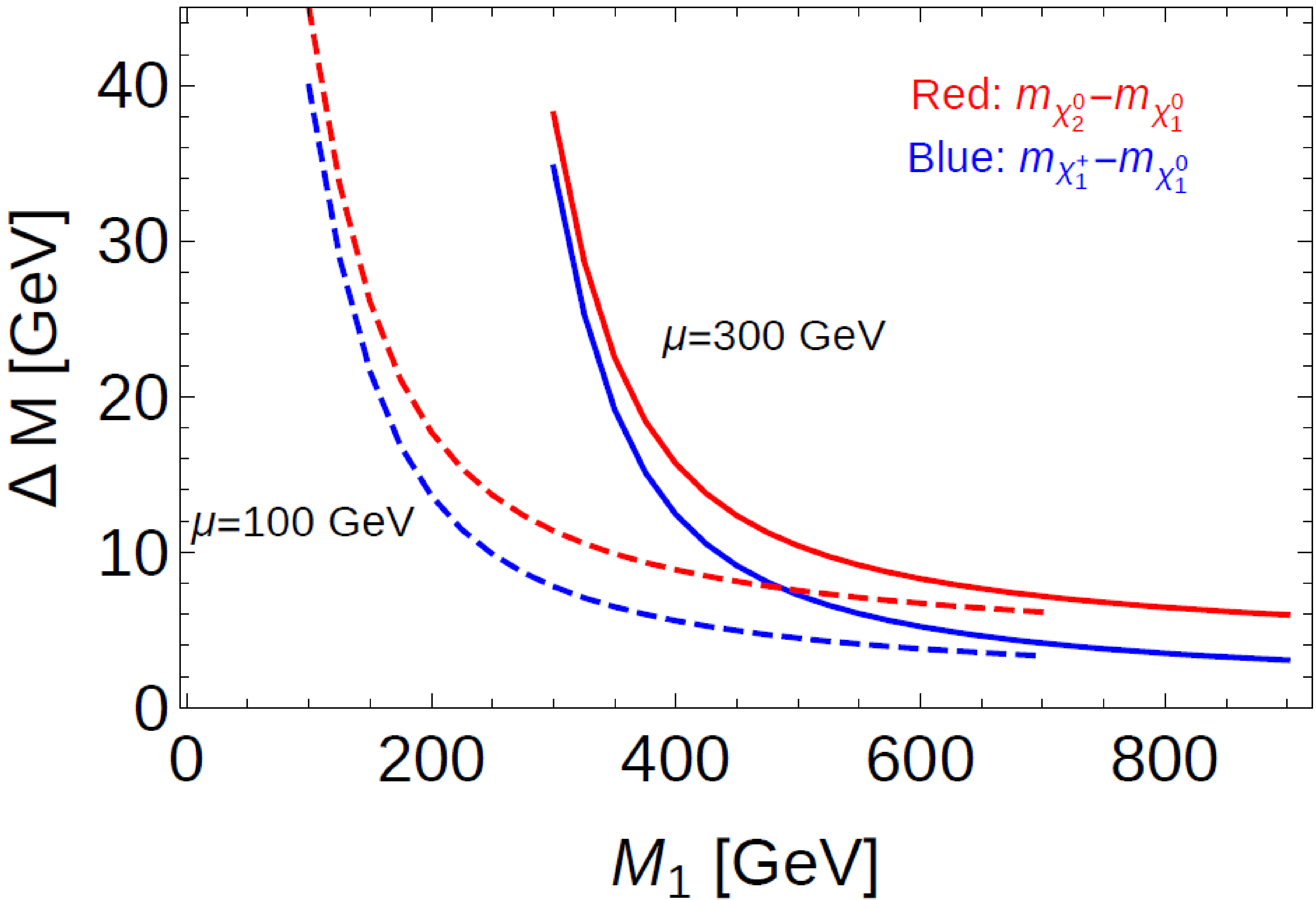
$$L = c\tau \simeq 0.01\text{ cm}\left(\frac{\Delta m}{1\text{ GeV}}\right)^{-5} \quad \tilde\chi_2^0 \to f\bar f\tilde\chi_1^0 \text{ (Z-exchange)}$$

$$L = c\tau \simeq 0.006\text{ cm}\left(\frac{\Delta m}{1\text{ GeV}}\right)^{-5} \quad \tilde\chi_1^\pm \to f f'\tilde\chi_1^0 \text{ (W-exchange)}$$

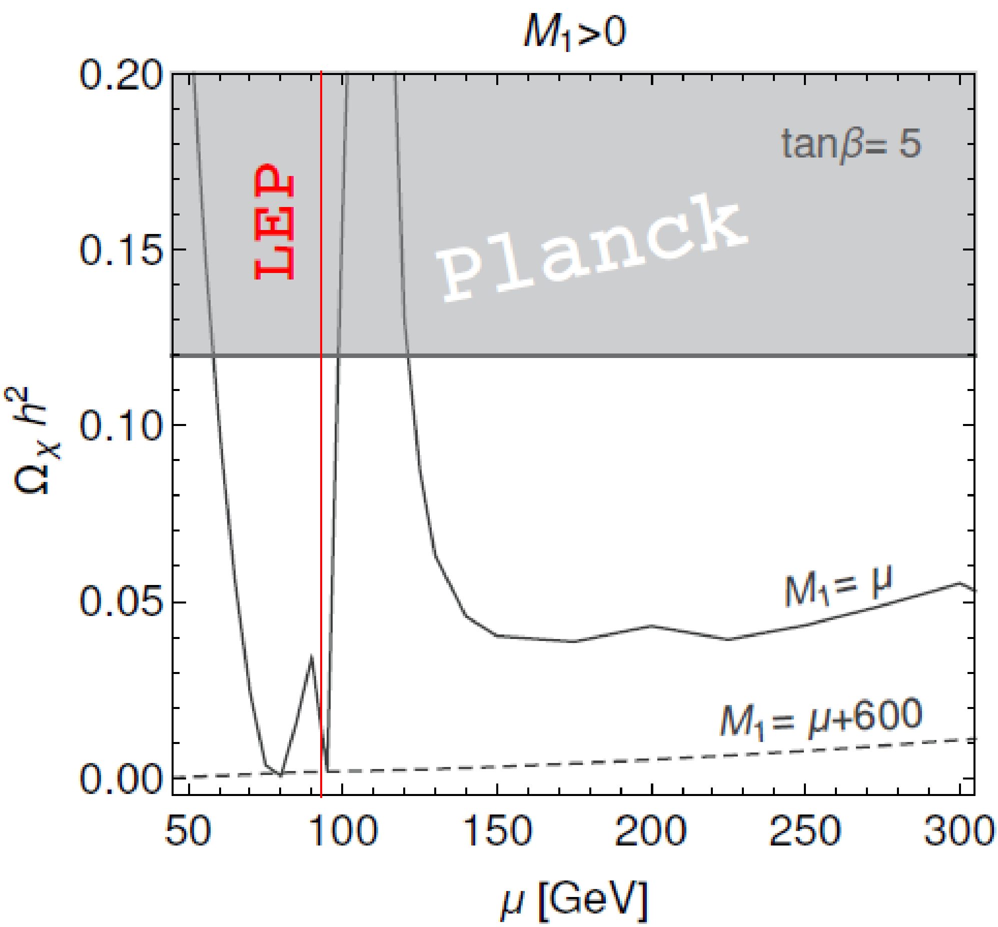
$\Delta m < 1$ GeV → displaced vertices ~0.1mm
$\Delta m < 0.1$ GeV → DM is collider stable

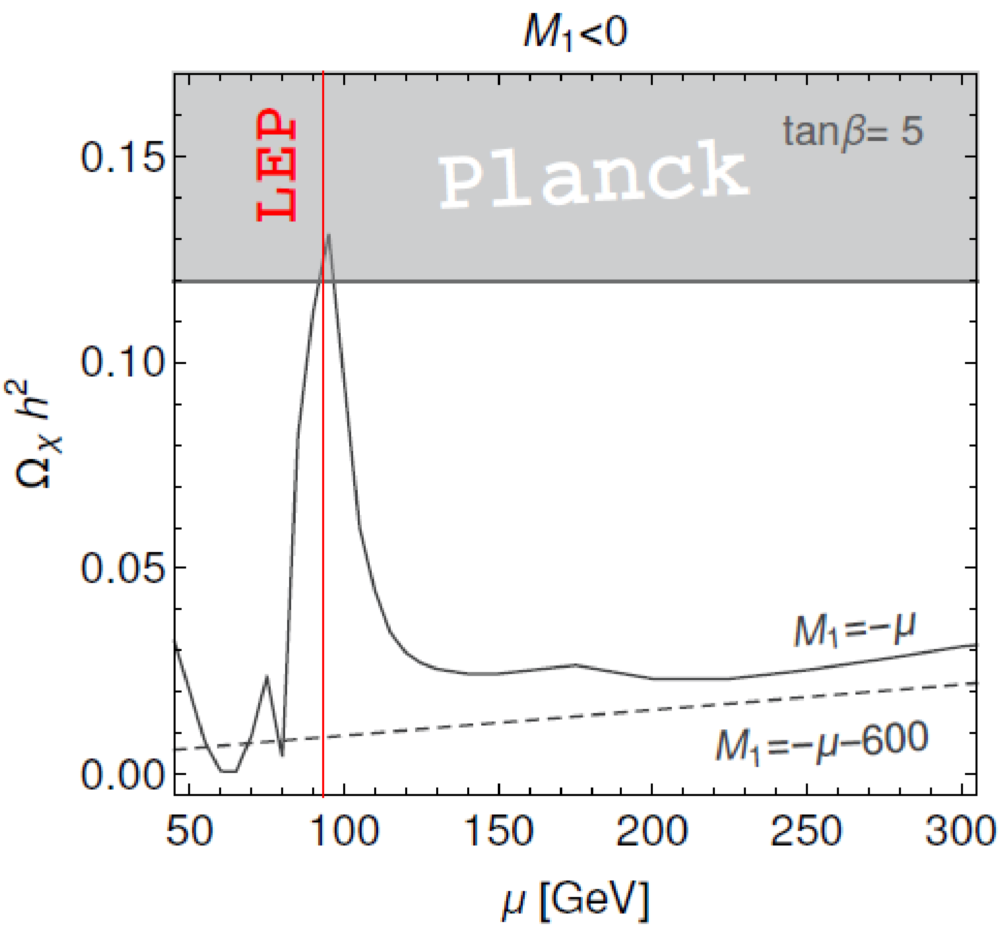


$\Delta M = m_{\chi\pm} - m_{\chi^0}$ VS M_1 plane



Dark Matter Relic Density





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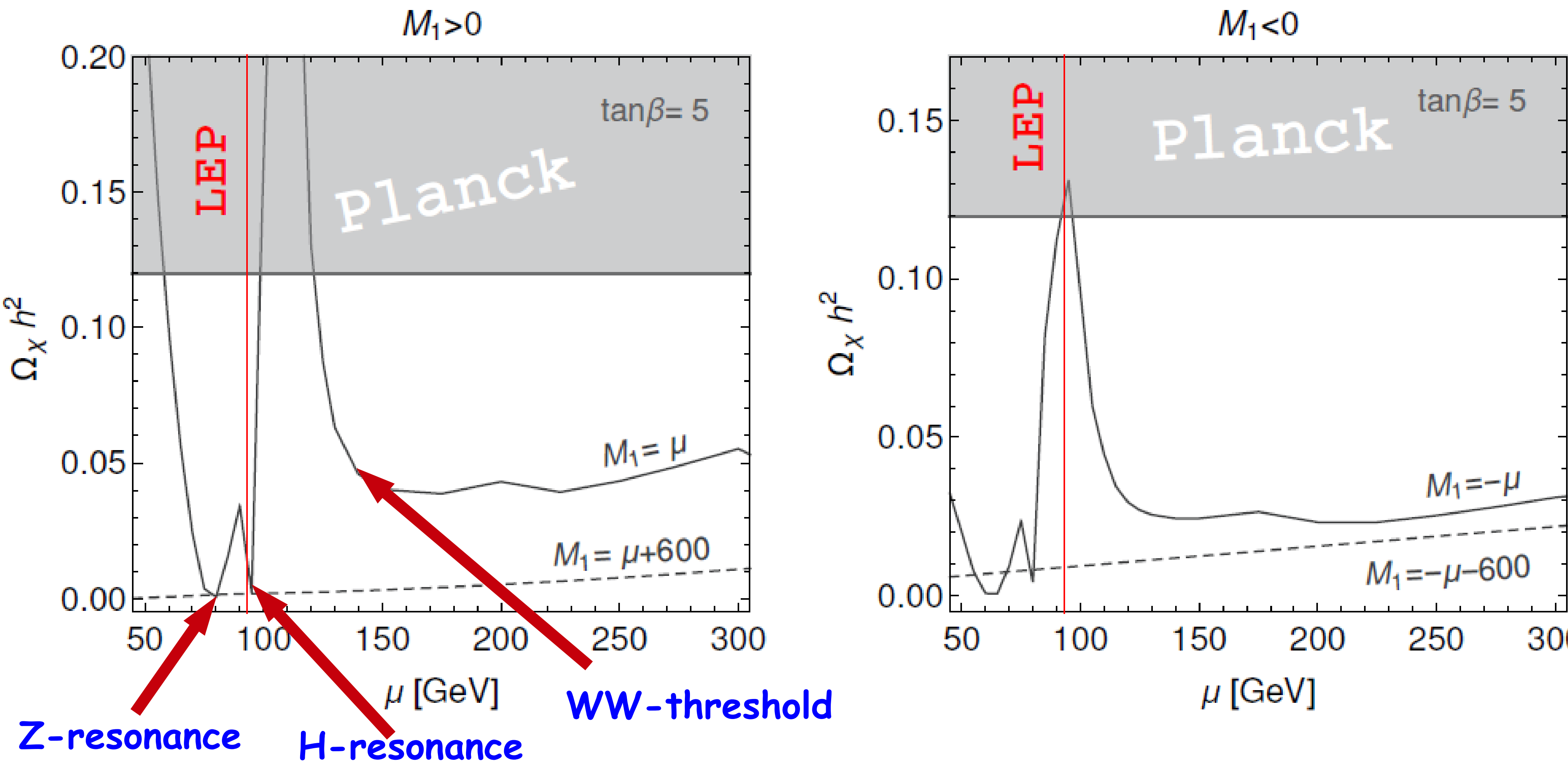
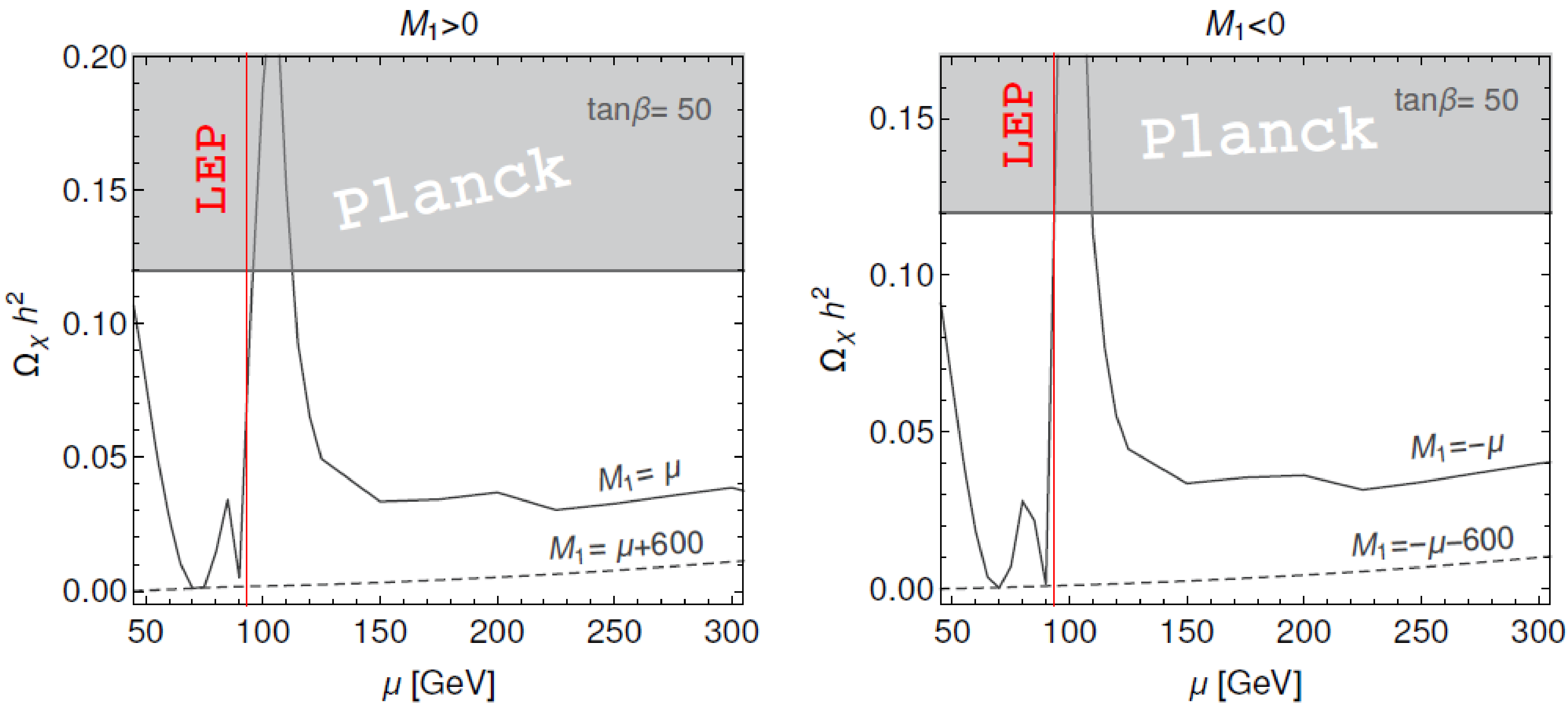


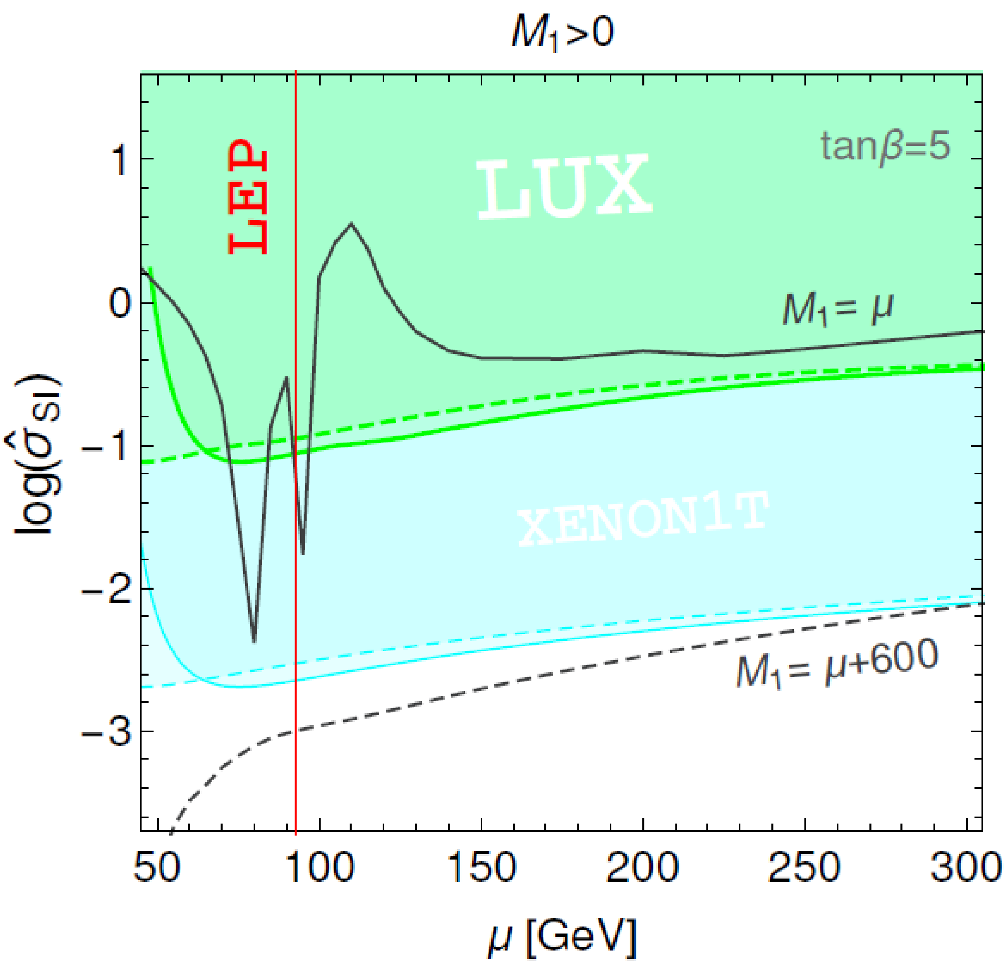
- **DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes**

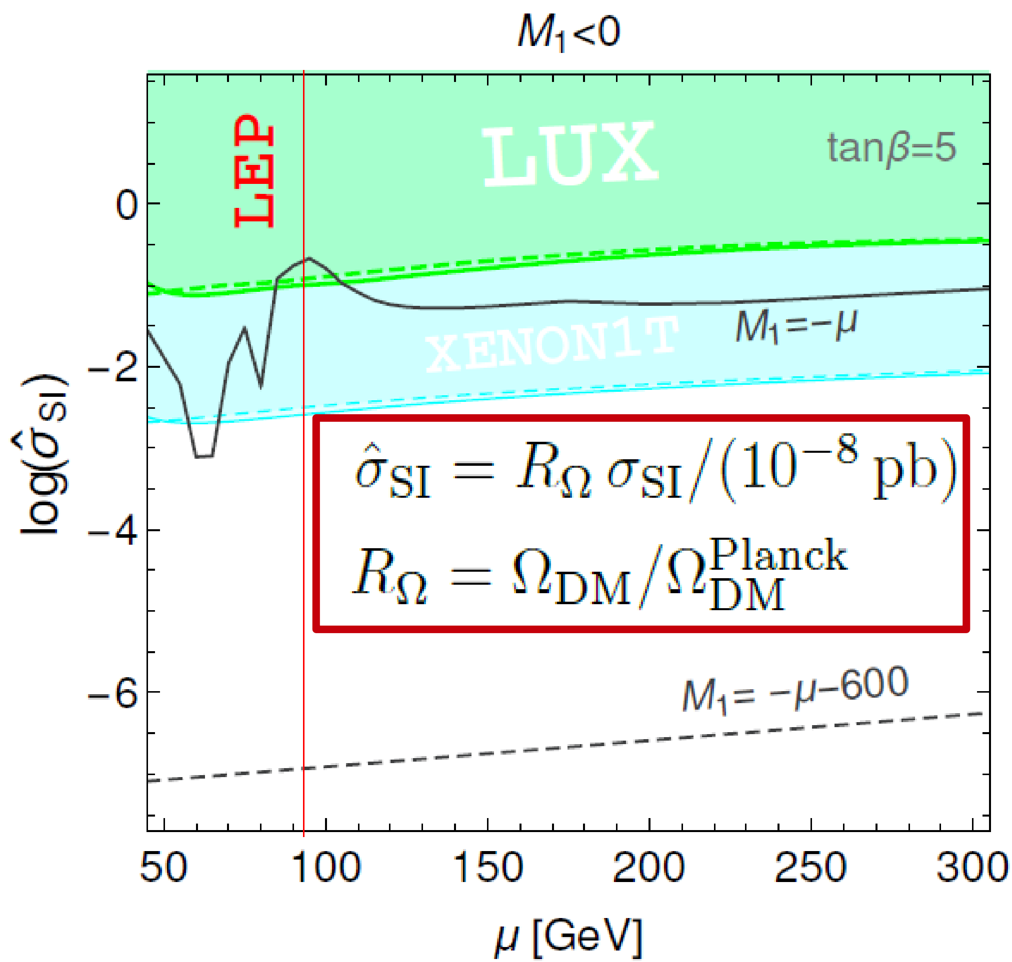
Dark Matter Relic Density



- **The pattern is independent of tanb**

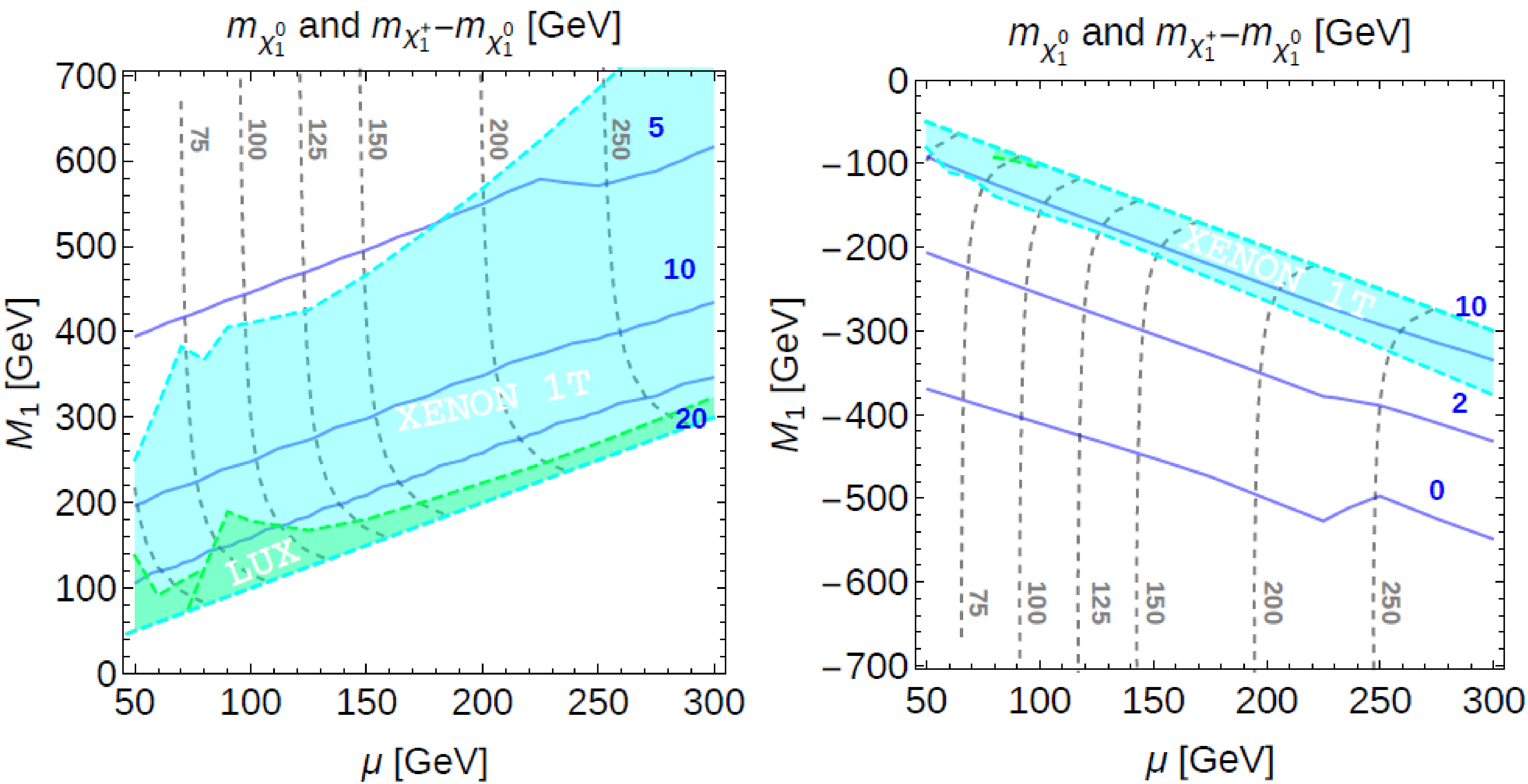
Direct Detection Prospects





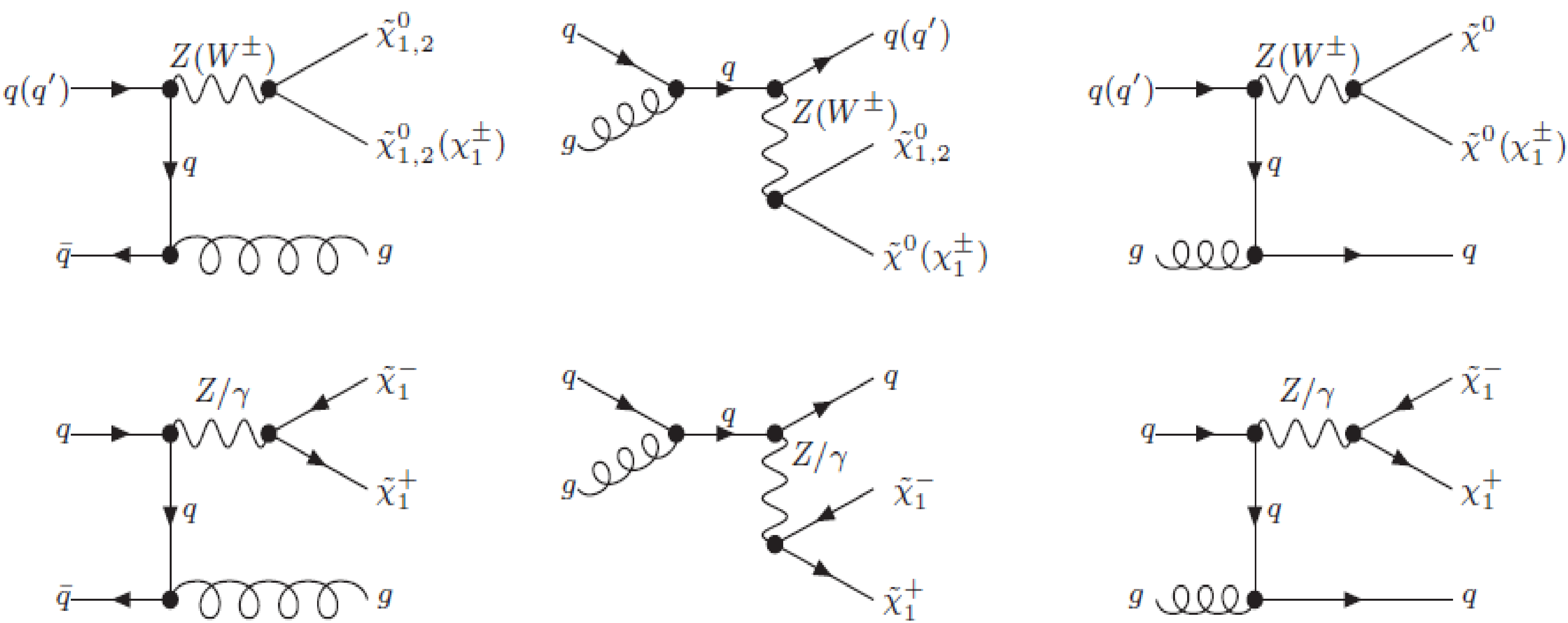
- **DD cross section rescaled with the relic density is low in the small ΔM region. Chance for the LHC?**

DD in M_1–μ plane



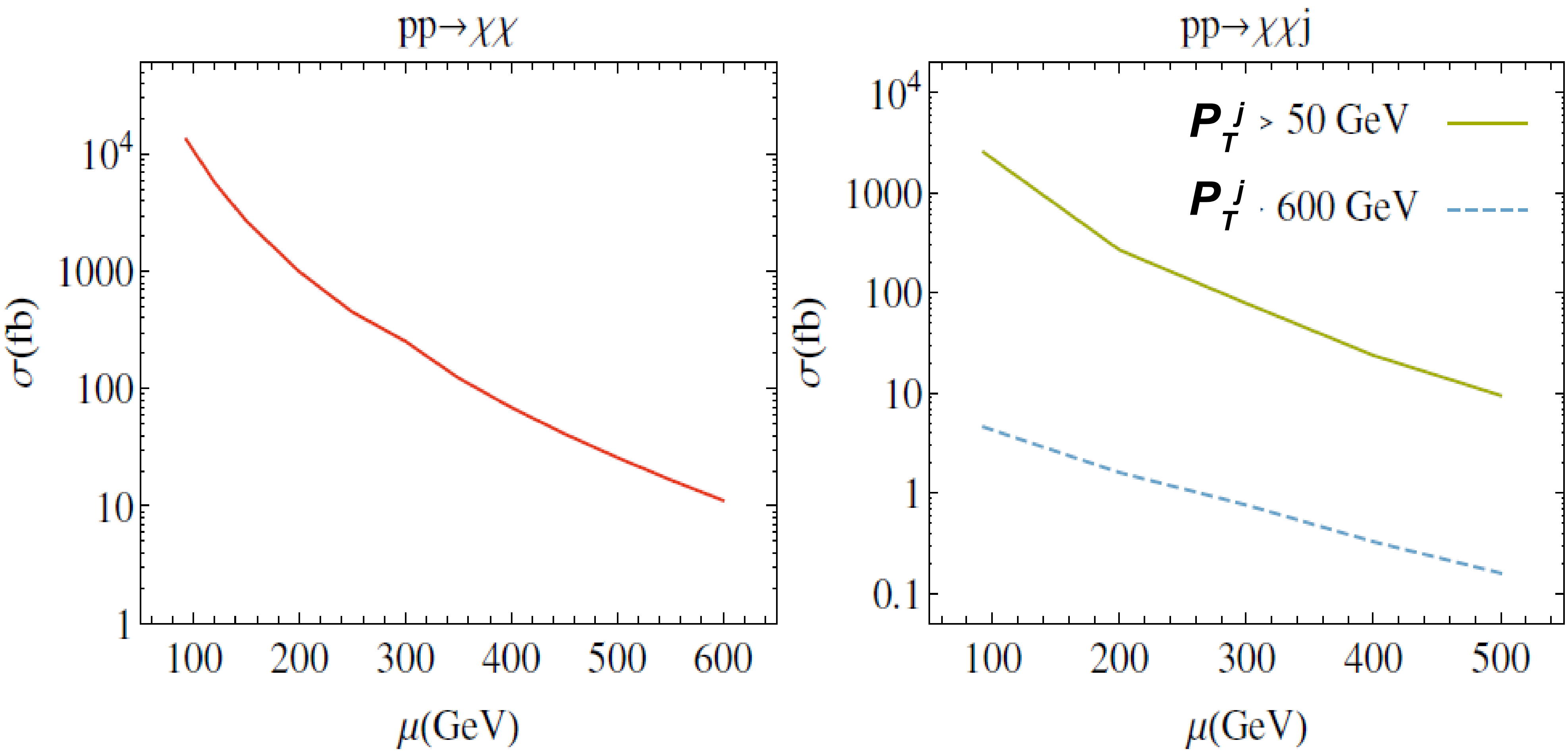
LHC potential to probe NSUSY space

through the pp → $\chi\chi j$: $\chi = \chi^0_{1,2}$, $\chi^\pm_1$ process



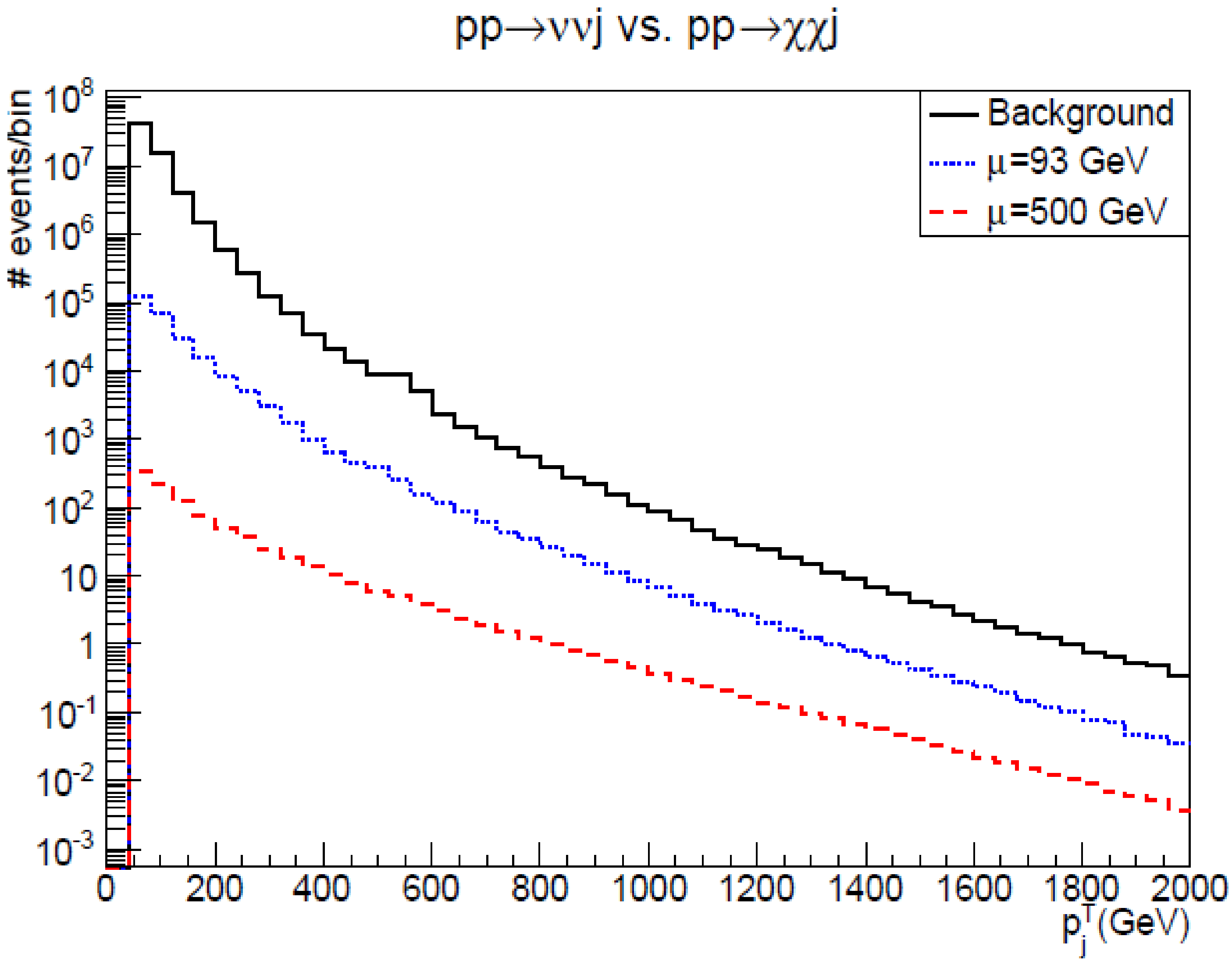
LHC sensitivity to CHS

through the pp → $\chi\chi j$: $\chi = \chi^0_{1,2}$, $\chi^\pm_1$ process



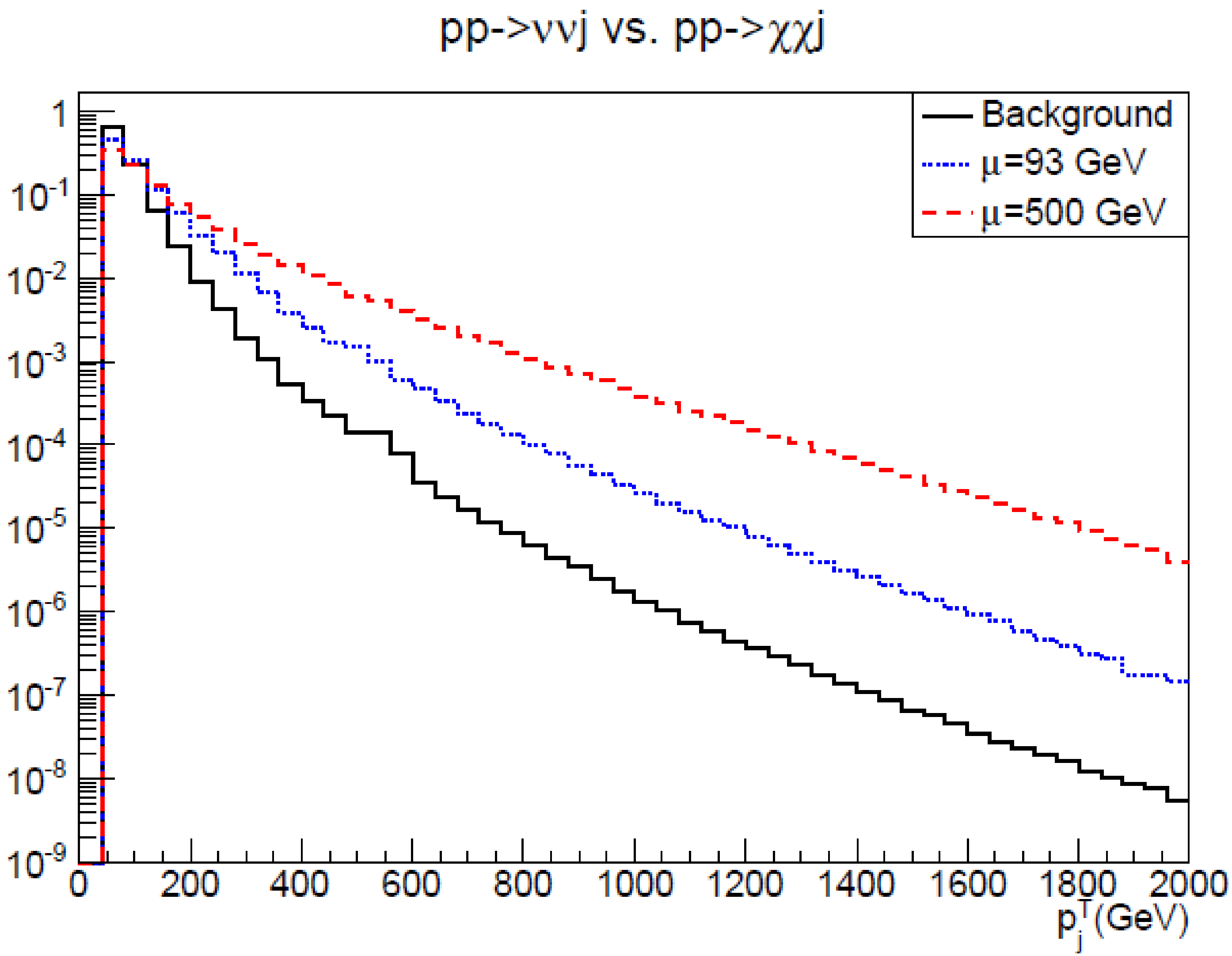
Signal vs Background analysis

difference in rates is quite pessimistic ...



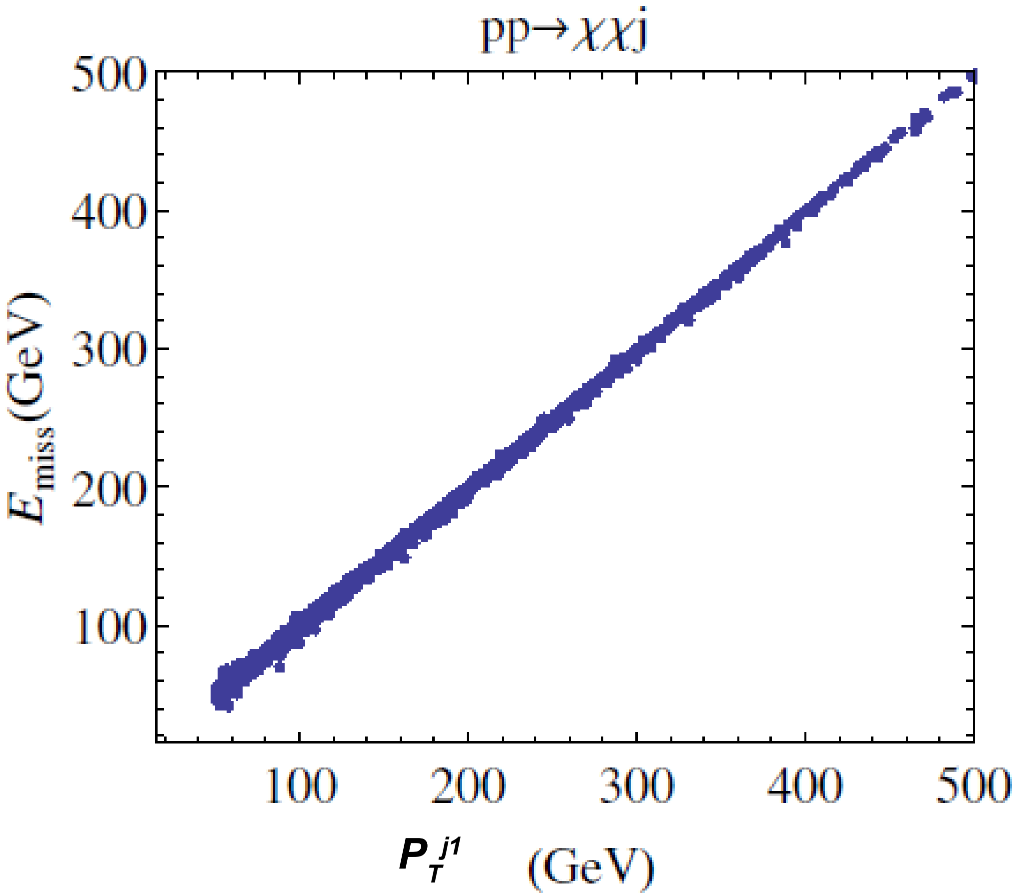
Signal vs Background analysis

but the difference in shapes is quite encouraging!

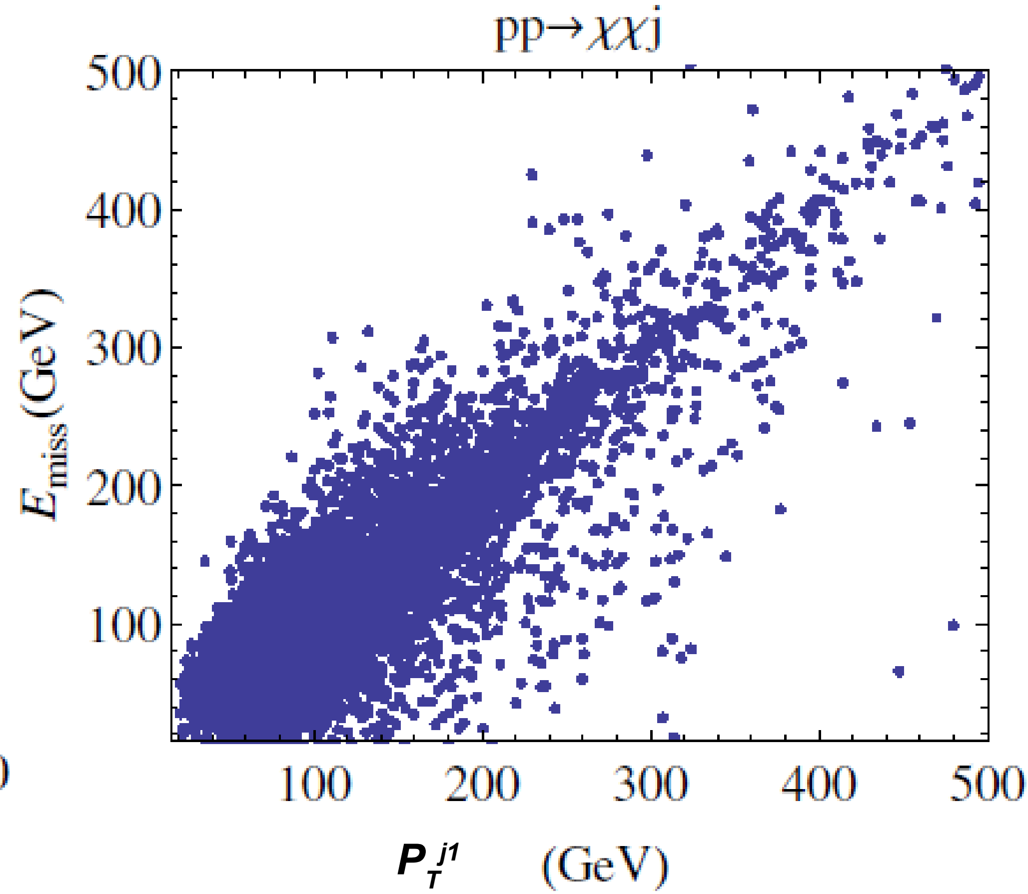


Parton vs Detector simulation level

Parton level

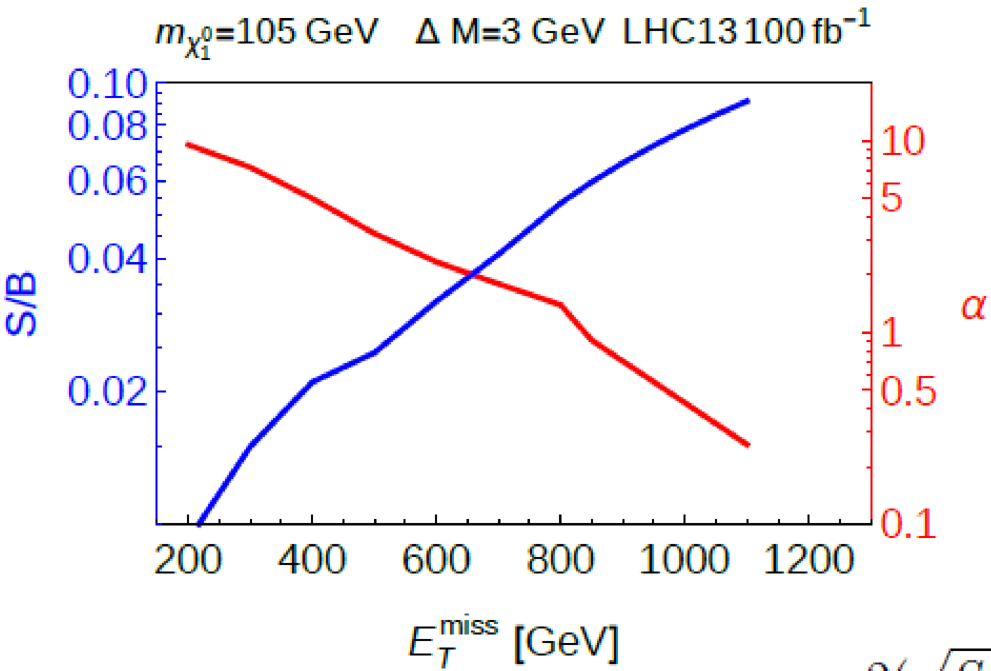


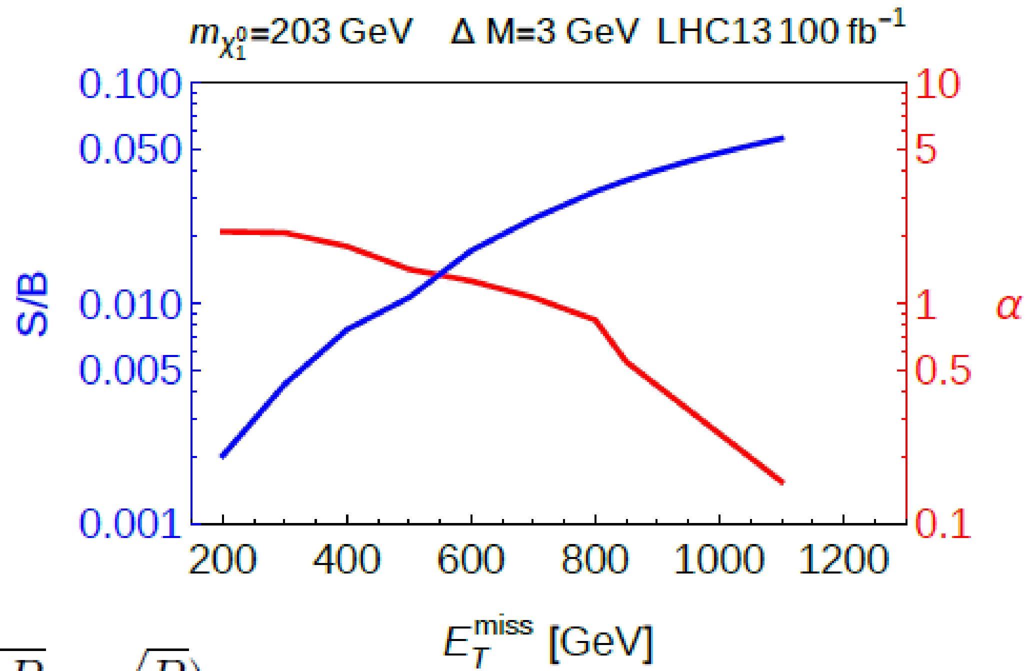
Delphes level



- the lack of the perfect p_T^{j1} vs MET correlations leads to a visible difference of the S/B ratio and significance, and should be taken into account.

S/B vs Signal significance





$$\alpha = 2(\sqrt{S+B} - \sqrt{B})$$

	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ GeV	$\mu = 500$ GeV
$p^T_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 5$	6.4 E+7	2.9 E+8	2.6 E+5	948
Veto $p^T_{e^\pm,\mu^\pm/\tau^\pm}$ >10/20 GeV	6.2 E+7	1.2 E+8	2.5 E+5	921
p^T_j >500 GeV	2.5 E+4	2.0 E+4	1051	32
$p^T_j = \not{E}_T$ >500 GeV	1.5 E+4	4.1 E+3	747	27
$p^T_j = \not{E}_T$ >1000 GeV	315 (375)	65 (32)	21 (31)	2 (2)
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$p^T_j = \not{E}_T$ >2000 GeV	1 (1)	0 (0)	0 (1)	0 (0)

There is a strong tension between S/B and signal significance

- **Higher S/B needs high E_t^{miss} cut to reach an acceptable systematic**
- **Higher significance needs low (< 500 GeV) E_t^{miss} cut**

What is the minimal S/B value one can deal with?

- **S/B systematic study by ATLAS and CMS LHC@8:**

  sources of systematic uncertainty and their contributions (in %) to the total uncertainty on the Z(νν) background from CMS PAS EXO-12-048

E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Statistics (N^{obs})	1.7	2.6	3.9	5.6	7.6	10.9	14.6
Background (N^{bgd})	0.8	0.6	0.8	0.2	0.0	0.0	0.0
Acceptance (A)	2.0	2.0	2.0	2.1	2.1	2.2	2.4
Selection efficiency (ϵ)	2.0	2.0	2.1	2.2	2.4	2.7	3.1
Total	4.5	4.9	5.8	7.1	8.9	12.1	15.6

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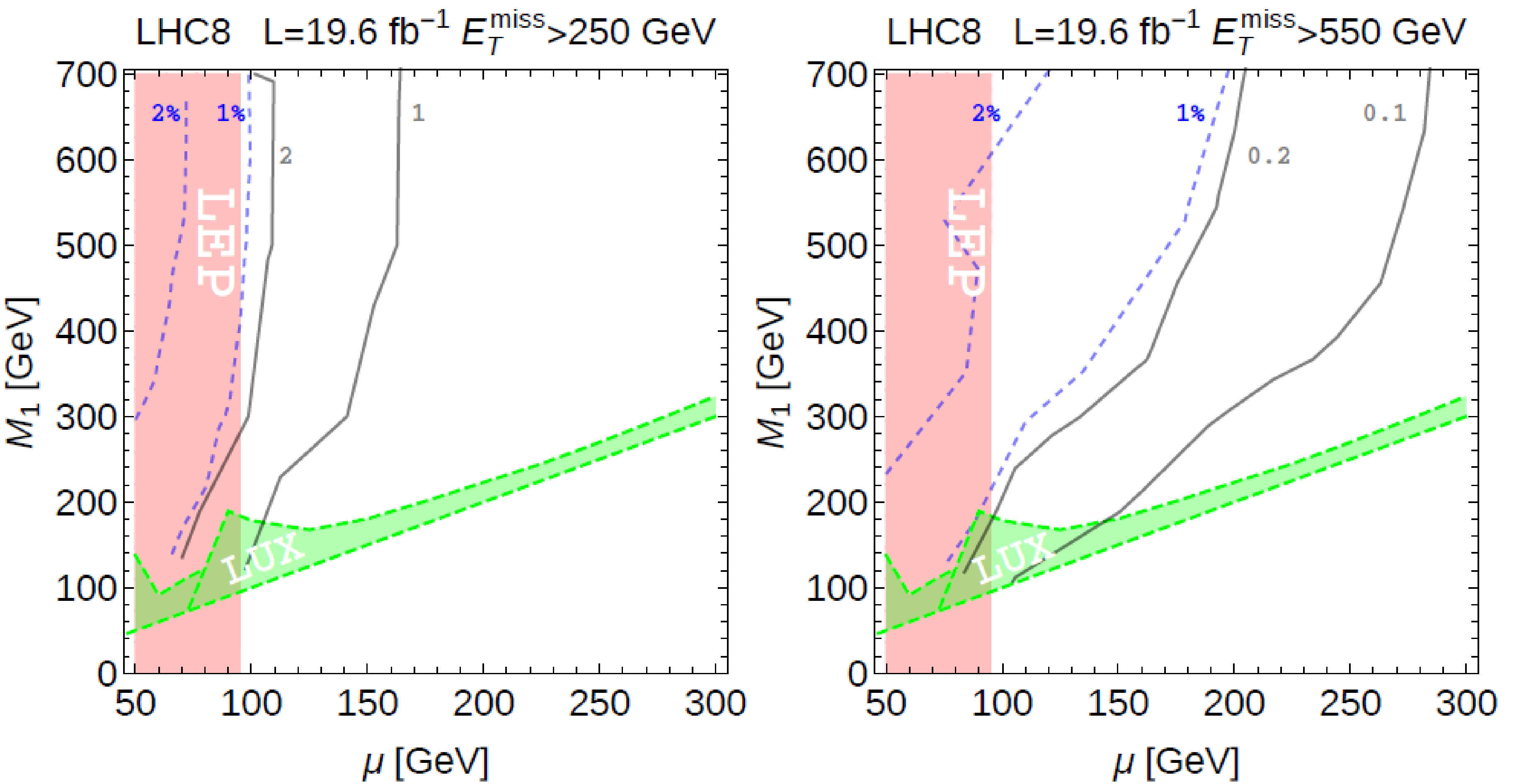
- **So, the realistic S/B ratio we can afford is ~ 5% or more**

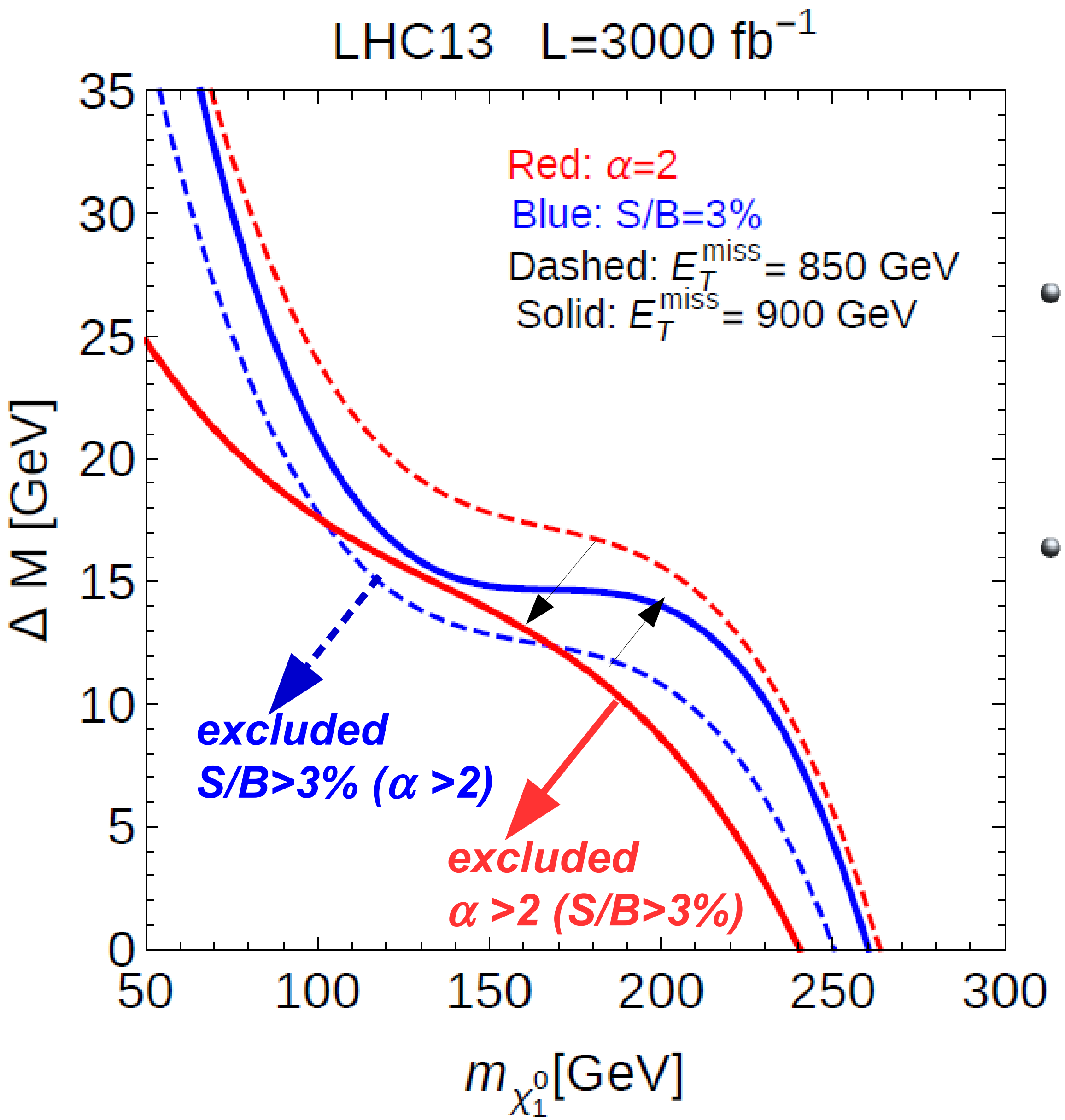
Interpreting LHC@8TeV results (CMS EXO-12-048)

Selection	W+jets	Z+j	$Z(\nu\nu)$+j	$t\bar{t}$	QCD	Single top	Total
Cross section (pb)	229.0	34.1	588.3	225.2	1904.8	113.5	
$E_T^{\rm miss} > 550$ GeV	136	1	429	3	0	0	569



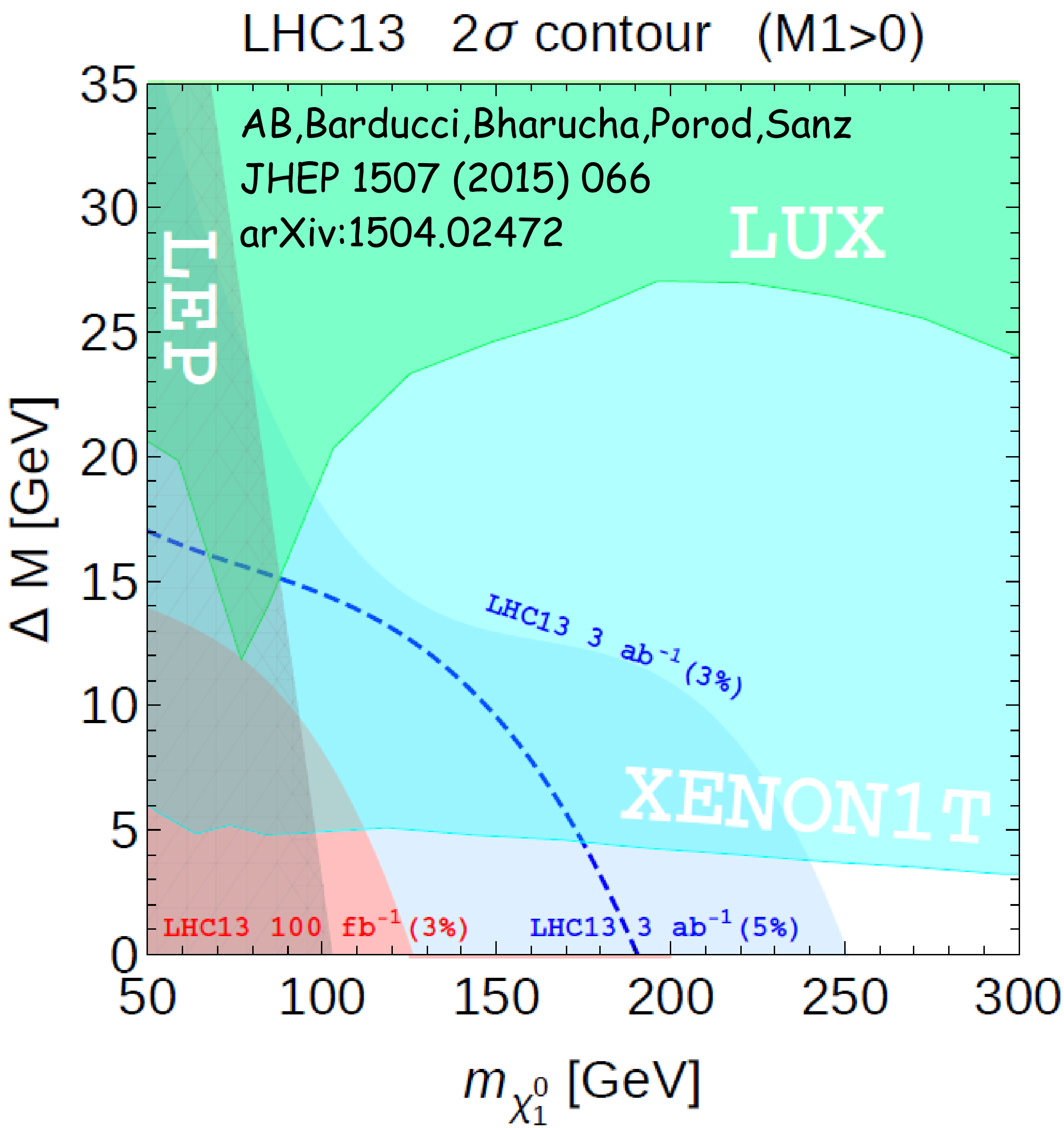
- **Both S/B and Significance are too low – so LHC@8 is unfortunately not sensitive to NSUSY space ...**

Optimisation of the $E_{T\ miss}$ cut



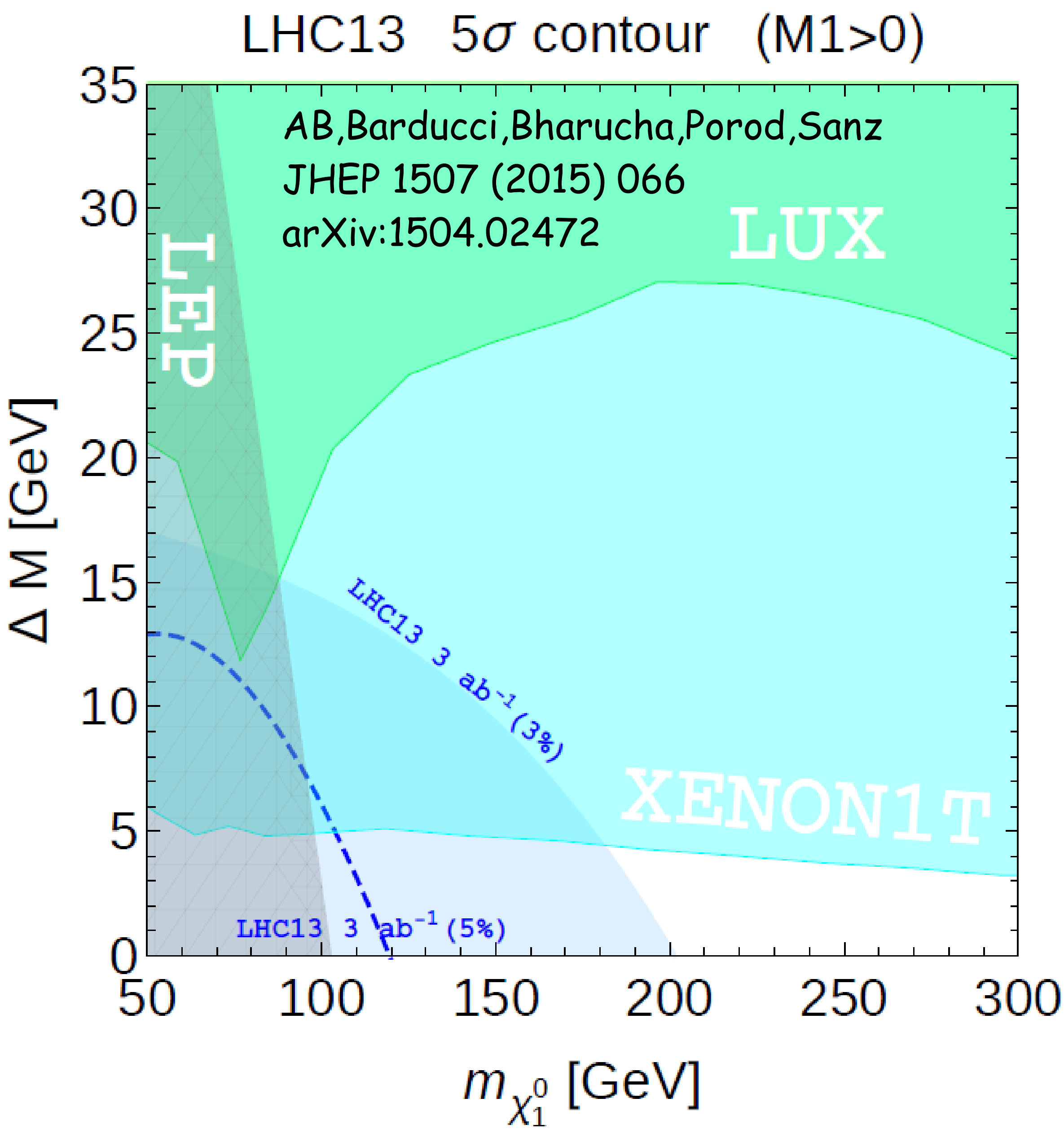
- The shapes of S/B and α contours are very similar - easy to optimise $E_{T\ miss}$ cut
- We chose $E_{T\ miss}$ value to bring S/B and α iso-contours together: they move into opposite directions

LHC@13 Reach for NSUSY



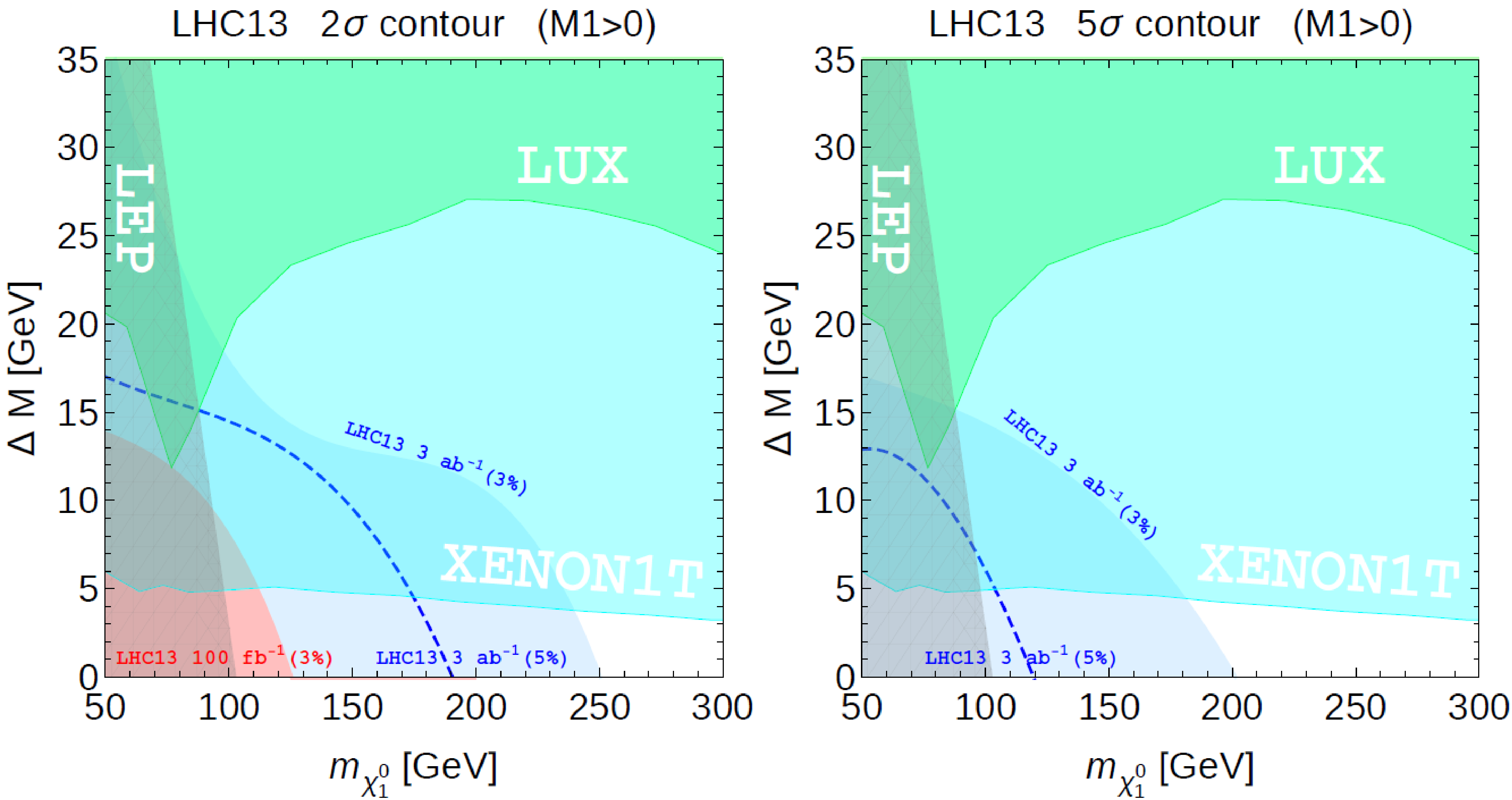
- 3% and 5% S/B BM for 3 ab^{-1} and 100 fb^{-1} integrated luminocity
- LUX and XENON1T are sensitive to the upper end (larger ΔM) of NSUSY
- For S/B ~ 3% (based on ATLAS studies), LHC will be sensitive to DM mass up to 250 GeV @95% CL with 3 ab^{-1} integrated luminosity

LHC@13 Reach for NSUSY



- 3% and 5% S/B BM for 3 ab^{-1} and 100 fb^{-1} integrated luminosity
- LUX and XENON1T are sensitive to the upper end (larger ΔM) of NSUSY
- For S/B ~ 3% (based on ATLAS studies), LHC can discover DM with the mass up to 200 GeV with 3 ab^{-1} integrated luminosity

LHC@13 Reach for NSUSY



Similar recent studies:

- **Han,Kobakhidze,Liu,Saavedra,Wu,Yang '13 :**

  "NSUSY can be probed up to 200 GeV at 5 sigma level with 1.5 ab^{-1}"

  but S/B < 1% for 200 GeV LSP – not quite realistic to probe

- **Baer, Mustafayev,Tata '14 :**

  "NSUSY can not be probed at the LHC, since S/B ~ 1%"

  too conservative, since S/B can be improved with high P_T cuts, this however requires high luminosity to keep statistics up

- **Han,Kribs,Martin,Menon '14**

  interpreted LHC@8TeV results, found sensitivity up to 70-90 GeV

  study was done at the parton level

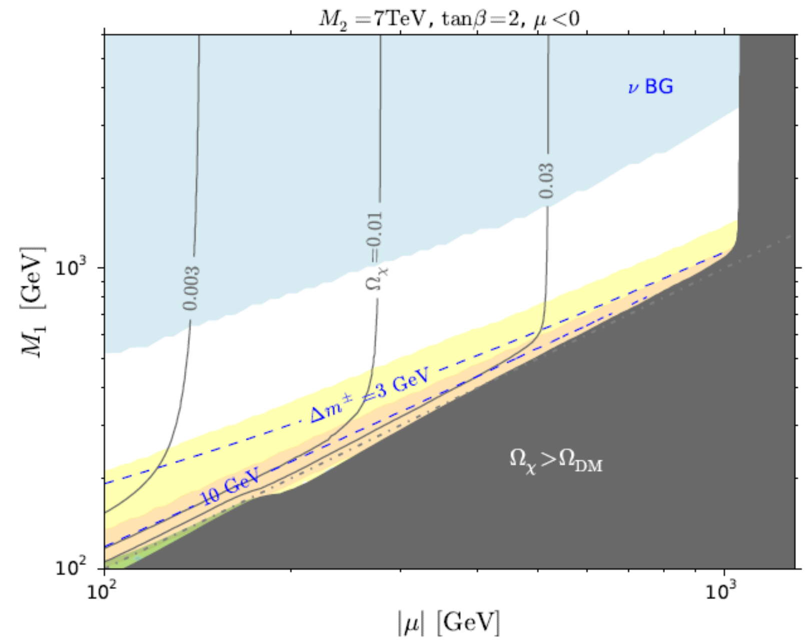
  At the detector level (as we have found) both S/B and significance are too low for LHC@8TeV to be sensitive to NSUSY

OUTLOOK

- ***There are blind spots for DM DD***

$$c_{hXX} \approx \frac{g_1}{2} \sin\theta_W M_Z \frac{M_1 + \mu \sin(2\beta)}{\mu^2 - M_1^2}$$

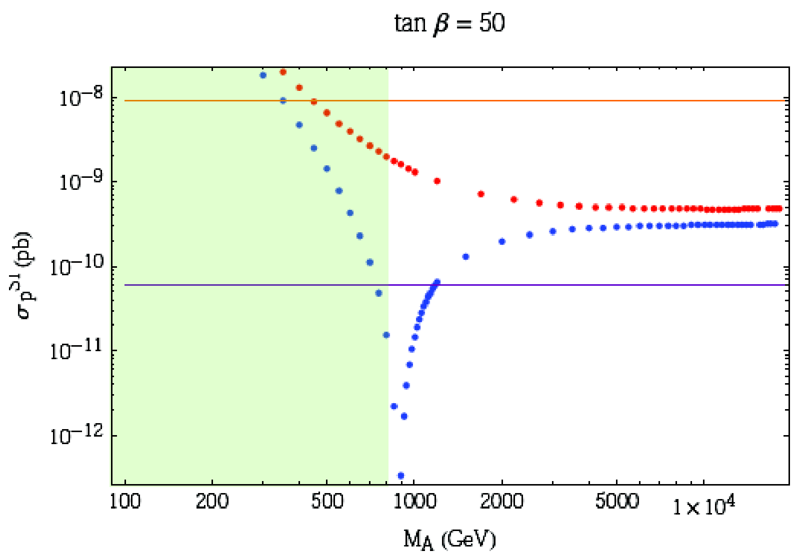
Badziak, Delgado,Olechowski, Pokorski,Sakurai arXiv:1506.07177



  - ***high tanb region: h ↔ H cancellation***

$$a_d \sim \frac{m_d}{\cos\beta}\left[\cos\beta(m_\chi + \mu\sin 2\beta)\,\frac{1}{m_h^2} - \mu\sin\beta\cos 2\beta\,\frac{1}{m_H^2}\right]$$

Huang, Wagner, arXiv:1404.0392



- **Signatures to cover ΔM>10 GeV region**
  - **di-leptons + MET (+ γ)**
  - **VBF (di-leptons + MET)**
  - **?**

Conclusions

- Light Higgsino (LH) DM is well-motivated but hard to test: LH DM with 100 GeV mass and above is consistent will all experimental data ! (the best limit comes from LHEP so far)

- Assuming S/B ~ 3% control is possible LHC@13 can
  - probe LH DM up to 250 GeV @ 95% CL
  - or discover LH DM with the mass up to 200 GeV

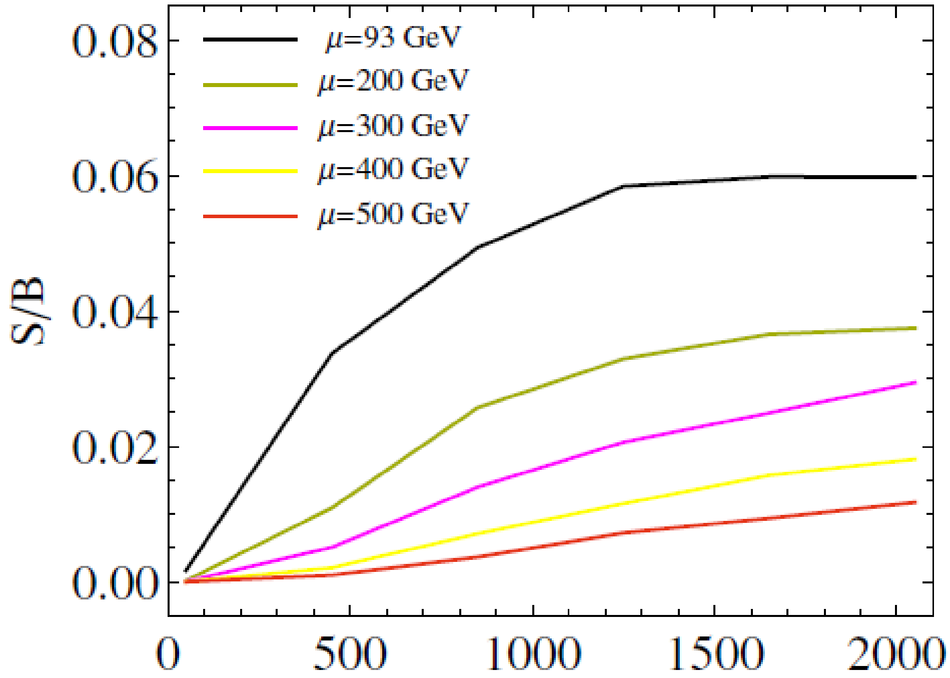
- So, LHC has a good chance to discover LH DM, the lightest SUSY particle, even if squarks and gluinos are heavy

- DDM search experiments – LUX and XENON1T are very complementary to LHC - they probe LH DM space with $\Delta M > 5$ GeV

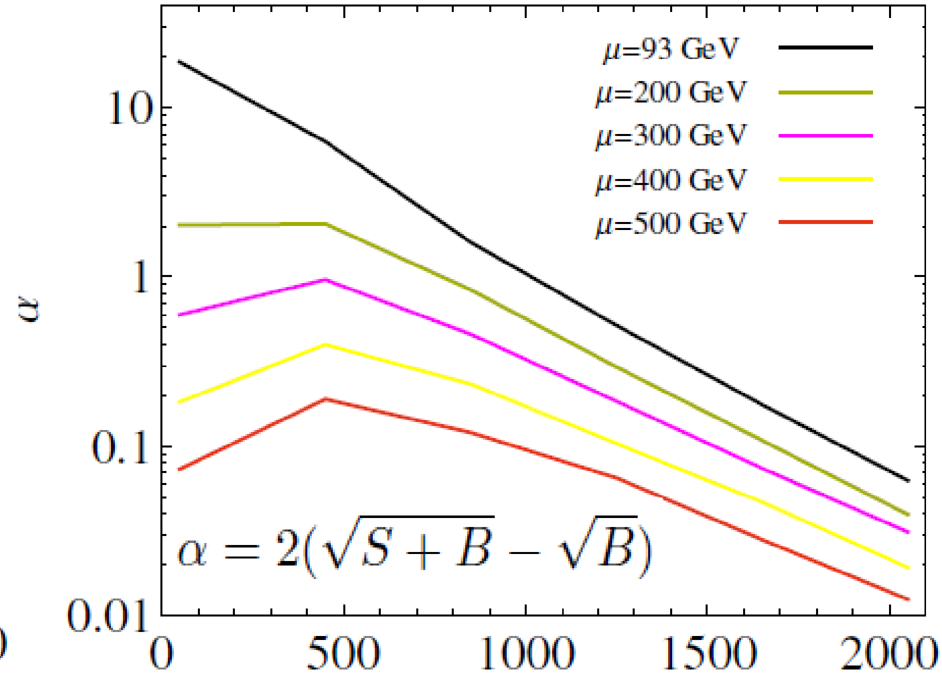
Thank you!

Backup

S/B vs Signal significance



P_T^{j1}/E_T^{miss} cut (GeV)



LHC@13TeV, 100 fb^{-1}

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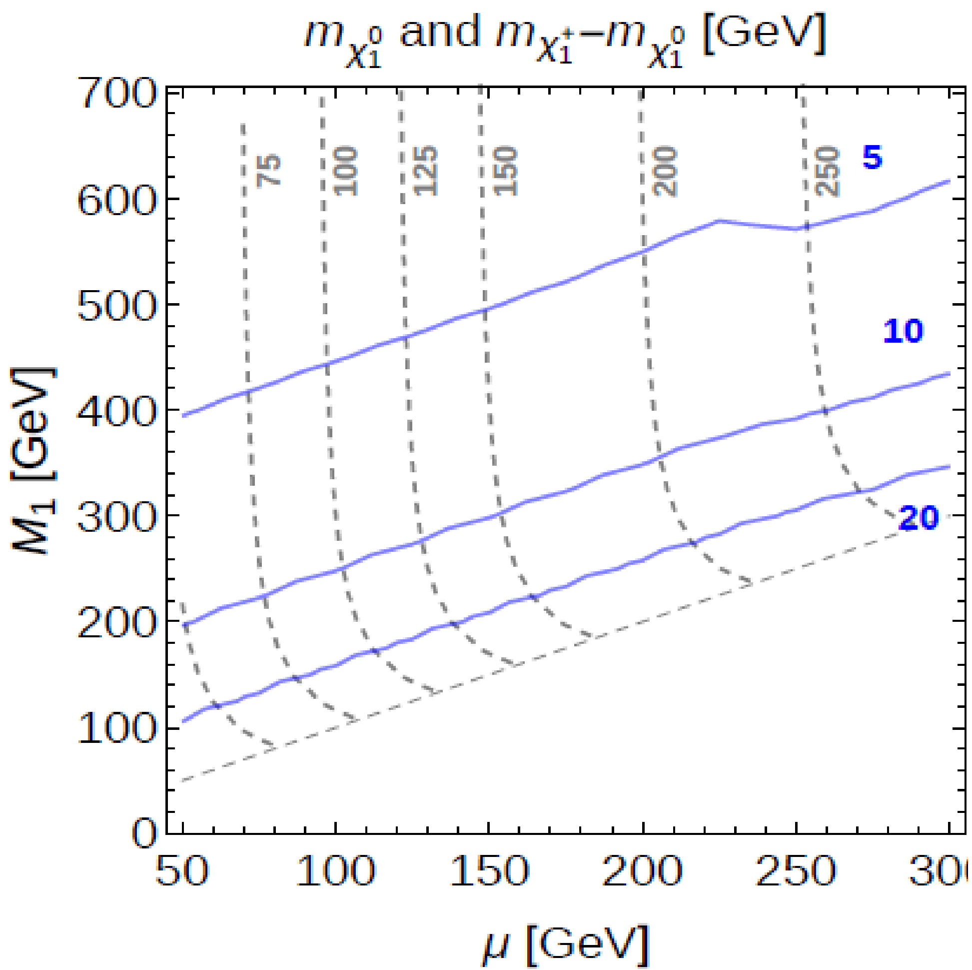
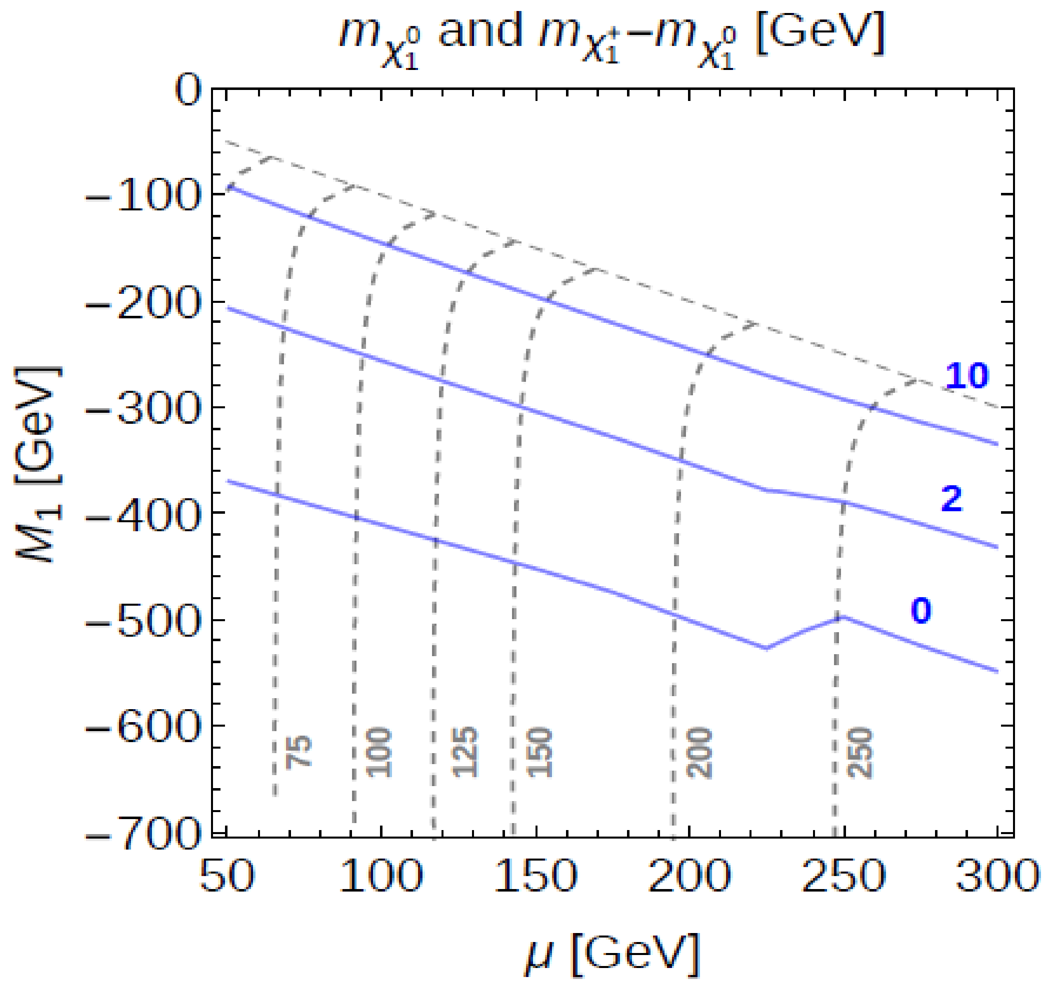
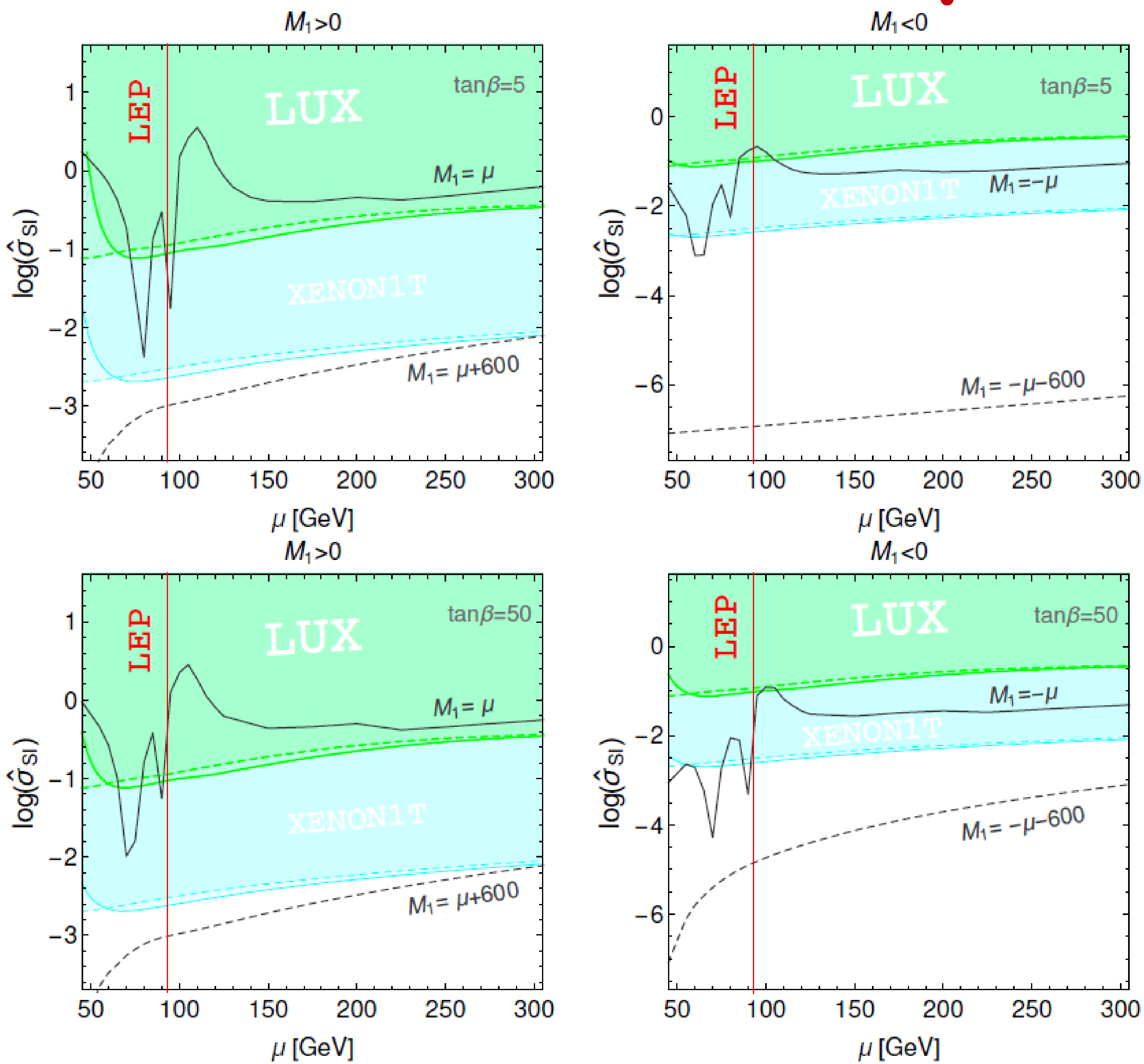
- There is a strong tension between S/B and signal significance
- S/B pushes E_t^{miss} cut up towards an acceptable systematic
- significance requires comparatively low (below 500 GeV) E_t^{miss} cut

ΔM pattern for M_1>0 and M_1<0 cases





Direct Detection Prospects



LHC@13 Reach for NSUSY