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

Alexander Belyaev

NExT

Southampton University & Rutherford Appleton Laboratory

December 8, 2015

Particle Physics at the Dawn of the LHC13

ICTP SAIFR

International Centre for Theoretical Physics
South American Institute for Fundamental Research

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Organizers: → Thanks to the organisers!

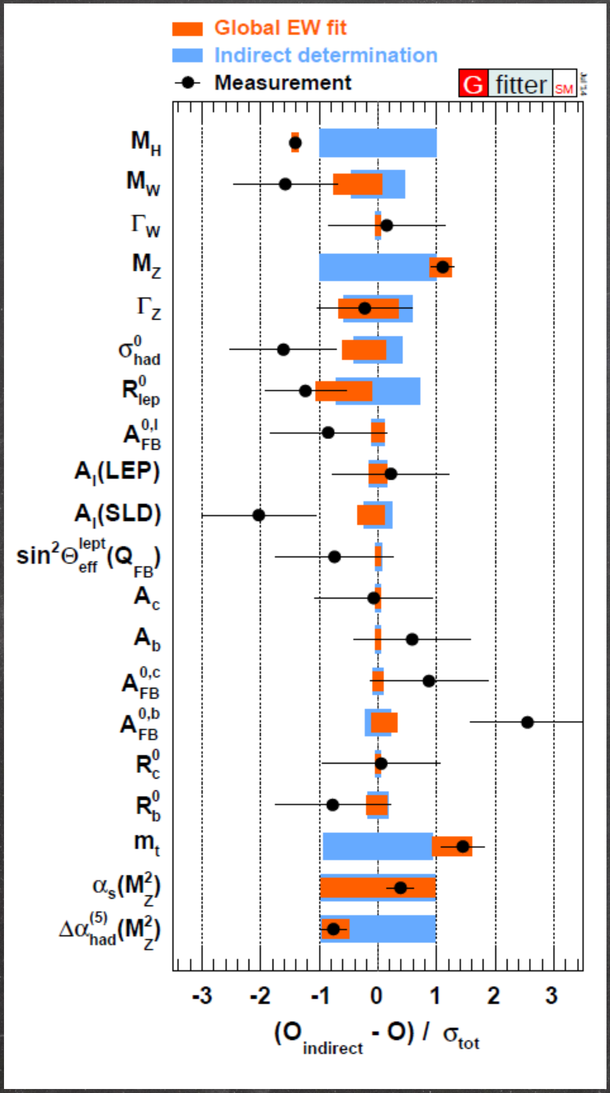
ICTP SAIFR

Eduardo Pontón (IFT-UNESP & ICTP-SAIFR), **Mariano Quirós** (IFAE-Barcelona), **Rogério Rosenfeld** (IFT-UNESP & ICTP-SAIFR)

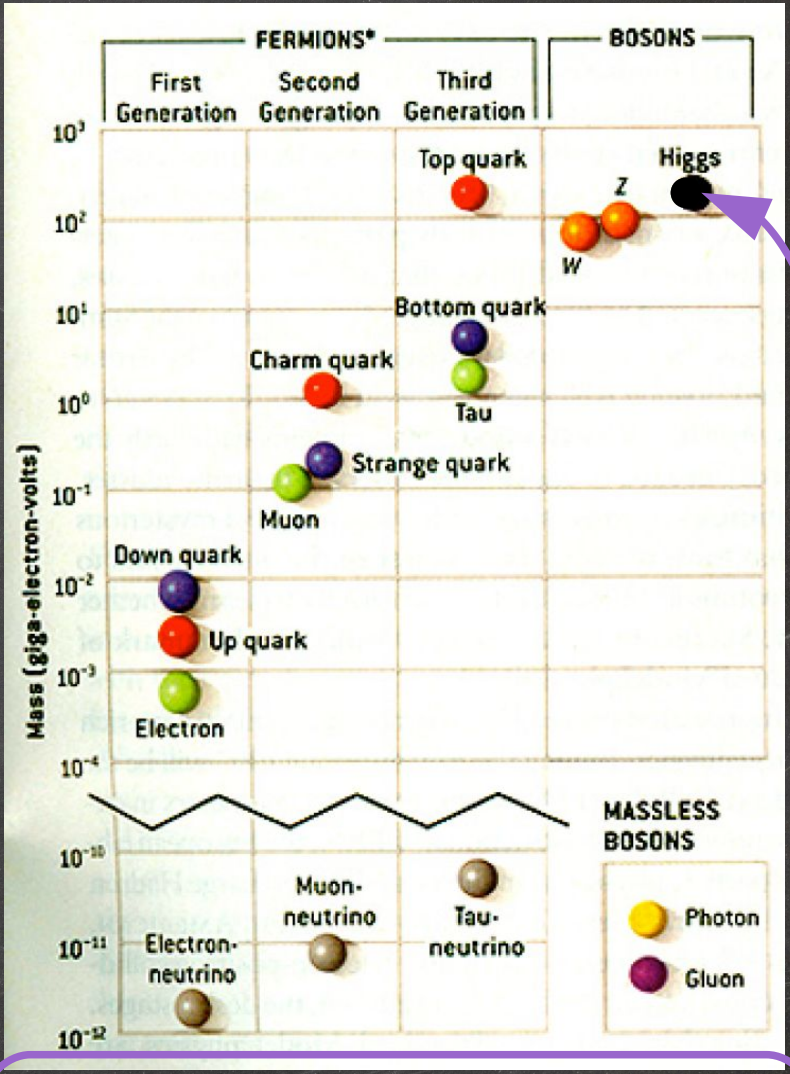
OUTLINE

- Motivation for BSM
- General approach for SUSY hunt
- DM search interplay
- Beyond MSSM
- 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



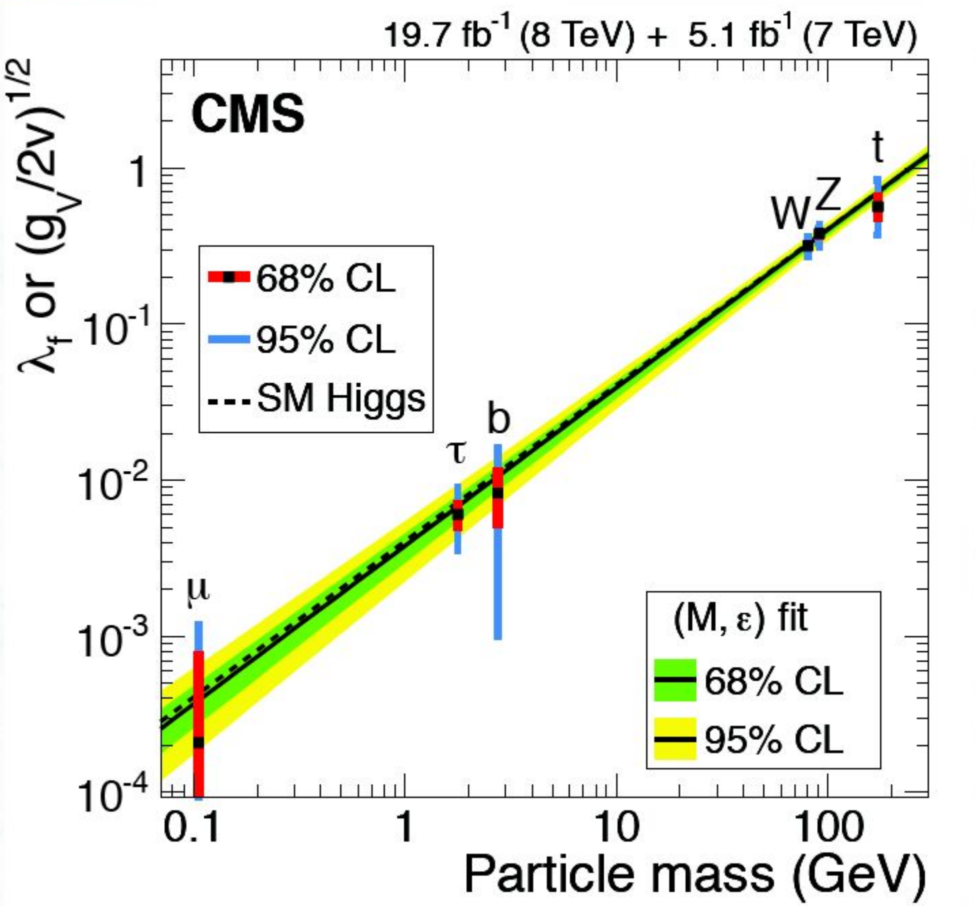
The last missing particle – Higgs boson with ~125 GeV mass is discovered on the 4th of July 2012

Higgs Boson Status

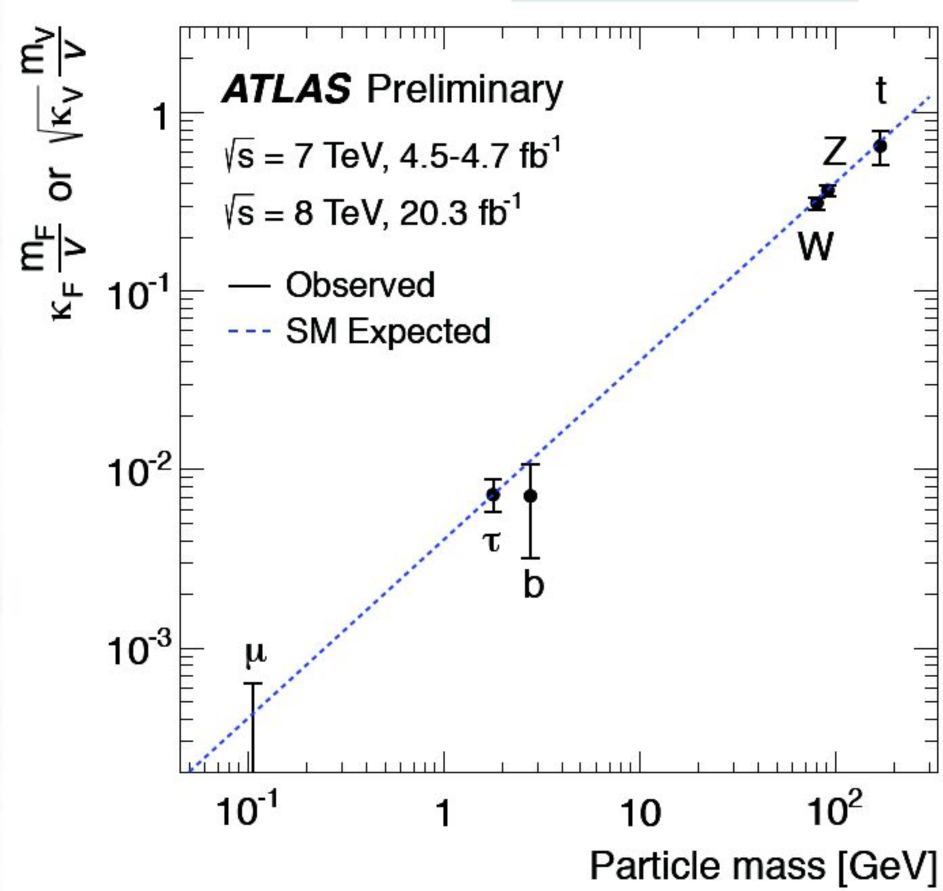
λ = Yukawa coupling for fermions
√g/2v = couplings for W/Z bosons

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

EPJ C75 (2015) 5, 212



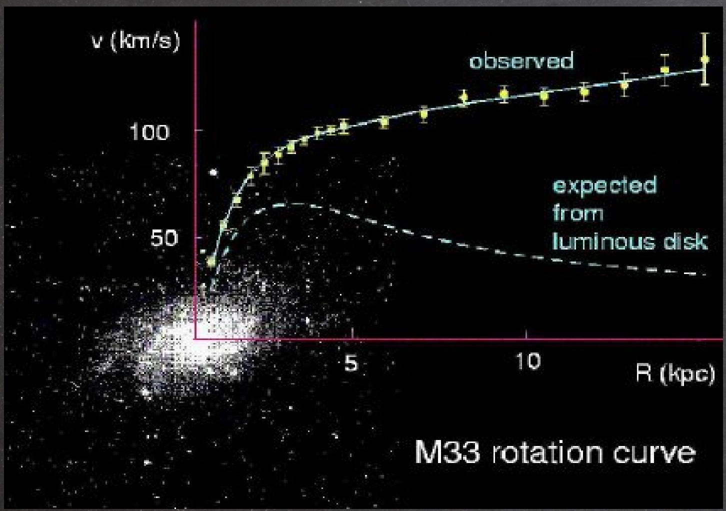
ATLAS-CONF-2015-007



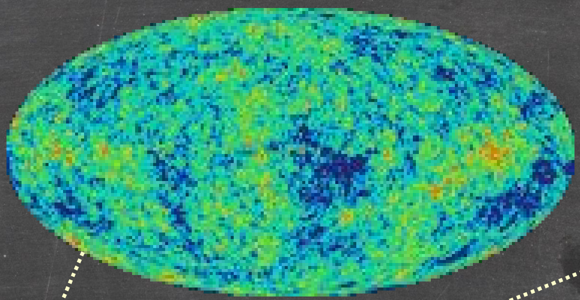
SM is empirically incomplete

- 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

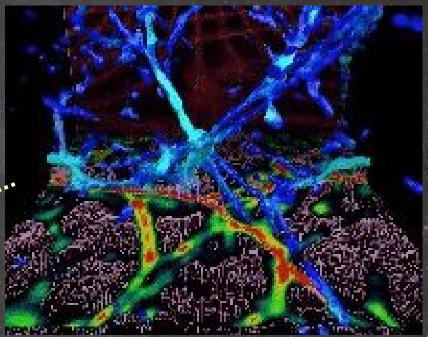
Galactic rotation curves



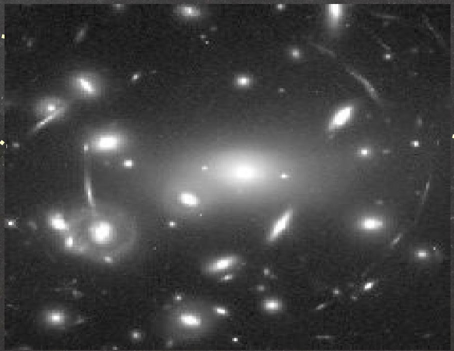
CMB: WMAP and PLANCK



Large Scale Structures



Gravitational lensing



Bullet cluster

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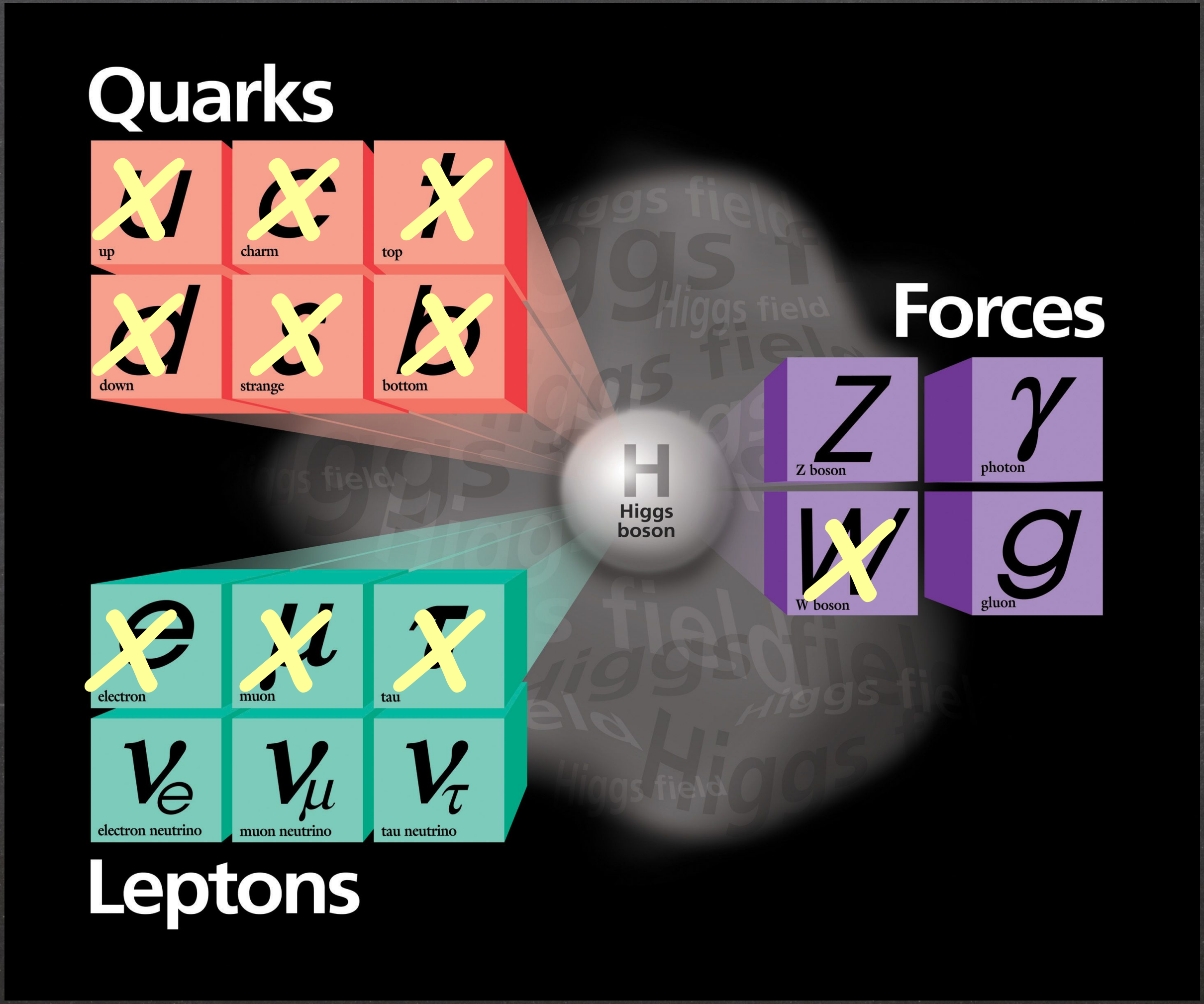

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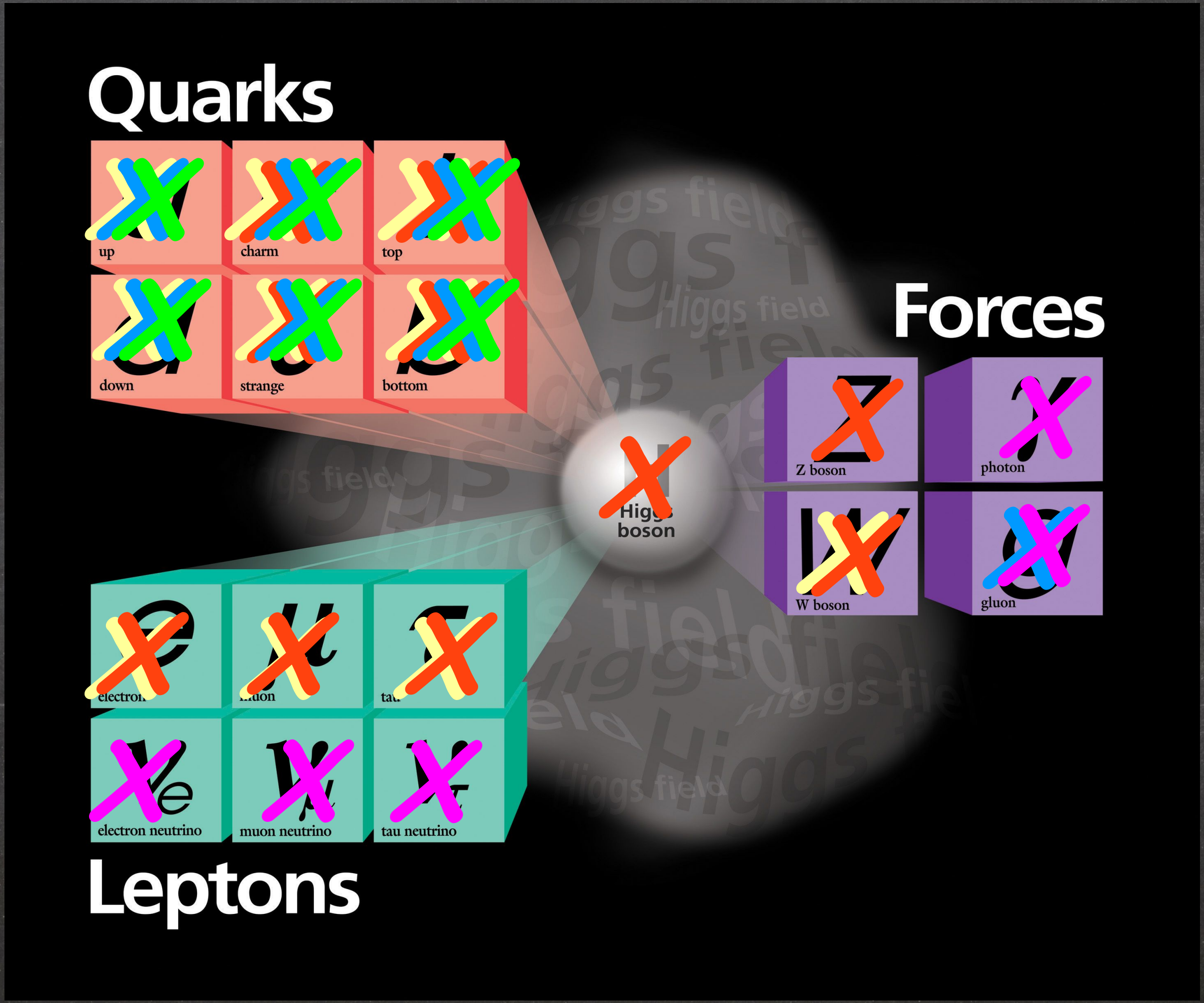
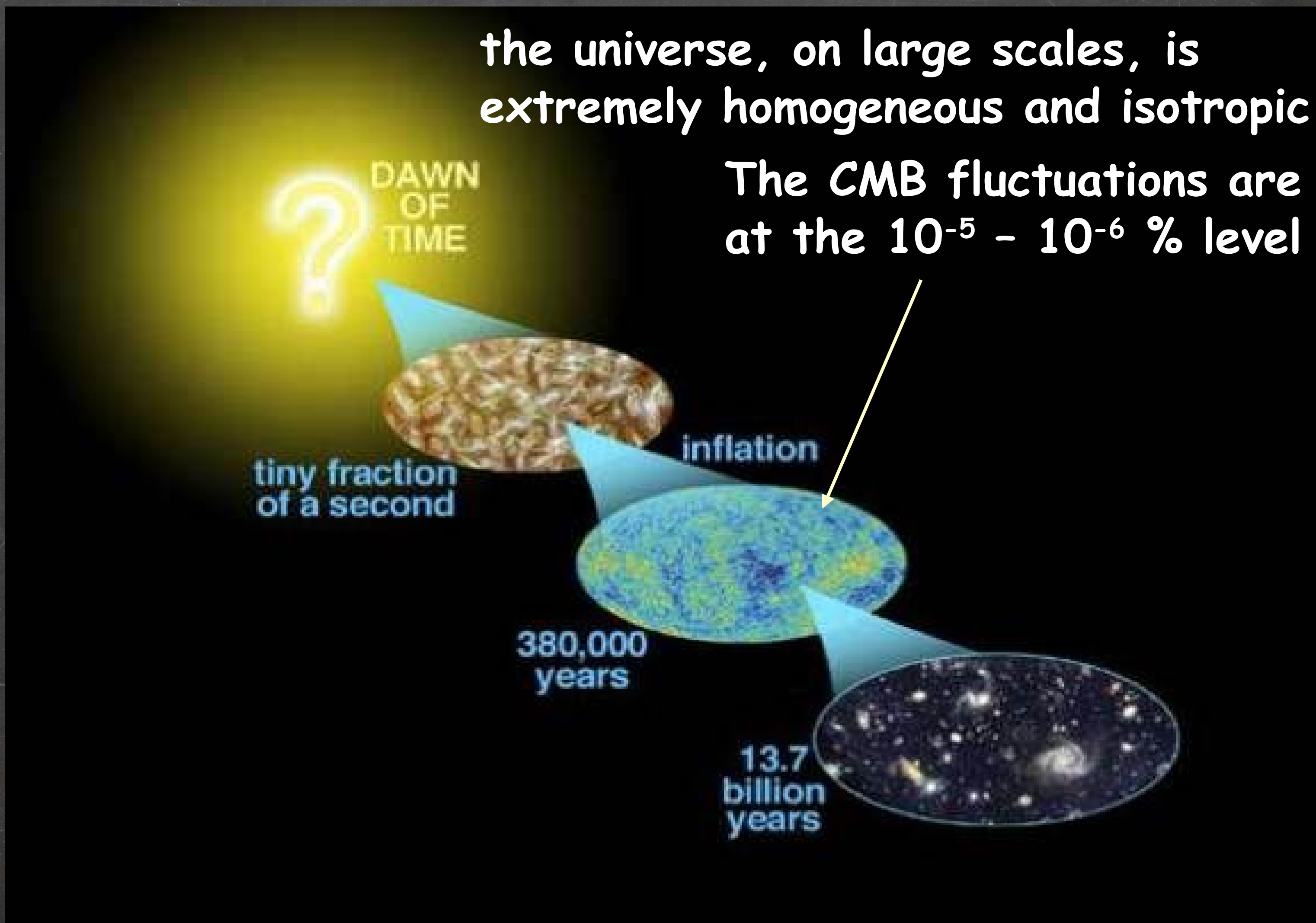


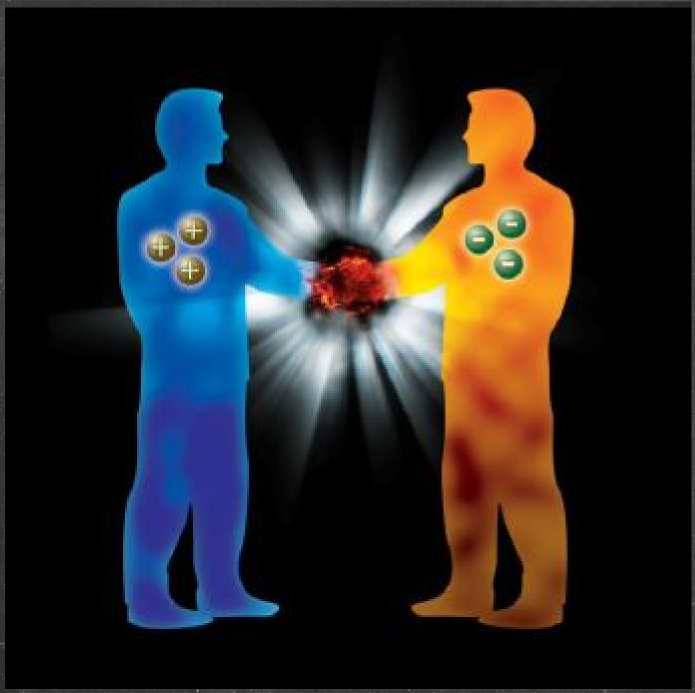
SM is empirically incomplete

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



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.



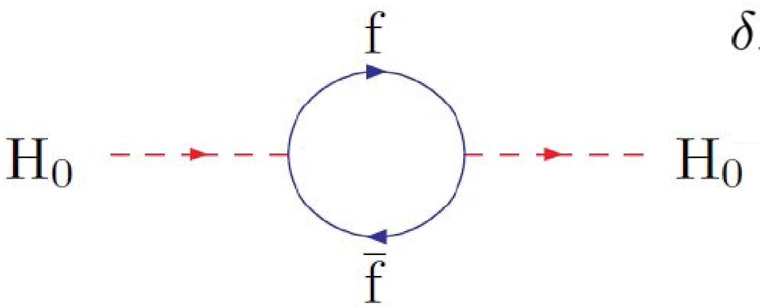
The amount of CP violation in the SM which could lead to baryon-antibaryon asymmetry is too small (would provide BAU orders of magnitude below the observed one)

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

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.



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

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

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

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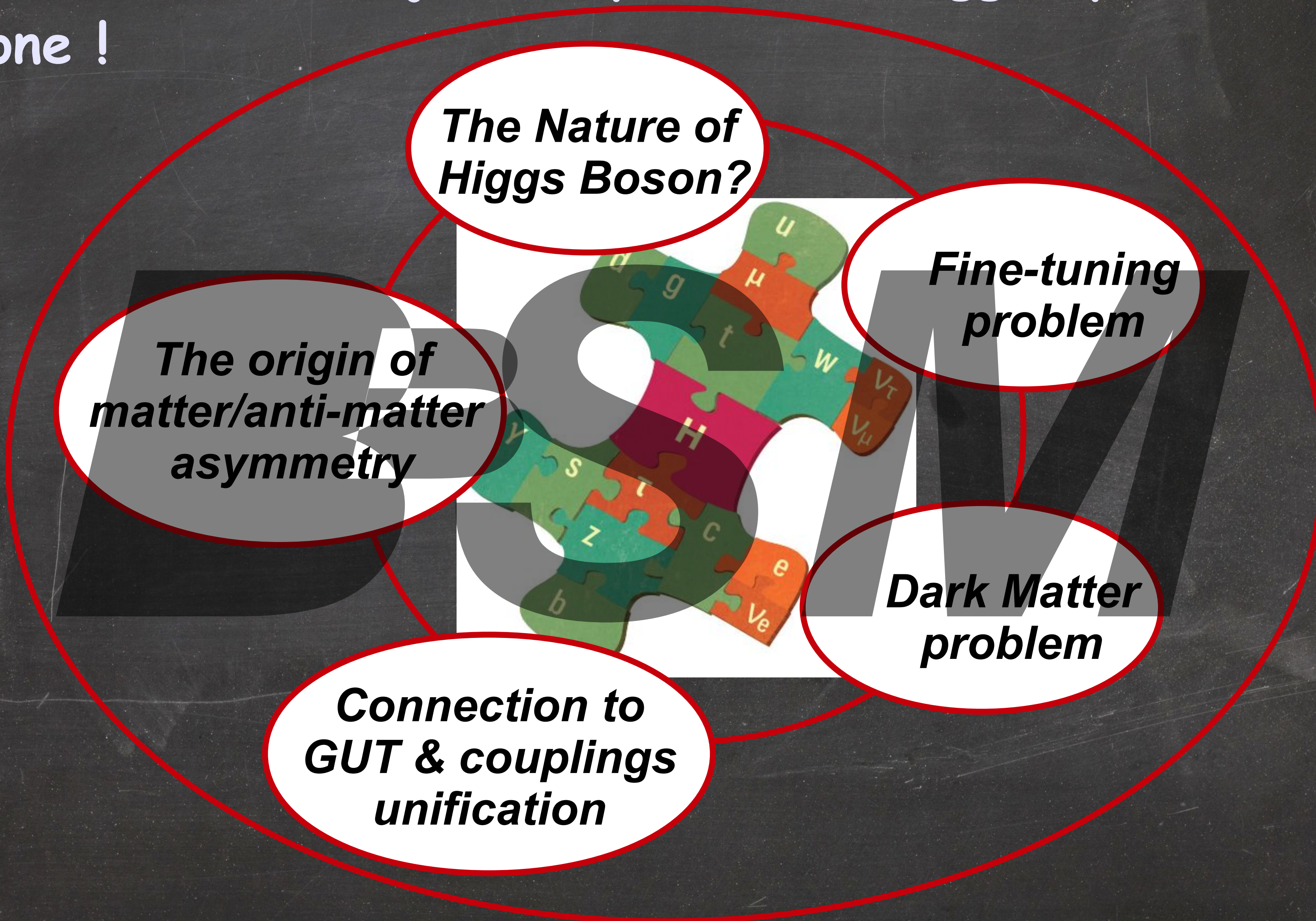
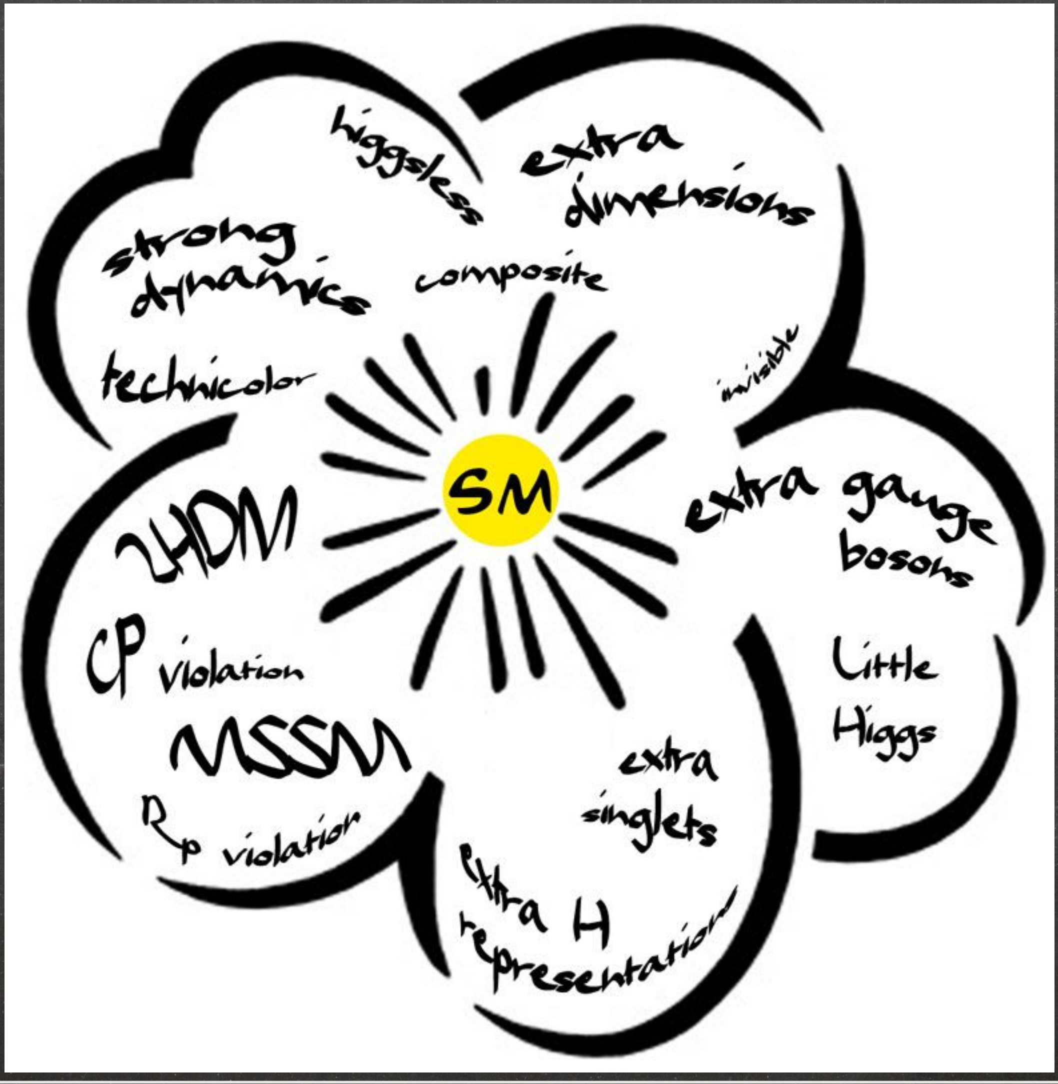
But the SM itself is just a piece of a bigger puzzle - BSM one !



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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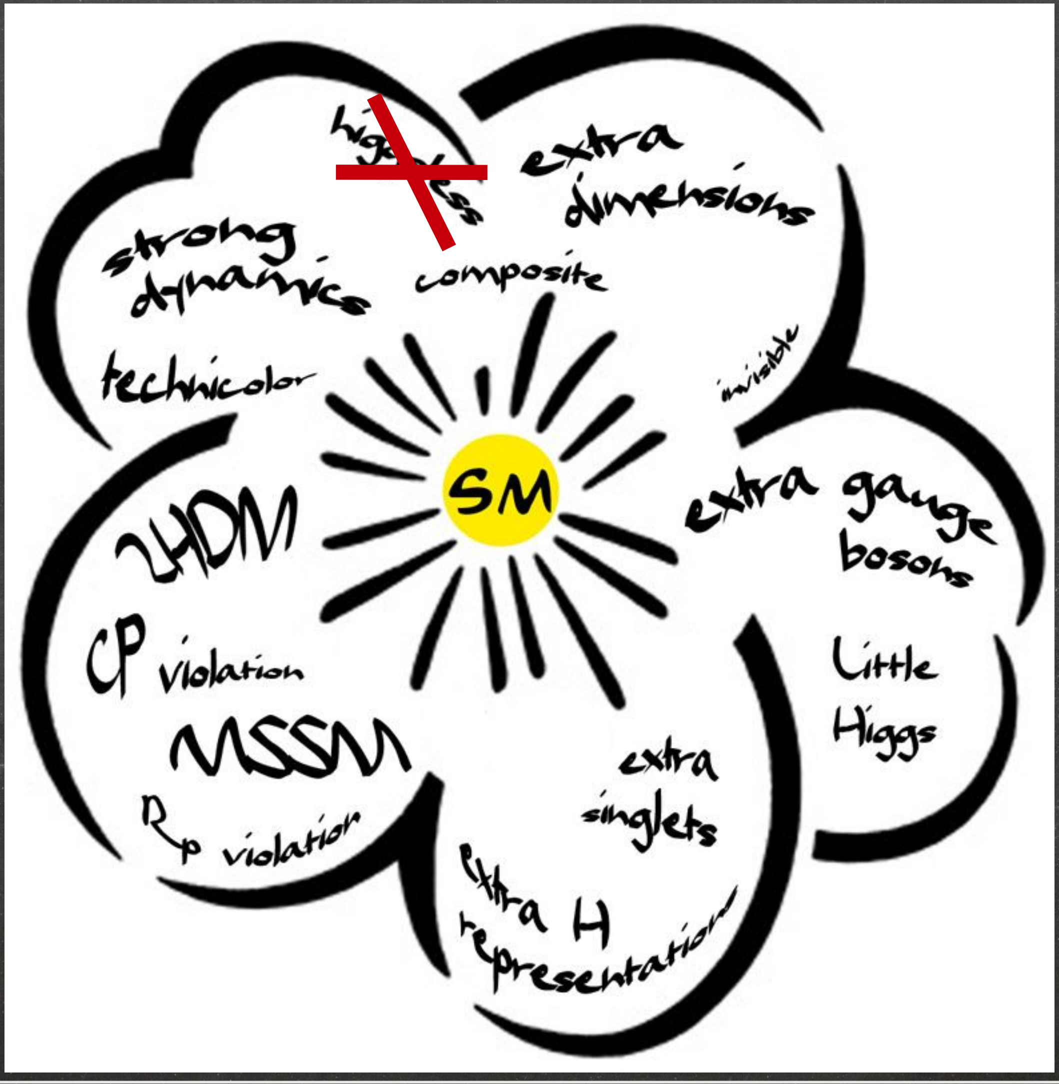

Present Status

What do we know about Dark Matter?

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Spin ?

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Mass ?

What do we know about Dark Matter?

Spin ☐?

Mass ☐?

Stable

Yes ☐? No ☐?

symmetry behind stability ☐?

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Spin ?

Mass ?

Stable

Yes ? No ?

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Thermal relic

Yes ? No ?

What do we know about Dark Matter?

Spin ?

Mass ?

Stable
- Yes ? No ?
- symmetry behind stability ?

Couplings
- gravity V
- Weak ?
- Higgs ?
- Quarks/gluons ?
- Leptons ?
- New sector ?

Thermal relic
- Yes ? No ?

SUSY

Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

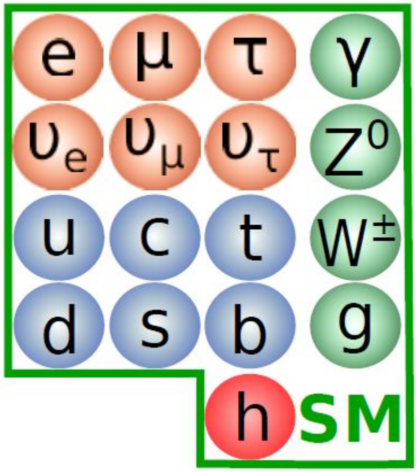
$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

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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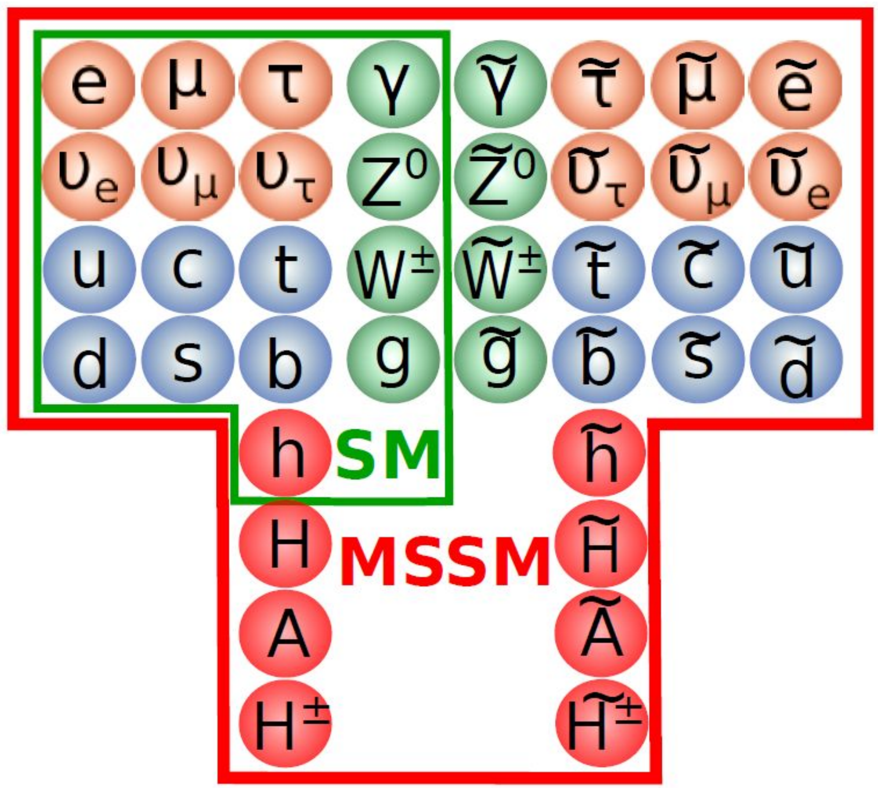

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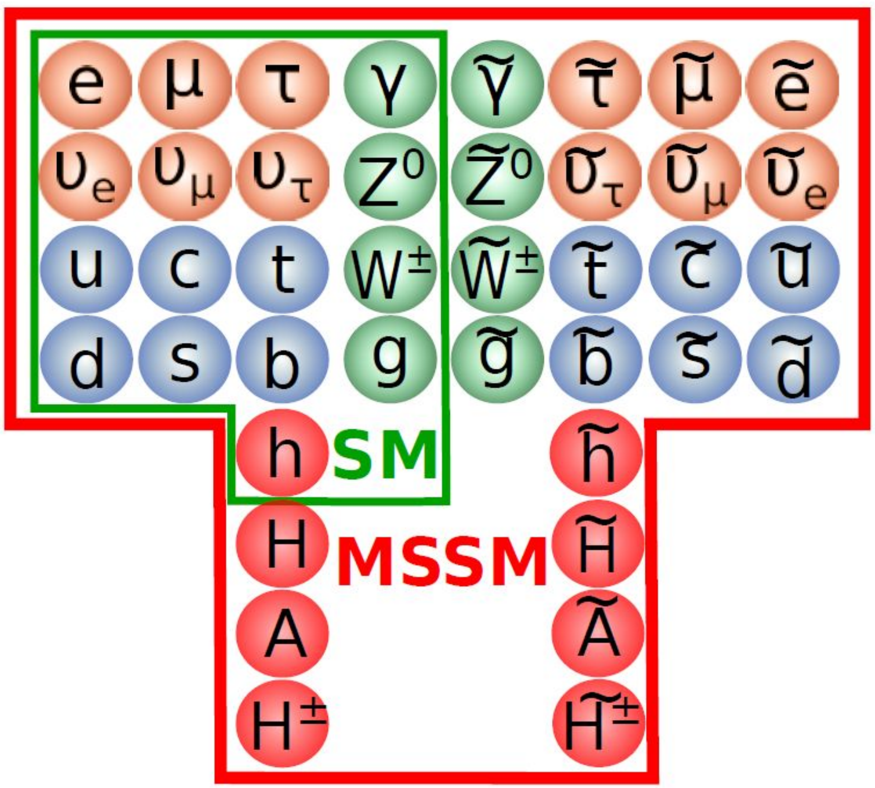

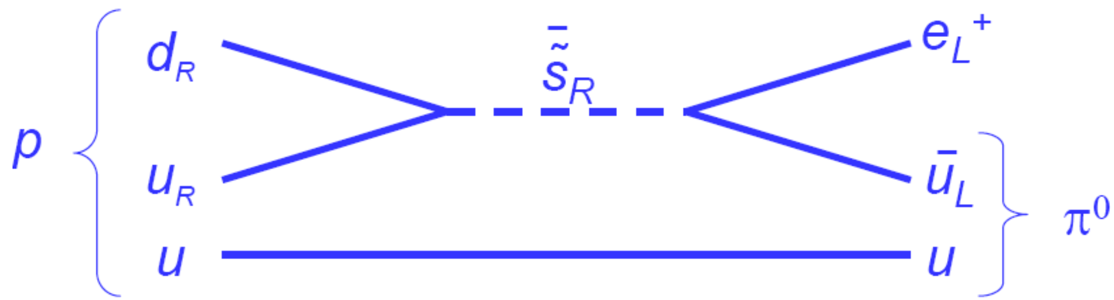

could give rise the proton decay!

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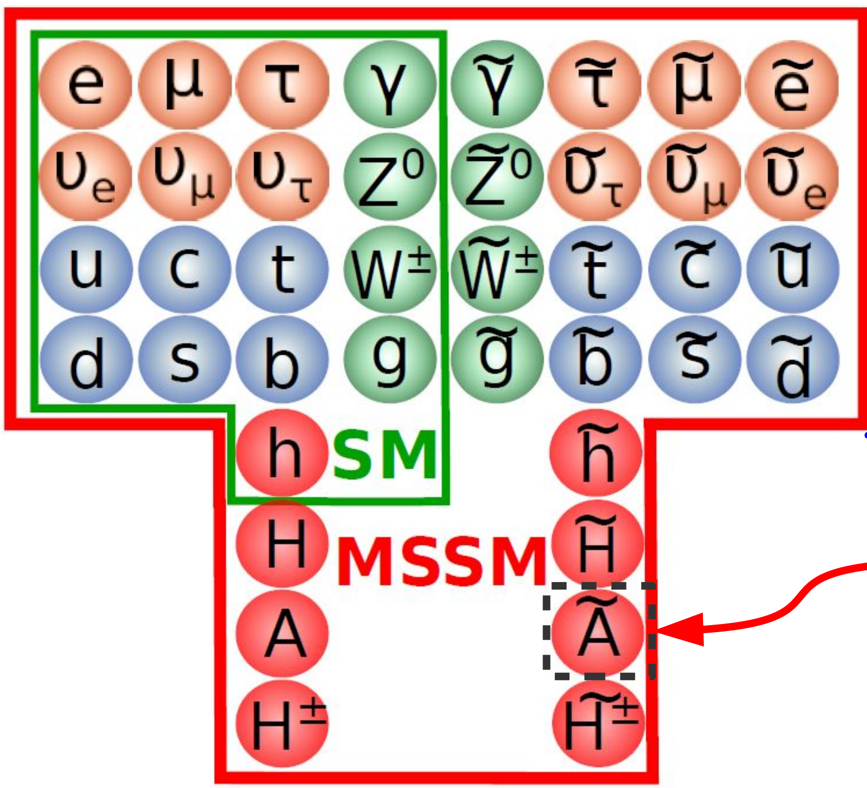

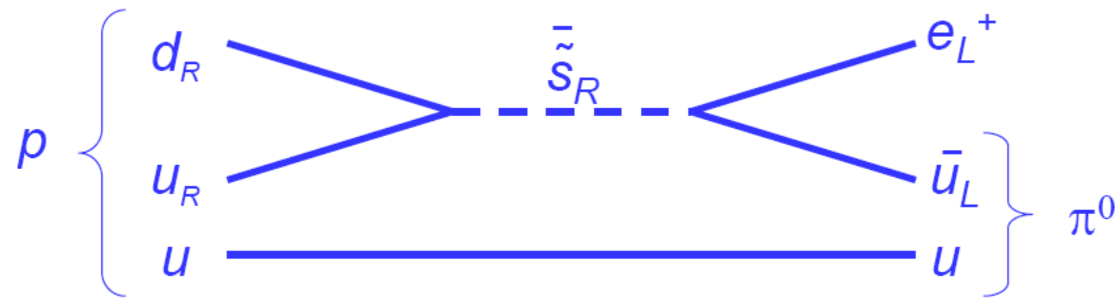

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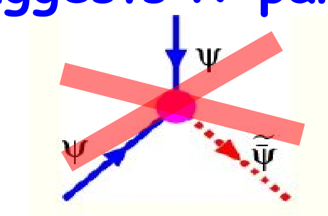
the absence of proton decay suggests R-parity

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



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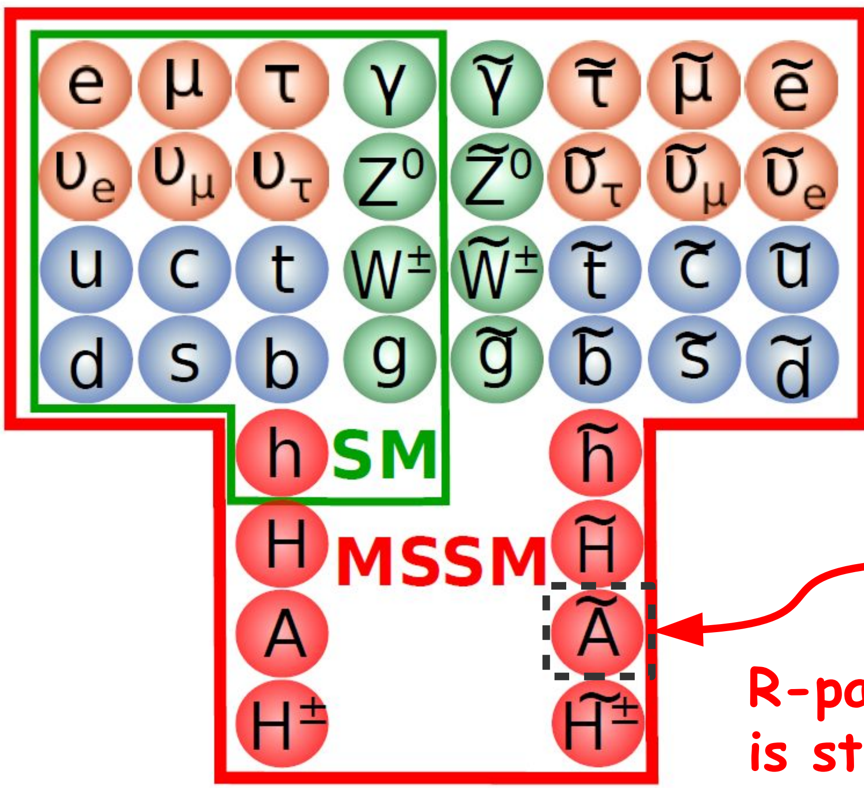

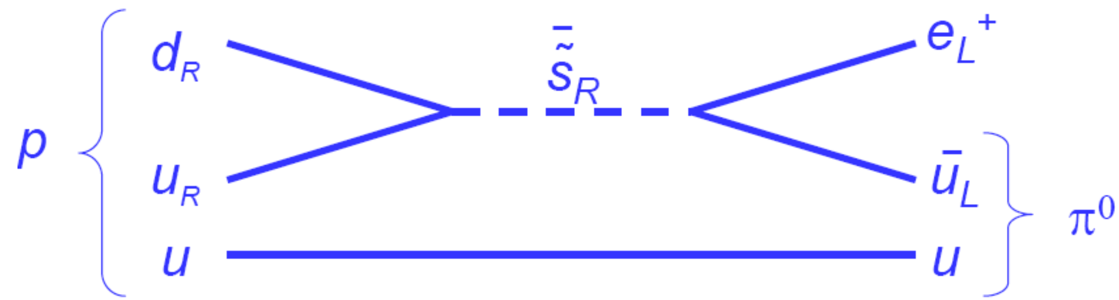

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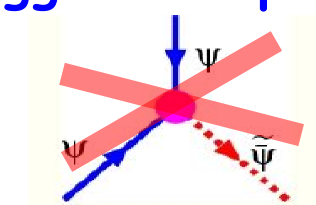
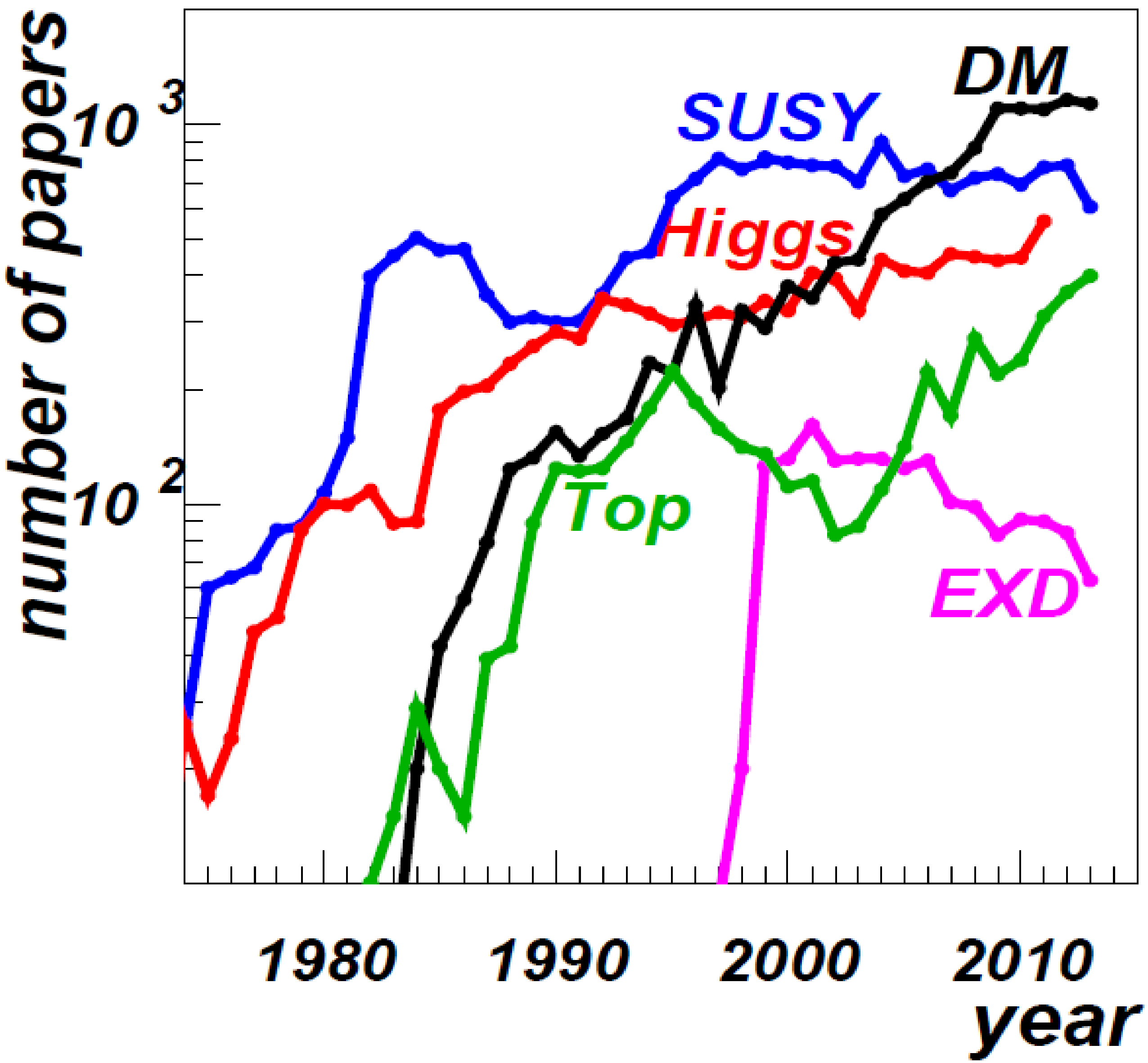


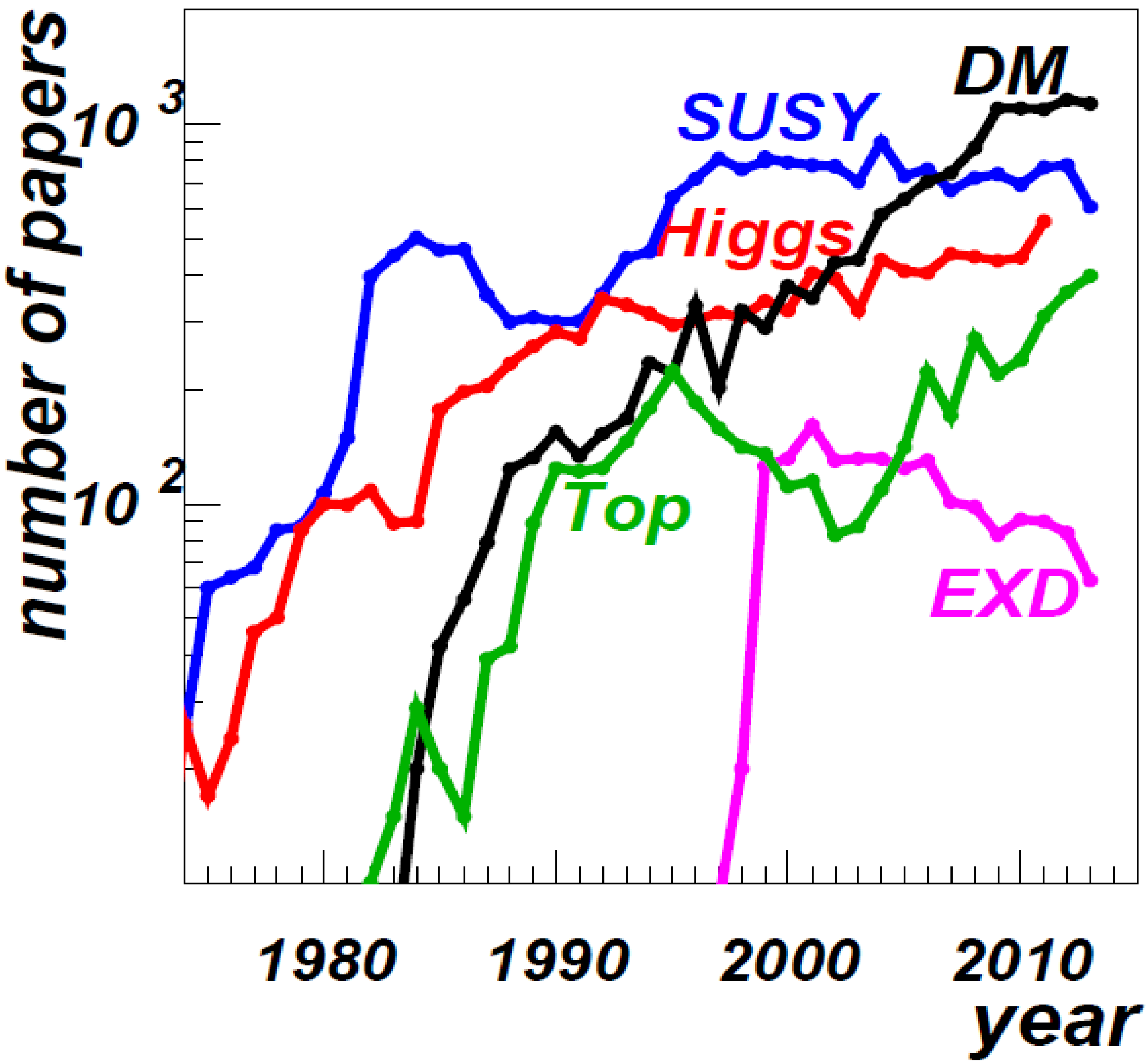
R-parity guarantees Lightest SUSY particle (LSP) is stable – DM candidate!

We are still inspired by this beauty ...



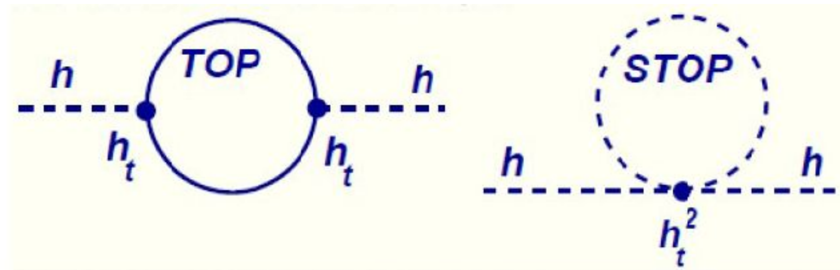
We are still inspired by this beauty ...

after more than 30 year unsuccessful searches ...

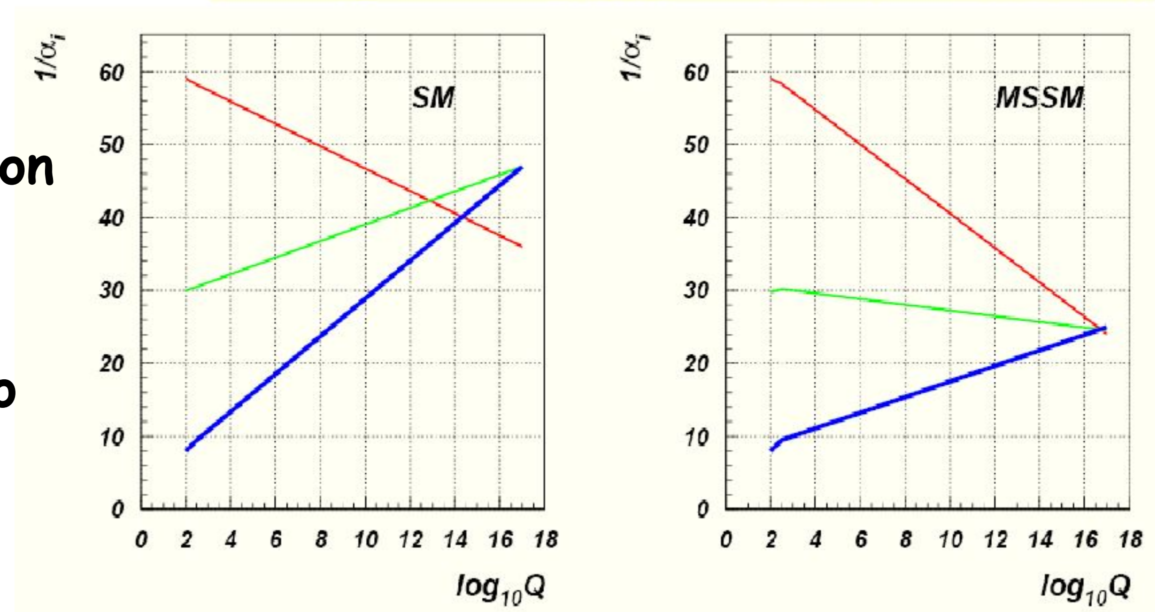


Beauty of SUSY

- 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



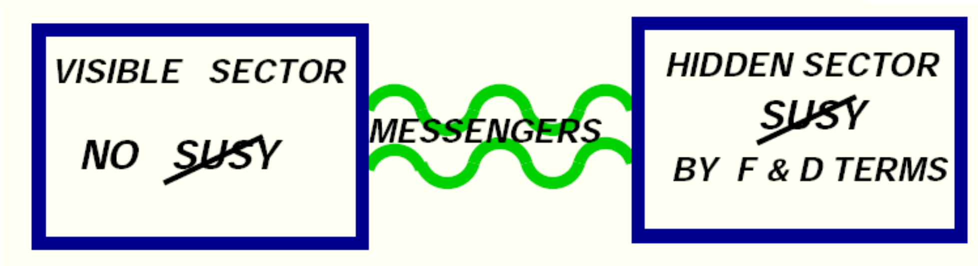
$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



It was not deliberately designed to solve the SM problems!

SUSY breaking and mSUGRA scenario

- SUSY is not observed $\Rightarrow$ must be broken



Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

$$\mathcal{L}^{MSSM}_{soft} = \underbrace{\sum_{i,j} B_{ij}\mu_{ij}S_iS_j}_{\text{bilinear terms}} + \underbrace{\sum_{ij} m^2_{ij}S_iS^\dagger_j}_{\text{scalar mass terms}} + \underbrace{\sum_{i,j,k} A_{ijk}f_{ijk}S_iS_jS_k}_{\text{trilinear scalar interactions}} + \underbrace{\sum_{A,\alpha} M_{A\alpha}\bar{\lambda}_{A\alpha}\lambda_{A\alpha}}_{\text{gaugino mass terms}}$$

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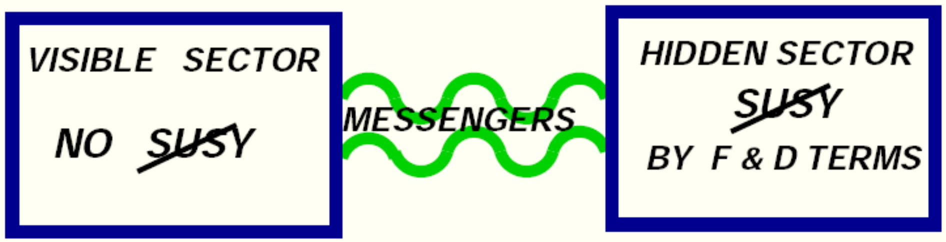

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- SUGRA: the hidden sector communicates with visible one via gravity – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

SUGRA: $M_a = f_a \frac{\langle F \rangle}{M_P}$ $\quad m^2_{ij} = k_{ij}\frac{|\langle F \rangle|^2}{M_P^2}$ $\quad A_{ijk} = y_{ijk}\frac{\langle F \rangle}{M_P}$

mSUGRA: $\Longrightarrow m_{1/2}$ $\quad \Longrightarrow m_0^2$ $\quad \Longrightarrow A_0$

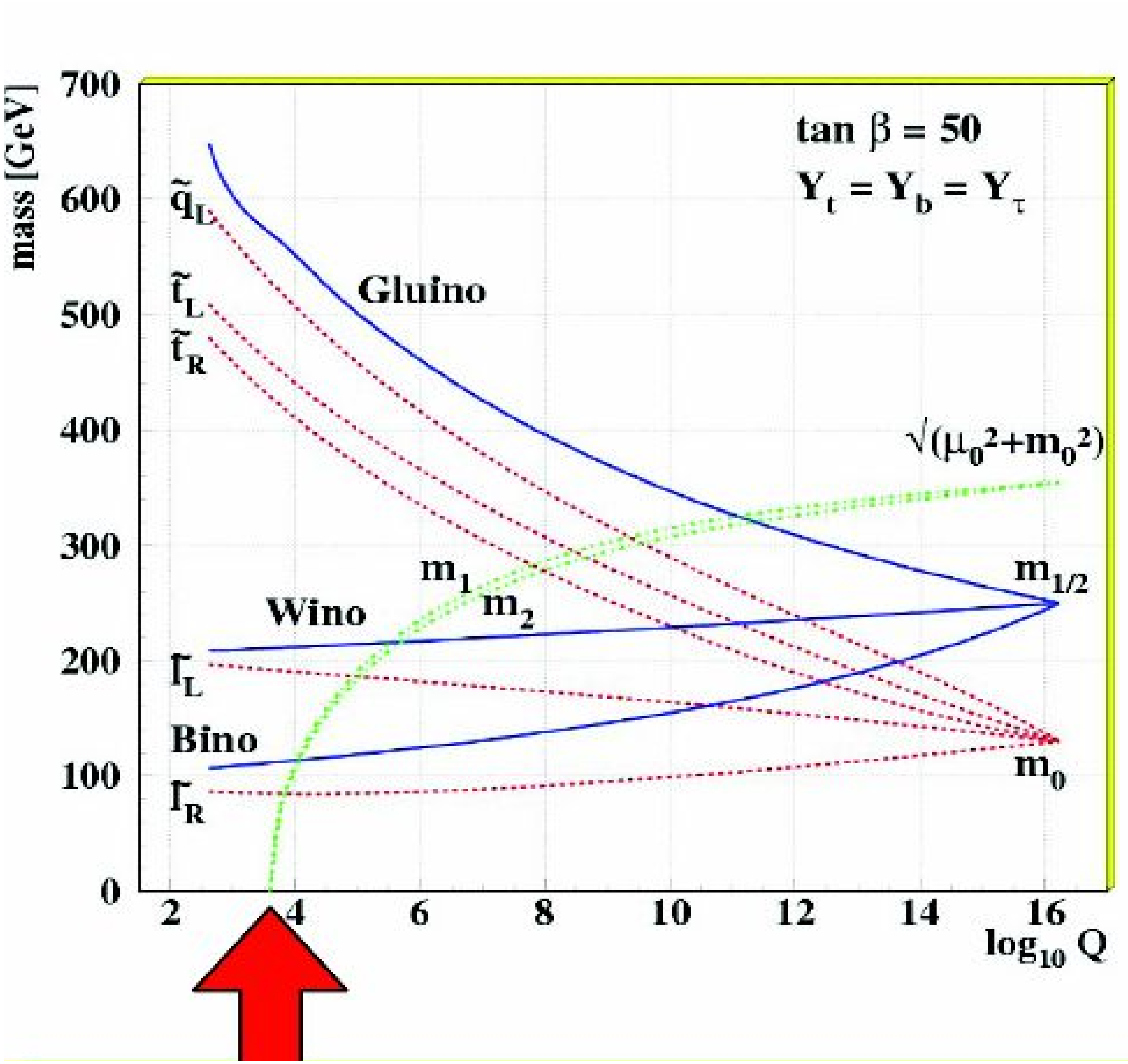
flat Kähler metric takes care of constraining of Flavor violating processes

- $sign(\mu)$, μ^2 value is fixed by the minim condition for Higgs potential
- B - parameter – usually expressed via $\tan\beta$
- $\Rightarrow$ mSUGRA parameters: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

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

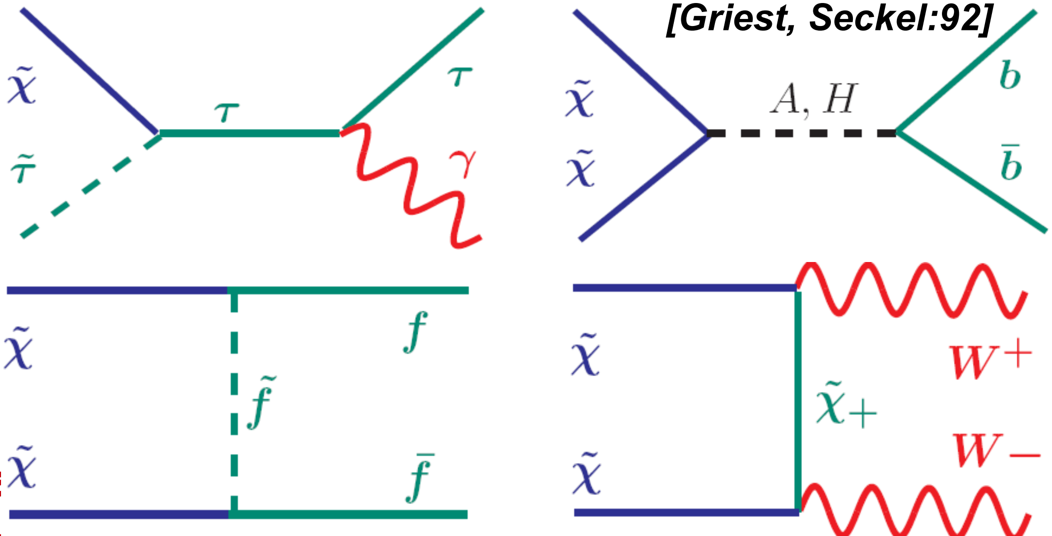
Evolution of neutralino relic density

Challenge is to evaluate thousands annihilation/co-annihilation diagrams

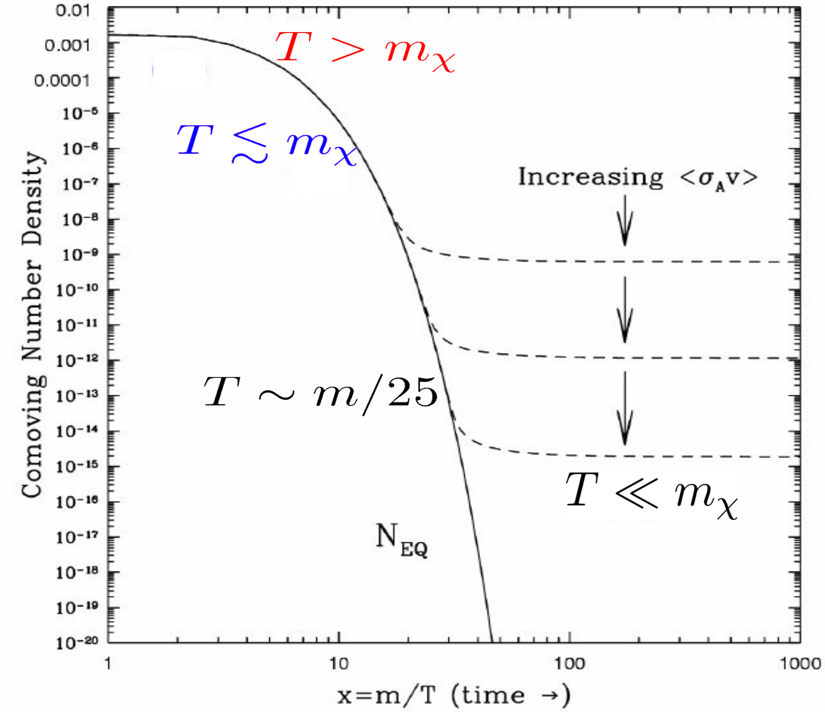
time evolution of number density is given by Boltzmann equation

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

[Griest, Seckel:92]



$\langle \sigma_A v \rangle$



re

thermal equilibrium stage:

universe cools:

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

neutralinos "freeze-out" at

$T > m_\chi, \quad \chi\chi \leftrightarrow f\bar{f}$

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

$$T_F \sim m/25$$

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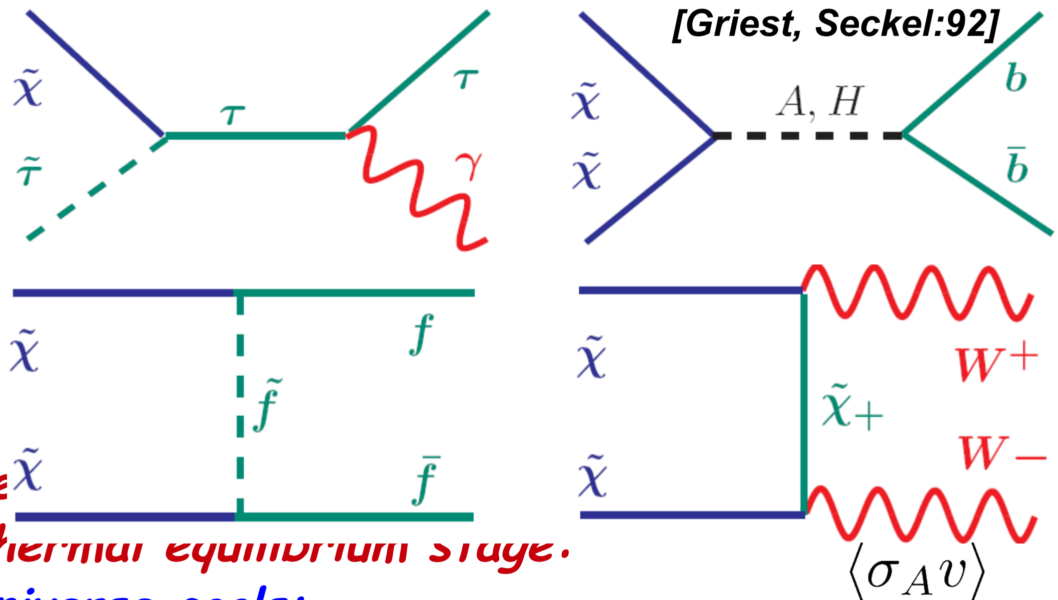

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Packages:
MicrOMEGAs(Pukhov et al), DarkSusy, ISARED

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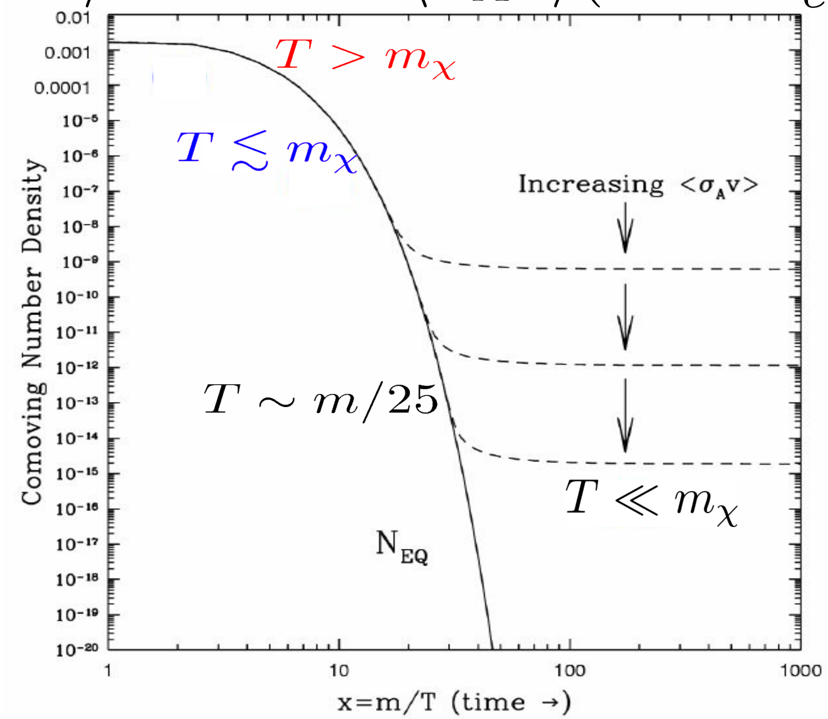


$$\Omega_\chi = \frac{10^{-10}\text{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

$$\langle\sigma_A v\rangle = 1\text{pb}$$

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

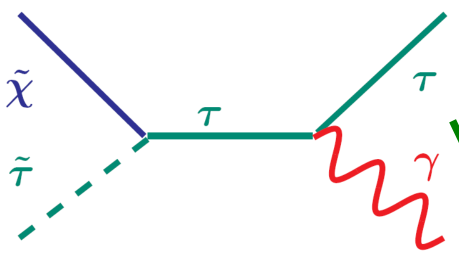
$$m = 100\text{GeV}$$

mass of the mediator

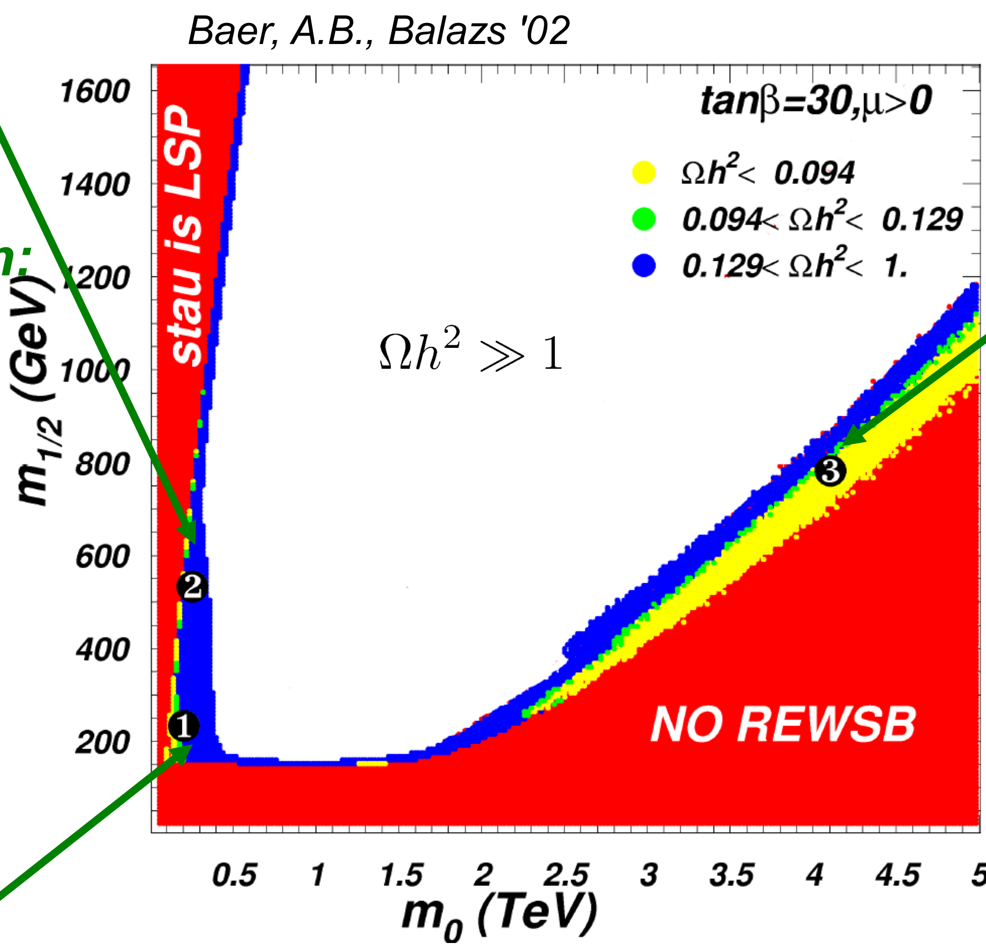
Neutralino relic density in mSUGRA

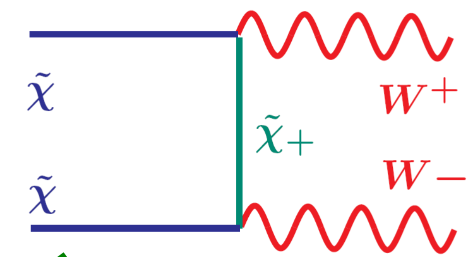
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

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



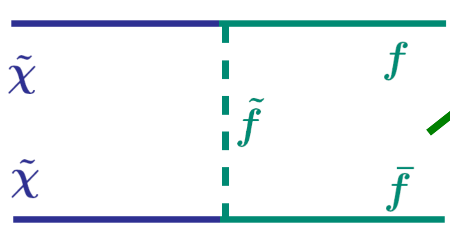
2. stau coannihilation:
degenerate χ and stau





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

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

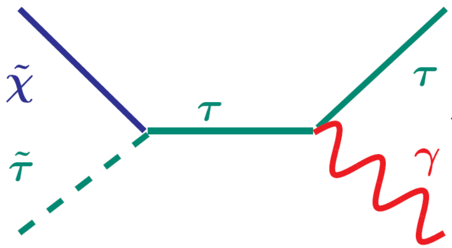


1. bulk region: ***light sfermions***

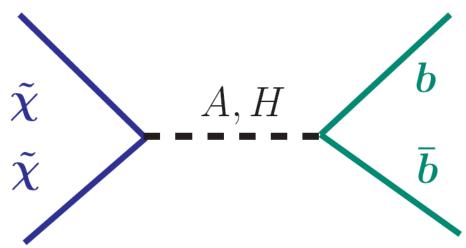
Neutralino relic density in mSUGRA

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

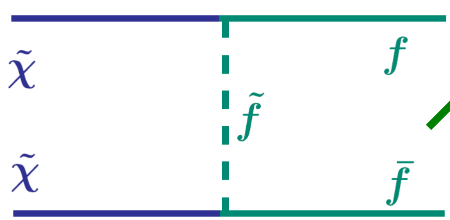
special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$



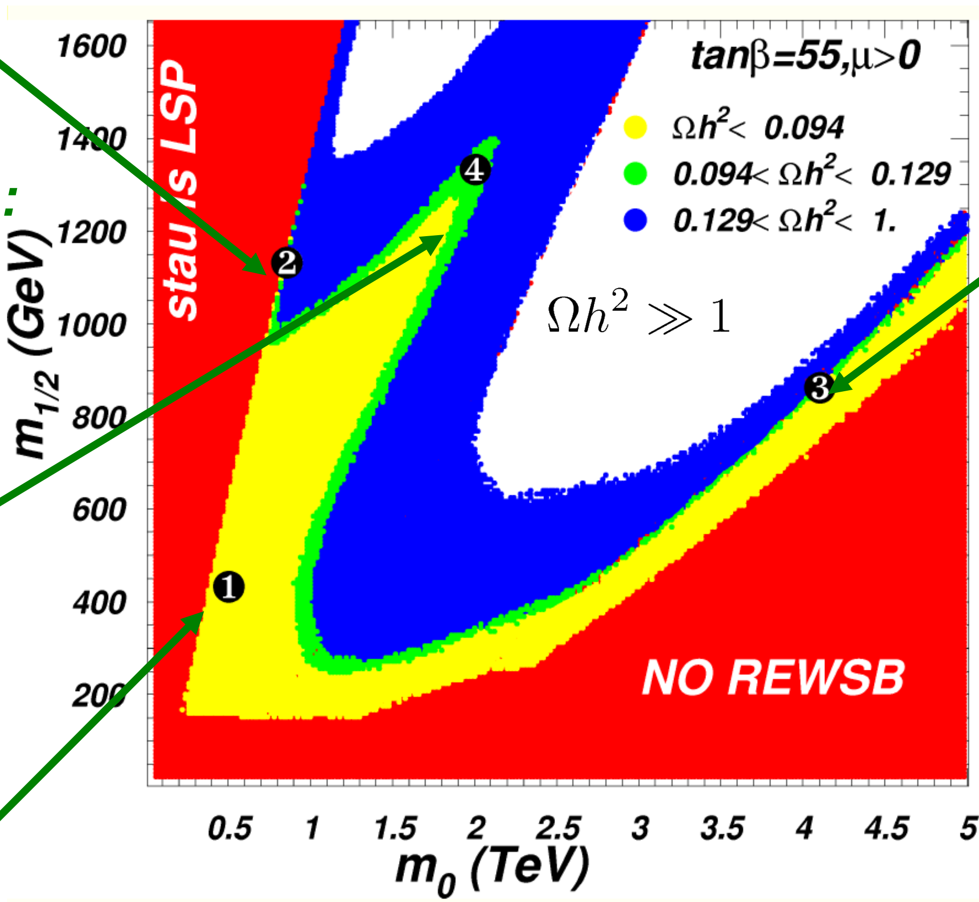
2. stau coannihilation:
degenerate χ and stau



4. funnel: ***(large tanβ)***
annihilation via A, H



Baer, A.B., Balazs '02



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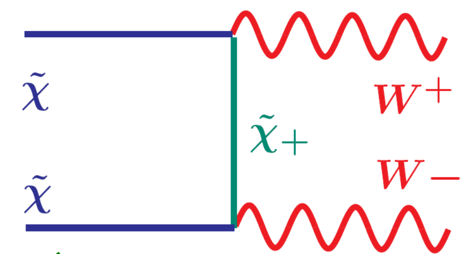


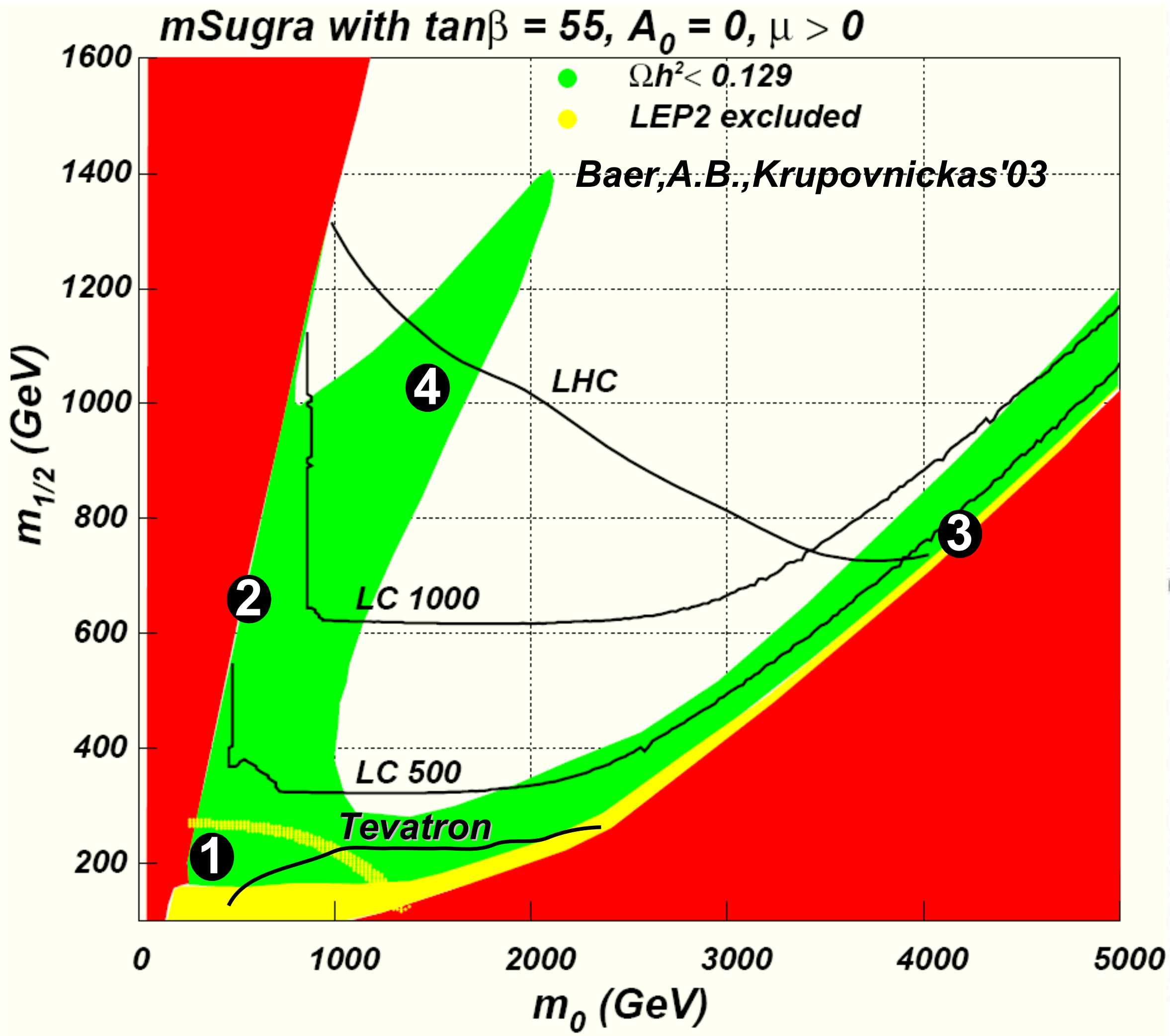
3. focus point:
mixed neutralino, low μ, importance of higgsino-wino component

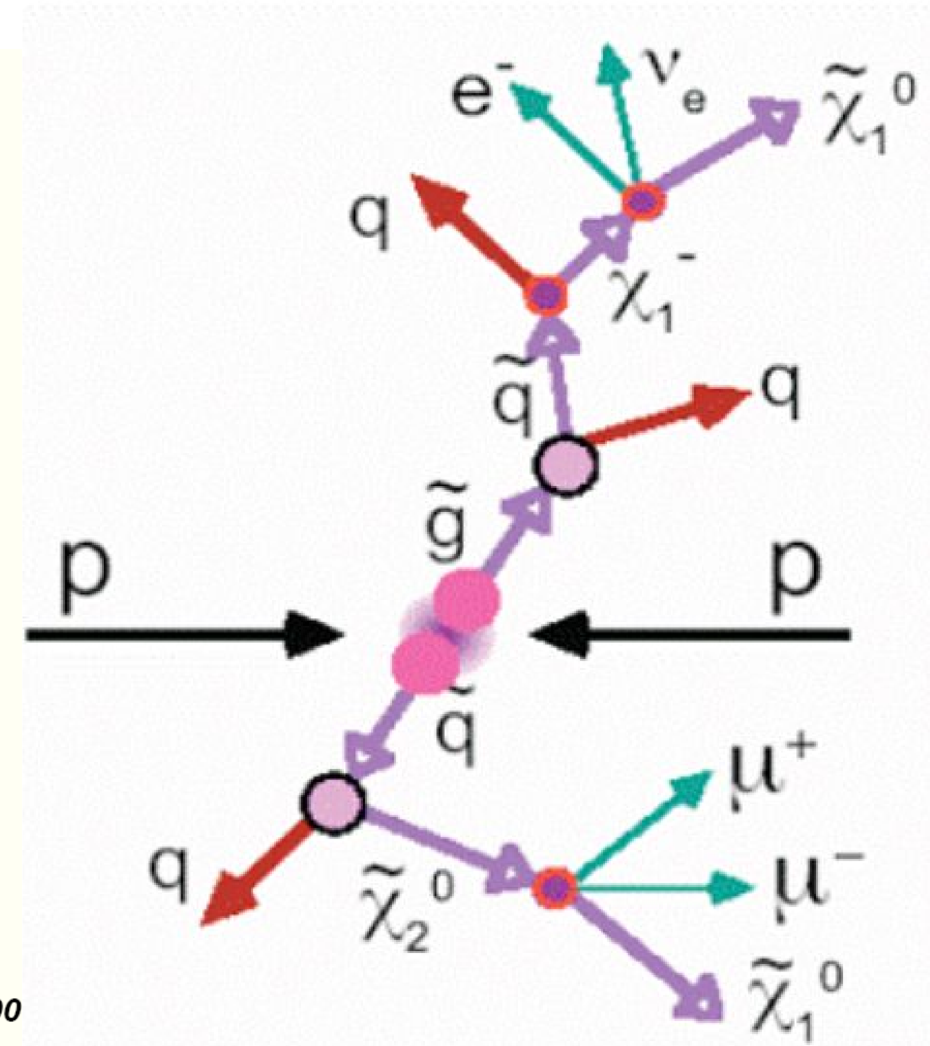
$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2 m_{1/2}^2$$

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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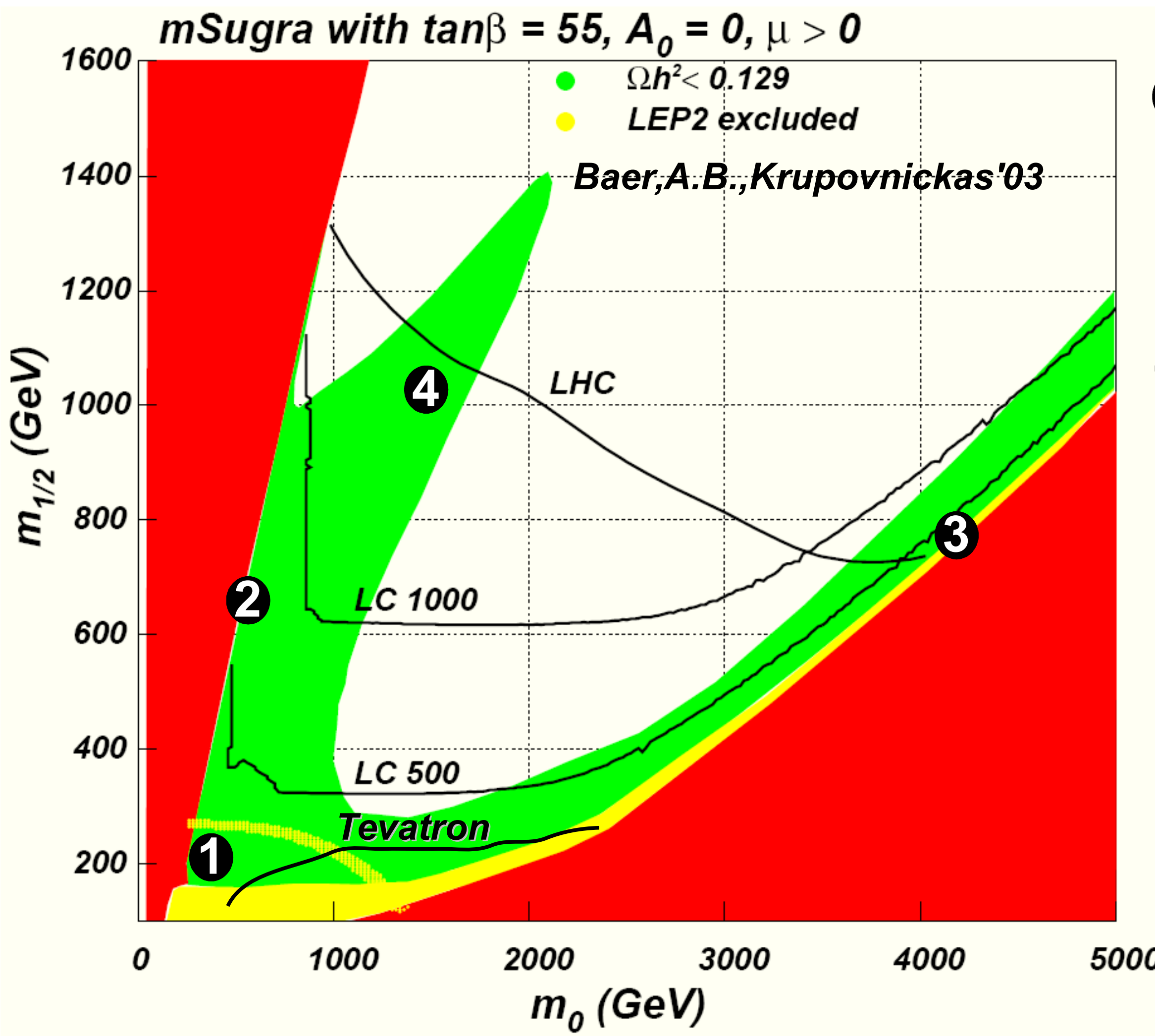
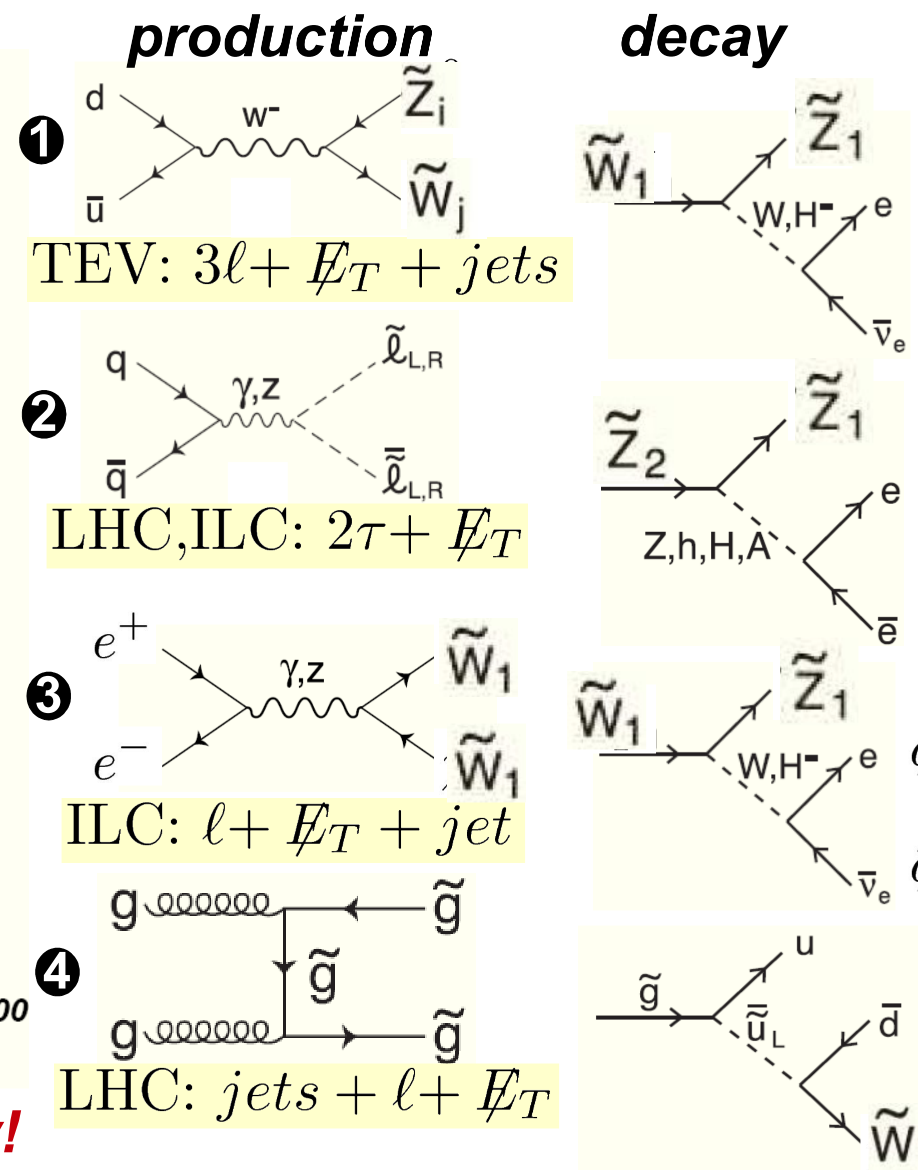


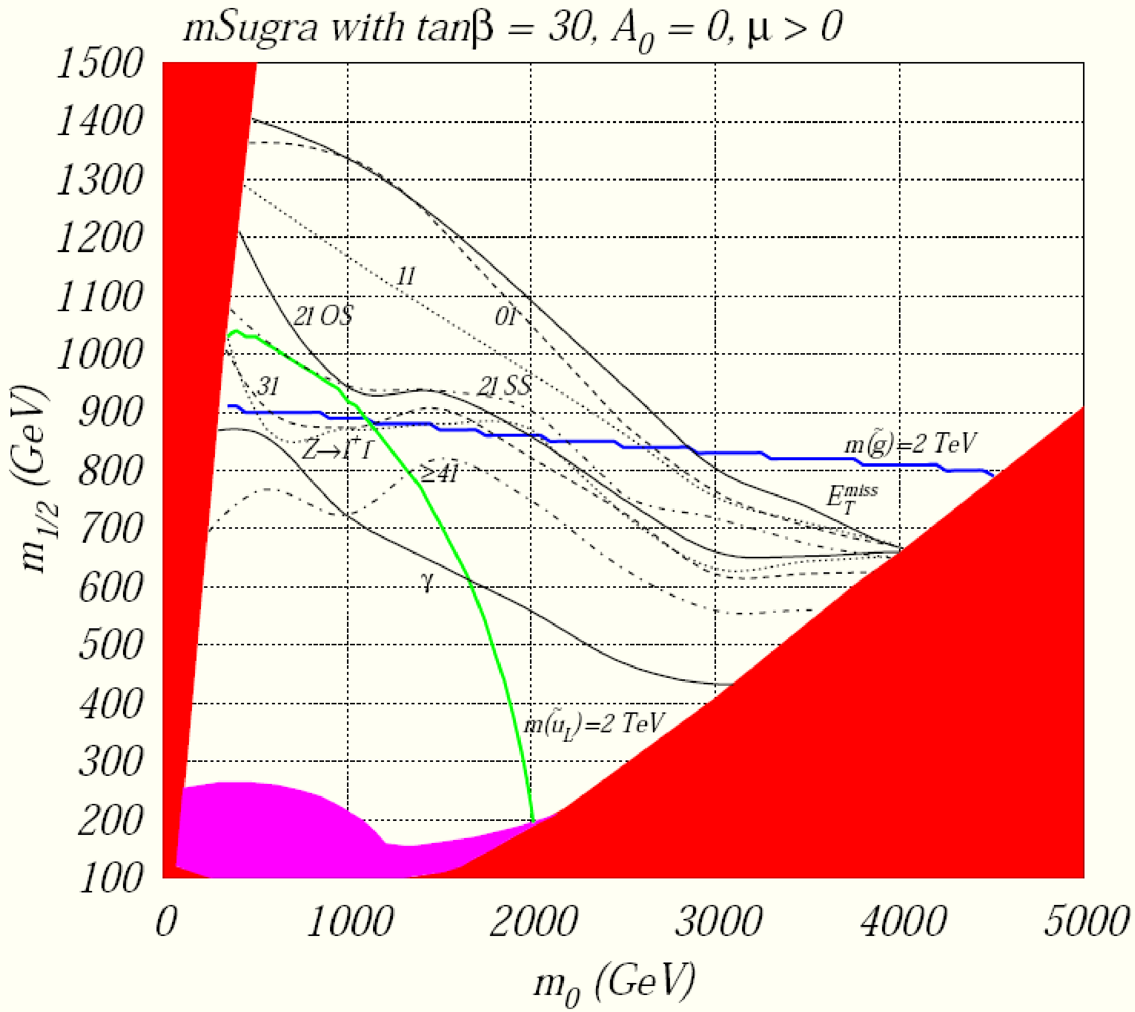


LHC and ILC are highly complementary!

Collider signatures in DM allowed regions

$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV   BG: $W + jets$, $Z + jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$

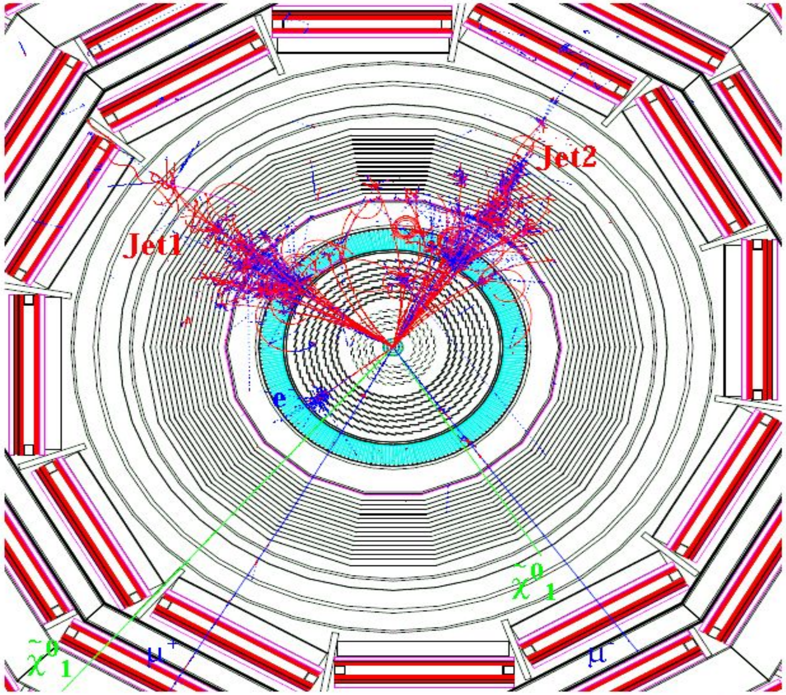
- $\not{E}_T+$ jets
- $1\ell+ \not{E}_T+$ jets
- $opposite - sign\ (OS)\ 2\ell+ \not{E}_T+$ jets
- $same - sign\ (SS) 2\ell+ \not{E}_T+$ jets
- $3\ell+ \not{E}_T+$ jets
- $4\ell+ \not{E}_T+$ jets
- $5\ell+ \not{E}_T+$ jets



reach to m $\tilde{g} \sim 1.8$ (3) TeV for high (low)m_0

SUSY event with 3 lepton + 2 Jets signature

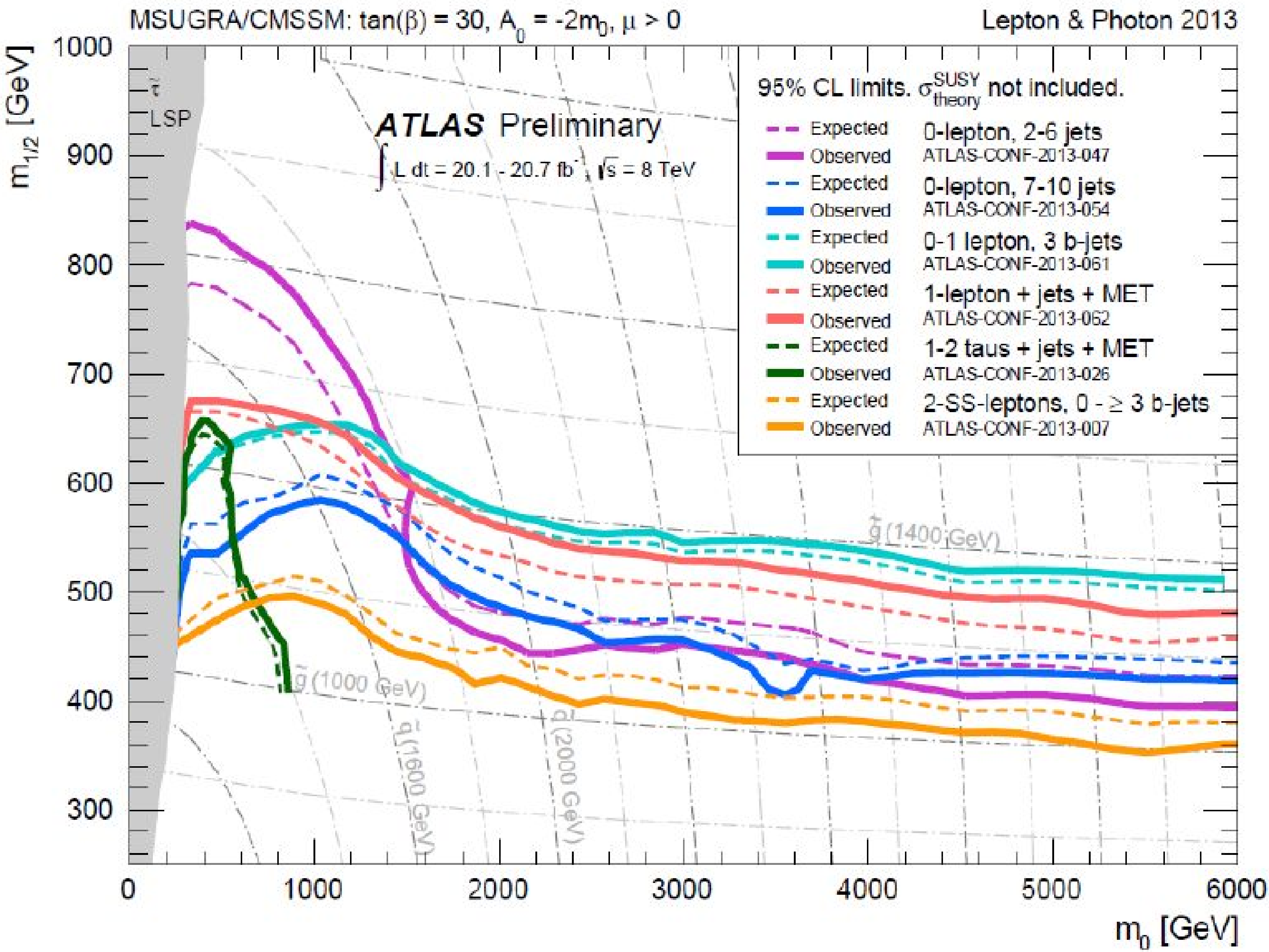
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV, tanβ = 2, A_0 = 0, μ < 0, m($\tilde{q}$) = 686 GeV, m($\tilde{g}$) = 766 GeV, m($\tilde{\chi}^0_2$) = 257 GeV, m($\tilde{\chi}^0_1$) = 128 GeV.



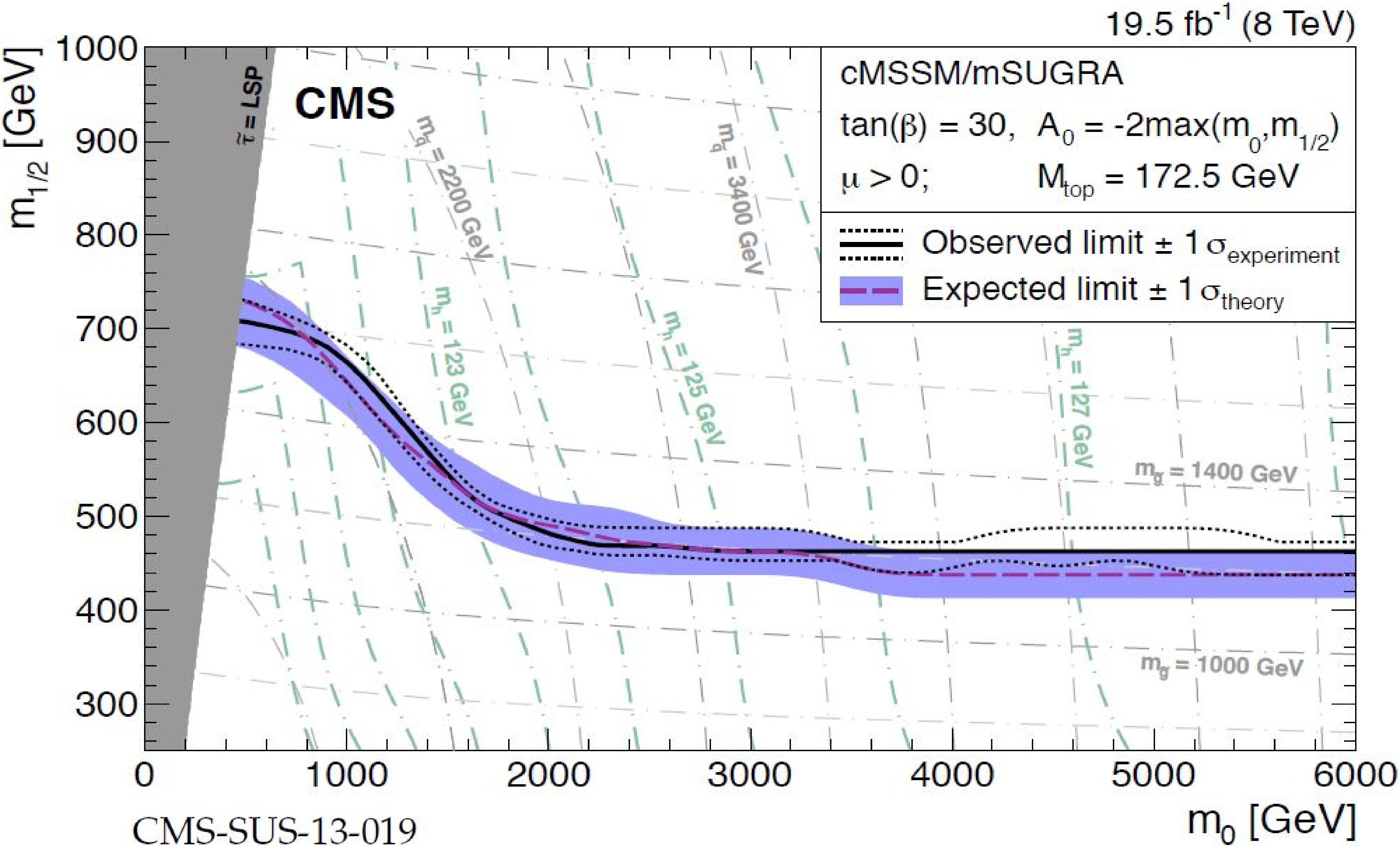
Leptons:	Jets:	Sparticles:
$p_t(\mu^+)$ = 55.2 GeV	E_t(Jet1) = 237 GeV	$p_t(\tilde{\chi}^0_1)$ = 95.1 GeV
$p_t(\mu^-)$ = 44.3 GeV	E_t(Jet2) = 339 GeV	$p_t(\tilde{\chi}^0_1)$ = 190 GeV
$p_t(e^-)$ = 43.9 GeV		

Charged particles with p_t > 2 GeV, |η| < 3 are shown; neutrons are not shown; no pile up events superimposed.

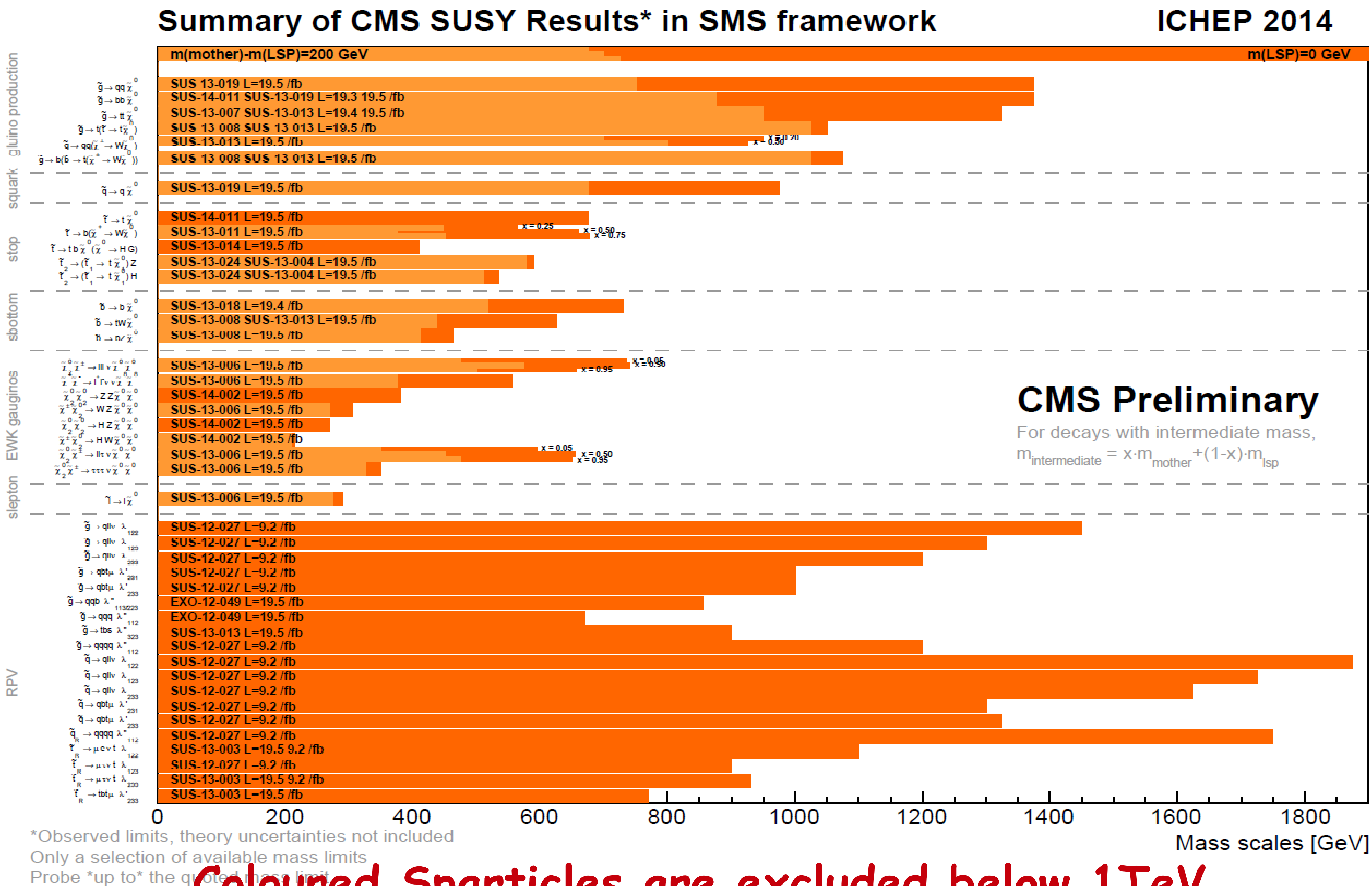
Limits from LHC8 for mSUGRA scenario



Limits from LHC8 for mSUGRA scenario

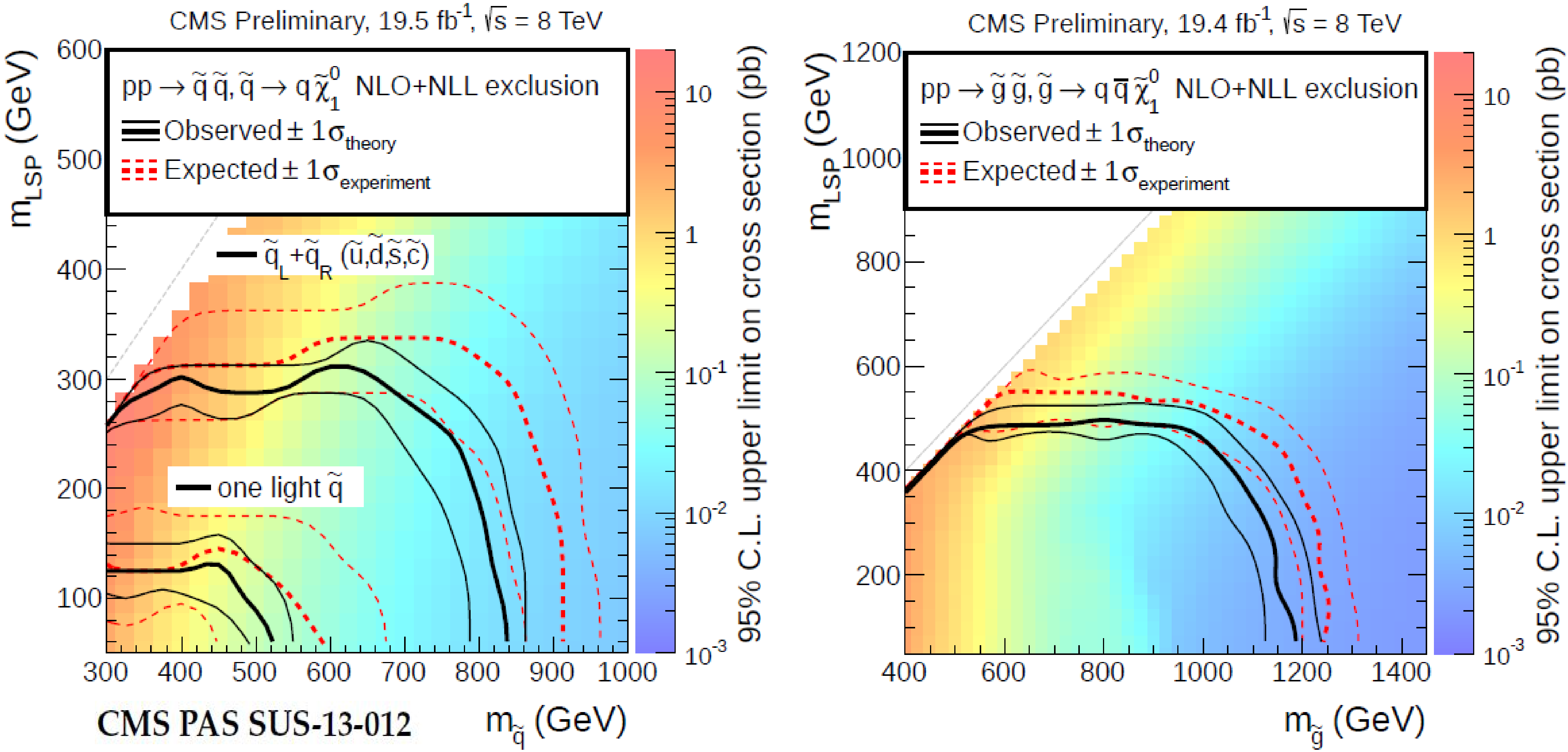


No SUSY hint from the experimental searches ...



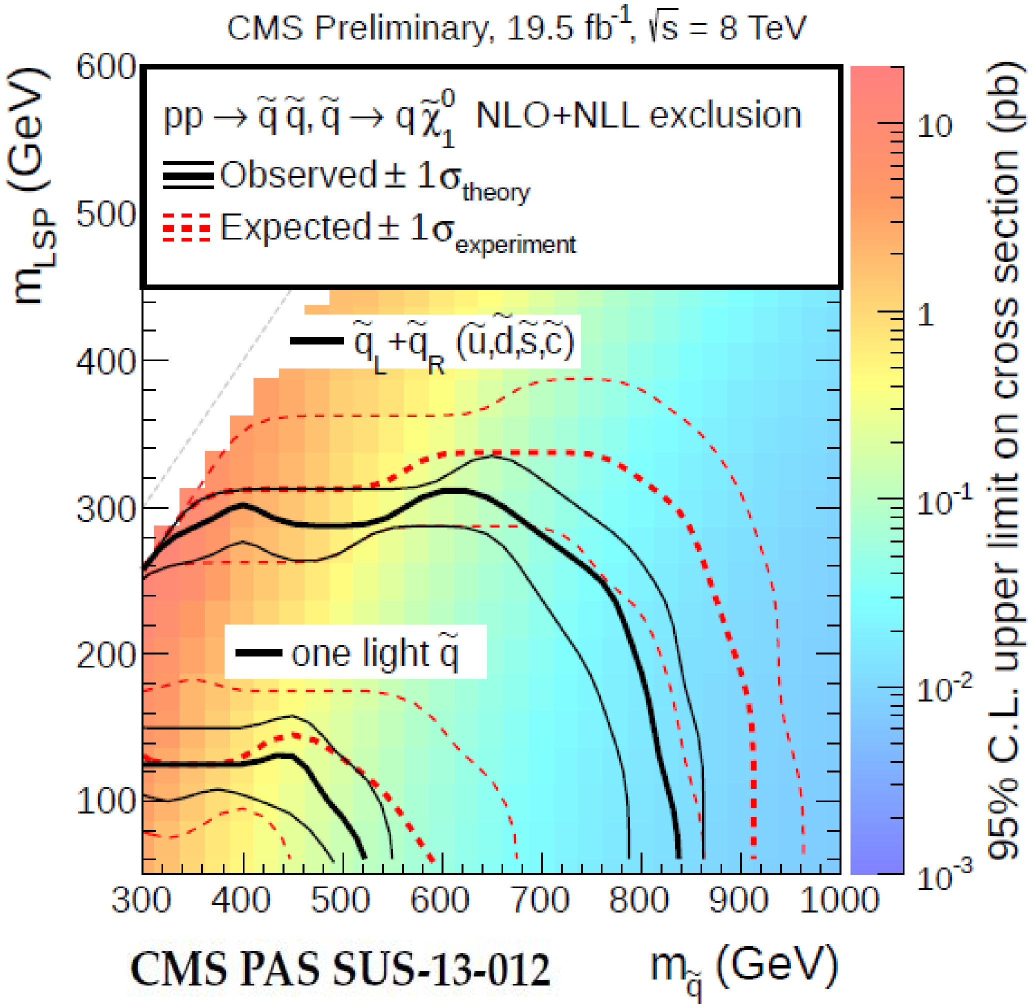
Coloured Sparticles are excluded below 1TeV for the large enough mass gap with LSP

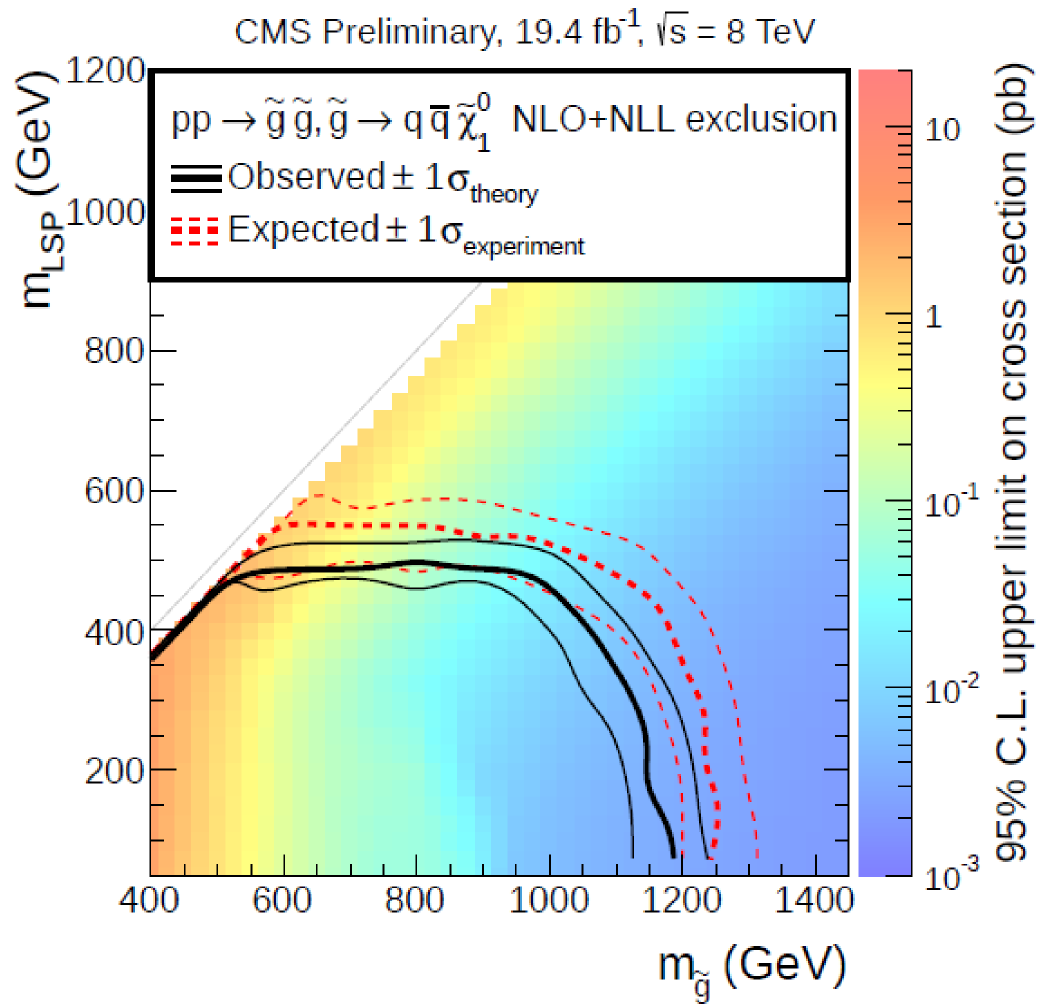
What is about DM mass?



CMS PAS SUS-13-012

What is about DM mass?



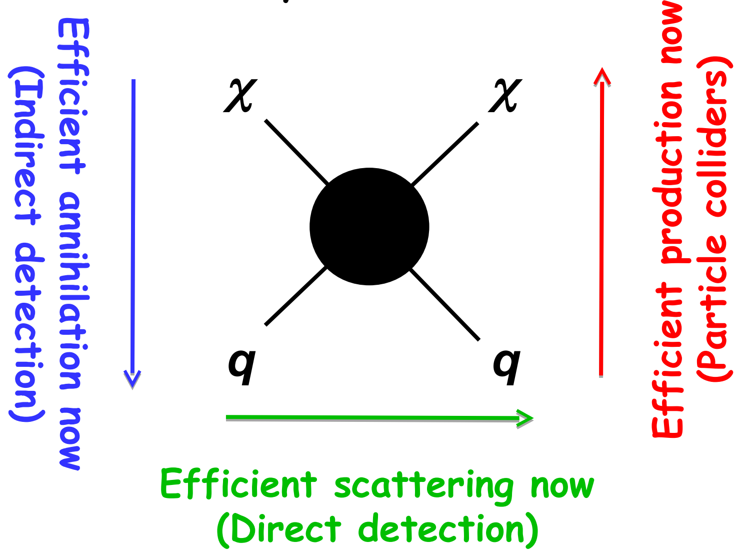


There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1 TeV

Complementarity of DM searches (from 2004)

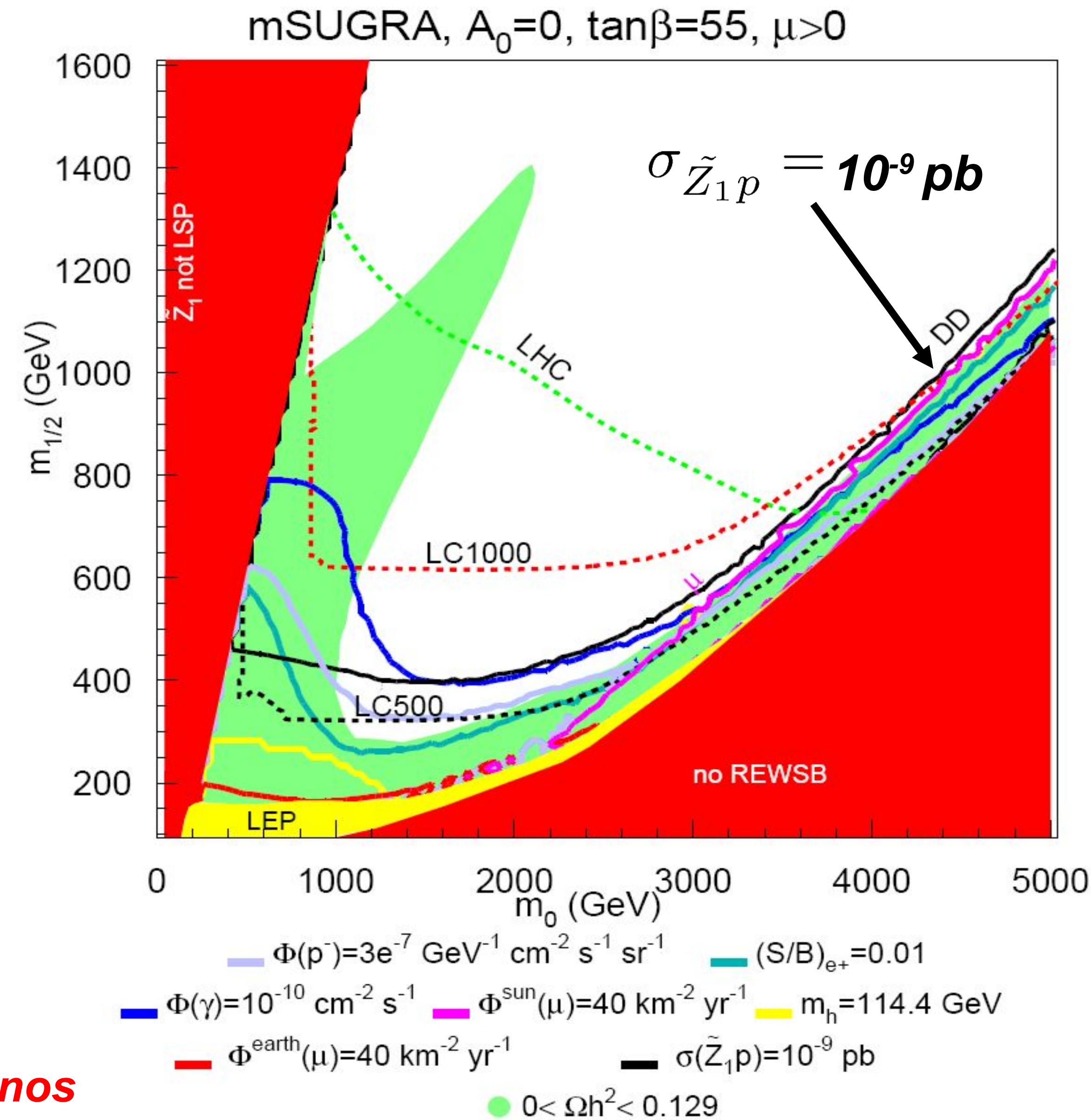
DM direct detection:
neutralino scattering off nuclei

Correct relic density → Efficient annihilation



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

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



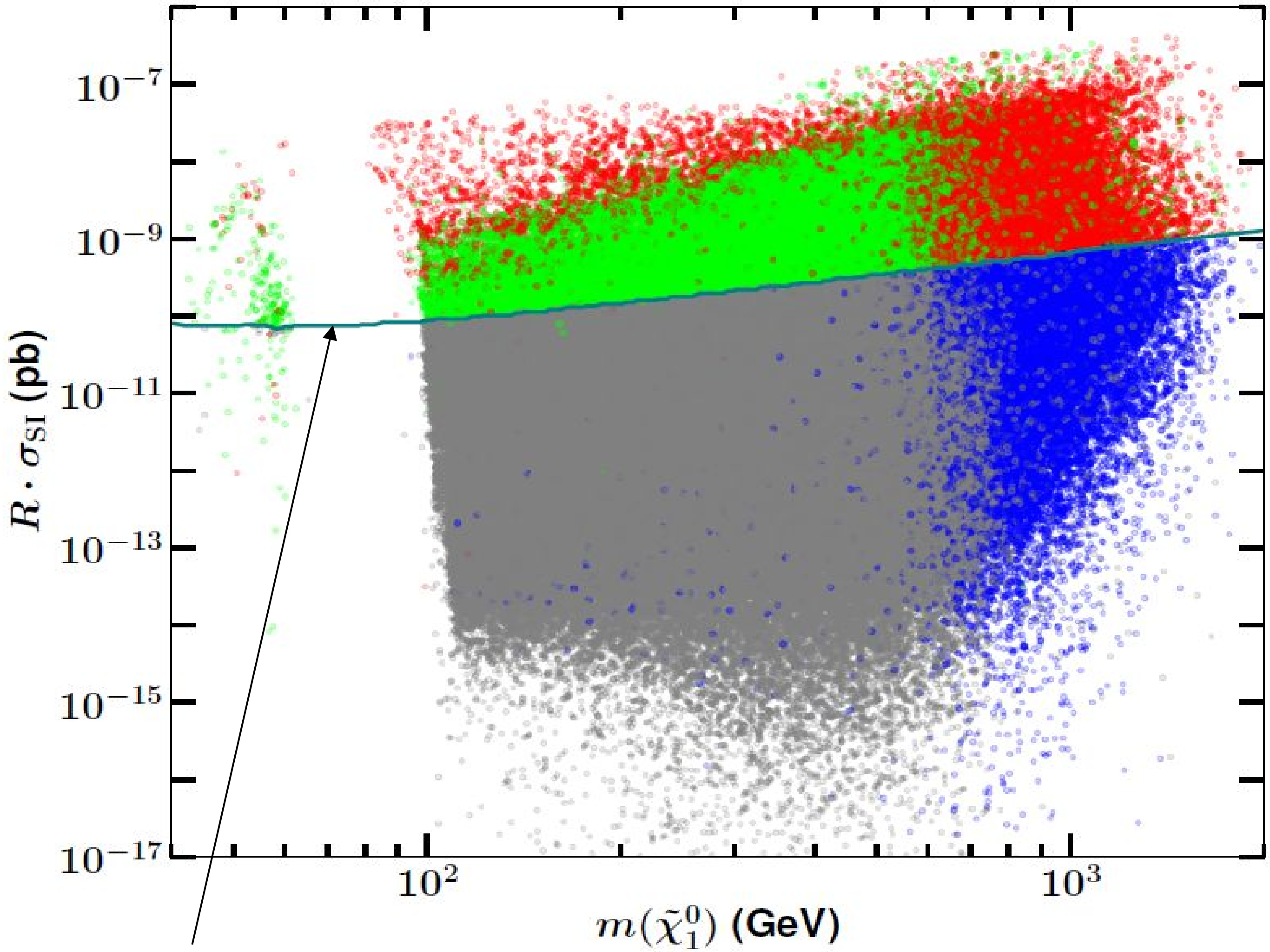
DM indirect detection:

signatures from neutralino annihilation
in halo, core of the Earth and Sun
photons, anti-protons, positrons, neutrinos

Neutrino telescopes: Amanda, Icecube, Antares

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

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

The EW measure requires that there be 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**

$$|\mu^2| \simeq M_Z^2$$
$$|m_{H_u}^2| \simeq M_Z^2$$

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

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

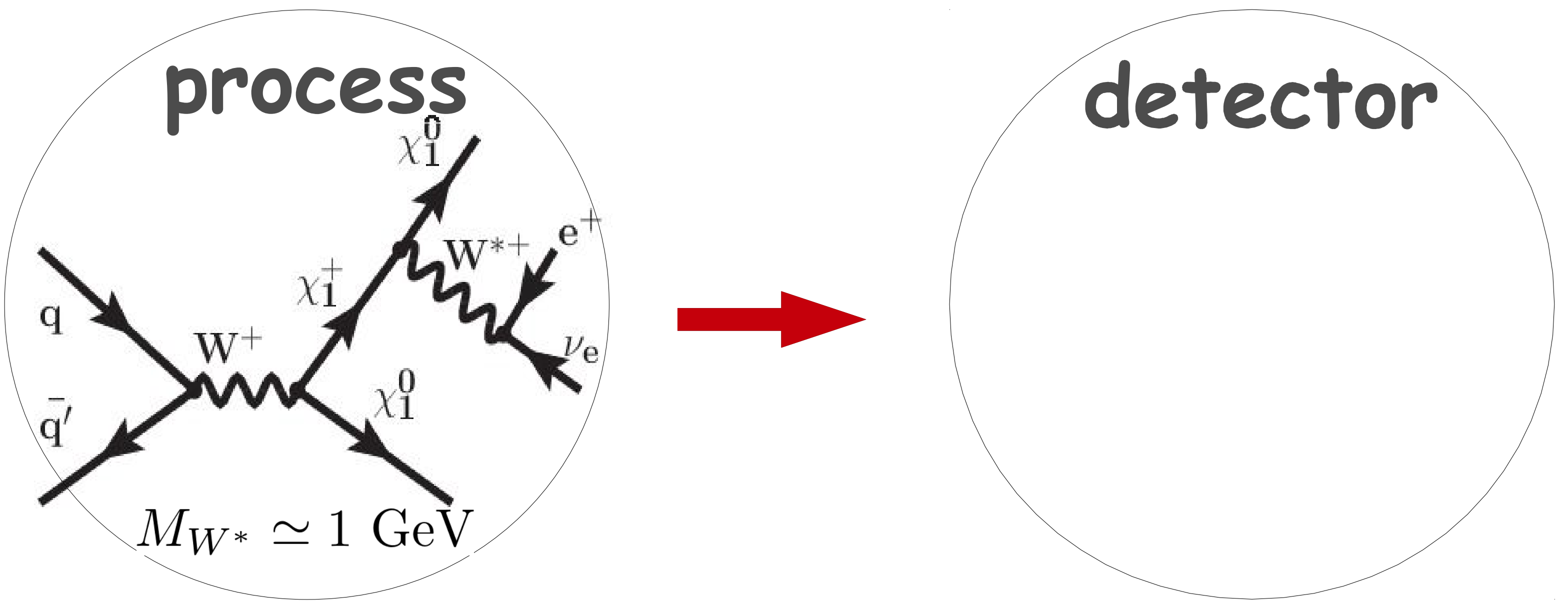
neutralinos

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

- Case of μ << 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, indicating that a weak scale SUSY spectrum is likely non-universal

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 as happen in FFP scenario.
- The only way to probe FFP 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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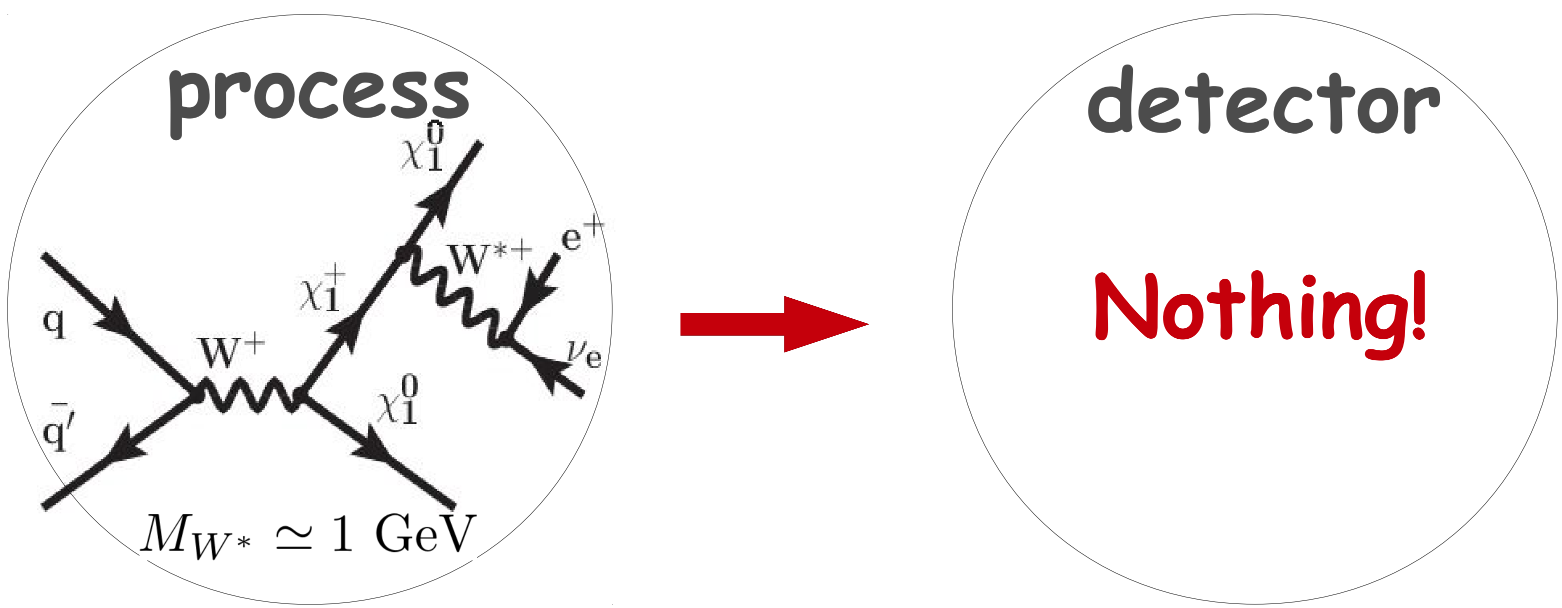

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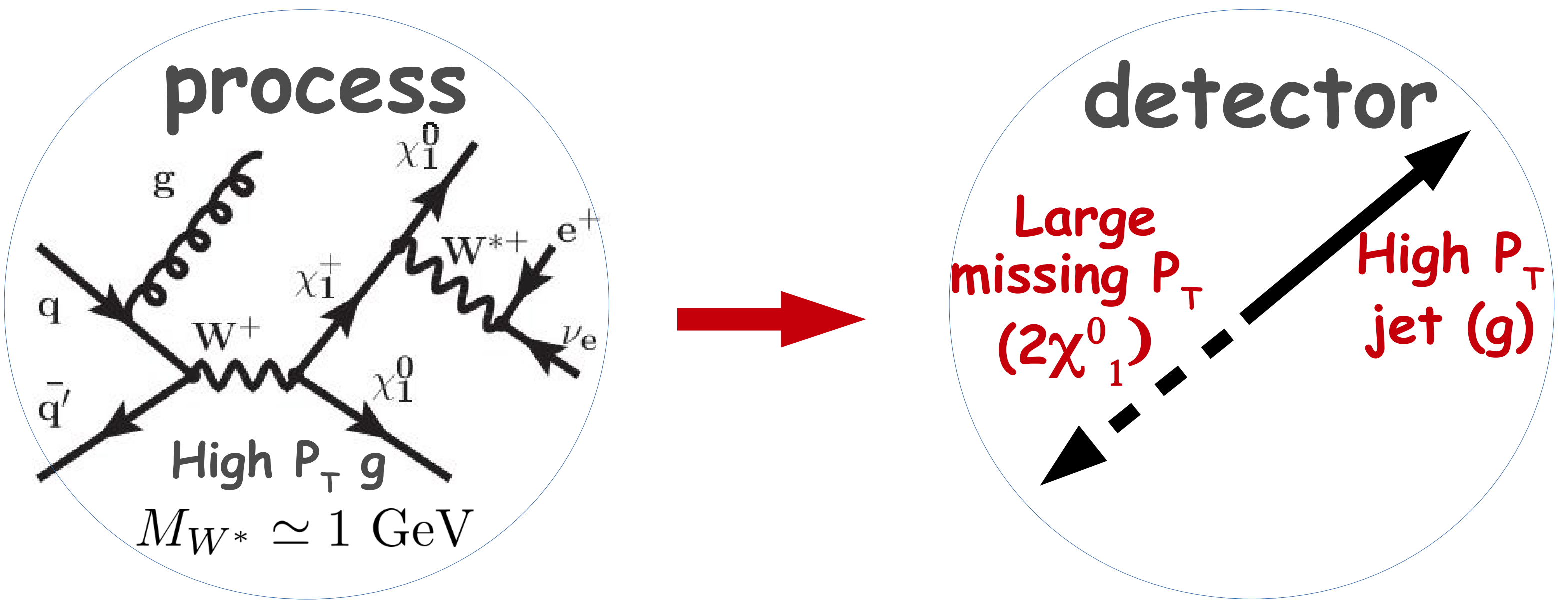

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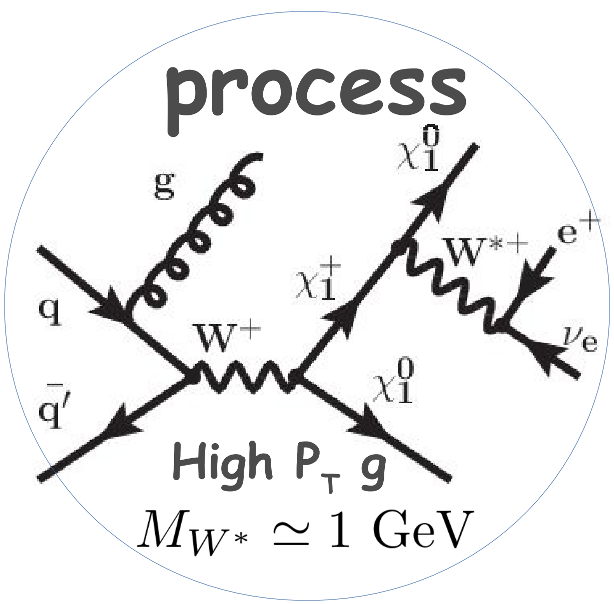
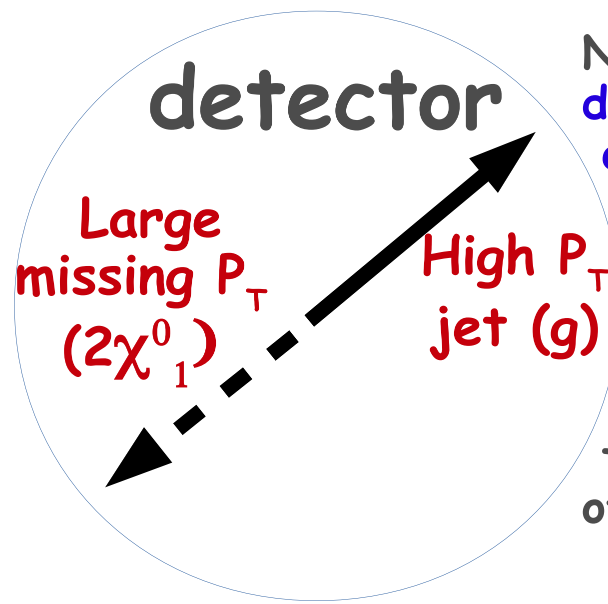




Note that W* decay products do not get large boost – it is proportional to the mass of W* which is much smaller than the mass of the LSP

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

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

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

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

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

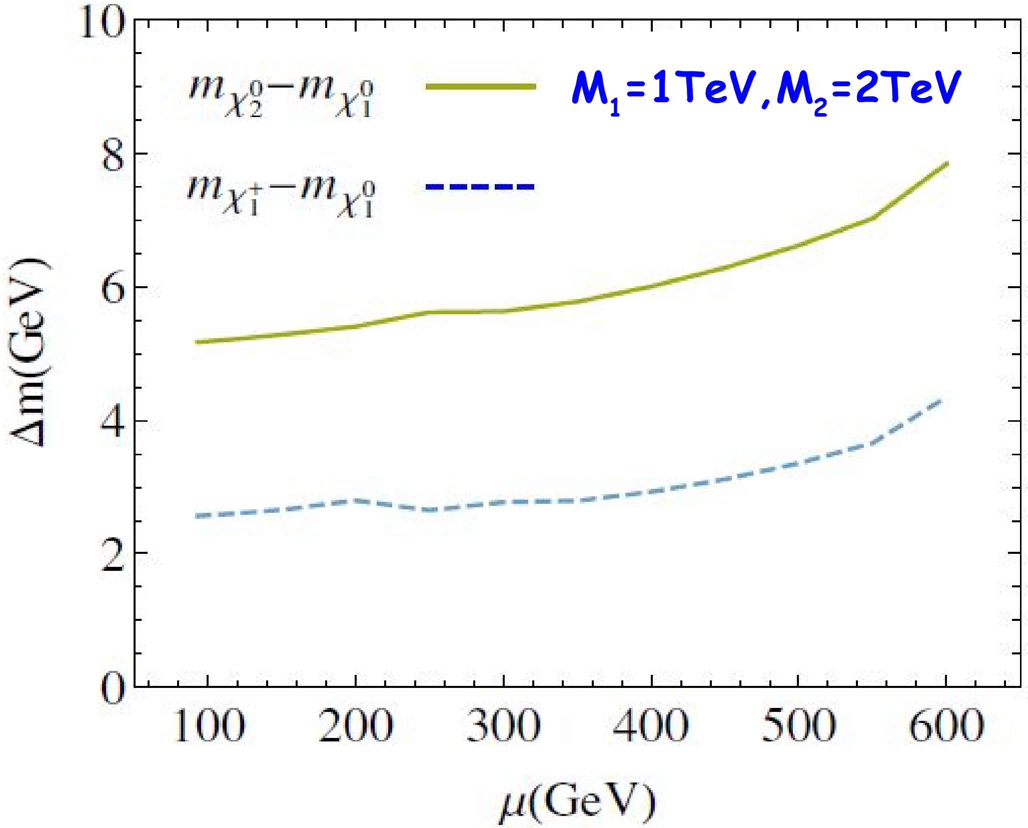
$$\Gamma(\tilde\chi_1^\pm, \tilde\chi_2^0 \to f\, f'\, \tilde\chi_1^0) = \frac{C^4}{120\pi^3}\frac{\Delta m^5}{\Lambda^4}$$

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

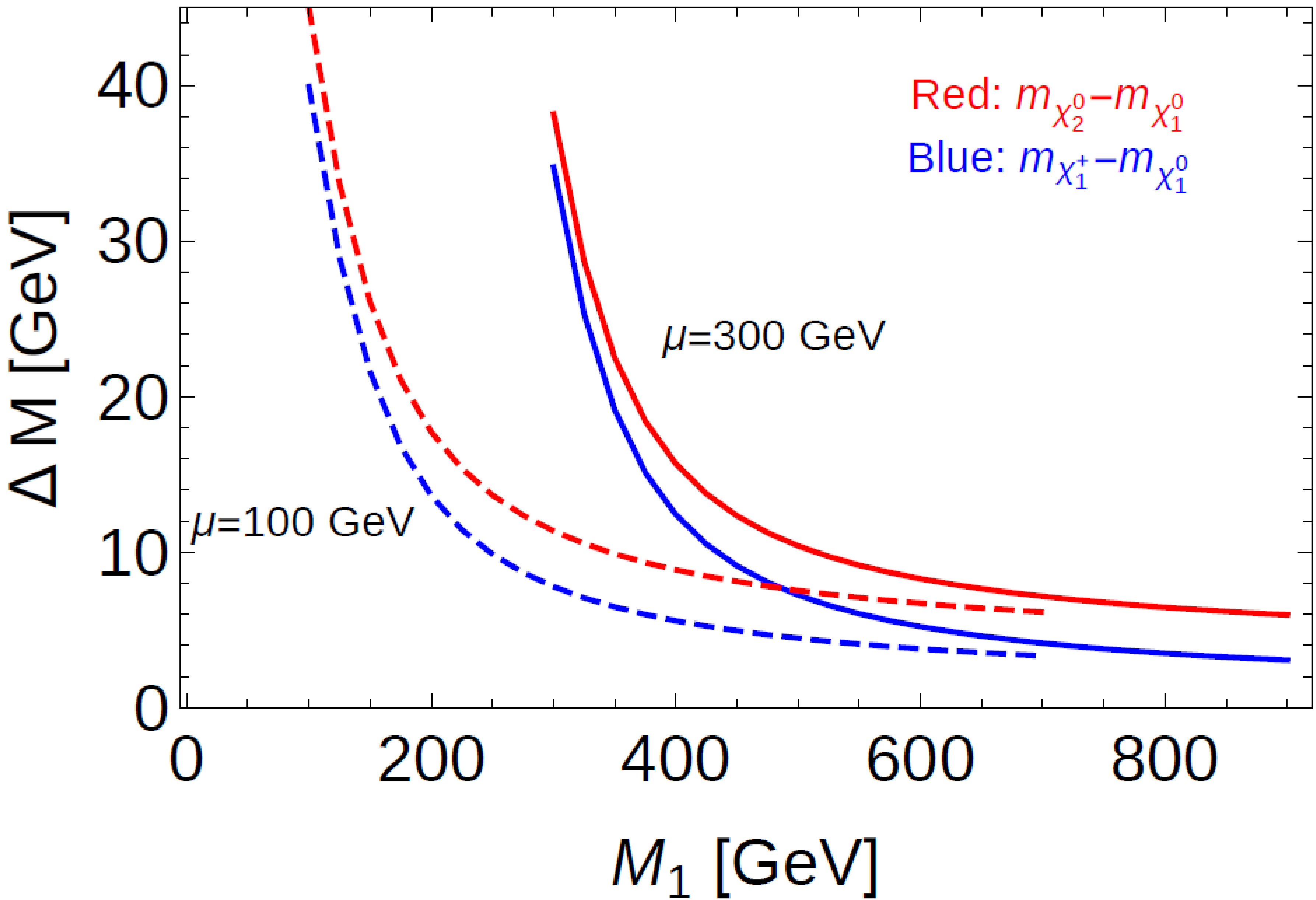
$$L = c\tau \simeq 0.01\ \text{cm}\left(\frac{\Delta m}{1\ \text{GeV}}\right)^{-5} \quad \tilde\chi_2^0 \to f\bar f\tilde\chi_1^0 \ \text{(Z-exchange)}$$

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

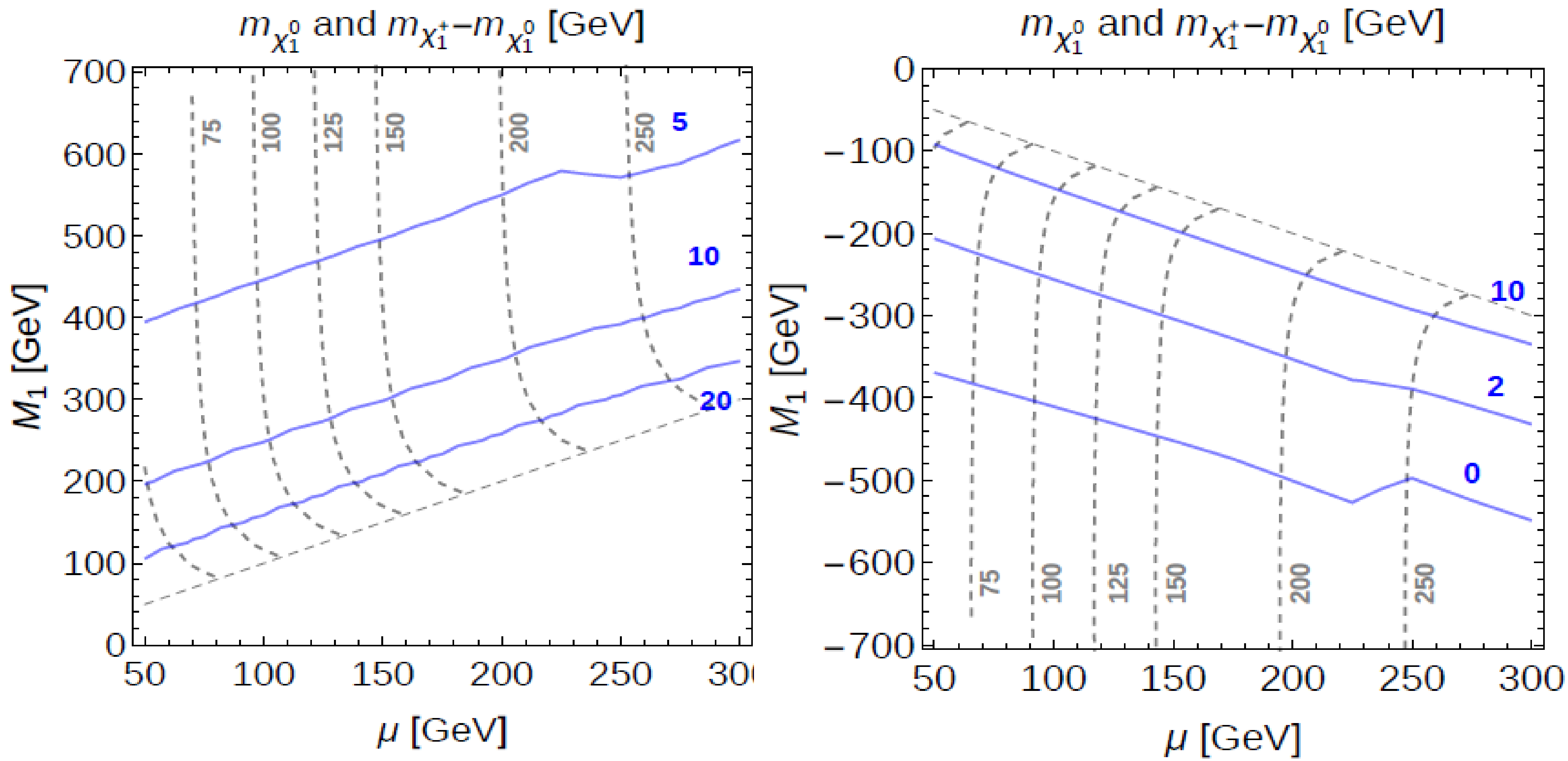
for Δm < 1 GeV we expect to start seeing displaced vertices ~ 0.1mm



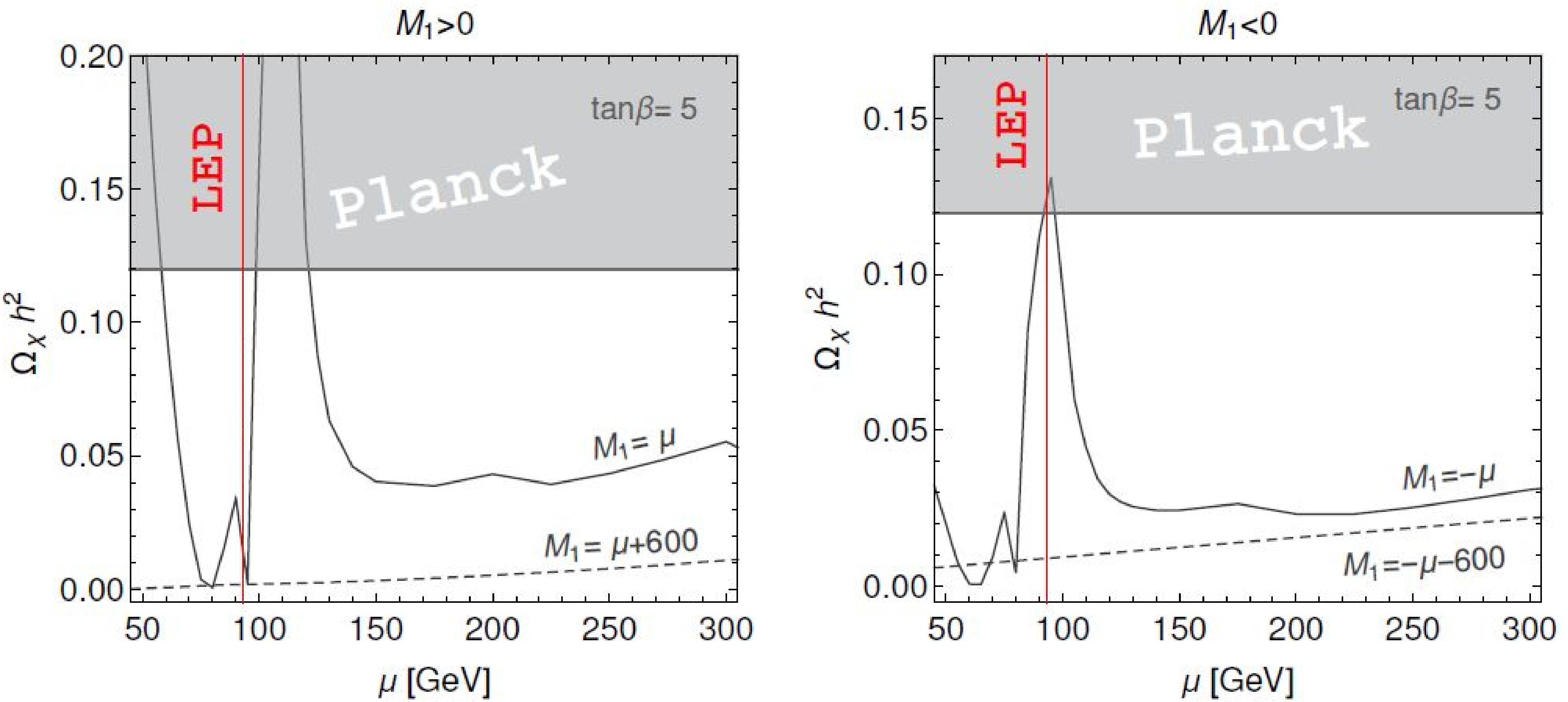
$\Delta M = m_{\chi^\pm} - m_{\chi^0}$ VS M_1 plane



ΔM pattern for $M_1>0$ and $M_1<0$ cases



Dark Matter Relic Density



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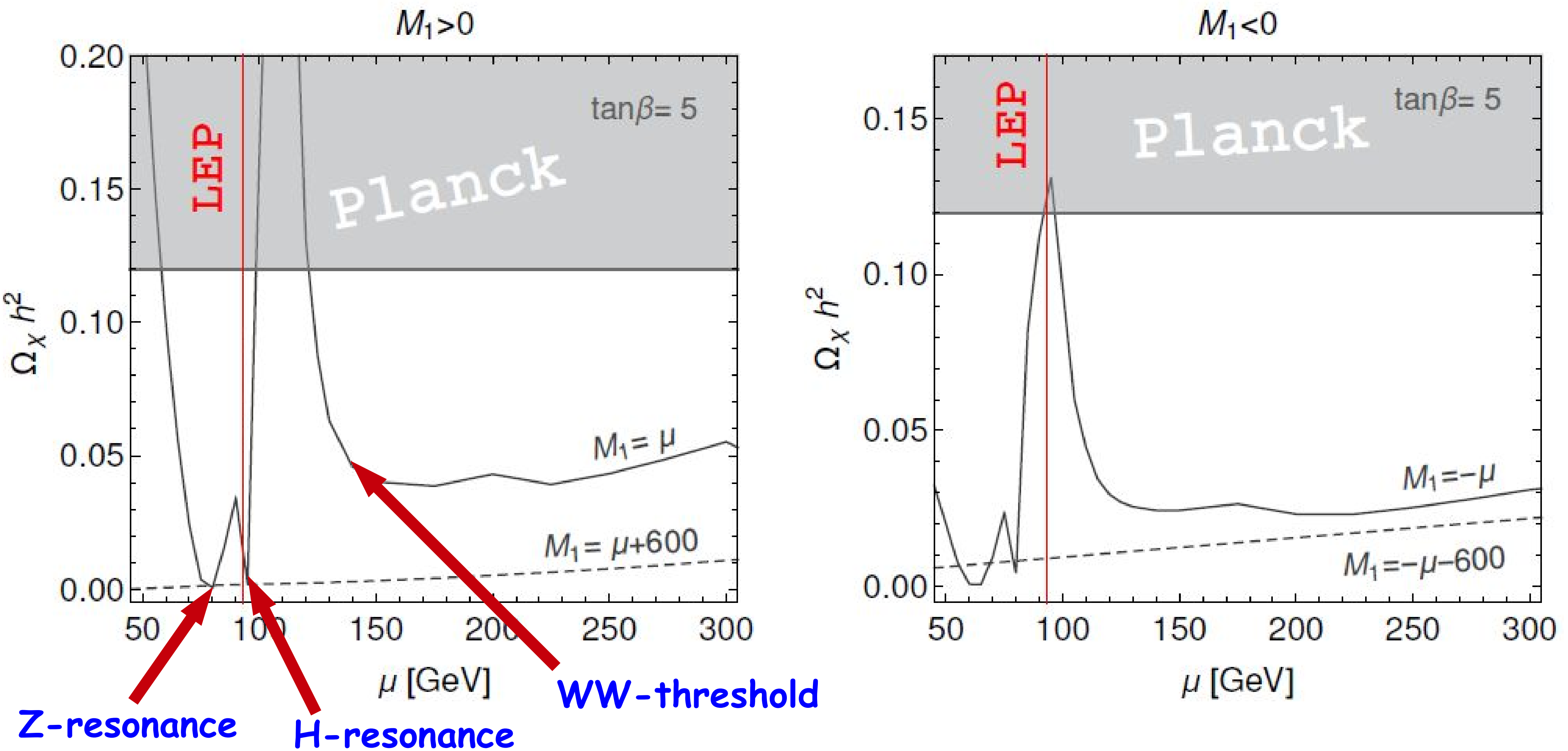

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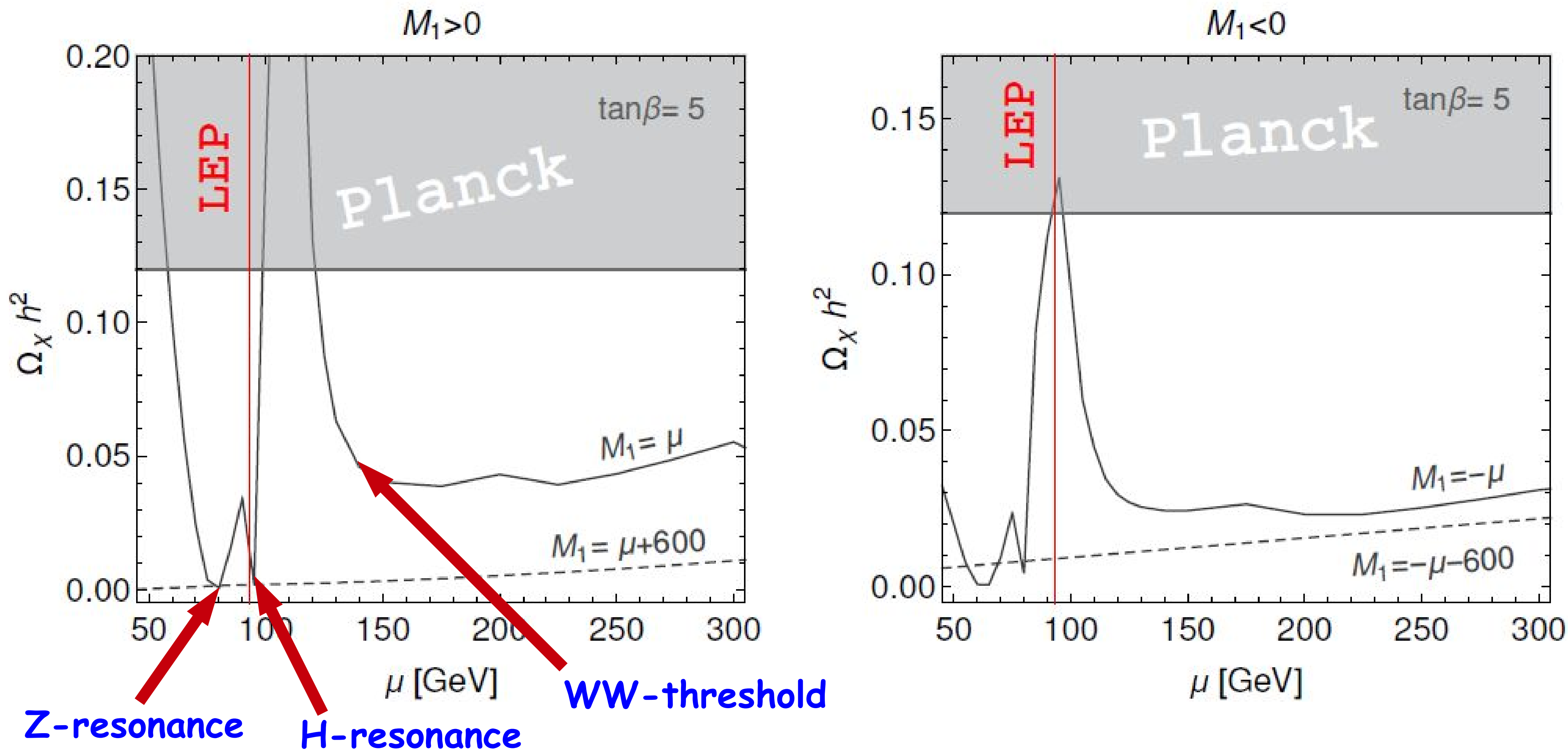
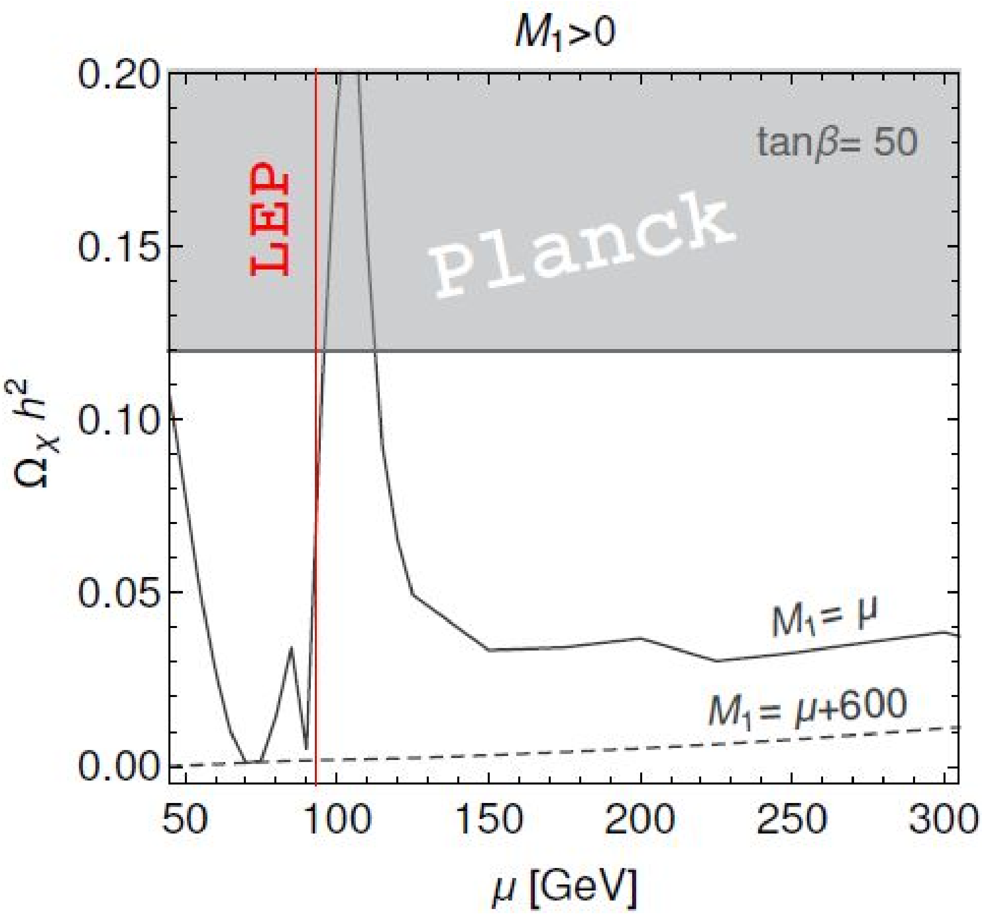
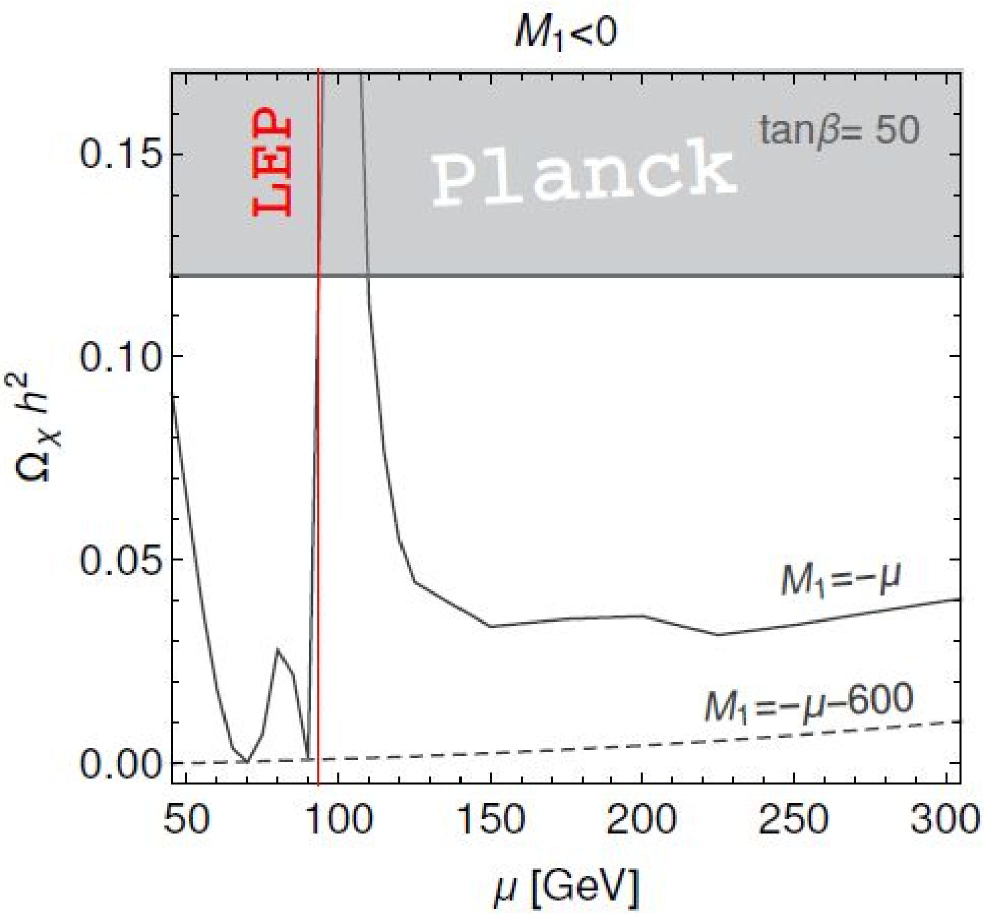


- DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes

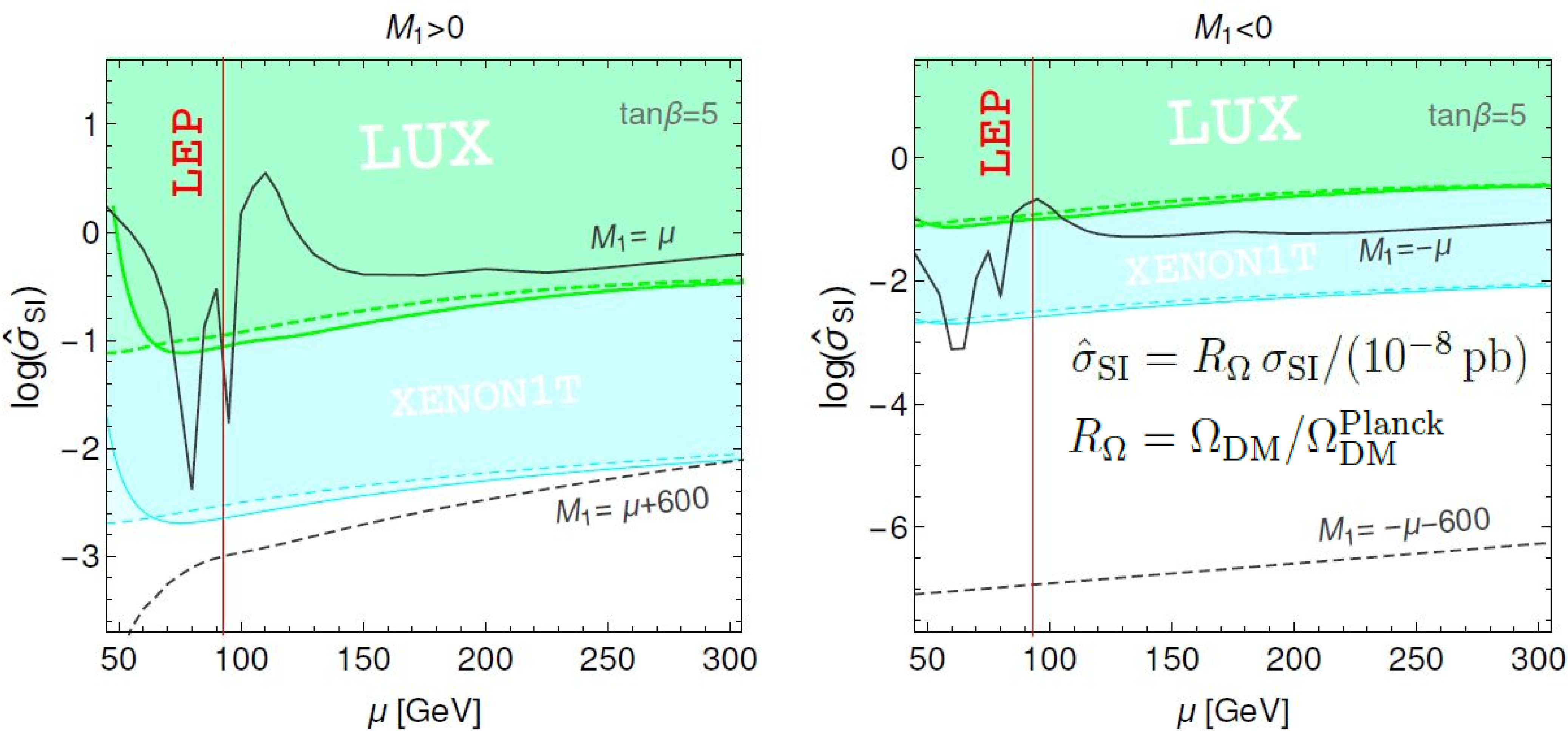
Dark Matter Relic Density





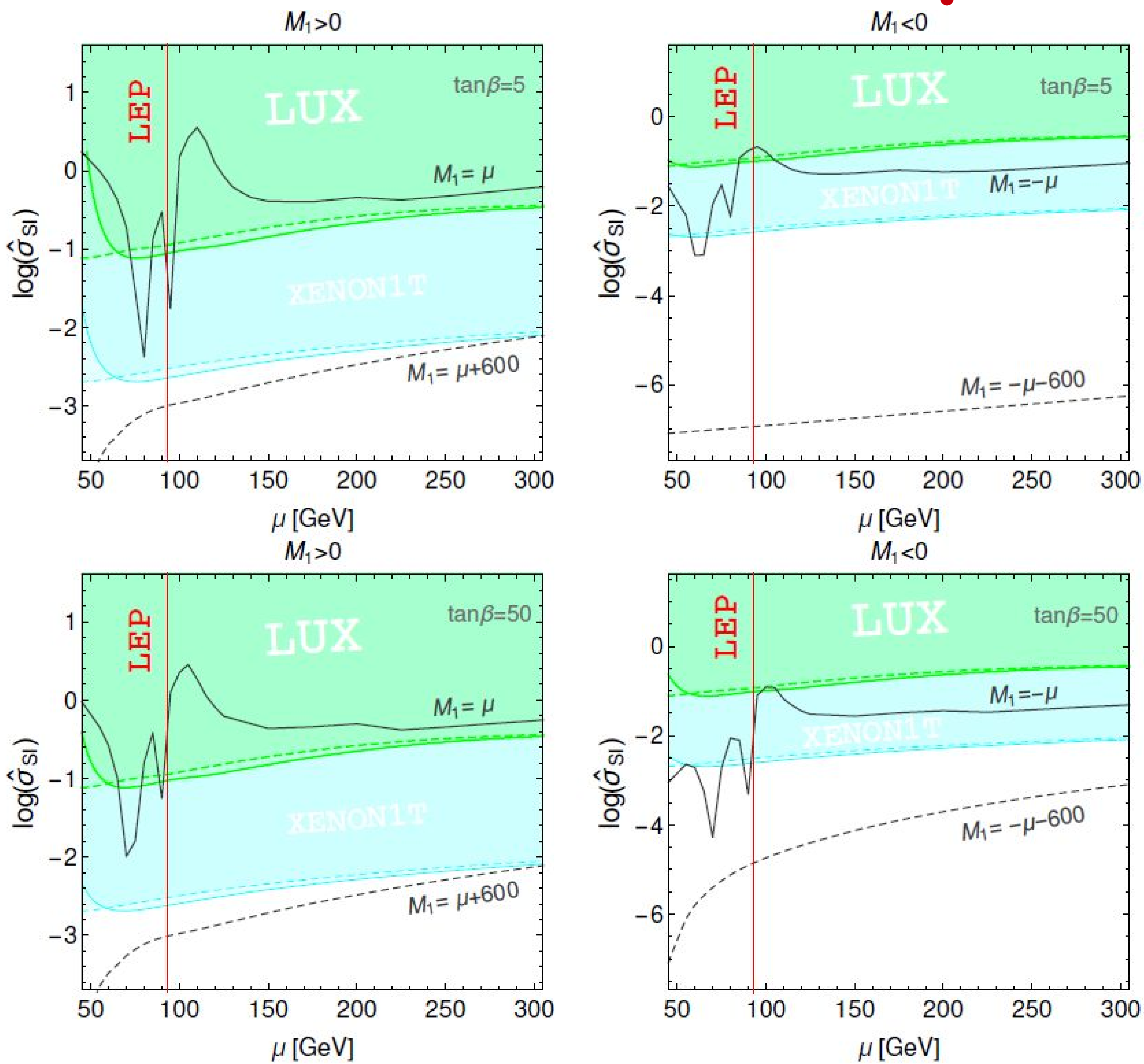
- **The pattern is independent of tanβ**

Direct Detection Prospects

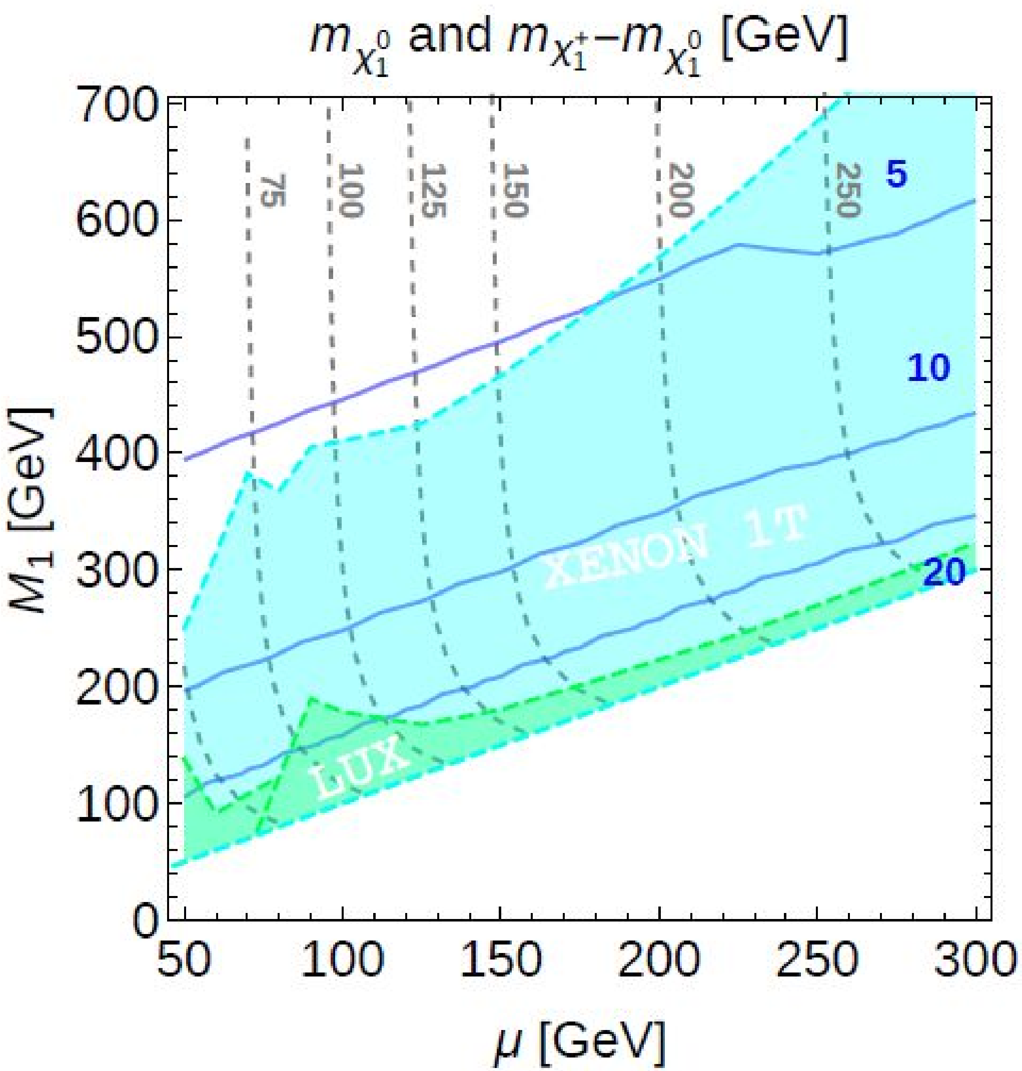


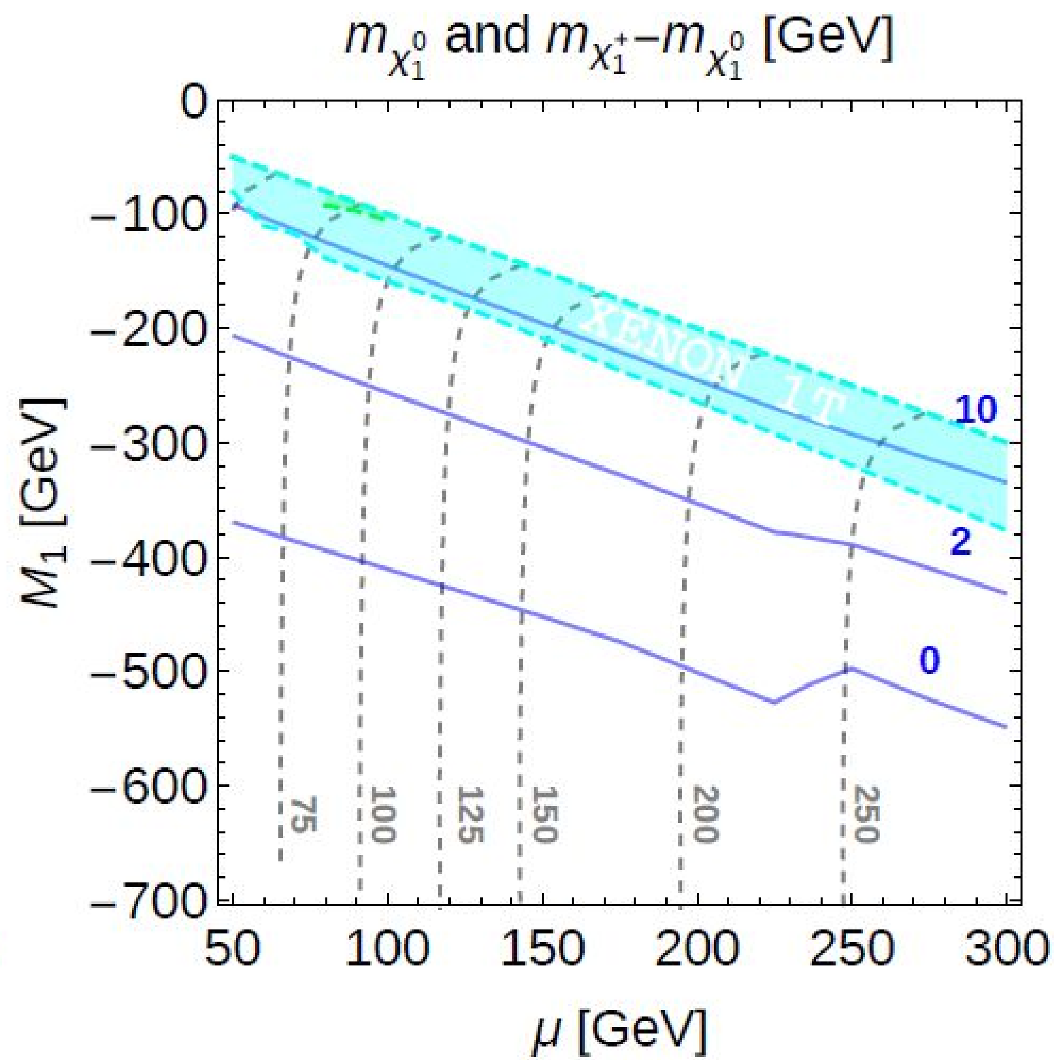
- DD cross section rescaled with the relic density is low in the small ΔM region. Chance for the LHC?

Direct Detection Prospects



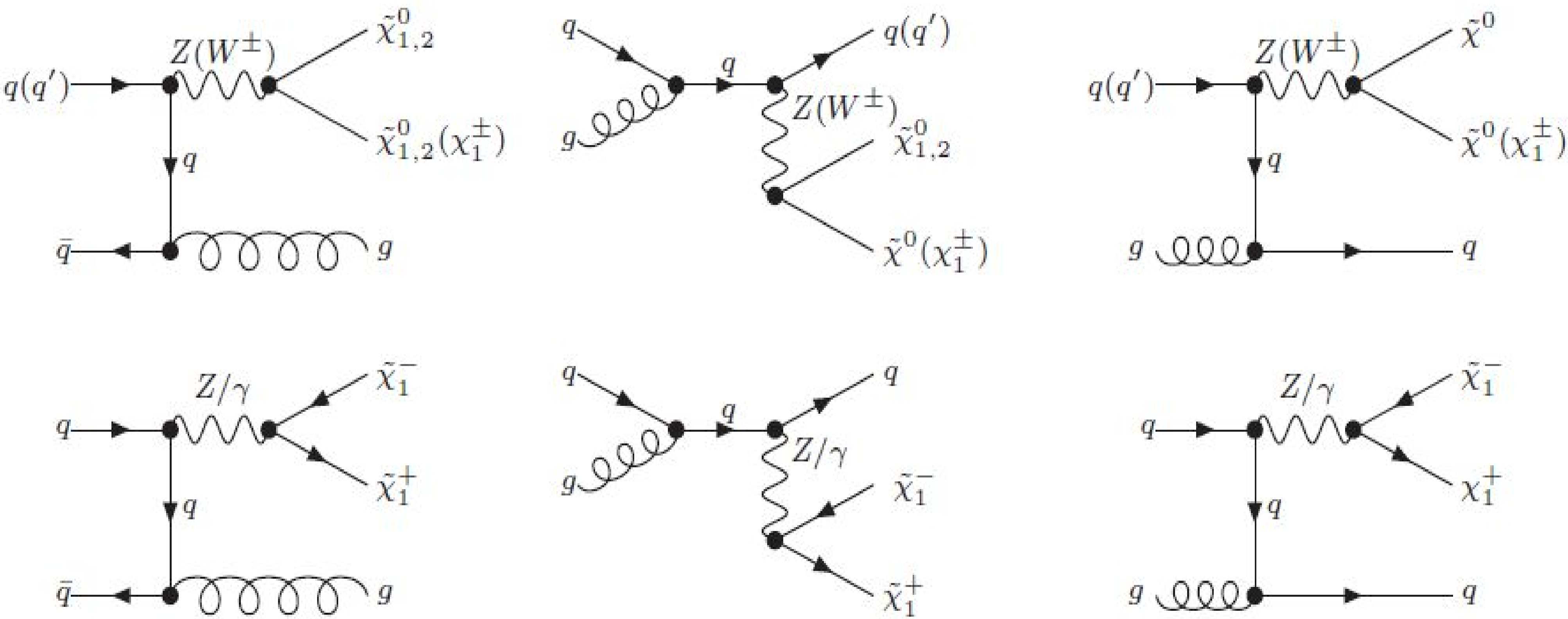
DD in M_1-μ plane





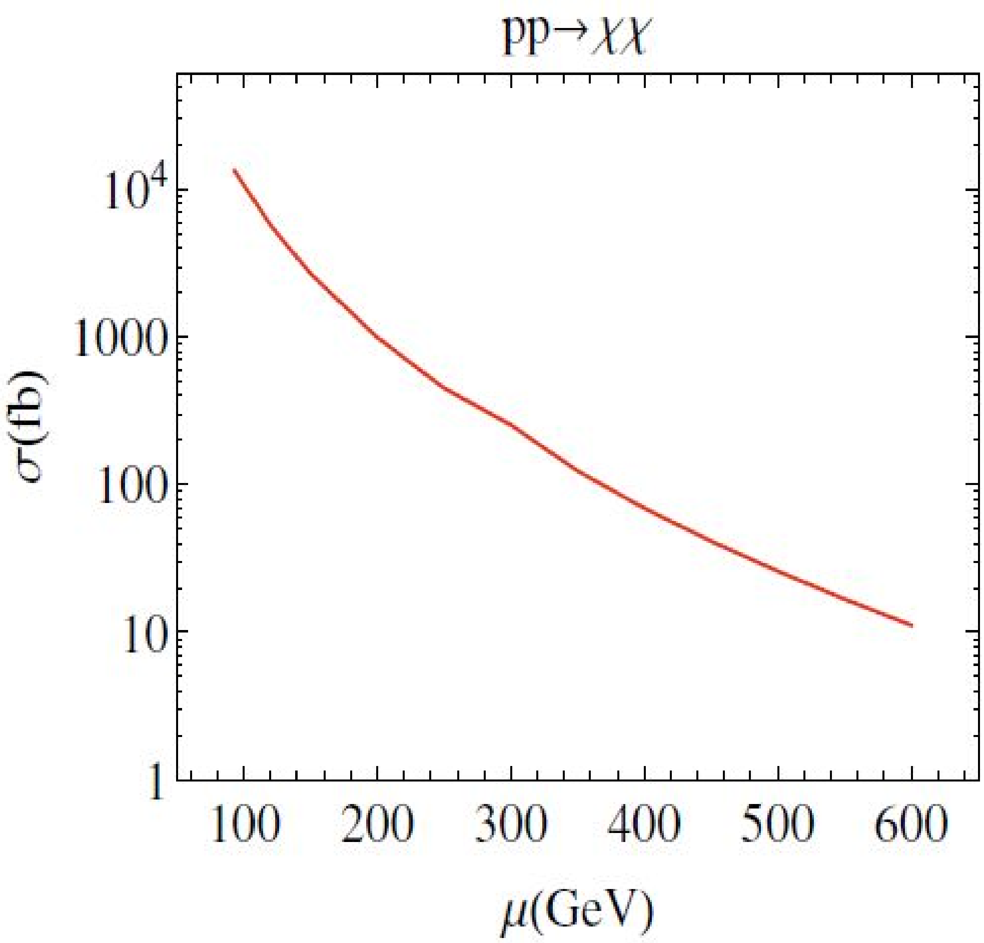
LHC potential to probe NSUSY space

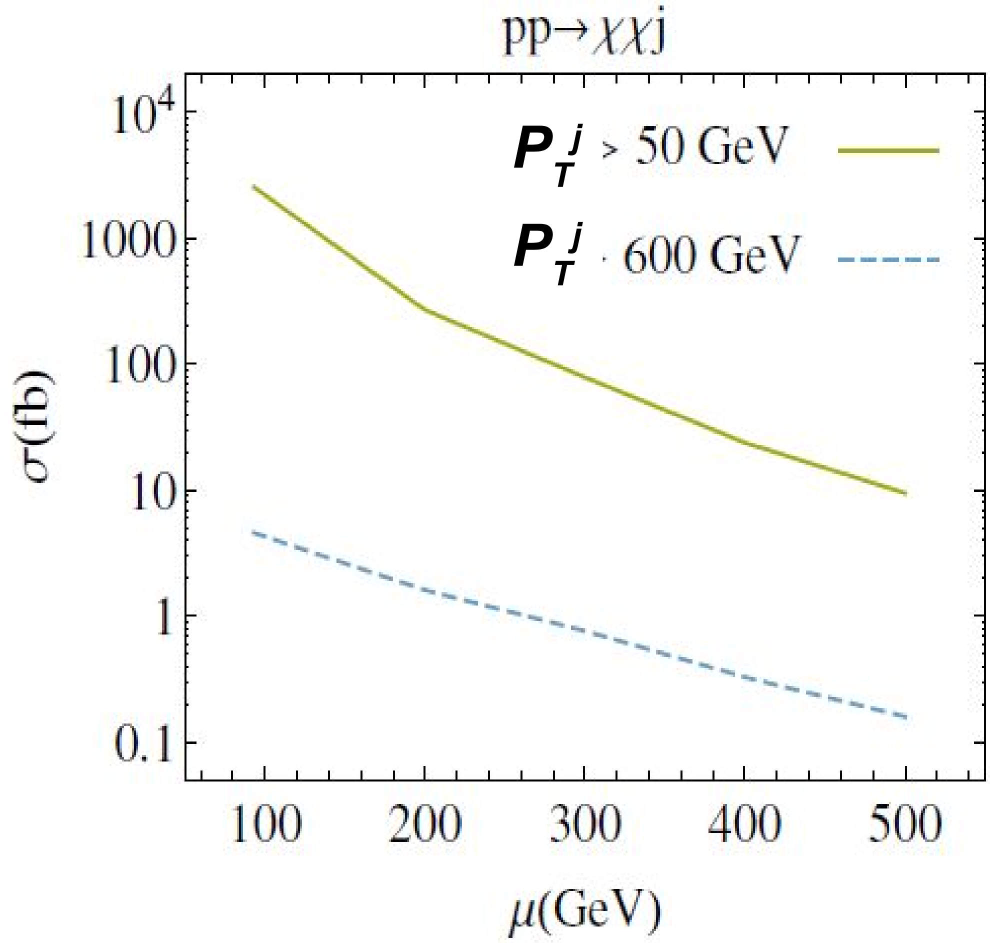
through the $pp \to \chi\chi j$: $\chi = \chi^0_{1,2}$, $\chi^\pm_1$ process



LHC sensitivity to FFP

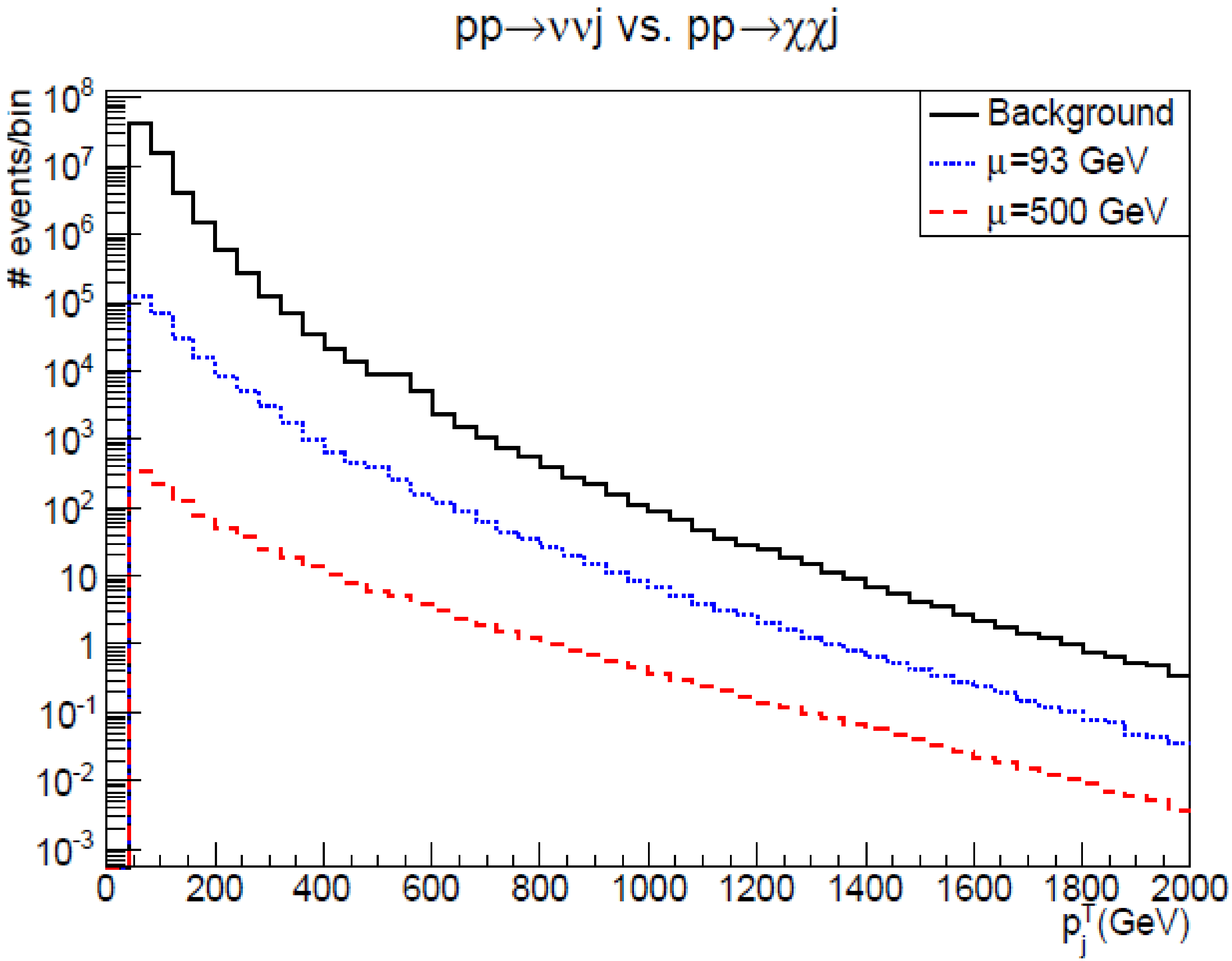
through the pp → $\chi\chi j$: $\chi = \chi^0_{1,2}$, $\chi^\pm_1$ process





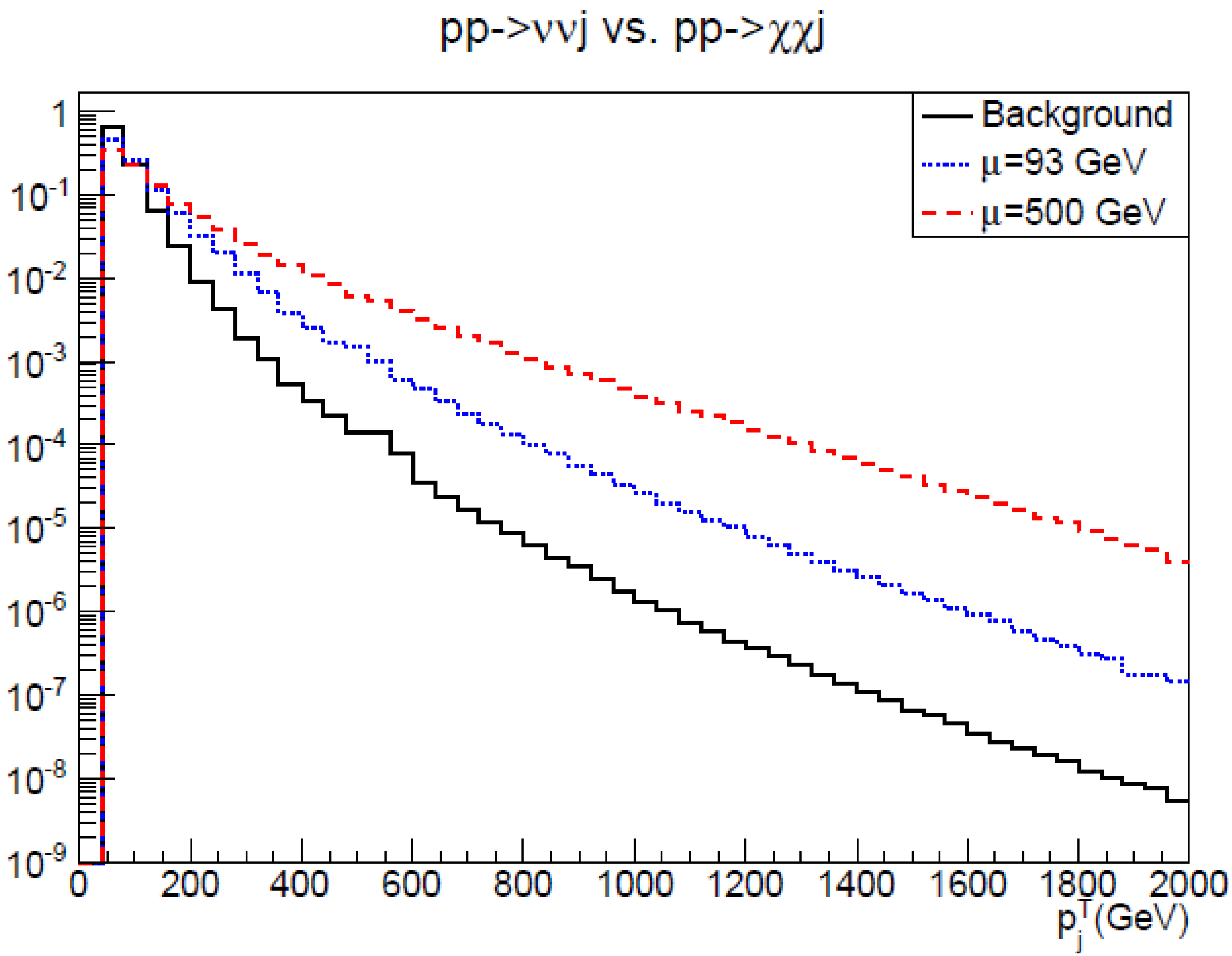
Signal vs Background analysis

difference in rates is quite pessimistic ...



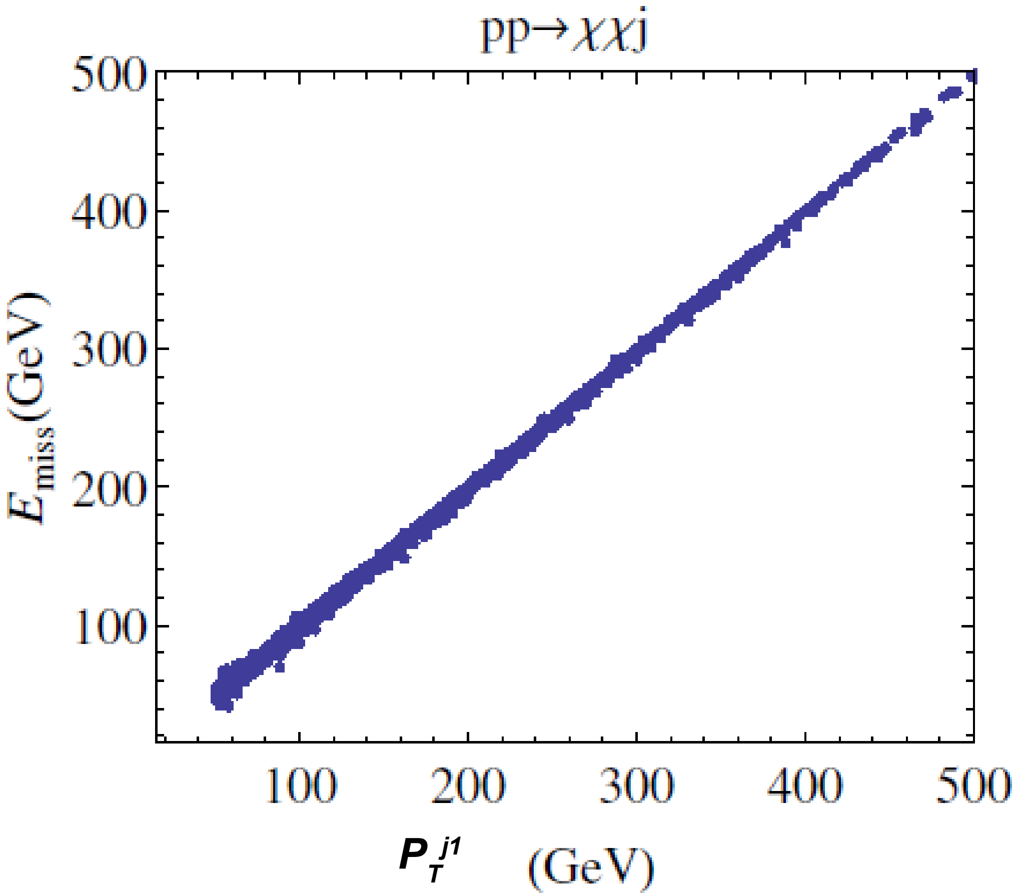
Signal vs Background analysis

but the difference in shapes is quite encouraging!

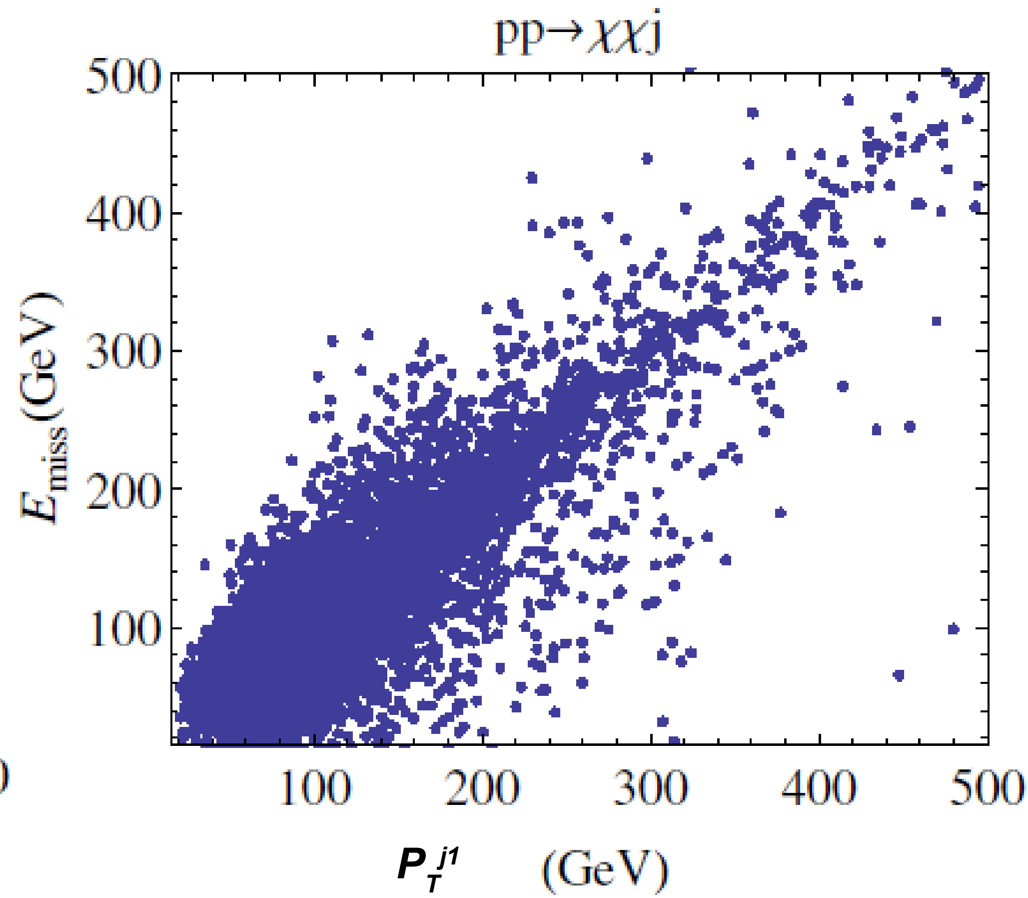


Parton vs Detector simulation level

Parton level

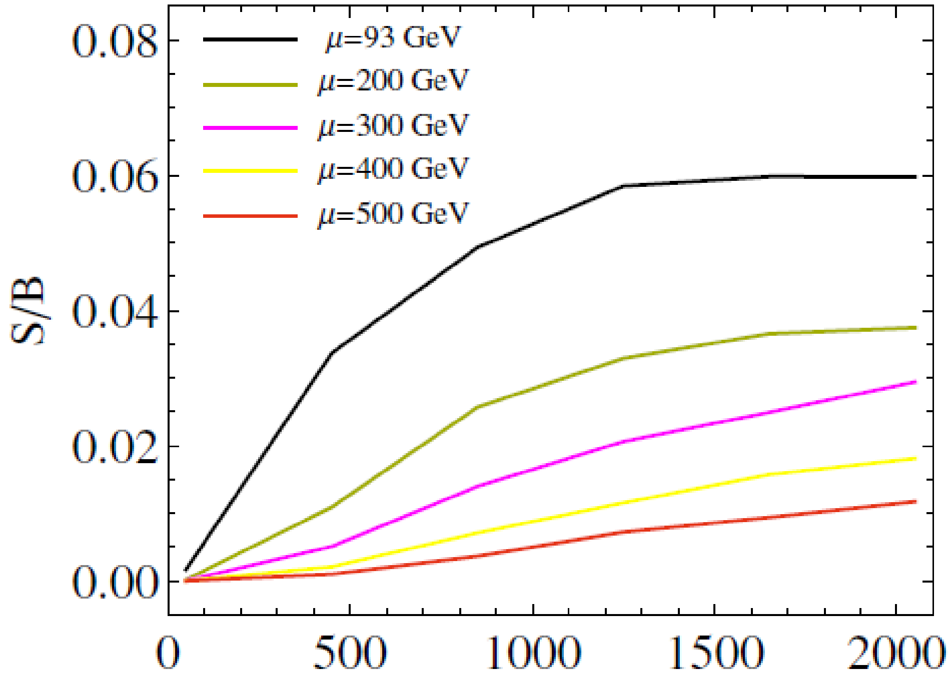


Delphes level

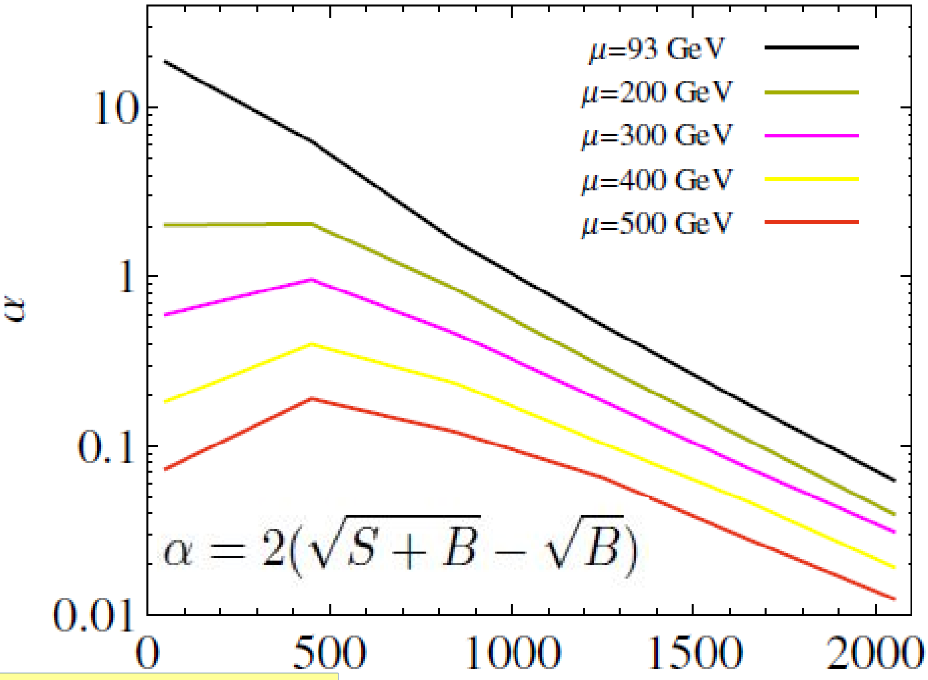


- the lack of the perfect p_T^{j1} vs MET correlations leads to a visible difference of the S/B ratio and significance, and should be taken into account.

S/B vs Signal significance



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



	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ 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)
$p^T_j = \not{E}_T$ >1500 GeV	18 (20)	2 (1)	1 (2)	0 (0)
$p^T_j = \not{E}_T$ >2000 GeV	1 (1)	0 (0)	0 (1)	0 (0)

- There is a strong tension 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

What is the minimal S/B is accessible?

- **the respected systematic error has been studies by ATLAS and CMS LHC@8 collaborations**

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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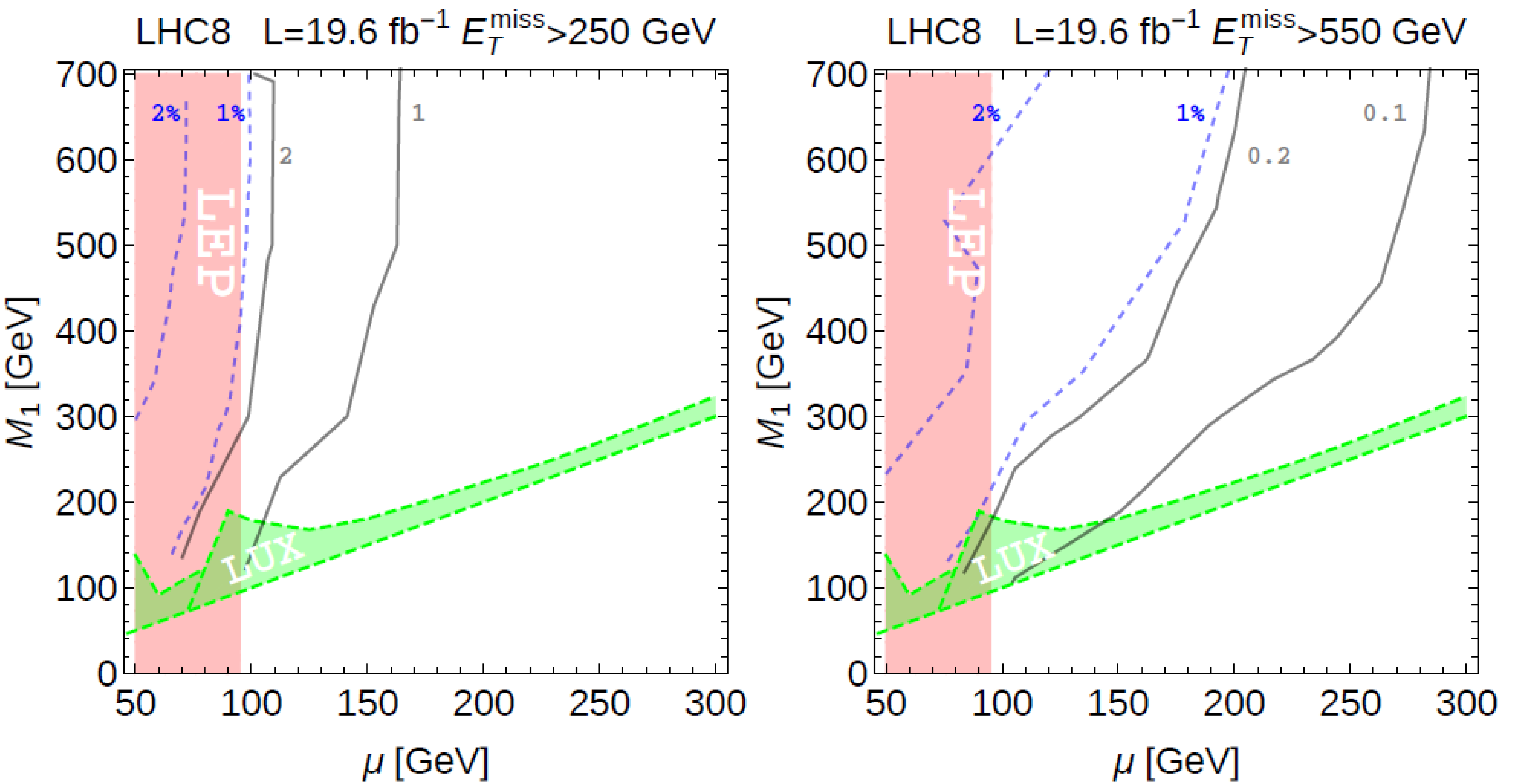
- So, the realistic (or even optimistic!) S/B one should be looking at is ~ 5% or more

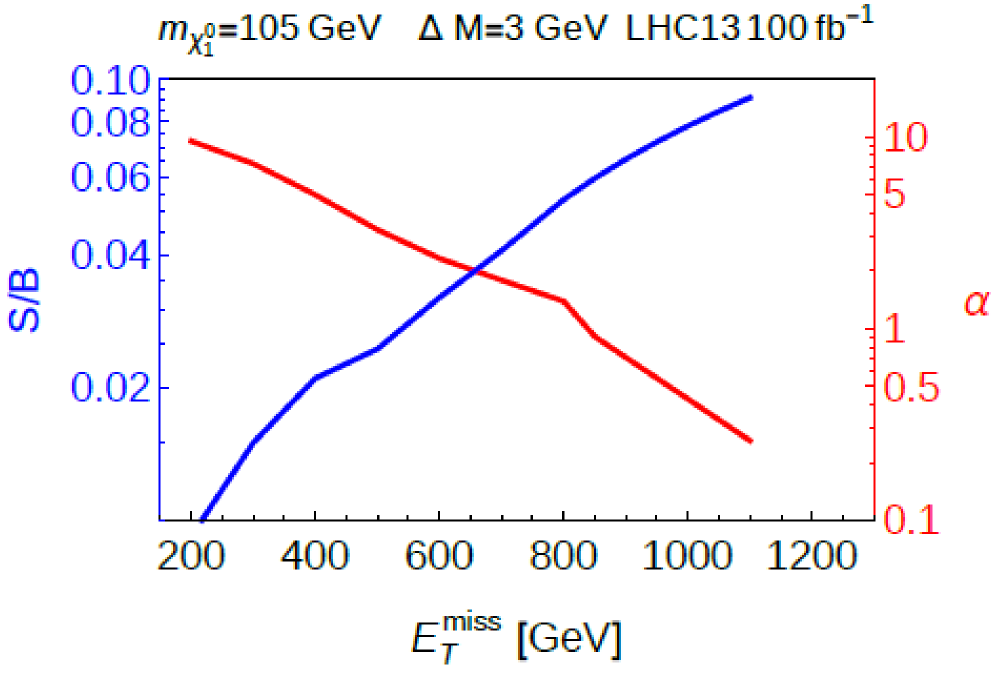
Interpreting LHC@8TeV results (CMS EXO-12-048)

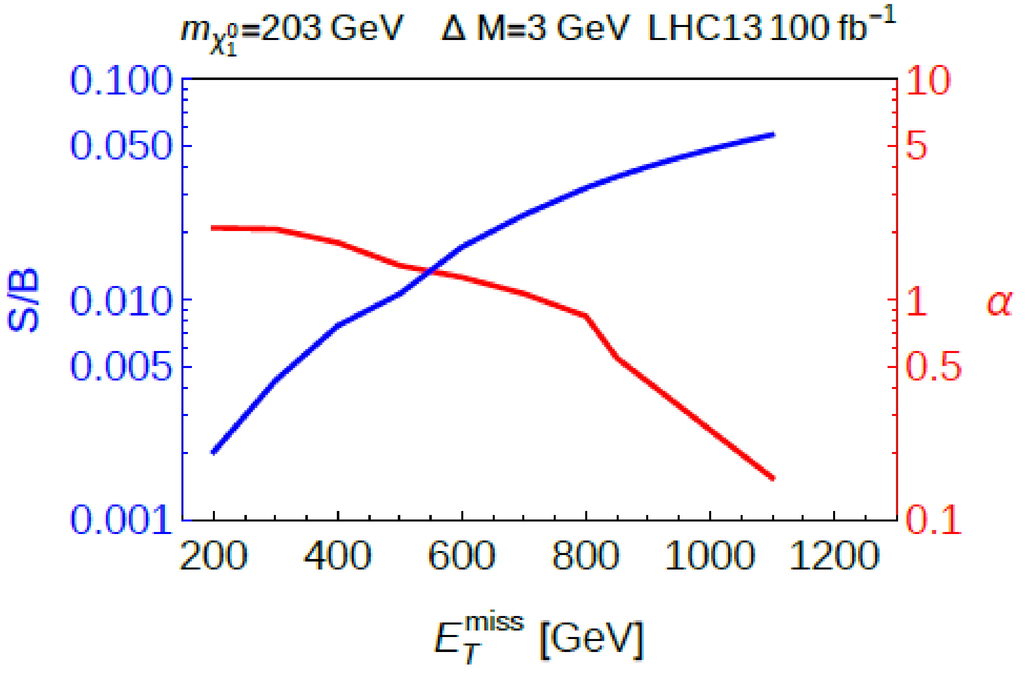
Selection	W+jets	Z+j	Z($\nu\nu$)+j	$t\bar{t}$	QCD	Single top	Total
Cross section (pb)	229.0	34.1	588.3	225.2	1904.8	113.5	
$E_T^{miss} > 550$ GeV	136	1	429	3	0	0	569



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

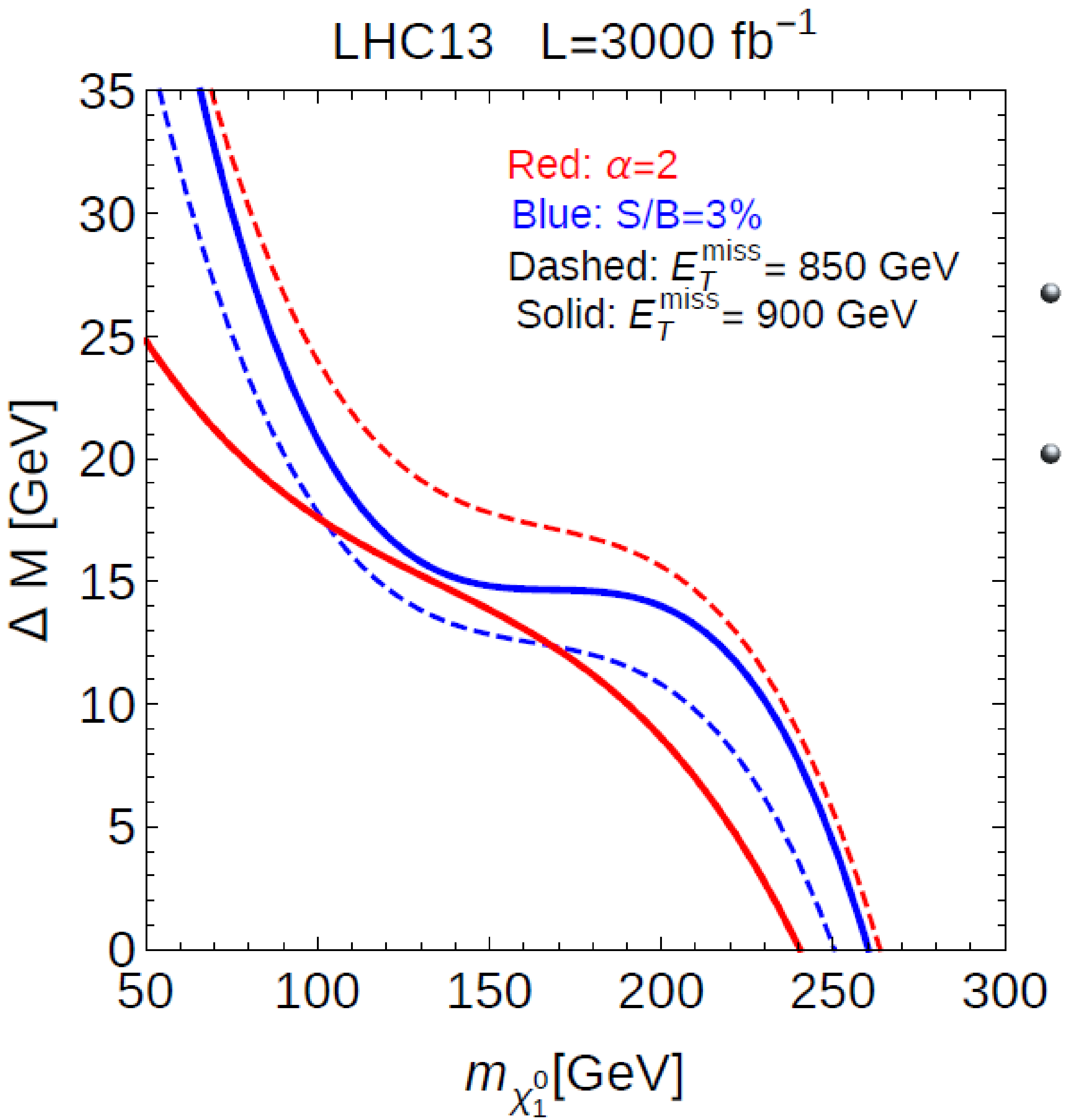
LHC@13 TeV potential to probe NSUSY





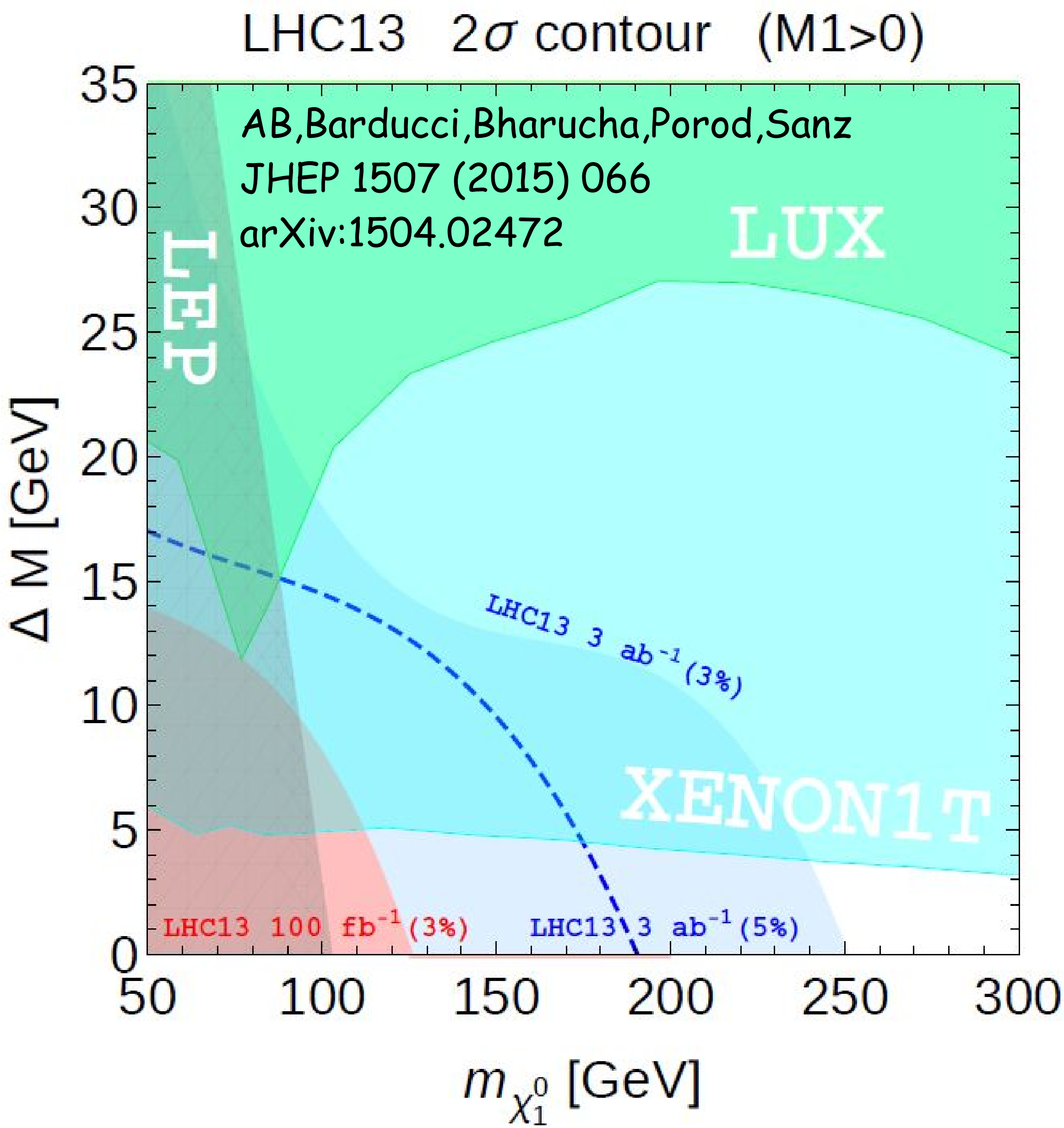
- **S/B vs significance tension requires very high luminosity to allow high (~1 TeV) missing E_T cut and keep α above 2 at the same time!**

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



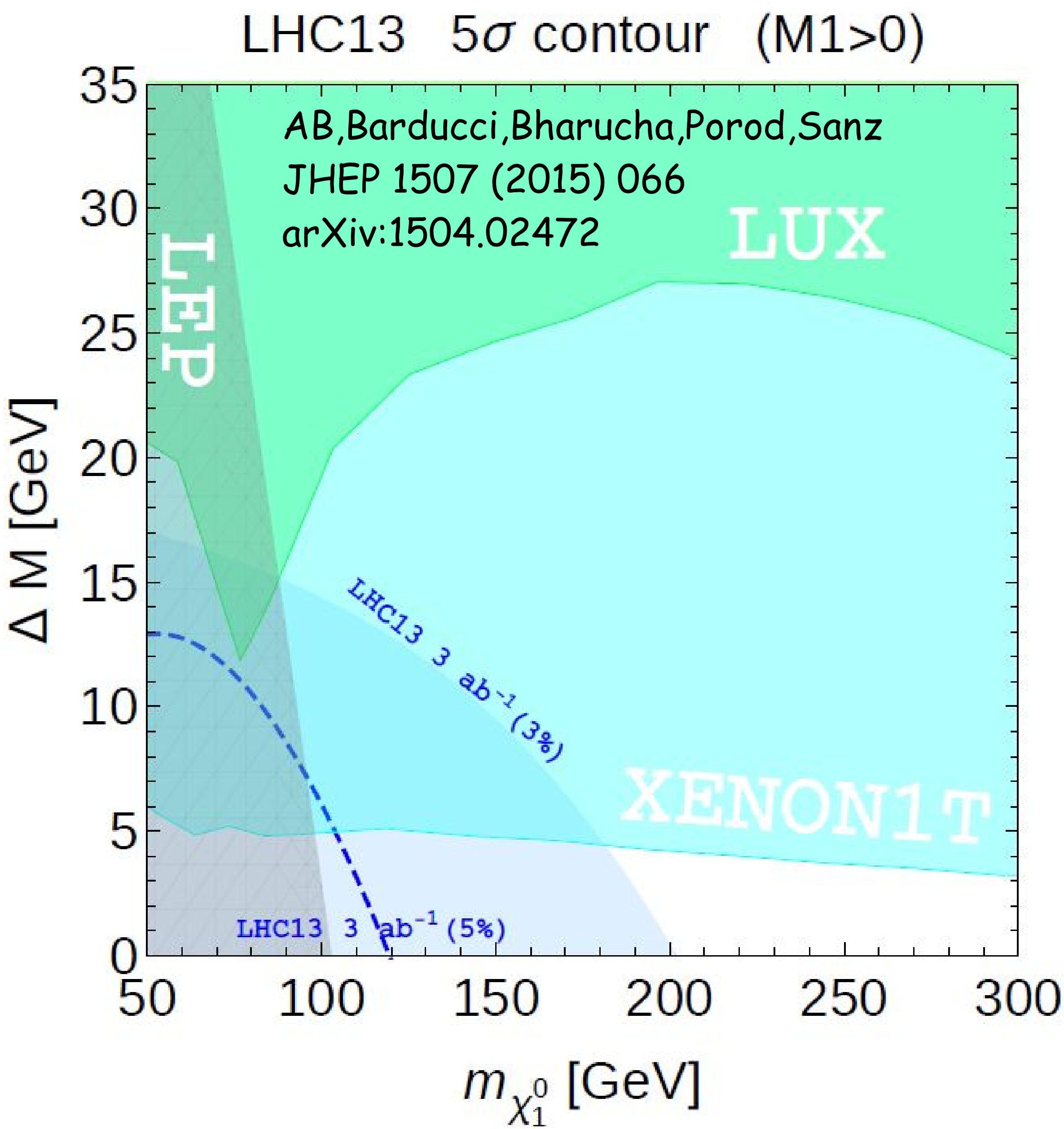
- The shapes of S/B and α contours are correlated
- The idea is to chose $E_{T\ miss}$ which brings S/B and α iso-contours together

LHC@13 Reach for NSUSY



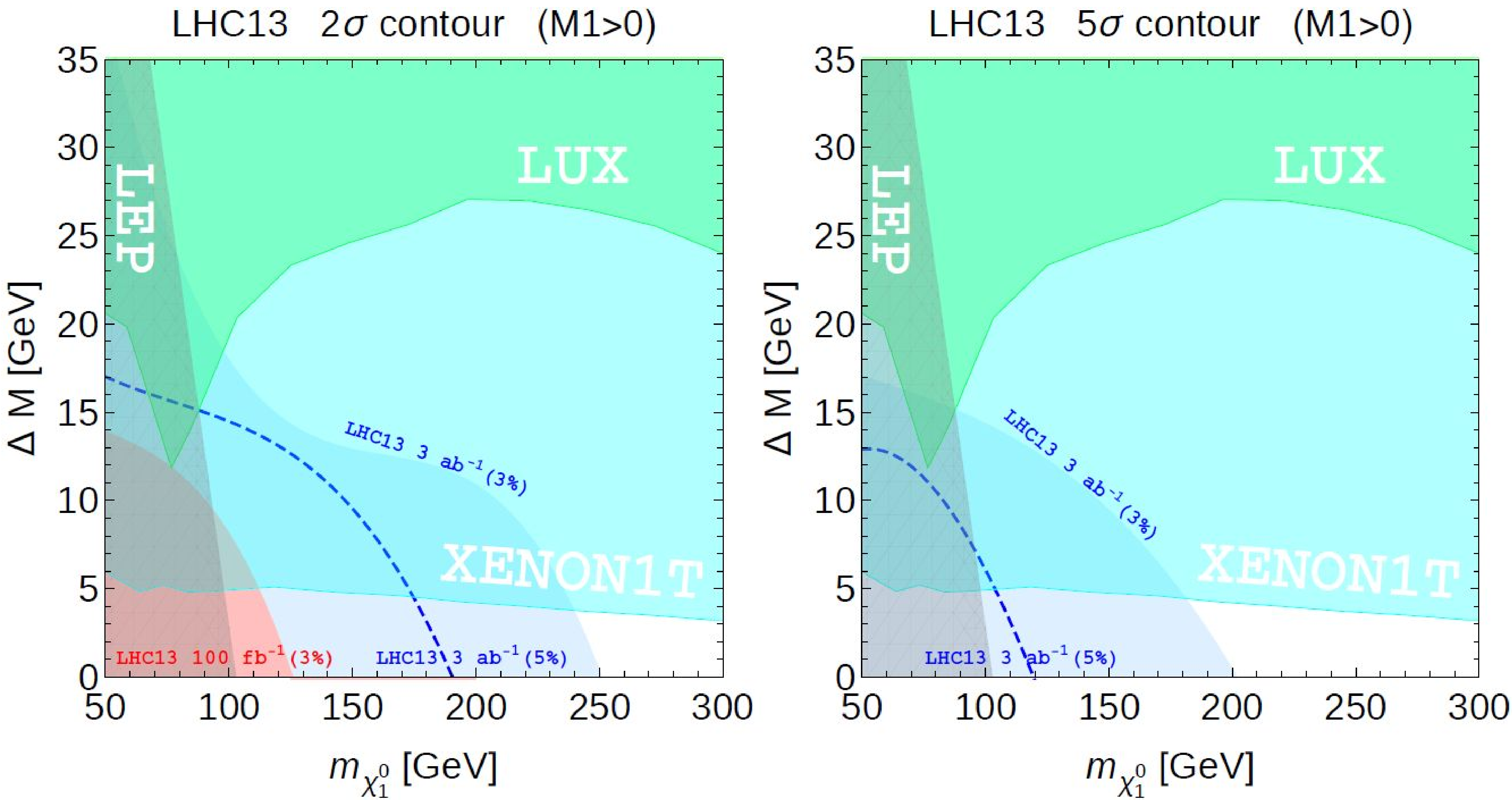
- 3% and 5% cases for S/B are taken
- 3 ab^{-1} and 100 fb^{-1} cases
- LUX and XENON1T are sensitive to the upper end of NSUSY
- assuming S/B ≃ 3% (based on ATLAS studies) the sensitivity of the LHC could extend up to 250 GeV LSP mass (95% CL) for 3 ab^{-1}luminocity
- mass gap above 250 GeV requires further attention

LHC@13 Reach for NSUSY

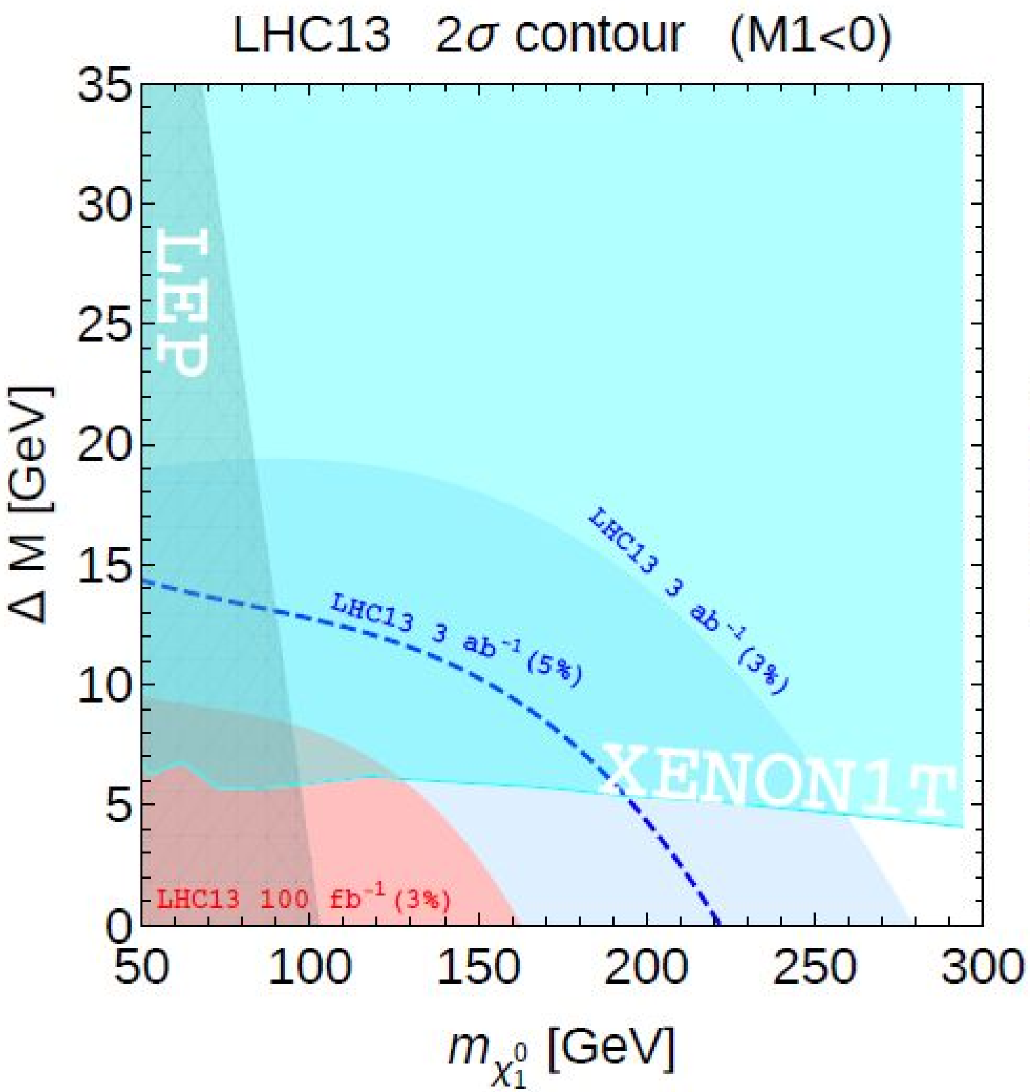


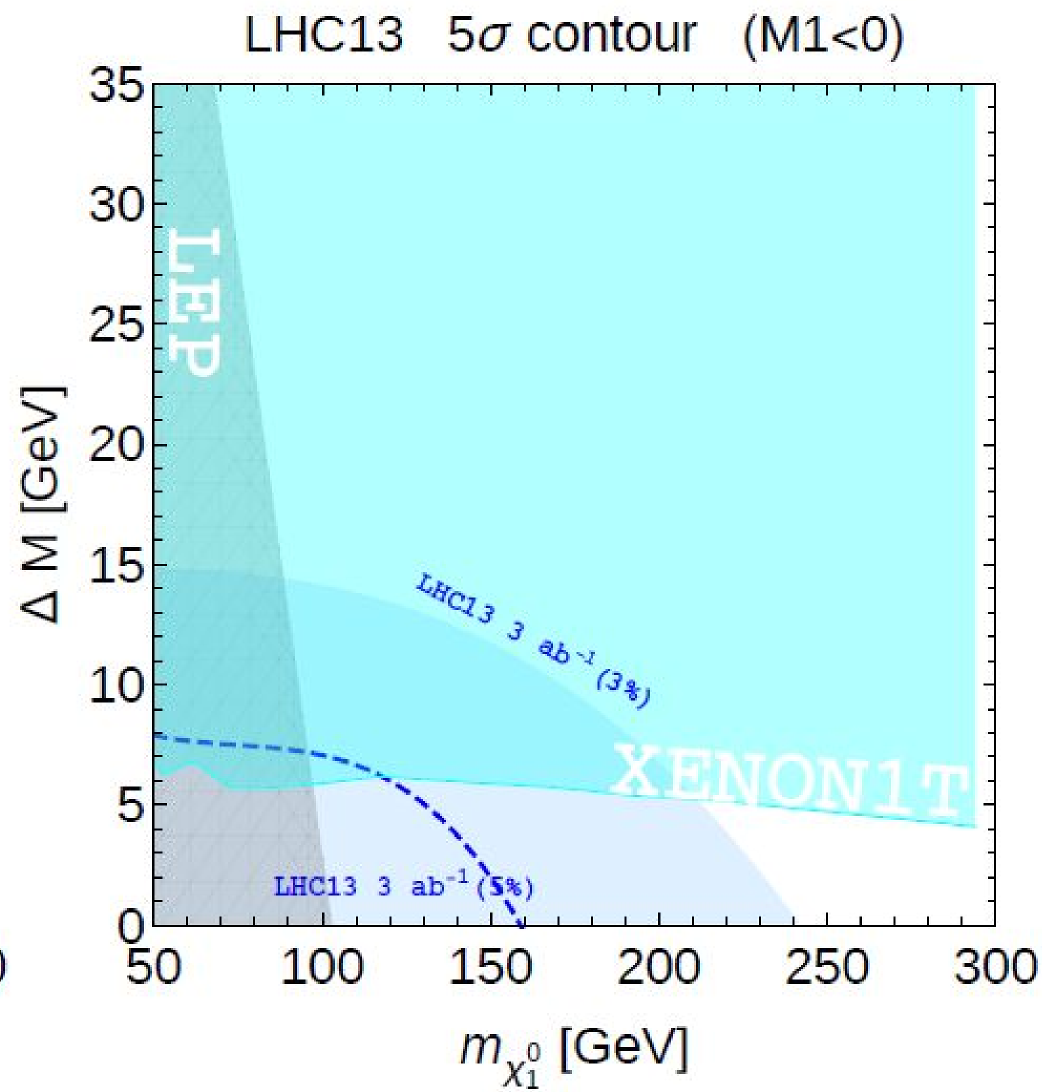
- 3% and 5% cases for S/B are taken
- 3 ab^{-1} and 100 fb^{-1} cases
- LUX and XENON1T are sensitive to the upper end of NSUSY
- assuming S/B ≃ 3% (based on ATLAS studies) the sensitivity of the LHC could extend up to 200 GeV LSP mass (5σ) for 3 ab^{-1}luminocity

LHC@13 Reach for NSUSY



LHC@13 Reach for NSUSY





Discussion

- **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%"
    may be bit 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, while at the detector level we have found that both S/B and significance are too low for LHC@8TeV to be sensitive to NSUSY

- **How important is the jet matching for this study?**
  - we have performed simulation starting from the hard P^j_T cut (500 GeV) to gain as much statistics as possible
  - we have checked that matching (up to the 3 jet) does not have visible effect

Conclusions

- NSUSY with light Higgsinos is well-motivated but hard to test - is not excluded (!)
- so far we have ~ 100 GeV limit from LEP
- We have shown that in reality LHC@13 has potential to probe light Higgsinos up to about 250 GeV if S/B ~ 3% (or better) control is possible
- DDM search experiments – LUX and XENON1T are very complementary for $\Delta M > 5$ GeV
- M_{DM} above 250 GeV requires further exploration (ILC?)

Conclusions

- FFP with light Higgsinos is well-motivated but hard to test – is not excluded (!)
- so far we have ~ 100 GeV limit from LEP, and it is very important not to miss this scenario
- We have shown that in reality LHC@13 has potential to probe light Higgsinos up to about 130 GeV if S/B ~ 5% (or better) control is possible
- DDM search experiments – LUX and XENON1T are very complementary (from about 320 GeV)
- Mass gap 130-320 GeV requires a further exploration (ILC)

Final remarks

- SUSY cannot be experimentally ruled out!
  - It can only be discovered (optimists).
  - Or abandoned (pessimists)

Lets be optimists!

Original statement from Leszek Roszkowski: "Low energy SUSY cannot be experimentally ruled out. It can only be discovered. Or else abandoned."

Thank you!

Obrigado!