Selected Highlights on theory and phenomenology of Dark Matter

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OUTLINE

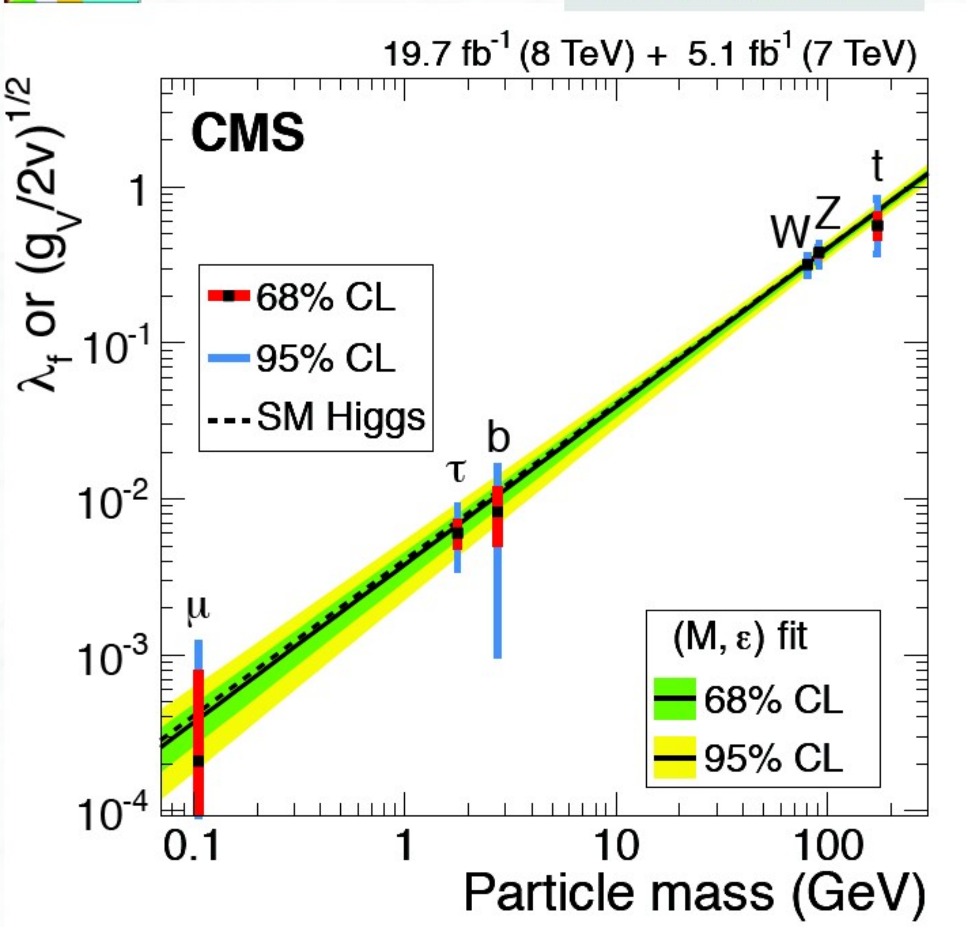
- CDM as an empirical evidence of BSM physics
- DM theories
- Interplay of DM search experiments
- Beyond conventional scenarios
- Conclusions

The the Standard Model is very successful from collider point of view

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



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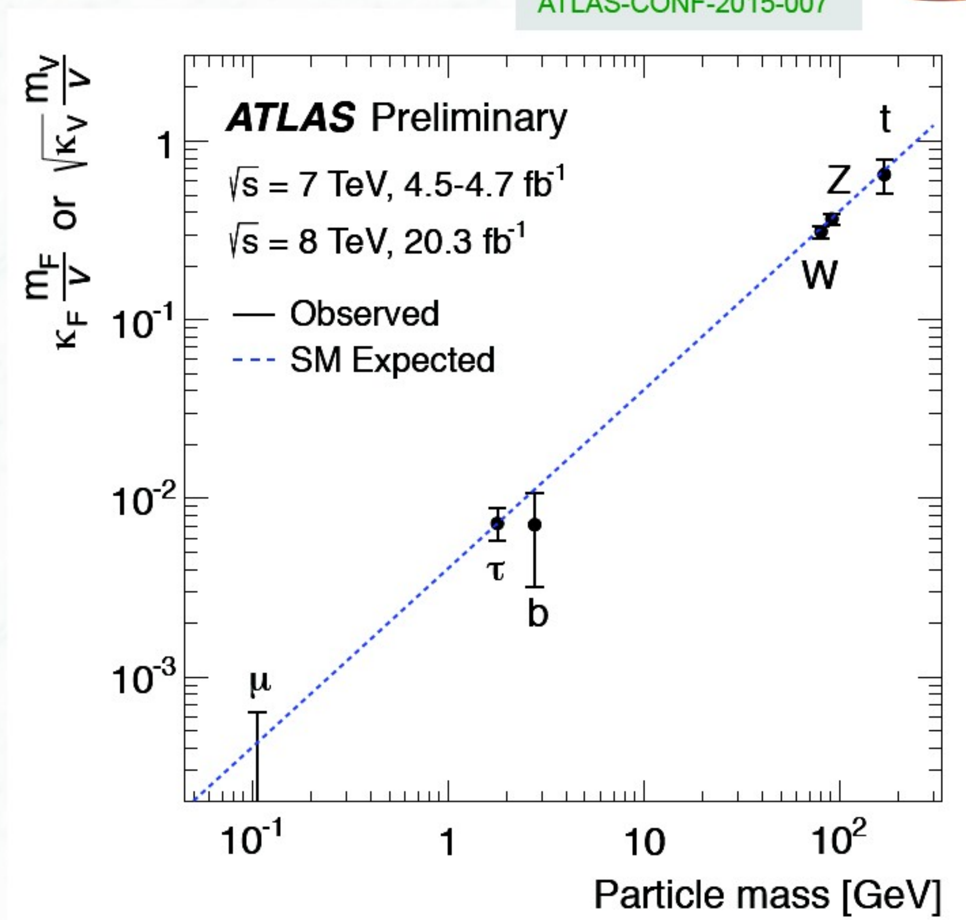
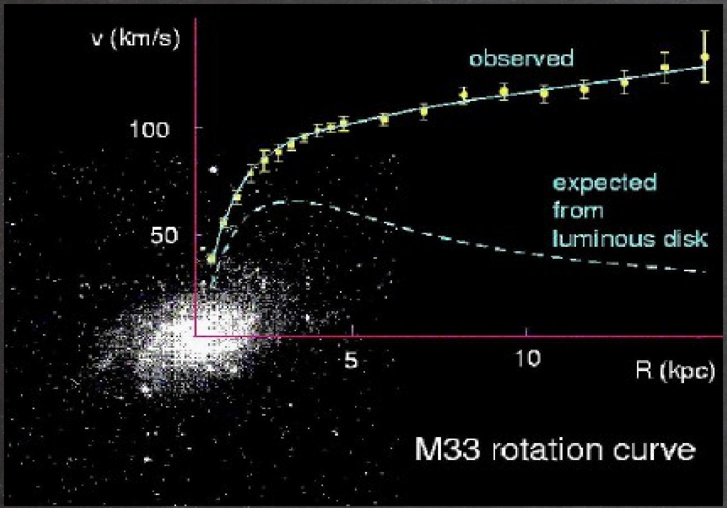


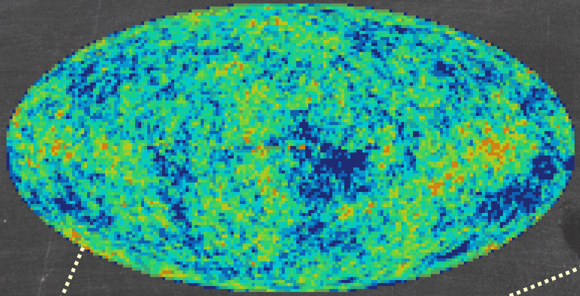
But at a bigger scale SM is empirically incomplete

- 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

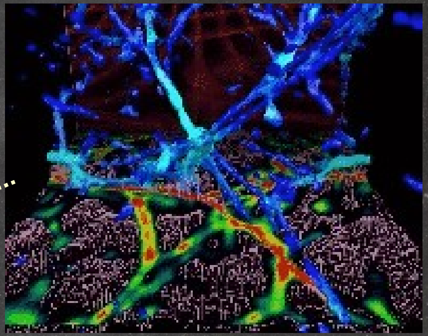
Galactic rotation curves

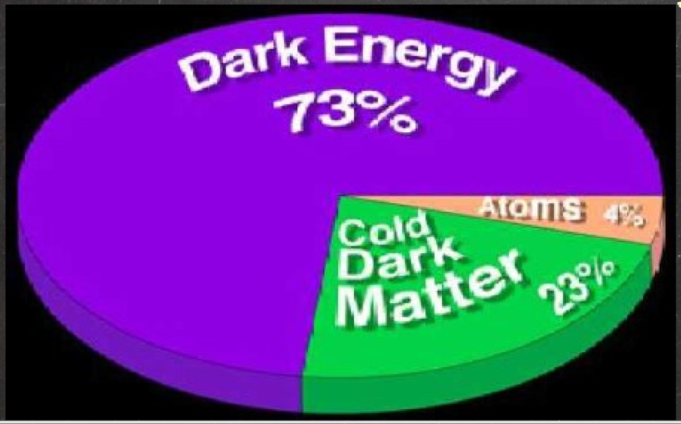


CMB: WMAP and PLANCK

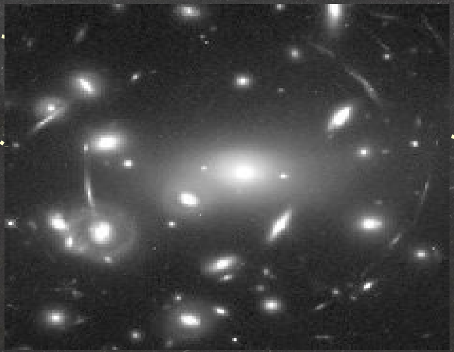


Large Scale Structures





Gravitational lensing



Bullet cluster

But at a bigger scale SM is empirically incomplete

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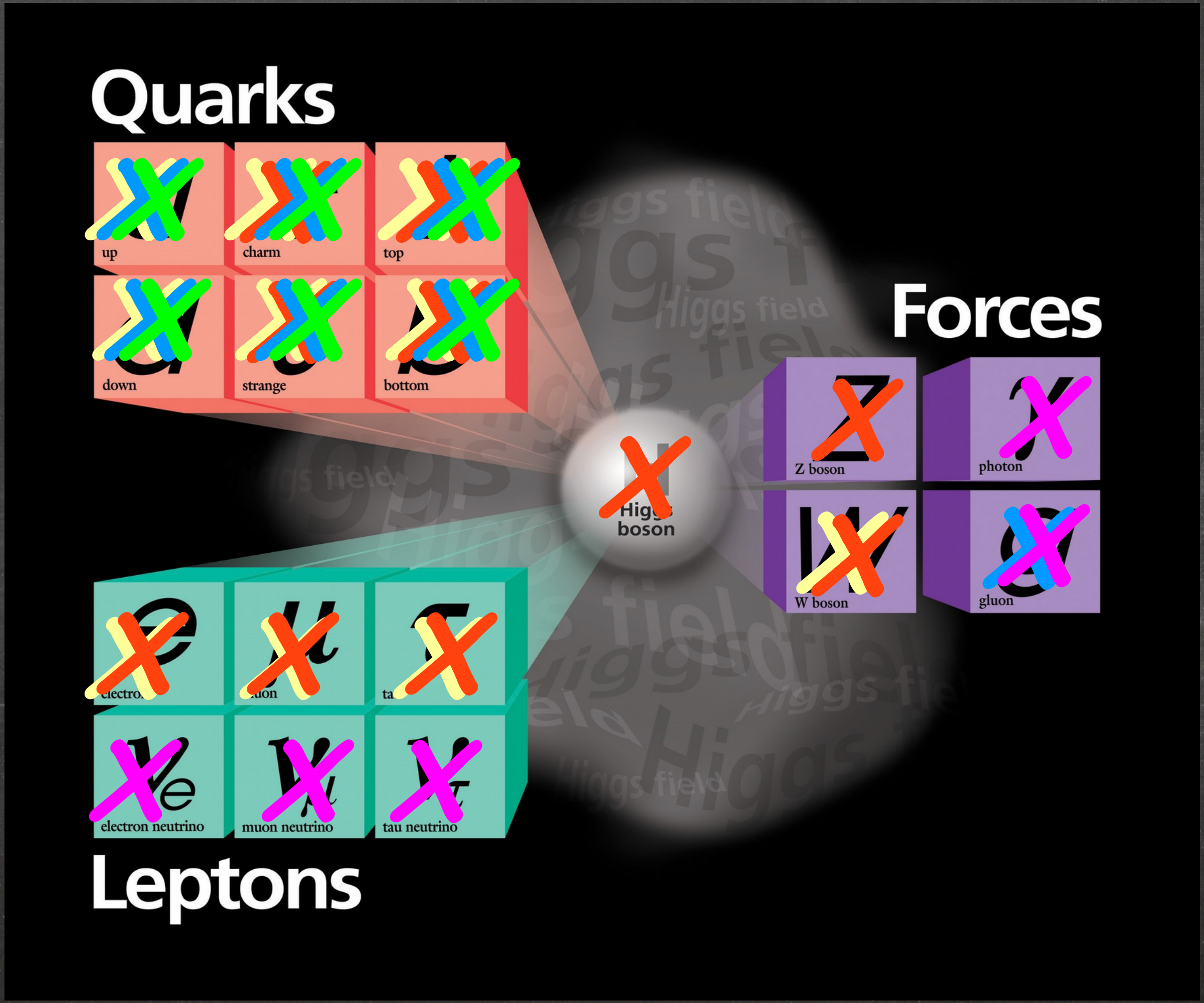
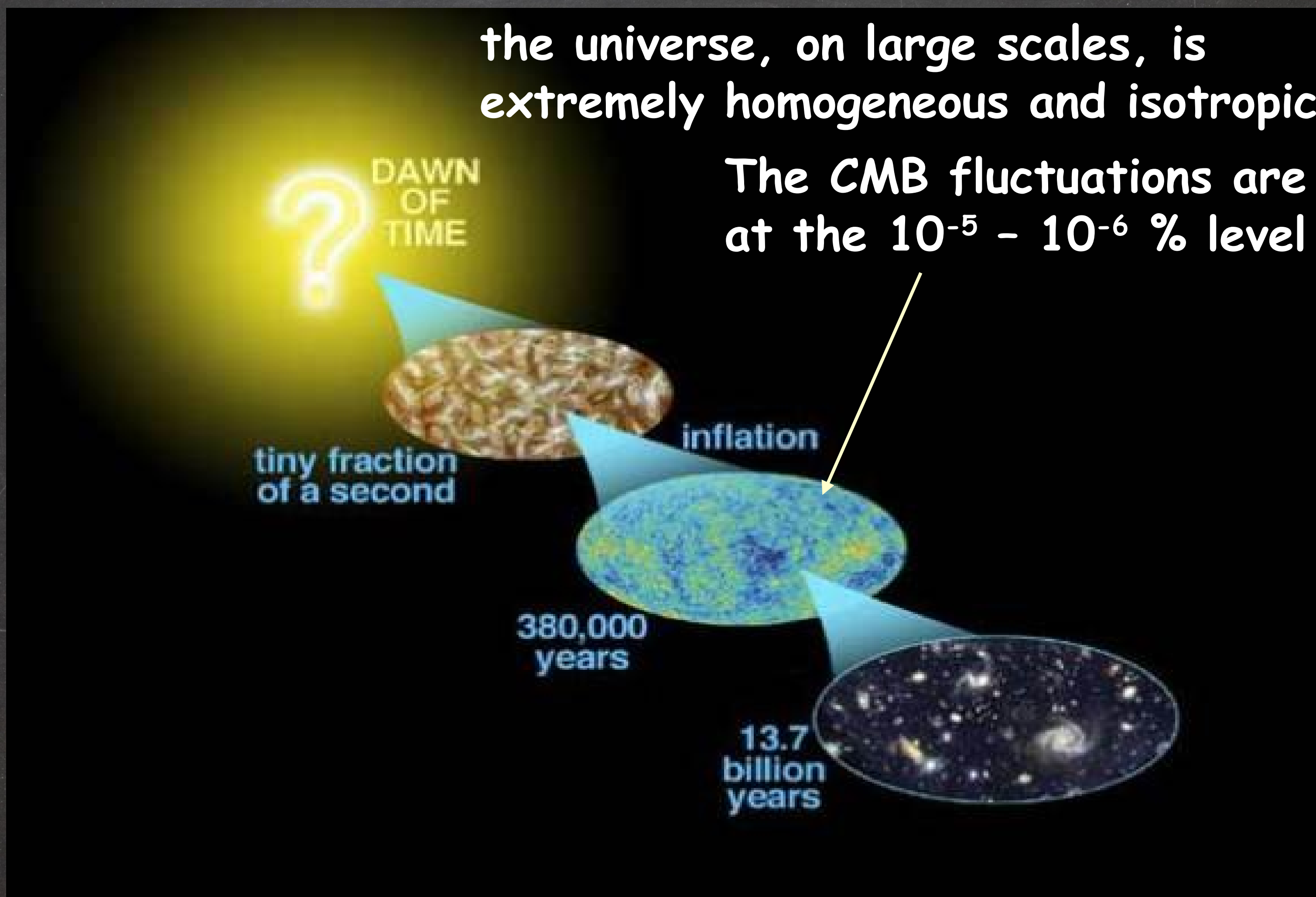


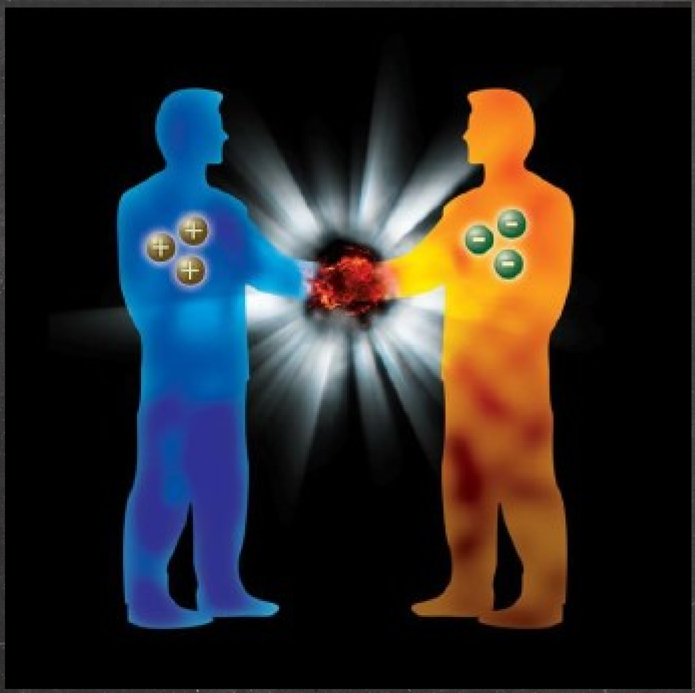
But at a bigger scale SM is empirically incomplete

- **the presence of scale-invariant, Gaussian, and apparently acausal density perturbations:** consistent with a period of inflation at early times. Higgs filed by itself can not provide inflation.



But at a bigger scale 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.

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

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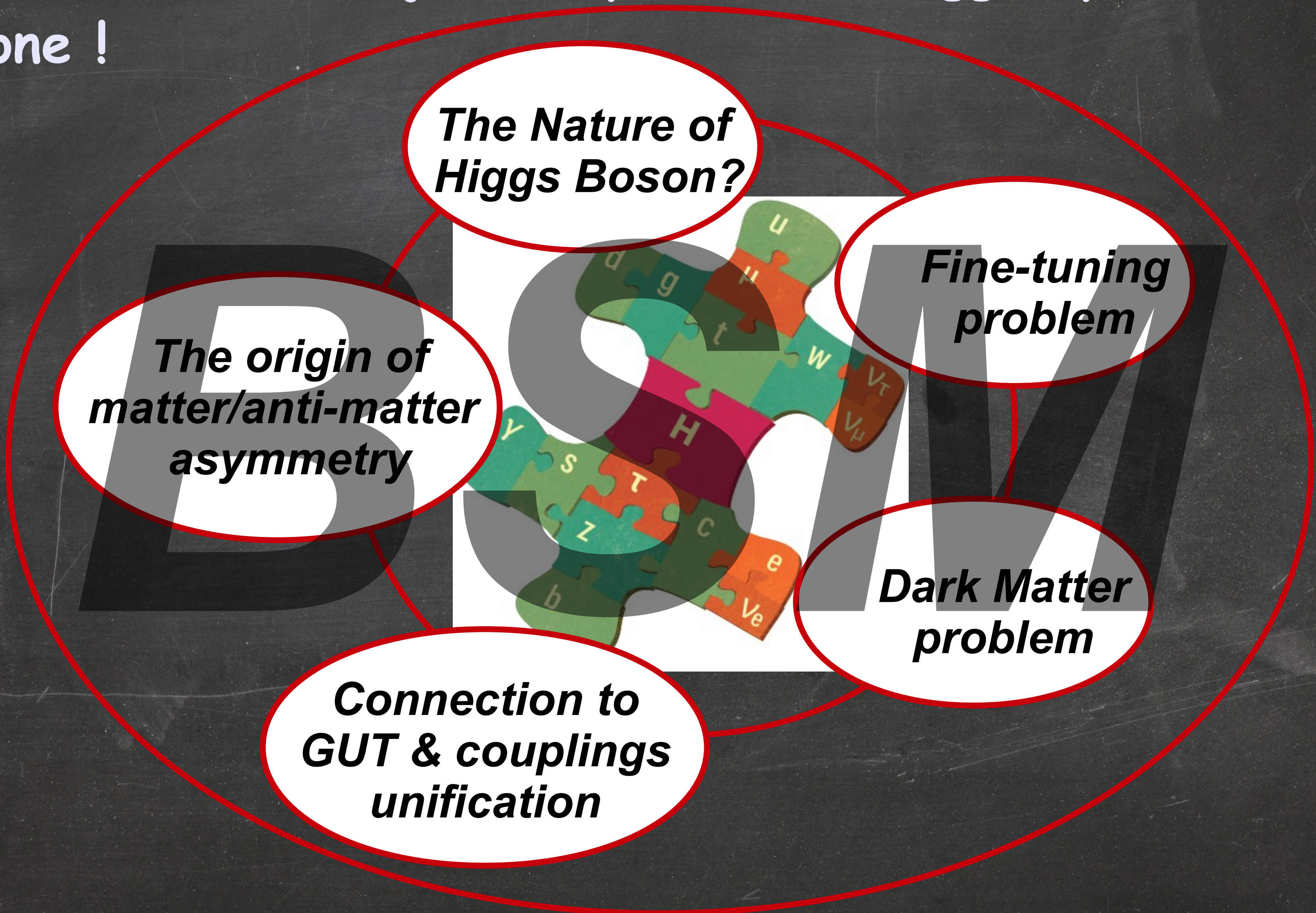
But the SM itself is just a piece of a bigger puzzle - BSM one !



What do we know about Dark Matter?

Spin $\boxed{?}$

Mass $\boxed{?}$

Stable

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

symmetry

behind stability $\boxed{?}$

Couplings

gravity $\boxed{V}$

Weak $\boxed{?}$

Higgs $\boxed{?}$

Quarks/gluons $\boxed{?}$

Leptons $\boxed{?}$

New sector $\boxed{?}$

Thermal relic

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

What do we know about Dark Matter?

- Stable or at least very long lived: $\tau > 10^{26}$sec
- Weakly interacting (at least gravitationally)
- Massive, but mass is not known/predicted
- Density $\approx$ 0.3 GeV/cm^3

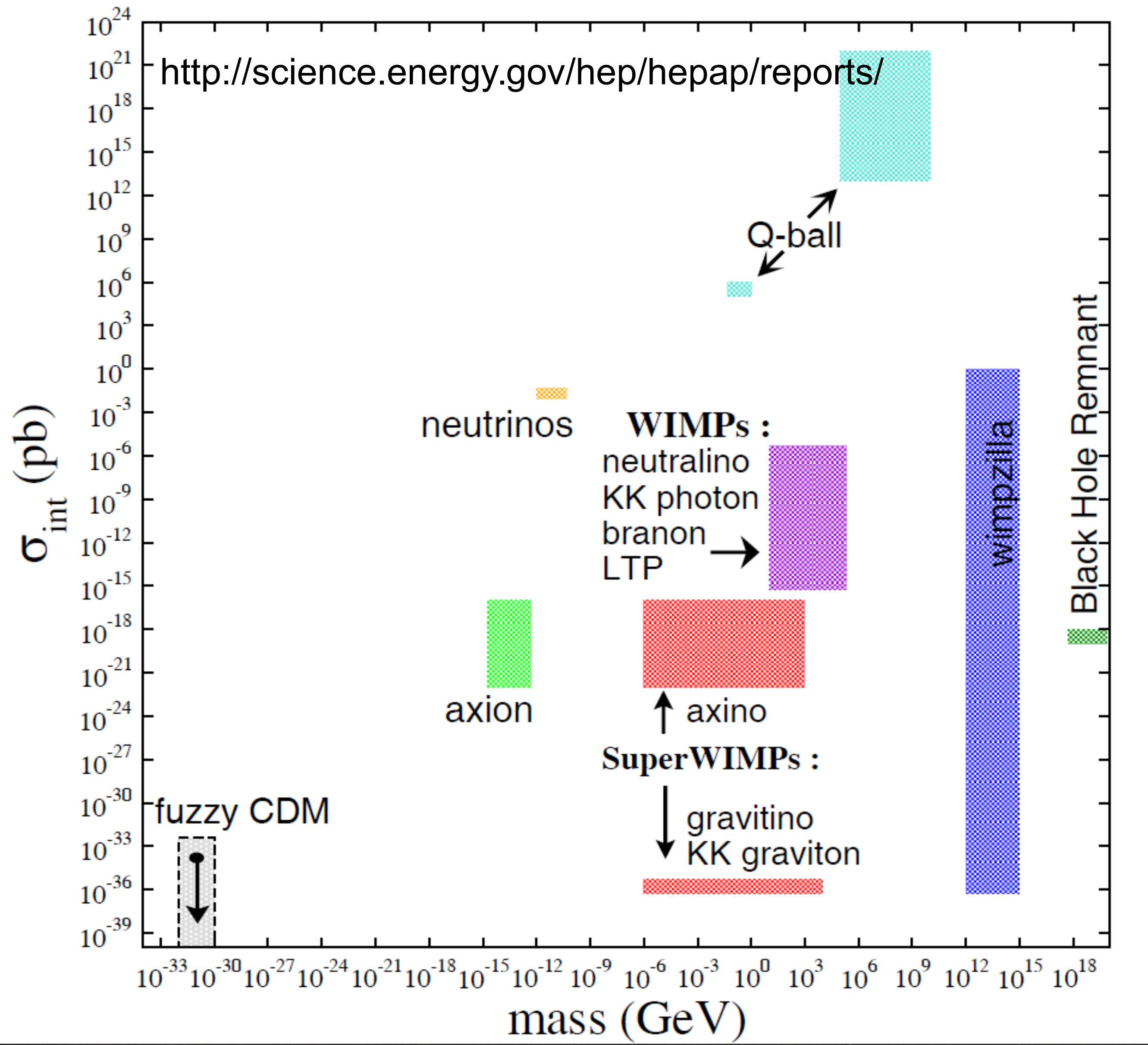
DM candidates: interaction vs mass

Suspect Relic	Mass	Origin t, T	Abundance cm^{-3}
Invisible Axion	10^{-5}eV	10^{-30}sec, 10^{12}GeV	10^{9}
Light Neutrino	30 eV	1 sec, 1 MeV	100
Photino—Gravitino	keV	10^{-4}sec, 100 MeV	10
Photino—Sneutrino—Neutralino—Axino—Heavy Neutrino	GeV	10^{-3}sec, 10 MeV	10^{-5}
Magnetic Monopoles	10^{16}GeV	10^{-34}sec, 10^{14}GeV	10^{-21}
Pyrgons—Maximons—Newtorites	10^{19}GeV	10^{-43}sec, 10^{19}GeV	10^{-24}
Quark Nuggets	$\simeq 10^{15}$g	10^{-5}sec, 300 MeV	10^{-44}
Primordial Black Holes	$\gtrsim 10^{15}$g	$\gtrsim 10^{-12}$sec, $\lesssim 10^{3}$GeV	$\lesssim 10^{-44}$

Table 9.1: WIMP candidates for the dark matter. The cosmic abundance required for closure density is $n_{WIMP} \simeq 1.05h^2 \times 10^{-5}\text{cm}^{-3}/m_{WIMP}(\text{GeV})$.

Kolb & Turner

DM candidates: interaction vs mass



- Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
- Wimpzillas: very massive non-thermal WIMPs [Kolb,Chung,Riotto'98]
- Q-balls: topological solitons that occur in QFT [Coleman '86]
- EW scale WIMPs, protected by parity – LSP, LKP, LTP particles
- SuperWIMPs: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)
- Neutrinos: usual neutrinos are too light- HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM
- Axions: $$\frac{\theta_{QCD}}{32pi^2} F^{\mu\nu} \tilde{F}^{\mu\nu}$$

θ_{QCD} is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence

DM candidates: theory space

Paolo Gondolo, WIN2015

- neutrinos (hot)
- sterile neutrinos, gravitinos (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics

- Bose-Einstein condensates, axions, axion clusters
- solitons (Q-balls, B-balls, ...)
- supermassive wimpzillas

} non-thermal relics

Mass range

10^{-22} eV (10^{-56}g) B.E.C.s
10^{-8} $M_\odot$ (10^{+25}g) axion clusters

Interaction strength range

Only gravitational: wimpzillas
Strongly interacting: B-balls

DM candidates: hot-cold-warm

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Hot dark matter

- relativistic at kinetic decoupling (start of free streaming)
- big structures form first, then fragment

light neutrinos

Cold dark matter

- non-relativistic at kinetic decoupling
- small structures form first, then merge

neutralinos, axions, WIMPZILLAs, solitons

Warm dark matter

- semi-relativistic at kinetic decoupling
- smallest structures are erased

sterile neutrinos, gravitinos

DM candidates: thermal - non-thermal

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Thermal relics

in thermal equilibrium in the early universe

neutrinos, neutralinos, other WIMPs, ...

Non-thermal relics

not in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ...

SUSY
as an example

Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

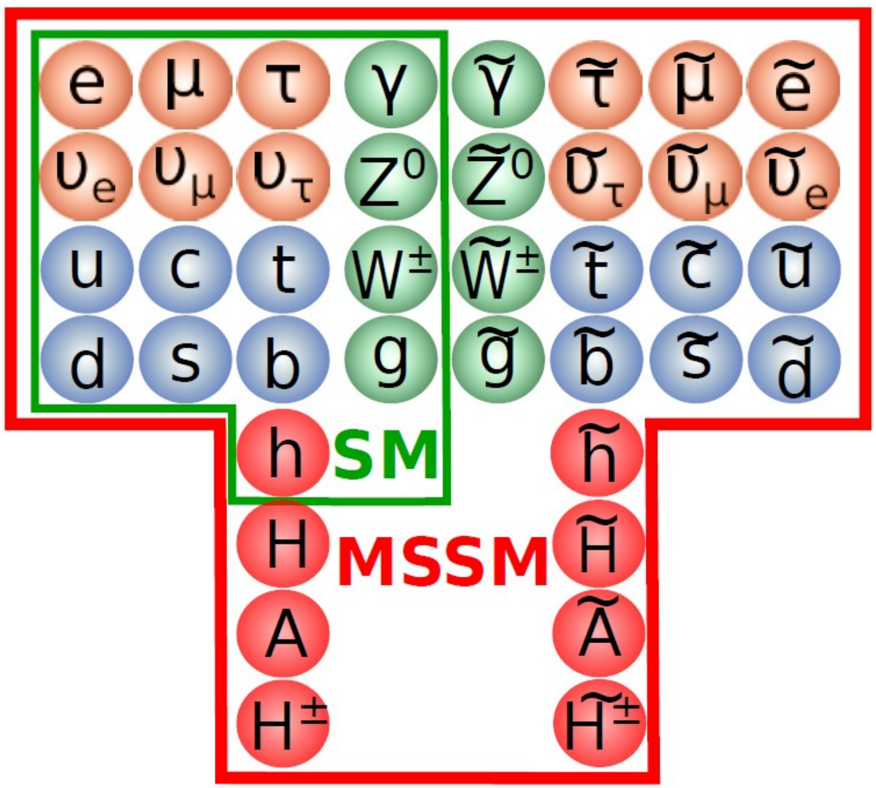
$$Q|\mathrm{BOSON}\rangle = |\mathrm{FERMION}\rangle, \quad Q|\mathrm{FERMION}\rangle = |\mathrm{BOSON}\rangle$$

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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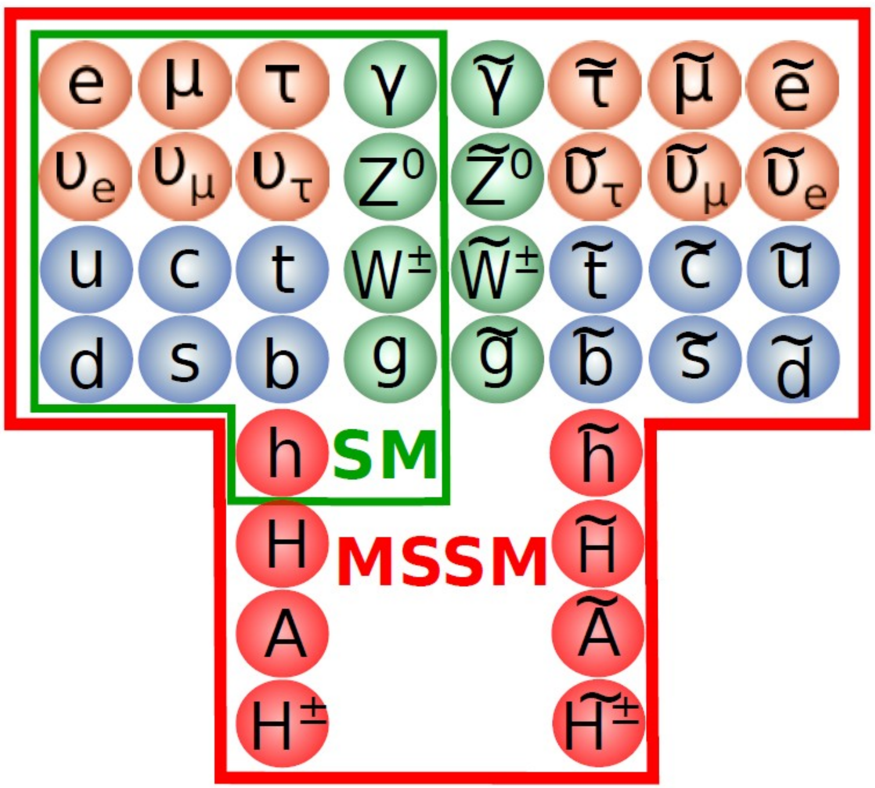

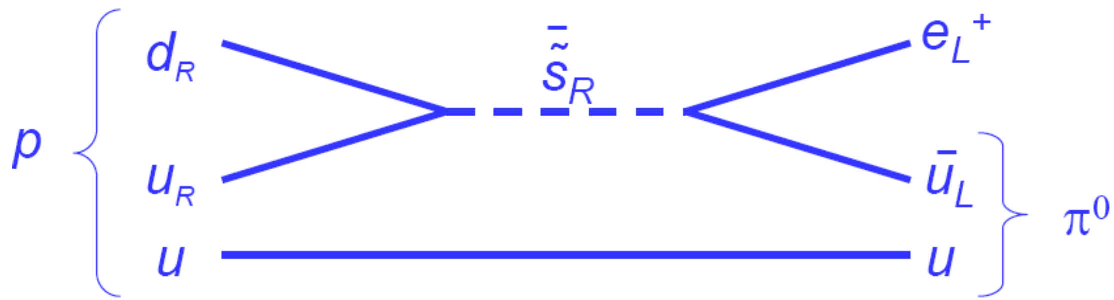

could give rise the proton decay!

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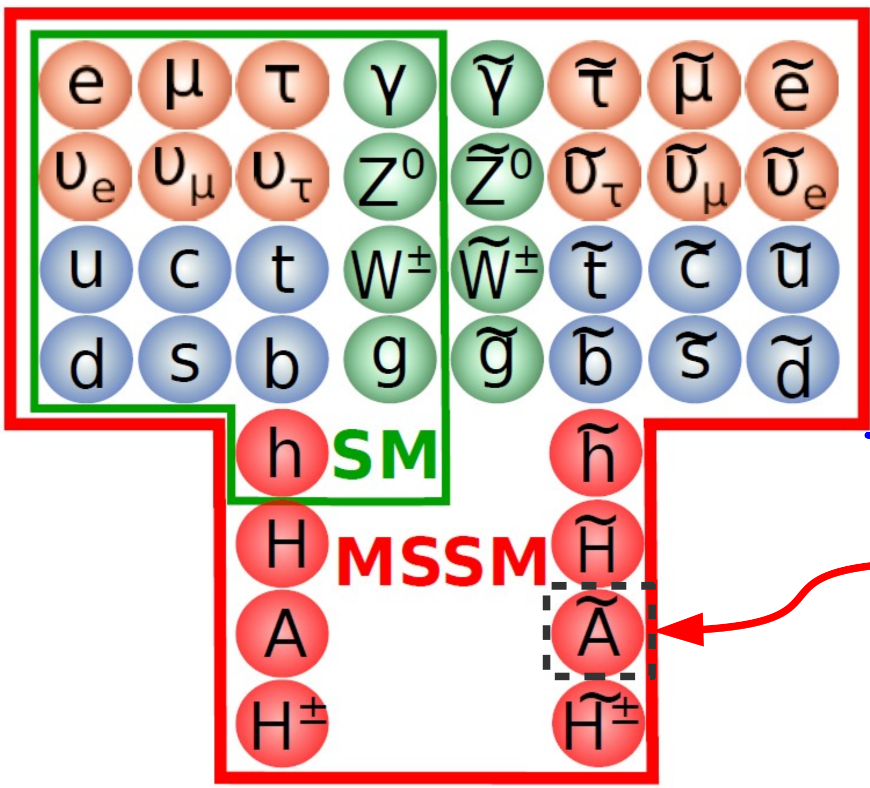
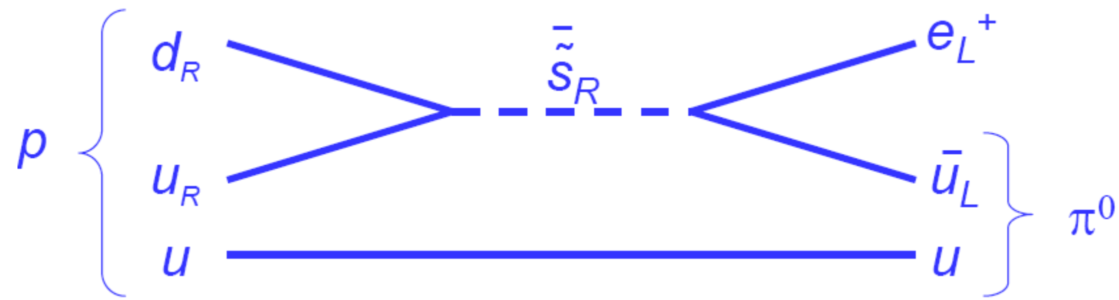
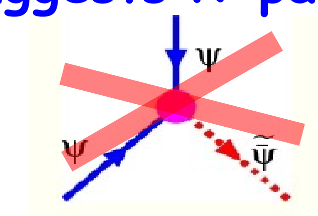




could give rise the proton decay!

the absence of proton decay suggests R-parity

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



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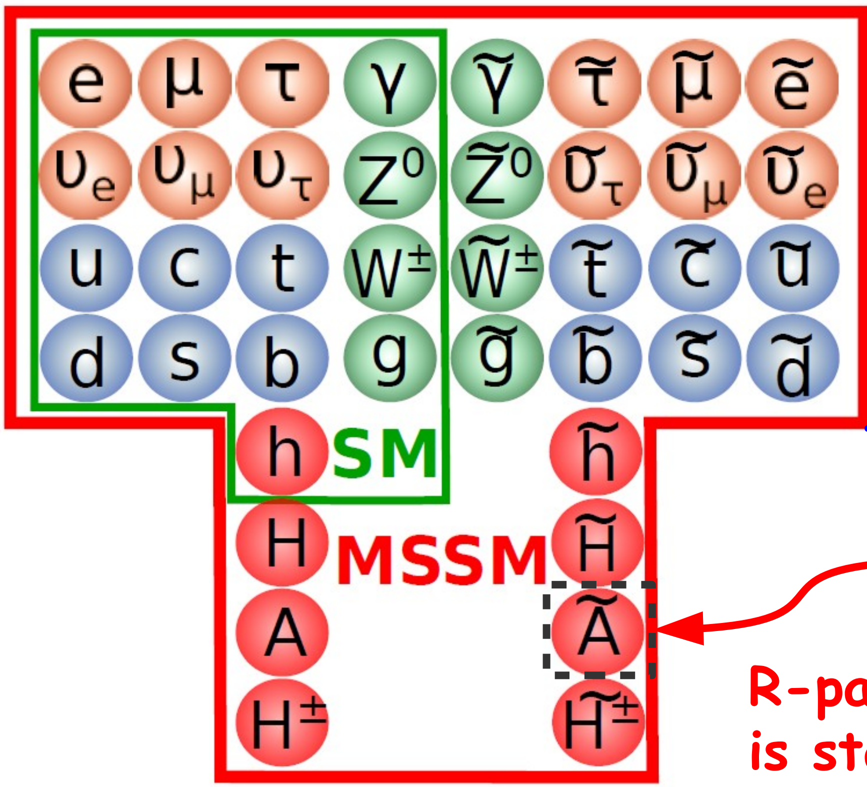

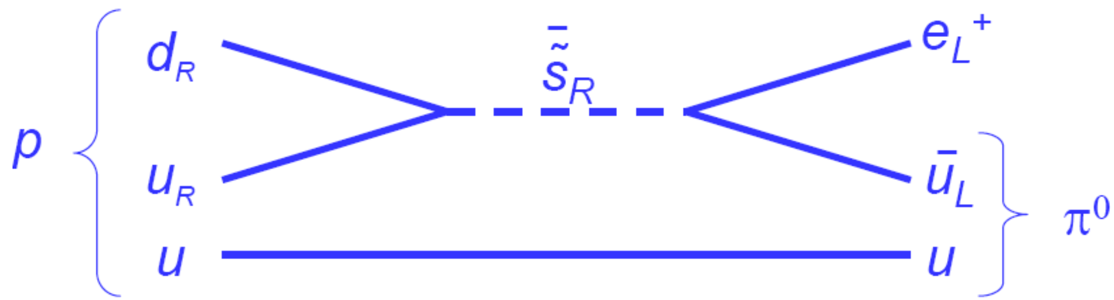

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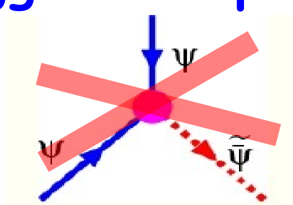
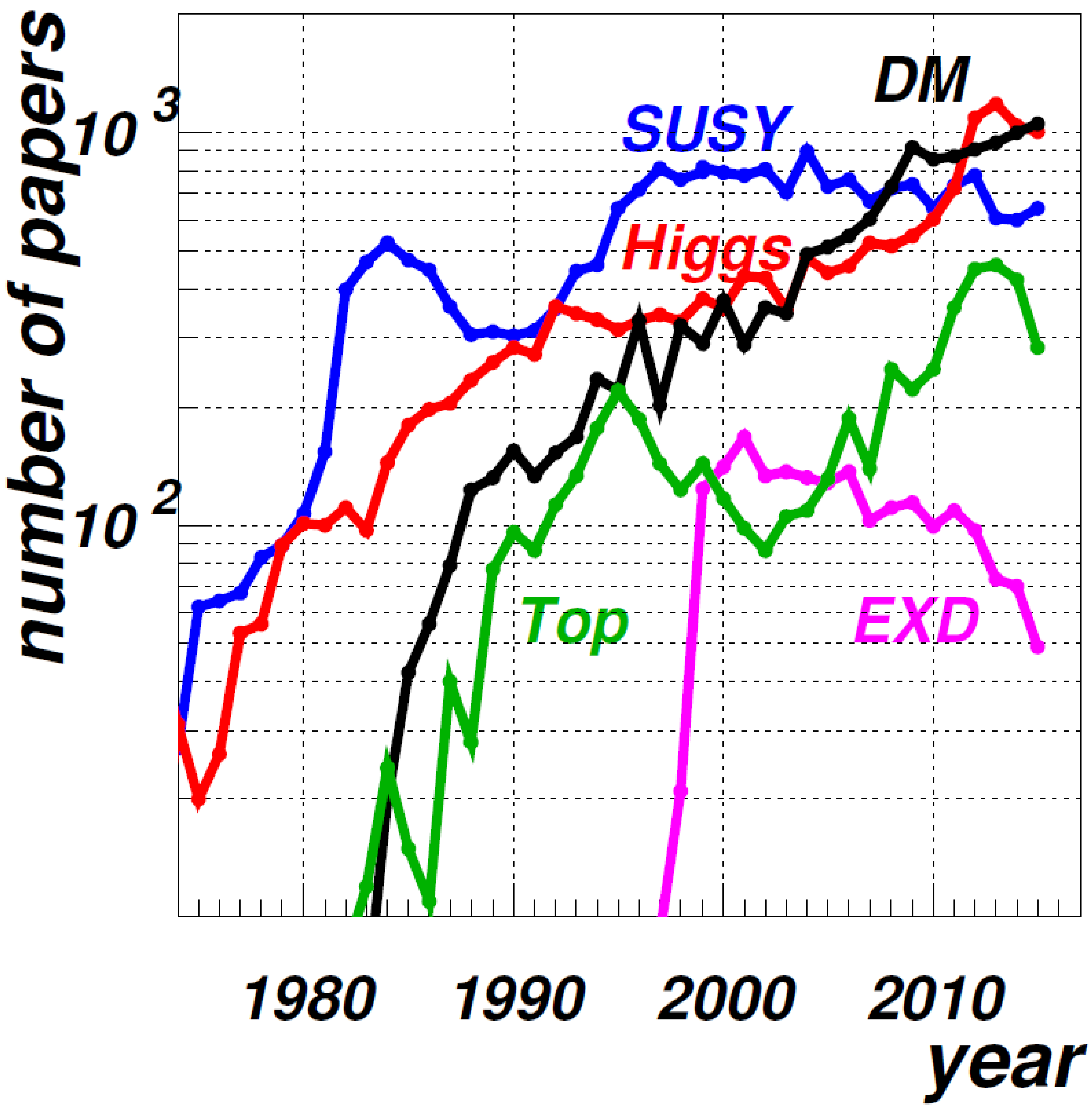


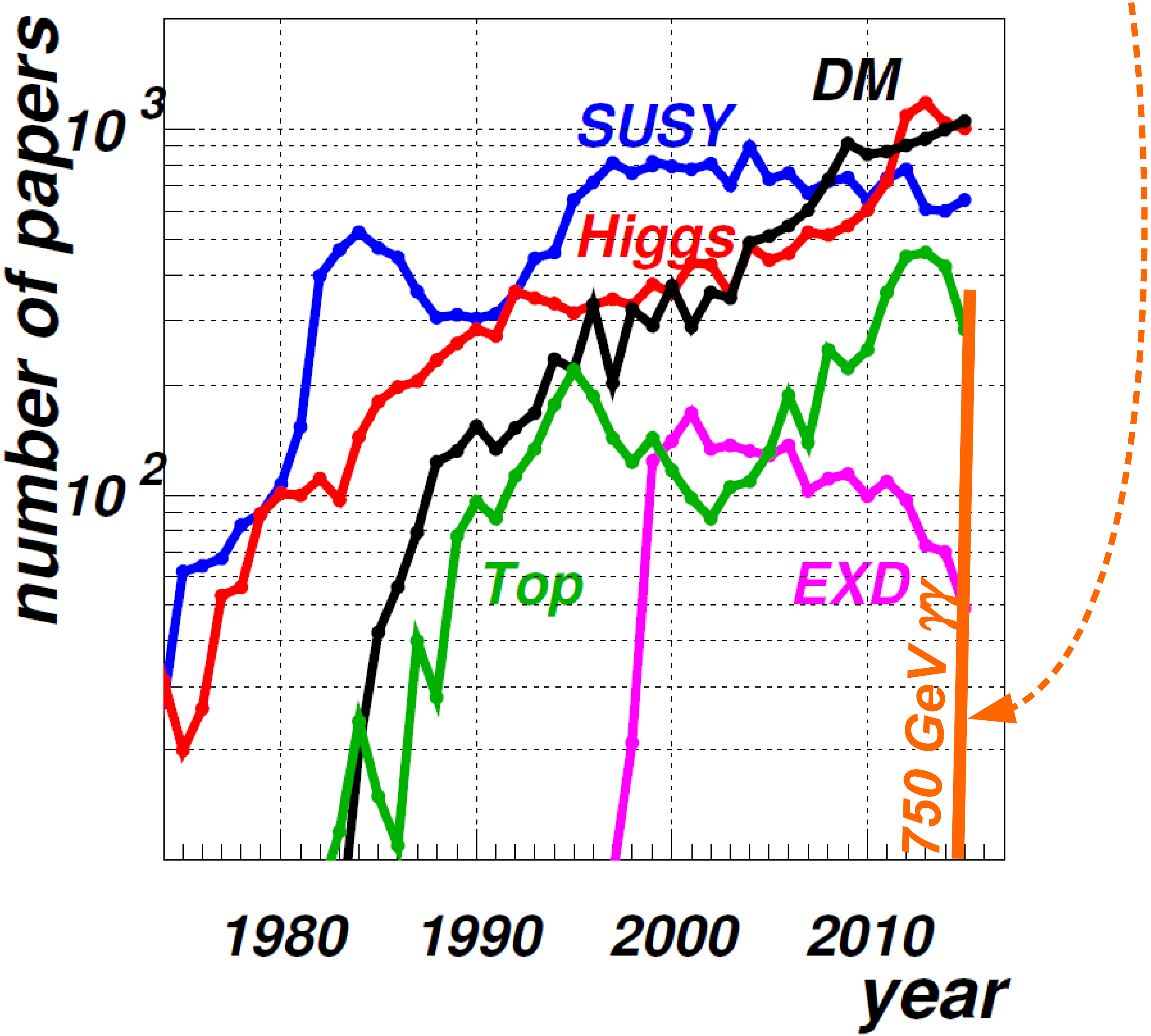
R-parity guarantees Lightest SUSY particle (LSP) is stable – DM candidate!

Many of us are still inspired by SUSY

even after more than 30 year unsuccessful searches ...

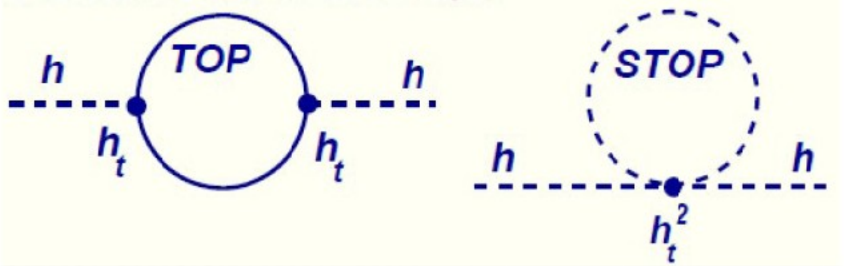


Another source of inspiration?!

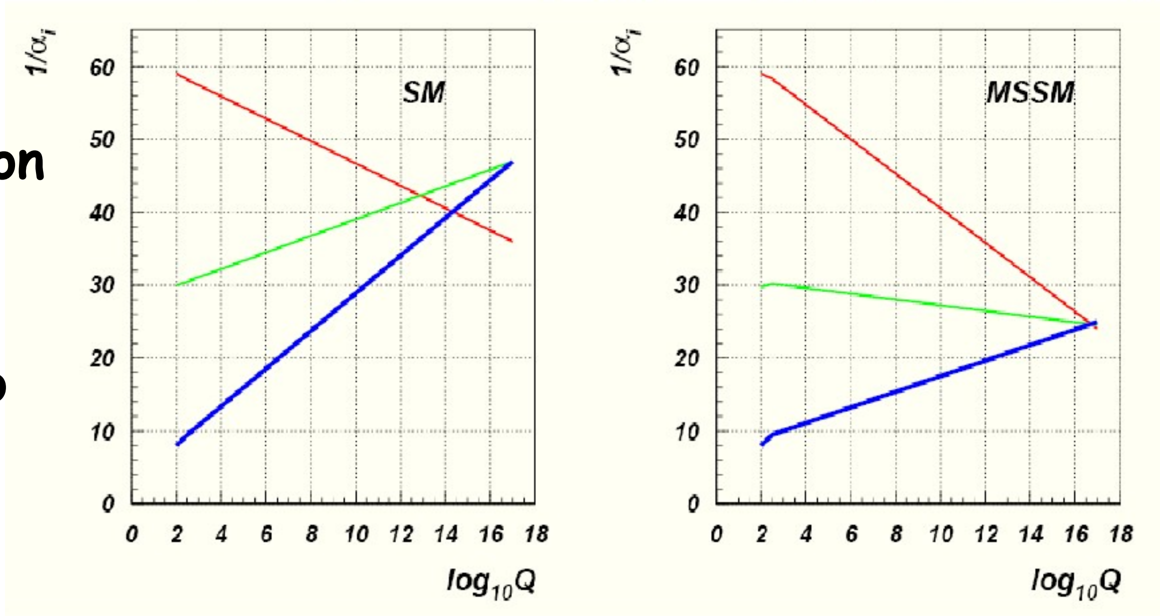


Beauty of SUSY

- 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



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

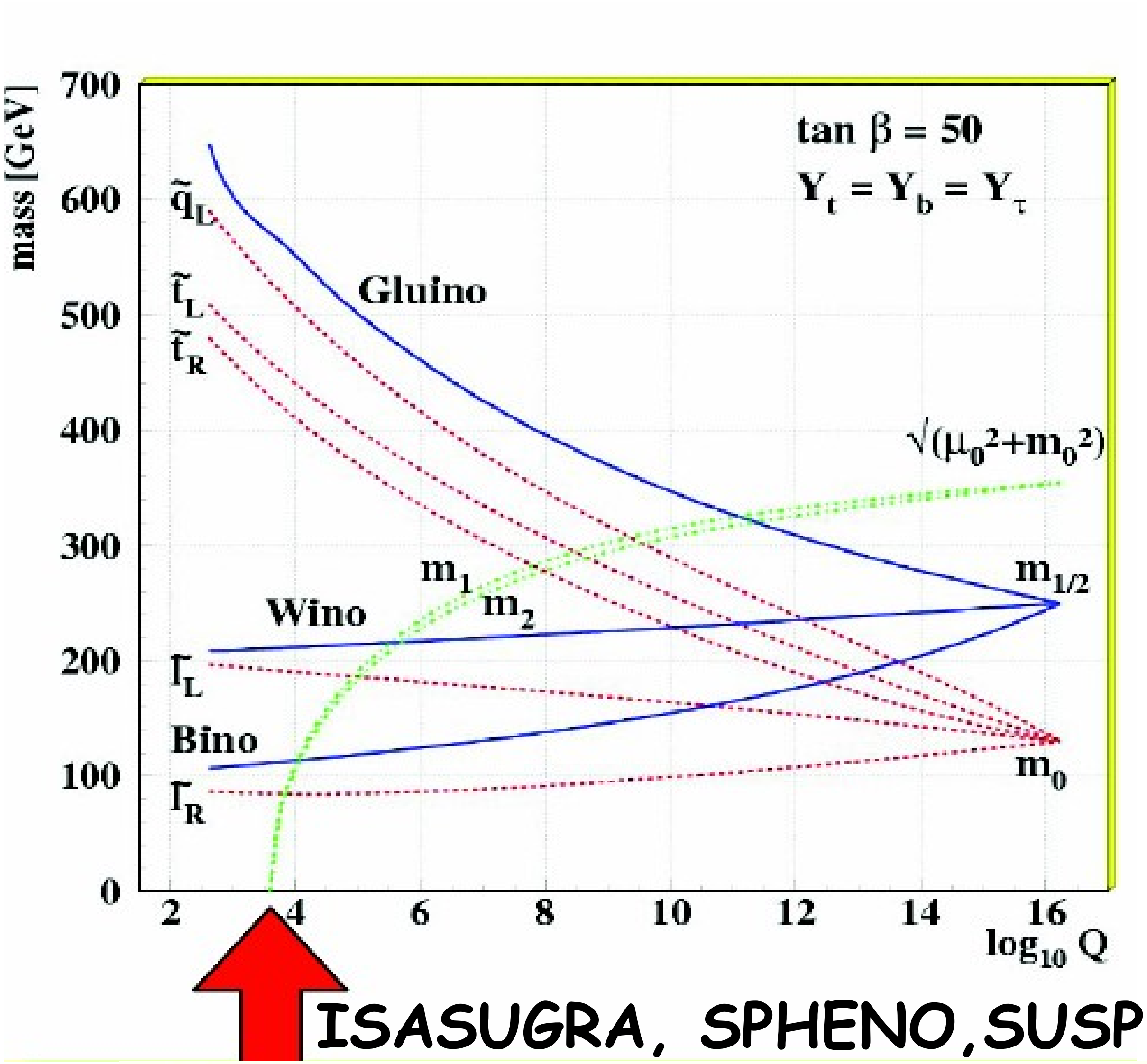


It was not deliberately designed to solve the SM problems!

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

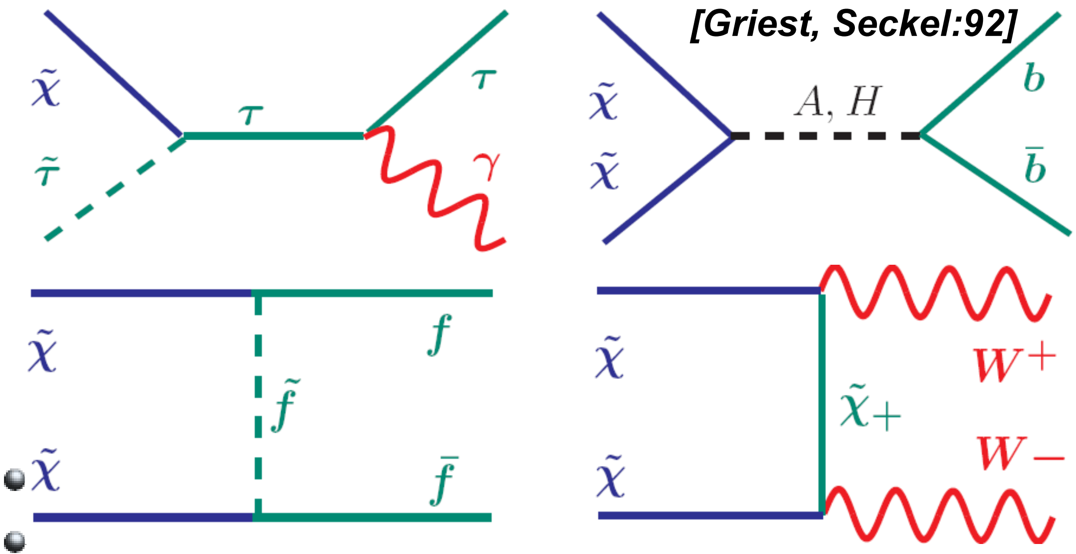
tan(beta) = v1/v2

ISASUGRA, SPHENO, SUSPECT, SOFTSUSY

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

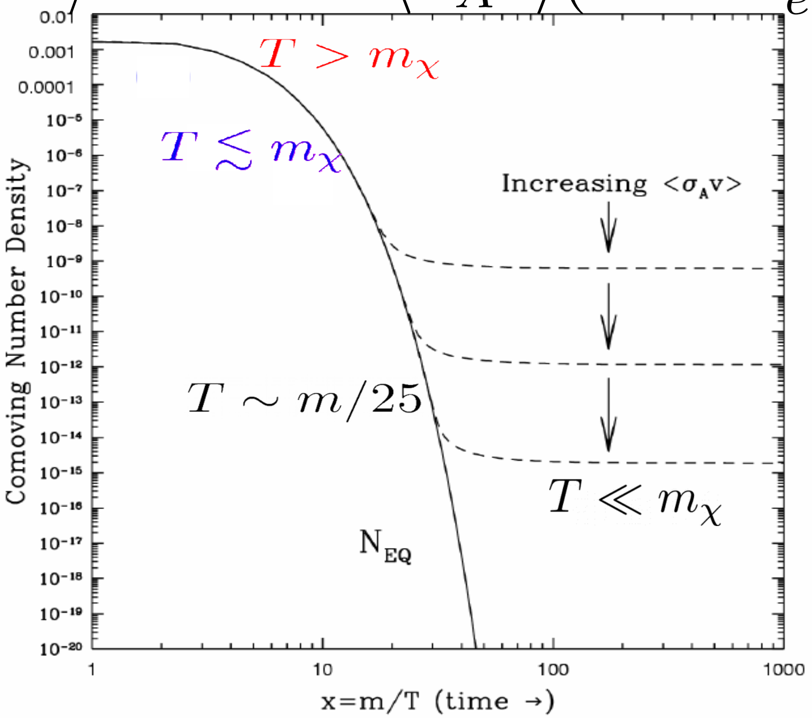
Evolution of neutralino relic density

- Challenge is to evaluate thousands annihilation/co-annihilation diagrams



time evolution of number density is given by Boltzmann equation

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



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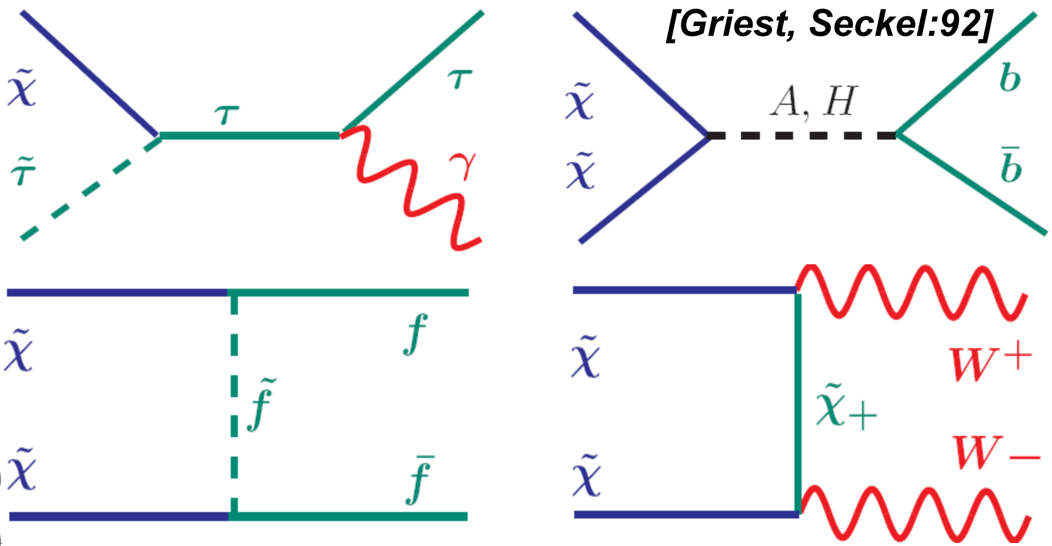

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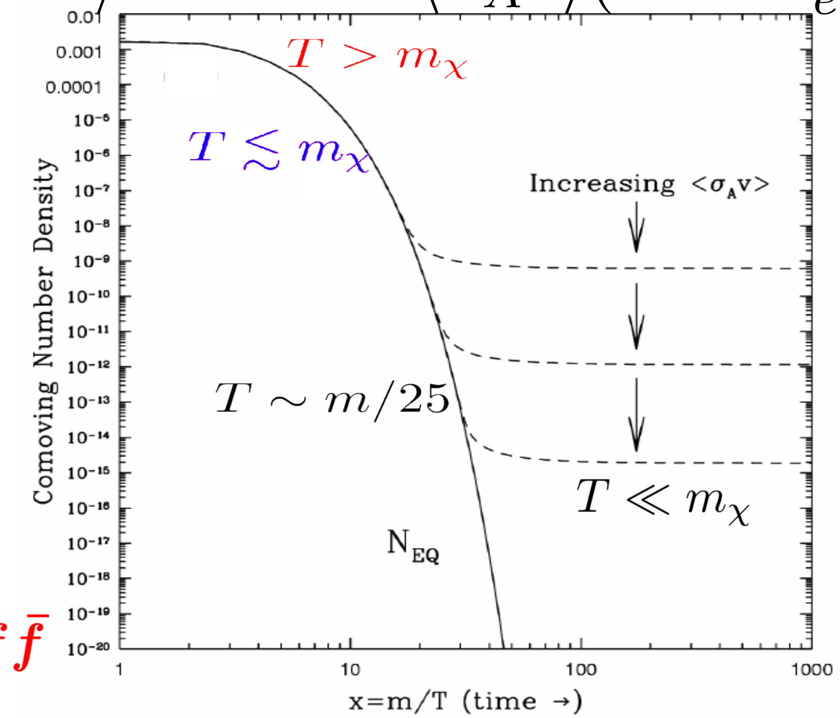

- relic density depends crucially on $\langle\sigma_A v\rangle$
- thermal equilibrium stage: $T > m_\chi,\quad \chi\chi \leftrightarrow f\bar{f}$

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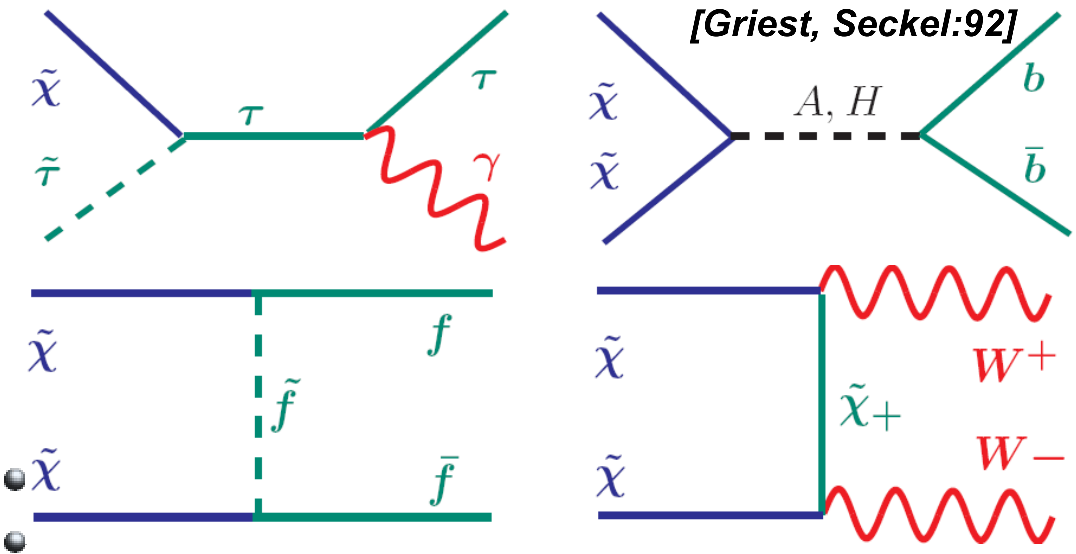
[Griest, Seckel:92]



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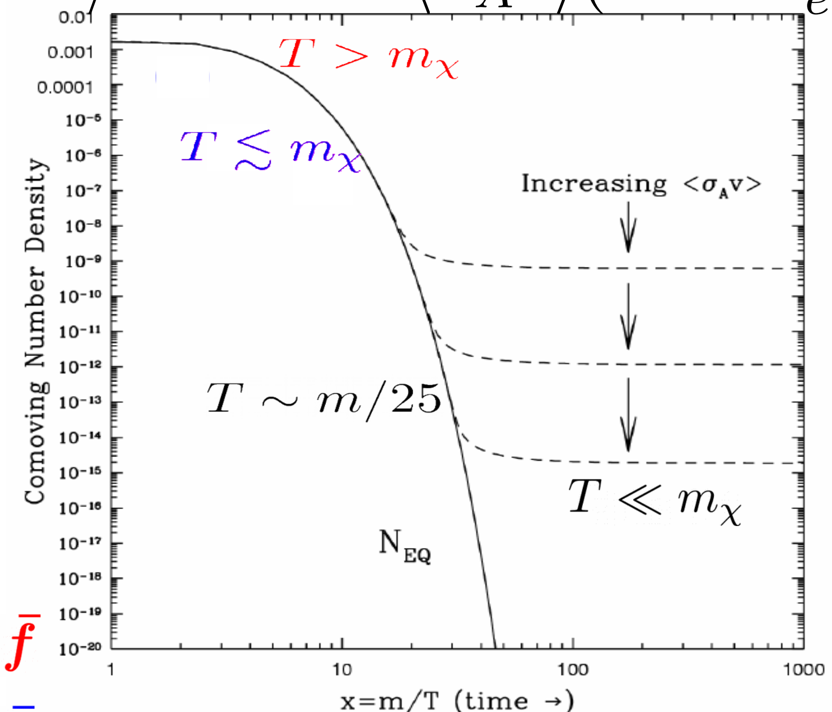

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  $n = n_{eq} \sim e^{-m/T}$

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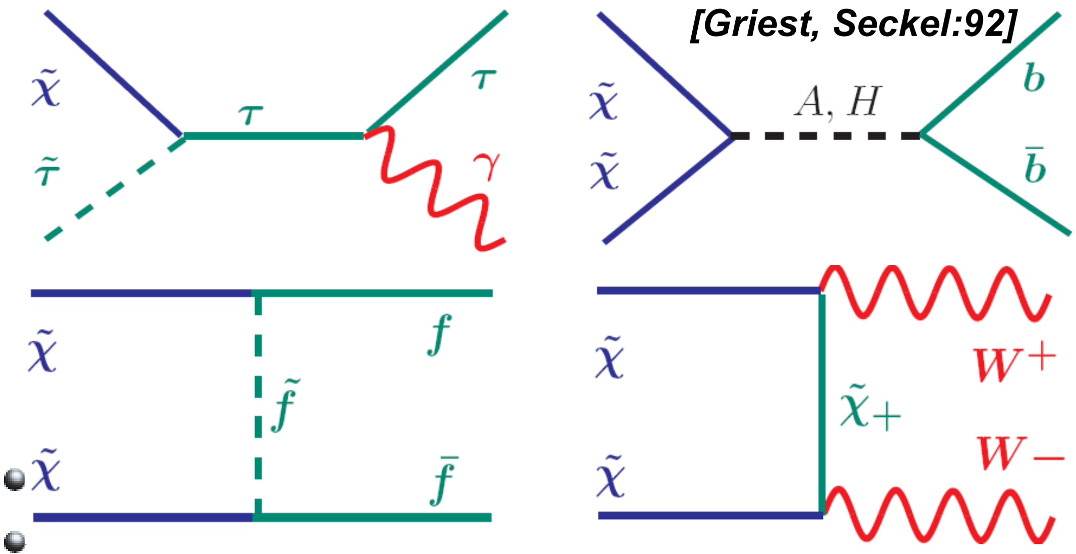

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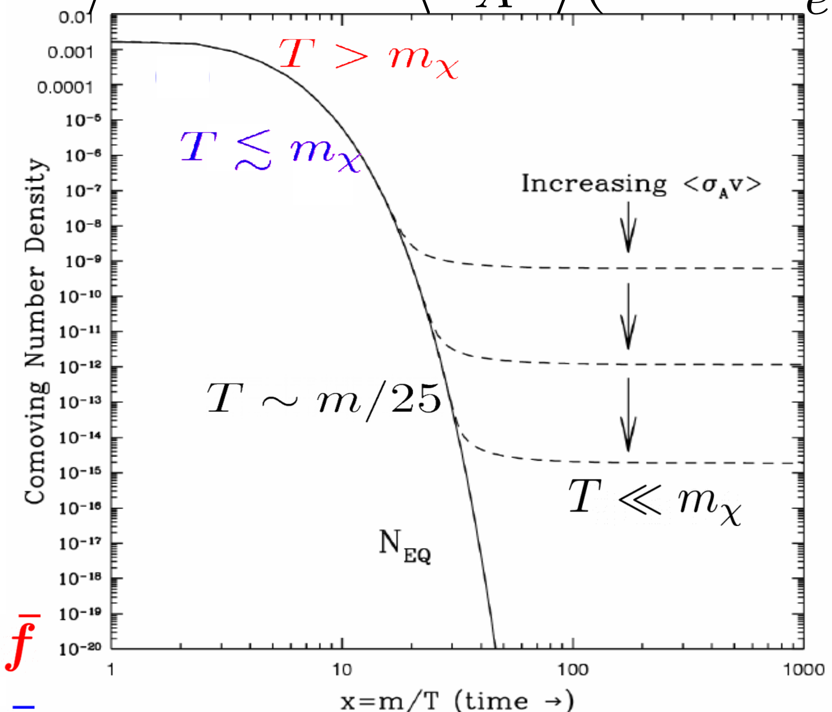

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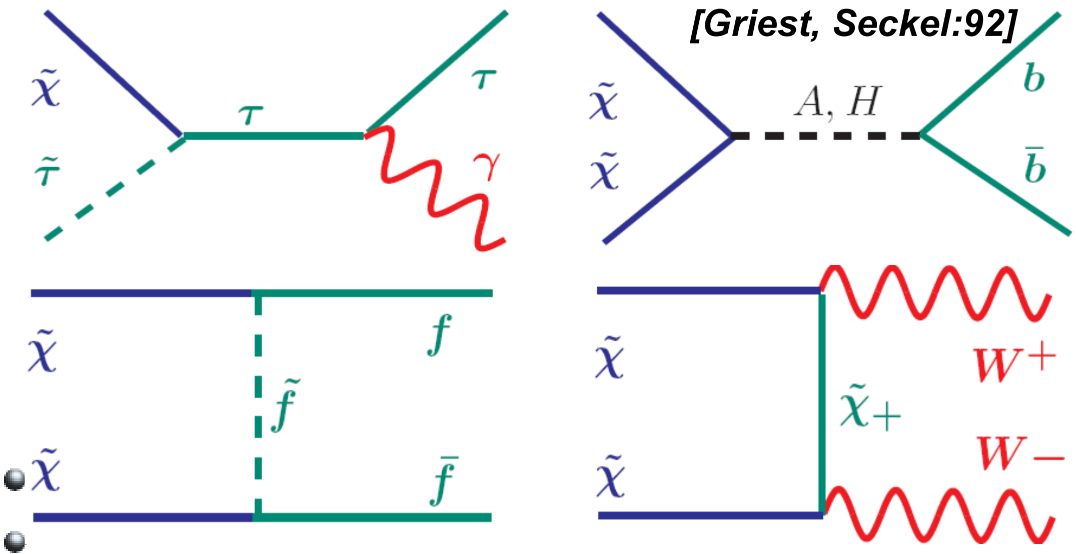

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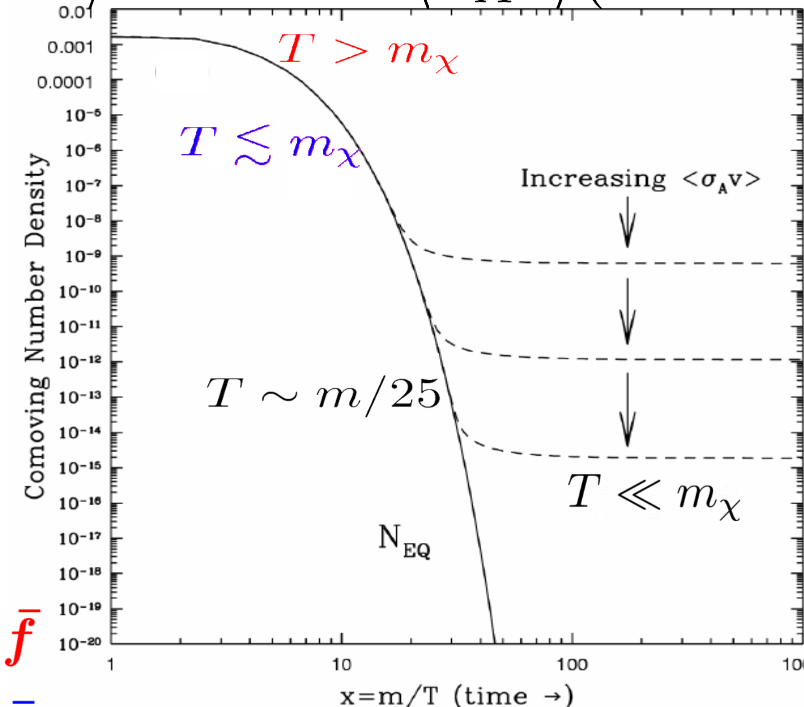

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Packages:

MicrOMEGAs, DarkSusy, ISARED, MadDM

Evolution of neutralino relic density

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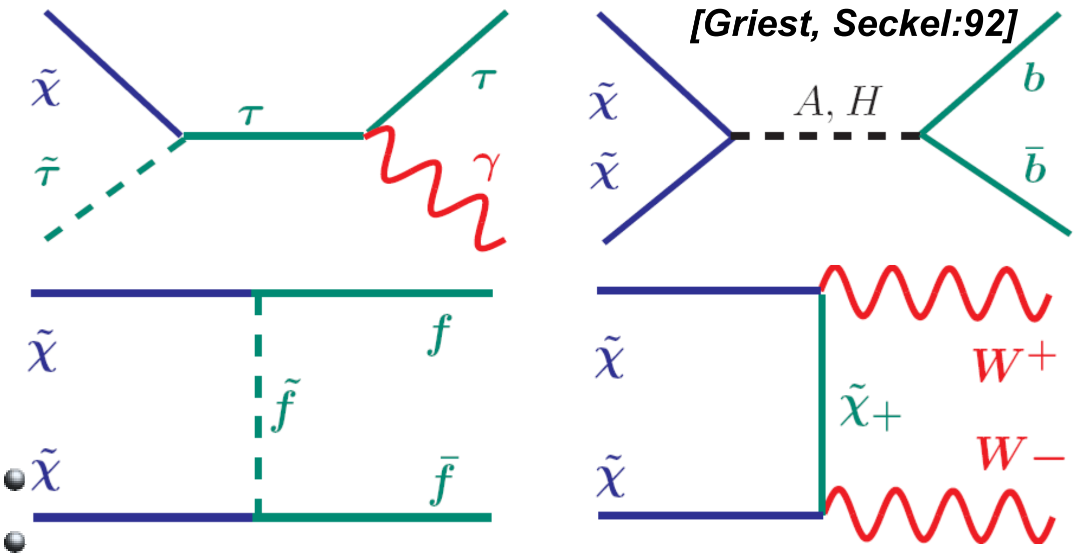
[Griest, Seckel:92]



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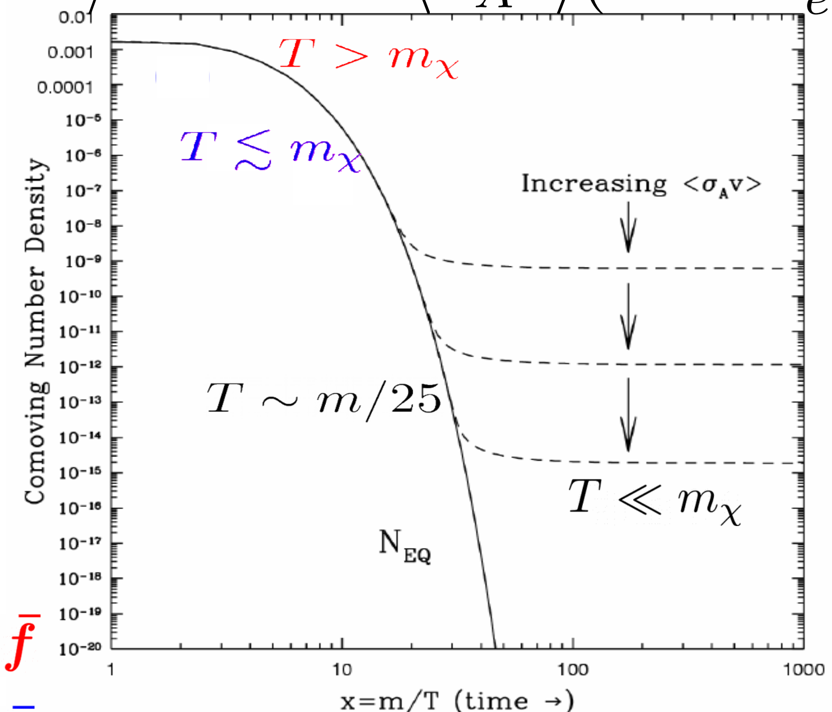

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$$\Omega_\chi = \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

$$\Omega_\chi h^2 \rightarrow \langle \sigma_A v \rangle = 1\mathrm{pb}$$

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

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

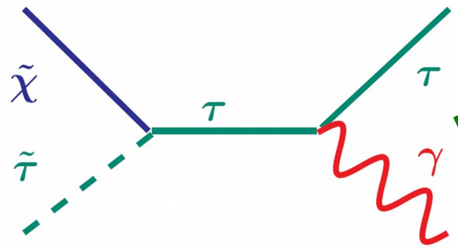
mass of the mediator

Packages:
MicrOMEGAs, DarkSusy, ISARED, MadDM

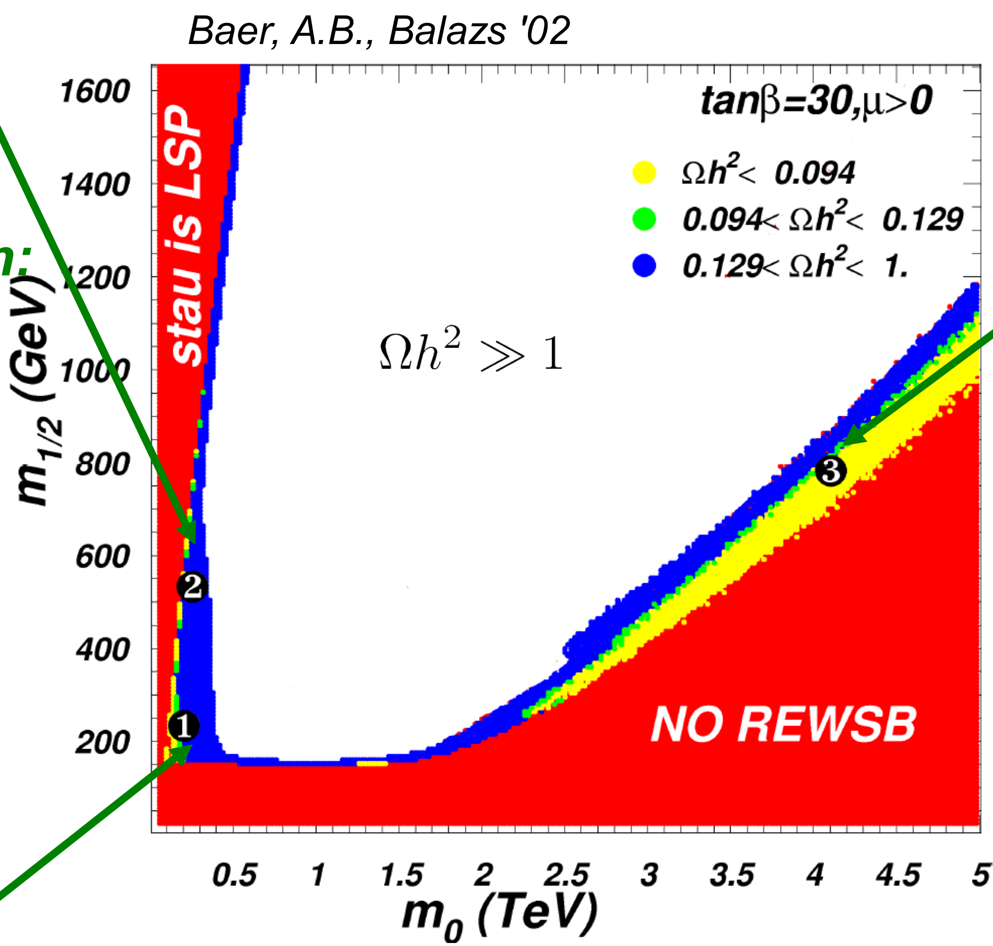
Neutralino relic density in mSUGRA

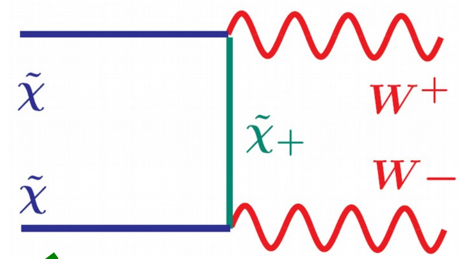
most of the parameter space is ruled out $\Omega h^2 \gg 1$

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



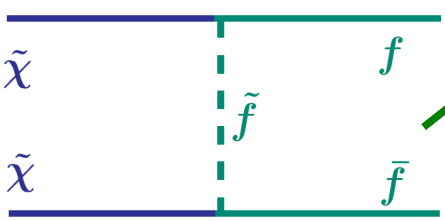
2. stau coannihilation:
degenerate χ and stau





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

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

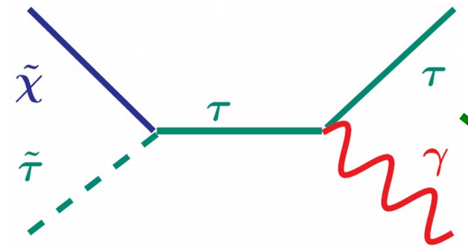


1. bulk region: ***light sfermions***

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 $0.094 < \Omega h^2 < 0.129$



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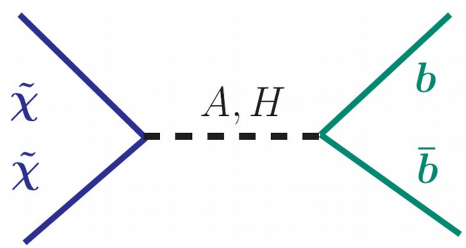
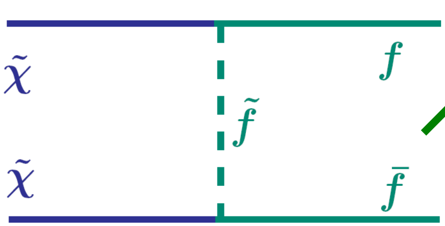
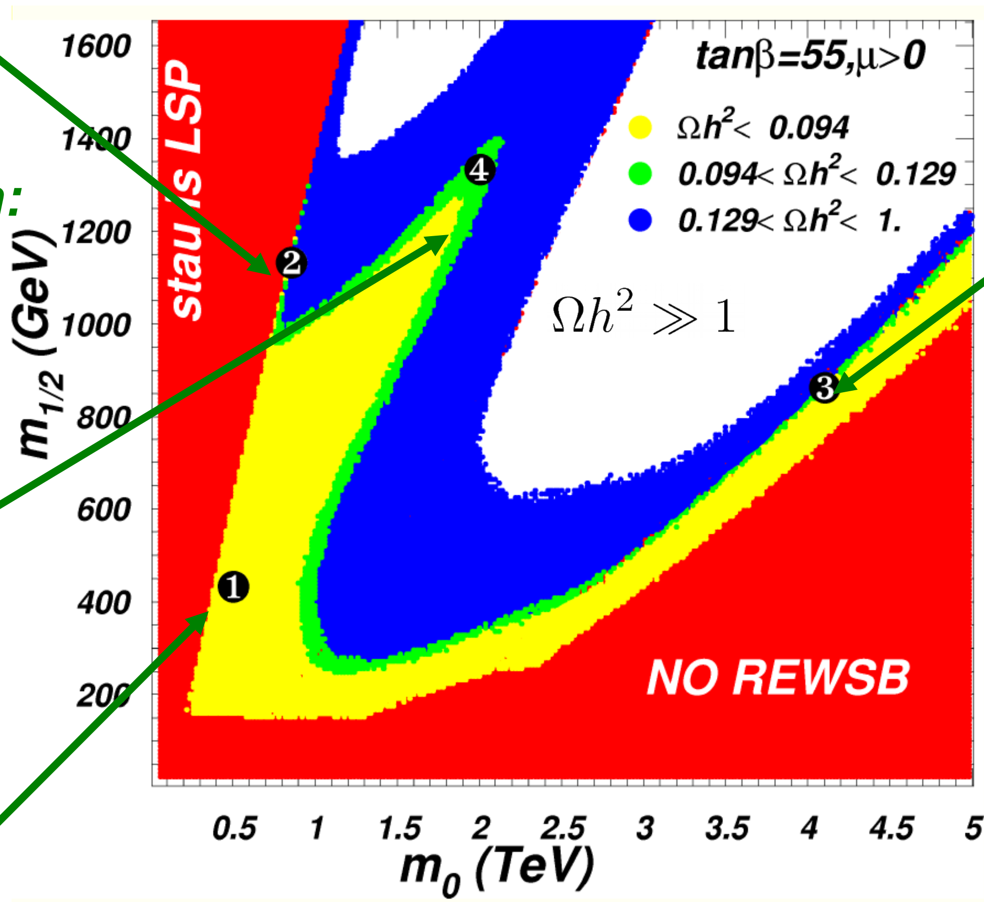


4. funnel: *(large tanβ)*
annihilation via A, H



Baer, A.B., Balazs '02



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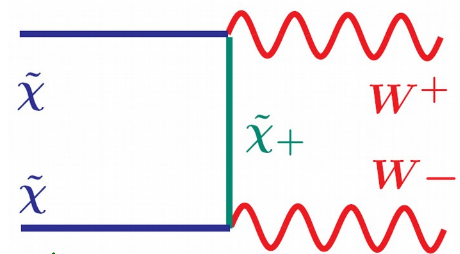

3. focus point:
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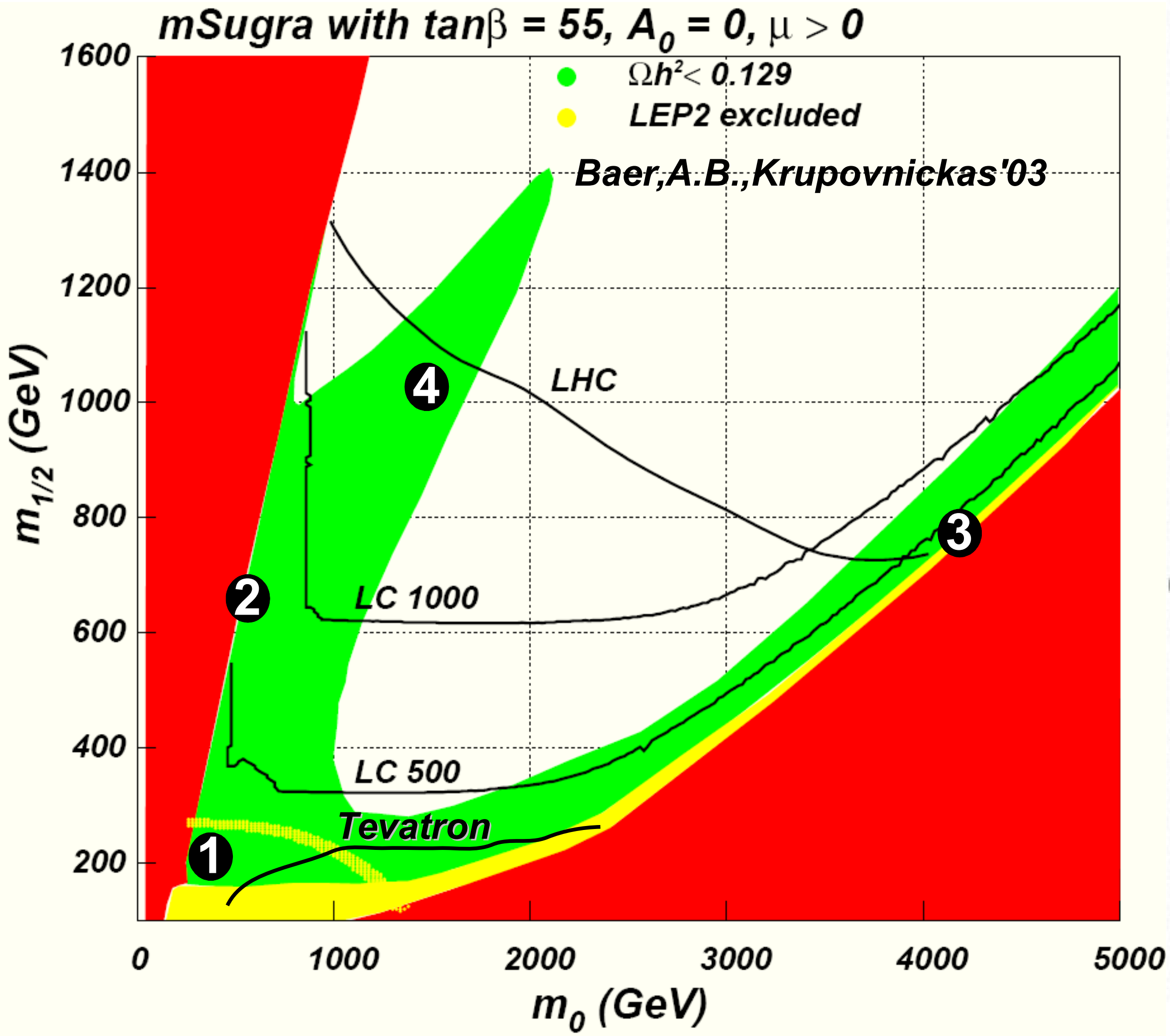
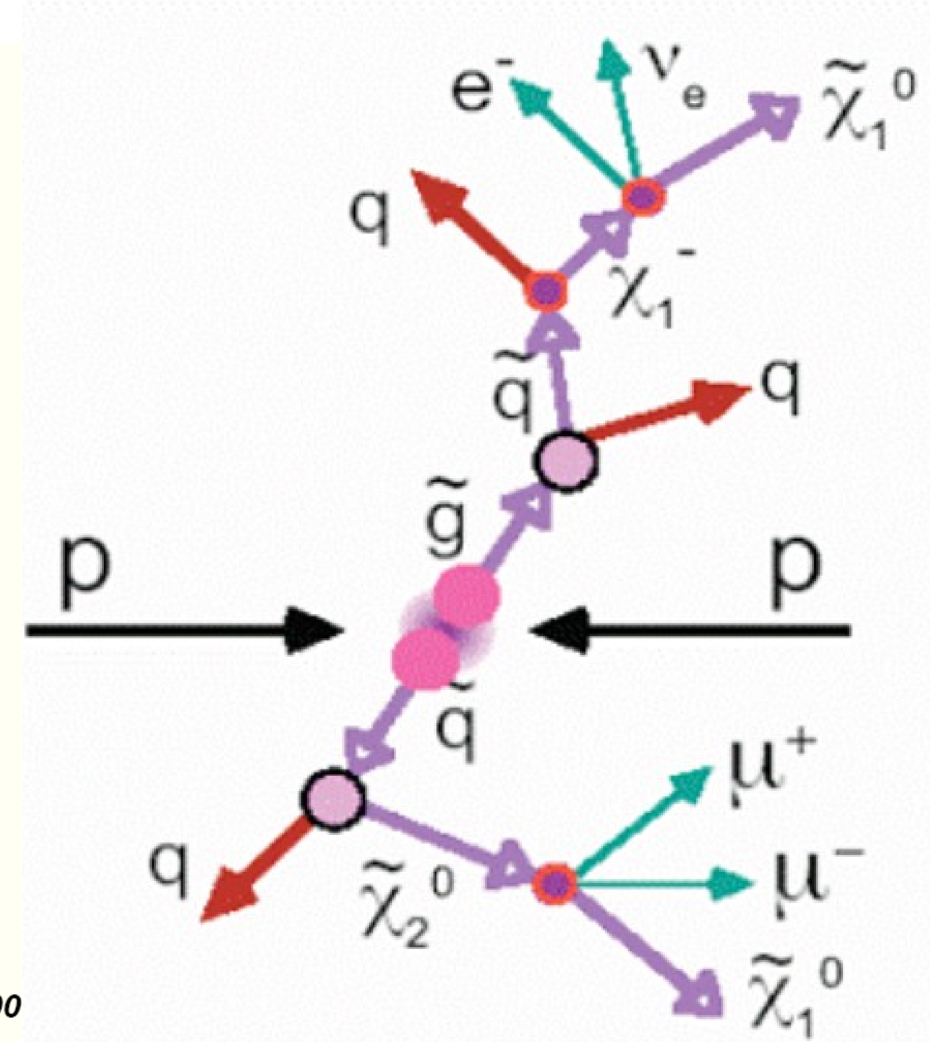
$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$

additional regions:
Z/h annihilation
stop coannihilation

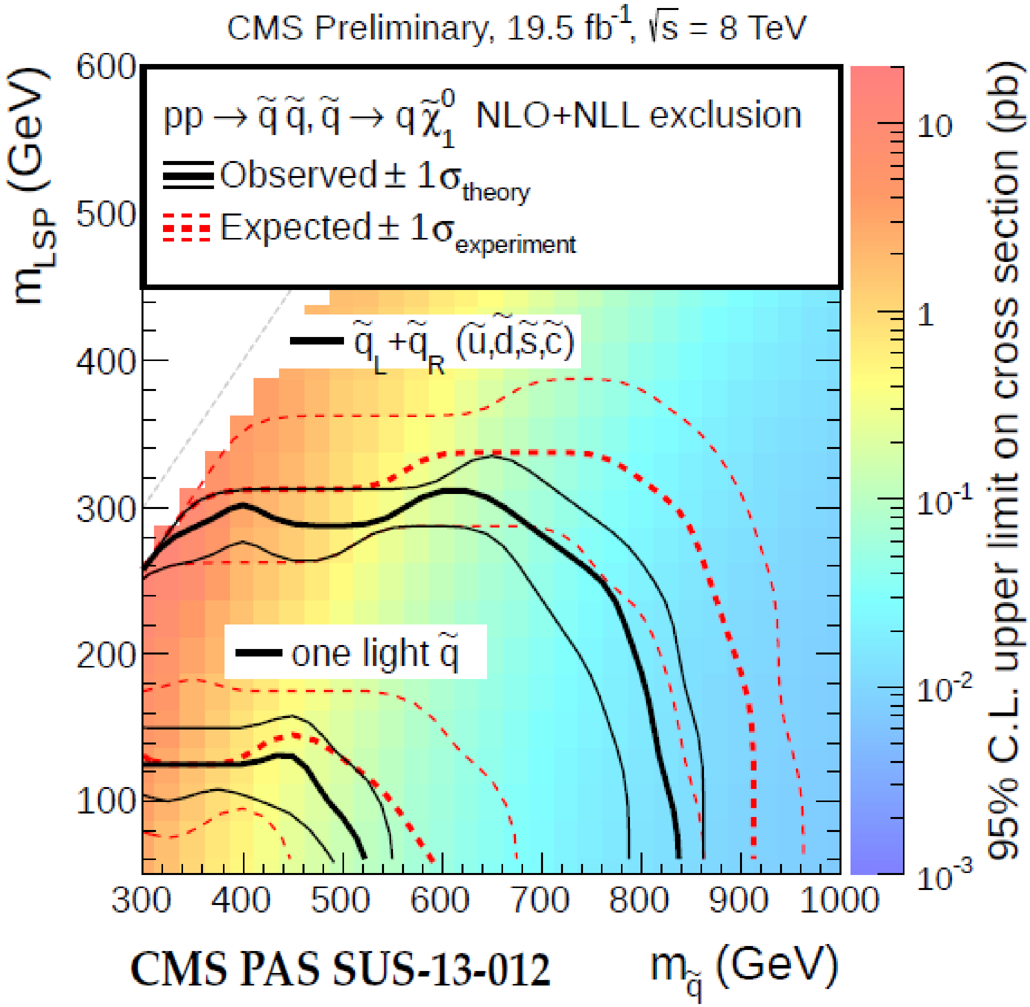
Collider signatures in DM allowed regions

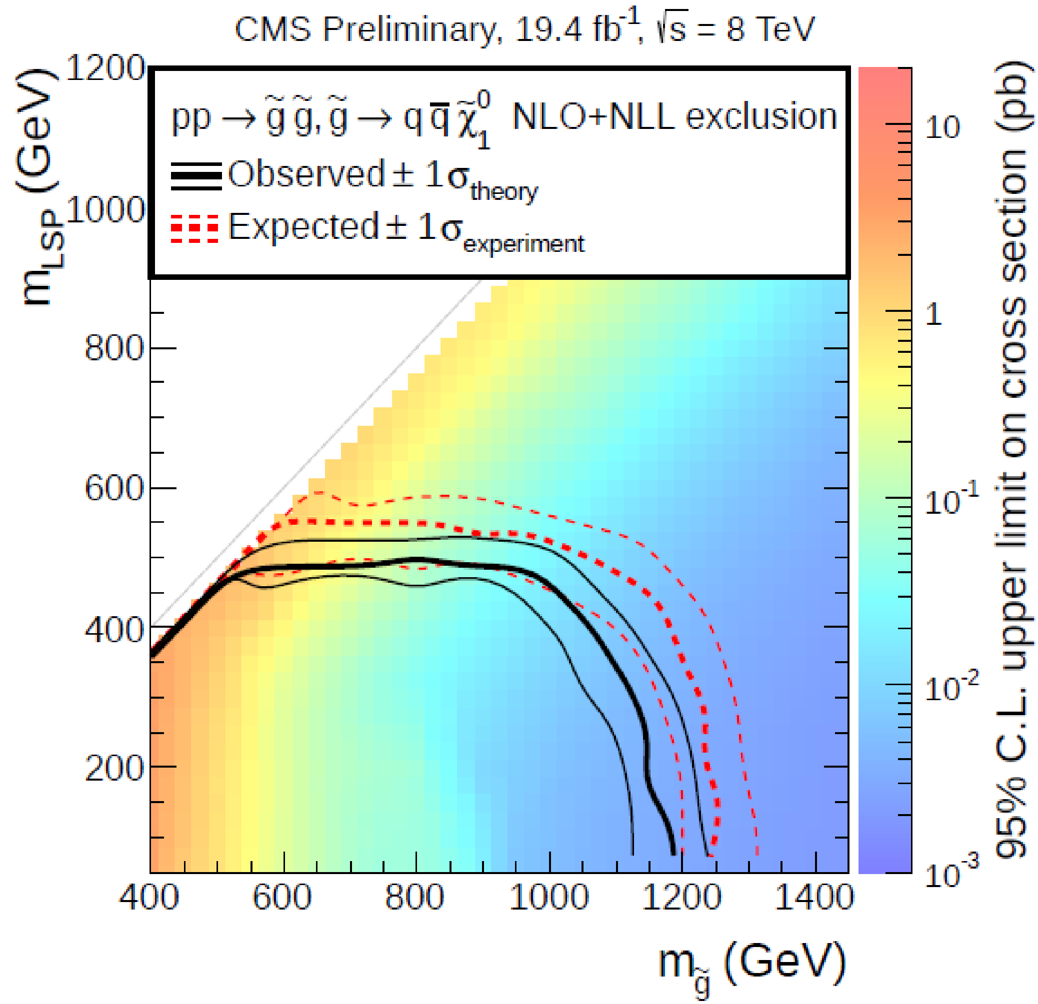
- **DM allowed regions are difficult for the observation at the colliders: stau(stop) co-annihilation , FP region:** **small visible energy release**





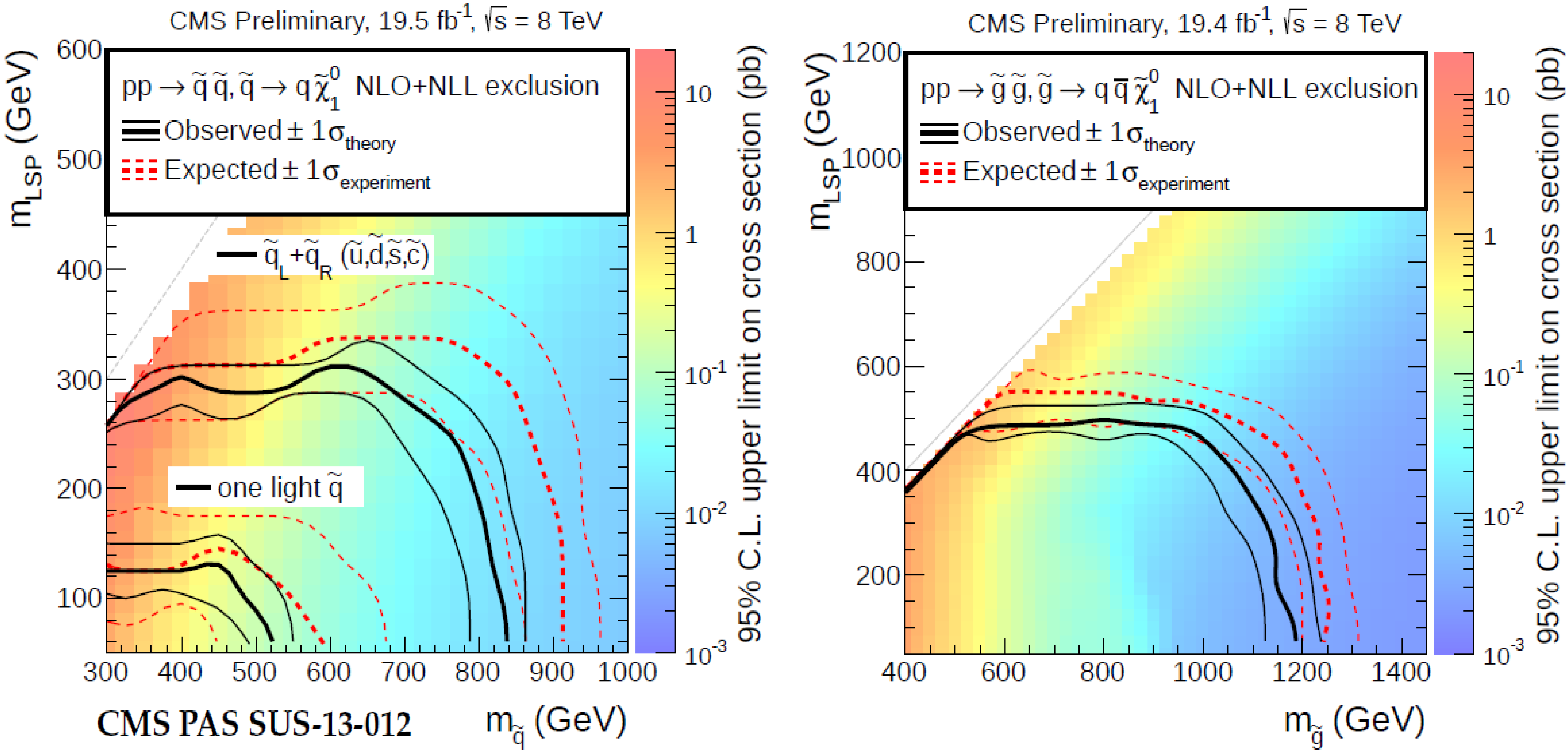
What is about DM mass?





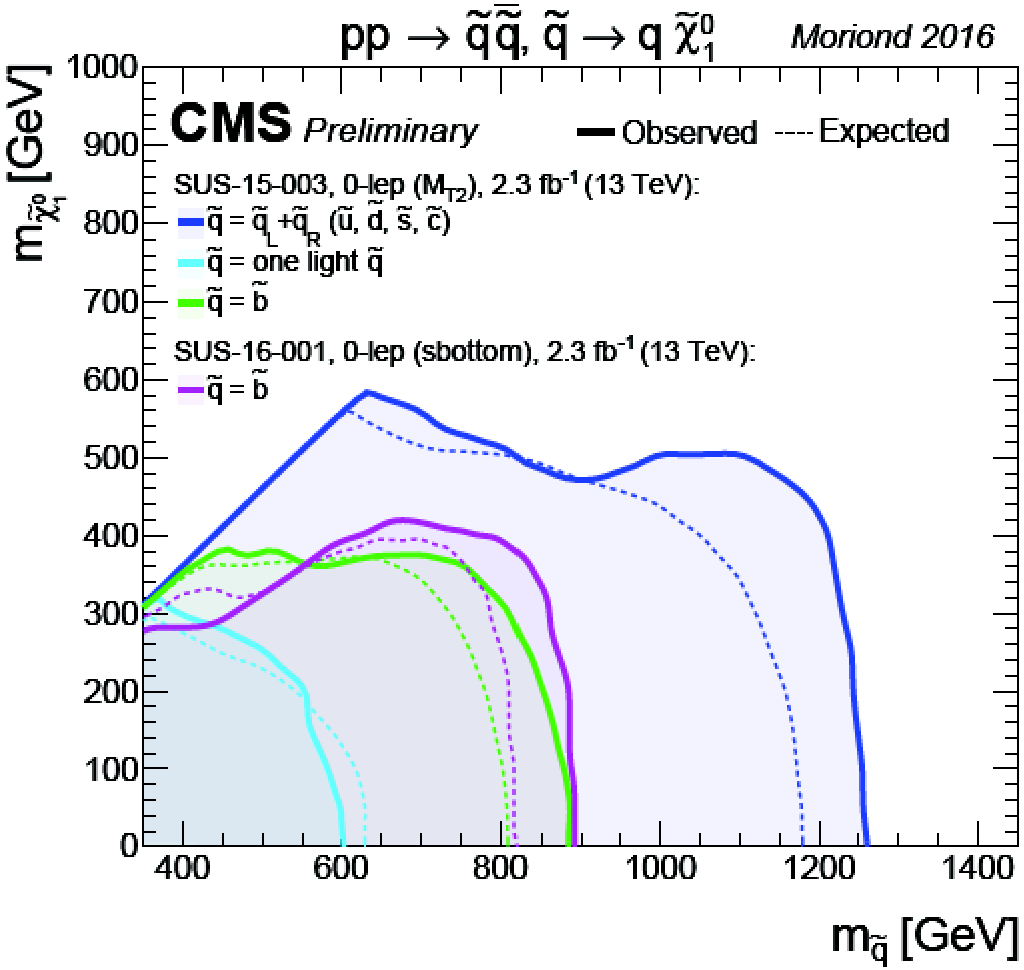
CMS PAS SUS-13-012

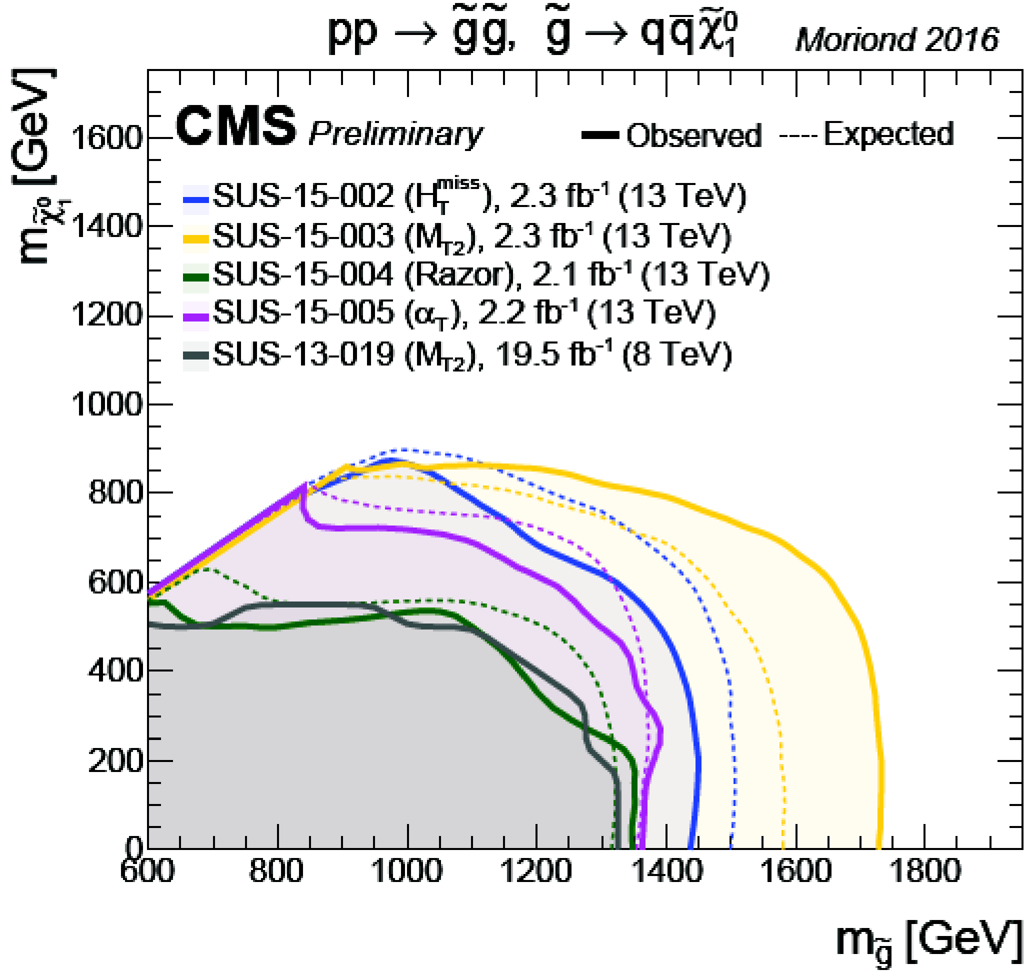
What is about DM mass?



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?





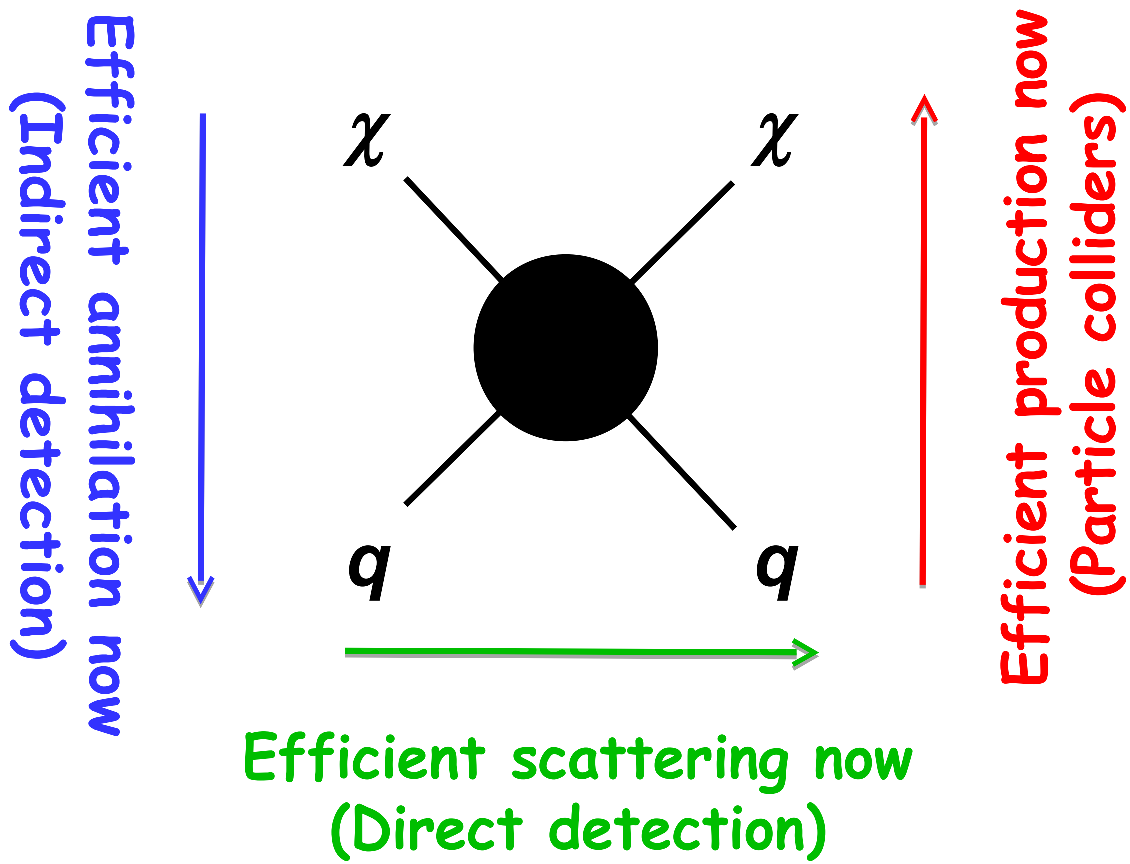
There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.7 TeV

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



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

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photons,
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Neutrino telescopes:
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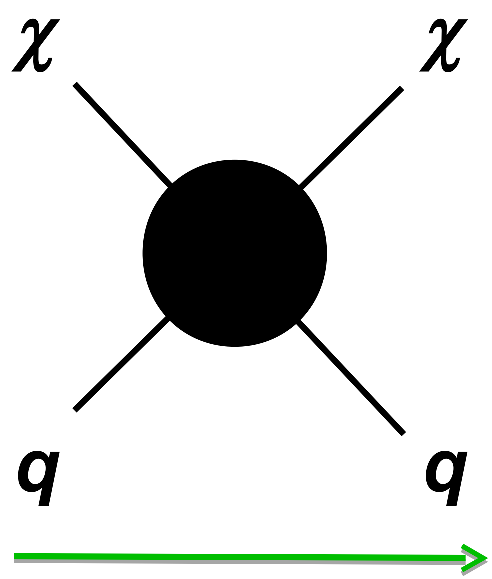
Efficient annihilation now
(Indirect detection)



Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

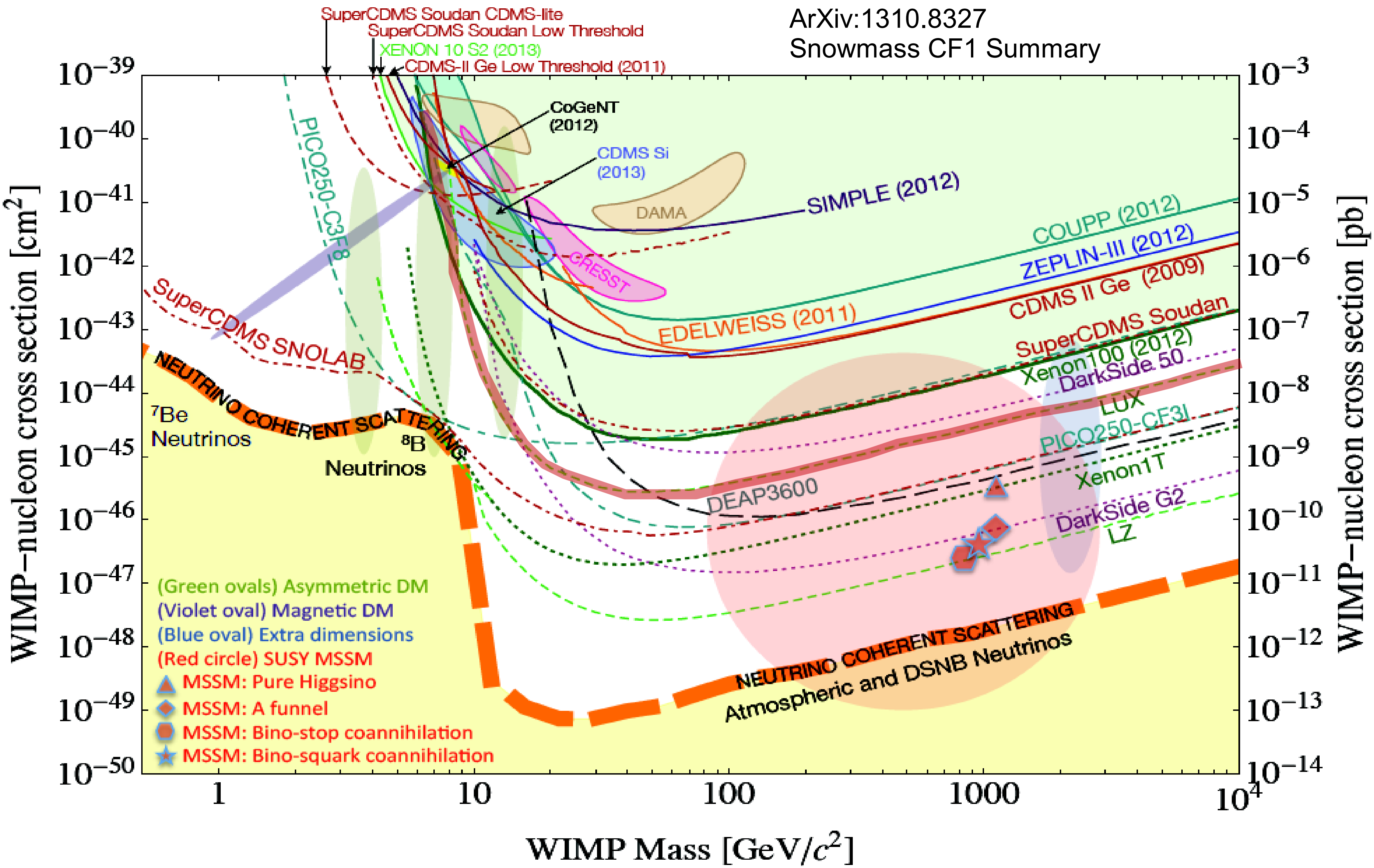
DM direct detection: neutralino scattering off nuclei

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

Warning! This picture is not quite generic: high rate of annihilation does not always guarantee high rate for DD!

Summary of DM search potential

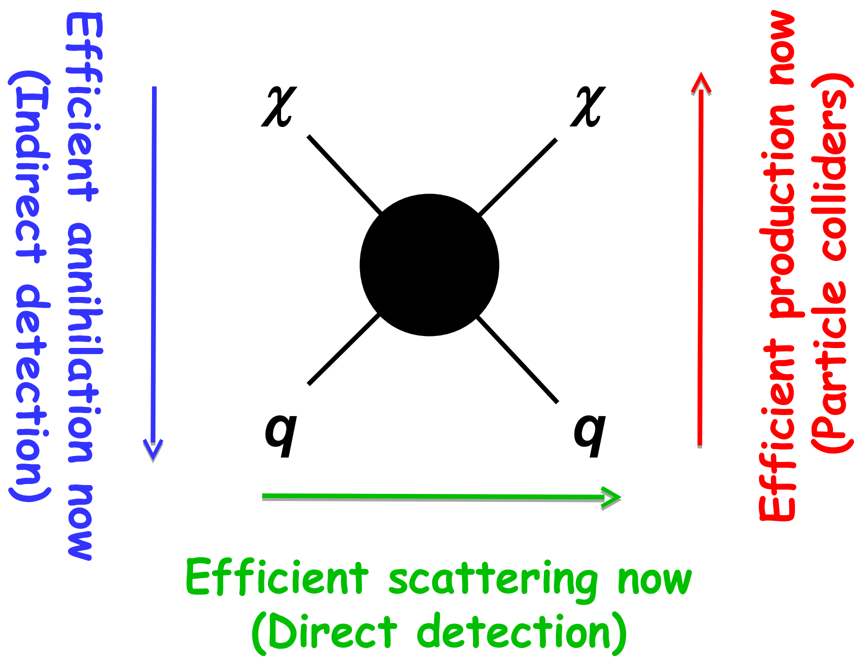
ArXiv:1310.8327
Snowmass CF1 Summary

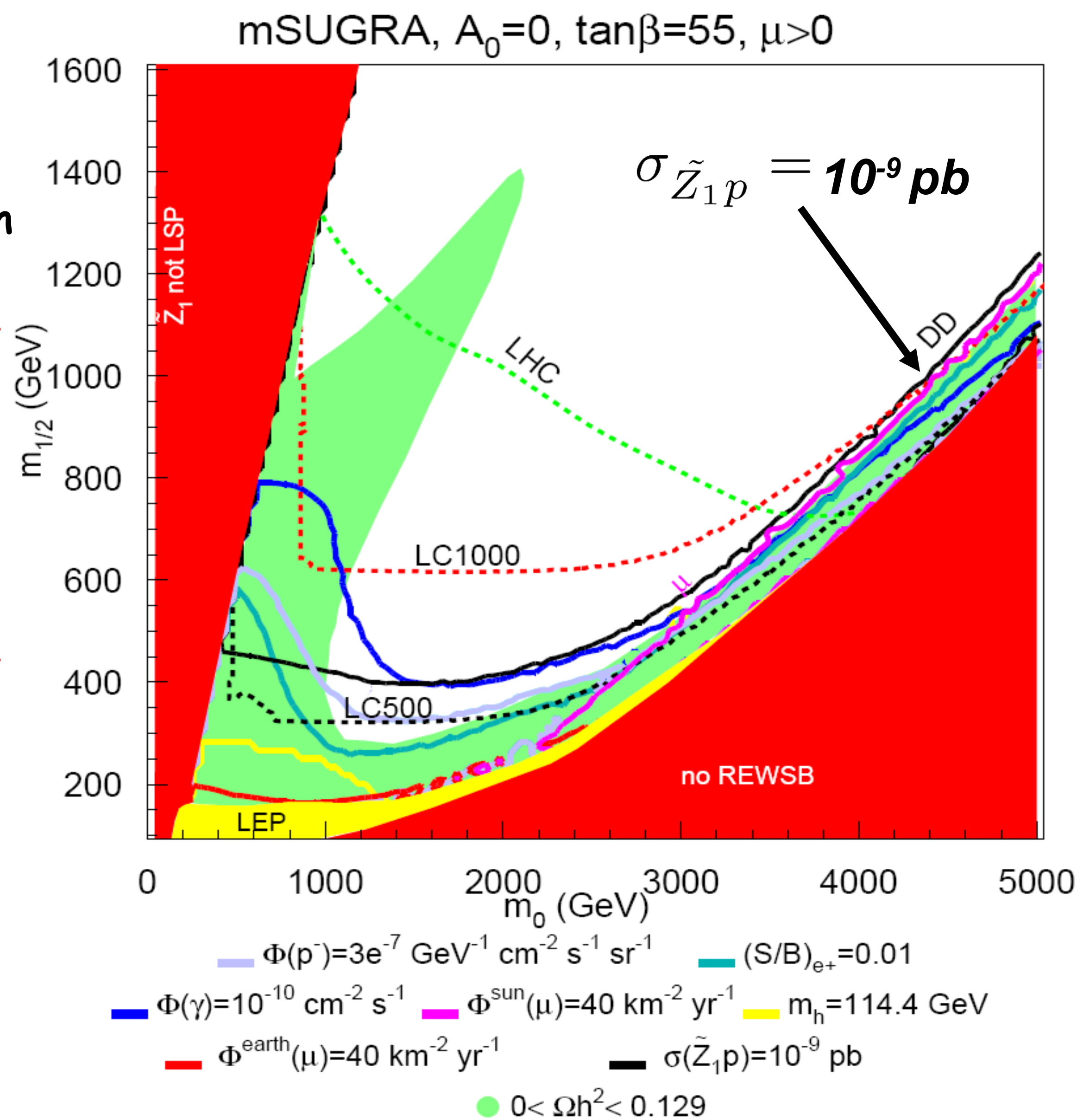


Complementarity of DM searches

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

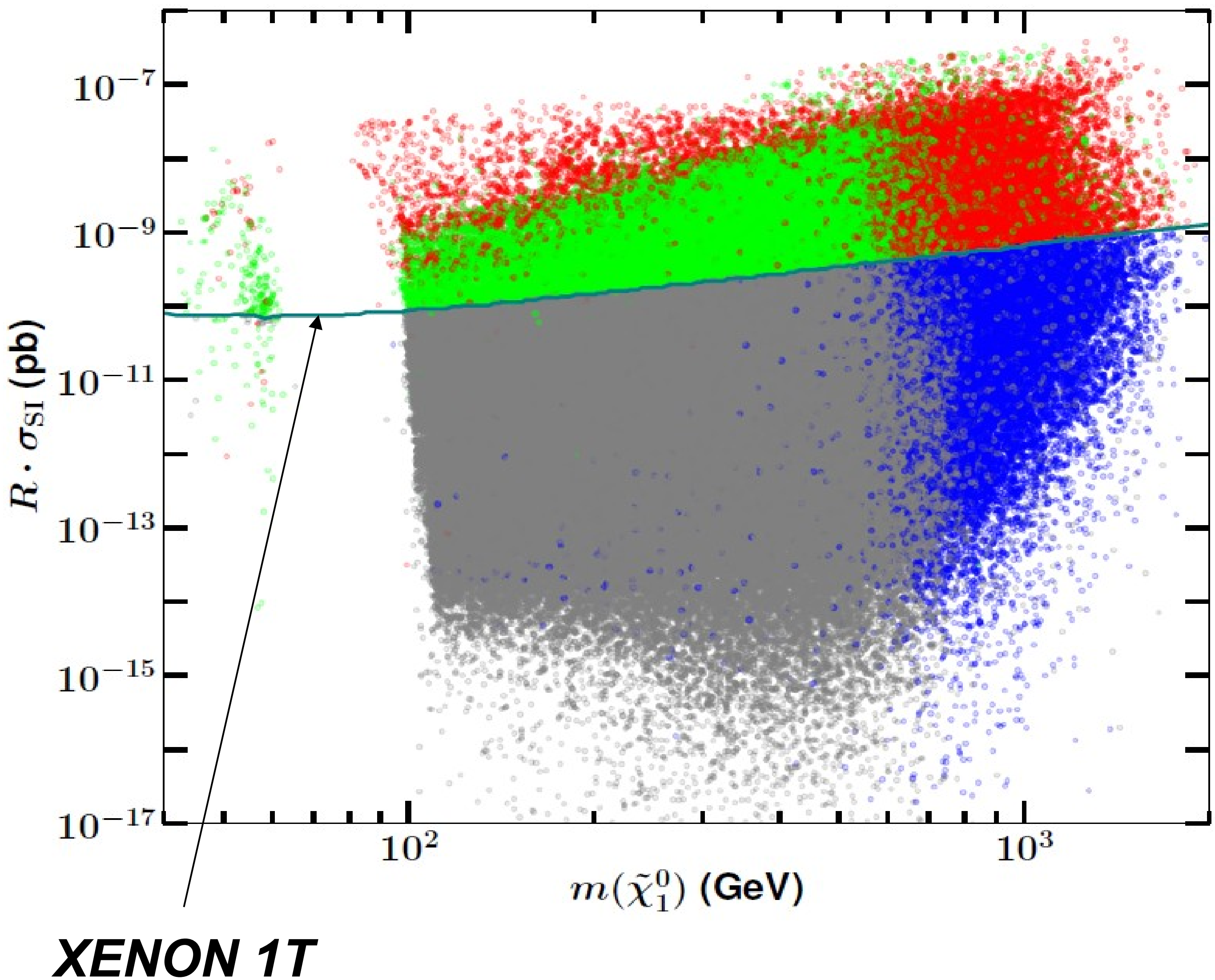
Correct relic density → Efficient annihilation





pMSSM combined results

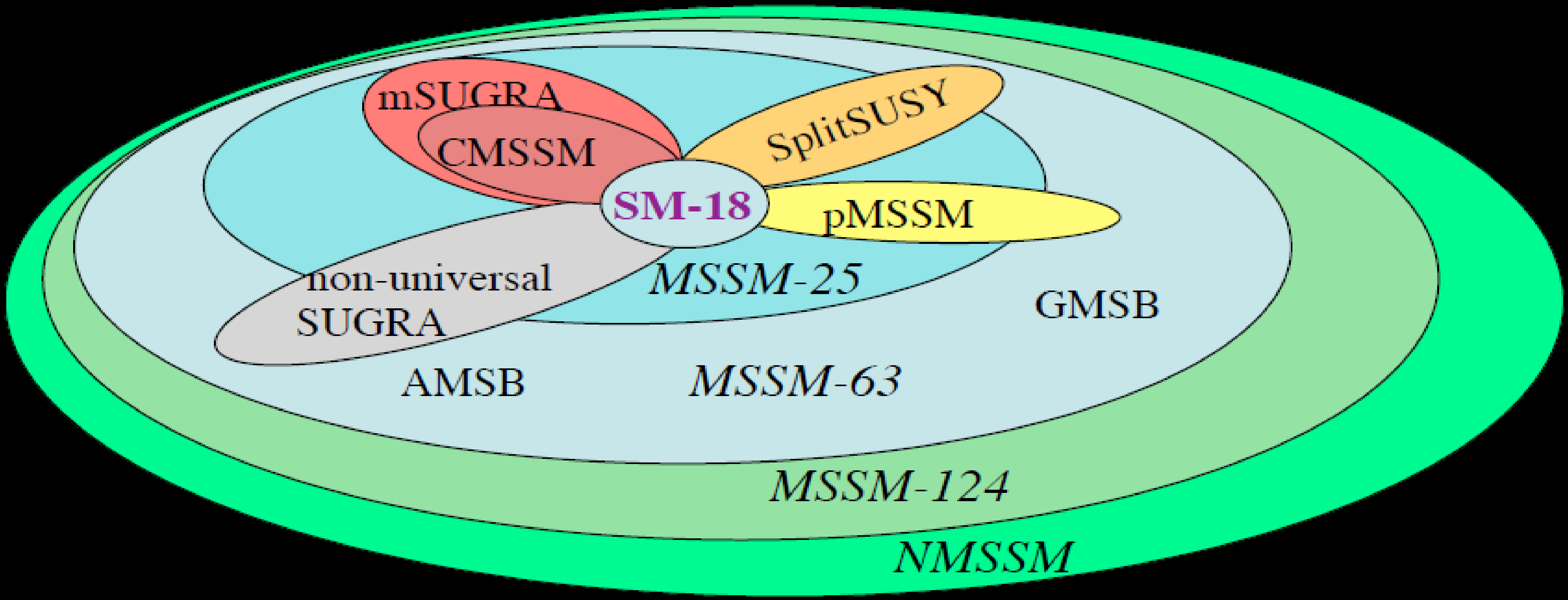
ArXiv:1305.6921: Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett



dark matter can be discovered

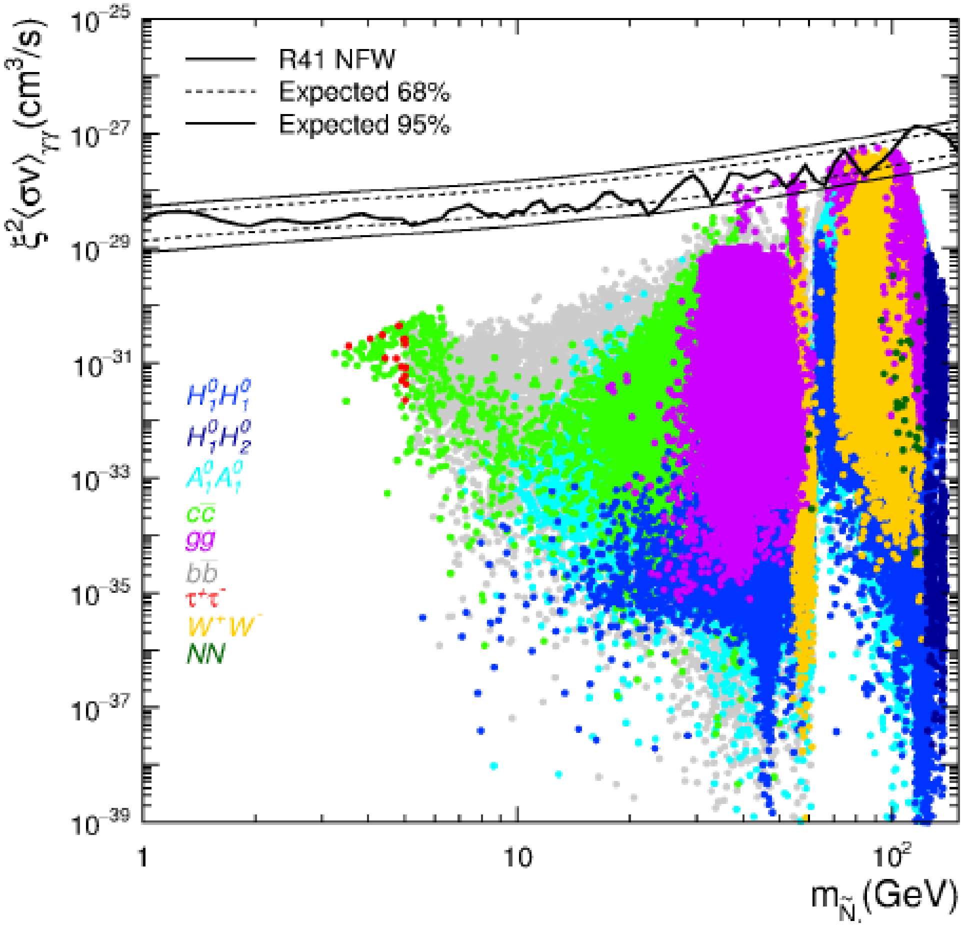
- **in DD experiments**
- **in ID experiments**
- **in both, DD and ID**
- **may be discovered at the upgraded LHC, but escape detection in future DD or ID detection experiments**

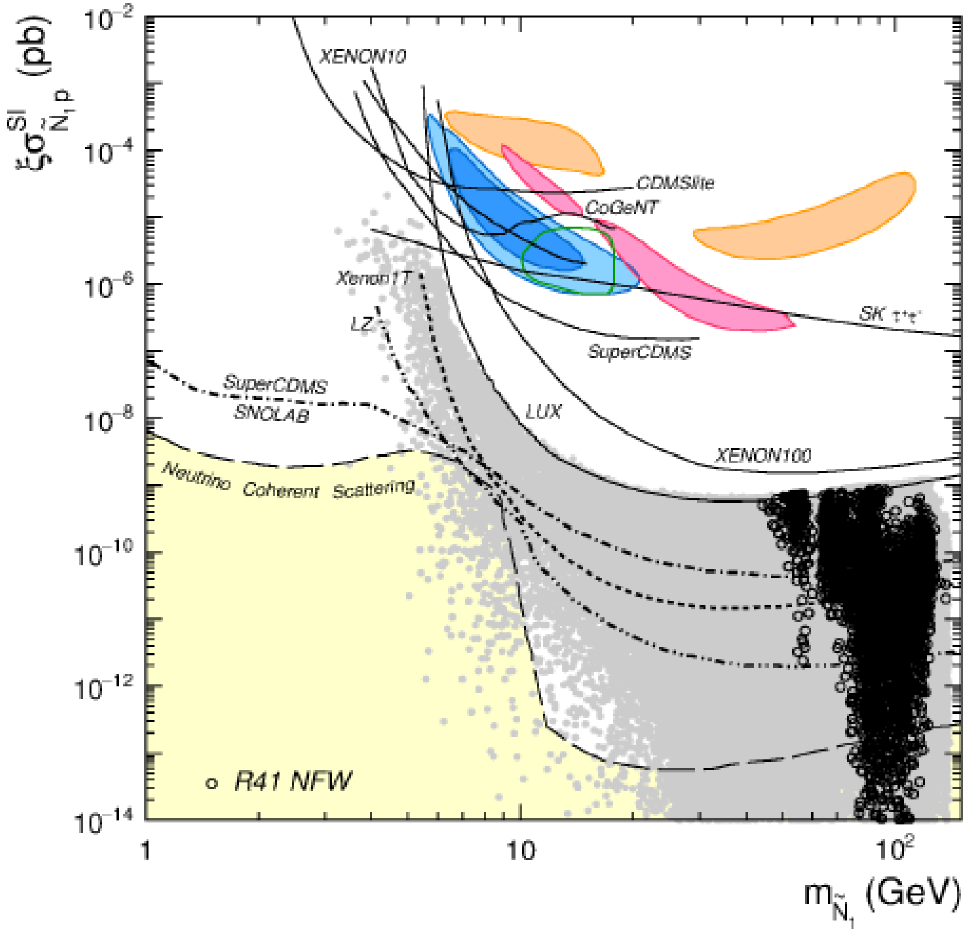
Beyond MSSM


mSUGRA
CMSSM
SplitSUSY
SM-18
pMSSM
non-universal
SUGRA
MSSM-25
GMSB
AMSB
MSSM-63
MSSM-124
NMSSM

NMSSM with RH sneutrino DM

Cerdeno, Peiro, Robles
arXiv:1507.08974





$\gamma\gamma$ ID signal is enhanced in case of RH sneutrino DM, so in case of signal observed by FERMI-LAT, neutralino and sneutrino DM cases can be distinguished

From NMSSM to E_6SSM: solving μ problem

MSSM superpotential:

$$W = y_u \bar{u} Q H_u + y_d \bar{d} Q H_d + y_e \bar{e} L H_d + \mu H_u H_d$$

$$\mu \sim m_{\rm soft} \quad \text{rather than} \quad \mu \sim M_{Pl} \quad ?$$

A common way to solve the μ problem is to introduce a scalar, S.

$$\lambda S H_u H_d \quad \text{and} \quad \langle S \rangle = \frac{s}{\sqrt{2}} \sim m_{\rm soft} \sim 1\,\text{TeV} \quad \Rightarrow \quad \mu_{\rm eff} = \frac{\lambda s}{\sqrt{2}}$$

- **NMSSM:** A cubic term, S^3, is also added, breaking the U(1) down to a discrete Z_3. This could lead to cosmological domain walls and overclosure of the Universe.
- **USSM:** The U(1) is gauged and a massive Z' appear. However, the theory is not anomaly free.
- **E_6SSM:** The gauged U(1) is a remnant of a broken E_6. Anomaly cancellation is assured by having particles in complete **27**s of E_6 at the TeV scale.

King, Moretti, Nevzorov '05

$$\tilde{\chi}^0_{\rm int} = (\overbrace{\underbrace{\tilde{B}\;\; \tilde{W}^3\;\; \tilde{H}^0_d\;\; \tilde{H}^0_u}_{\text{MSSM}} \mid \tilde{S}\;\; \tilde{B}'}^{\text{USSM}} \mid \overbrace{\tilde{H}^0_{d2}\;\; \tilde{H}^0_{u2}\;\; \tilde{S}_2 \mid \tilde{H}^0_{d1}\;\; \tilde{H}^0_{u1}\;\; \tilde{S}_1}^{\text{inert } E_6\text{SSM states}})^T$$

"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

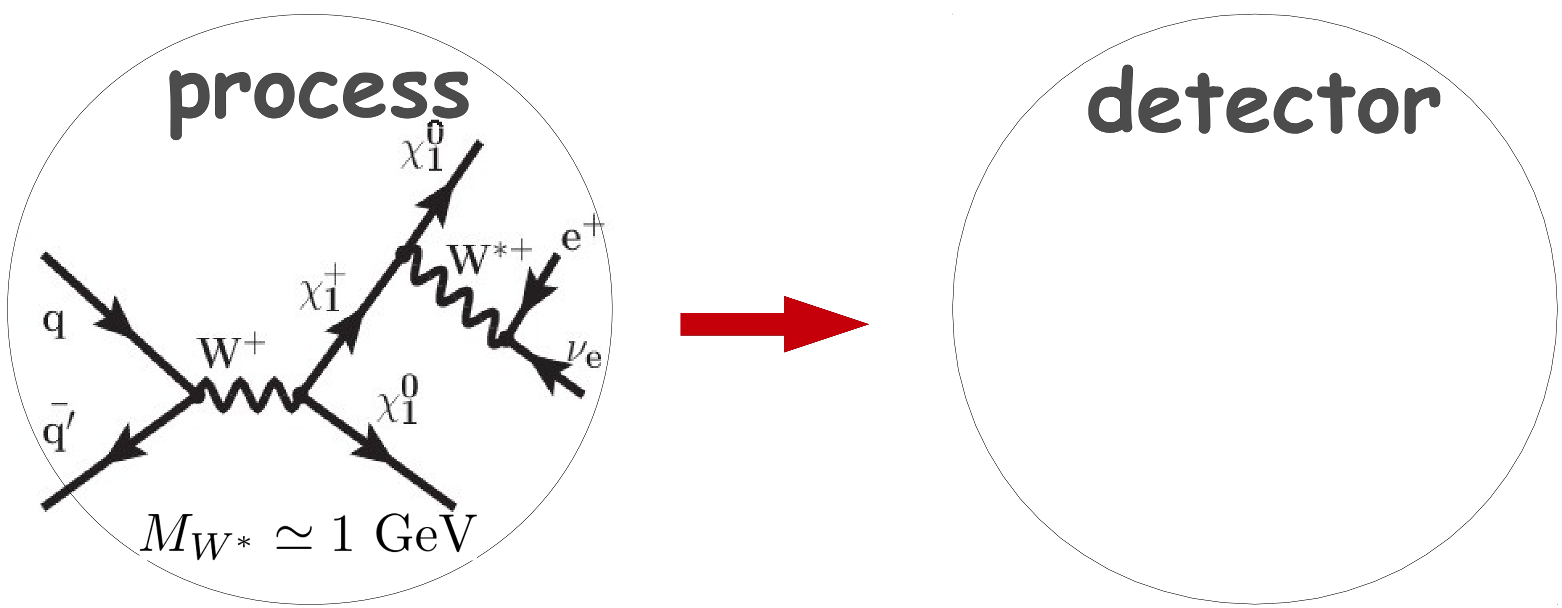
$$M_2 \text{ real}, \qquad M_1 = |M_1| e^{-\Phi_1}, \qquad \mu = |\mu| e^{i\Phi_\mu}$$

- 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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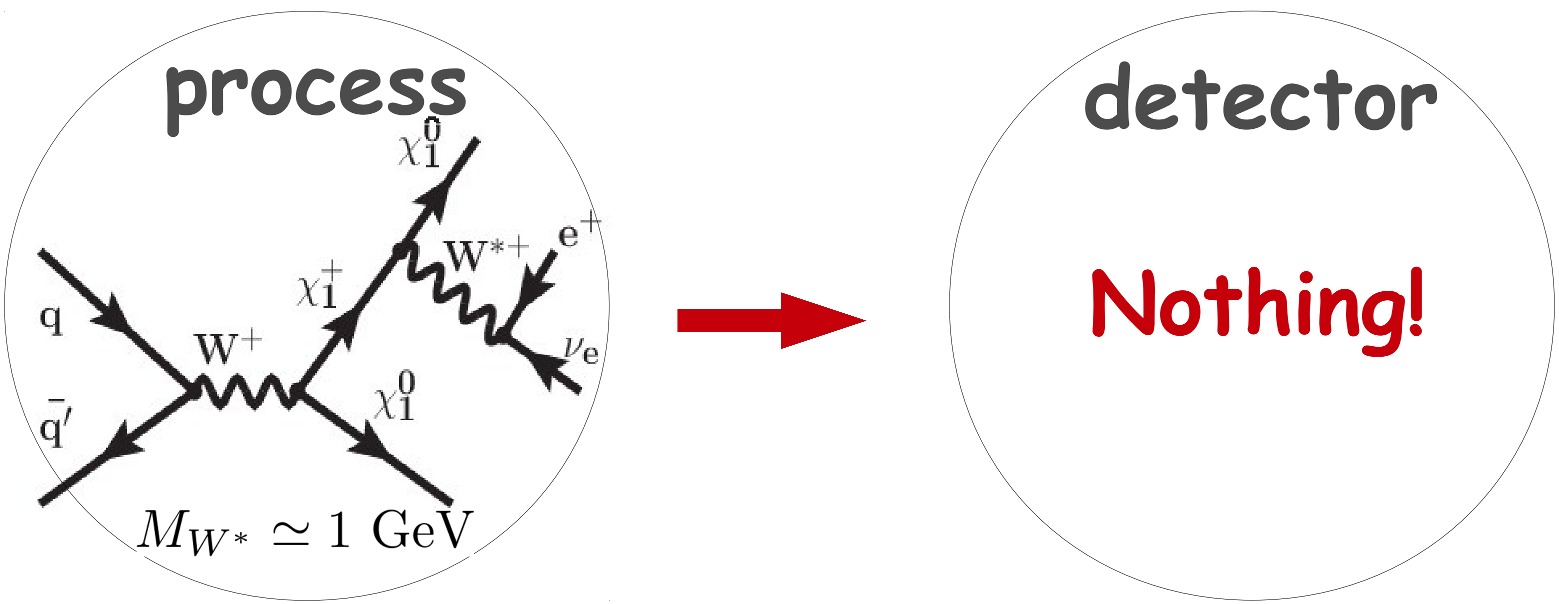

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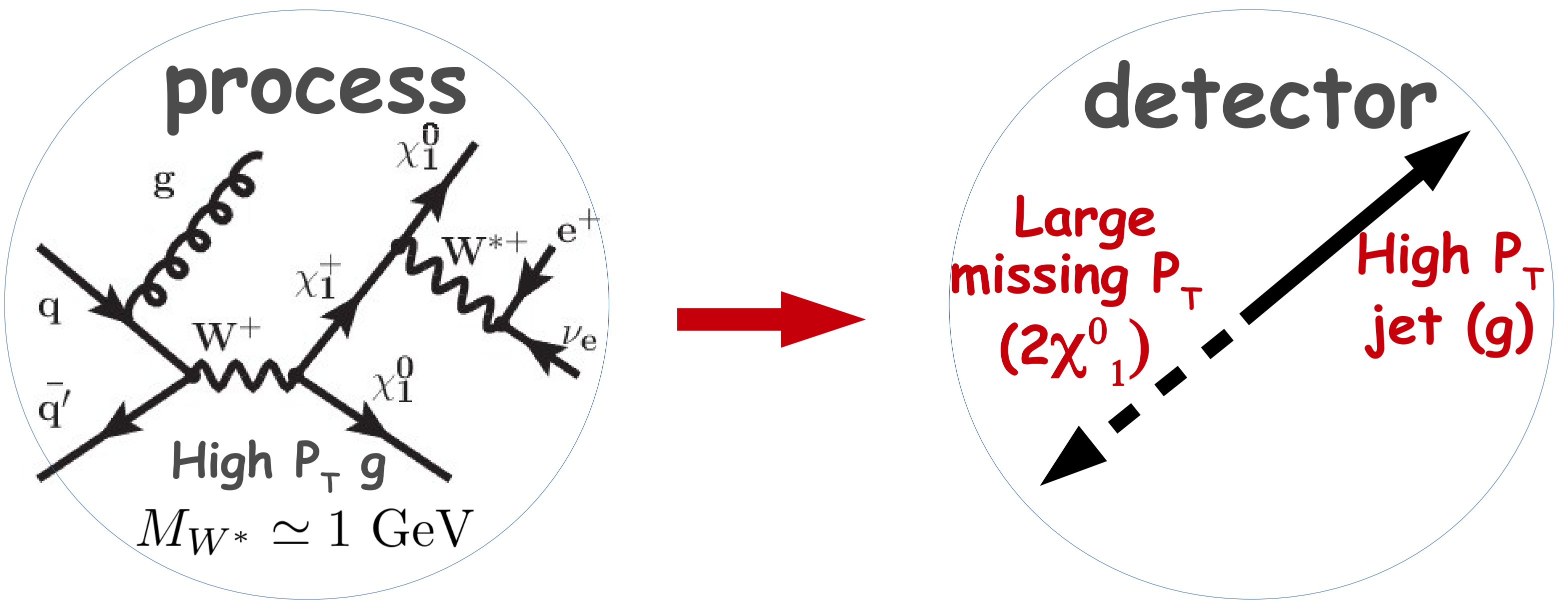
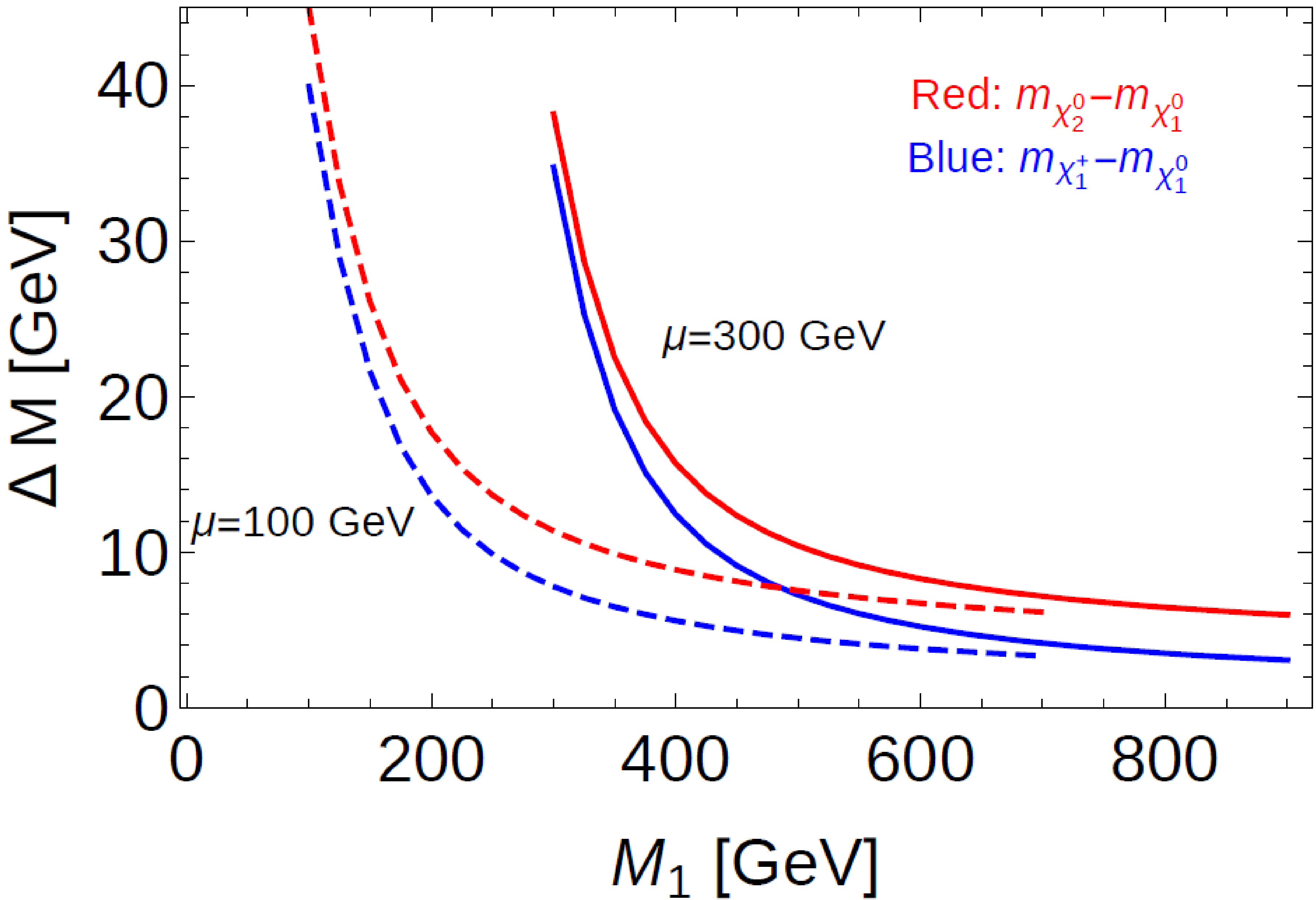
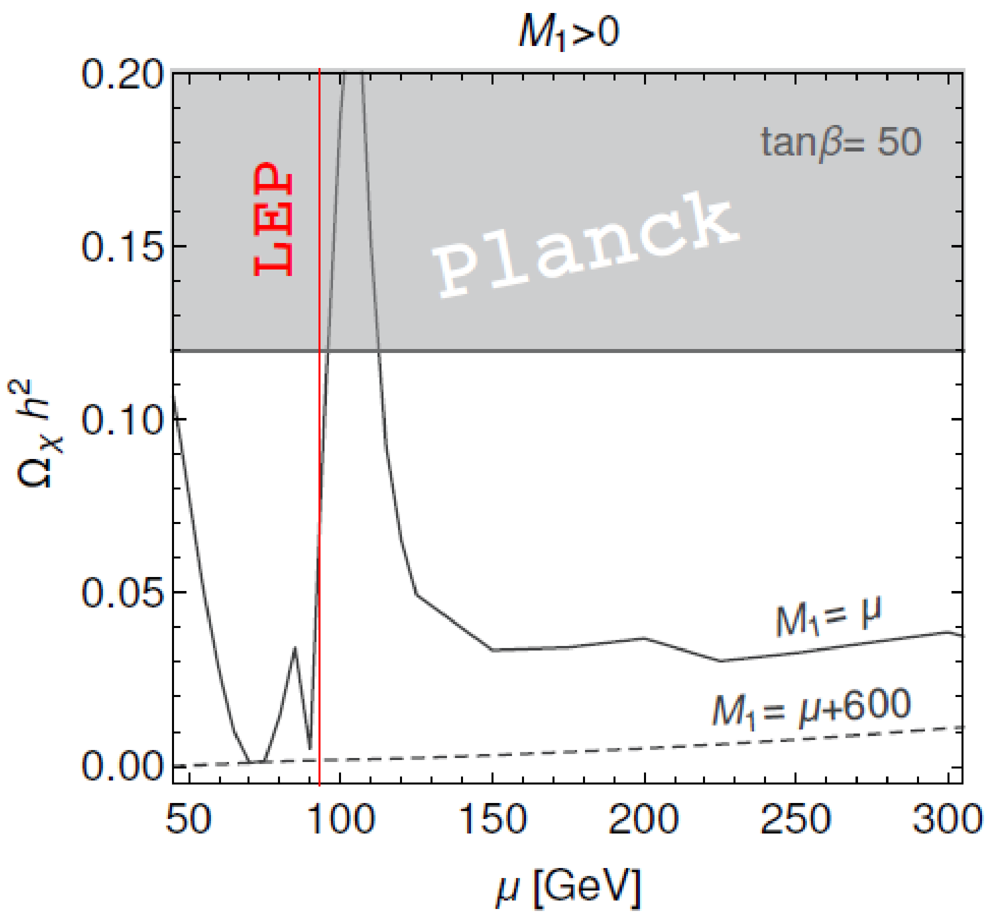
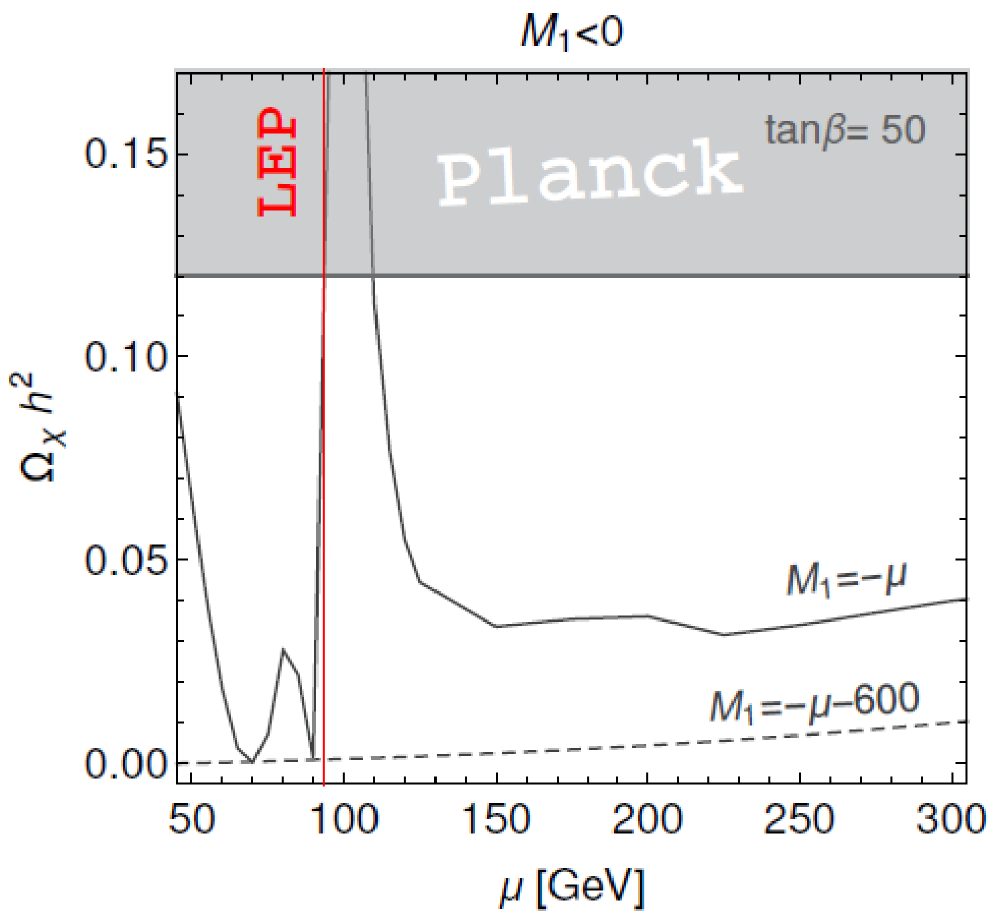


$\Delta M = m_{\chi^\pm} - m_{\chi^0}$ VS M_1 plane



Dark Matter Relic Density

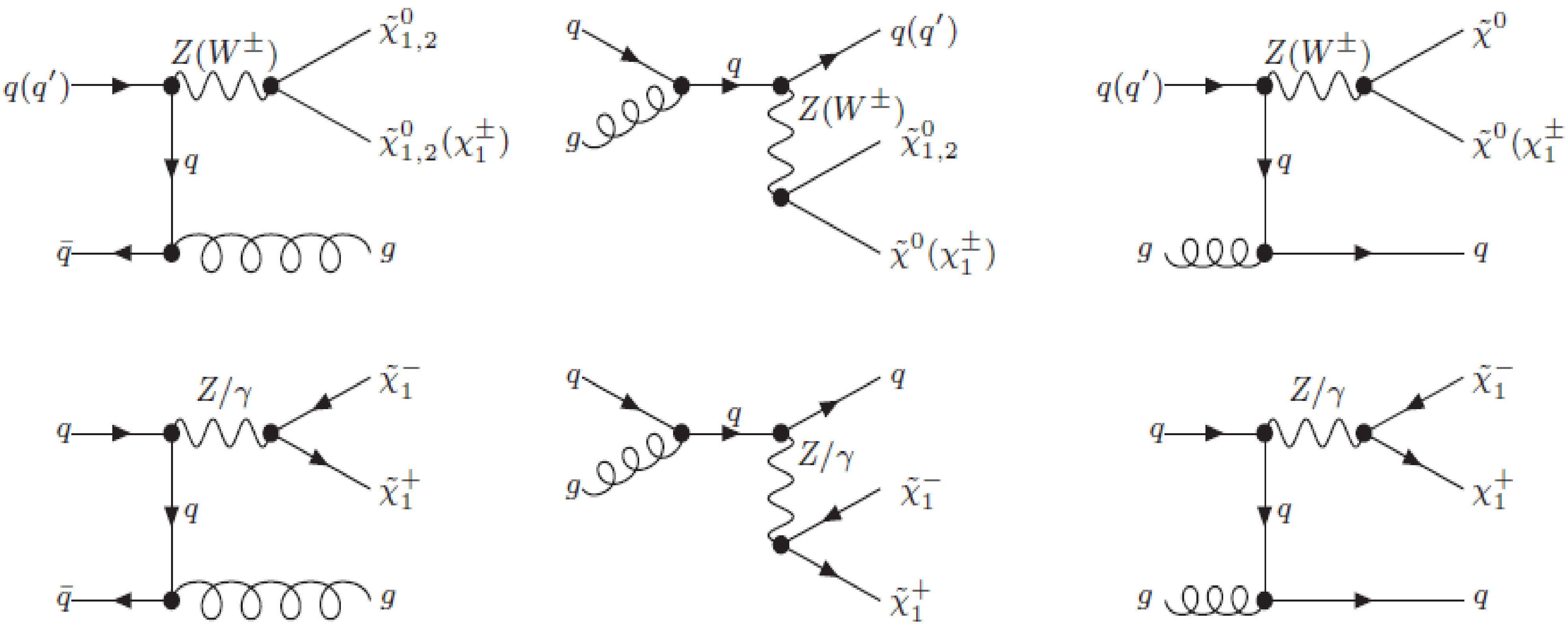




- **The pattern is independent of tanb**

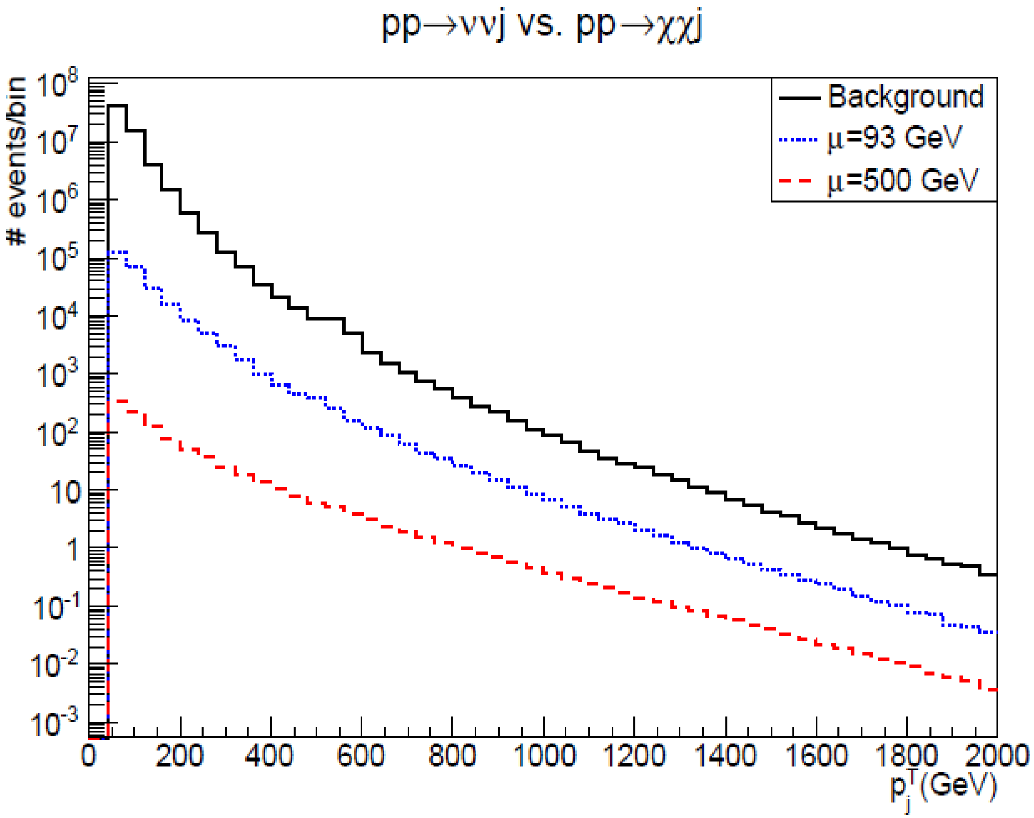
LHC potential to probe NSUSY space

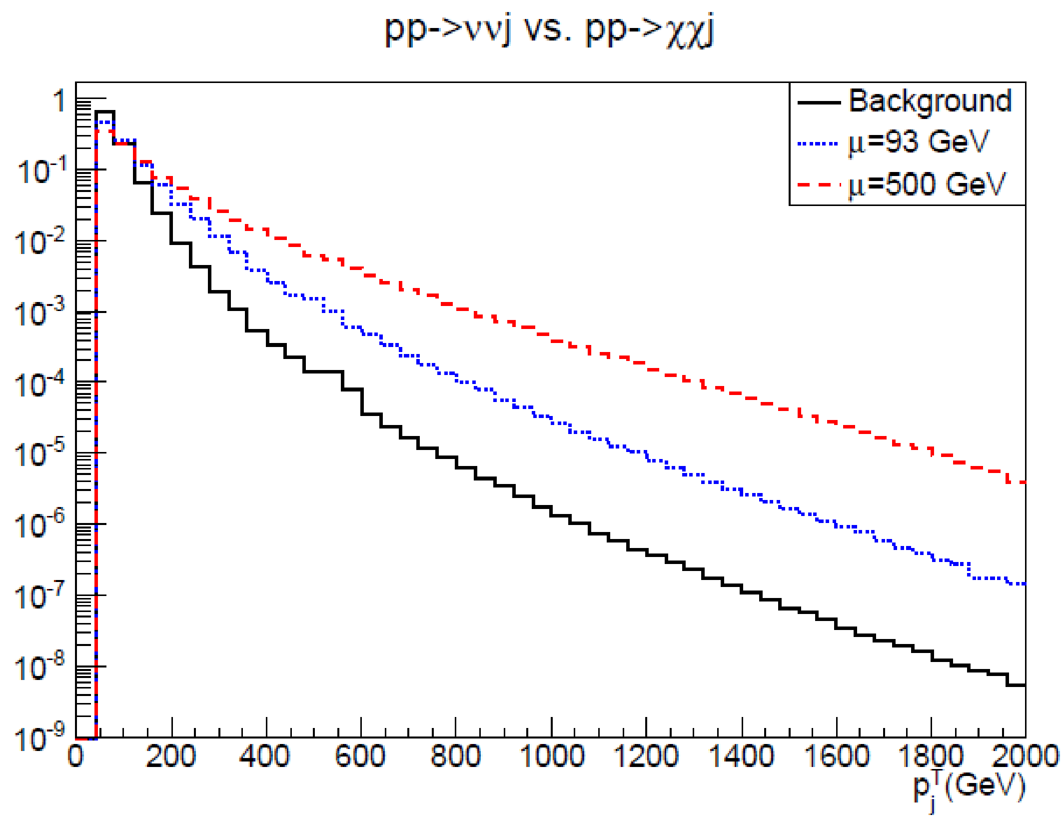
through the $pp \to \chi\chi j$: $\chi = \chi^0_{1,2}$, $\chi^\pm_1$ process



Signal vs Background

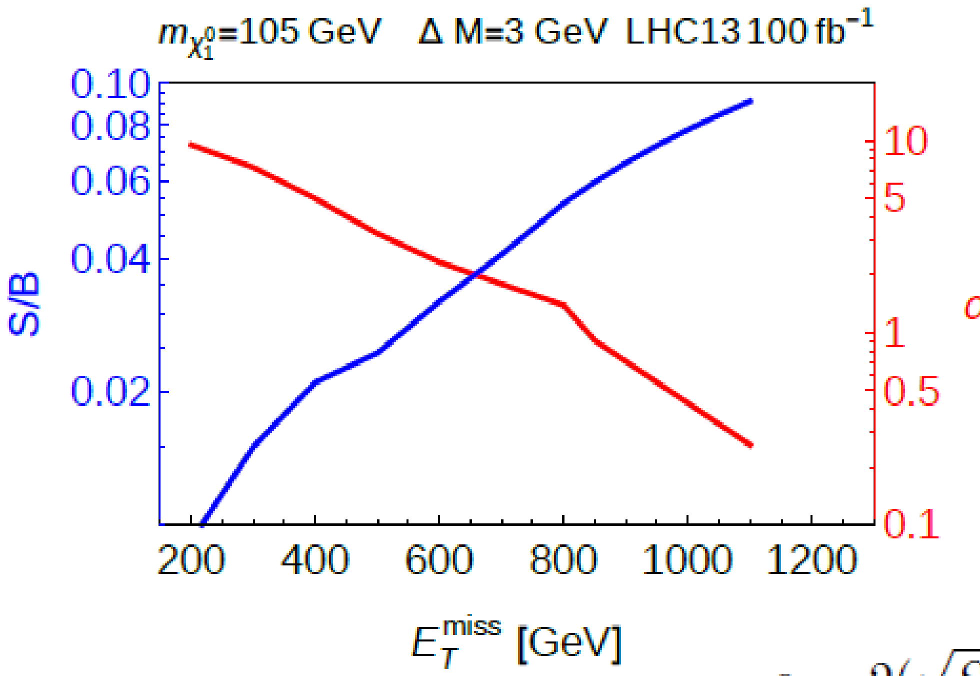
- difference in rates is pessimistic ...
- **but the difference in shapes is encouraging!**

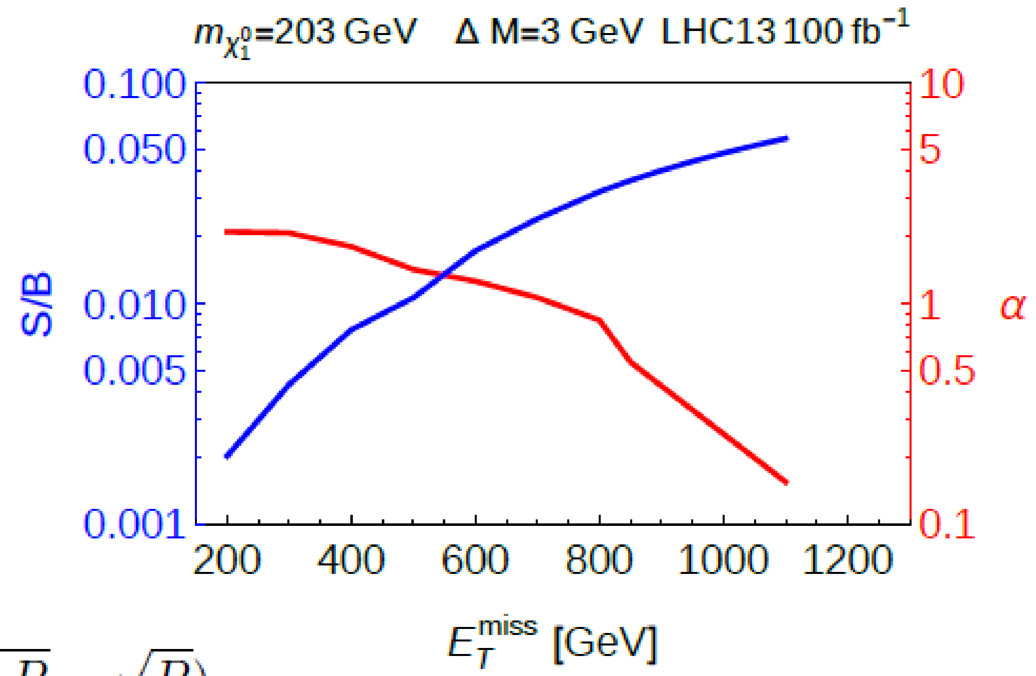




Signal and Zj background parton-level p_T^j distributions for the 13 TeV LHC
Left: p_T^j distributions for 100 fb^{-1}
Right: normalised signal and Zj background distributions.

S/B vs Signal significance





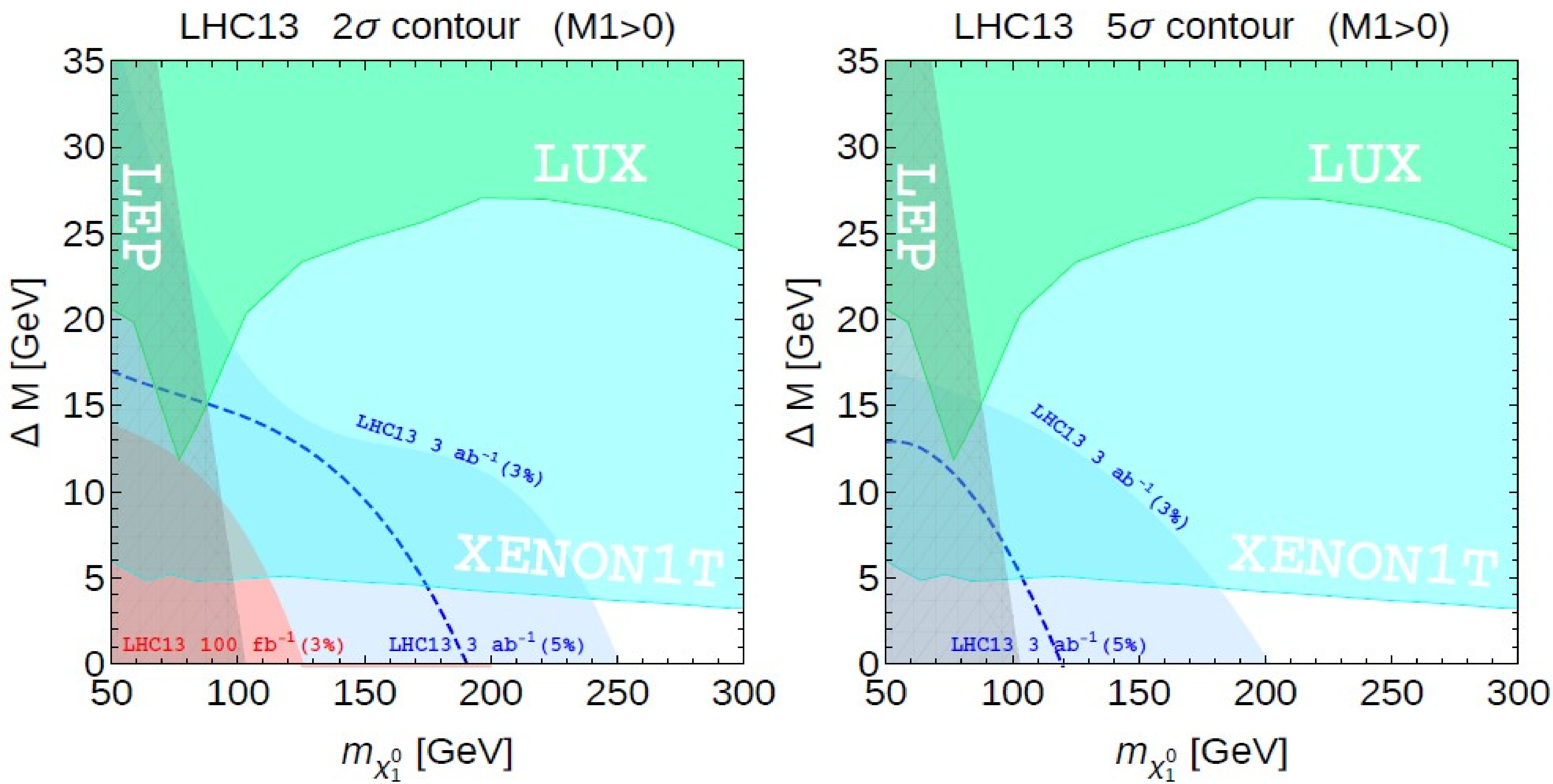
$$\alpha = 2(\sqrt{S+B} - \sqrt{B})$$

	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ 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)
$p^T_j = \not{E}_T$ >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 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**

LHC/DM direct detection sensitivity to CHS



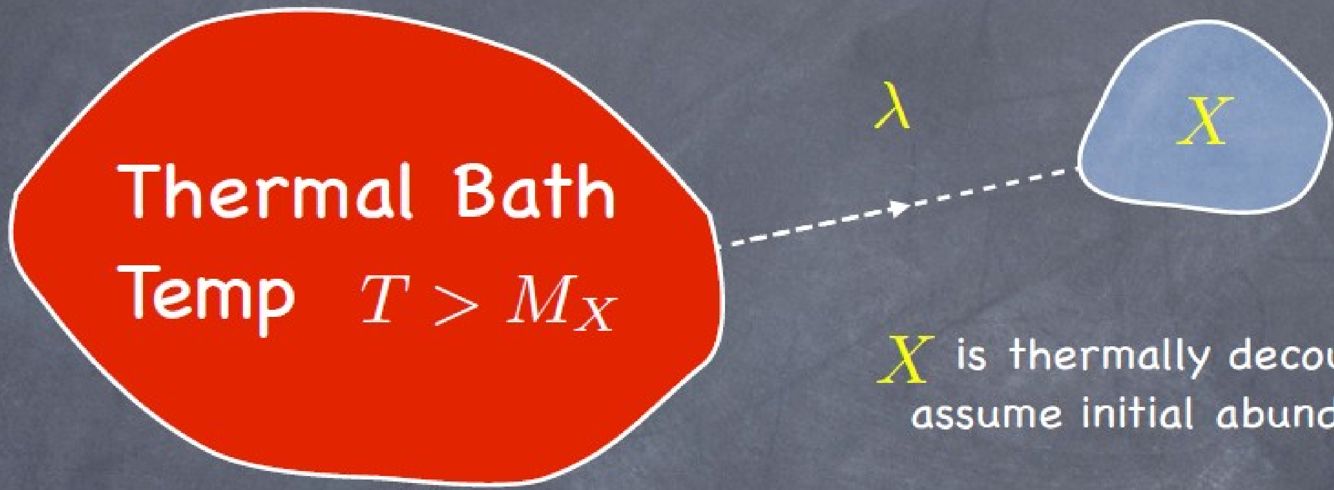
AB,Barducci,Bharucha,Porod,Sanz, *JHEP 1507 (2015) 066, arXiv:1504.02472*

- SUSY DM, can be around the corner (~100 GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small ΔM (NSUSY) region

Beyond thermal DM WIMP scenario

Freeze-in overview

- Freeze-in is relevant for particles that are feebly coupled (Via renormalisable couplings) – λ
  Feebly Interacting Massive Particles (FIMPs) X



X is thermally decoupled and we assume initial abundance negligible

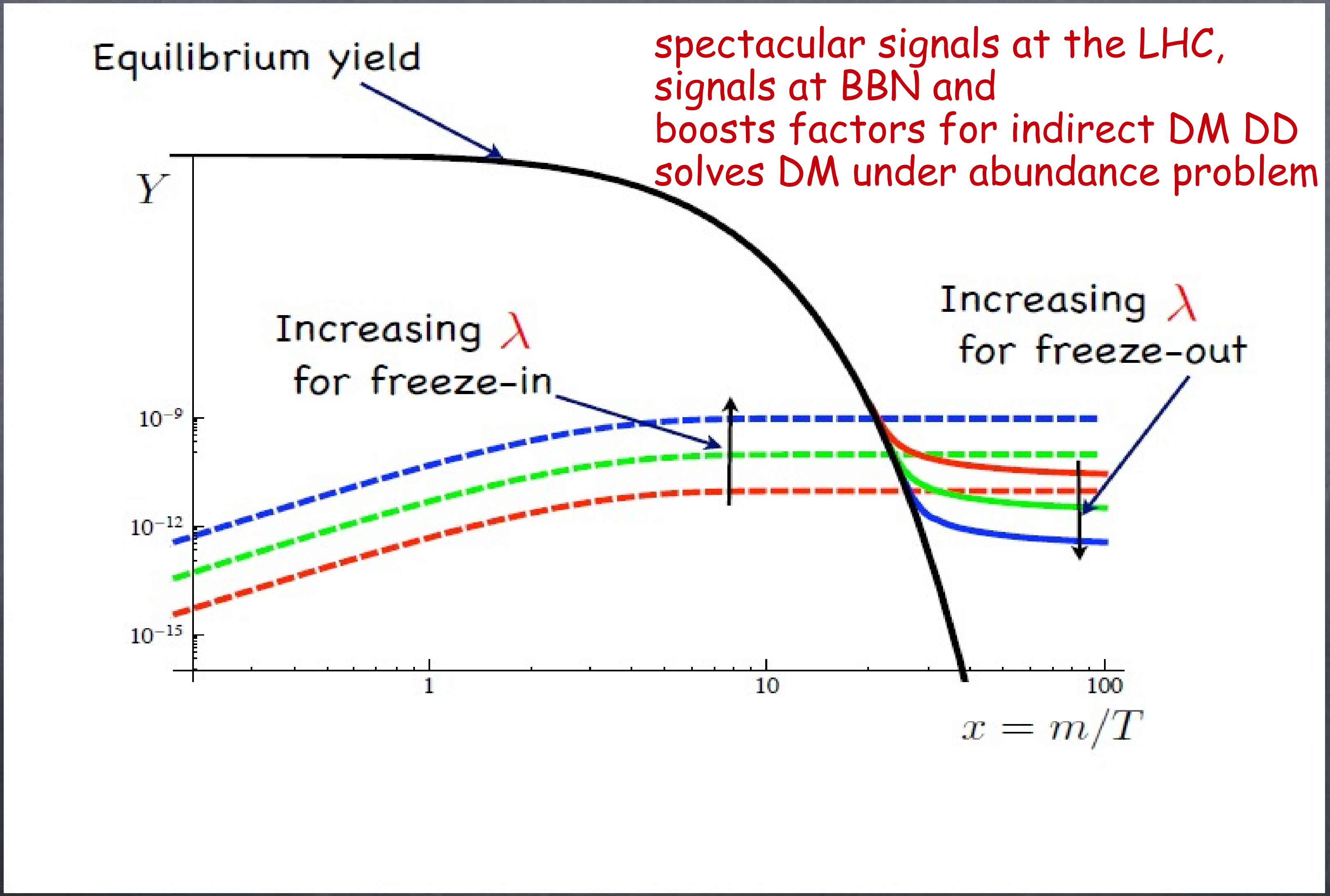
- Although interactions are feeble they lead to some X production
- Dominant production of X occurs at $T \sim M_X$ IR dominant
- Increasing the interaction strength increases the yield

opposite to Freeze-out...

Steve West

Freeze-in vs Freeze-out

- As T drops below mass of relevant particle, DM abundance is heading towards (freeze-in) or away from (freeze-out) thermal equilibrium



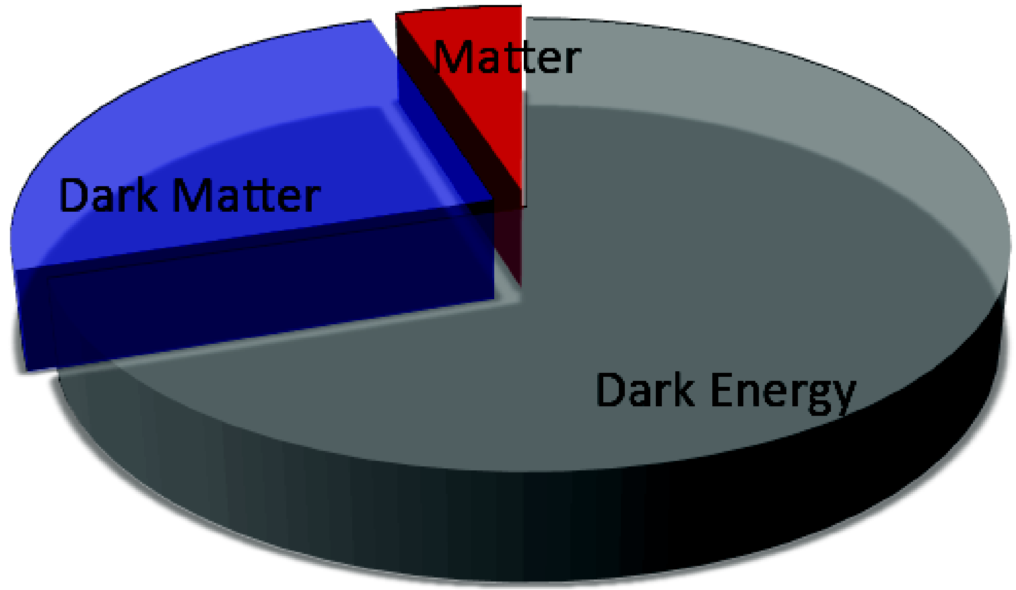
Steve West

ASYMMETRIC DARK MATTER

ASYMMETRIC DARK MATTER

$\Omega_B \sim 0.05$

Baryons, but no antibaryons



$\Omega_{DM}/\Omega_B \sim 5$

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD} Dynamical	Baryons No antibaryons	U(1) Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium Asymmetry	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

Asymmetric Dark Matter (ADM)

- ADM motivated by the asymmetry of baryonic matter and the desire to explain $\Omega_{\rm DM}/\Omega_{\rm B} \simeq 5$
- New Strong Dynamics, e.g. Technicolor, natural framework for ADM – solves the problem of DM under-abundance for strongly interacting theories
- ADM from NSD has implications for collider searches, capture in stars, structure formation!
- ADM scenario much less investigated than standard WIMP paradigm – much to do!

Characterisation of DM in generic models

- **If DM is produced at the LHC:**
  - **We need to be able to identify the underlying model.**
    - SUSY?, Extra Dimensions?, Inert Two Higgs Doublet Model?
  - **We need to know:**
    - **Mass, Spin, Mediator properties.**
- **Also:** From LHC DM forum (arXiv:1507.00966)
  - "Different spins of Dark Matter particles will typically give similar results….. Thus the choice of Dirac fermion Dark Matter should be sufficient as benchmarks for the upcoming Run-2 searches."
- **Crucial to understand if this is true: Important for future exclusion and discovery DM studies.**

- **Study the effects of DM spin on observables at the LHC for Spin=0 and Spin=1/2, for events with a mono-jet (more generally mono-X).**
- Consider contact interactions first: simplest case.
  - Complete set of DIM6 operators involving two SM quarks (gluons) and two DM particles.
- **Extend to consider simplified models.**
- **Explore LHC potential to differentiate DM spins (ongoing)**

DIM6 operators – an update

Dirac Fermion DM	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	[D1]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}q$	[D2]
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}\gamma^5 q$	[D3]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	[D4]
$\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ **NEW**	[D1T]
$\frac{i}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi + \bar{\chi}q\bar{q}\gamma^5\chi)$	[D2T]
$\frac{1}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi - \bar{\chi}q\bar{q}\gamma^5\chi)$	[D3T]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5 q\bar{q}\gamma^5\chi$	[D4T]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	[D5]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	[D6]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	[D7]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	[D8]
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	[D9]
$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	[D10]

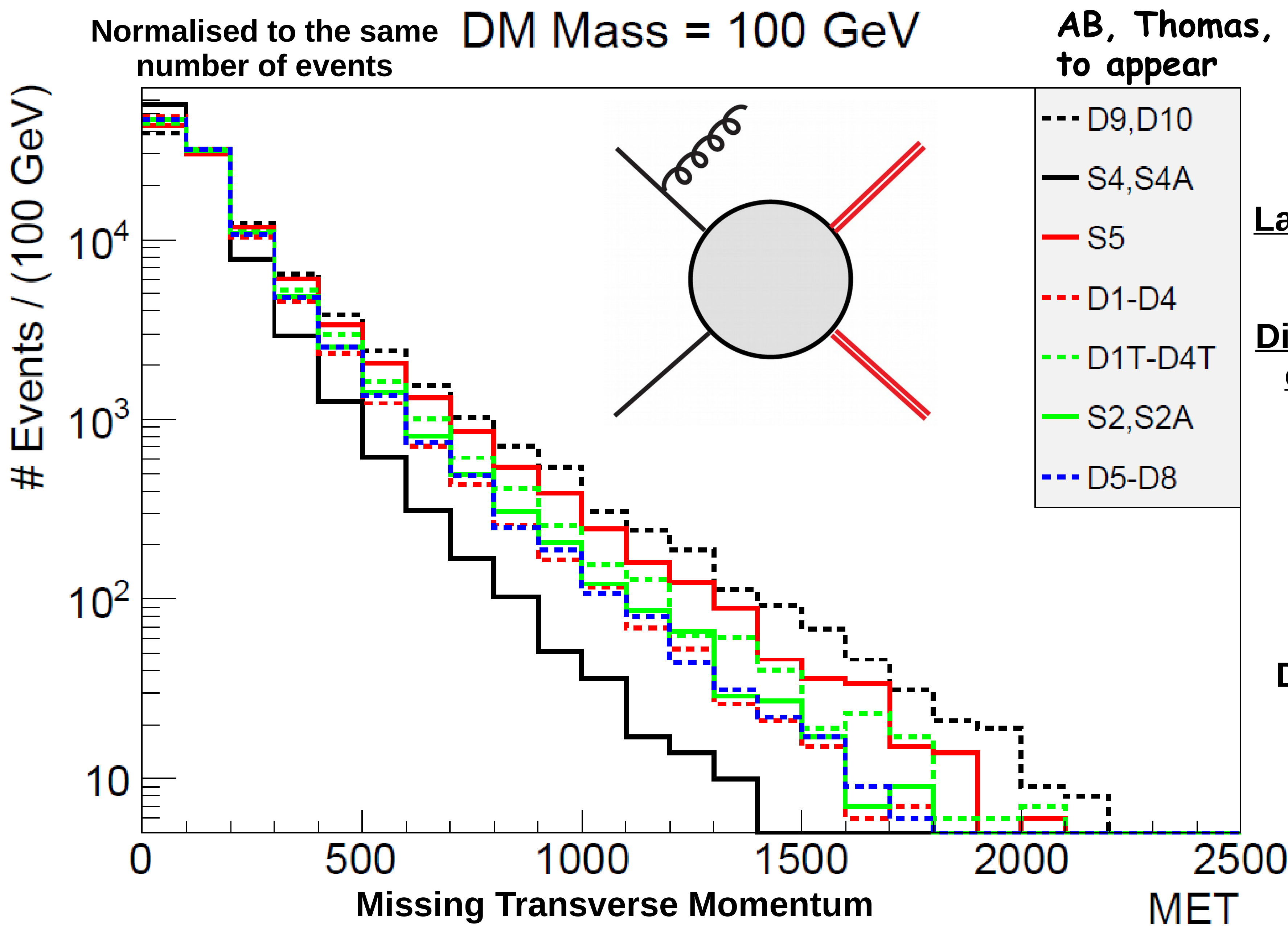
Real or Complex Scalar DM	
$\cancel{\frac{1}{\Lambda^2}\partial_\mu(\phi^{(\dagger)}\phi)\bar{q}\gamma^\mu q}$ **Intergration by part = 0**	[S1]
$\cancel{\frac{1}{\Lambda^2}\partial_\mu(\phi^{(\dagger)}\phi)\bar{q}\gamma^\mu\gamma^5 q}$	[S1A]
$\frac{i}{\Lambda^2}[\phi^\dagger(\partial_\mu\phi) - (\partial_\mu\phi^\dagger)\phi]\bar{q}\gamma^\mu q$	[S2]
$\frac{i}{\Lambda^2}[\phi^\dagger(\partial_\mu\phi) - (\partial_\mu\phi^\dagger)\phi]\bar{q}\gamma^\mu\gamma^5 q$	[S2A]
$\cancel{\frac{i}{\Lambda^2}\phi^{(\dagger)}\phi(\bar{q}\overleftrightarrow{\not{D}}q)}$ **Can be reduced to S4/S4A by EM**	[S3]
$\cancel{\frac{i}{\Lambda^2}\phi^{(\dagger)}\phi(\bar{q}\overleftrightarrow{\not{D}}\gamma^5 q)}$	[S3A]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}q\Phi \Longrightarrow \frac{\tilde{m}}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}q$	[S4]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}\gamma^5 q\Phi \Longrightarrow \frac{\tilde{m}}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}\gamma^5 q$	[S4A]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi G^{\mu\nu}G^{\mu\nu}$	[S5]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$	[S5A]

We re-analyse the list of DIM 6 operators studied by Goodman,Ibe, Rajaraman, Shepherd, Tait, Yu, arXiv:1008.1783

MET distributions for Contact interactions

Normalised to the same number of events

AB, Thomas, Panizzi to appear



Large kinematic differences between Distinct Groups of operators

D9, D10

S5,S5A

D1T-D4T

S2-S2A

D1-D4 D5-D8

S4, S4A

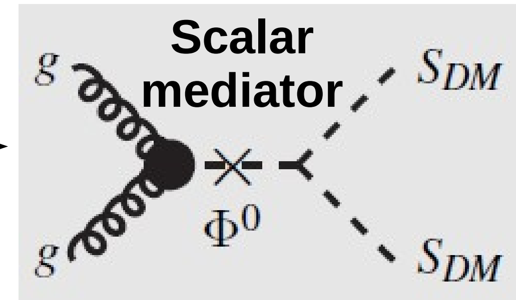
Mapping CI with Simplified models

D9 (D10)

$$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \quad ?$$

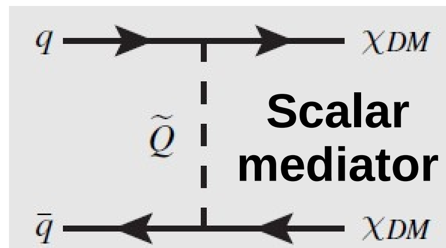
S5 S5A

$$\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu} \qquad \frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu} \longrightarrow$$



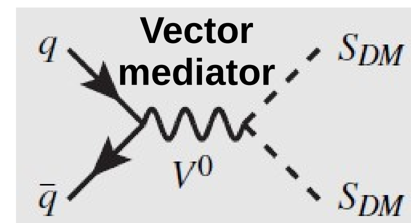
D1T-D4T

$$\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi \longrightarrow$$



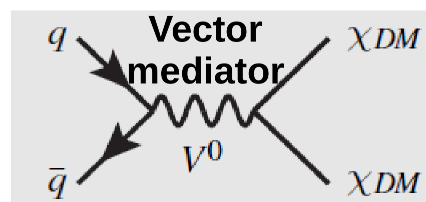
S2-S2A

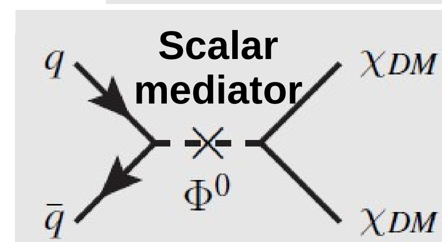
$$\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi-(\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q \longrightarrow$$



D1-D4 D5-D8

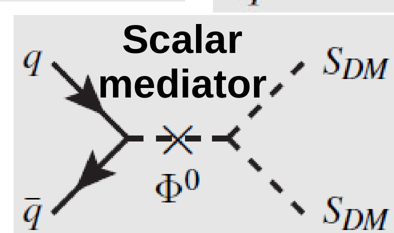
$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \qquad \frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q \longrightarrow$$



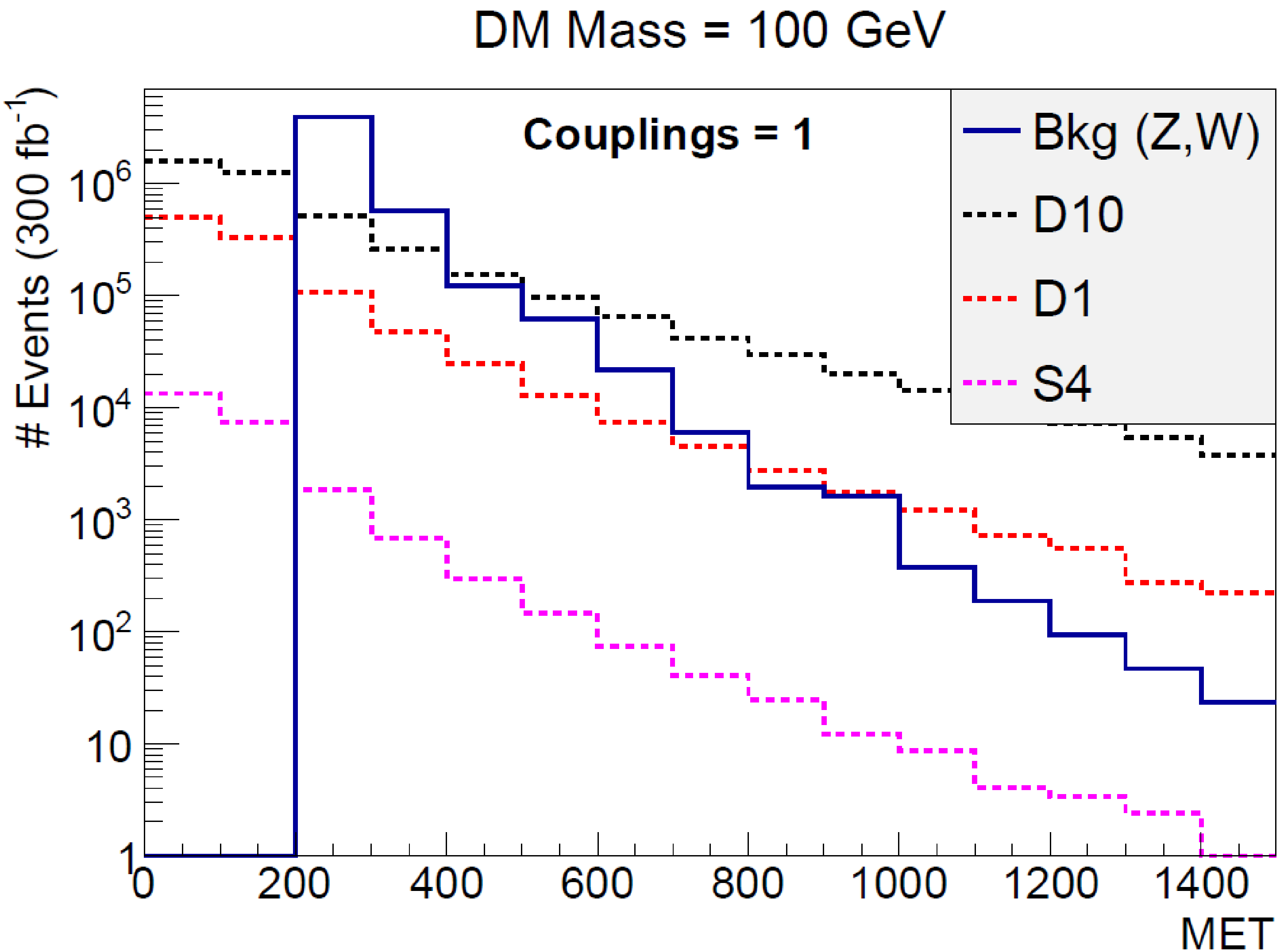


S4 (S4A)

$$\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q \longrightarrow$$



Effects for Signal vs BG analysis



MET > 200:
 D10 eff = 0.30
 D1 eff = 0.20
 S4 eff = 0.13
 D10/S4 = 2.3

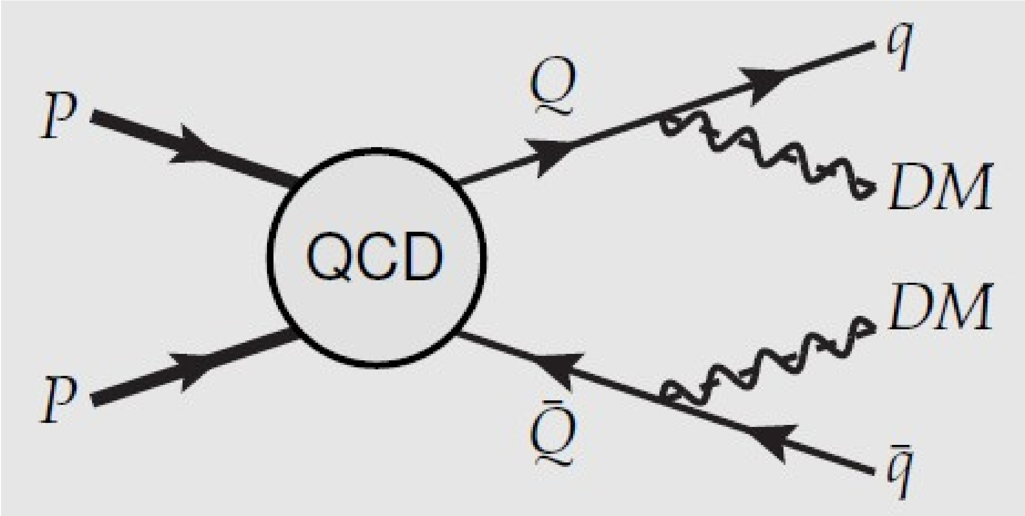
MET > 500:
 D10 eff = 0.074
 D1 eff = 0.031
 S4 eff = 0.014
 D10/S4 = 5.5

MET > 1000:
 D10 eff = 0.012
 D1 eff = 0.0033
 S4 eff = 0.0010
 D10/S4 = 12

- Different signal vs background MET distributions.
- Increase S/B ratio for large MET cuts.
- **Large differences in efficiencies of different operators. Important for exclusion/discovery studies.**

Model-specific DM signatures

- Just pair DM production via different mediators – monojet signature
- DM production from Top-partners decays



Cacciapaglia,Deandrea, Ellis, Marrouche, Panizzi arXiv:1302.4750 [hep-ph]
Edelhäuser, Krämer, SonneveldarXiv:1501.03942 [hep-ph]

- Limits are model-specific – depend also on the mass gap between Q and DM
- Do not forget to evaluate DM DD rates and the relic density!

Conclusions

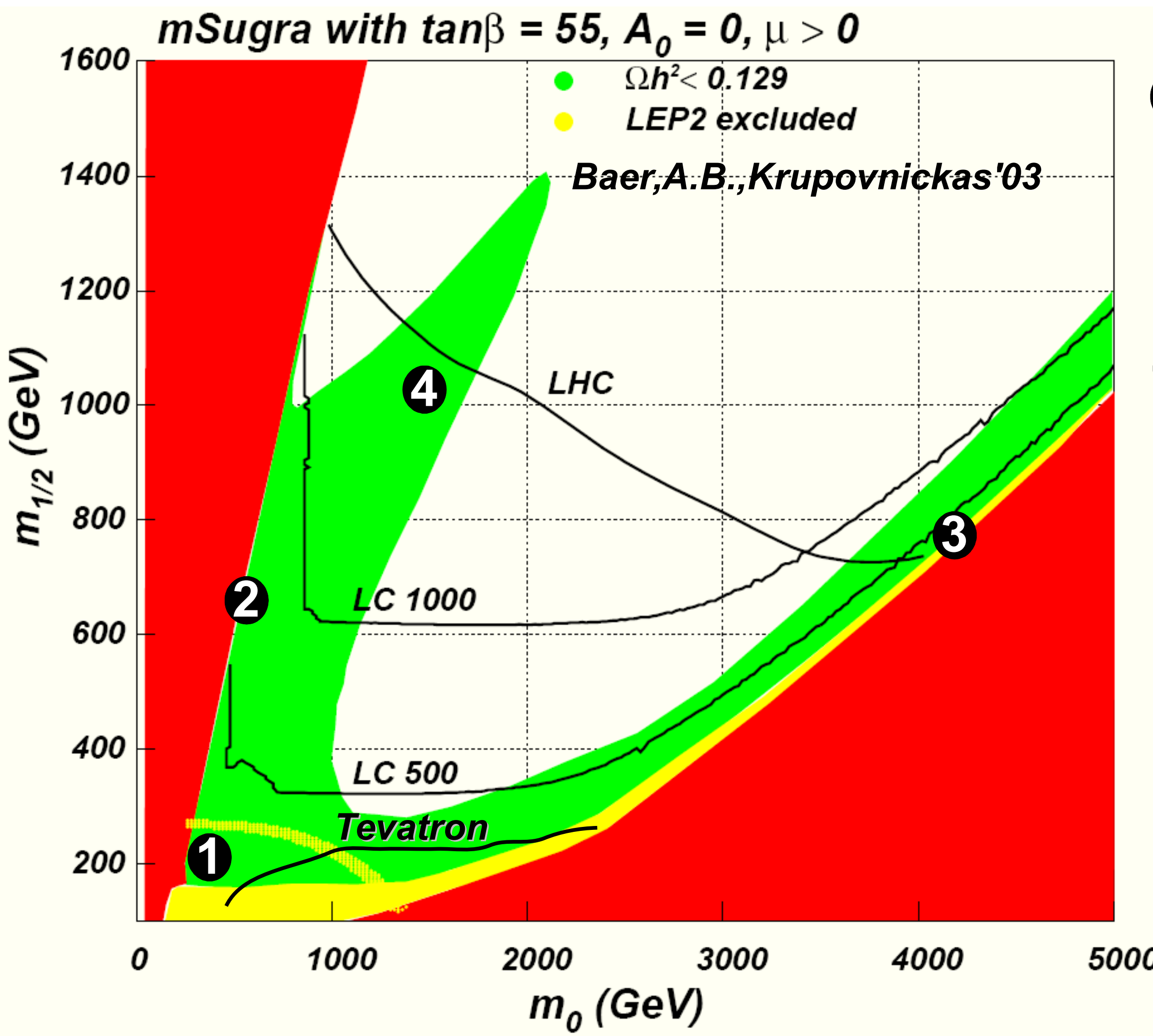
- There is evidence for non-baryonic cold dark matter and there are many candidates for DM particles
- WIMP can be “around the corner” with 100 GeV mass, but it is very hard to probe weakly produced DM
    - the Zj BG is very large - need to control systematics, NLO and NNLO, PDF uncertainty
    - Assuming S/B ~ 3% control LHC@13 can probe DM up to 250 GeV
    - DD rates are also low, but there is great DD/LHC complementarity
- Freeze-in/FIMP - new signatures, e.g. displaced vertices, solution of DM under-abundance for all promising models
- Asymmetric DM scenario - yet more interesting direction to explore, especially for TC-like models (750 GeV $\gamma\gamma$ events)
- Characterisation of DM spin from Contact Interactions using mono-jet signature is promising (least for some operators)

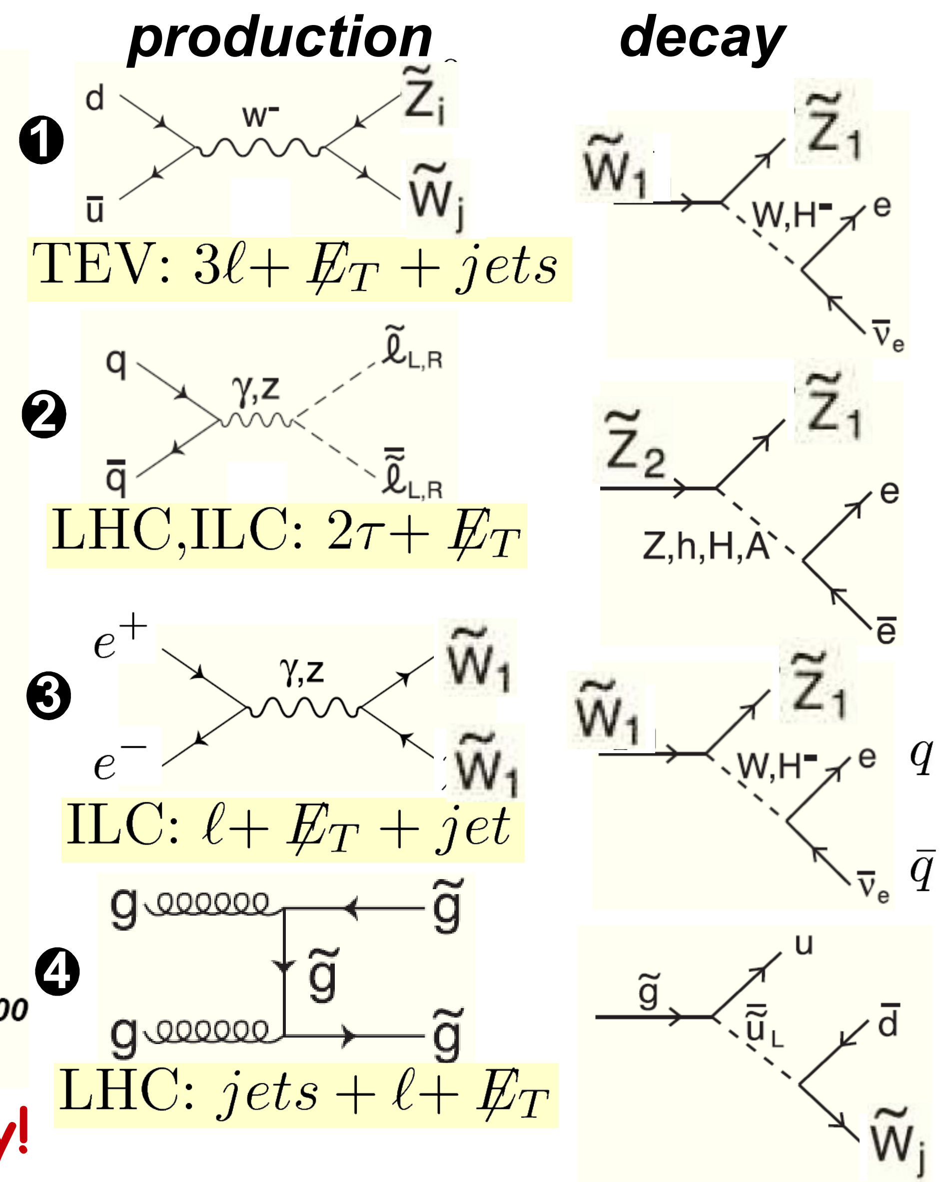
Thank you!

Backup

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



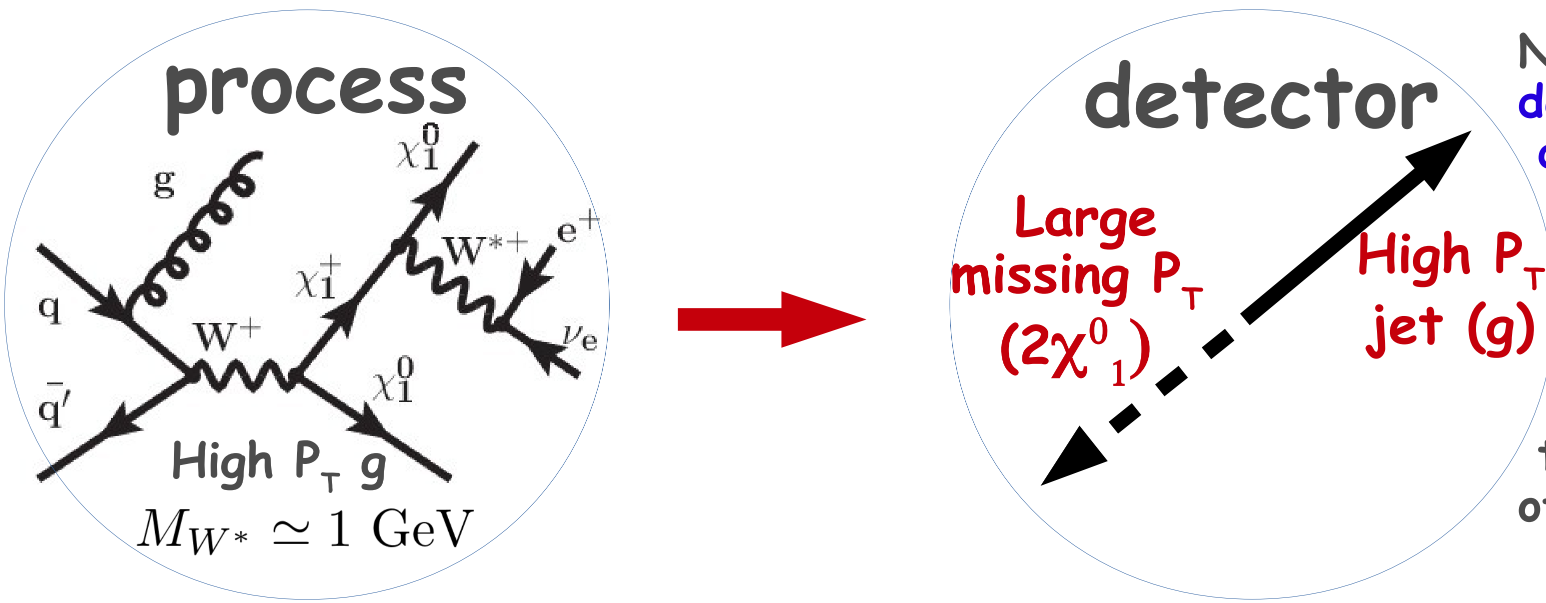


LHC and ILC are highly complementary!

CHS Mass Spectrum and Challenge for the LHC

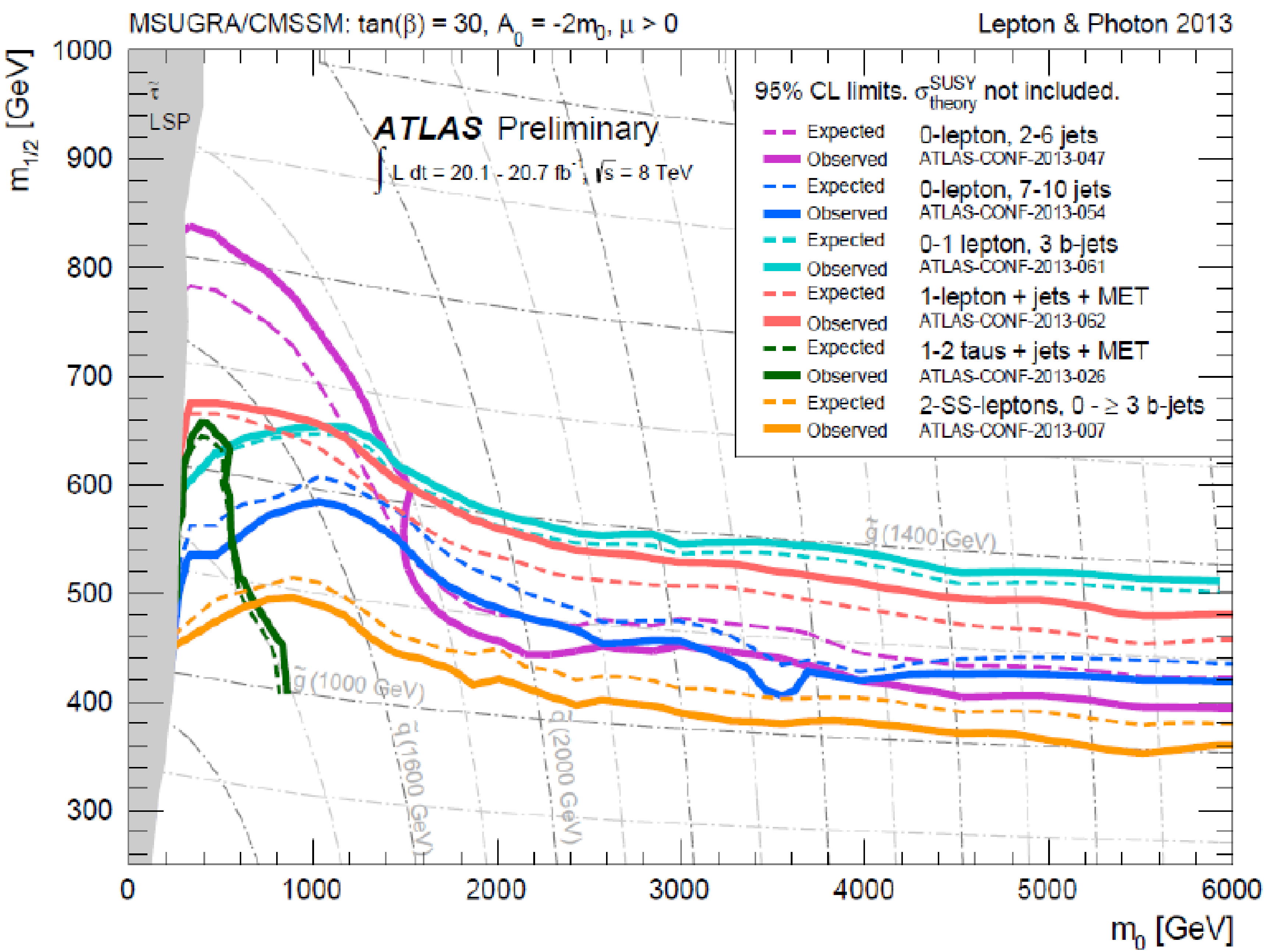
- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature

- 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

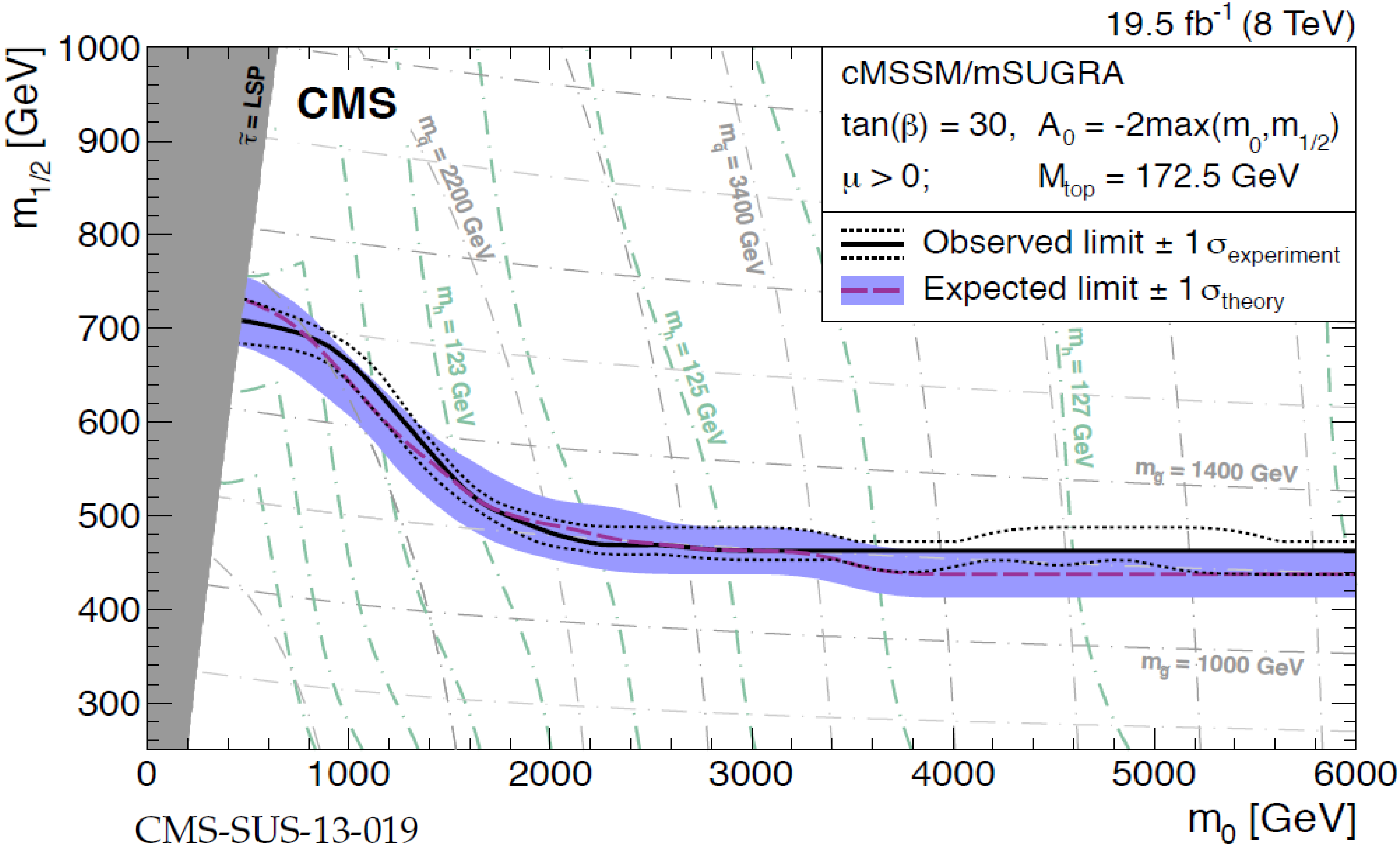


Note that W* decay products do not get large boost – it is proportional to the mass of W* which is much smaller than the mass of the LSP

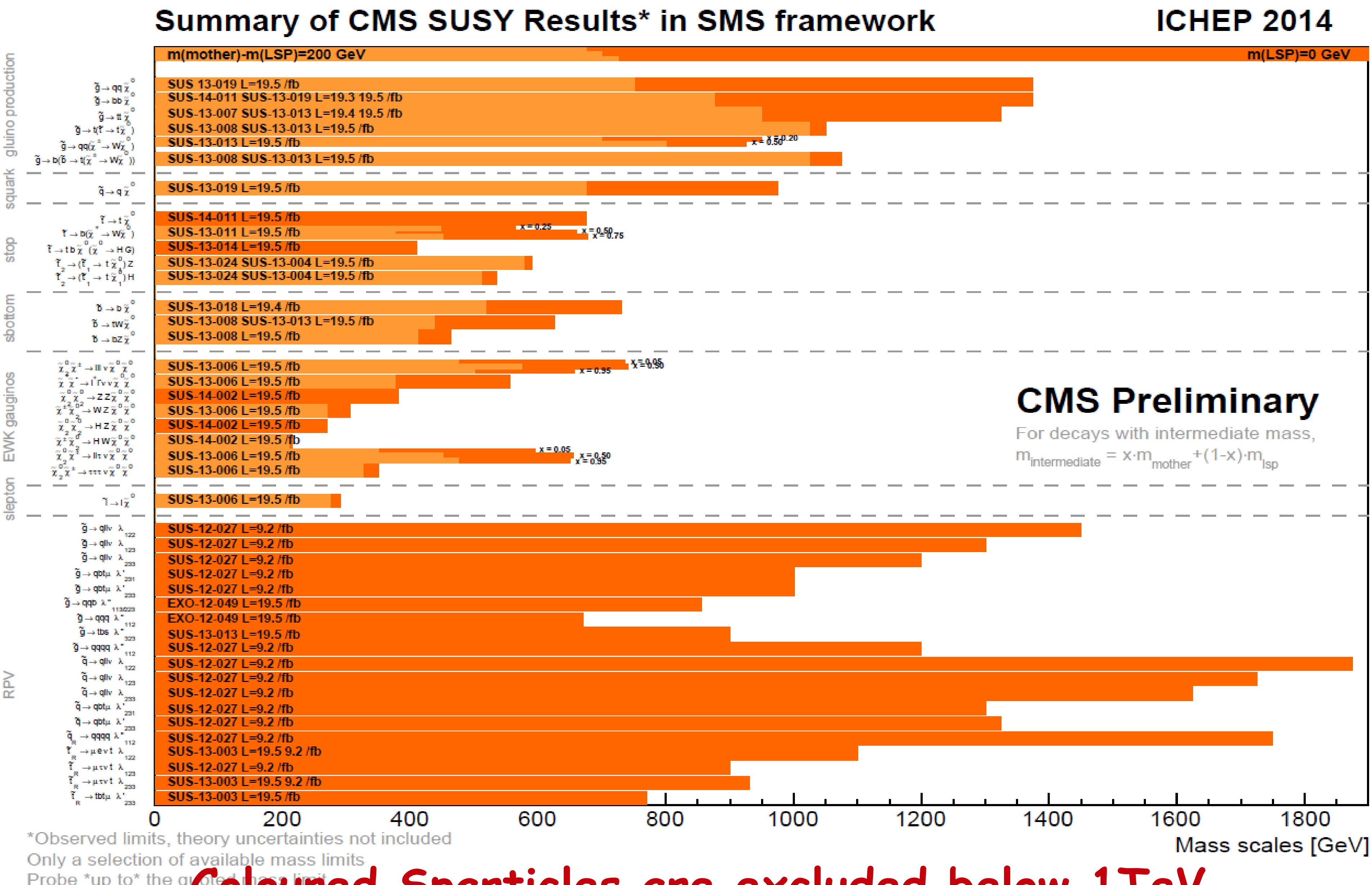
Limits from LHC8 for mSUGRA scenario



Limits from LHC8 for mSUGRA scenario



No SUSY hint from the experimental searches …



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

The EW measure of Fine Tuning

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

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

$$\frac{m_Z^2}{2} = \frac{(m^2_{H_d} + \Sigma^d_d) - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m^2_{H_u} - \mu^2$$

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

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

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

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

$$m_{\tilde\chi^0_{1,2}} \simeq \mp\left[|\mu| \mp \frac{m_Z^2}{2}(1\pm s_{2\beta})\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)\right]$$
$$m_{\tilde\chi_1^\pm} \simeq |\mu|\left(1+\frac{\alpha(m_Z)}{\pi}\left(2+\ln\frac{m_Z^2}{\mu^2}\right)\right) - s_{2\beta}\frac{m_W^2}{M_2}$$

$$\Delta m_o = m_{\tilde\chi^0_2} - m_{\tilde\chi^0_1} \simeq m_Z^2\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)$$
$$\Delta m_\pm = m_{\tilde\chi^\pm_1} - m_{\tilde\chi^0_1} \simeq \frac{\Delta m_0}{2} + \mu\frac{\alpha(m_Z)}{\pi}\left(2+\ln\frac{m_Z^2}{\mu^2}\right)$$

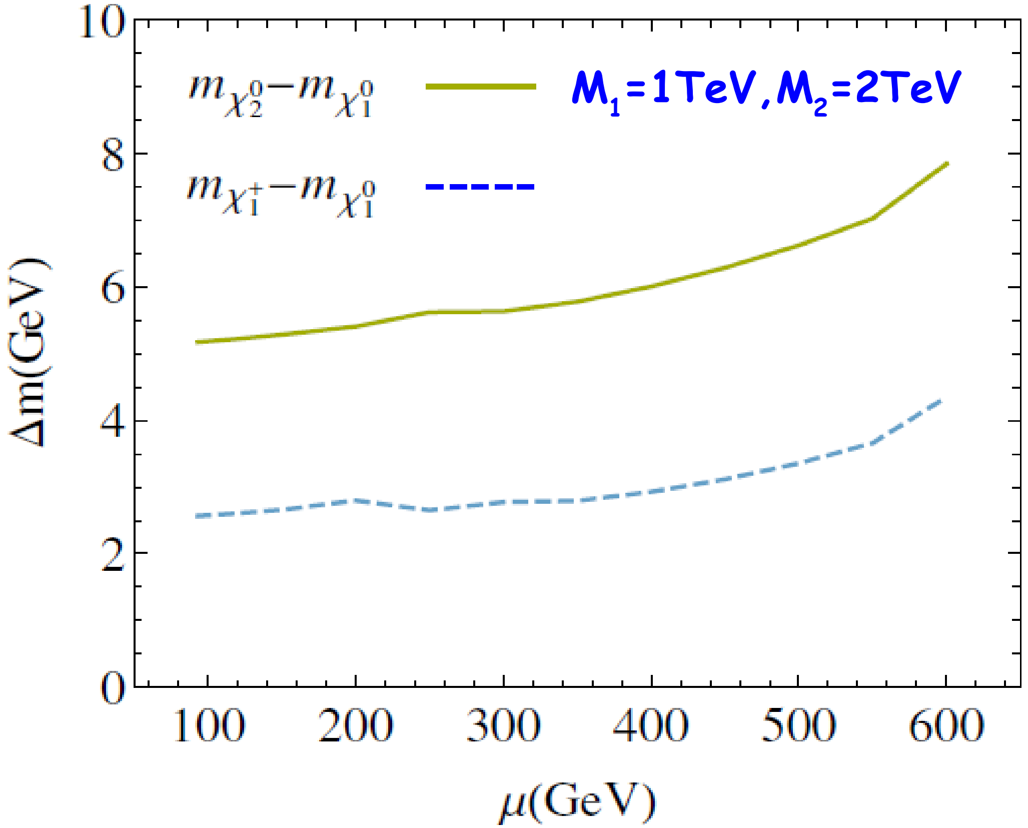
$$\boxed{\Gamma(\tilde\chi_1^\pm, \tilde\chi_2^0 \to f\, f'\, \tilde\chi_1^0) = \frac{C^4}{120\pi^3}\frac{\Delta m^5}{\Lambda^4}}$$

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

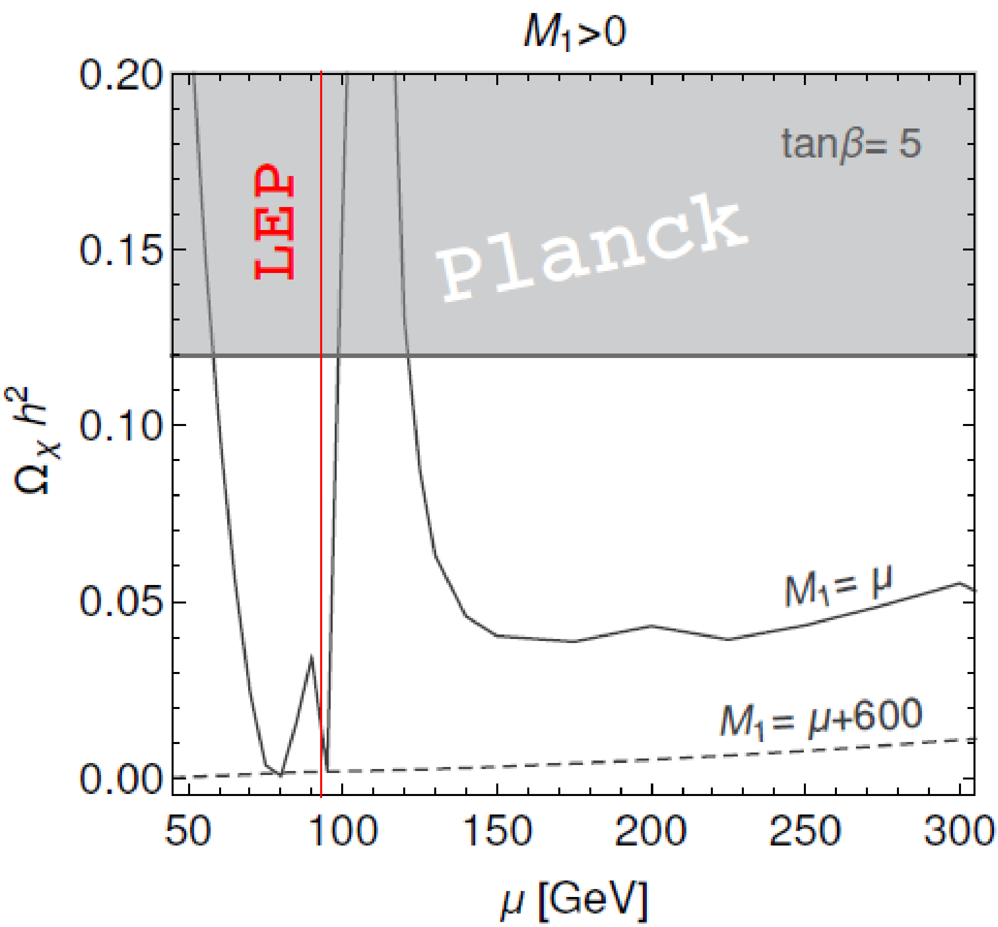
$$L = c\tau \simeq 0.01\ \text{cm}\left(\frac{\Delta m}{1\ \text{GeV}}\right)^{-5} \quad \tilde\chi_2^0 \to f\bar f\tilde\chi_1^0 \ \text{(Z-exchange)}$$

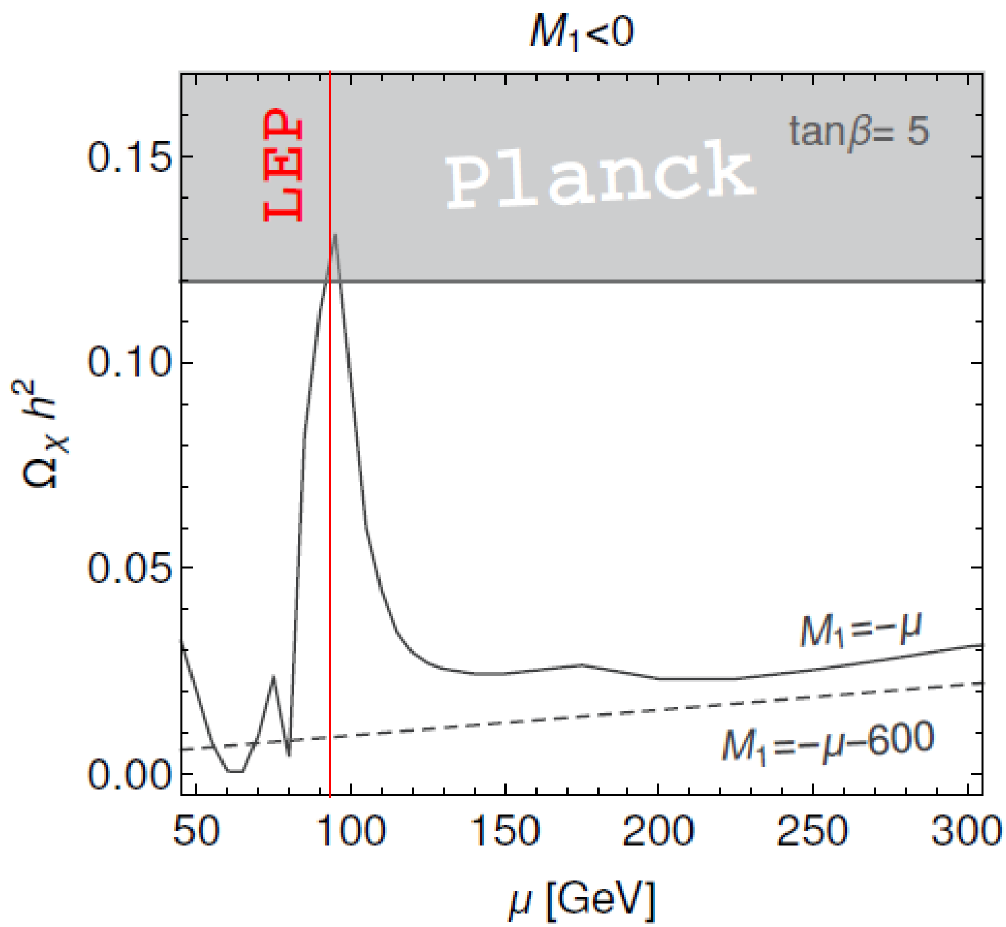
$$L = c\tau \simeq 0.006\ \text{cm}\left(\frac{\Delta m}{1\ \text{GeV}}\right)^{-5} \quad \tilde\chi_1^\pm \to f\, f'\, \tilde\chi_1^0 \ \text{(W-exchange)}$$

Δm < 1 GeV → displaced vertices ~0.1mm
Δm < 0.1 GeV → DM is collider stable

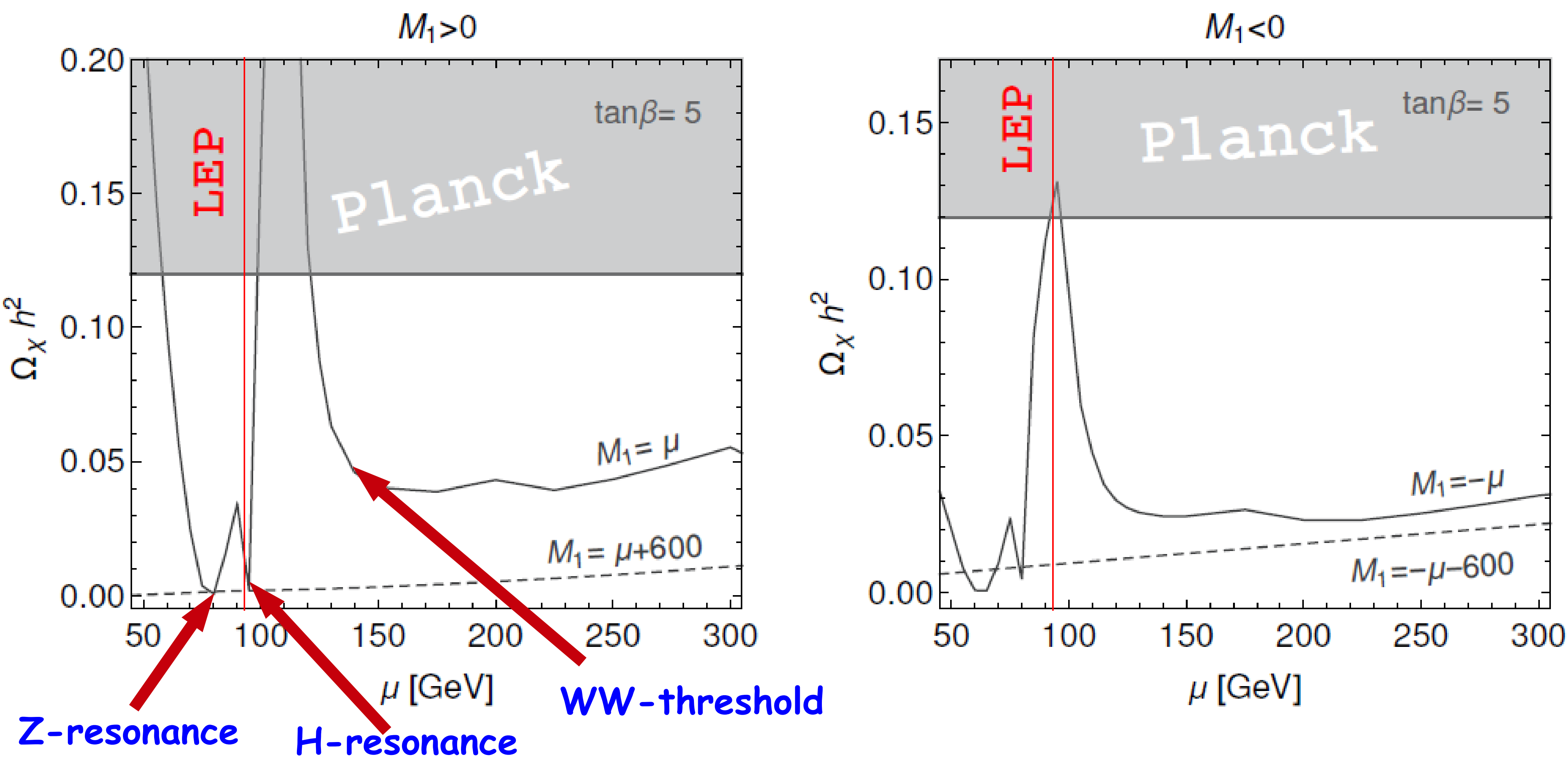


Dark Matter Relic Density



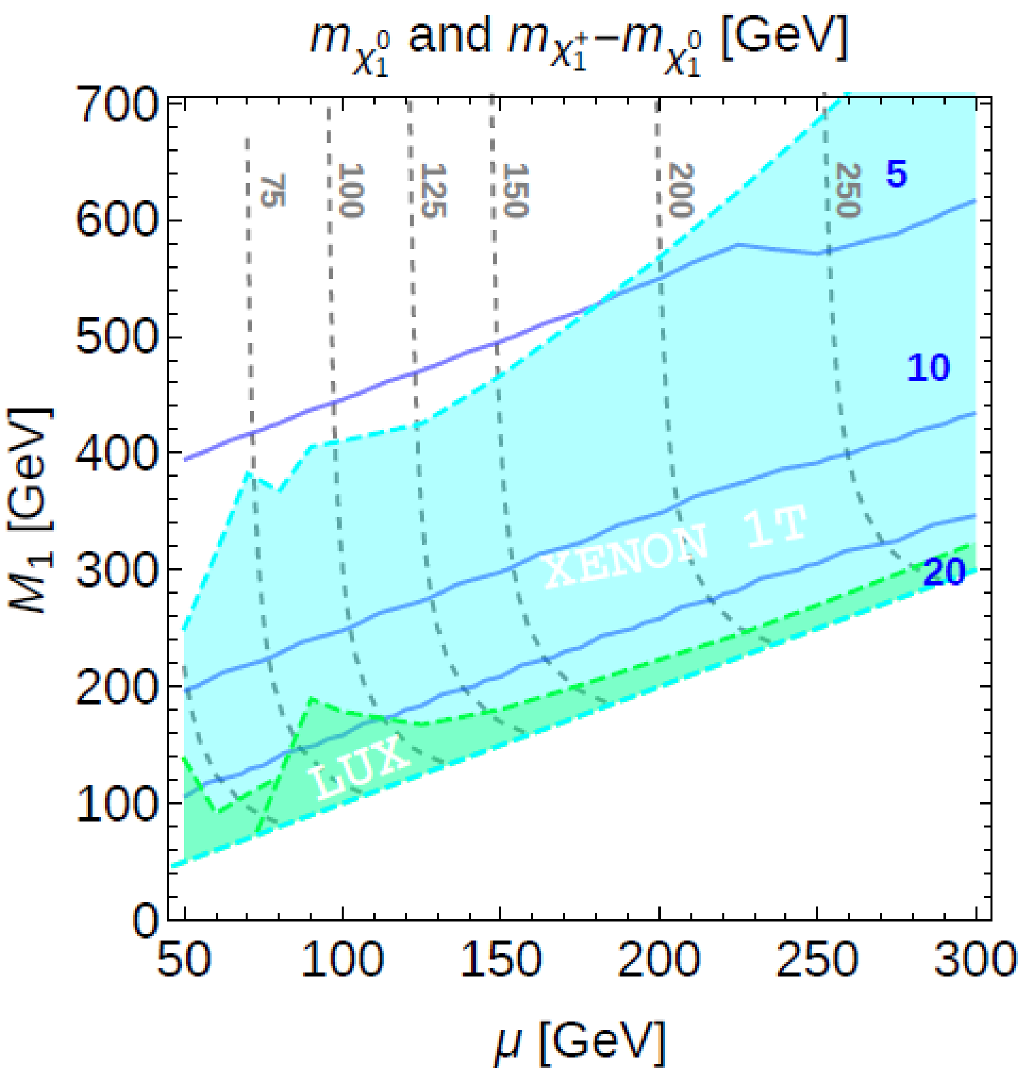


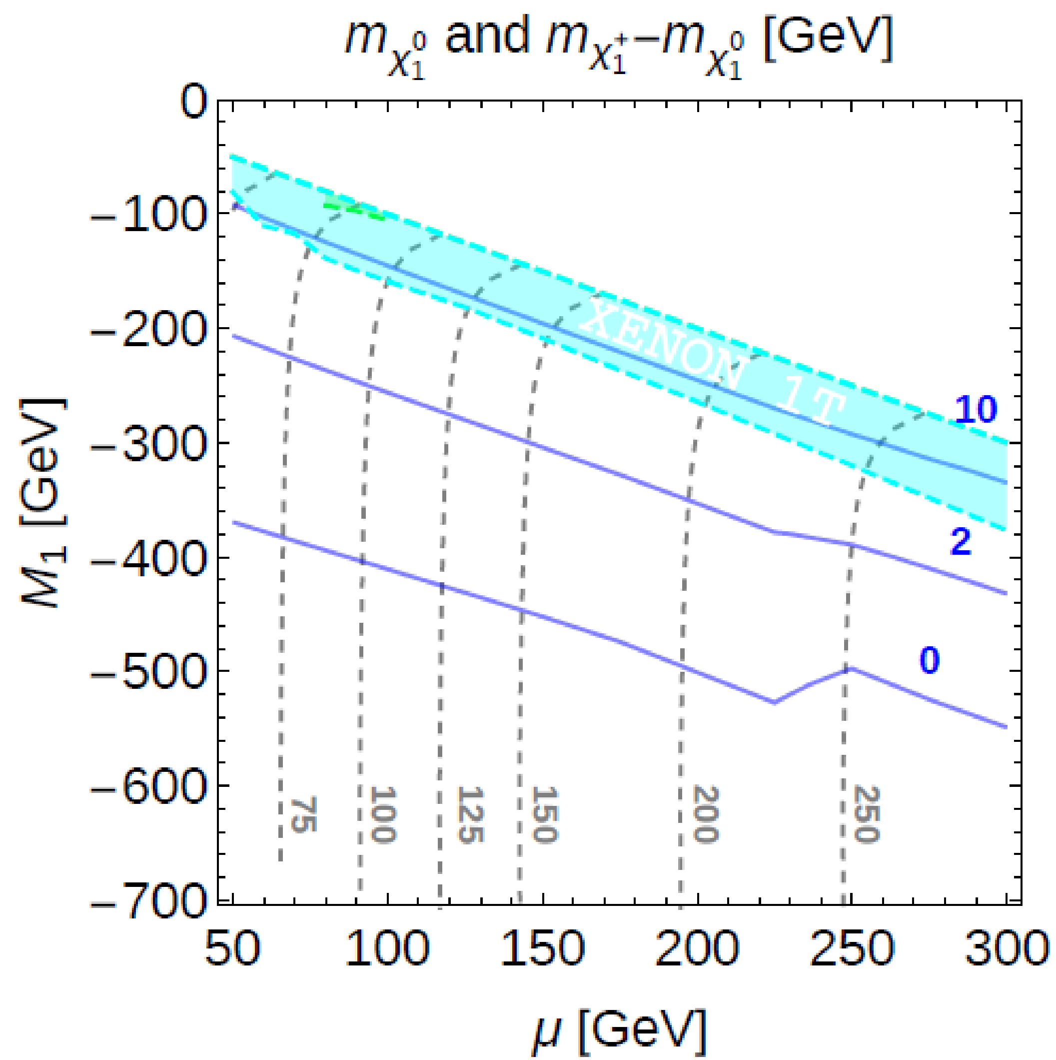
Dark Matter Relic Density



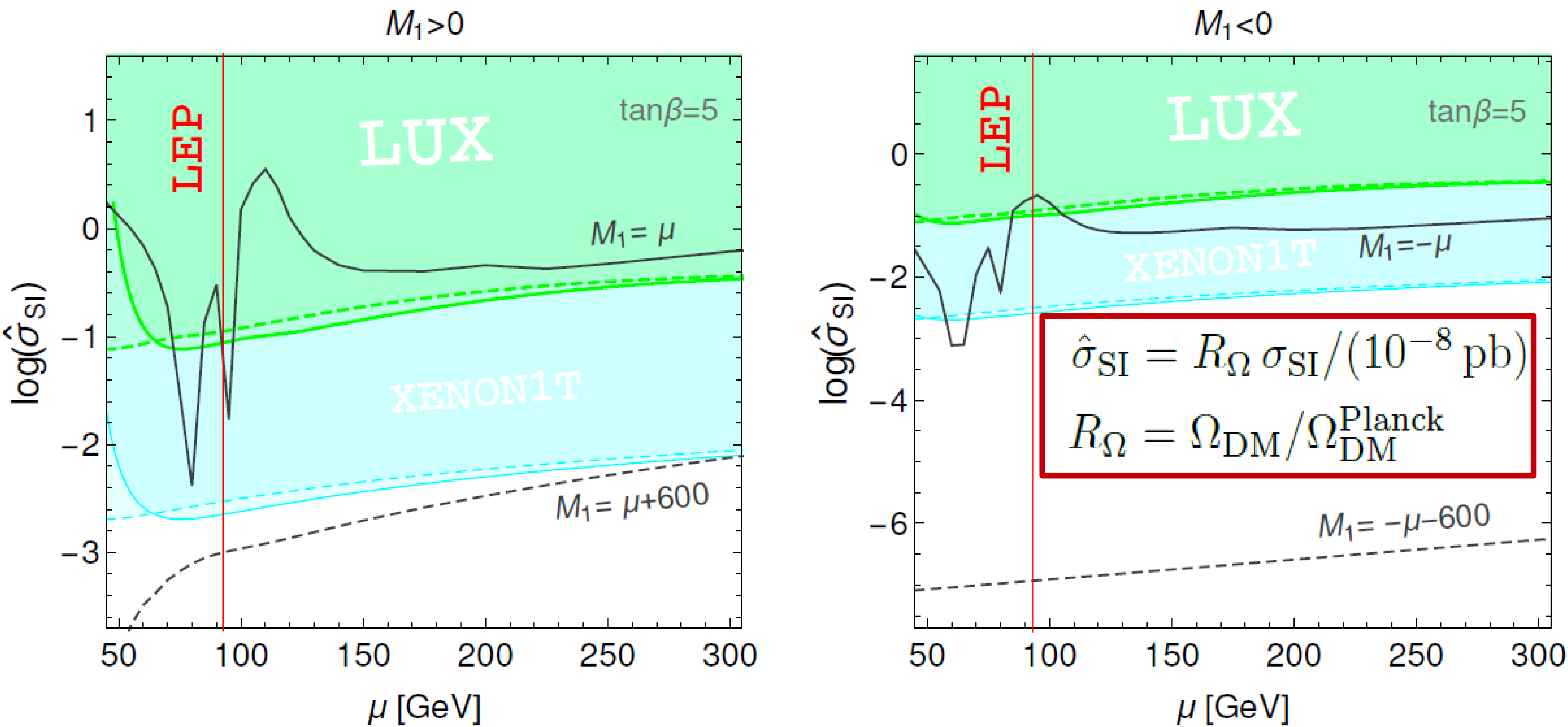
- **DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes**

DD in M_1-μ plane



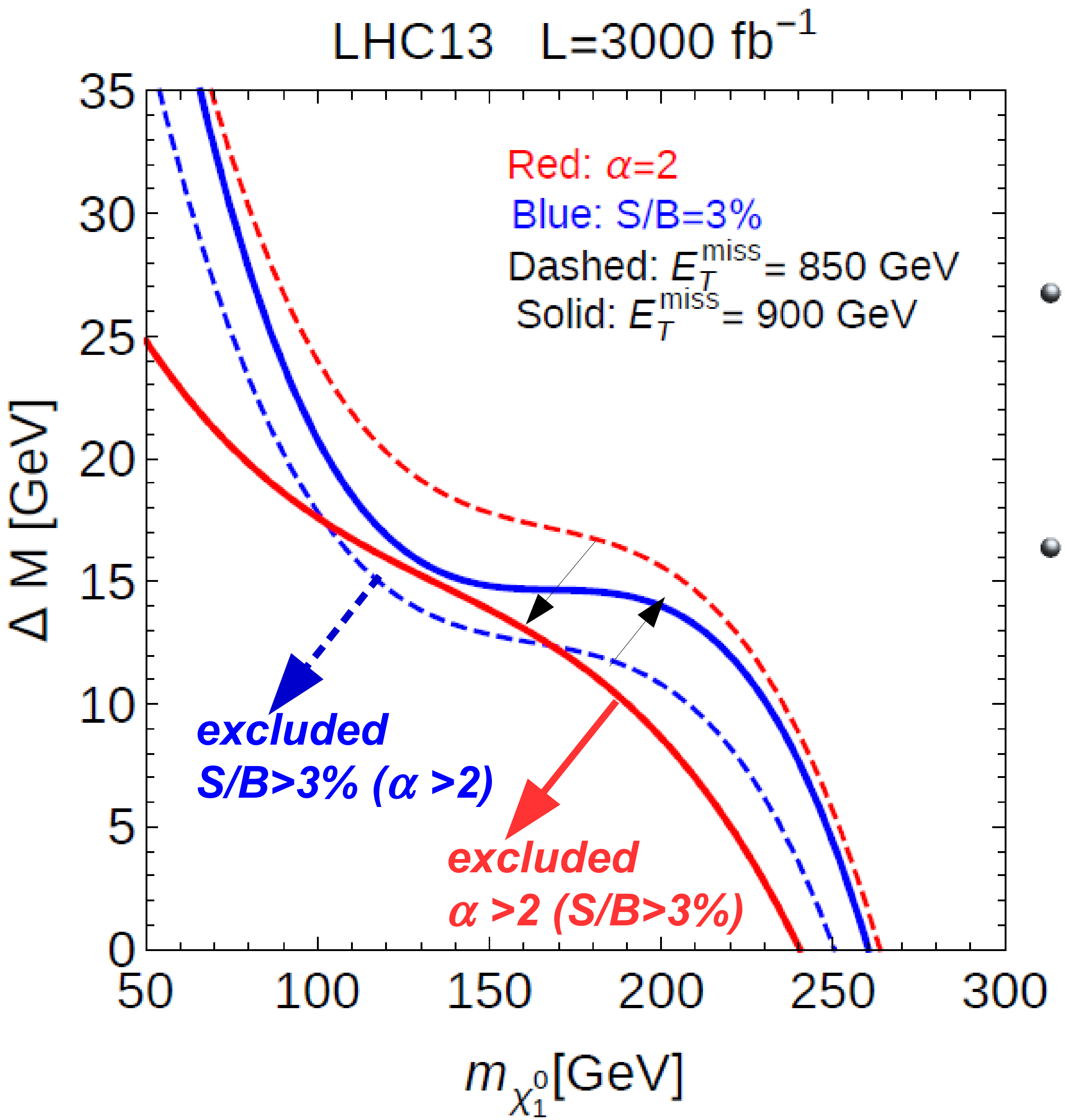


Direct Detection Prospects



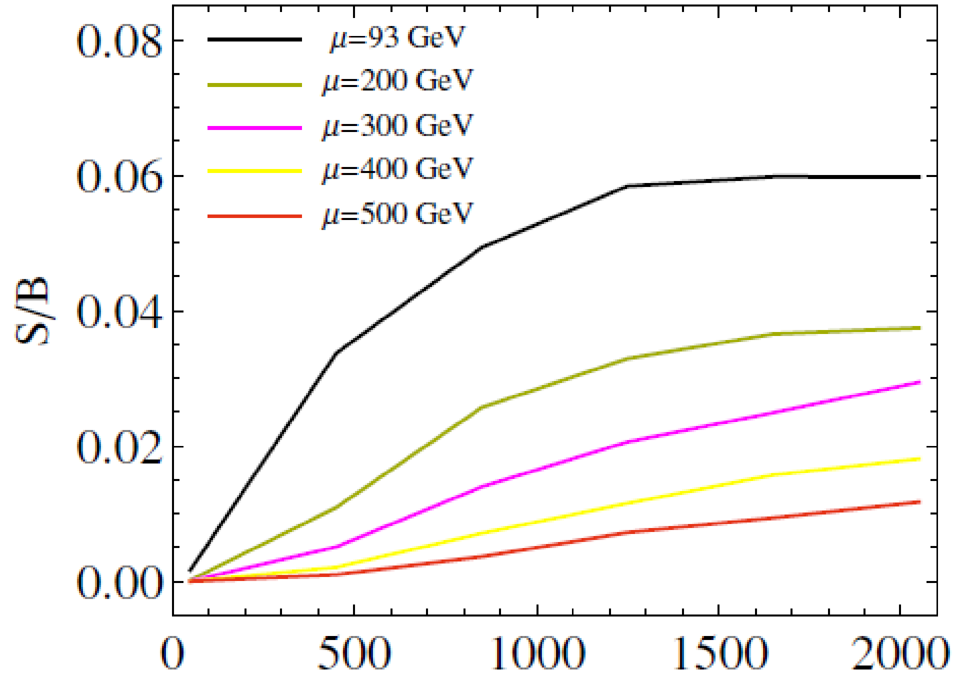
- **DD cross section rescaled with the relic density is low in the small ΔM region. Chance for the LHC?**

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



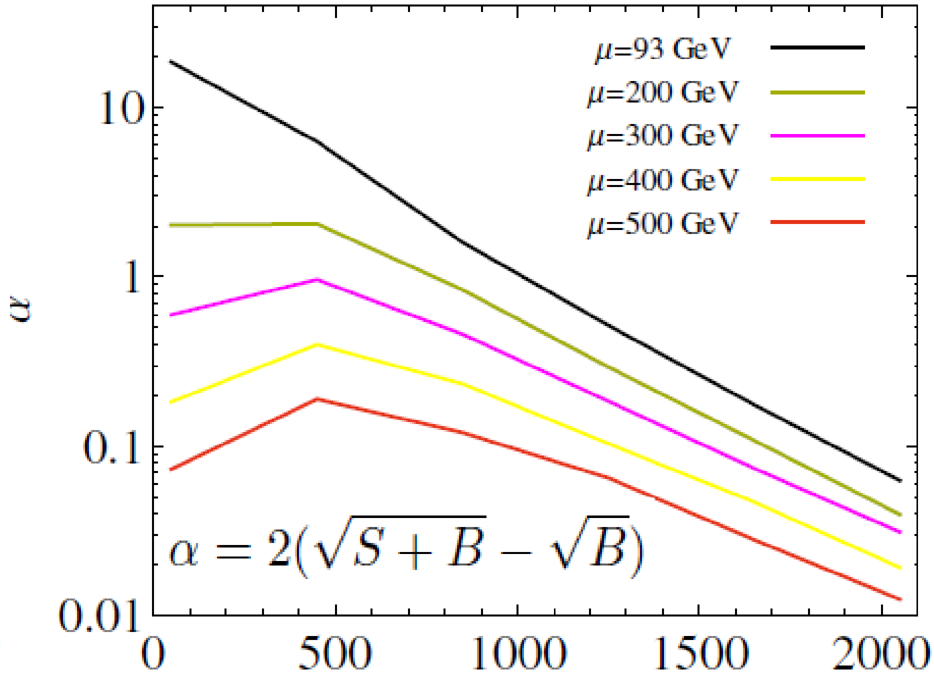
- The shapes of S/B and α contours are very similar - easy to optimise $E_{T\ miss}$ cut
- We chose $E_{T\ miss}$ value to bring S/B and α iso-contours together: they move into opposite directions

S/B vs Signal significance



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

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

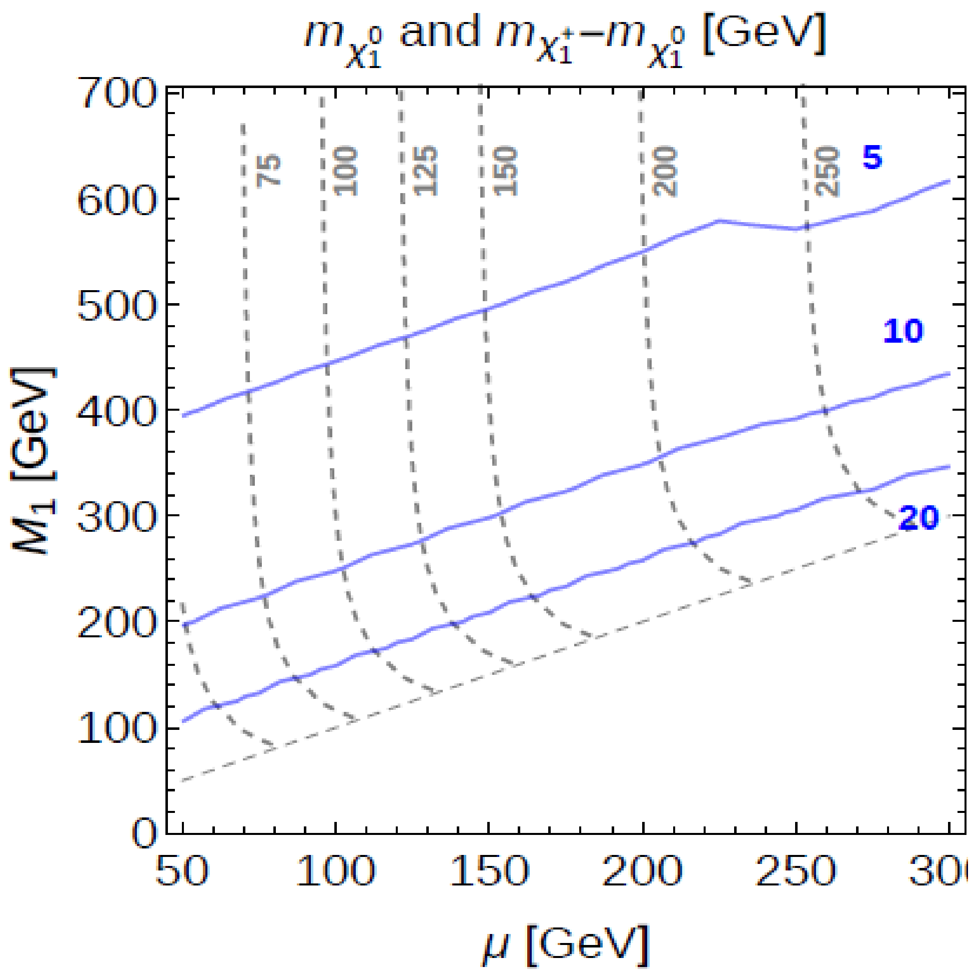


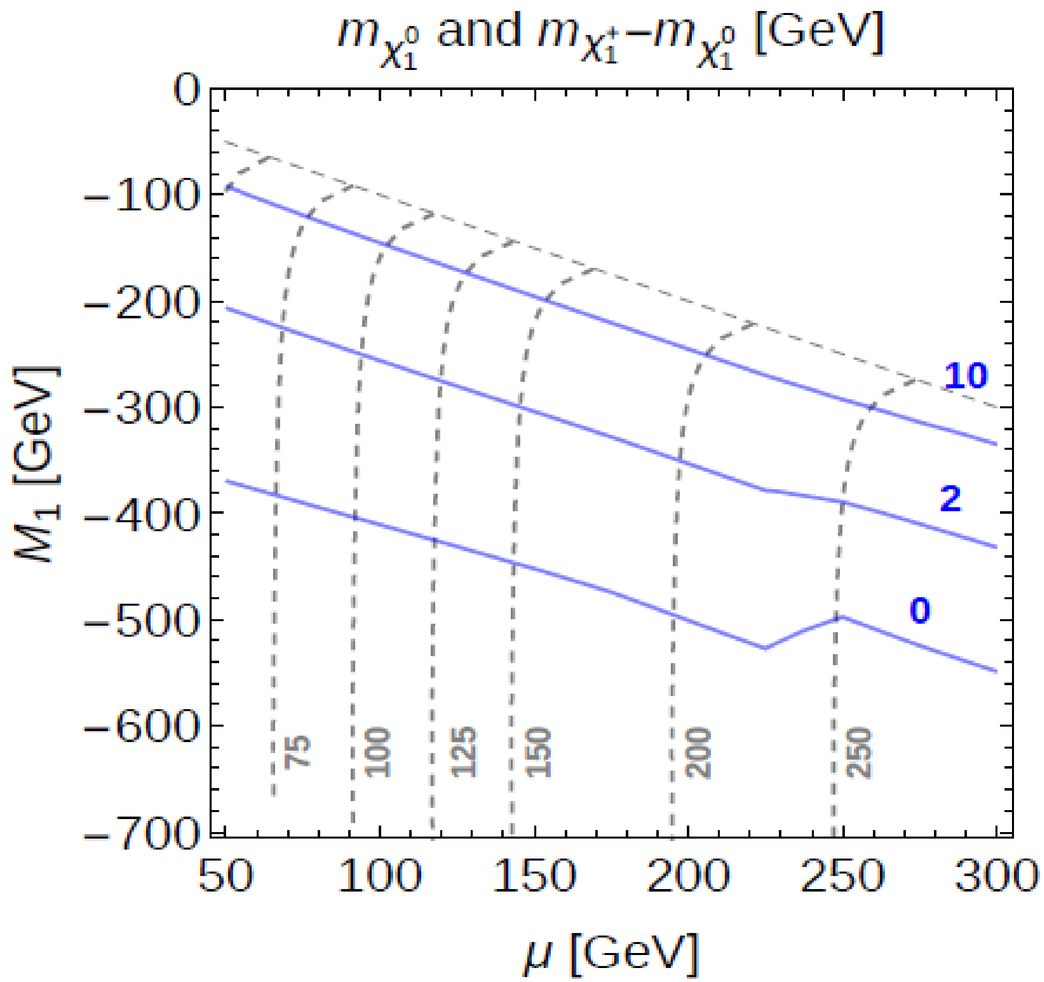
P_T^{j1}/E_T^{miss} cut (GeV)

	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ 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 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

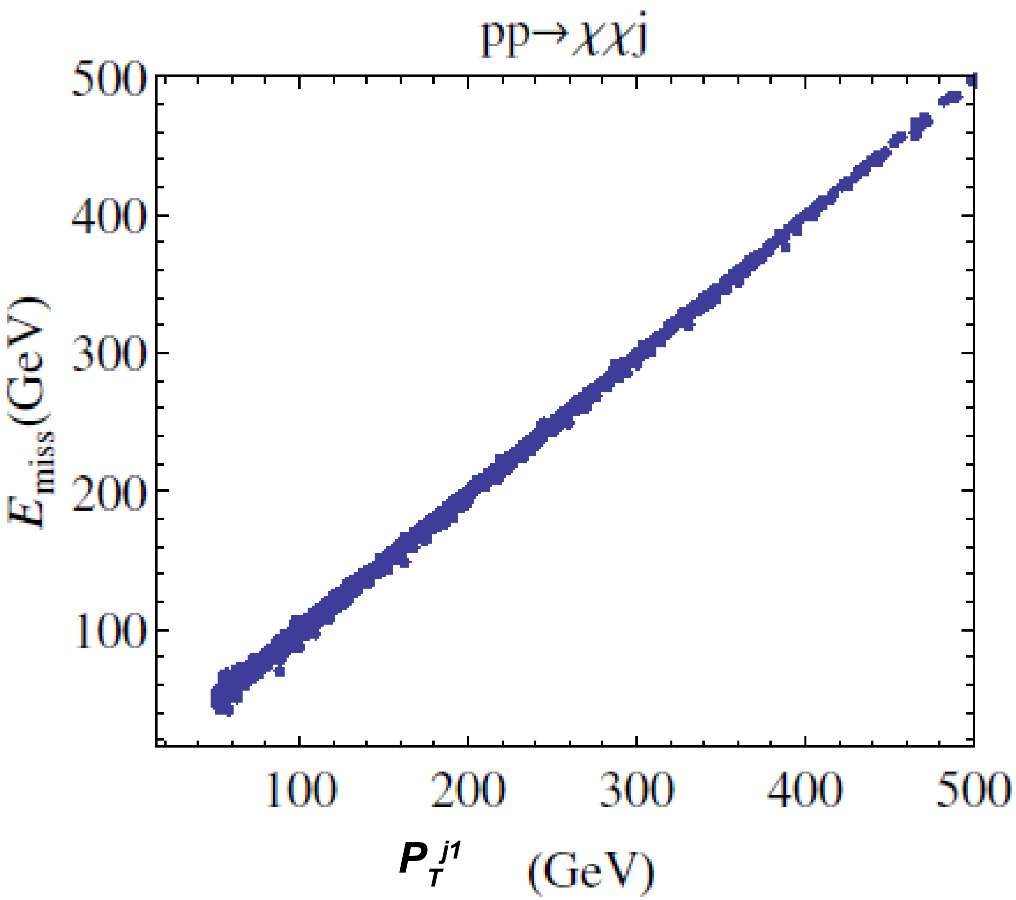
ΔM pattern for $M_1>0$ and $M_1<0$ cases



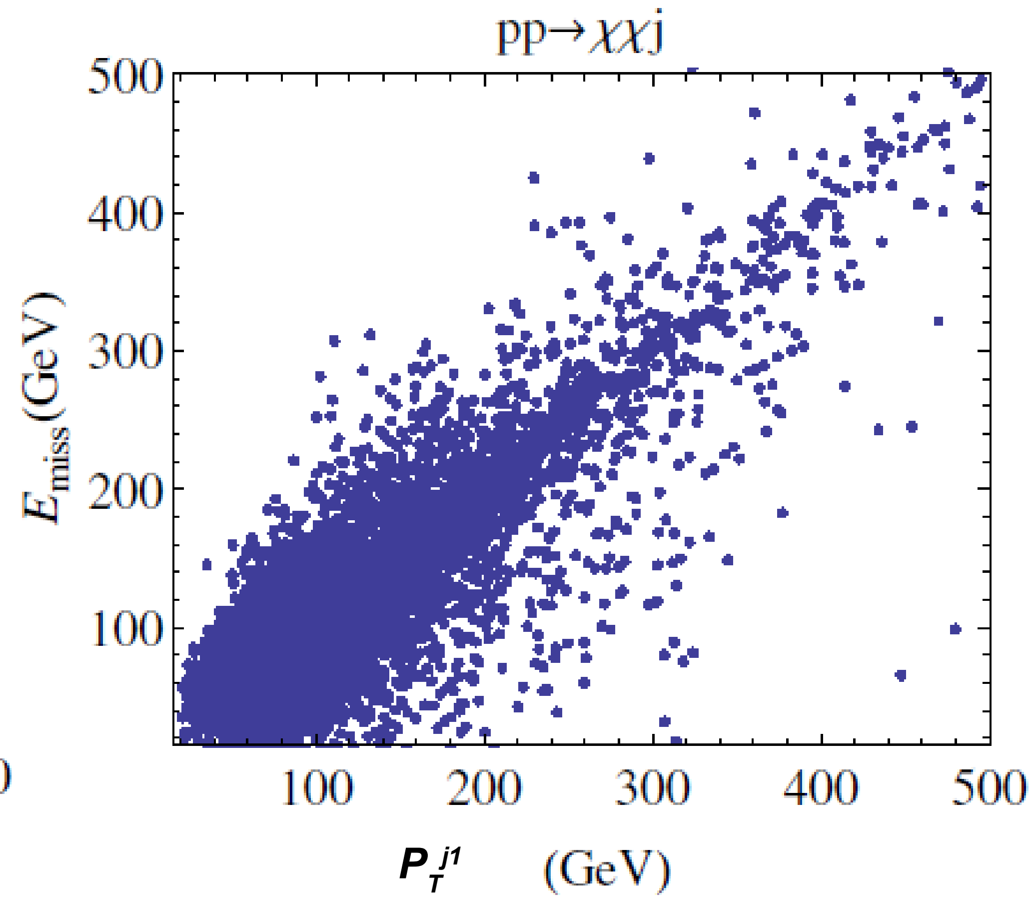


Parton vs Detector simulation level

Parton level



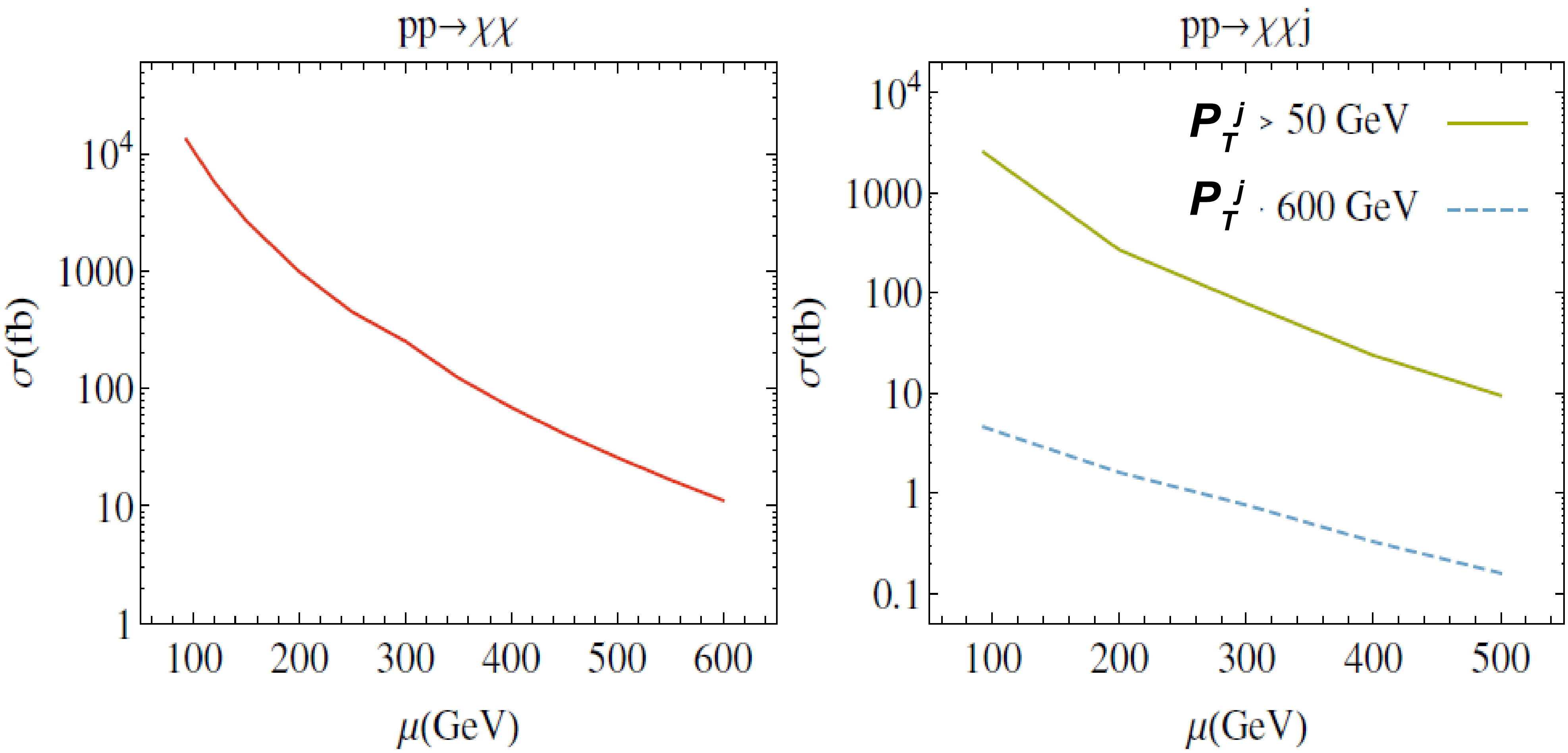
Delphes level



- 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.

LHC sensitivity to CHS

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



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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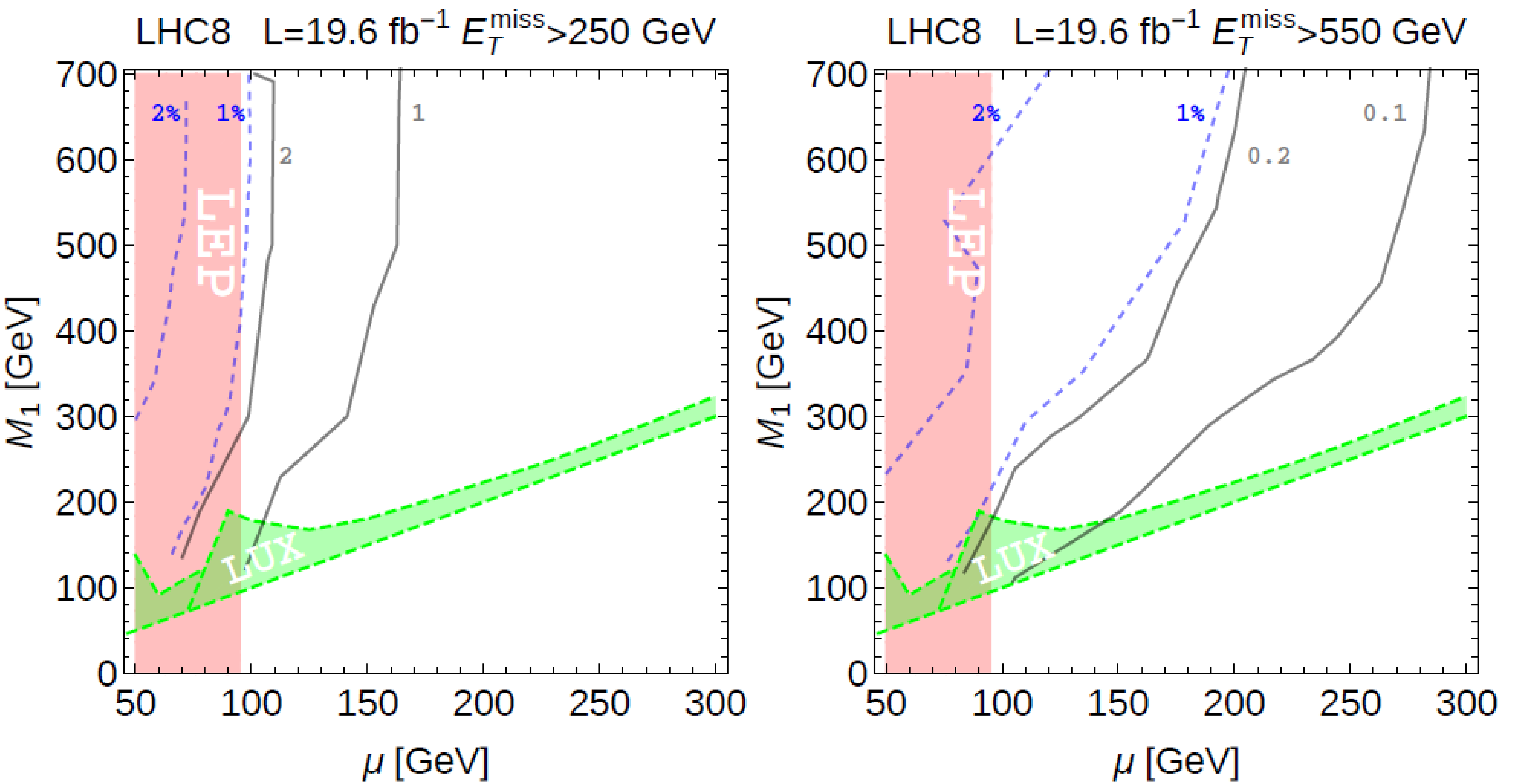
Total	4.5	4.9	5.8	7.1	8.9	12.1	15.6

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

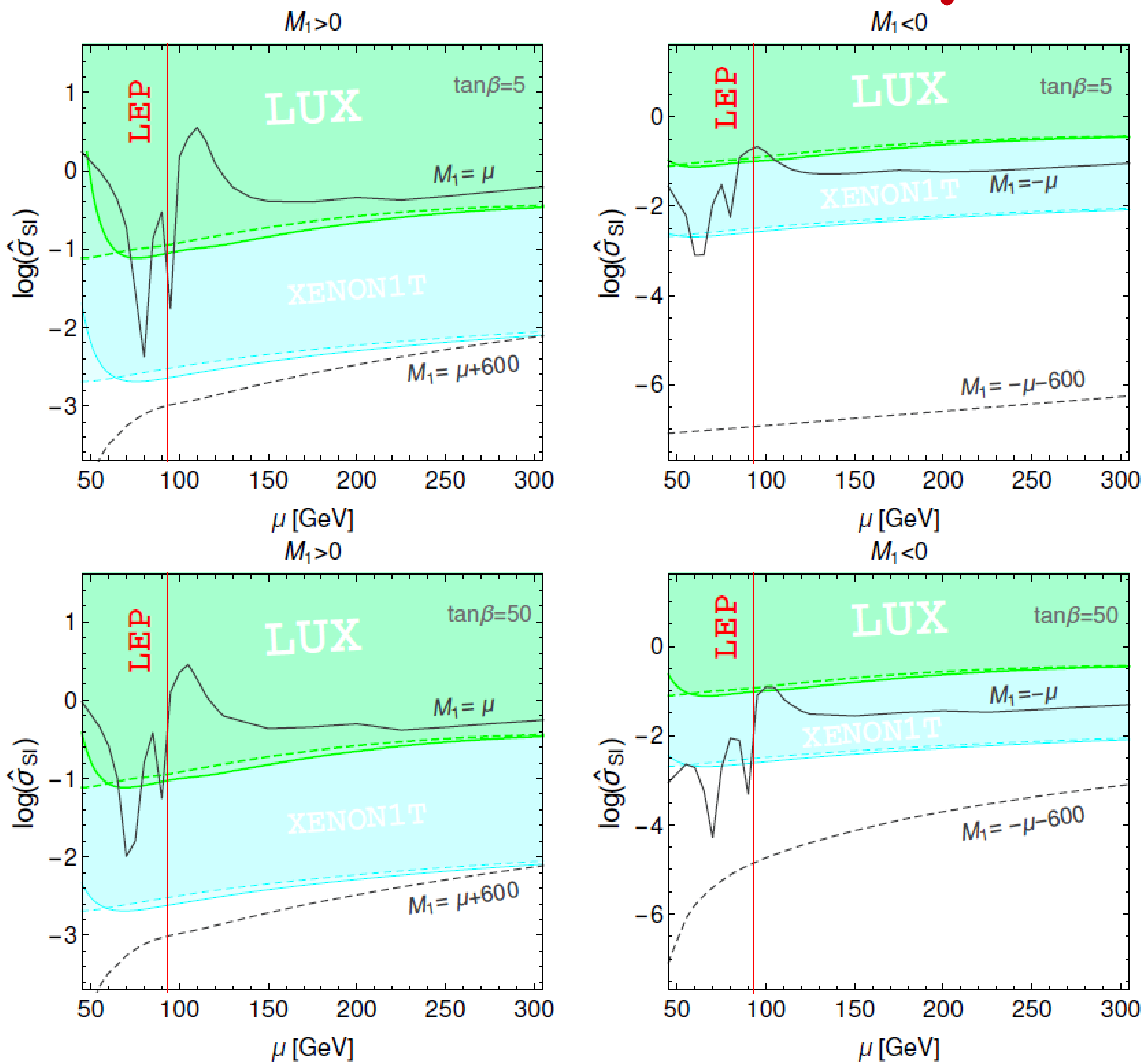
Interpreting LHC@8TeV results (CMS EXO-12-048)

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

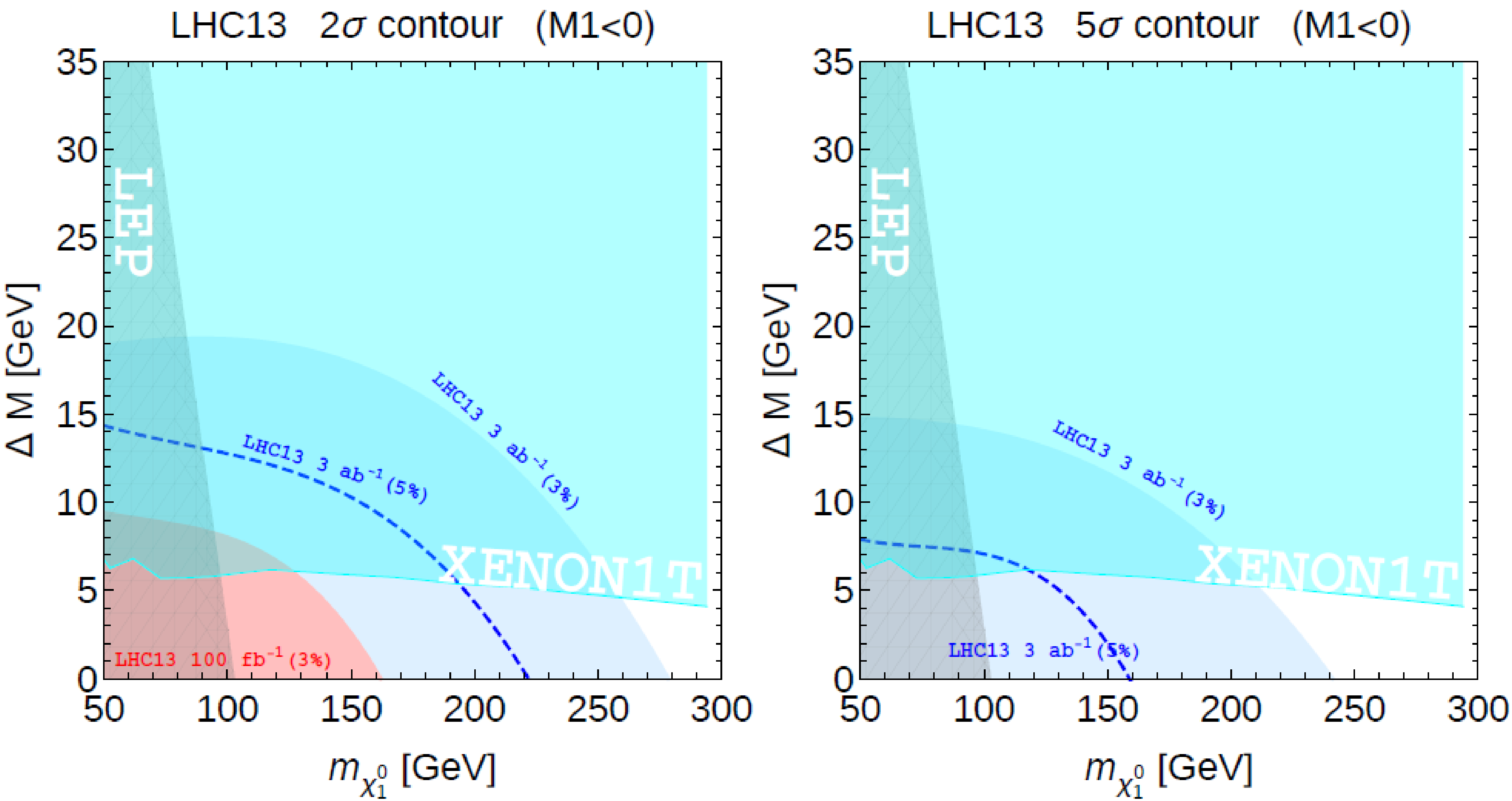


- **Both S/B and Significance are too low – so LHC@8 is unfortunately not sensitive to NSUSY space ...**

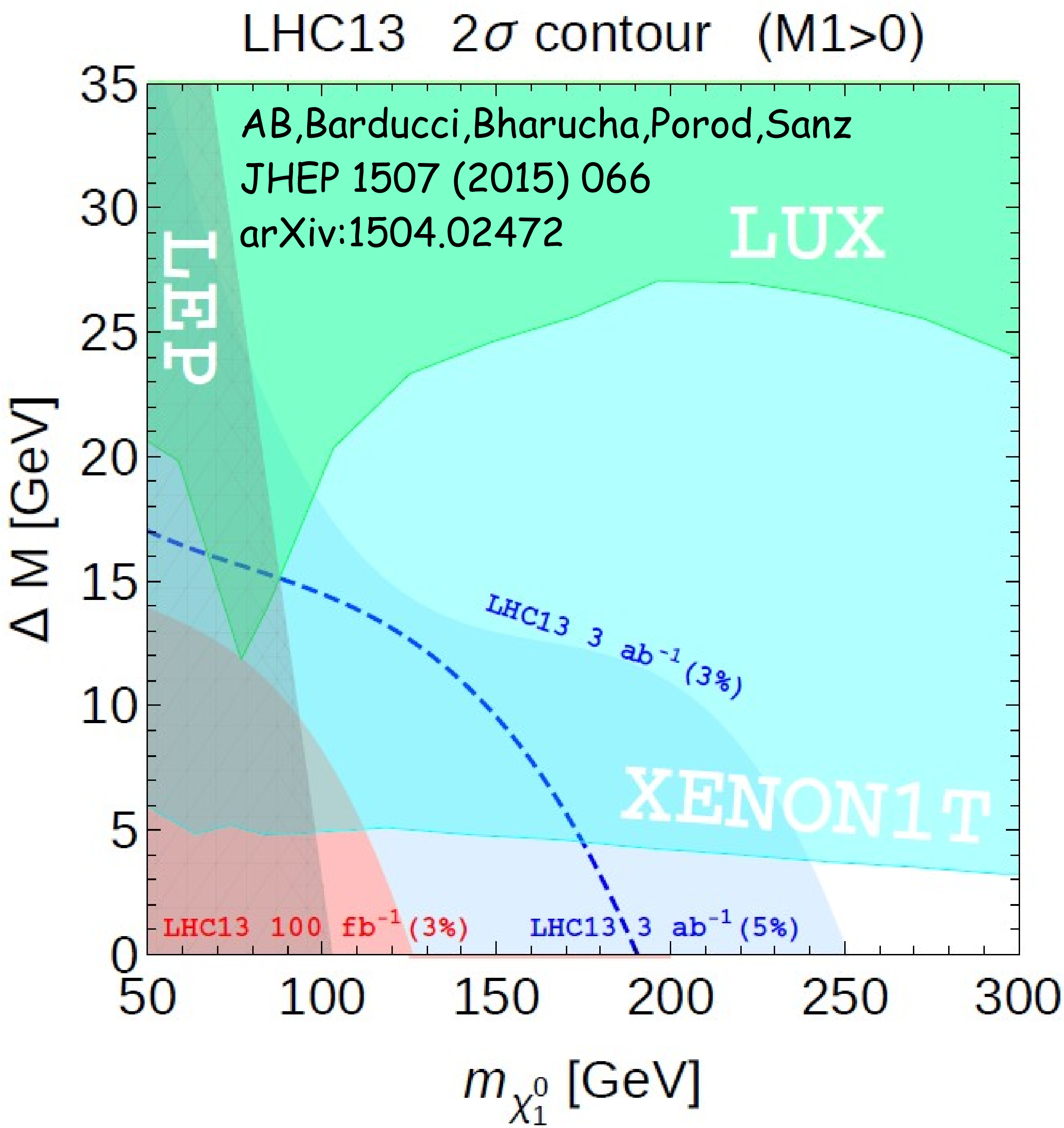
Direct Detection Prospects



LHC@13 Reach for NSUSY

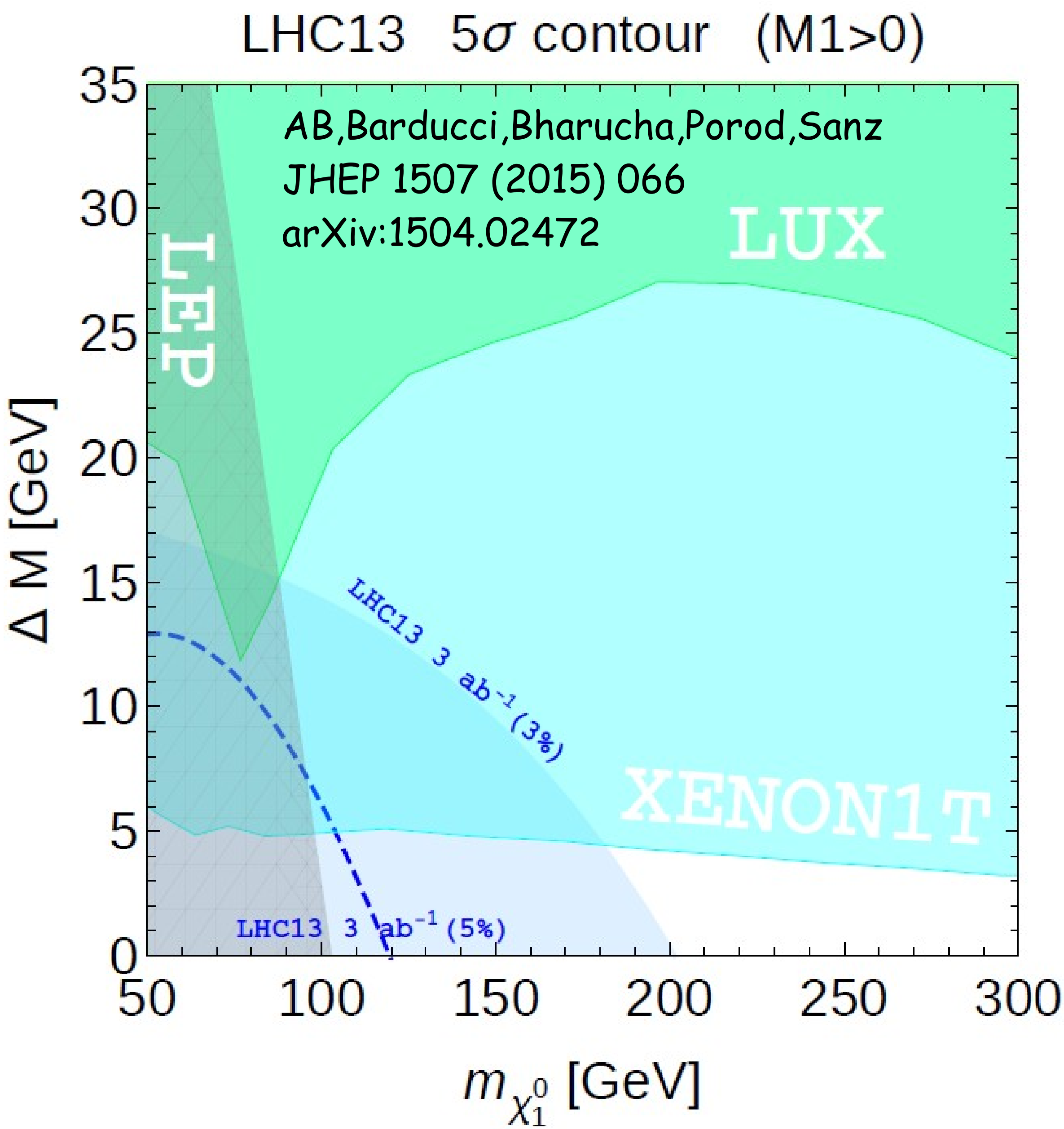


LHC@13 Reach for NSUSY



- 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**

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

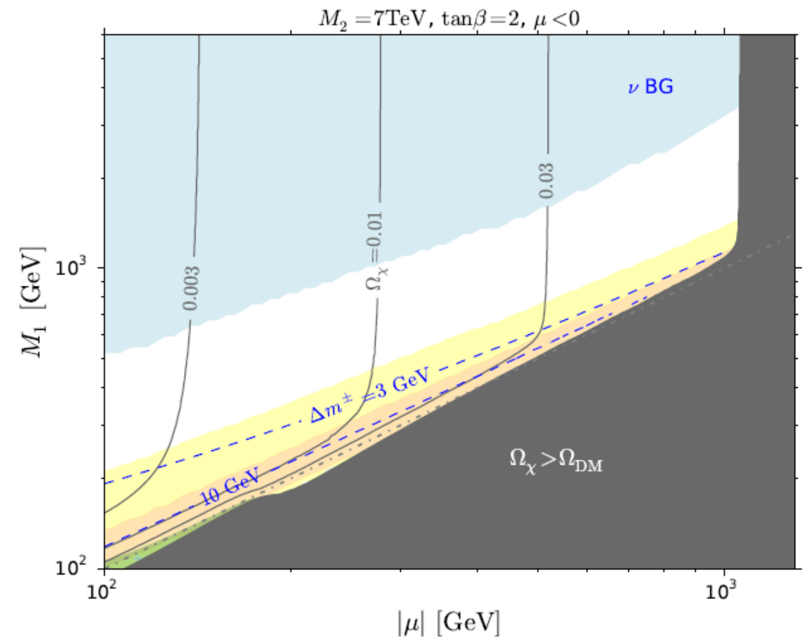
- **Han,Kribs,Martin,Menon '14**

  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

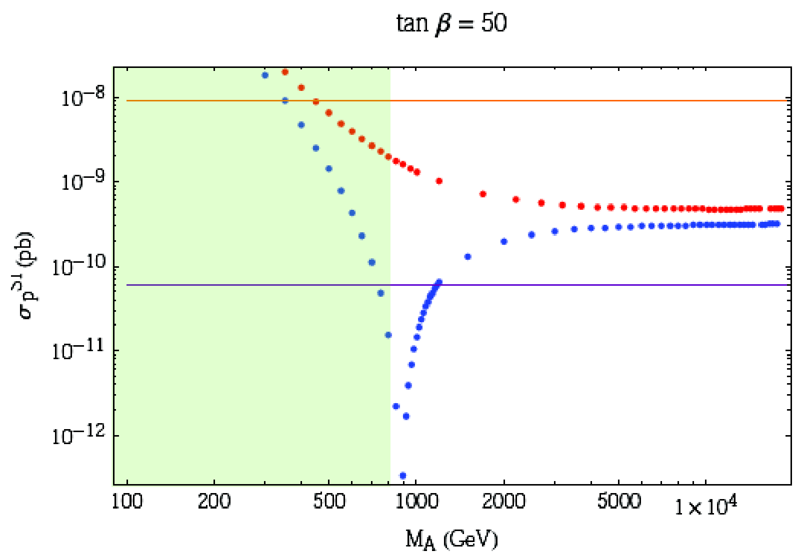
OUTLOOK



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

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

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)
  - ?