SUSY Dark Matter

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

HELMHOLTZ GEMEINSCHAFT

Allianz für Astroteilchenphysik

HAP Dark Matter 2015

21-23 September 2015
Karlsruhe Institute of Technology

Local Organisation:
Klaus Eitel, Marie-Christine Kauffmann, Thomas Schwetz-Mangold

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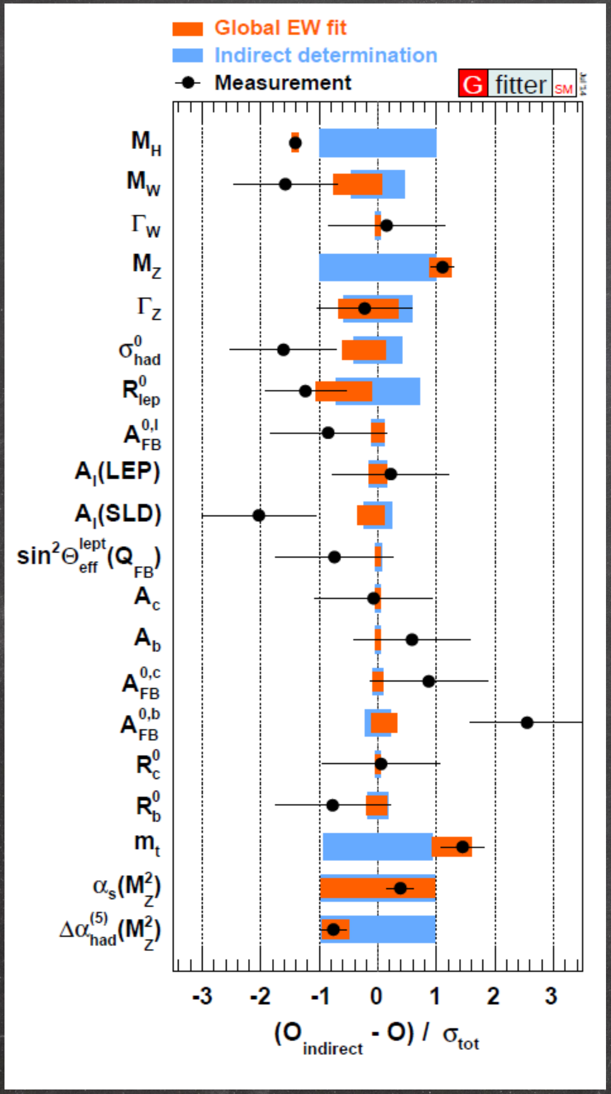
Thanks to the organisers!

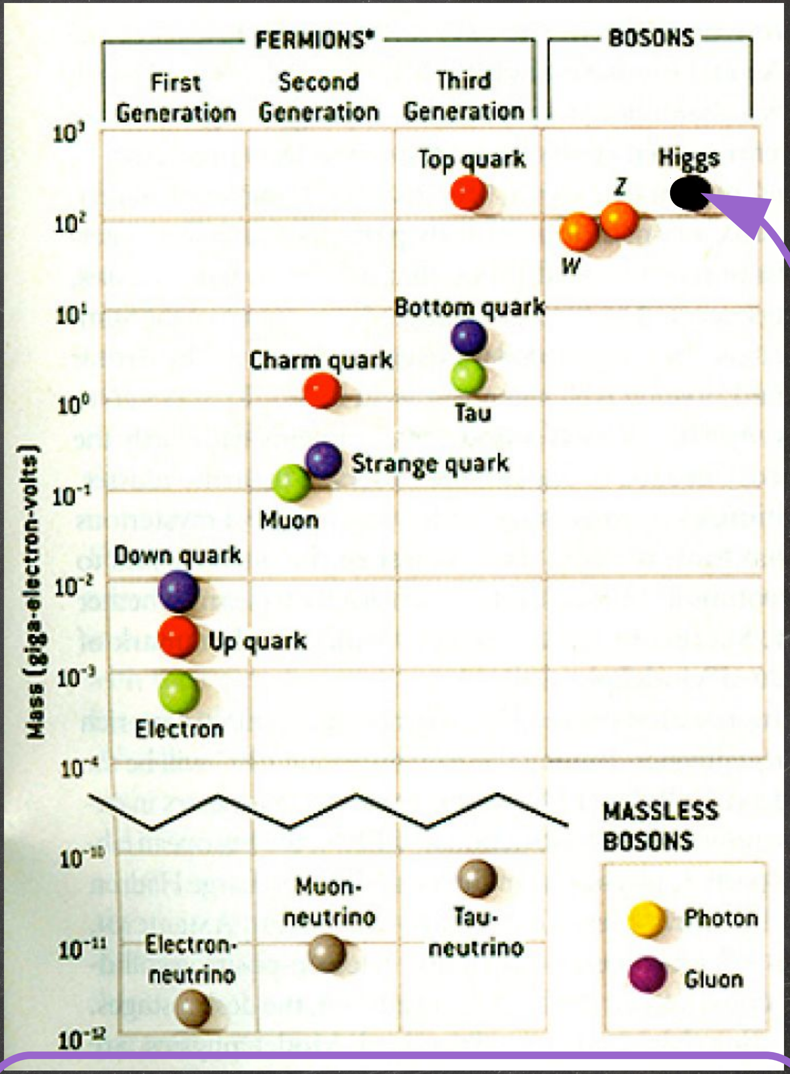
OUTLINE

- Motivation for BSM
- SUSY as one of the most compelling one
- 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

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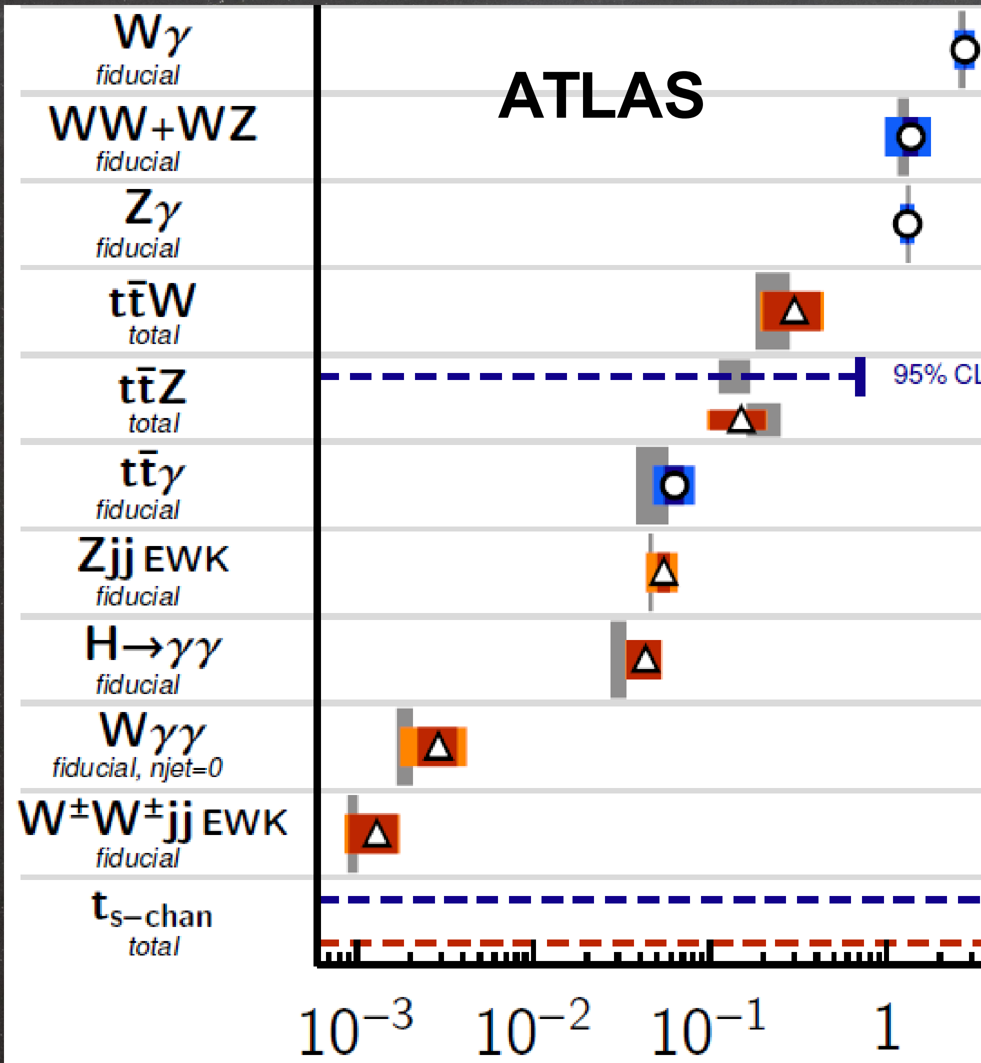
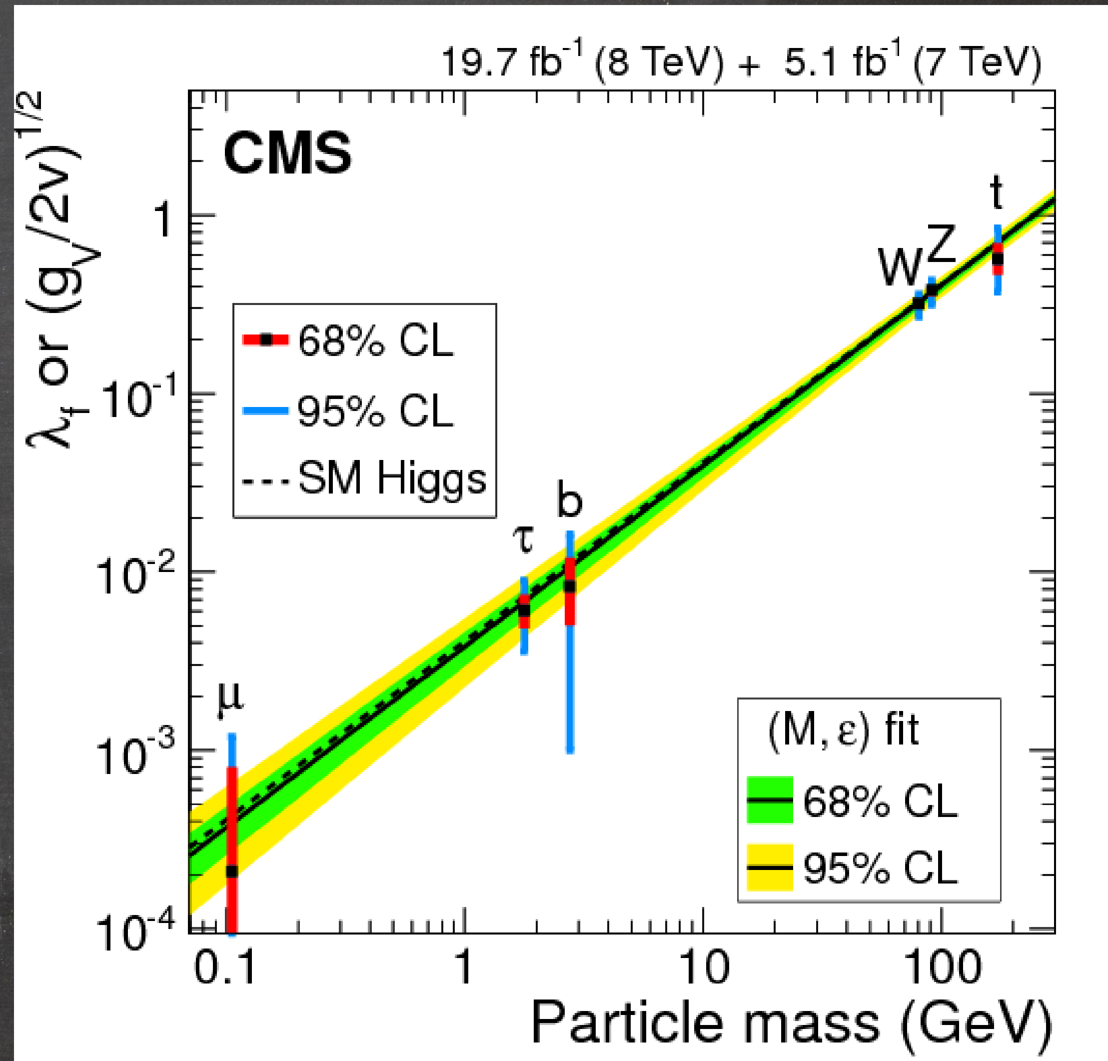
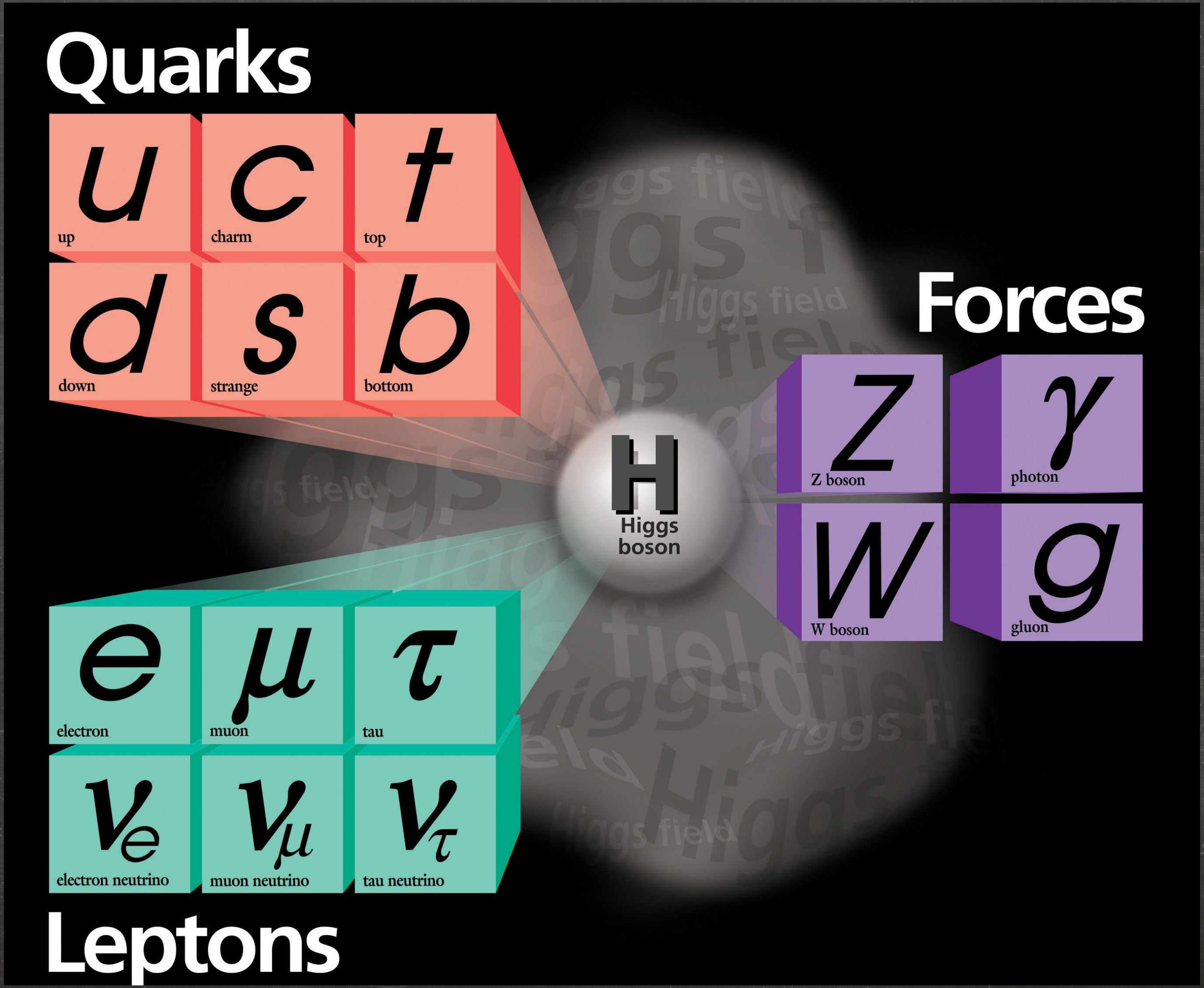




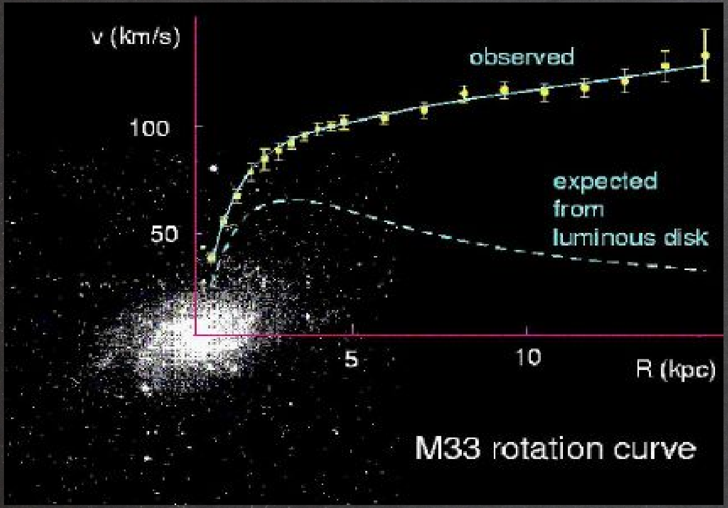
So, if SM works so good, why we are looking beyond?!



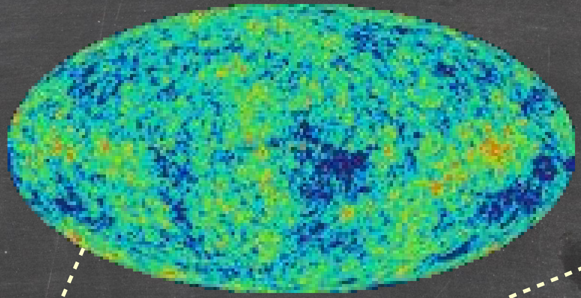
SM is empirically incomplete

- 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

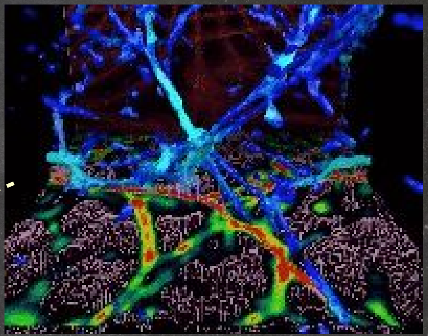
Galactic rotation curves



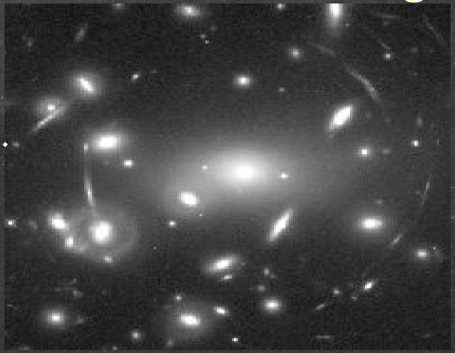
CMB: WMAP and PLANCK



Large Scale Structures



Gravitational lensing



Bullet cluster

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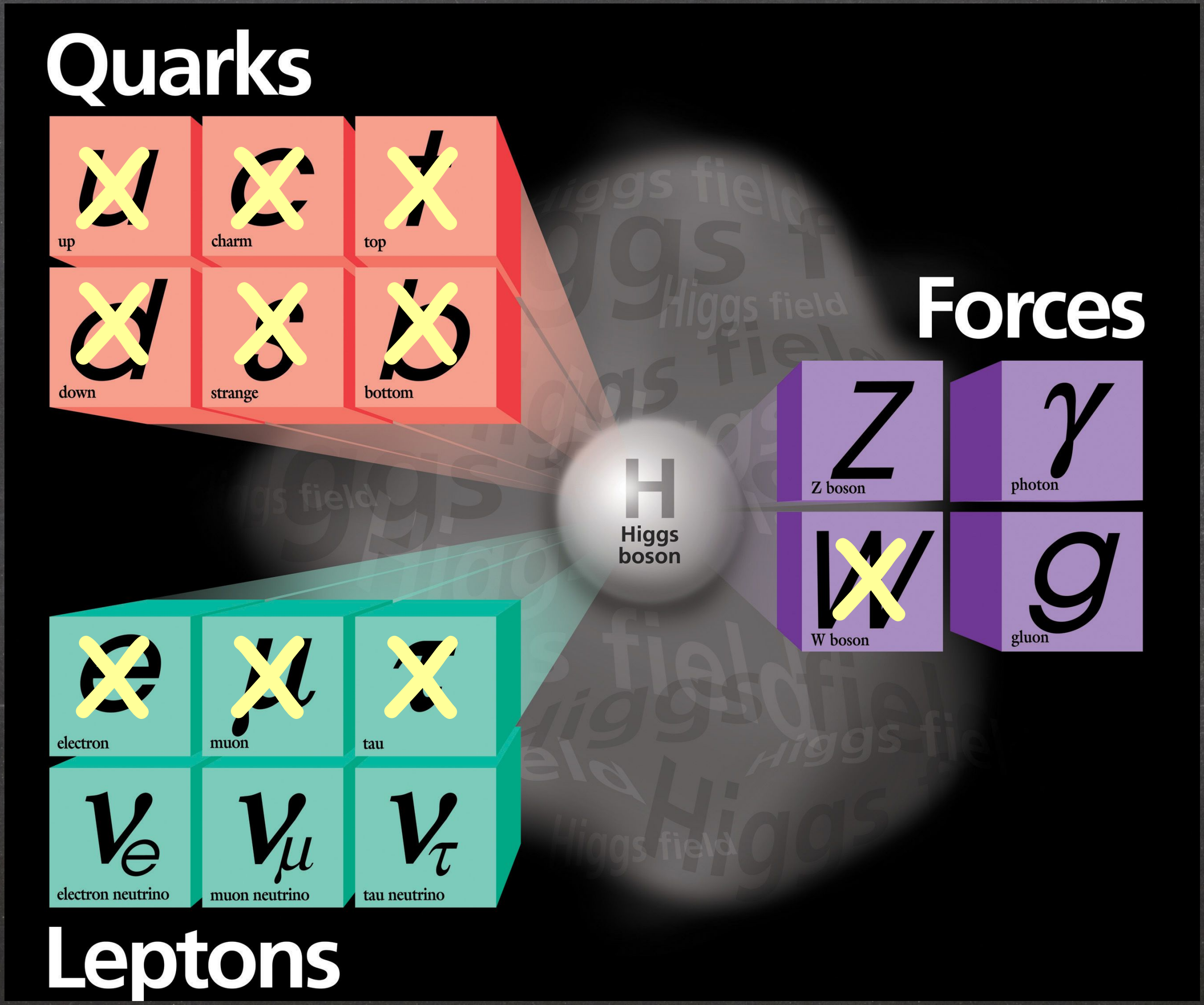

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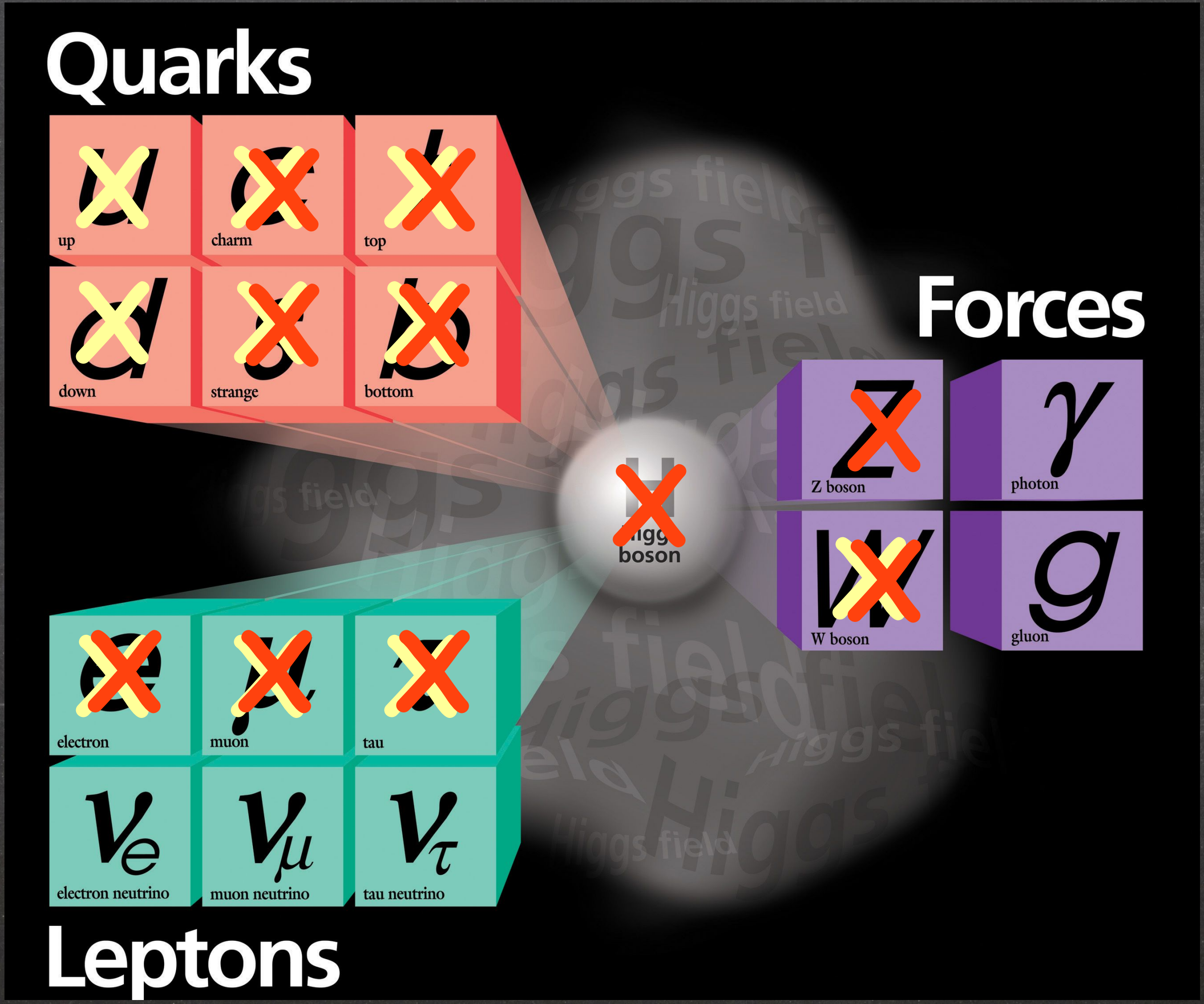

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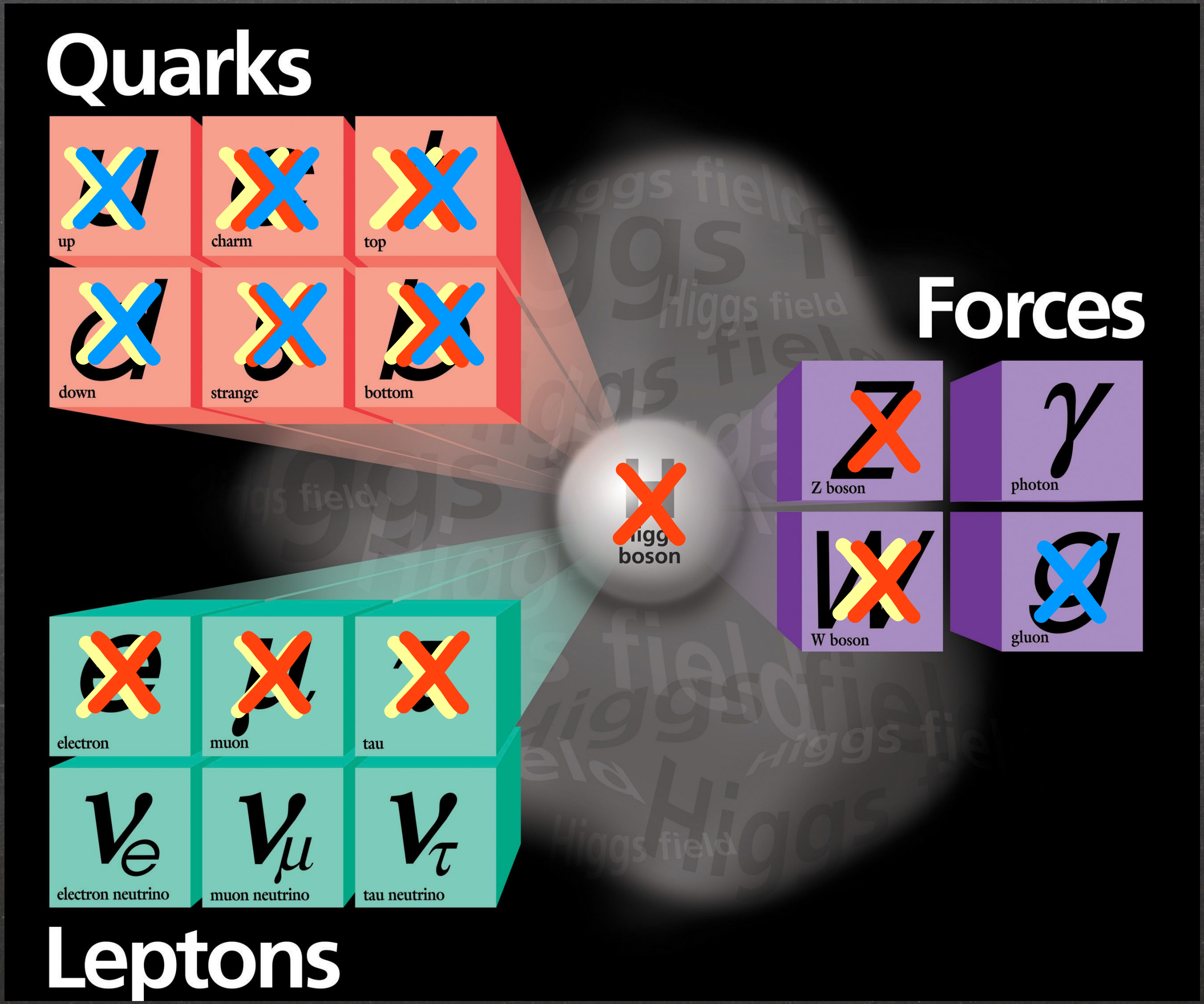

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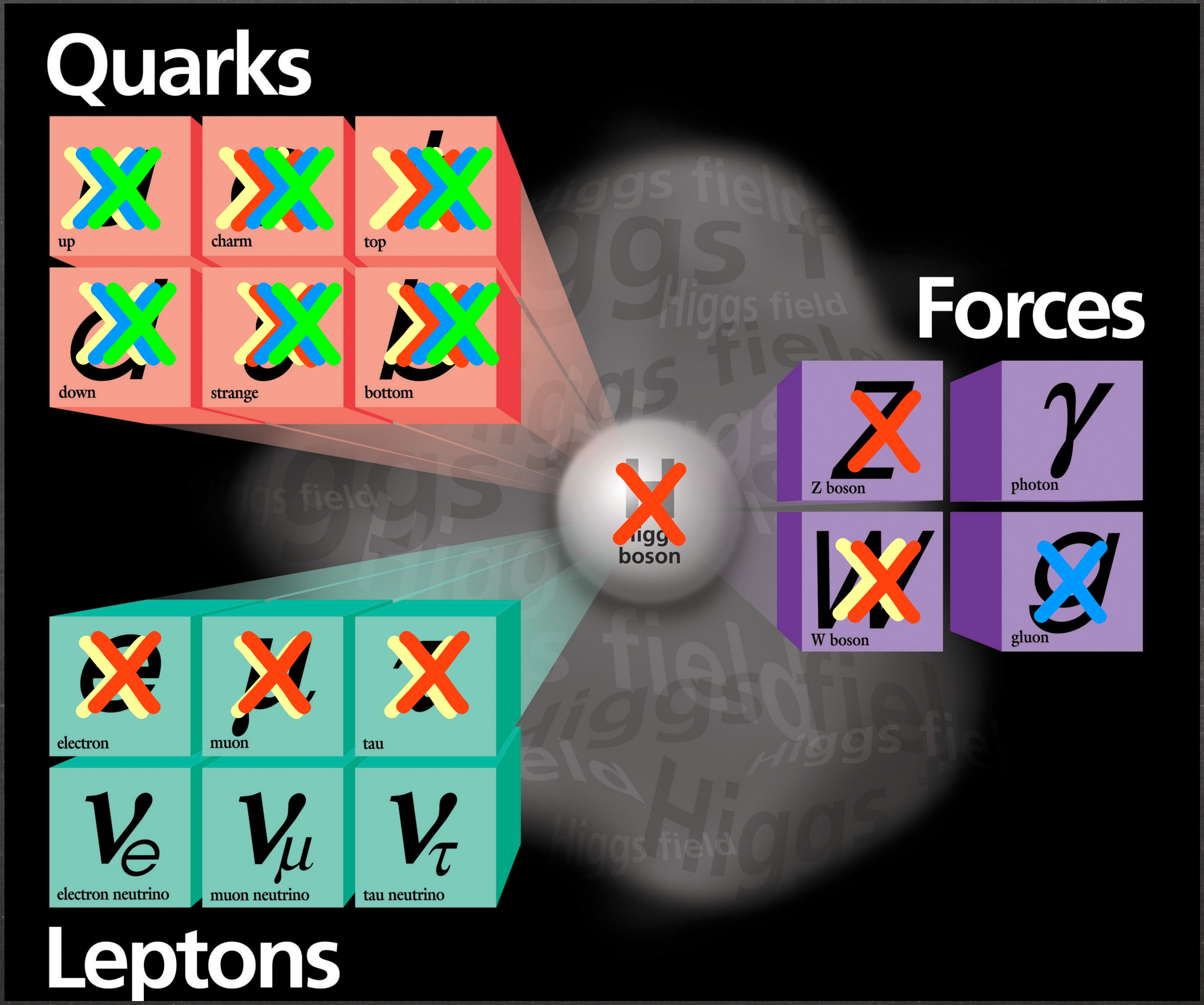

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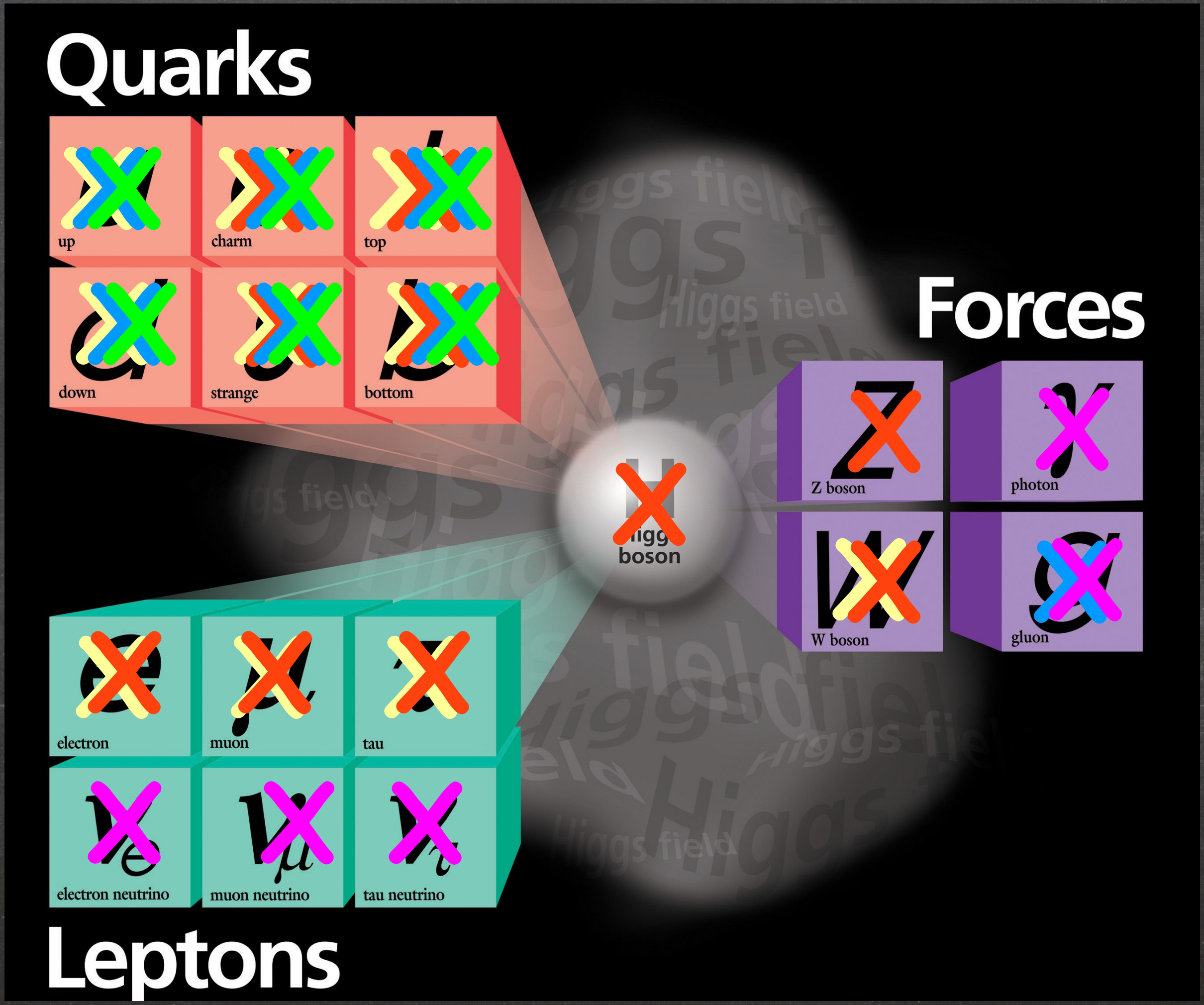
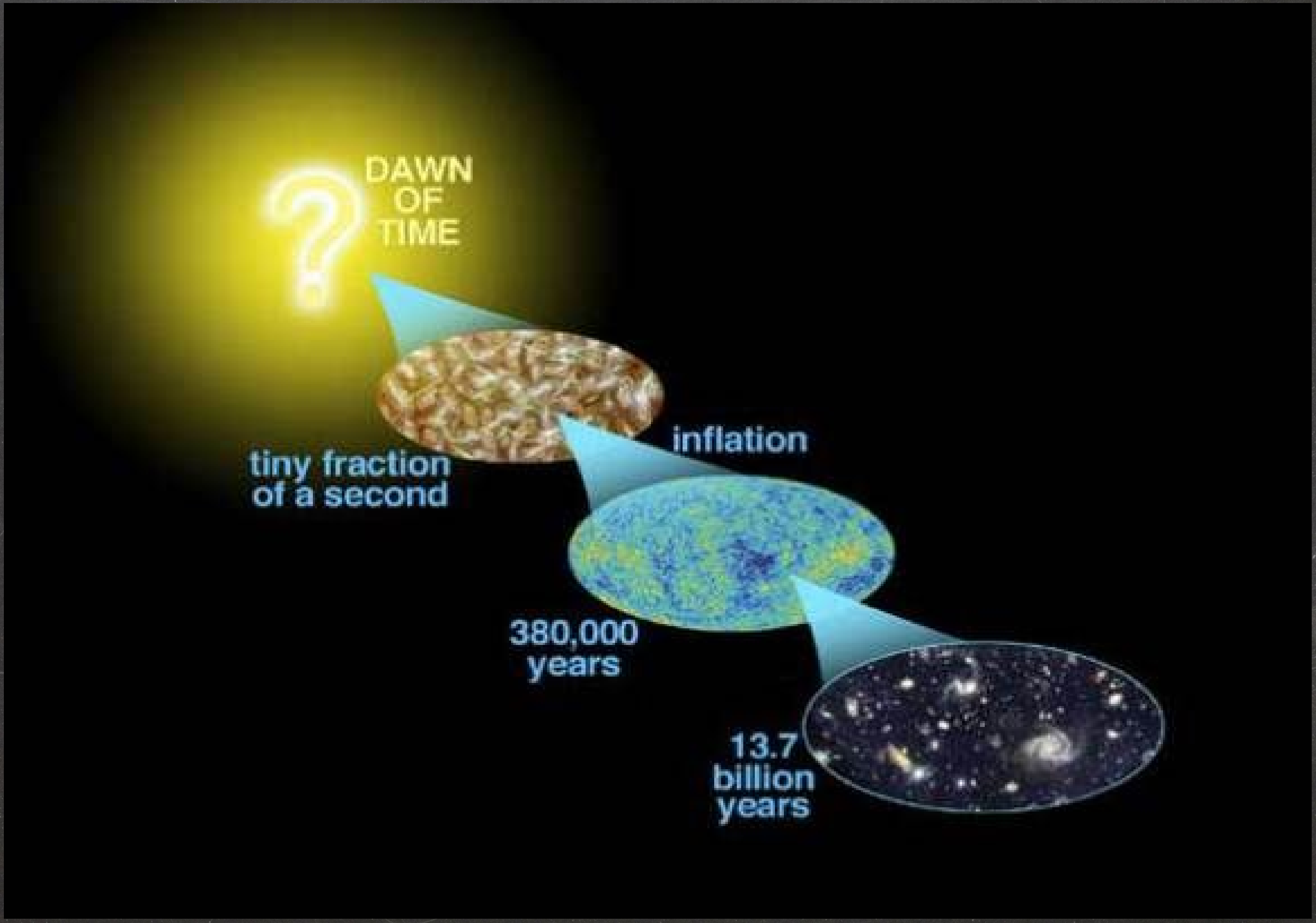


SM is empirically incomplete

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



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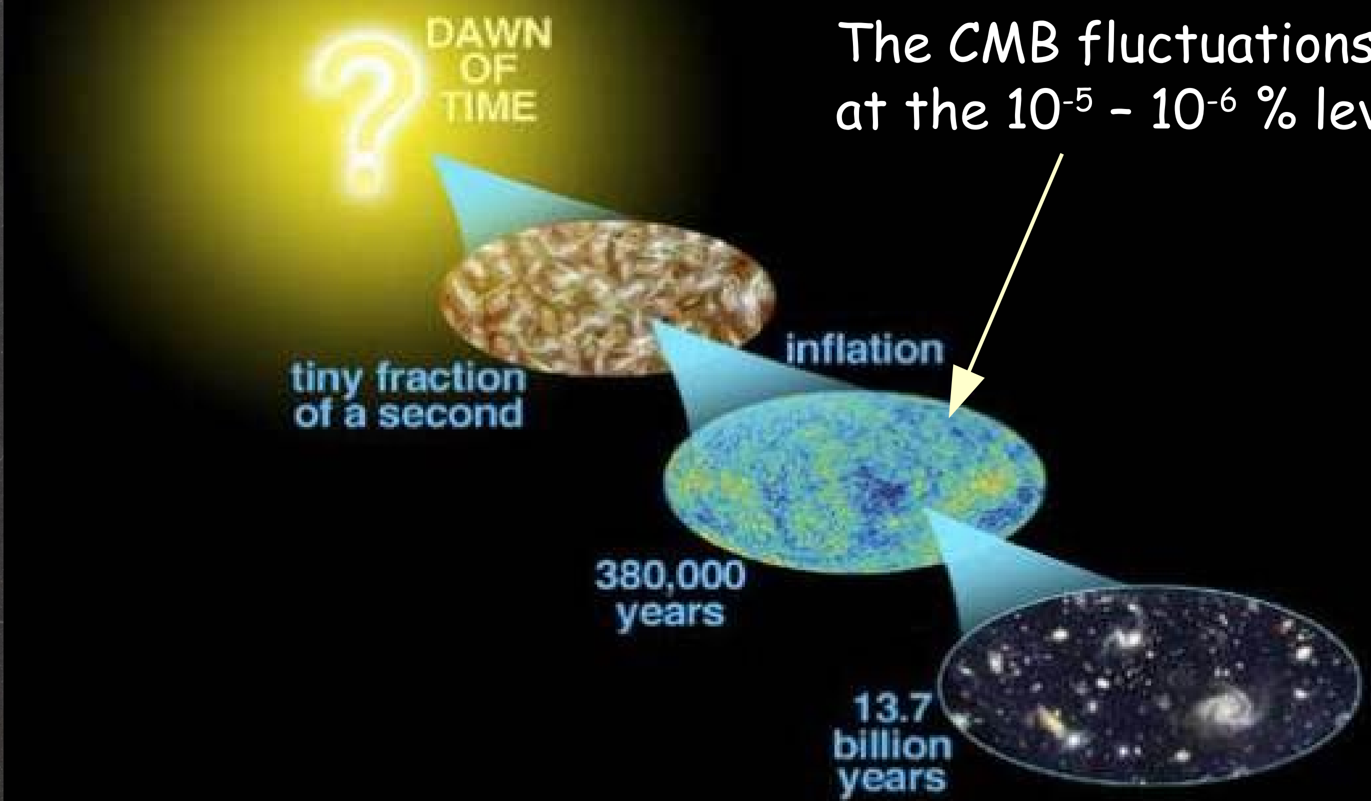
the universe, on large scales, is extremely homogeneous and isotropic

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



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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)

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

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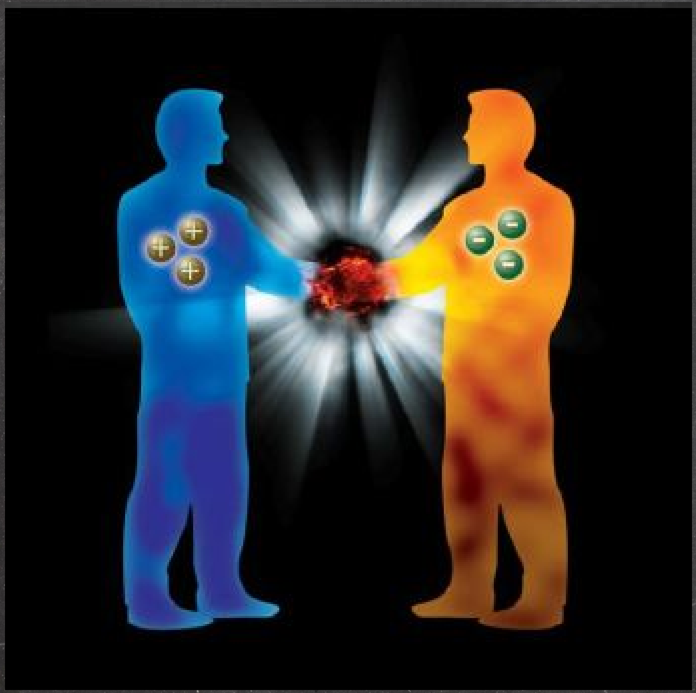

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Empirical problems of the SM stated above have been established beyond reasonable doubt.

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

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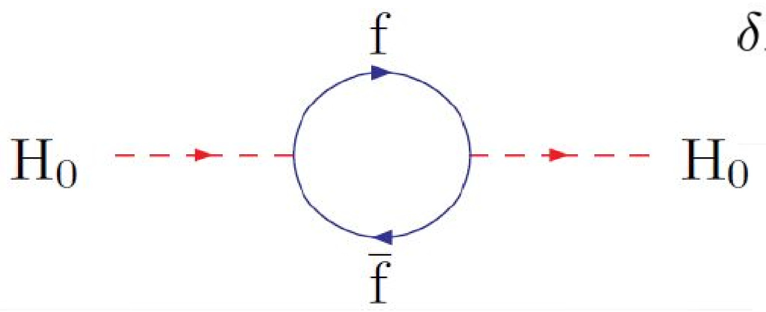
- **the hierarchy between the weak and other presumed scales:** as above, but now the question is **how to get a TeV from the Planck scale.**



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

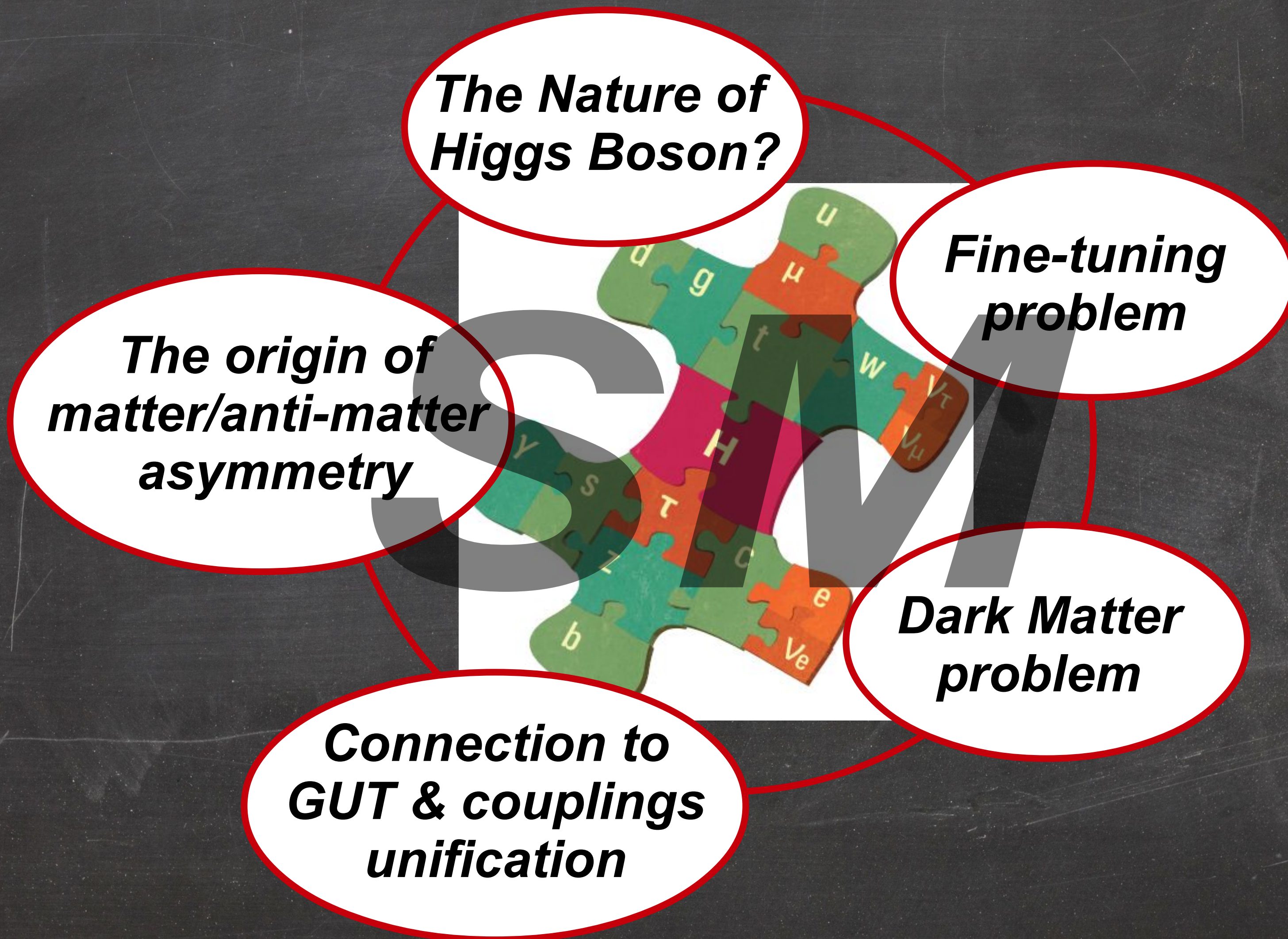
$$= \frac{|g_f|^2}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2\ln\left(\Lambda/m_f\right)\right]$$

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

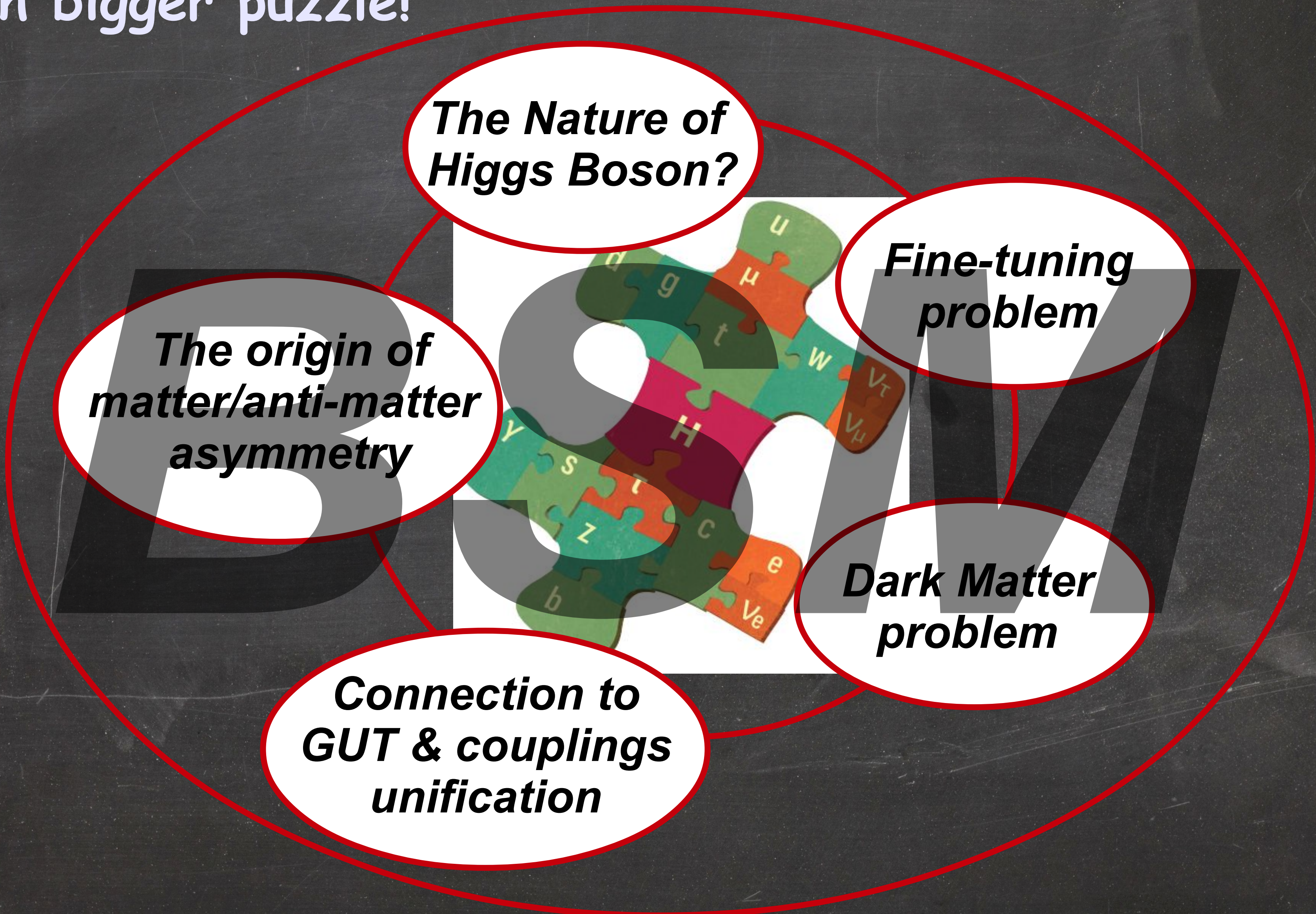
there is a cancellation of over 30 orders of magnitude to have 125 GeV Higgs

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

Higgs Boson Discovery has completed the puzzle of the Standard model ...
But it raised even more questions to be addressed!

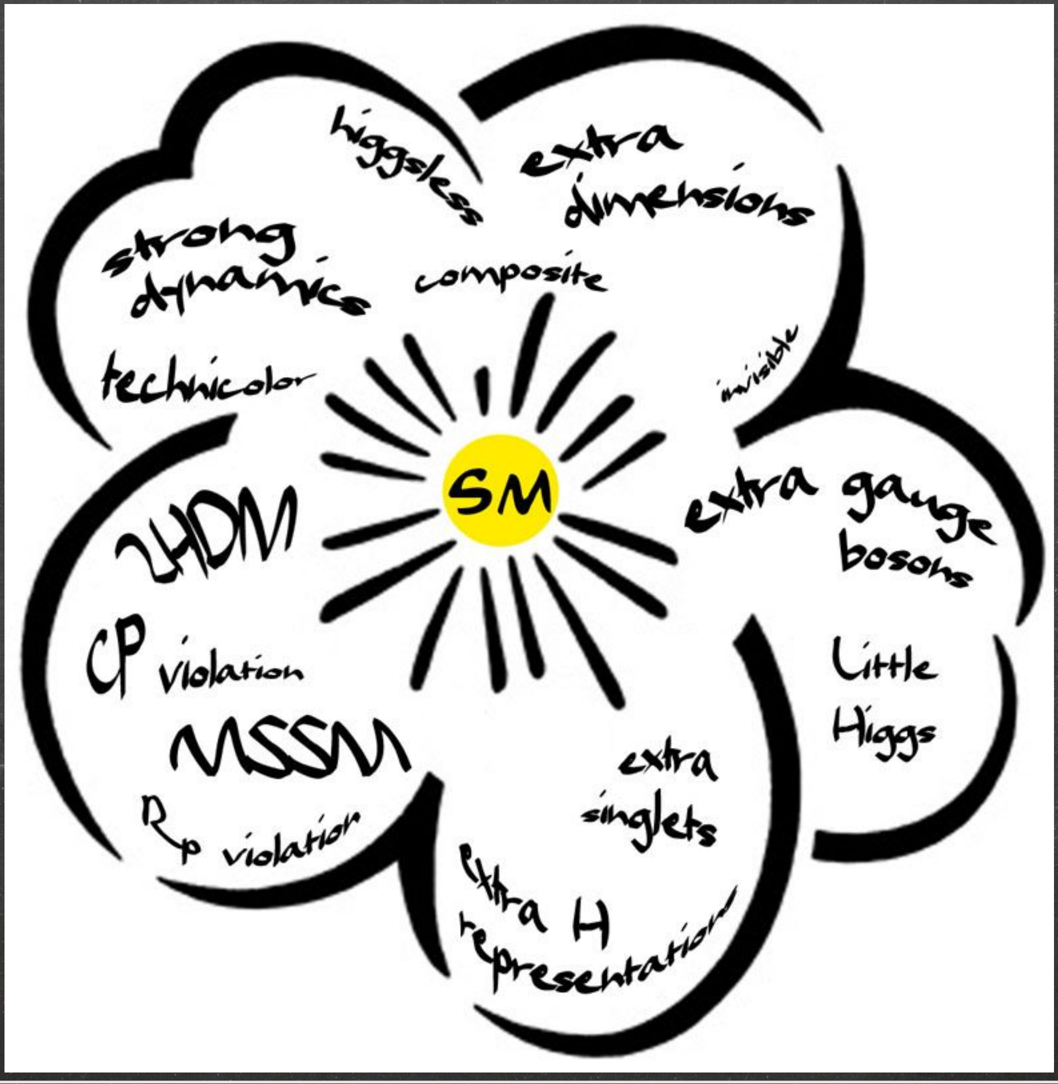


Higgs boson is consistent with main compelling BSM theories, so the pattern we have is just a piece of a much bigger puzzle!



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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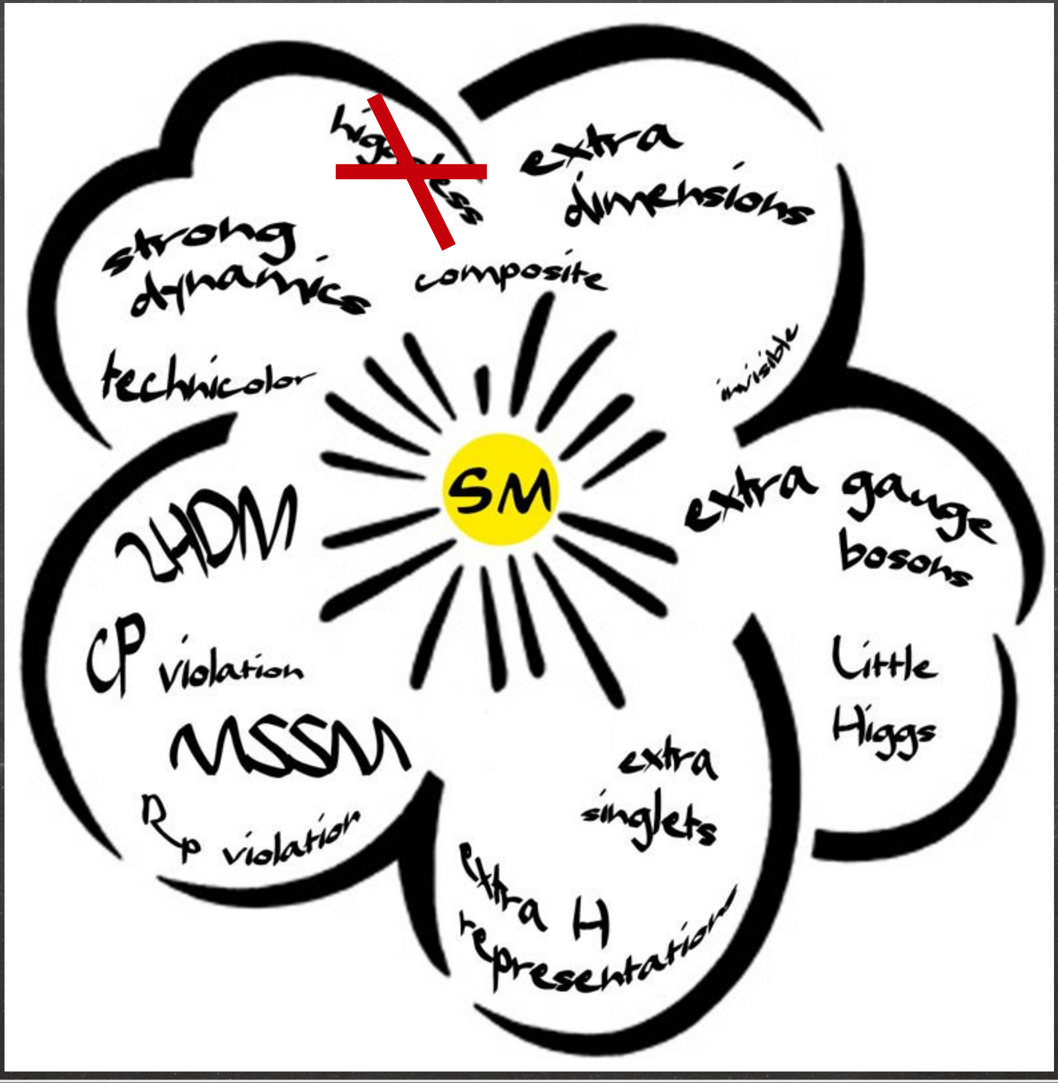

Present Status

What do we know about Dark Matter?

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Spin ?

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Mass ?

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Spin ?

Mass ?

Stable

Yes ? No ?

symmetry behind stability ?

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Thermal relic

Yes ? No ?

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Yes ? No ?

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Couplings

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

Thermal relic

Yes ? No ?

Why SUSY is so compelling?

Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

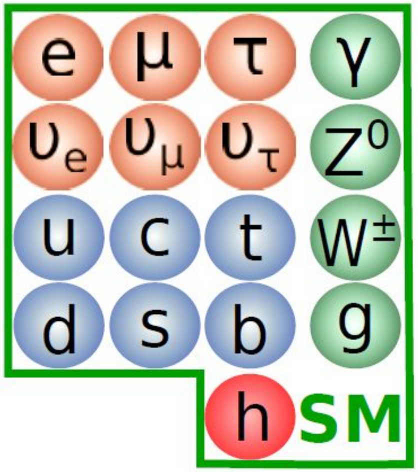
$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

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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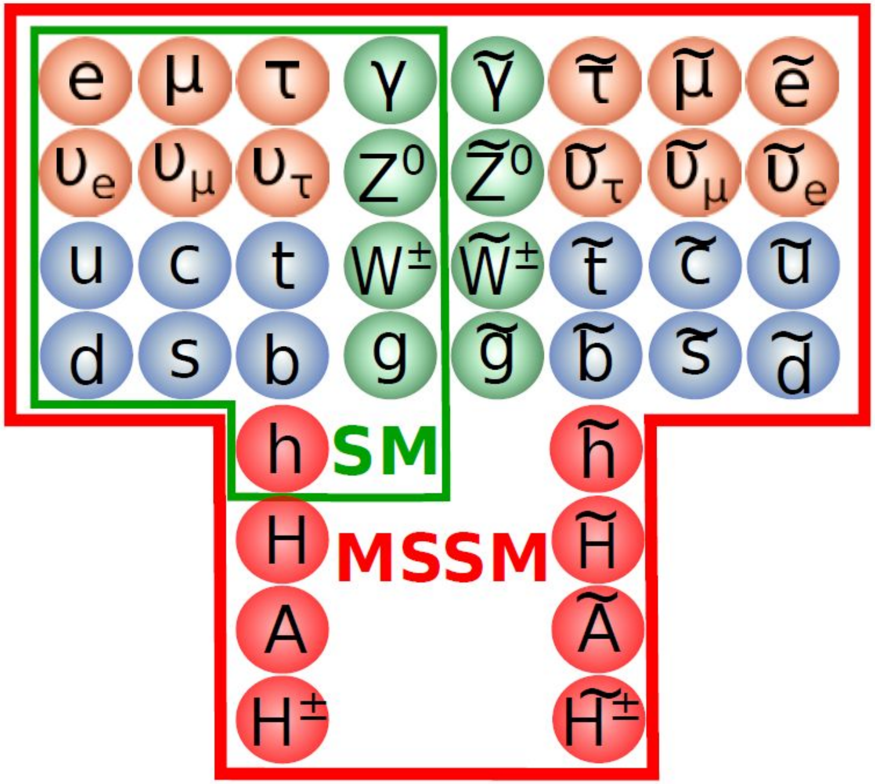

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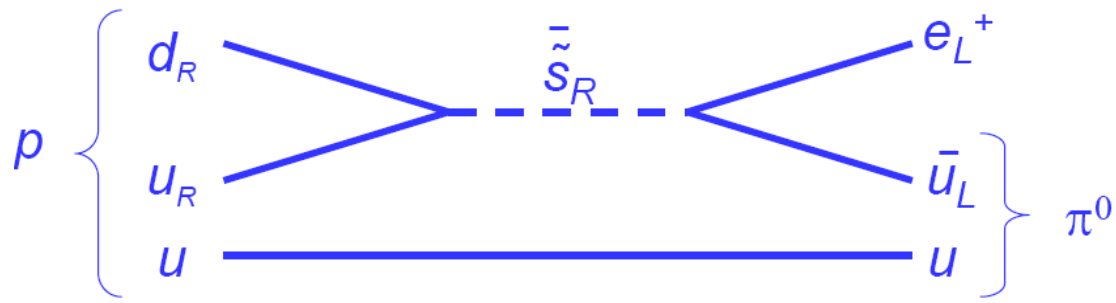
Particle	SUSY partner
e,ν,u,d *spin 1/2*	$\widetilde{e},\widetilde{\nu},\widetilde{u},\widetilde{d}$ *spin 0*
γ,W,Z h,H,A,H± *spin 1 and 0*	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^\pm$ $\tilde{\chi}_1^0\cdots\tilde{\chi}_4^0$ *spin 1/2*



could give rise the proton decay!

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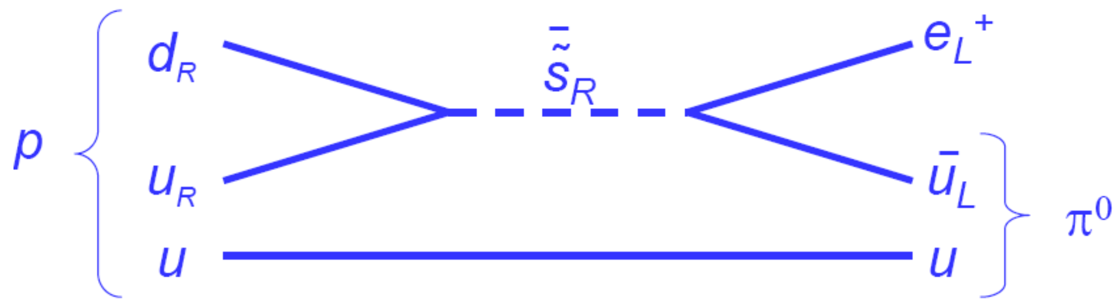
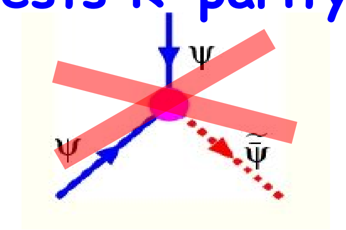


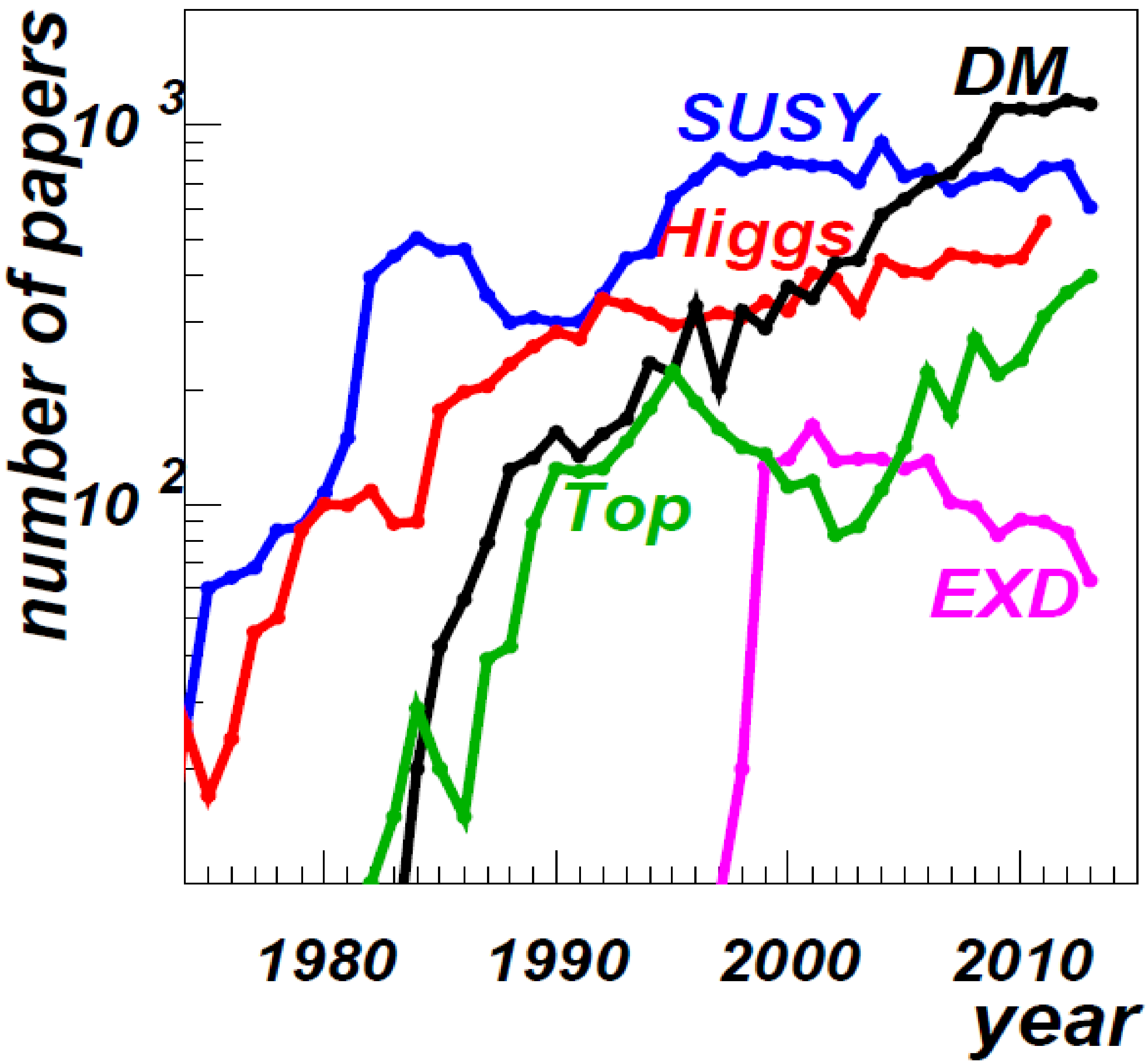
the absence of proton decay suggests R-parity

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



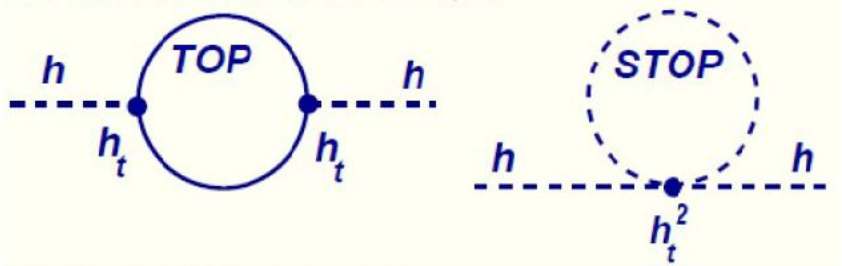
R-parity guarantees Lightest SUSY particle (LSP) is stable – DM candidate!

We are still inspired by this beauty In spite of more than 30 year unsuccessful searches ... Why?!

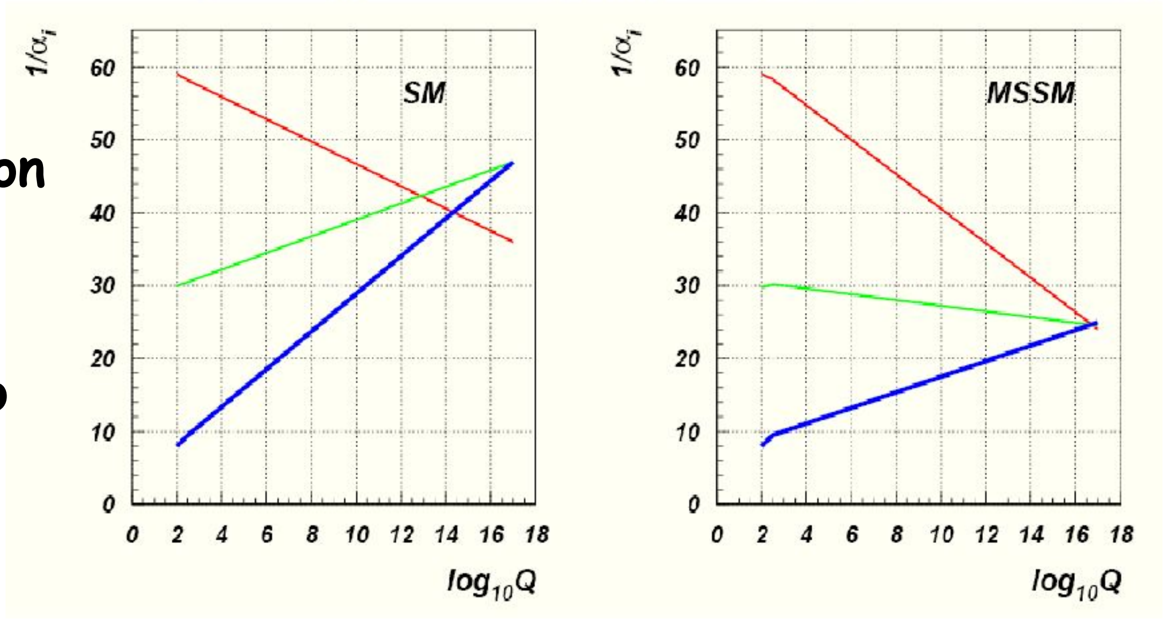


Beauty of SUSY

- 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



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



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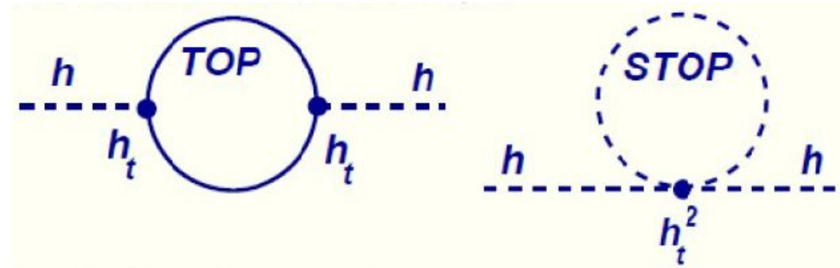

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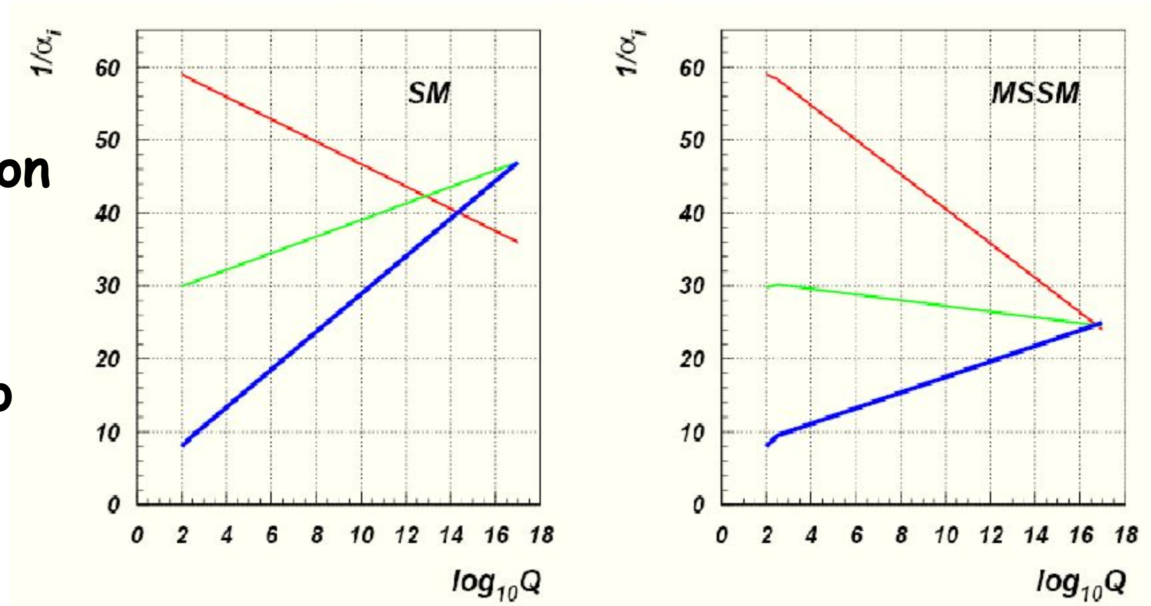
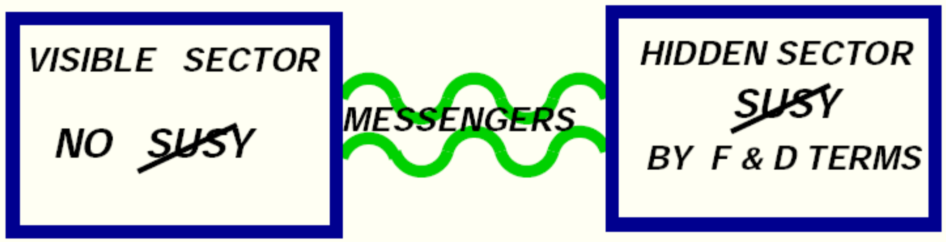


It was not deliberately designed to solve the SM problems!

SUSY breaking and mSUGRA scenario

- SUSY is not observed ⇒ must be broken



Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

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

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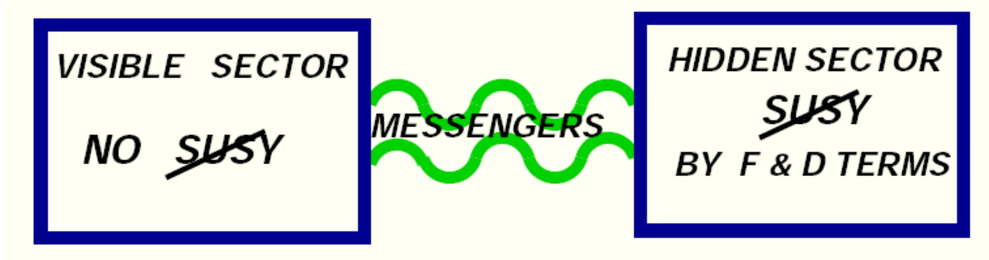

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- SUGRA: the hidden sector communicates with visible one via gravity
  – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

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

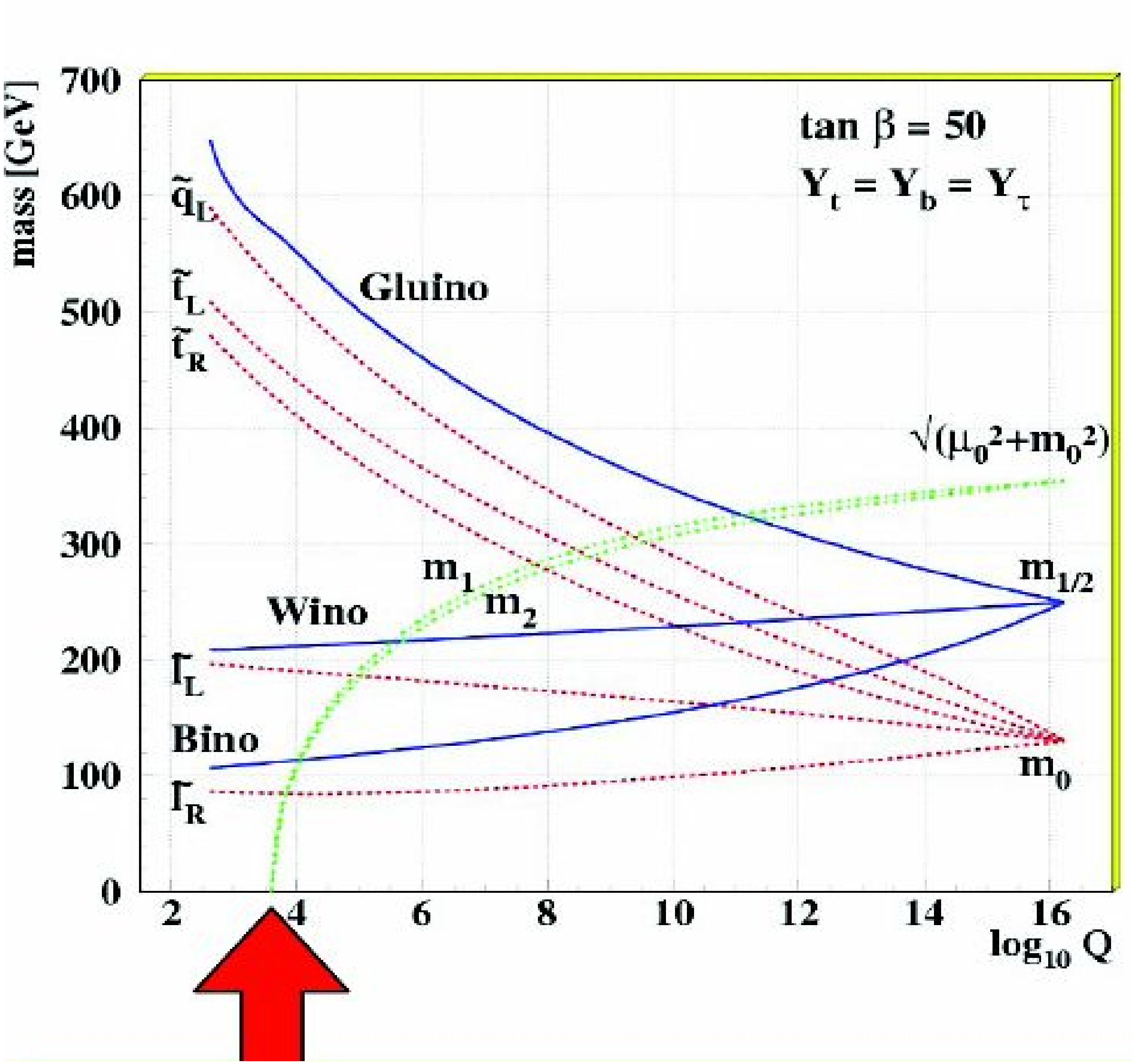
flat Kähler metric takes care of constraining of Flavor violating processes

- $sign(\mu)$, 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

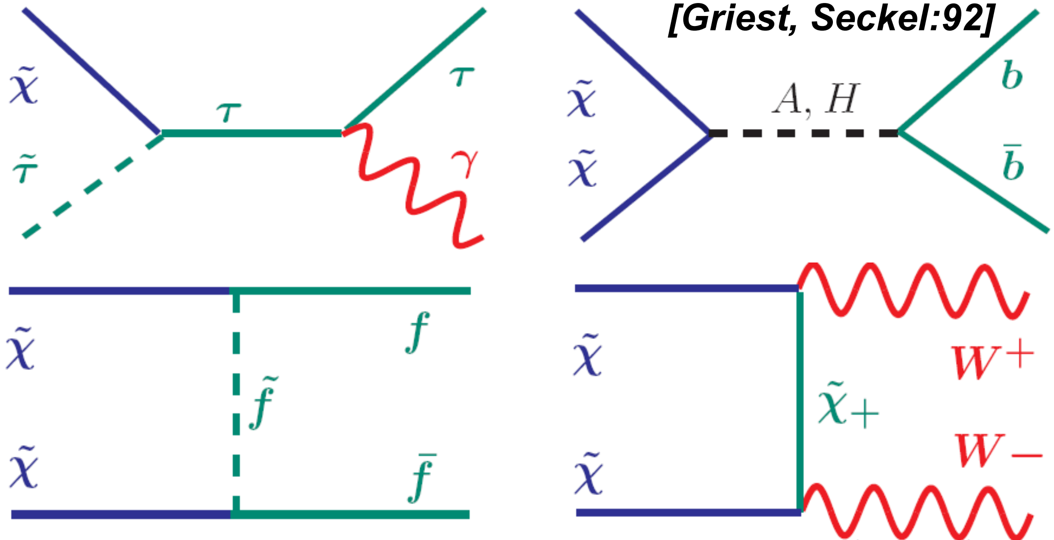
tan(beta) = v1/v2

ISASUGRA, SPHENO,SUSPECT,SOFTSUSY

Evolution of neutralino relic density

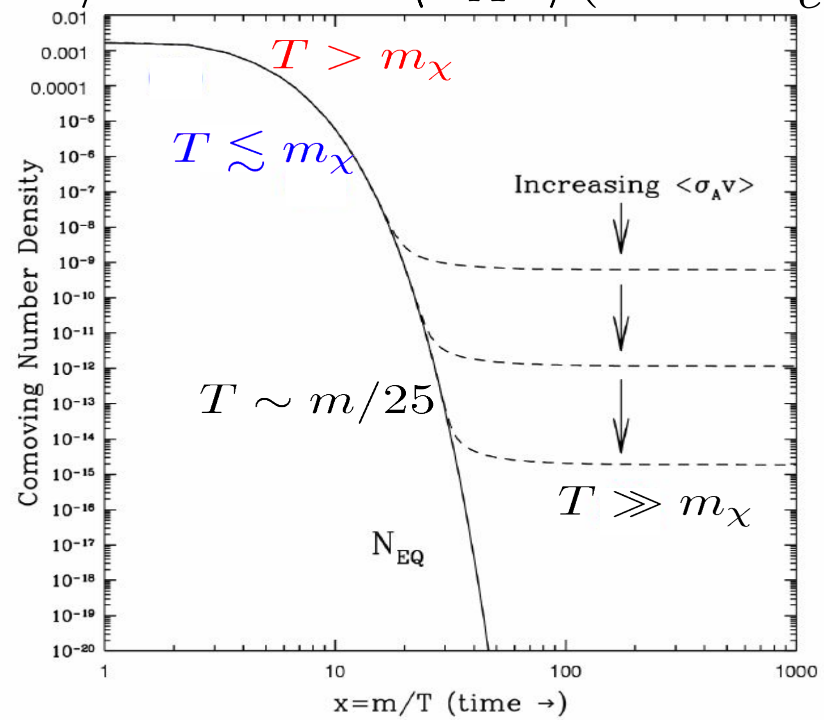
- Challenge is to evaluate thousands annihilation/co-annihilation diagrams

[Griest, Seckel:92]



time evolution of number density is given by Boltzmann equation

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



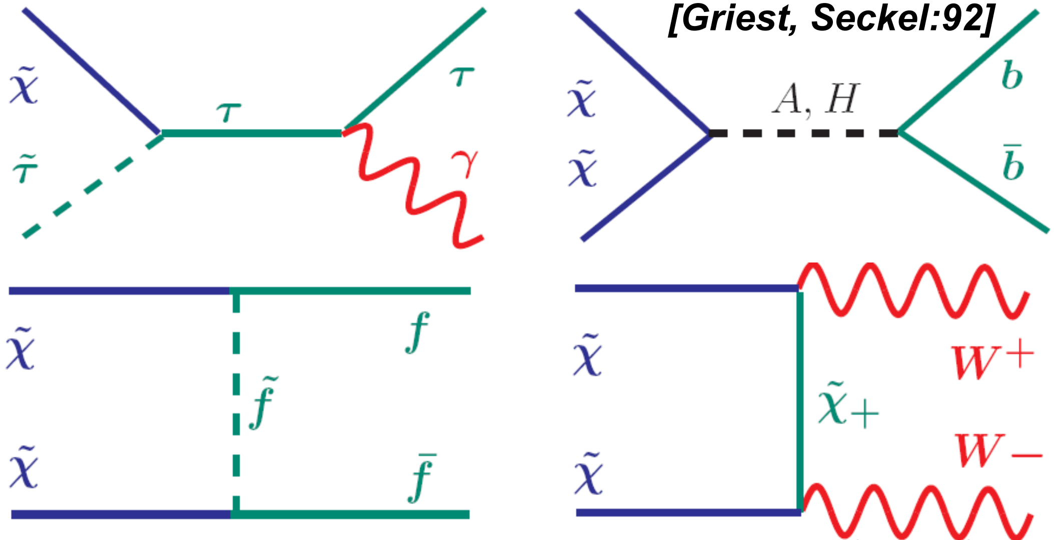
- relic density depends crucially on $\langle\sigma_A v\rangle$
- thermal equilibrium stage: $T > m_\chi, \quad \chi\chi \leftrightarrow f\bar{f}$
- universe cools: $T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$

  $n = n_{eq} \sim e^{-m/T}$
- neutralinos "freeze-out" at $T_F \sim m/25$

Evolution of neutralino relic density

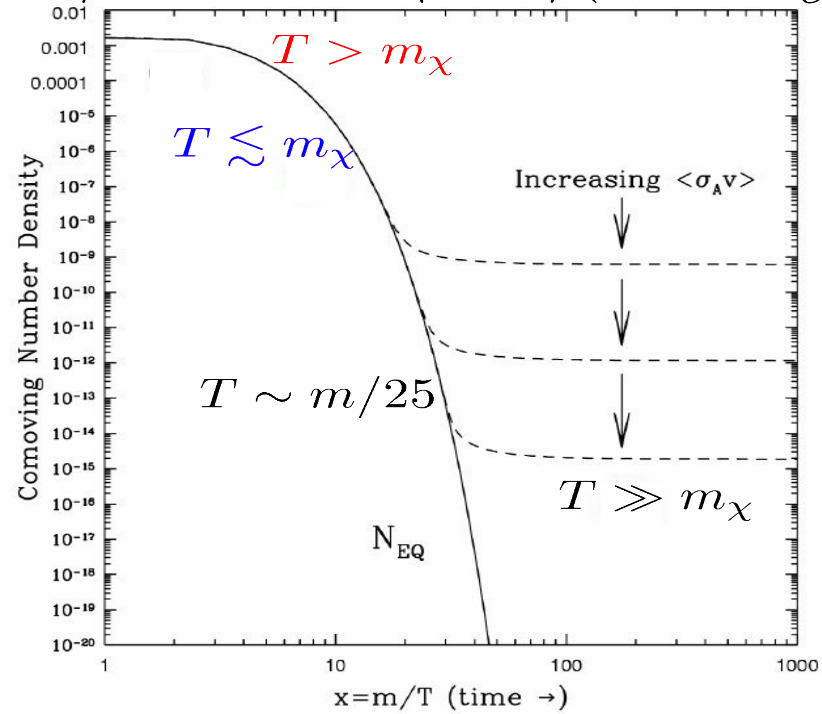
- Challenge is to evaluate thousands annihilation/co-annihilation diagrams

[Griest, Seckel:92]



time evolution of number density is given by Boltzmann equation

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



- relic density depends crucially on $\langle\sigma_A v\rangle$
- thermal equilibrium stage: $T > m_\chi,\quad \chi\chi \leftrightarrow f\bar{f}$
- universe cools: $T \lesssim m_\chi,\quad \chi\chi \not\leftrightarrow f\bar{f}$

  $n = n_{eq} \sim e^{-m/T}$
- neutralinos "freeze-out" at $T_F \sim m/25$

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

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

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

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

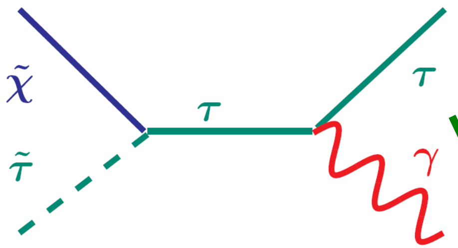
mass of the mediator

Tools:
MicrOMEGAs, DarkSusy, ISARED, MadDM

Neutralino relic density in mSUGRA

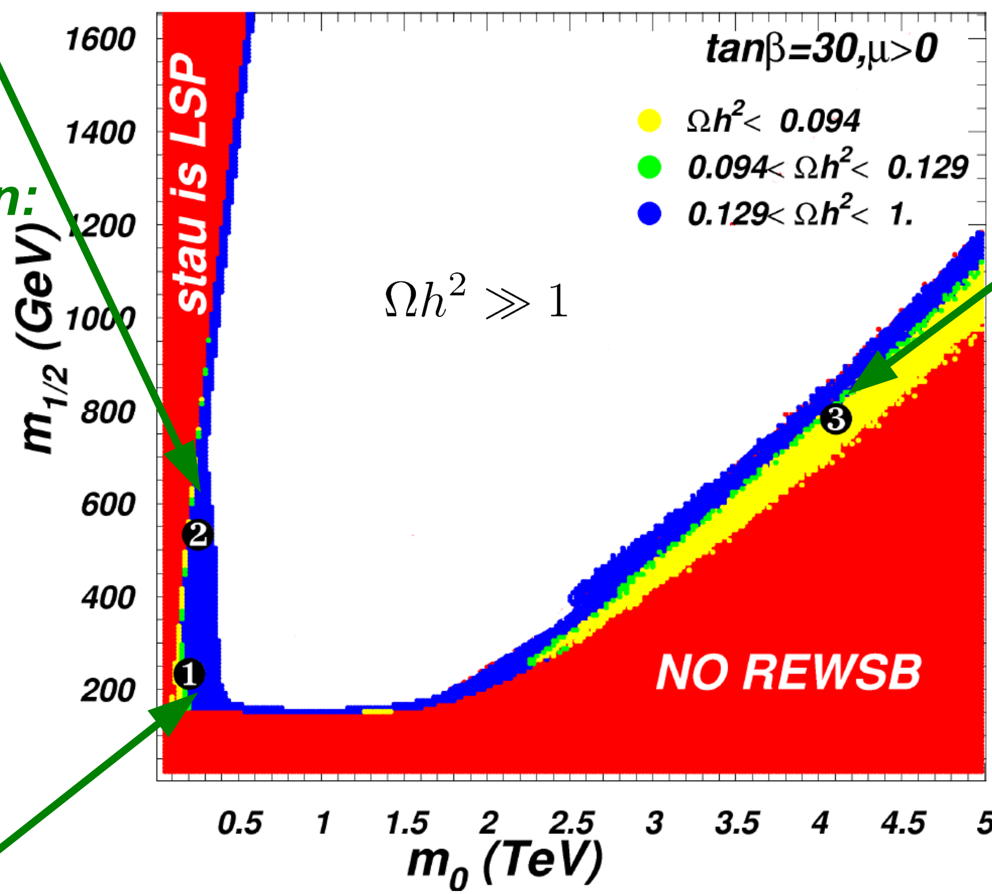
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

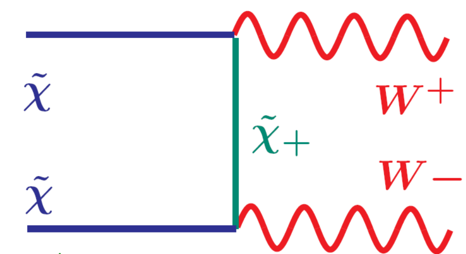
special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$



2. stau coannihilation:
degenerate χ and stau

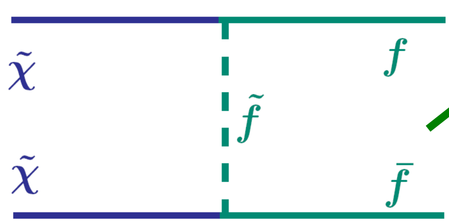
Baer, A.B., Balazs '02





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***

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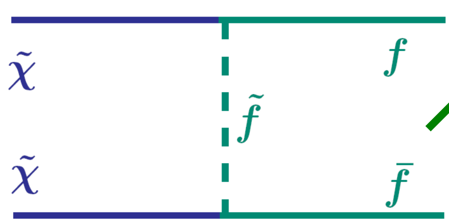

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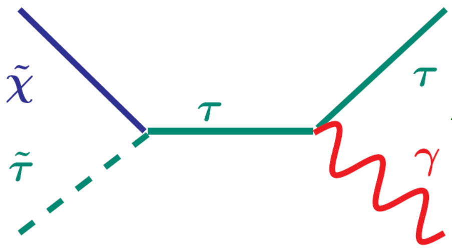
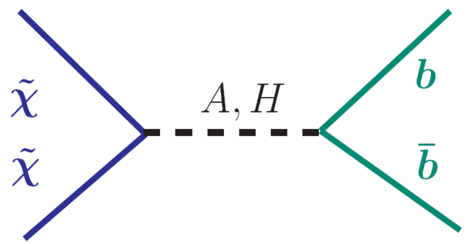
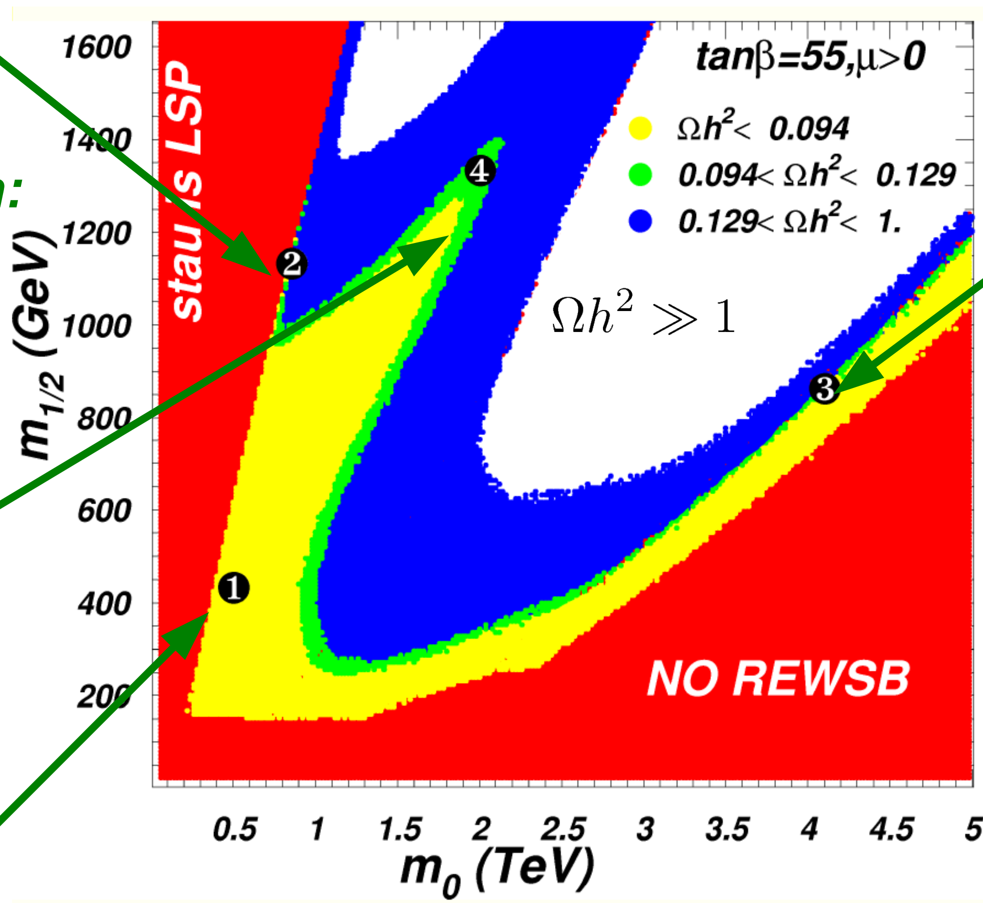


4. funnel: **(large tanβ)**
annihilation via A, H



Baer, A.B., Balazs '02



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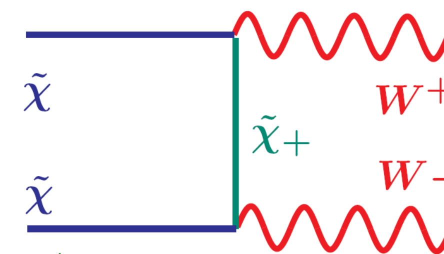

3. focus point:
mixed neutralino,
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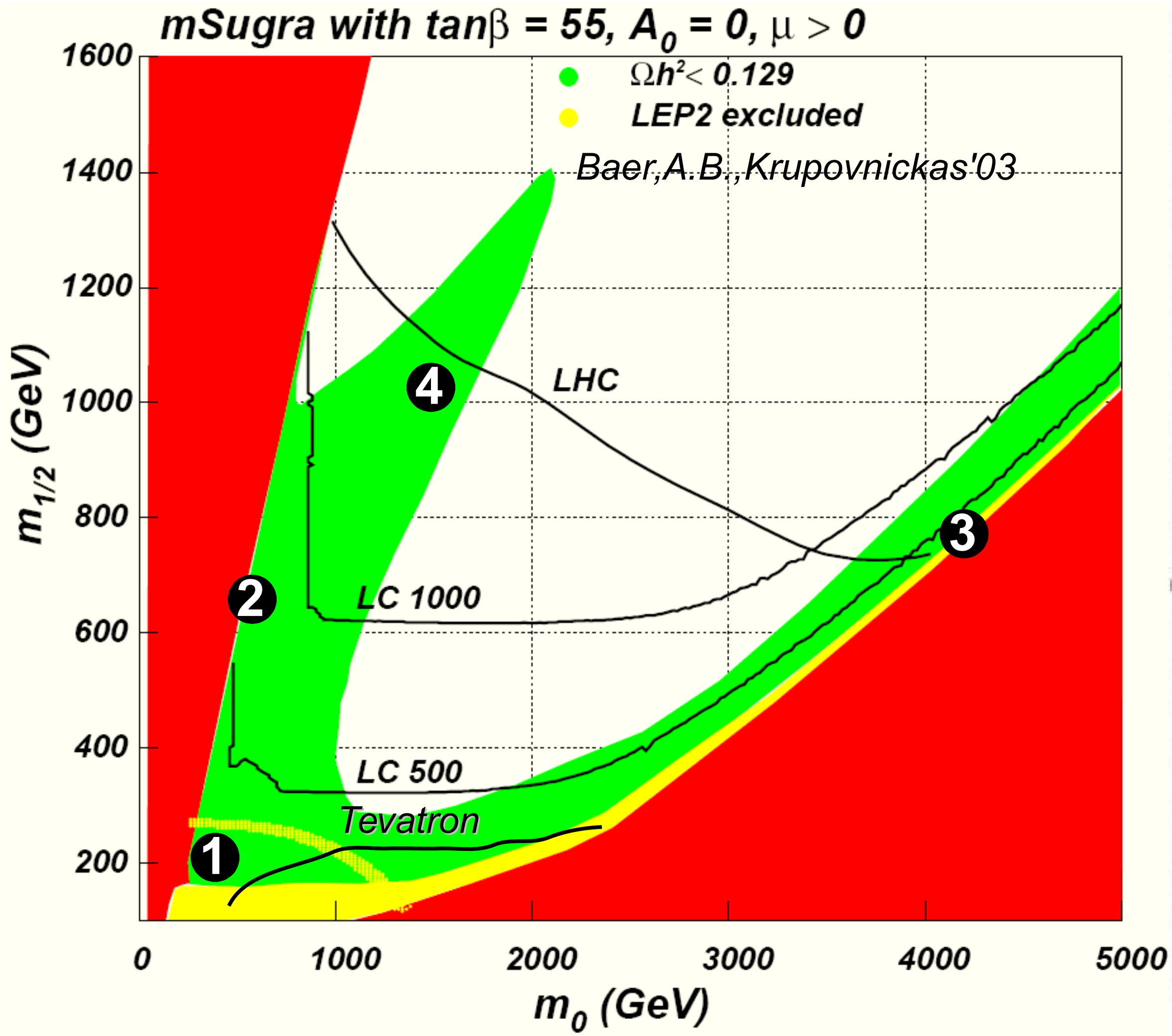
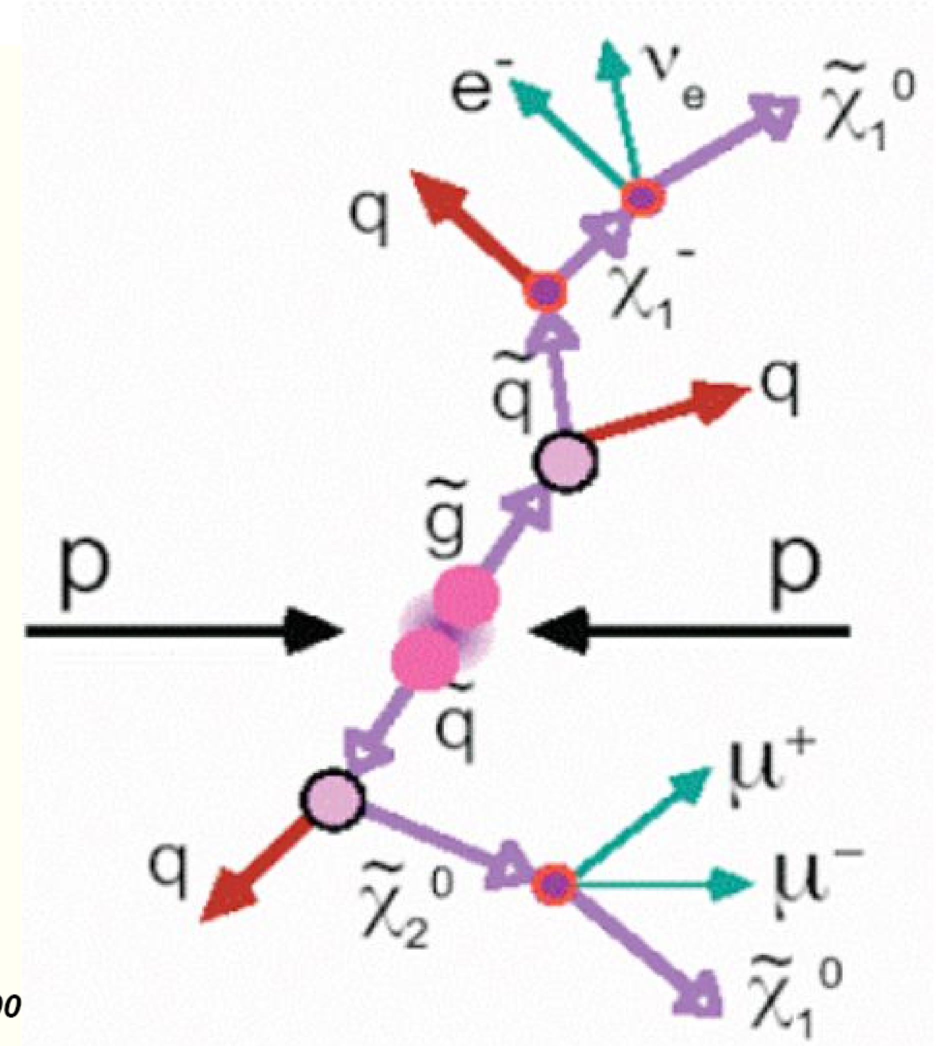
$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$

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***





Collider signatures in DM allowed regions

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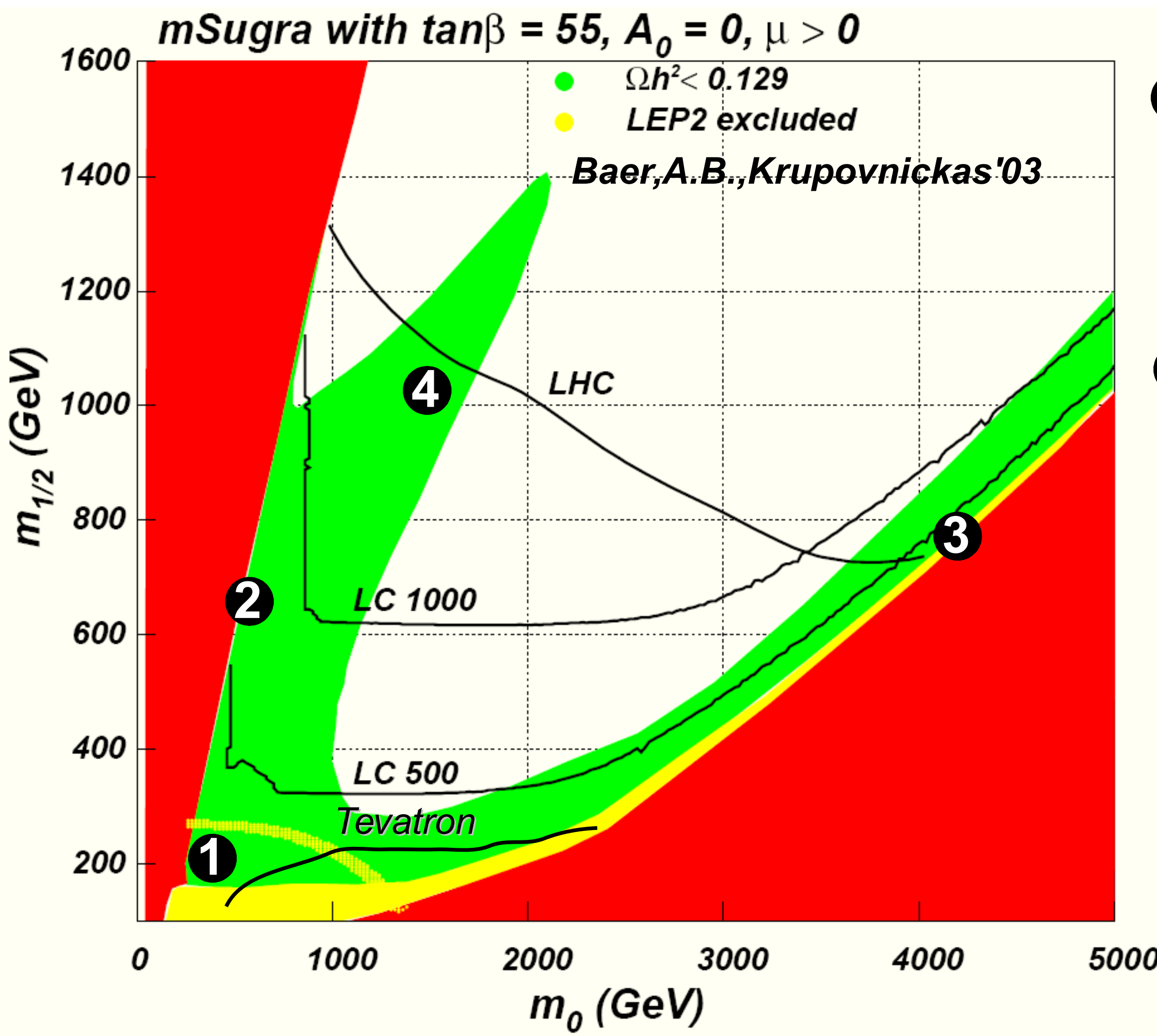
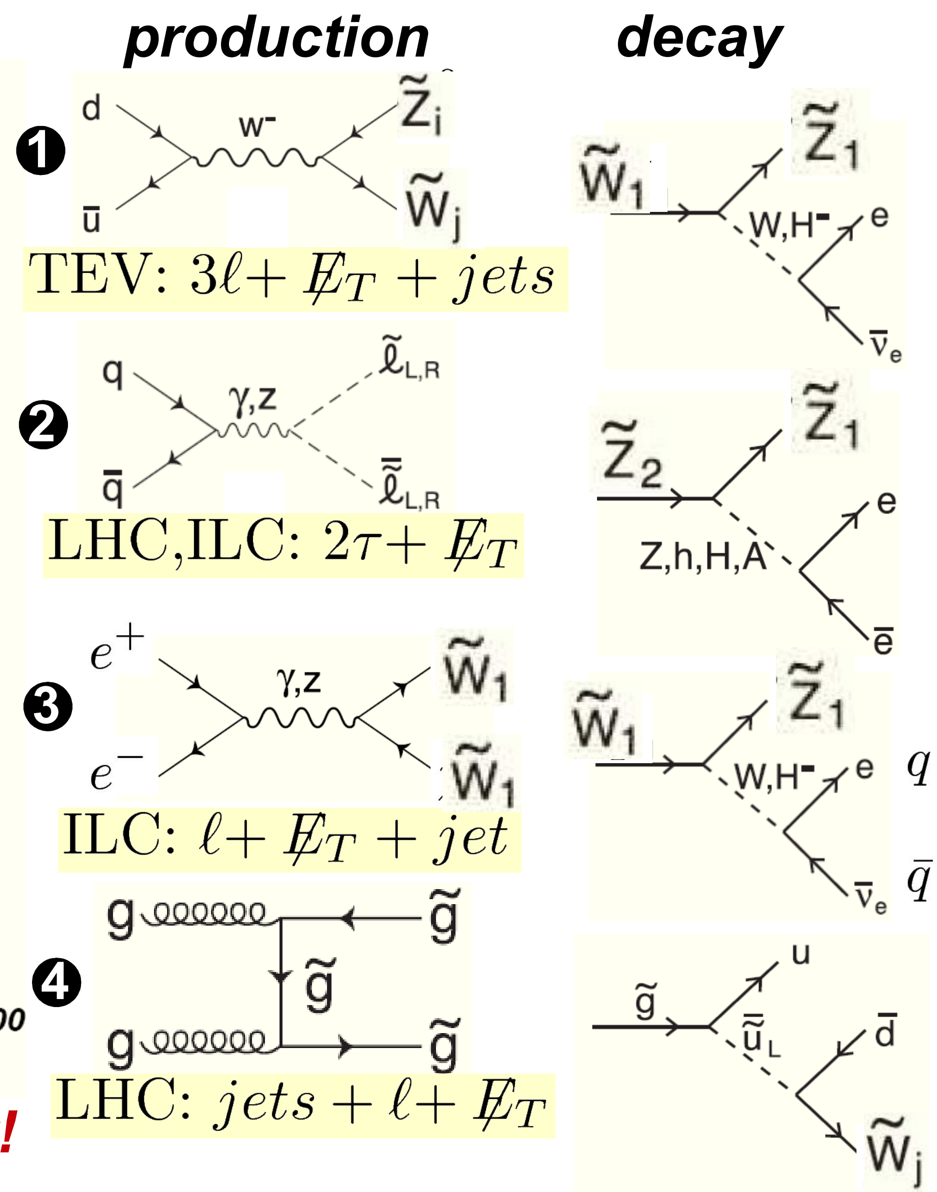


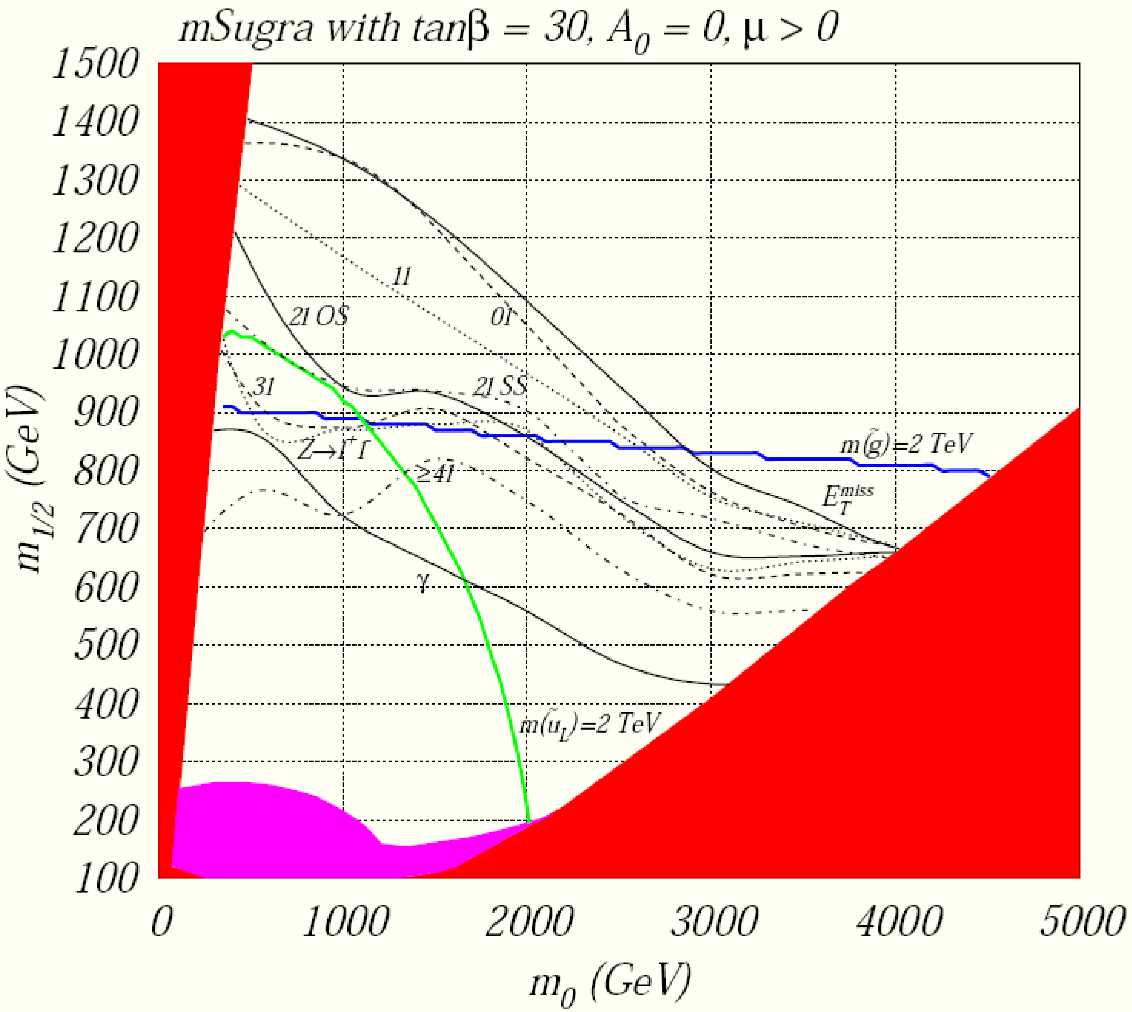


LHC and ILC are highly complementary!

Collider signatures in DM allowed regions

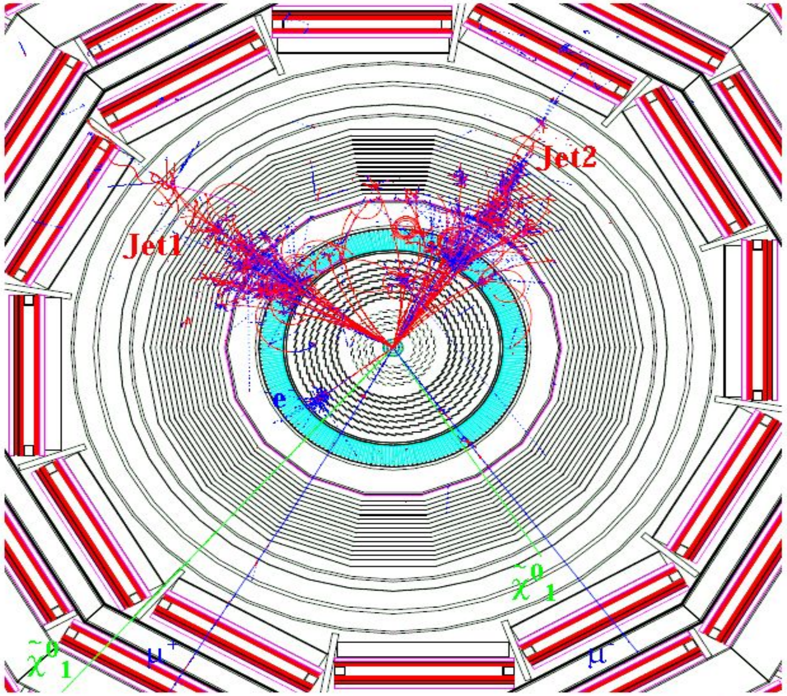
$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV   BG: $W + jets$, $Z + jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$

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



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.

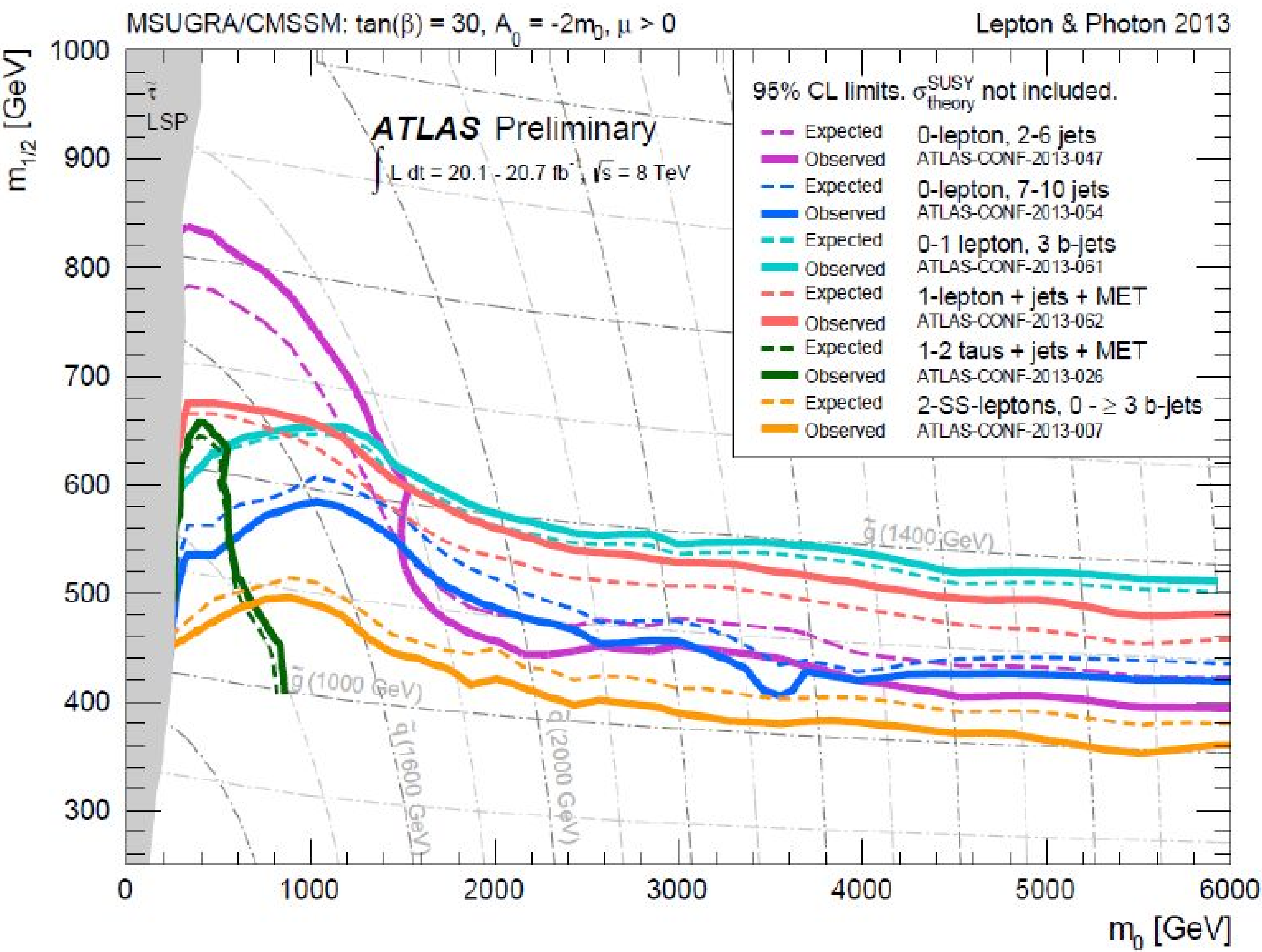


Leptons:	Jets:	Sparticles:
$p_t(\mu^+)$ = 55.2 GeV	E_t(Jet1) = 237 GeV	$p_t(\tilde{\chi}^0_1)$ = 95.1 GeV
$p_t(\mu^-)$ = 44.3 GeV	E_t(Jet2) = 339 GeV	$p_t(\tilde{\chi}^0_1)$ = 190 GeV
$p_t(e^-)$ = 43.9 GeV		

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

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

Limits from LHC8 for mSUGRA scenario



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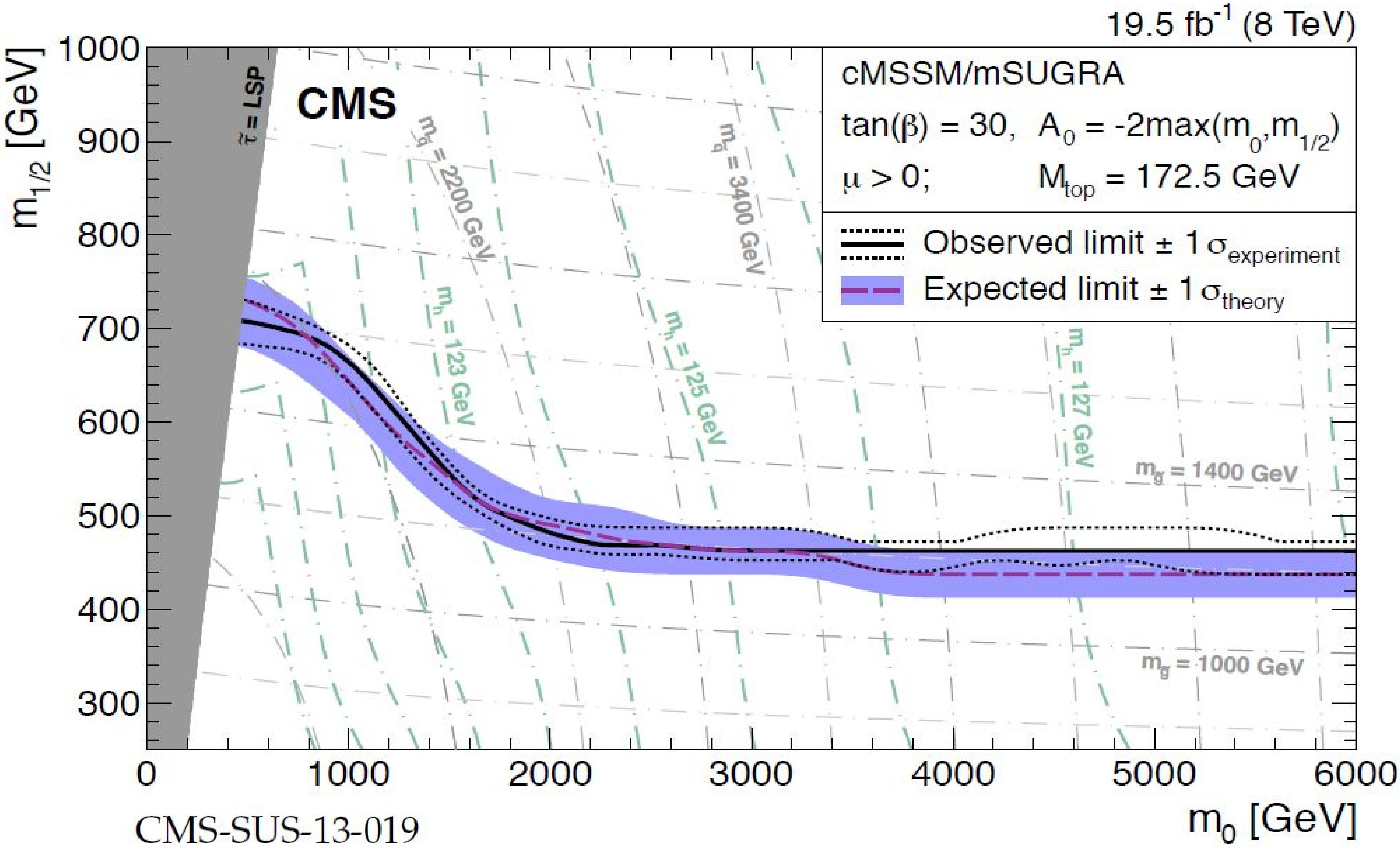
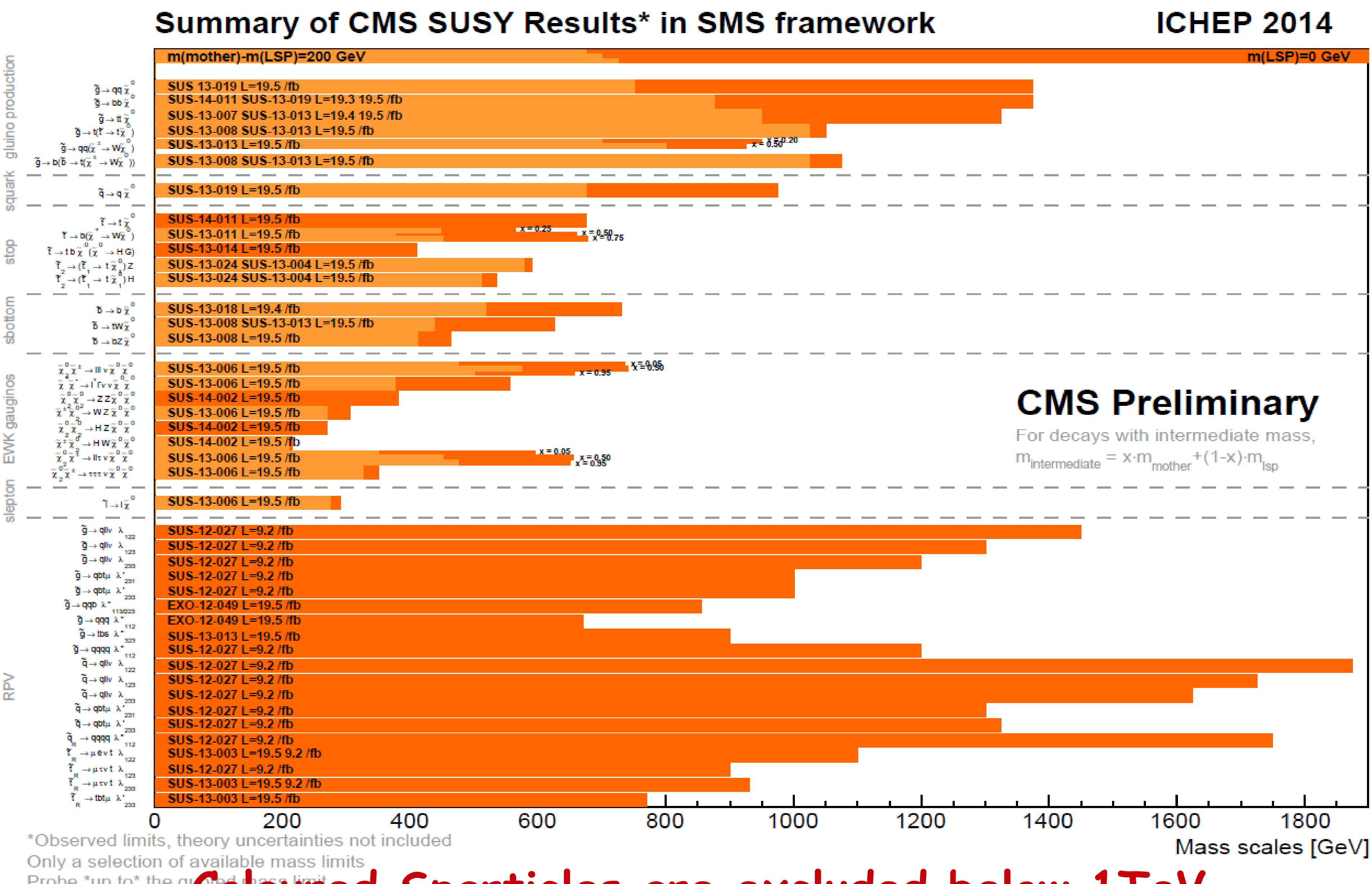
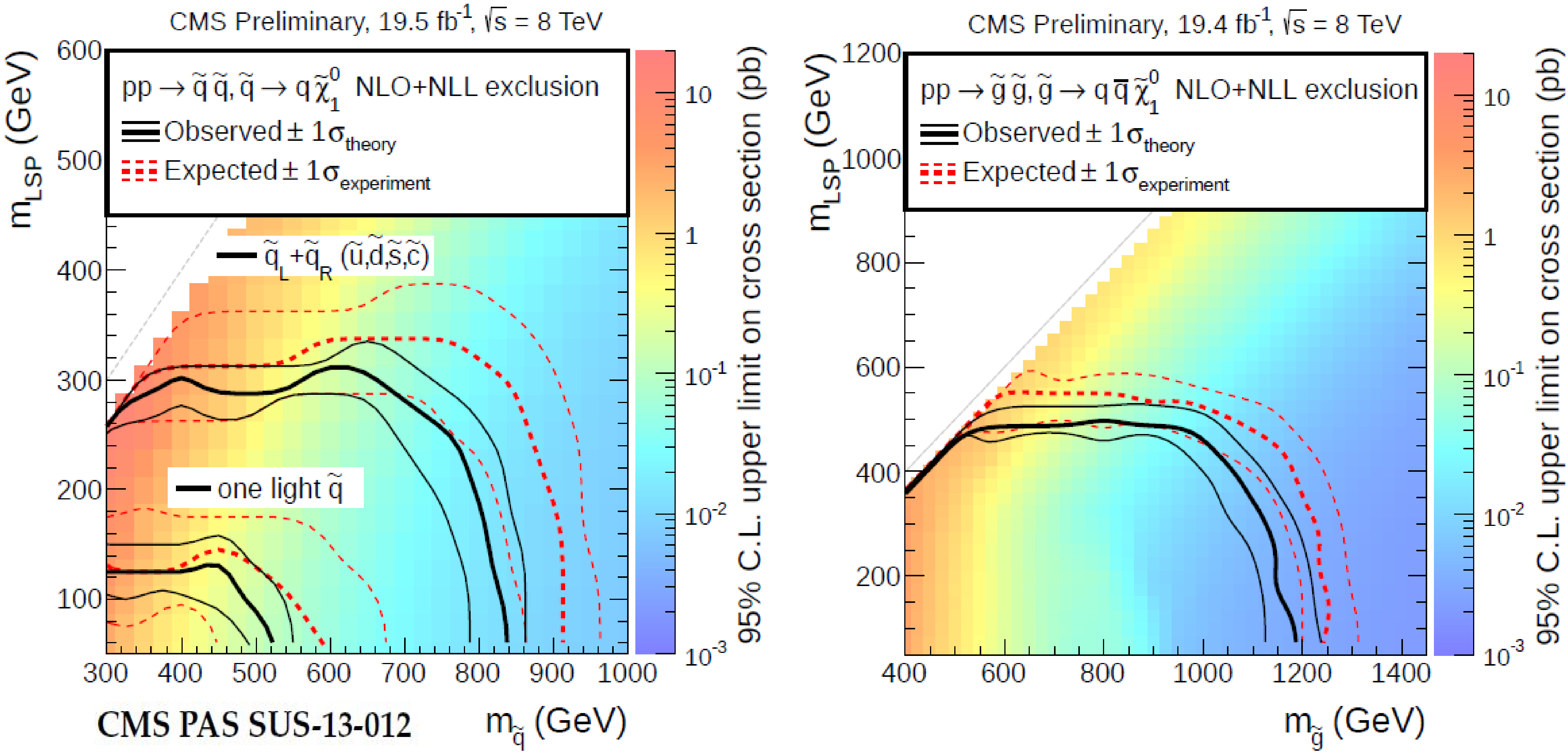


No SUSY hint from the experimental searches ...



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

What is about DM mass?



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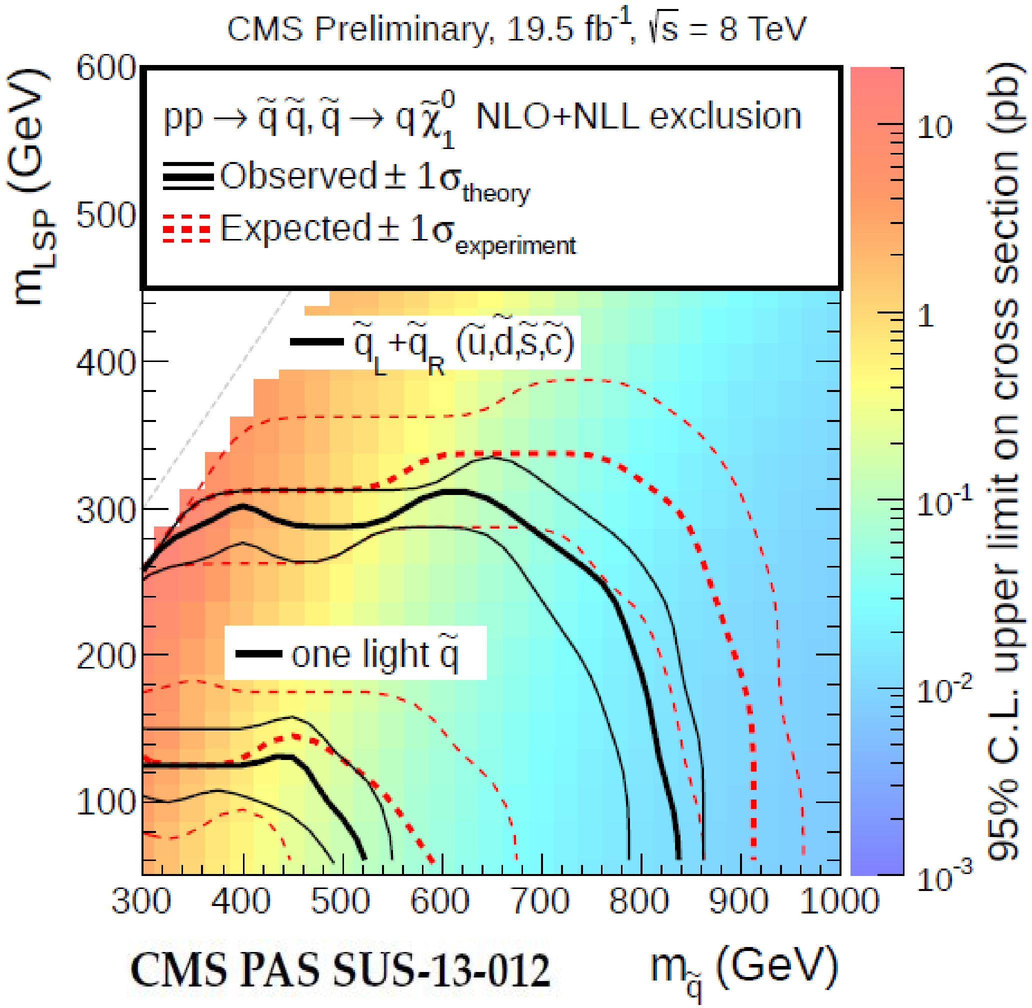
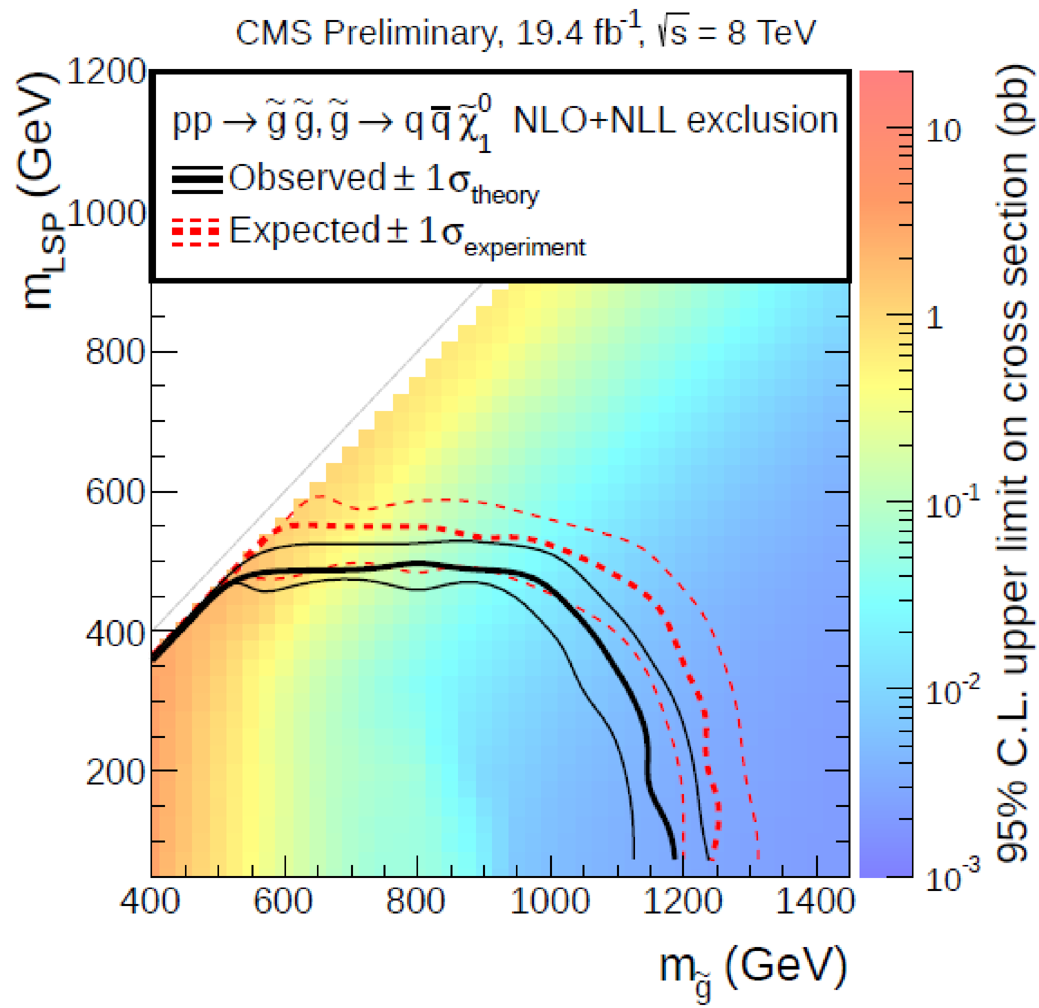


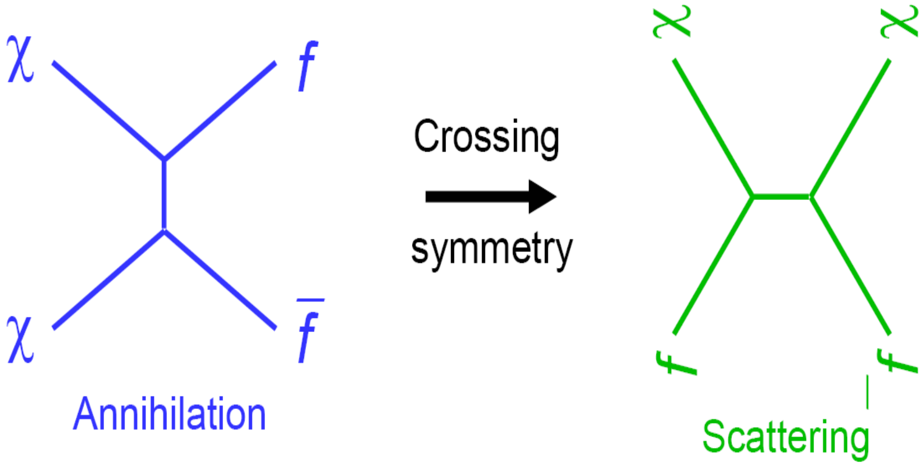


There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1 TeV

Complementarity of DM searches (from 2004)

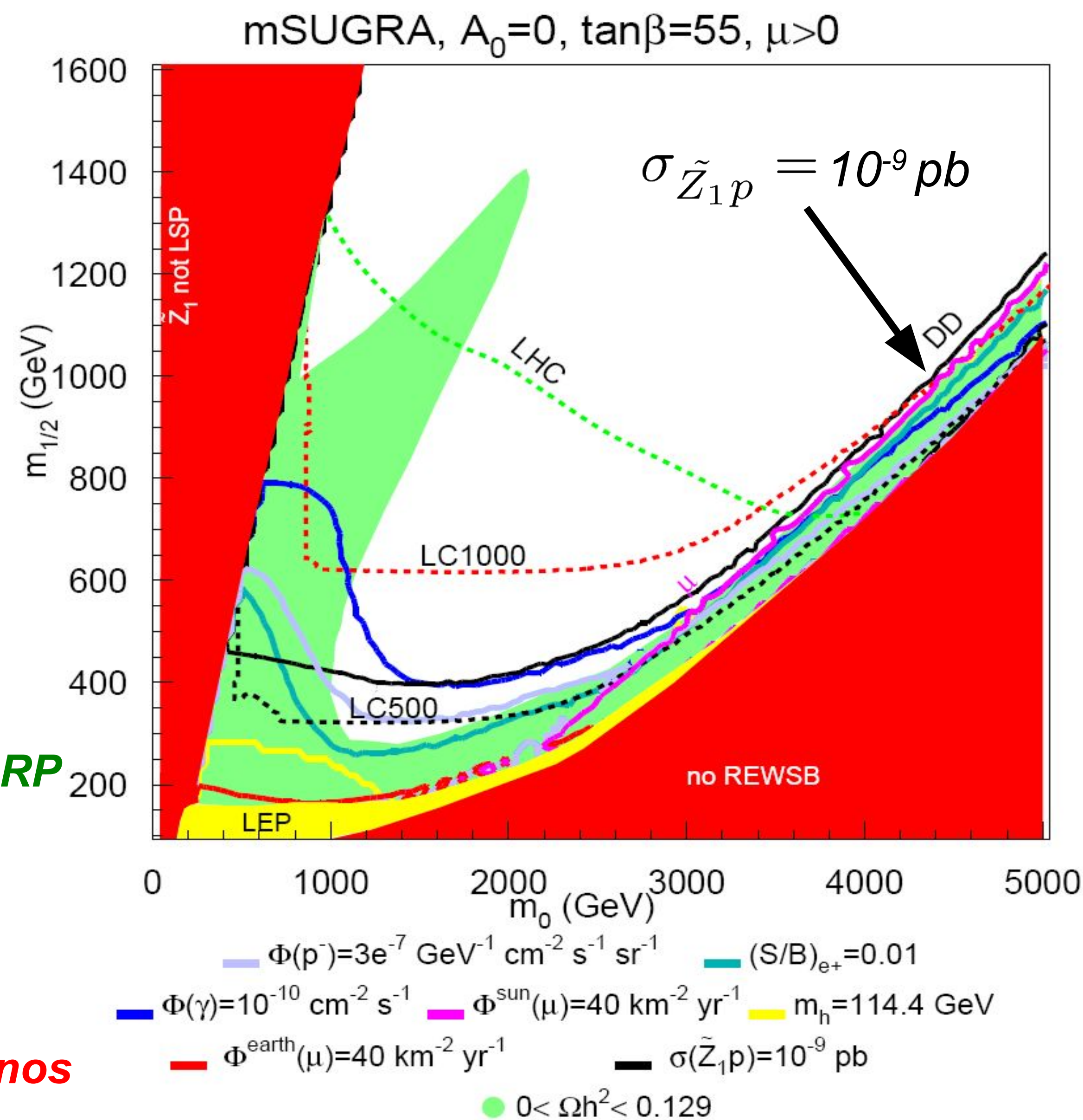
DM direct detection:

neutralino scattering off nuclei



Stage 1: CDMS1, Edelweiss, Zeplin1
Stage 2: CDMS2, CRESST2, Zeplin2
Stage 3: SuperCDMS, Zeplin 1 ton, WARP

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



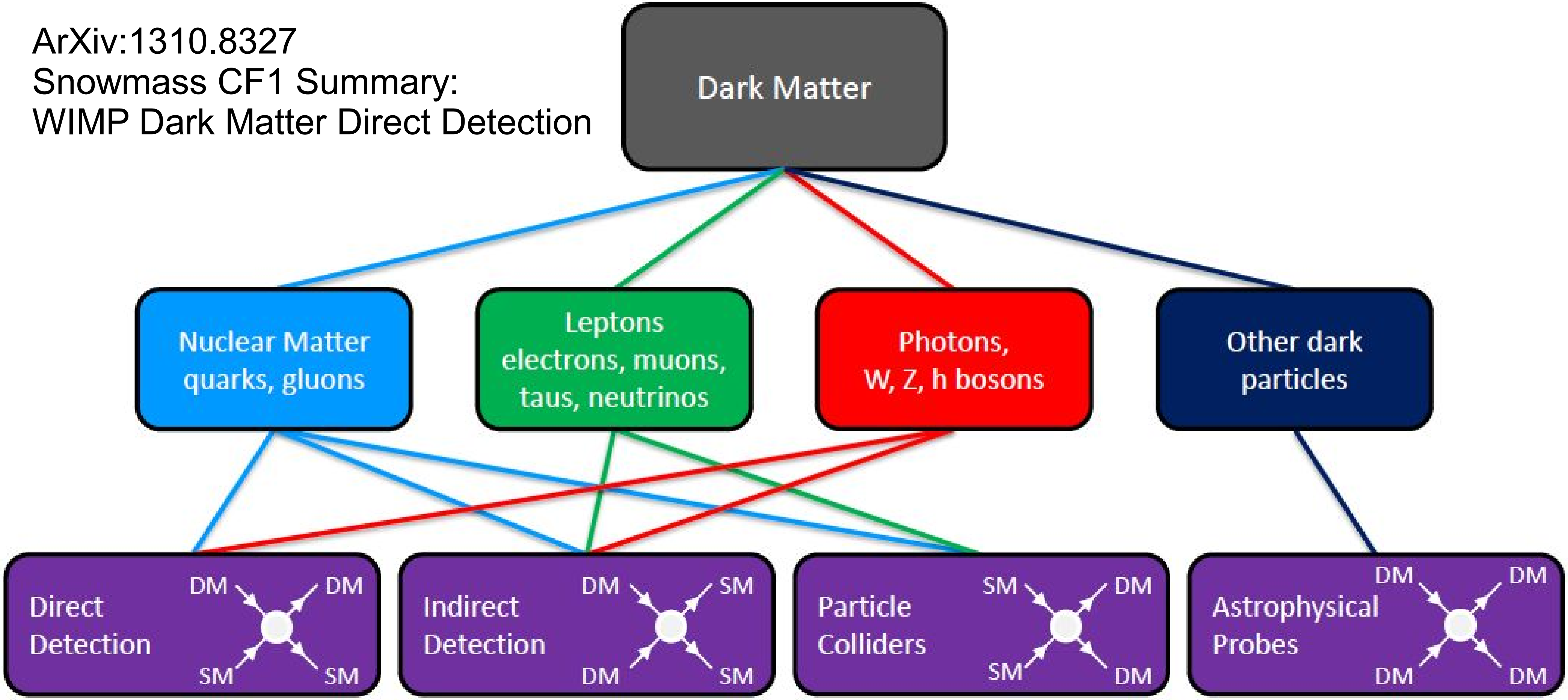
DM indirect detection:

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

Neutrino telescopes: Amanda, Icecube, Antares

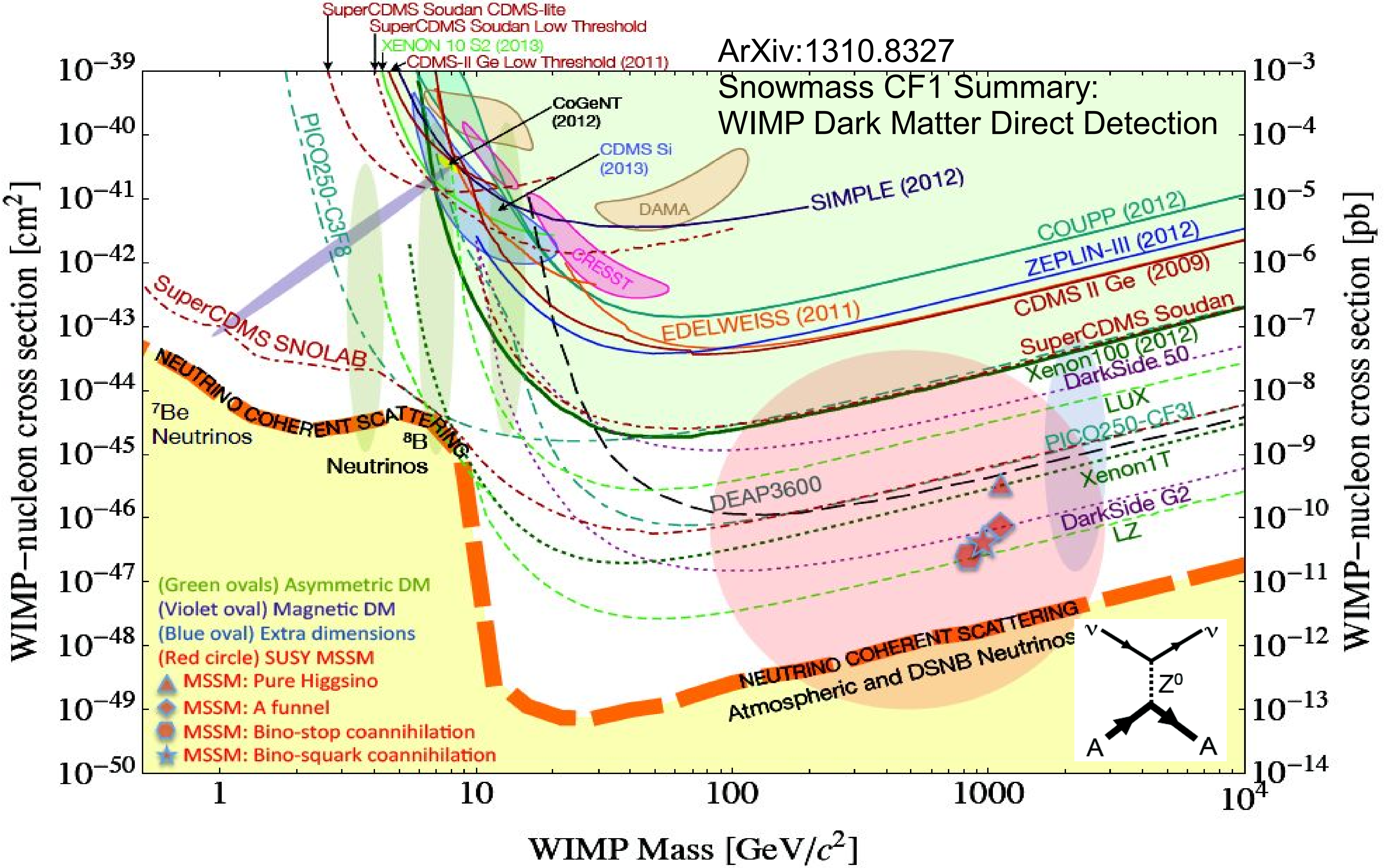
Complementarity of DM searches (Snowmass 2013)

ArXiv:1310.8327
Snowmass CF1 Summary:
WIMP Dark Matter Direct Detection



P. Cushman, C. Galbiati, D. N. McKinsey, H. Robertson, T. M. P. Tait, D. Bauer, A. Borgland, B. Cabrera, F. Calaprice, J. Cooley, T. Empl, R. Essig, E. Figueroa-Feliciano, R. Gaitskell, S. Golwala, J. Hall, R. Hill, A. Hime, E. Hoppe, L. Hsu, E. Hungerford, R. Jacobsen, M. Kelsey, R. F. Lang, W. H. Lippincott, B. Loer, S. Luitz, V. Mandic, J. Mardon, J. Maricic, R. Maruyama, R. Mahapatra, H. Nelson, J. Orrell, K. Palladino, E. Pantic, R. Partridge, A. Ryd, T. Saab, B. Sadoulet, R. Schnee, W. Shepherd, A. Sonnenschein, P. Sorensen, M. Szydagis, T. Volansky, M. Witherell, D. Wright, K. Zurek

Complementarity of Direct DM search



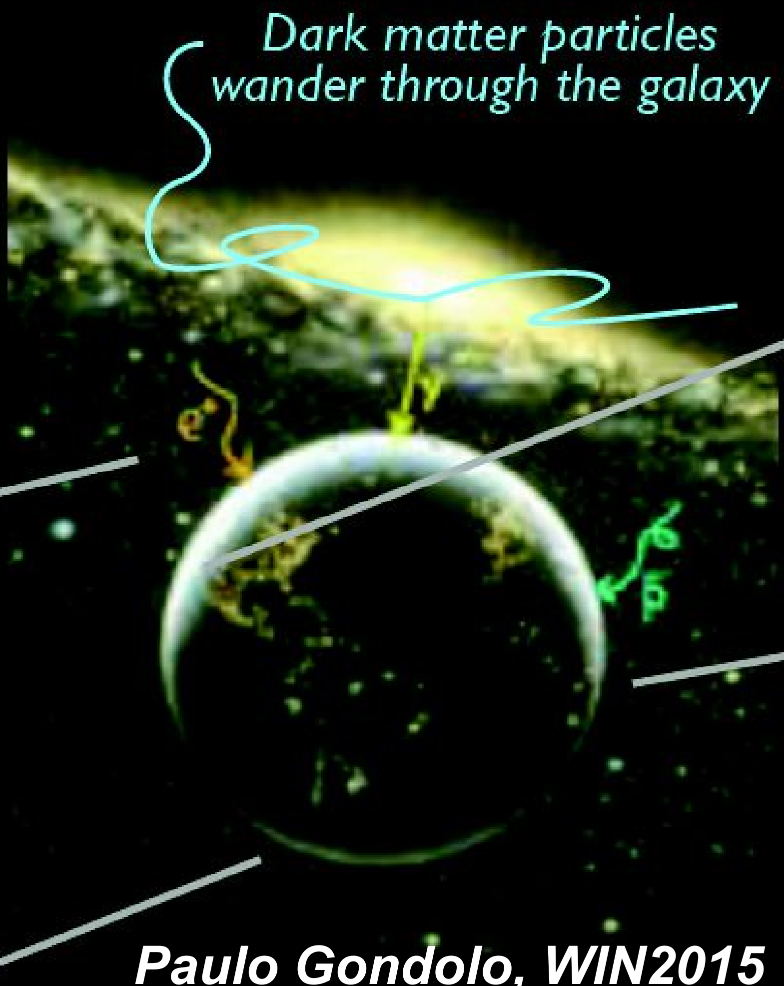
Indirect detection of particle dark matter

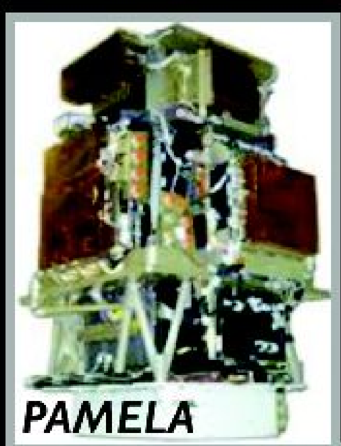
The principle

Dark matter particles transform into ordinary particles, which are then detected or inferred

HEAT
BESS
PAMELA
AMS
GAPS
EGRET
HESS
MAGIC
VERITAS
GLAST
STACEE
CTA
...

Gunn, Lee, Lerche, Schramm, Steigman 1978; Stecker 1978





Gamma-rays, positrons, antiprotons from our galaxy and beyond

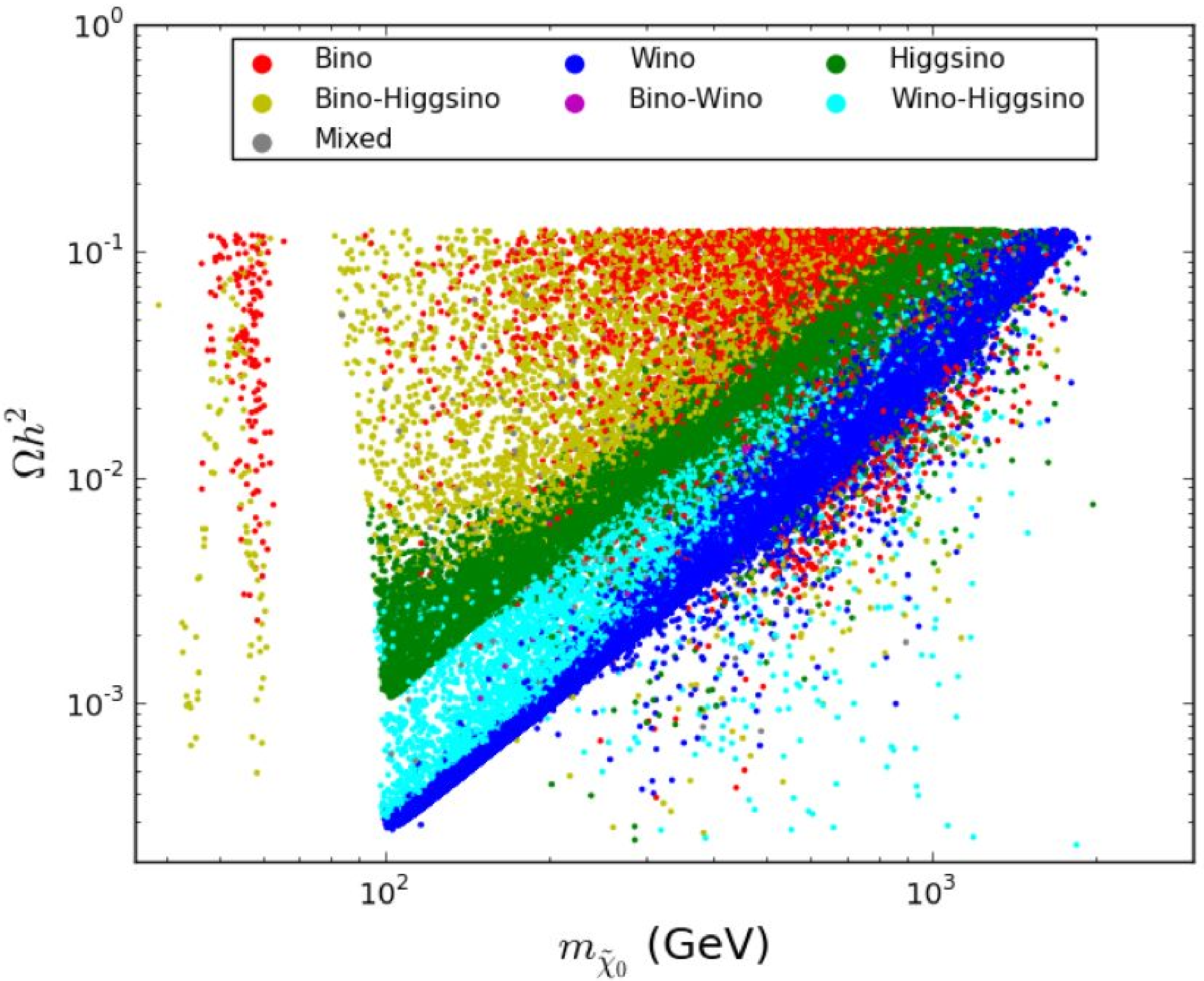
Paulo Gondolo, WIN2015

Example of Generic pMSSM study

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

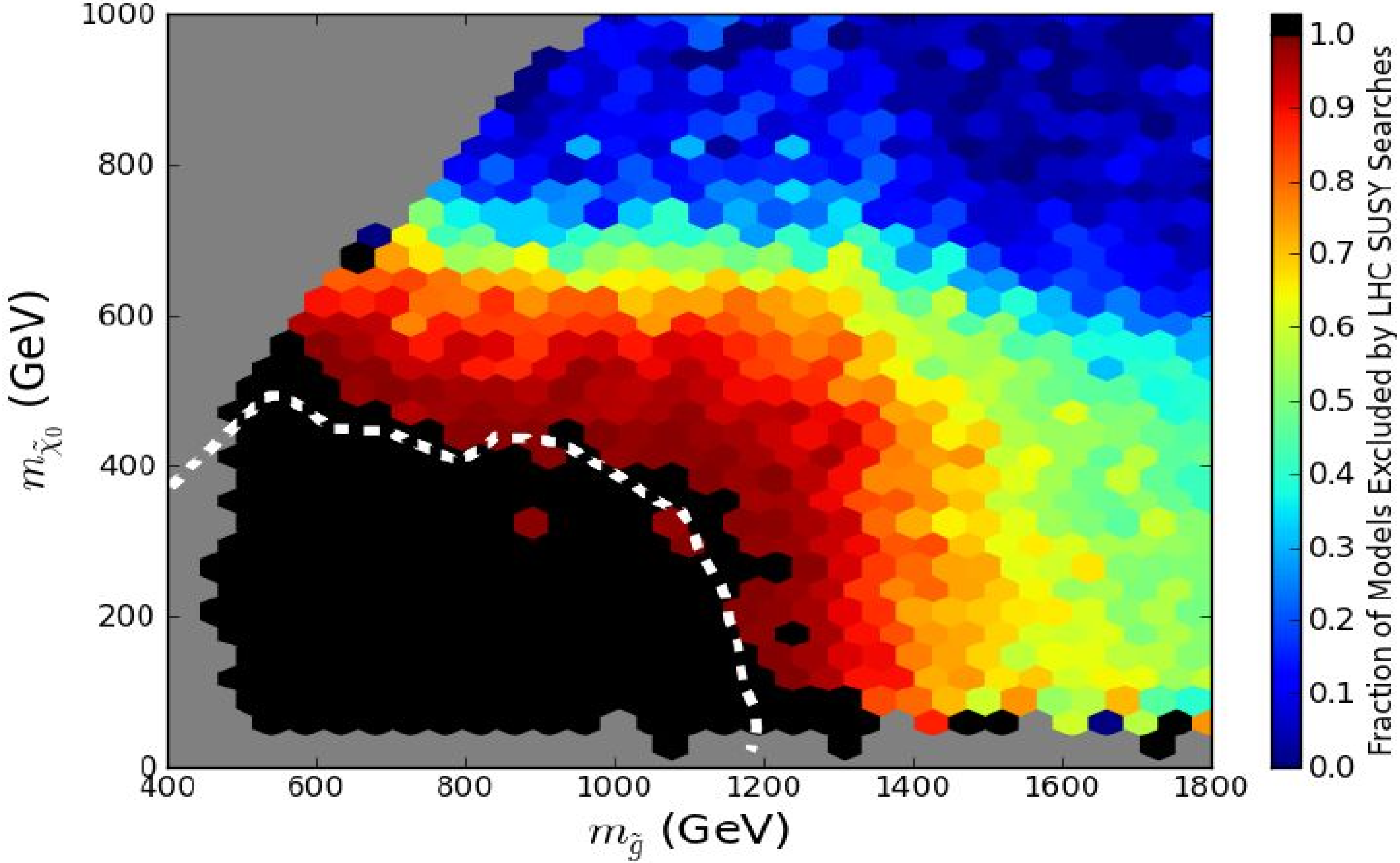
19-parametric space

$m_{\tilde{L}(e)_{1,2,3}}$	100 GeV – 4 TeV
$m_{\tilde{Q}(q)_{1,2}}$	400 GeV – 4 TeV
$m_{\tilde{Q}(q)_3}$	200 GeV – 4 TeV
$\lvert M_1 \rvert$	50 GeV – 4 TeV
$\lvert M_2 \rvert$	100 GeV – 4 TeV
$\lvert \mu \rvert$	100 GeV – 4 TeV
M_3	400 GeV – 4 TeV
$\lvert A_{t,b,\tau} \rvert$	0 GeV – 4 TeV
M_A	100 GeV – 4 TeV
$\tan\beta$	1 - 60
$m_{3/2}$	1 eV–1 TeV ($\tilde{G}$ LSP)

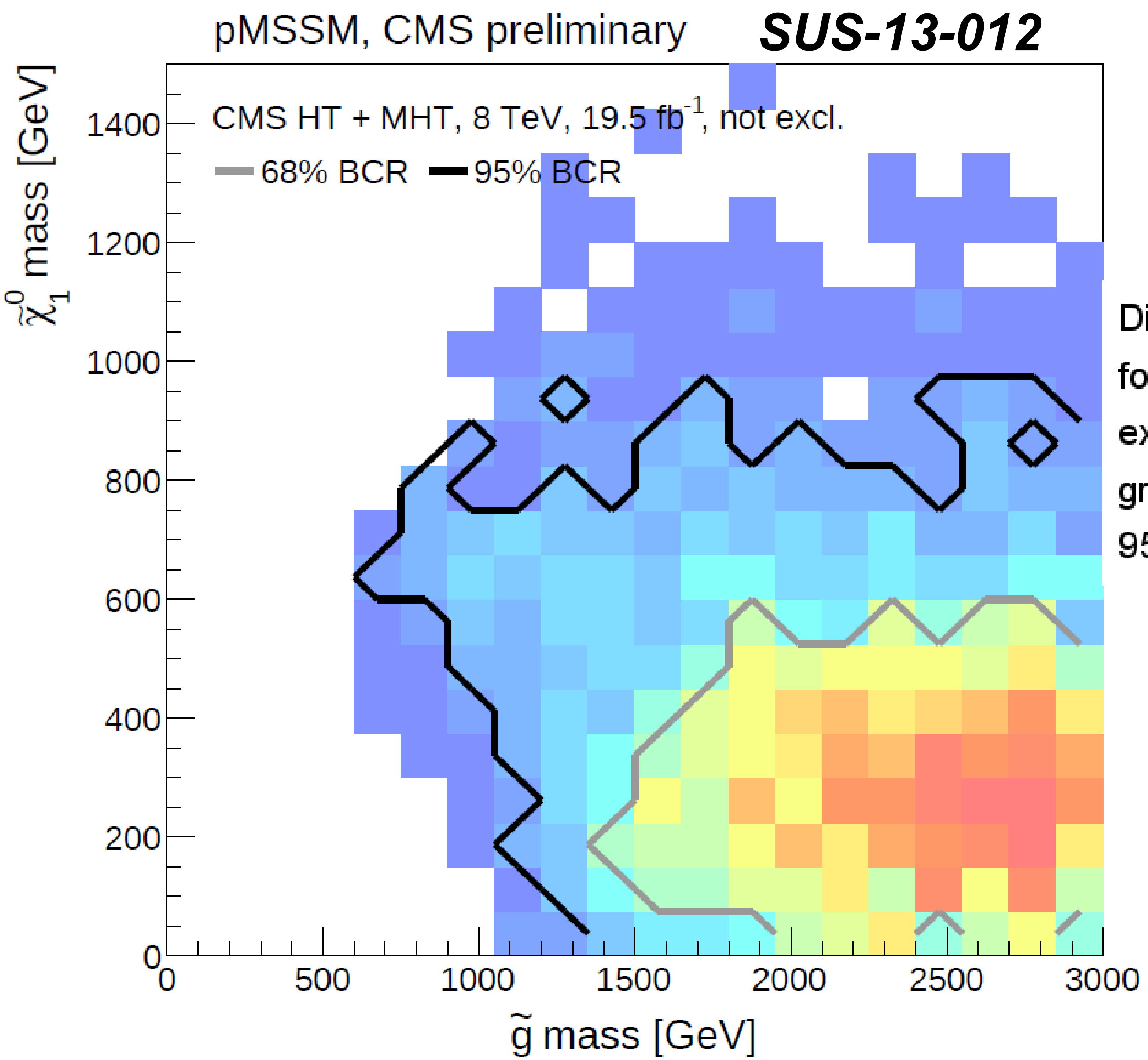


pMSSM projections for 8 TeV LHC

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



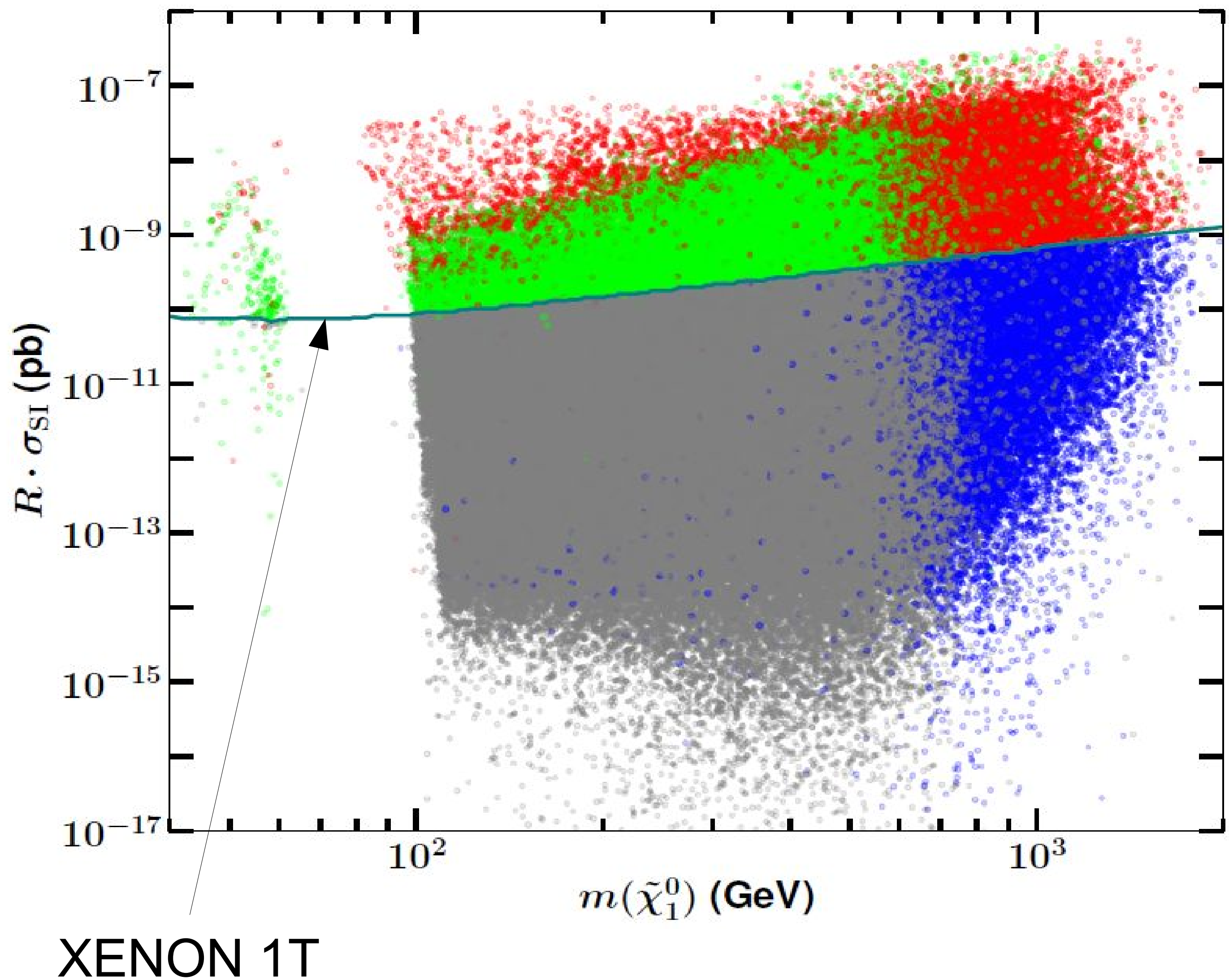
pMSSM limits from 8 TeV LHC



Distribution of ~g mass versus ~χ_1^0 mass for the sampled pMSSM points non excluded by the HT + MHT analysis. The grey and black contours enclose 68% and 95% of the non-excluded points.

pMSSM combined results

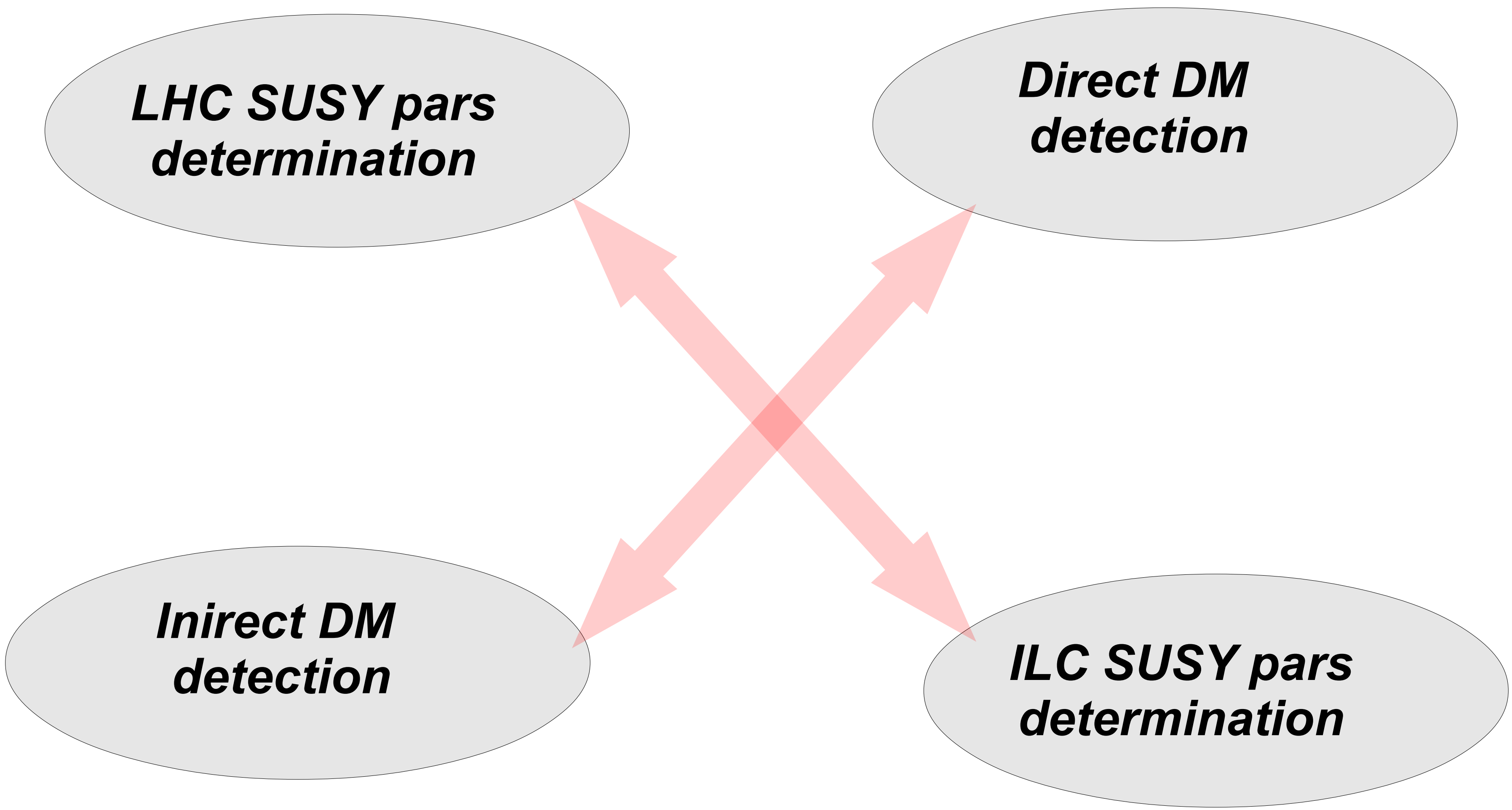
ArXiv:1305.6921: Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett



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

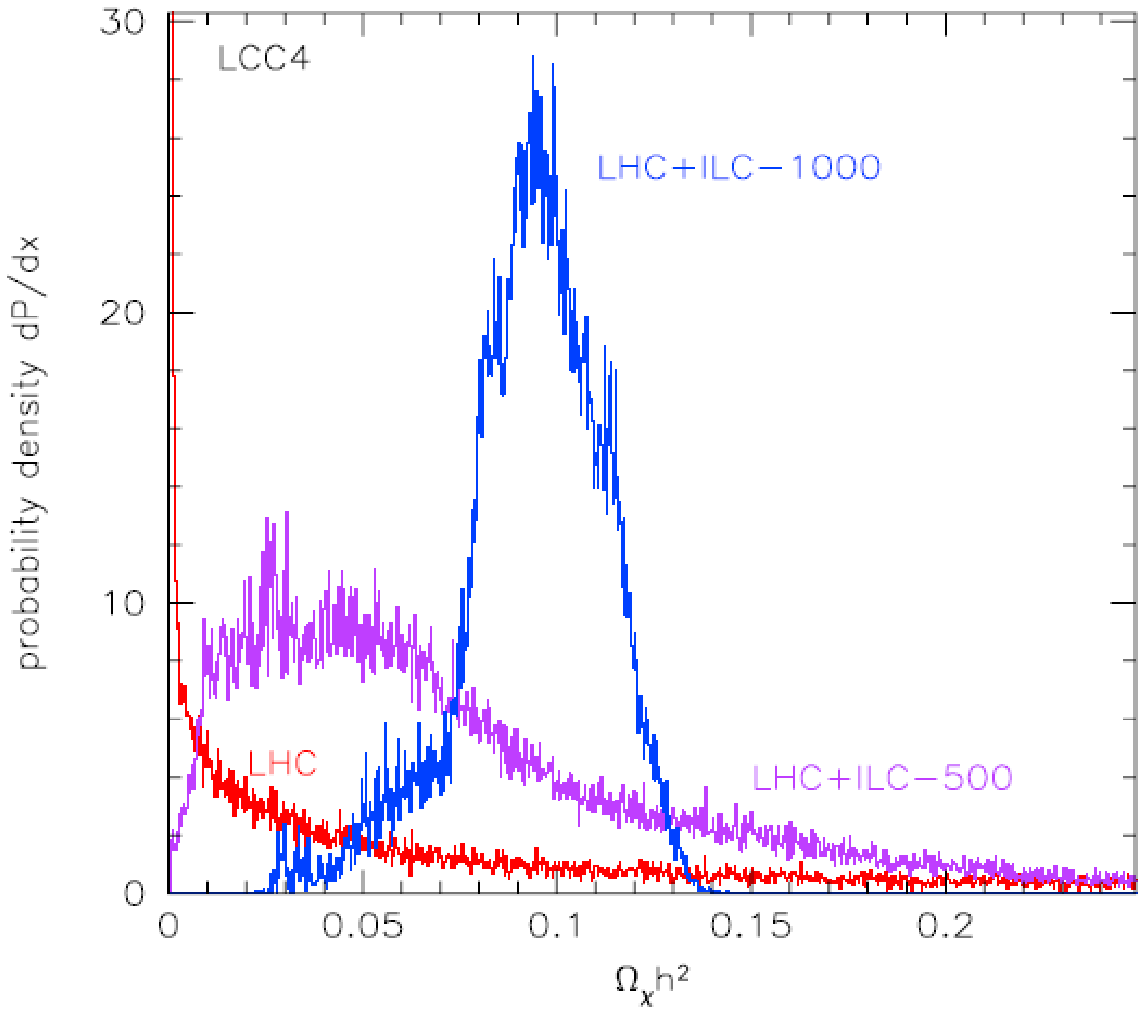
LHC/ILC and DD/IDD complementarity provides a multiple cross check of measured model parameters



LHC/ILC and DD/IDD complementarity provides a multiple cross check of measured model parameters

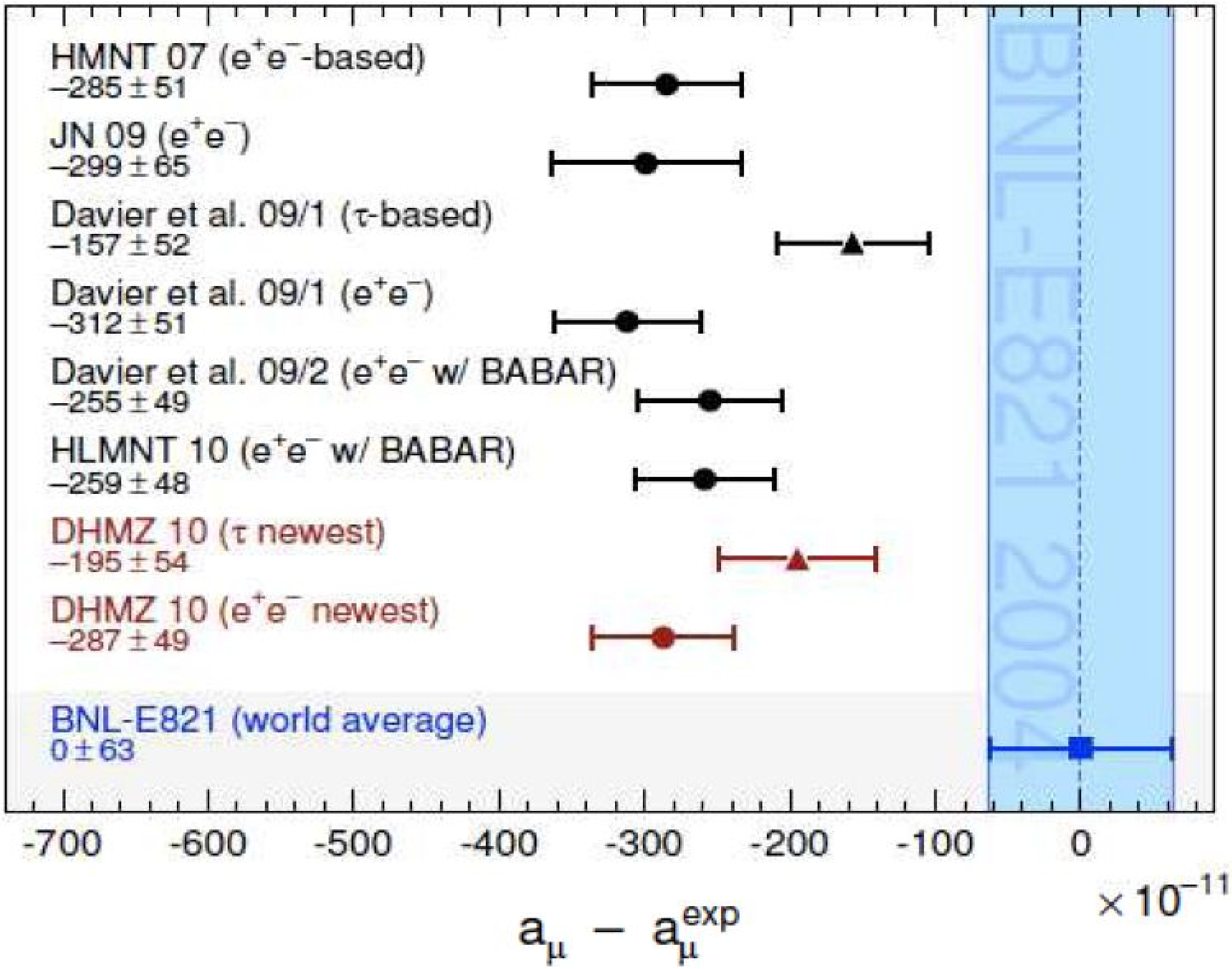
flavor/CP conserving MSSM: 24 parameters

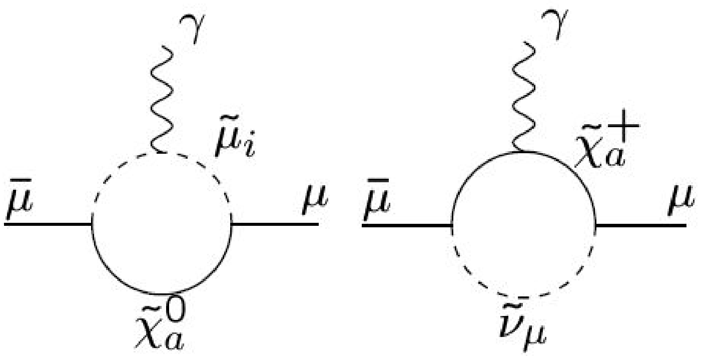
The LCC4 benchmark
m_0 = 380 GeV
$m_{1/2}$ = 420 GeV
$\tan\beta$ = 53
A0 = 0
$\mu > 0$
has been studied and the importance of Γ_A for fitting SUSY parameters was noted.
LHC was considered incapable of measuring Γ_A.



Baltz, Battaglia, Peskin, Wizansky,'06

Implications of g_μ - 2

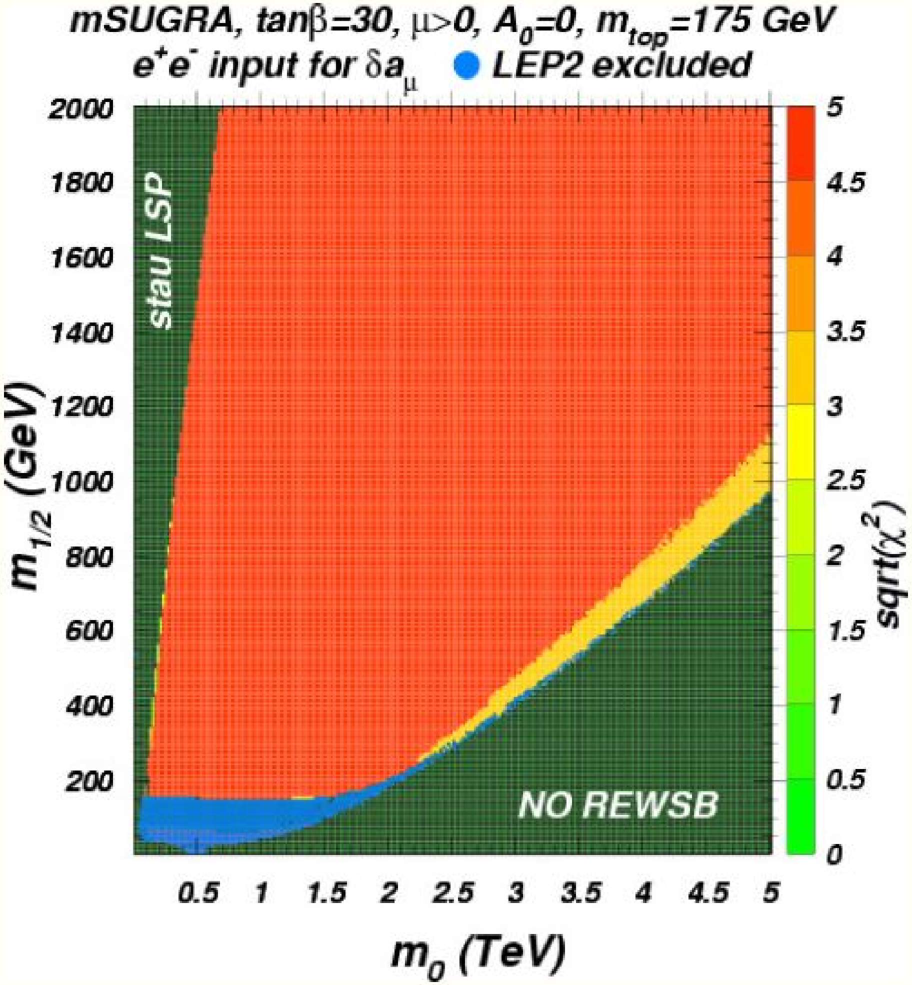




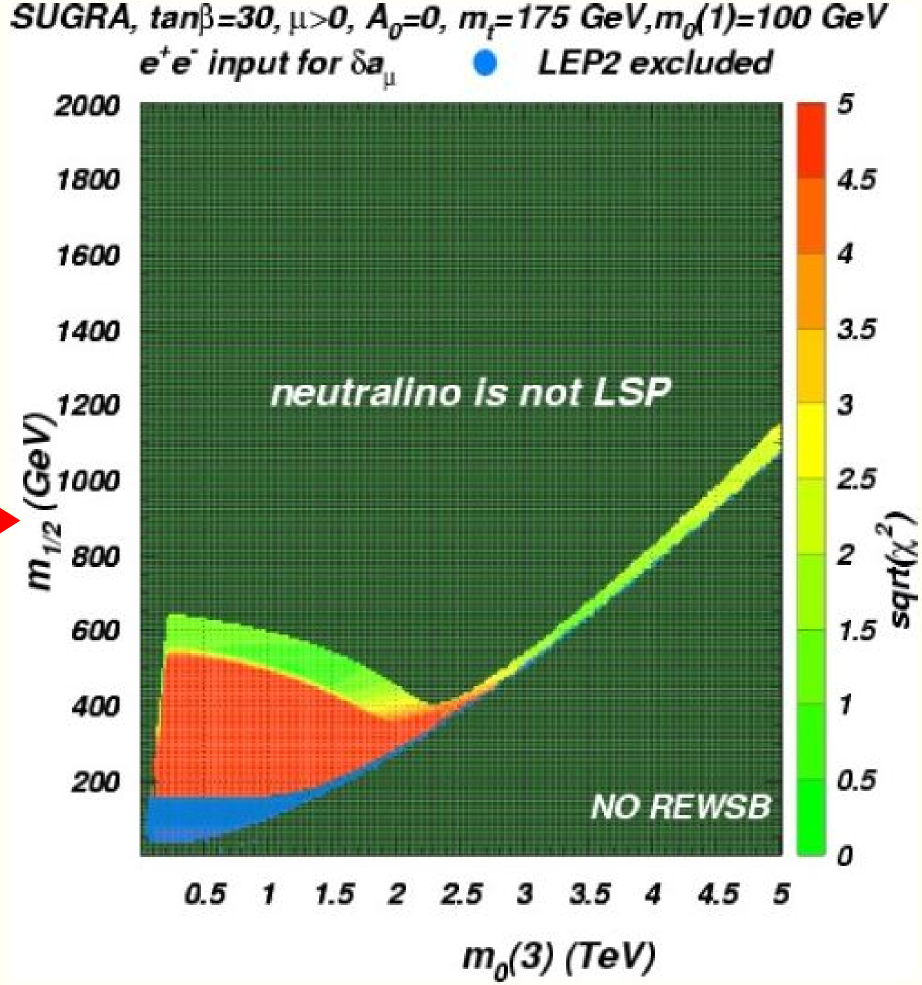
$$a_\mu^{\rm SUSY} \approx \frac{\alpha}{\pi\, 8 s_W^2} \tan\beta\, {\rm sign}(\mu)\, \frac{m_\mu^2}{M_{\rm SUSY}^2}$$

gμ - 2 implies generational splitting

- Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: *hard to realize in mSUGRA model.*
- one step beyond universality solves the problem! [Baer,AB,Krupovnikas,Mustafayev]
  $[m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)] \rightarrow [m_0(1), m_0(3), m_H, m_{1/2}, A_0, \tan\beta, sign(\mu)]$



→

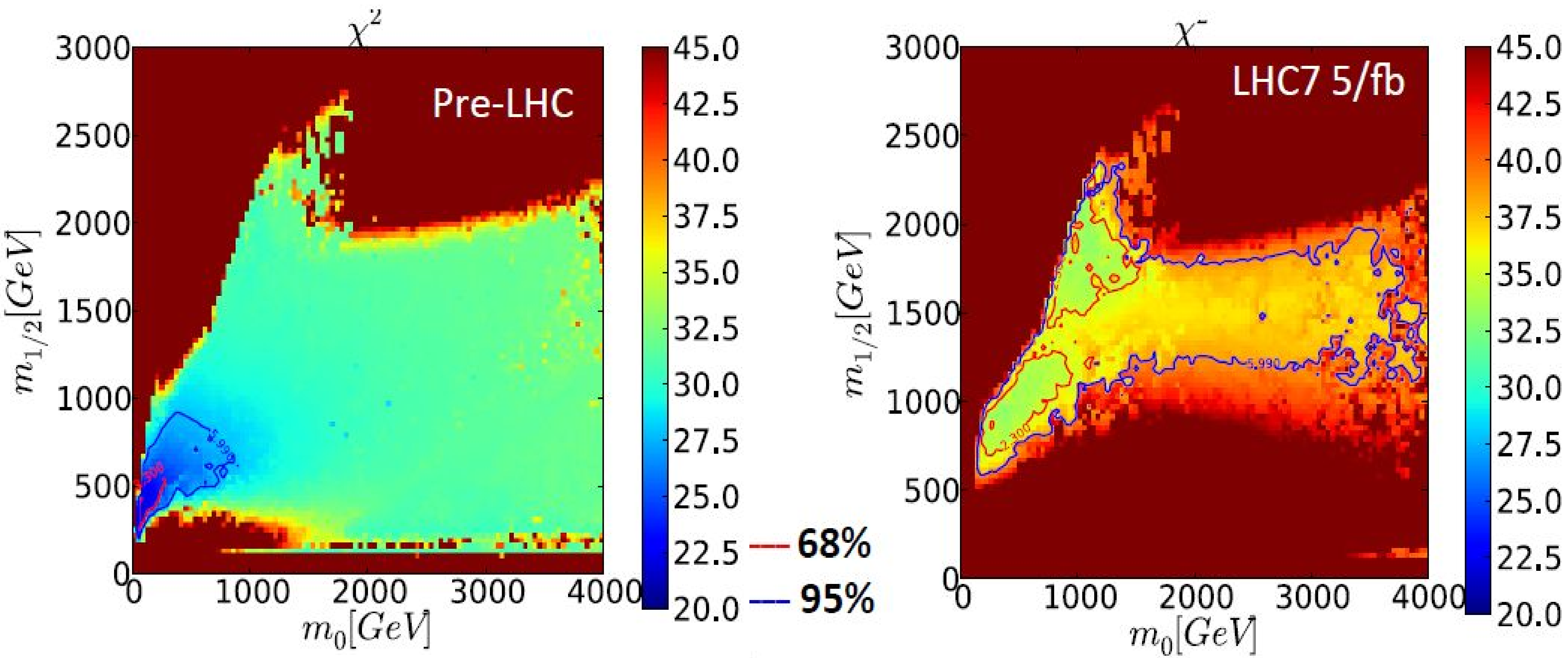


- $B_H^0 - B_L^0 = \Delta m_B$ mass splitting bound is safe

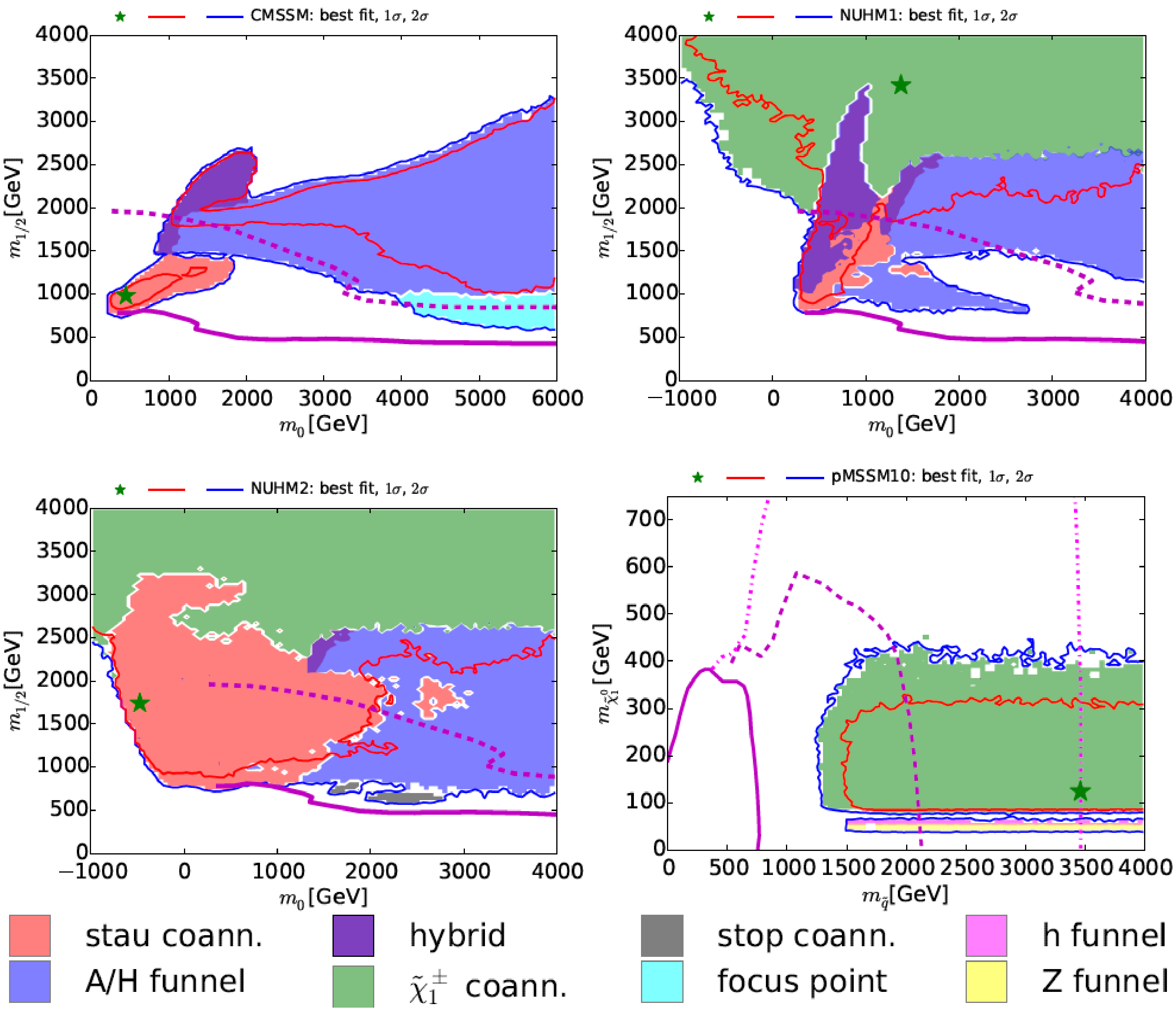
Implications of LHC search for SUSY fits

Buchmueller, Cavanaugh, De Roeck, Dolan, Ellis, Flaecher, Heinemeyer, Isidori, Marrouche, Martınez, Santos, Olive, Rogerson, Ronga, de Vries, Weiglein,

Global frequentist fits to the CMSSM using the MasterCode framework

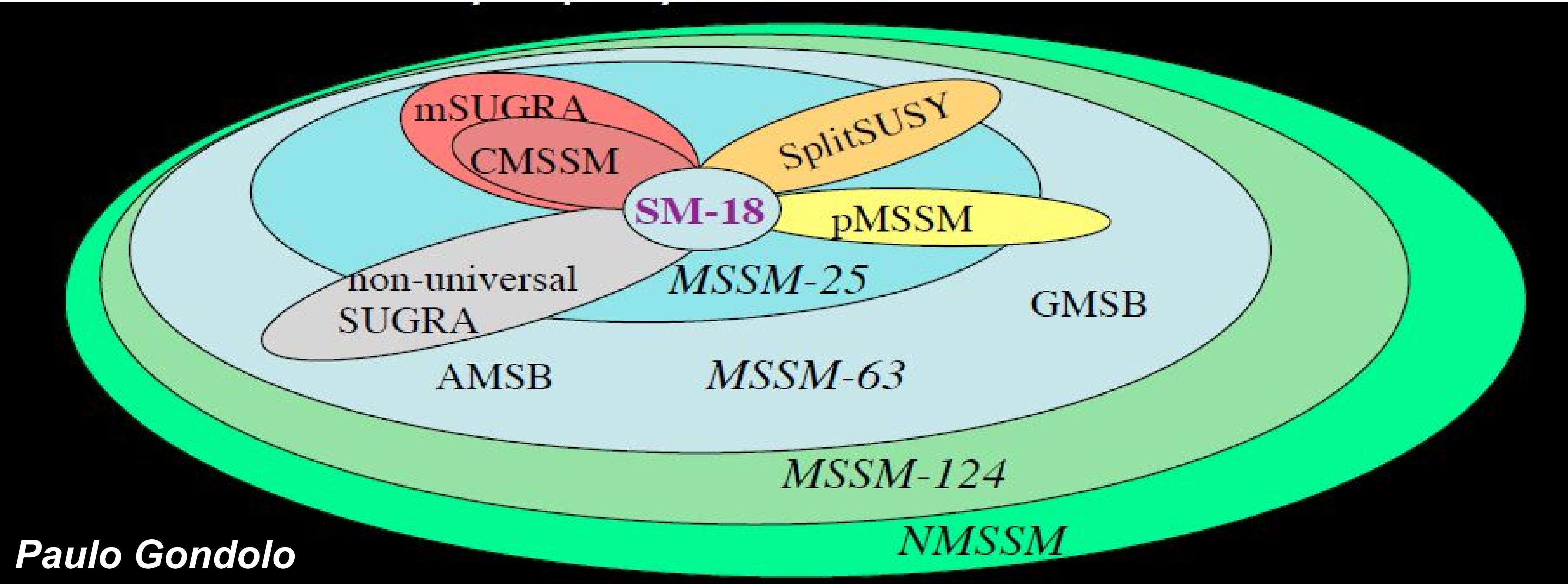


The status of non-universal MSSM models



Buchmueller,Cavanaugh
De Roeck,Dolan, Ellis,
Flaecher, Heinemeyer,
Isidori, Marrouche,
Martınez, Santos, Olive,
Rogerson, Ronga, de Vries,
Weiglein,

Beyond MSSM


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

From NMSSM to E_6SSM: solving μ problem

MSSM superpotential:

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

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

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

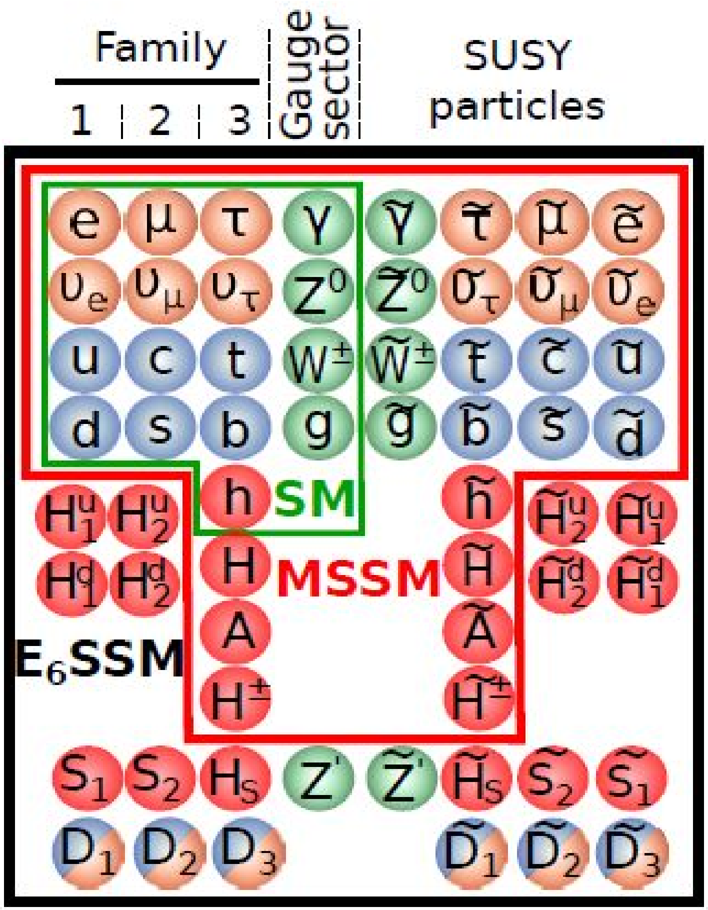
$$\lambda S H_u H_d \qquad \text{and} \qquad \langle S \rangle = \frac{s}{\sqrt{2}} \sim m_{\text{soft}} \sim 1\text{TeV} \qquad \Rightarrow \qquad \mu_{\text{eff}} = \frac{\lambda s}{\sqrt{2}}$$

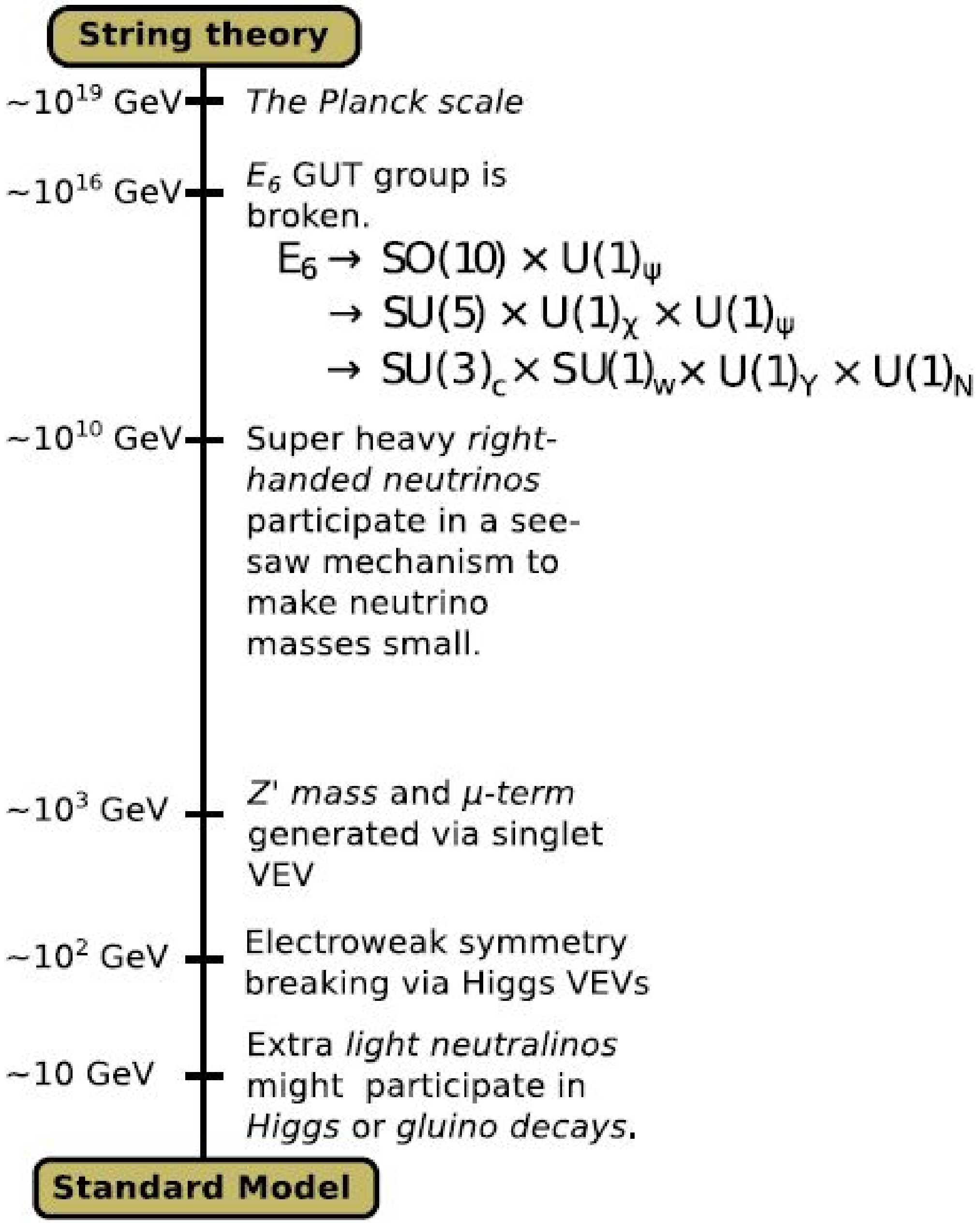
- **NMSSM:** A cubic term, S^3, is also added, breaking the U(1) down to a discrete Z_3. This could lead to cosmological domain walls and overclosure of the Universe.
- **USSM:** The U(1) is gauged and a massive Z' appear. However, the theory is not anomaly free.
- **E_6SSM:** The gauged U(1) is a remnant 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

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

From NMSSM to E_6SSM: solving μ problem

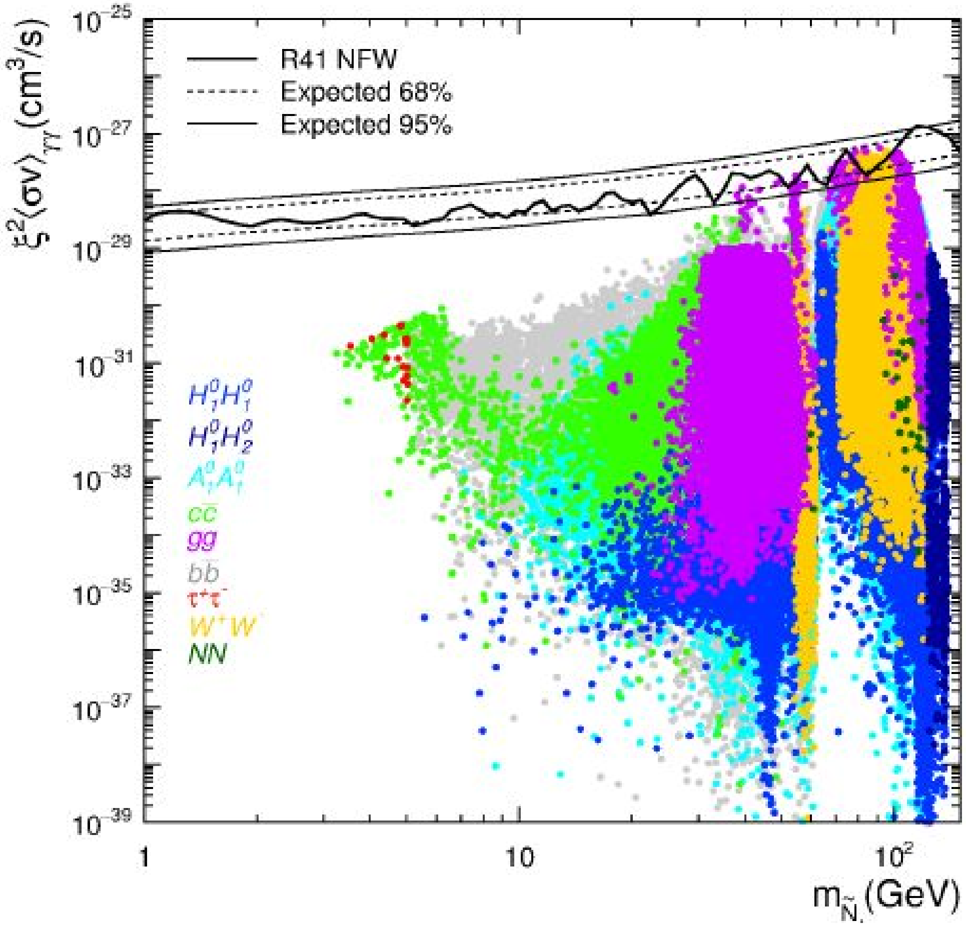


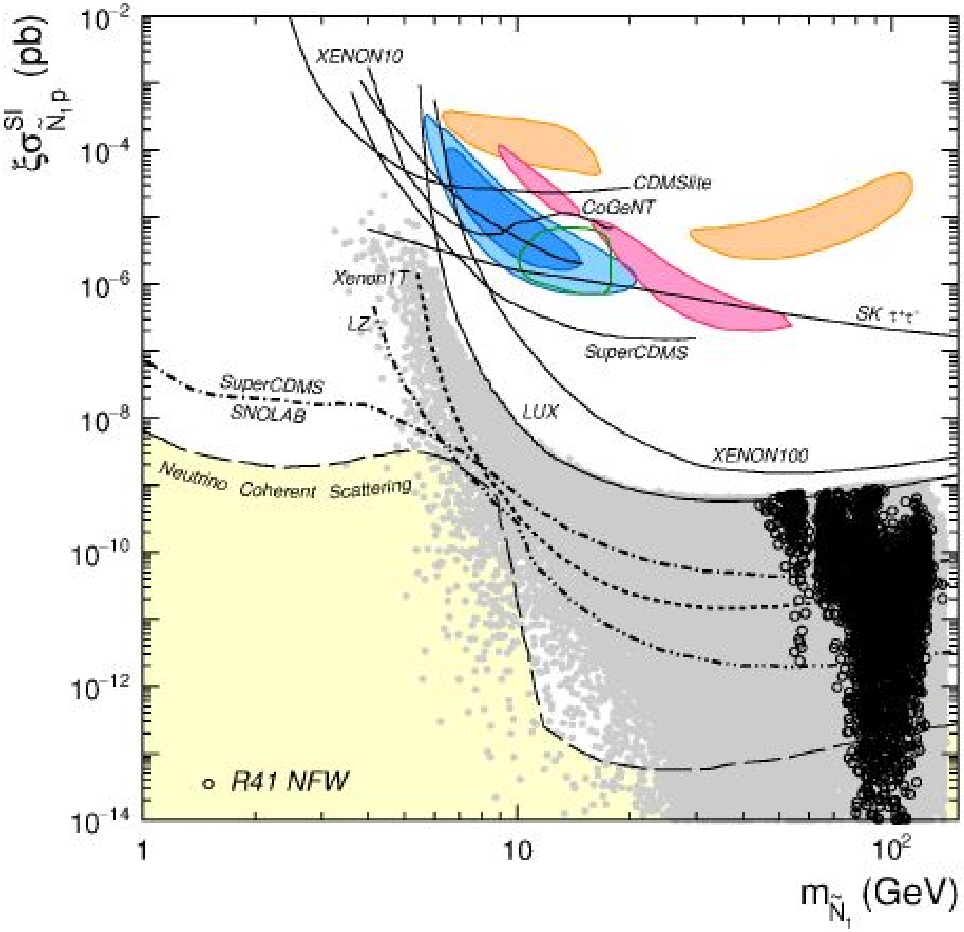


- String theory motivated model
- One extra surviving $U(1)'$
- Extra particles from complete 27s of E_6

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

SUSY DM candidates

- **Neutralino – WIMP -the most studied**
  Goldberg 1983; Ellis, Hagelin, Nanopoulos, Olive, Srednicki 1984;....

- **Sneutrino – WIMP- non-universal MSSM, nMSSM,...**
  Falk, Olive, Srednicki 1994; Baer, Belyaev, Krupovnikas, Mustafayev 2002; Asaka, Ishiwata, Moroi 2006; McDonald 2007; Lee, Matchev, Nasri 2007; Deppisch, Pilaftsis 2008; Cerdeno, Munoz, Seto 2009; Cerdeno, Seto 2009 ...

- **Gravitino - SuperWIMP**
  Feng, Rajaraman, Takayama 2003; Ellis, Olive, Santoso, Spanos 2004; Feng, Su, Takayama, 2004;...

- **Axinos (SuperWIMPs)**
  Tamvakis, Wyler 1982; Nilles, Raby 1982; Goto, Yamaguchi 1992; Covi, Kim, Kim, Roszkowski 2001; Covi, Roszkowski, Ruiz de Austri, Small 2004; ...

Remark on EW measure of Fine Tuning

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

The EW measure requires that there be no large/unnatural cancellations in deriving m_Z from the weak scale scalar potential:

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

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**

$$|\mu^2| \simeq M_Z^2$$
$$|m^2_{H_u}| \simeq M_Z^2$$

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

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

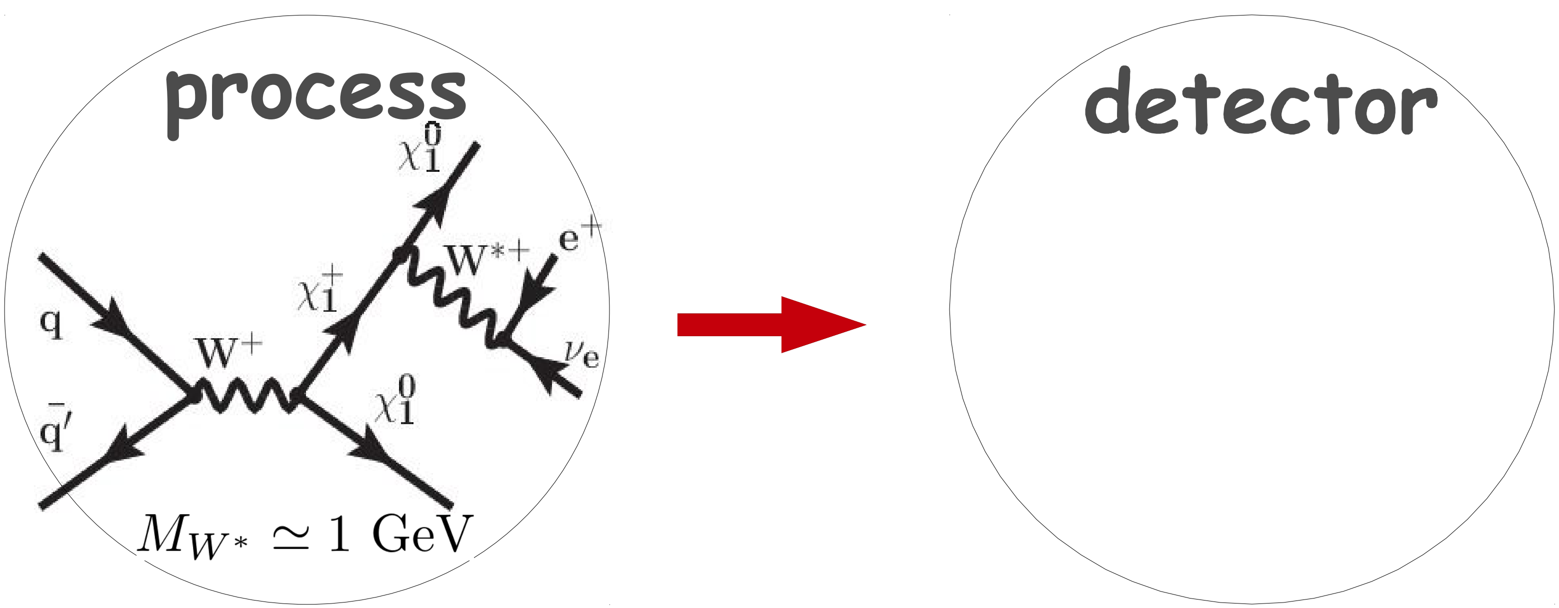
neutralinos

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

- 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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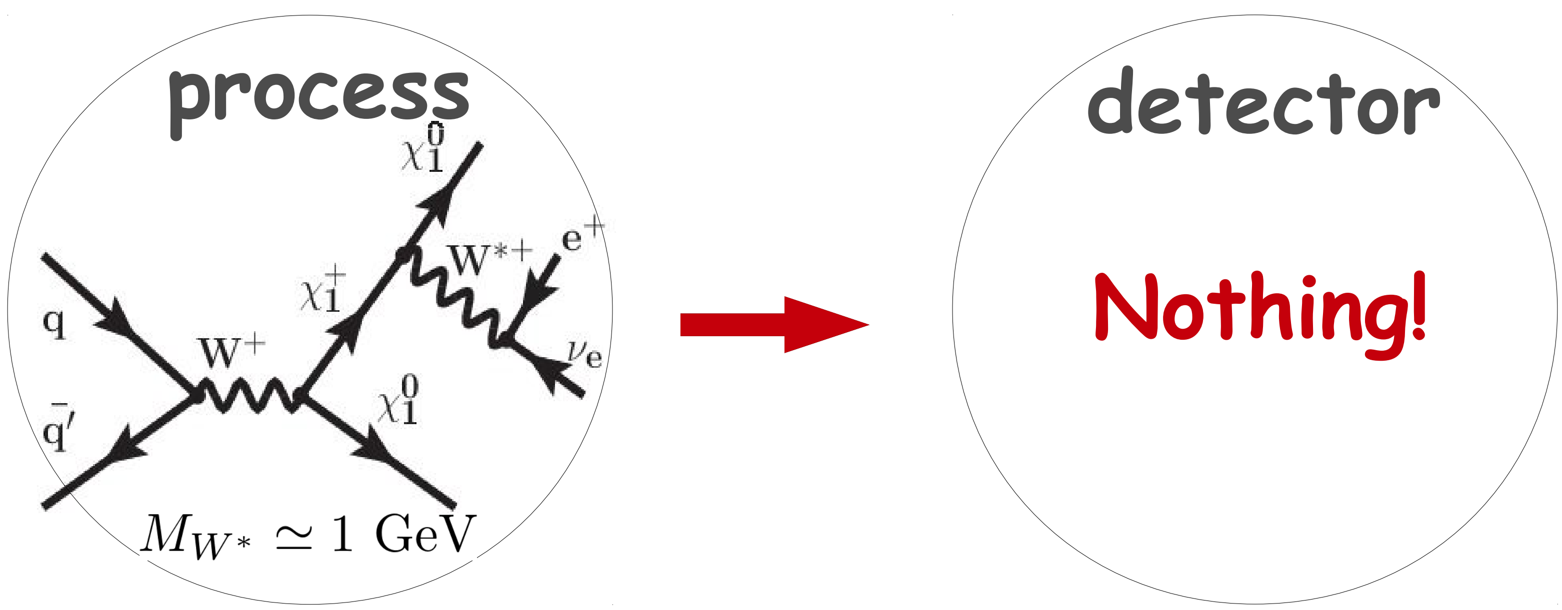

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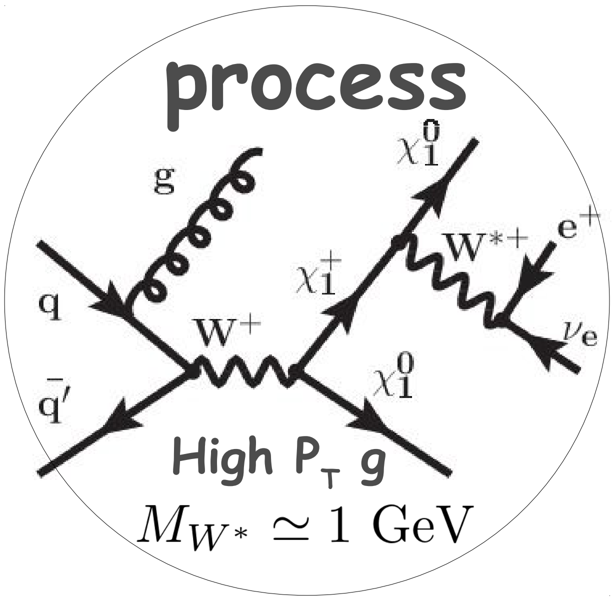

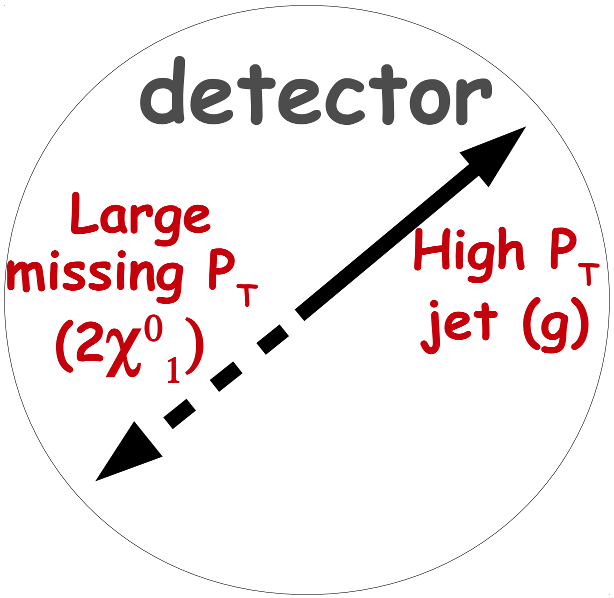

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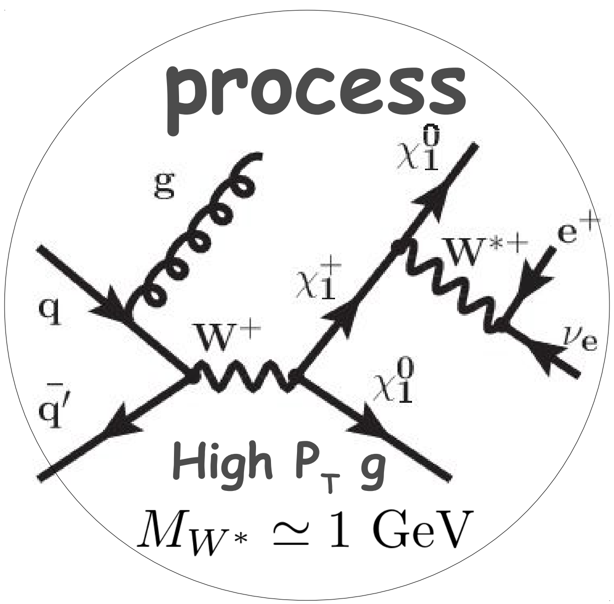
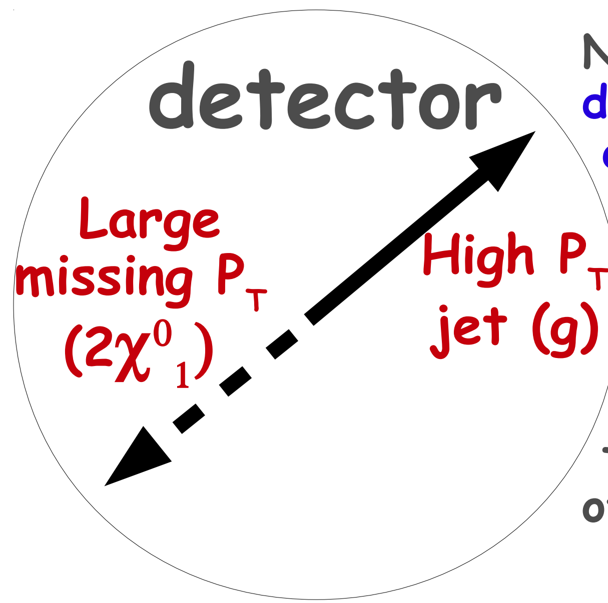
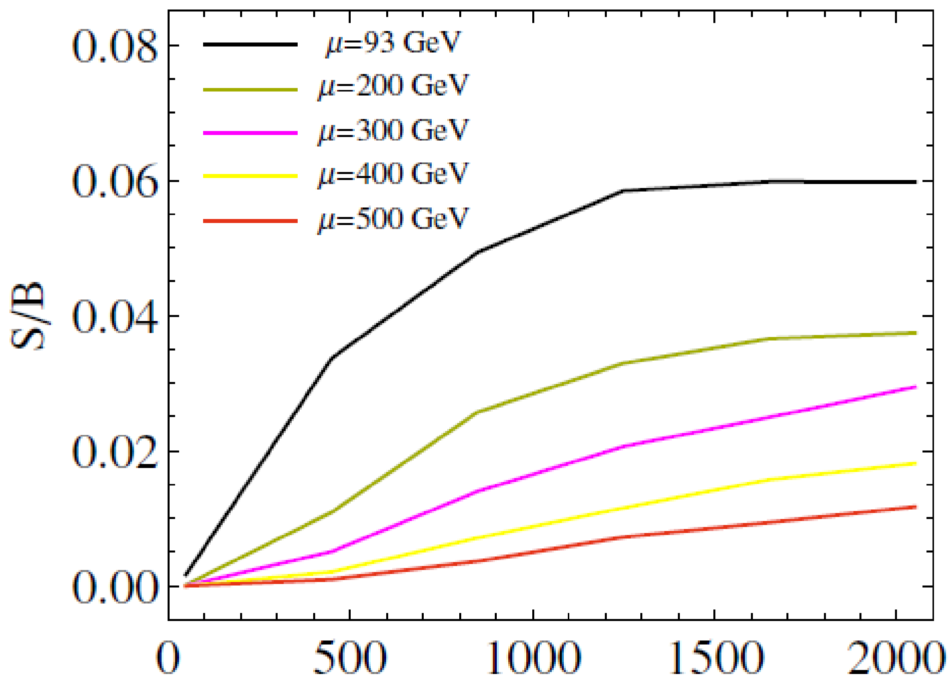


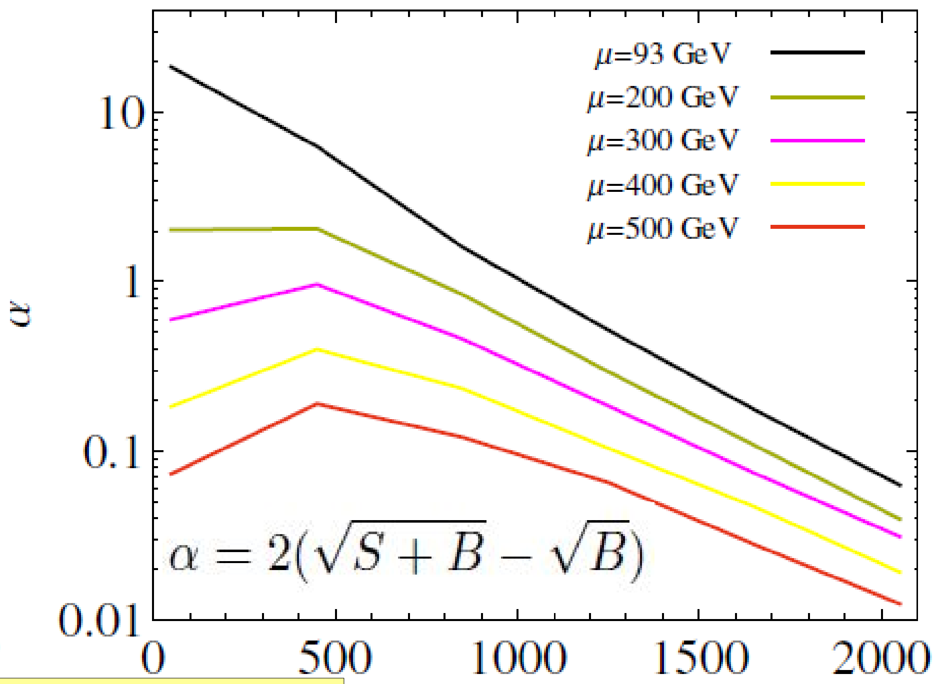


Note that W* decay products do not get large boost – it is proportional to the mass of W* which is much smaller than the mass of the LSP

S/B vs Signal significance



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



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

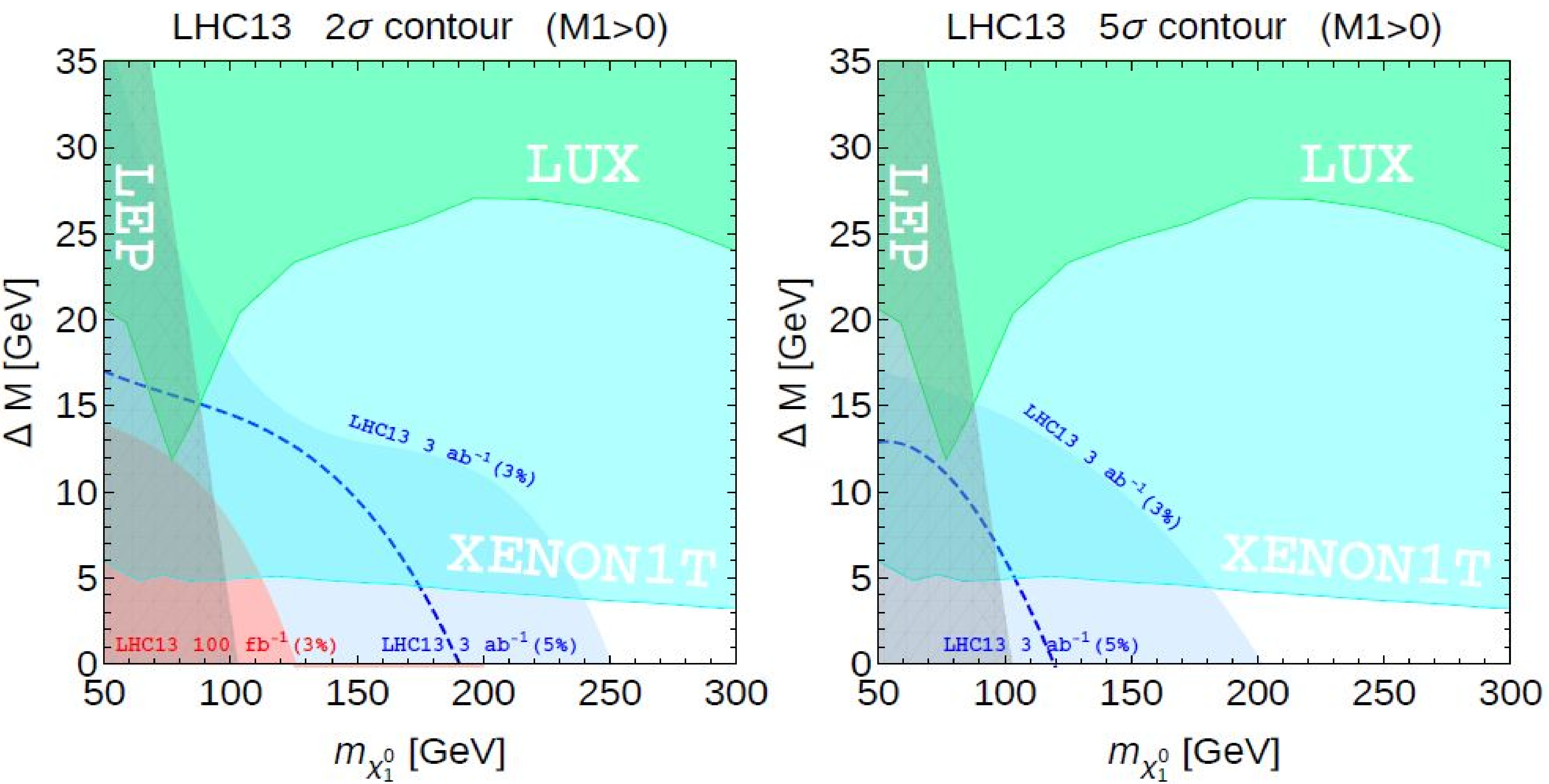
LHC@13TeV, 100 fb^{-1}

Z->νν is very problematic background!

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

LHC/DM direct detection sensitivity to CHS



"Uncovering Natural Supersymmetry via the interplay between the LHC and Direct Dark Matter Detection", Barducci,AB,Bharucha,Porod,Sanz, arXiv:1504.02472 (JHEP)

- **SUSY, at least DM, can be around the corner (100 GeV), it is just very hard to detect it!**

Conclusions

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

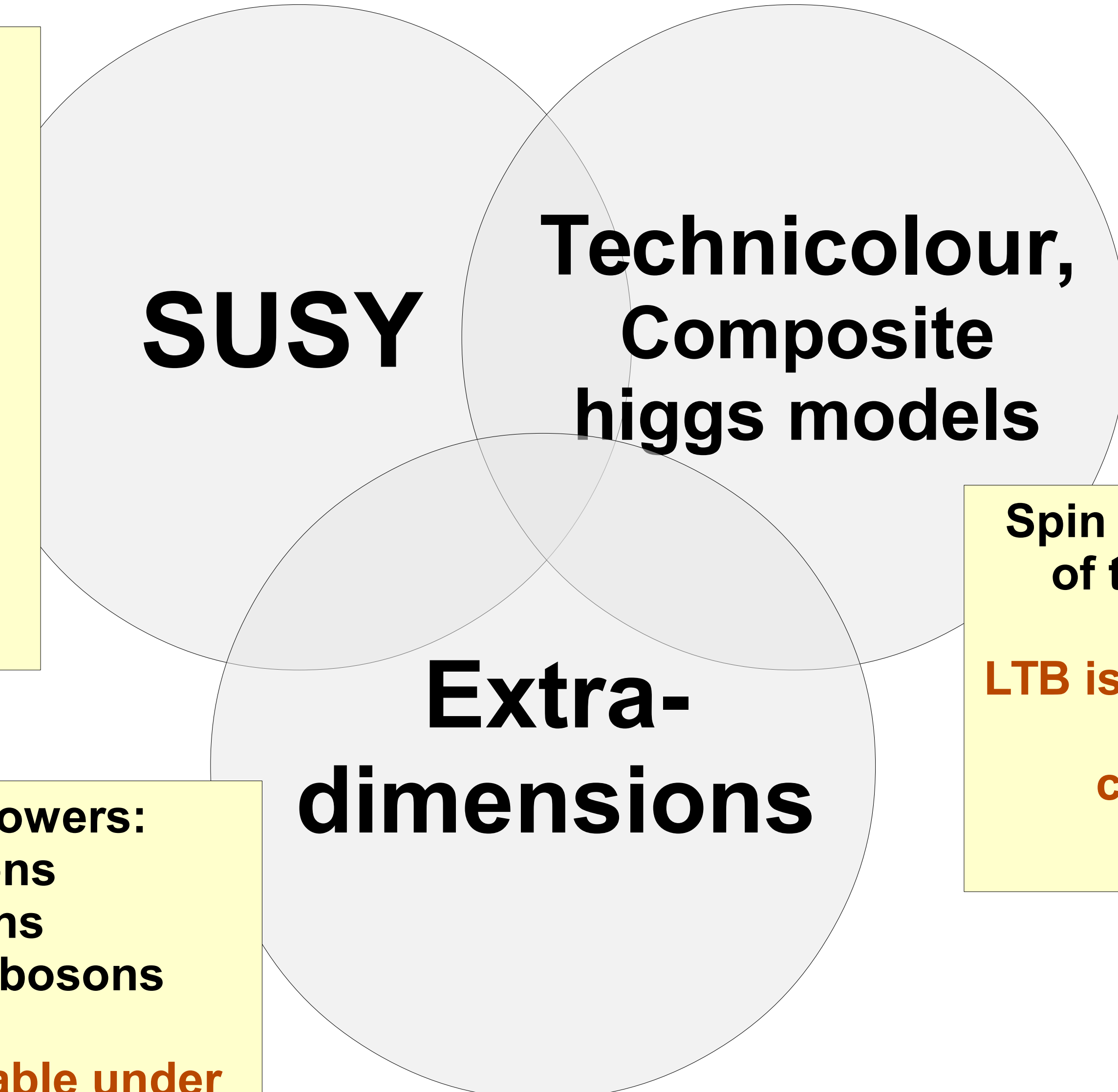
Lets be optimists!

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

Thank you!

Backup Slides

Theories and new particles



SUSY partners

New gauge bosons (USSM, E6SSM)

Exotics – diquarks, LQ (E6SSM)

LSP is stable under the R-parity

Spin 0,1 bound states of techni-quarks:

LTB is stable under the TB number conservation

KK – towers:
KK-gravitons
KK-fermions
KK-gauge bosons

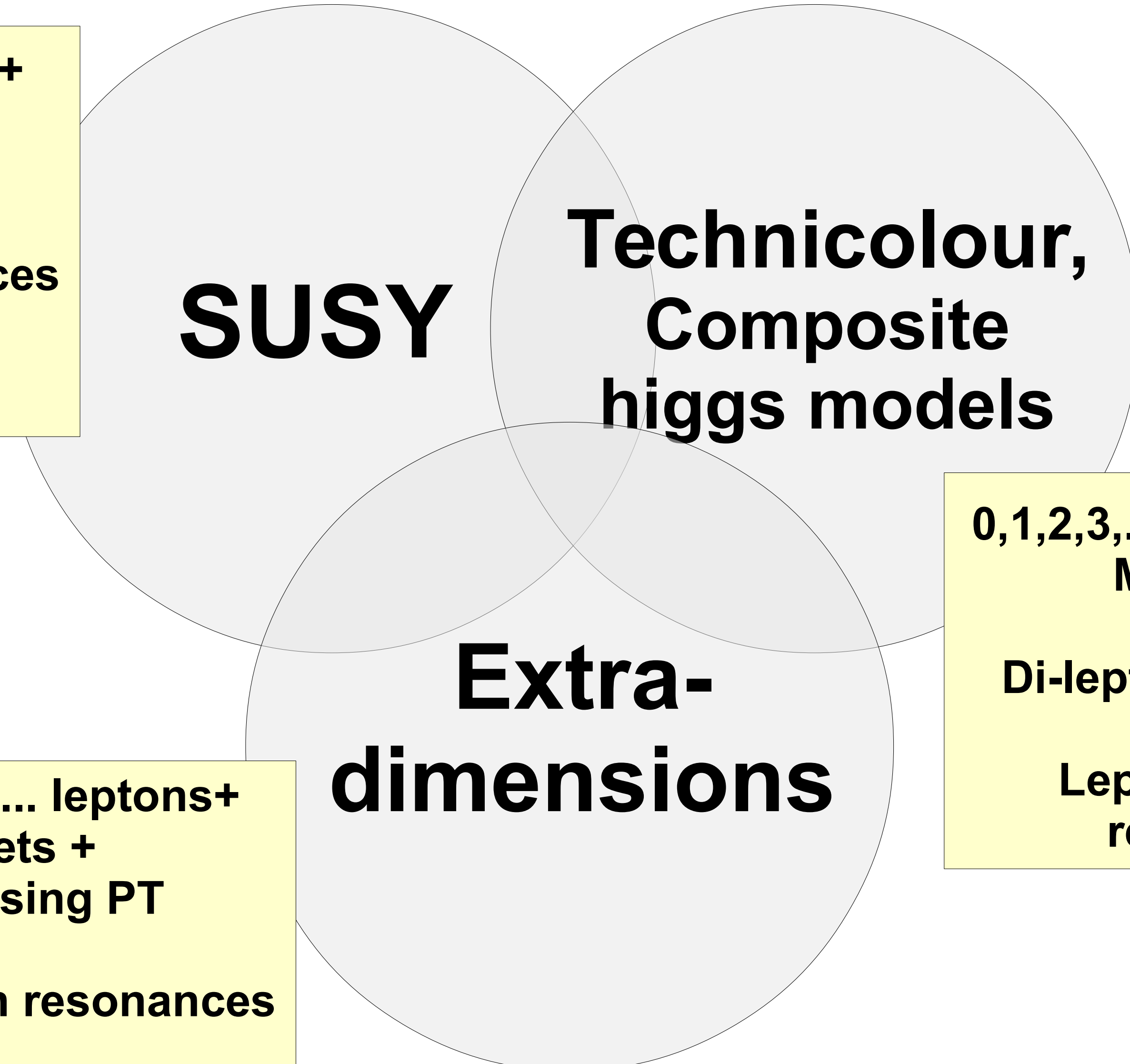
LKP is stable under the KK-parity (UED)

Theories and new signatures

0,1,2,3,... leptons+
jets +
Missing PT

Di-lepton resonances

Same-sign leptons



0,1,2,3,... leptons+ jets +
Missing PT

Di-lepton resonances

Lepton-neutrino
resonances

0,1,2,3,... leptons+
jets +
Missing PT

Di-lepton resonances

Same-sign leptons

Signatures can be really similar!

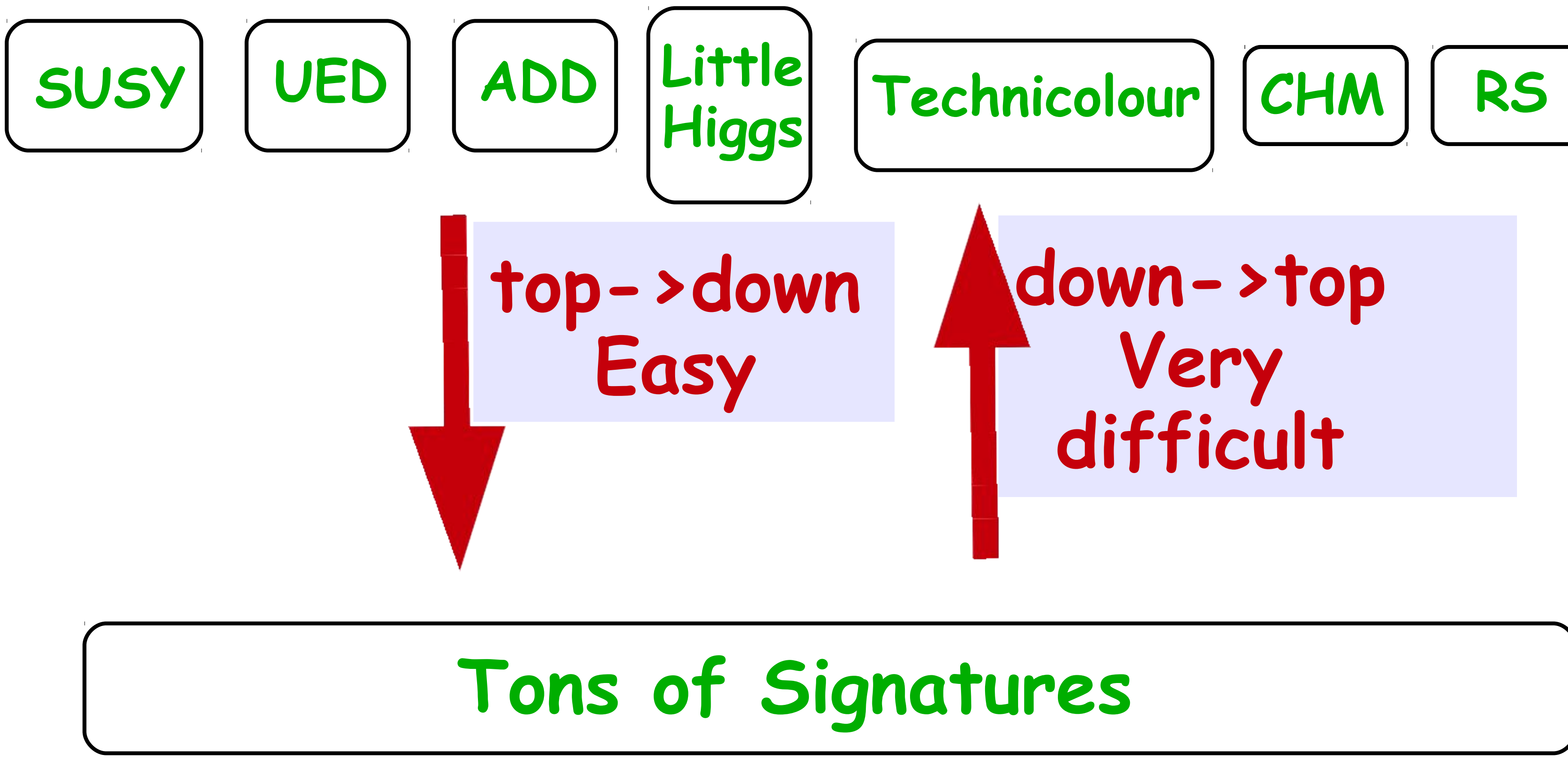
The main problem is to decode an underlying theory from the complicated set of signatures: down->top

SUSY | UED | ADD | Little Higgs | Technicolour | CHM | RS

top->down
Easy

Tons of Signatures

The main problem is to decode an underlying theory from the complicated set of signatures: down->top



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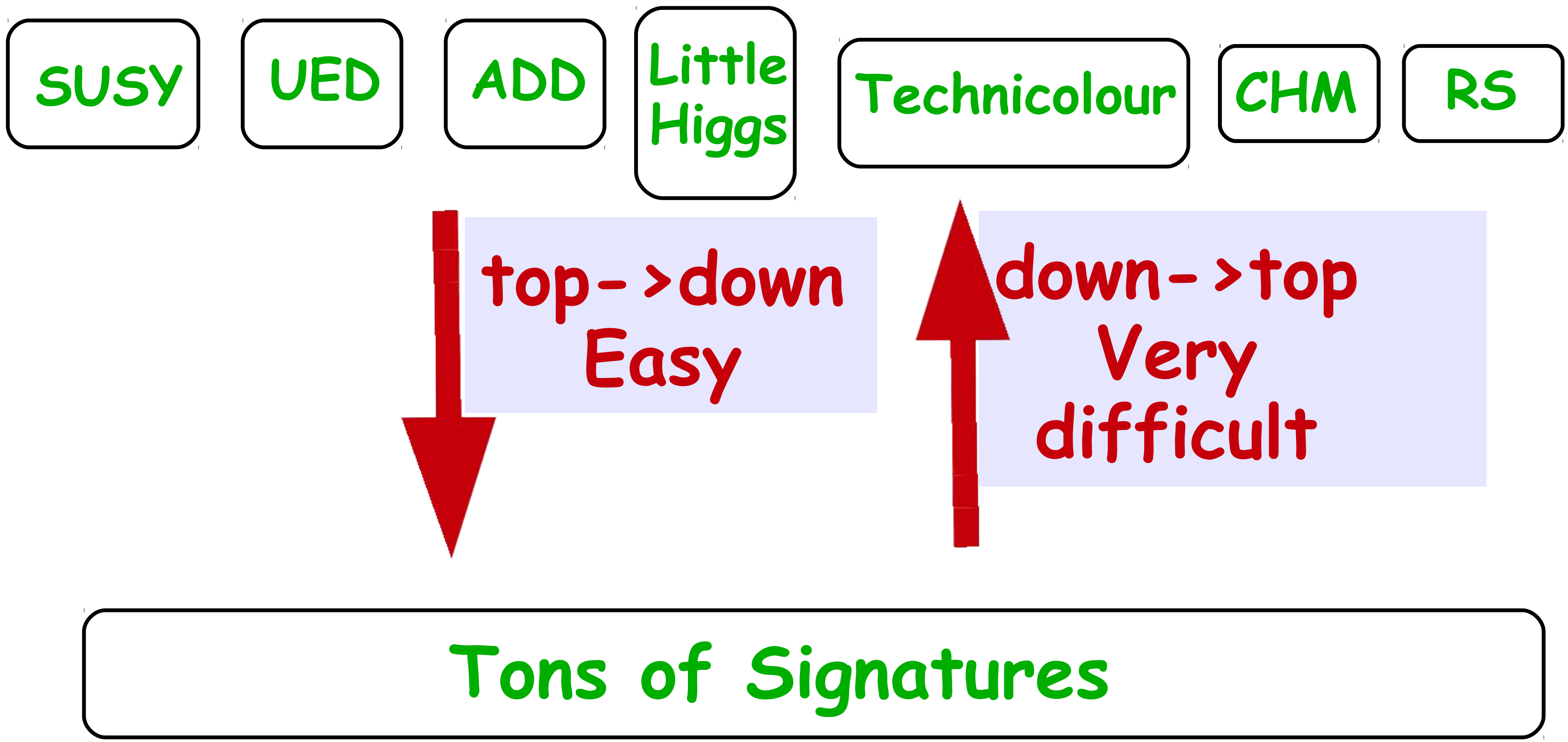

HEPMDB

High Energy Physics Model Data Base

https://hepmdb.soton.ac.uk/

Remarks on the fine-tuning problem

- Actually the problem cannot be strictly formulated in the context of the Standard Model – the Higgs mass is not calculable
- However the this problem is related to yet unknown mechanism of underlying theory where Higgs mass is calculable! In this BSM theory Higgs mass should not have tremendous fine-tuing.
- There is no hint yet about such a mechanism – and this is the main source of our worries about fine-tuning