LNF SPRING SCHOOL 06

COSMOLOGY AT COLLIDERS

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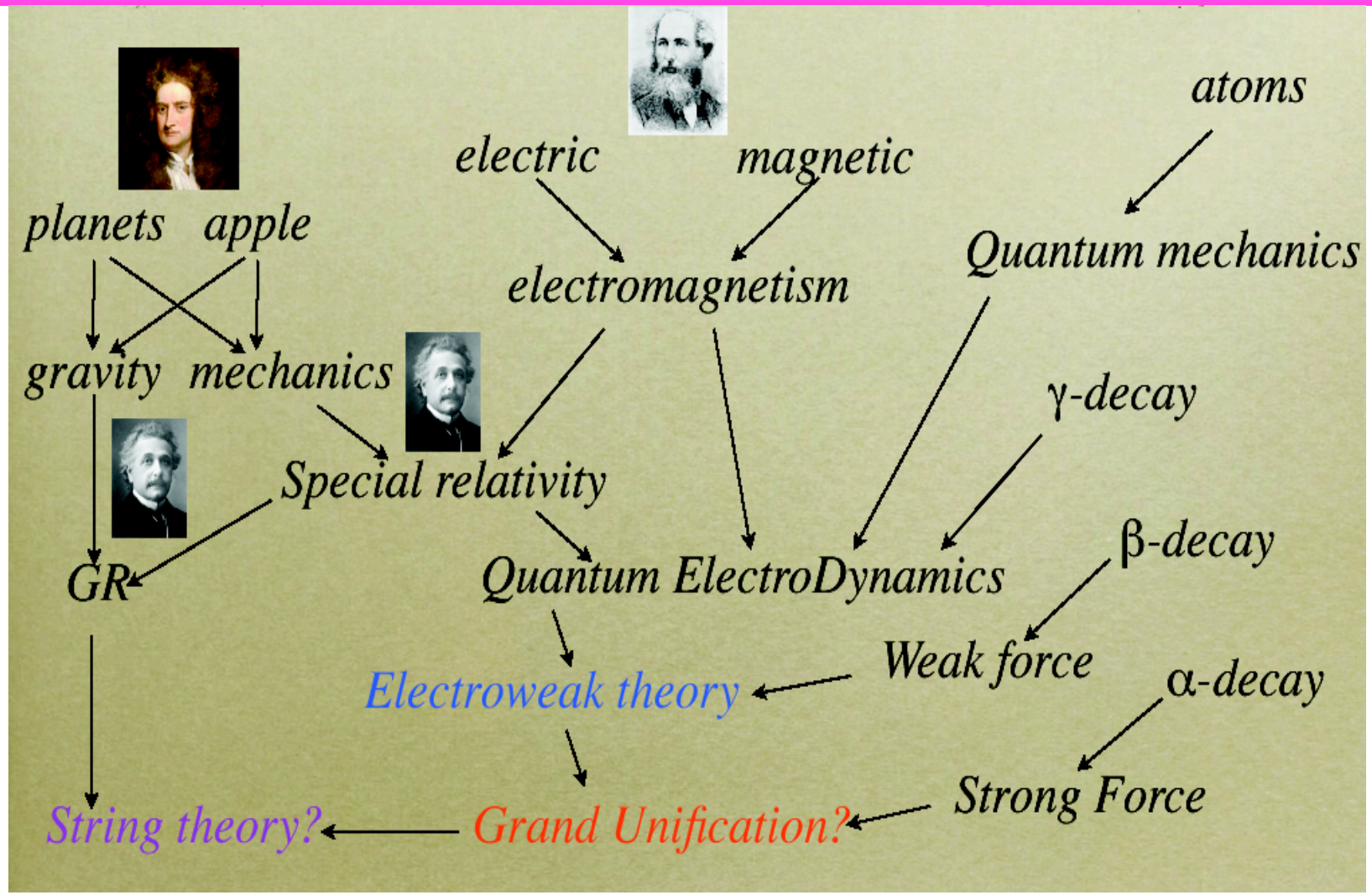
⇒ Particle Physics SM: (amazingly) good description of fundamental interactions down to distances of O (10^{-18} m.)

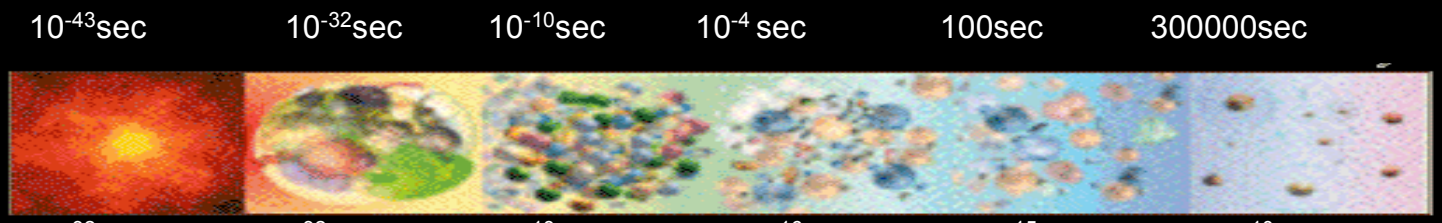
⇒ The Standard Models of Particle Physics and Cosmology confront themselves: reasons for New Physics, chances to detect it in experiments on Earth and in Space

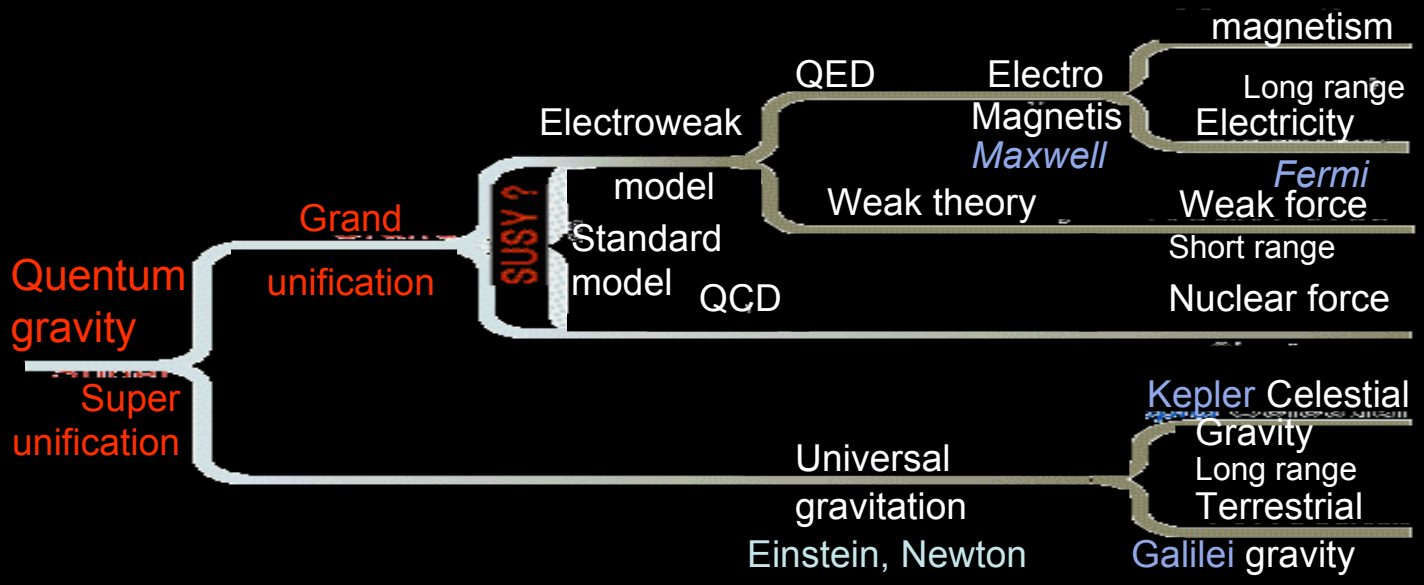
UNIFICATION of FUNDAMENTAL INTERACTIONS

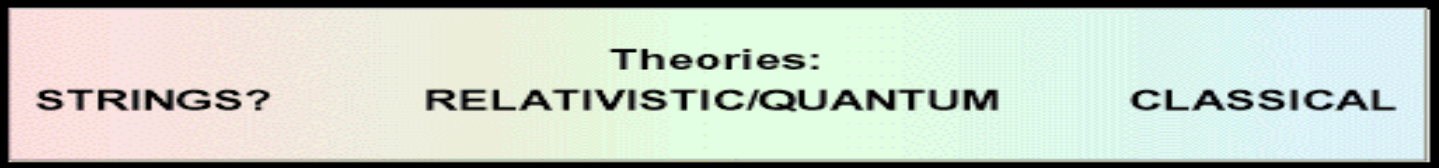


Courtesy of H. Murayama

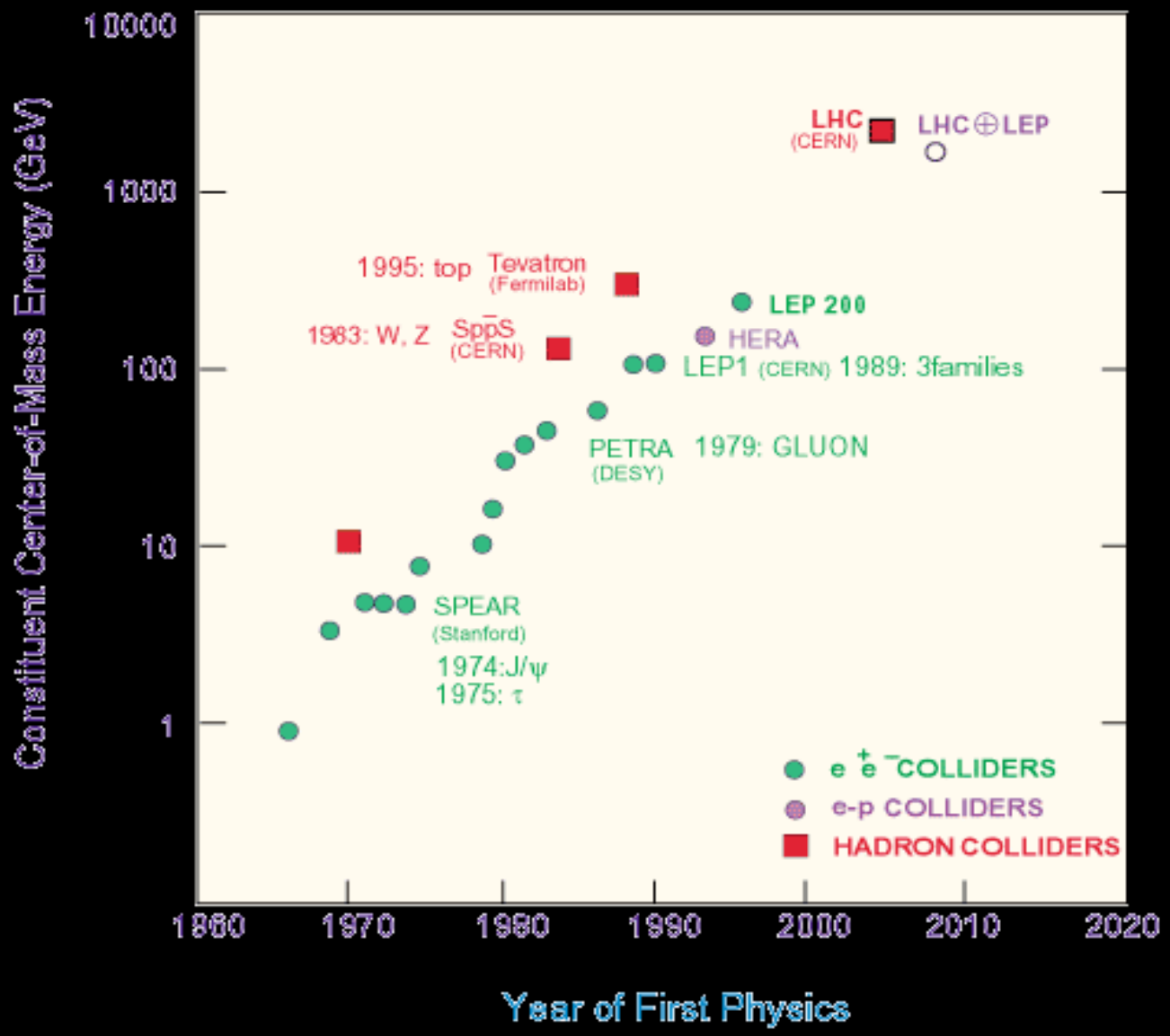
THE STANDARD MODELS AND THEIR SINERGY







Going up in Energy



WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

- HIGH ENERGY PHYSICS

NO (but $A_{FB}^{Z \to bb}$……)

- FCNC, CP≠

NO (but b → $sq\bar{q}$ penguin …)

- HIGH PRECISION LOW-EN.

NO (but $(g-2)_\mu$ …)

- NEUTRINO PHYSICS

YES $m_\nu \neq 0$, $\theta_\nu \neq 0$

- COSMO - PARTICLE PHYSICS

YES (DM, ΔB_{cosm}, INFLAT., DE)

THEORETICAL REASONS

- INTRINSIC INCONSISTENCY OF SM AS QFT

NO (spont. broken gauge theory without anomalies)

- NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

YES (hierarchy, unification, flavor)

TRADITIONAL ROAD TO NEW PHYSICS: HIGH ENERGY

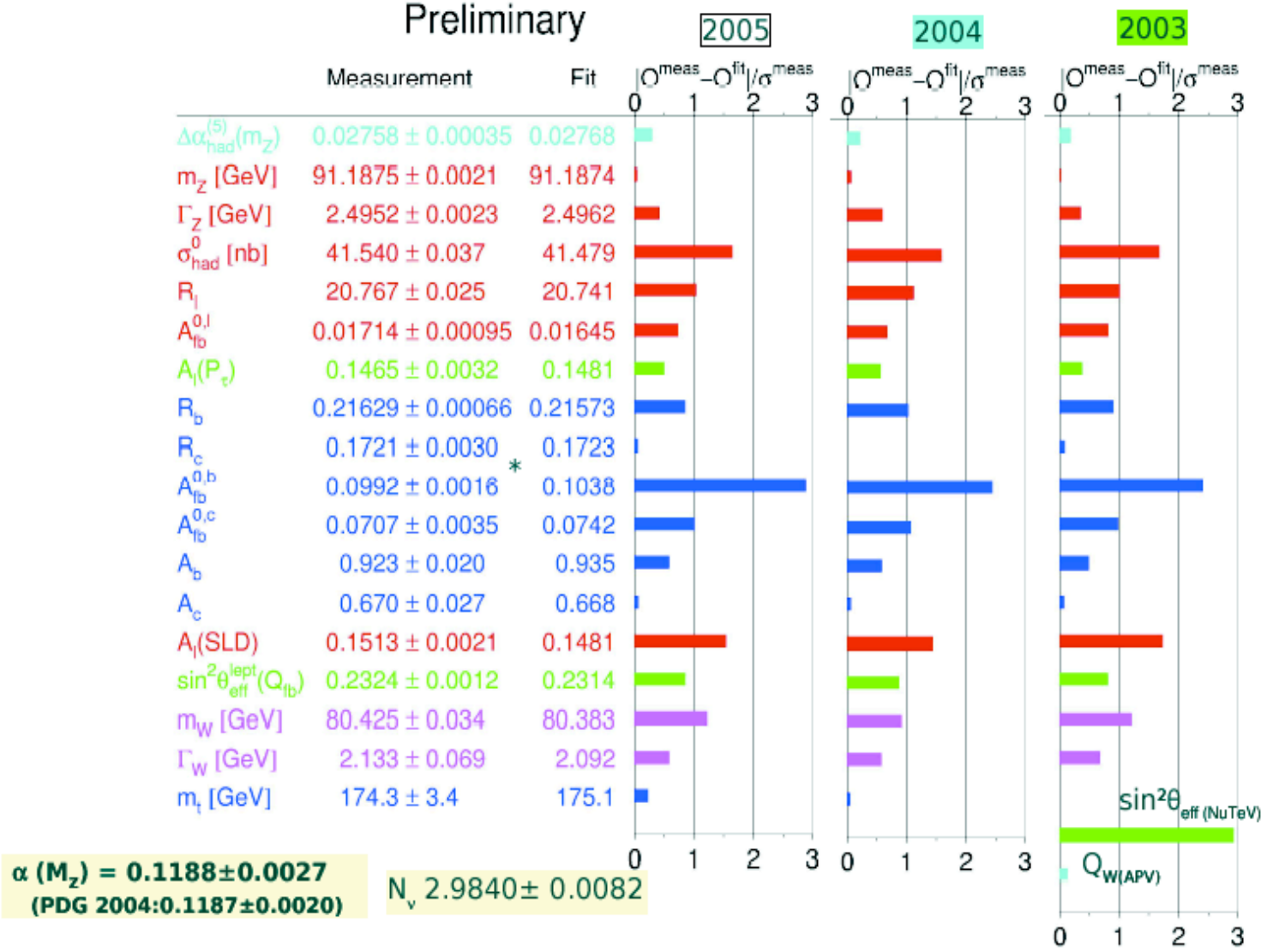
- DISCOVERY 1 : Have enough energy, produce new particles, observe new interactions

-DISCOVERY 2: Precision tests. Probing QFT at the loop level (radiative corrections), observe effects due to the exchange of the new particles at the virtual level, as deviations from what the established theory predicts

- UNDERSTANDING: Measure enough “observables” to reconstruct the theory behind such new phenomena

Electroweak Precision Tests: SM Confirmed!

The EW fit: picture confirmed



$\alpha(M_Z) = 0.1188 \pm 0.0027$
(PDG 2004:0.1187±0.0020)

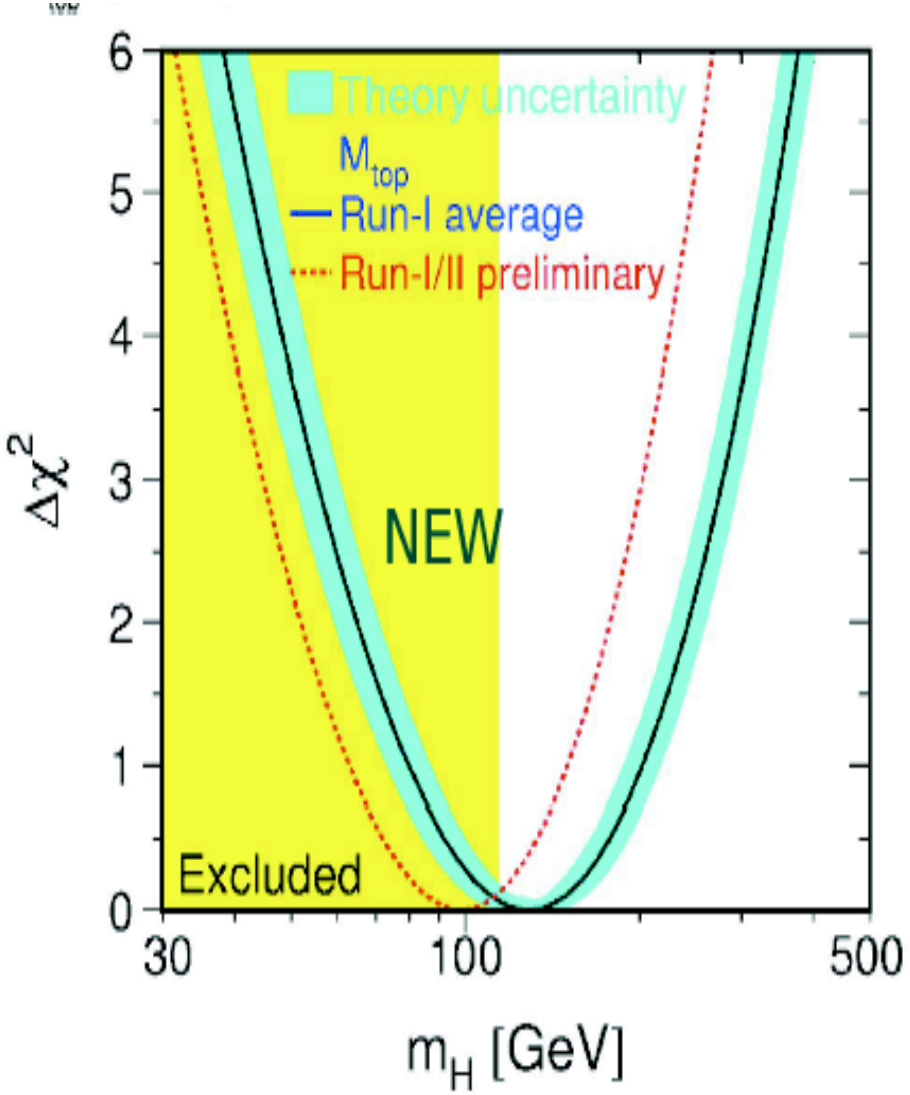
N_ν 2.9840± 0.0082

Where all masses come from: the HIGGS particle

$M_{Higgs} = 98^{+52}_{-26}$ GeV

$M_{higgs} < 208$ GeV @95% C.L.

The Higgs has already "shown up" as a VIRTUAL particle in electroweak radiative effects



NO NEW PARTICLES AND/OR NEW INTERACTIONS BEYOND THE SM HAVE BEEN OBSERVED SO FAR

- Lower bounds on candidate new particles become tighter and tighter

  Ex.: bounds on the masses of the SUSY partners of ordinary particles keep increasing (for colored SUSY particles in 200 - 300 GeV range, for the others in the 100 GeV range)

- Lower bounds on the energy scale where new physics beyond the SM should set in keep increasing

  Ex.: compositeness scale, energy scale at which new dimensions should show up, etc.

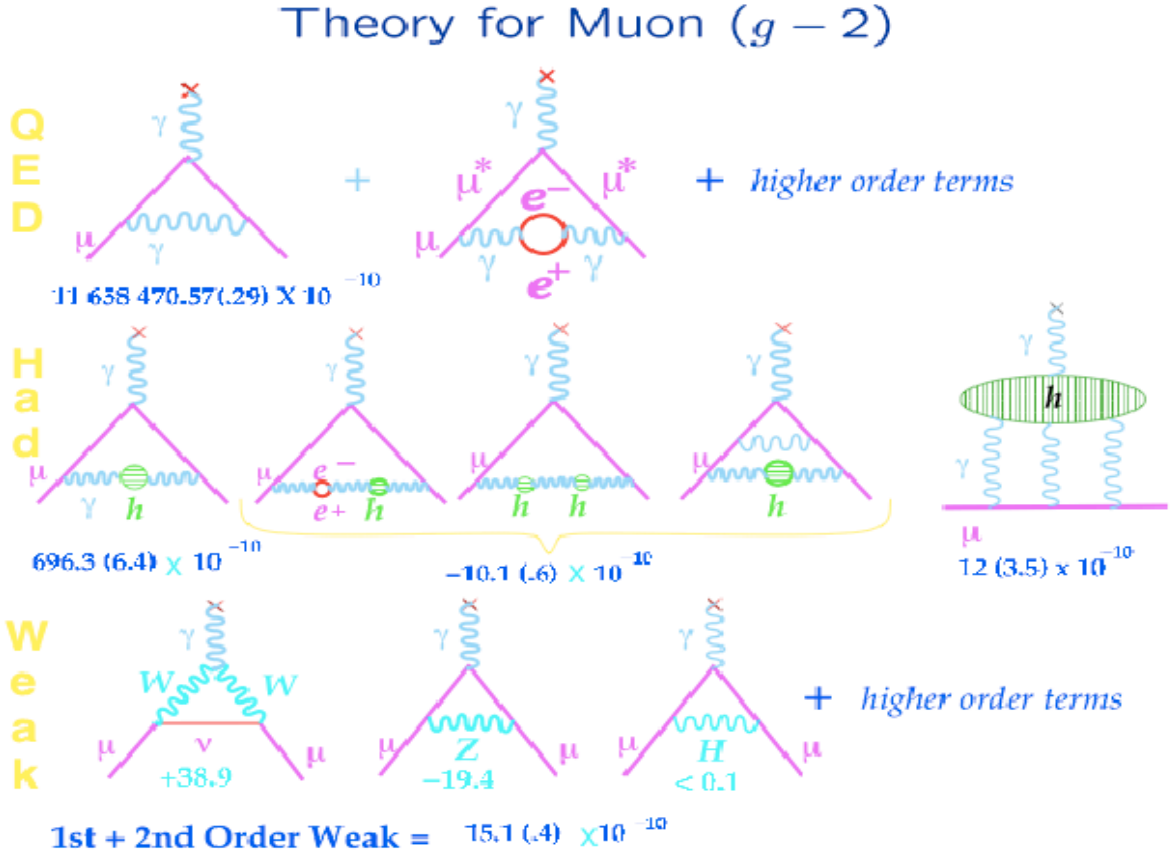
LOW-ENERGY VERY HIGH PRECISION TESTS

- Measuring some low-energy observable with extremely high precision, we can observe effects of deviations from the SM predictions induced by the exchange of new (virtual) particles at the multi-loop level

Best example: the anomalous magnetic moments of electrons and muons

The anomalous magnetic moment of the muon

The BNL g-2 experiment



Flavor Physics: the Triumph of the CKM flavor structure of the SM

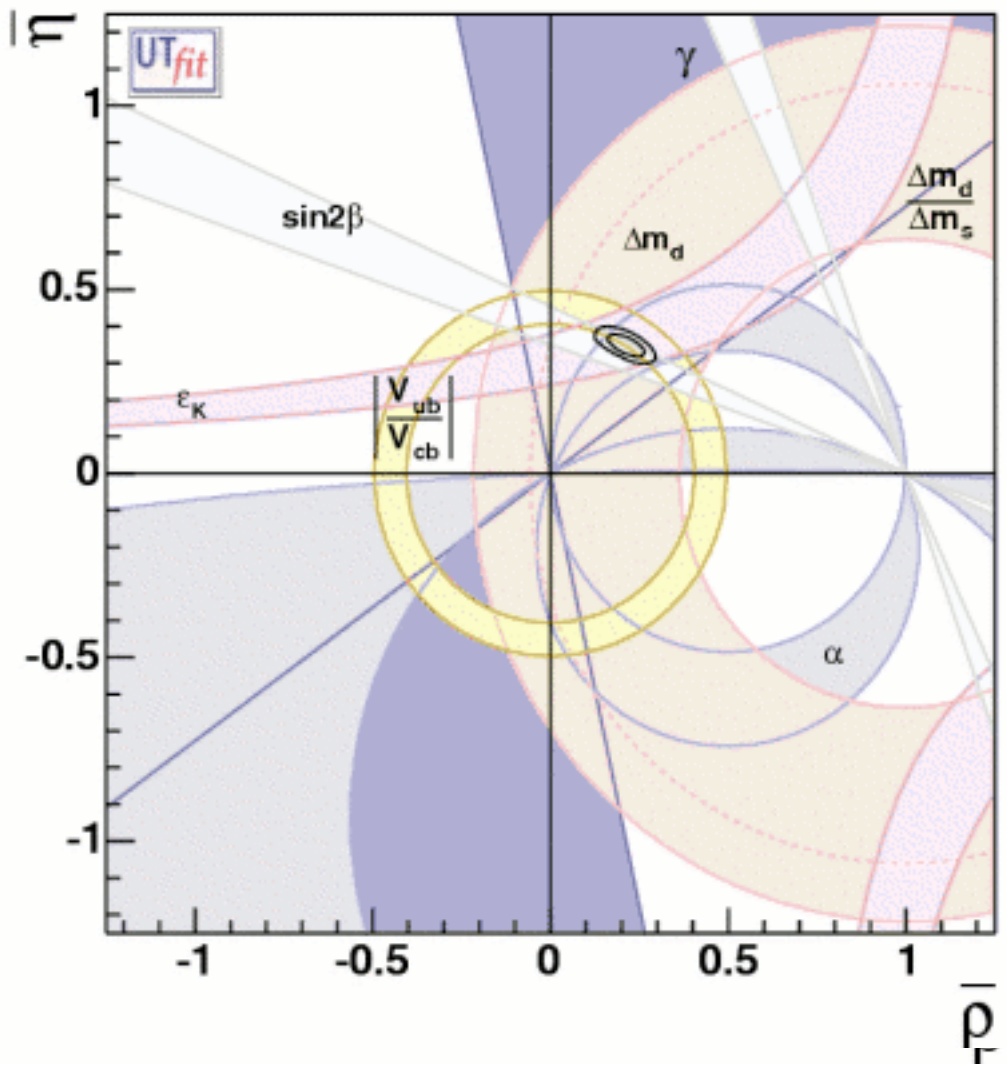
Quark Sector

- *1964 Fitch and Cronin discover CP violation (indirect CP in neutral K)*
- *1999 CPLEAR establishes T violation in K mixing*
- *2000 KTeV/NA48 establish direct CP violation in ε'/ε*
- *2002 BABAR/Belle establish indirect CP violation in B_d meson, confirming Kobayashi-Maskawa theory*

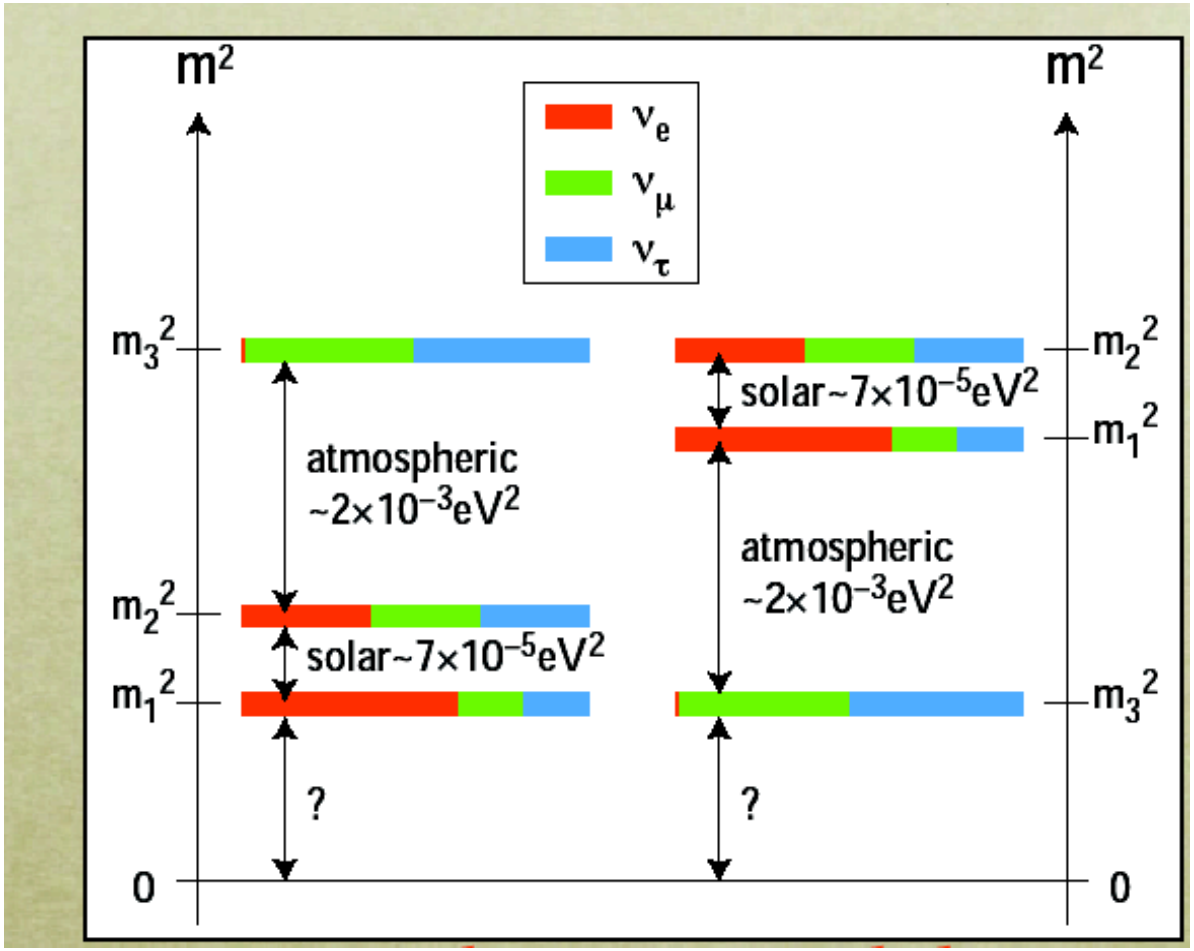
By now we have achieved a "redundant" determination of the CKM mixing elements entering the quark mixing in the SM, i.e. we are probing the validity of the CKM ansatz predicted by the SM

The CKM flavor structure of the SM is the DOMINANT SOURCE of the hadronic flavor mixing (with new physics sources of flavor confined to be not larger than 20% of the CKM source)

PROBING THE CKM PARADIGM OF THE SM THROUGH THE UNITARITY TRIANGLE FIT



Neutrinos are MASSIVE: New Physics IS there!



THE FATE OF LEPTON NUMBER

L VIOLATED

υ Majorana ferm.

SMALLNESS of m_υ

L CONSERVED

υ Dirac ferm.

(dull option)

$h\ \bar{\upsilon}_L H\ \upsilon_R \longrightarrow m_\upsilon = h\ \langle H \rangle$ $\qquad M_\upsilon < 5$ eV $\rightarrow h < 10^{-11}$

EXTRA-DIM. ν_R in the bulk: small overlap?

PRESENCE OF A NEW PHYSICAL MASS SCALE

NEW HIGH SCALE

NEW LOW SCALE

SEE - SAW MECHAN.

Minkowski; Gell-Mann, Ramond, SlansKy, Vanagida

ν_R ENLARGEMENT OF THE FERMIONIC SPECTRUM

$M \upsilon_R \upsilon_R + h\ \upsilon_L \bar{\phi} \upsilon_R$

	υ_L	υ_R
υ_L	~O	$h \langle \bar{\phi} \rangle$
υ_R	$h \langle \bar{\phi} \rangle$	M

LR Models?

MAJORON MODELS

Gelmini, Roncadelli

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

$h\ \upsilon_L \upsilon_L\ \Delta$

$m\upsilon = h \langle \Delta \rangle$

N.B.: EXCLUDED BY LEP!

MICRO

PARTICLE PHYSICS

GWS STANDARD MODEL

MACRO

COSMOLOGY

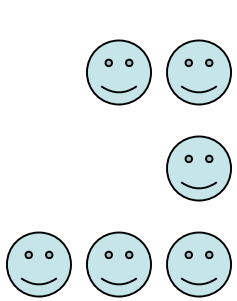
HOT BIG BANG STANDARD MODEL

HAPPY MARRIAGE

Ex: NUCLEOSYNTHESIS

BUT ALSO

POINTS OF FRICTION



-COSMIC MATTER-ANTIMATTER ASYMMETRY

-INFLATION

- DARK MATTER + DARK ENERGY

"OBSERVATIONAL" EVIDENCE FOR NEW PHYSICS BEYOND THE **(PARTICLE PHYSICS)** STANDARD MODEL

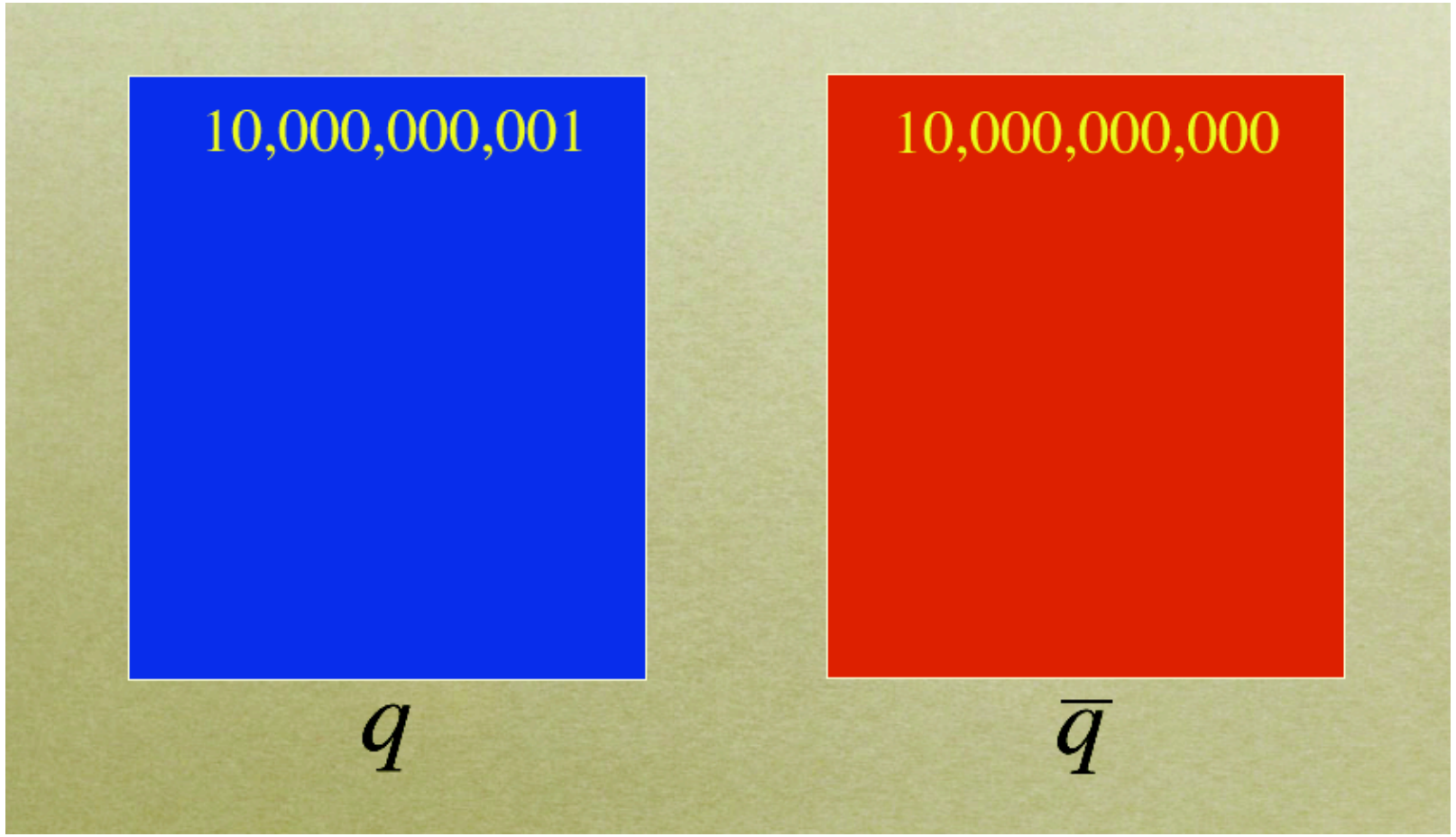
THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$

- NO EVIDENCE OF ANTIMATTER WITHIN THE SOLAR SYSTEM
- ANTIPROTONS IN COSMIC RAYS: IN AGREEMENT WITH PRODUCTION AS SECONDARIES IN COLLISIONS
- IF IN CLUSTER OF GALAXIES WE HAD AN ADMIXTURE OF GALAXIES MADE OF MATTER AND ANTIMATTER ⟶ THE PHOTON FLUX PRODUCED BY MATTER-ANTIMATTER ANNIHILATION IN THE CLUSTER WOULD EXCEED THE OBSERVED GAMMA FLUX
- IF $N_{ba.} = N_{antibar}$ AND NO SEPARATION WELL BEFORE THEY DECOUPLE . WE WOULD BE LEFT WITH $N_{bar.}/N_{photon} << 10^{-10}$
- IF BARYONS-ANTIBARYONS ARE SEPARATED EARLIER ⟶ DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

↓

- ONLY MATTER IS PRESENT
- HOW TO DYNAMICALLY PRODUCE A BARYON-ANTIBARYON ASYMMETRY STARTING FROM A SYMMETRIC SITUATION

COSMIC MATTER-ANTIMATTER ASYMMETRY



Murayama

SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

- SM DOES NOT SATISFY AT LEAST TWO OF THE THREE SACHAROV'S NECESSARY CONDITIONS FOR A DYNAMICAL BARYOGENESIS:

- NOT ENOUGH CP VIOLATION IN THE SM → NEED FOR NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX
- FOR $M_{HIGGS} > 80$ GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

→ NEED NEW PHYSICS BEYOND SM. IN PARTICULAR, FASCINATING POSSIBILITY: THE ENTIRE MATTER IN THE UNIVERSE ORIGINATES FROM THE SAME MECHANISM RESPONSIBLE FOR THE EXTREME SMALLNESS OF NEUTRINO MASSES

MATTER-ANTIMATTER ASYMMETRY ⟷ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

- Key-ingredient of the SEE-SAW mechanism for neutrino masses: large Majorana mass for RIGHT-HANDED neutrino
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such LEPTON ASYMMETRY can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (Fukugita-Yanagida mechanism for leptogenesis)

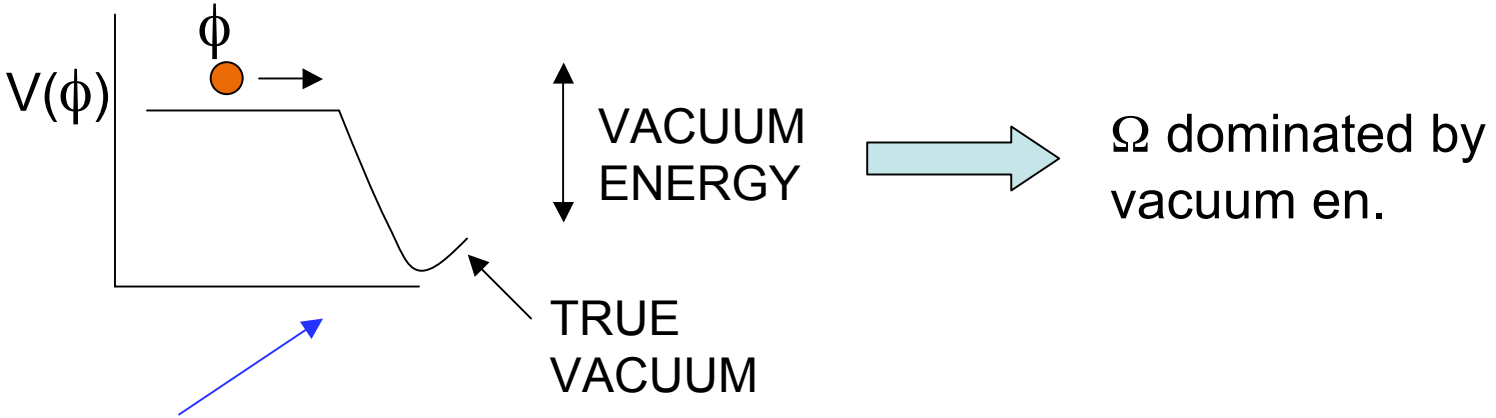
INFLATION

SEVERE COSMOGICAL PROBLEMS

- CAUSALITY (isotropy of CMBR)
- FLATNESS (Ω close to 1 today)
- AGE OF THE UNIV.
- PRIMORDIAL MONOPOLES

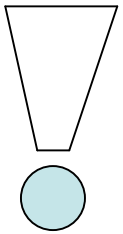
COMMON SOLUTION FOR THESE PROBLEMS

VERY FAST (EXPONENTIAL) EXPANSION IN THE UNIV.



NO WAY TO GET AN "INFLATIONARY SCALAR POTENTIAL" IN THE STANDARD MODEL

NO ROOM IN THE PARTICLE PHYSICS STANDARD MODEL FOR INFLATION



$V=\mu^2 \phi^2 + \lambda\phi^4 \longrightarrow$ no inflation

Need to extend the SM scalar potential

Ex: GUT's, SUSY GUT's,…

ENERGY SCALE OF "INFLATIONARY PHYSICS":

LIKELY TO BE » Mw

DIFFICULT BUT NOT IMPOSSIBLE TO OBTAIN ELECTROWEAK INFLATION IN SM EXTENSIONS

The dark components of the Universe as the most pressing cry for NEW PHYSICS BEYOND THE PARTICLE PHYSICS SM

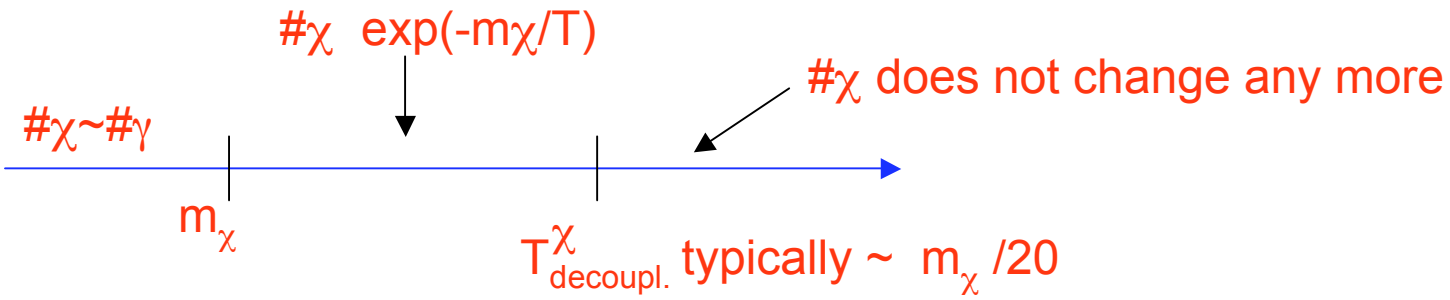
Ω_{DM}= 23% ± 4% ; Ω_B= 4% ± 0.4%; Ω_Λ = 73% ± 4%

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of New Physics beyond SM

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B → EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM

- QUALITATIVE: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD → NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM !

WIMPS (Weakly Interacting Massive Particles)



Ω_χ depends on particle physics ($\sigma^{\chi}_{annih.}$) and "cosmological" quantities (H, T_0, …

$$\Omega\chi\, h^2 \simeq \frac{10^{-3}}{\langle(\sigma_{annih.})\, V\, \chi\rangle \quad TeV^2}$$

$\langle(\sigma_{annih.})\, V\, \chi\rangle \sim \alpha^2 / M^2\chi$

TeV^2 → From $T^0\, M_{plaeli}$

$\Omega\chi h^2$ in the range 10^{-2} -10^{-1} to be cosmologically interesting (for DM)

$m\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\Omega\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) ENLARGEMENT OF THE SM	(x^μ, θ) Anticomm. Coord.	(x^μ, j^i) New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) SELECTION RULE	R-PARITY LSP	KK-PARITY LKP	T-PARITY LTP
→ DISCRETE SYMM.	Neutralino spin 1/2	spin1	spin0
→ STABLE NEW PART.	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE "L" NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV *	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

* But abandoning gaugino-masss unif. → Possible to have m_{LSP} down to 7 GeV

Bottino, Donato, Fornengo, Scopel

NATURALNESS OF STABLE WIMPS IN TeV NEW PHYSICS
or
CAN WE BUY 2 AND PAY 1

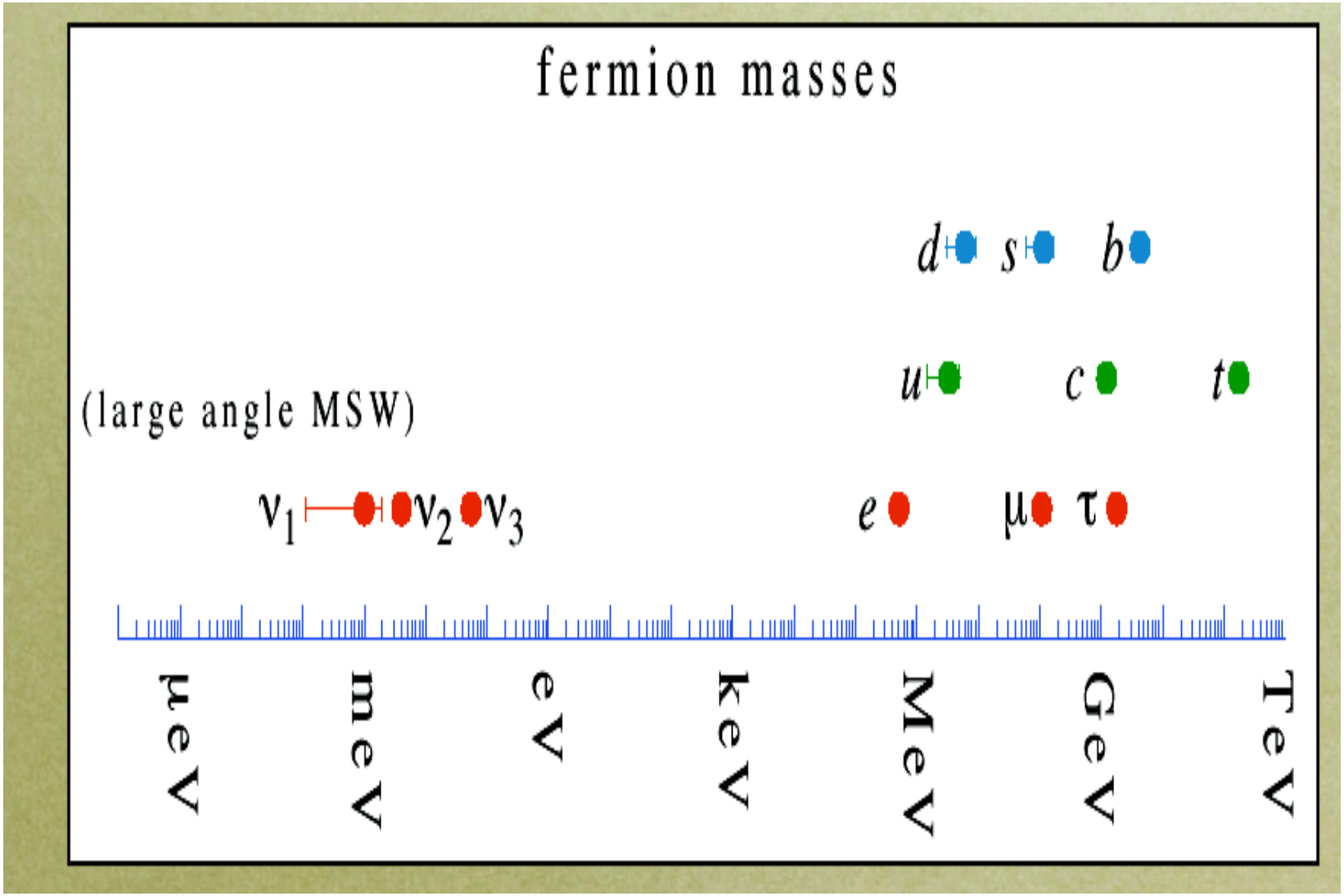
TeV New Physics needed if you consider the gauge hierarchy issue a real problem ⟶ need for an "ultraviolet completion" of the SM to yield an ultraviolet cut-off to the growth of the Higgs mass.

Such ultraviolet completion may cause severe phenomenological problems (new particles and interaction terms at the TeV scale).

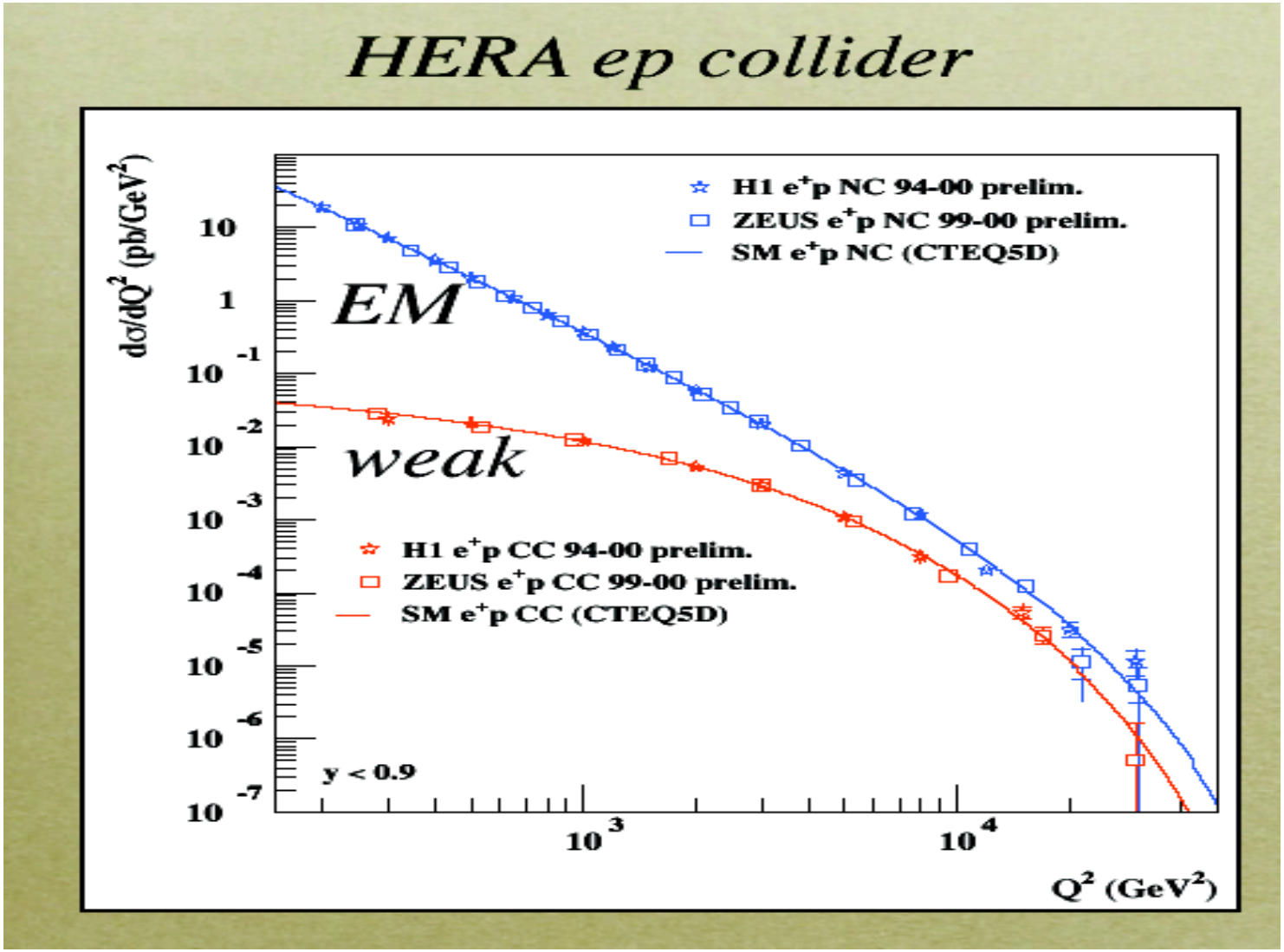
Example: low-energy SUSY ⟶ new particles (sfermions) carry baryon (squarks) or lepton (sleptons) quantum numbers. It becomes possible to construct dim.4 operators which violate either B or L. Simultaneous presence of B and L violating operators leads to four fermion operators inducing proton decay with the mediation of SUSY (TeV!!!) particles

NEED A SELECTION RULE TO PREVENT SUCH FATAL OPERATORS

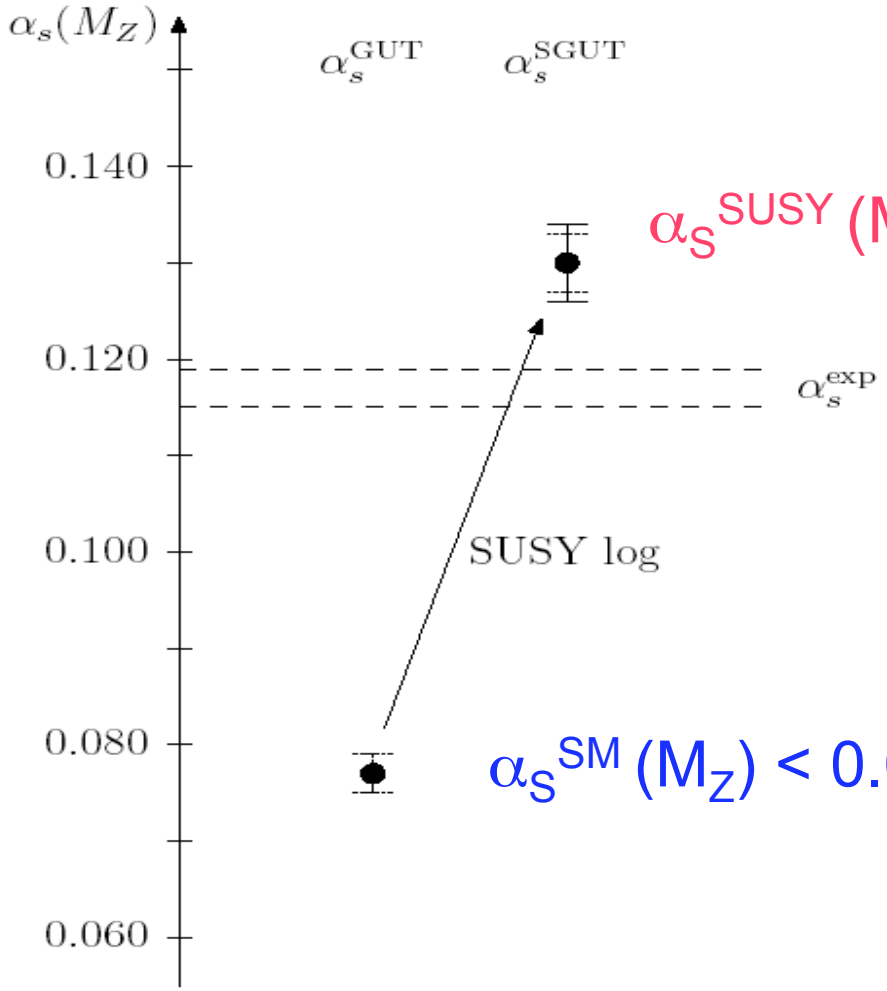
THE FERMION MASS PUZZLE



Fundamental COUPLING CONSTANTS are NOT CONSTANT



Fundamental interactions unify



$\alpha_S^{SUSY}(M_Z)$

$\alpha_S^{exp}(M_Z)=0.117\pm0.002$

$\alpha_S^{SM}(M_Z) < 0.080$

Hall, Nomura

"MASS PROTECTION"

For FERMIONS, VECTOR (GAUGE) and SCALAR BOSONS

SIMMETRY PROTECTION

- -FERMIONS → chiral symmetry
  f_L f_R not invariant under SU(2)x U(1)
- -VECTOR BOSONS → gauge symmetry

→ FERMIONS and W,Z VECTOR BOSONS can get a mass only when the elw. symmetry is broken m_f, $m_w \leq \langle H \rangle$

NO SYMMETRY PROTECTION FOR SCALAR MASSES

"INDUCED MASS PROTECTION"

→ Create a symmetry (SUPERSIMMETRY)
Such that FERMIONS ⟷ BONUS

So that the fermion mass "protection" acts also on bosons as long as SUSY is exact

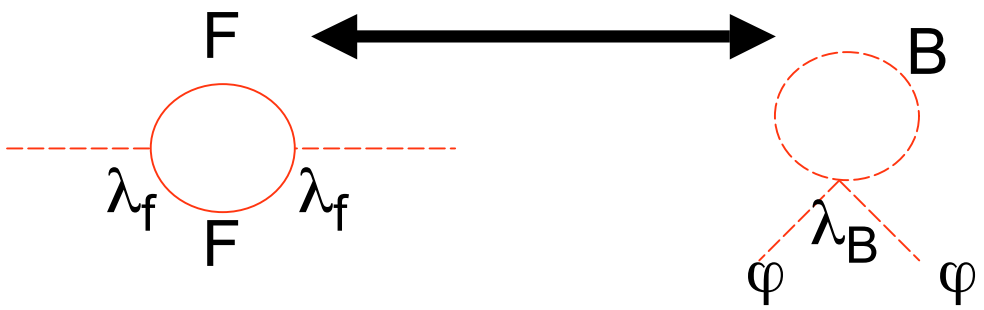
⇒ SUSY BRAKING ~ SCALE OF 0 (10^2-10^3 Gev)

→ LOW ENERGY SUSY

HIERARCHY PROBLEM: THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1TeV ⟶ LOW ENERGY SUSY

$m_\varphi^2 \propto \Lambda^2$ ⟶ Scale of susy breaking



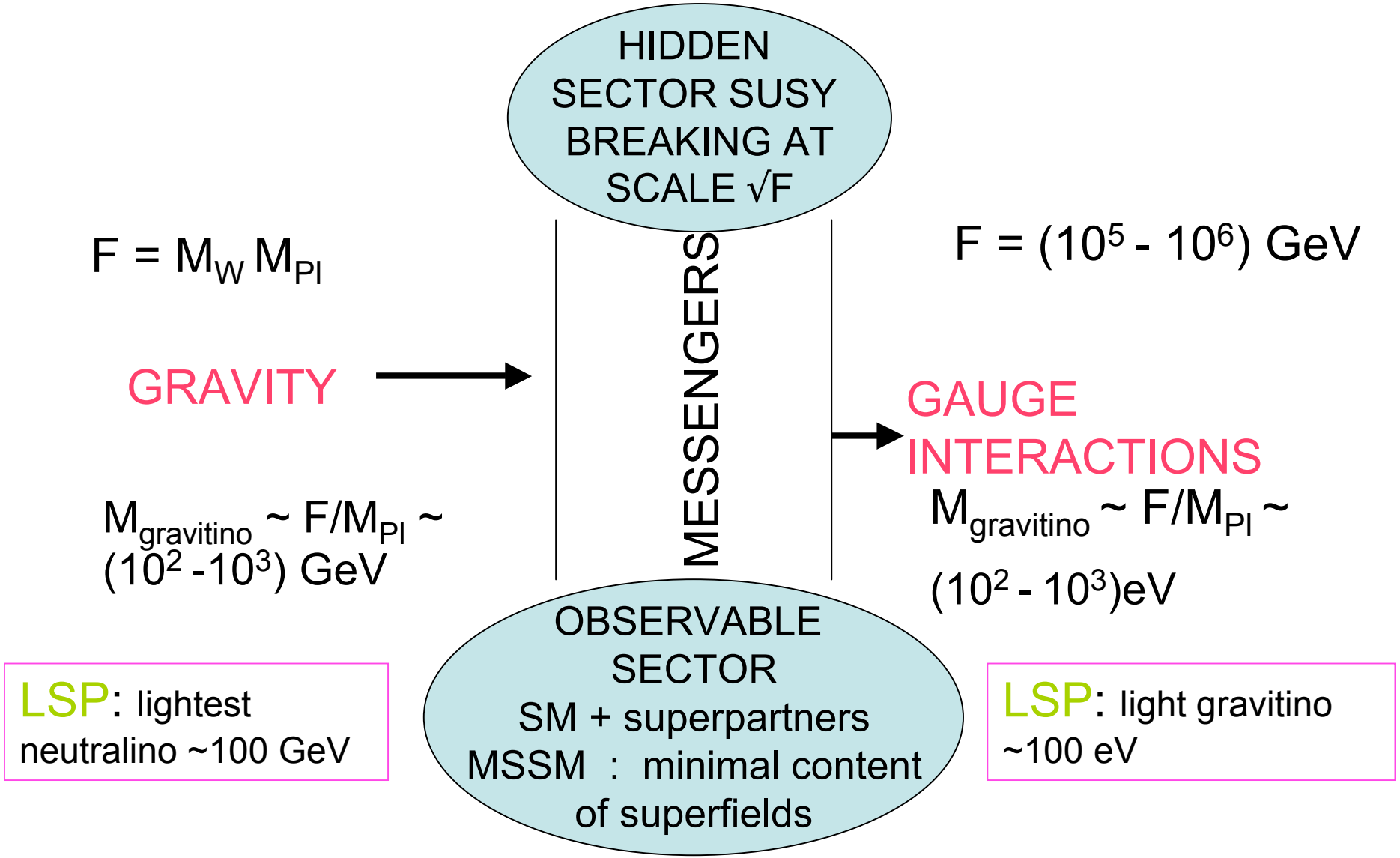
$$Sm^2_{\varphi} \sim \frac{(\lambda_B - \lambda^2_f)}{16\pi^2} \Lambda^2$$

⟶ $[m^2_B - m^2_F]^{1/2} \sim 1/\sqrt{G_F}$

$\begin{pmatrix} B \\ F \end{pmatrix}$ In SUSY multiplet

SPLITTING IN MASS BETWEEN B and F of O (ELW. SCALE)

WHICH SUSY


HIDDEN SECTOR SUSY BREAKING AT SCALE √F
F = $M_W M_{Pl}$
GRAVITY
$M_{gravitino}$ ~ F/M_{Pl} ~ (10^2 -10^3) GeV
MESSENGERS
F = (10^5 - 10^6) GeV
GAUGE INTERACTIONS
$M_{gravitino}$ ~ F/M_{Pl} ~ (10^2 - 10^3)eV
OBSERVABLE SECTOR
SM + superpartners
MSSM : minimal content of superfields
LSP: lightest neutralino ~100 GeV
LSP: light gravitino ~100 eV

MSSM (Minimal SUSY SM)

- Minimal content of SUSY partners to supersymmetrize the SM (2 Higgs doublets required)
- R parity is imposed
- SUSY is broken explicitly, but softly, adding a the most general set of:

i) Scalar masses

ii) Trilinear scalar terms

iii) Gaugino masses

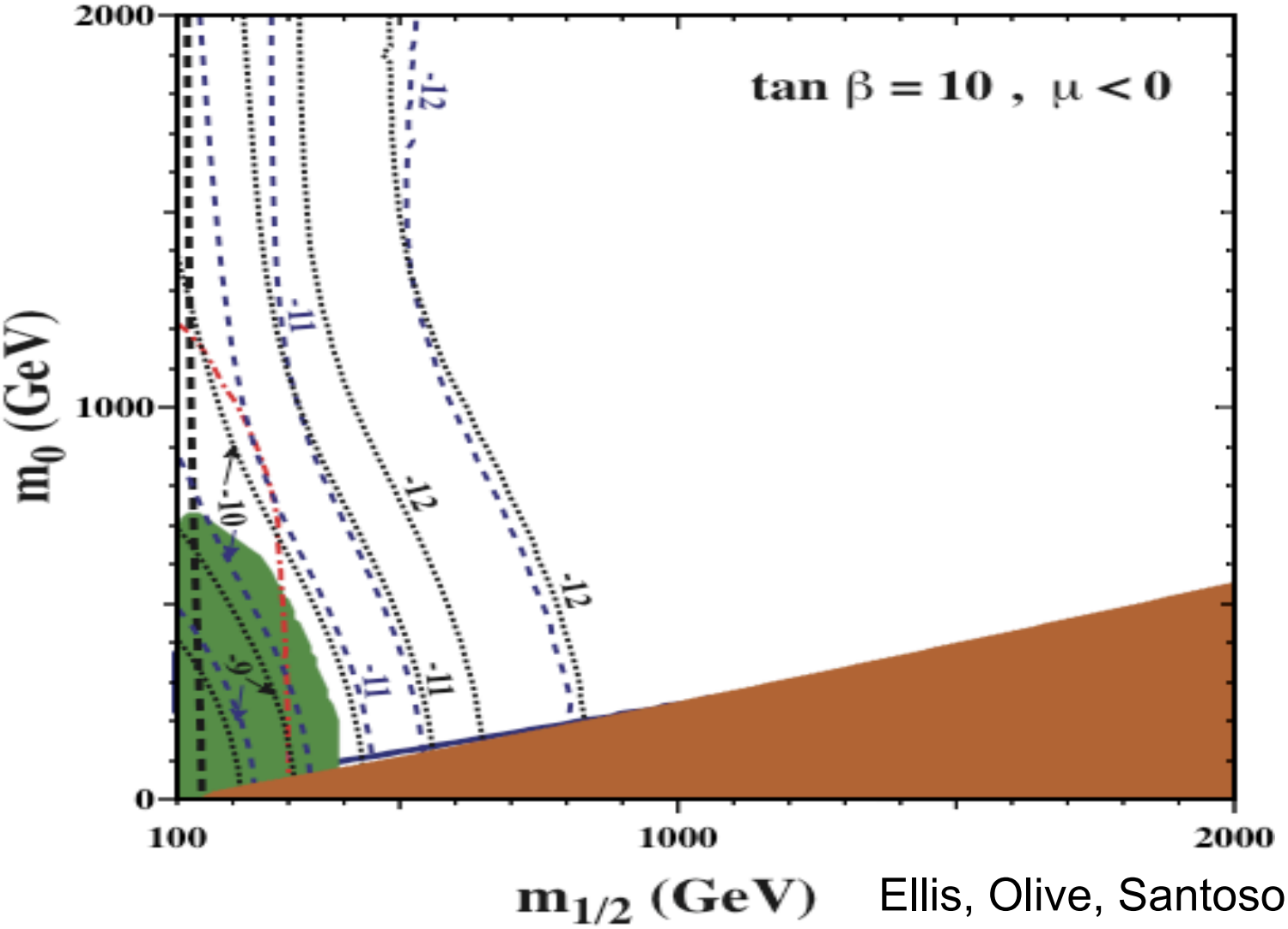
THE MOST GENERAL MSSM EXHIBITS 124 PARAMETERS!

CONSTRAINED MSSM or MINIMAL SUPERGRAVITY (mSUGRA)

Imposing : FLAVOR UNIVERSALITY OF THE SOFT SCALAR TERMS + GAUGINO UNIFICATION

DRASTIC REDUCTION ON THE FREE PARAM.ONLY 5 INDIP. PARAM. + REDUCTION TO 4 IMPOSING THE RADIATIVE BREAKING OF THE ELW. SYMMETRY

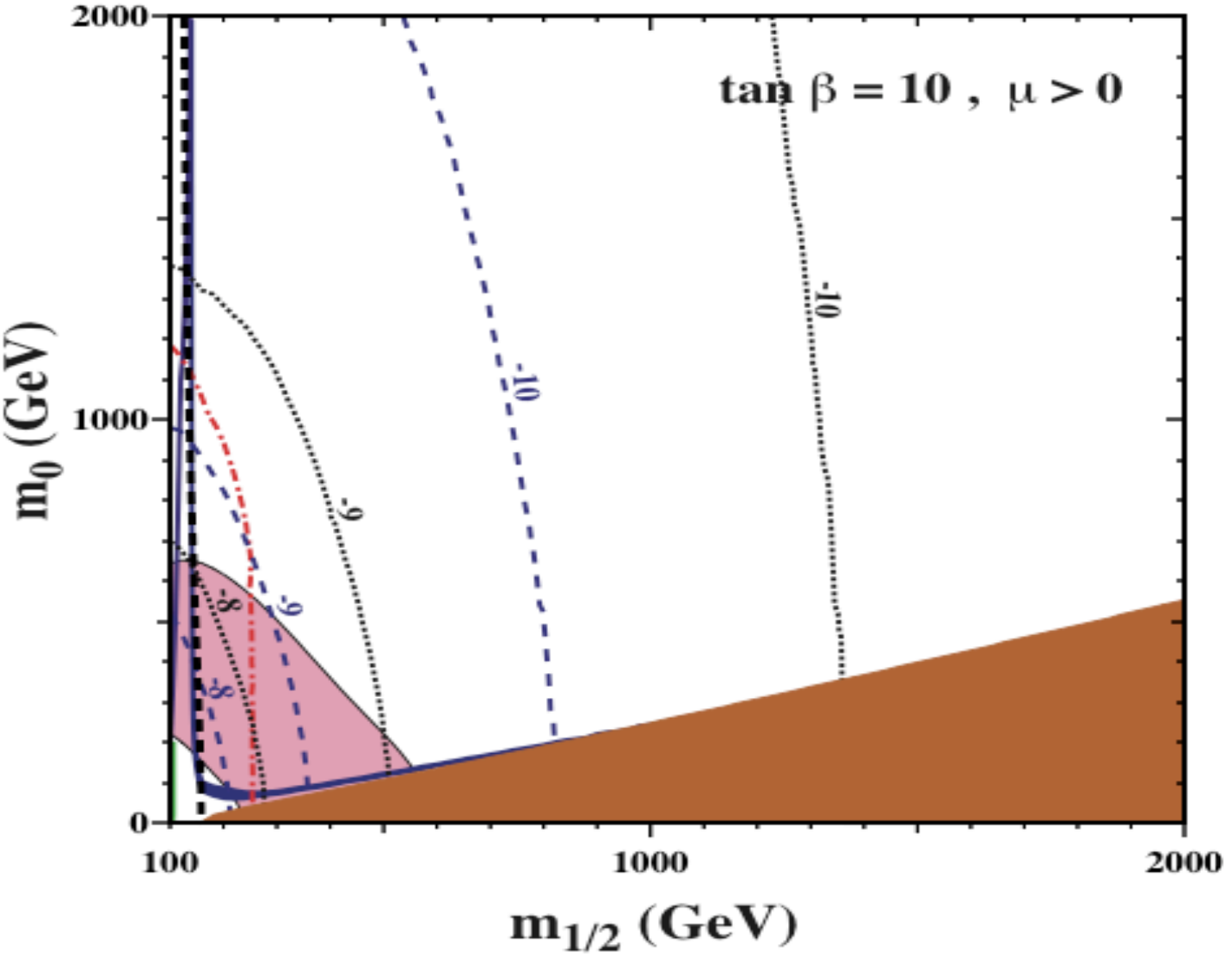
Tightness of the DM constraint on minimal supergravity



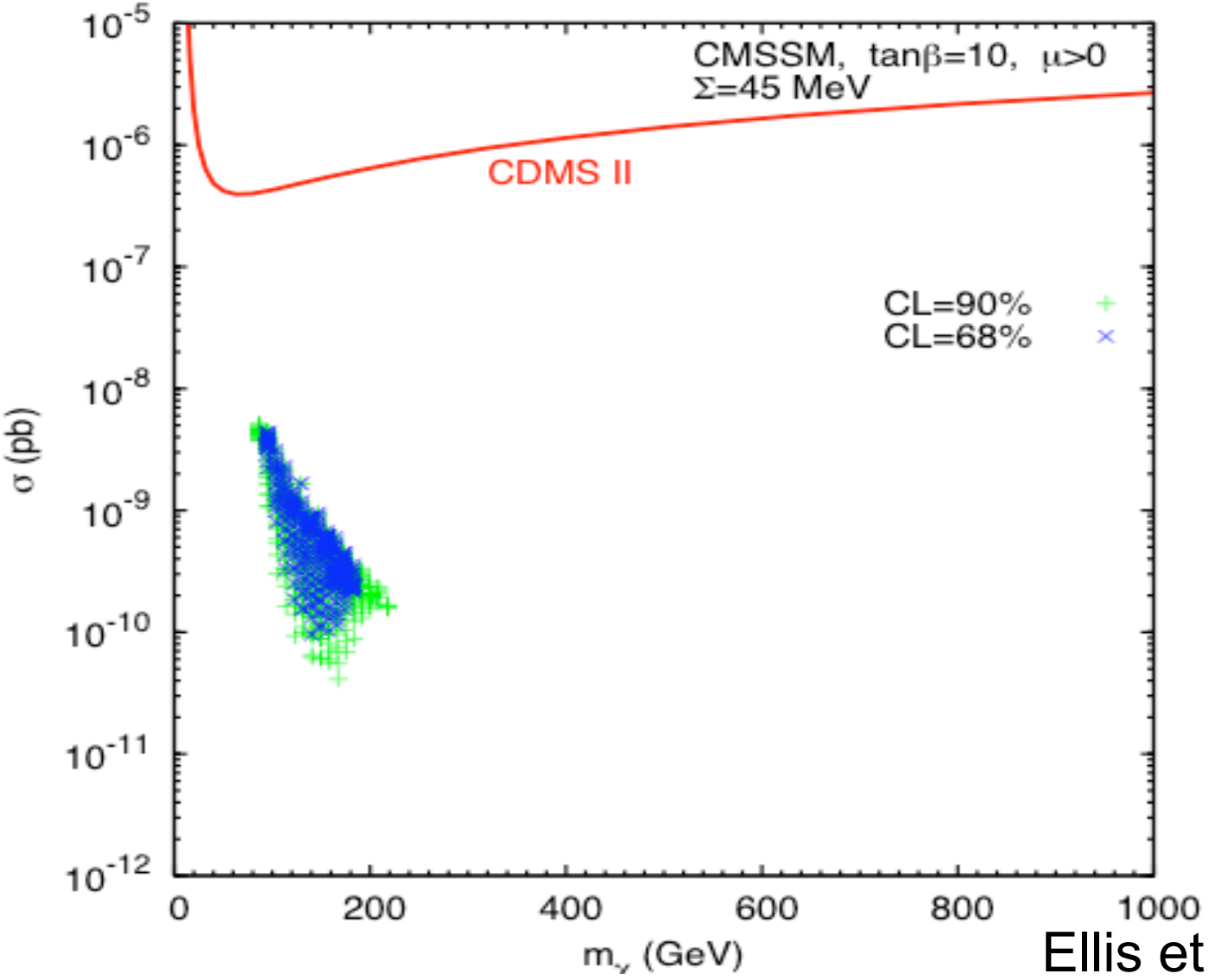
Ellis, Olive, Santoso, Spanos

Tightness of the DM constraints in Minimal Supergravity

Ellis et al.

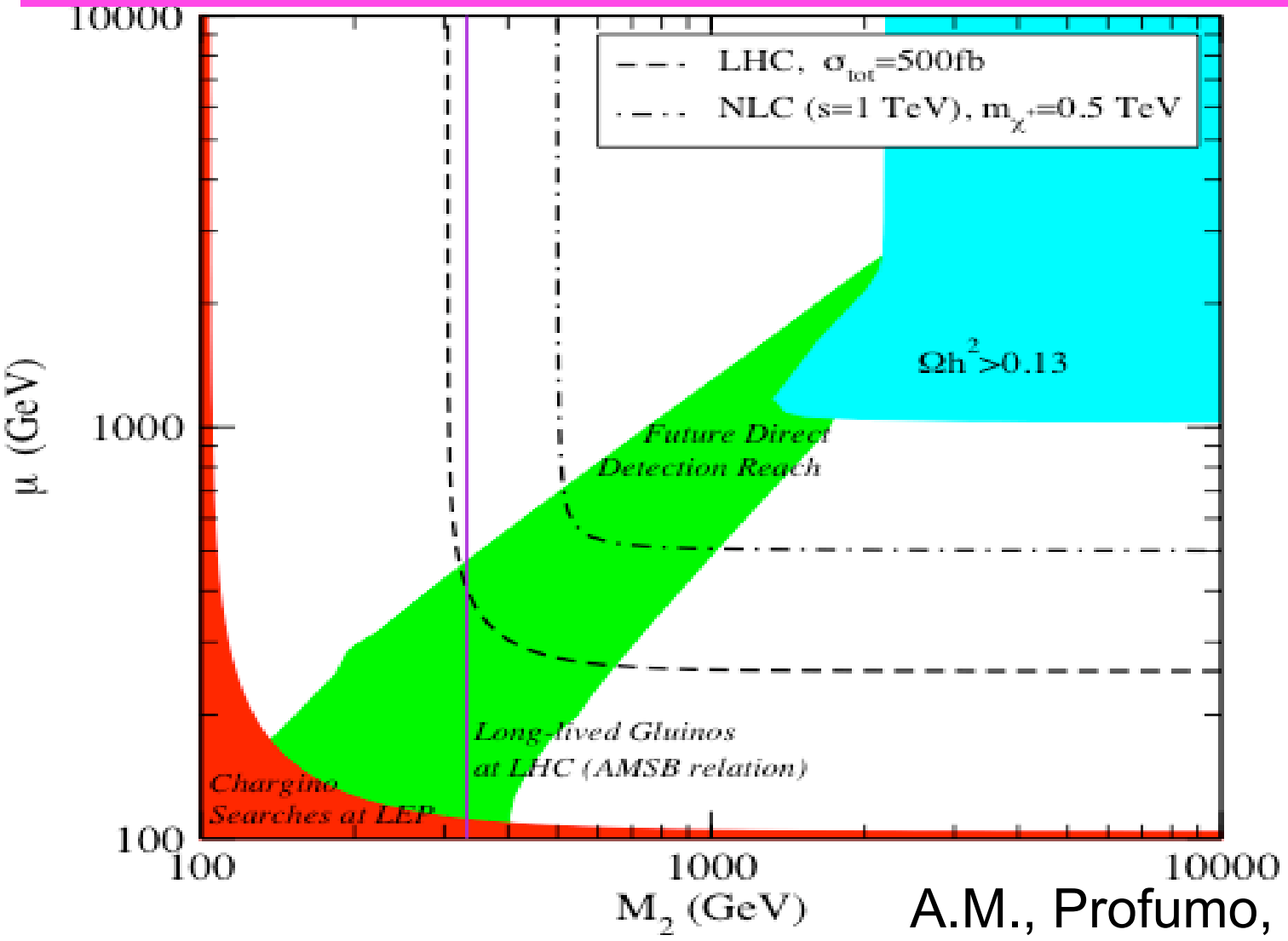


DM SUSY:HOW FAR ARE WE IN DIRECT SEARCHES?



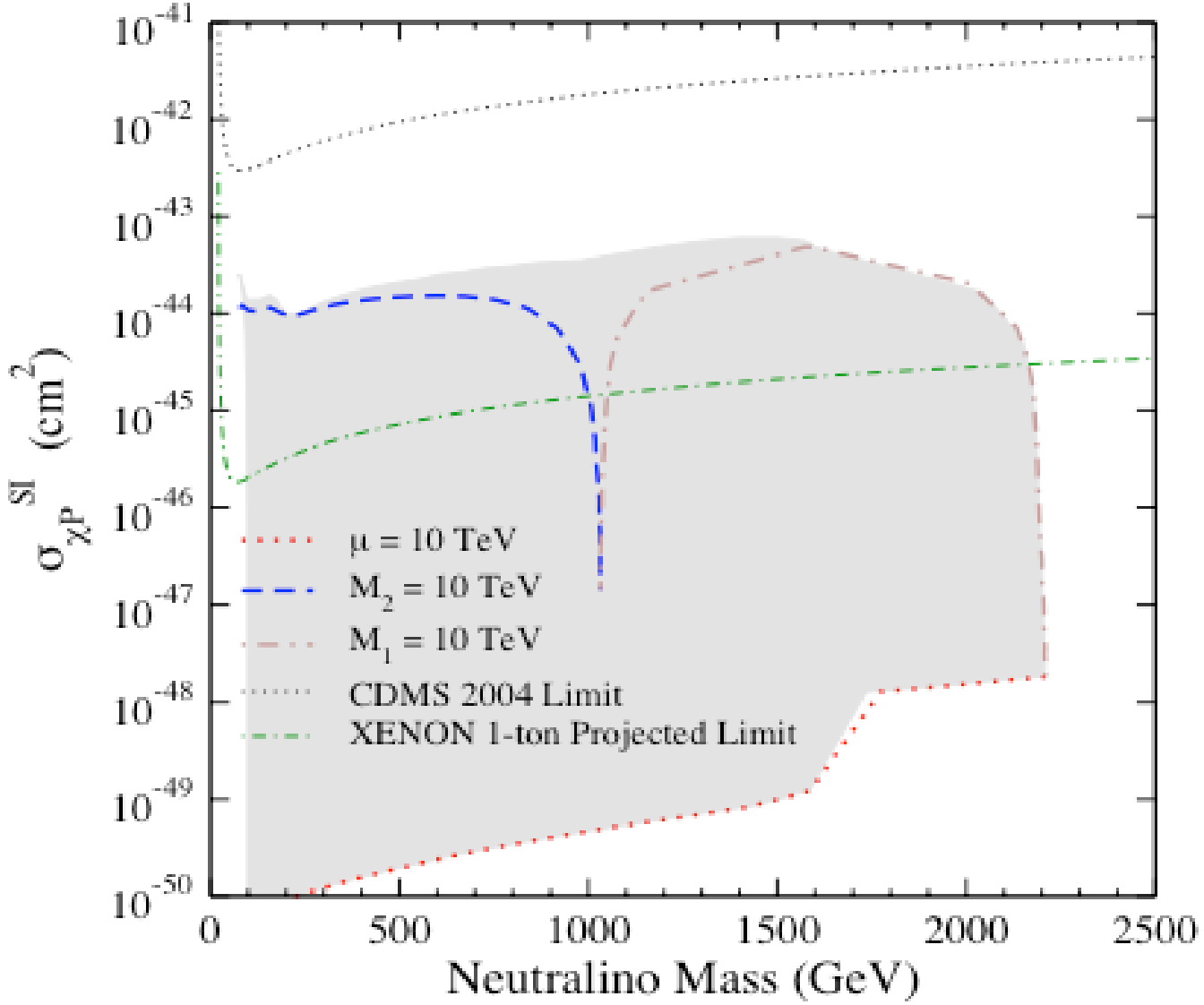
Ellis et al.

LHC, ILC, DM SEARCHES SENSITIVITIES



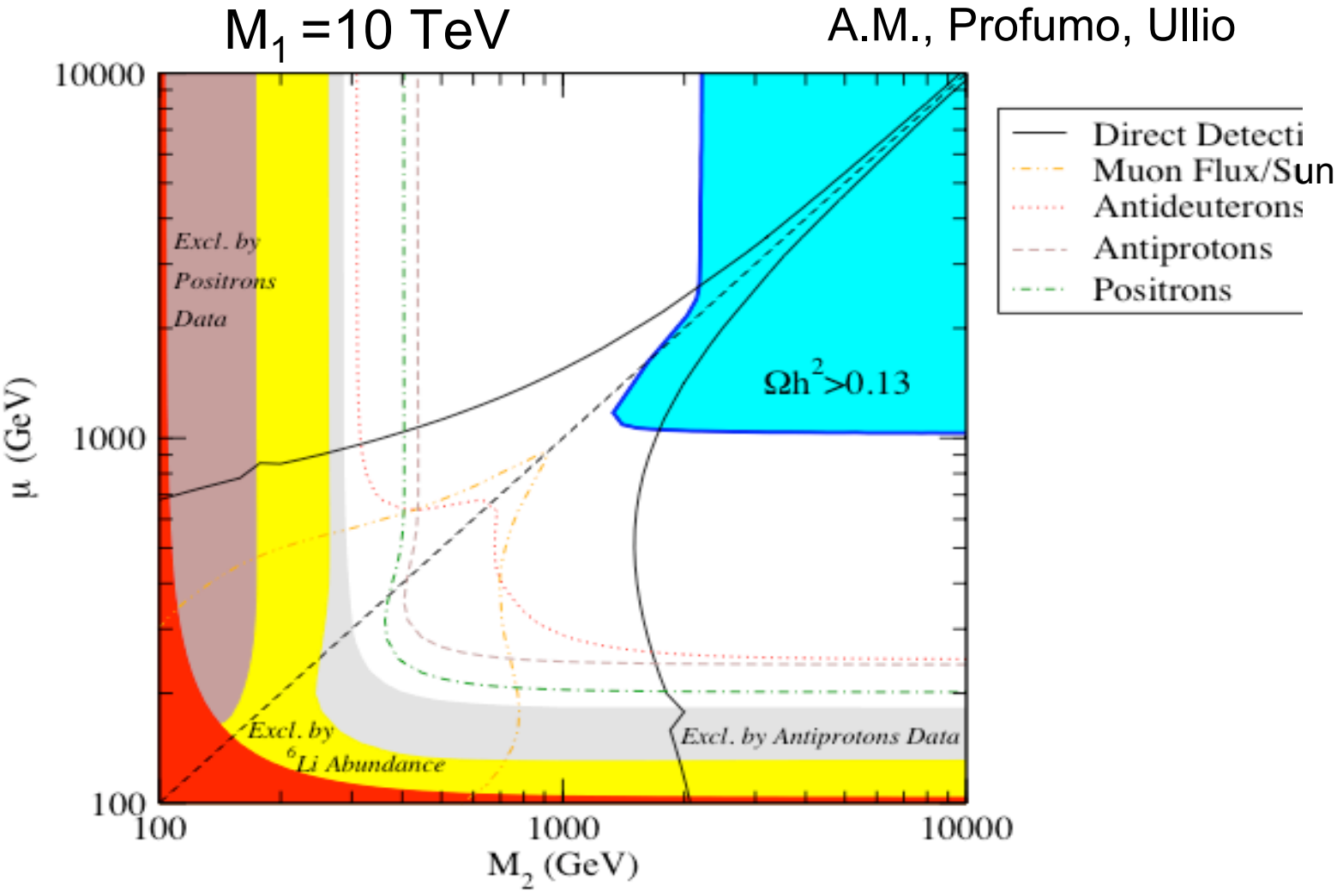
A.M., Profumo, Ullio

PRESENT AND NEXT GENERATION DM SEARCHES (TeV SUSY case)



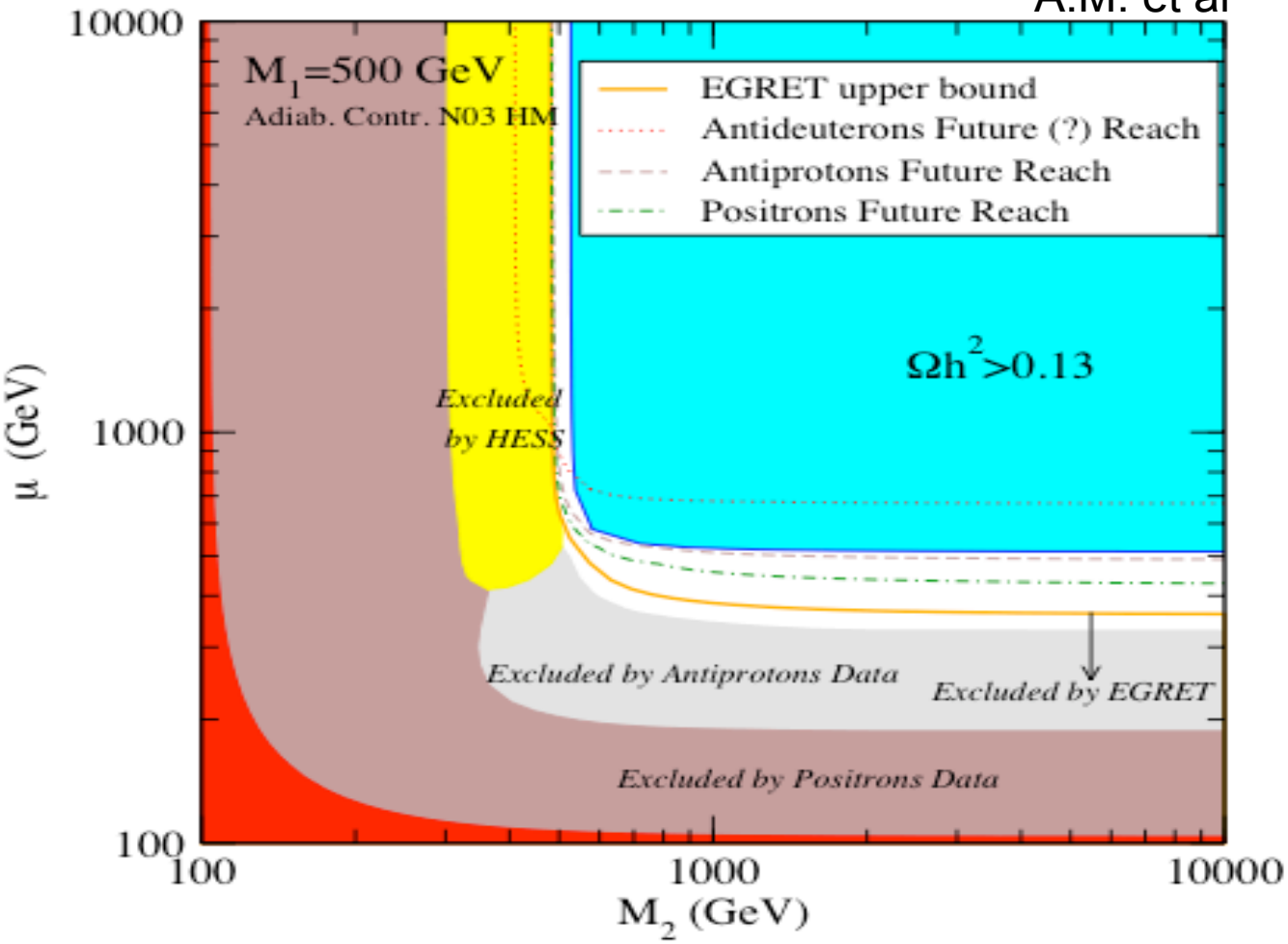
A.M, Profumo, Ullio

COMPLEMENTARITY OF DIRECT AND INDIRECT DM SEARCHES

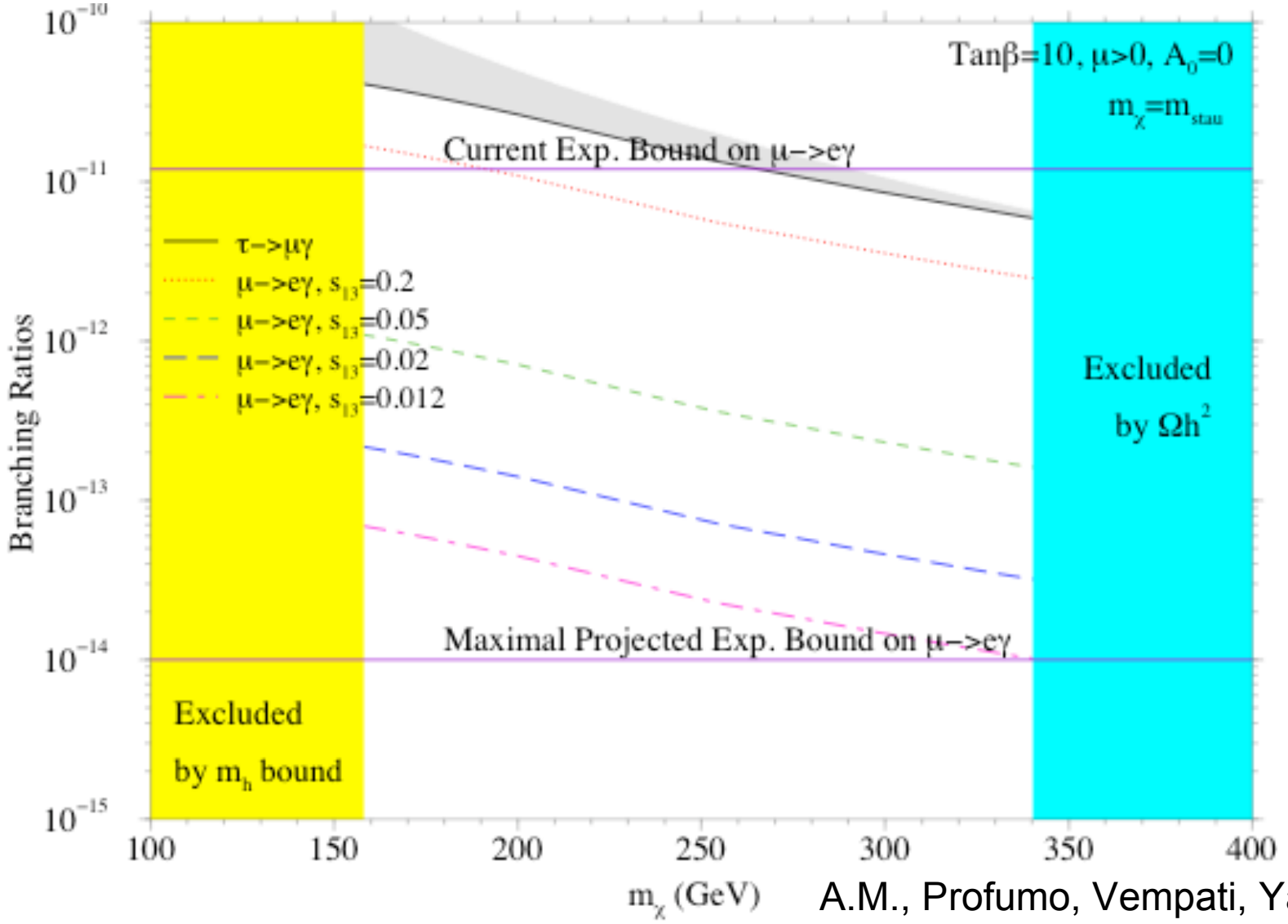


EXPLORATION OF THE SUSY PARAMETER SPACE USING DIRECT AND INDIRECT DM SEARCHES

A.M. et al



PROBING SUSY THROUGH LFV



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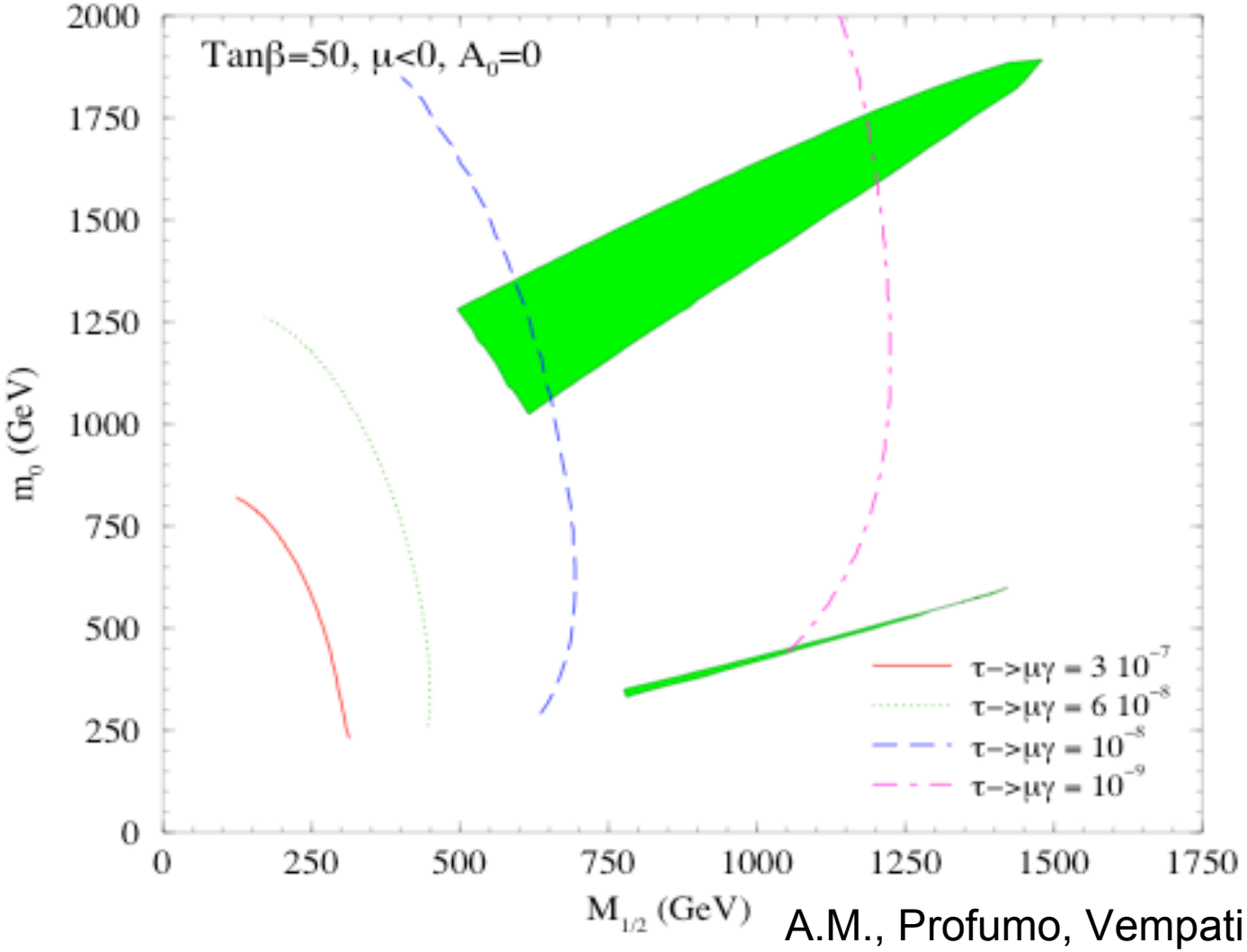
LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



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SEARCHING FOR WIMPs

WIMPS HYPOTHESIS

DM made of partcles with mass 10Gev - 1Tev

ELW scale

With WEAK INTERACT

LHC, ILC may PRODUCE WIMPS

WIMPS escape the detector → MISSING ENERGY SIGNATURE

FROM "KNOW" COSM. ABUNDANCE OF WIMPs → PREDICTION FOR WIMP PRODUCTION AT COLLIDERS WITHOUT SPECYFING THE PART. PHYSICS MODEL OF WIMPs

BIRKEDAL, MATCHEV, PERELSTEIN , FENG,SU, TAKAYAMA

DO THEY "KNOW" EACH OTHER?

- DIRECT INTERACTION ϕ (quintessence) WITH DARK MATTER

DANGER:
ϕ Very LIGHT
$m\phi \sim H_0^{-1} \sim 10^{-33}$ eV

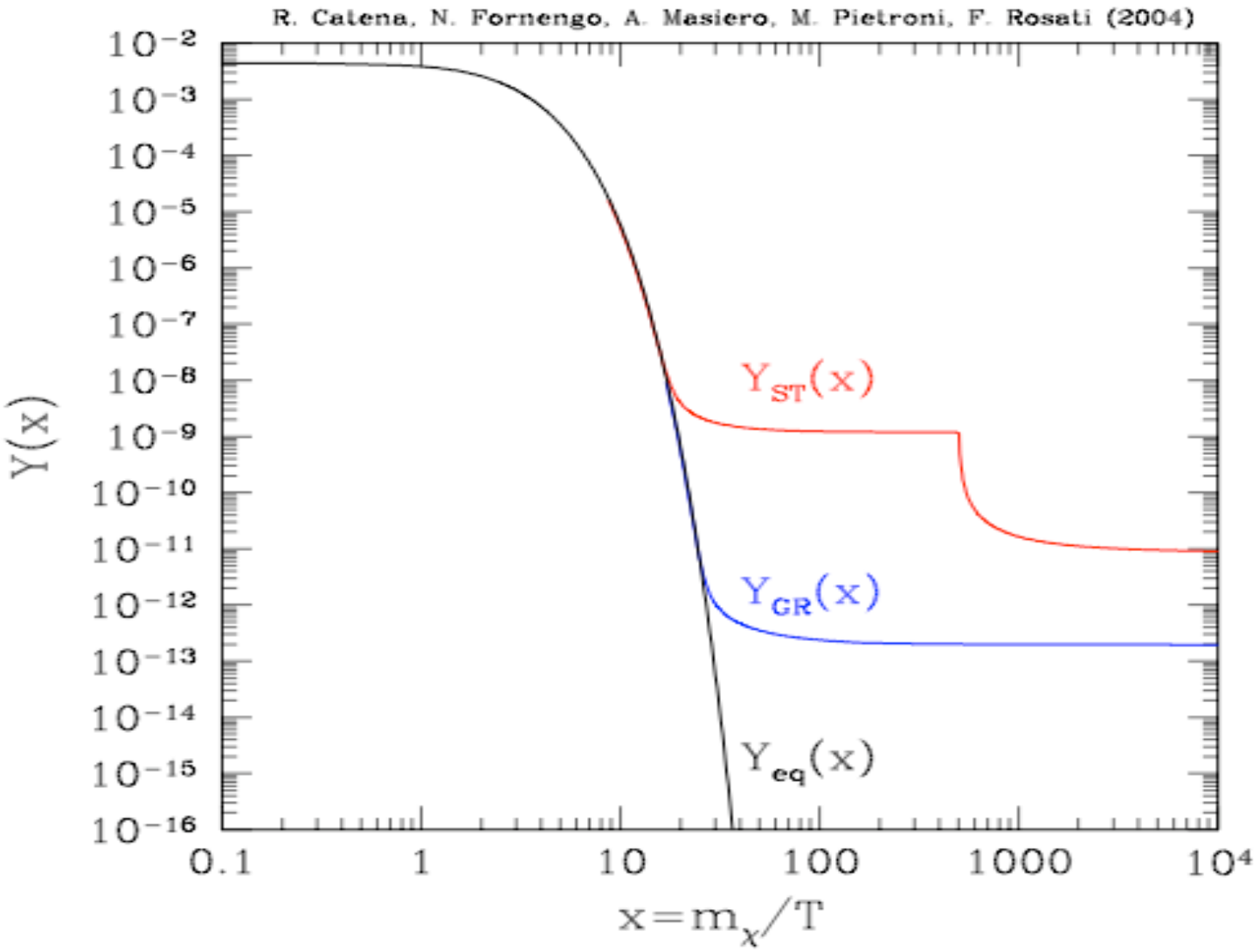
→ Threat of violation of the equivalence principle
constancy of the fundamental "constants",…

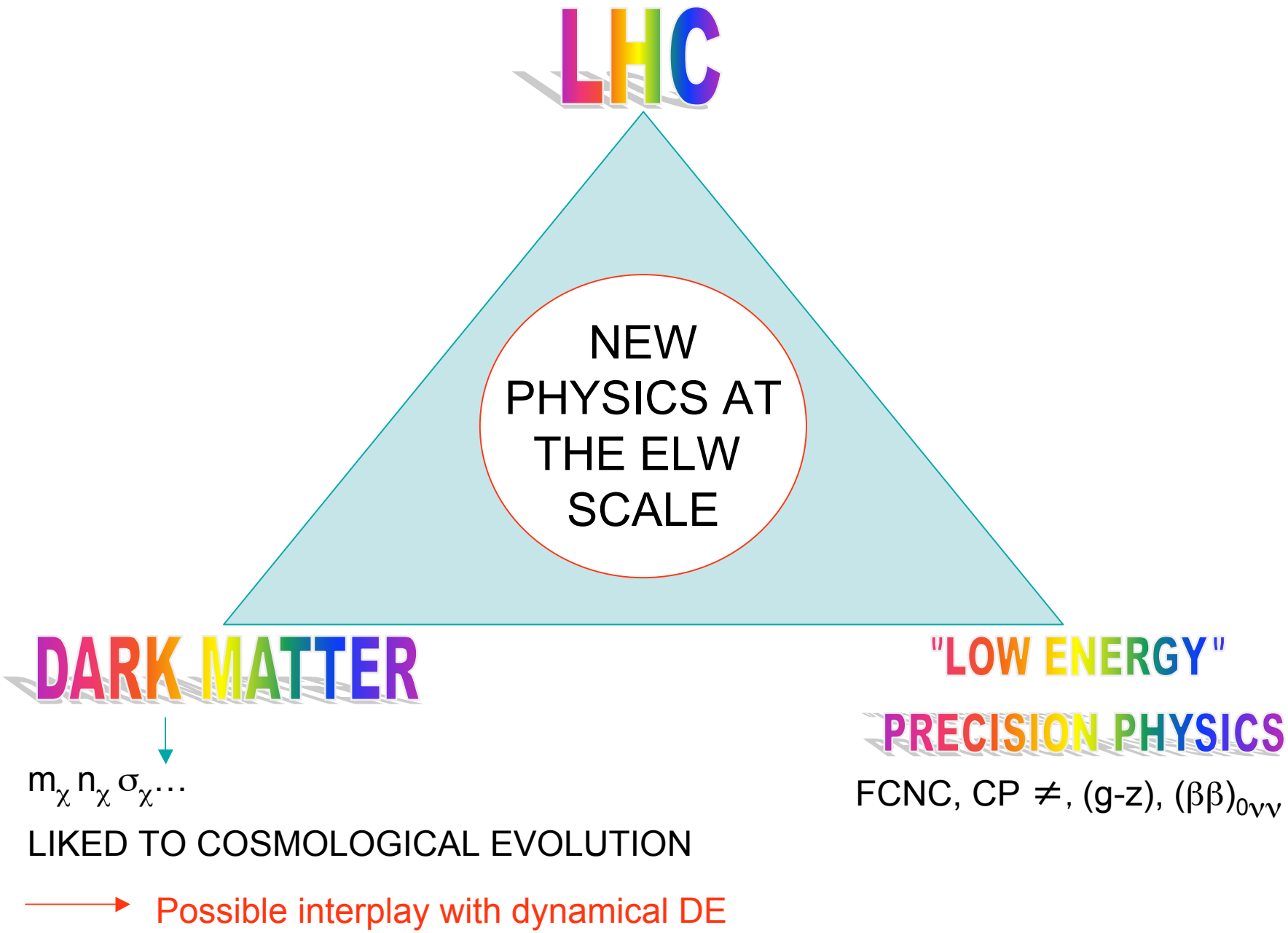
- INFLUENCE OF ϕ ON THE NATURE AND THE ABUNDANCE OF CDM

Modifications of the standard picture of
WIMPs FREEZE - OUT

CDM CANDIDATES

NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY





m_χ n_χ σ_χ…

LIKED TO COSMOLOGICAL EVOLUTION

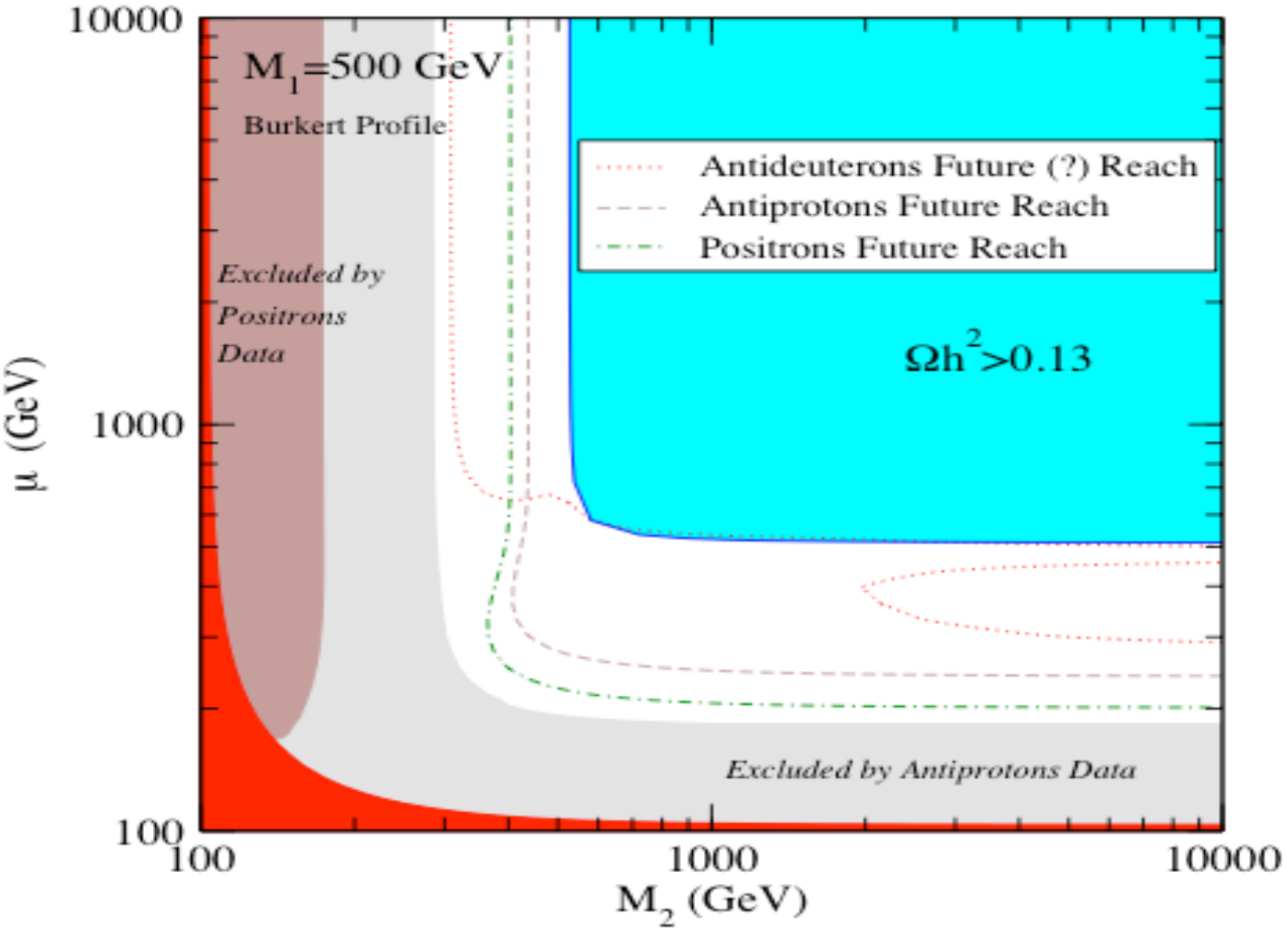
FCNC, CP ≠, (g-z), $(\beta\beta)_{0\nu\nu}$

→ Possible interplay with dynamical DE

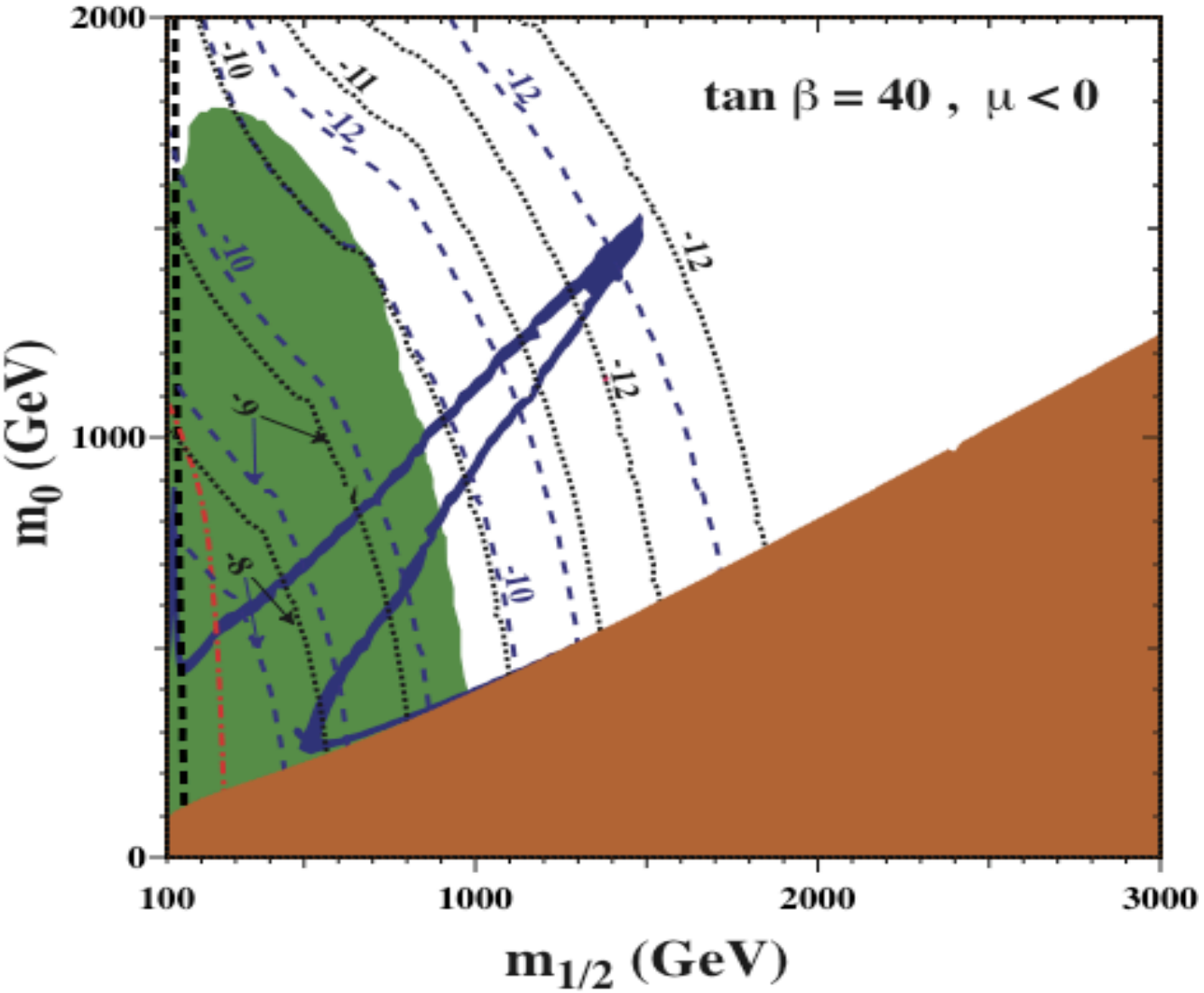
BACK-UP SLIDES

Large Hadron collider (LHC) at CERN

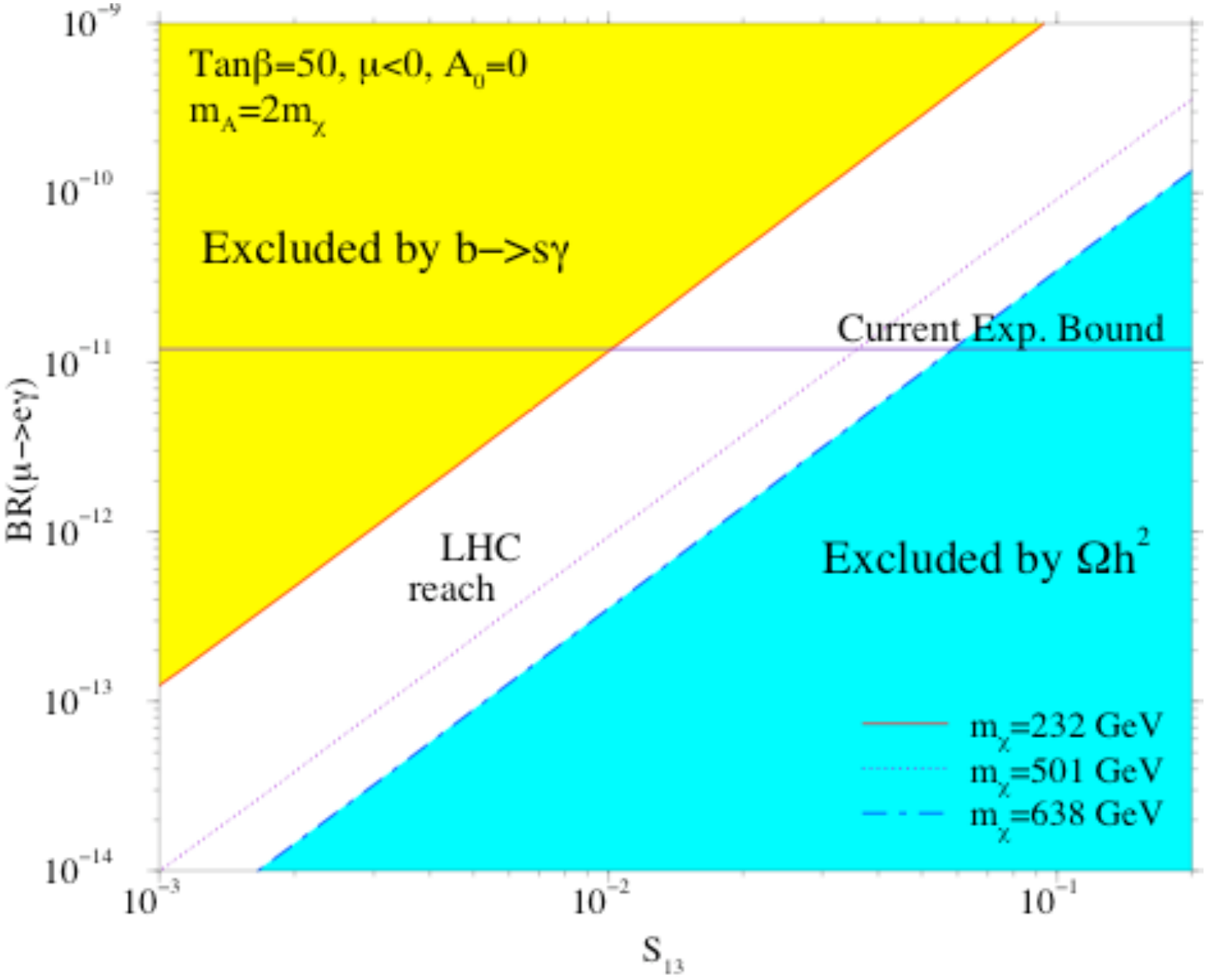
PROBING SUSY THROUGH ANTIMATTER SEARCHES



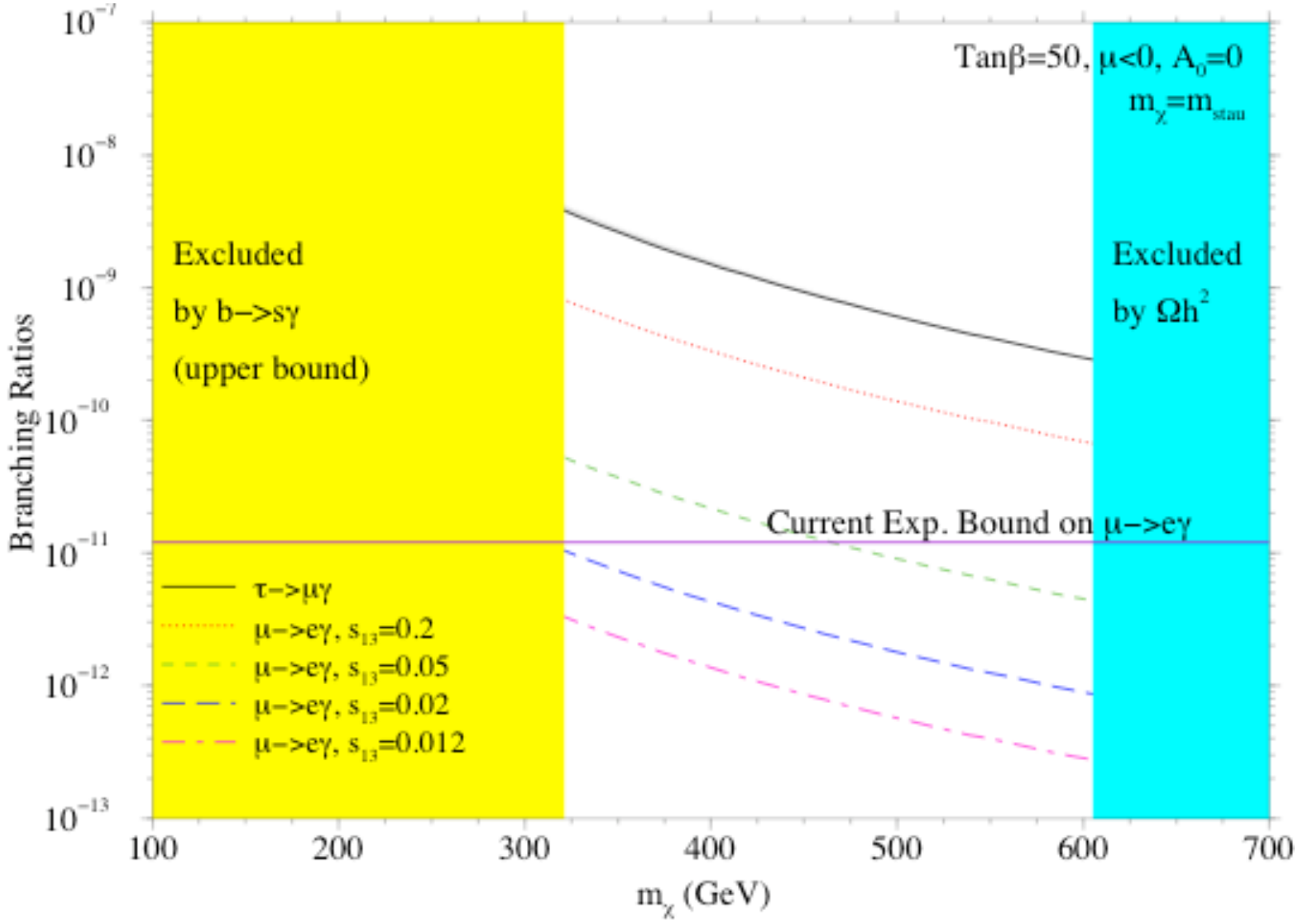
Tightness …3


tan β = 40 , μ < 0
2000
1000
0
100
1000
2000
3000
m0 (GeV)
m1/2 (GeV)
-10
-11
-12
-12
-10
-12
-12
-9
-8
-10

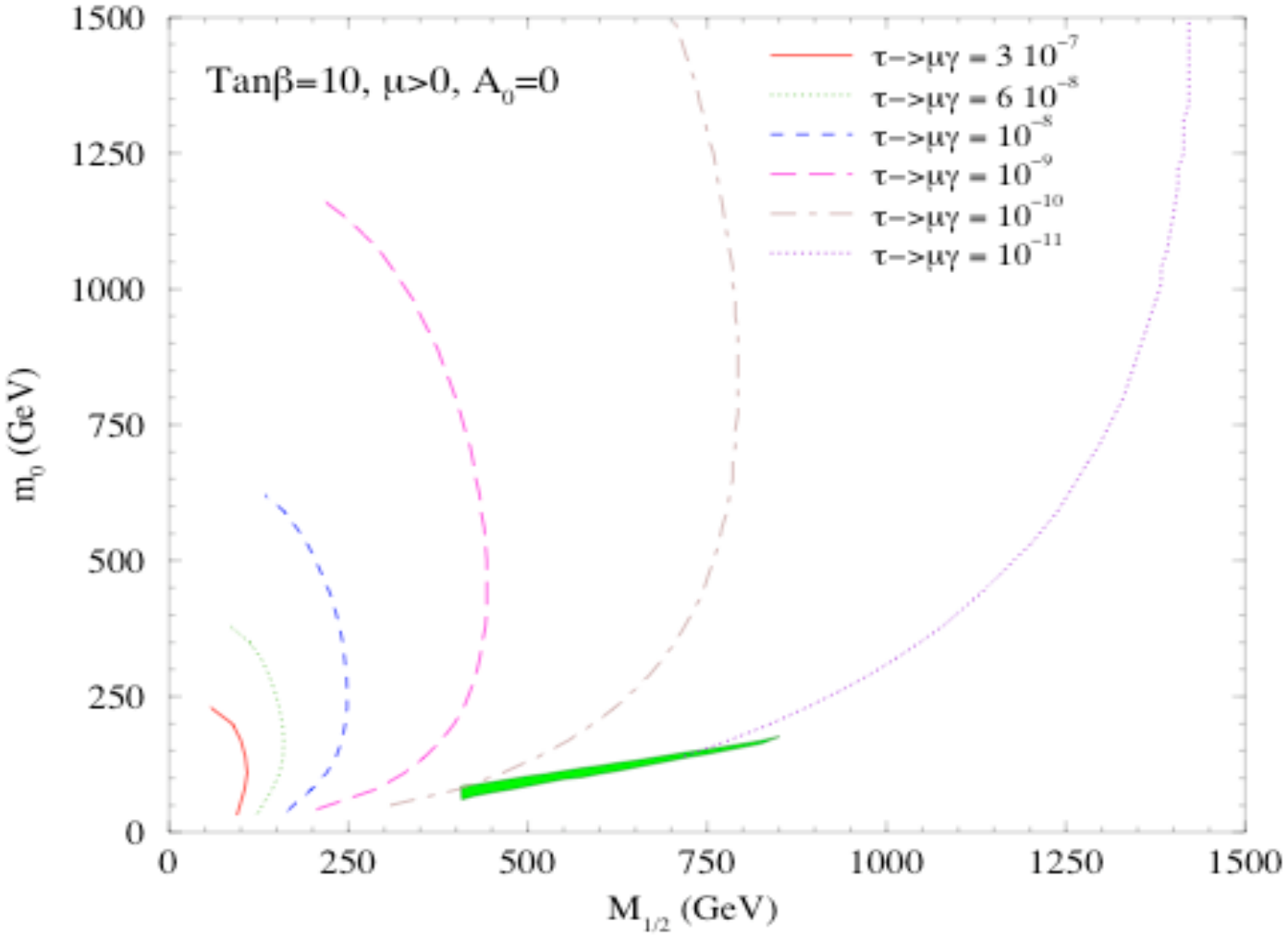
LHC REACH VS. LFV SENSITIVITY



PROBING SUSY THROUGH LFV 2



LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



Searching for New Physics at the Fermi Scale

Colliders at Fermi Scale

LEP

HERA

$\bar{p}$
TEVATRON
p

-> e+e- collider(2000)
E_{cm}=90-209 GeV
Lumi=900 pb-1/exp.(phys)
ALEPH,DELPHI
L3,OPAL

SLC: polarized e^+e^-
at Z peak

-> $e^{\pm}p$ collider
E_{cm}=320 GeV
H1, ZEUS
HERA I 120 pb-1/expt(phys.)
HERA II 2007 ->700 pb^{-1}(delivered,$e^{\pm}$,$\pm P_e$)

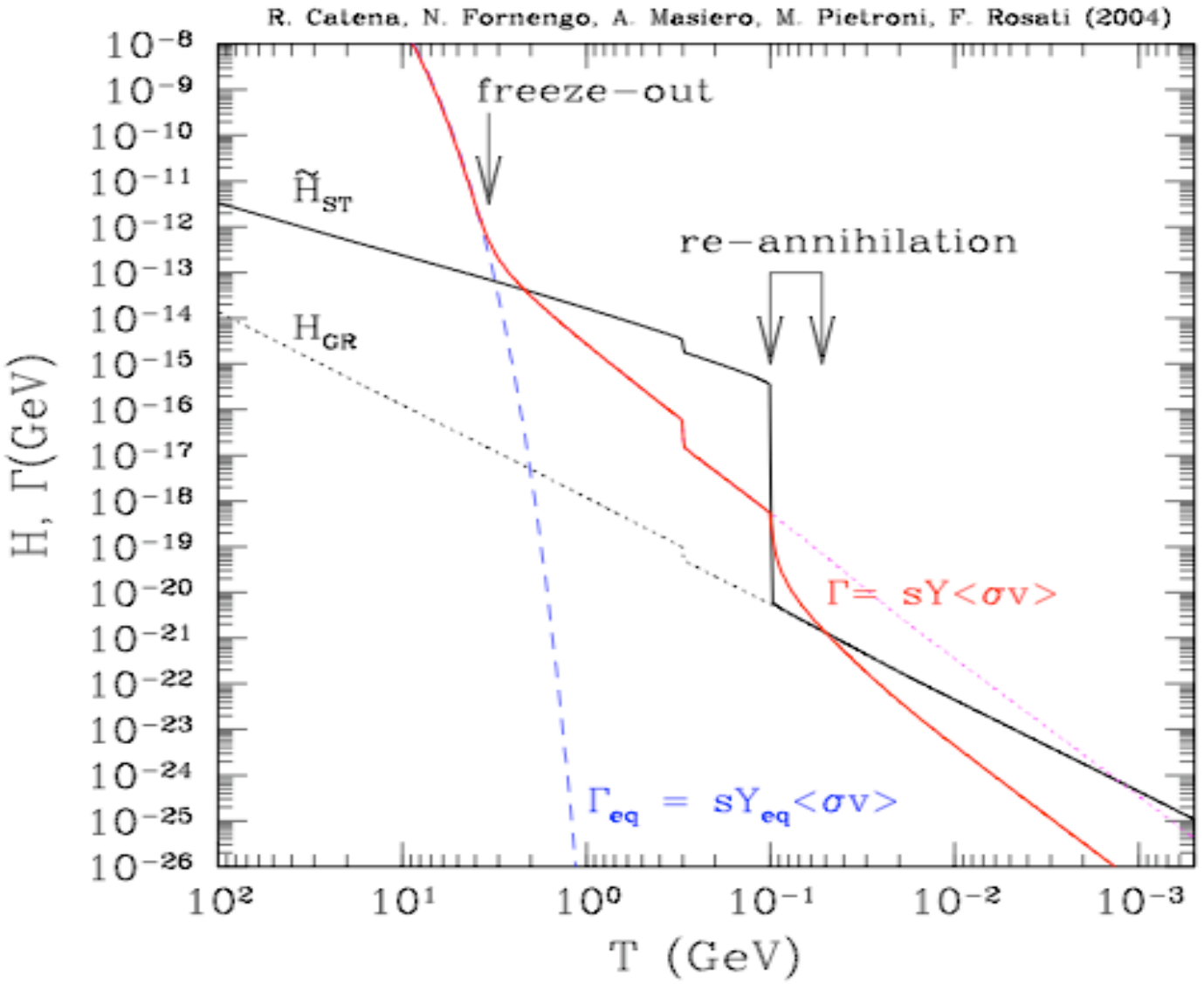
-> $p\bar{p}$ collider: CDF, D0

Run I E_{cm}=1.8 TeV
130 pb^{-1}/exp.(phys.)

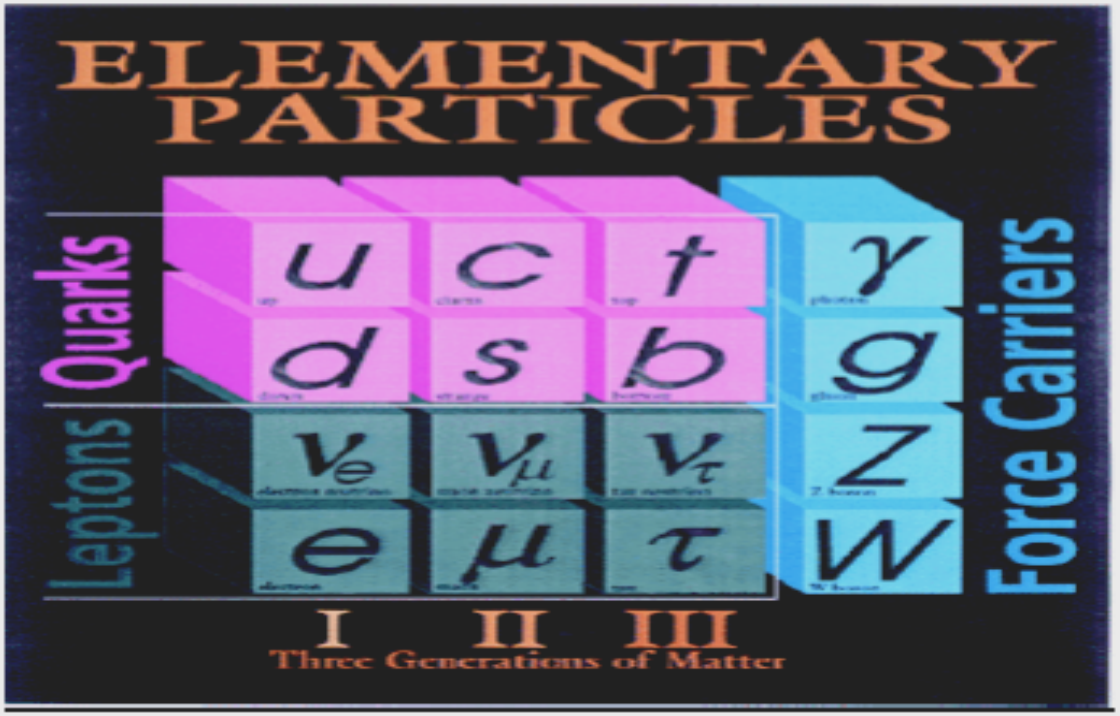
Run II E_{cm}=1.96 TeV
1fb^{-1} delivered
2009 -> 4-8 fb^{-1}

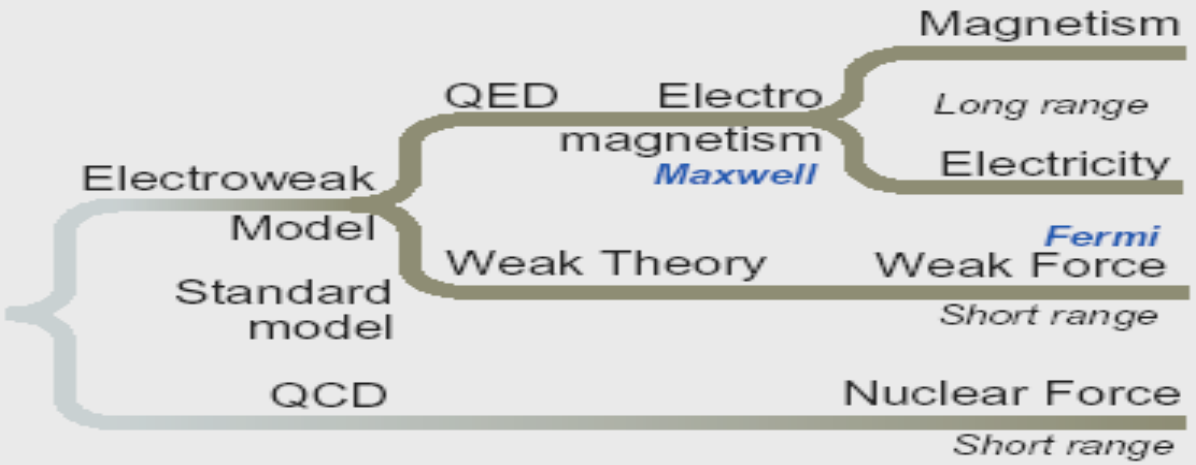
Many other interesting results from lower energy facilities

FREEZE-OUT IN SCALAR-TENSOR THEORIES OF GRAVITY

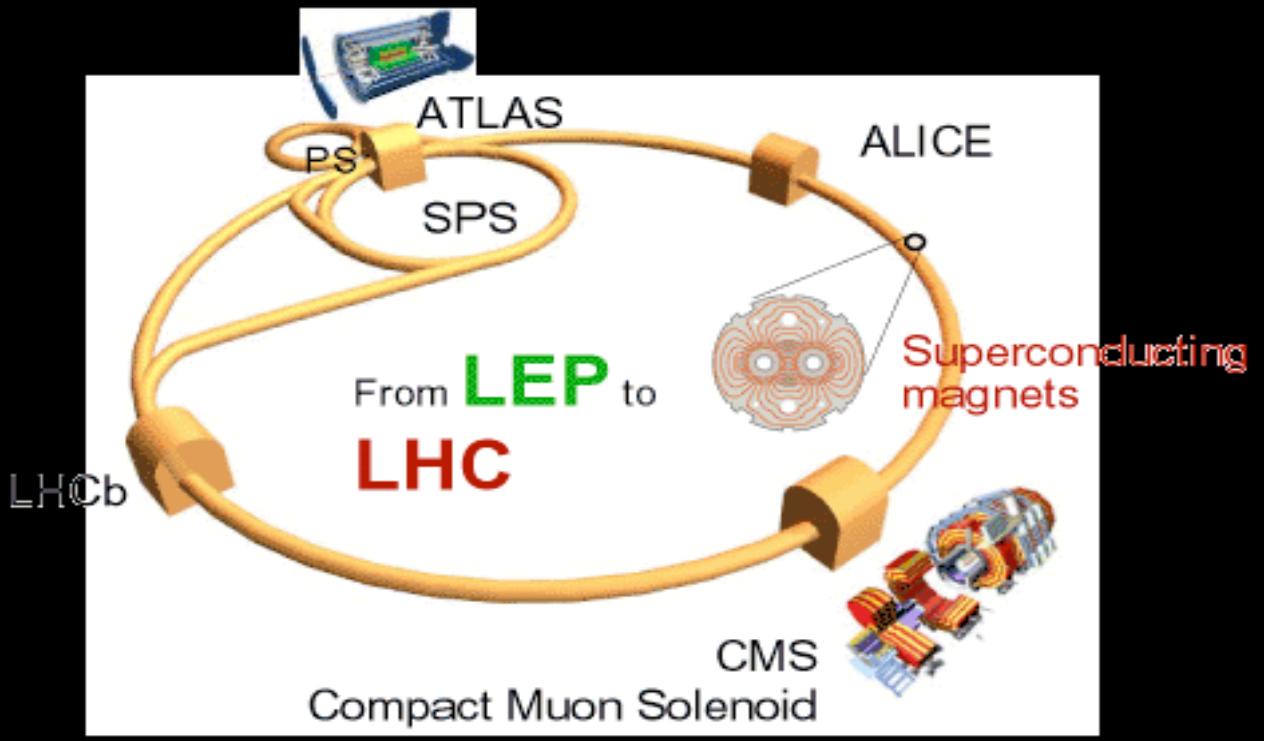


THE G-W-S STANDARD MODEL





LHC: THE DISCOVERY MACHINE FOR THE NEW PHYSICS AT THE TEV SCALE



	Beams	Energy GeV	Luminosity
LEP	e+ e-	200	10^{32} cm^{-2}s^{-1}
LHC	**p p**	**14000**	**10^{34}**
	Pb Pb	1,312,000	10^{27}