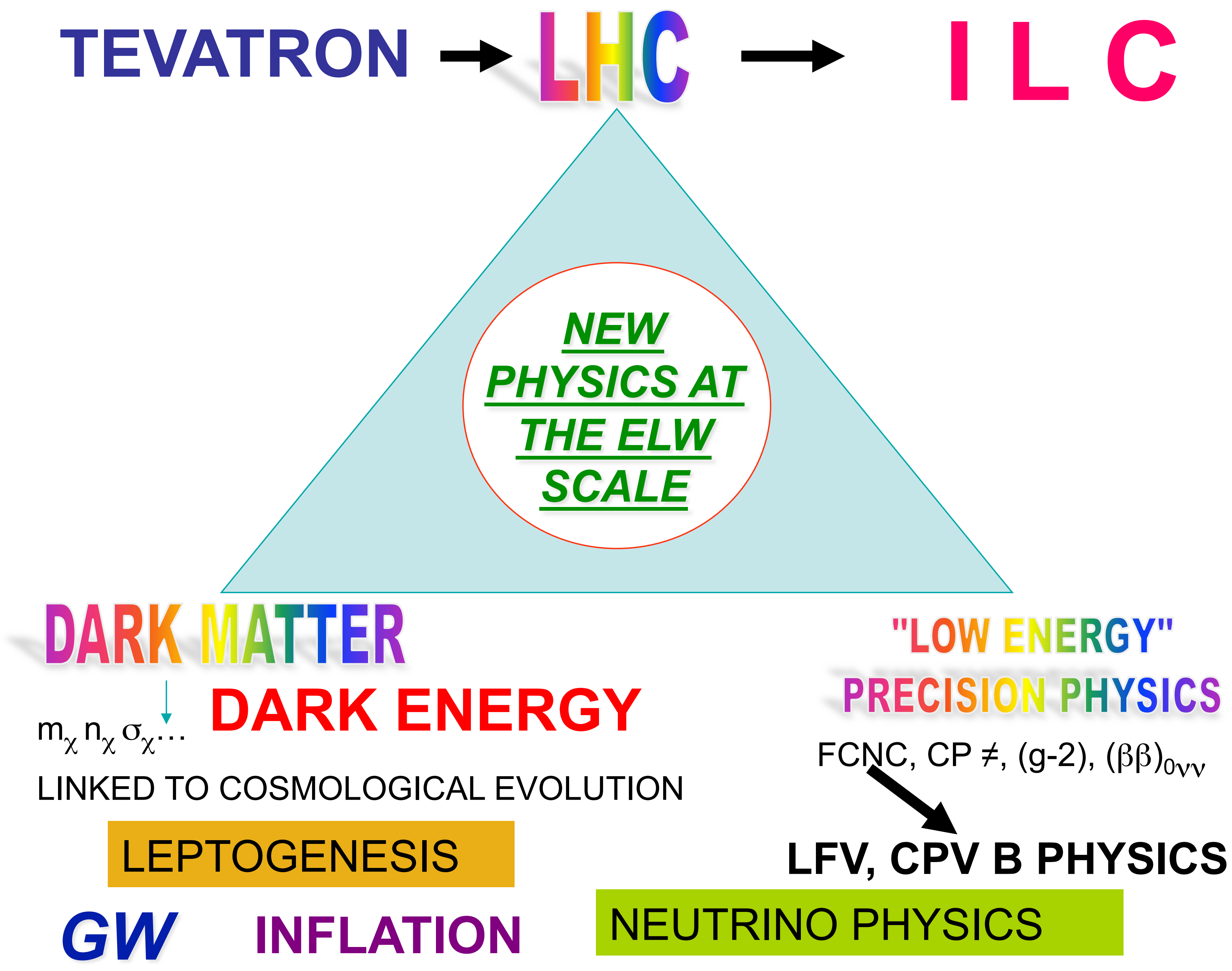
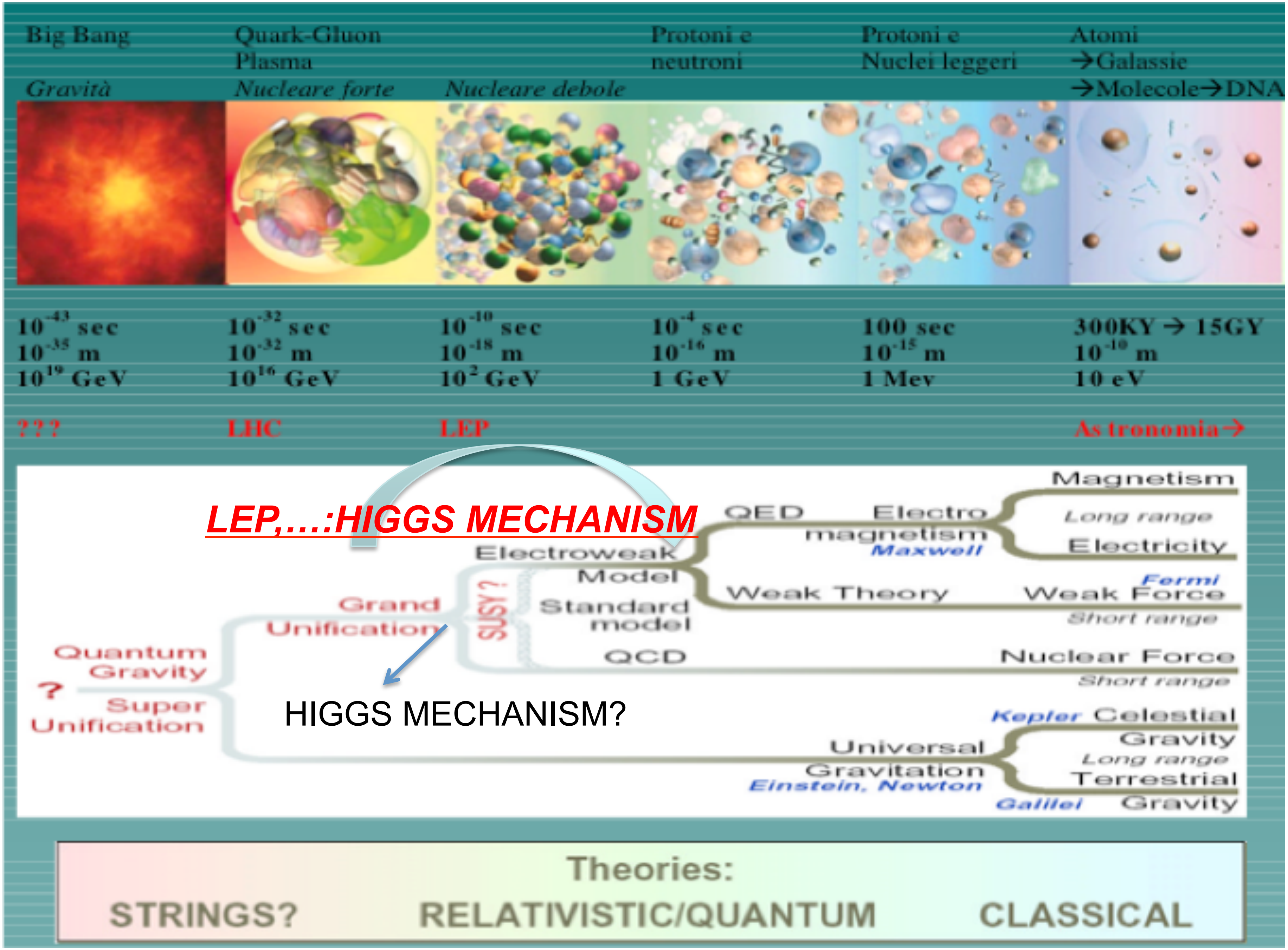
Univ. di Napoli, Dipt. Di Fisica, 15 giugno 2012

HIGGS BOSON, DARK MATTER and LHC: la grande sfida della Nuova Fisica

Antonio Masiero

Univ. di Padova e INFN


TEVATRON
LHC
I L C
NEW PHYSICS AT THE ELW SCALE
DARK MATTER
$m_\chi\ n_\chi\ \sigma_\chi$…
DARK ENERGY
LINKED TO COSMOLOGICAL EVOLUTION
LEPTOGENESIS
GW
INFLATION
"LOW ENERGY"
PRECISION PHYSICS
FCNC, CP ≠, (g-2), $(\beta\beta)_{0\nu\nu}$
LFV, CPV B PHYSICS
NEUTRINO PHYSICS



Big Bang
Gravità
Quark-Gluon Plasma
Nucleare forte
Nucleare debole
Protoni e neutroni
Protoni e Nuclei leggeri
Atomi →Galassie →Molecole→DNA
10^-43 sec 10^-35 m 10^19 GeV
10^-32 sec 10^-32 m 10^16 GeV
10^-10 sec 10^-18 m 10^2 GeV
10^-4 sec 10^-16 m 1 GeV
100 sec 10^-15 m 1 Mev
300KY → 15GY 10^-10 m 10 eV
???
LHC
LEP
Astronomia→
LEP,…:HIGGS MECHANISM
QED
Electro magnetism
Maxwell
Magnetism
Long range
Electricity
Electroweak Model
Weak Theory
Fermi
Weak Force
Short range
Grand Unification
SUSY ?
Standard model
QCD
Nuclear Force
Short range
Quantum Gravity
?
Super Unification
HIGGS MECHANISM?
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL

SOMETHING is needed at the TeV scale to enforce the unitarity of the electroweak theory

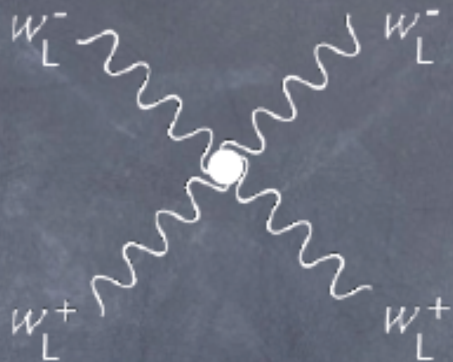
What is the mechanism of EWSB?

susy, LH... models assume that we already know the answer to

What is unitarizing the WW scattering amplitudes?

W_L & Z_L part of EWSB sector ⊃ W scattering is a probe of Higgs sector interactions

$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M}\frac{\vec{k}}{|\vec{k}|}\right)$$



$$A = g^2 \left(\frac{E}{M_W}\right)^2$$

loss of perturbative unitarity around 1.2 TeV

Weakly coupled models

Grojean

prototype: Susy

susy partners ~ 100 GeV

Strongly coupled models

prototype: Technicolor

rho meson ~ 1 TeV

Different signatures at the LHC!

The Higgs problem is central in particle physics today

Altarelli LP09

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ eV)^4$

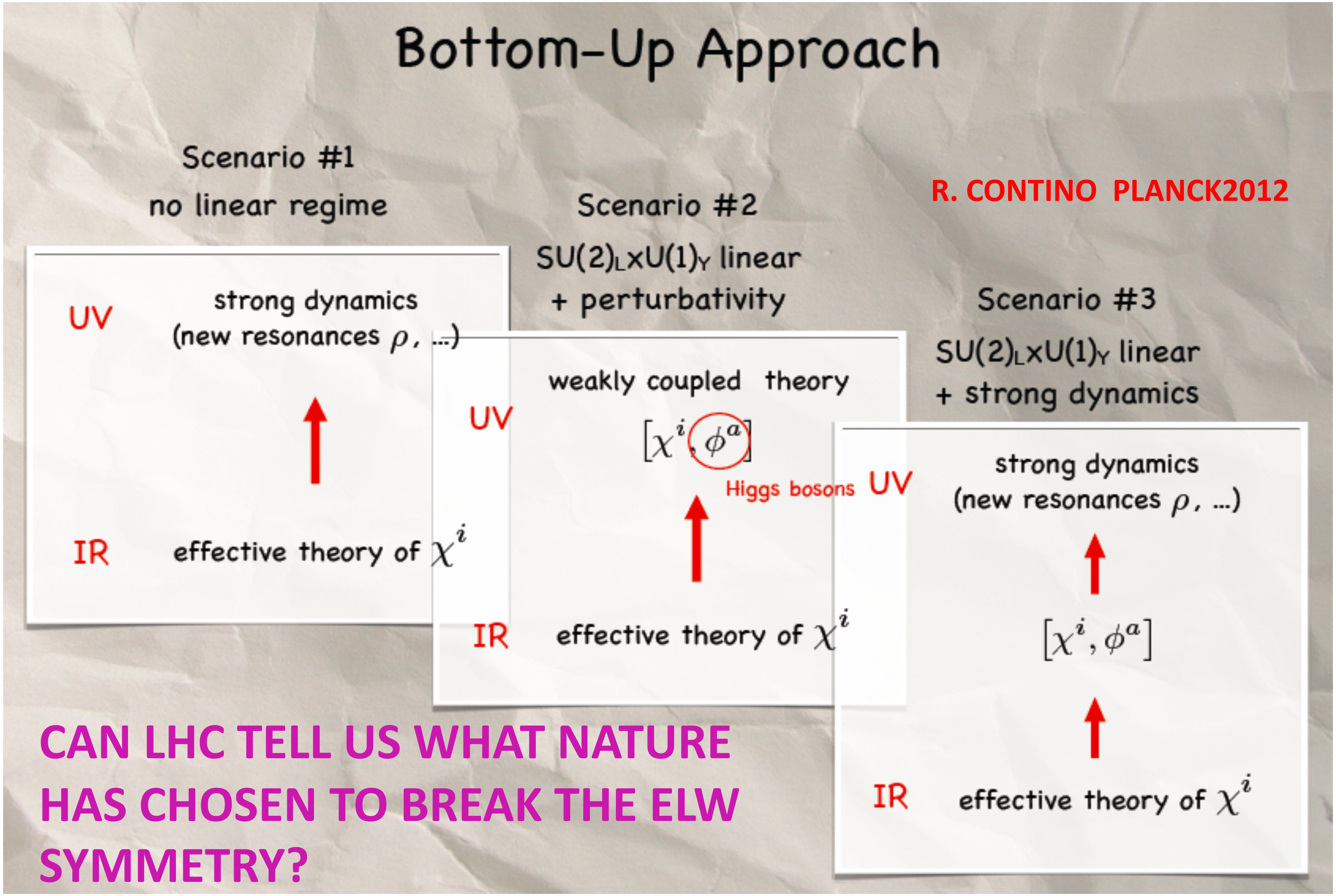
Possible instability
depending on m_H

Origin of quadratic
divergences.
Hierarchy problem

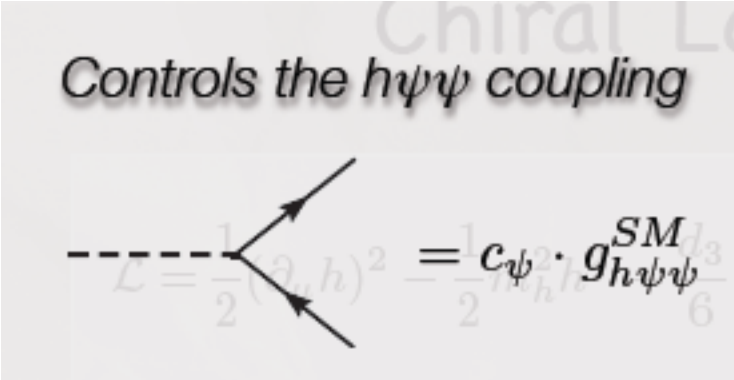
The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

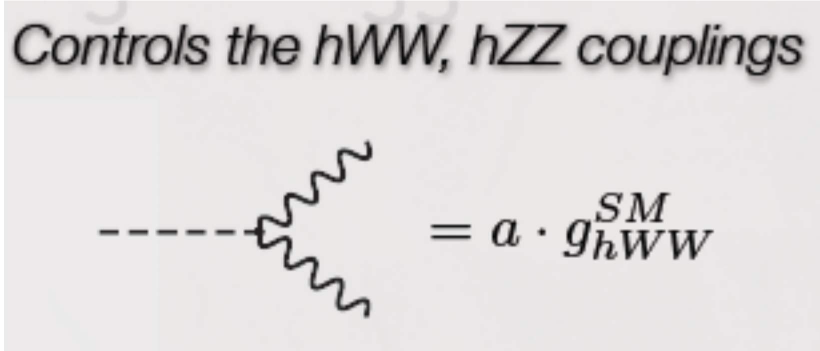
EWSB: WITH OR WITHOUT A HIGGS BOSON

R. CONTINO PLANCK2012

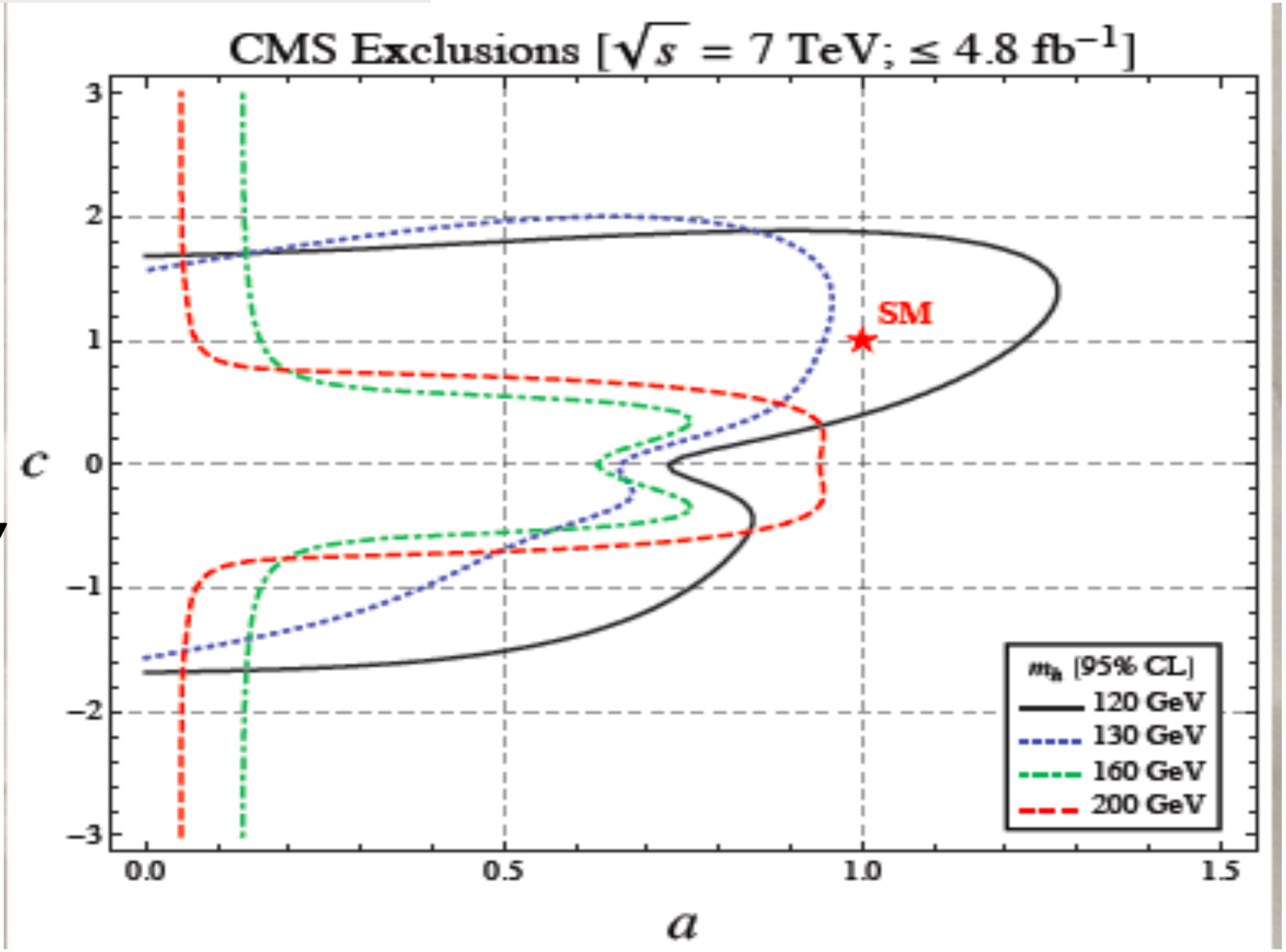


CAN LHC TELL US WHAT NATURE HAS CHOSEN TO BREAK THE ELW SYMMETRY?



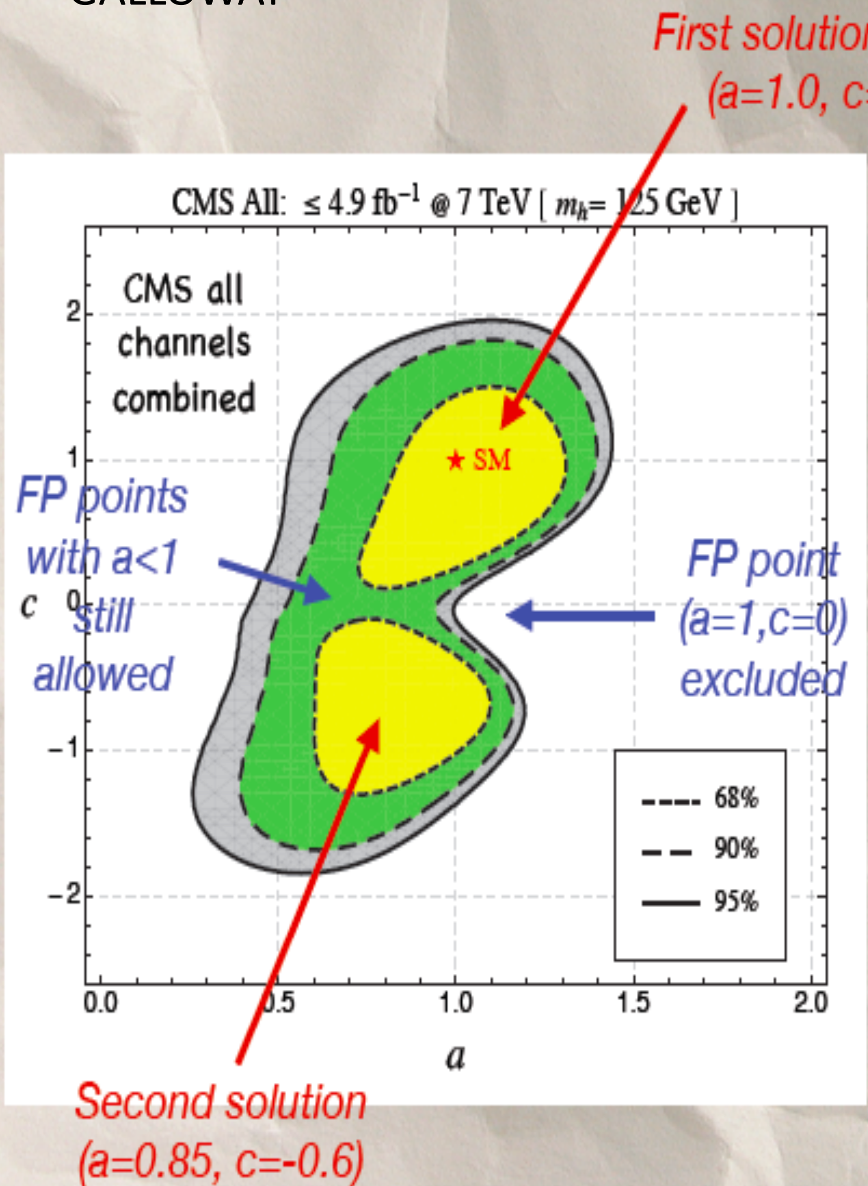


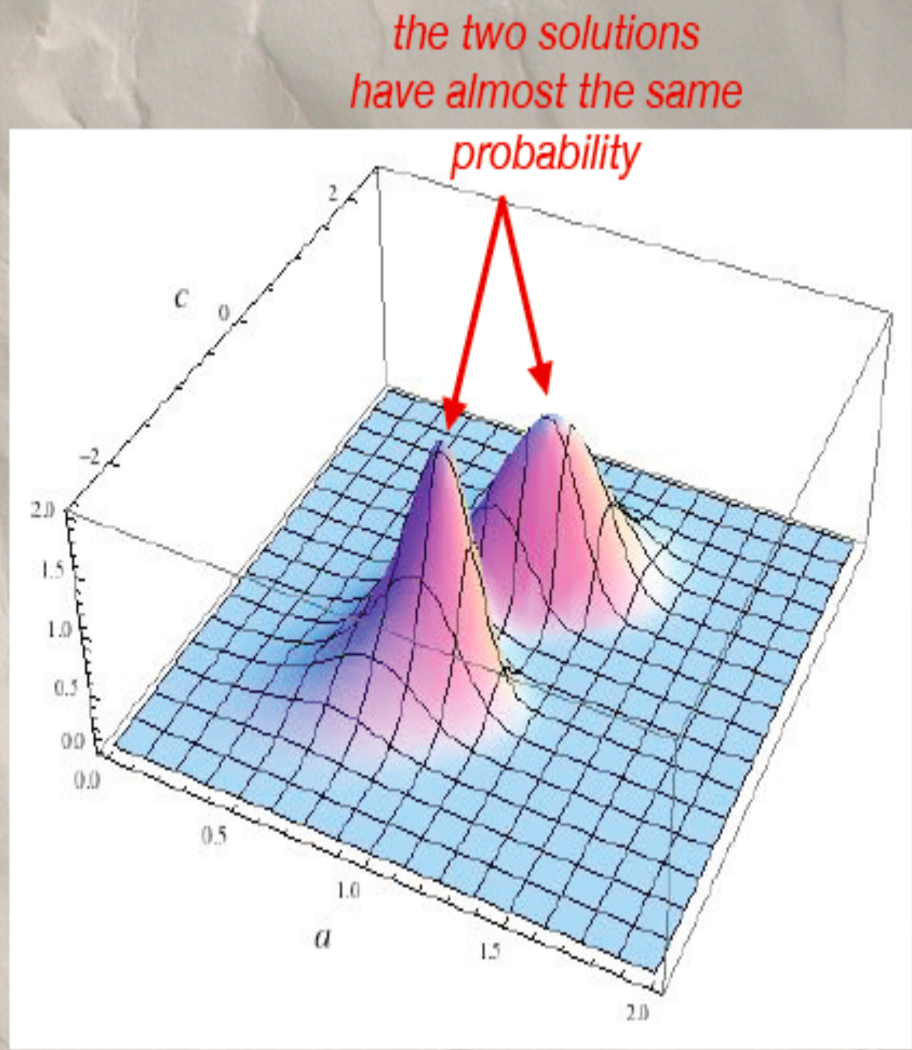
AZATOV,
CONTINO,
GALLOWAY

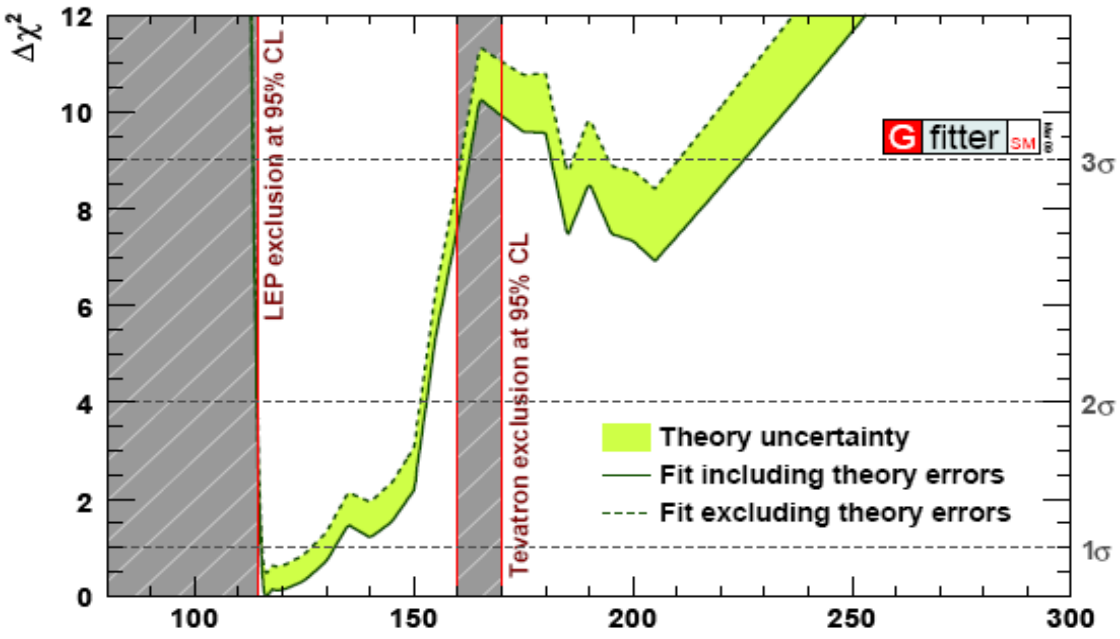


Fit at m_H=125GeV

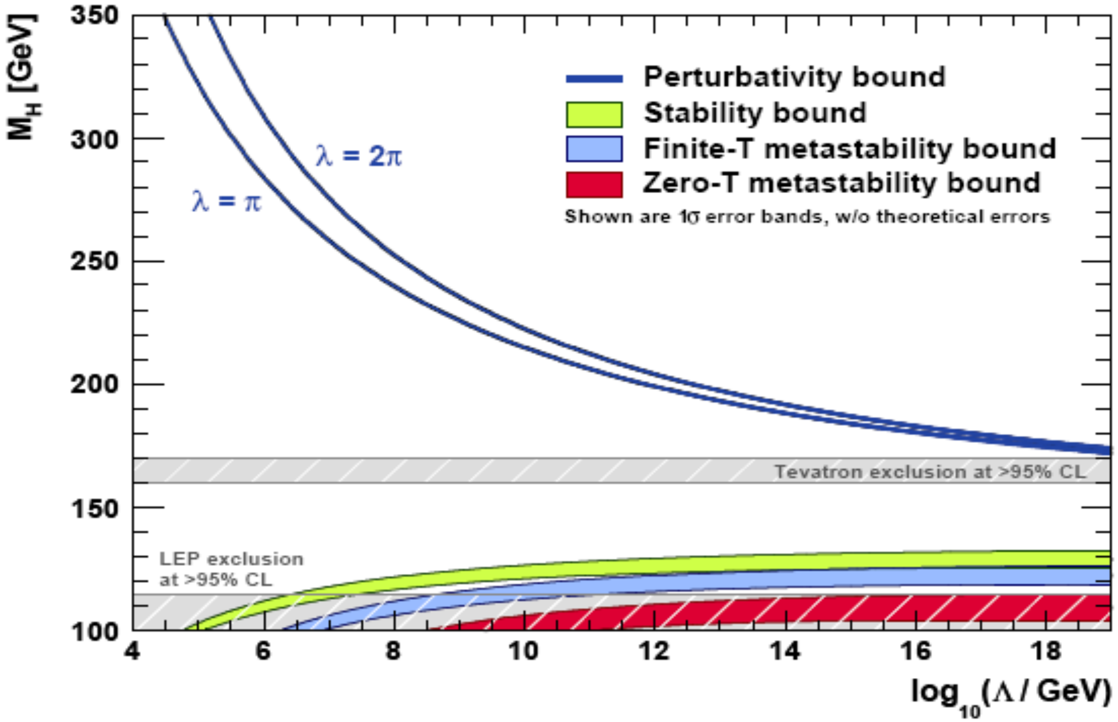
AZATOV, CONTINO, GALLOWAY







a light higgs (or something mimicking it) is definitely favored



the big desert between the TeV and the GUT scales only if the higgs is a narrow band between 130 and 180

Ellis, Espinosa, Giudice, Hoecker, Riotto

GENERAL FEATURES OF NEW PHYSICS AT THE ELW. SCALE

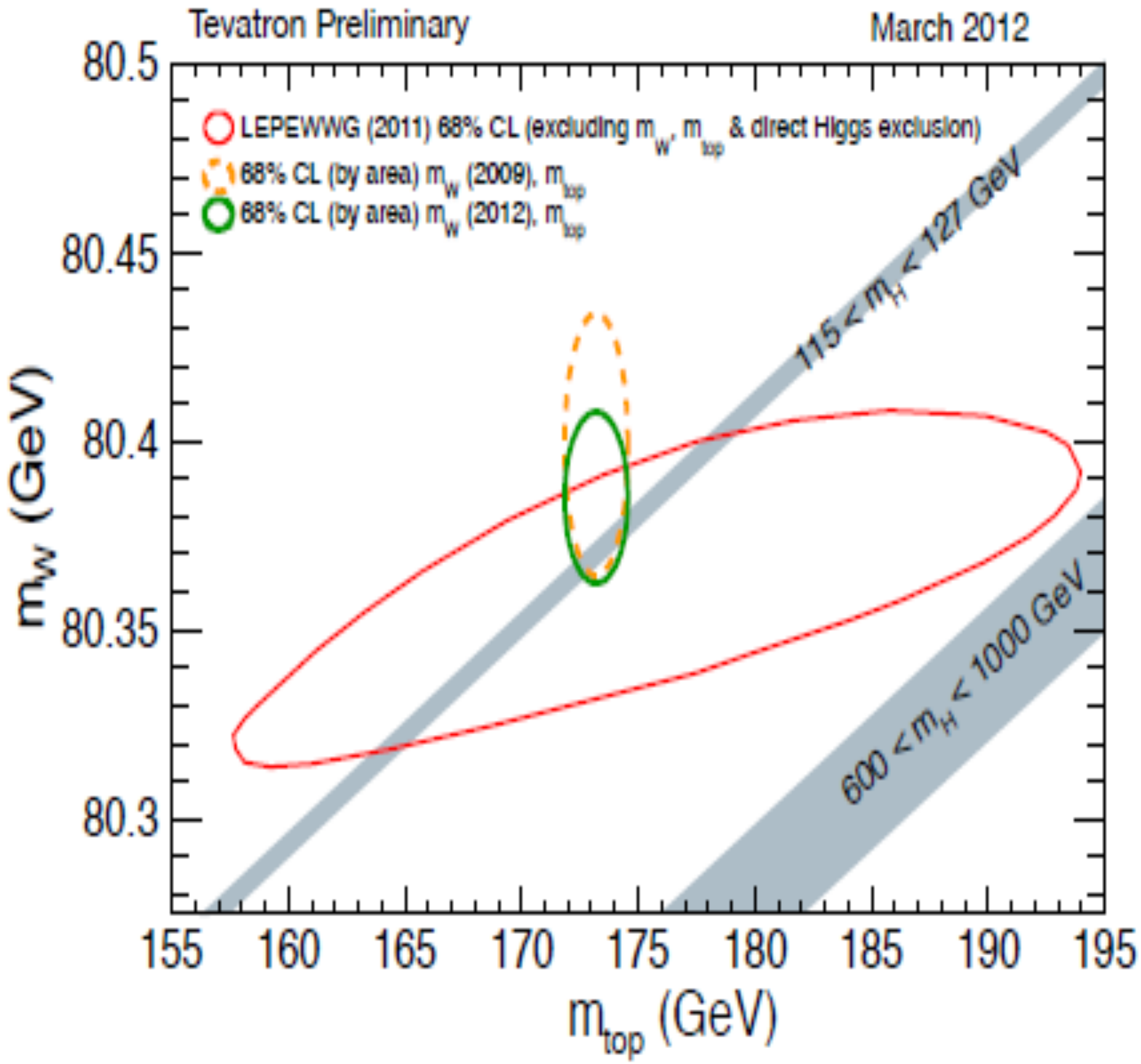
- Some amount of **fine-tuning** (typically at the % level) is required to pass unscathed the elw. precision tests, the higgs mass bound and the direct search for new particles at accelerators.
- The **higgs is typically rather light** (<200 GeV) apart from the extreme case of the "Higgsless proposal"
- All models provide **signatures which are (more or less) accessible to LHC physics** (including the higgsless case where new KK states are needed to provide the unitarity of the theory)

With M_W = 80385±15 MeV

$M_H = 94^{+29}_{-24}$ GeV

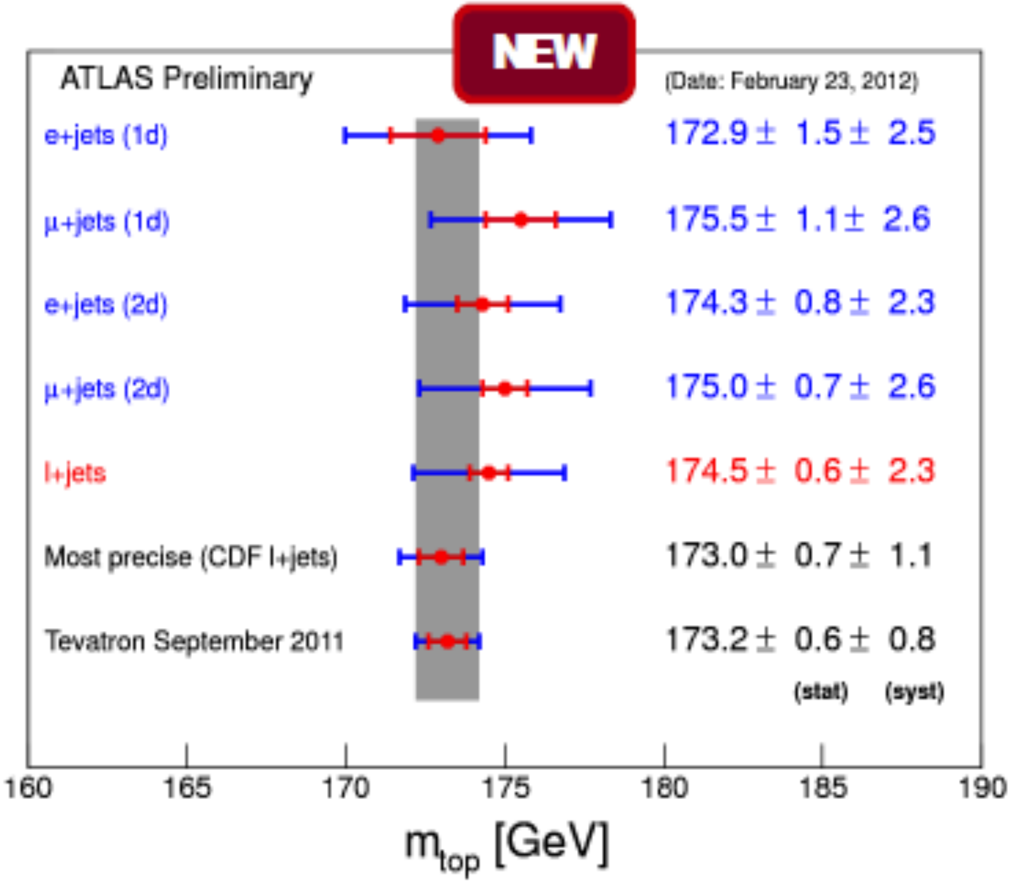
M_H < 152 GeV @95% CL

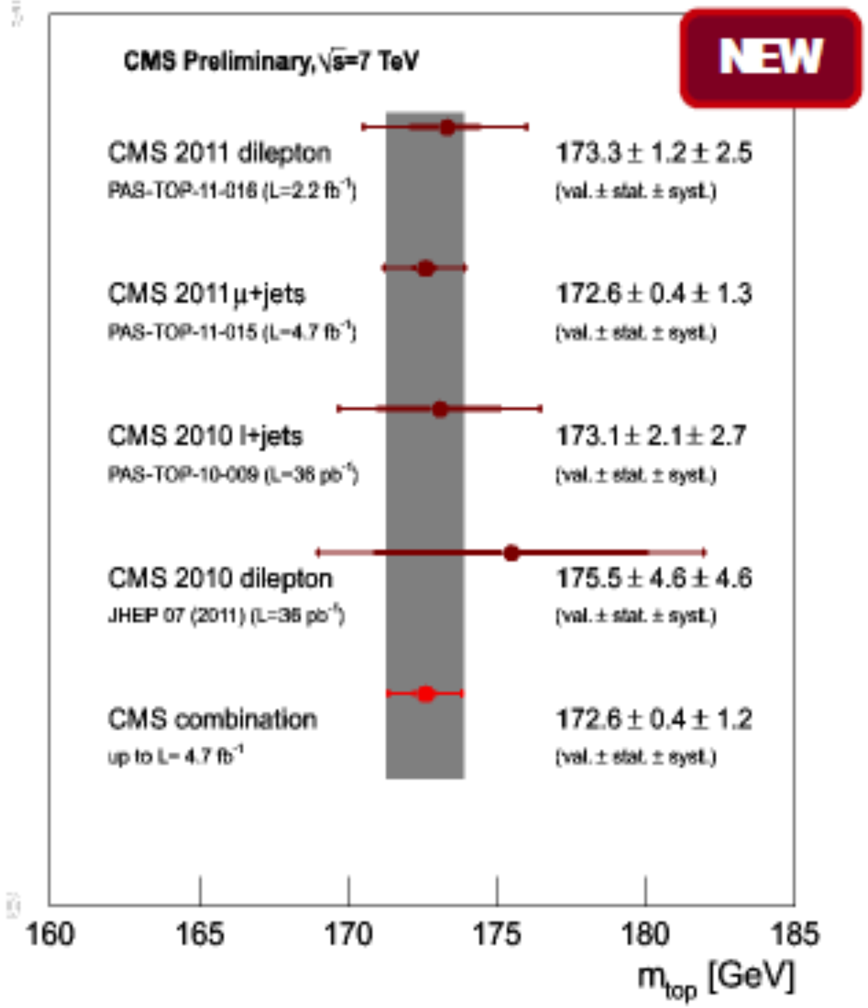
LEPEWWG/ZFitter



Top mass combination

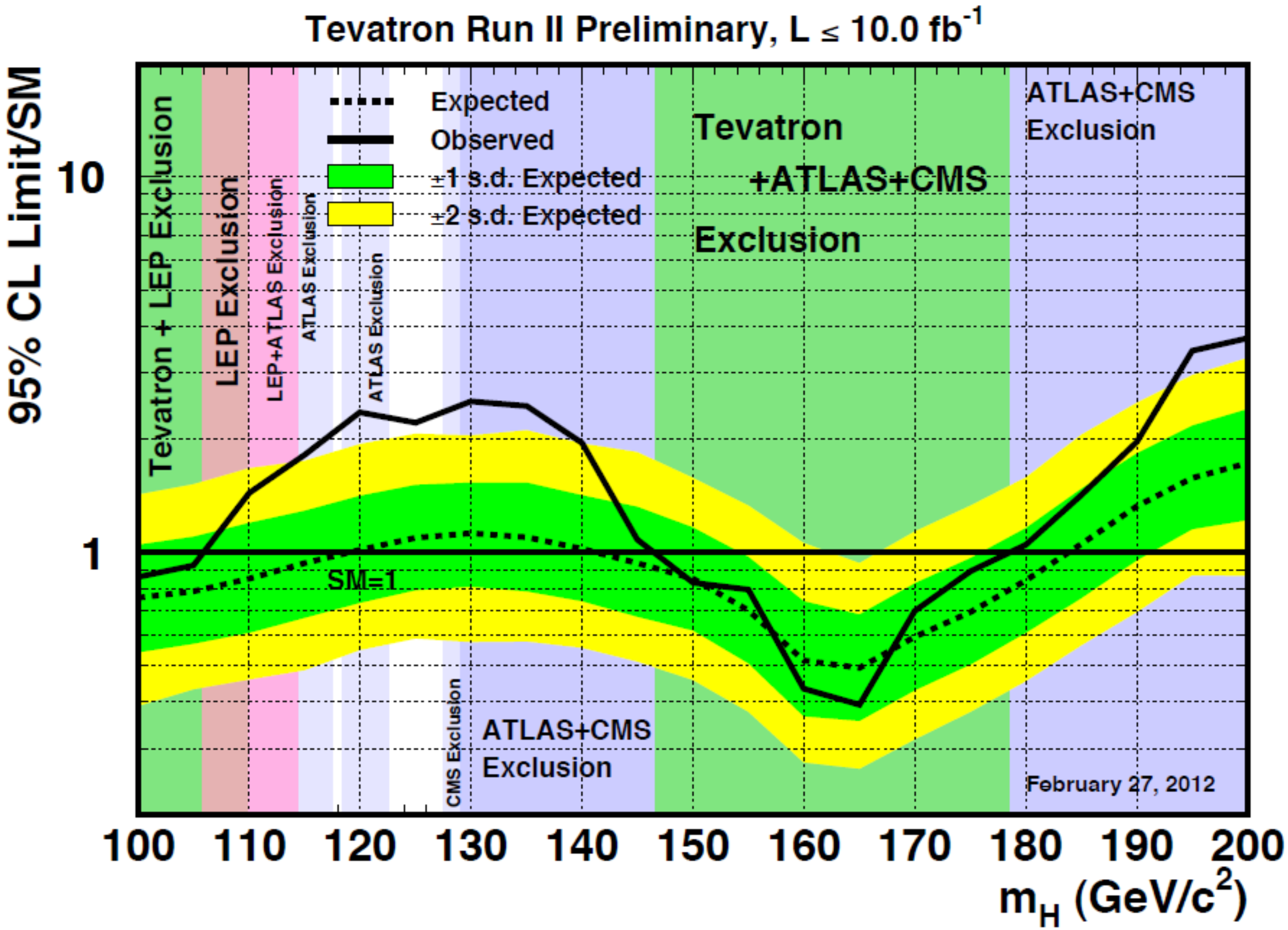
CMS-PAS-TOP-11-018

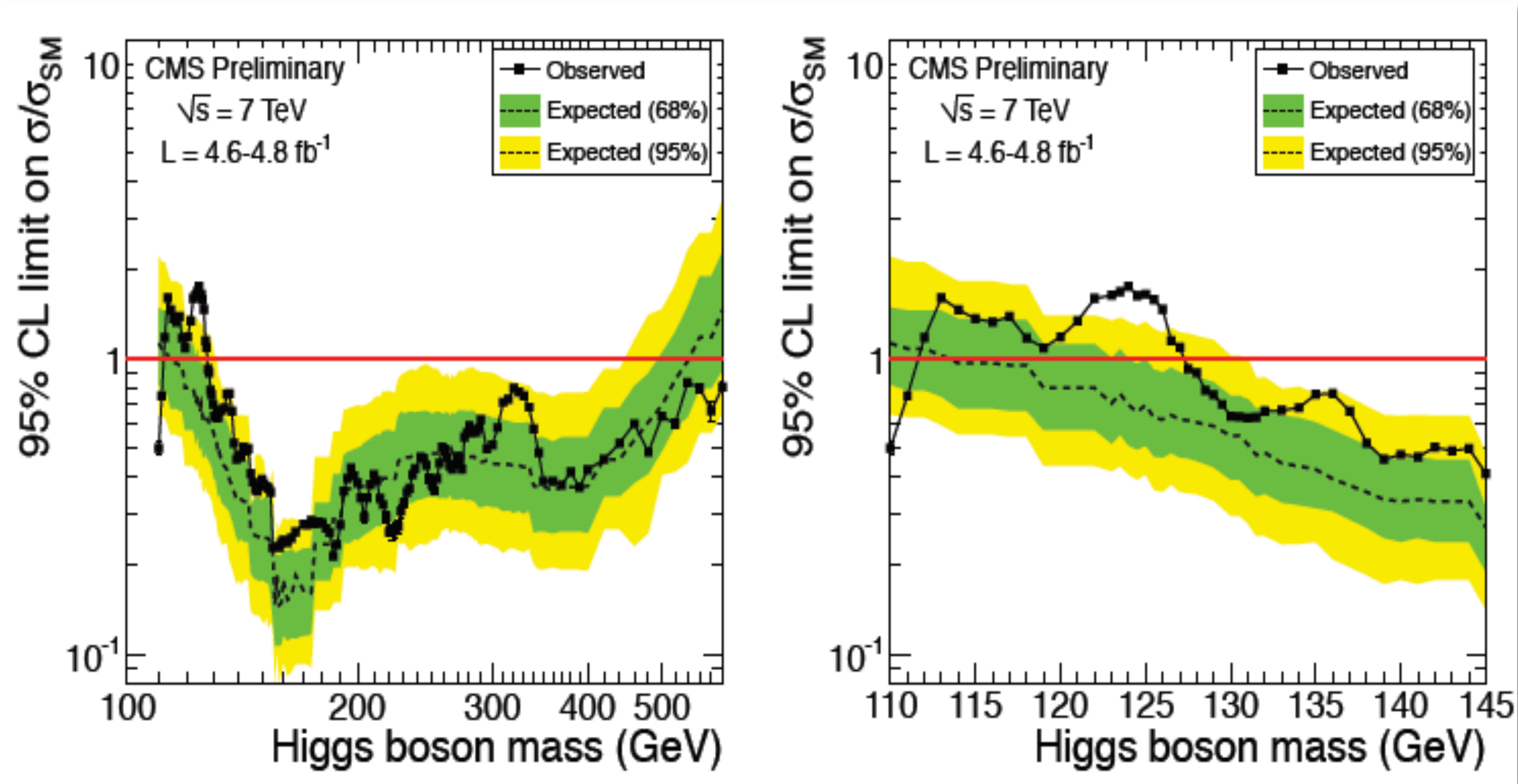




- **… and LHC combination is on the way**
- "Back of the envelope" calculation indicates that result will help decrease the current uncertainty from the Tevatron (partially uncorrelated systematics + higher statistics)

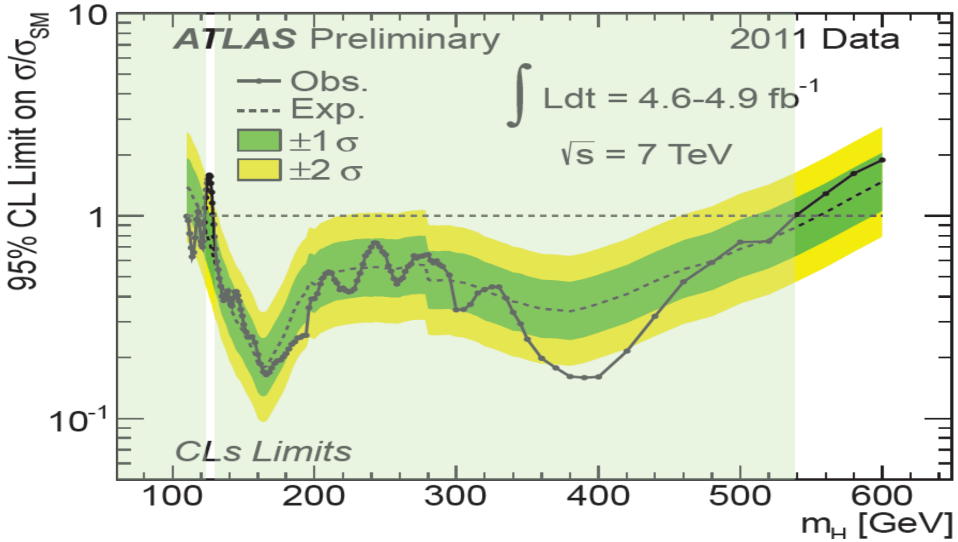
From M. Kirby
Fermilab users meeting – June 12-13, 2012
Higgs limits:
Tevatron combined

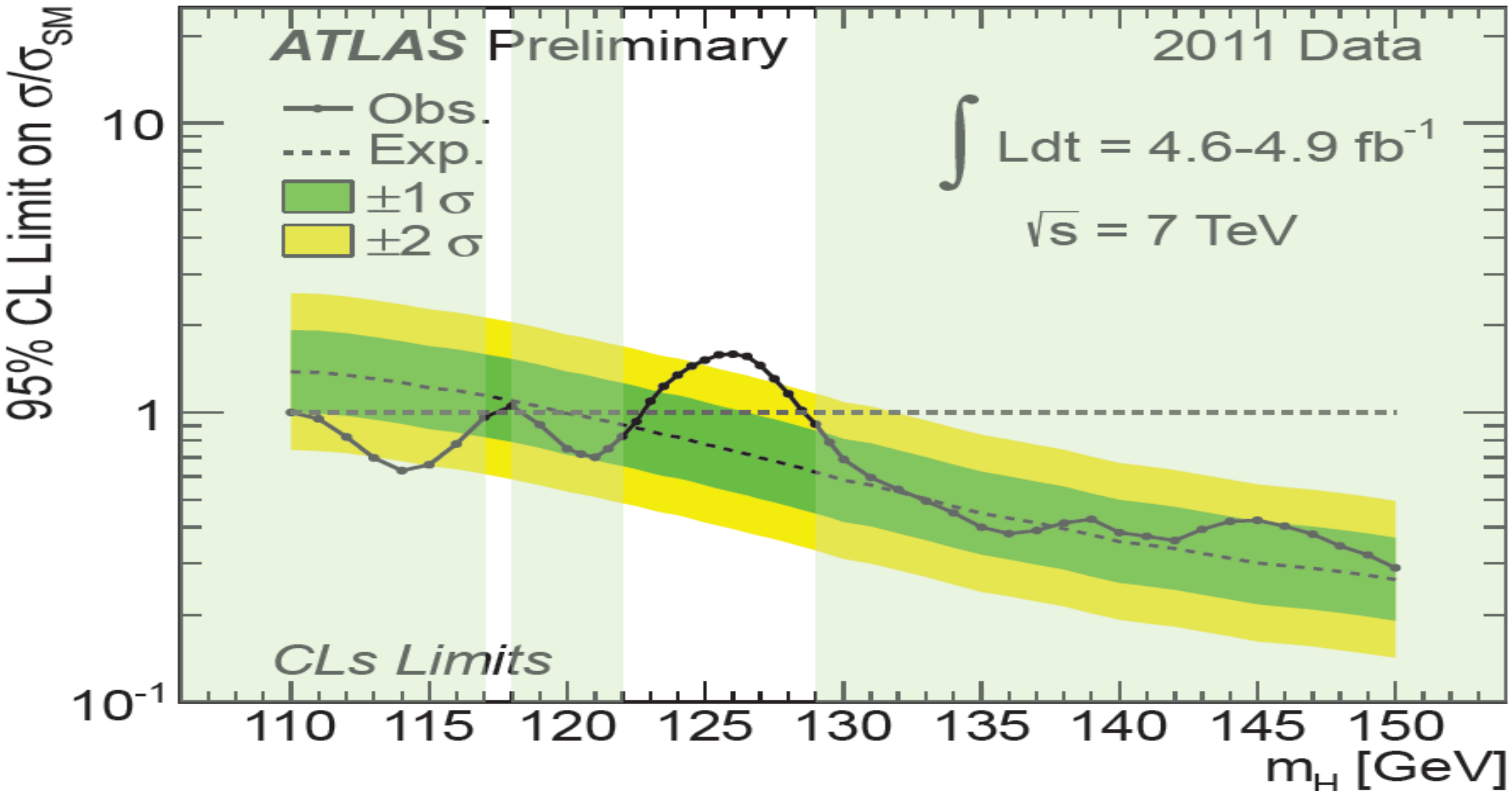




New combination
PLHC June 4-9, 2012 - Vancouver
Higgs limits:
CMS 2011 data

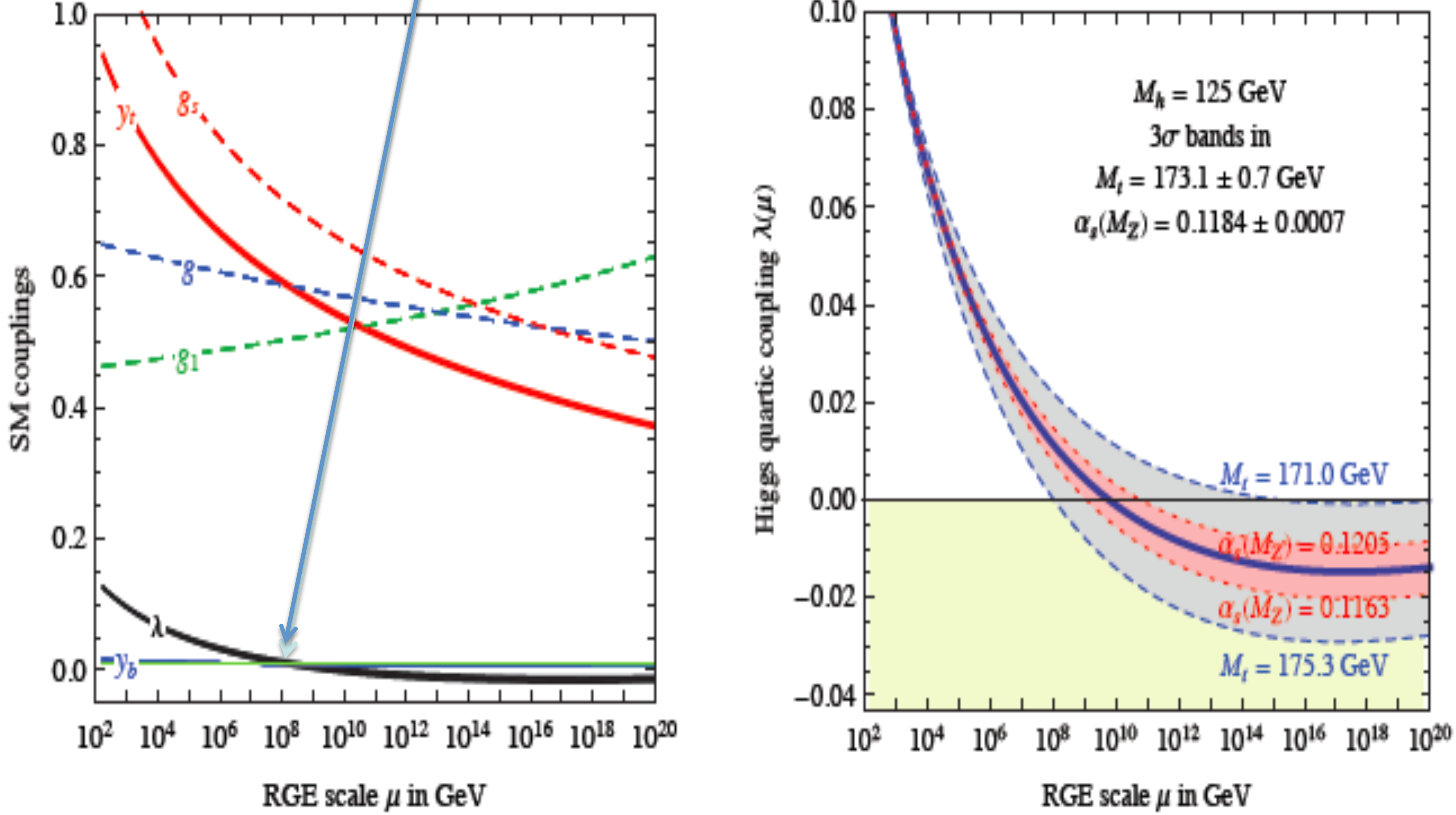
New combination
PLHC June 4-9, 2012 –
 Vancouver
Higgs limits:
ATLAS 2011 data



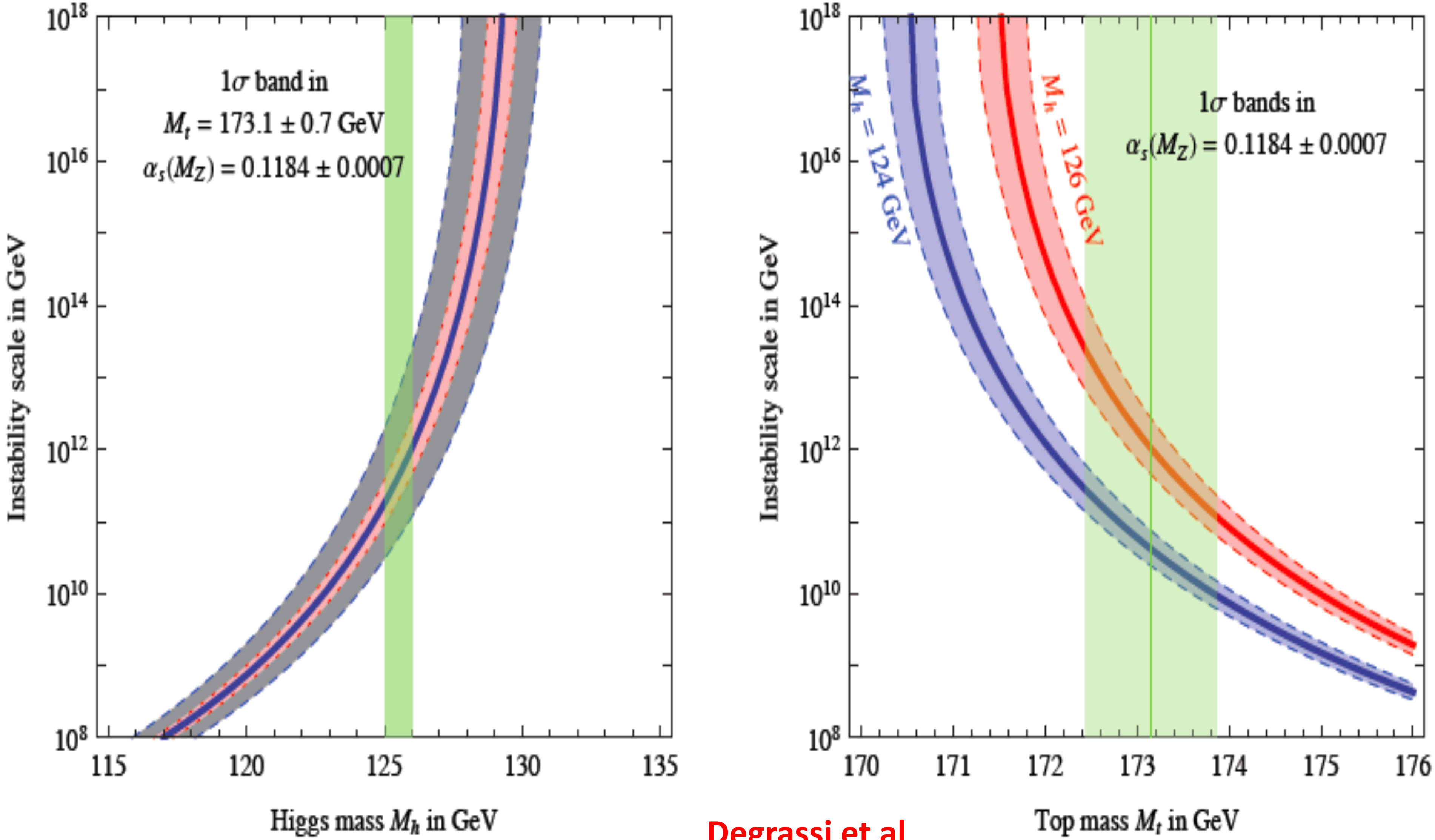


STABILITY vs. INSTABILITY OF OUR VACUUM

Giuseppe Degrassi, Stefano Di Vita, Joan Elias-Miro, Jose R. Espinosa, Gian F. Giudice, Gino Isidori, Alessandro Strumia   1205.6497v1 [hep-ph]

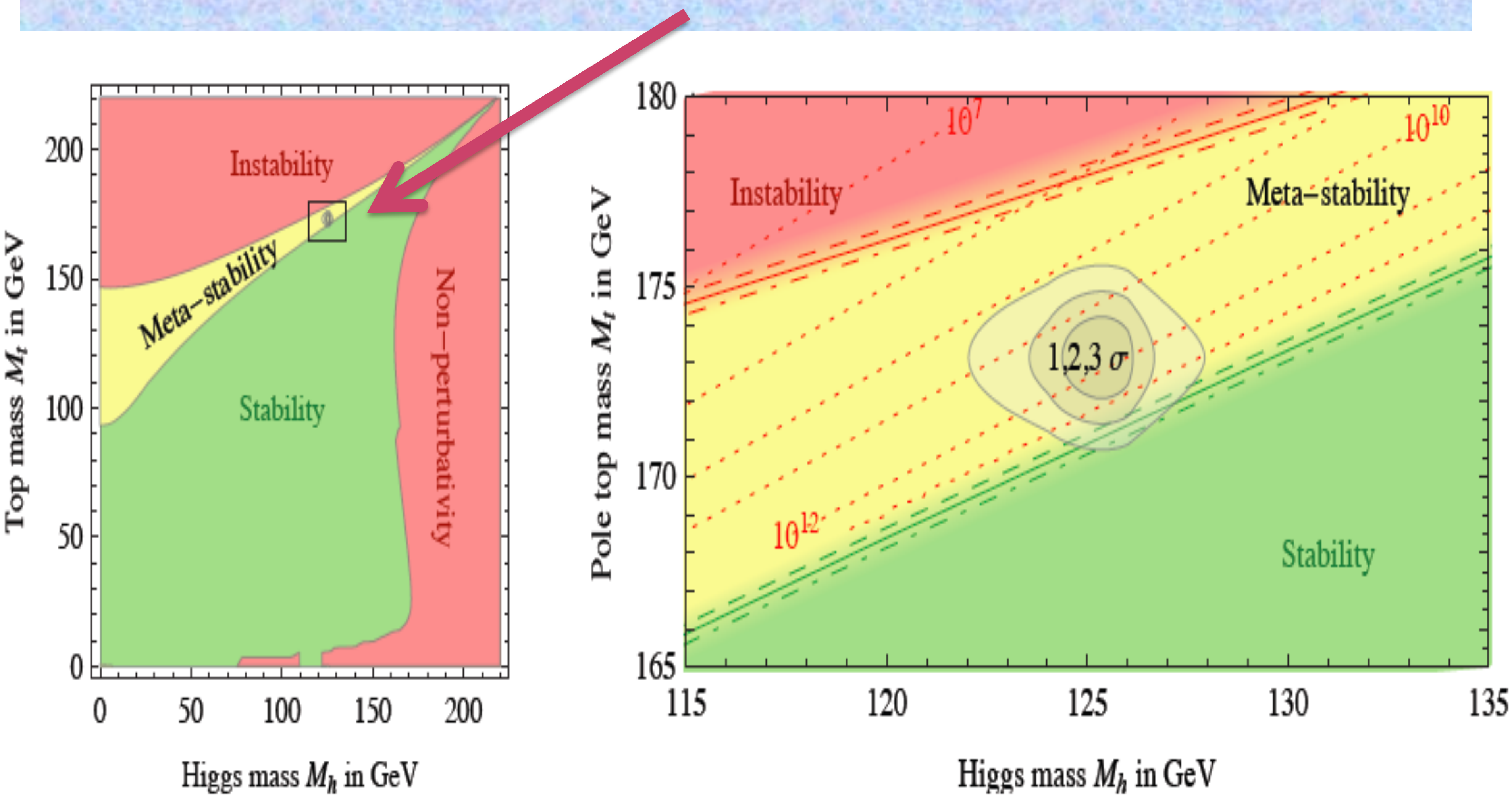


ELW VACUUM INSTABILITY SCALE



Degrassi et al

VITA SPERICOLATA IN UN "PROBABILE" UNIVERSO METASTABILE



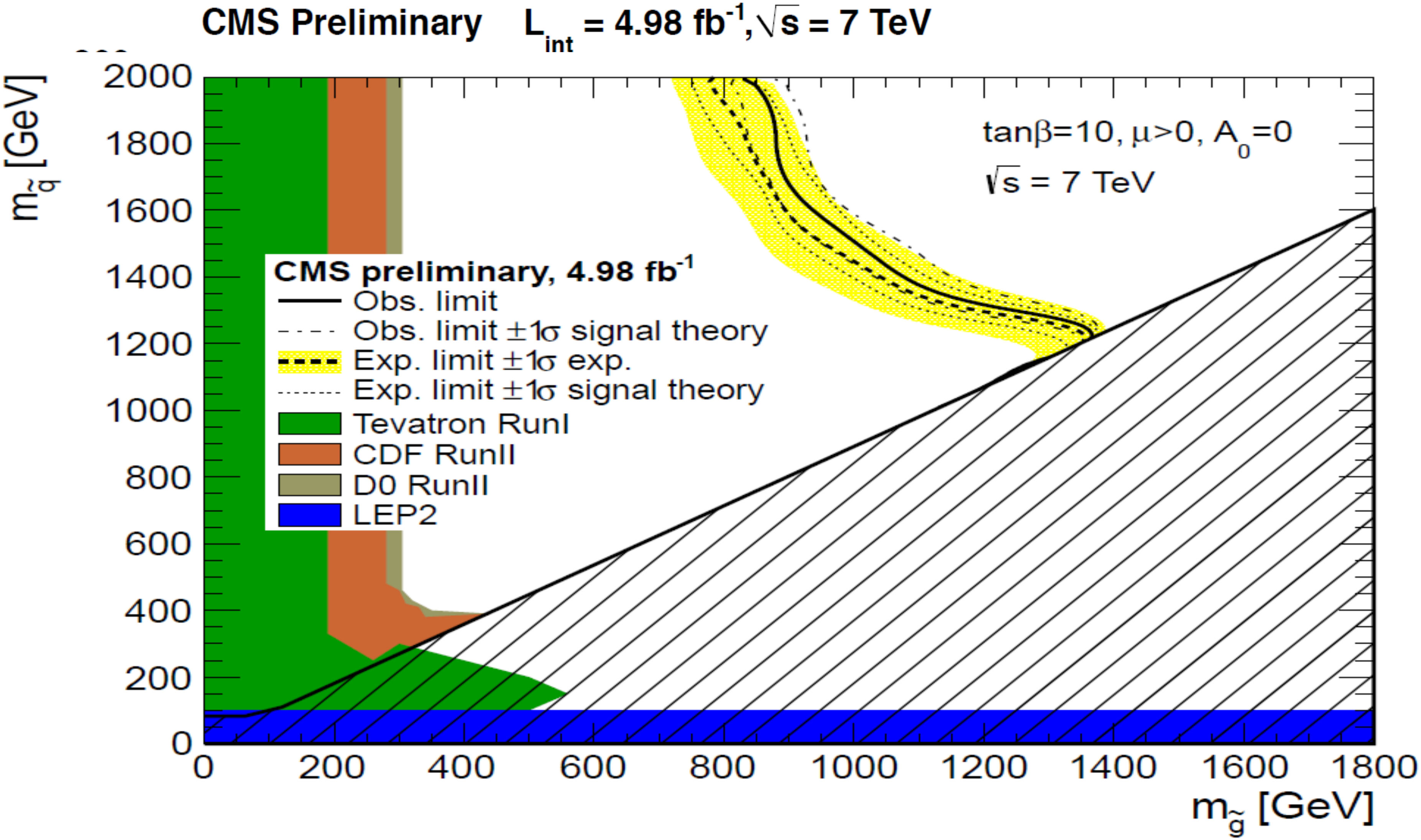
DEGRASSI ET AL

L'IMPORTANZA DI AVERE UNA MISURA PRECISA DELLE MASSE DI TOP E HIGGS

Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	Total combined in quadrature	± 1.5 GeV
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{QCD})$ correction to M_t	± 0.6 GeV
y_t	QCD threshold at 4 loops	± 0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	± 0.2 GeV
Theory	Total combined in quadrature	± 1.0 GeV

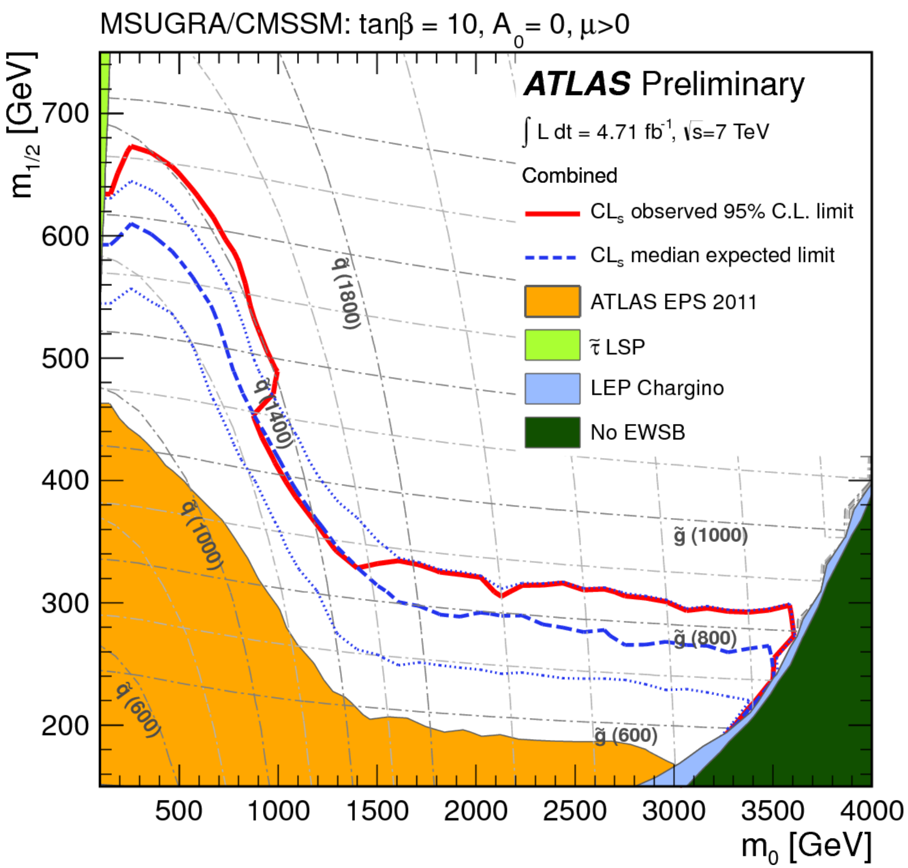
SE ALLA FINE DI QUESTO RUN DI LHC SI TROVA UN "HIGGS STANDARD" CON ACCOPPIAMENTI –pur misurati con modesta precisione - "STANDARD", cioe' in sintonia con quanto previsto nel SM, ACQUISTA INTERESSE UN LINEAR COLLIDER TOP- E HIGGS- FACTORY!

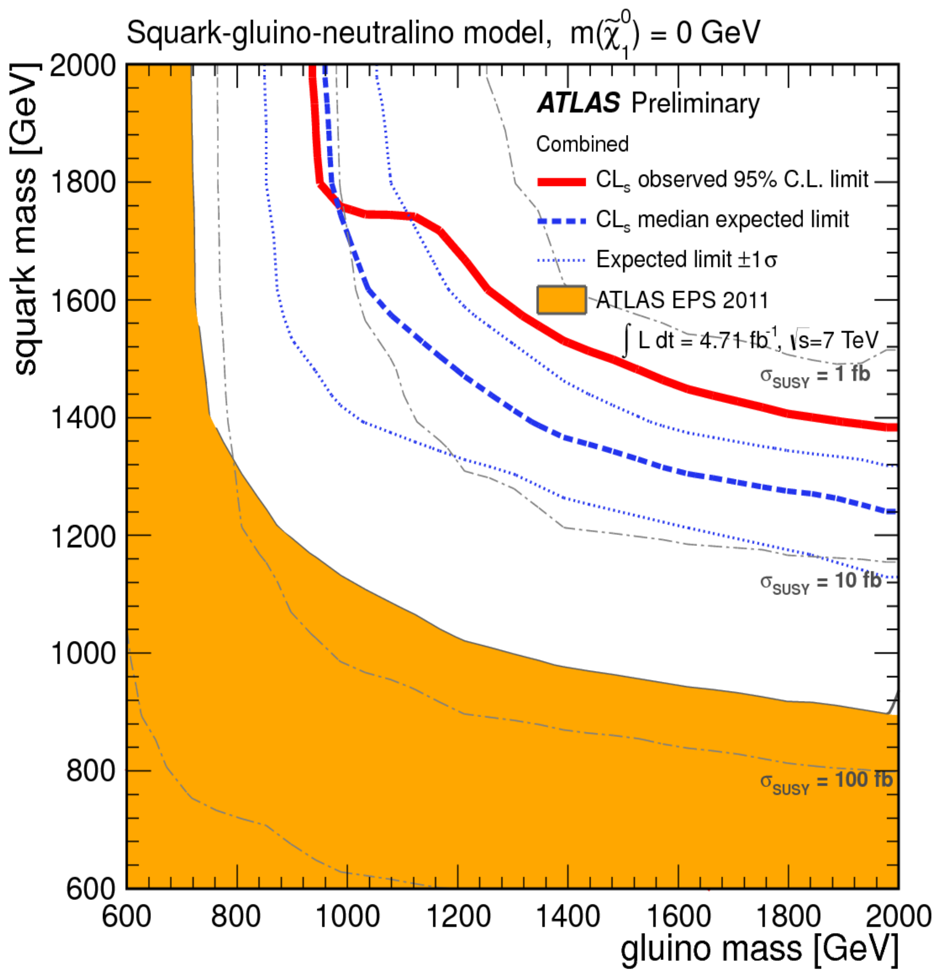
VITA DURA PER SUSY

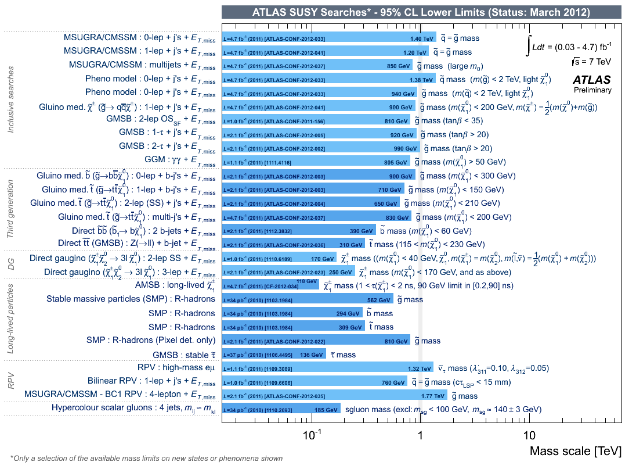


SUSY limits

PLHC June 4-9, 2012 – Vancouver CMS 2011 data







SUSY limits

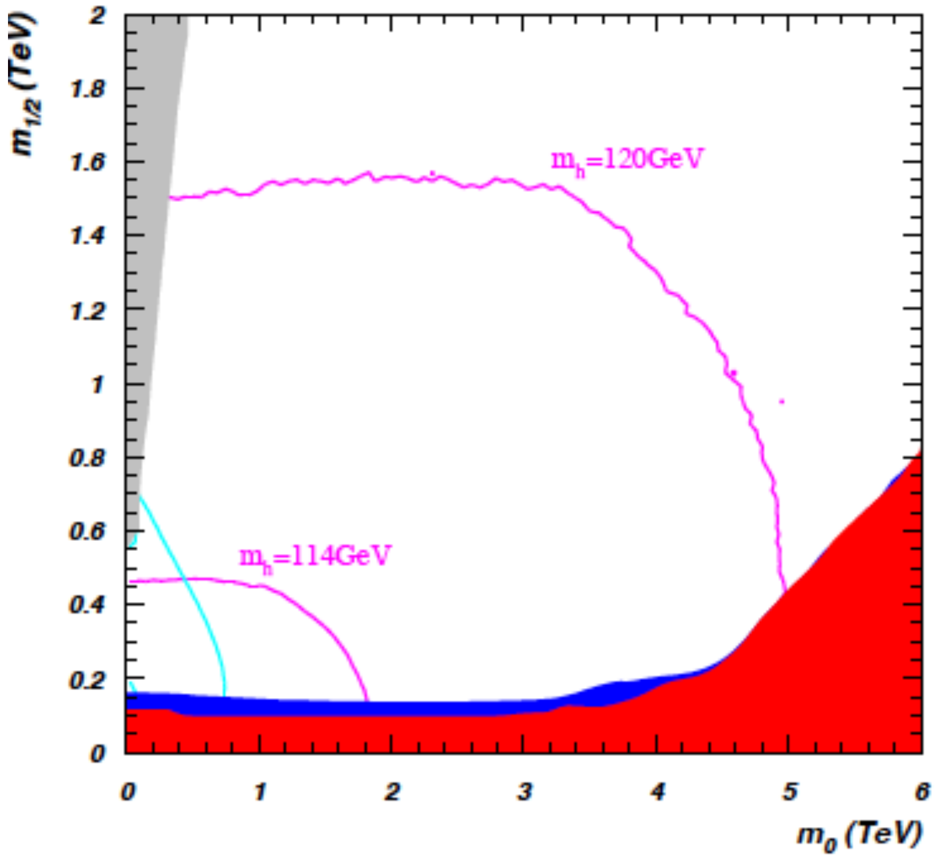
CIPAMP May 29-June 2, 2012 - Florida

ATLAS 2011 data

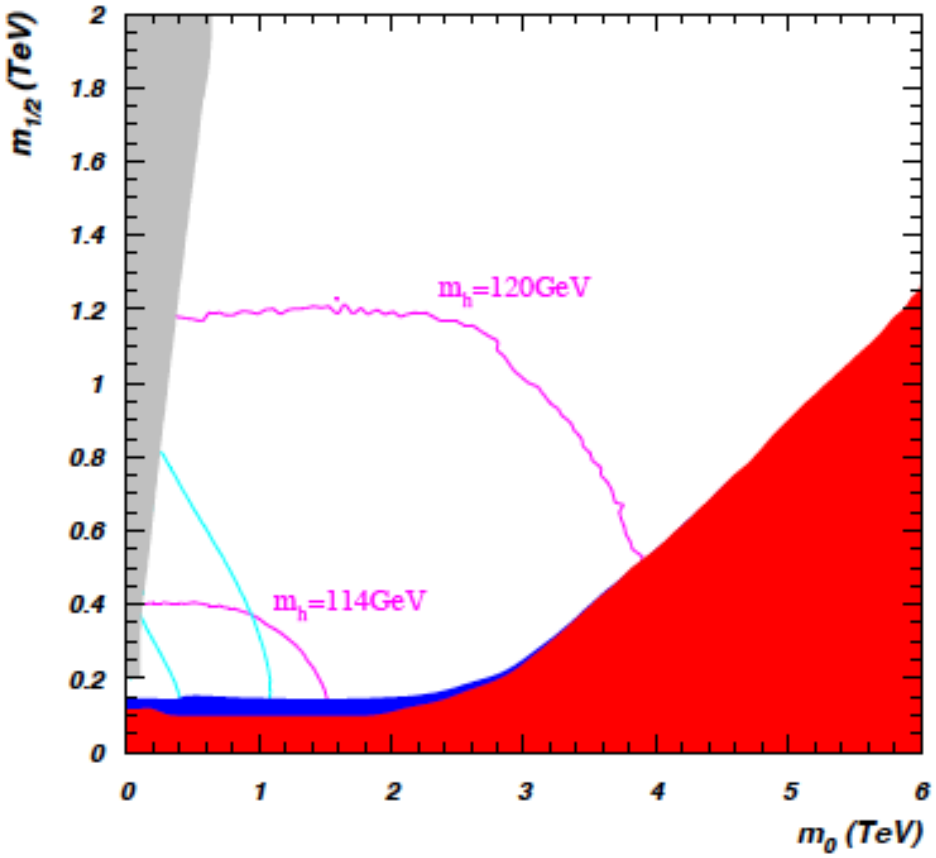
Hard times for the most constrained minimal SUSY extension of the SM

BAER, BARGER MUSTAFAYEV

mSUGRA: tanβ=10, A_0 =0, μ >0, m_t =173.3 GeV

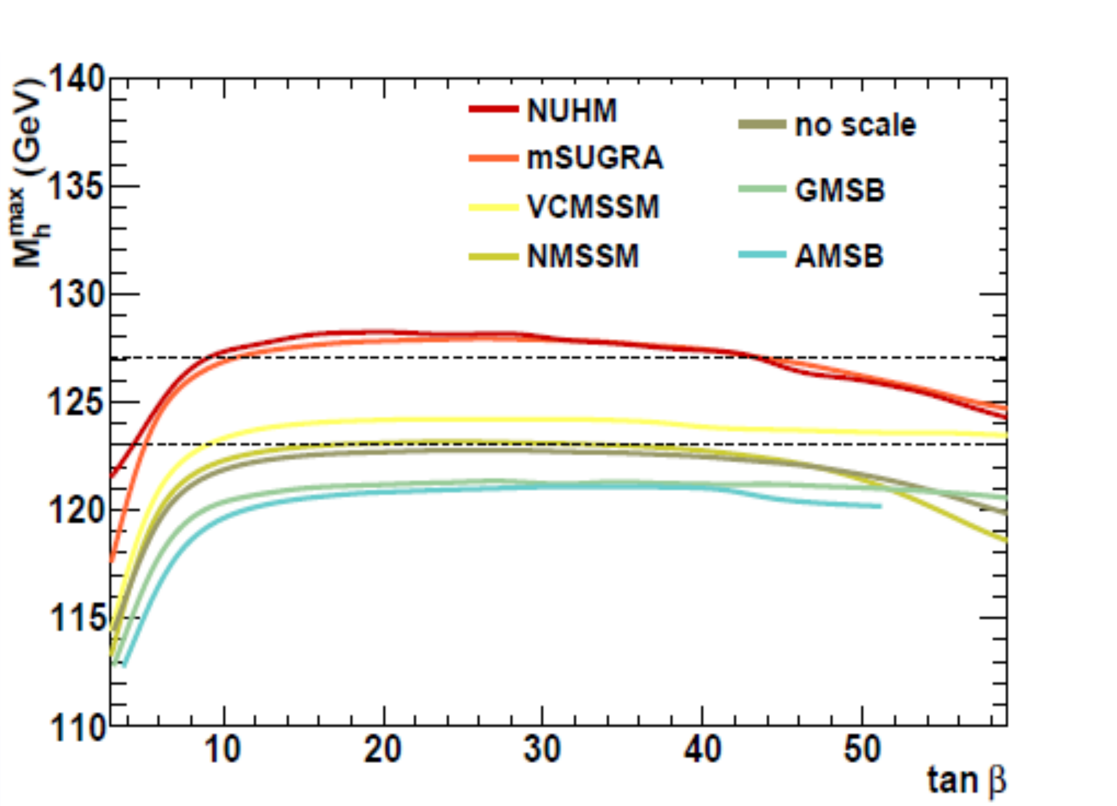


mSUGRA: tanβ =30, A_0 =0, μ >0, m_t =173.3 GeV



Consequences of a 125 GeV Higgs on constrained MSSM scenarios

Maximal Higgs masses



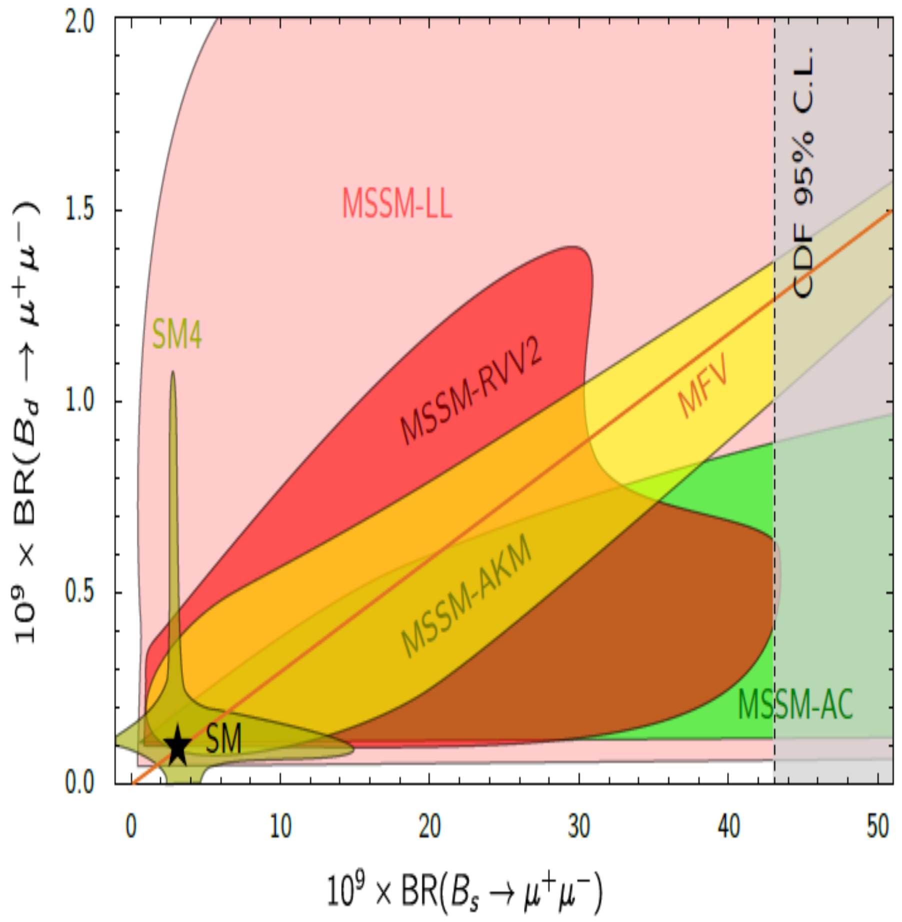
A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

End of AMSB and GMSB in their minimal versions!

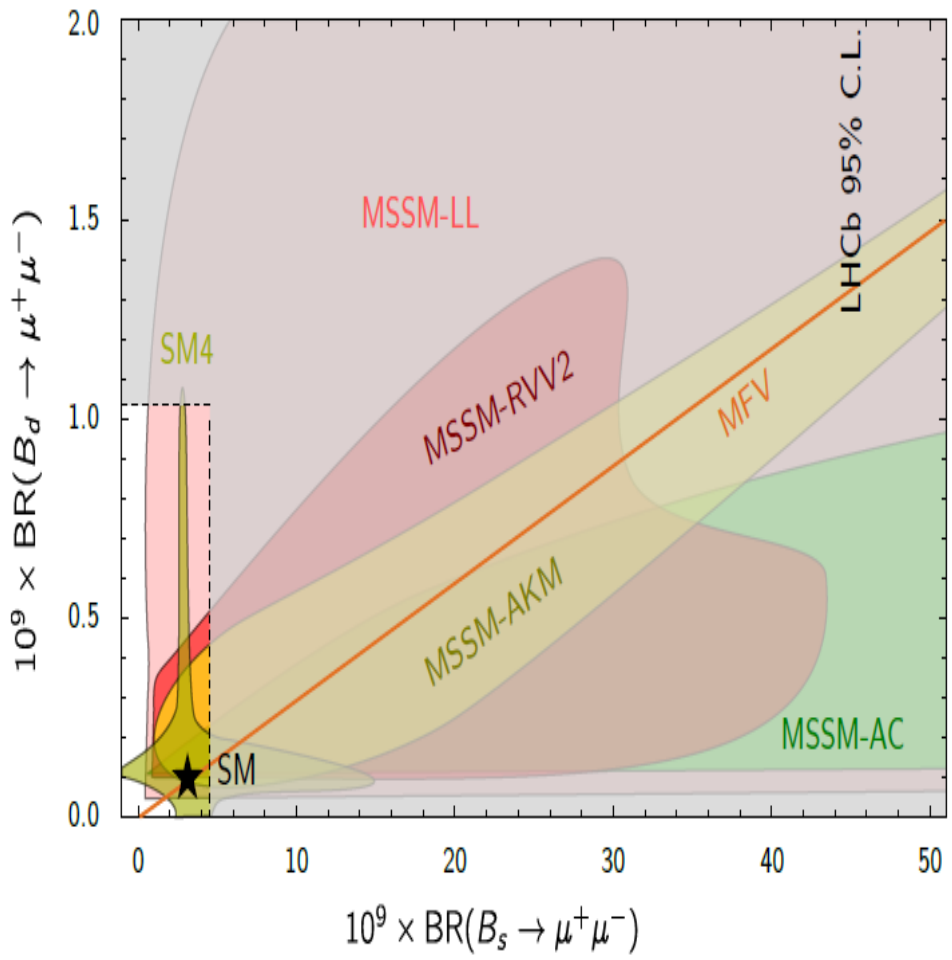
David Straub: arXiv:1205.6094

2011



2012

ATLAS, CMS and **LHCb** results combined:
BPH-12-009, ATLAS-CONF-2012-061, LHCb-CONF-2012-017



WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

- HIGH ENERGY PHYSICS

NO (but A_{FB}…… $^{Z \longrightarrow bb}$)

- FCNC, CP≠

NO (but CPV in Bs, sin2β tension…)

- HIGH PRECISION LOW-EN.

NO (but $(g\text{-}2)_\mu$ …)

- **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)

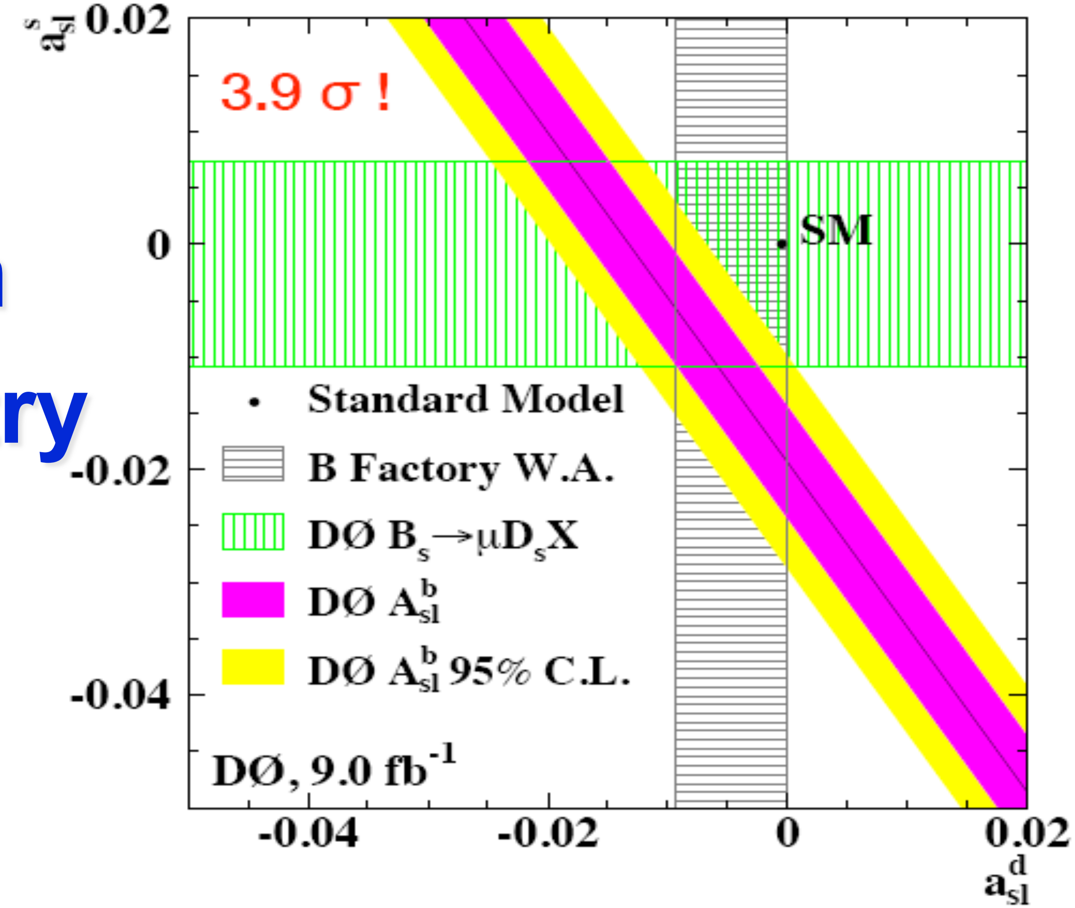
- NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

YES **(hierarchy, unification, flavor)**

EVIDENCE OF NP ALONG THE HIGH INTENSITY ROAD?

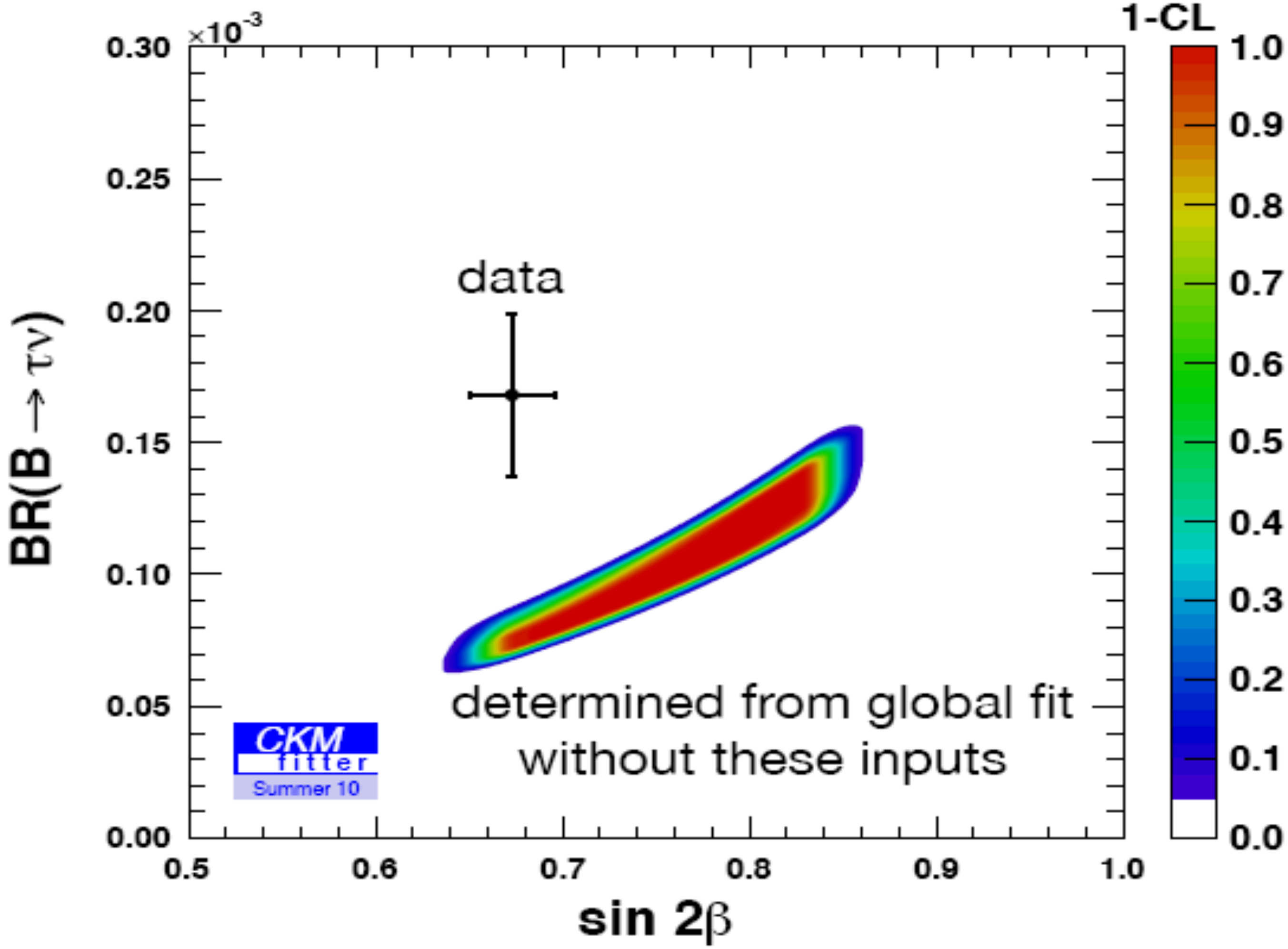
- "FLAVOR COLDS for the SM:

Like-sign dimuon charge asymmetry



But ***tension*** in the UT fit even neglecting CPV in the B_s mixing

Lenz, Nierste + CKMfitter (2010)



Direct CPV in $D^0 \to \pi^+\pi^-, K^+K^-$:

CPV in mixing (indirect) can be related to direct CPV via the relation:

$$A_{CP}(h^+h^-) = a_{CP}^{\text{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} a_{CP}^{\text{ind}}(h^+h^-)$$

$\langle t \rangle/\tau$ = 1 at B factories, ~2.5 at CDF (displaced trigger)

Independent of the final state

Considering $\pi\pi$ or KK final states we can build the difference:

$$A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta a_{CP}\ (\text{direct}) + \Delta\langle t \rangle/\tau\ a_{CP}^{\text{ind}}$$

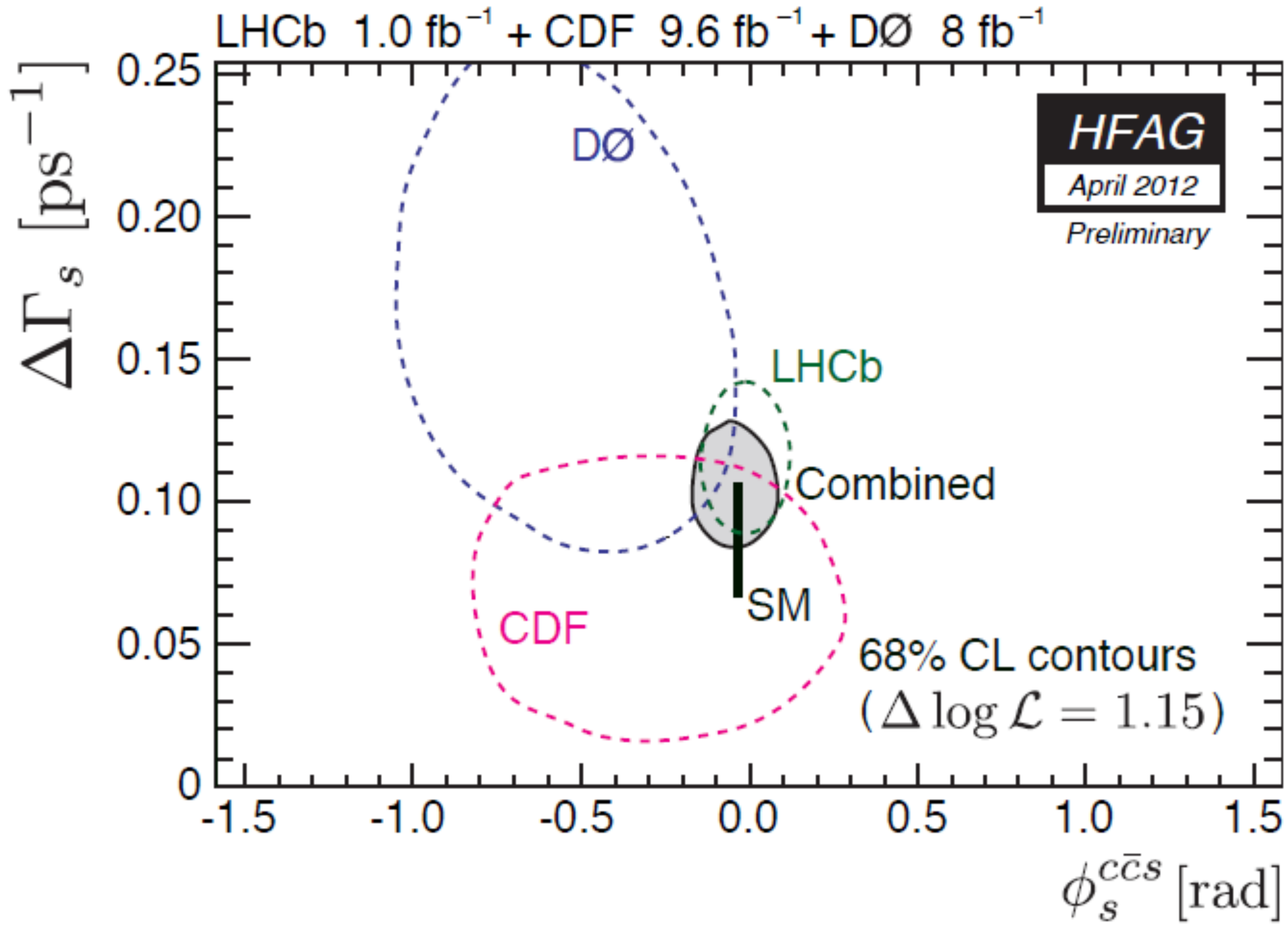
HCP 2011: LHCb, 620 pb^{-1} : first evidence (3.5 σ) of CPV in charm:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$$

Moriond 2012: CDF, 9.6 fb^{-1}, confirms this result

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.62 \pm 0.21 \pm 0.10)\ \%$$

Combination of LHCb and CDF results in a 3.8 σ deviations from zero.

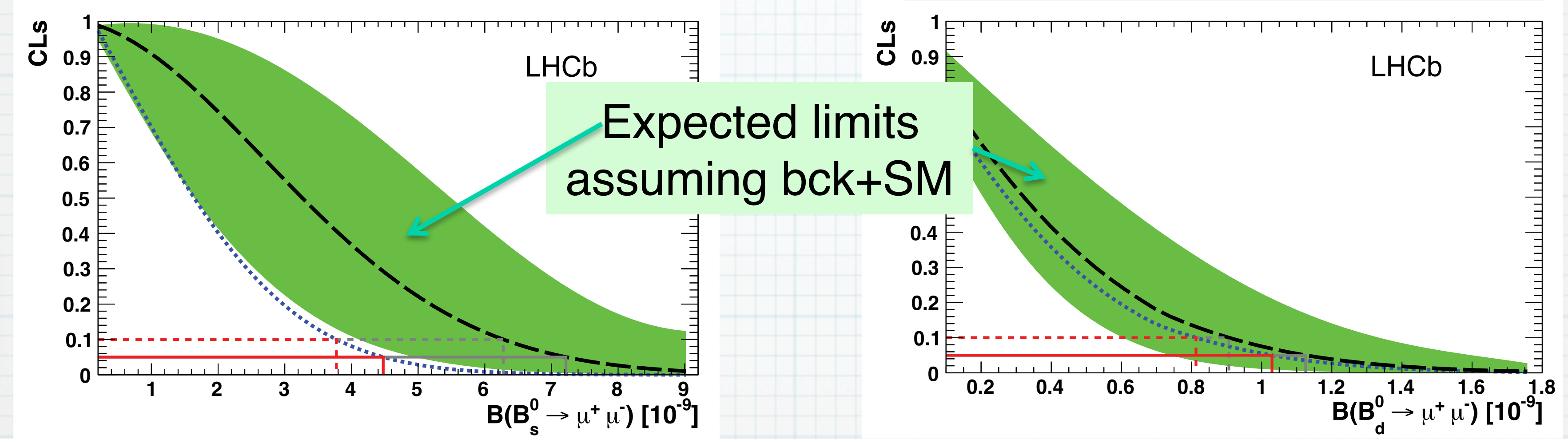


Ref.	Mode	$\phi_s = \phi_s^{ccs}$	$\Delta\Gamma_s$ (ps^{-1})
CDF Note 10778 (2012)	$J/\psi\phi$	$[-0.60,\ 0.12]$, 68% CL	$0.068 \pm 0.026 \pm 0.007$
DØ, PRD D85 032006 (2012)	$J/\psi\phi$	$-0.55^{+0.38}_{-0.36}$	$0.163^{+0.065}_{-0.064}$
LHCb-CONF-2012-002	$J/\psi\phi$	$-0.001 \pm 0.101 \pm 0.027$	$0.116 \pm 0.018 \pm 0.006$
LHCb, arXiv:1204.5675	$J/\psi\pi\pi$	$-0.019^{+0.173+0.004}_{-0.174-0.003}$	—
Combined [HFAG'2012]		$-0.044^{+0.090}_{-0.085}$	$+0.105 \pm 0.015$

LHCb: Search for $B_s(B_d) \rightarrow \mu^+\mu^-$

$B(B_s \rightarrow \mu\mu) < 4.5 \; 10^{-9}$ at 95% CL

$B(B \rightarrow \mu\mu) < 10.3 \; 10^{-10}$ at 95% CL



arXiv 1203.4493

mode	limit	at 90 % C.L.	at 95 % C.L.
$B^0_s \rightarrow \mu^+\mu^-$	expected bg+SM	6.3×10^{-9}	7.2×10^{-9}
	expected bg only	2.8×10^{-8}	3.4×10^{-9}
	observed	3.8×10^{-8}	4.5×10^{-9}
$B^0 \rightarrow \mu^+\mu^-$	expected	9.1×10^{-10}	11.3×10^{-10}
	observed	8.1×10^{-8}	10.3×10^{-10}

- SM prediction (FCNC, helicity suppressed)
  - SM $B(B_s \rightarrow \mu\mu) = (3.2 \pm 0.2) \; 10^{-9}$
  - SM $B(B \rightarrow \mu\mu) = (0.1 \pm 0.01) \; 10^{-9}$

arXiv:1005.5310
arXiv:1012.1447

CMS expected limit with 4.9 fb^{-1} only 15% worse wrt LHCb

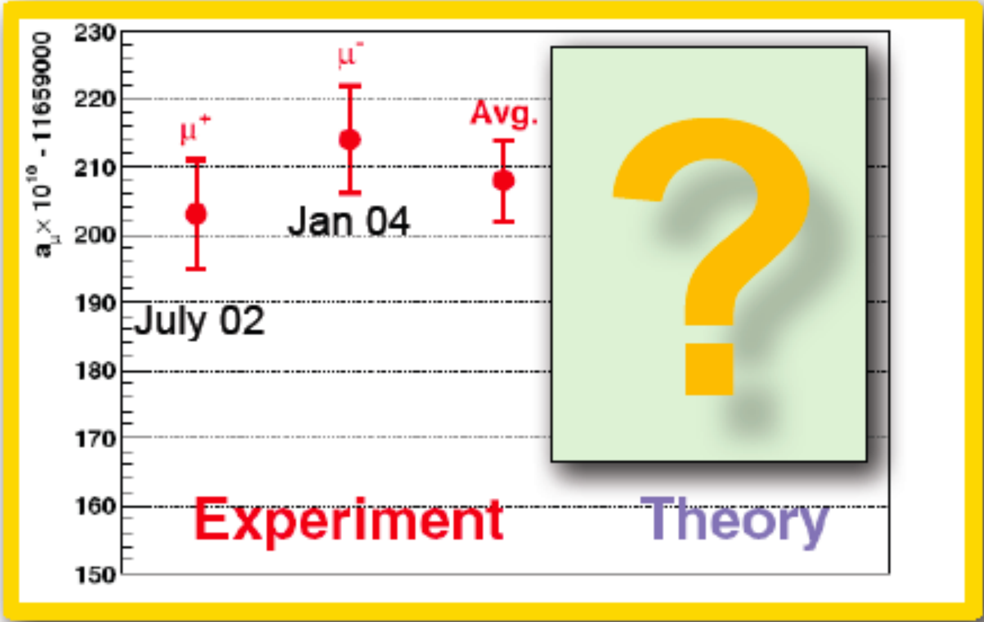
Observed limit BR < 7.7 × 10^{-9} CMS-PAS-BPH-11-020

upper limit (95%CL)	observed	expected
$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

arXiv: 1110.3568

ATLAS preliminary limit with 2.4 fb^{-1} **BR < 2.2 × 10^{-8}** ATLAS-CONF 2011-145

The muon g-2: the experimental result



- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments proposed at:
  - Fermilab (E989), aiming at 0.14ppm → Has now Stage 1 Approval!
  - J-PARC aiming at 0.1 ppm

  [D. Hertzog & N. Saito, U.Paris, Feb 2010; B.Lee Roberts & T. Mibe, Tau2010]
- **Are theorists ready for this (amazing) precision? No(t yet)**

The muon g-2: Standard Model vs. Experiment

Adding up all contributions, we get the following SM predictions and comparisons with the measured value:

$a_\mu^{EXP} = 116592089\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072
with latest value of $\lambda=\mu_\mu/\mu_p$ (CODATA'06)

	$a_\mu^{SM} \times 10^{11}$	$(\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}) \times 10^{11}$	σ
[1]	116 591 782 (59)	307 (86)	3.6
[2]	116 591 802 (49)	287 (80)	3.6
[3]	116 591 828 (50)	261 (80)	3.2
[4]	116 591 894 (54)	195 (83)	2.4

with a_μ^{HHO}(lbl) = 105 (26) x 10^{-11}

[1] F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1

[2] Davier et al, EPJ C71 (2011) 1515 (includes BaBar and KLOE10 2π)

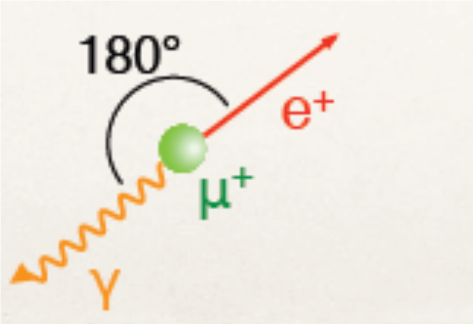
[3] HLMNT11: Hagiwara et al, JPG38 (2011) 085003 (incl BaBar and KLOE10 2π)

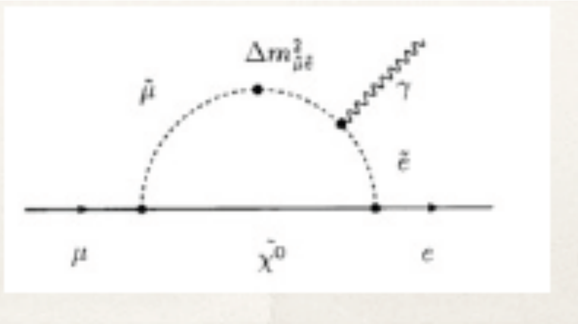
[4] Davier et al, Eur.PJ C71 (2011) 1515, τ data.

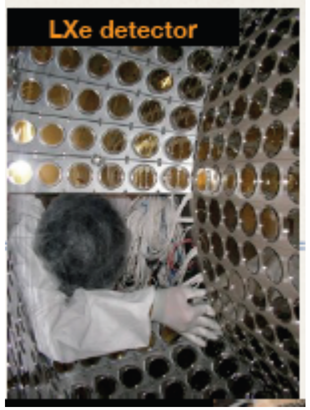
Note that the th. error is now about the same as the exp. one

MEG expt @ PSI

3 10^7 μ/s

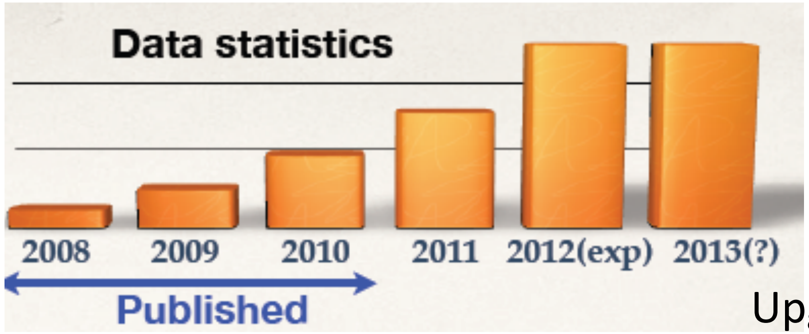






Liq Xe calorimeter
DE/E =4% at 50 MeV

New upper limit: $B\ (\mu \to e\gamma) < 2.4\times10^{-12}$ *(90%C.L.)*

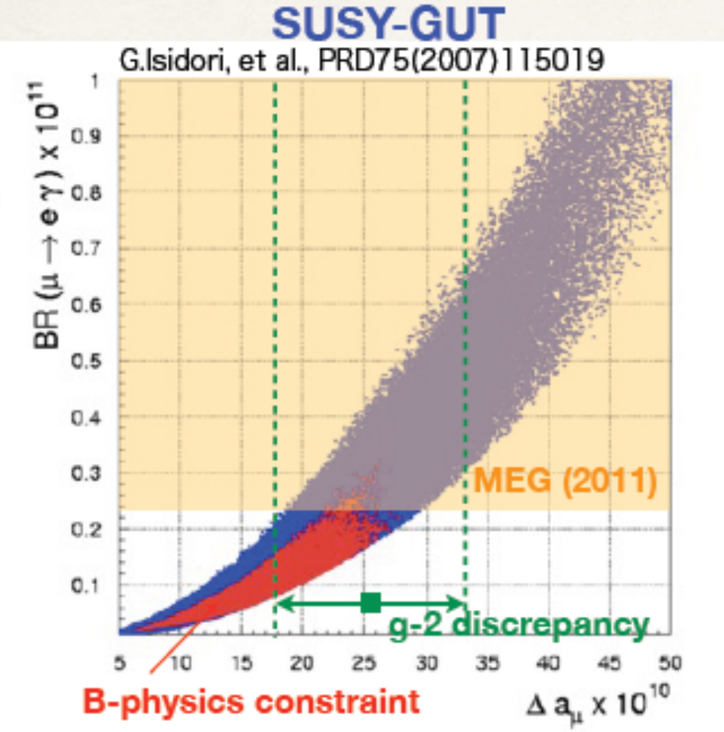


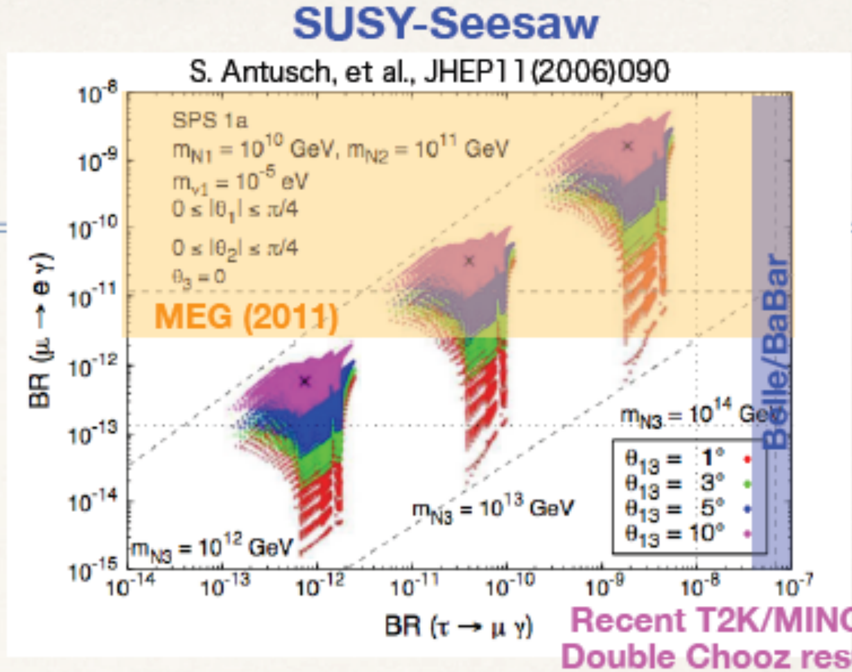
Upgrade?

Will continue run and upgrade detector towards 10^{-14} sensitivity

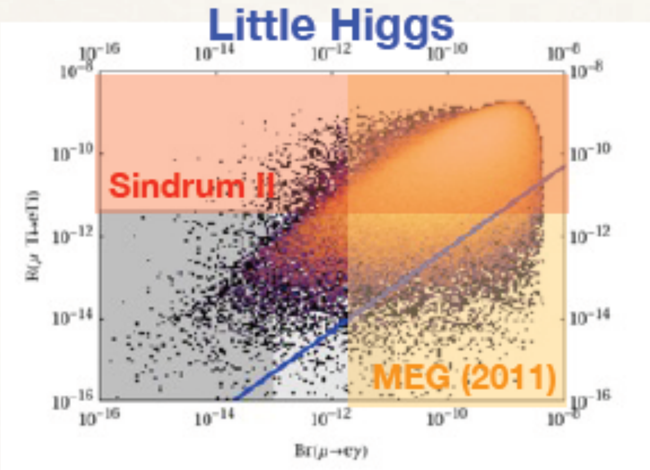
Also: mu2e at FNAL, COMET at KEK, mu3e LOI at PSI…

MEG Constrains New Physics

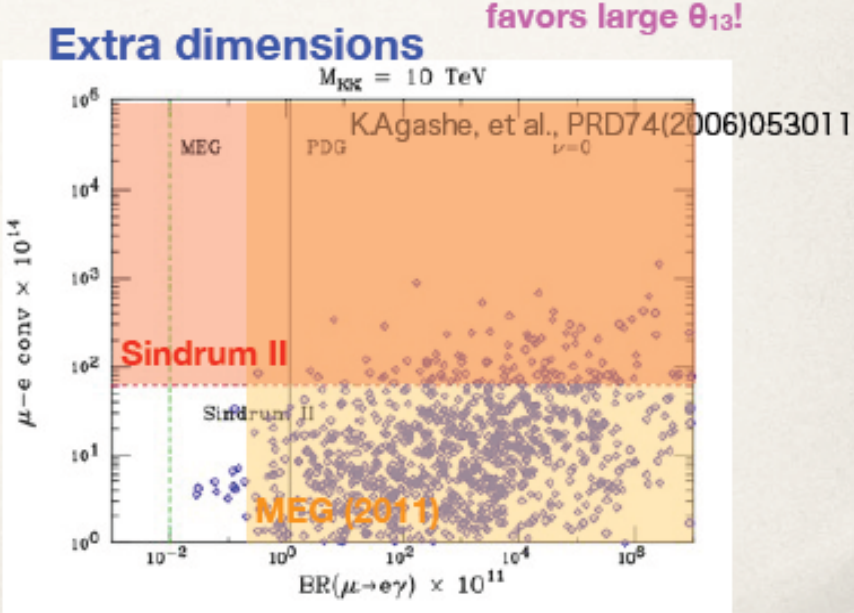




Recent T2K/MINOS/ Double Chooz results favors large θ_{13}!



M.Blanke et al., Acta Phys.Polon.B41(2010)657



MICRO

PARTICLE PHYSICS

GWS STANDARD MODEL

MACRO

COSMOLOGY

HOT BIG BANG
STANDARD MODEL

HAPPY MARRIAGE
Ex: **NUCLEOSYNTHESIS**

NUCLEAR ASTROPHYSICS

BUT ALSO

POINTS OF FRICTION

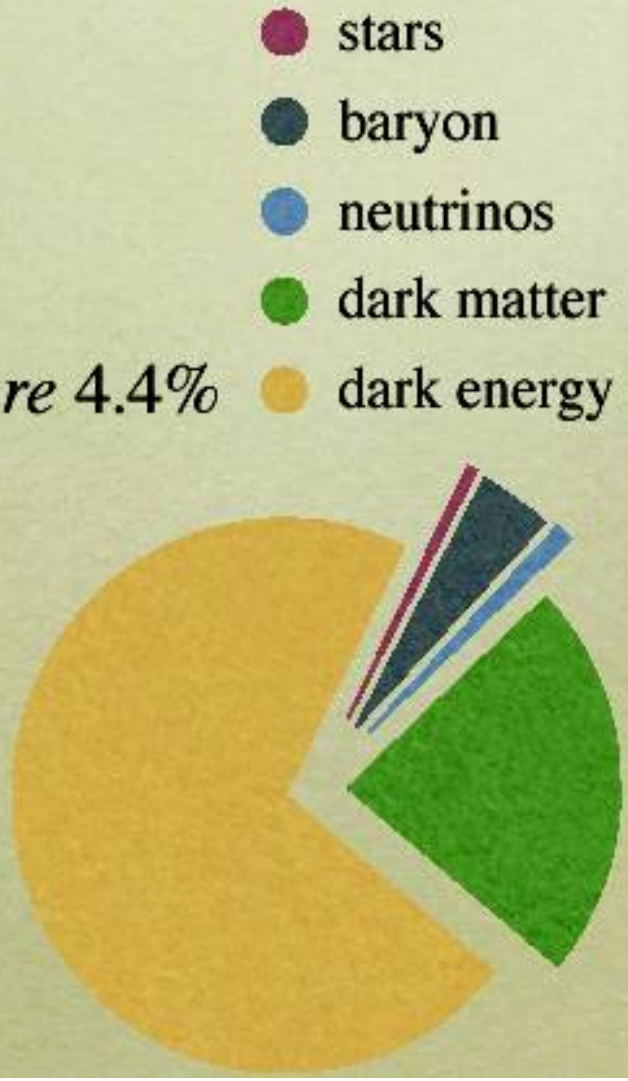
NEW SOURCE OF CP VIOLATION

- **COSMIC MATTER-ANTIMATTER ASYMMETRY**
- **INFLATION** ***NEW SCALAR POTENTIAL***
- **DARK MATTER + DARK ENERGY**
  NEW PARTICLES AND INTERACTIONS

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

THE ENERGY BUDGET OF THE UNIVERSE

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~0.1–1.5%*
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter 23%*
- *Dark Energy 73%*
- *Anti-Matter 0%*
- *Higgs Bose-Einstein condensate* $\sim 10^{62}\%$*??*

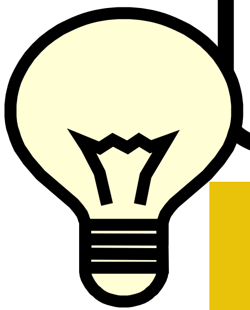


COULD (AT LEAST SOME OF) THE "OBSERVATIONAL" NEW PHYSICS BE LINKED TO THE ULTRAVIOLET COMPLETION OF THE SM AT THE ELW. SCALE ?

The Energy Scale from the “Observational” New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation

NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE



The Energy Scale from the “Theoretical” New Physics

☆ ☆ ☆ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale**

+

☆ **CORRECT GRAND UNIFICATION “CALLS” FOR NEW PARTICLES AT THE ELW. SCALE**

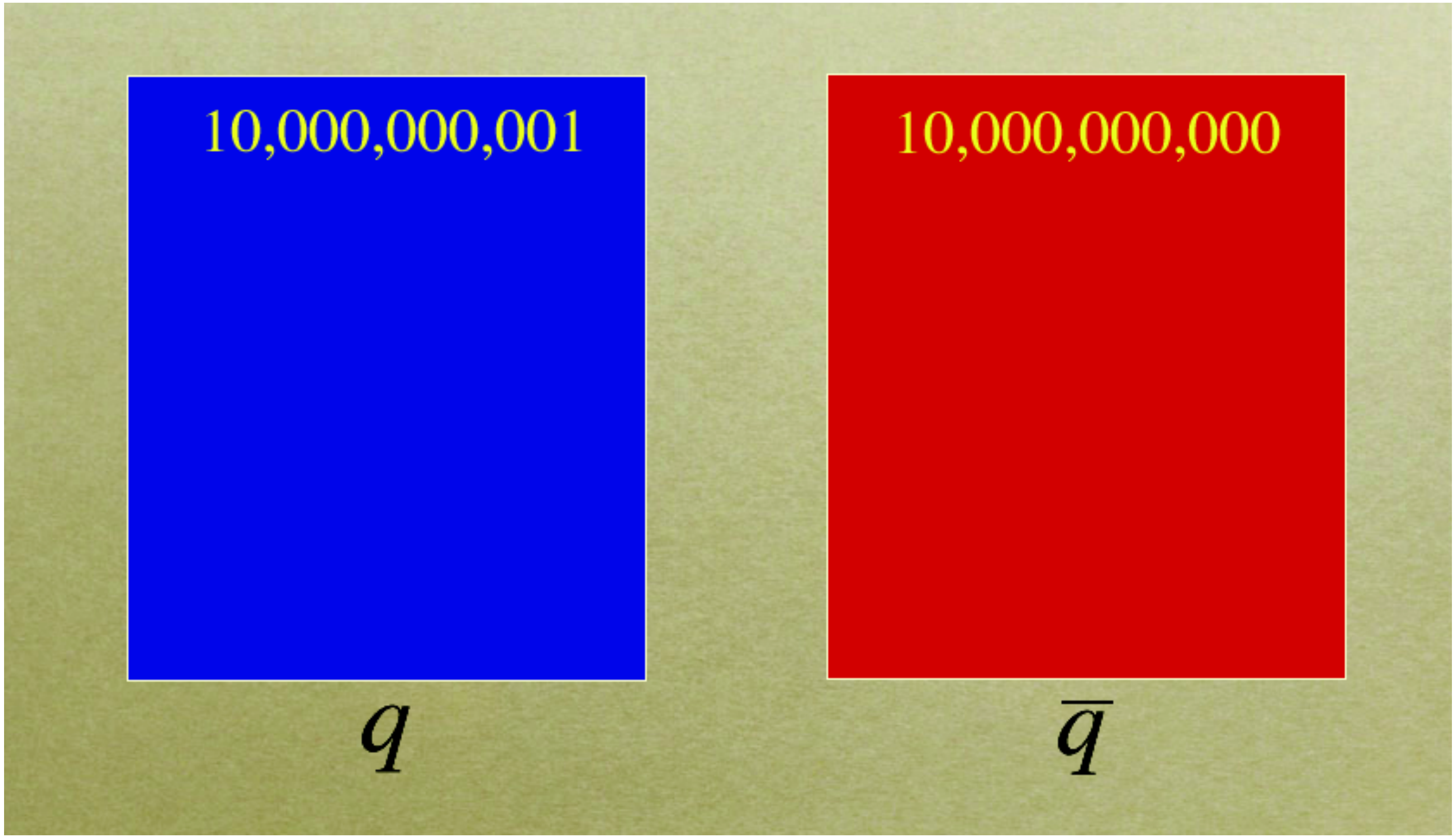
THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$

- 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 $\longrightarrow$ 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 $\longrightarrow$ DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

$\Downarrow$

- 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

:

- **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. Connection to LFV, too?

- 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**)

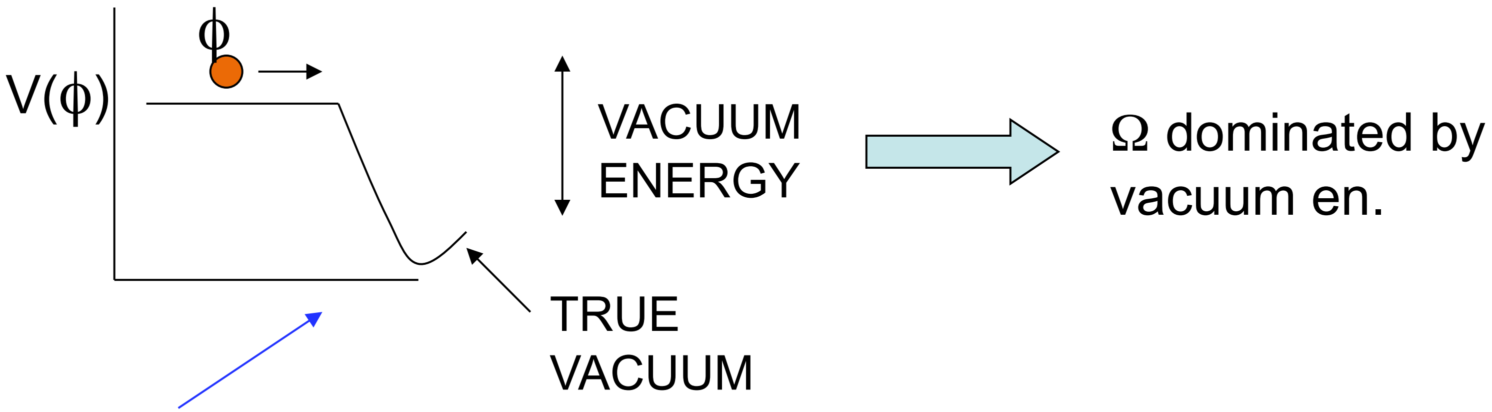
INFLATION

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 $\gg$ Mw

DIFFICULT BUT NOT IMPOSSIBLE TO OBTAIN ELECTROWEAK INFLATION IN SM EXTENSIONS

For some inflationary models → large amount of primordial gravitational waves

HOW TO COPE WITH THE HIERARCHY PROBLEM

- LOW-ENERGY SUSY
- LARGE EXTRA DIMENSIONS
- DYNAMICAL SYMMETRY BREAKING OF THE ELW. SYMMETRY
- LANDSCAPE APPROACH (ANTHROPIC PRINCIPLE)

ROADS TO GO BEYOND THE STANDARD MODEL (I)

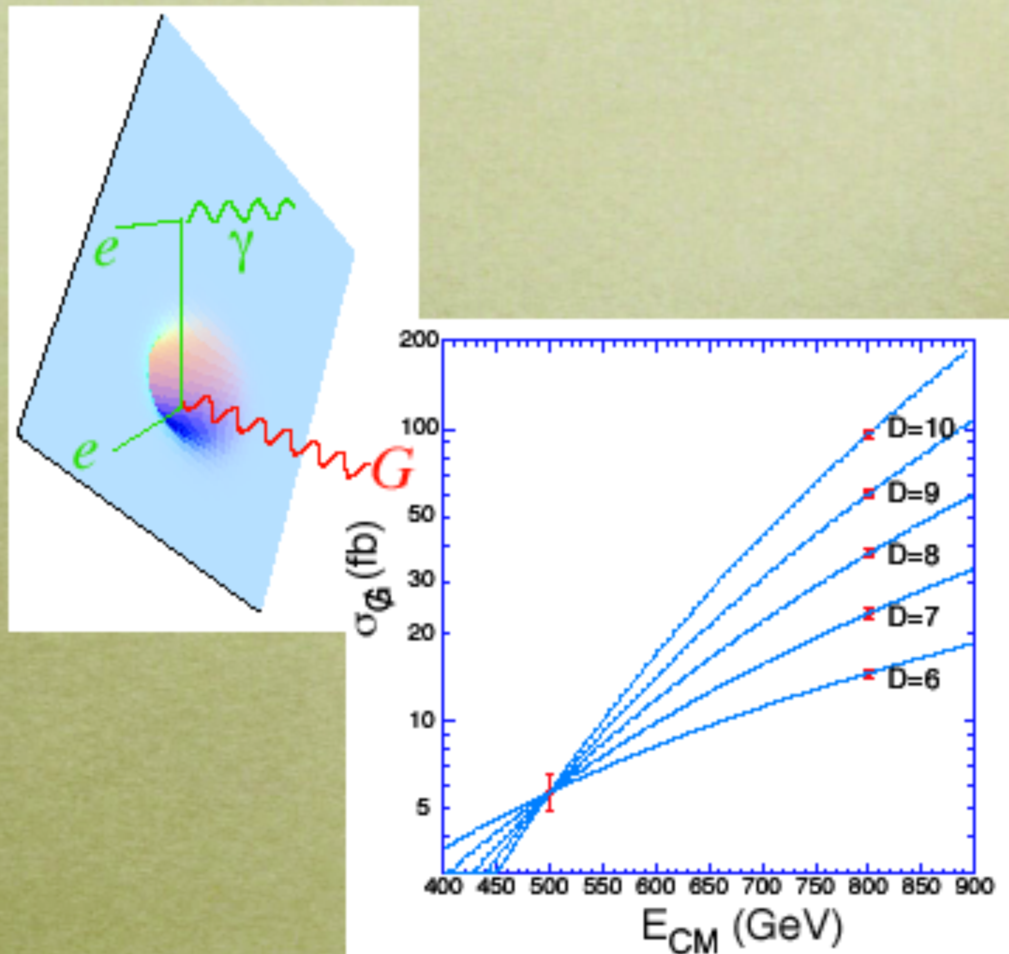
1) **THERE EXISTS NO NEW PHYSICAL ENERGY SCALE ABOVE THE ELW. SCALE**: gravity is an extremely weak force not because of the enormous value of the Planck scale, but because of the existence of **NEW DIMENSIONS** beyond the usual 3+1 space-time where (most of) the gravity flux lines get "dispersed"

→ **VISIBILITY AT LHC**: there exist "excited" states of the ordinary particles (**Kaluza-Klein states**) and some of them are accessible at LHC (the lightest KK state may be a stable particle and it can constitute the DM)

Hidden Dimensions

- *Hidden dimensions*
- *Can emit graviton into the bulk*
- *Events with apparent energy imbalance*

How many extra dimensions are there?



ROADS TO GO BEYOND THE STANDARD MODEL (II)

- **2) NO NEED TO "PROTECT" THE HIGGS MASS AT THE ELW. SCALE: THE HIGGS IS A COMPOSITE OBJECT (for instance, a fermion condensate) WHOSE COMPOSITENESS SCALE IS THE ELW. SCALE (cfr. the pion mass case)**

⟶ **VISIBILITY AT LHC: THERE EXIST NEW (STRONG) INTERACTIONS AT THE ELW. SCALE WHICH PRODUCE THE HIGGS CONDENSATE** (new resonances,, new bound states, a new rescaled QCD at 1 TeV)

ROADS TO GO BEYOND THE STANDARD MODEL (III)

- 3) THE MASS OF THE ELEMENTARY HIGGS BOSON IS "PROTECTED" AT THE ELW. SCALE BECAUSE OF THE PRESENCE AT THAT ENERGY OF A NEW SYMMETRY, THE **SUPERSYMMETRY (SUSY)**
  → **VISIBILITY AT LHC**: WE'LL SEE (SOME OF) THE **SUSY PARTICLES AND THEIR INTERACTIONS**. THE LIGHTEST SUSY PARTCILE (**LSP**) IS LIKELY TO BE STABLE AND PROVIDE THE **DM**. **AT THE SAME TIME, WE COULD DISCOVER SUSY AND THE SOURCE OF 90% OF THE ENTIRE MATTER PRESENT IN THE UNIVERSE.**

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 !**

DM → NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) SM - if Newton is right at scales>size of the Solar System

- $\Omega_{DM} = 0.233 \pm 0.013$ *
- $\Omega_{baryons} = 0.0462 \pm 0.0015$ **

*from CMB (5 yrs. of WMAP) + Type I Supernovae + Baryon Acoustic Oscillations (BAO)

**CMB + TypeI SN + BAO in agreement with Nucleosynthesis (BBN)

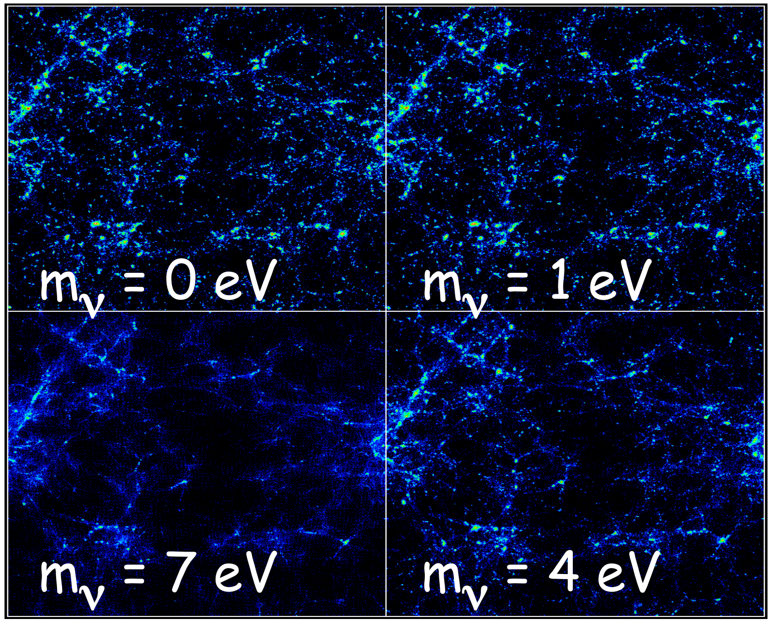
THE RISE AND FALL OF NEUTRINOS AS DARK MATTER

- Massive neutrinos: only candidates in the SM to account for DM. From here the "prejudice" of neutrinos of a few eV to correctly account for DM

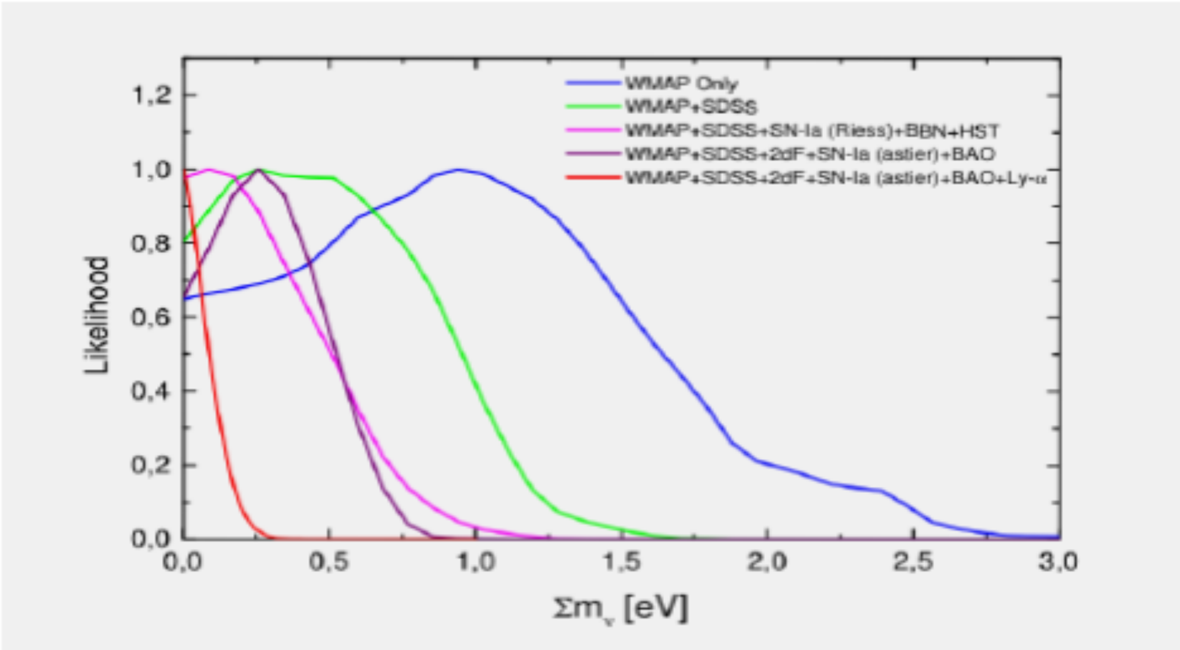
- Neutrinos decouple at ~1 MeV ; being their mass<<decoupling temperature, neutrinos remain relativistic for a long time. Being very fast, they smooth out any possible growth of density fluctuation forbidding the formation of proto-structures.

- The "weight" of neutrinos in the DM budget is severely limited by the observations disfavoring scenarios where first superlarge structures arise and then galaxies originate from their fragmentation

LSS PATTERN AND NEUTRINO MASSES



(E..g., Ma 1996)



Cosmological Bounds on the sum of the masses of the 3 neutrinos from increasingly rich samples of data sets

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Fogli et al., Phys. Rev. D 75, 053001 (2007)

TEN COMMANDMENTS TO BE A “GOOD” DM CANDIDATE

BERTONE, A.M., TAOSO

- **TO MATCH THE APPROPRIATE RELIC DENSITY**
- **TO BE COLD**
- **TO BE NEUTRAL**
- **TO BE CONSISTENT WITH BBN**
- **TO LEAVE STELLAR EVOLUTION UNCHANGED**
- **TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS**
- **TO BE CONSISTENT WITH DIRECT DM SEARCHES**
- **TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS**
- **TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS**
- **“TO BE PROBED EXPERIMENTALLY”**

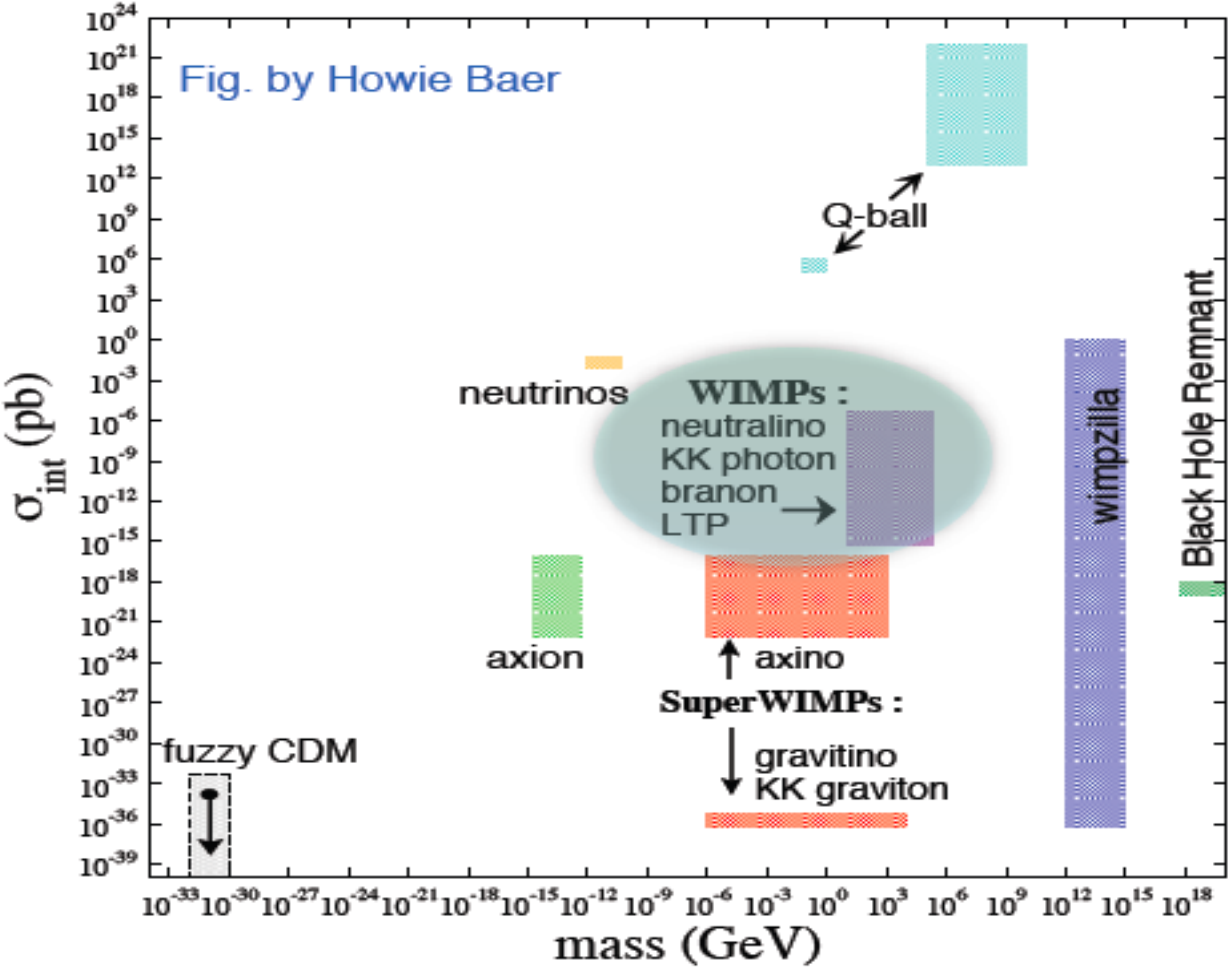


Fig. by Howie Baer
Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
σ_{int} (pb)
mass (GeV)

Expected Rates in a Terrestrial Detector

Astrophysics

$$R \sim N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle$$

Particle physics

N = number of target nuclei in a detector

ρ_χ = local density of the dark matter in the Milky Way

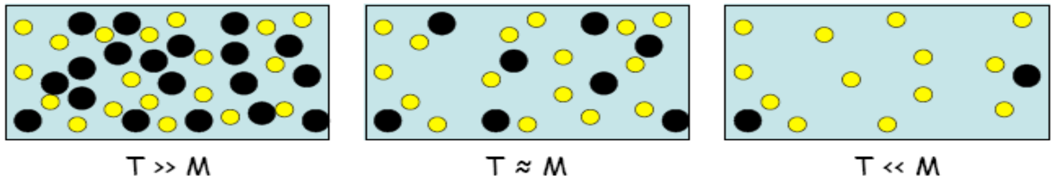
<V> = mean WIMP velocity relative to the target

m_χ = WIMP-mass

$\sigma_{\chi N}$ =cross section for WIMP-nucleus elastic scattering

***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** **?**



WIMPS (Weakly Interacting Massive Particles)

$\#\chi \sim \#\gamma$ m_χ

$\#\chi$ exp($-m\chi/T\chi$)

$\#\chi$ does not change any more

$T_{decoupl.}$ typically ~ m_χ /20

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

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{<(\sigma_{annih.})\, V\chi>\ \ \mathrm{TeV}^2}$$

$<(\sigma_{annih.})\, V\chi>$ ~ α^2 / M^2_χ

TeV^2 → From $T^0\, M_{Planck}$

COSMO – PARTICLE CONSPIRACY

$\Omega\chi h^2$ 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} !!!

THERMAL RELICS (WIMP in thermodyn.equilibrium with the plasma until $T_{decoupl}$)

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) **ENLARGEMENT OF THE SM**	(x^{μ}, θ)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	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

SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY ⟶ LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

WHO IS THE LSP?

- **SUPERGRAVITY** (transmission of the SUSY breaking from the hidden to the obsevable sector occurring via gravitational interactions): best candidate to play the role of LSP:

  NEUTRALINO (i.e., the lightest of the four eigenstates of the 4x4 neutralino mass matrix)

In **CMSSM**: the LSP neutralino is almost entirely a BINO

DM ⟺ THE ORIGIN OF THE SUSY BREAKING

HIDDEN SECTOR SUSY BREAKING AT SCALE $\sqrt{F}$

MESSENGERS

OBSERVABLE SECTOR
SM + superpartners
MSSM : minimal content of superfields

DM NEUTRALINO

$F = M_W M_{Pl}$

GRAVITY →

$M_{gravitino}$ $\sim F/M_{Pl} \sim$

$(10^2 - 10^3)$ GeV

DM GRAVITINO

$F = (10^5 - 10^6)$ GeV

→ GAUGE INTERACTIONS

$M_{gravitino}$ $\sim F/M_{Pl} \sim$

$(10^2 - 10^3)$ eV

GRAVITINO LSP?

- **GAUGE MEDIATED SUSY BREAKING**

(GMSB) : LSP likely to be the GRAVITINO (it can be so light that it is more a warm DM than a cold DM candidate)

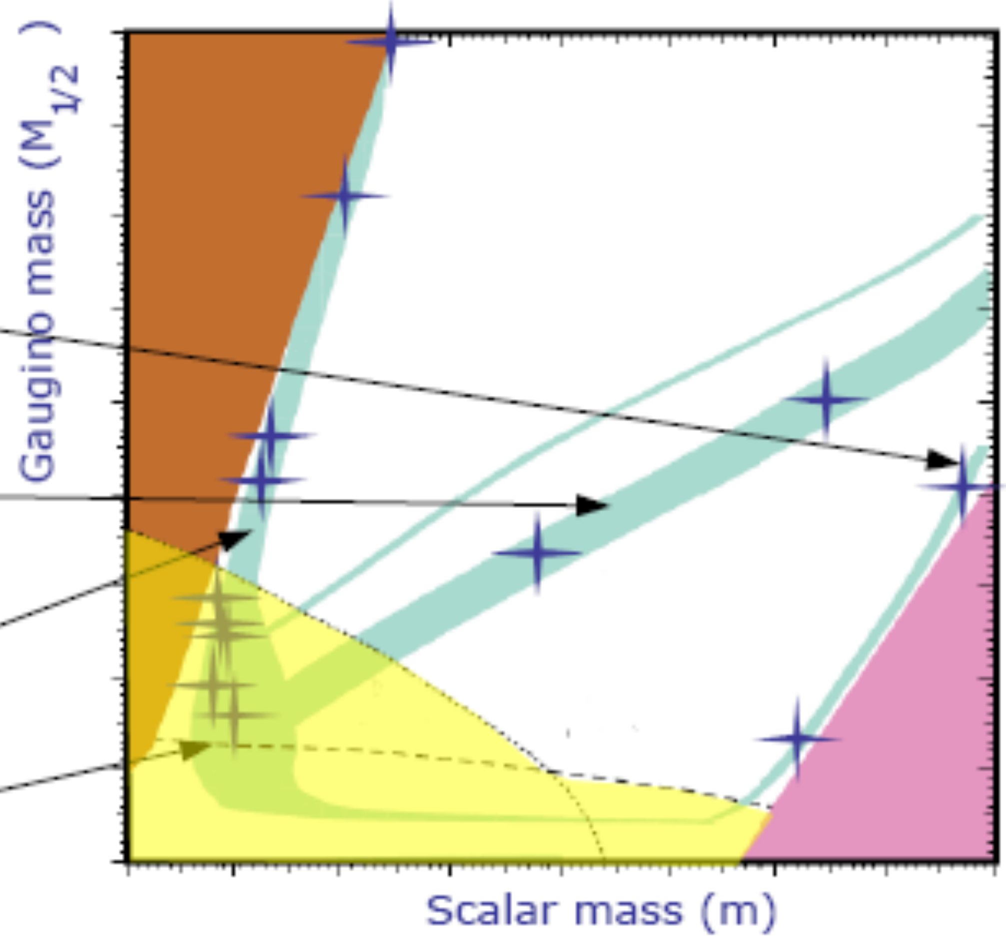
Although we cannot directly detect the gravitino, there could be interesting signatures from the **next to the LSP (NLSP)** : for instance the s-tau could decay into tau and gravitino, Possibly with a very long life time, even of the order of days or months

LHC reach in the SUSY parameter space (example CMSSM – A, M, m, tanβ, μ)

Regions compatible with Neutralino DM (having correct relic density)

- Focus-Point region (Higgsino-Bino neutralino)
- Resonant annihilation (with pesudoscalar Higgs
- Coannihilation region (small LSP-NLSP mass difference)
- Bulk (small SUSY masses)

Mostly excluded by LEP constraints (still available in non-minimal models)

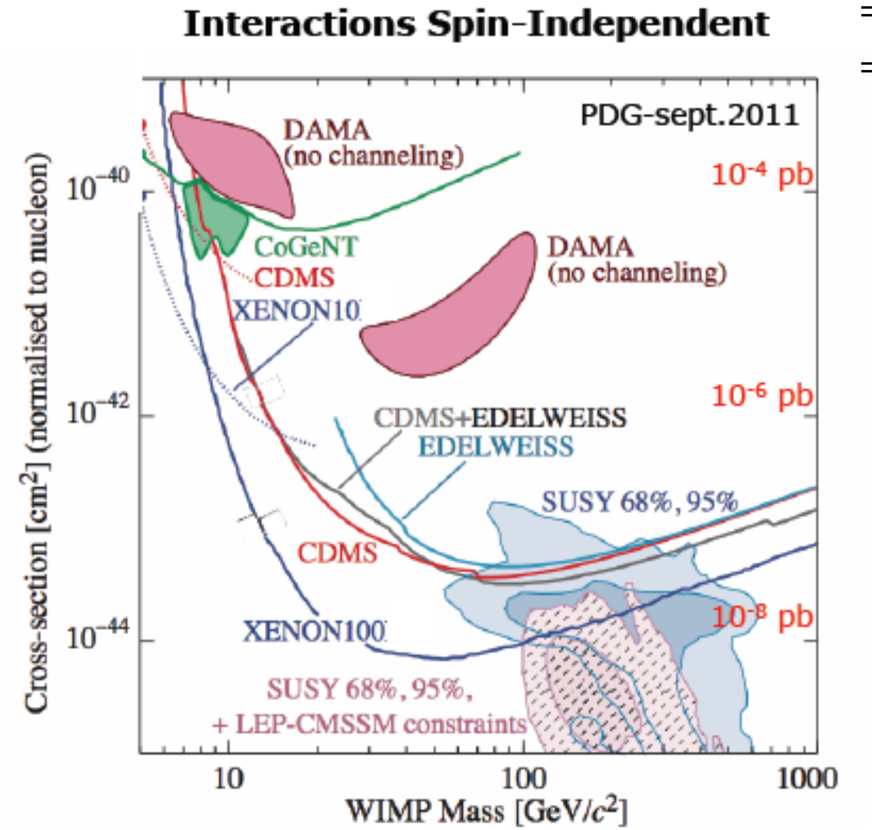


(see e.g., Ellis, Ferstl, Olive)

Cerdeno '09

Direct searches: results

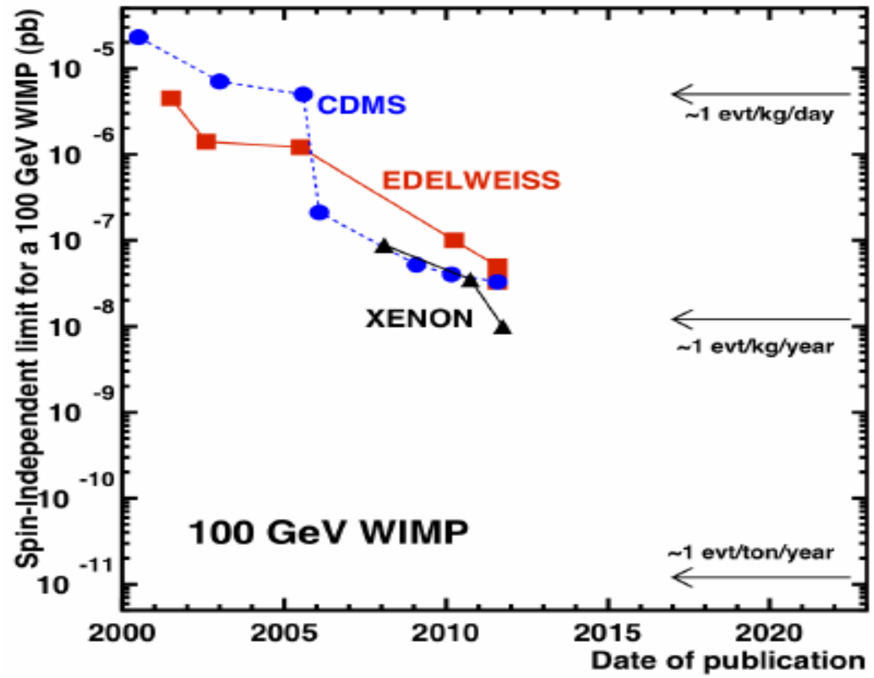
- Status of the search



- Most competitive limits (@ 50-100 GeV):

⇒ Xe: **XENON100** ($7x10^{-9}$ pb) and **Zeplin** ($4x10^{-8}$ pb)

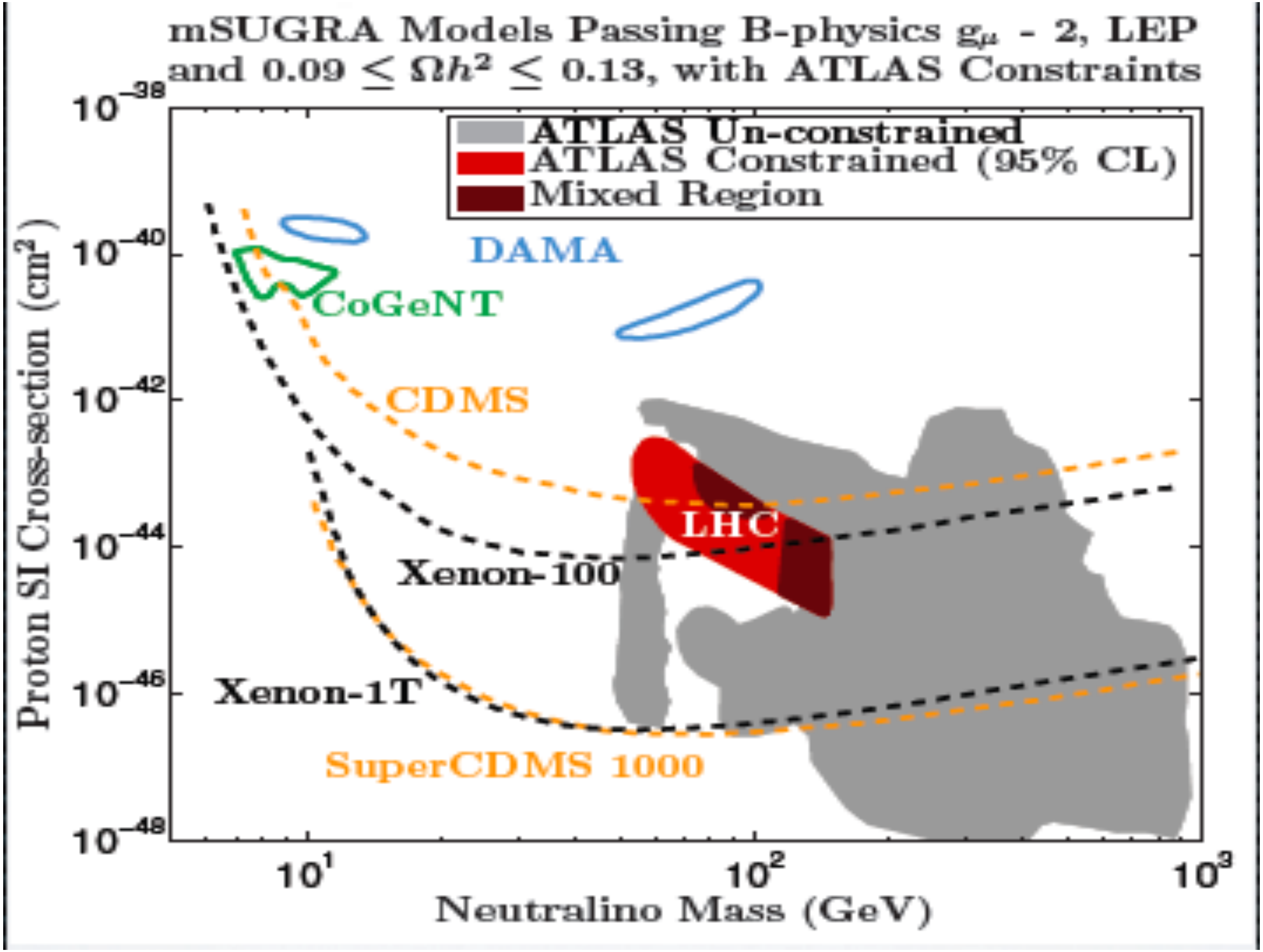
⇒ Ge: bolometers: **CDMS** and **EDELWEISS** ($3x10^{-8}$ pb)



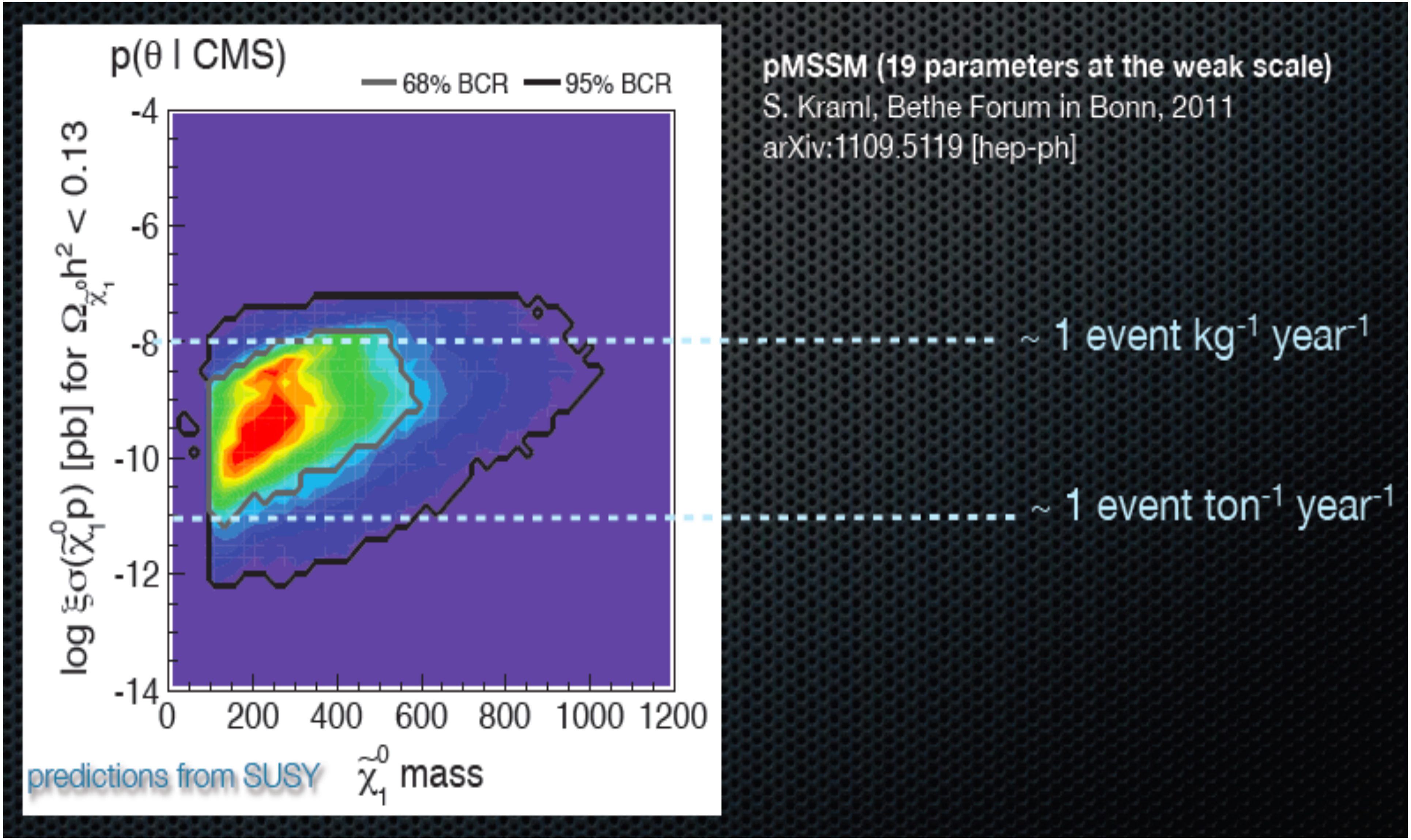
Sensitivity at $5x10^{-9}$ pb (@ 100 GeV) will be reached soon (by XENON 100)

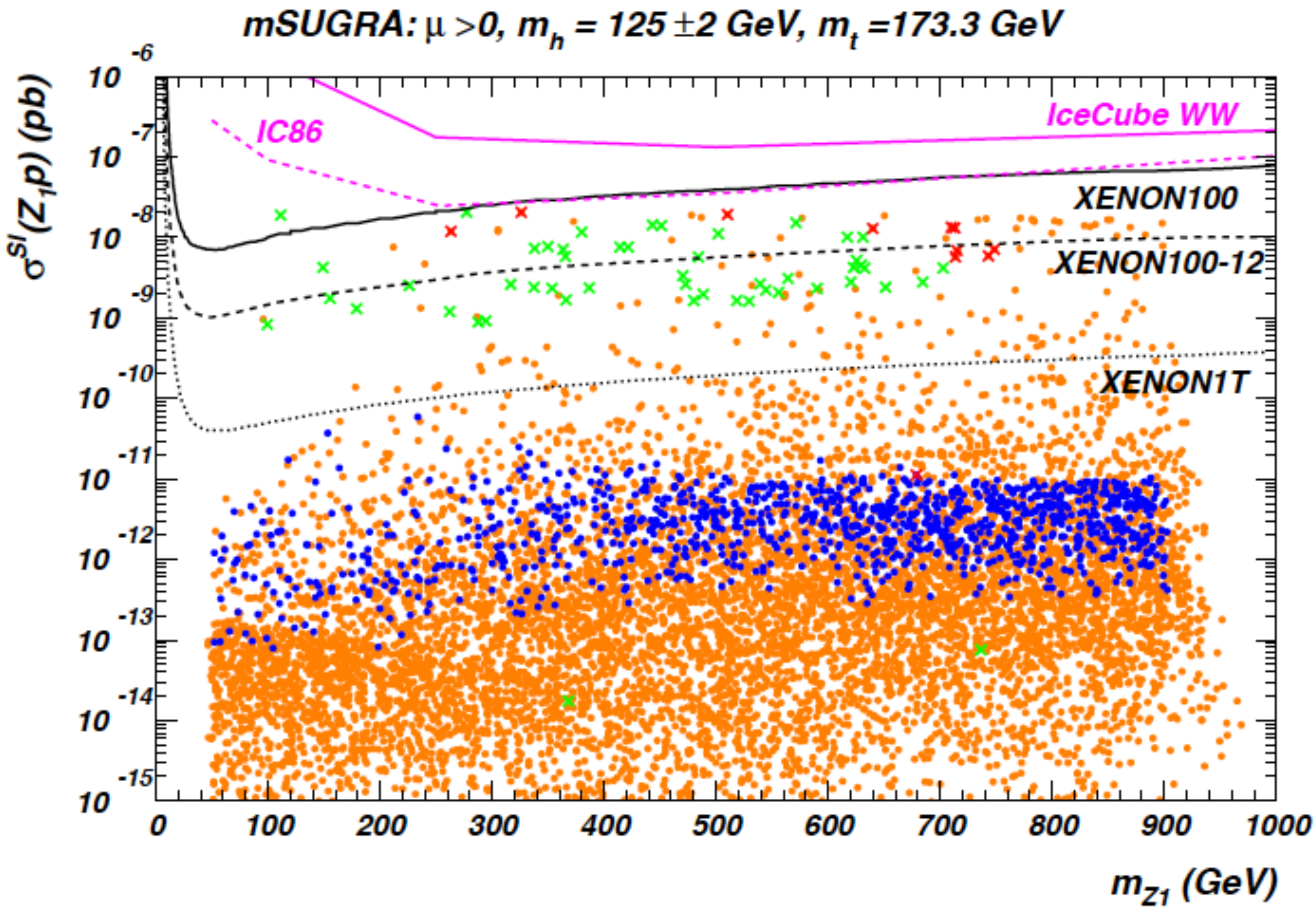
Future: **XENON 1 ton** - $5x10^{-11}$ pb (2013-2015: installations)
Prospects for bolometers: 1 t experiment in US (**GEODM**) and Europe (**EURECA**) < $x10^{-10}$ pb

- Hints for signals at low WIMP masses (< 10 GeV): **DAMA** modulation signal, **CoGeNT**, **CRESST**: Situation not clear at the moment.


mSUGRA Models Passing B-physics g_μ - 2, LEP
and $0.09 \leq \Omega h^2 \leq 0.13$, with ATLAS Constraints
ATLAS Un-constrained
ATLAS Constrained (95% CL)
Mixed Region
DAMA
CoGeNT
CDMS
LHC
Xenon-100
Xenon-1T
SuperCDMS 1000
Proton SI Cross-section (cm^2)
Neutralino Mass (GeV)
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^1
10^2
10^3

SPOTTING THE NEUTRALINO WITH DM 1-TON DETECTORS





mSUGRA: μ >0, m_h = 125 ±2 GeV, m_t =173.3 GeV
σ^SI(Z_1p) (pb)
m_Z1 (GeV)
IceCube WW
IC86
XENON100
XENON100-12
XENON1T
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
0
100
200
300
400
500
600
700
800
900
1000

DM and NON-STANDARD COSMOLOGIES BEFORE NUCLEOSYNTHESIS

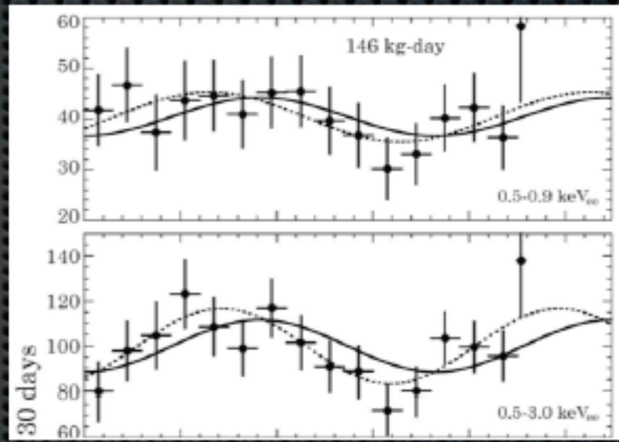
- **NEUTRALINO RELIC DENSITY MAY DIFFER FROM ITS STANDARD VALUE**, i.e. the value it gets when the expansion rate of the Universe is what is expected in Standard Cosmology (EX.: **SCALAR-TENSOR THEORIES OF GRAVITY**, **KINATION**, **EXTRA-DIM. RANDALL-SUNDRUM TYPE II MODEL**, ETC.)

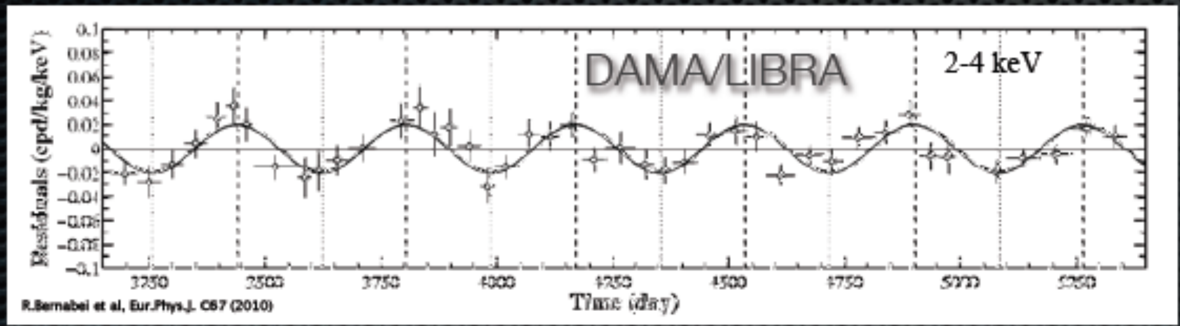
- **WIMPS MAY BE "COLDER"**, i.e. they may have smaller typical velocities and, hence, they may lead to smaller masses for the first structures which form **GELMINI, GONDOLO**

Modulation: DAMA/LIBRA, CoGeNT

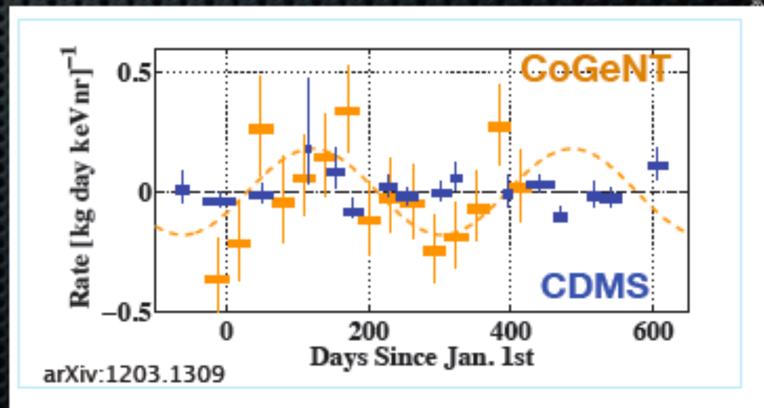
- DAMA/LIBRA (250 kg NaI, 0.82 tons-year): 8.9-σ effect
- CoGeNT (330 g HPGe, 450 d): 2.8-σ effect

CoGeNT





CDMS

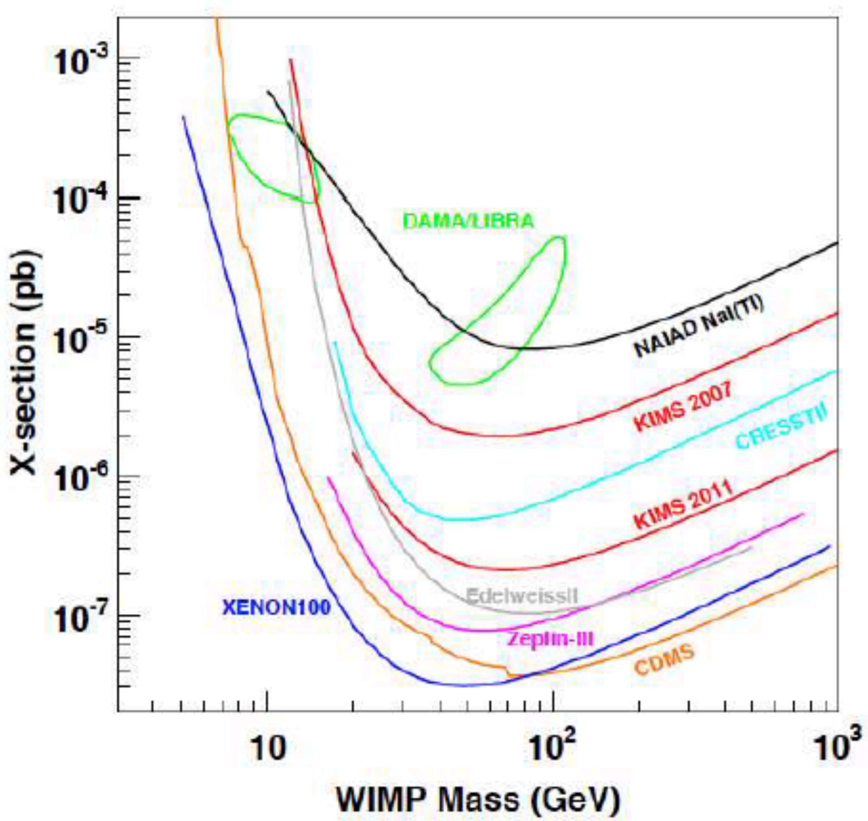


- Origin of the time variation in the observed rate - unclear!
- Movement of the Earth-Sun system through the dark matter halo?
- Environmental?

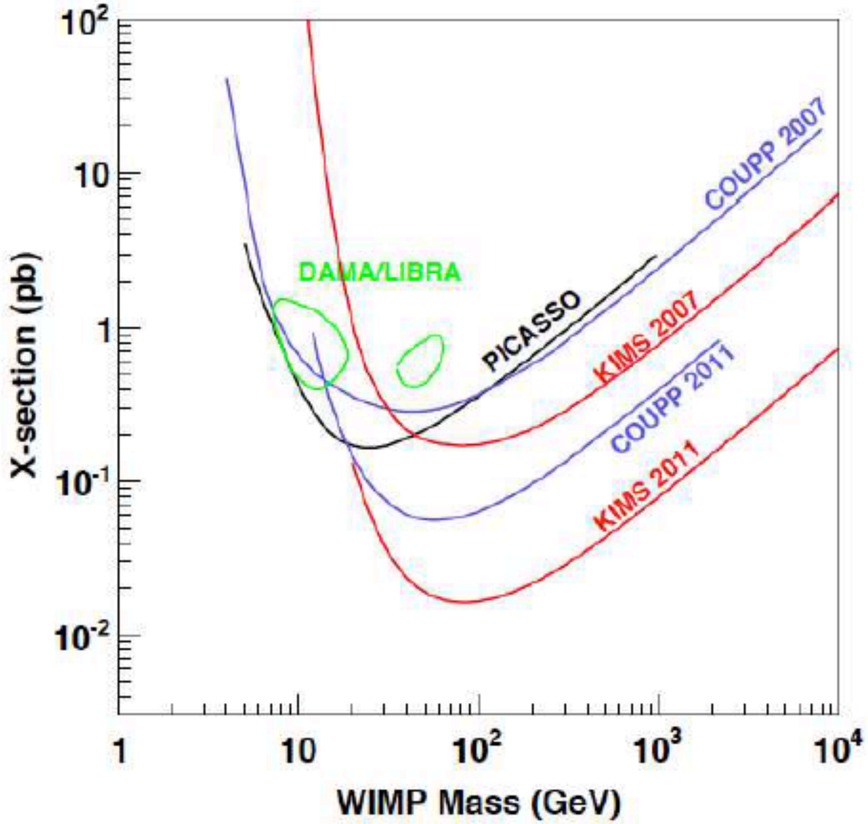
utrino 2012, Kyoto

The new exclusion limits from KIMS

However KIMS is making use of CsI instead of NaI !!!



Spin-Independent interaction

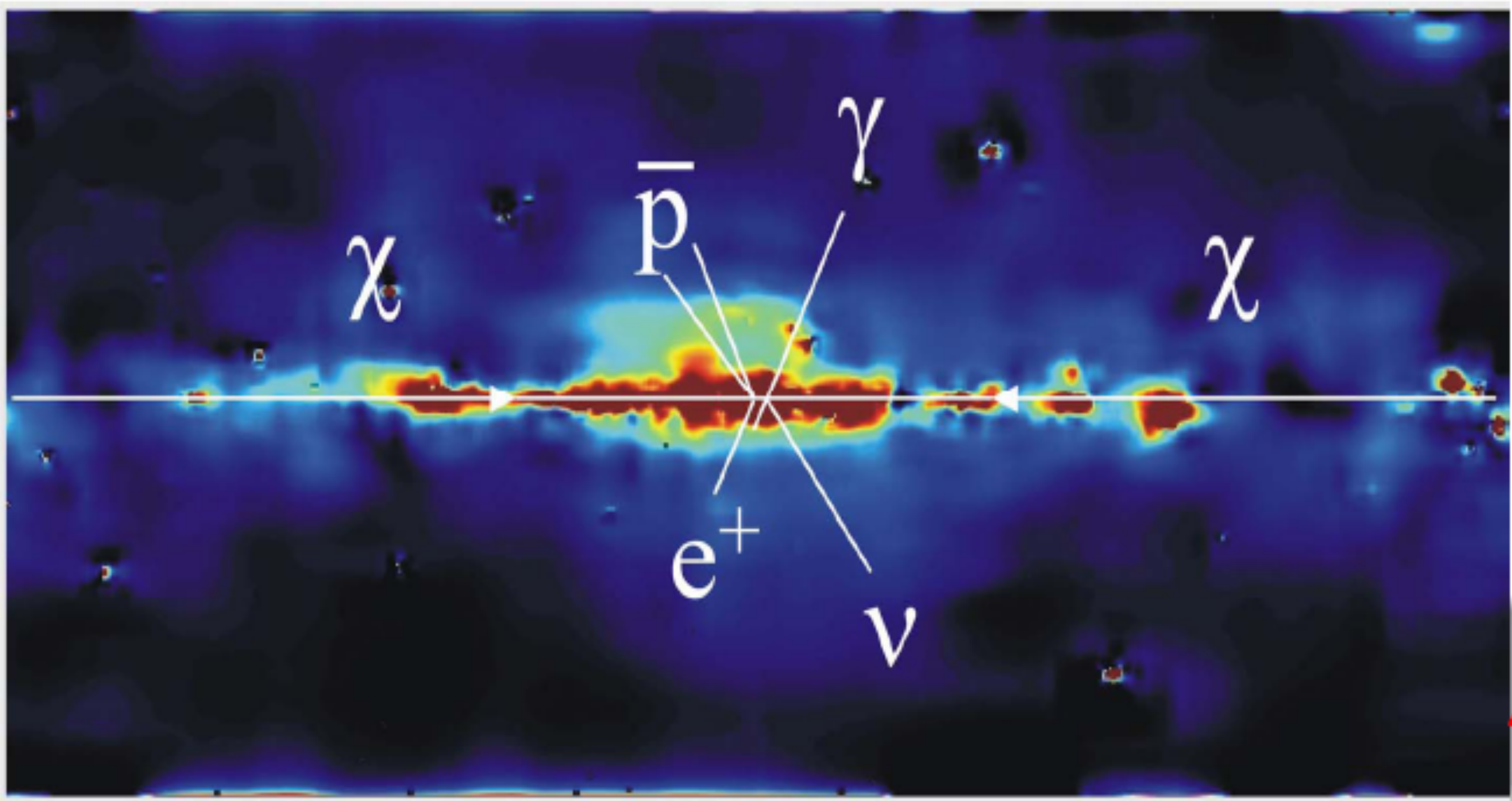


Spin-dependent
proton interaction

Kim, KIMS DM

DM INDIRECT DETECTION

- WIMP-WIMP annihilation in the galactic halos may be detected through production of γ, neutrinos, anti-matter.



?

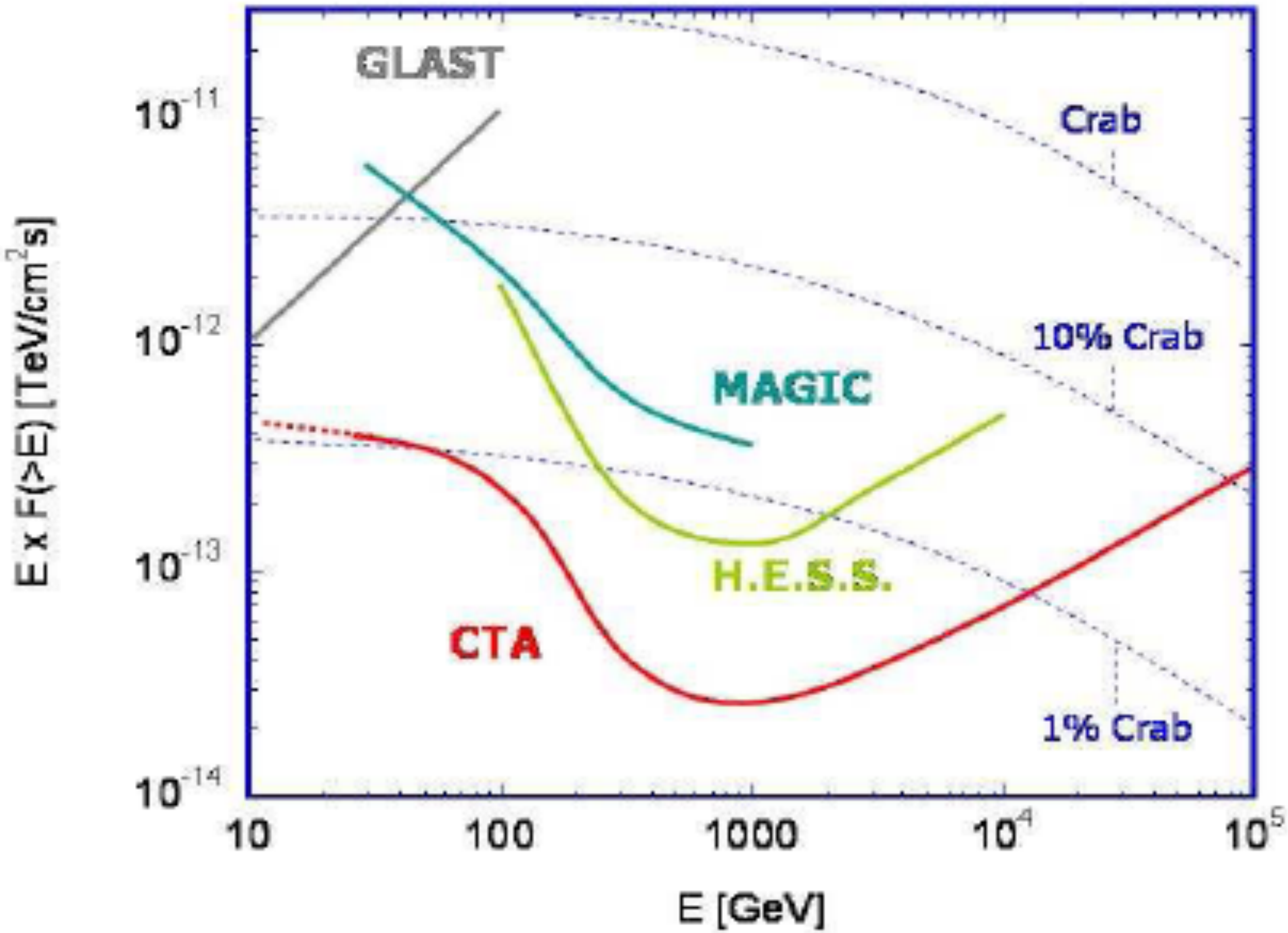
INDIRECT SEARCHES OF DM

- **WIMPs collected inside celestial bodies** (Earth, Sun): their annihilations produce energetic neutrinos
- **WIMPs in the DM halo**: WIMP annihilations can take place (in particular, their rate can be enhanced with there exists a CLUMPY distribution of DM as computer simulations of the DM distribution in the galaxies seem to suggest. From the WIMP annihilation:

-- **energetic neutrinos** (under-ice, under-water exps Amanda, Antares, Nemo, Nestor, …)

--photons in tens of GeV range (gamma astronomy on ground Magic, Hess, … or in space Agile, FERMI-Glast…)

--antimatter: look for an excess of antimatter w.r.t. what is expected in cosmic rays (space exps. Pamela, AMS, …)

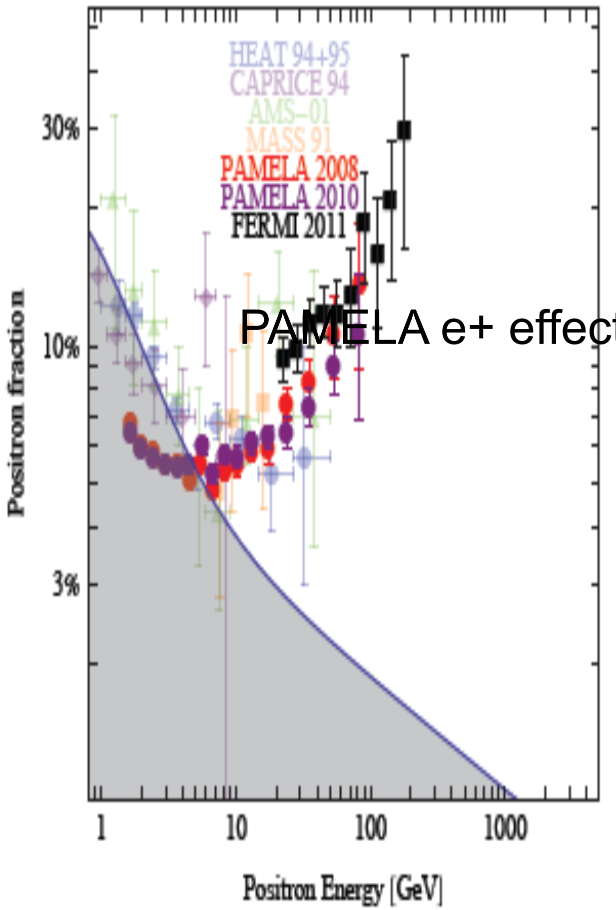


GLAST
MAGIC
H.E.S.S.
CTA
Crab
10% Crab
1% Crab
E x F(>E) [TeV/cm²s]
E [GeV]
10
100
1000
10^4
10^5
10^{-11}
10^{-12}
10^{-13}
10^{-14}

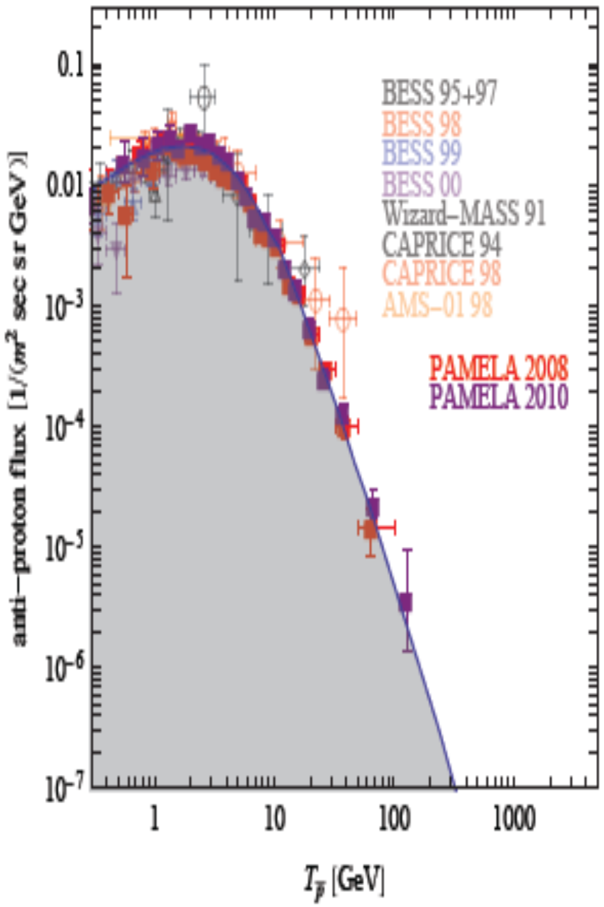
NO COVINCING SIGNAL OF DM ANNIHALATION FROM PHOTONS, NEUTRINOS AND ANTIMATTER

- Charged particles (**PAMELA**, **FERMI**, **ATIC-2**, **PPB-BETS**, **HESS**)

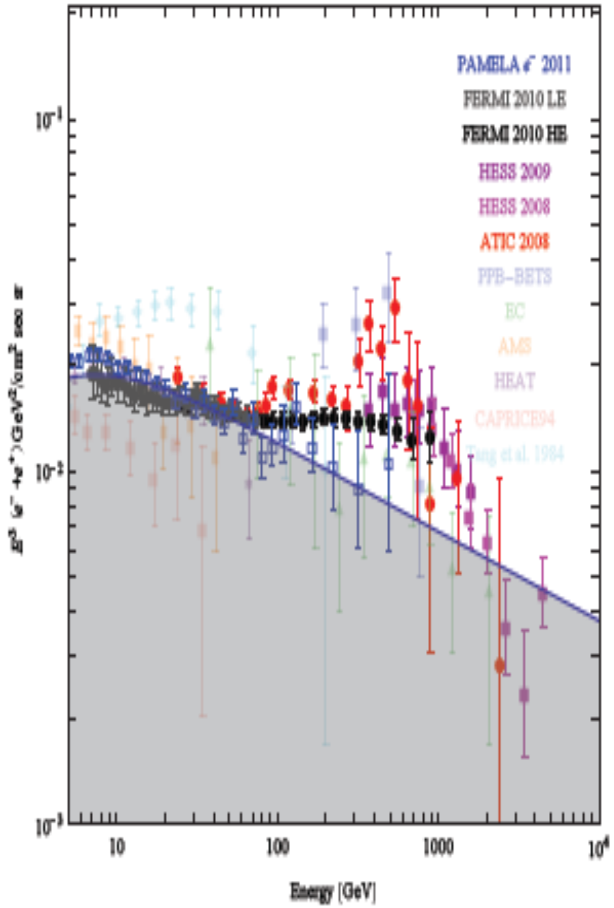
Positron fraction



Antiprotons



Electrons+positrons



SOURCE OF ASTROPHYSICAL NATURE?

A FINAL CONSIDERATION

- **HALF-EMPTY GLASS**: hints only for a "standard" higgs (standard couplings, standard mass…) ; no signal for new physics at LHC; no signal for DM in direct or indirect searches ; no signal for LFV, anomalous FCNC, anomalous CPV; …

A FINAL CONSIDERATION

- **HALF-FULL GLASS**: close to the discovery of the mechanism for electroweak breaking, the higgs boson; the value of its mass could be "peculiar", i.e. it could hint at relevant new possibilities for our understanding of the hierarchy problem and … of the future of the Universe; impressive prospects for DM searches, deeper comprehension for neutrino physics, possible breakthroughs for our understanding of the flavor physics etc.

Drawing by G. Martinelli

I keep telling my students that they are lucky that they happen to work in the moment when finally we'll have **ANSWERS from Nature** through our **experiments!**