Zurich Phenomenology Workshop 2013: Particle Physics in the LHC Era, Zurich, 7 – 9 January 2013

CORNERING TeV NEW PHYSICS through the LHC, FLAVOR and ASTROPARTICLE ALLIANCE

Antonio Masiero
Univ. of Padova and INFN

2012: the conquest of a new energy scale in physics

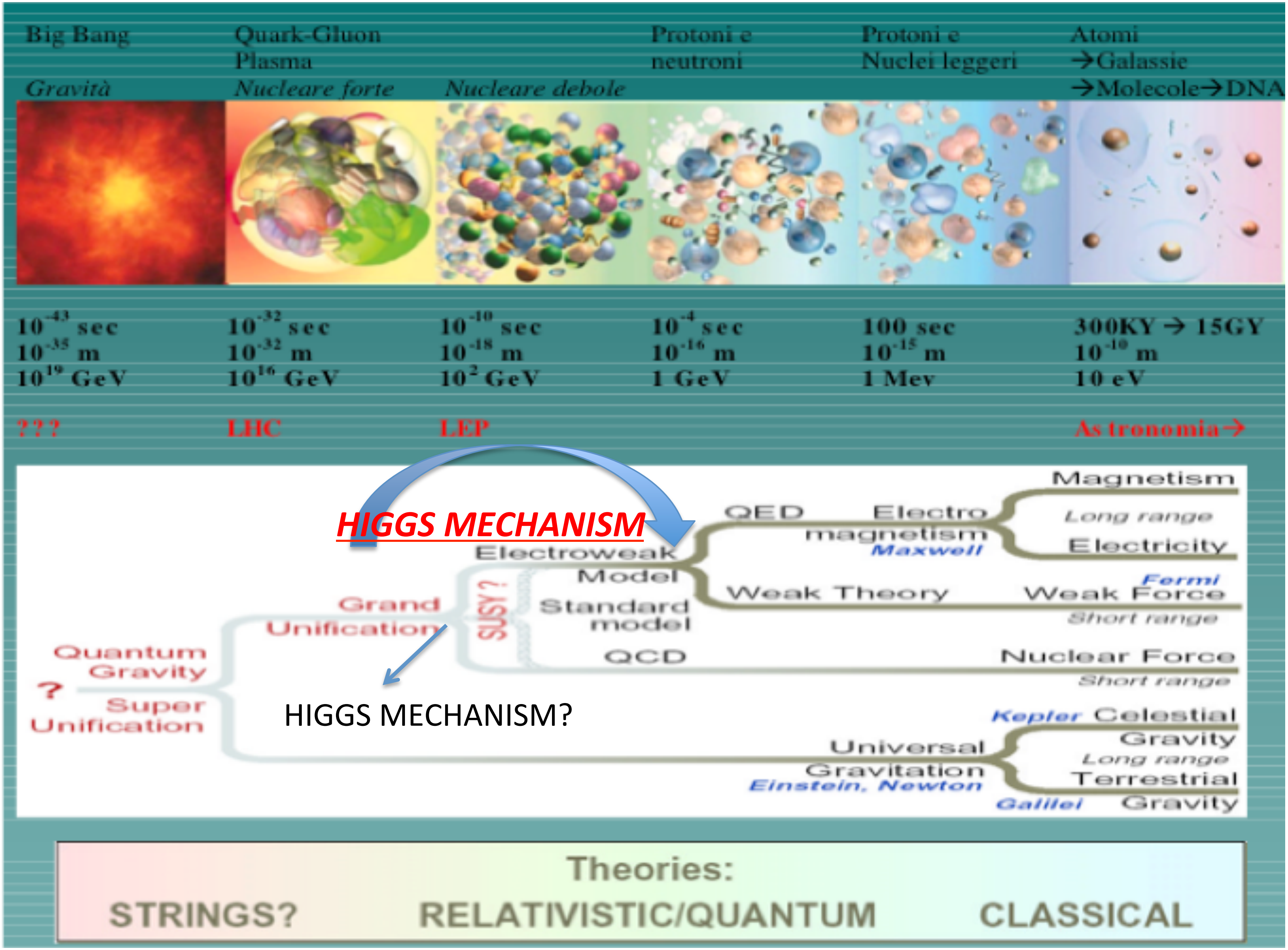
- ~1900 **ATOMIC SCALE** **10^{-8} cm.** $1/(\alpha m_e)$
- ~1970 **STRONG SCALE** **10^{-13} cm.** $M e^{-2\Pi/\alpha_s b}$
- ~2010 **WEAK SCALE** **10^{-17} cm.** TeV^{-1}

FUNDAMENTAL OR **DERIVED SCALE**?

EX. **EXTRA-DIMENSIONS**
or
TeV STRING THEORY

EX.: **TECHNICOLOR** or
SUSY with ELW RAD. BREAKING

NEW PARTICLES AT THE TEV SCALE?



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→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak
Model
Fermi
Weak Theory
Weak Force
Short range
Grand Unification
SUSY?
Standard model
Quantum Gravity
?
Super Unification
QCD
Nuclear Force
Short range
HIGGS MECHANISM?
Kepler
Celestial Gravity
Universal Gravitation
Einstein, Newton
Long range
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL

MICRO
PARTICLE PHYSICS
GWS STANDARD MODEL

MACRO
COSMOLOGY
HOT BIG BANG
STANDARD MODEL

HAPPY MARRIAGE
Ex: NUCLEOSYNTHESIS

BUT ALSO

POINTS OF FRICTION

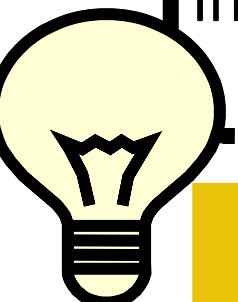
- -COSMIC MATTER-ANTIMATTER ASYMMETRY
- -INFLATION
- - DARK MATTER + DARK ENERGY

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

The 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**

3 WAYS TO IMPLEMENT THE HIGGS MECHANISM

- **NO HIGGS PARTICLE**: **HIGGSLESS** MODEL (almost) killed by LHC (unlikely the observed scalar is an "impostor", however not impossible – ex. dilaton, radion. Possibility of mixing of an "authentic" Higgs with the "impostor"…)

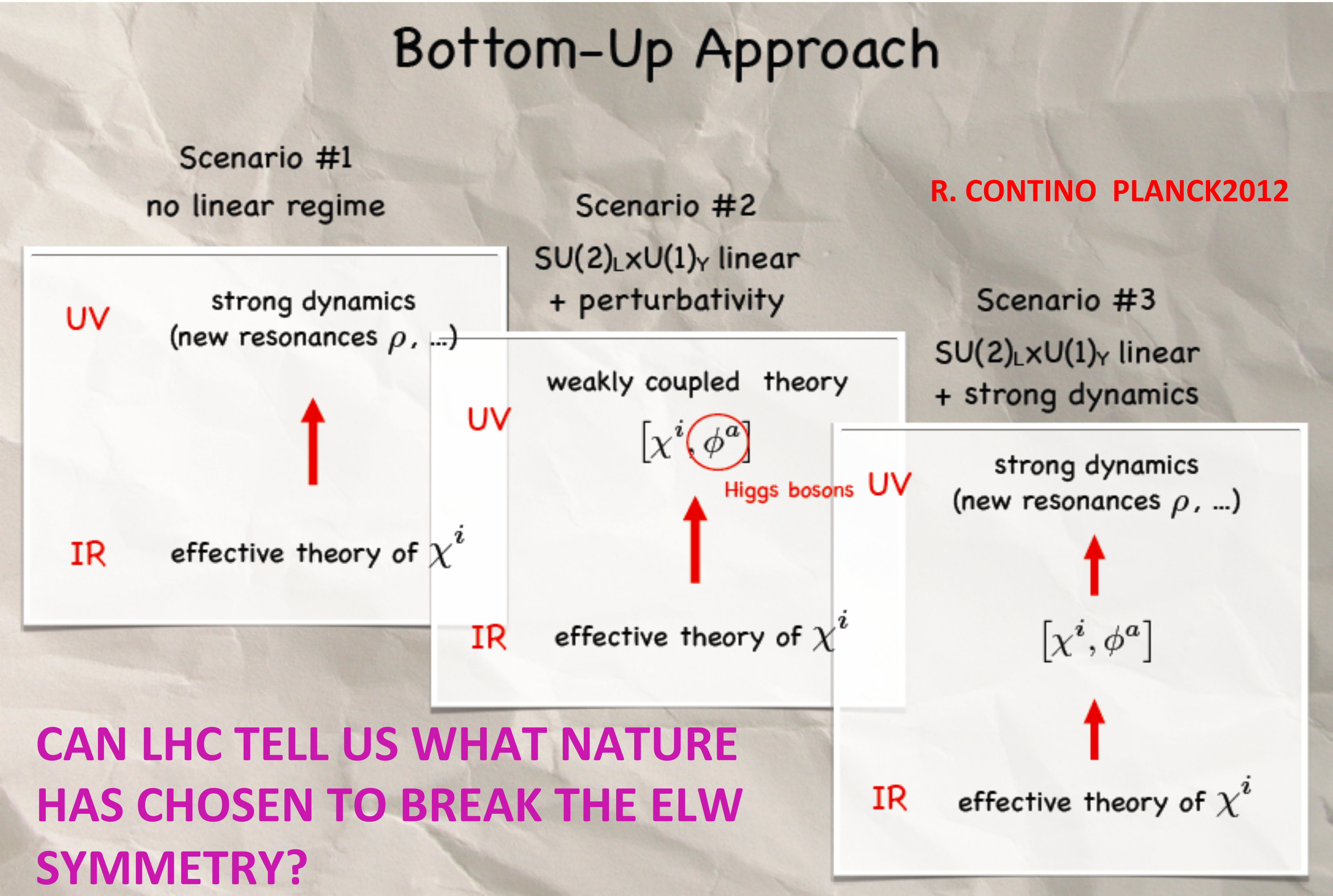
- **COMPOSITE HIGGS**: PSEUDO-GOLDSTONE BOSON

- **ELEMENTARY HIGGS**

A) FINE-TUNED (unnatural Higgs – anthropic road, high-scale fundamental theory taking care of it, …)

B) NATURAL (protection mechanism: low-energy SUSY; inexistence of the scale hierarchy problem: extra dimensions, warped space, …)

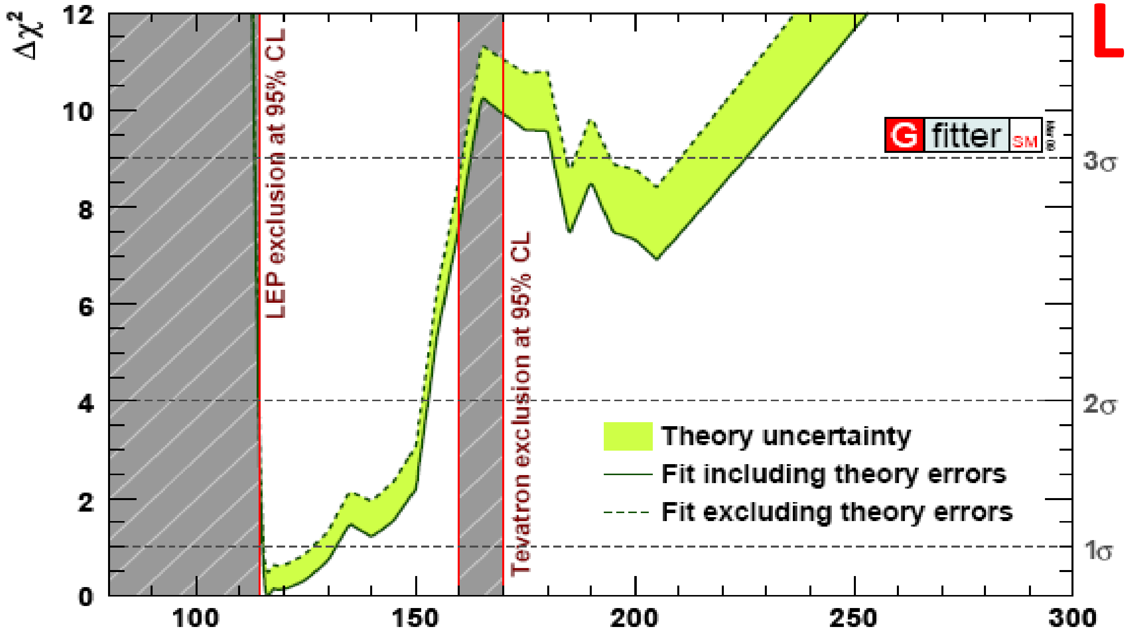
EWSB: WITH OR WITHOUT A HIGGS BOSON



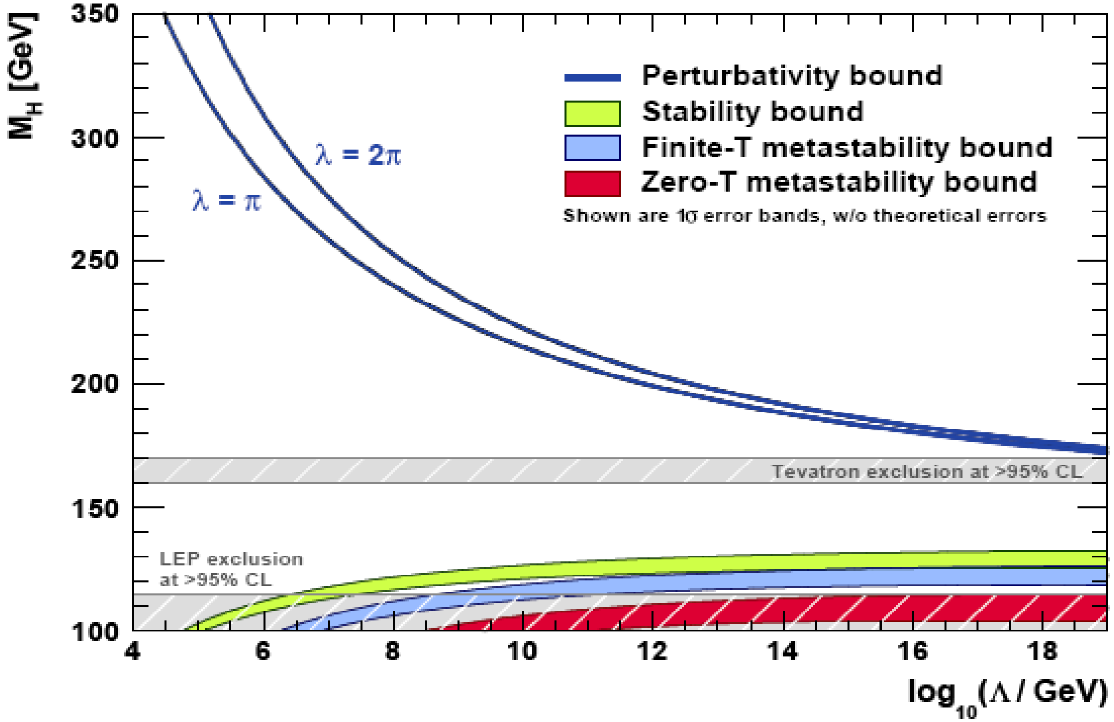
R. CONTINO PLANCK2012

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

LEP, SLC, TEVATRON LEGACY



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

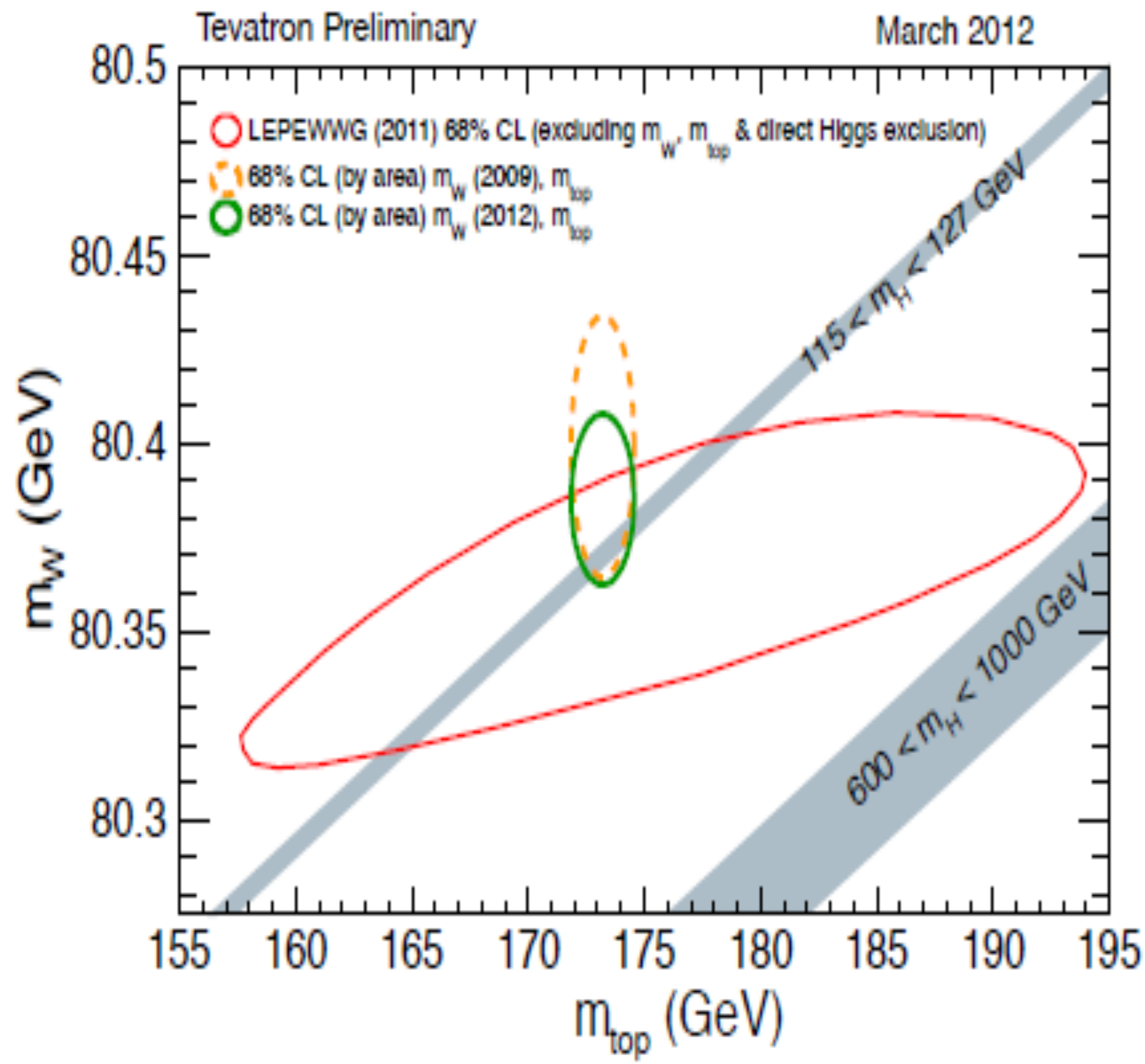
OUR "VIRTUAL" ENCOUNTER WITH THE HIGGS BOSON (OR "SOMETHING" MIMICKING IT)

With $M_W = 80385 \pm 15$ MeV

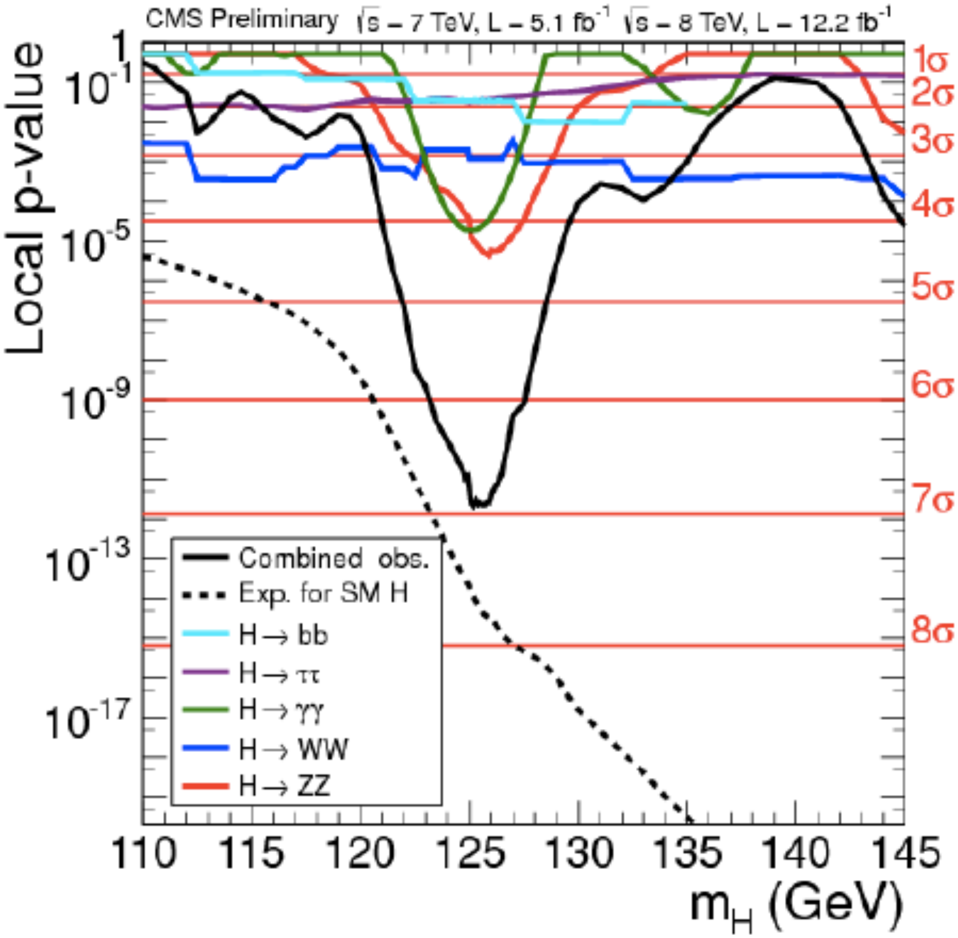
$M_H = 94^{+29}_{-24}$ GeV

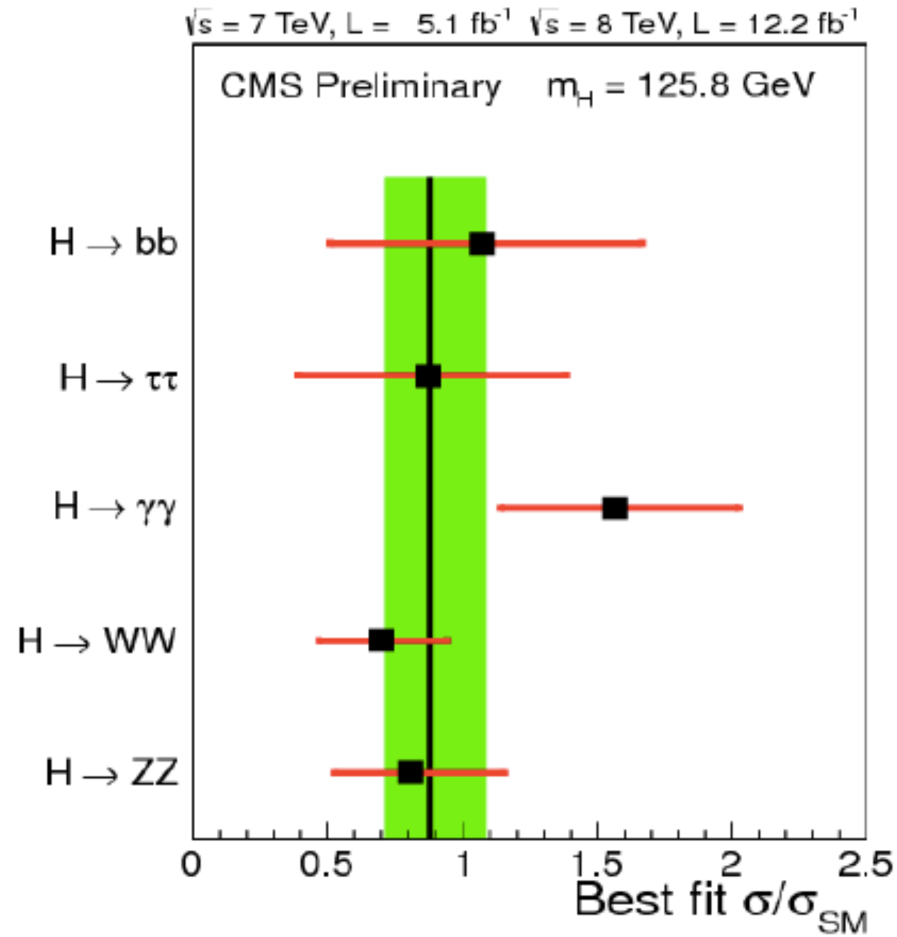
$M_H < 152$ GeV @95% CL

LEPEWWG/ZFitter



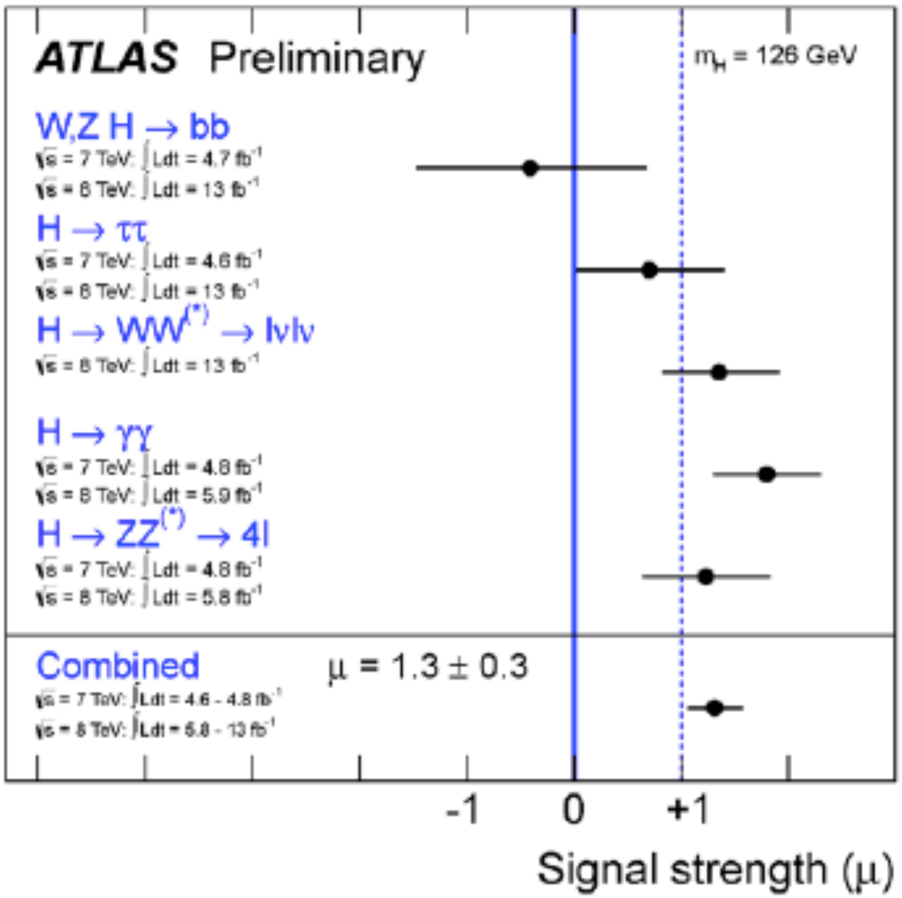
Combination of Higgs Results





Overall significance and signal strength

– observed: 6.9; expected: 7.8 [signal strength: 0.88 ± 0.21]



- Previous result in July paper, using 2011 analyses of ττ and bb, July analyses for γγ, 4-lepton, and WW, gave $\mu = 1.4 \pm 0.3$
- New result is $\mu = 1.3 \pm 0.3$
- Assuming a common μ for all measurements, compatibility is 36%.
- Compatibility with SM μ=1 with observed measurement is 23%.

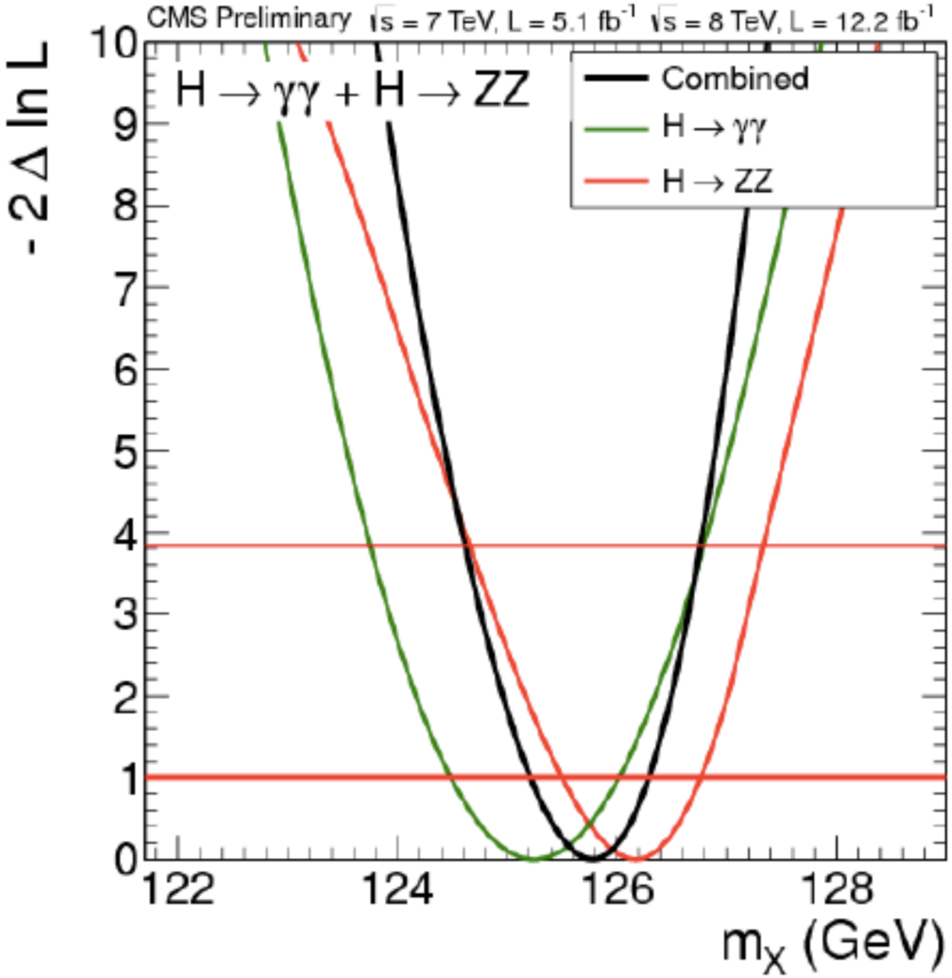
K. EINSWEILER, HPC, KYOTO, NOV. 2012

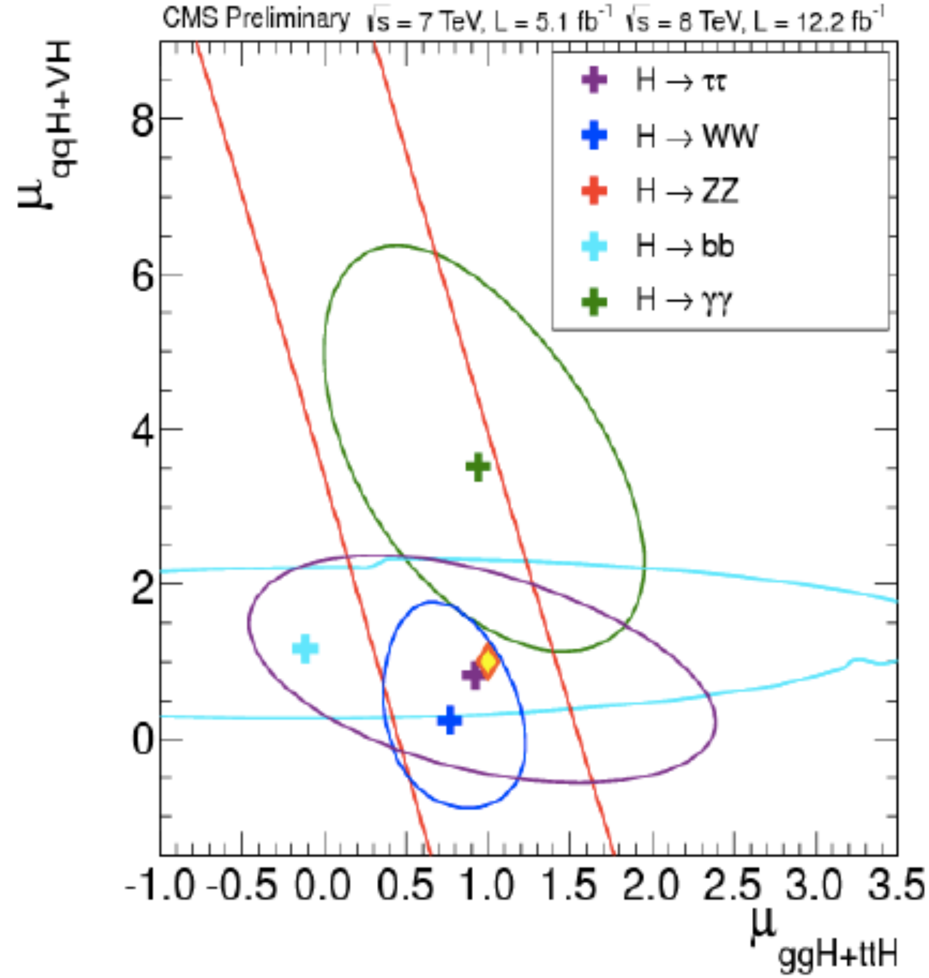
– New ττ and bb analyses using full 2012 data sample presented. Approaching SM μ=1 sensitivity, however both channels remain compatible with either background-only hypothesis or SM Higgs hypothesis. Improvements underway for full 2012 data sample.

– Updated combination of μ values for each channel presented. Globally, results are compatible with SM Higgs expectations. At m_H = 126 GeV, $\mu = 1.3 \pm 0.3$.

– Shifting from a search-based to a measurement-based program presents many challenges. In particular, final fitting and fit models, undergoing much deeper scrutiny and optimization.

Combination of Higgs Results





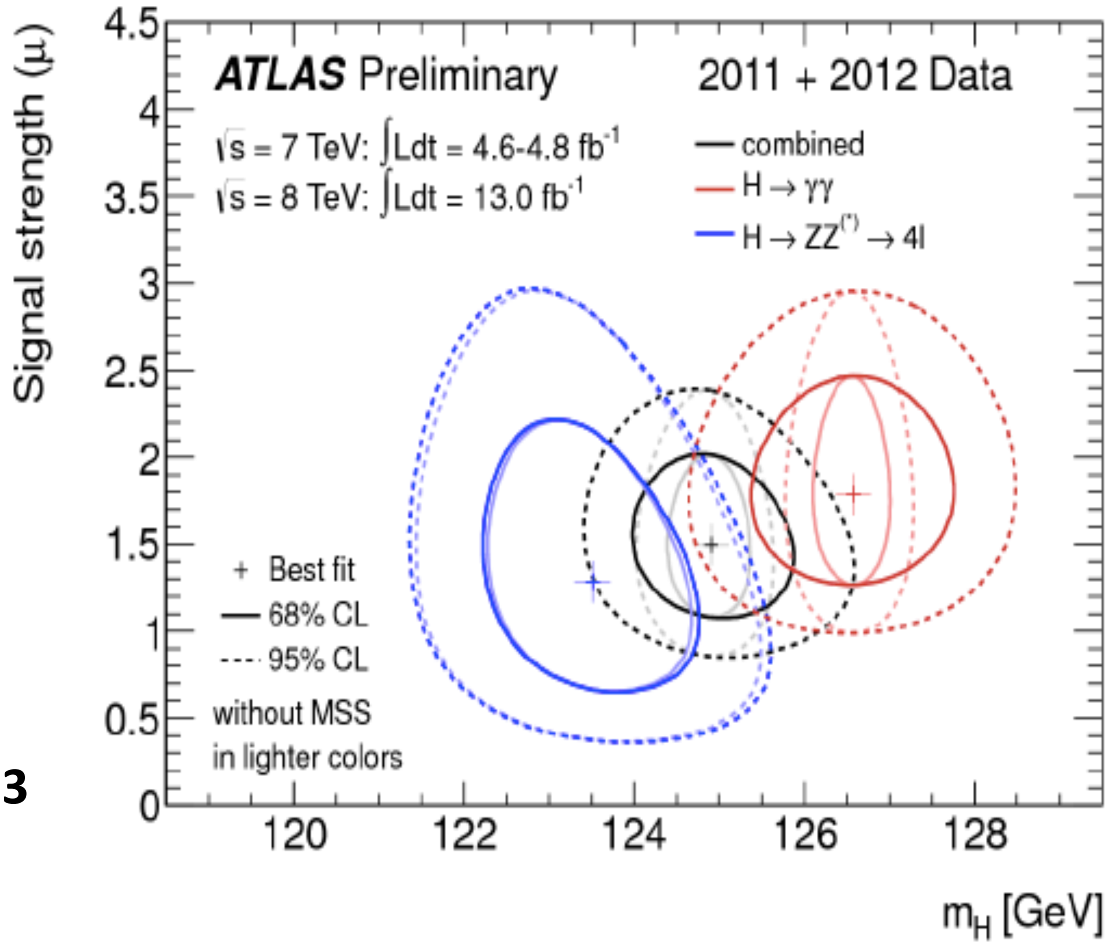
Mass measurement and production strength

C. PAUS, HPC, '12

- m_χ = 125.8 ± 0.4(stat) ± 0.4 (syst) GeV
- Signal strengths consistent with each other and with SM


TWIN PEAKS
WELCOME
TWIN PEAKS
Population

- Mass 125.2 +/- 0.3 +/- 0.6 GeV
- Strength 1.35 +/- 0.24
- Small mass tension between γγ and ZZ channels
  - Δm= 3.0 + 1.1 -1.0 GeV
  -



I.HINCHLIFFE, H-D FEST, 2013

ITS COUPLINGS: IMPOSTOR, A HIGGS OR THE (SM) HIGGS ?

- Strictly sticking to the data, we **cannot exclude** the logical possibility that the observed particle is **not connected to EWSB** (however, *Subtle* is the *Lord, but malicious* He is *not* …)

- **The "a" vs. "the" dispute** decided by 5 numbers:

$$\mathcal{L}^{eff}_{<m_h} \approx c_V\left(\frac{2m_W^2}{v}W^+_\mu W^-_\mu + \frac{m_Z^2}{v}Z^2_\mu\right)h + c_b\frac{m_b}{v}\bar{b}bh + c_\tau\frac{m_\tau}{v}\bar{\tau}\tau h$$
$$+c^\gamma\frac{2\alpha}{9\pi v}F^2_{\mu\nu}h + c^g\frac{\alpha_S}{12\pi v}G^2_{\mu\nu}h$$
$$+\mathcal{L}(h\to inv)$$

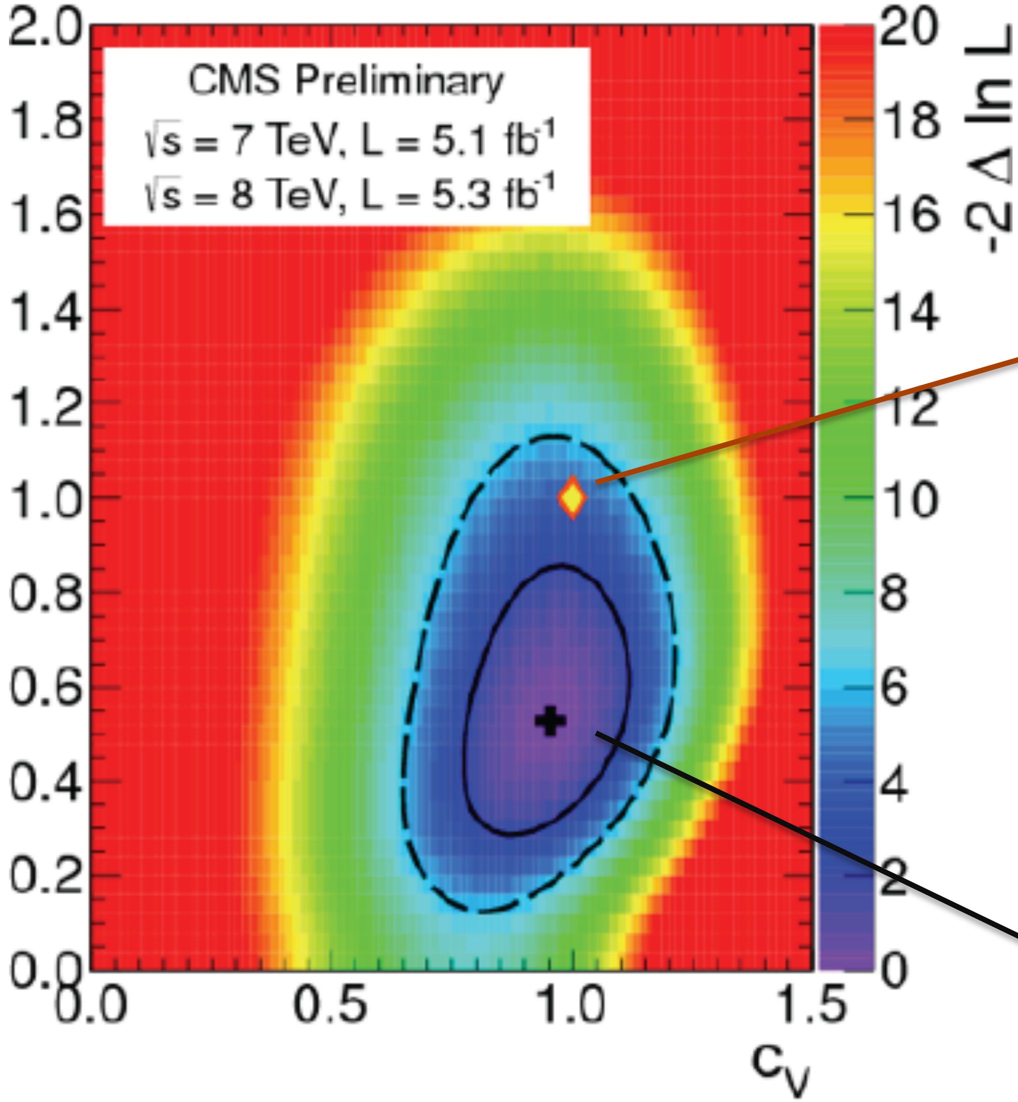
$$c^\gamma = c_t + \frac{9}{2}\delta c^\gamma$$
$$c^g = c_t + \delta c^g$$

In the SM all 5 $c = 1$ and $\mathcal{L}(h\to inv) \approx 0$

BARBIERI, ICHEP2012

1 step - go from 5 to 2: c_V and c_F

- If EW symmetry breaking via the Higgs mechanism: **H couplings to W and Z** in a well-defined ratio protected by a custodial symmetry → c_V
- The **couplings to all the fermions** are assumed to scale with a common factor c_F
- Then: all **tree-level Higgs couplings** can be expressed in terms of **only 2 param.**, c_V and c_F
- If the loop-induced couplings Hgg and Hγγ receive contributions only from SM particles and there is no H invisible decay, then **all partial widths scale either as c_V^2 or c_F^2 at LO, with the only exception of $\Gamma_{\gamma\gamma}$ scaling as $|\alpha c_W+\beta c_t|^2$**



SM Higgs

In agreement with the SM within 95%CL

Some tension to be addressed with more data and more channels at disposal

HOW TO GO NON-STANDARD

- **H MIXES WITH OTHER SCALARS** (e.g. 2HDM, MSSM, NMSSM, …) → all couplings possibly affected
- **H IS NOT AN ELEMENTARY PARTICLE** → all couplings possibly affected
- **H DECAYS INTO STATES THAT HAVE BEEN MISSED** (e.g., into invisible particles which do not interact or interact very weakly in the detector, into indiscernible particles which cannot be distinguished against the large background) ***H → inv***
- **LOOPS IN H PRODUCTION** (ex. g fusion) OR **IN H DECAYS** (ex. H→gg, H→ γγ) **ARE MODIFIED BECAUSE OF NEW VIRTUAL PARTICLES RUNNING INSIDE THEM** → **c^g and c^γ affected**

IF there is TeV NEW PHYSICS → not difficult to get variations of O(1) w.r.t. the SM expectations on the above 5 Higgs couplings

What is it ?

J. ELLIS in Dine-Haber Fest, 2013

- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - **Some *prima facie* evidence that it does**
- Quantum (loop) corrections?
  - **$\gamma\gamma$ coupling > Standard Model?**
- What are its self-couplings? **Wait for HL-LHC …?**

HOW PRECISE CAN WE BE ON AN SM-LIKE HIGGS PRODUCTION × BR at the LHC?

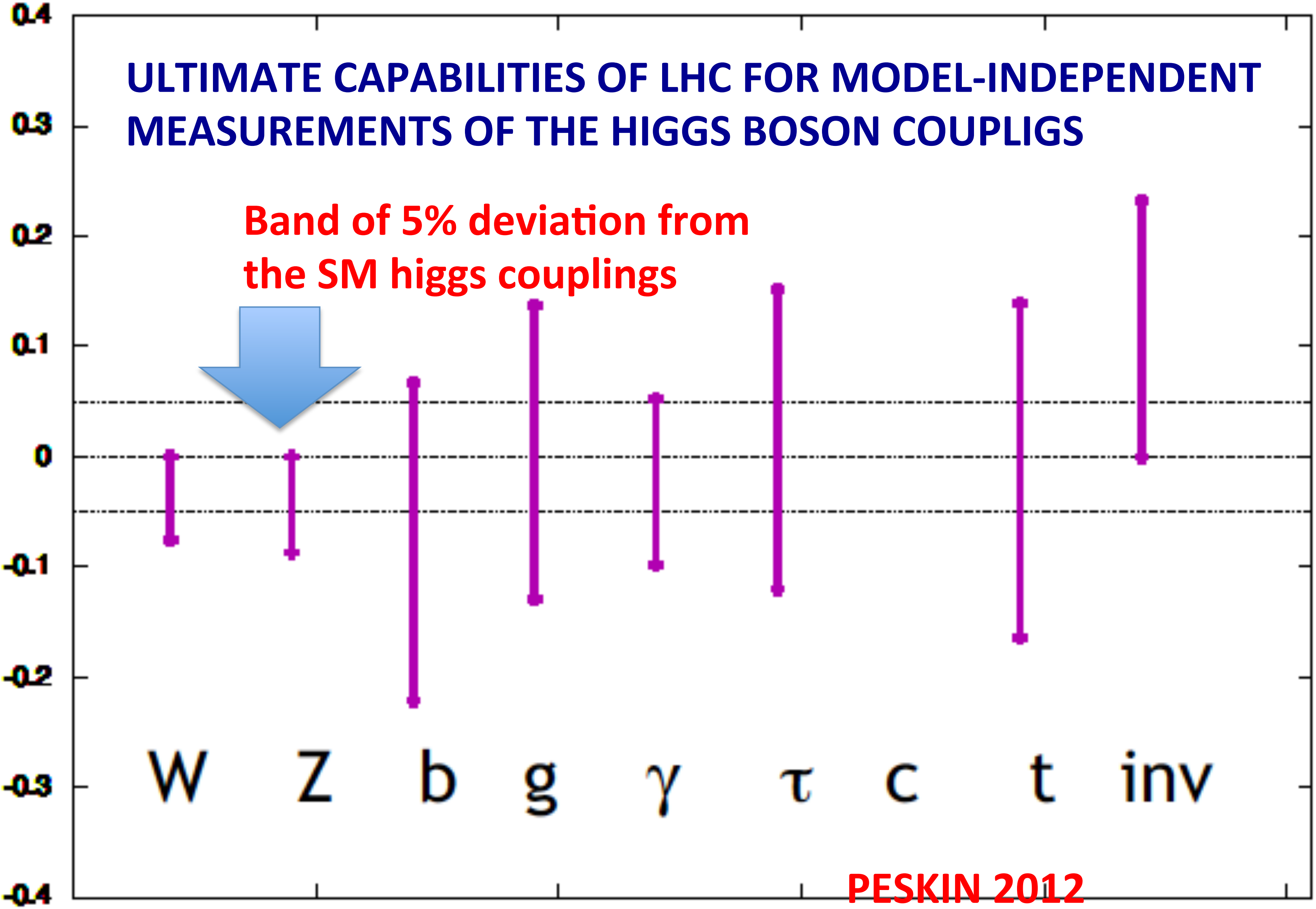
Decay	Prod	$10\ \mathrm{fb}^{-1}$ 7 - 8 TeV	$60\ \mathrm{fb}^{-1}$ 8 TeV	$300\ \mathrm{fb}^{-1}$ 14 TeV
$H \to b\bar{b}$	VH	70%	30%	10 %
$H \to b\bar{b}$	$t\bar{t}H$	-	60%	10 %
$H \to \tau\tau$	ggH	64%	40%	10 %
$H \to \tau\tau$	qqH		40%	10 %
$H \to \gamma\gamma$	ggH	38%	20%	6 %
$H \to \gamma\gamma$	qqH		40%	10 %
$H \to WW^*$	ggH	42%	16%	5 %
$H \to WW^*$	qqH	-	60%	16 %
$H \to ZZ^*$	ggH	40%	16%	5 %
c_V	-	10%	-	2%
c_F	-	25%	-	5%

M_H fixed at 125 GeV

Assuming that the **stat. errors scale with the luminosity**, whilst **the syst. and theor. errors remain the same**

WG Contribution to the Open Symposium of the EU Strategy
P. Anger et al.

$g(hAA)/g(hAA)|_{SM}-1$ LHC at 14 TeV with 300 fb^{-1}



LC at √s = 250 GeV: a HIGGS FACTORY

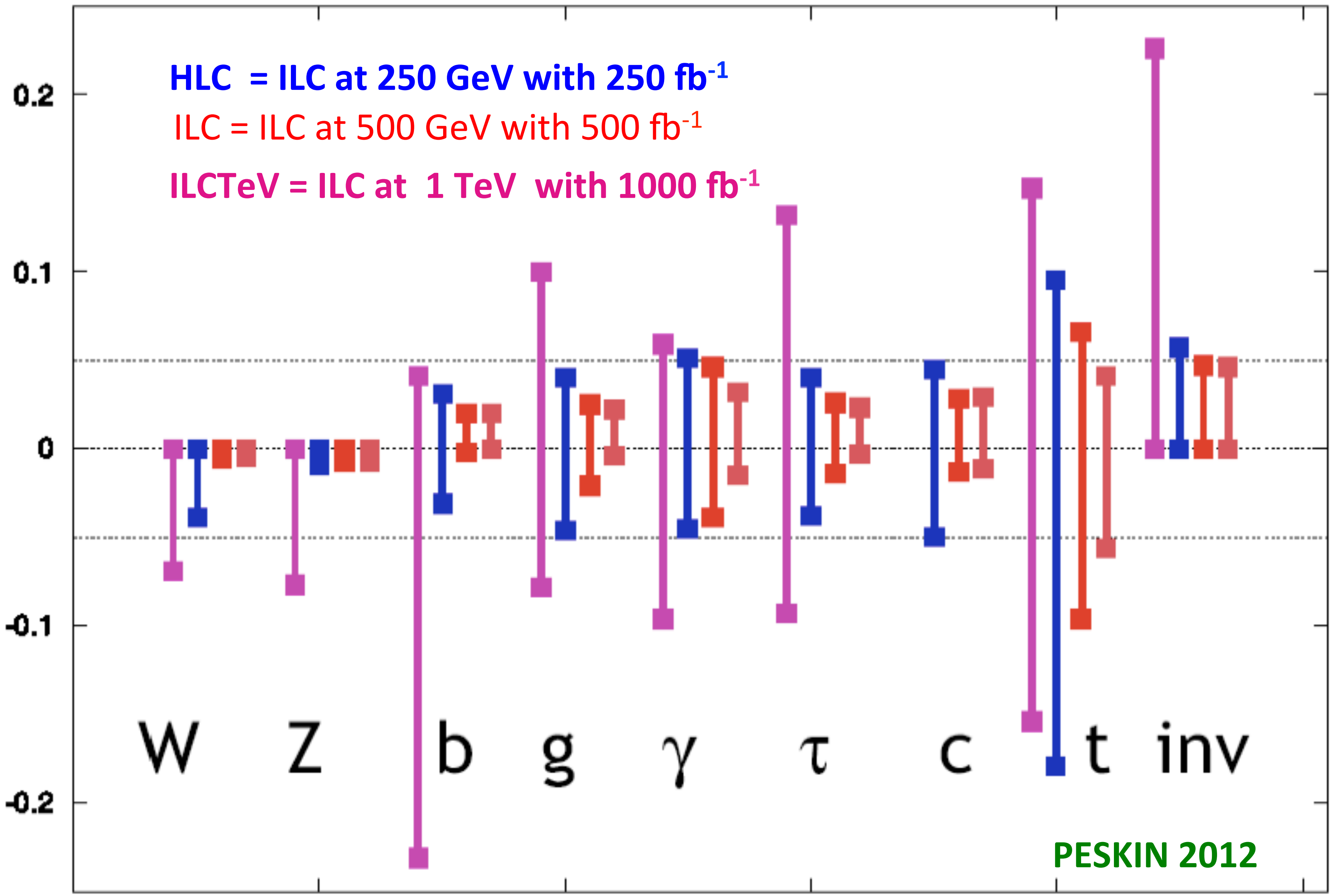
- Expected **O(10^5) Higgs bosons for ~ 250 fb^{-1}**
- Accuracies on **Higgs couplings** for M_H = 125 GeV (on individual couplings and not only on products of production cross section × BR)

g / BR	g_{HWW}	g_{HZZ}	g_{Hbb}	g_{Hcc}	$g_{H\tau\tau}$	g_{Htt}	g_{HHH}	BR($\gamma\gamma$)	BR(gg)	BR(invis.)
Precision	1.4 %	1.4 %	1.4 %	2.0 %	2.5 %	15 %	40 %	15 %	5 %	0.5 %

Baer et al., ILC Detailed Baseline Design report 2012

PRECISION ON THE MEASUREMENT OF M_H : 0.03%

Probing additional non-SM-like Higgs bosons: the 125 GeV Higgs could be the second lightest Higgs in the spectrum → lighter Higgs (maybe below the LEP limit for a SM-like Higgs) with reduced couplings to gauge bosons g(hAA)/g(hAA)|$_{SM}$-1 LHC/ILC1/ILC/ILCTeV



e^+e^- Collider Summary

Accelerator →Physical quantity ↓	LHC 300fb^{-1} /exp	HL-LHC 3000fb^{-1} /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2021	2030	2035	2045	2035	2035
N_H	1.7 x 10^7	1.7 x 10^8	5 10^4 ZH	(10^5 ZH) (1.4 10^5 Hvv)	4 10^5ZH	2 10^6 ZH
m_H (MeV)	100	50	35	35	26	7
$\Delta\Gamma_{H}/\Gamma_H$	--	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	--	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30	<10	--	--	14%	7%

ICFA Higgs Factory Workshop
Fermilab, Nov. 2012

STRONG JAPANESE INTEREST, BOTH FROM THE SCIENTIFIC AND THE POLITICAL COMMUNITIES, IN REALIZING THE ILC

ILC appears in the LDP Election Manifesto

32　科学技術政策の強力な推進力となる
真の「司令塔」機能の再構築

資源の少ないわが国にとって、今後の社会・経済をさらに発展させるため、企業の研究開発投資が激減する中、新たな成長に向けて国主導で科学技術イノベーションをリードするのが喫緊の課題です。

しかし、年間約 3.6 兆円にも及ぶ科学技術関係予算については、文部科学省を中心に、経済産業省や厚生労働省等、関係省庁に予算が配分され、各省内で同様な研究が行われている事例も見受けられ、縦割りの弊害が顕著です。また、限られた予算にも関わらず、効果的な配分が行われていないのが現状です。

そこで、産業の生命線である科学技術を国家戦略として推進し、「価値の創造拠点」とするべく、総合科学技術会議の「権限」「体制」「予算システム」を抜本的に強化し、真の「司令塔」機能へと再構築します。

具体的には、各省庁の縦割りを排し、強力な予算配分権限を集中させ、適正な評価を行うことができる人材育成とシステムの構築を行います。例えば、素粒子物理分野の大規模プロジェクトである ILC（国際リニアコライダー※研究所建設）計画等を含む国際科学イノベーション拠点作りに日本が主導的な役割を果たせるなど、再生医療※や創エネ・省エネ・蓄エネ等の重点分野を産学の知を結集した国家戦略として強力に推進します。

A very urgent issue for the leaders of the country is to take the lead in science and technology innovation and aim for new growth in order to develop the future society and economy.

… and make Japan play a leading role in the formation of an international scientific innovation base that includes, for example, the plan for the ILC …

HOW MUCH PRECISION IS NEEDED?

Examples: (references in arXiv:1208.5152)

M. Peskin, Theoretical Summary Lecture for Higgs Hunting 2012

Supersymmetry:

$$g(\tau)/SM = 1 + 10\% \left(\frac{400\ \mathrm{GeV}}{m_A}\right)^2$$

$$g(b)/SM = g(\tau)/SM + (1-3)\%$$

Little Higgs:

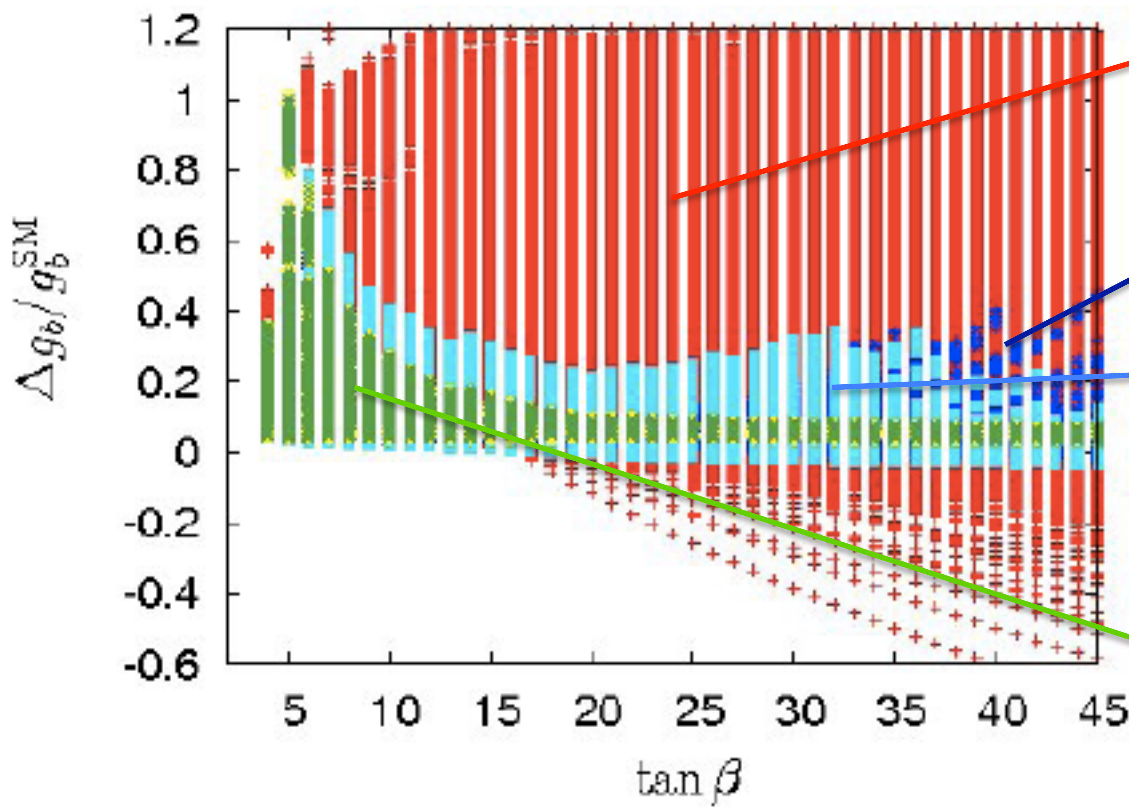
$$g(g)/SM = 1 + (5-9)\%$$

$$g(\gamma)/SM = 1 + (5-6)\%$$

Composite Higgs:

$$g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

reach: roughly 3 TeV in new particle masses for the most sensitive deviations.



RED: several Higgses are discovered at LHC

DARKBLUE: excluded by BR (b →sγ) constraint

LIGHTBLUE: at least one stop has mass < 1 TeV

GREEN: both top squarks are heavier than 1.5 TeV

	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

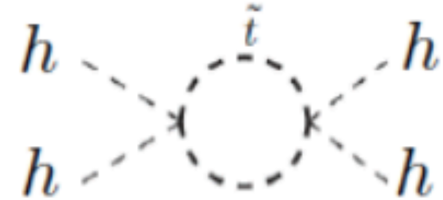
GUPTA, RZEHAK, WELLS 2012

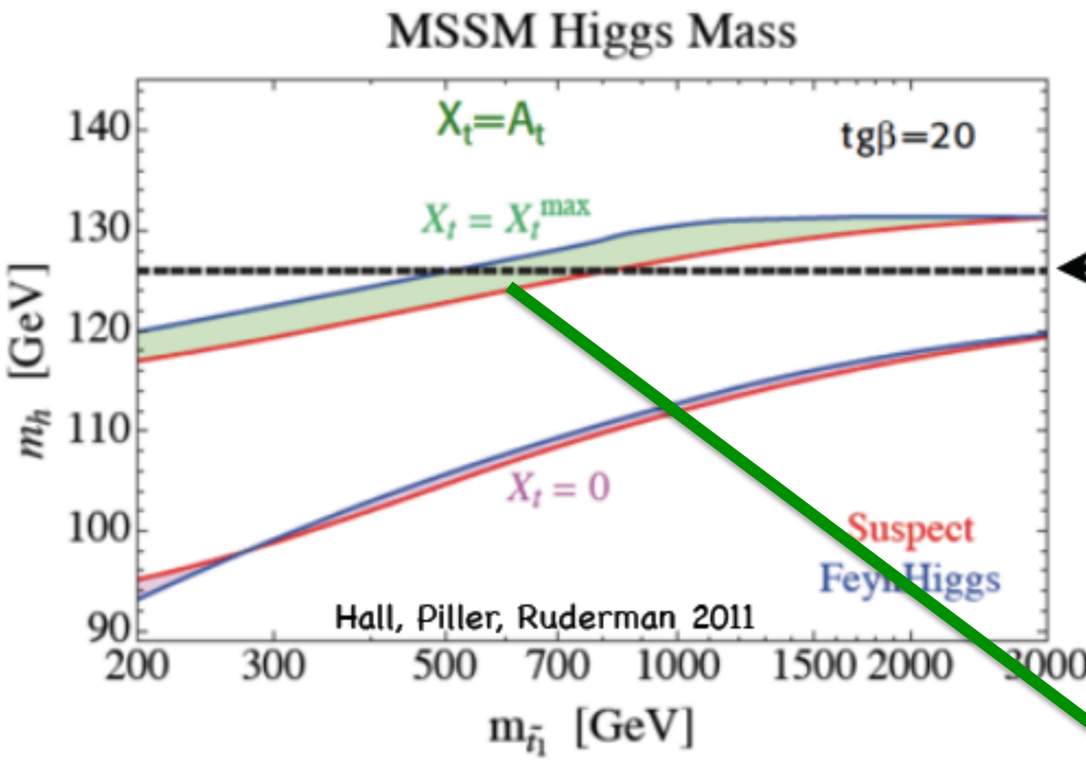
MSSM

COPING WITH A HIGGS MASS OF 125 GEV?

the two players to raise the Higgs mass

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$





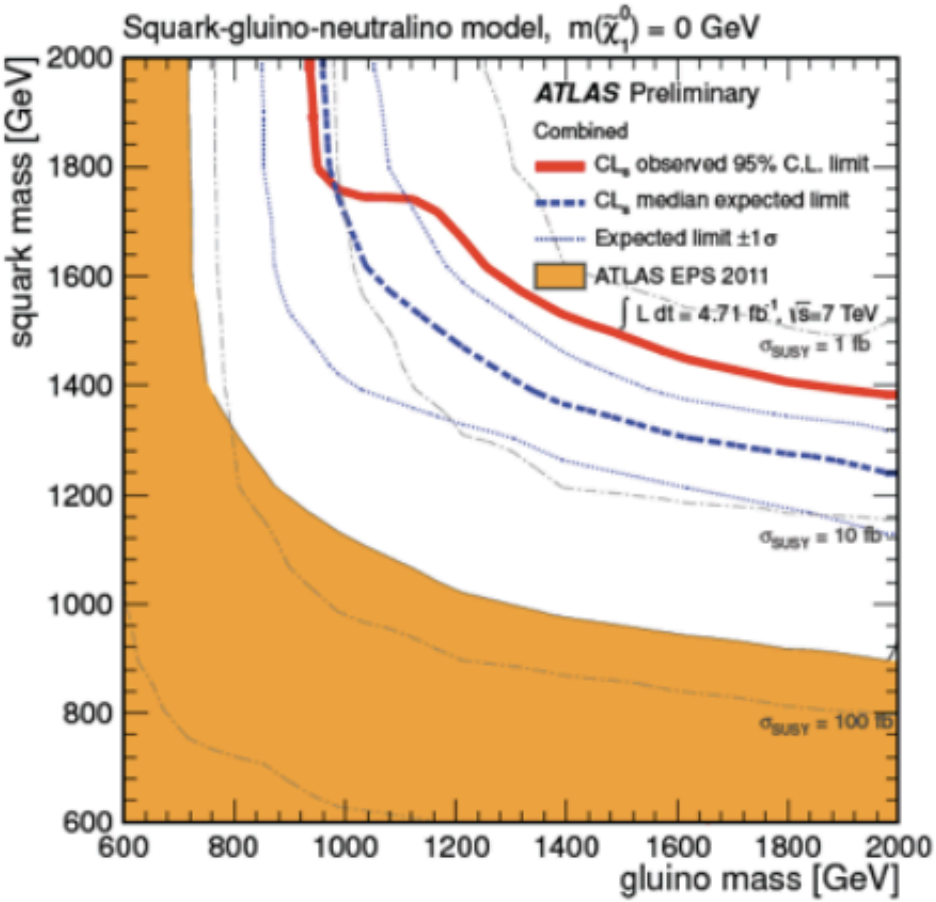
POSSIBLE TO HAVE A LIGHT STOP IF ONE MOVES FROM THE MSSM TO THE

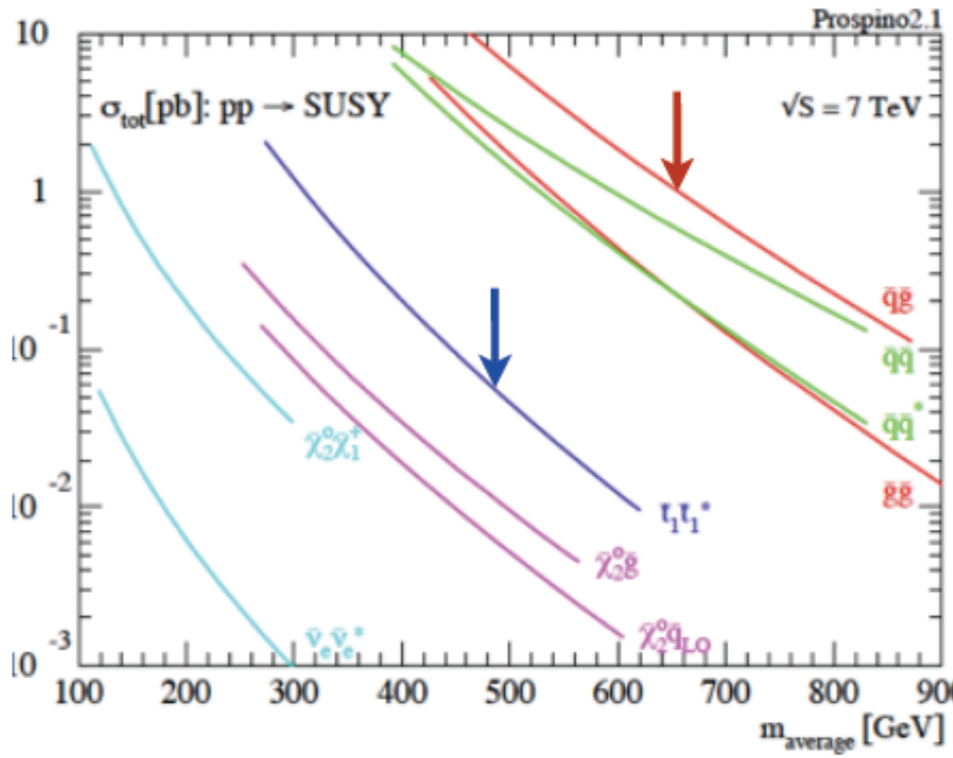
NMSSM

WITH ONE ADDITIONAL SINGLET

Possible for the MSSM to have a light Higgs of mass=125 GeV, but need for **not so light stop**

IS LOW-ENERGY SUSY STILL ALIVE?





$$g\ q \longrightarrow \tilde{g}\ \tilde{q}$$
$$q\ q \longrightarrow \tilde{q}\ \tilde{q}$$
$$q\ \bar{q} \longrightarrow \tilde{q}\ \tilde{q}^*$$

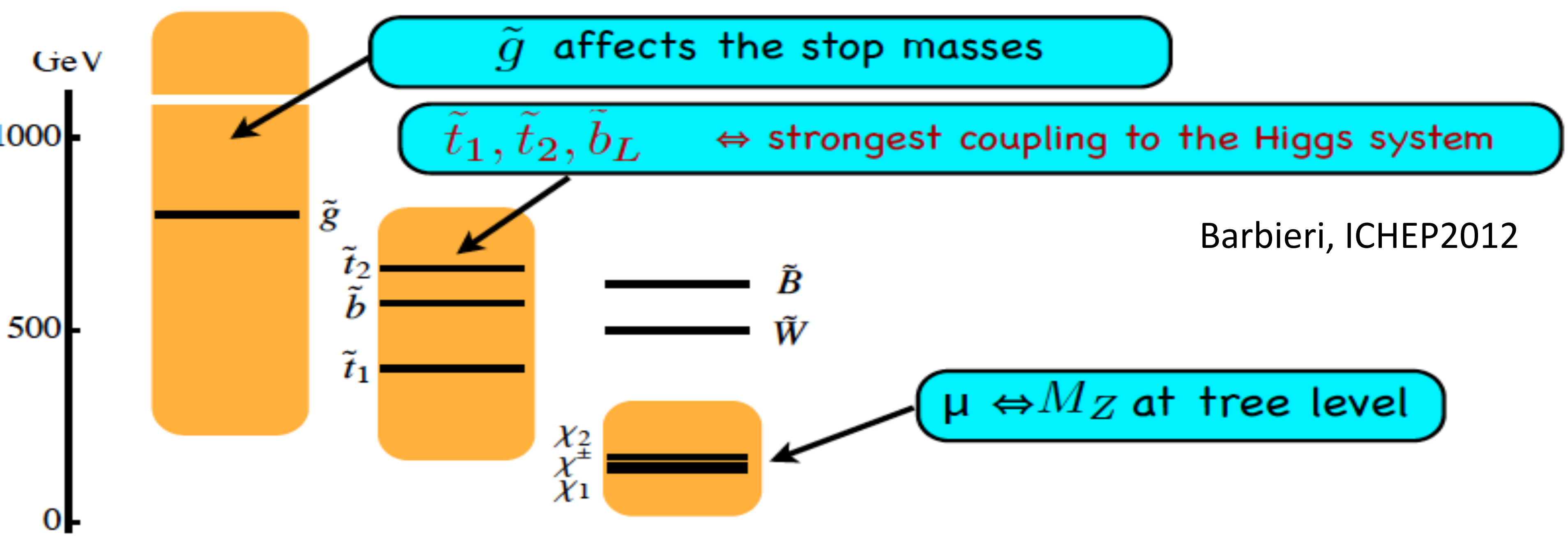
$$\Rightarrow m_{\tilde{g}}, m_{\tilde{q}_{1,2}} > 1 \div 1.5\ TeV$$

Stop and **sbottom**
not so stringently constrained

NATURAL SUSY

LOW-ENERGY SUSY to cope with the gauge hierarchy problem: only the SUSY particles involved in the cancellation of the quadratic div. to the Higgs mass have to remain “light”

“s-particles at their naturalness limit”

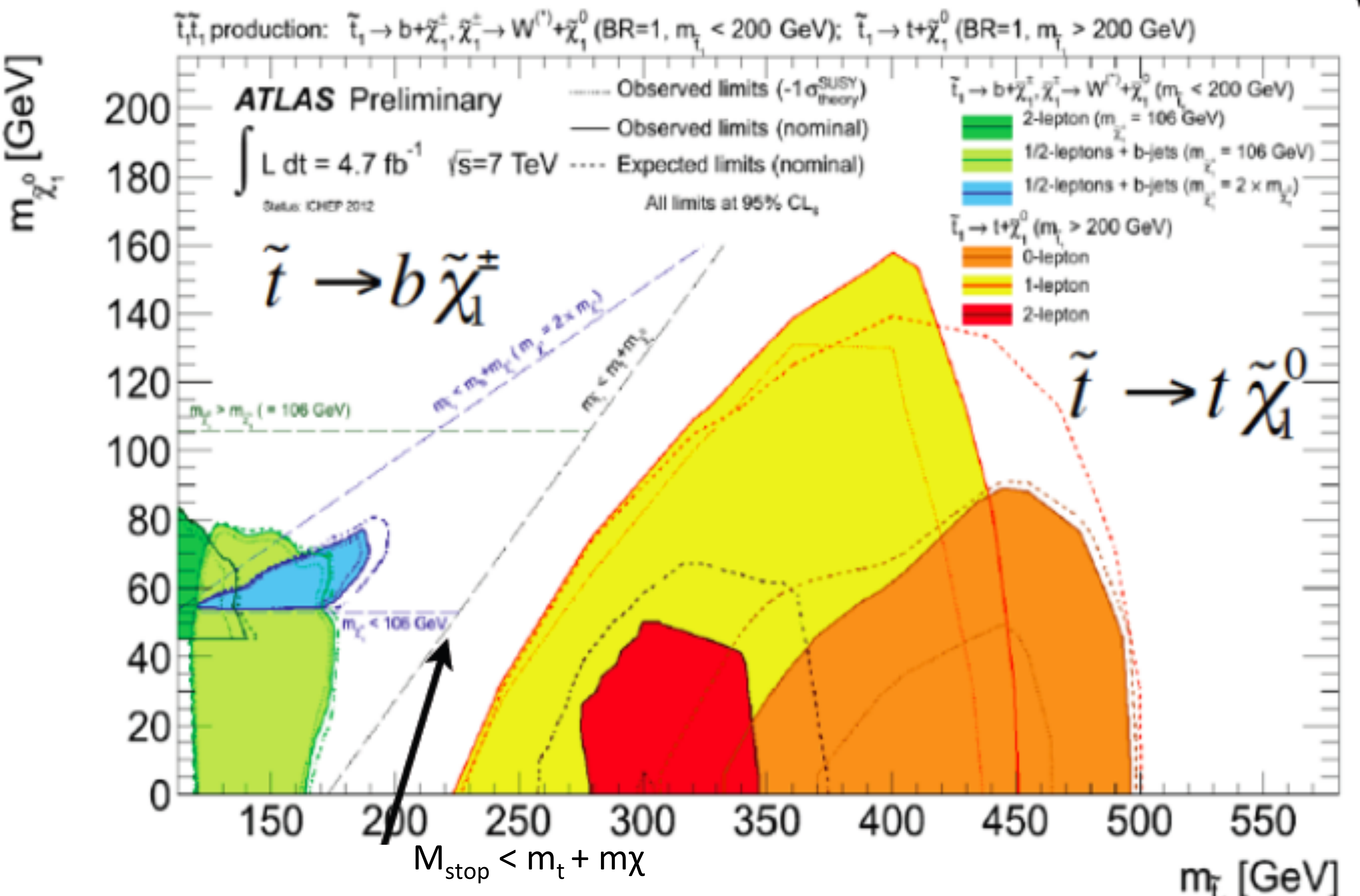


Barbieri, ICHEP2012

orange areas indicative and dependent on how the Higgs boson gets its mass

$\tilde{B}, \tilde{W}$ not much constrained but expected below $m_{\tilde{g}}$

Hunting for a light s-top



$M_{stop} < m_t + m\chi$

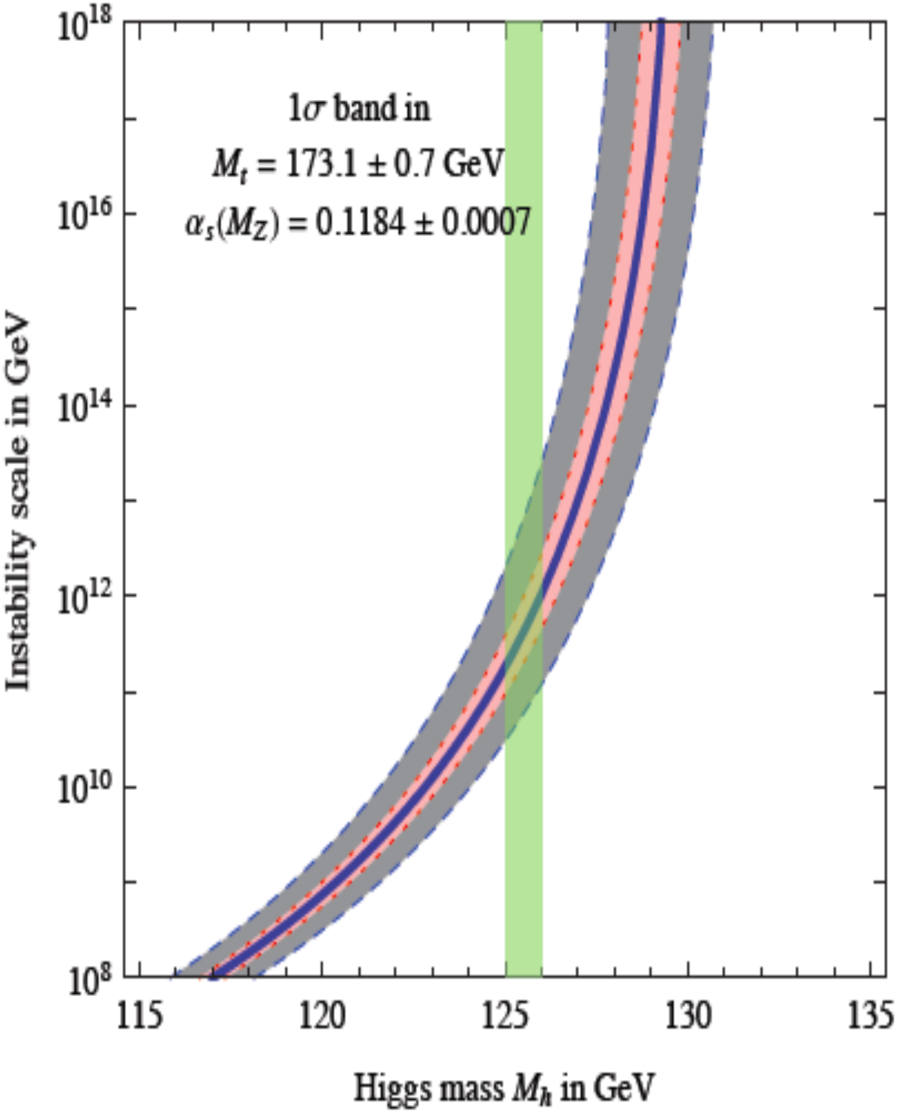
LOW-ENERGY NEW PHYSICS and the DILEMMA:

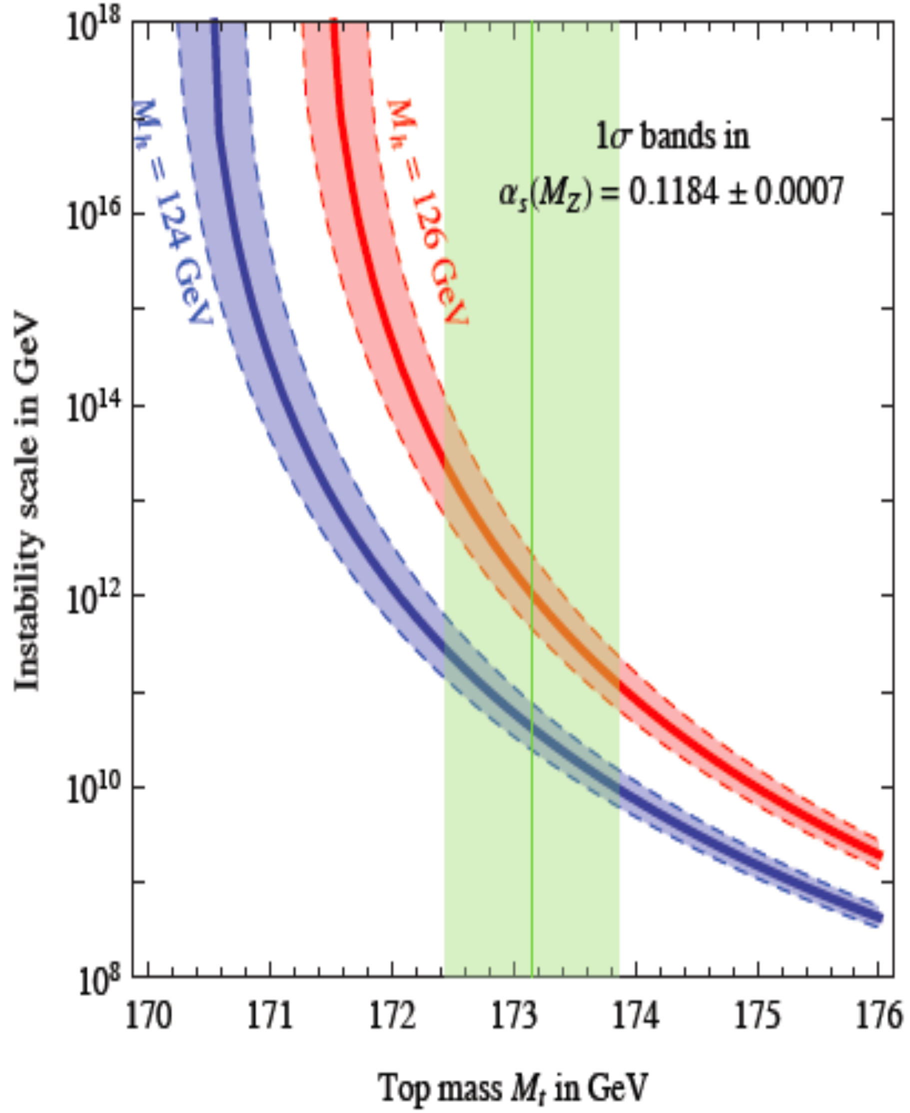
NATURAL or FINE-TUNED HIGGS

- Higgs mass **PROTECTION** through **SYMMETRIES**: SUSY, Higgs as a **Pseudo Goldstone boson**
- New **STRONG INTERACTION** near the TeV scale (+ Higgs as a PGB)
- **TeV UV saturation** (little-large hierarchies identified) : extra-dimensions around the corner
- Randall-Sundrum path: **warped space-time**
- **Fine-tuning (for the Higgs mass, for the cosmological constant) is a fictitious problem: anthropic (environmental) selection, multiverse, 10^{500} vacua of String theories, …**

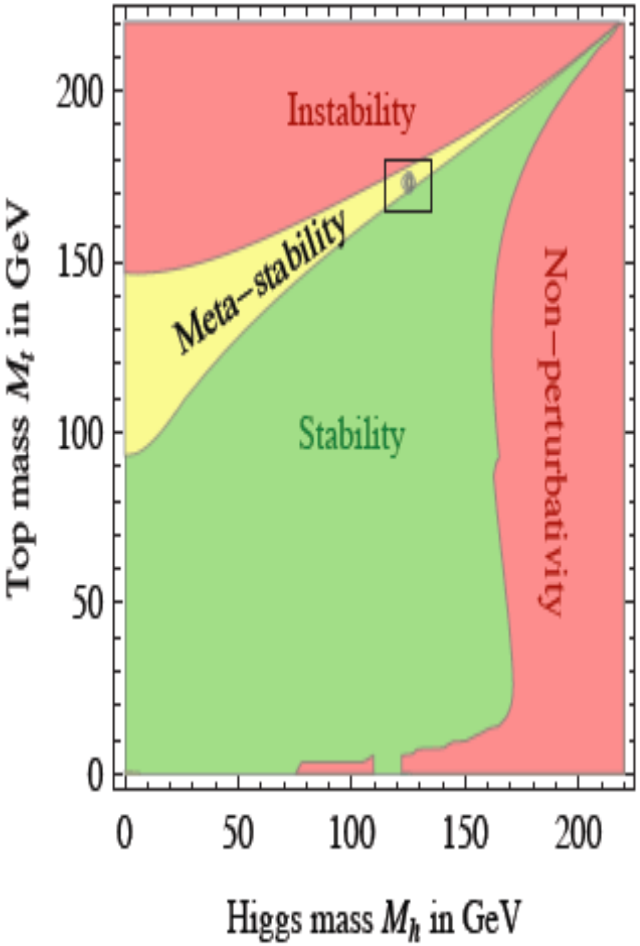
TOP and HIGGS MASSES decide on the VACUUM STABILITY of our UNIVERSE

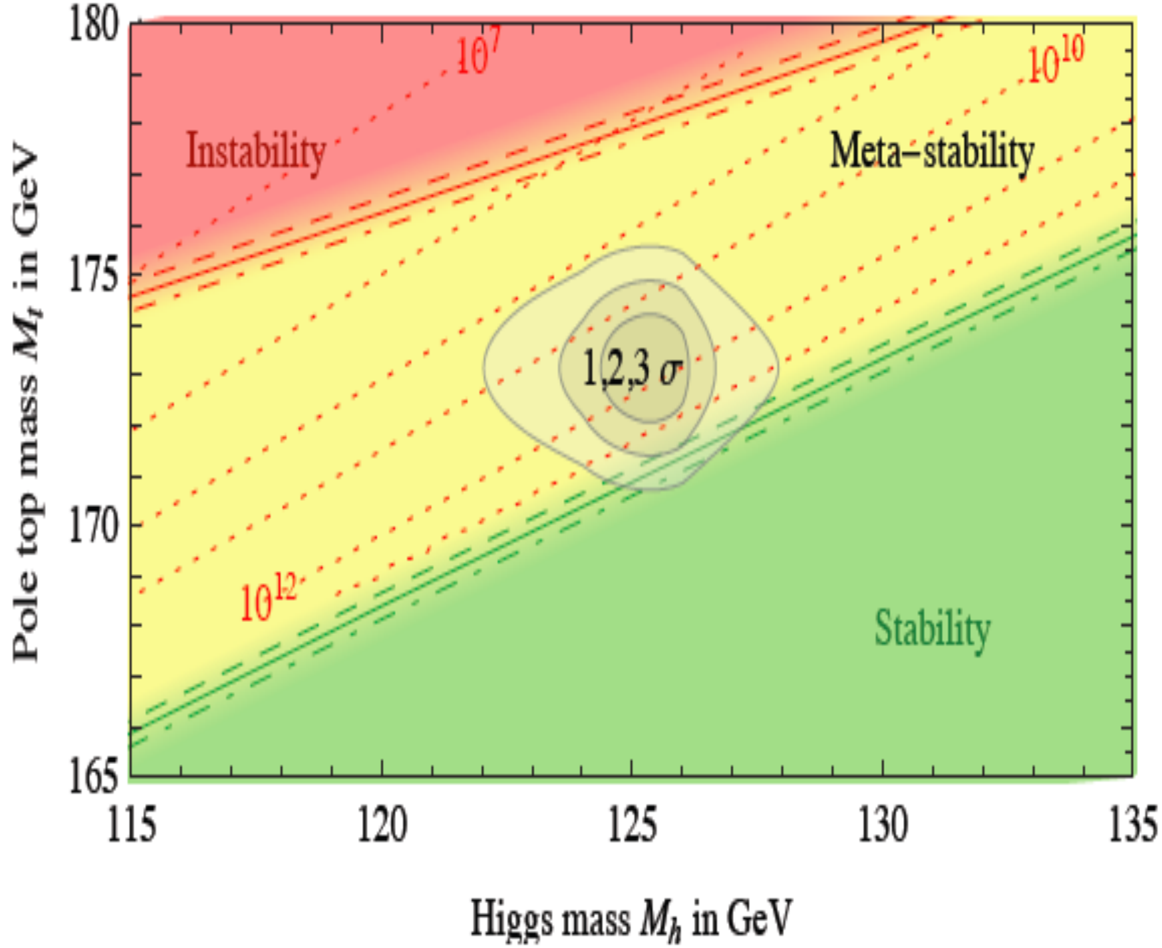
DEGRASSI et al 2012





LIVING DANGEREOUSLY IN A "PROBABLE" METASTABLE UNIVERSE





BEZRUKOV, KALMIKOV, KNIEHL, SHAPOSHNIKOV 2012;
DEGRASSI, DI VITA, ELIAS-MIRO', ESPINOSA, GIUDICE, ISIDORI, STRUMIA 2012

FIRST COMPLETE ANALYSIS NNLO OF THE SM HIGGS POTENTIAL

ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

DEGRASSI ET AL

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

INTRINSIC DIFFICULTY TO "DEFINE" WHAT THE TOP MASS IS AT A **HADRON COLLIDER** WITH UNCERTAINTY $\leq$ 1 GeV

Some thoughts on this part: Higgs and beyond

- Reminder: **we got a piece** (a very important one, but just a piece) of **a large mosaic still unknown** – let's not hurry to draw conclusions (in particular on the absence of "visible" new physics at the TeV scale …)
- There seems to be **no entirely "natural" theory** to account for the **naturalness** (i.e. gauge hierarchy) problem in the ELW symmetry breaking. . Already known from LEP, now more and more evident
- **VIRTUALITY vs. REALITY**? (i.e., look for NP through its virtual effects – ex. deviations in the Higgs couplings – or through the production and detection of its new particles). At this moment the **"virtual path" seems attractive**; however, one has to recognize also the limits of the virtual path: i) the barrier of the **theoretical uncertainties**; ii) the difficult interpretation of potential discrepancies with the SM expectations.

At the end we badly need "reality" to say that we "know" something.

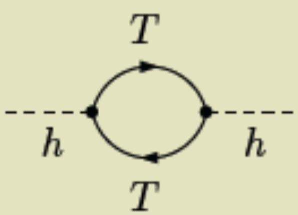
Higgs and flavor physics as indirect BSM probes

NEUBERT SUSY2012

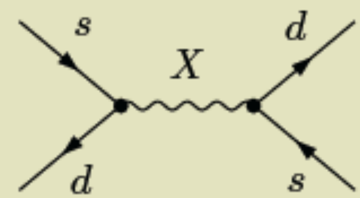
$$\mathcal{L}_{\rm EFT} = \Lambda_{\rm UV}^2\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2} + \ldots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

$\Downarrow$



$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\rm UV}^2$



$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

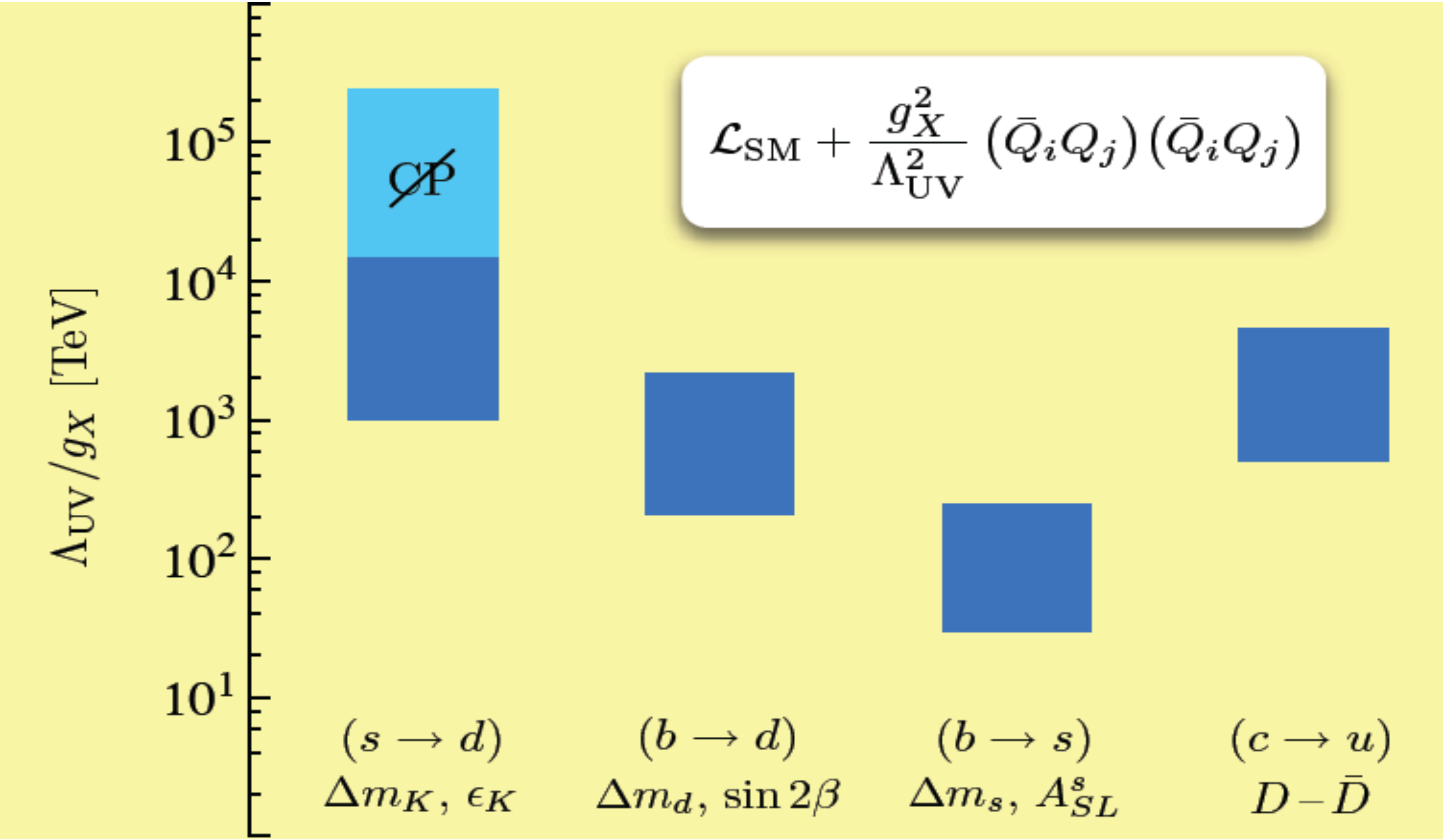
$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\qquad$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

Possible solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

(i) $\Lambda_{\rm UV} >> 1$ TeV: **Higgs fine tuned**, new particles too heavy for LHC

(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a **flavor symmetry**

FCNC and GENERIC FLAVOURED NEW PHYSICS



Generic bounds on New Physics scale (for $g_X \sim 1$)

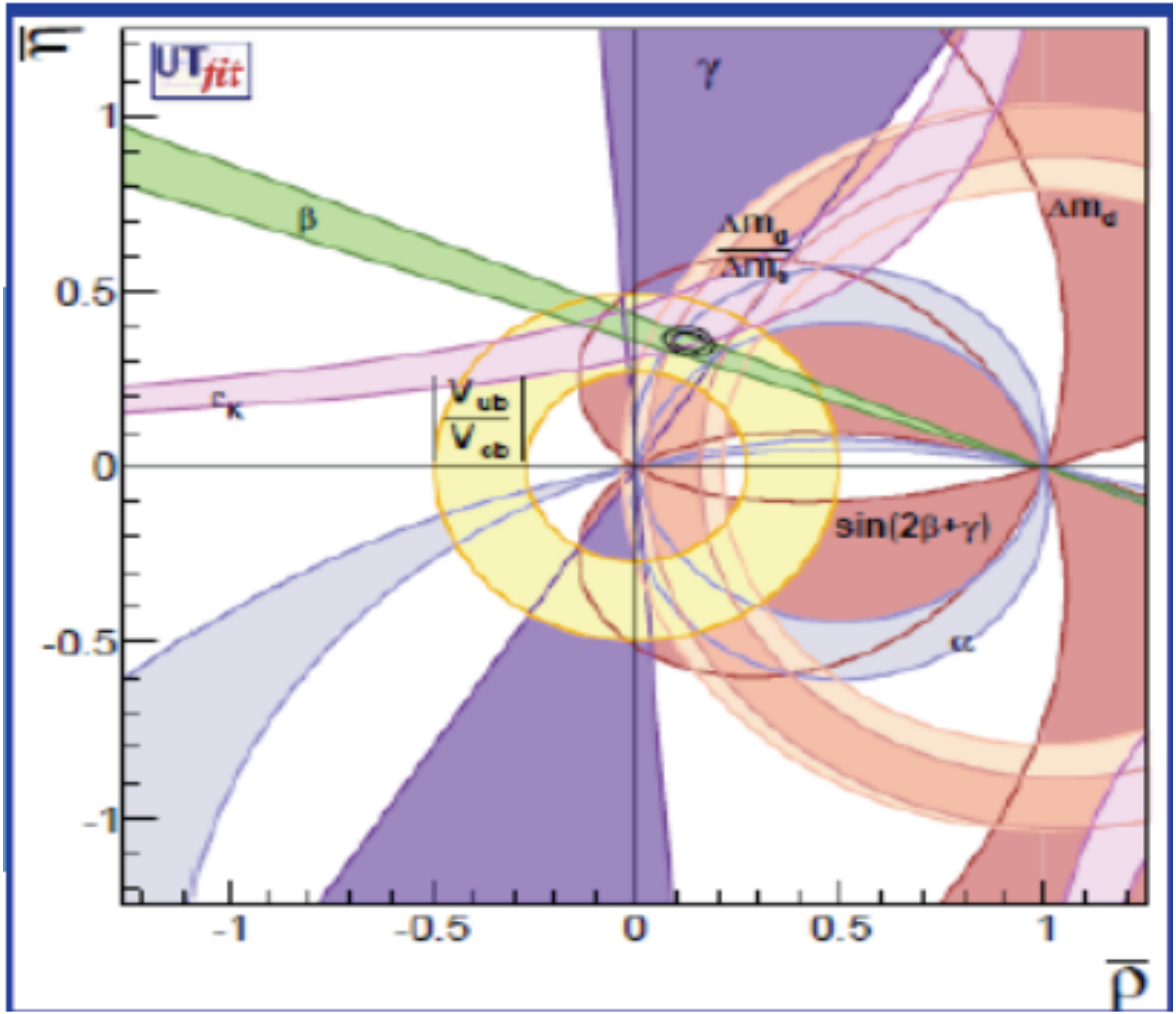
Isidori, Nir, Perez

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{NP}$$

$$\mathcal{L}_{eff}^{NP} = \Sigma_i \frac{c_i}{\Lambda_{NP}^2} O_i$$

Operator	Bounds on Λ in TeV ($c_{ij} = 1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; \lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D; \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s}; S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s}; S_{\psi\phi}$

the (almost complete) CKM triumph



THE FLAVOUR PROBLEMS

FERMION MASSES

What is the rationale hiding behind the spectrum of fermion masses and mixing angles (our “**Balmer lines**” problem)

→ **LACK OF A FLAVOUR “THEORY”**

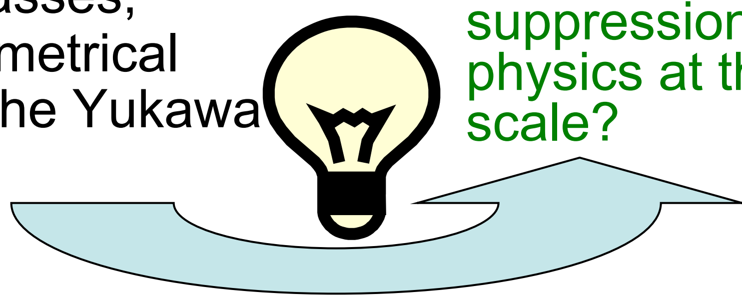
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

FCNC

Flavour changing neutral current (FCNC) processes are suppressed.

In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix.**

How to cope with such delicate suppression if the there is new physics at the electroweak scale?



From a closer look

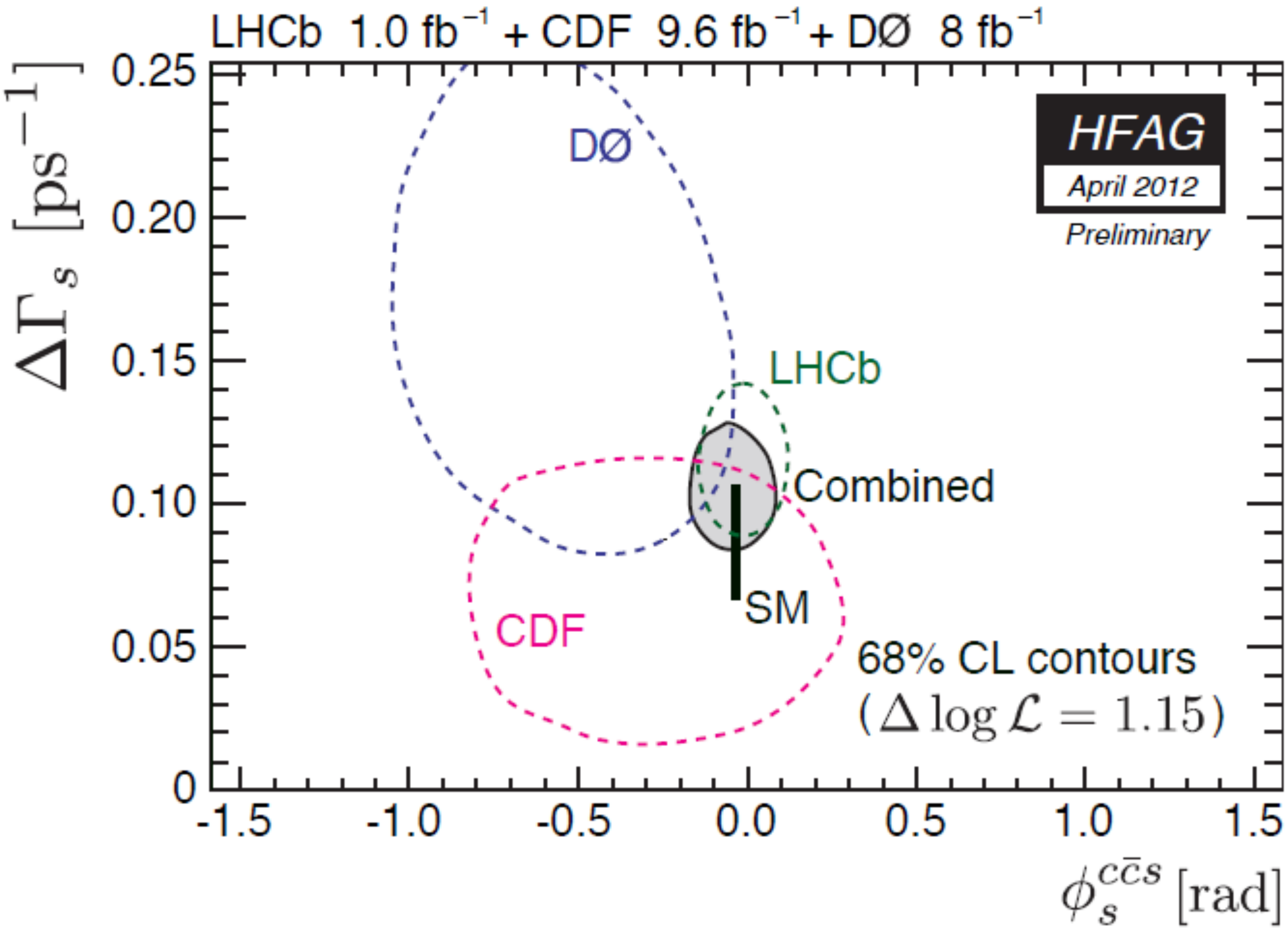
UTfit

From the UTA (excluding its exp. constraint) → Prediction

	Prediction	Measurement	Pull
$\sin 2\beta$	0.81±0.05	0.680±0.023	2.4 ←
γ	68°±3°	76°±11°	<1
α	88°±4°	91°±6°	<1
$\lvert V_{cb}\rvert \cdot 10^3$	42.3±0.9	41.0±1.0	<1
$\lvert V_{ub}\rvert \cdot 10^3$	3.62±0.14	3.82±0.56	<1
$\varepsilon_K \cdot 10^3$	1.96±0.20	2.23±0.01	1.4 ←
$BR(B \to \tau\nu) \cdot 10^4$	0.82±0.08	1.67±0.30	-2.7 ←

TARANTINO ICHEP2012

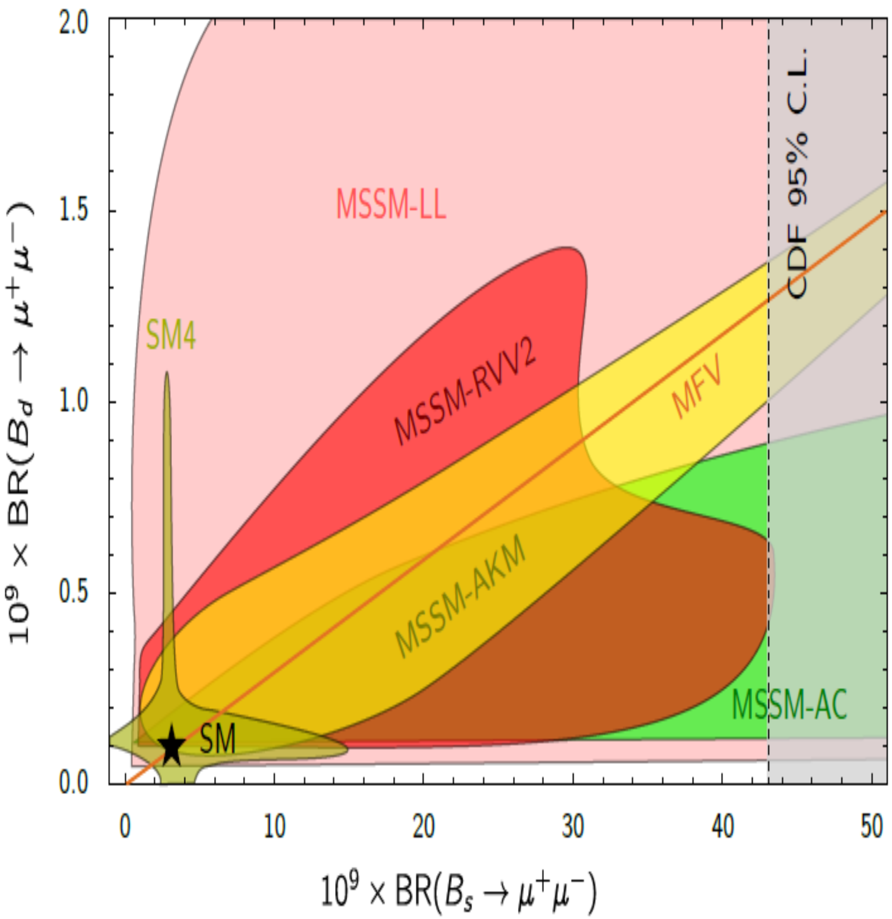
LHCb and CPV in the B_s decays



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]		$-0.044^{+0.090}_{-0.085}$	$+0.105 \pm 0.015$

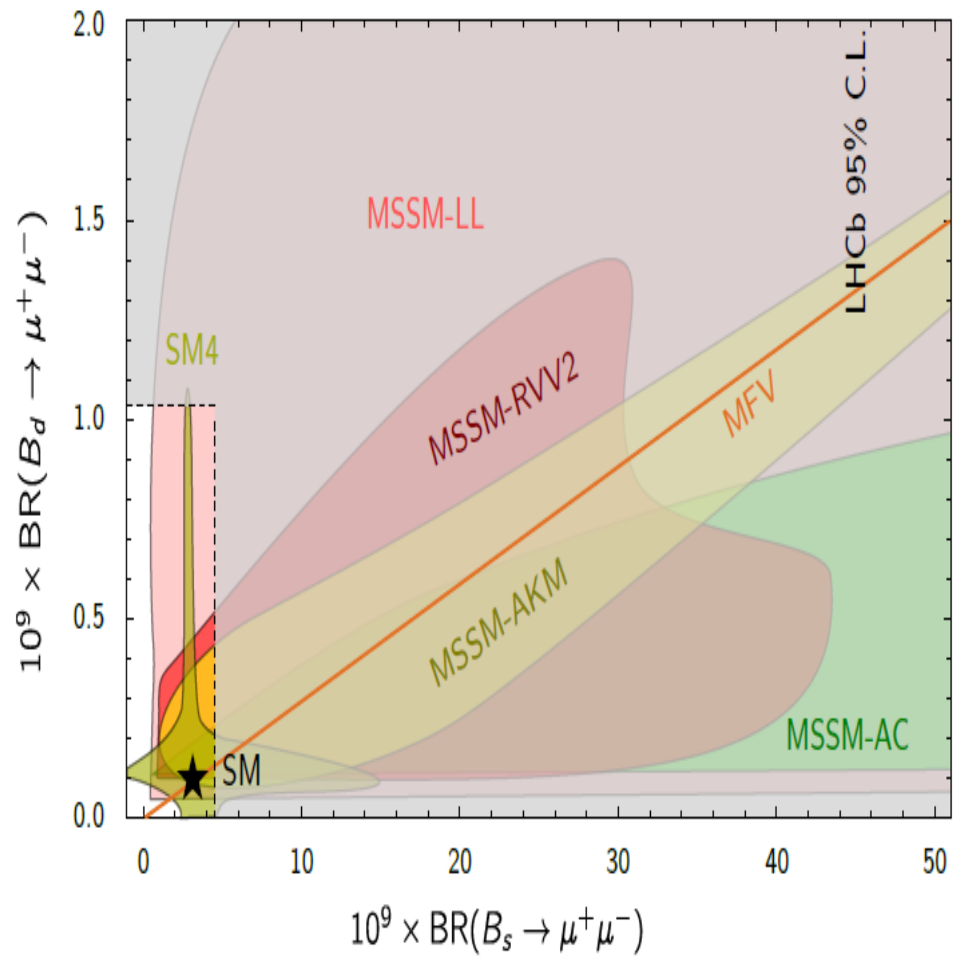
David Straub: arXiv:1205.6094

2011



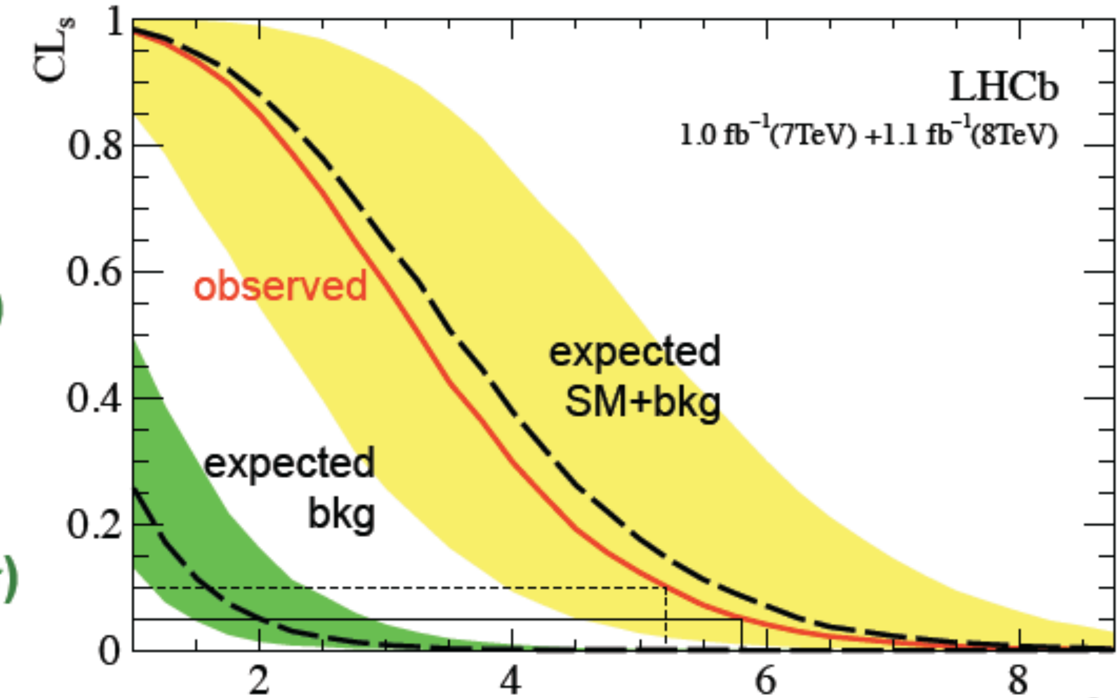
2012

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



Results for $B_s \to \mu^+\mu^-$: Limits and significance

- Evaluate compatibility with background only and background+signal hypotheses (CLs method)
  - 2011+2012: bkg only p-value: 5×10^{-4} (corresponds to 3.5σ)
  - 2012 alone bkg only p-value: 9×10^{-4} (corresponds to $3.3\ \sigma$)



The branching fraction is measured as

$$BR(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

- This is the first evidence of the decay $B_s \to \mu^+\mu^-$!

DIRECT CPV IN $D^0 \rightarrow \pi^+\pi^-, K^+K^-$

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

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

2012: fom CDF, 9.6 fb^{-1}, + LHCb + BELLE

$$\Delta A_{CP} \equiv A_{CP}\left(K^+K^-\right) - A_{CP}\left(\pi^+\pi^-\right) = (-0.74 \pm 0.15)\%$$

This result demands an enhancement of the suppressed CKM amplitudes of the SM of a factor approx. 5 – 10 Isidori, Kamenik, Ligeti, Perez 2011

But the charm quark is ***TOO HEAVY*** to apply the ChPT, while, at the same time, it is ***TOO LIGHT*** to trust the Heavy Quark Effective approach : ***HENCE IT IS NOT IMPOSSIBLE THAT THE SM IS ONCE AGAIN FINDING A WAYOUT TO SURVIVE!*** Golden, Grinstein 1989; Brod, Kagan, Zupan 2011

ON THE OTHER IT REMAINS POSSIBLE THAT NEW PHYSICS IS SHOWING UP... Giudice, Isidori, Paradisi 2012; Barbieri, Buttazzo, Sala e Straub 2012

POSSIBLE SURPRISES FROM THE KAON TOO → NA62 ?

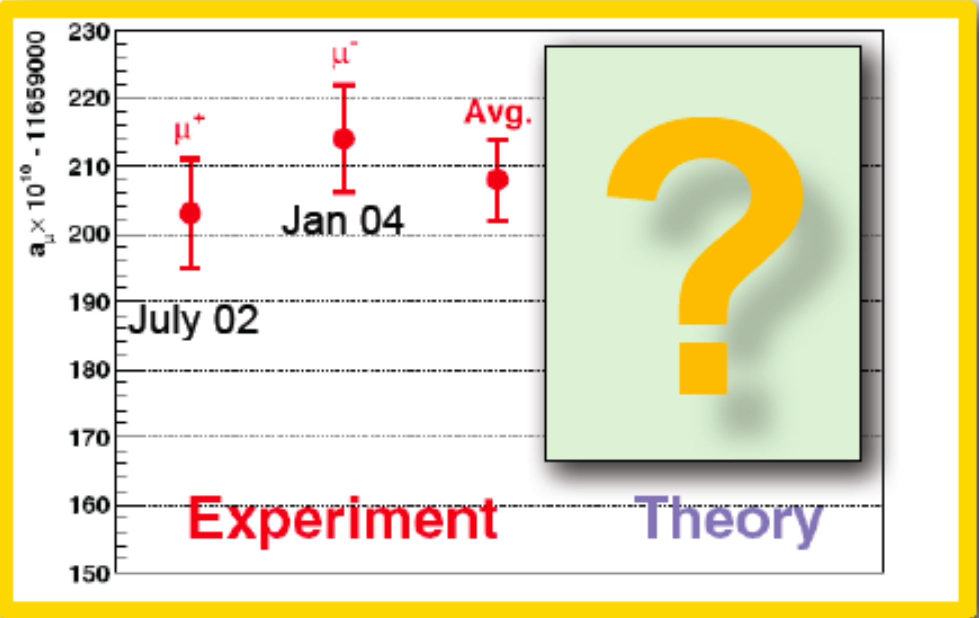
TARANTINO ICHEP2012

On the Lattice side: Ten Years Ago → Today

Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]		UTA Lattice inputs 2012 [www.utfit.org]	
$\hat{B}_K$	0.86(15)	[17%]	0.75(2)	[3%]
f_{Bs}	238(31) MeV	[13%]	233(10) MeV	[4%]
f_{Bs}/f_B	1.24(7)	[6%]	1.20(2)	[1.5%]
$\hat{B}_{Bs}$	1.34(12)	[9%]	1.33(6)	[5%]
B_{Bs}/B_B	1.00(3) (quenched, $\mu_l > m_s/2$, ...)	[3%]	1.05(7)	[7%]
$F_{D*}(1)$	0.91(3)	[3%]	0.92(2)	[2%]
$F_+^{B\to\pi}$	--	[20%]	--	[11%]

- The last 10 years teach us that Lattice QCD has made important progresses (quenched->unquenched , higher computational power, better algorithms)
- More recently further improvements are being realized: simulations at the physical point, discretization effects well under control (in the light and heavy sectors), N_f=2+1+1, ...

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)

M. PASSERA 2012

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

M. PASSERA 2012

with $a_\mu^{HHO}(lbl) = 105\ (26) \times 10^{-11}$

[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

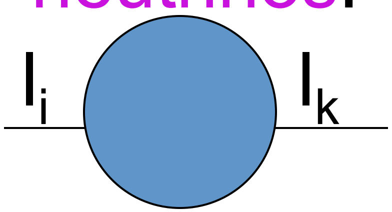
THE EDM CHALLENGE

FOR **ANY** **NEW PHYSICS AT THE TEV SCALE** WITH **NEW SOURCES OF CP VIOLATION** → NEED FOR **FINE-TUNING** TO PASS THE EDM TESTS OR SOME **DYNAMICS TO SUPPRESS THE CPV** IN FLAVOR CONSERVING EDMS

$$|d_{\rm n}| < 2.9 \times 10^{-26} e \text{ cm } (90\%\text{C.L.}),$$
$$|d_{\rm Tl}| < 9.0 \times 10^{-25} e \text{ cm } (90\%\text{C.L.}),$$
$$|d_{\rm Hg}| < 3.1 \times 10^{-29} e \text{ cm } (95\%\text{C.L.}).$$

LFV and NEW PHYSICS

- Flavor in the HADRONIC SECTOR:
  CKM paradigm
- Flavor in the LEPTONIC SECTOR:
  - Neutrino masses and (large) mixings
  - Extreme smallness of LFV in the charged lepton sector of the SM with massive neutrinos:

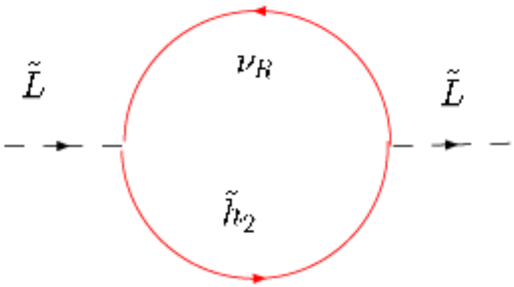


suppressed by $(m_{\nu_i}^2 - m_{\nu_k}^2) / M_W^2$

SUSY SEESAW: *Flavor universal SUSY breaking and yet* ***large lepton flavor violation***

Borzumati, A. M. 1986 (after discussions with W. Marciano and A. Sanda)

$$L = f_l \, \overline{e}_R L h_1 + f_\nu \, \overline{\nu}_R L h_2 + M \, \nu_R \nu_R$$



$$\left(m^2_{\tilde{L}}\right)_{ij} \simeq \frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(f_\nu^\dagger f_\nu\right)_{ij} \log\frac{M}{M_G}$$

Non-diagonality of the slepton mass matrix in the basis of diagonal lepton mass matrix depends on the **unitary matrix U which diagonalizes ($f_\nu^+ f_\nu$)**

LFV in SUSY seesaw

L. Calibbi, NuFact 2012

In SUSY, new fields interacting with the MSSM fields enter the radiative corrections of the sfermion masses

Hall Kostelecky Raby '86

⇨ This applies to the new seesaw interactions: generically induce LFV in the slepton mass matrix!

Type I $$(\tilde{m}_L^2)_{ij} \propto m_0^2 \sum_k (\mathbf{Y}_N^*)_{ki} (\mathbf{Y}_N)_{kj} \ln \left(\frac{M_X}{M_{R_K}} \right)$$

Borzumati Masiero '86

Type II $$(\tilde{m}_L^2)_{ij} \propto m_0^2 (\mathbf{Y}_\Delta{}^\dagger \mathbf{Y}_\Delta)_{ij} \ln \left(\frac{M_X}{M_\Delta} \right) \propto m_0^2 (\mathbf{m}_\nu{}^\dagger \mathbf{m}_\nu)_{ij} \ln \left(\frac{M_X}{M_\Delta} \right)$$

$U \hat{\mathbf{m}}_\nu^2 U^\dagger$

A. Rossi '02; Rossi Joaquim '06

Type III Similar to type I

Biggio LC '10; Esteves et al. '10

Thorough analysis of LFV in these 3 kinds of Seesaw in the SUSY context

M. HIRSCH, F. JOAQUIM, A. VICENTE arXiv: 1207.6635 [hep-ph]

How Large LFV in SUSY SEESAW?

- 1) Size of the **Dirac neutrino couplings f_ν**
- 2) Size of the **diagonalizing matrix U**

In **MSSM seesaw** or in **SUSY SU(5)** (Moroi): not possible to correlate the neutrino Yukawa couplings to know Yukawas;

In **SUSY SO(10)** (A.M., Vempati, Vives) at least one neutrino Dirac Yukawa coupling has to be of the **order of the top Yukawa coupling** one large of O(1) f_ν

U → two "extreme" cases:

a) **U with "small" entries** → ***U = CKM***;
b) **U with "large" entries** with the exception of the 13 entry → ***U = PMNS*** matrix responsible for the diagonalization of the neutrino mass matrix

THE STRONG ENHANCEMENT OF LFV IN SUSY SEESAW MODELS CAN OCCUR

EVEN IF THE MECHANISM RESPONSIBLE FOR SUSY BREAKING IS ABSOLUTELY FLAVOR BLIND

IMPACT OF

HIGGS $124.5\ \text{GeV} \lesssim m_h \lesssim 126.5\ \text{GeV}$

LFV LIMITS $\text{BR}(\mu \to e + \gamma) < 2.4 \times 10^{-12}\ (90\%\ \text{CL})$.

θ_{13}

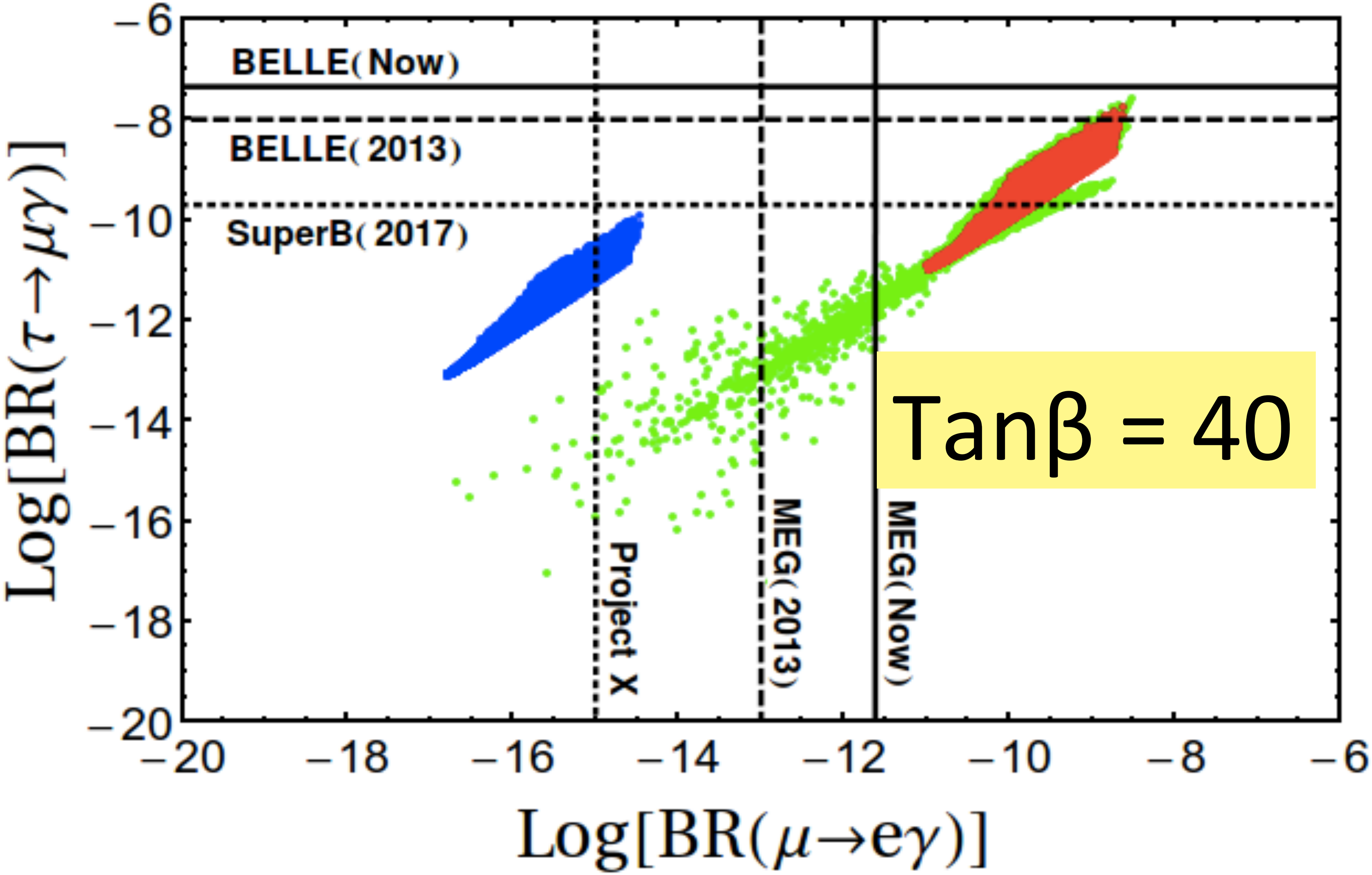
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$$

on SUSY GUTs where neutrinos get mass through the SEE-SAW MECHANISM

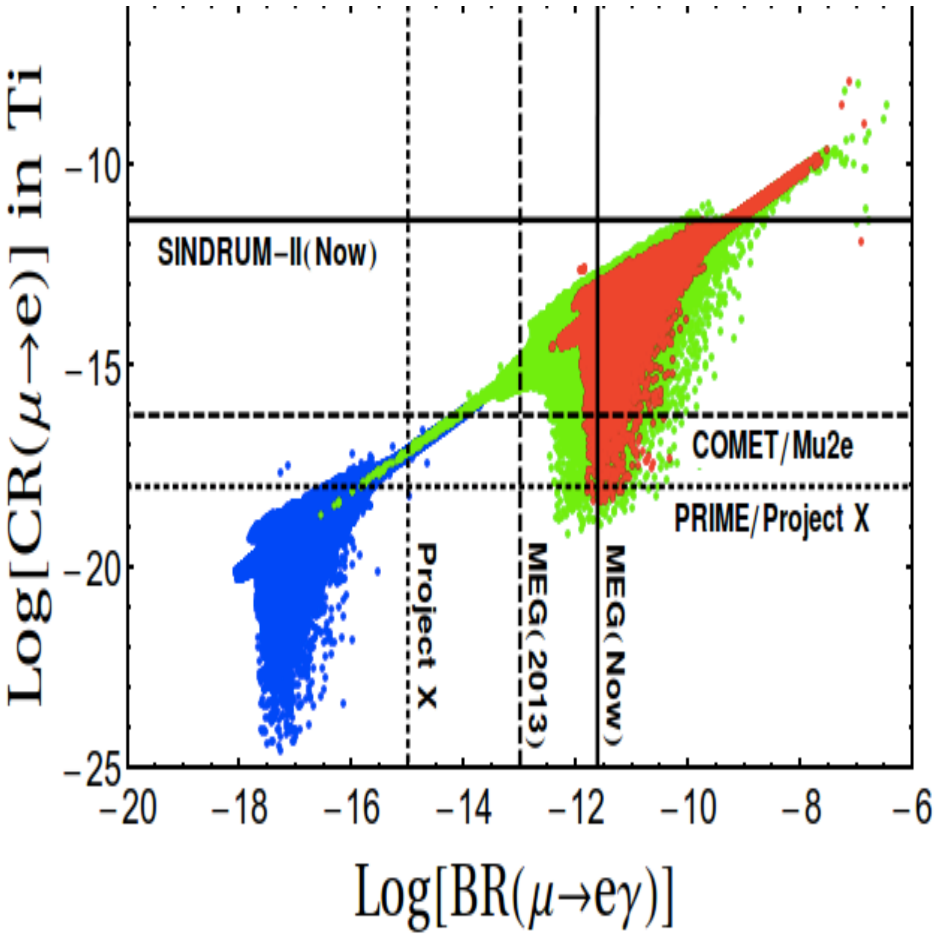
L. Calibbi, D. Chowdhury,A.M., K.M. Patel and S.K. Vempati arXiv:1207.7227v1 [hep-ph]

τ → μγ vs. μ → eγ sensitivities

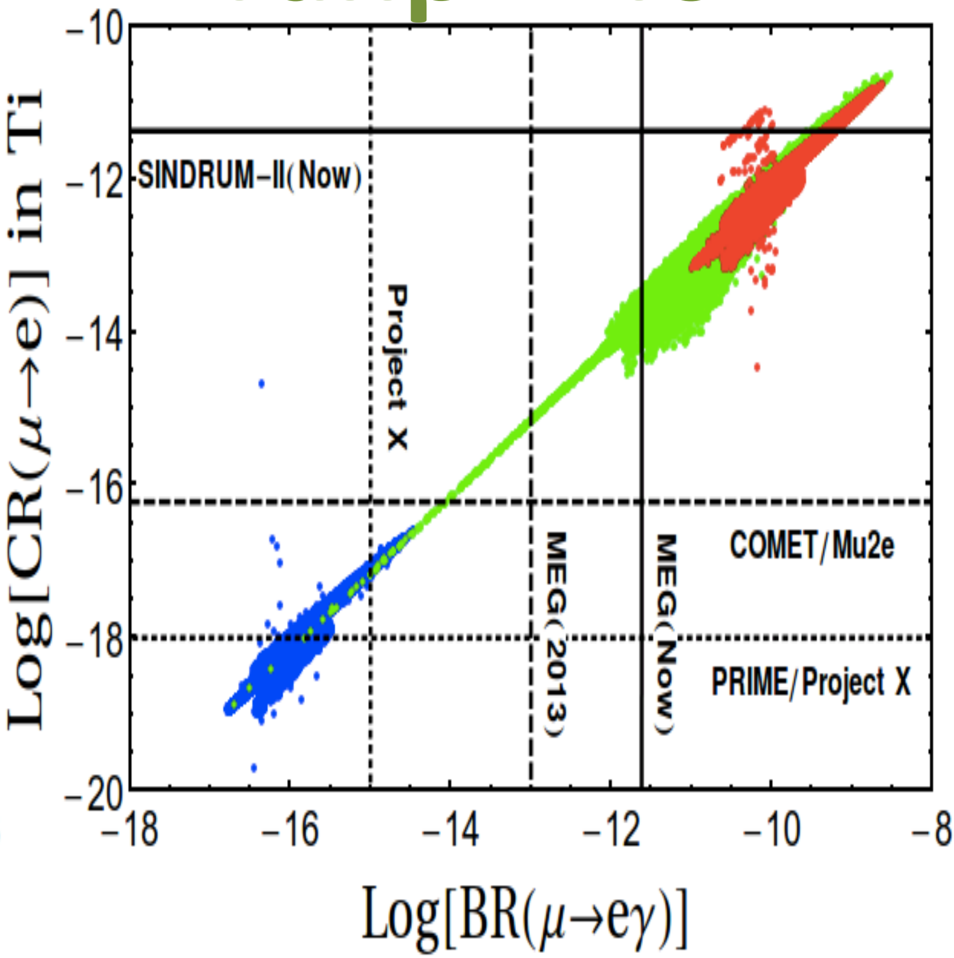


μ – e conversion vs μ → eγ

Tanβ = 10



Tanβ = 40



Some thoughts on the "flavor path" to TeV New Physics

- Out of the **3 traditional theoretical shortcomings of the SM:** i) lack of true unification; ii) gauge hierarchy; iii) no explanation for the fermion masses and mixings (flavor question within the SM) , this latter issue is the one with the **least progress in the last decades** (we still completely lack a flavor theory – unfortunately the (very) good knowledge of the CKM structure has not helped us much in this direction
- Today question: with all the existing constraints, how can it be that NP shows up only in very specific "corners" that we have not experimentally probed yet? The **lack of a flavor theory tells us that what we consider unlikely "coincidences" may be just a fruit of such ignorance** (think of finding $\rho = 1$ without knowing the ELW gauge theory)
- In my view, in this moment of relevance of the "virtuality" as a gate to access NP, the flavor path remains imporatnt: **SLOW DECOUPLING OF NEW PHYSICS IN VIRTUAL EFFECTS W.R.T. PHYSICAL PRODUCTS**

ν : WHERE WE STAND AND WHERE WE'RE HEADING TO

δm^2_{12} ✓ SOLARS+KAMLAND $\delta m^2_{12} = (7.9 +/- 0.7)\ 10^{-5} eV^2$

θ_{12} ✓ SOLARS+KAMLAND $\sin^2(2\theta_{12}) = 0.82 +/- 0.055$

Addressed by accelerator neutrino experiments

δm^2_{23} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.4 +/- 0.4)\ 10^{-3}\ eV^2$

θ_{23} ✓ ATMOSPHERICS $\sin^2(2\theta_{23}) > 0.95$

θ_{13} ✓ $\sin^2 2\theta_{13} = 0.1$

LSND/Steriles ? ★

δ_{CP} ★★

Mass hierarchy ★★

Σm_ν BETA DECAY END POINT $\Sigma m_\nu < 6.6$ eV ★★★

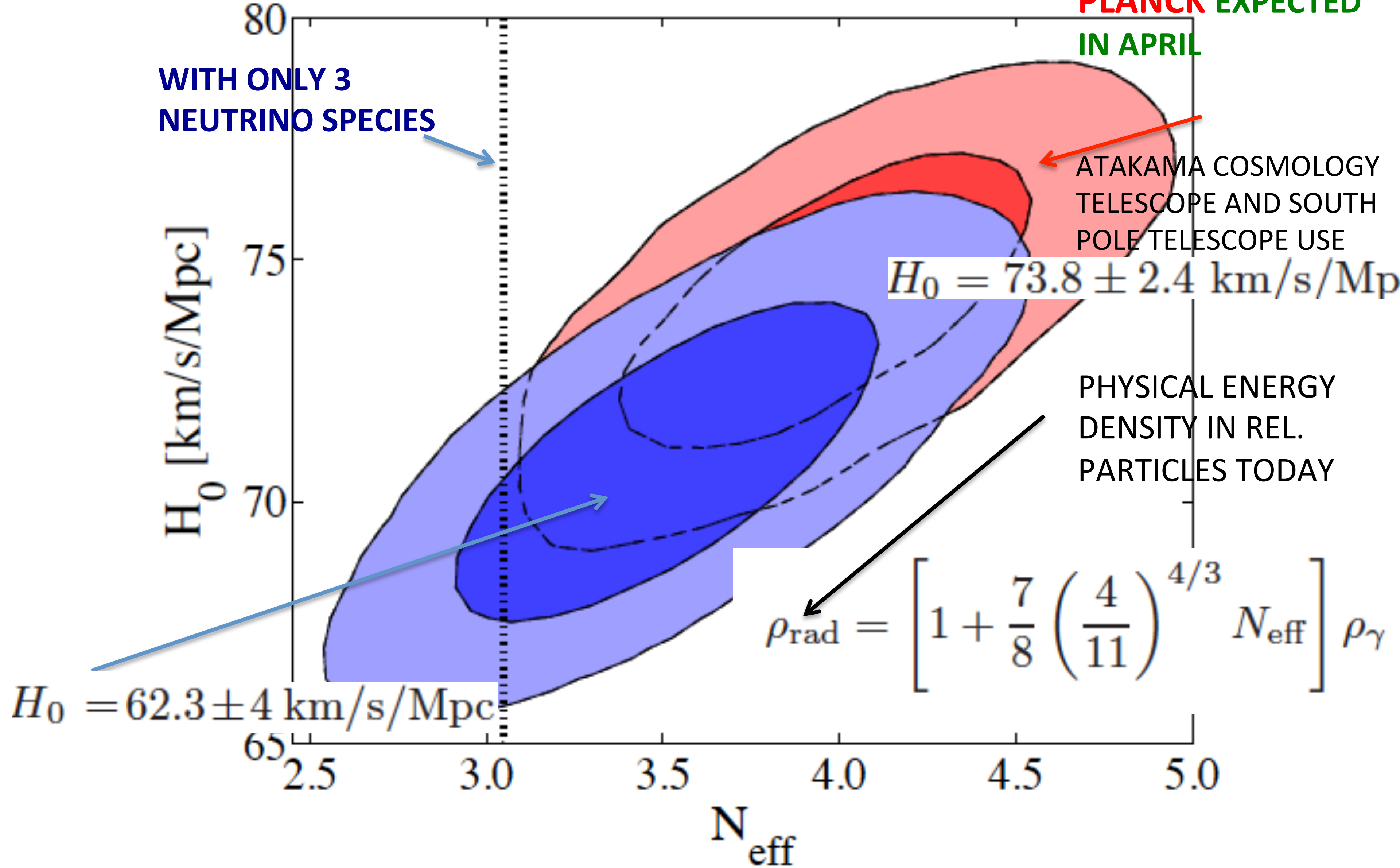
Dirac/Majorana ★★★★ ★

ACCORDING TO MY PERSONAL TASTE

HINTS FROM COSMOLOGY IN FAVOR OF > 3 ν SPECIES?

“DARK RADIATION”

NEW RELEVANT DATA FROM PLANCK EXPECTED IN APRIL



CALABRESE, ARCHIDIACONA, MELCHIORRI, RATRA 2012

Limit on the SUM of the ν masses from COSMOLOGY

- WMAP 7yr
- SDSS III 8th data release
- Hubble space telescope H

R. De Putter et al, arXiv: 1201.1909 [astro-ph.CO]

$\Sigma m < 0.26$ eV (95 % CL)

Conservative bias

$\Sigma m < 0.36$ eV (95 % CL)

Bounds presented at ICHEP 2012

- WMAP 7yr
- Observable Hubble parameter data (OHD)
- H_0 (in correlation with σ_8)

M. Moresco, et al., arXiv:1201.6658 [astro-ph.CO]

$\Sigma m < 0.24$ eV (68 % CL)

Future: $\Sigma m < 0.08$ eV

Double beta decay: status

GIULIANI IFAE2012

In 1998, when neutrino flavour oscillations were discovered, the « old-generation » **Heidelberg-Moscow** experiment (^{76}Ge, Ge diodes) was leading in terms of sensitivity.

Today, it is still the most sensitive experiment in 0ν-DBD → **Difficult subject, slow progresses**

Klapdor's claim → $T^0_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25}$ y - $\langle M_{\beta\beta} \rangle = (0.30^{+0.02}_{-0.03})$ eV

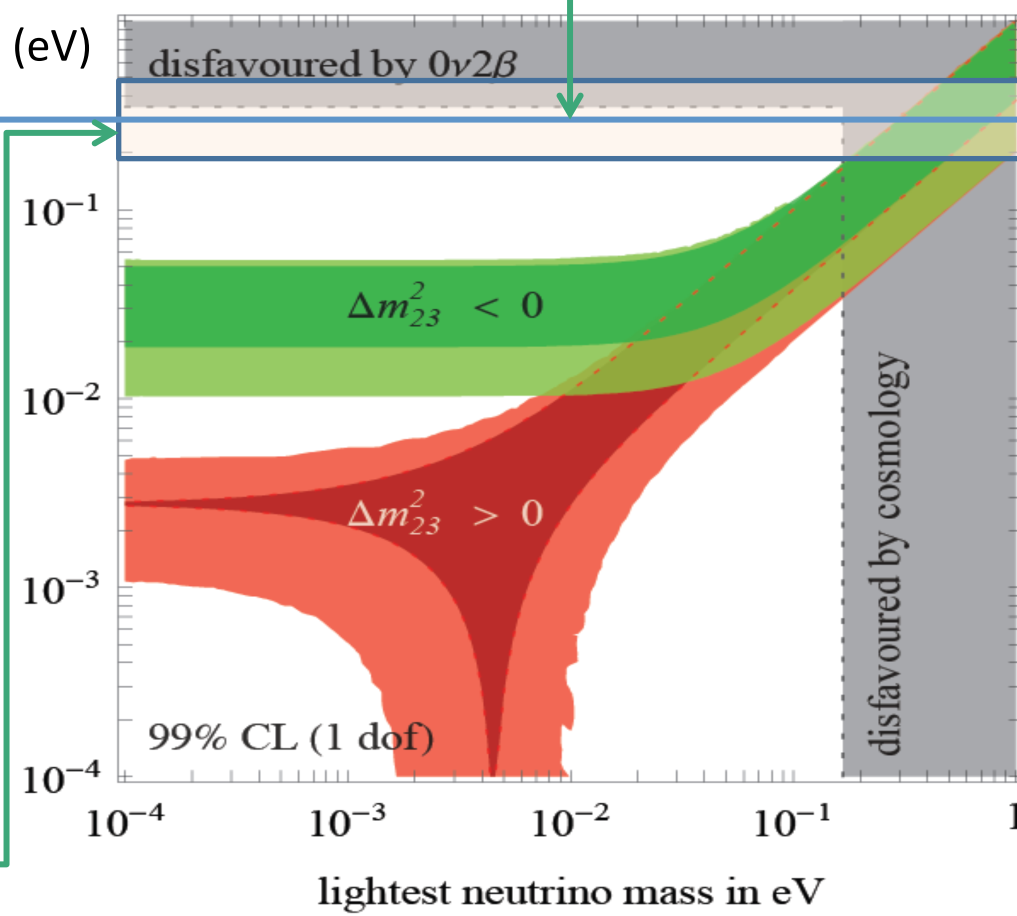
New searches, with different techniques, have similar sensitivities

« Medium Generation »
- **CUORICINO** bolometers
- **NEMO3** Tracking+calorimeter

« New Generation »
- **KamLAND-Zen** Large mass scintillator

Similar sensitivity

$\langle M_{\beta\beta} \rangle < 0.3 – 0.6$ eV



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 !**

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

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

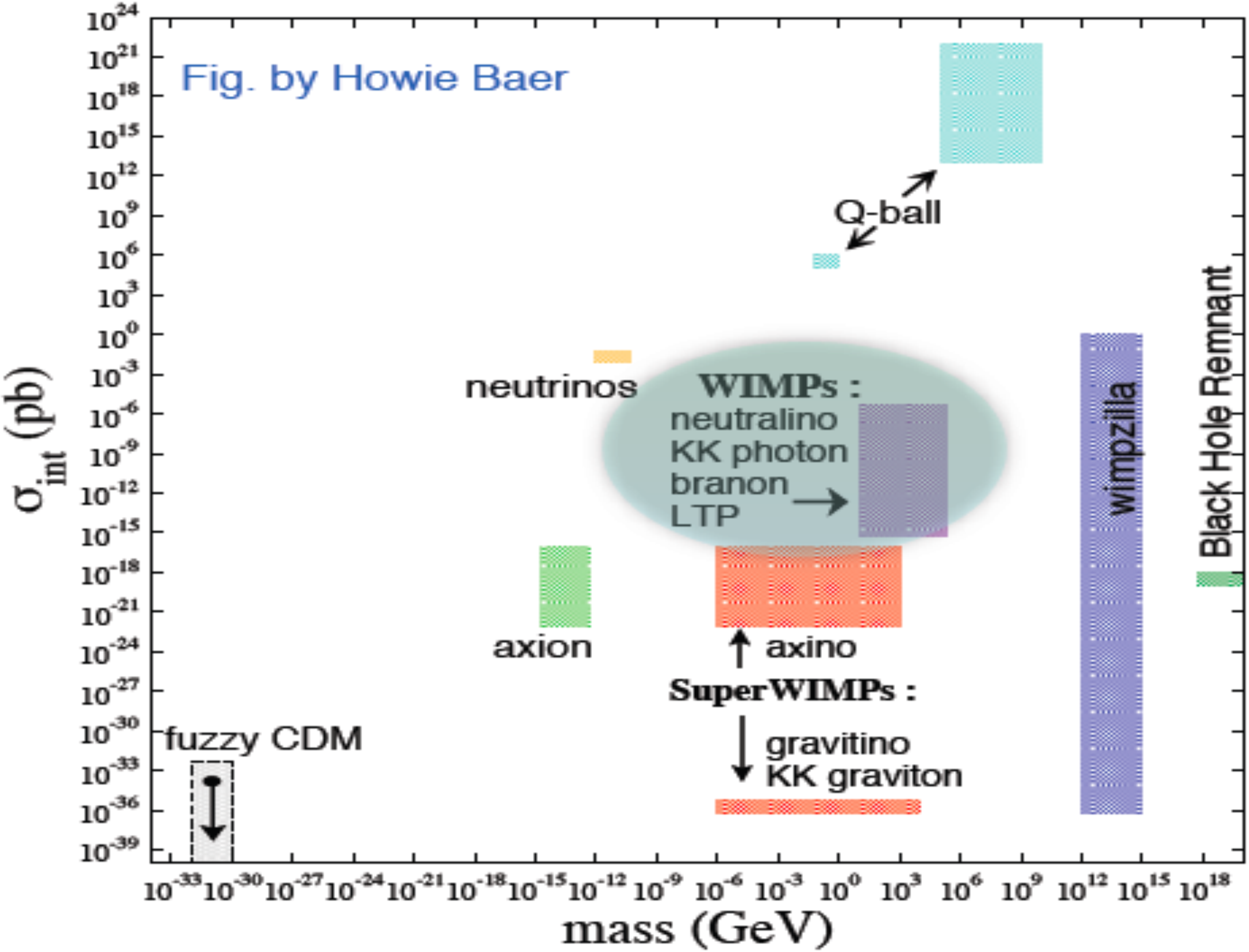


Fig. by Howie Baer
Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
σ_{int} (pb)
mass (GeV)

CONNECTION DM – ELW. SCALE

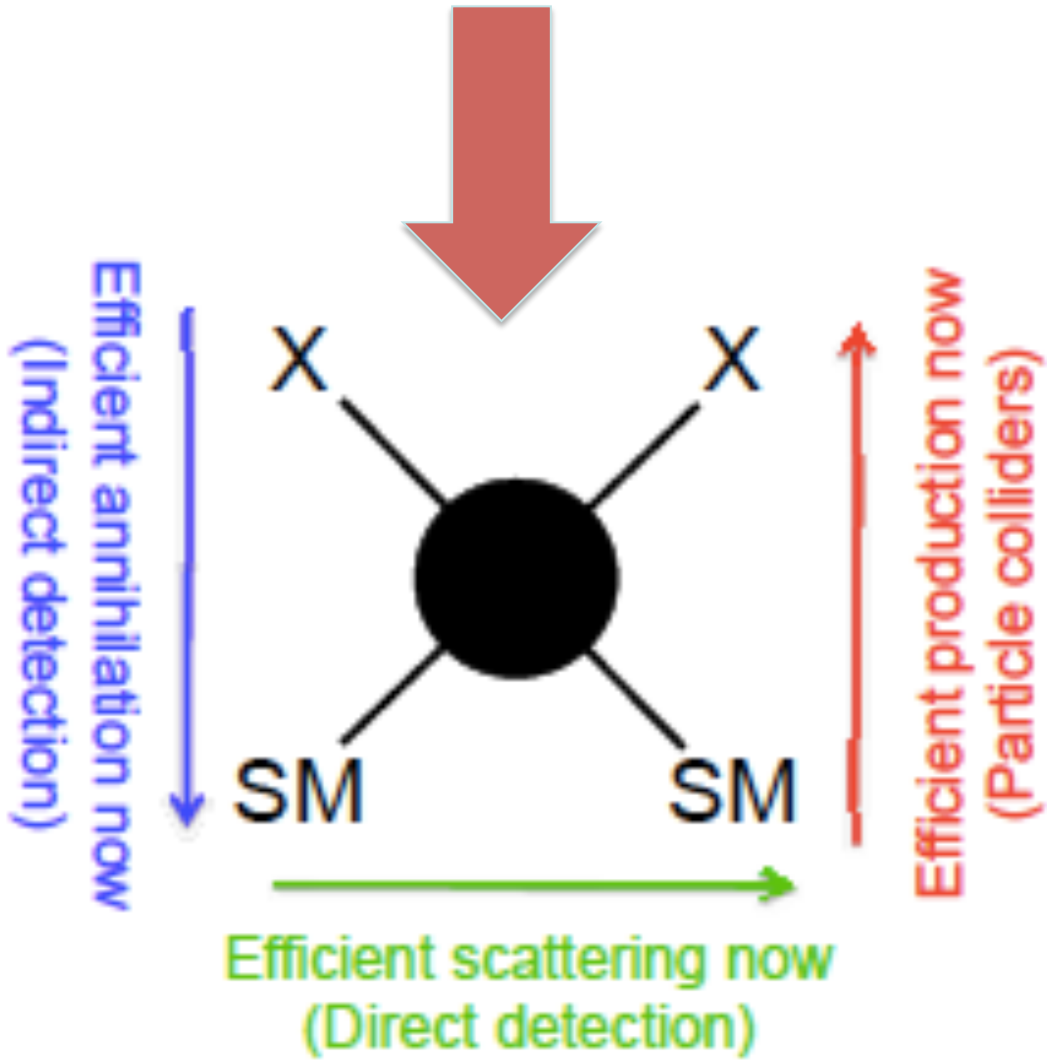
THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	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

DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today



Low-mass region:

either unexplained backgrounds in DAMA, CoGeNT, and CRESST-II, …

or

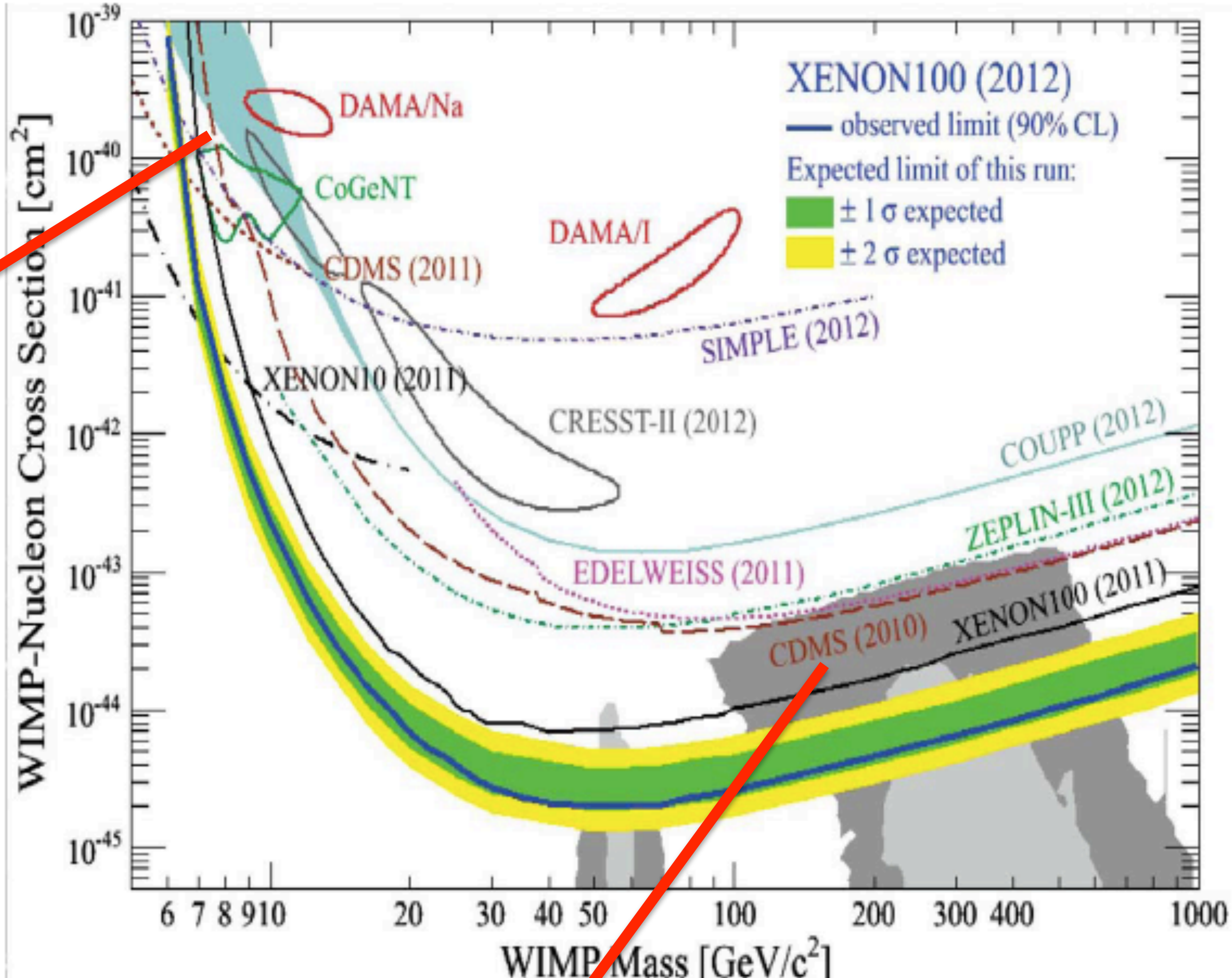
… other experiments do not understand low recoil energy calibration, …

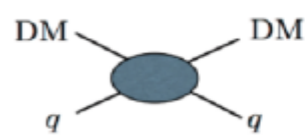
or

… can't compare different experiments

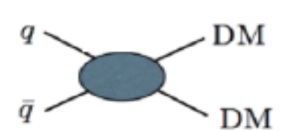
Kolb SUSY2012

Relevant to intensify the efforts here: ex. **asymmetric DM** with **DM particles of mass~ baryon mass given that ρ_{DM} not much different from ρ_B**



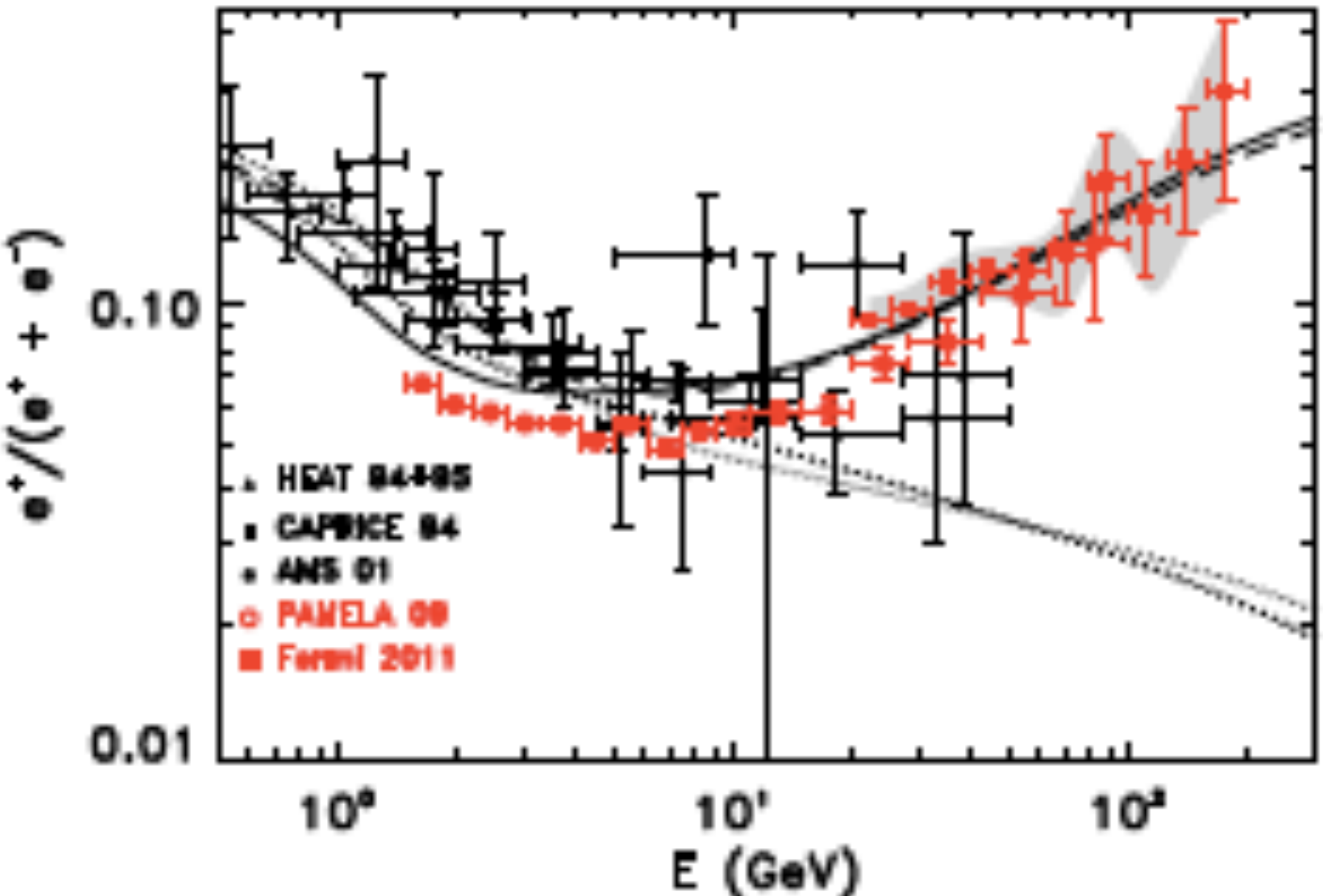


Direct Detection (t-channel)

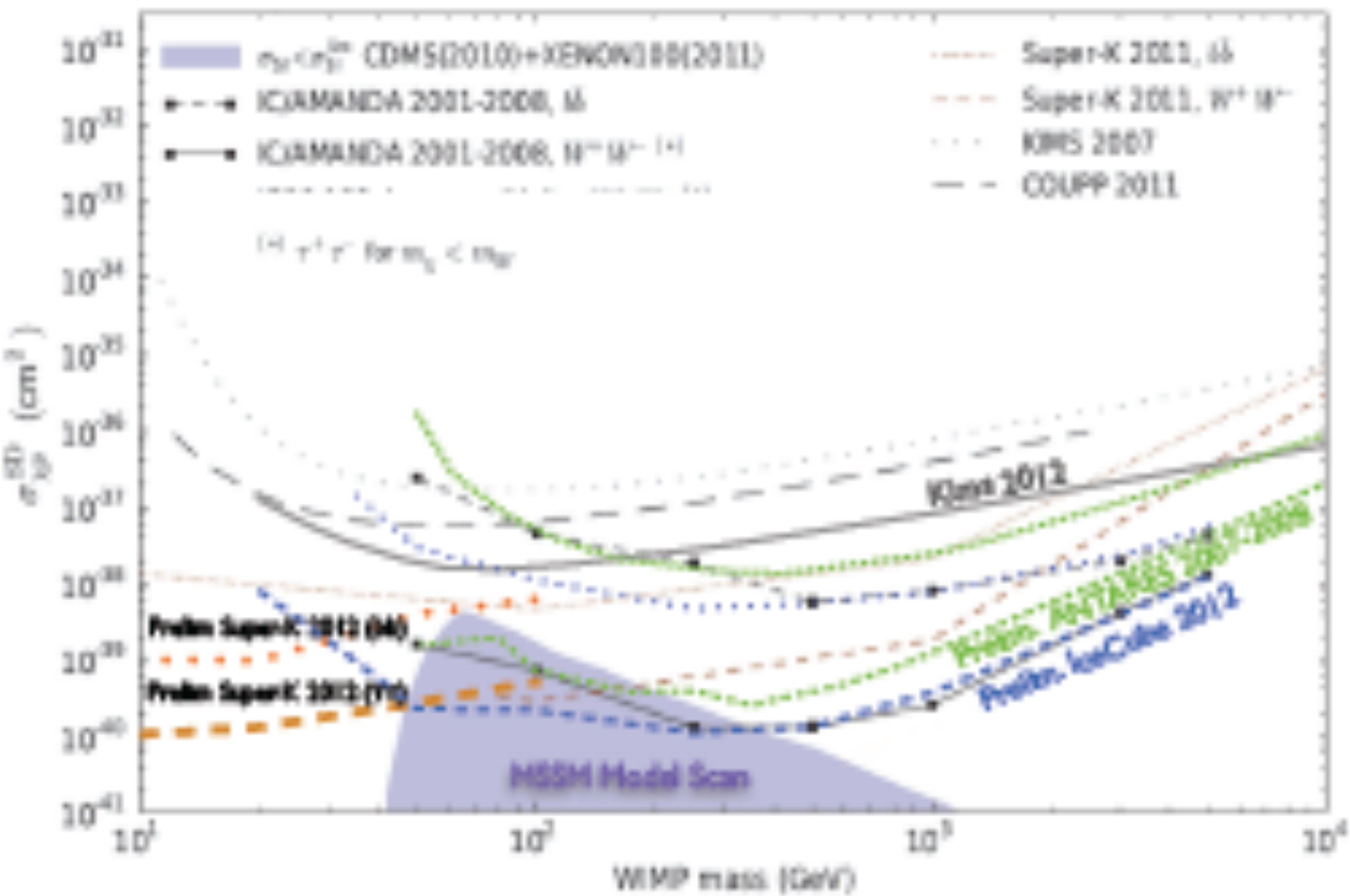


Collider Searches (s-channel)

POSITRON EXCESS: FERMI confirms and extends PAMELA results

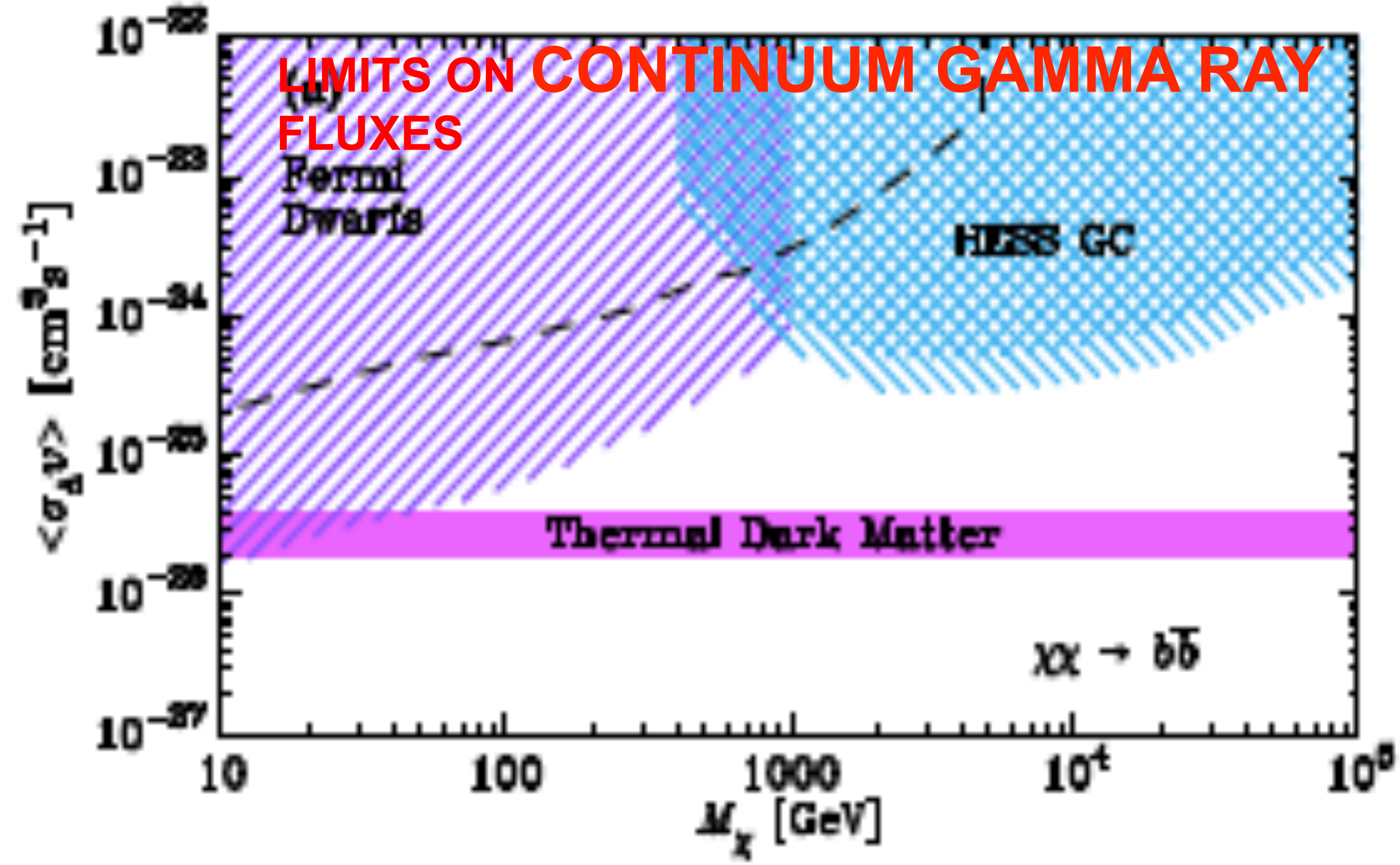


LIMITS ON THE **WIMP-PROTON SPIN-DEPENDENT SCATTERING CROSS SECTION** from searches for **WIMPs ANNIHILATING TO NEUTRINOS IN THE SUN**



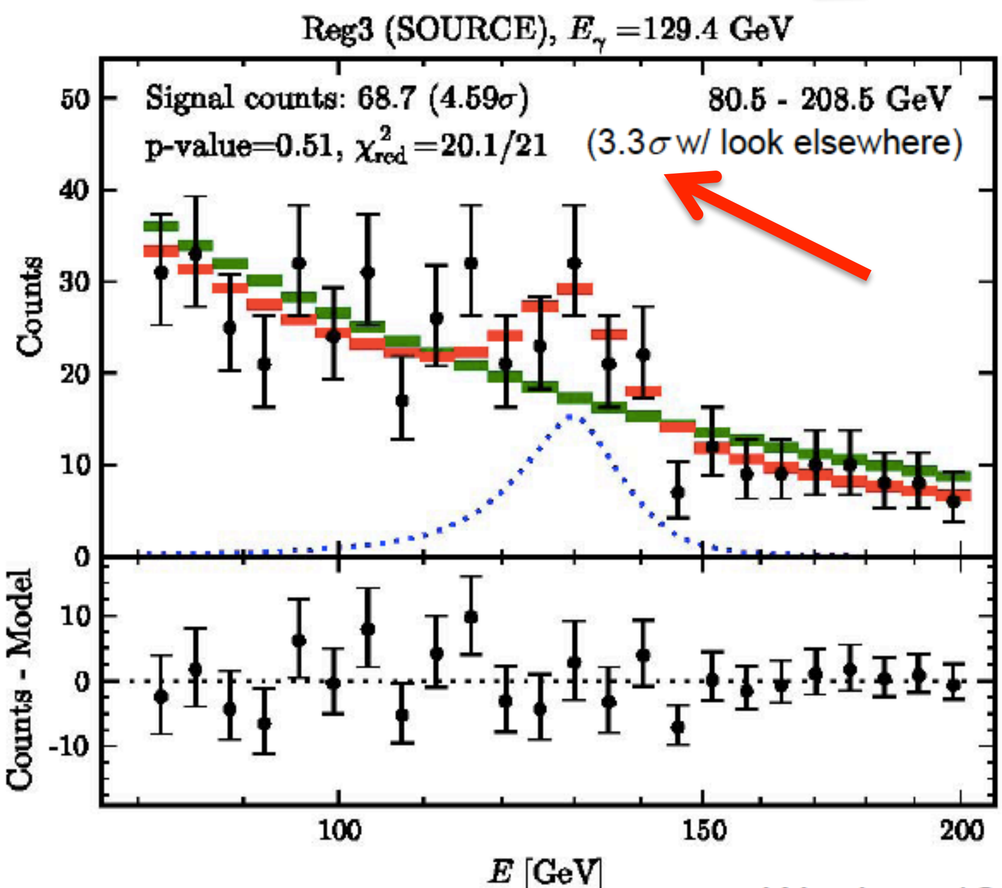
INDIRECT DETECTION IN GAMMA RAYS

LIMITS ON CONTINUUM GAMMA RAY FLUXES



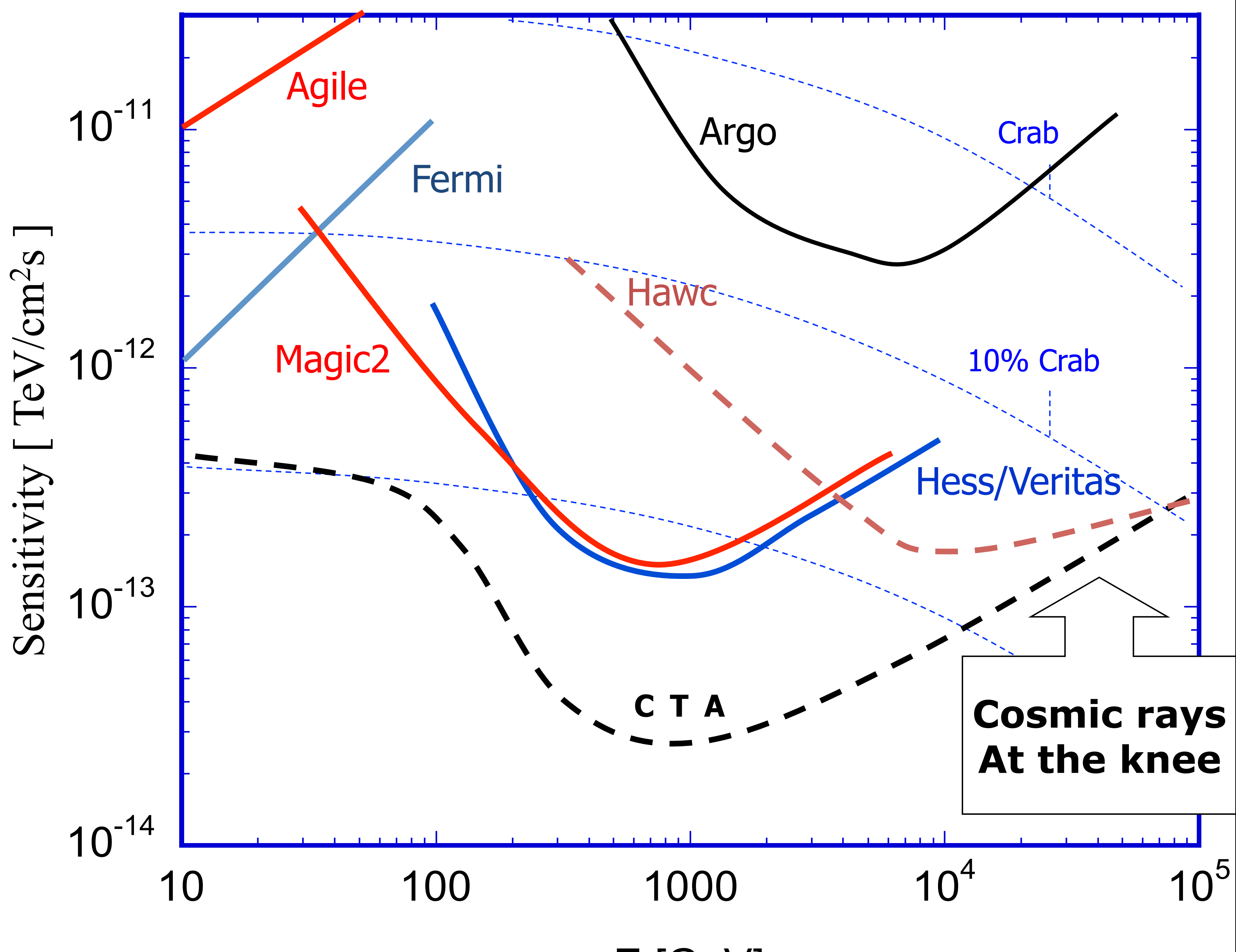
DM INDIRECT SEARCHES:
another surprise

Fermi/GLAST Line



After the PAMELA positron excess, this is **the source of excitement for the DM searchers through detection of gamma-lines emitted from DM annihilation** … but so many signals of this kind have come and gone away…

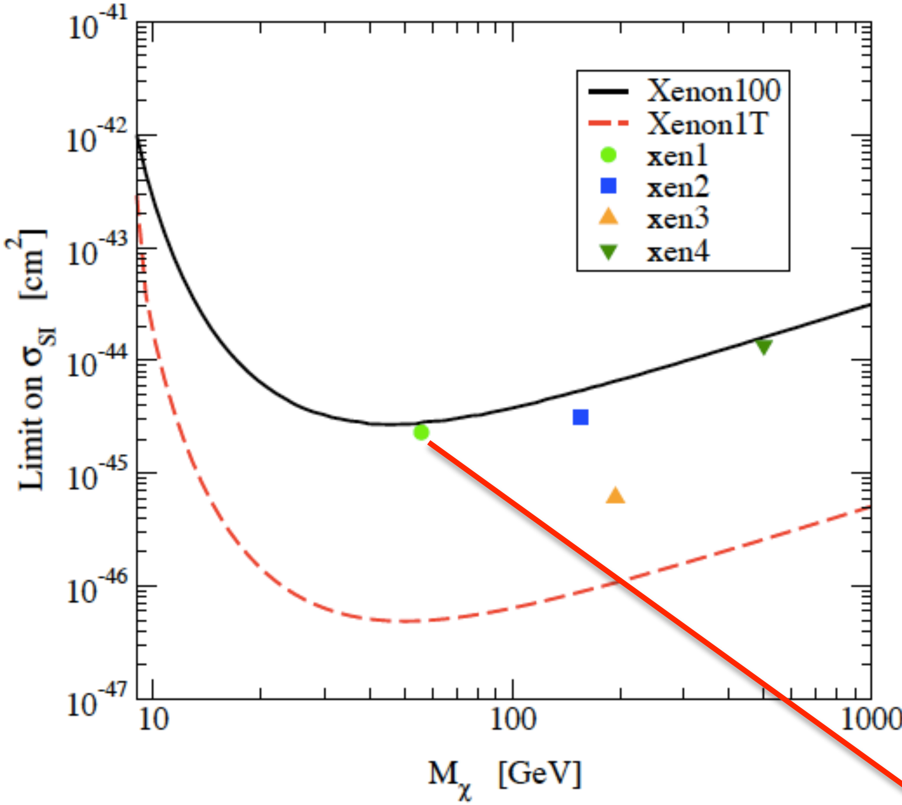
Weniger 1204.2797

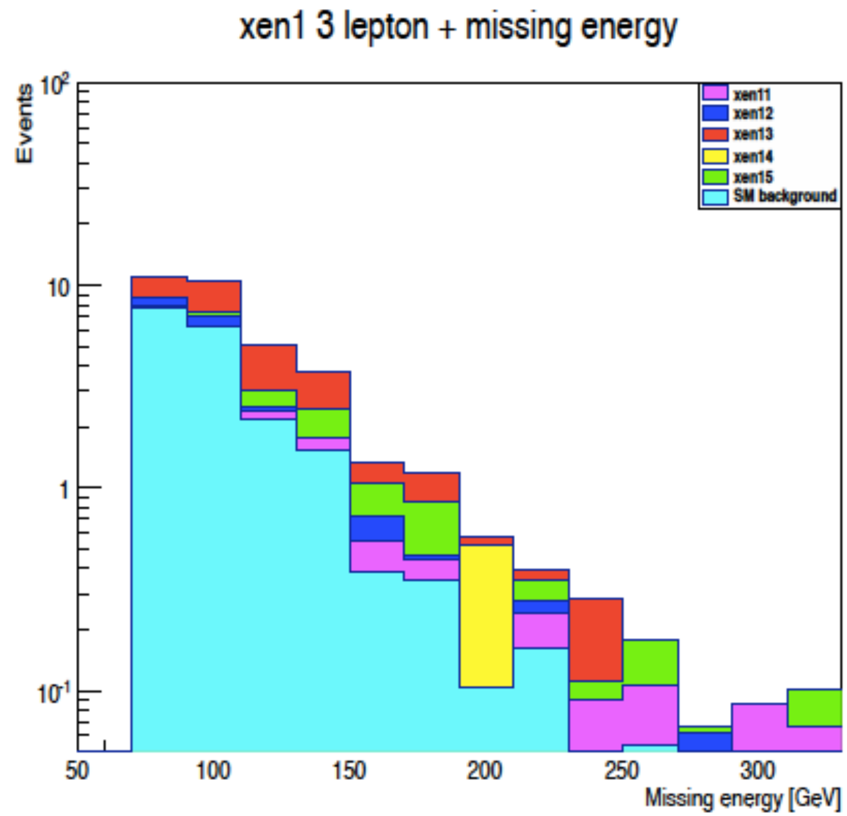


Alessandro De Angelis

INTERPLAY BETWEEN
DIRECT AND LHC DM SEARCHES

ARCADI, CATENA, ULLIO 1211.5159





MISSING ENERGY DISTRIBUTION FOR THE EVENTS INCLUDING 3 LEPTONS IN THE FINAL STATE FOR THE BENCHMARK POINT xen1 FOR A RUN OF LHC AT 7 TeV and a LUMINOSITY of 4.7 fb^{-1}

Some final considerations

- This is indeed **an exciting moment in all the three frontiers of High Energy, High Intensity and Astroparticle physics**
- The celebrated dilemma: is there **new physics to stabilize the ELW symmetry breaking scale** (i.e. TeV NP) or is there **the big desert**? Becomes more articulated:

i) TeV NP physics (testable - along the "real" path, i.e. observing its new particles, or at least some of them) ;

ii) **more and more unnatural NP related to the ELW breaking (more chances in a near future for the "virtual path");**

iii) **no need to stabilize the ELW scale, big desert or possibly some remnant at lower energies (tests of the validity of the SM up to very large scales, for instance its vacuum stability)?**