Cosmology and the LHC

New TeV scale physics ⇄ **Cosmological signatures**

mainly from
- dark matter
- baryogenesis

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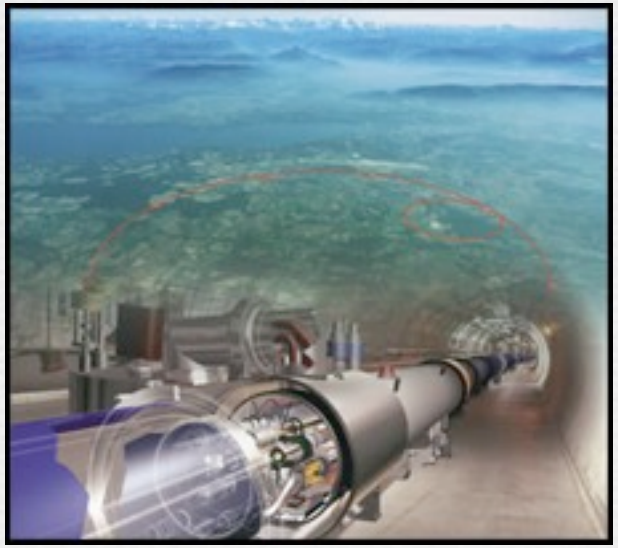
CERN-Th

2010: First collisions at the LHC

Direct exploration of the TeV scale has started

main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?



The Standard Model of Particle Physics

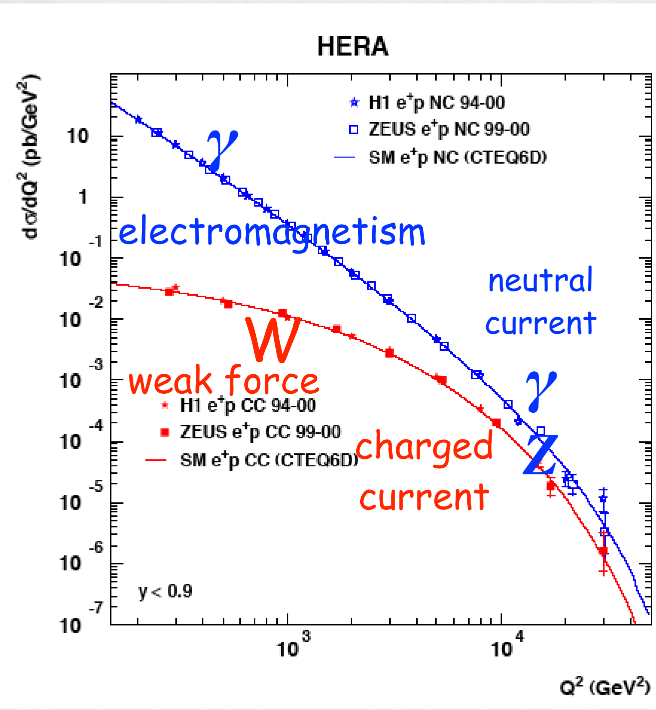
Forces | **Matter** | **Background**

$$\mathcal{L}_{\text{Standard Model}} = - F^{a}_{\mu\nu} F^{a\mu\nu} + (\lambda_{ij}\, \Psi_i \Psi_j\, h + h.c) + N_i M_{ij} N_j + |D_\mu\, h|^2 - V(h)$$

- $-F^{a}_{\mu\nu} F^{a\mu\nu}$ (Forces): gauge sector
- $(\lambda_{ij}\, \Psi_i \Psi_j\, h + h.c)$ (Matter): flavour sector
- $N_i M_{ij} N_j$ (Matter): neutrino mass sector (if Majorana)
- $|D_\mu\, h|^2 - V(h)$ (Background): (spontaneous) electroweak symmetry breaking sector

$SU(3)_C \times SU(2)_L \times U(1)_Y$

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

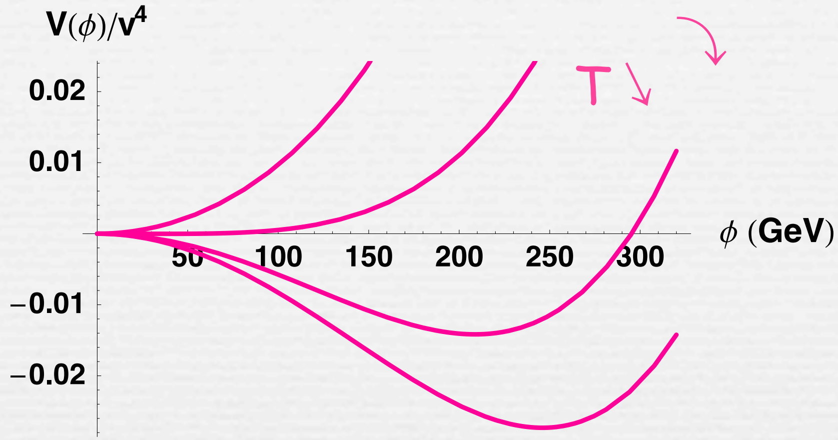


The Higgs is the only remaining unobserved piece

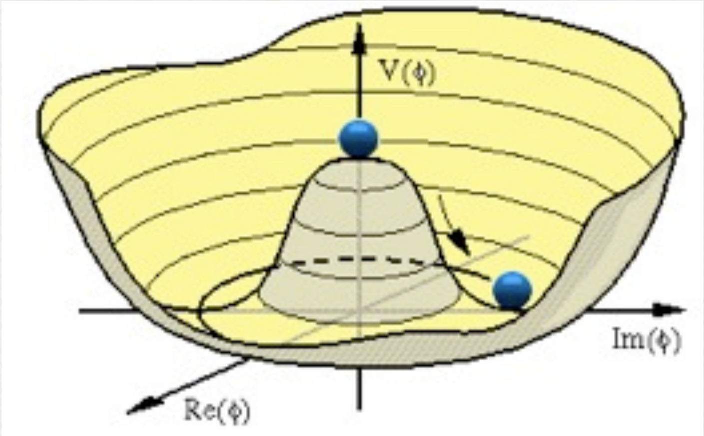
and a portal to new physics hidden sectors

The (adhoc) Higgs Mechanism

EW symmetry breaking is described by the condensation of a scalar field



The Higgs selects a vacuum state by developing a non zero background value. When it does so, it gives mass to SM particles it couples to.

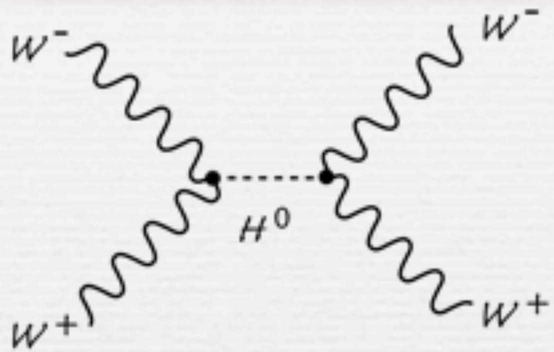


the puzzle:

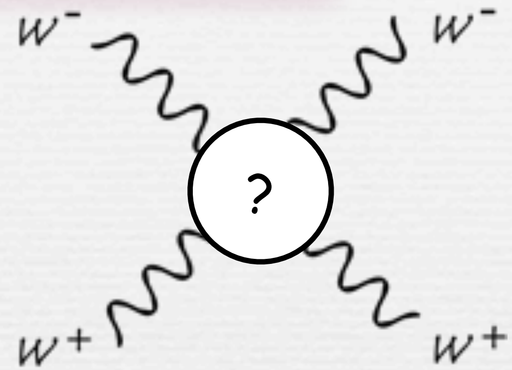
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

Electroweak symmetry breaking: 2 main questions

- What is unitarizing the $W_L W_L$ scattering amplitude?

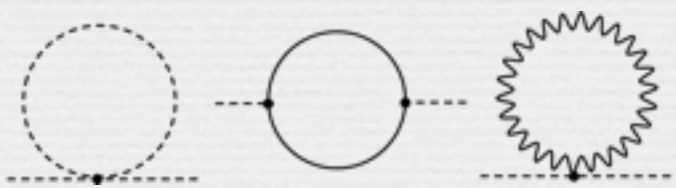


the Higgs or something else?



- What is cancelling the divergent diagrams?

(i.e what is keeping the Higgs light?)
: Hierarchy problem



$\Rightarrow \delta M_H^2 \propto \Lambda^2$

Λ , the maximum mass scale that the theory describes

strong sensitivity on UV unknown physics

need new degrees of freedom & new symmetries to cancel the divergences

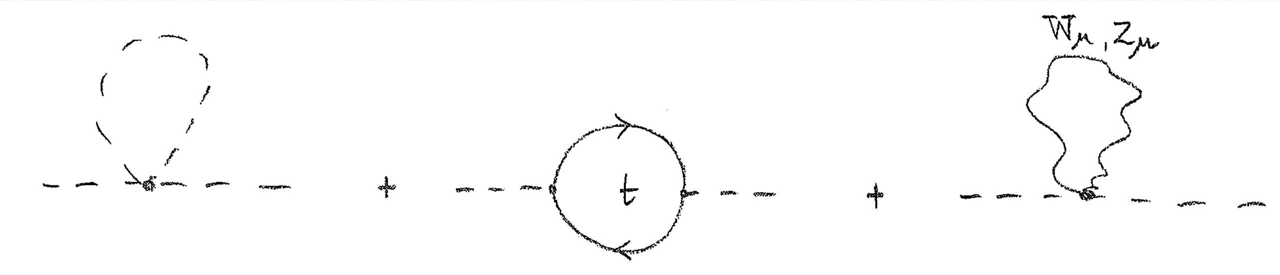
supersymmetry, gauge-Higgs unification, Higgs as a pseudo-goldstone boson...

→ theoretical need for new physics at the TeV scale

The naturalness scale of the Standard Model

Why is the Higgs boson light?

its mass parameter receives radiative corrections



$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \sim -(0.23\ \Lambda)^2$$

(assuming the same Λ for all terms)

Λ , the maximum mass scale that the theory describes

strong sensitivity on UV unknown physics

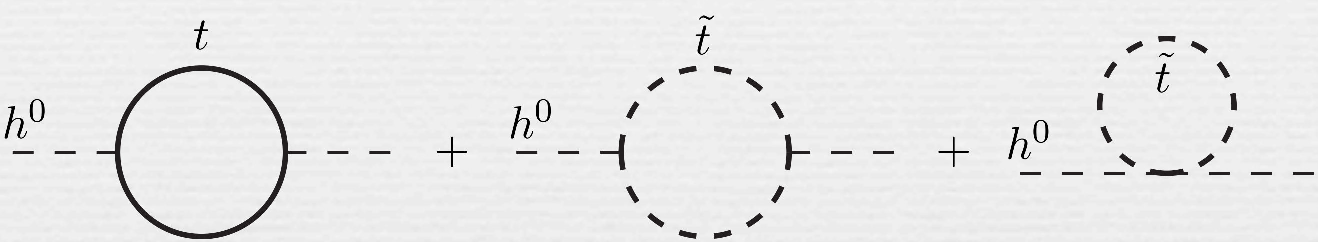
Λ=5 TeV -> cancellation between tree level and radiative contributions

required by already 2 orders of magnitude

The Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry can solve the “big” hierarchy and naturalness is preserved up to very high scales if superparticle masses are at the weak scale

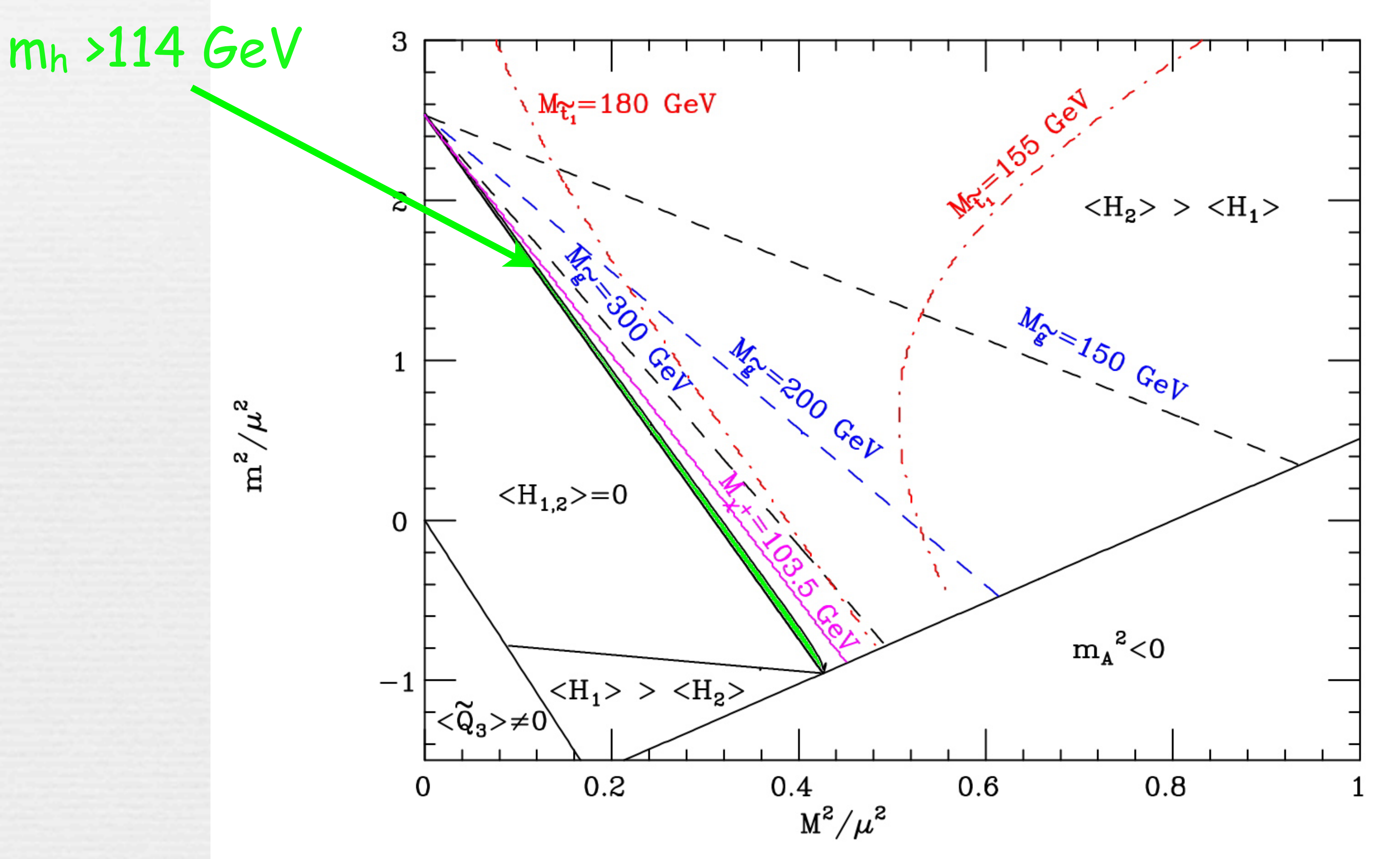
$\Delta(m_{h^0}^2) =$



$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$$

The naturalness problem of the MSSM

The problem with the MSSM: we did not see the Higgs at LEP

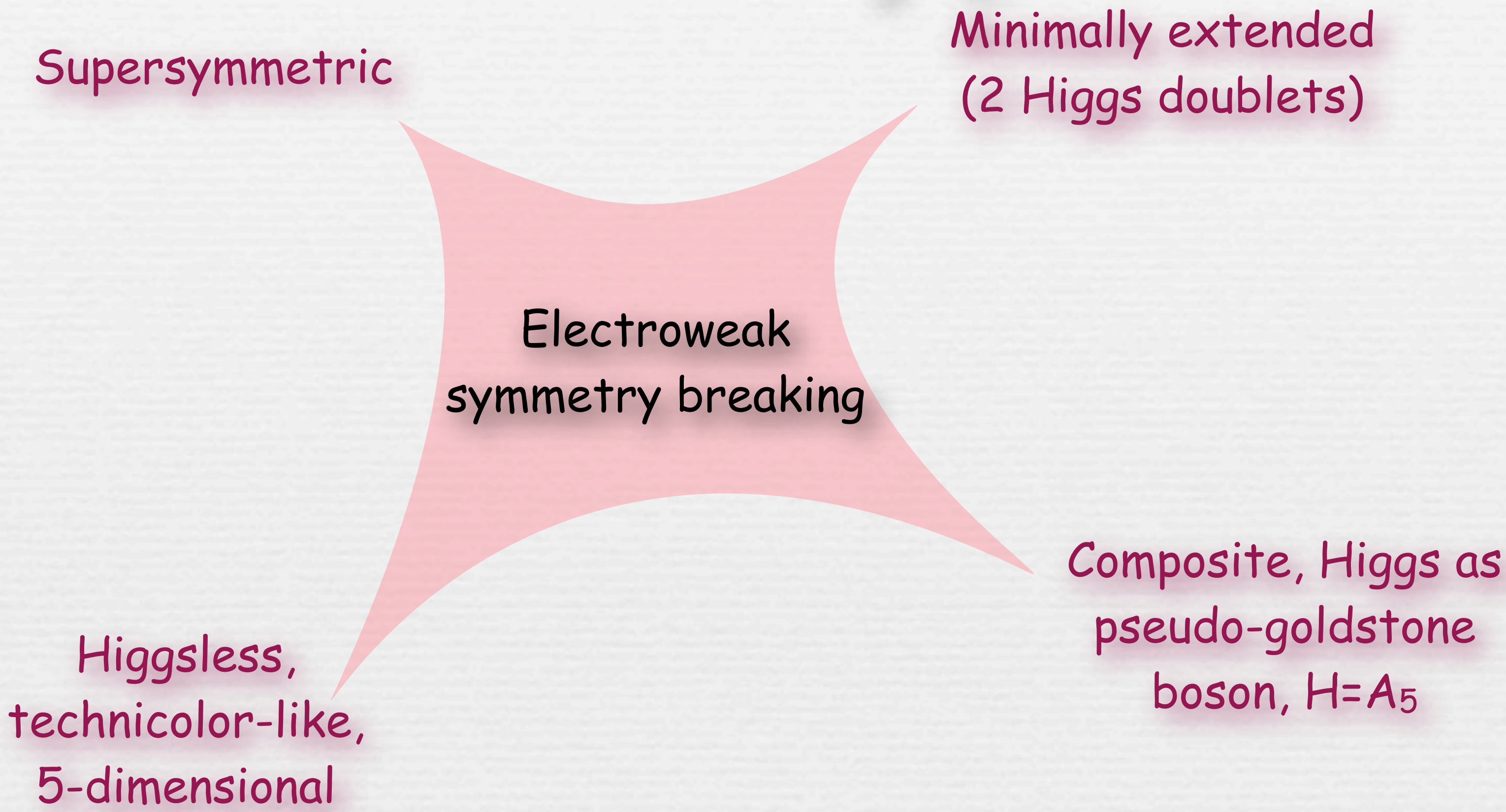


status of msugra pre-LHC [Giudice & Rattazzi, '06]

Addressing the hierarchy problem with a new symmetry

fermion	vector	scalar
$\Psi \to e^{i\theta\gamma_5}\ \Psi$	$A_\mu \to A_\mu + \partial\theta$	$H \to H + \theta$
Ψ massless:	A_μ massless:	H massless:
protected by chiral symmetry	protected by gauge invariance	protected by a global symmetry
$\Psi \overset{\text{SUSY}}{\longleftrightarrow} H$	In 5 dimensions: $H=A_5$	

Which new physics?



In all explicit examples, without unwarranted cancellations, new phenomena are required at a scale $\Lambda \sim [3\text{-}5] \times M_{Higgs}$

Beyond the weakly coupled elementary supersymmetric Higgs boson paradigm:

The strongly coupled "Higgs": Composite Higgs or Higgsless (e.g. technicolor)

Assumption: there is a new strongly interacting sector at the Tev scale responsible for EW symmetry breaking.

if replica of QCD at the TeV scale, Higgs= $\langle Q'\bar{Q}'\rangle$ condensate

-> no light scalar playing the role of the higgs: Higgsless

->main objection: conflict with e lectroweak precision tests

-> a solution: a composite light higgs arising as a pseudo-goldstone boson

The Higgs as a kind of pion from a new strong sector?

Quantum numbers of the Goldstones fixed by the symmetry breaking pattern in the strong sector:

$G \to H$

Higgs scalars as pseudo-Nambu-Goldstone bosons of new dynamics above the weak scale

New strong sector endowed with a global symmetry G spontaneously broken to H
→ delivers a set of Nambu Goldstone bosons

global symm. on u,d

strong int.

QCD: $SU(2)_L \times SU(2)_R \xrightarrow{SU(3)_c} SU(2)_V \supset U(1)_Q$

6 - 3 = 3 PNGB $\pi^{\pm}, \pi_0$

global symm. on techniquarks

Composite Higgs: $SO(6) \times U(1)_x \xrightarrow{SU(N_c)} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

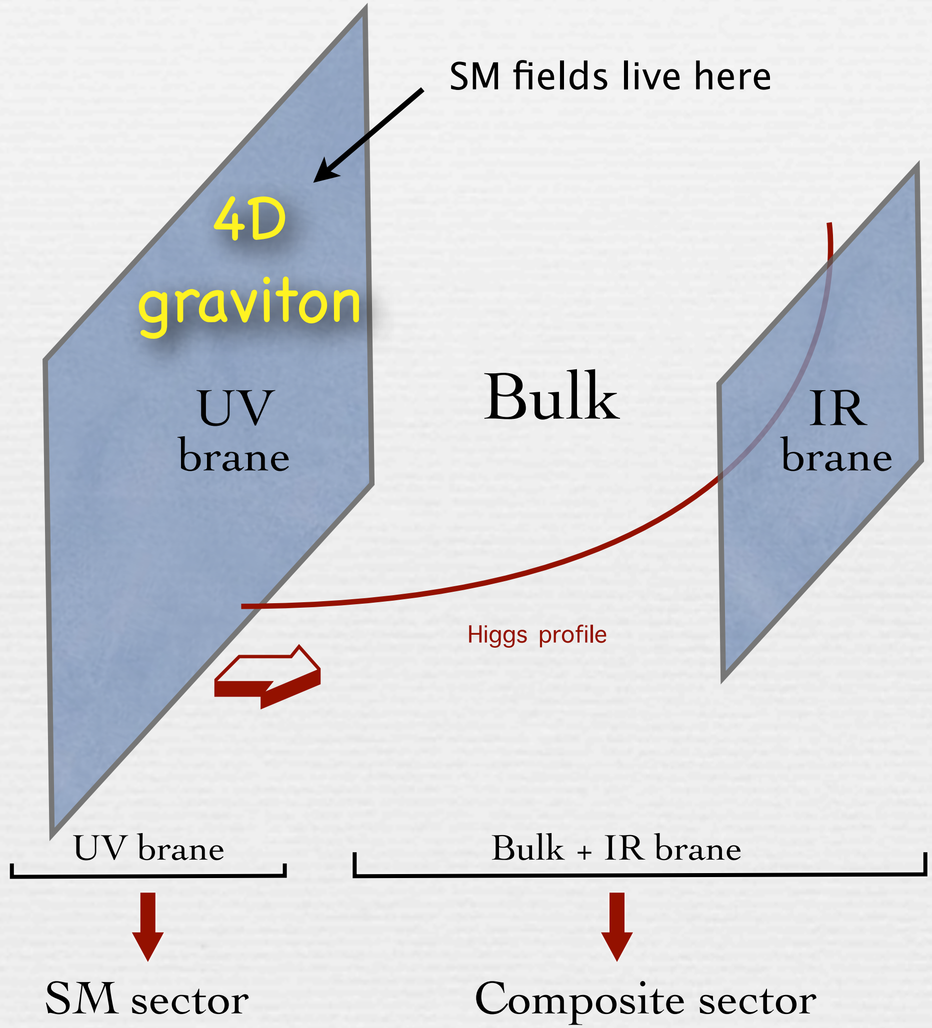
16 - 11 = 5 PNGB H, S

SO(5)/SO(4) -> SM Higgs
SO(6)/SO(5) -> SM + Singlet
SO(6)/SO(4) -> 2 Higgs Doublet Model

associated LHC tests

Extra-Dimensional point of view: Warped Geometry

Space-time is a slice of AdS_5



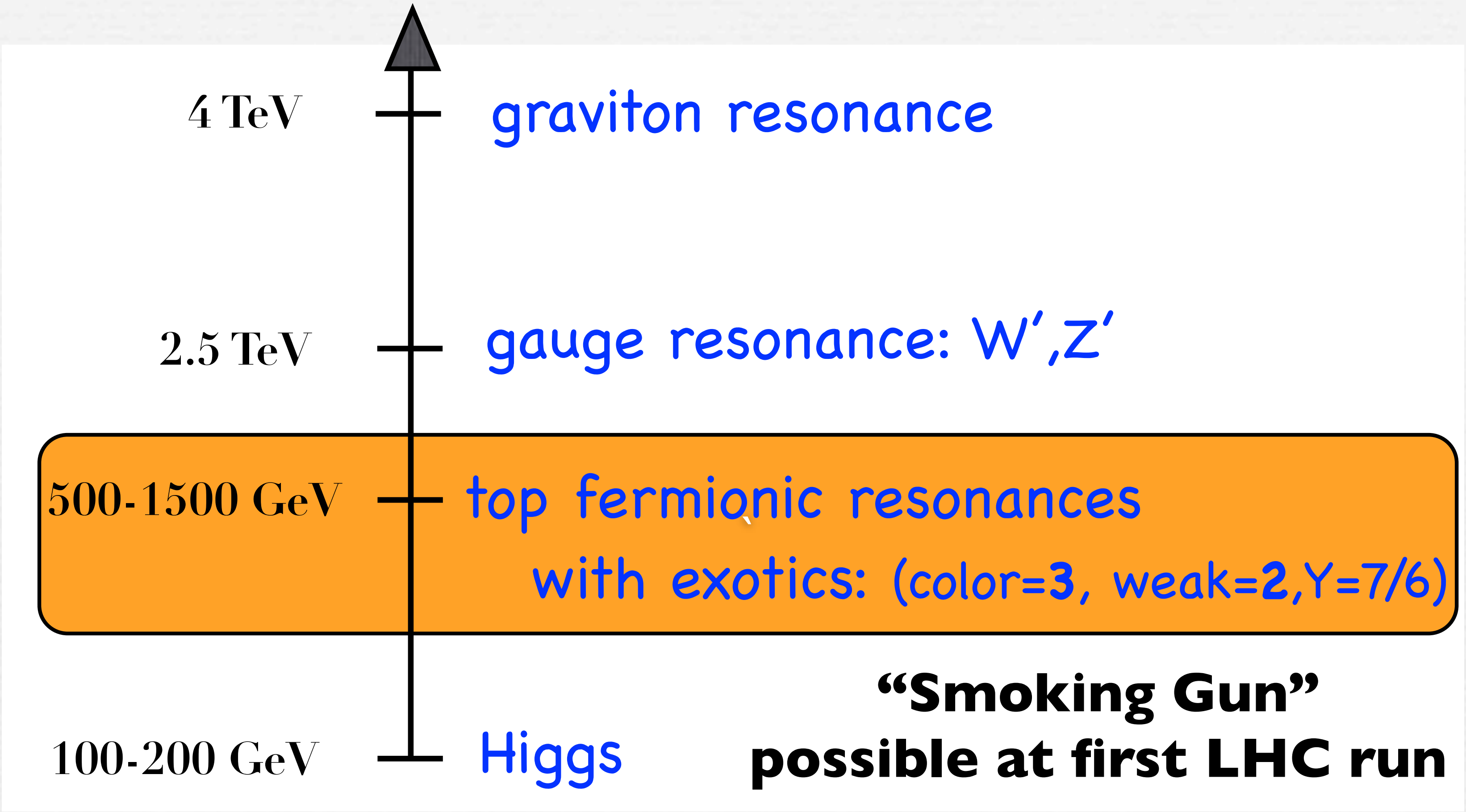
An almost CFT that becomes strongly interacting at the TeV scale & spontaneously breaks the conformal invariance

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

- Like in QCD, spectrum of resonances (Kaluza-Klein states)



- Most natural DM candidate: The lightest Technibaryon can be stable by TechniBaryon Number conservation (as baryons in QCD).

The Hierarchy Problem has been the guideline of theorists for over 30 years

The main goal of the LHC:

Understand why $M_{EW} \ll M_{Planck}$

We are at a turning point. Within the next few years, we will know what is lying behind the EW scale.

Imagine what our universe would look like if electroweak symmetry was not broken

- quarks and leptons would be massless

- mass of proton and neutron (the strong force confines quarks into hadrons) would be a little changed

- proton becomes heavier than neutron (due to its electrostatic self energy) ! no more stable

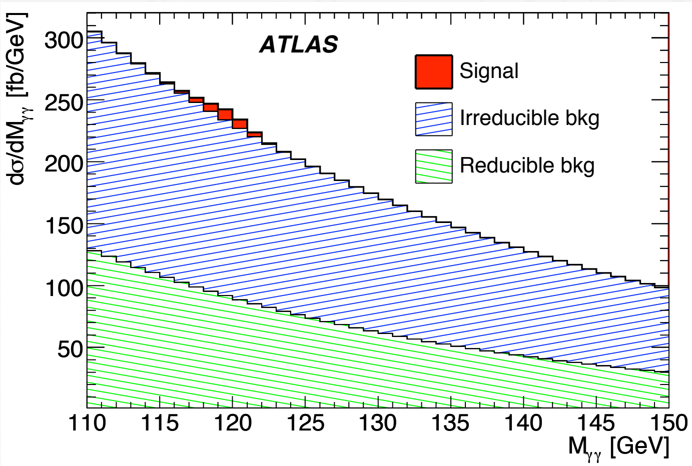
-> no hydrogen atom

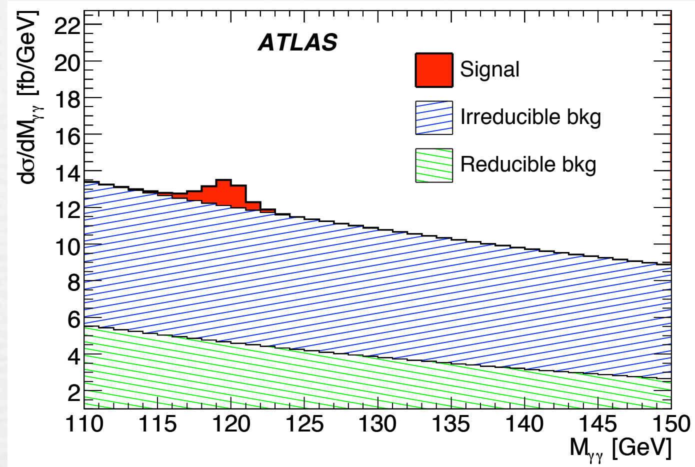
-> very different primordial nucleosynthesis

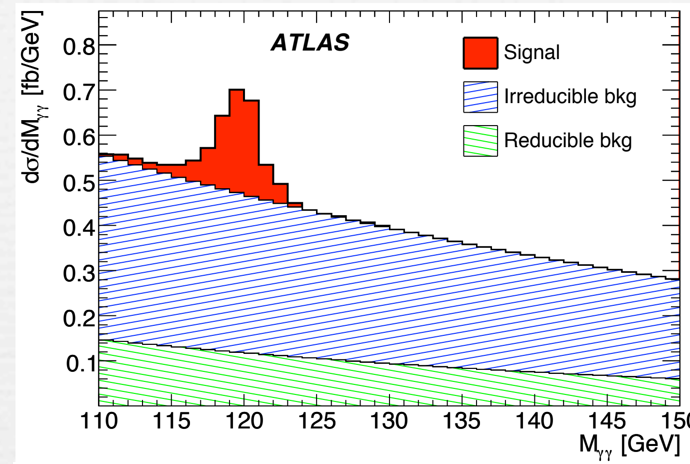
-> a profoundly different (and terribly boring) universe

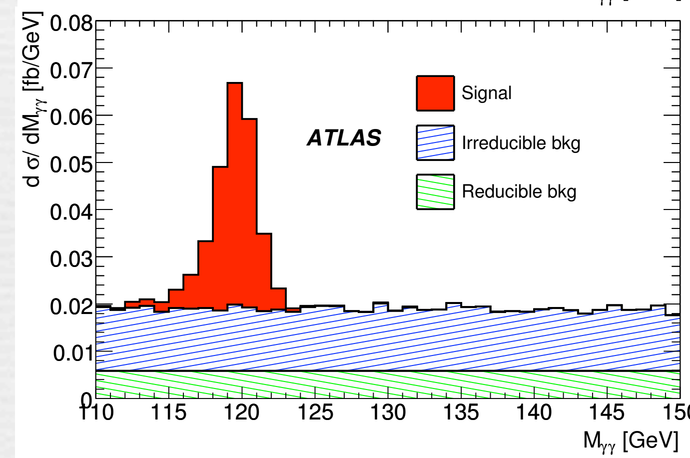
What questions the LHC experiments try to answer :

● Does a Higgs boson exist ?









If yes :

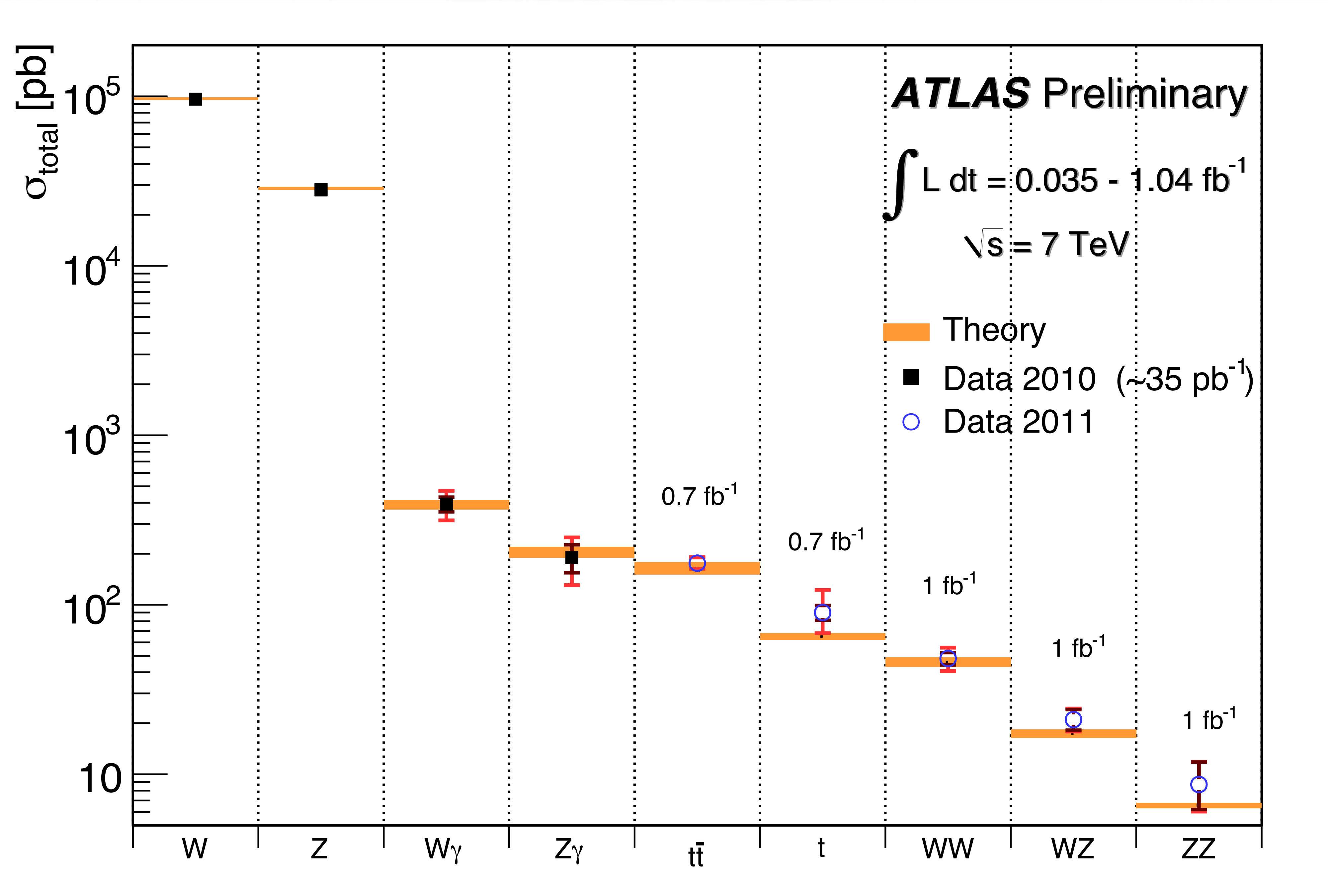
- is there only one ?
- what are its mass, width, quantum numbers ?
- what are its couplings to itself and other particles
- Spin determination
- CP properties
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed ?

If not, be ready for

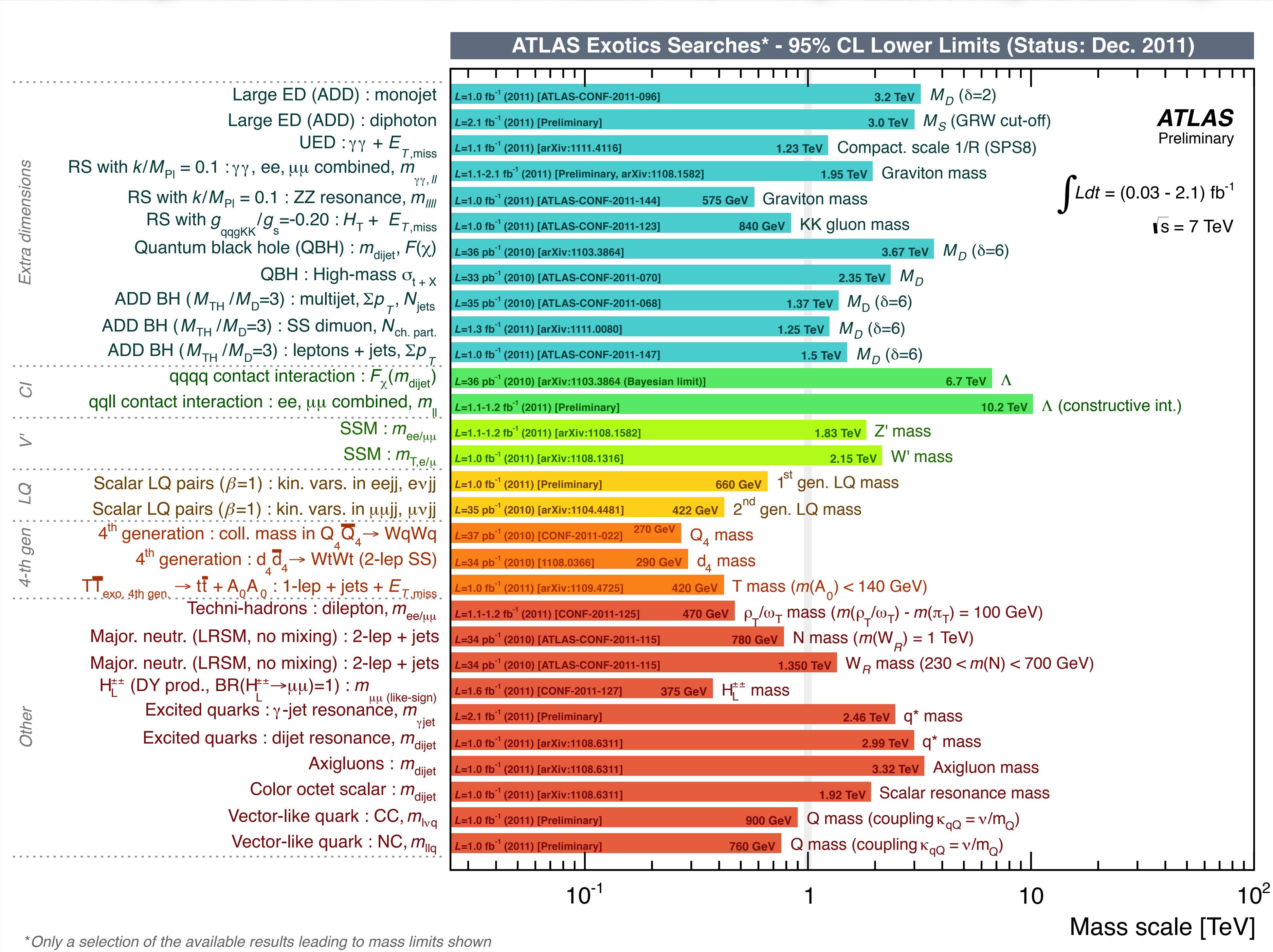
- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as W', Z' (KK) resonances, technicolor, etc...

● Searches for other new particles: Do they play any role in EW symmetry breaking?

So far, everything amazingly consistent with the Standard Model

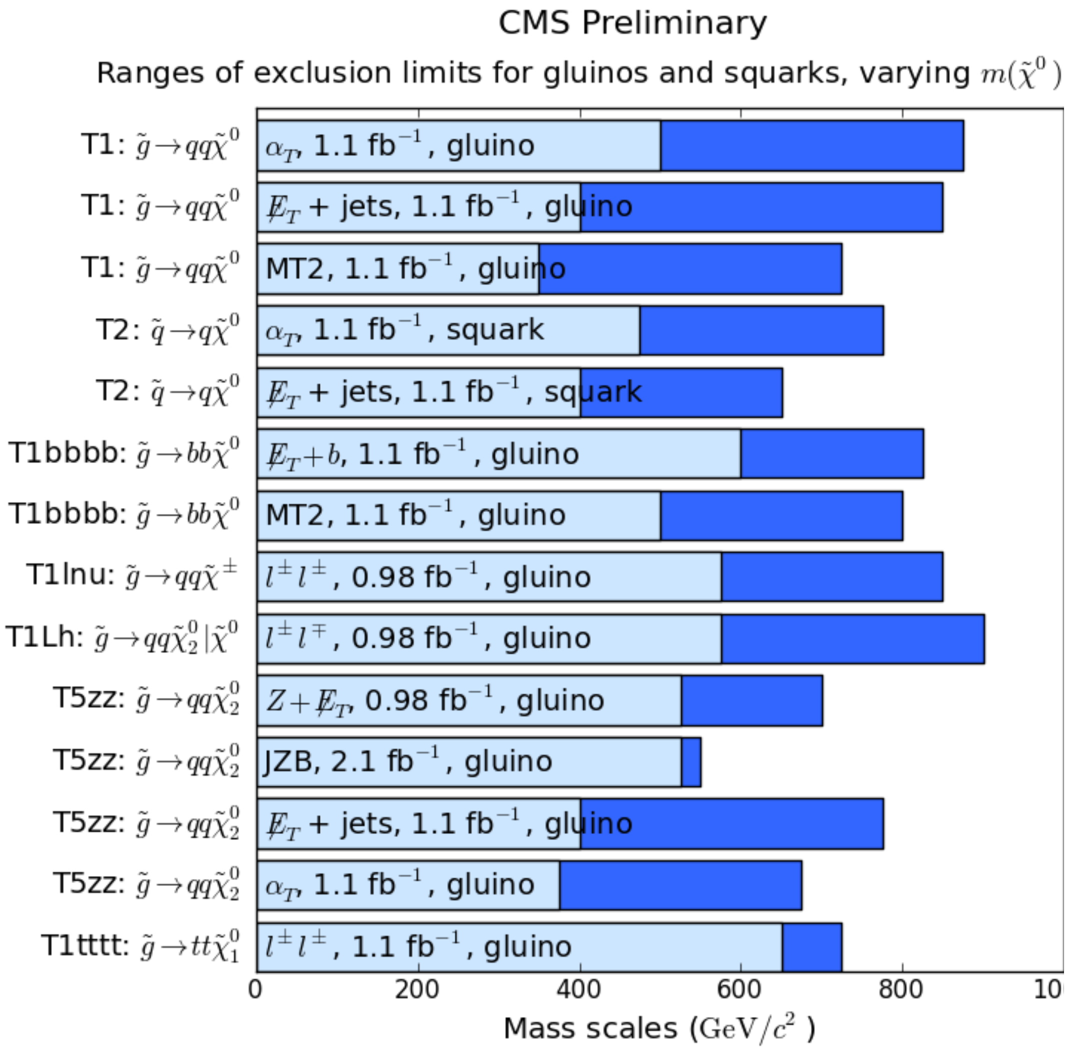


Exploration of the TeV scale territory definitely underway

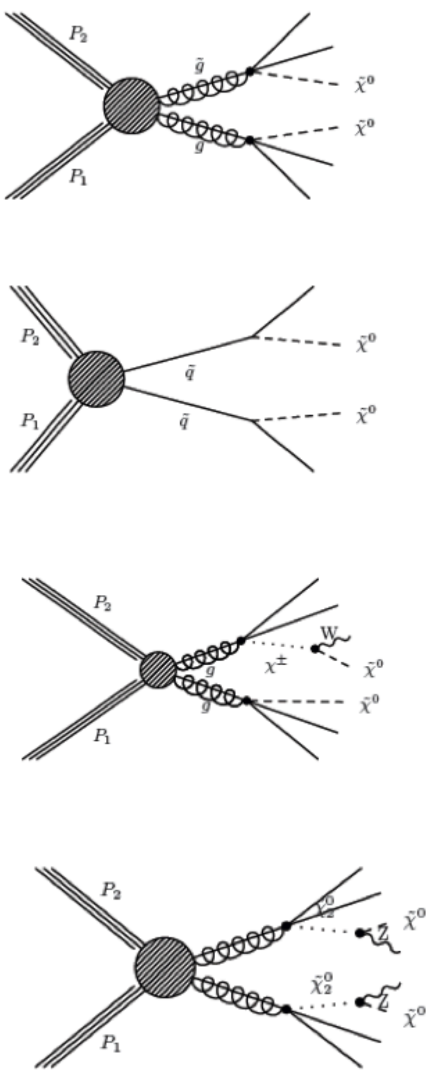


Searches for SUSY at CMS

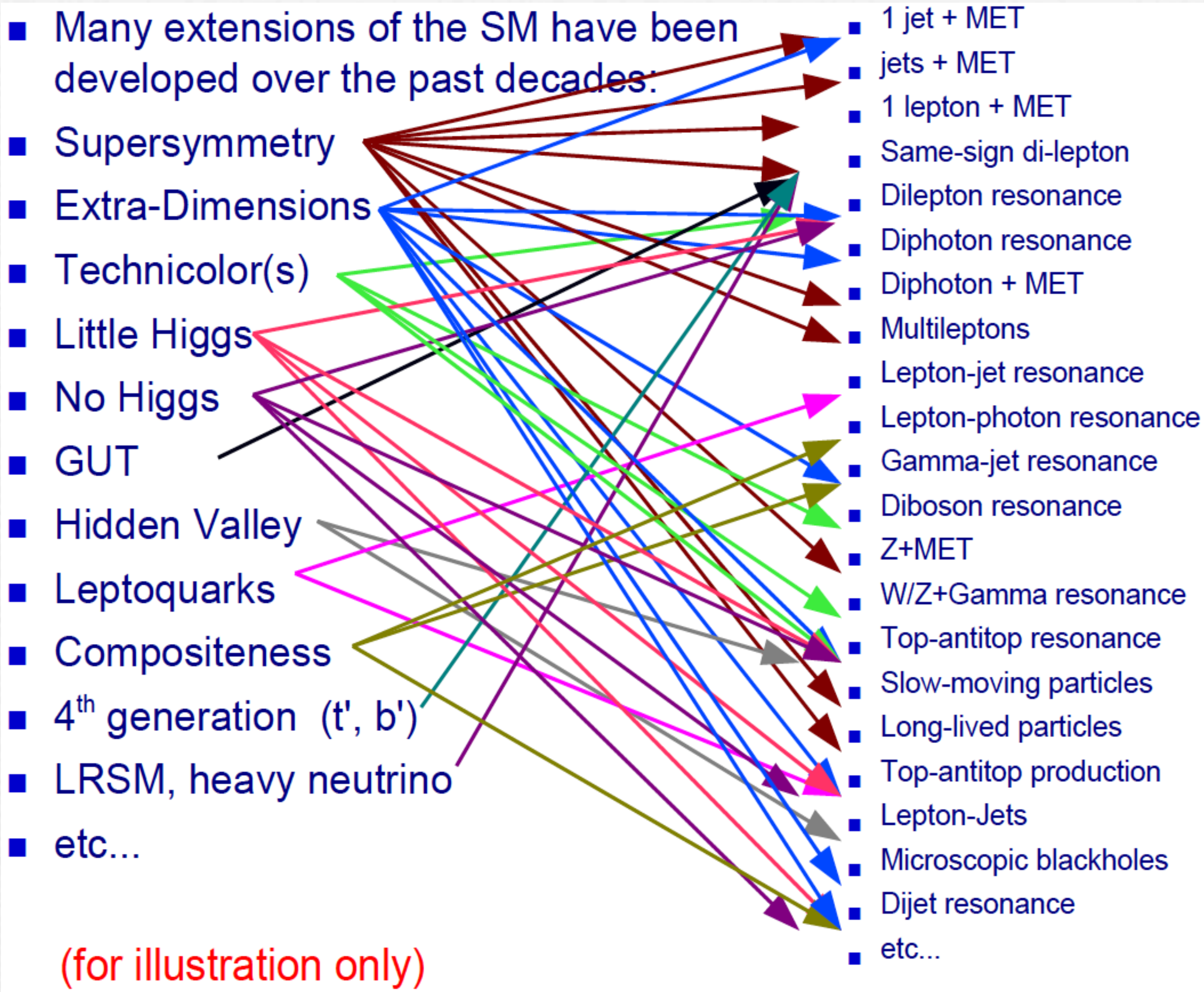
1 fb^{-1} summary



For limits on $m(\tilde{g}), m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\text{prod}} = \sigma^{\text{NLO-QCD}}$.
$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g}) - 200$ GeV/c^2 (light blue).

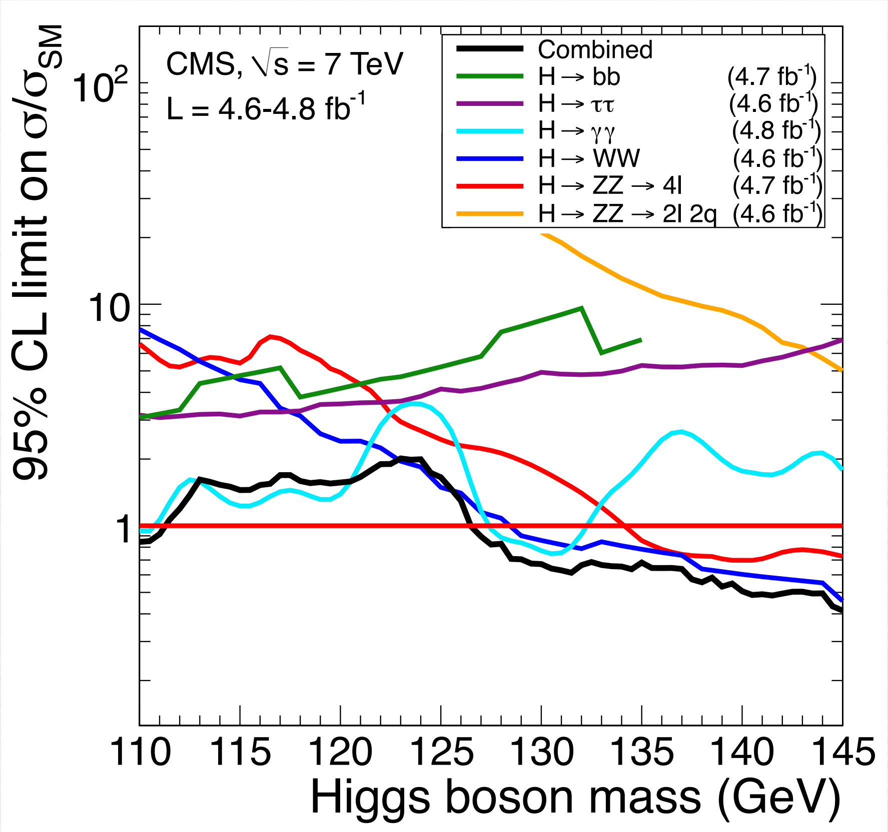


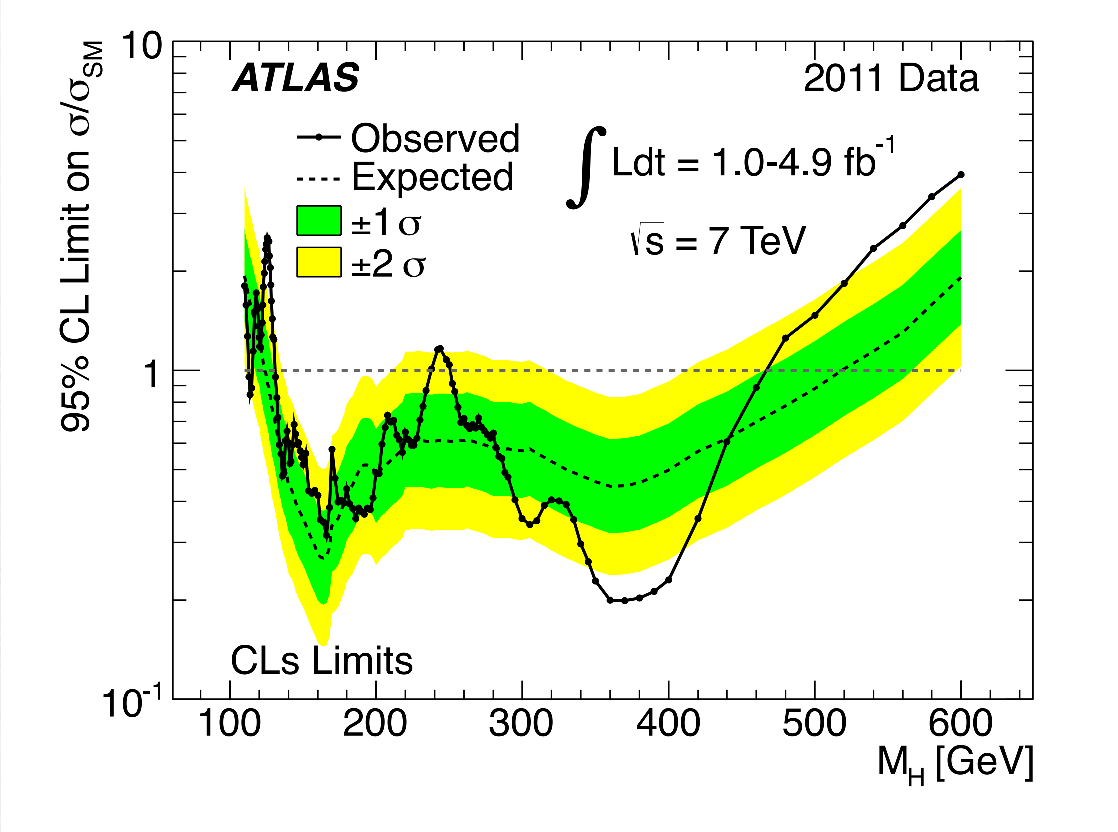
not yet any sign of new physics, despite extensive effort



Higgs hunting

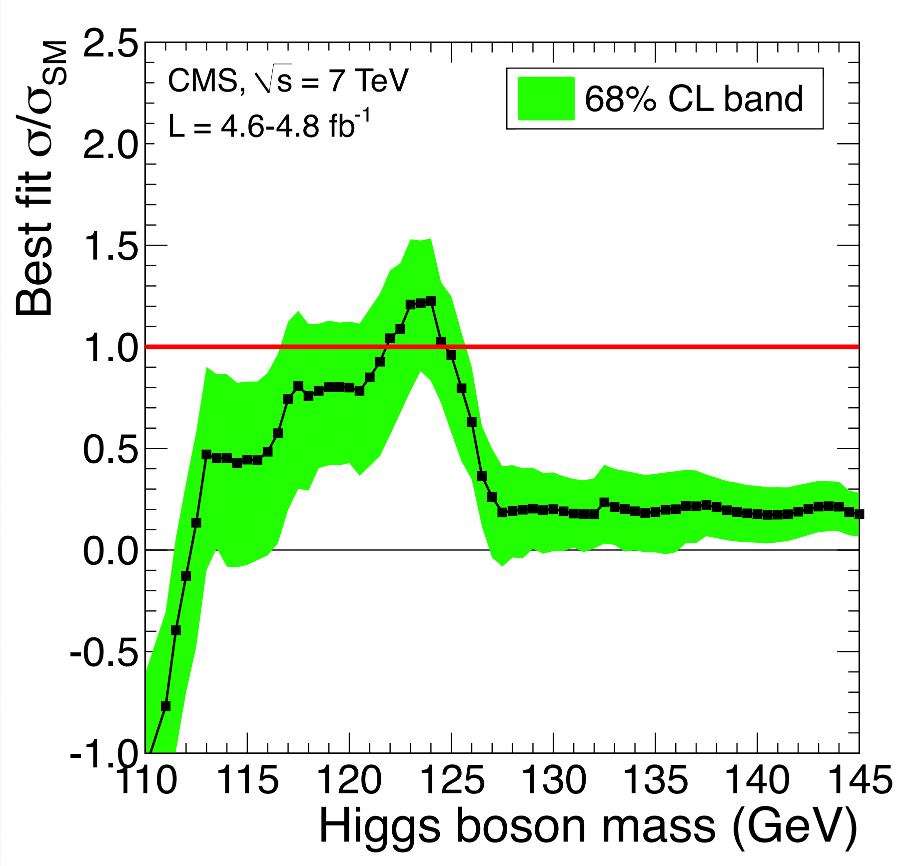
SM Higgs excluded in the 129-525 GeV mass range @ 99% CL

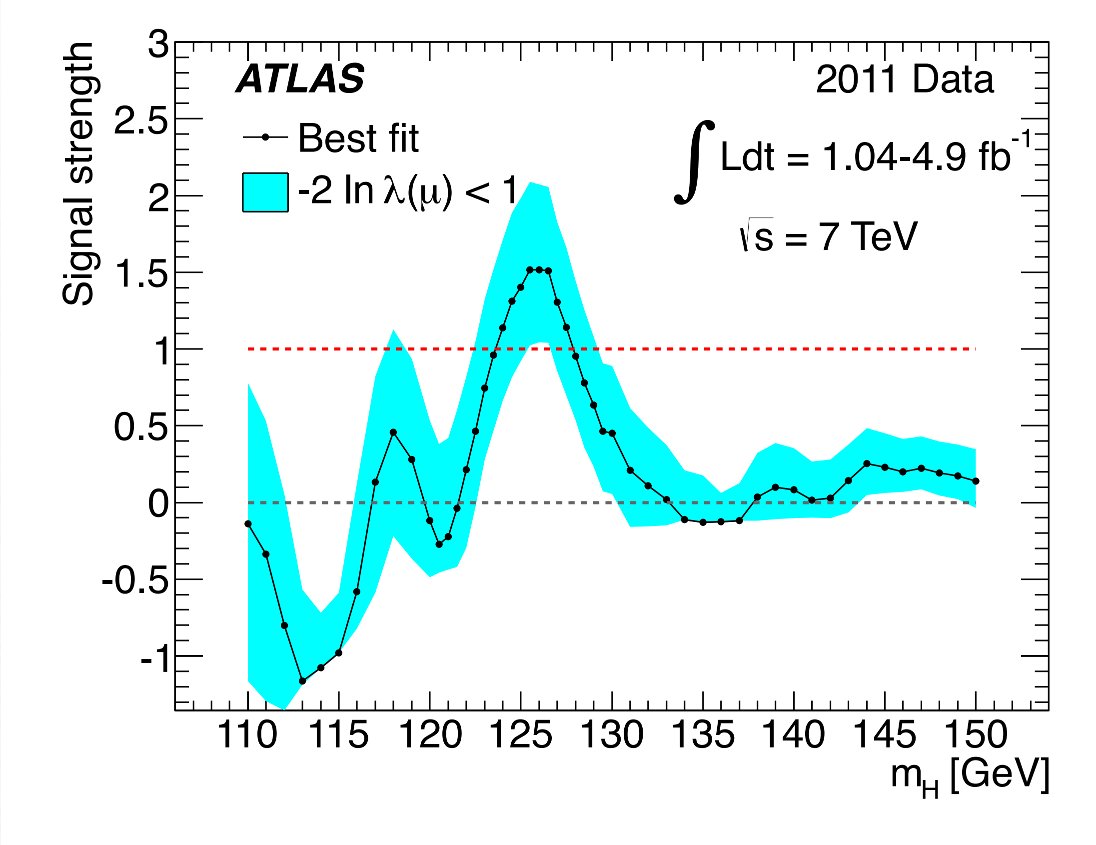




Hints for the Higgs

124 GeV or 126 GeV ?



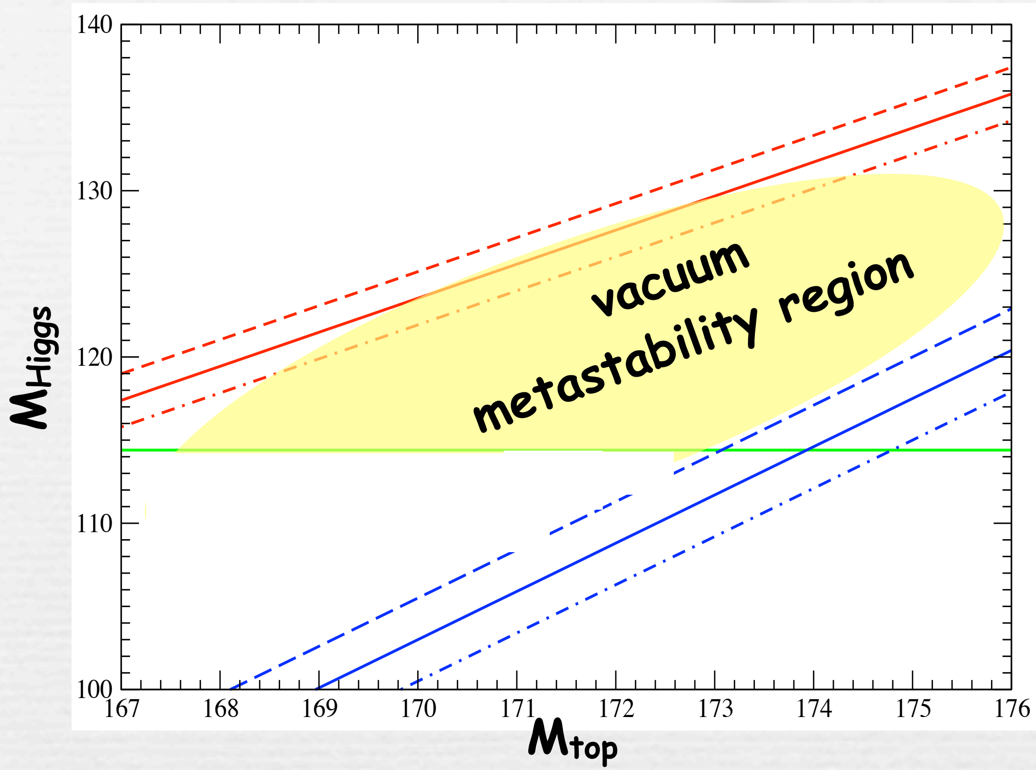


3.1 σ excess at 124 GeV

3.6 σ excess at 126 GeV

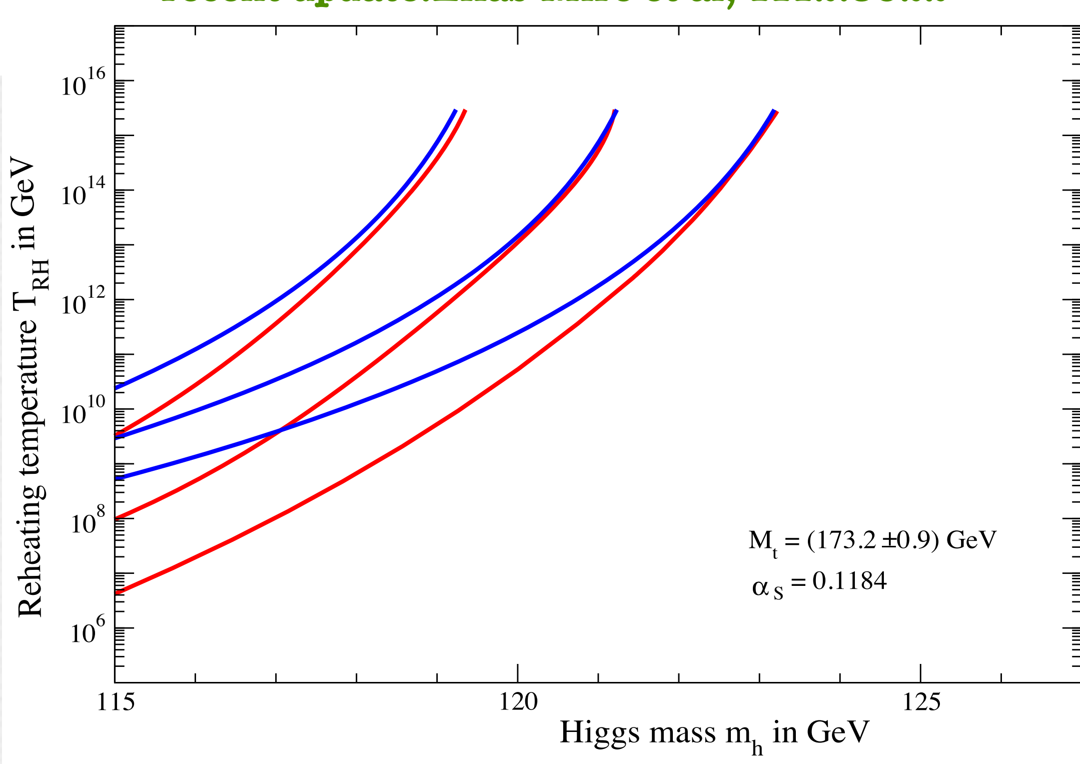
Cosmological implications of Standard Model Higgs mass measurement

Espinosa-Giudice-Riotto'07



(assuming a desert between the EW scale and the scale of inflation)

recent update:Elias-Miro et al, 1112.3022



--> No bound on the reheat temperature if $M_H \sim 125$ GeV

relevant for leptogenesis

LHC will most likely not provide the final answer

Searching for complementary probes of the EW symmetry breaking mechanism in cosmological observables

New TeV scale physics ⇄ **Cosmological signatures**

mainly from
- dark matter
- baryogenesis

(see also recent interest in higgs inflation)

2 major observations unexplained by the Standard Model

that may have something to do with new physics at the electroweak scale

- the Dark Matter of the Universe

Some invisible transparent matter (that does not interact with photons) which presence is deduced through its gravitational effects

- the (quasi) absence of antimatter in the universe

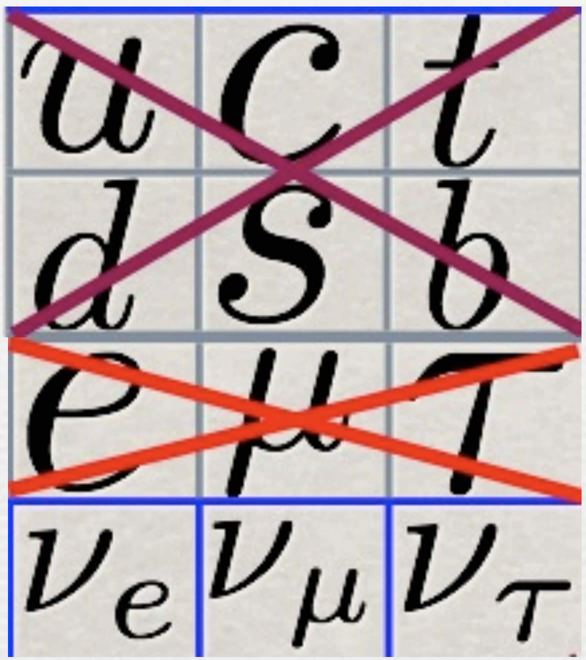
baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

Why can't dark matter be explained by the Standard Model?

Matter

quarks

leptons



I II III

3 families of matter

Forces

force mediators

charged/unstable

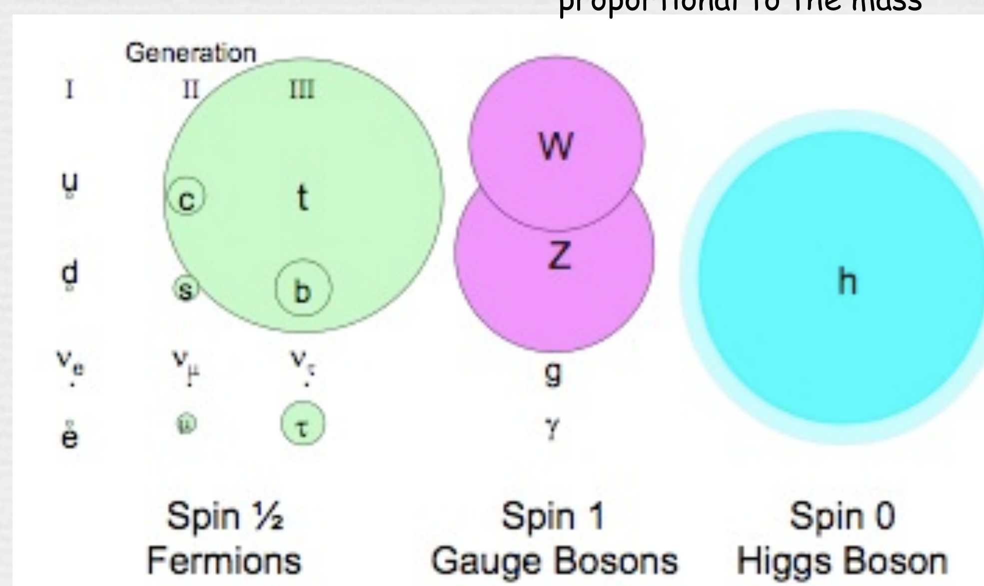
baryonic

massless

contribution to the energy budget of the universe

Particle	Ω	type
Baryons	4 - 5 %	cold
Neutrinos	< 2 %	hot
Dark matter	20 - 26 %	cold

radius of circle is proportional to the mass



Dark Matter candidates

Two main possibilities:

very light & only gravitationally coupled (or with equivalently suppressed couplings) -> stable on cosmological scales

Long-lived
(stable on cosmological scales)

$$\tau_{DM} > \tau_{universe} \sim 10^{18}\ s$$

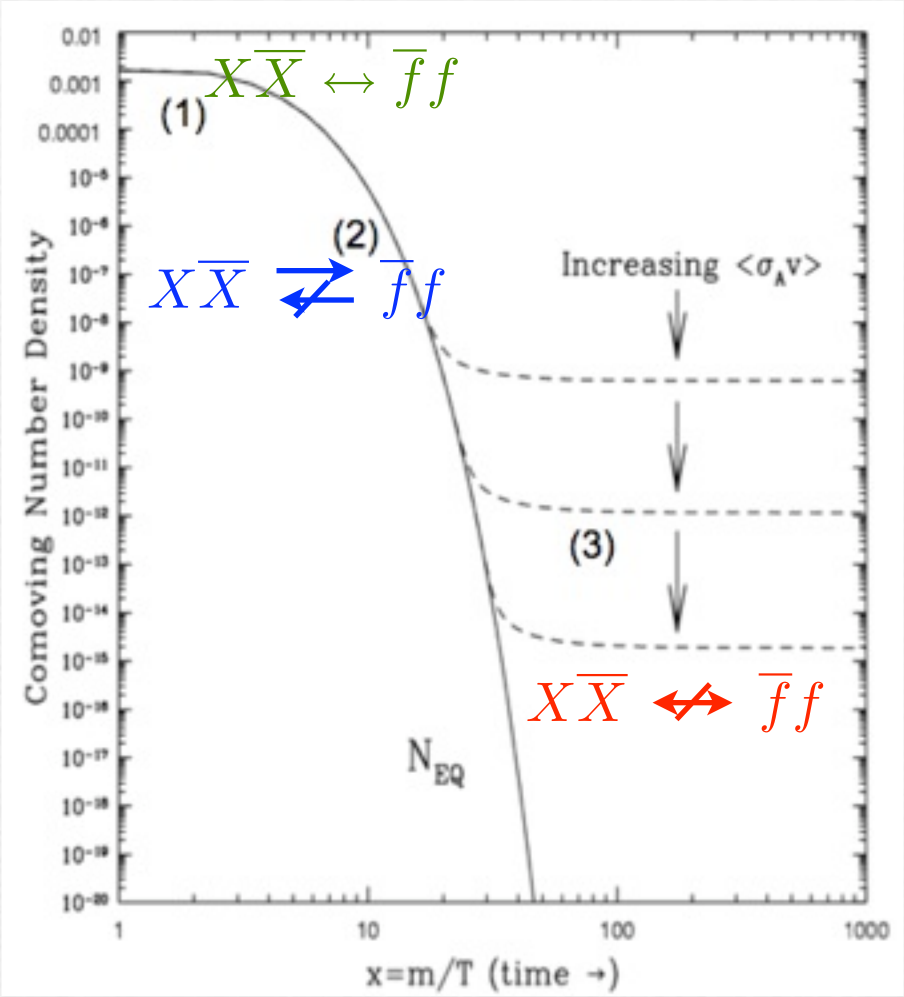
sizably interacting (but not strongly) with the SM -> symmetry needed to guarantee stability

stable by a symmetry

-> WIMP

The WIMP relic abundance follows from the generic thermal freeze-out mechanism in the expanding universe

$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_T^2)$$



freese-out :

$$H \sim \frac{\sqrt{g}T^2}{M_P} \sim \Gamma = n\sigma v$$

Thermal relic: $\Omega\ h^2 \propto 1/\langle\sigma_{anni}\ v\rangle$

$\Rightarrow \langle\sigma_{anni}\ v\rangle \approx 1$ pb

$\sigma \sim \alpha^2/m^2$

$\Rightarrow$ m ~ 100 GeV

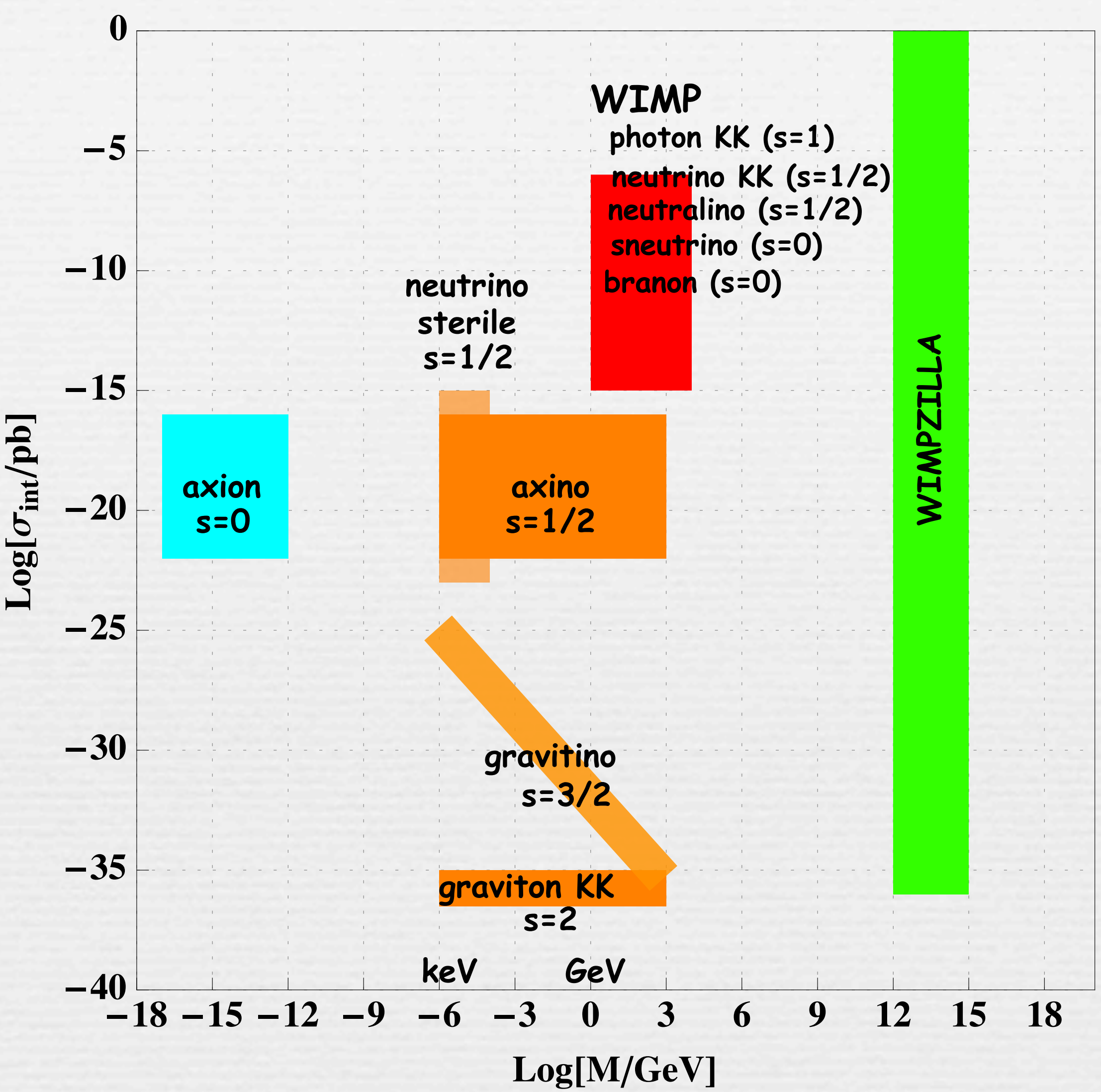
The "WIMP miracle"

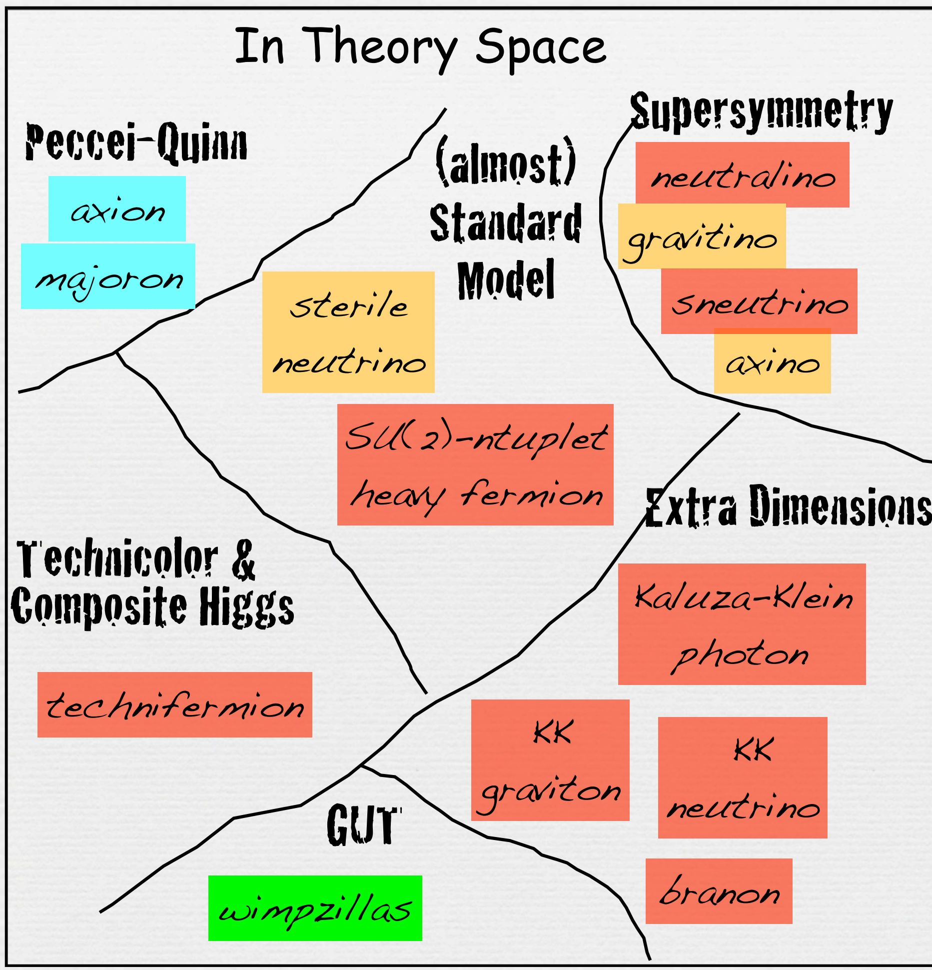
$$\Omega_{DM} \approx \frac{O(1)\ \text{pb}}{\sigma_{anni}}$$

→ a particle with a typical EW-scale cross section

$\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

Dark Matter Candidates with $\Omega_{DM} \sim 1$

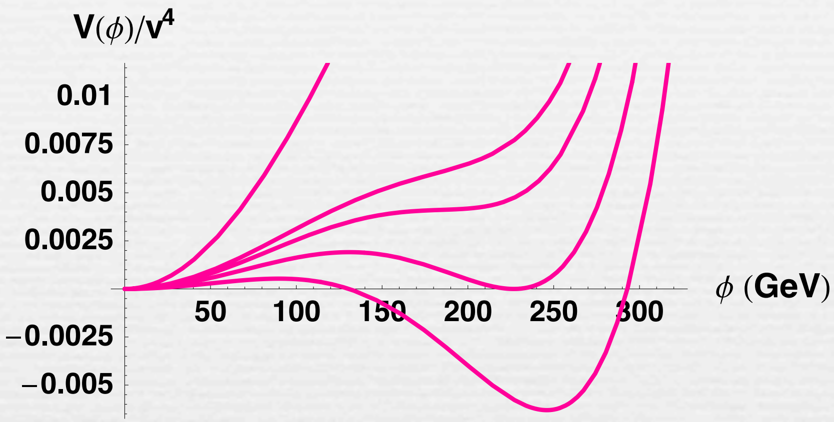


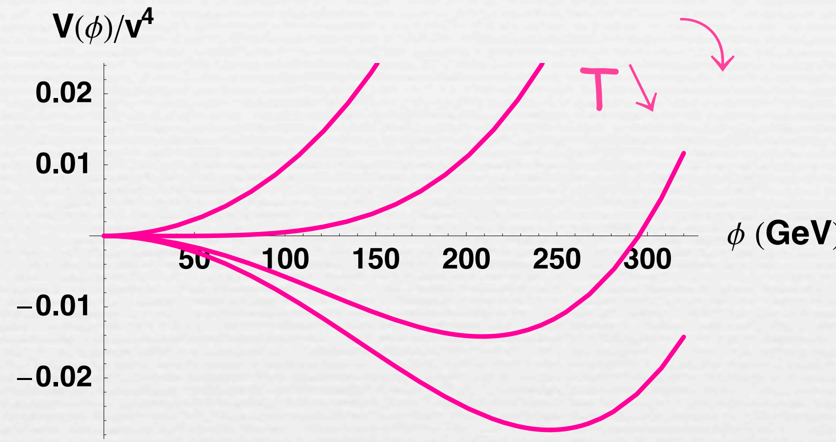


good to keep in mind if no sign of wimp detection within the next decade ...

What is the nature of the electroweak phase transition ?

first-order or second-order?





LHC will provide insight as it will shed light on the Higgs sector

Question intensively studied within the Minimal Supersymmetric Standard Model (MSSM). However, not so beyond the MSSM (gauge-higgs unification in extra dimensions, composite Higgs, Little Higgs, Higgsless...)

Why do we care?

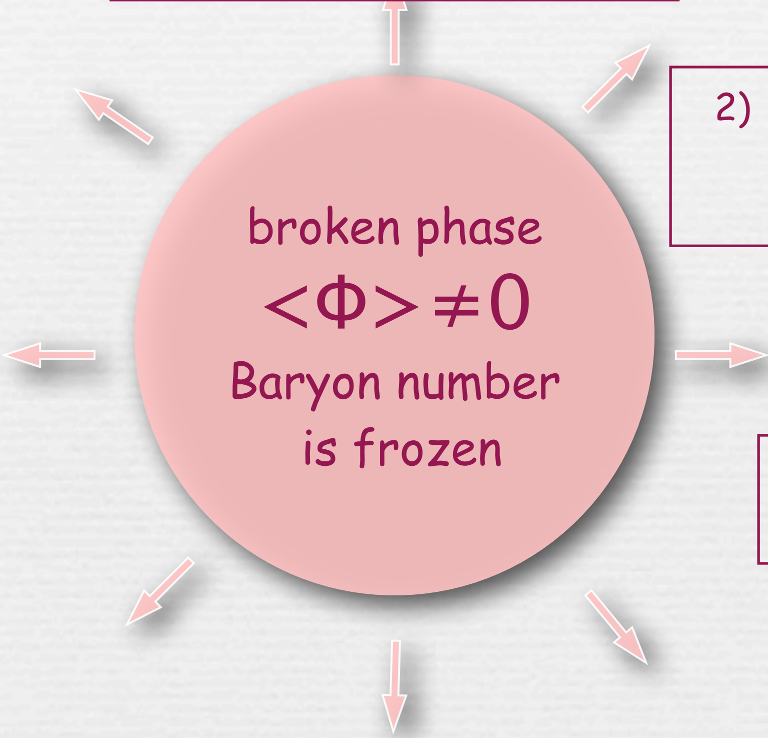
1) Nature and properties of the EW phase transition reflect information on the dynamics behind EW symmetry breaking (e.g weakly or strongly interacting).

2) Crucial for reliable computations of electroweak baryogenesis

Besides, out -of-equilibrium dynamics during the EW phase transition may be relevant for non-thermal dark matter production

Baryon asymmetry and the EW scale

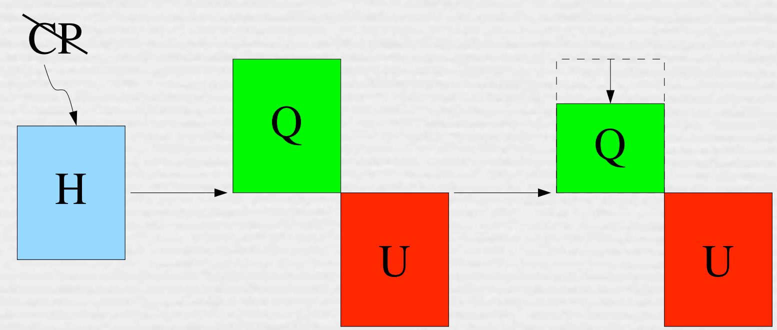
1) nucleation and expansion of bubbles of broken phase



2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux in front of the wall

3) In symmetric phase, $\langle\Phi\rangle = 0$, very active sphalerons convert chiral asymmetry into baryon asymmetry



Electroweak baryogenesis mechanism relies on a first-order phase transition

In the SM, a 1rst-order phase transition can occur due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 \; -ET\phi^3$$

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

Sum over all bosons which couple to the Higgs

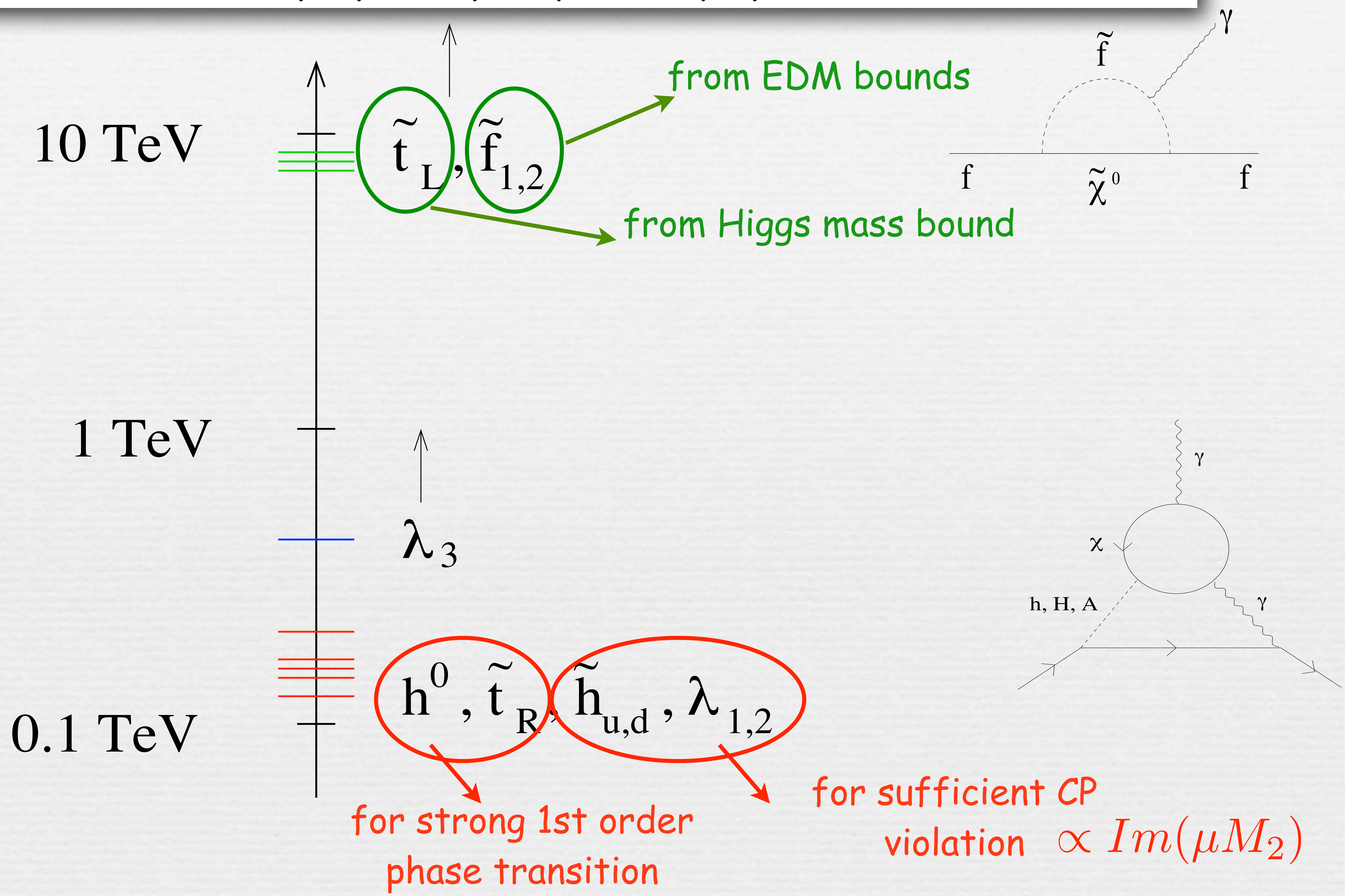
In the SM: $\sum_i \simeq \sum_{W,Z}$ ⇒ not enough

for mh>72 GeV, no 1st order phase transition

In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

The (fine-tuned) MSSM EW baryogenesis window:
A Stop-split supersymmetry spectrum



The light stop scenario: testable at the LHC, although challenging.

bounds get relaxed when adding singlets or in BSSM

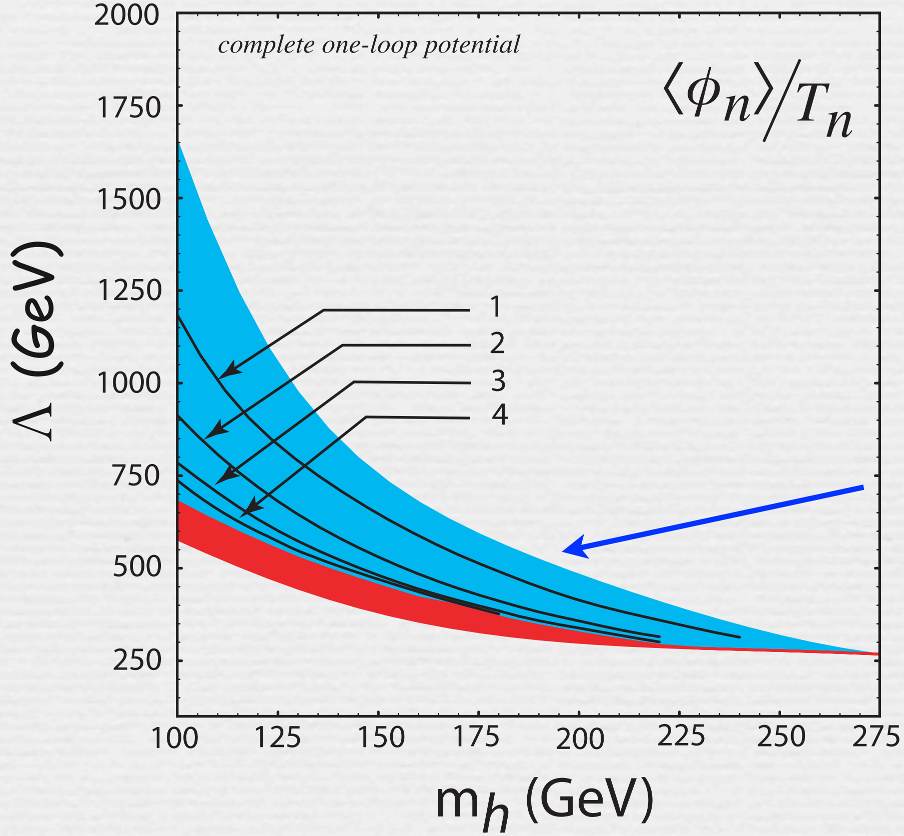
Effective field theory approach

add a non-renormalizable Φ^6 term to the SM Higgs potential and allow a negative quartic coupling

$$V(\Phi) = \mu_h^2|\Phi|^2 - \lambda|\Phi|^4 + \frac{|\Phi|^6}{\Lambda^2}$$

"strength" of the transition does not rely on the one-loop thermally generated negative self cubic Higgs coupling

strong enough for EW baryogenesis if $\Lambda \lesssim$ 1.3 TeV



region where EW phase transition is 1st order

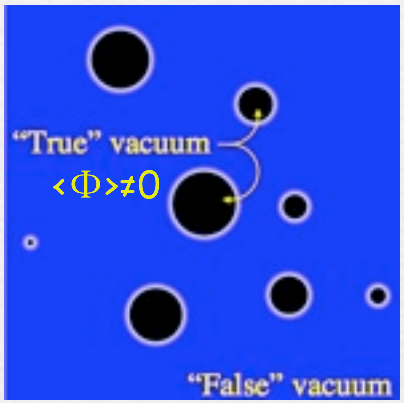
Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

Smoking gun signature

Randall-Servant'06
Konstandin,Nardini,Quiros'10
Konstandin-Servant'11

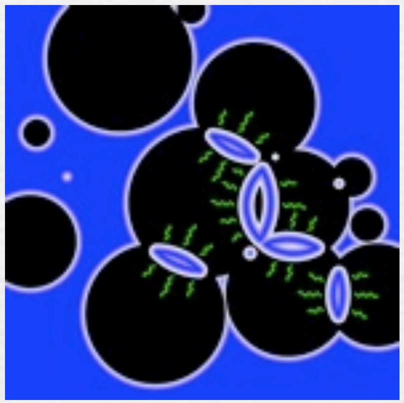
Stochastic background of gravitational radiation

Bubble nucleation



$\langle \Phi \rangle = 0$

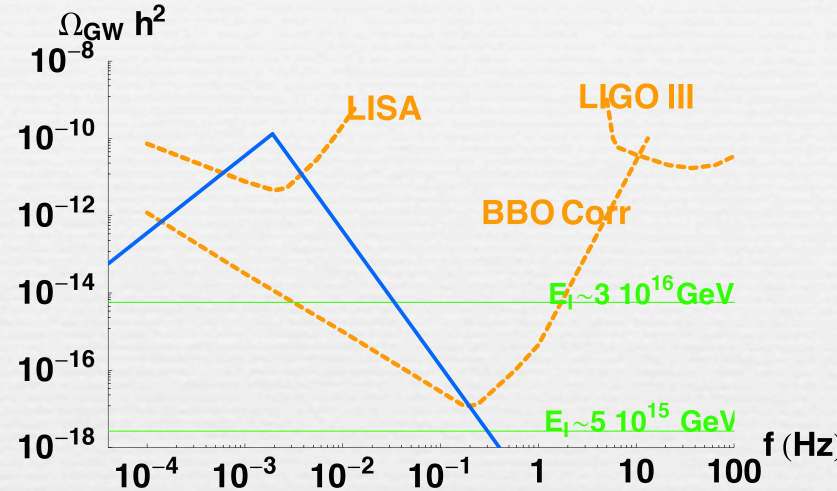
Bubble percolation



Fluid flows

turbulence

Magnetic fields



violent process if $v_b \sim O(1)$

$$\Omega_{GW} \sim \frac{1}{(\beta/H)^2}\kappa^2$$

Detection of a GW stochastic background peaked in the milliHertz:
a signature of near conformal dynamics et the TeV scale

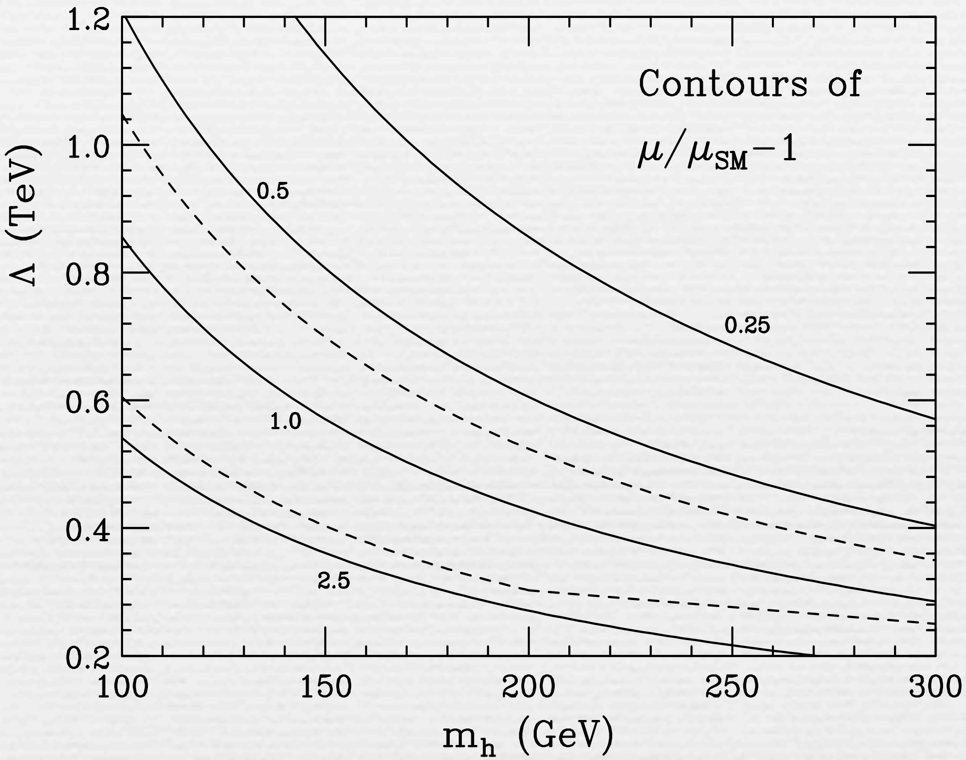
Typically large deviations to the Higgs self-couplings

$$\mathcal{L} = \frac{m_H^2}{2} H^2 + \frac{\mu}{3!} H^3 + \frac{\eta}{4!} H^4 + \ldots$$

where

$$\mu = 3\frac{m_H^2}{v_0} + 6\ \frac{v_0^3}{\Lambda^2}$$

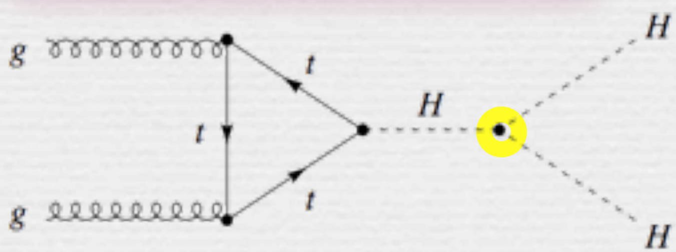
$$\eta = 3\frac{m_H^2}{v_0^2} + 36\ \frac{v_0^2}{\Lambda^2}$$



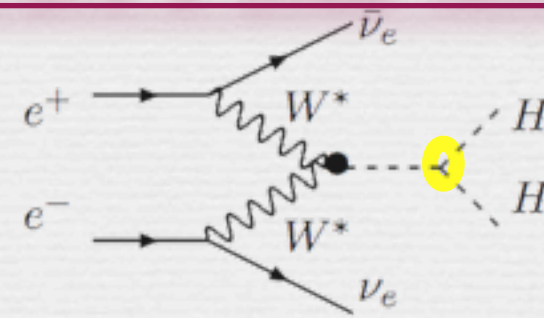
The dotted lines delimit the region for a strong 1rst order phase transition

deviations between a factor 0.7 and 2

at a Hadron Collider

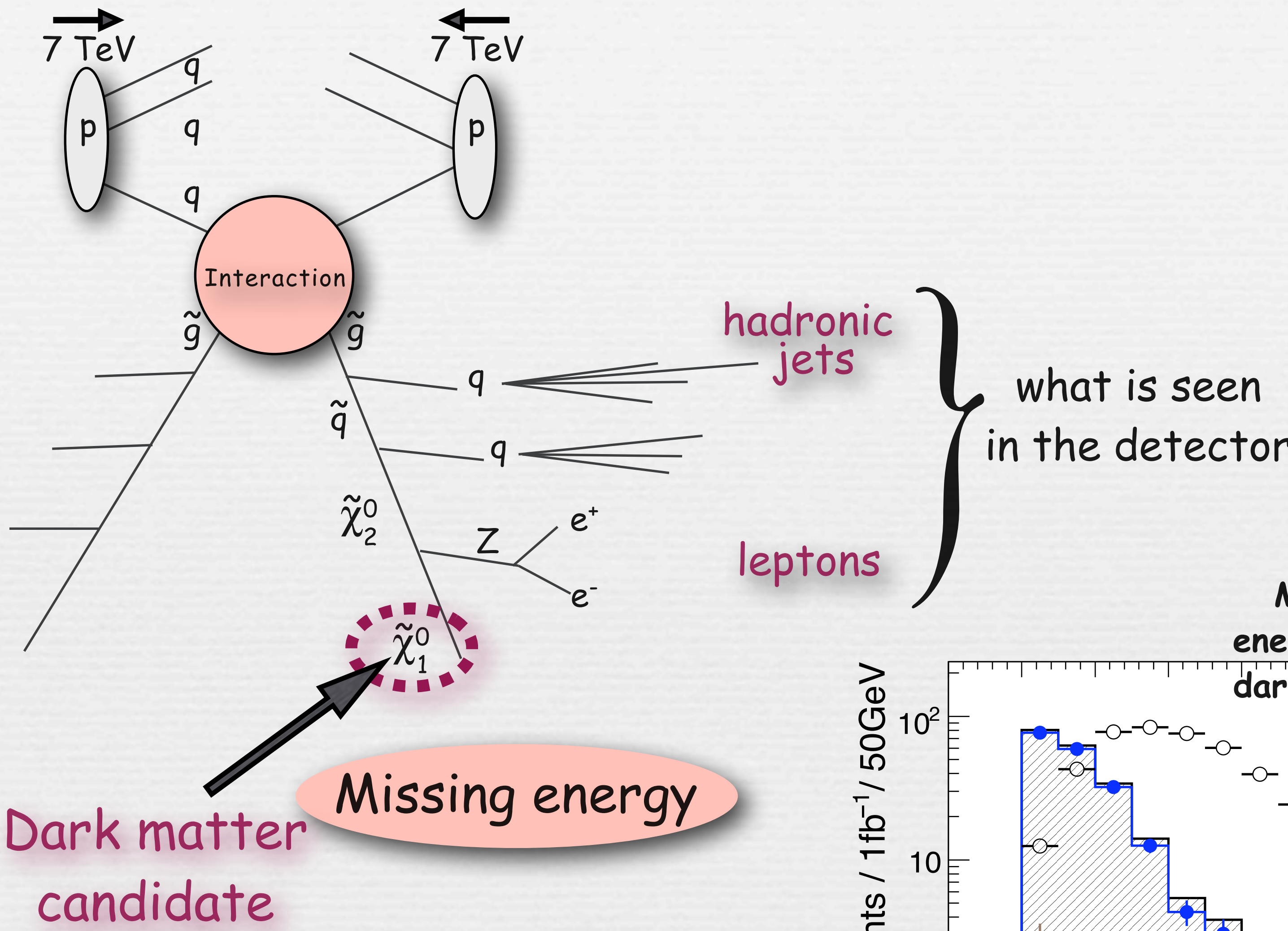


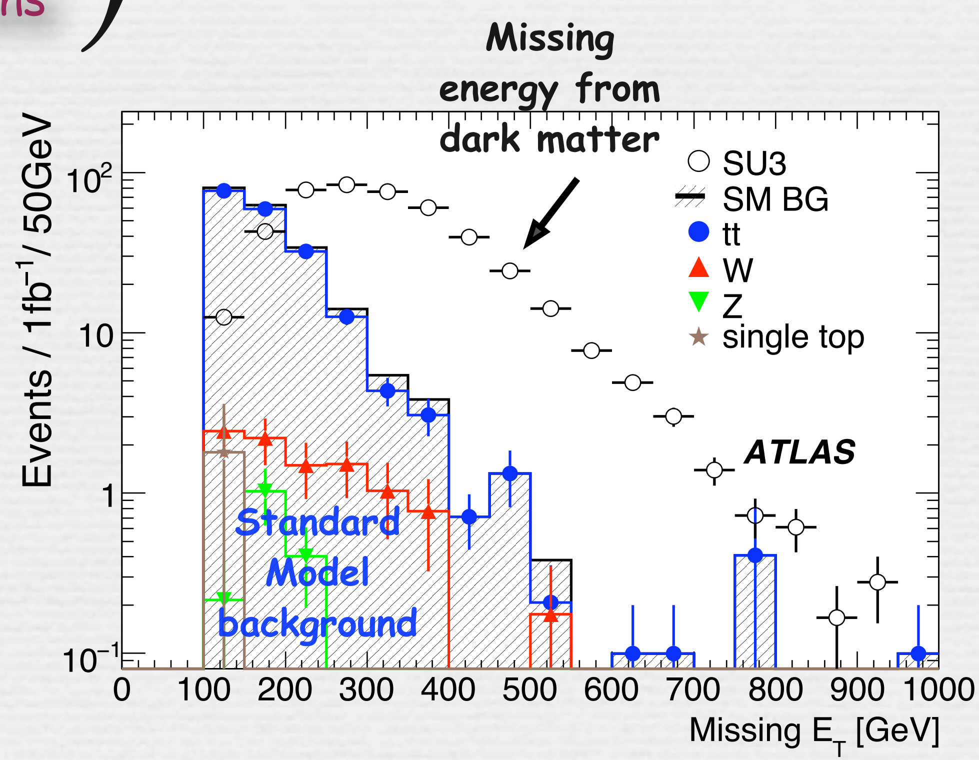
at an $e^+ e^-$ Linear Collider



Testing the WIMP paradigm

Producing Dark Matter at LHC = "Missing Energy" events

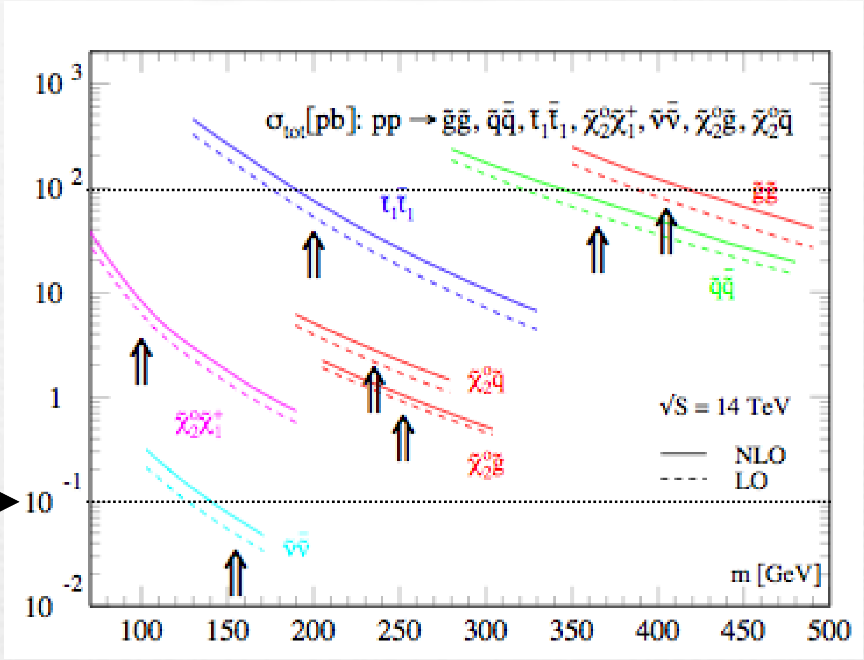




Event rate

100 evts in 1 pb^{-1} →

100 evts in 1 fb^{-1} →



$L \sim 10^{33} cm^{-2} s^{-1} \sim 10\ fb^{-1}\ year^{-1}$

$\sigma \sim O(10)$ pb → ~ 10^5 wimps/year

Detecting large missing energy events will not be enough to prove that we have produced dark matter (with lifetime > $H^{-1} \sim 10^{17}$ s)

LHC: not sufficient to provide all answers

LHC sees missing energy events and measures mass for new particles

but what is the underlying theory?

Spins are difficult to measure (need for $e^+ e^-$ Linear Collider)

Solving the Dark Matter problem requires

1) detecting dark matter in the galaxy (from its annihilation products)

2) studying its properties in the laboratory

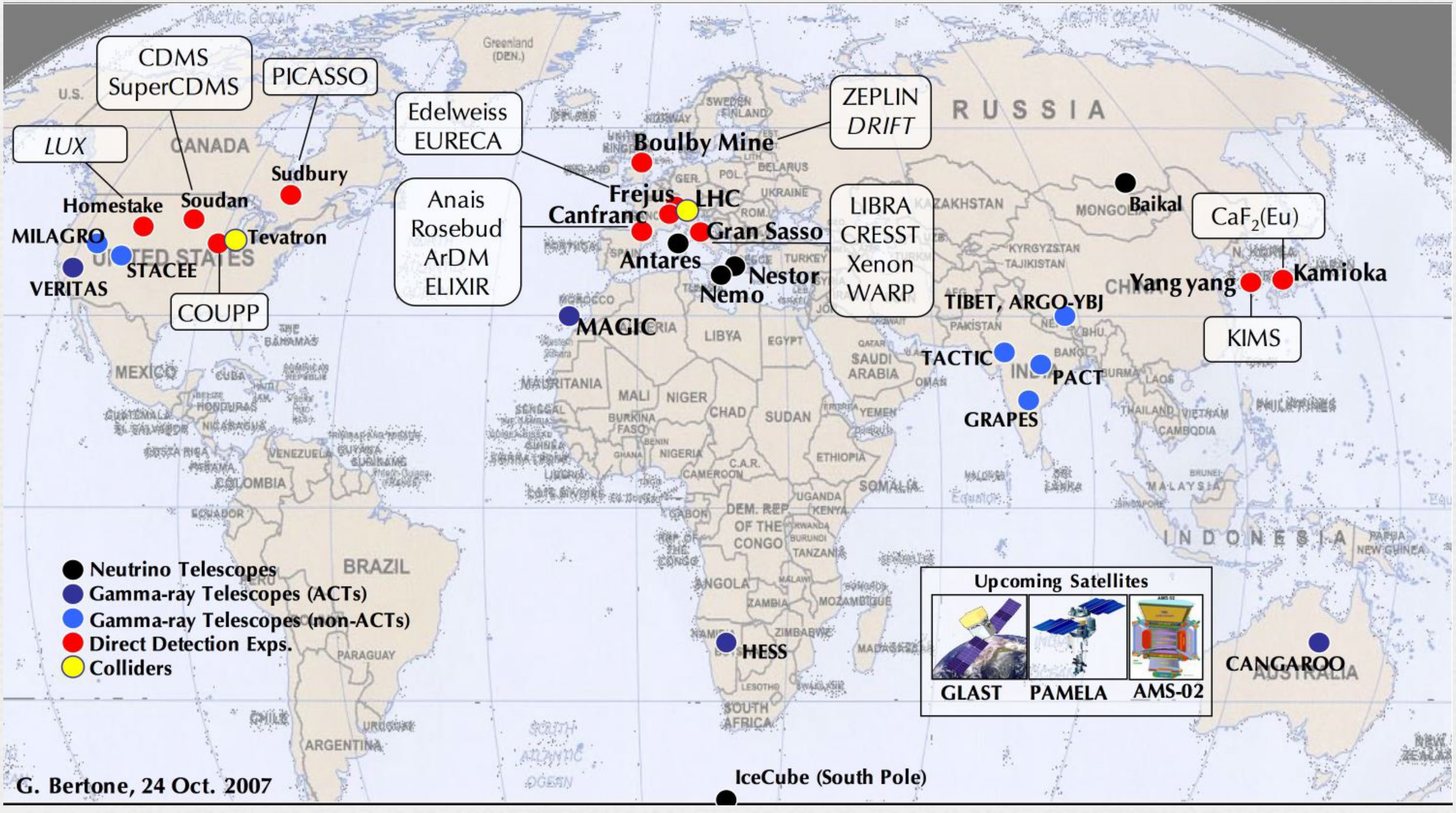
3) being able to make the connection between the two

Need complementarity of particle astrophysics (direct/indirect experiments) to identify the nature of the Dark Matter particle

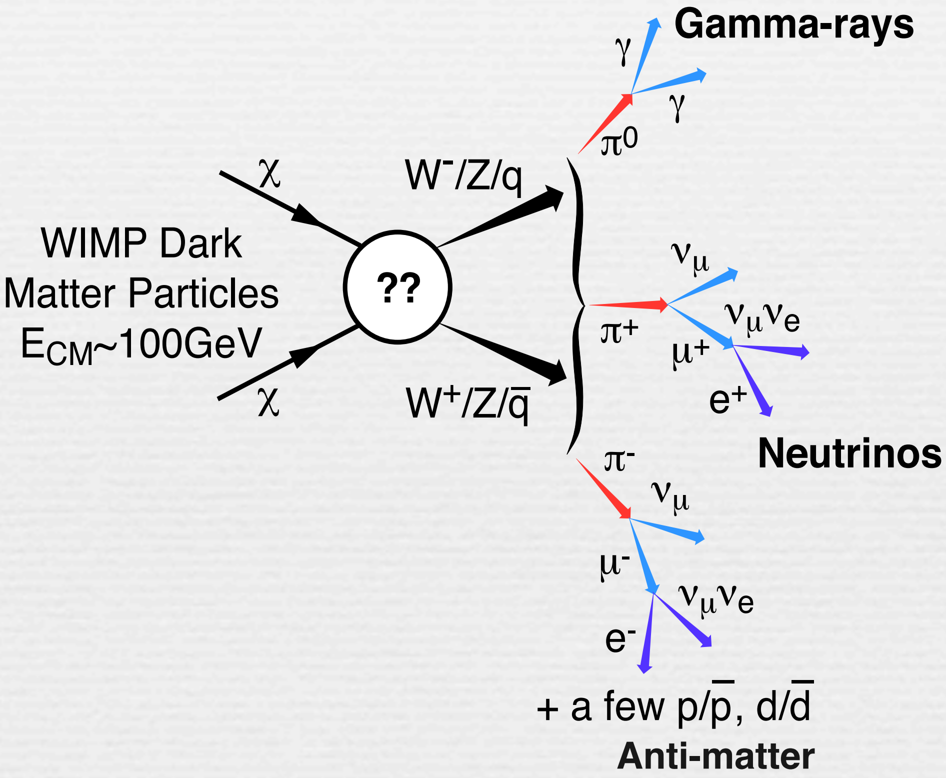
The Dark Matter Decade

Huge experimental effort towards the identification of Dark Matter

Indirect		Direct	Collider experiments
Antimatter Neutrinos Gamma Rays	Signature of Annihilation in space	Elastic Scattering signature in underground labs	Missing Energy signature in high energy accelerators



WIMP indirect detection

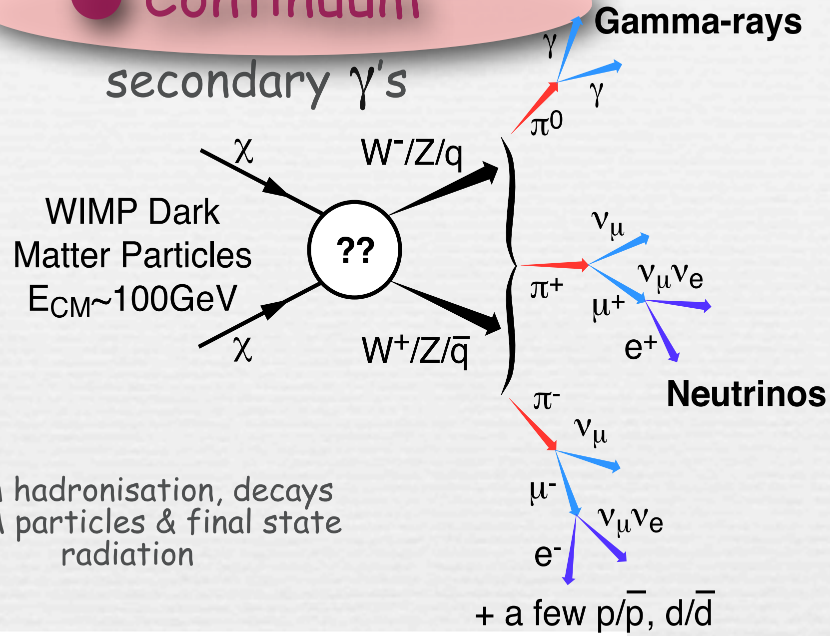


Seeing the light from Dark Matter

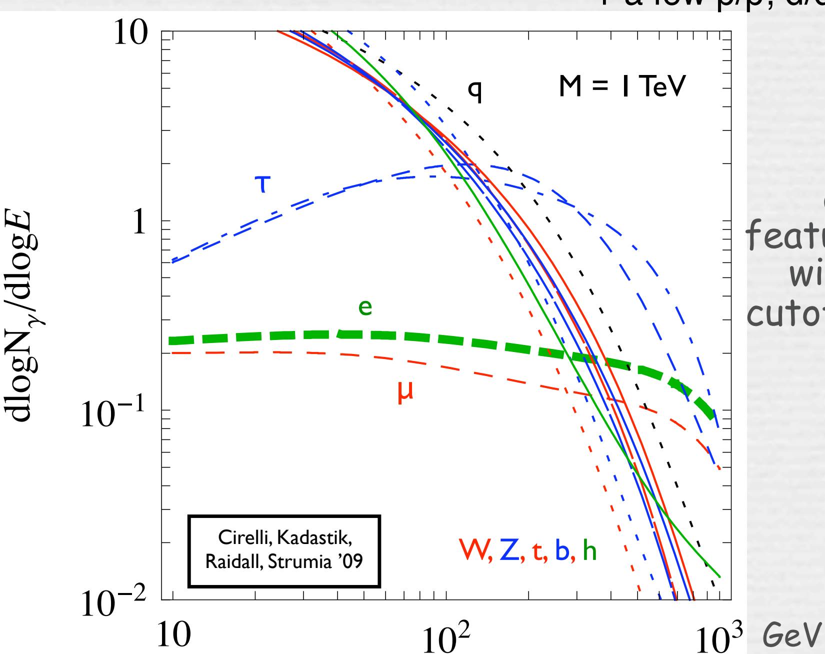
γ's from DM annihilations consist of 2 components

Continuum

secondary γ's



from hadronisation, decays of SM particles & final state radiation

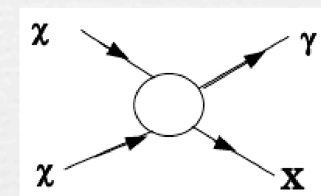


almost featureless but with sharp cutoff at Wimp mass

Lines

primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

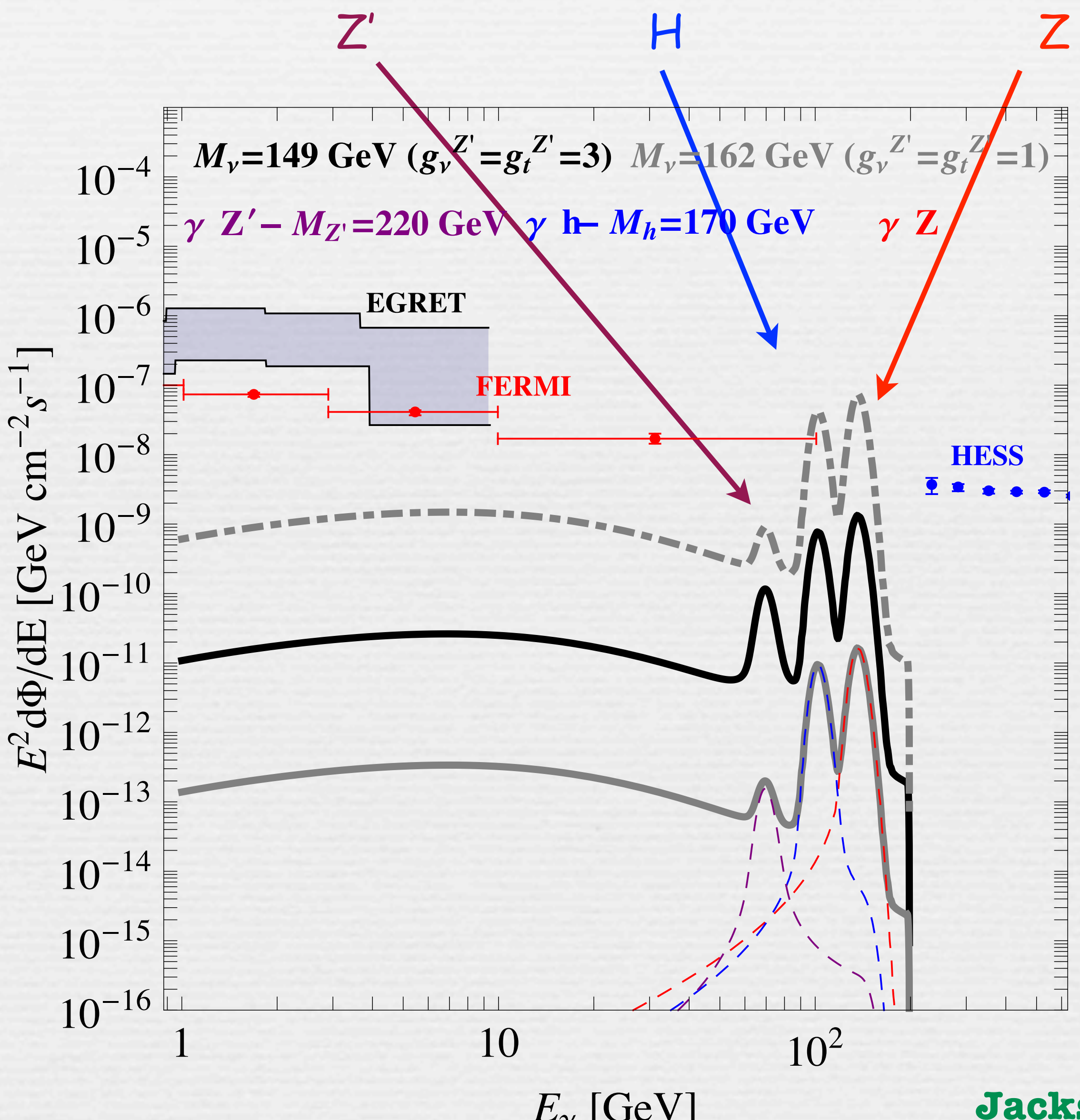
☺ -> striking spectral feature, SMOKING GUN signature of Dark Matter

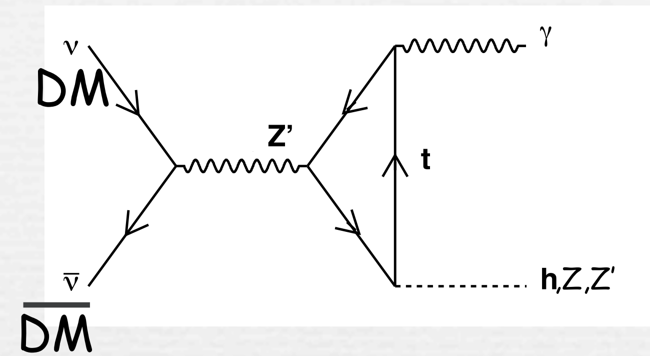
☹ lines are usually small (loop-suppressed) compared to continuum

Bergstrom, Ullio, Buckley '98

Higgs in Space!

γ-ray lines from the Galactic Center $\Delta\Omega = 10^{-5}$ sr





Spectra for parameters leading to correct relic density and satisfying direct detection constraints

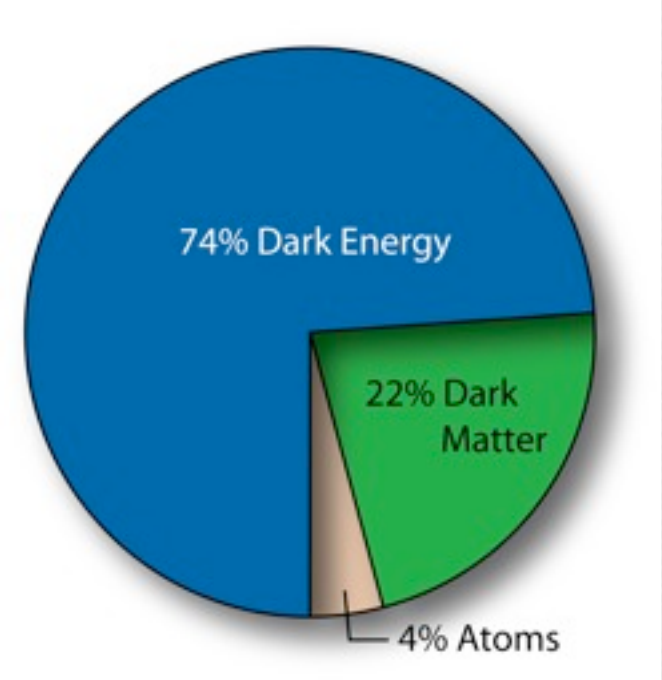
NFW profile

adiabatically contracted

Jackson, Servant, Shaughnessy, Tait, Taoso,'09

beyond the standard WIMP paradigm ...

Are the Dark Matter and baryon abundances related ?



$\Omega_{DM} \approx$ 5-6 $\Omega_{baryons}$

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

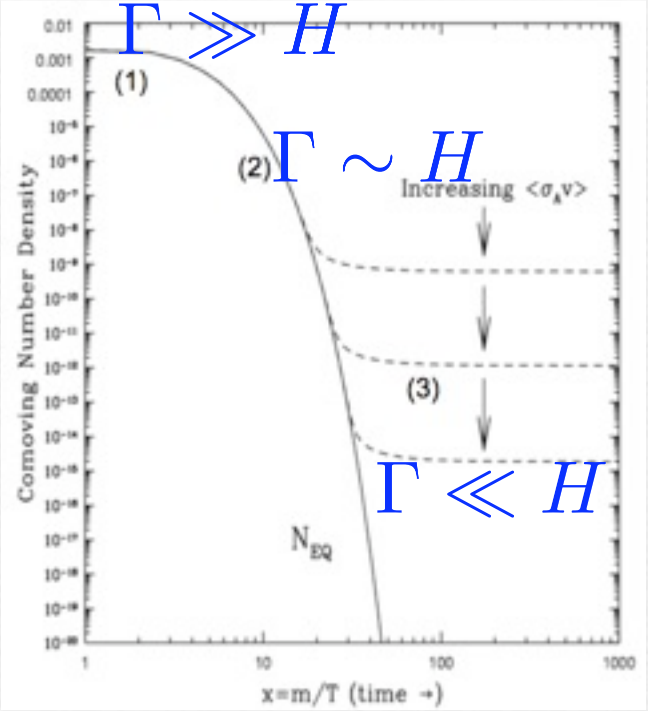
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + ...$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T}/m_\pi^2 \sim H \sim \sqrt{g_*} T^2/m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001 Matter

10 000 000 000 Anti-matter

1 (us)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$

then $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm})m_{dm}}{(n_b - \overline{n}_b)m_b} \sim C\frac{m_{dm}}{m_b}$$

conservation of global charge: $$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

if efficient annihilations: $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}}\frac{m_{dm}}{m_b}$$ ⟶ typical expected mass ~ GeV

two possibilities:

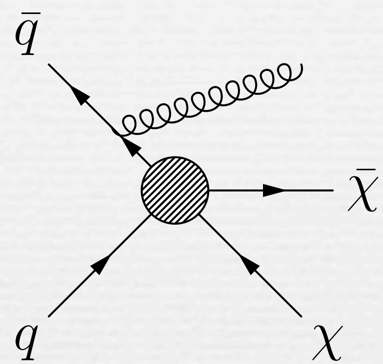
1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

Collider constraints

Fox-Harnik-Kopp-Tsai '11

Use ATLAS and CMS searches in the mono-jet + missing E_T final state



Set limits on couplings of DM to SM in Effective Field Theory Approach

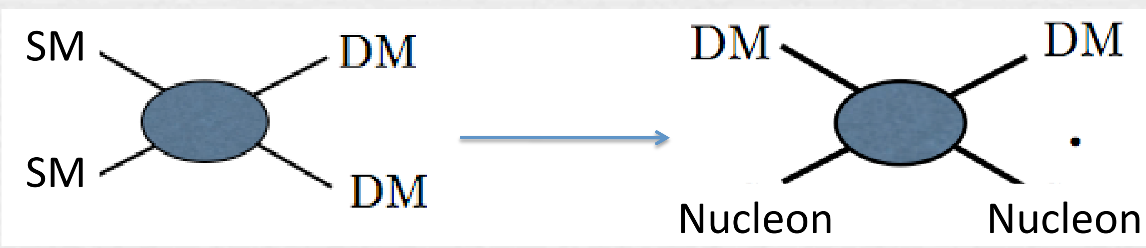
$$\mathcal{O}_1 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}q)(\bar{\chi}\chi)\ ,$$

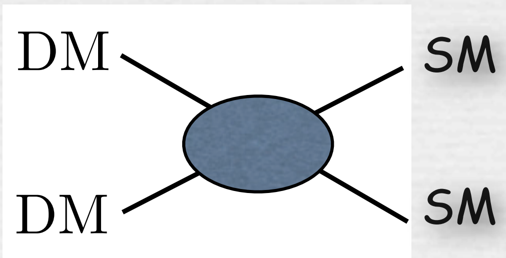
$$\mathcal{O}_2 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi)$$

$$\mathcal{O}_3 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}\gamma_\mu\gamma_5 q)(\bar{\chi}\gamma^\mu\gamma_5\chi)$$

$$\mathcal{O}_4 = \frac{i\,g_\chi\,g_q}{q^2 - M^2}(\bar{q}\gamma_5 q)(\bar{\chi}\gamma_5\chi)\ ,$$

Convert these limits into bounds on cross sections relevant for direct and indirect detection

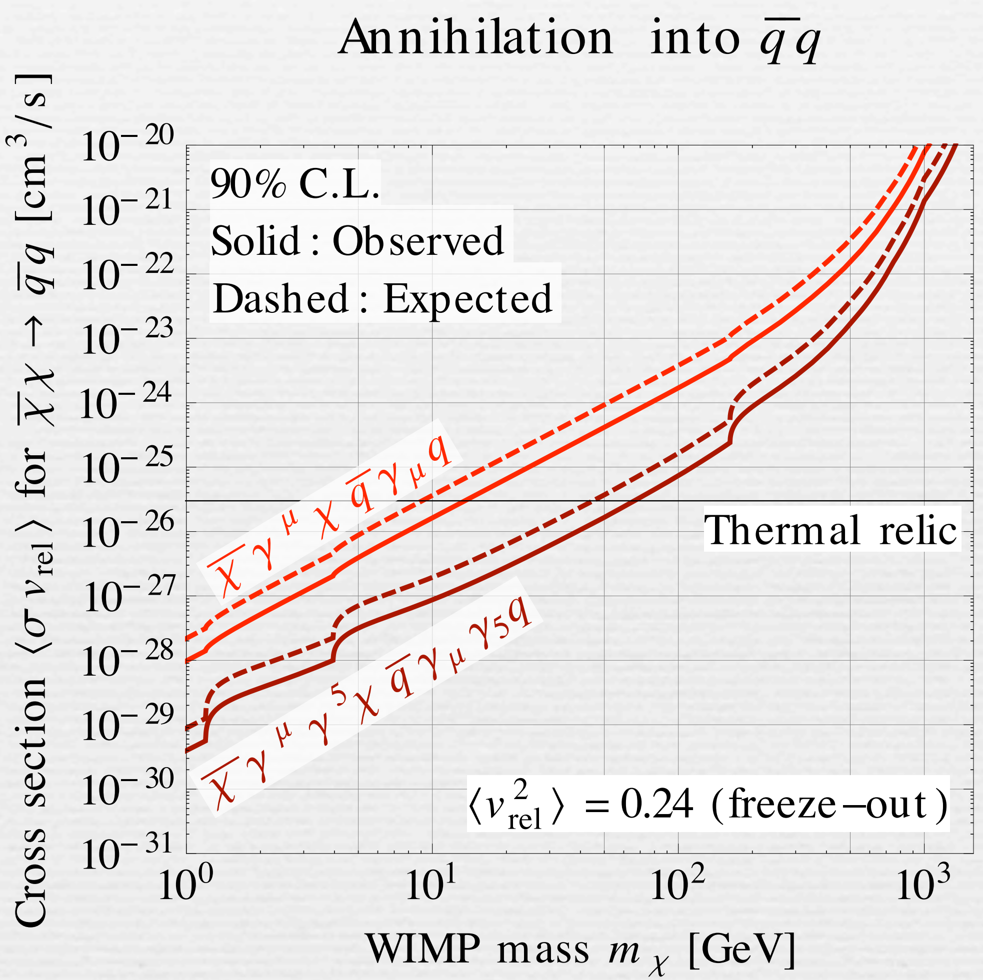




For certain types of operators: competitive limits!

ATLAS 7 TeV constraints on annihilation cross section

Fox-Harnik-Kopp-Tsai '11

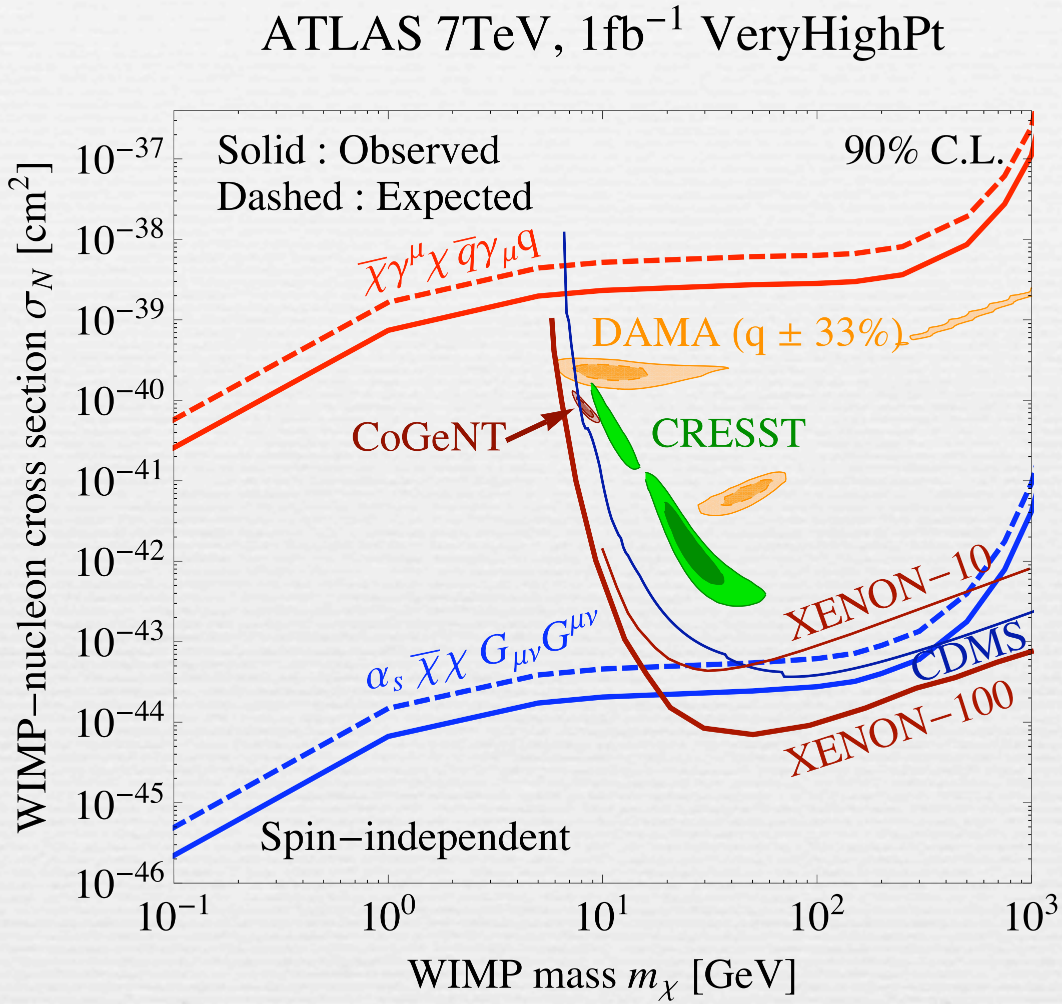


Thermal relic cross sections ruled out for m_DM<~15 GeV for vector couplings !

m_DM<~70 GeV for axial couplings !

Collider constraints on nucleon-WIMP scattering cross section

Fox-Harnik-Kopp-Tsai '11



Low mass LHC reach complementary to direct detection experiments!

no astrophysical uncertainties

Dark Matter and the CMB

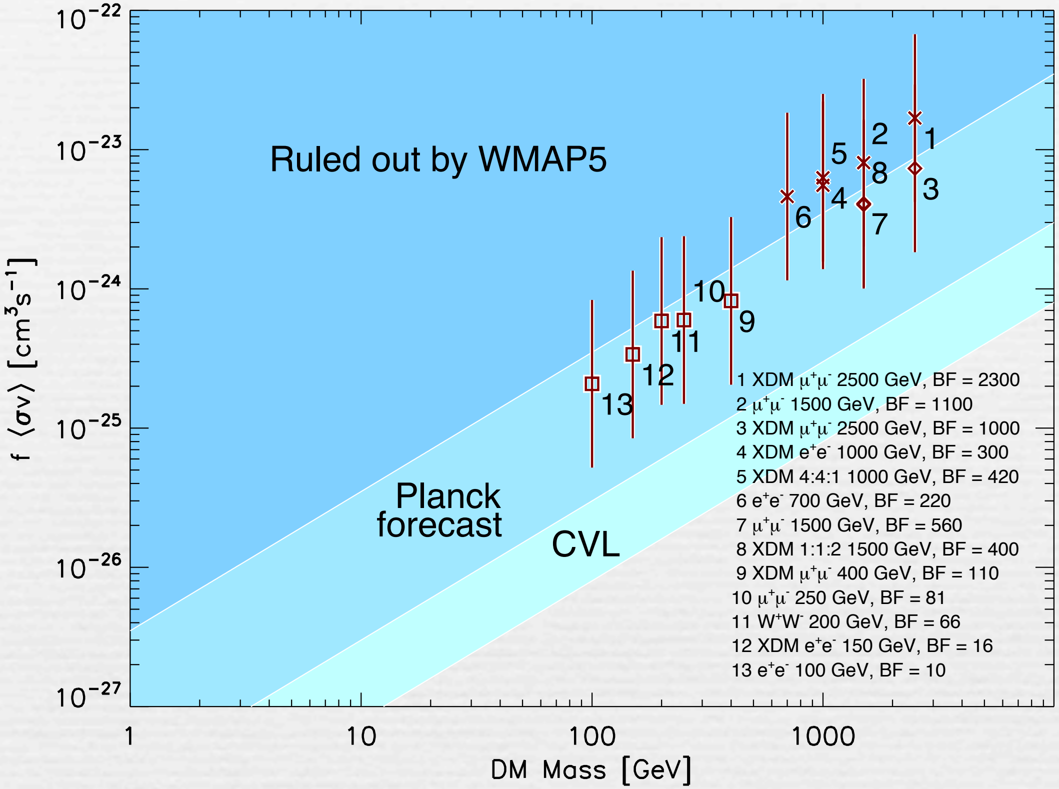
Accurate measurements of the CMB have the potential to probe the physics of dark matter beyond its gravitational interactions

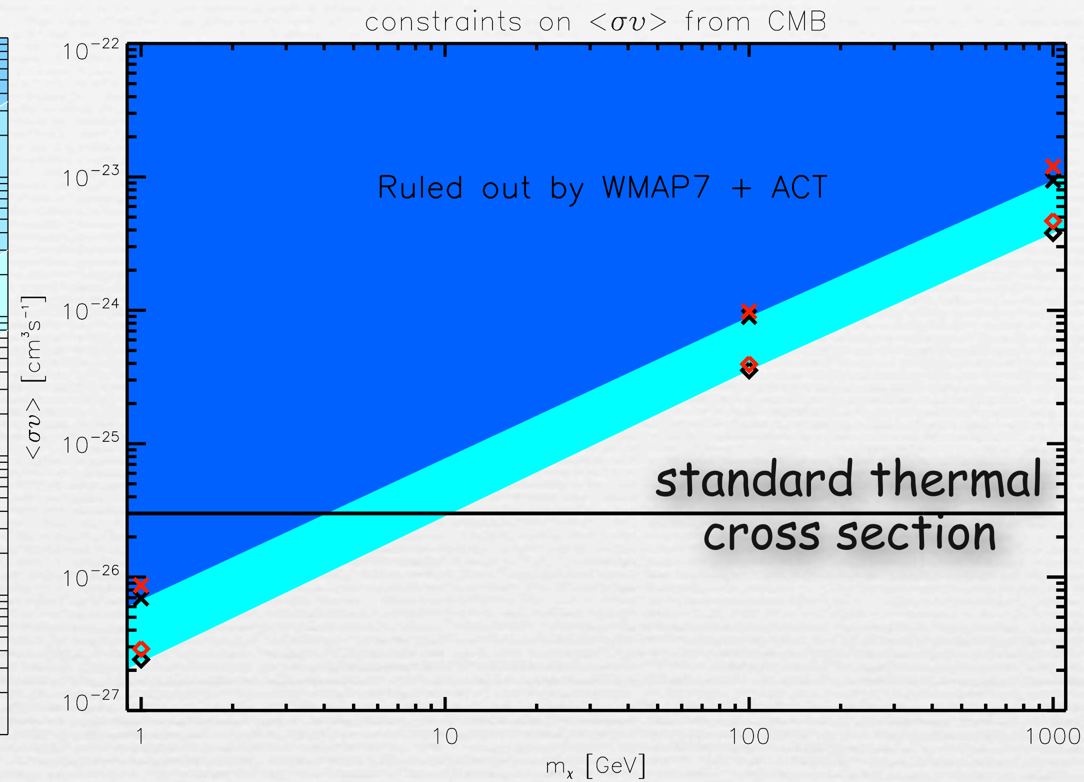
If DM is a thermal relic whose relic abundance is determined by its annihilation rate in the early universe, it modifies the ionization history of the universe and has a potentially measurable effect on the CMB

These constraints are independent of the DM distribution and galactic astrophysics in constrast with other indirect constraints and only depend on:

Ω_{DM} , m_{DM} , σ_0 and standard physics of recombination

Constraints from CMB measurements on the DM annihilation cross section



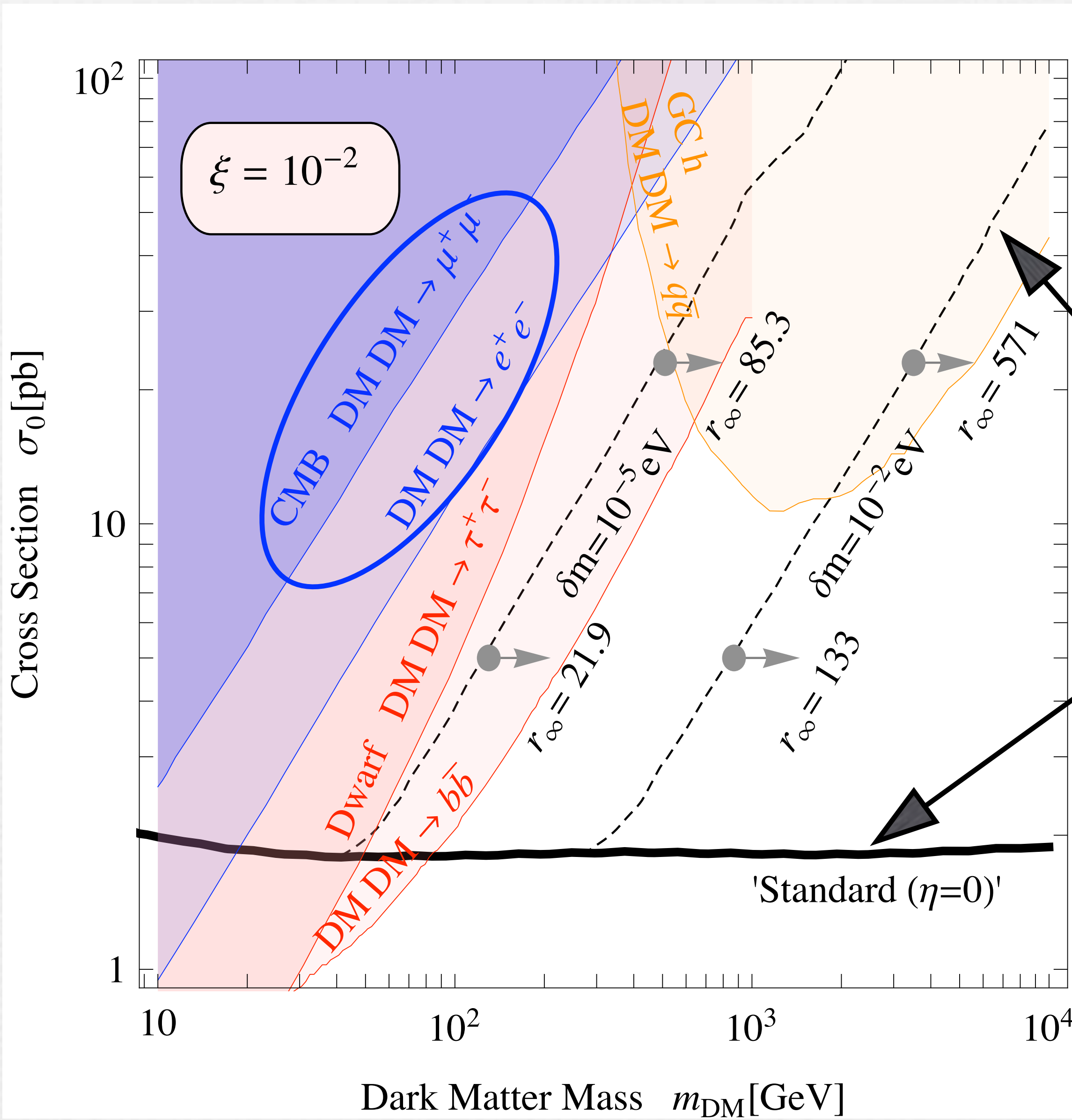


f is just the efficiency with which the WIMP rest mass energy liberated by annihilation is injected into the IGM

Slatyer, Padmanabhan, Finkbeiner '09

Galli et al, '09,'11

CMB versus Fermi constraints



contours with correct relic abundance

Large masses allowed !

Cirelli-Panci-Servant-Zaharijas '11

Opening the window for Asymmetric Dark Matter due to DM anti-DM oscillations

Conclusion

Dark Matter & Baryogenesis at the Electroweak scale:

both under testing !

Planck has its word to say on weak scale physics!
as it can provide interesting constraints
on models of WIMP annihilating dark matter