Dark Matter Candidates in Particle Physics

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Contents

- Why DM ?
- Neutrinos
- Baryonic DM
- Axion and axino
- Neutralino
- Light and Heavy Gravitinos
- Branon
- Lightest Kaluza-Klein mode in extra dimensions
- WIMPZILLA
- Strongly interacting DM
- Singlet scalars

Why DM ? - Rotation Curve

DM = nonluminous and nonabsorbing matter
Luminous Objects = stars, gas clouds, globular clusters, galaxies, etc.

- Galactic rotation curve
- $v(r) \propto \sqrt{M(r)/r}$
  $M(r)$: the mass inside the orbit of radius r
- $v \simeq 220 km/s$ at the location of our solar system and outside
  $\longrightarrow$ Dark Halo with $\rho \propto 1/r^2$, $M(r) \propto r$
  $\longrightarrow \Omega_{\mathrm{DM}} \equiv \rho_{\mathrm{DM}}/\rho_{\mathrm{crit}} > 0.1$
- $\rho_{\mathrm{DM}}^{\mathrm{local}} \simeq \frac{0.3\mathrm{GeV}}{\mathrm{cm}^3}$
  (see rotation curve) (Jeans, 1922)

Why DM ? - WMAP

- WMAP measures Anisotropy of CMB
- $\Omega_{\text{NonBaryonic}} h^2 = 0.111 \pm 0.006$
  $h =$: the Hubble constant in unit of 100 km/(s · Mpc)
- $\Omega_{\text{Baryonic}} h^2 = 0.023 \pm 0.001$
  including MACHOs, cold molecular gas clouds, etc.
  Nucleosynthesis : $0.012 \leq \Omega_{\text{Baryonic}} h^2 \leq 0.025$
  $\rightarrow$ Evidence for Nonbaryonic DM
  (see WMAP data)
- $\rho_{\text{DM}}^{\text{local}} \simeq 0.3 \frac{GeV}{cm^3}$
  from the motion of nearby stars transverse to the galactic plane (J.H. Jeans, 1922)

Properties of the DM Candidtaes

Clear evidence for New Physics beyond the SM

- Stable on cosmological time scale
- Weakly interacting with EM radiation to be dark
- Have right relic abundance
- Structure formation of the universe $\longrightarrow$ mostly COLD DM:
  nonrelativistic at the onset of galaxy formation (when there was a galactic mass inside the causal horizon)
- Candidates: primordial blackholes (BH's), neutrinos, singlet scalar, axion and axino, and WIMP(weakly interacting massive particle)'s, SIMP, WIMPZILLA,.....

Neutrino DM

- Structure formation of the universe $\rightarrow$ mostly COLD DM
  $\Omega_\nu h^2 \leq 0.0076$ (95 % CL)
- Neutrinos : only a small fraction of DM
- If $\Omega_\nu h^2$ larger, then structure formation has problem

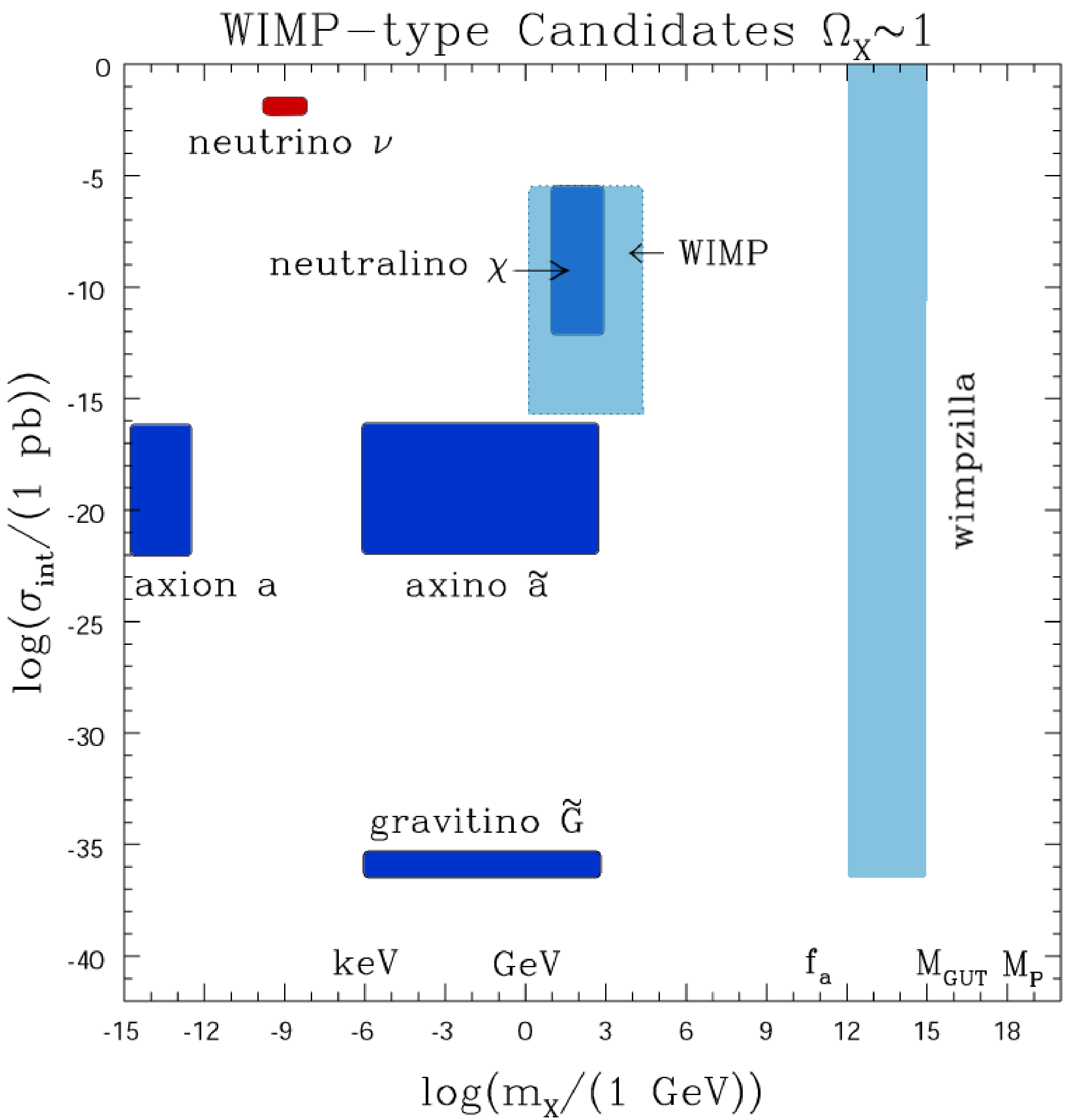
Baryonic DM

- MACHO (MAssive Compact Halo Object)'s can be detected by microlensing effect
- MACHO, EROS, OGLE collaborations mornitored the luminosity of mil. of stars in the in the Large and Small Magellanic Clouds for several years
- EROS: MACHO cannot contribute more than 20 % of the mass of galactic halo
- MACHO : Signal at 0.4 solar mass, an upper limit of 40 %
- Need Nonbaryonic DM !

New Physics for DM candidates

- No good candidate within the SM
- Another evidence for New Physics (NP) along with neutrino oscillations
- Many candidates in NP beyond the SM
  - Well motivated: neutralino, gravitino, axion, axino, branon, lightest KK particle, WIMPZILLA, your own recipe
  - Minimality: singlet scalar (just one more d.o.f.)
- Here mainly concerned with the DM candidates which can be detected at KIMS

WIMPs



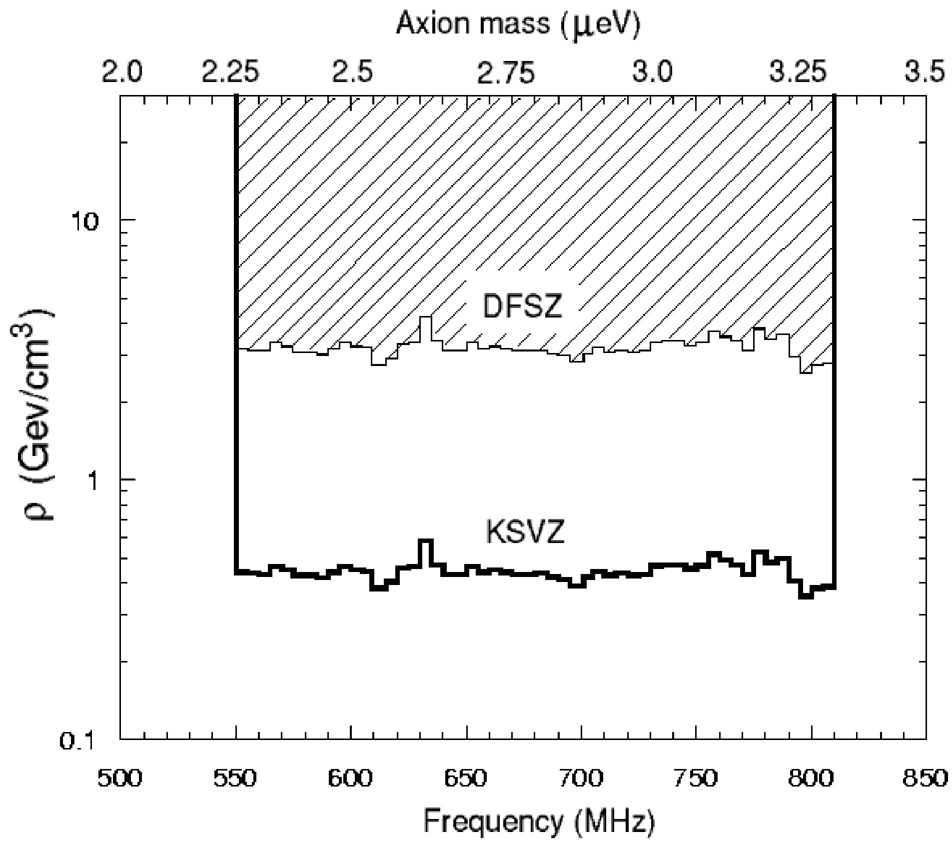
WIMP−type Candidates $\Omega_X \sim 1$
neutrino ν
neutralino χ
WIMP
wimpzilla
axion a
axino $\tilde{a}$
gravitino $\tilde{G}$
keV
GeV
f_a
M_{GUT}
M_P
$\log(\sigma_{int}/(1\ pb))$
$\log(m_X/(1\ GeV))$
0
-5
-10
-15
-20
-25
-30
-35
-40
-15
-12
-9
-6
-3
0
3
6
9
12
15
18

Axion DM

- A solution to string CP problem of QCD
- Naturally present in superstring theory, which is the only known theory of quantum gravity that is mathematically consistent
- Pseudo NG boson associated with global $U(1)_{\mathrm{PQ}}$ symmetry,
  $\longrightarrow$ Spontaneously broken at scale f_a
- Chiral symmetry breaking $\longrightarrow$ axion gets mass
  $m_a \simeq 0.6$ meV $\cdot 10^{10}$ GeV / f_a
- Current limits on f_a
  $5 \cdot 10^9$ GeV $\leq f_a \leq 10^{12}$ GeV
- Very light, but produced nonthermally $\longrightarrow$ Cold DM

Axion-Cont'd

- KSVZ : hadronic axion (tree level couplings to quarks only)
  DFSZ : axion couples to both quarks and leptons
- Search in $a \to \gamma$ conversion in strong B field due to a coupling $g_{a\gamma\gamma}$ (depending on the axion models)
- $\Omega_a h^2 = \kappa_a \left(f_a/10^{12}\mathrm{GeV}\right)^{1.175}\ \theta_i^2$
  $0.5 \lesssim \kappa_a \lesssim$ (a few)
- LLNL (California) excludes $2.9\mu V < m_a < 3.3\mu V$ ($f_a \simeq 4 \times 10^{13}$ GeV as a major component of the dark halo of our galaxy, if $g_{a\gamma\gamma}$ is near the upper end of the theoretically expected range)
- CARRACK (Kyoto)



LLNL Col. (Asztalos et al.)

WIMPs (χ)

- $10\mathrm{GeV} \lesssim m_\chi \lesssim$ a few TeV
- Thermal relic density can be calculated reliably
  $$\Omega_\chi h^2 \simeq \mathrm{const}\ \frac{T_0^3}{M_{Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\mathrm{pb}c}{\langle \sigma_A v \rangle}$$
  $T_0 = 2.73$K : the current CMB temperate
  M_{Pl} : PLanck mass
  σ_A : the annihilation cross section of a pair of χ's into the SM particles
  v : the rel. vel. in their cm frame
  $\langle ... \rangle$: thermal average
- Freeze out at $T_F \simeq m_\chi / 20$: nonrel. when decouples
- Heavy neutrino : not easy to make it stable

Neutralino DM

- Neutralino : LSP in many SUSY scenarios
- Good candidate for DM
- Can be detected directly by underground experiments via elastic scattering on target nuclei
- DAMA, CDMS, EDELWEISS, ZEPLIN, KIMS, etc.
- DAMA signal region : completely ruled out by CDMS
  cf. (In)direct DM detection is important in Split SUSY scenario,
  where all the scalar fermions (squarks, sleptons) are very heavy, and
  charginos and neutralinos are light ($\sim O(0.1) - O(1)$ TeV)
  (Masiero, Profumo, Ullio)

Heavy gravitino LSP

- Gravitino : spin 3/2 superpartner of graviton
- Interaction strength : $1/M_{pl} \longrightarrow$ extremely weak coupling
  $\longrightarrow$ No hope to observe it in the lab
- In supergravity theories, $m_{3/2} > m_{\rm SUSY}$ in many scenarios
- If $\tilde{G}$ is heavy and LSP, rich collider phenomenology (Feng et al. ; Buchmuller, Hamaguchi, et al.)

Light gravitino ($\tilde{G}$)

- Light gravitino : LSP in Gauge Mediation SUSY Breaking
- (in)direct detection impossible
- NLSP $\longrightarrow \tilde{G}$ + X
  $\chi^0 \longrightarrow \tilde{G} + \gamma$ or $\tilde{\tau}_1 \longrightarrow \tilde{G} + \tau$
  or stau can be long lived, does not decay inside the detector
  $\longrightarrow$ Charged particle with heavy mass
  cf. axino (spin 1/2 super partner of axion) shows a similar behavior inside the detector
  (Brandenburg et al.)

Branon-I (Dobado and Maroto et al)

- Brane world scenario : Antoniadis ; Arkani-Hamed, Dimopoulos, Dvali (ADD)
  SM particles on the brane ,   Gravity in the bulk
- Graviton KK contributions to Bhabha scattering : divergent at tree level
- Brane is not completely rigid (due to Relativity)
- Quantized brane fluctuation $\longrightarrow$ Branon
  (Bando, Kugo, ...)
- Goldstone boson associated with spontaneous breaking of translational invariance (cf. phonons in solid)
- Solves the divergence problem in Bhabha scattering using the form factors

Branon-II

- M_4 in a D dim bulk with $(x^{\mu=0,1,2,3}, y^{m=4,5,..D-1})$
  $ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu - g'_{mn}(y)dy^m dy^n$
  $W(0) = 1$
- $\pi^{\alpha=4,5,...D-1}(x)$: the brane fluctuations $\longrightarrow$ Branon when quantized
  cf. Elastic wave in solid $\longrightarrow$ Phonons when quantized
- f : brane tension $\tau \equiv f^4$
- $M^2_{\alpha\beta} = g^{\mu\nu} R_{\mu\nu\alpha\beta}|_{y=0}$
  - Massless branons in the flat case $W(y) = 1$
  - Massive branons in the warped case

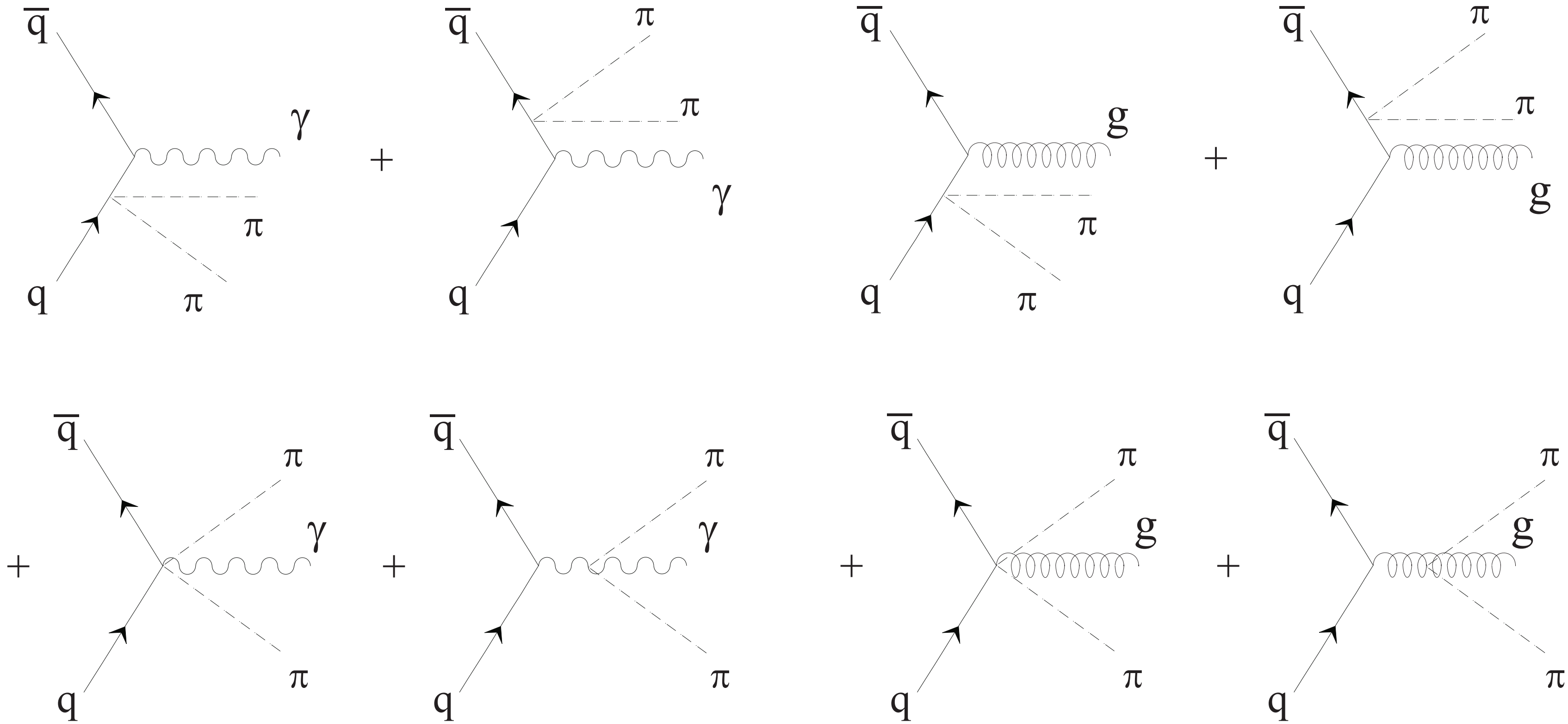
Branon-III (Dobado and Maroto et al)

- Branon Action

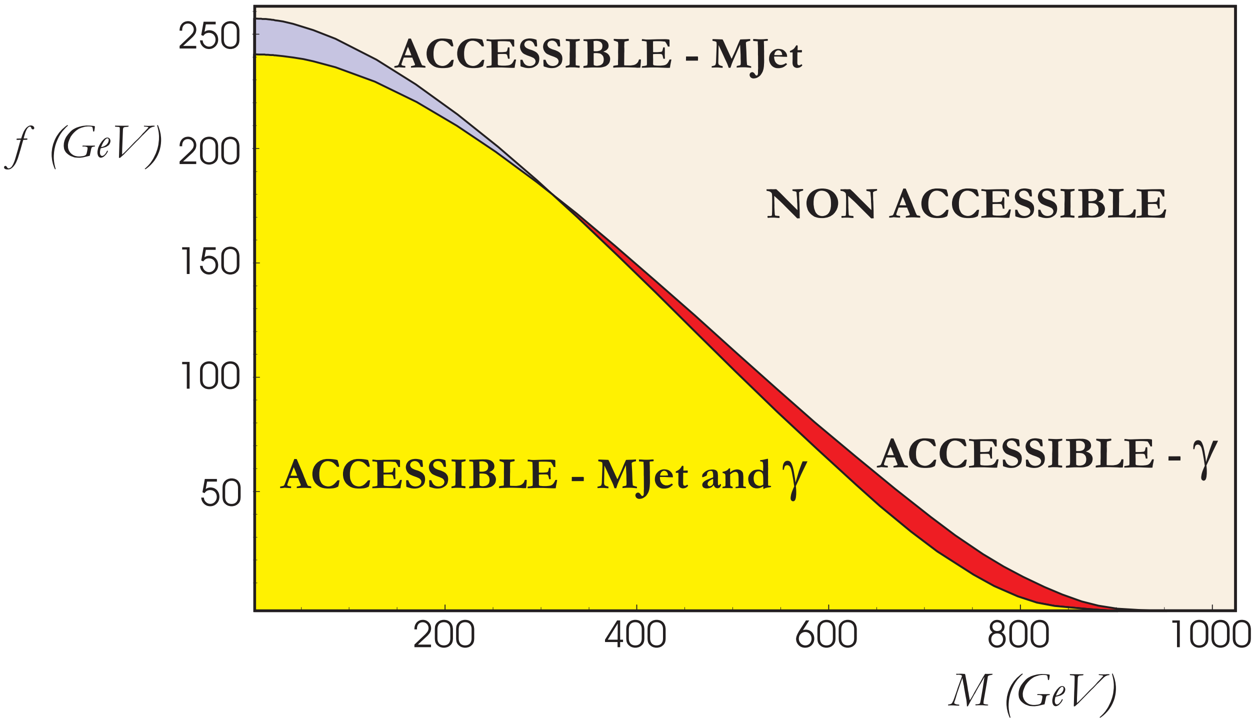
$$S_{\rm Br} = \int_{M_4} d^4x \, \sqrt{g} \, \left[\frac{1}{2} \left(g^{\mu\nu} \partial_\mu \pi^\alpha \partial_\nu \pi^\beta - M^2_{\alpha\beta} \pi^\alpha \pi^\beta \right) + \frac{1}{8f^4} \left(4\partial_\mu \pi^\alpha \partial_\nu \pi^\beta - M^2_{\alpha\beta} \pi^\alpha \pi^\beta g_{\mu\nu} \right) \, T^{\mu\nu}_{\rm SM} \right]$$

- Branons always interact with the SM particles in pairs $\rightarrow$ stable branon $\rightarrow$ Good candidate for DM
- Branons : WIMPS for large f
- Phenomenology in terms of two parameters f and M for one extra dim
- Collider limits
  LEP : $e^+e^- \rightarrow \gamma + 2$ branons : γ + missing energy signature Tevatron : monojet (or single-photon) + missing energy

Branon-Cont’d

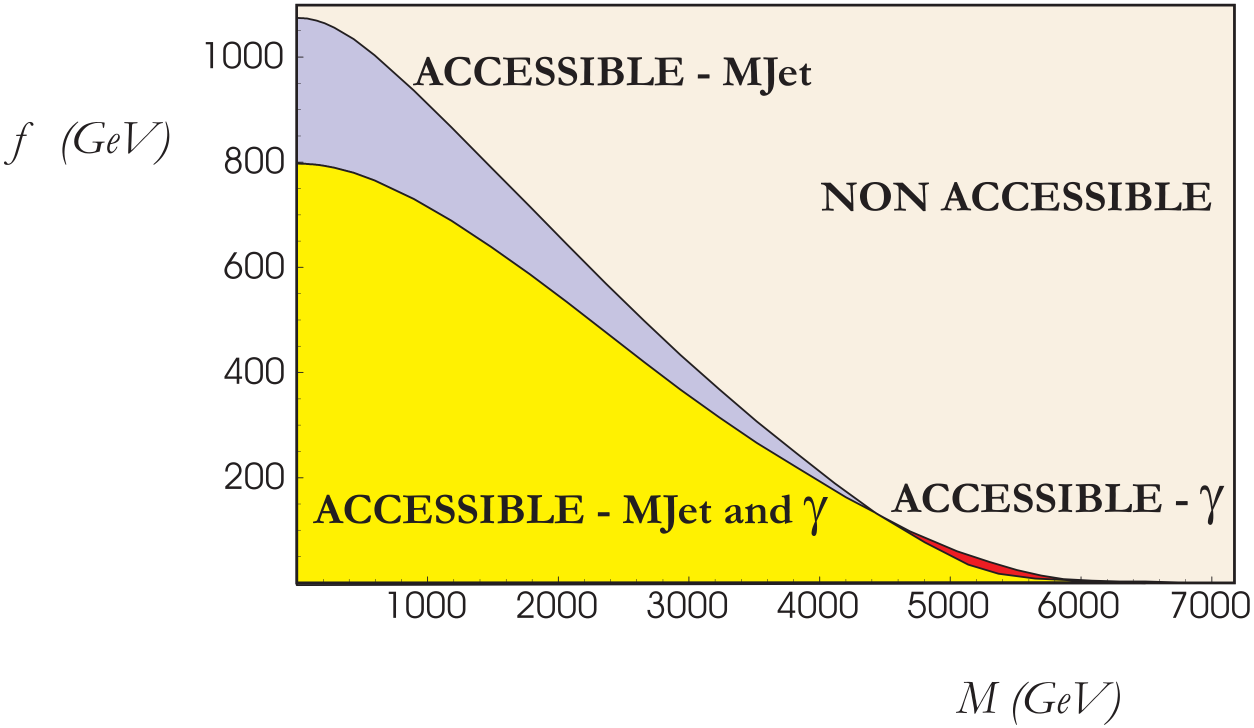


Branon-Cont'd



Tevatron Run II

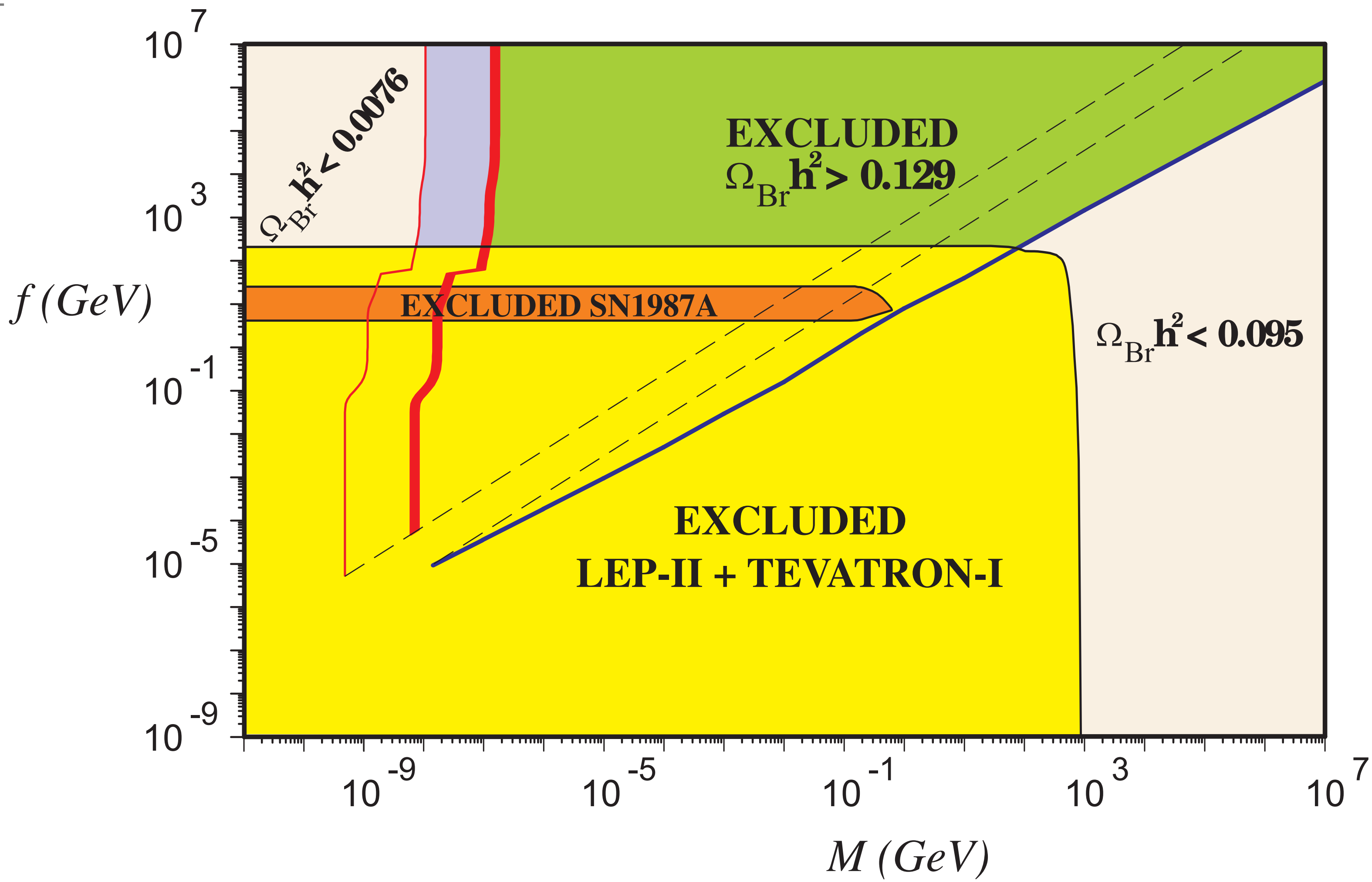
Branon-Cont'd



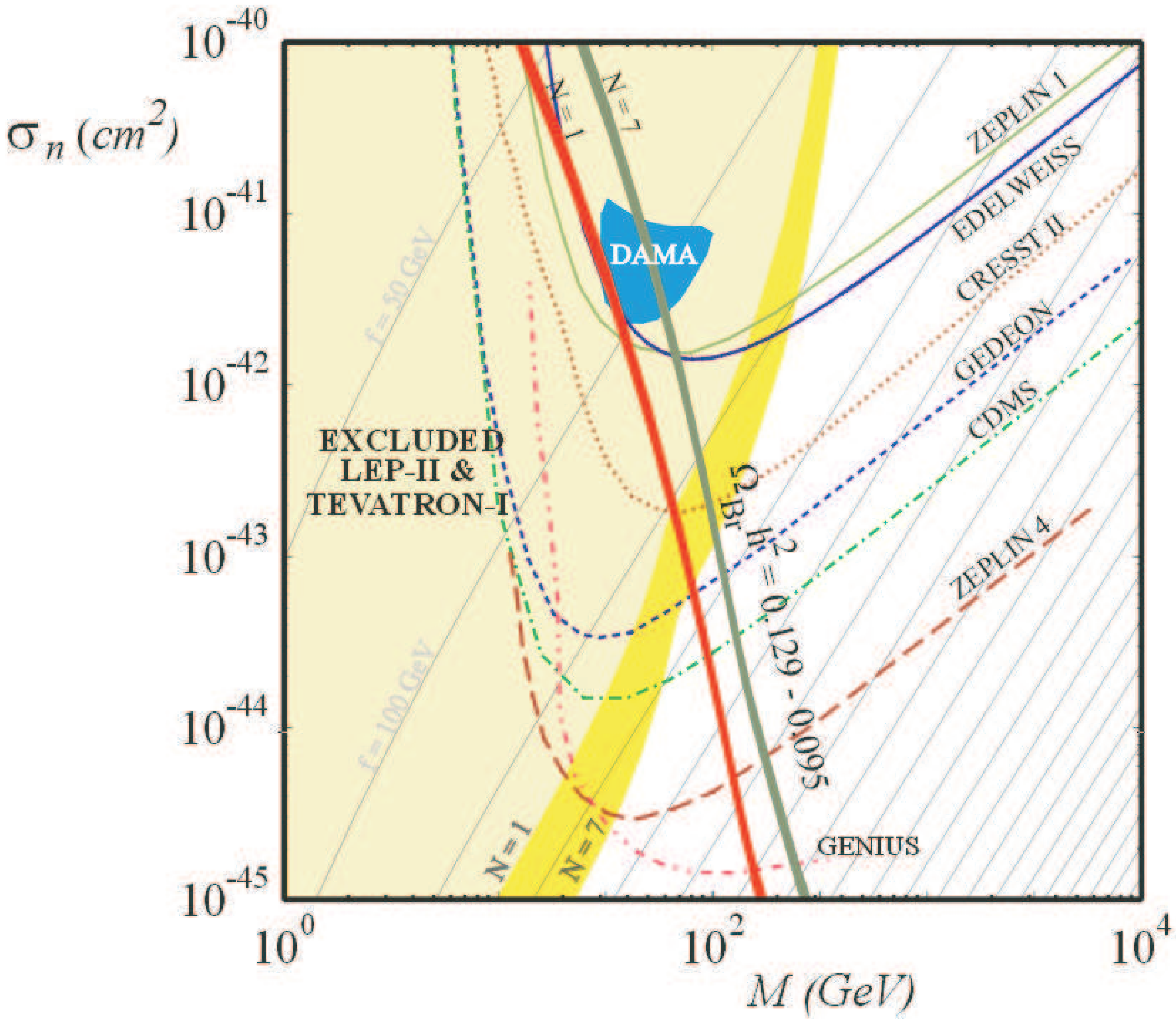
LHC

- Direct search or Indirect searches possible, but at much low rates

Branon-Cont'd



Branon-Cont'd



Lightest KK particle

- Extra Dimension $\rightarrow$ Extra massive particles

$$(\partial_\mu \partial^\mu + \partial_y \partial^y)\ \phi(x) e^{iky} = 0 \quad \rightarrow (\partial_\mu \partial^\mu + k^2)\phi(x) = 0$$

  Single valuedness of the Wave function in the 5-th dim $\rightarrow k = n/R$ (n=1,2,3....)

- Introduce some discrete parity (e.g., Z_2) to make it stable
  cf. R parity in SUSY models

- Lightest KK particles : Bosonic CDM candidate
  cf. Fermionic LSP in SUSY models

- Universal Extra Dimension (UED), Randall-Sundrum (RS), ...

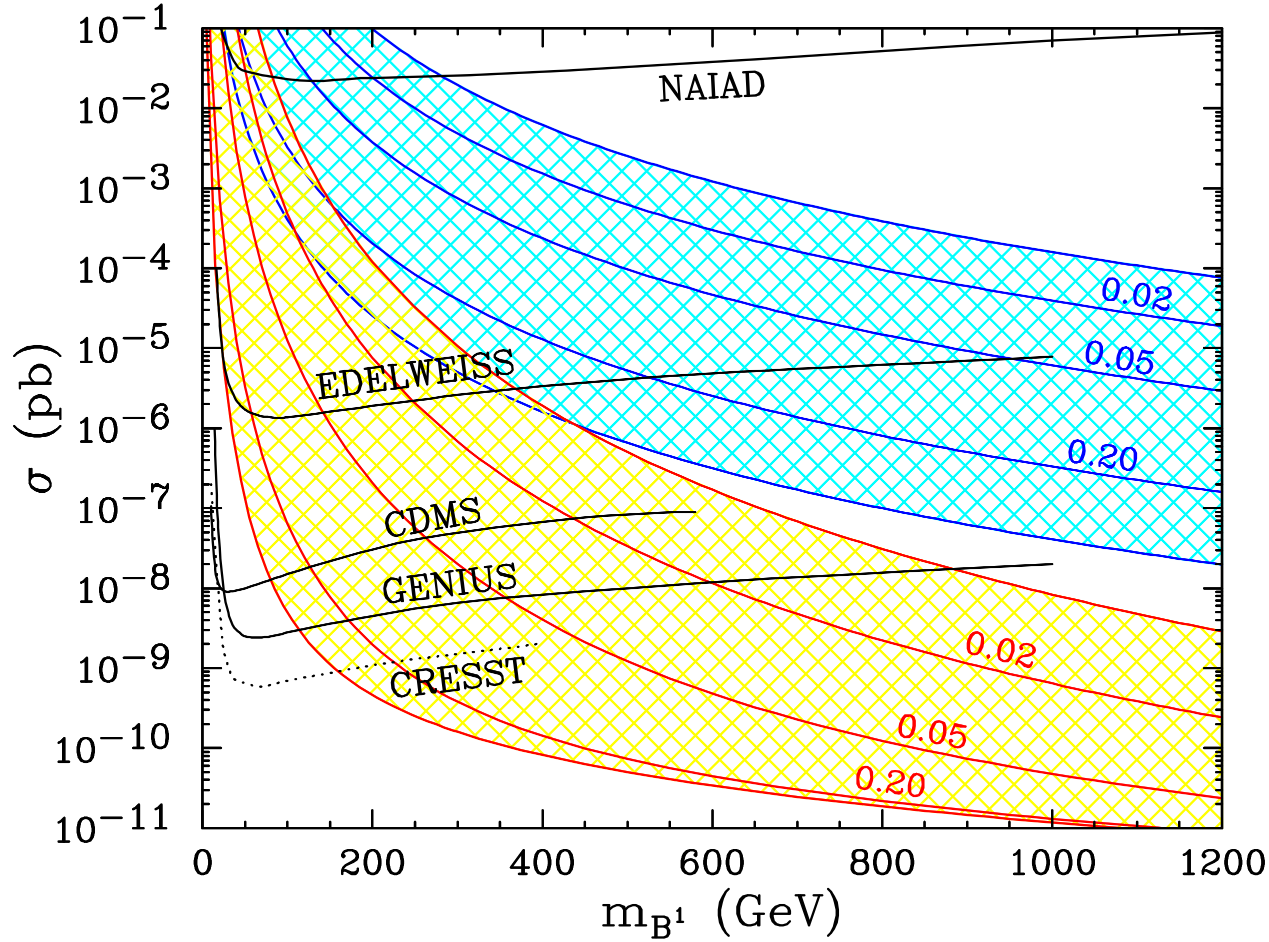
UED-I (Appelquist, Cheng, Dobrescu)

- One extra dim S^1/Z_2 with the size R
- SM particles propagate in the bulk
- All the 1st KK modes have mass $1/R$,
  which is modified by radiative corrections
- Electroweak precision tests $\longrightarrow 1/R > 300$ GeV
  Close to the current Tevatron sensitivity
- LHC can probe upto $1/R \lesssim 1.5$ TeV

UED-II

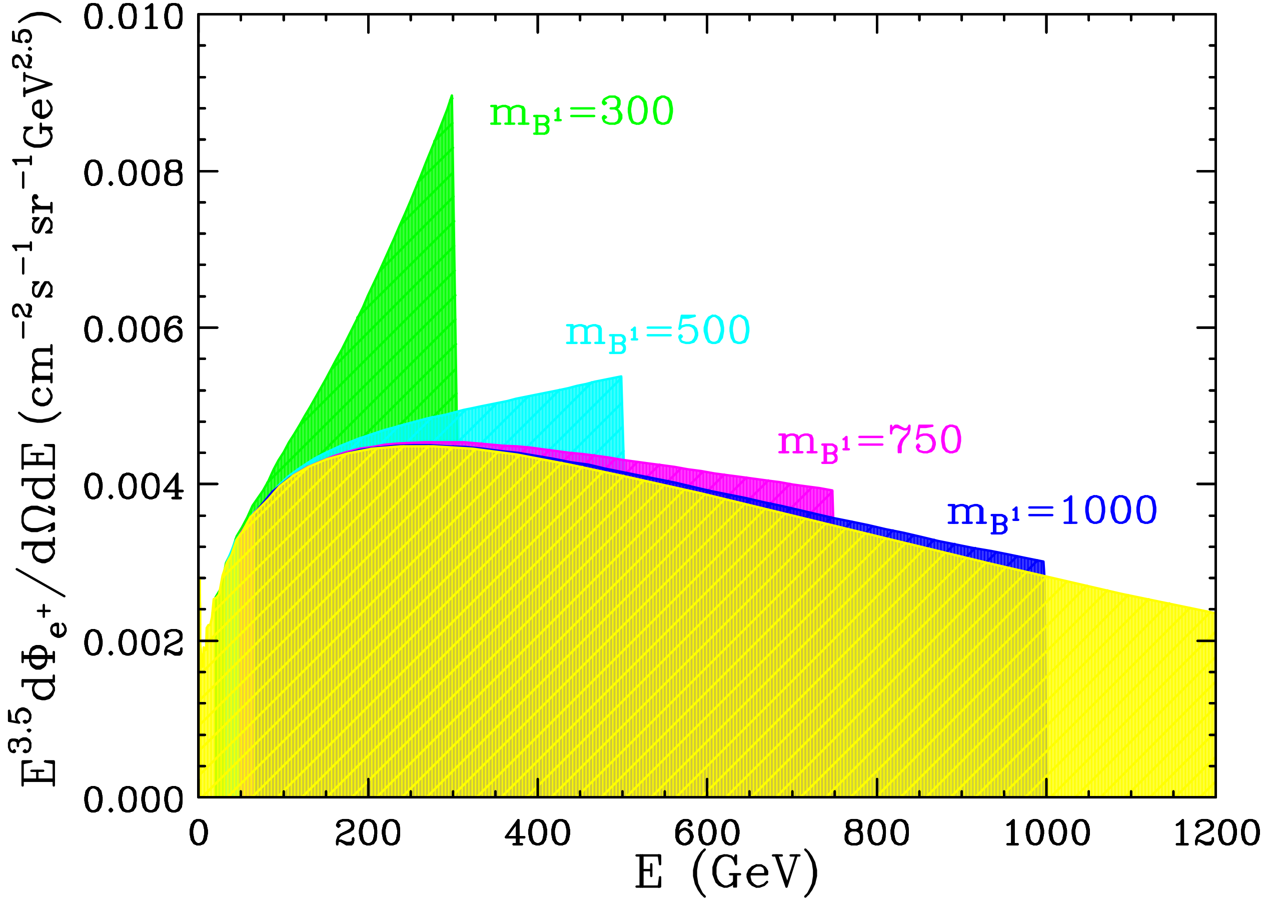
- B_1 : the lightest KK particle after radiative correction
  $\longrightarrow$ Natural candidate for CDM
  $\longrightarrow$ Produce primary e^+ and ν, unlike the SUSY LSP
- B_1 is bosonic, can annihilate effectively through S wave, unlike the neutralino LSP (P wave annihilation)
  $\longrightarrow$ Heavier m_{B_1} can accommodate the relic density (several hundred GeV to a few TeV)
  $\longrightarrow$ Harder e^+, γ and ν compared to the SUSY LSP
- Elastic scattering of B_1 on nuclei (Cheng, Feng, Matchev, PRL)
- Both direct and indirect searches in better shape compared to the SUSY LSP

UED-III



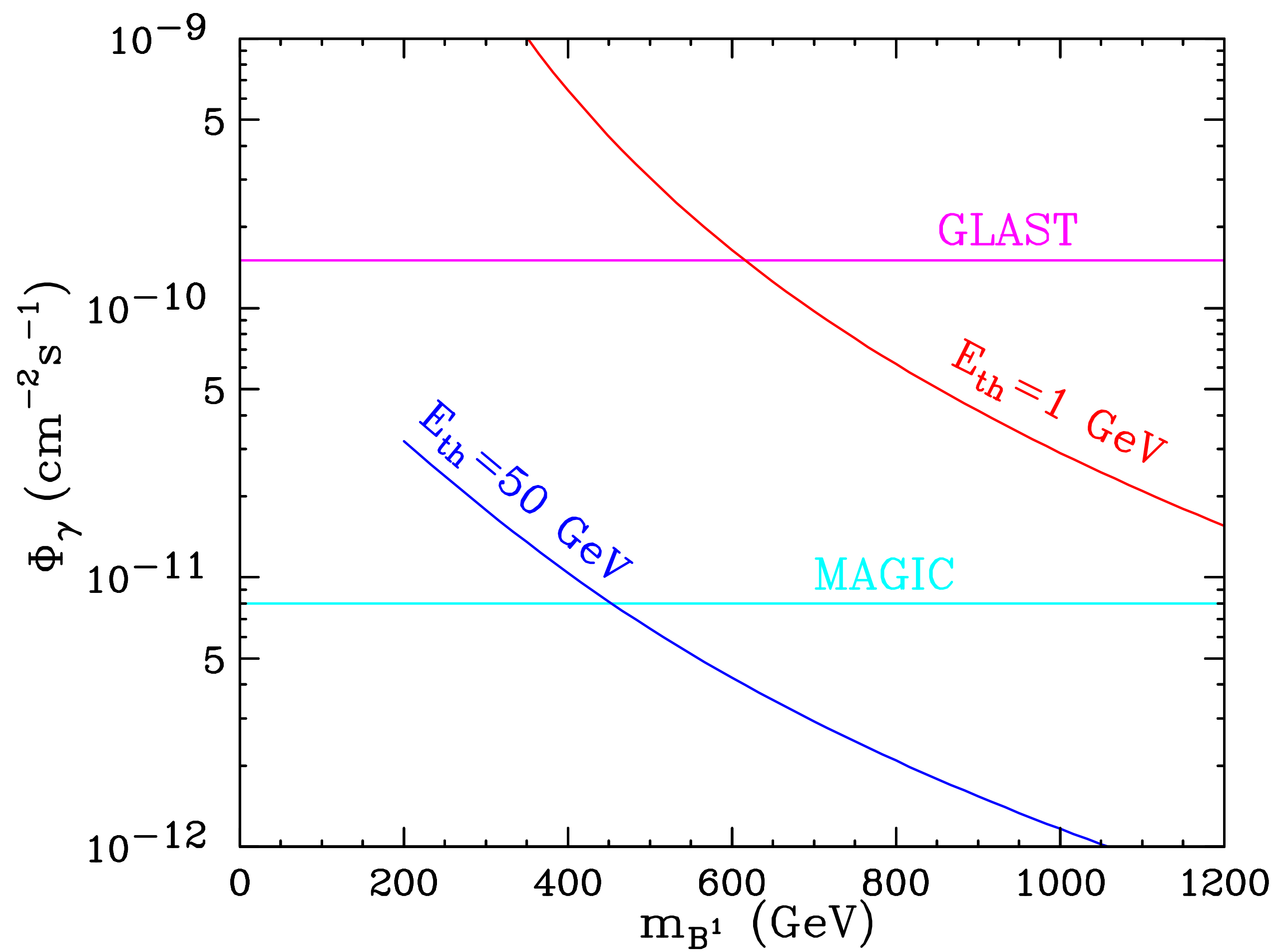
Spin-dep. proton cross sections (blue), along with the projected sensitivity of a 100 kg NAIAD array; and predicted spin-indep. proton cross sections (red), along with the current EDELWEISS sensitivity, and projected sensitivities

UED-IV



Predicted positron signals (dark shaded) above background (light shaded) as a function of positron energy for $= m_{e^1_L} = m_{e^1_R} = 100$, 500, 750, and 1000 GeV.

UED-V



Integrated photon flux as a function of for energy thresholds of 1 and 50 GeV. Projected sensitivities for GLAST and MAGIC are also shown.

Singlet scalar

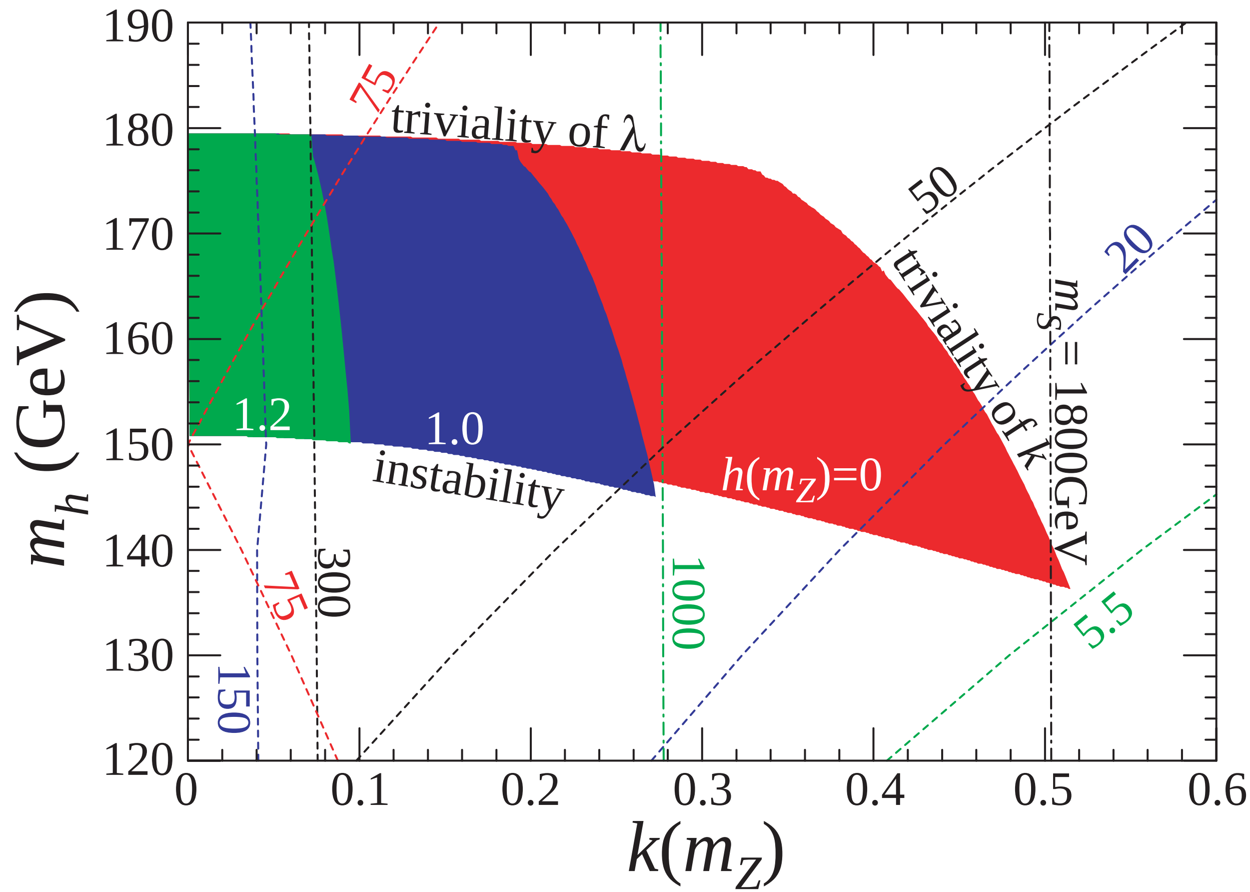
- The simplest extension of the SM for DM
  Just add one more additional degree of freedom
- One real scalar S with Z_2 parity -1
  $\longrightarrow$ Stability of S

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4$$

H : the SM Higgs
(C. Burgess et al.; Murayama et al)

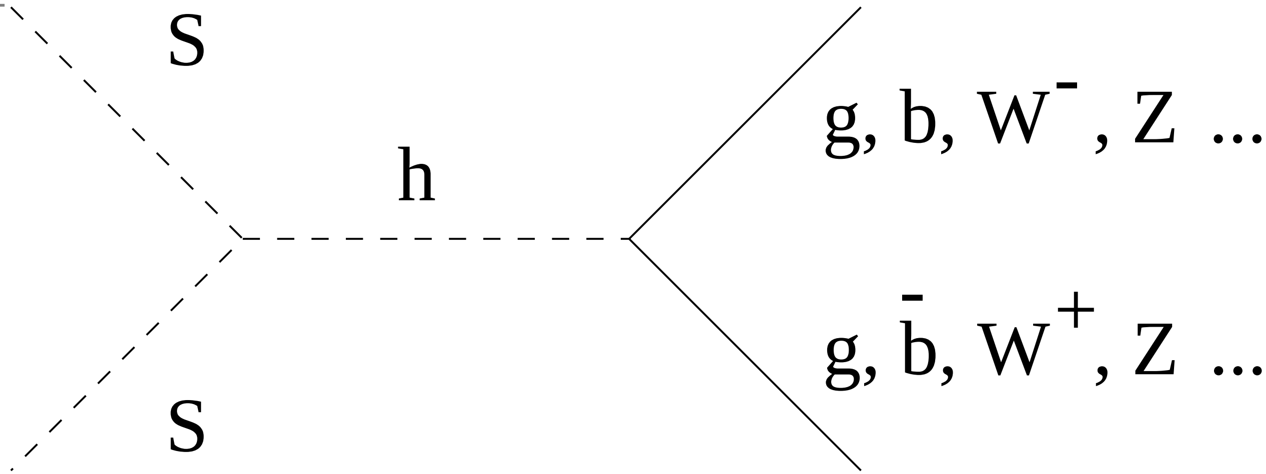
Singlet scalar-Cont'd

- prediction: 130 GeV $\lesssim m_h \lesssim$ 180 GeV



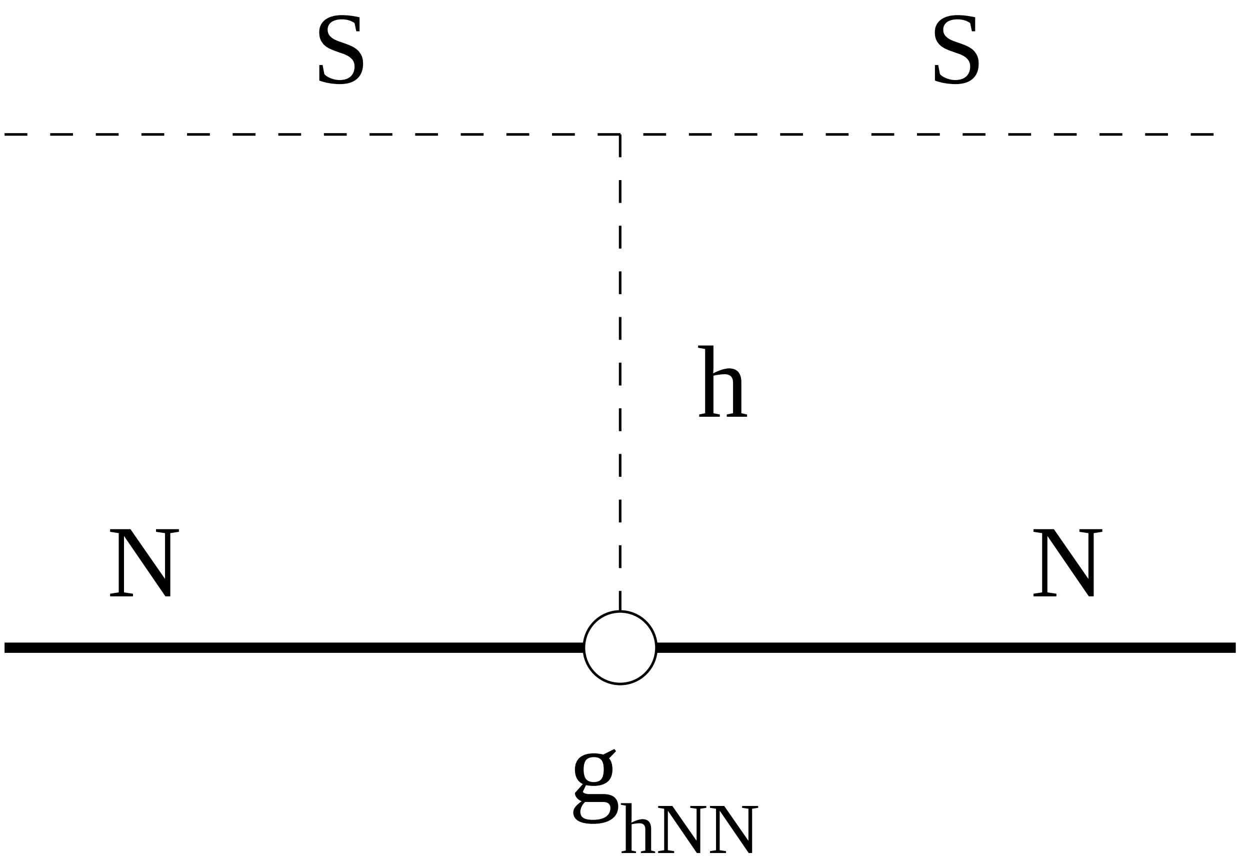
- Triviality and unitarity bound: 5.5 GeV $\lesssim m_S \lesssim$ 1.8 TeV

Singlet scalar-Annihilation

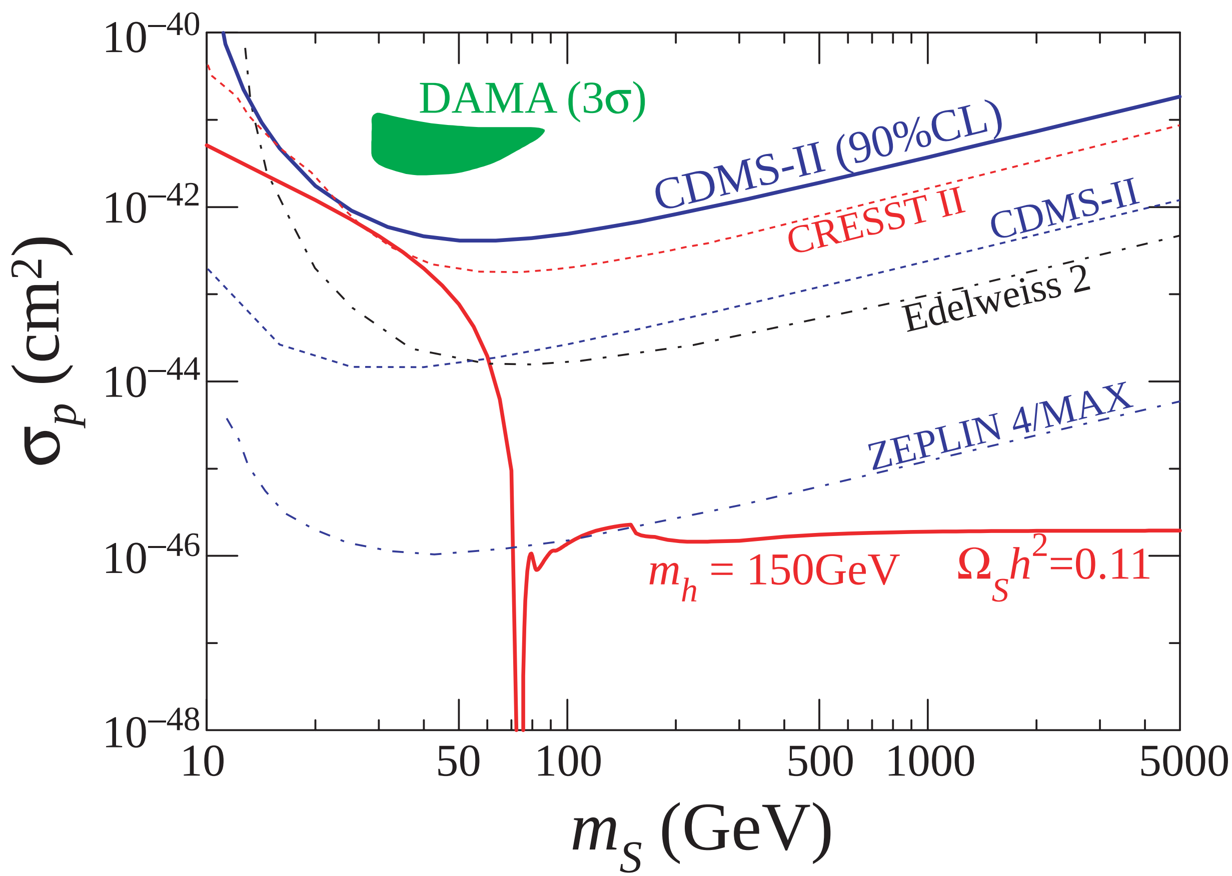


Easy to satisfy WMAP data (previous fig. for $\Omega_S h^2 = 0.11$)

Singlet scalar-Direct detection of relic S



Singlet scalar-Cont'd



$m_S = 75$ GeV : Annihilation through Higgs pole

Model-I

- Assume the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} - \frac{\lambda_H}{4}\,(H_1^\dagger H_1)^2 - \frac{\mu_1^2}{2}\,H_1^\dagger H_1 + \mathcal{L}_{\text{Yukawa}}$$

- Hidden sector lagrangian with new strong interaction

$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{h,f}} \overline{\mathcal{Q}}_k(i\mathcal{D}\cdot\gamma - M_{\mathcal{Q}_k})\mathcal{Q}_k$$

- Is it possible to achieve EWSB with $\mu_1^2 = 0$?
  $\rightarrow$ Yes ! (classical scale symemtry in the SM, but not in the hidden sector)
- Interaction between two sectors suppressed by powers of $1/\Lambda_{\text{mess}}$

Model-I

- For simplicity, assume $N_{h,f} = 2$ with $SU(2)_L \times SU(2)_R$ global chiral symmetry in the hidden sector, which is spontaneously broken into diagonal $SU(2)_V$, as in ordinary QCD with two light flavors (u, d)
- $\Lambda_{h,\chi} \approx 4\pi\Lambda_H$, where Λ_H is the hidden sector confining scale, and similar to the hidden sector pion decay constant
- First, construct the effective theory of the strongly interacting hidden sector for $N_{h,f} = 2$ and $M_{\mathcal{Q}_k} \ll \Lambda_{h,\chi}$
- Hidden sector pions: pseudo NG bsons
- Gell-Mann-Levy's Linear σ model (or Nonlinear σ model)
- Use linear σ model in Model-I

Model-I

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \left(\begin{array}{c} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{array} \right), \qquad H_2 = \left(\begin{array}{c} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{array} \right)$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

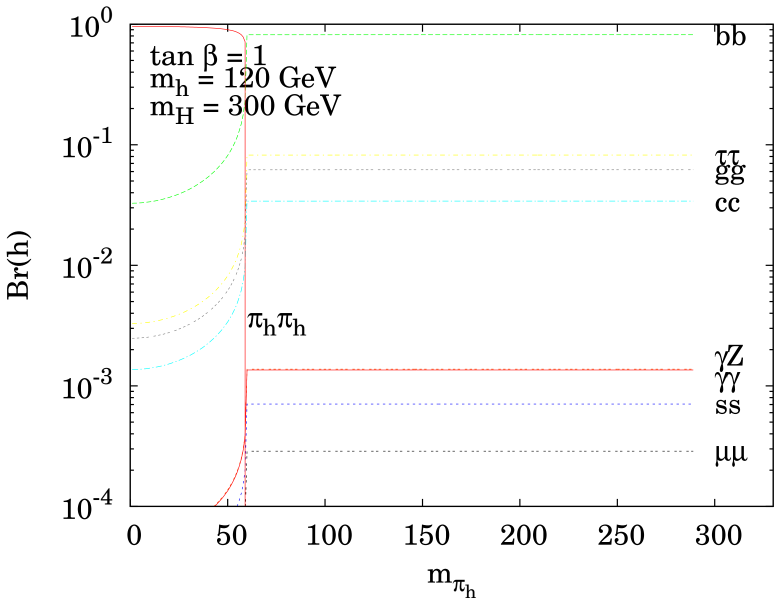
Model-I

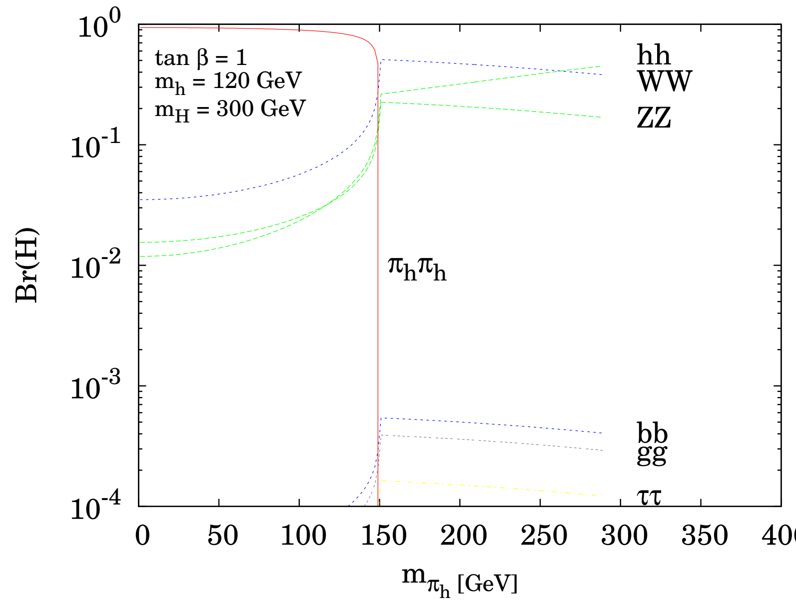
- Our model is similar to the usual two-Higgs doublet models with two important differences:
  - H_2 : SM singlet, not like in the usual two-Higgs doublet model, and W, Z get masses only from $\langle H_1 \rangle$, and not from $\langle H_2 \rangle$
    $\longrightarrow$ No problem with S and T parameters
  - $a\sigma_h$ term: new in our model, and breaks the chiral symmetry explicitly $\longrightarrow$ Massive CDM
- H_2 does not couple to the SM fermions
  $\longrightarrow$ No Higgs-mediated FCNC problem
- $\pi_h^{\pm,0}$: pseudo NG bosons, and stable due to chiral symmetry, without imposing ad hoc Z_2 symmetry as in many CDM models $\longrightarrow$ Good CDM candidate
- Charges of π_h are the I_3 quantum number, not electric charge

Model-I

- h and H are mixtures of $h_{\rm SM}$ and σ_h: partially composite
- $h(H) - V - V$ couplings : the same as the $H_{\rm SM} - V - V$ couplings modulo $\cos\alpha$ and $\sin\alpha$
- the same is true for the $h(H) - f - \bar{f}$ with SM fermions f couplings
- Productions of h and H at colliders are suppressed by $\cos^2\alpha$ and $\sin^2\alpha$, relative to the production of the SM Higgs with the same mass
- $h(H) - \pi_h - \pi_h$ couplings contribute to the invisible decays $h(H) \to \pi_h \pi_h$
- 4 parameters for $\mu_1^2 = 0$: $\tan\beta$, m_{π_h}, λ_1 and λ_2 or trade the last two with m_h and m_H

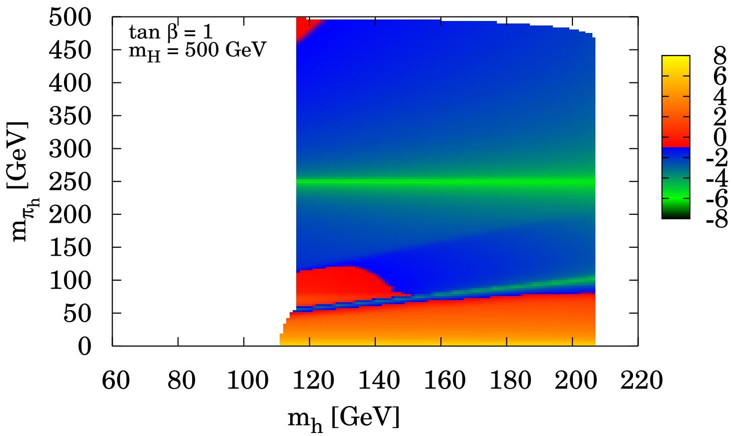
Model-I : Spectra and branching ratios

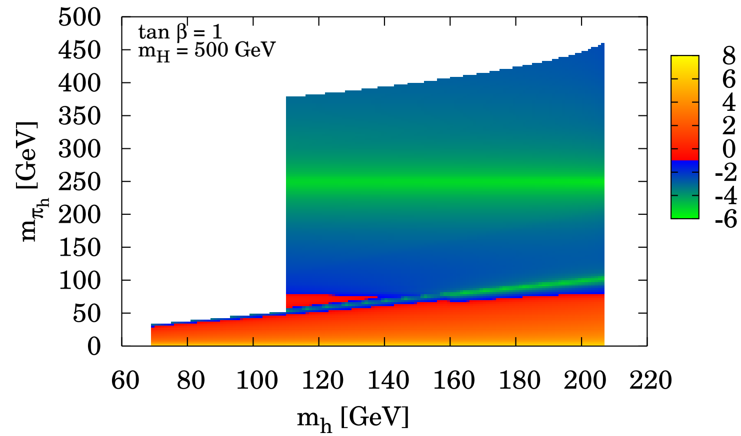




- Branching ratios of h and H as functions of m_{π_h} for $\tan\beta = 1$, $m_h = 120$ GeV and $m_H = 300$ GeV.
- $h, H \to \pi_h\pi_h$: invisible decay branching ratios make difficult to detect them at colliders

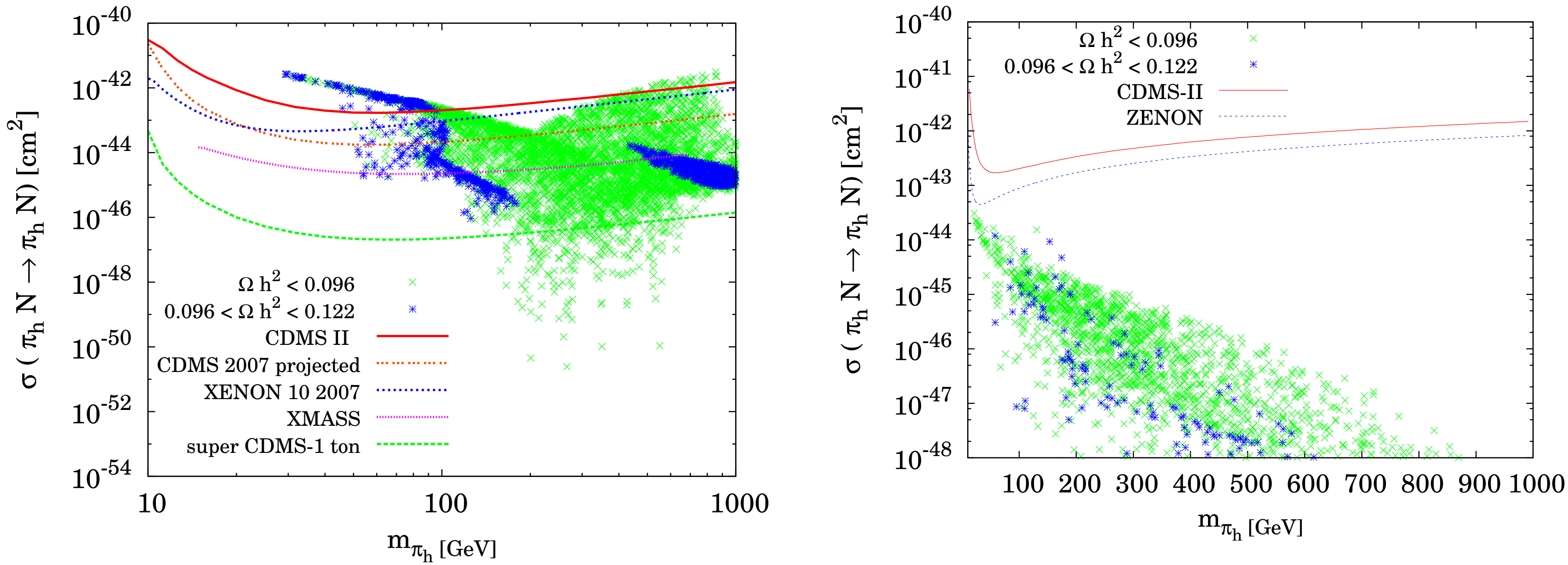
Model-I : Relic density of π_h





- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Model-I : Direct detection rate



- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

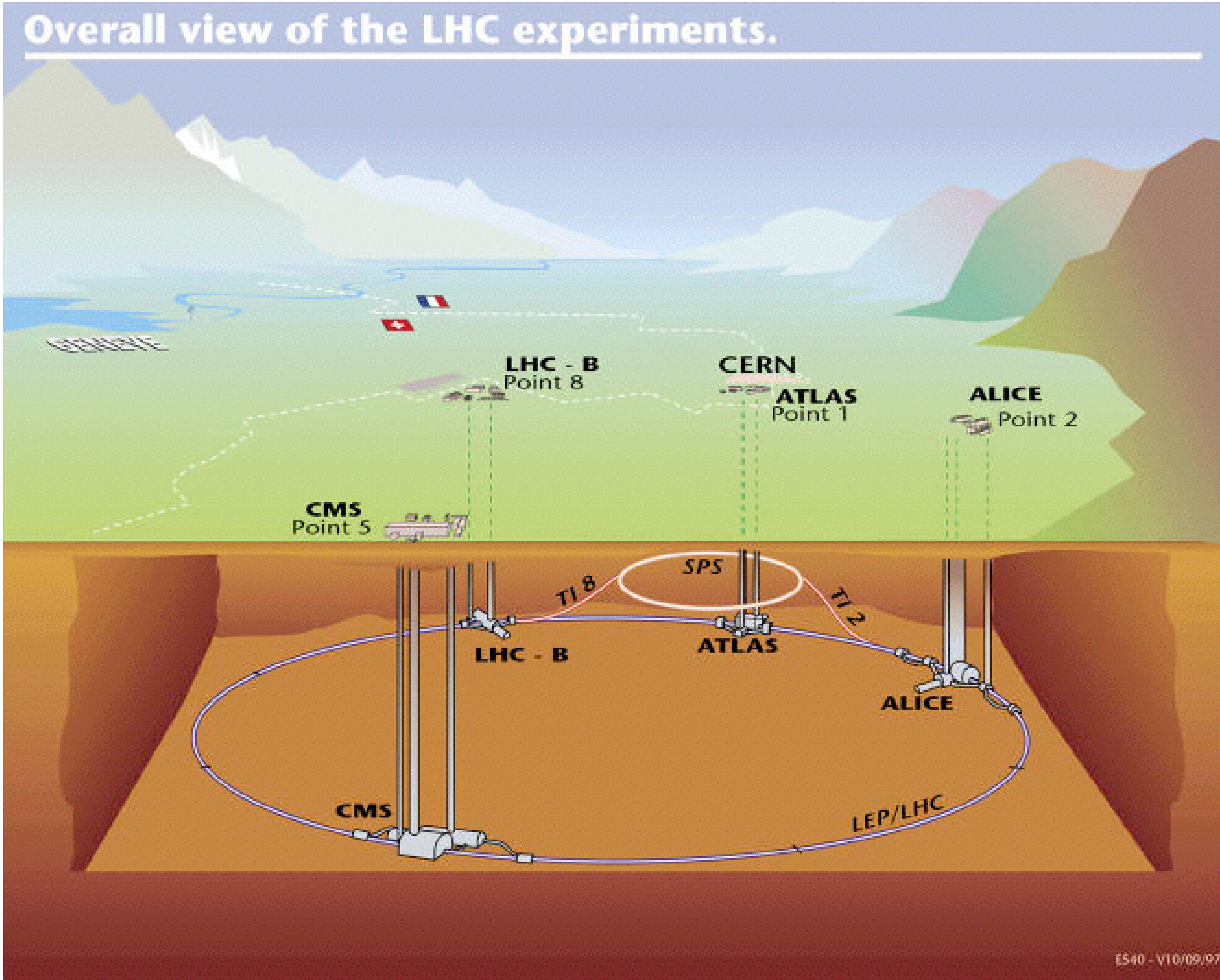
Summary Table

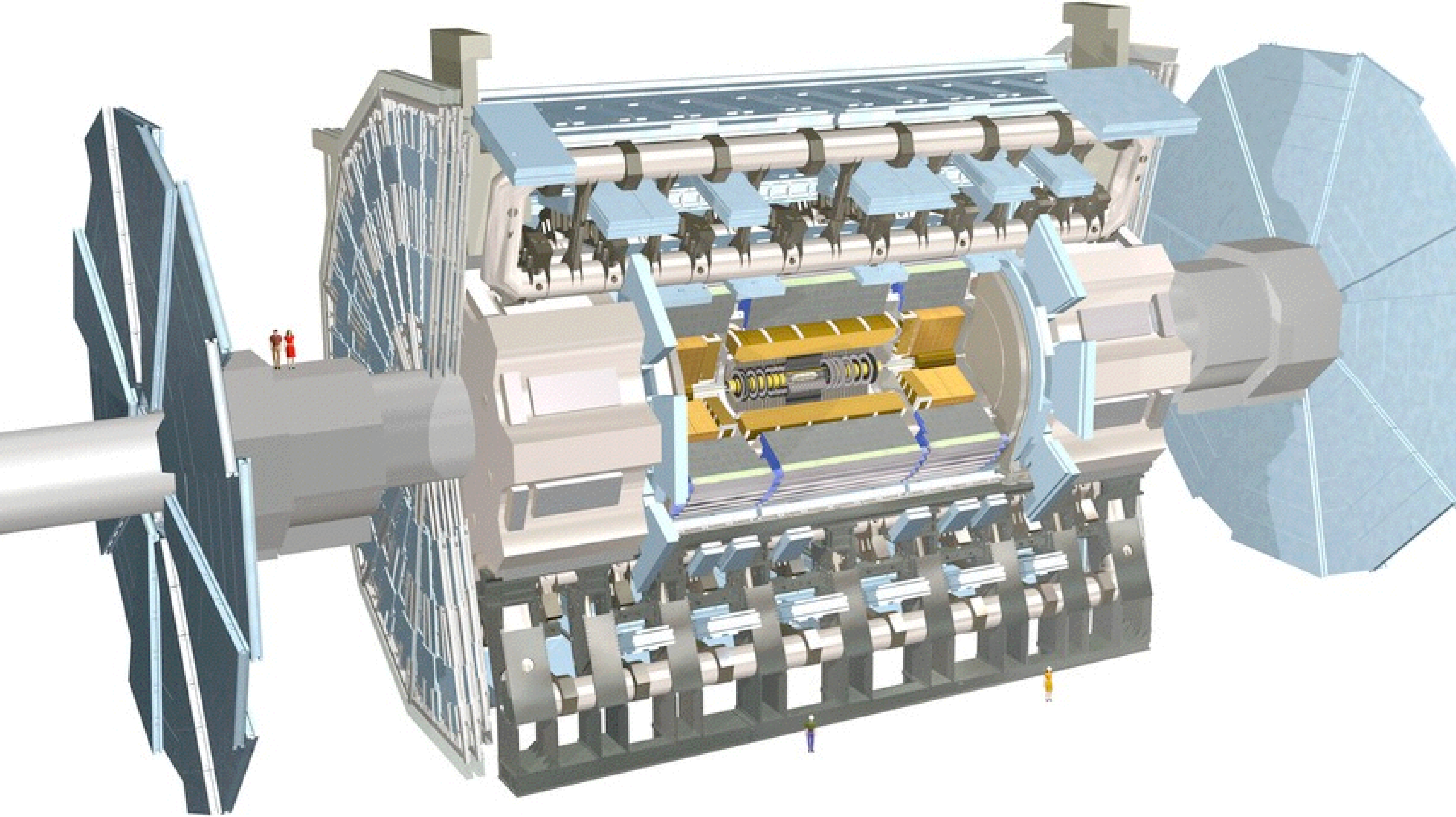
Table 1:

DM	Motivation	(In)Direct Det.	Collider
singlet scalar	minimality	Y	Y
axion	Strong CP	Y	N
axino	axion + SUSY	N	Y
neutralino	SUSY	Y	N
light gravitino	Gauge mediation	N	Y
heavy gravitino	SUGRA	N	Y
LKP	extra dim	Y	Y
branon	Brane world	Y	Y

the Geneva region

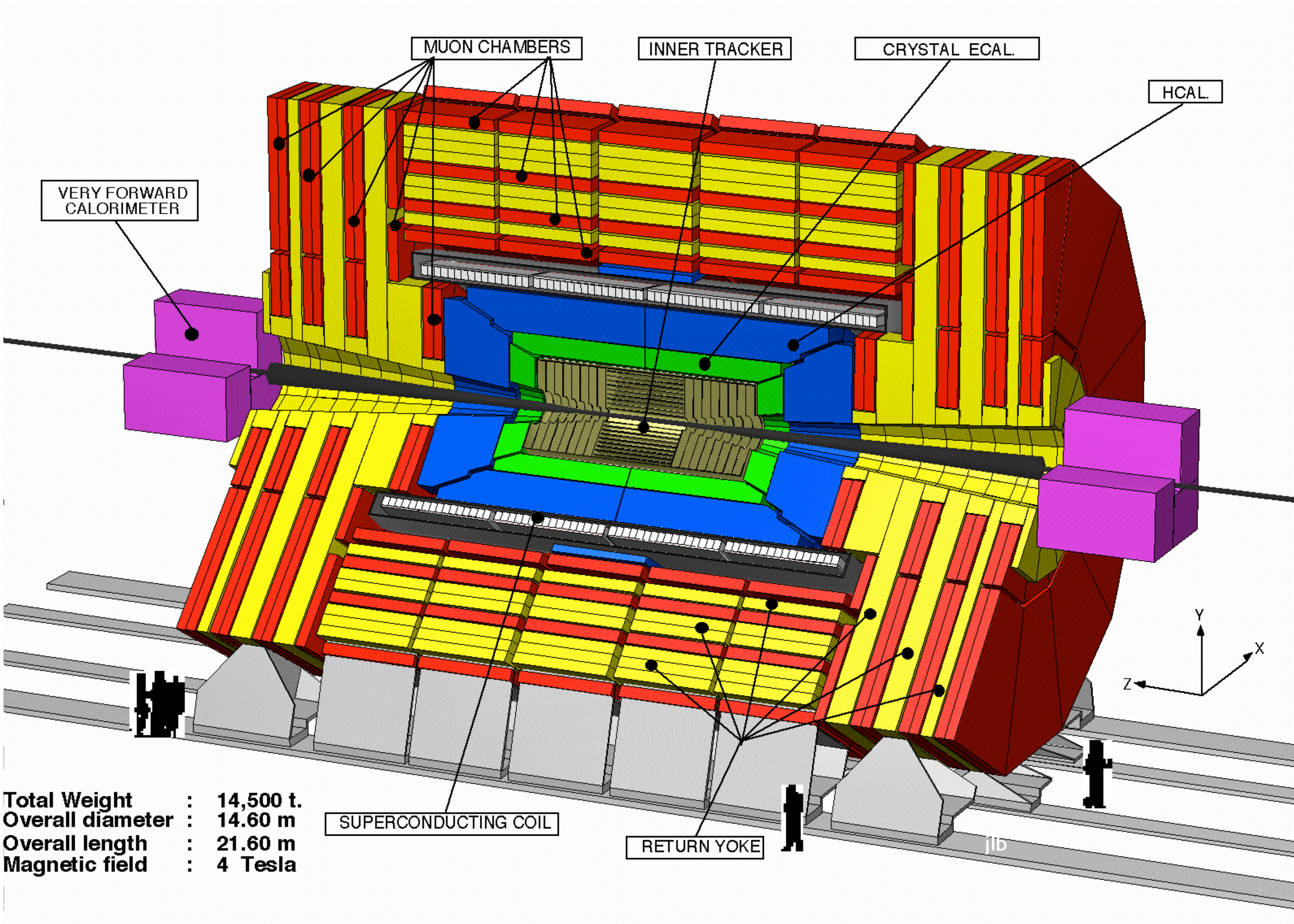
with the CERN Large Hadron Collider


Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

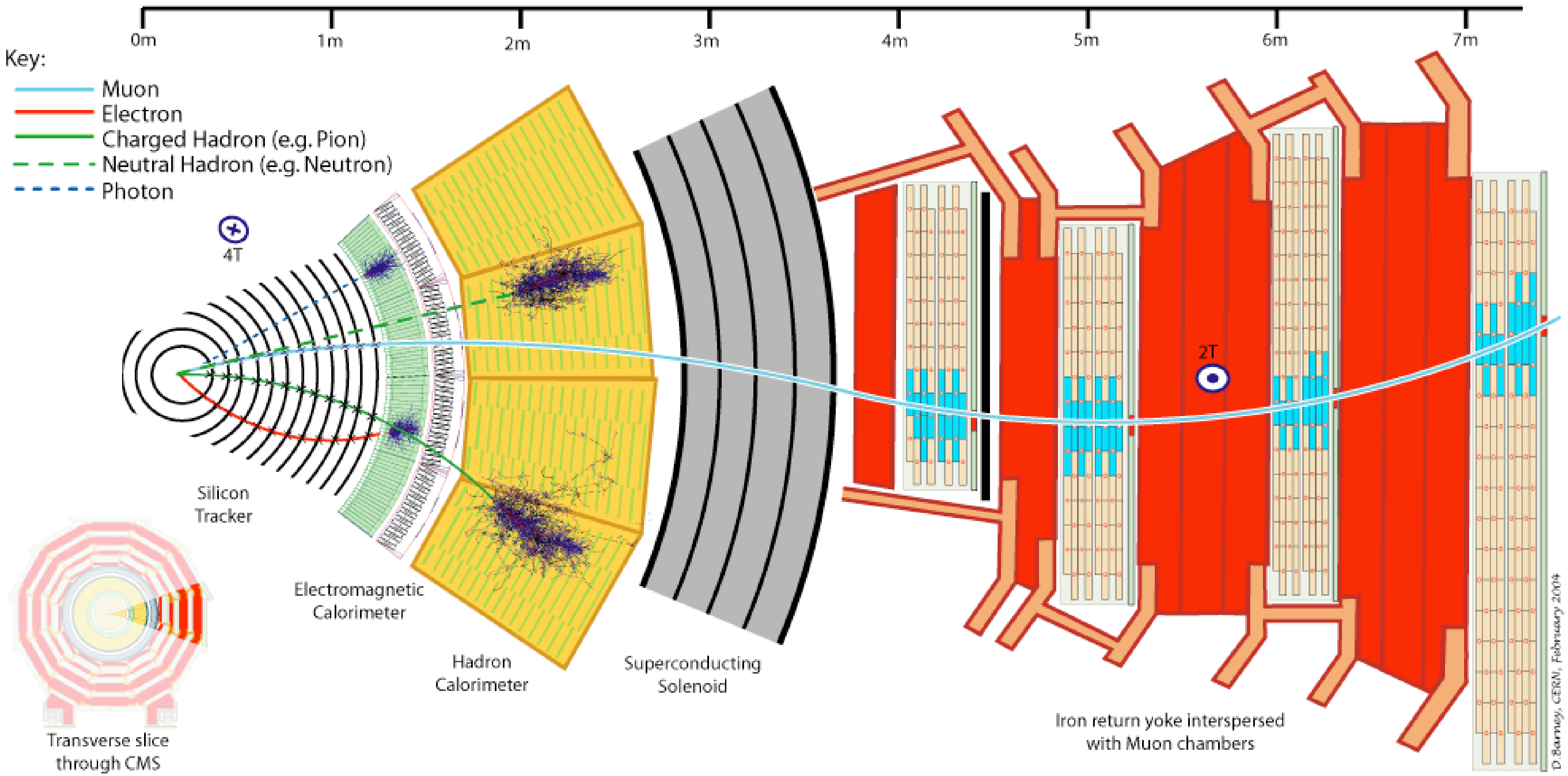


the ATLAS experiment

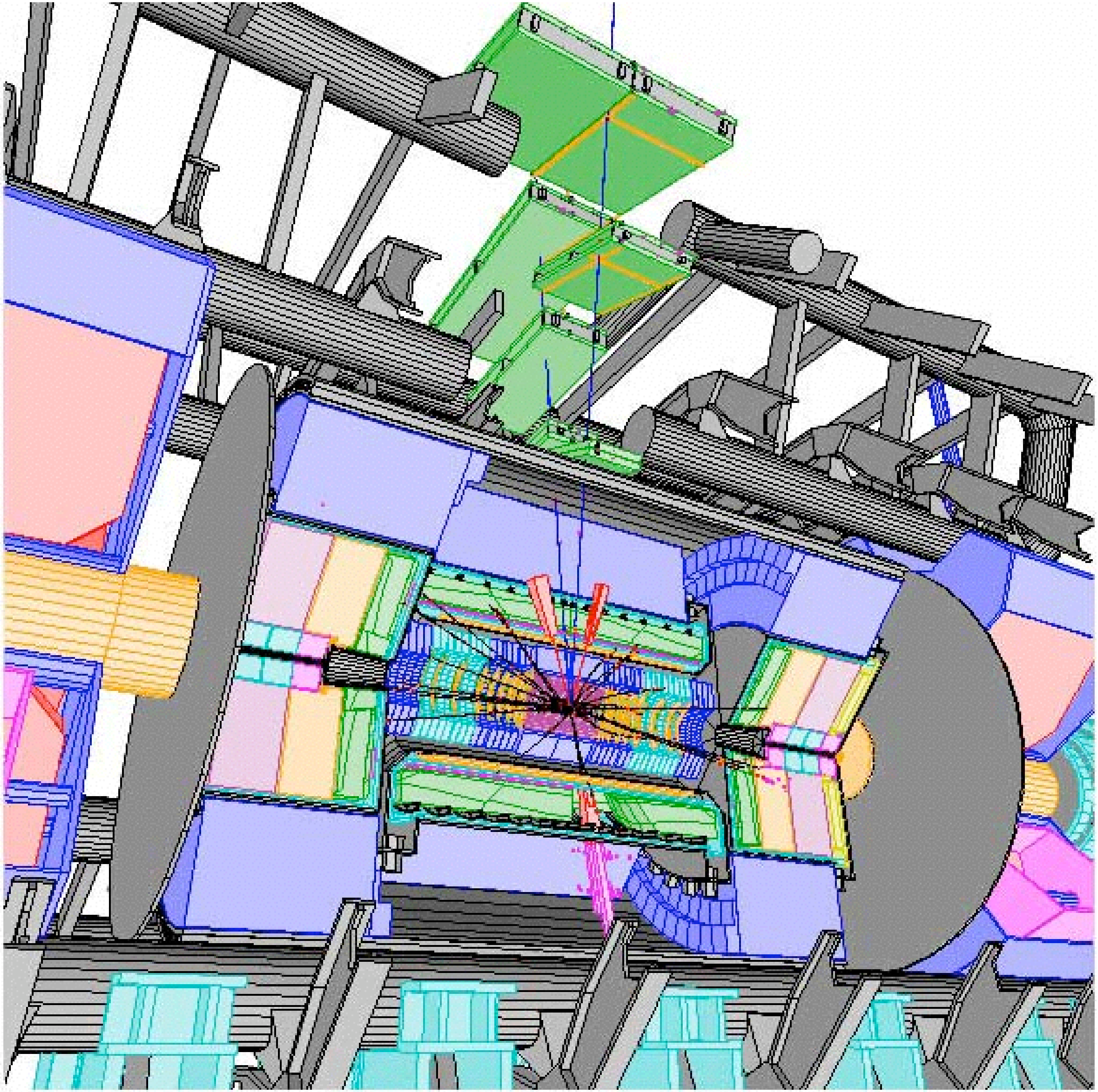
A Compact Solenoidal Detector for LHC



Total Weight	:	**14,500 t.**
Overall diameter	:	**14.60 m**
Overall length	:	**21.60 m**
Magnetic field	:	**4 Tesla**

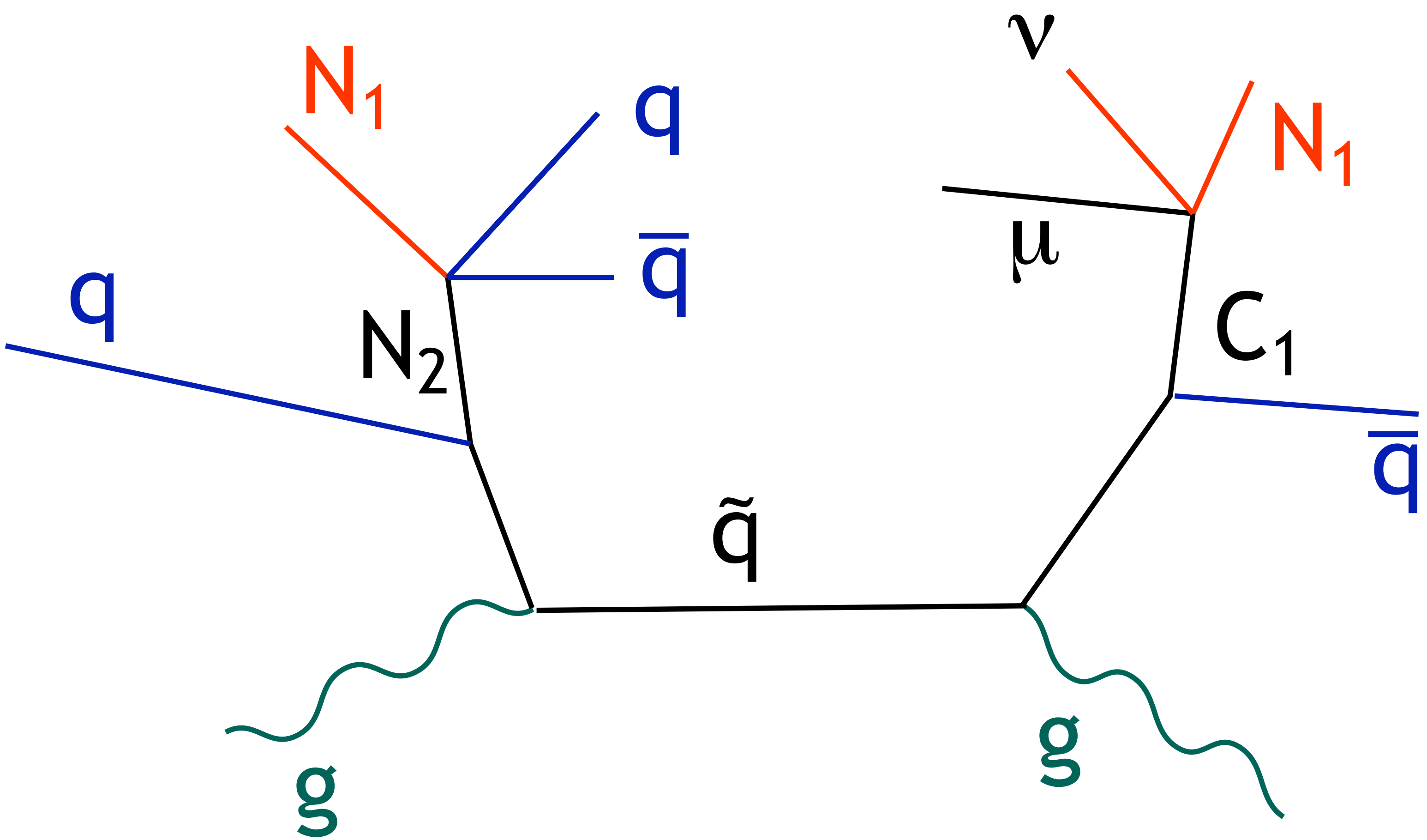


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004



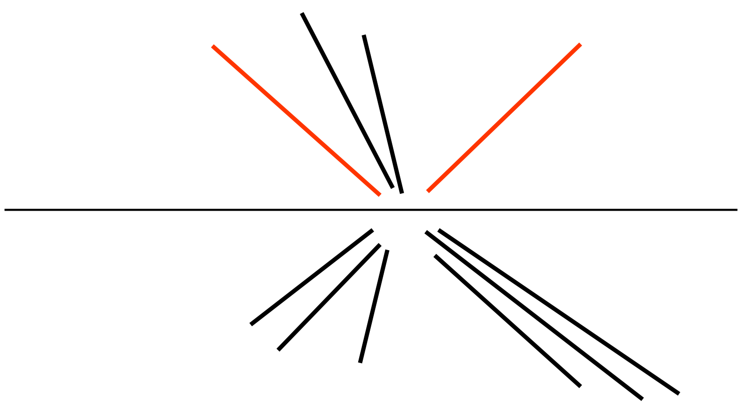
simulated high-
energy event in
ATLAS

Here is the sort of event we are looking for. A gluon-gluon collision produces a pair of heavy particles carrying the conserved quantum number of the WIMP. These particles decay, emitting quarks and leptons. The final decay product on each side is the WIMP, which exits the detector unobserved.



Now we come to the second question: Dark matter particles are invisible to an LHC detector.

Fortunately, if dark matter is part of a new sector of particles, some of which have strong interactions, there is expected to be plenty of other activity in these events. The events are characteristic in that they have large deposited energy and apparently unbalanced pT.



We have to identify these events from transverse energy flow only. Crucial variables are:

$$\not{E}_T \qquad H_T = \not{E}_T + \sum_i E_{Ti}$$

Conclusions

- $\Omega_{\rm DM}h^2 = 0.111 \pm 0.006$: clear evidence for nonbaryonic DM
  $\rightarrow$ calls for new physics beyond the SM
- Many DM candidates in particle physics models : axion, axino, neutralino, gravitino, branon, lightest KK particle (LKP), WIMPZILLA, real scalar, etc.
- Which one(s) ?
  Experiments will give answer to this question.
  Not easy at all, however.
  Need a lot of work, money and also good luck as well.