
The 11th ICFA Seminar on Future Perspectives in High-Energy Physics
Institute of High Energy Physics, CAS, October 27-30, 2014


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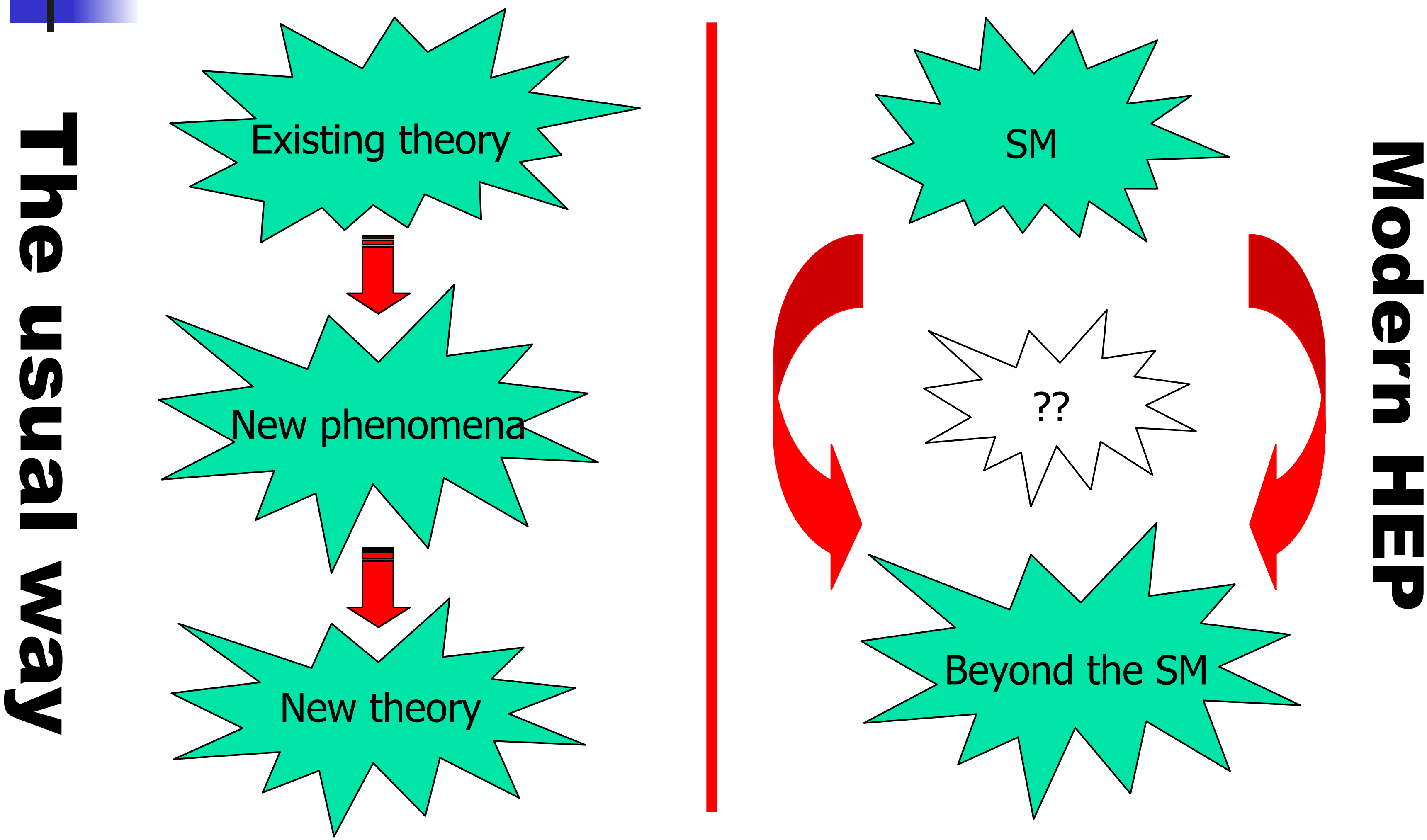
BEIJING

BEYOND THE STANDARD MODEL' 14

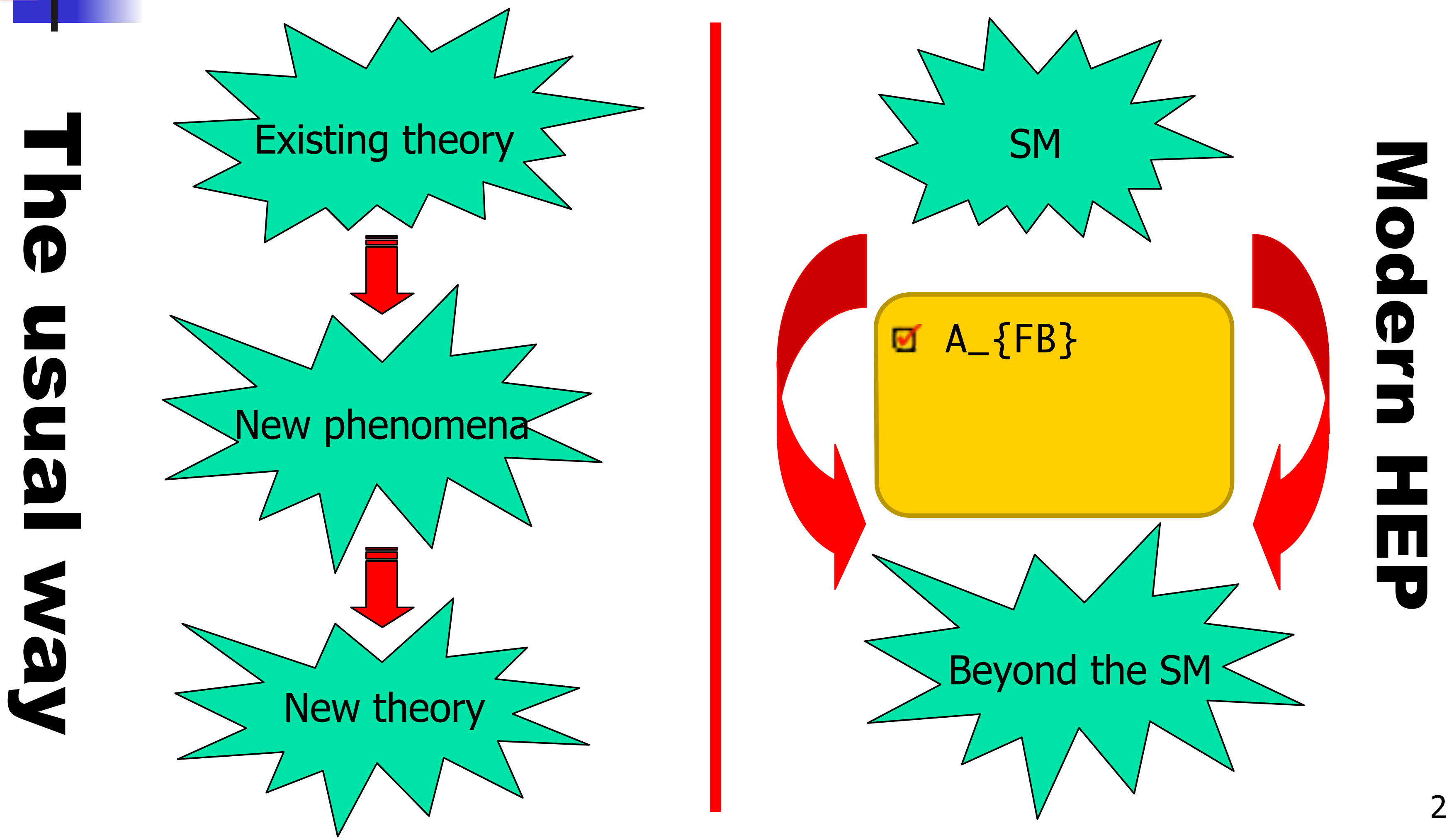
Dmitri Kazakov
Bogoliubov Lab, JINR (Dubna)

HEP Paradox



The usual way
Existing theory
New phenomena
New theory
SM
??
Beyond the SM
Modern HEP

HEP Paradox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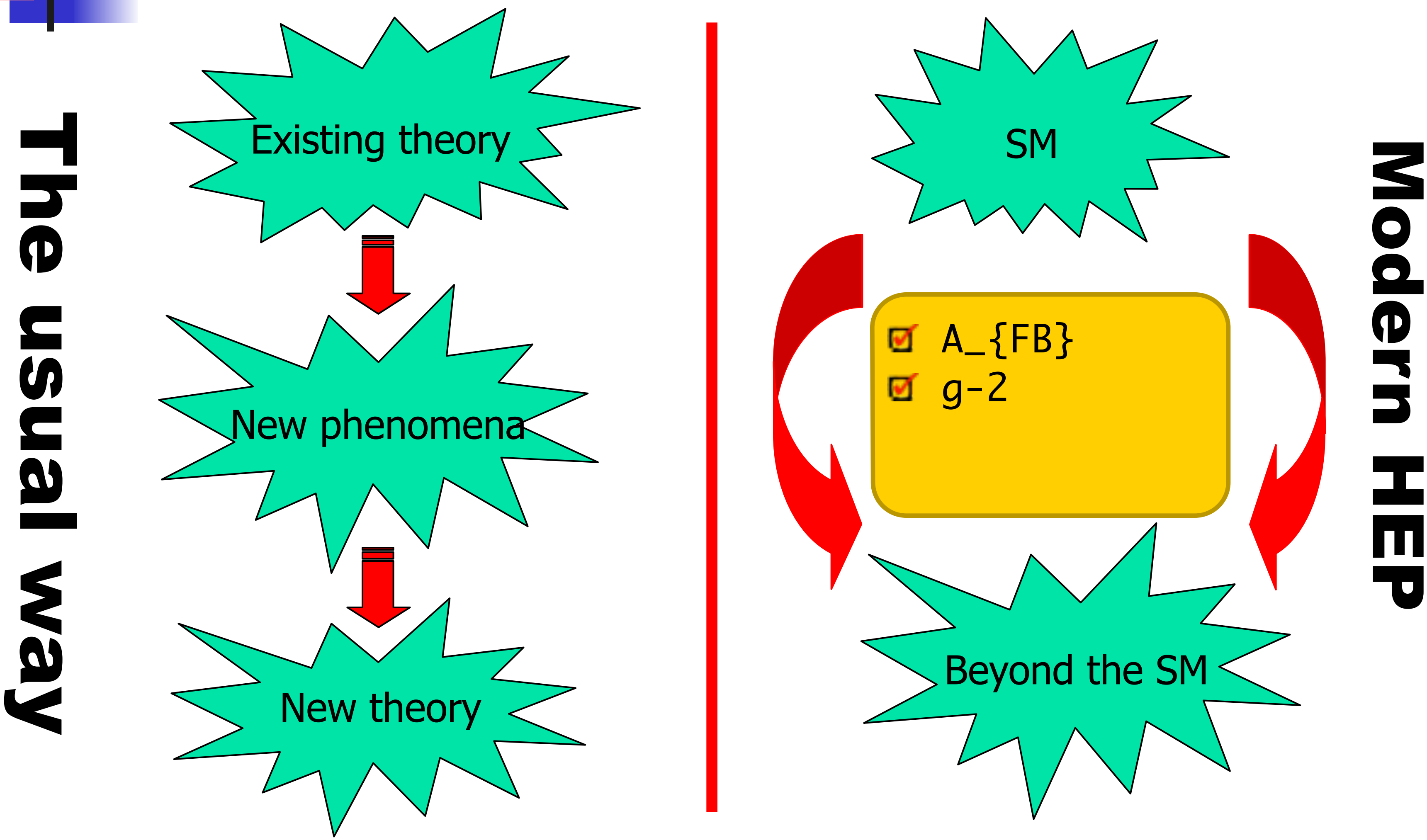

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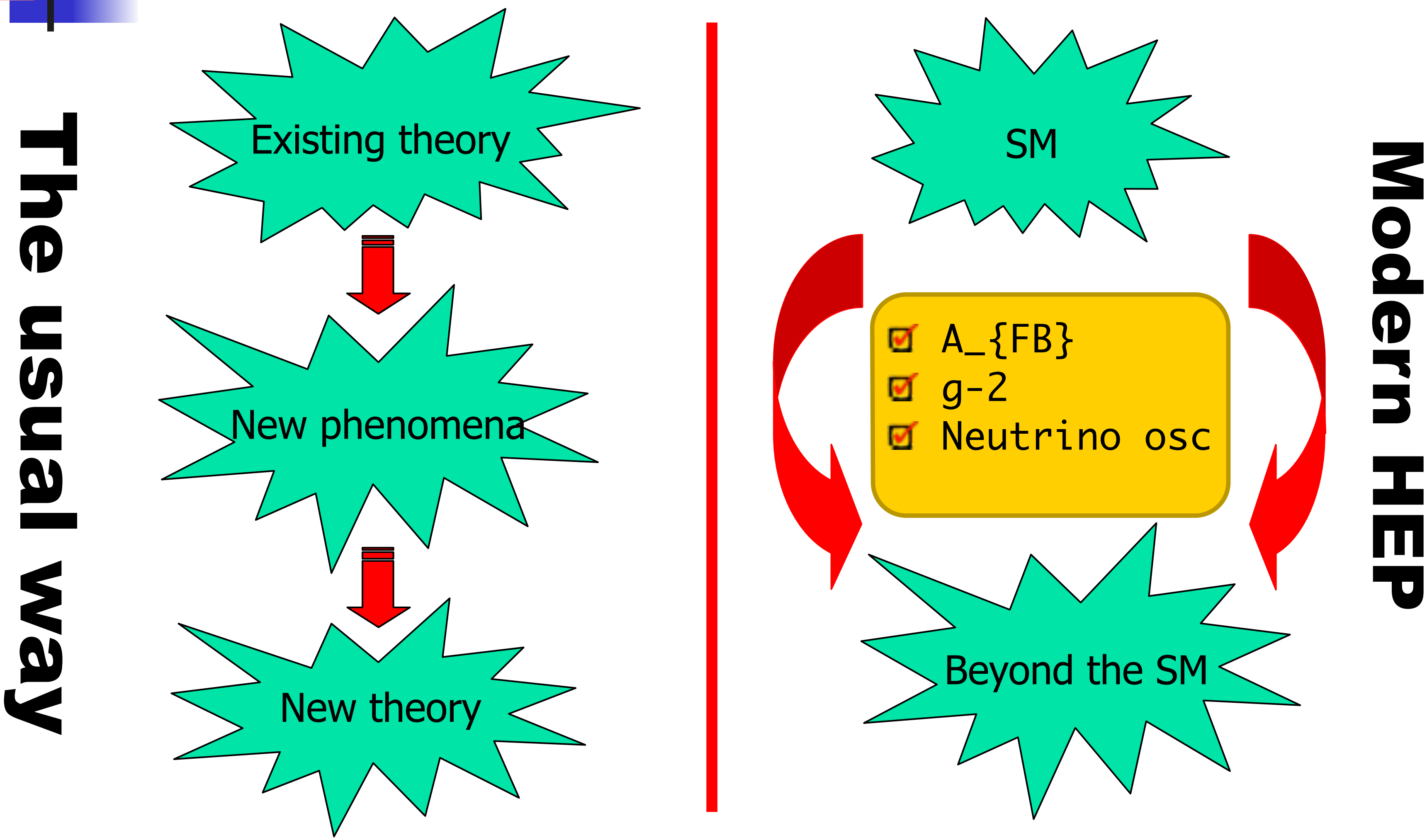

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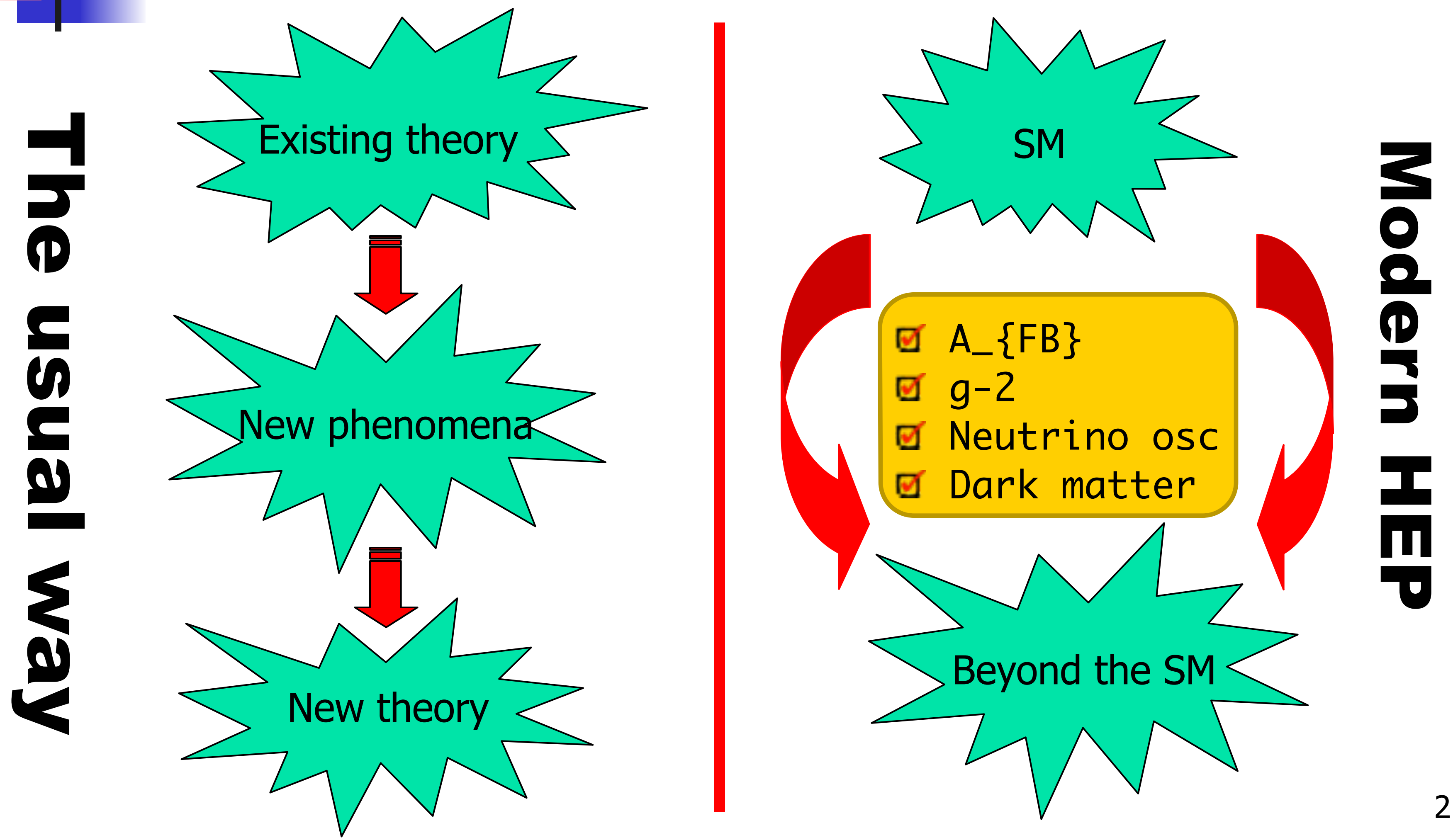
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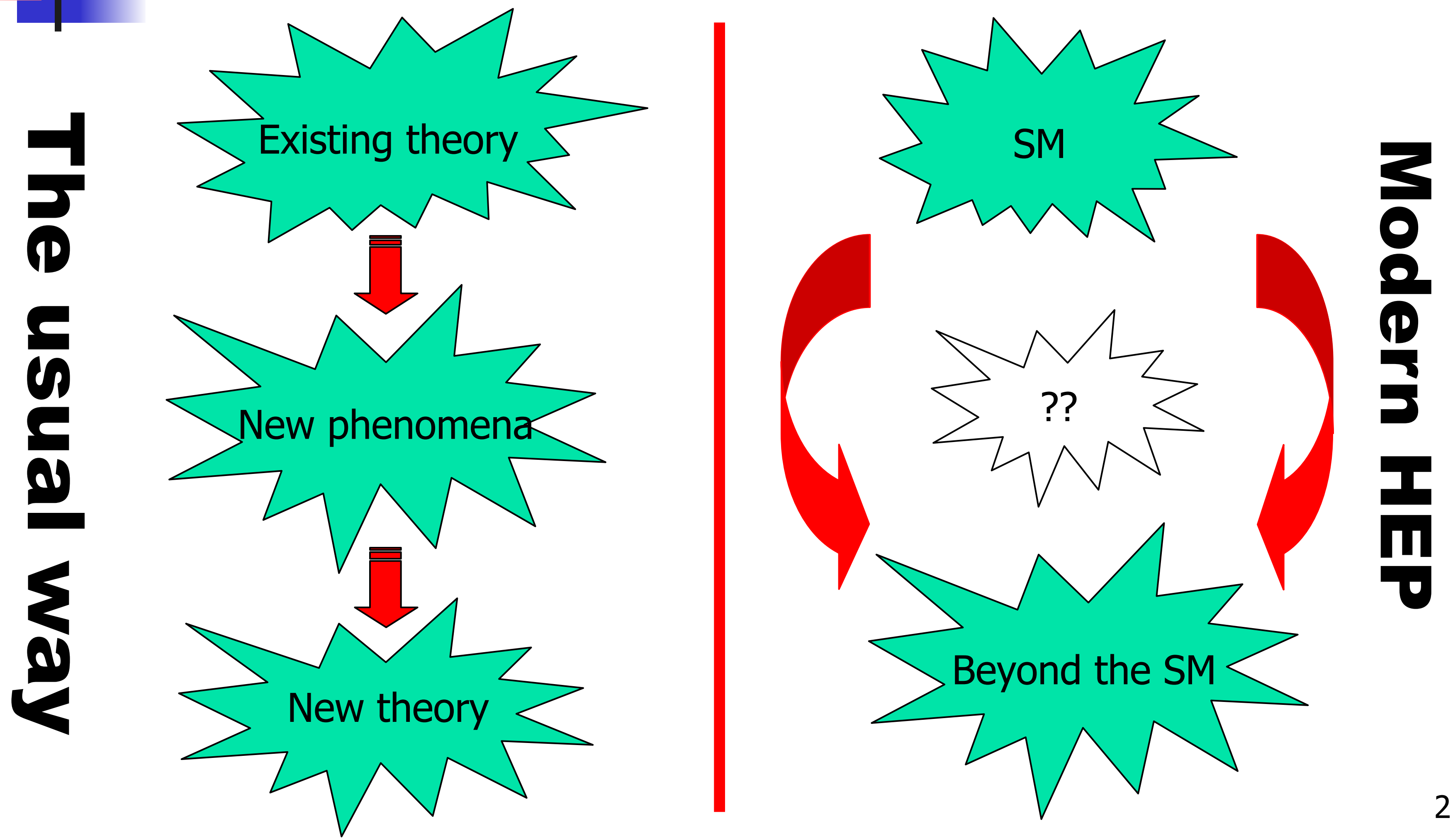
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The SM and Beyond

The problems of the SM:

- Inconsistency at high energies due to Landau pole
- Formal unification of strong and electroweak interactions
- CP-violation is not understood (strong CP-violation?)
- The origin of the mass spectrum is unclear
- Flavour mixing and the number of generations is arbitrary
- Instability of the EW vacuum
- Absence of feasible DM particle, Baryo- and Lepto-Genesis

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The ways beyond the SM:

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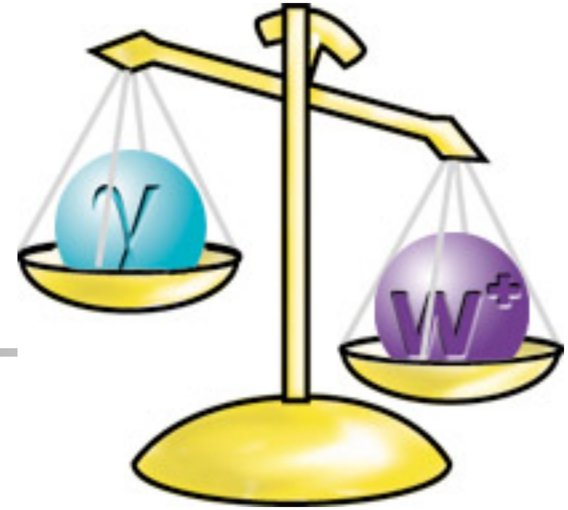
NEW fields with NEW interactions → Compositeness, Technicolour, preons

The Higgs boson

The Higgs boson (still problem #1)

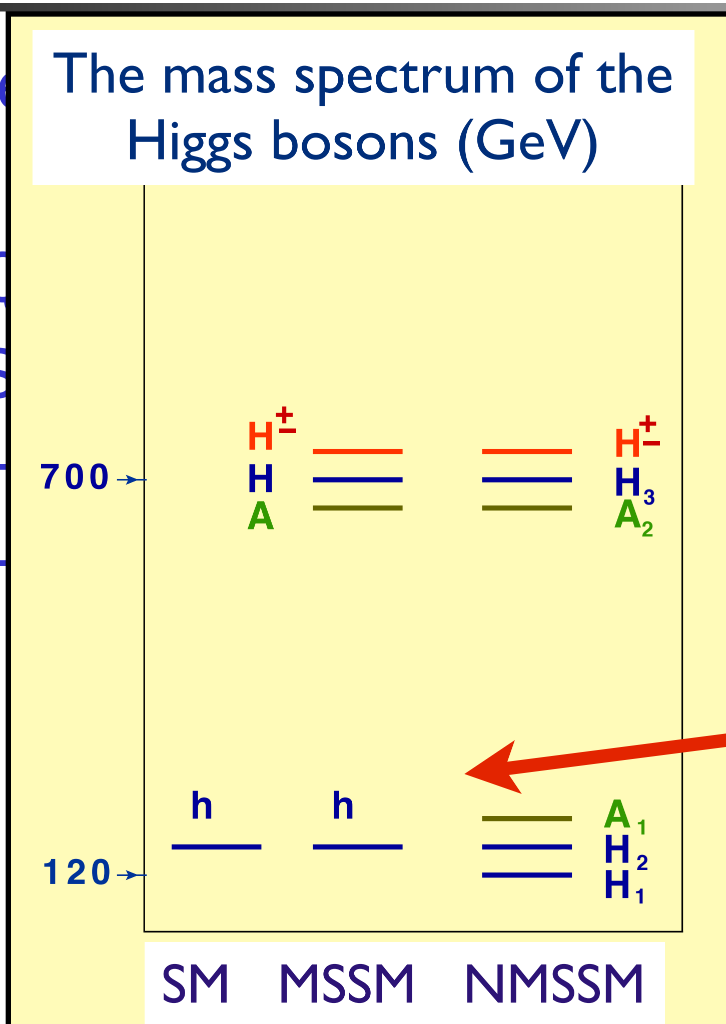
- Quantum numbers, mass/coupling ratio
- Second light Higgs boson
- Heavy neutral Higgs boson
- Heavy charged Higgs boson

The Higgs boson



The ... em #1)

- C ... /coupling ratio
- S
- H ... on
- H ... on



We may have found one of these states

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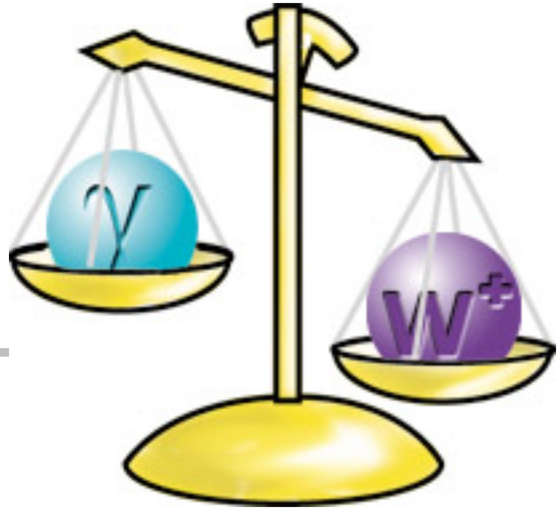
Is it the SM Higgs boson or not?

The Higgs boson



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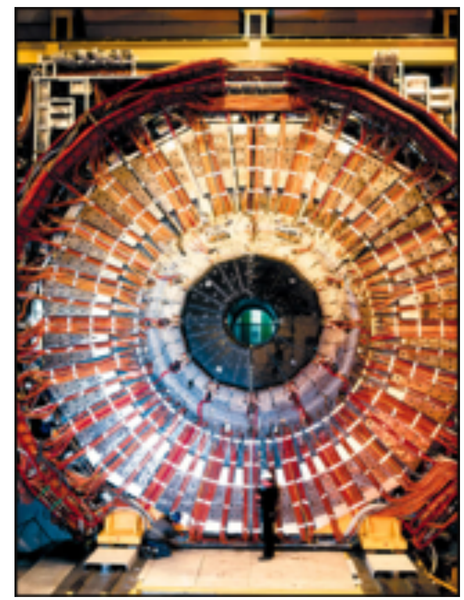
Is it the SM Higgs boson or not?

The task of vital importance.
May require the electron-positron collider

Physics beyond the SM

- Low Energy Supersymmetry
- Extra gauge bosons
- Free quarks
- Axions
- Monopoles
- Violation of Baryon number
- Violation of Lepton number
- Violation of Lorentz invariance
- Extra dimensions
- Modification of Newton law
- GUTs
- String/Brane World
- Compositeness



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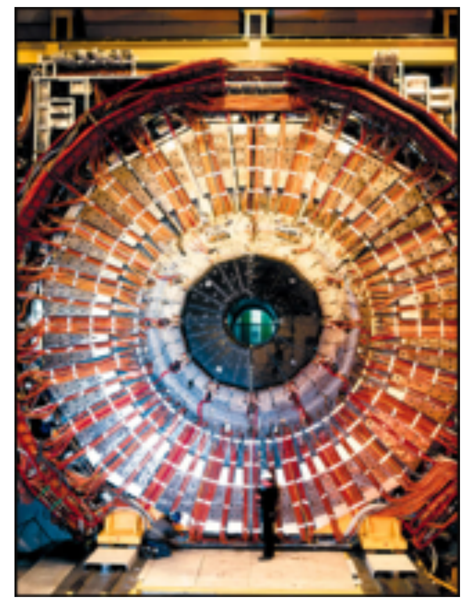
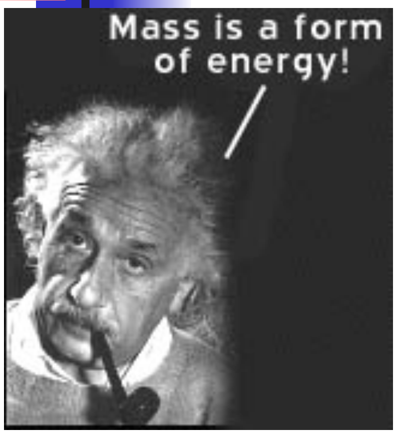
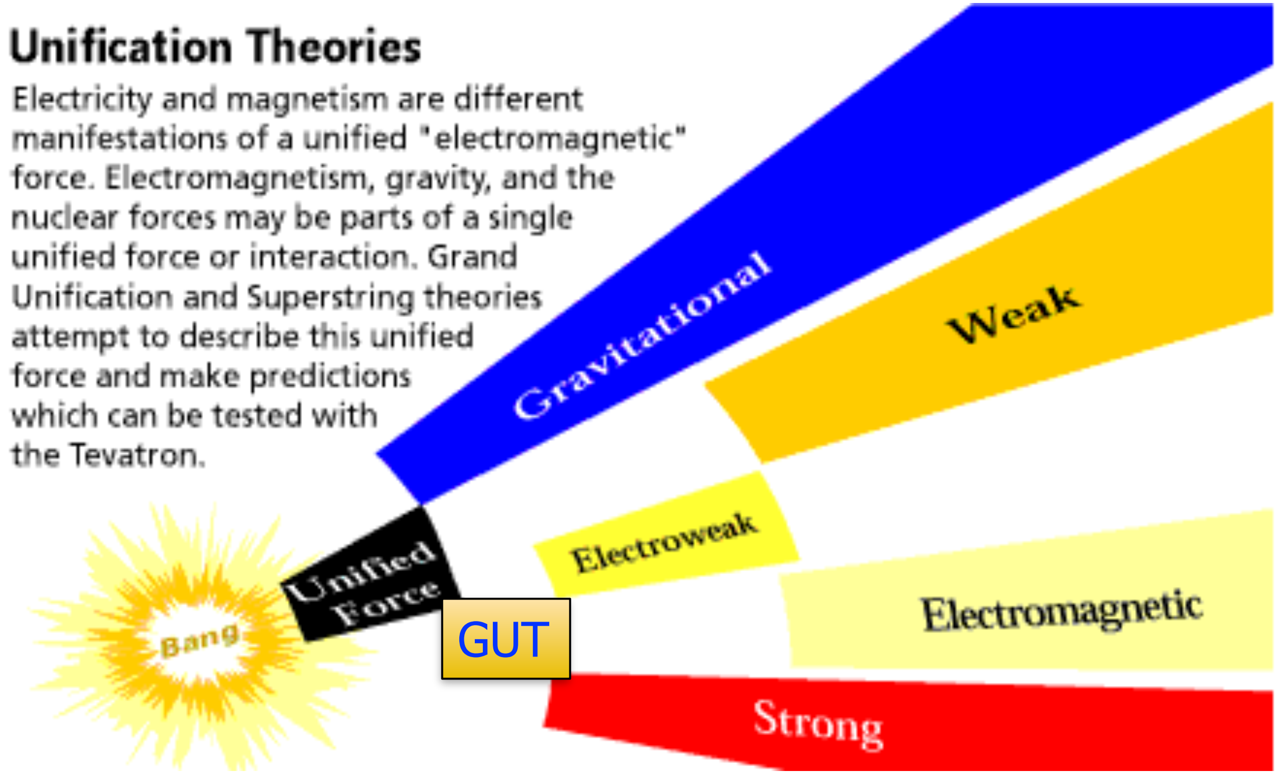


Not found so far …

Unification paradigm



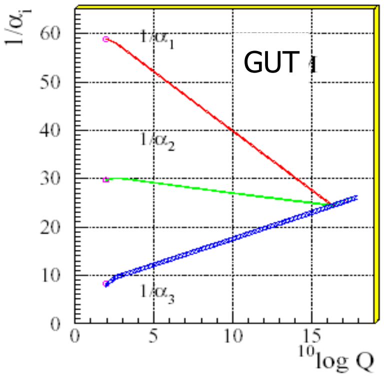


10^{-34} cm

D=10

- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is a new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible

Grand Unification



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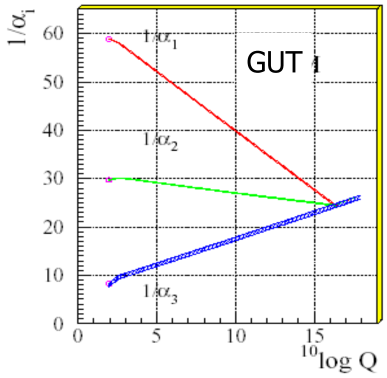
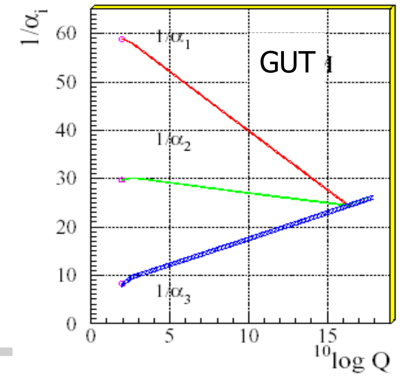


Solves many problems of the SM:

- absence of Landau pole
- Decreases the number of parameters
- All particles in a single representation (**16** of SO(10))
- Unifies quarks and leptons -> spectrum and mixings from «textures»
- A way to **B** and **L** violation



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<u>Creates new problems:</u>

- Hierarchy of scales $M_W/M_G \sim 10^{-14}$
- Large Higgs sector is needed for GUT symmetry breaking

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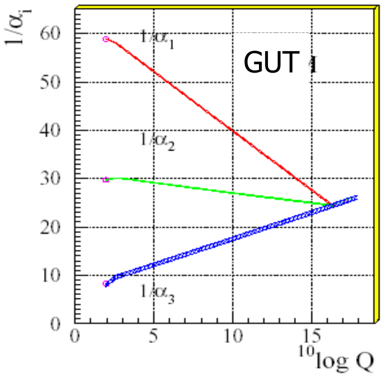

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- Proton decay $P \to e^+\pi, \quad P \to \bar{\nu}K^+$
- Neutron-antineutron oscillations
- $|\Delta(B-L)| = 1 \; (|\Delta(B-L)| = 2)$ processes

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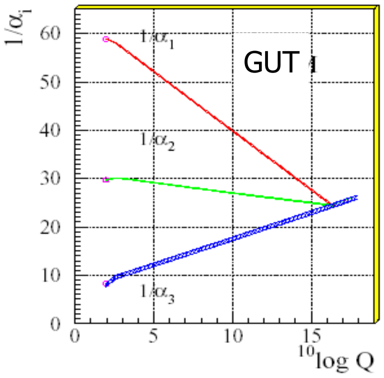

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Experiment:
mean life time > $10^{31} - 10^{33}$ years

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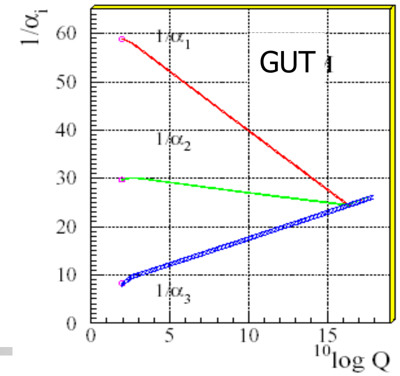

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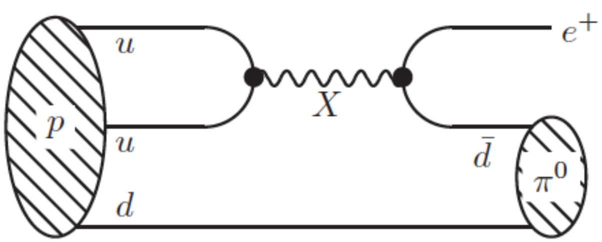
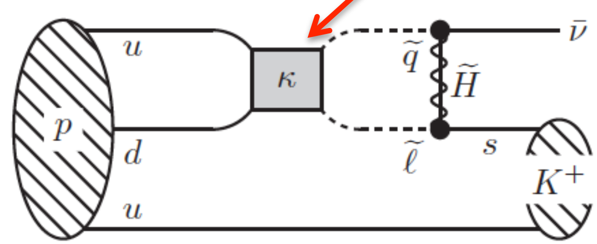
SUSY GUTS – Nucleon decay

$$\frac{1}{\Lambda} QQQL\big|_F$$



(a) Dimension 6.



(b) Dimension 5.

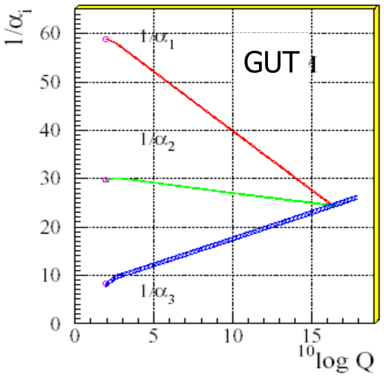
$$p \to \pi^0 + e^+$$

$$\tau_{p\to e^+\pi^0} > 1\times 10^{34}\,\text{yrs},\; M_X > 10^{16}\,GeV$$

$$p \to K^+ + \bar{\nu}$$

$$\tau_{p\to K^+\bar{\nu}} > 3.3\times 10^{33}\,yrs$$

Grand Unification



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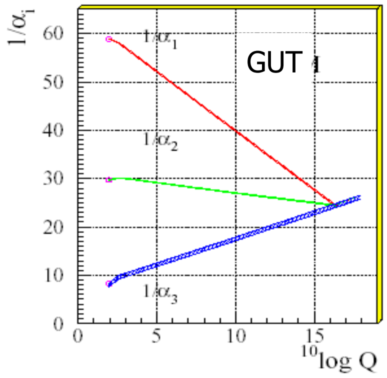

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- stabilization of the hierarchy

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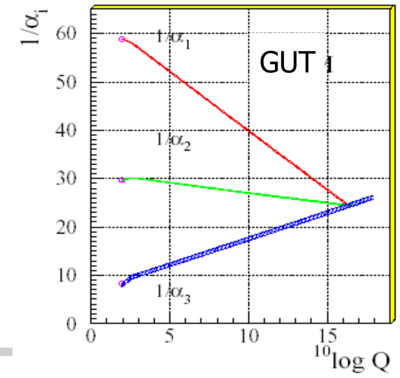

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→ Low energy SUSY

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Motivation for SUSY in particles physics

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Supersymmetry is a dream of a unified theory of all particles and interactions

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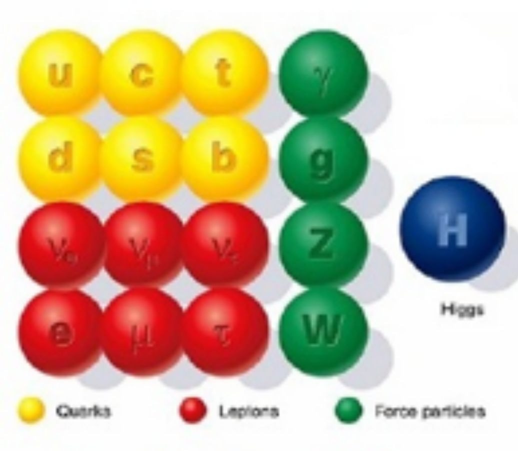

Standard particles

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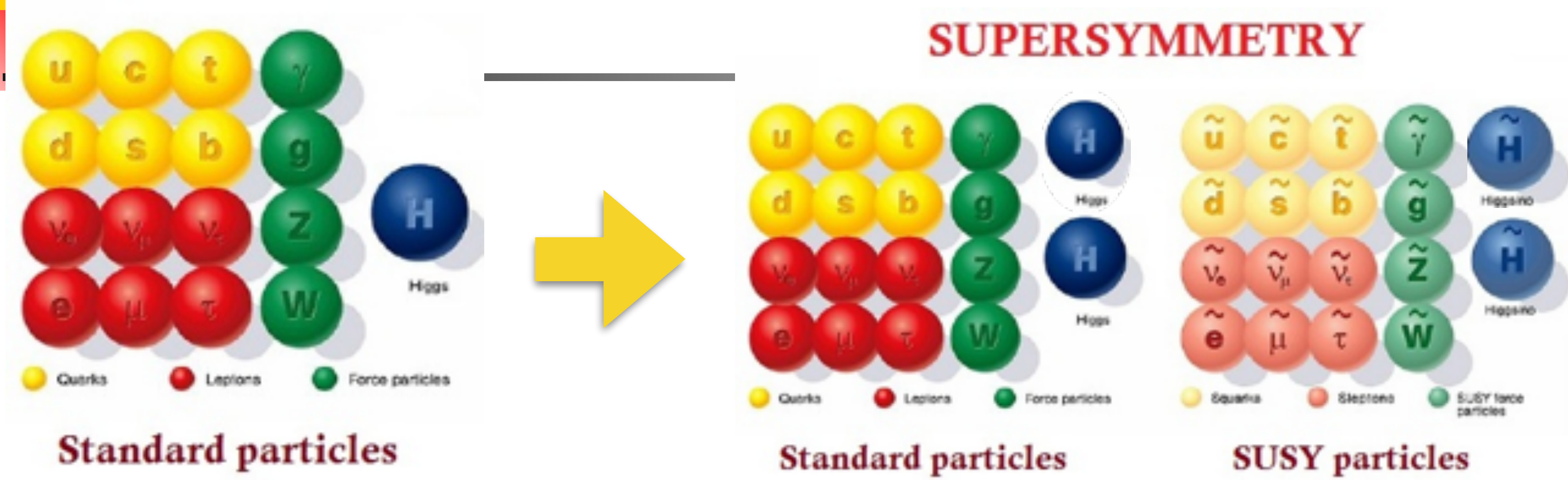

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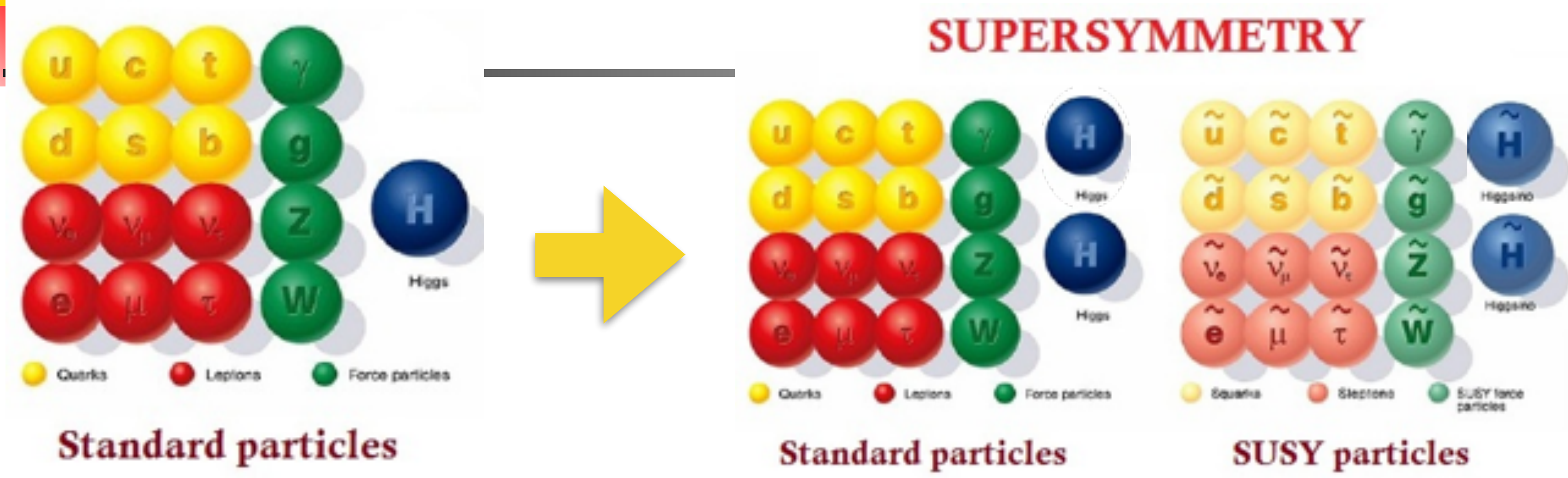

Why SUSY?

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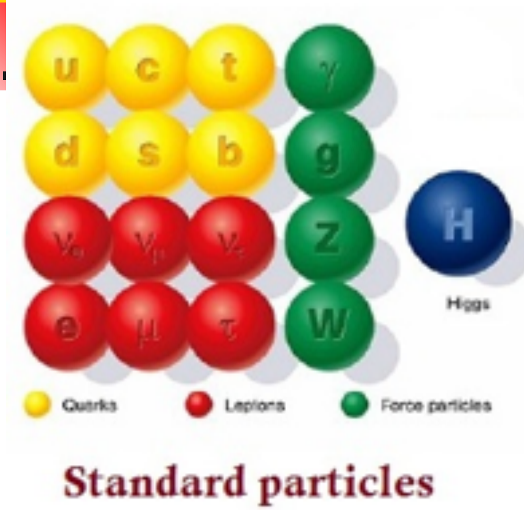

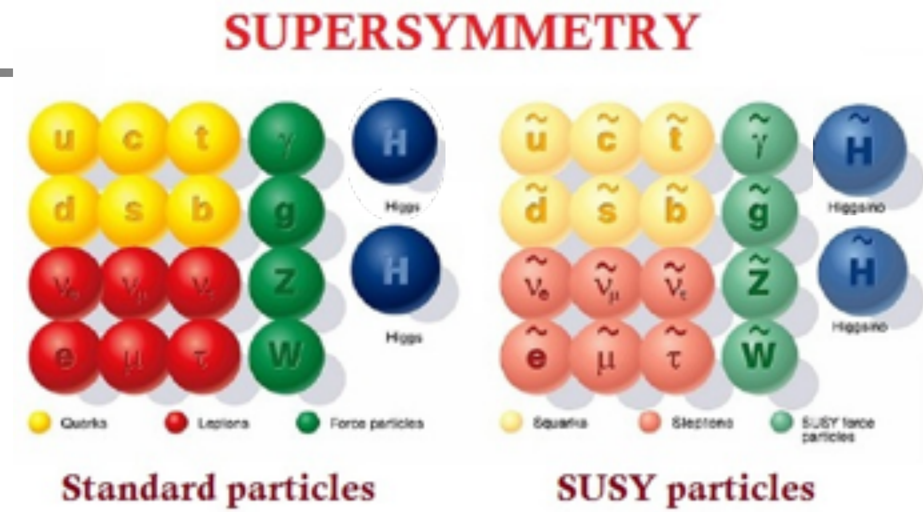

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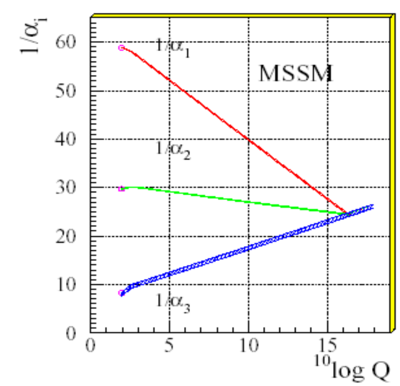

The basis of a grand Unified Theory

Motivation for SUSY in particles physics

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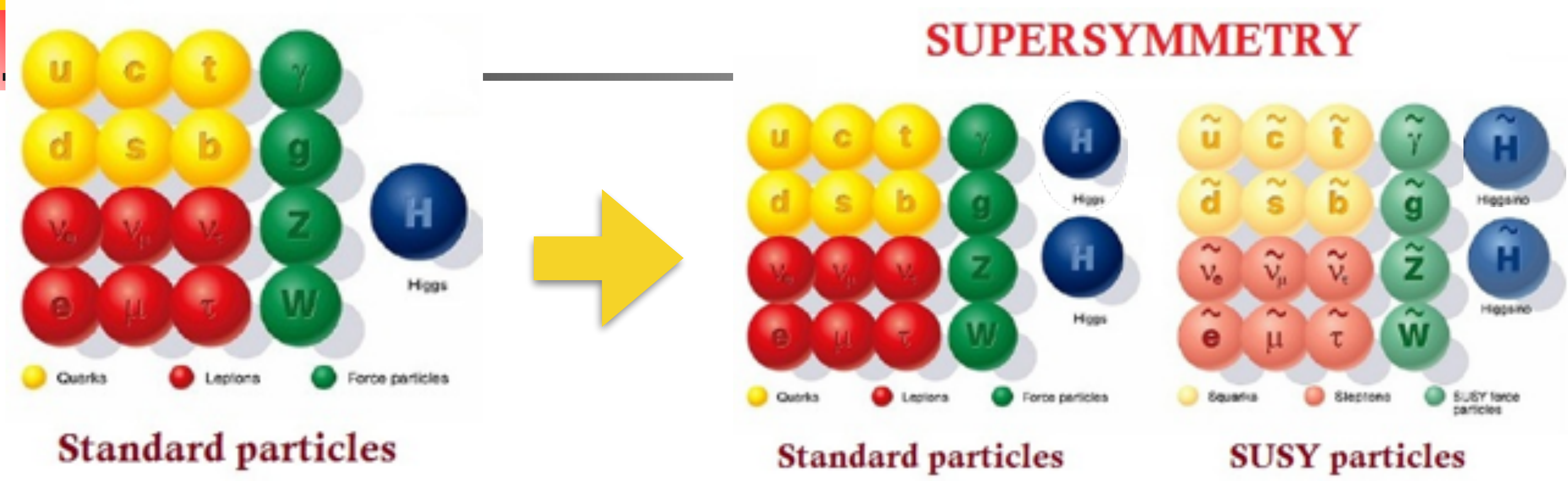
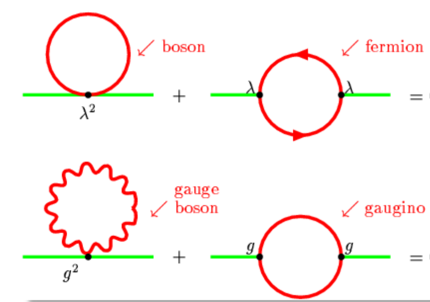


Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem

Cancellations of corrections and stabilization of the Higgs potential



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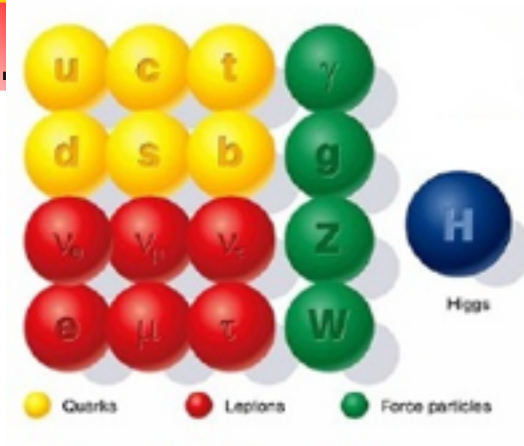
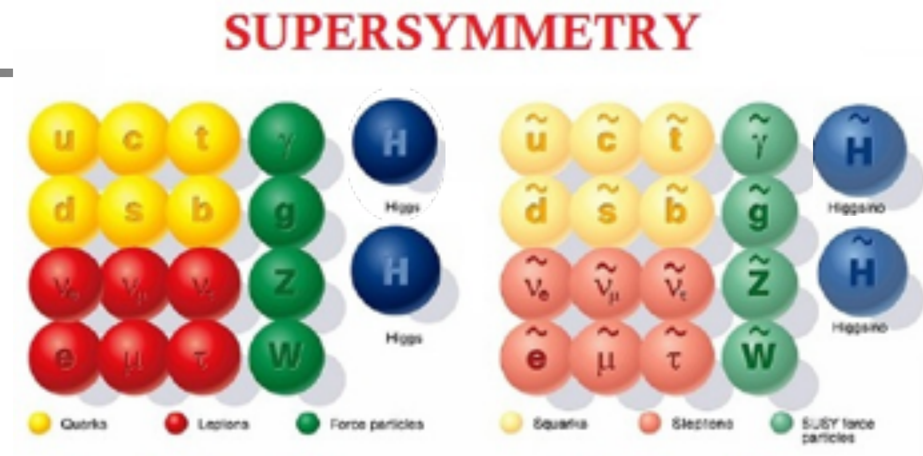


Standard particles



Standard particles

SUSY particles

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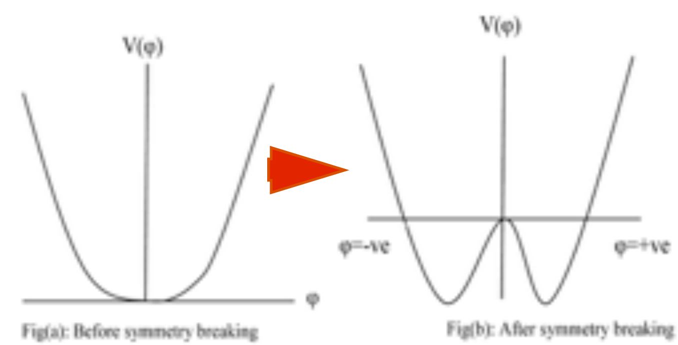
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation



Violation of symmetry comes from radiative corrections

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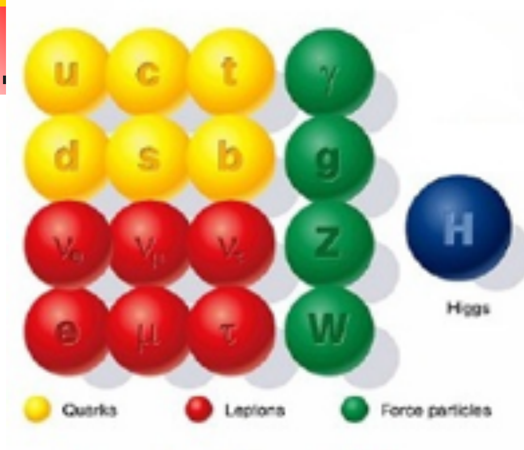

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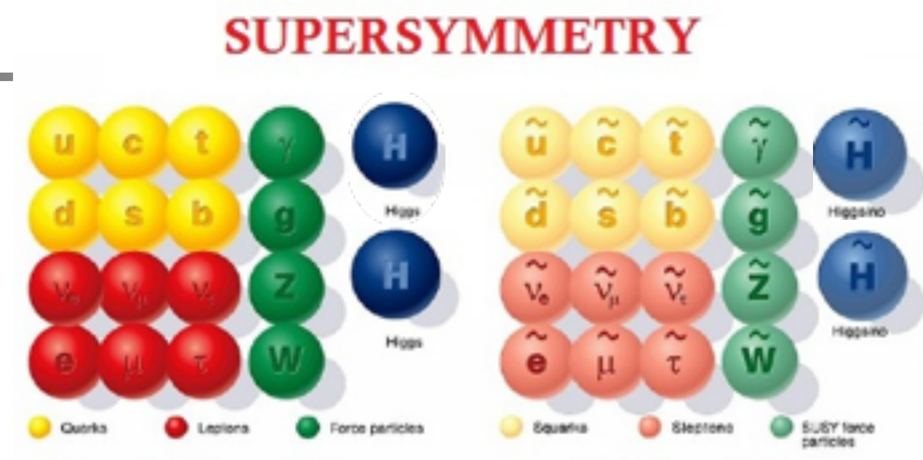

Standard particles SUSY particles

Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle

$$\tilde{\chi}^0 = N_1\tilde{\gamma} + N_2\tilde{z} + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0$$

Neutralino

Motivation for SUSY in particles physics

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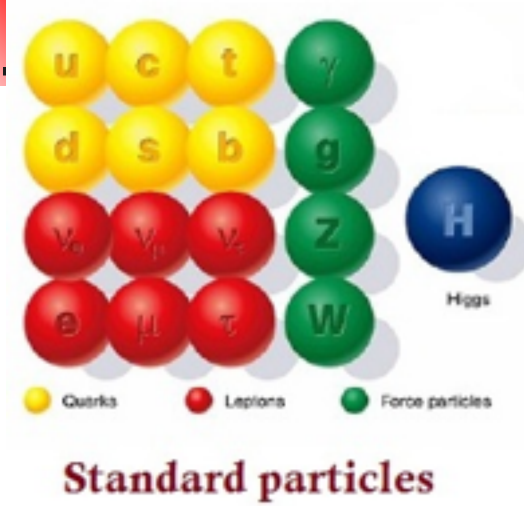

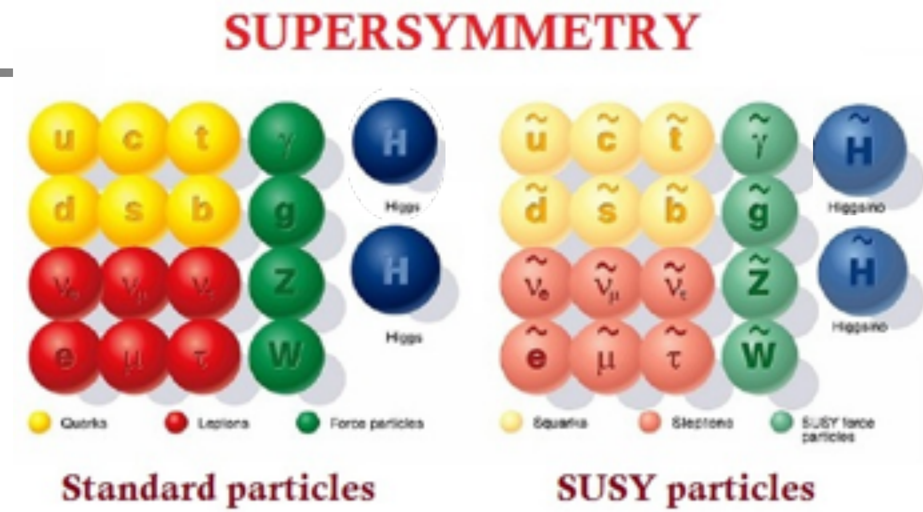

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- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle
- Unification with gravity!

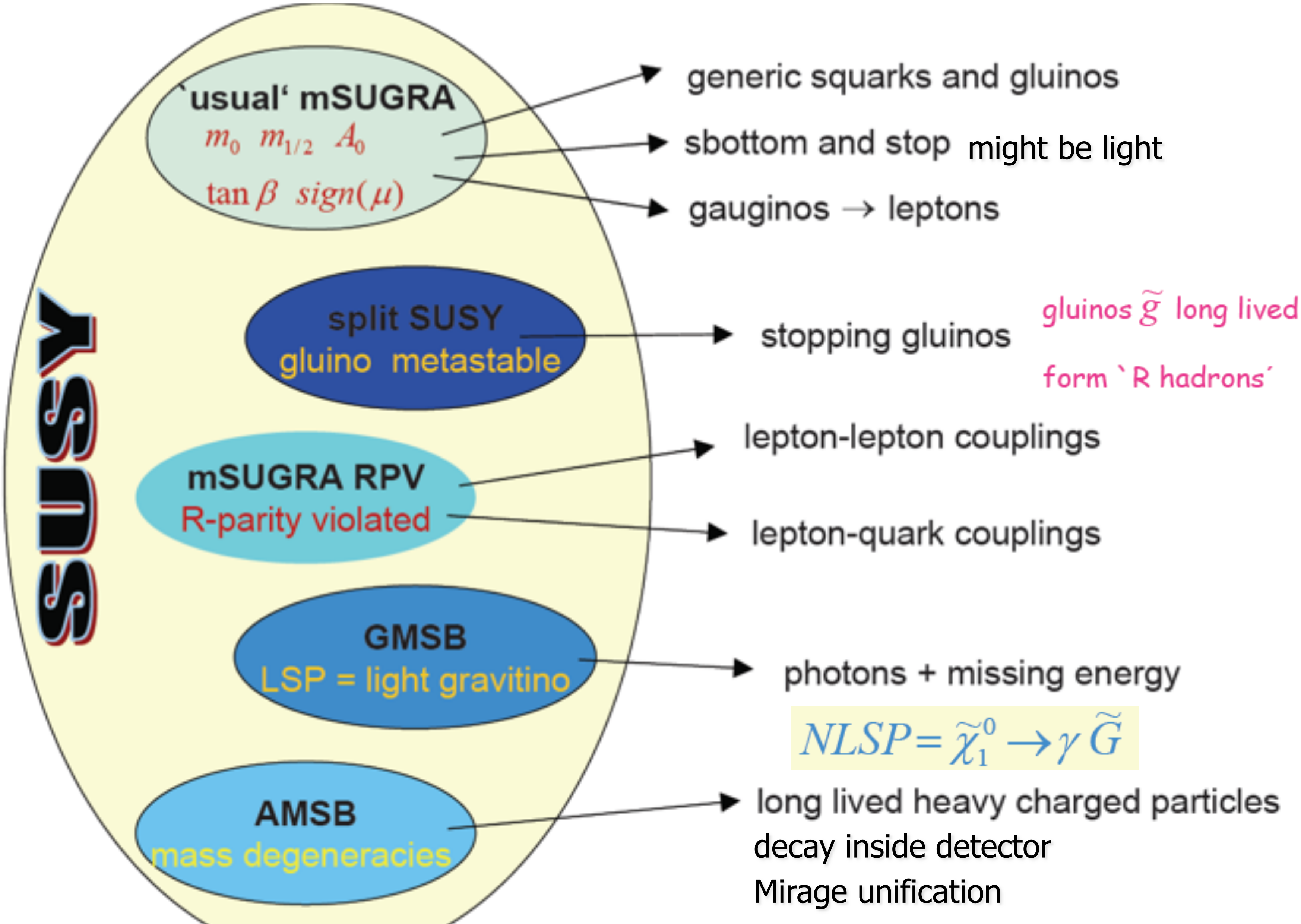
$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \bar{\delta}_{\bar\varepsilon}\} = 2(\varepsilon\sigma^\mu\bar{\varepsilon})P_\mu$$

$\varepsilon = \varepsilon(x)$ local coordinate transf. $\Rightarrow$ (super)gravity

Local supersymmetry = general relativity !

SUSY Models and Signatures

T.Hebbeker



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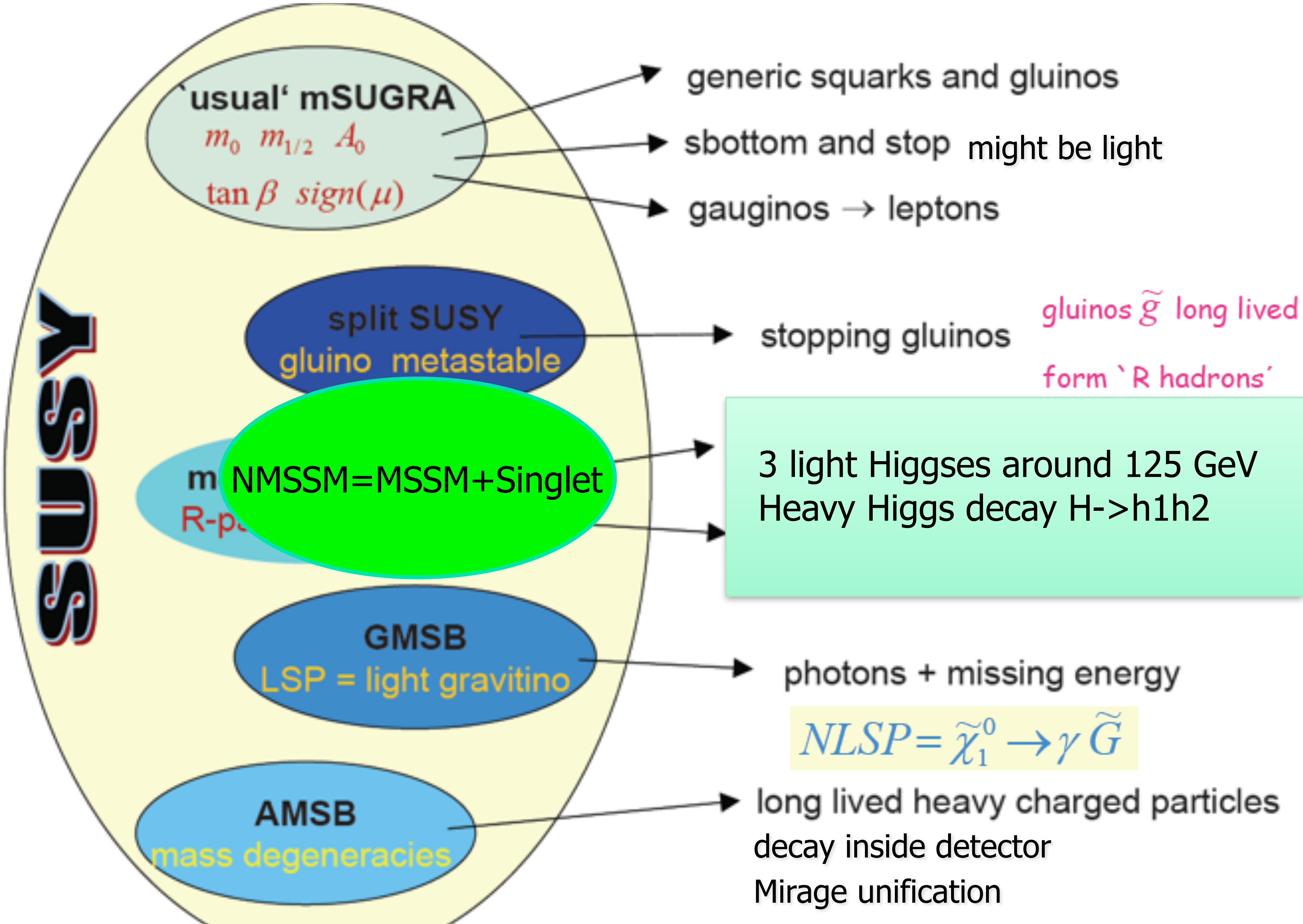

LHC reach at 7 and 14 TeV

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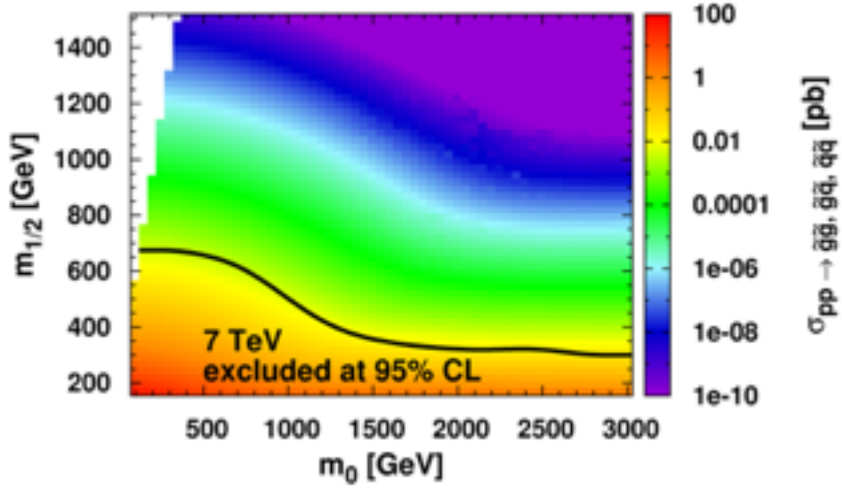

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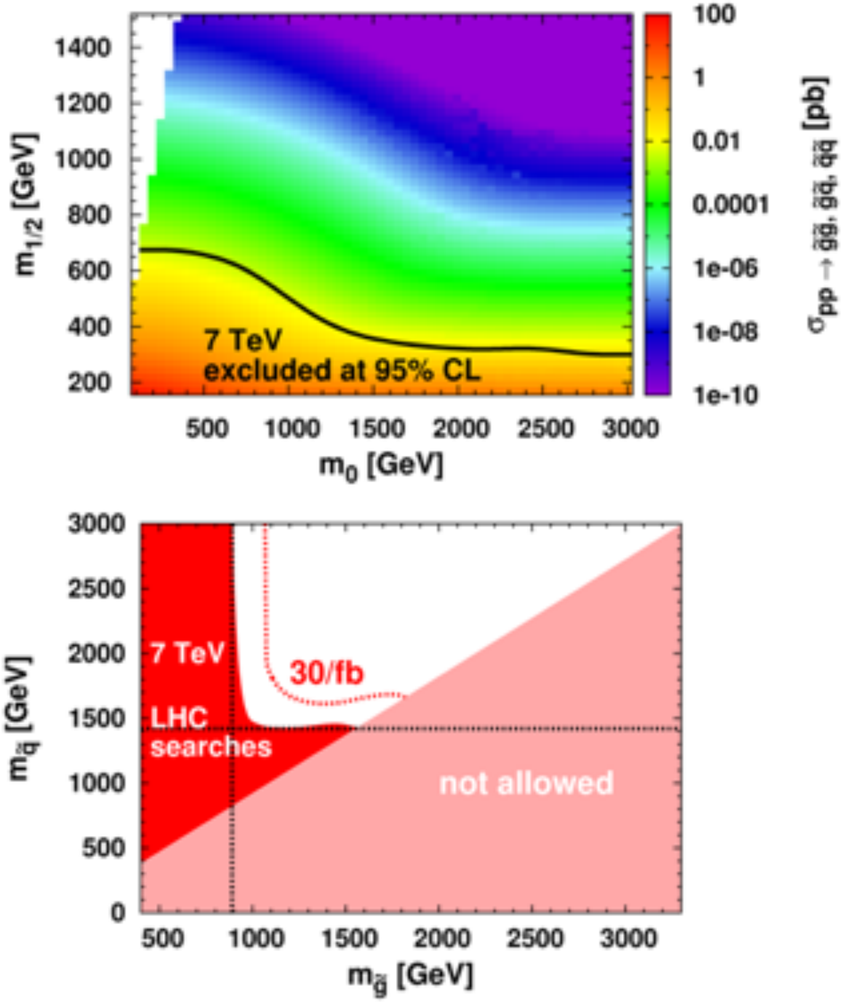

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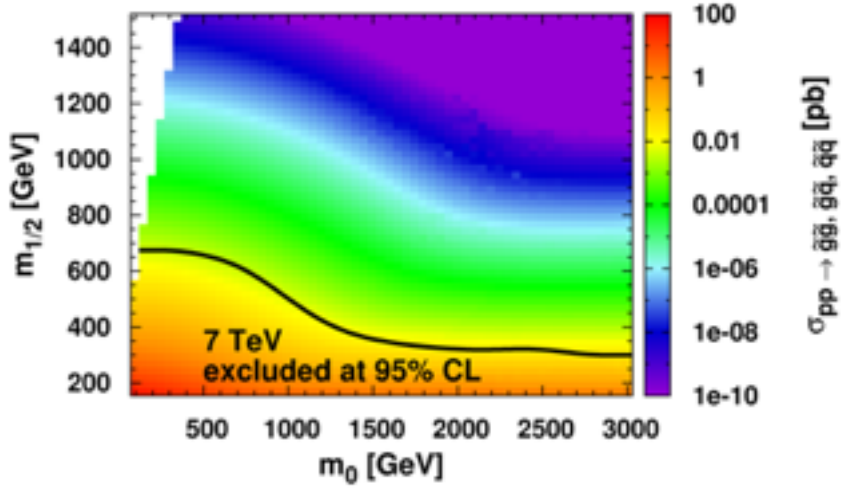

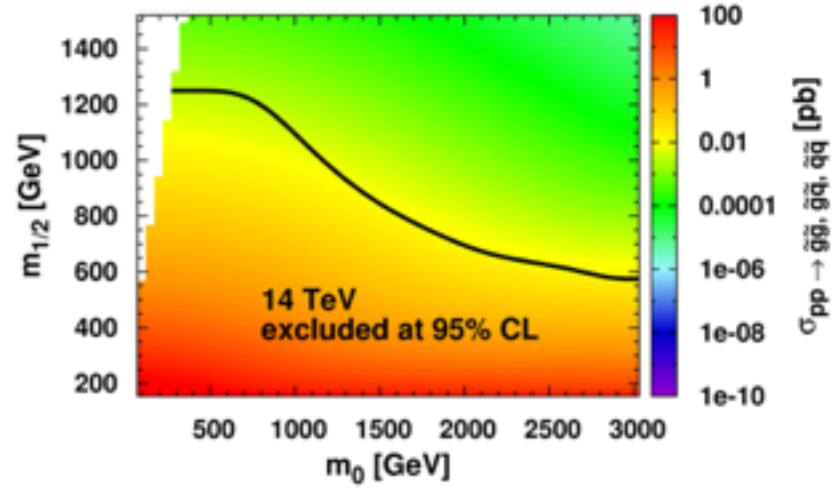

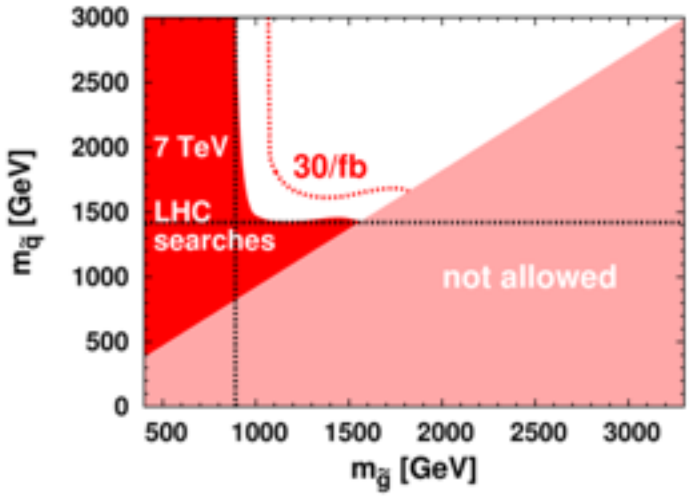

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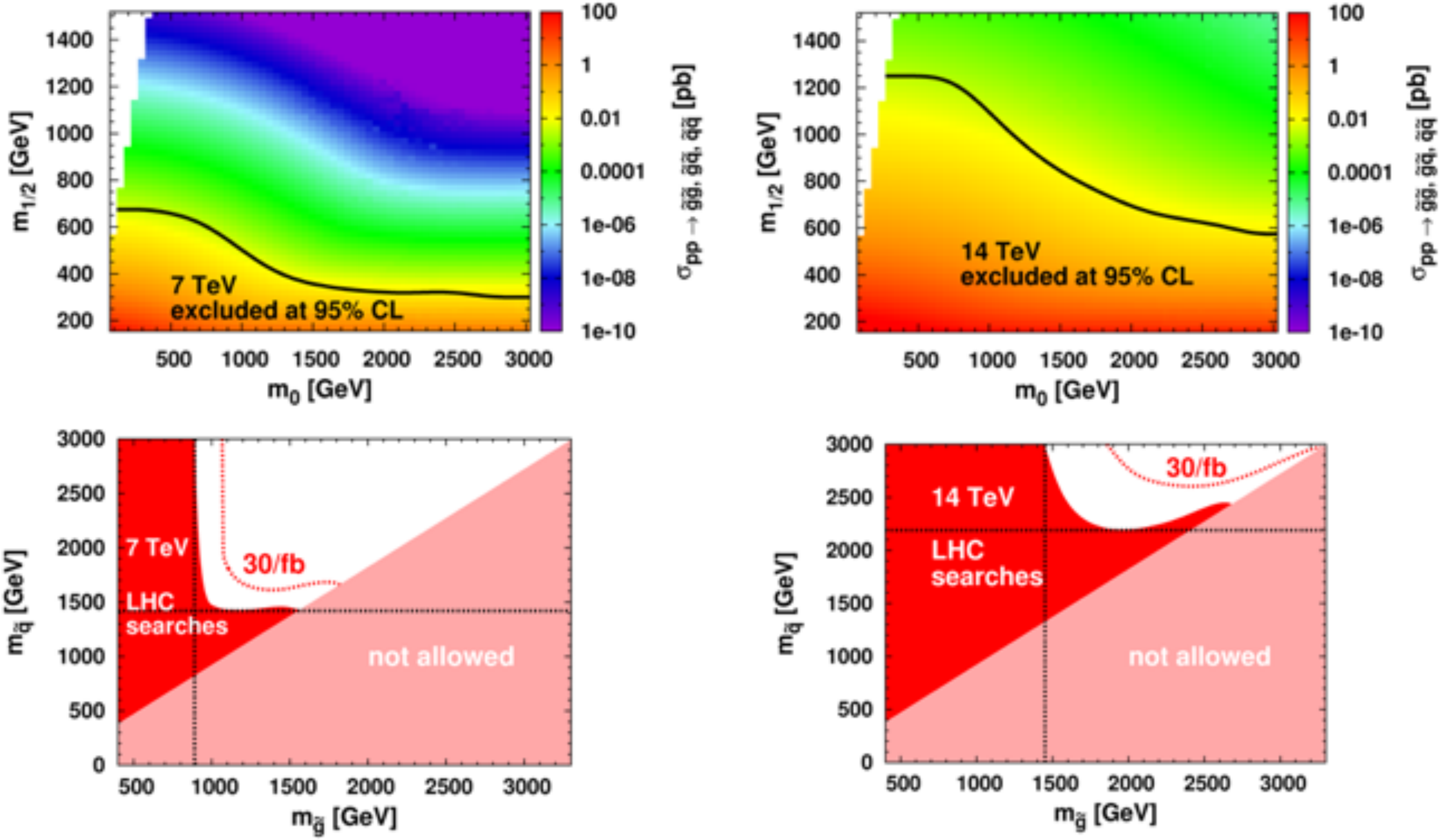

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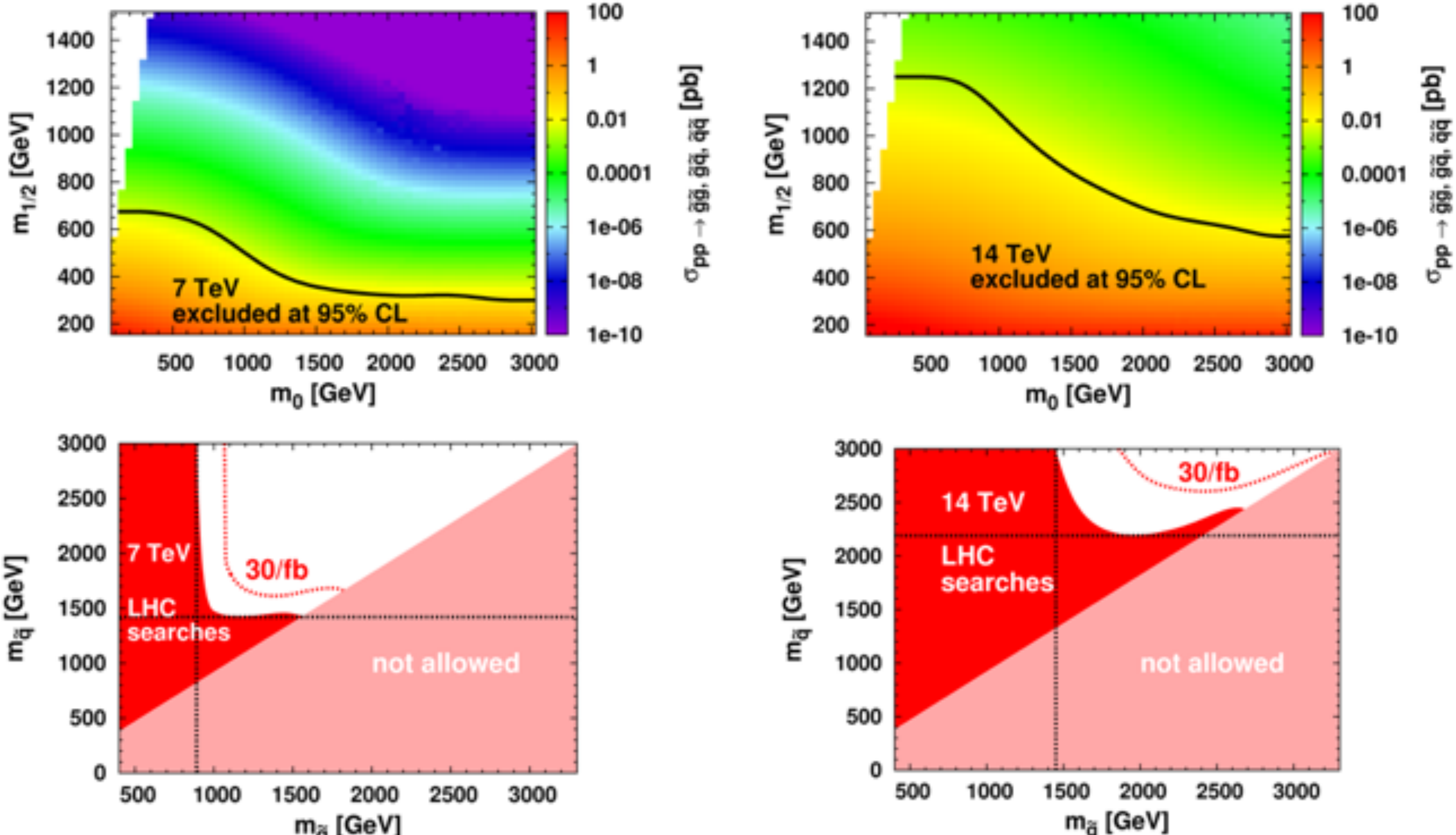

Energy is more important than luminosity

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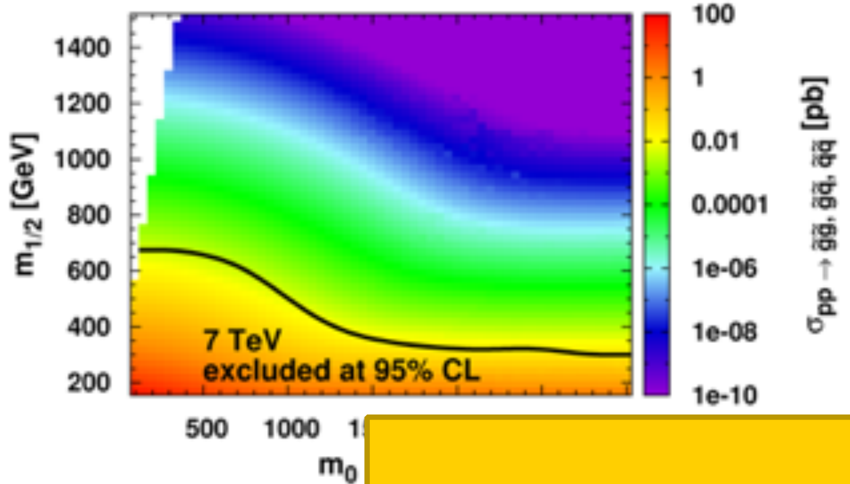
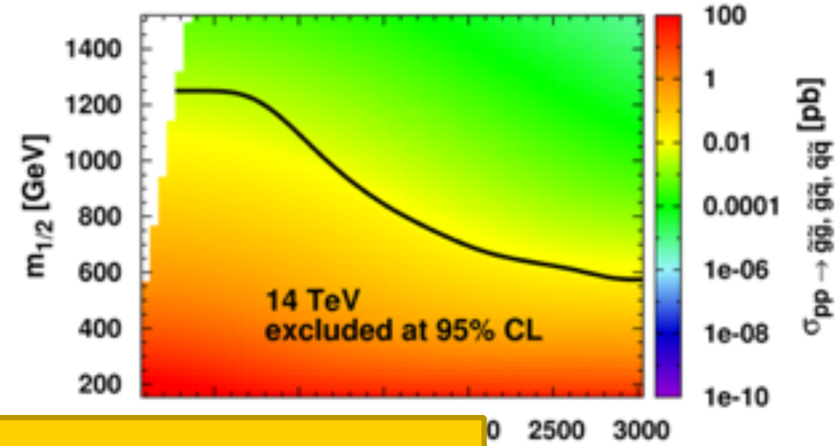
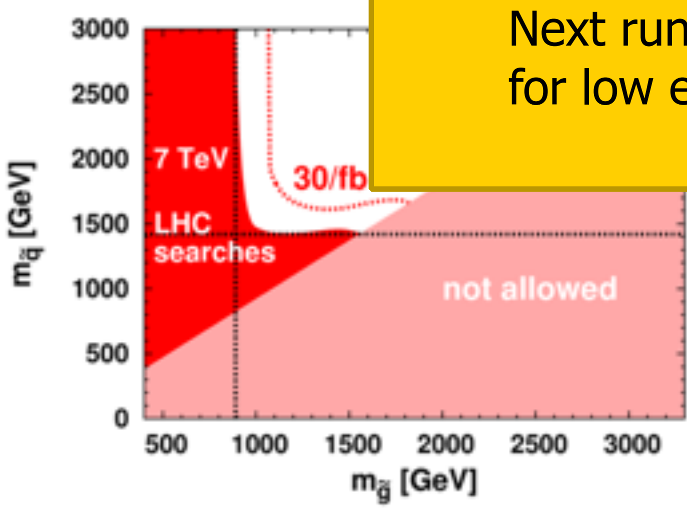
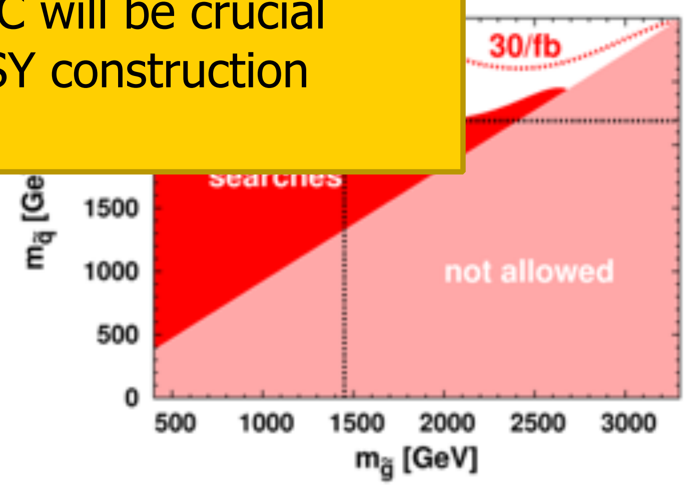




Next run of the LHC will be crucial
for low energy SUSY construction





Energy is more important than luminosity

Predictions
J.Bagger @ SUSY 2000 CERN

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SParticle Data Group

The SPDG is an international collaboration that reviews Sparticle Physics and related areas of Astrophysics, and compiles/analyzes data on particle properties. SPDG products are distributed to 130,000 physicists, teachers, and other interested people. The Review of Sparticle Physics is the most cited publication in particle physics during the last twenty years. Plots of SPDG statistics are available.

Mirror sites: USA (LBNL) Brazil CERN Italy (Genova) Japan (KEK) Russia (Novosibirsk) Russia (Protvino) UK (Durham)

Review of Sparticle Physics | Charts, Educational materials, Sparticle Adventure | Information and Databases
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The Review of Sparticle Physics

C. Caso *et al.* The European Physical Journal C103 (2018) 1 (2018 Authors)

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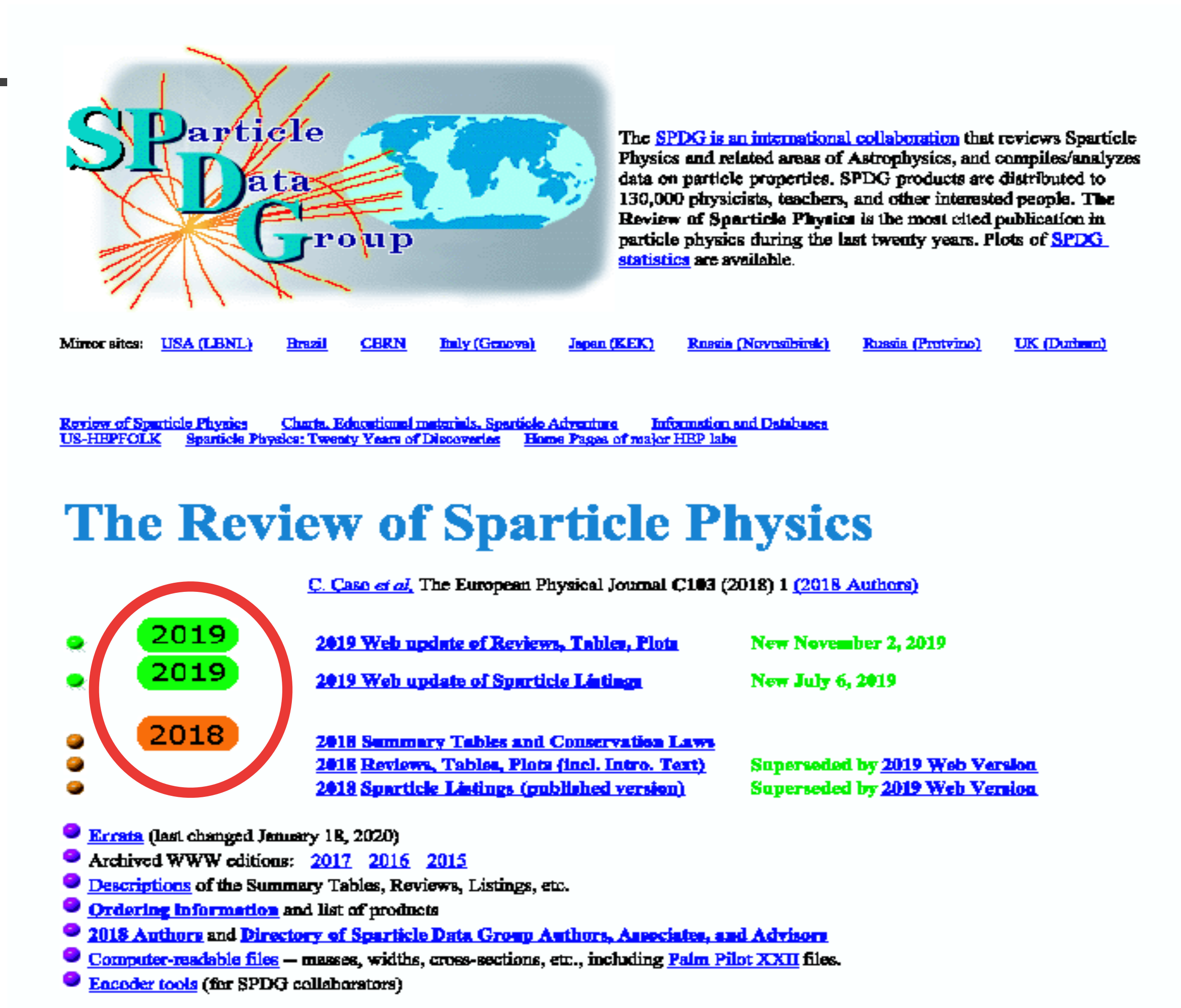
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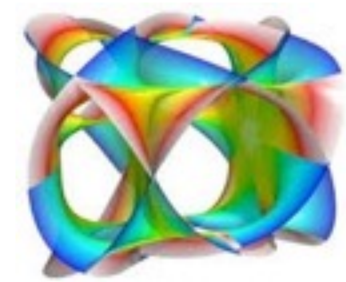
String Theory



Heterotic string

gravity + gauge kinetic terms [47]

$$\int [d^{10}x]\, \frac{1}{g_H^2} M_H^8 \mathcal{R}^{(10)} + \int [d^{10}x]\, \frac{1}{g_H^2} M_H^6 \mathcal{F}_{MN}^2$$

simplified units: $2 = \pi = 1$

Compactification in 4 dims on a 6-dim manifold of volume $V_6 \Rightarrow$

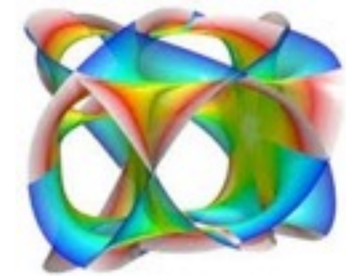
$$\int [d^4x]\, \frac{V_6}{g_H^2} M_H^8 \mathcal{R}^{(4)} + \int [d^4x]\, \frac{V_6}{g_H^2} M_H^6 \mathcal{F}_{\mu\nu}^2$$

$$\frac{V_6}{g_H^2} M_H^8 = M_P^2 \qquad \frac{V_6}{g_H^2} M_H^6 = 1/g^2 \qquad \Rightarrow$$

$$M_P^2 = \frac{1}{g^2} M_H^2 \quad \frac{1}{g^2} = \frac{1}{g_H^2} V_6 M_H^6 \quad \Rightarrow \quad M_H = g M_P \quad g_H = g\sqrt{V_6} M_H^3$$

$g_H \lesssim 1 \Rightarrow V_6 \sim$ string size

String Theory



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simplified units: 2 = π

Compactification in 4 dims on a 6-dim manifold of volum

- Theoretically most attractive framework
- Part of the unification paradigm
- Main motivation for extra D

$$\int [d^4x]\,\frac{V_6}{g_H^2} M_H^8\,\mathcal{R}^{(4)} + \int [d^4x]\,\frac{V_6}{g_H^2} M_H^6\,\mathcal{F}_{\mu\nu}^2$$

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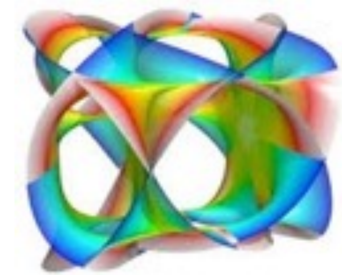


- Higgs from untwisted sector $\Rrightarrow$ gauge-Higgs unification

  $\lambda_{\rm top} = g_{\rm GUT} \Rrightarrow m_{\rm top} \sim$ IR fixed point $\simeq$ 170 GeV

- Yukawa couplings: hierarchies à le Froggatt-Nielsen

  discrete symmetries $\Rrightarrow$ couplings allowed with powers of a singlet field

  $\lambda_n \sim \Phi^n \qquad \langle\Phi\rangle \sim 0.1\, M_s \to$ hierarchies

  A single anomalous $U(1) \Rrightarrow \langle\Phi\rangle \neq 0$ to cancel the FI D-term

- R-neutrinos: natural framework for see-saw mechanism

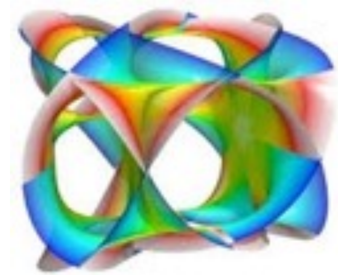
  $\langle h\rangle \nu_L \nu_R + M \nu_R \nu_R \qquad \langle h\rangle = v << M \Rrightarrow m_R \sim M\,;\, m_L \sim v^2/M$

- proton decay: problematic dim-5 operators

  in general need suppression higher than M_s or small couplings

- $\not{\rm SUSY}$ in a hidden sector from the other $E_8 \to$ gravity mediation

String Theory



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- proton decay: problematic dim-5 operators

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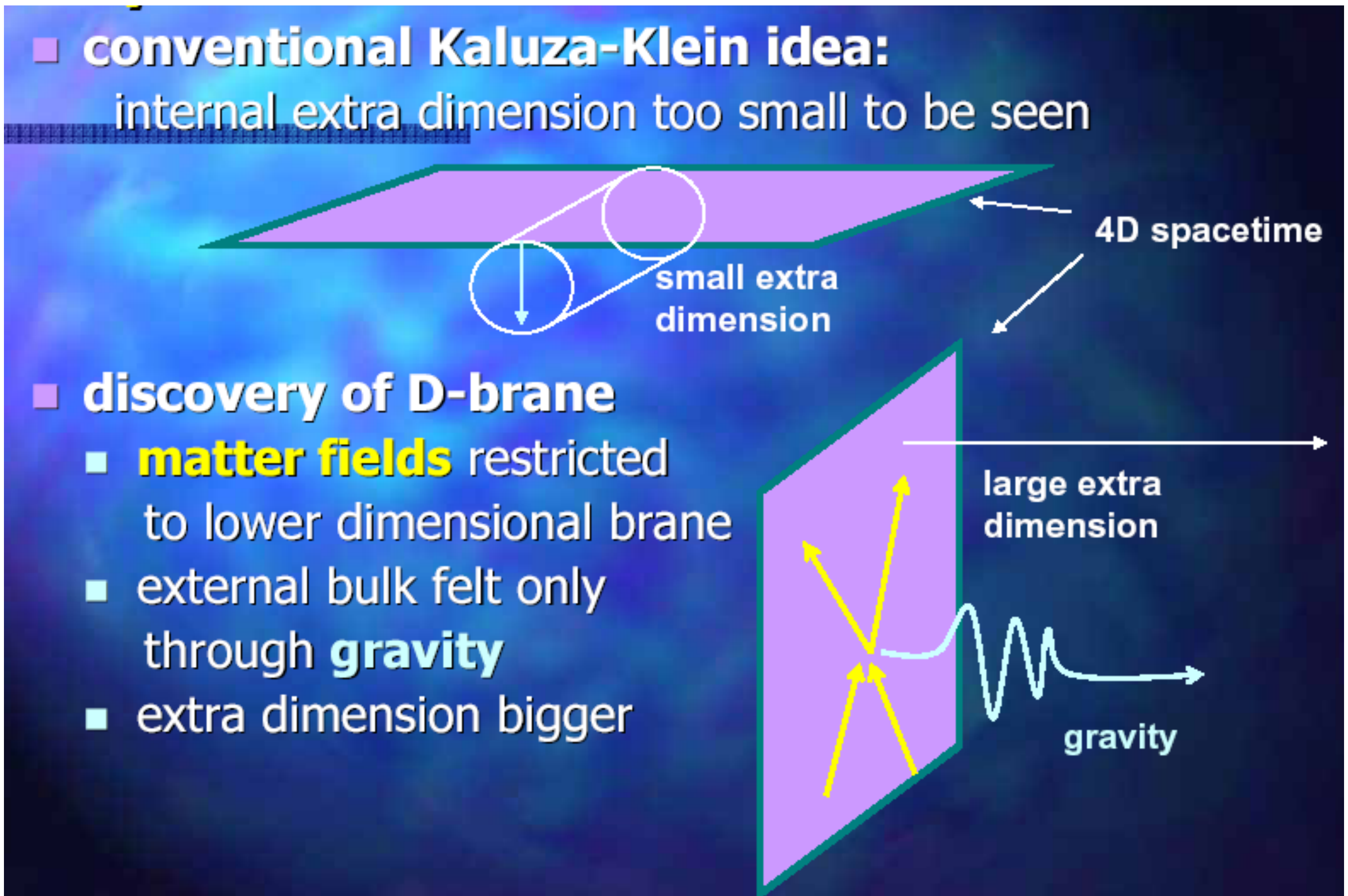
- S$\not{U}$SY in a hidden sector from the other $E_8 \rightarrow$ gravity mediation

- Potentially answering many questions
- Requires SUSY for stabilization
- Difficult to get low-energy outputs

Extra space-time dimensions



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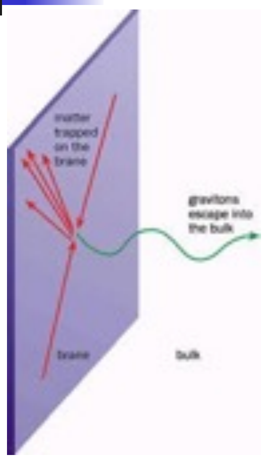

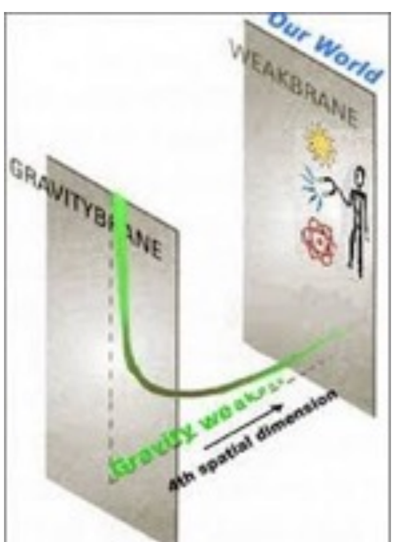

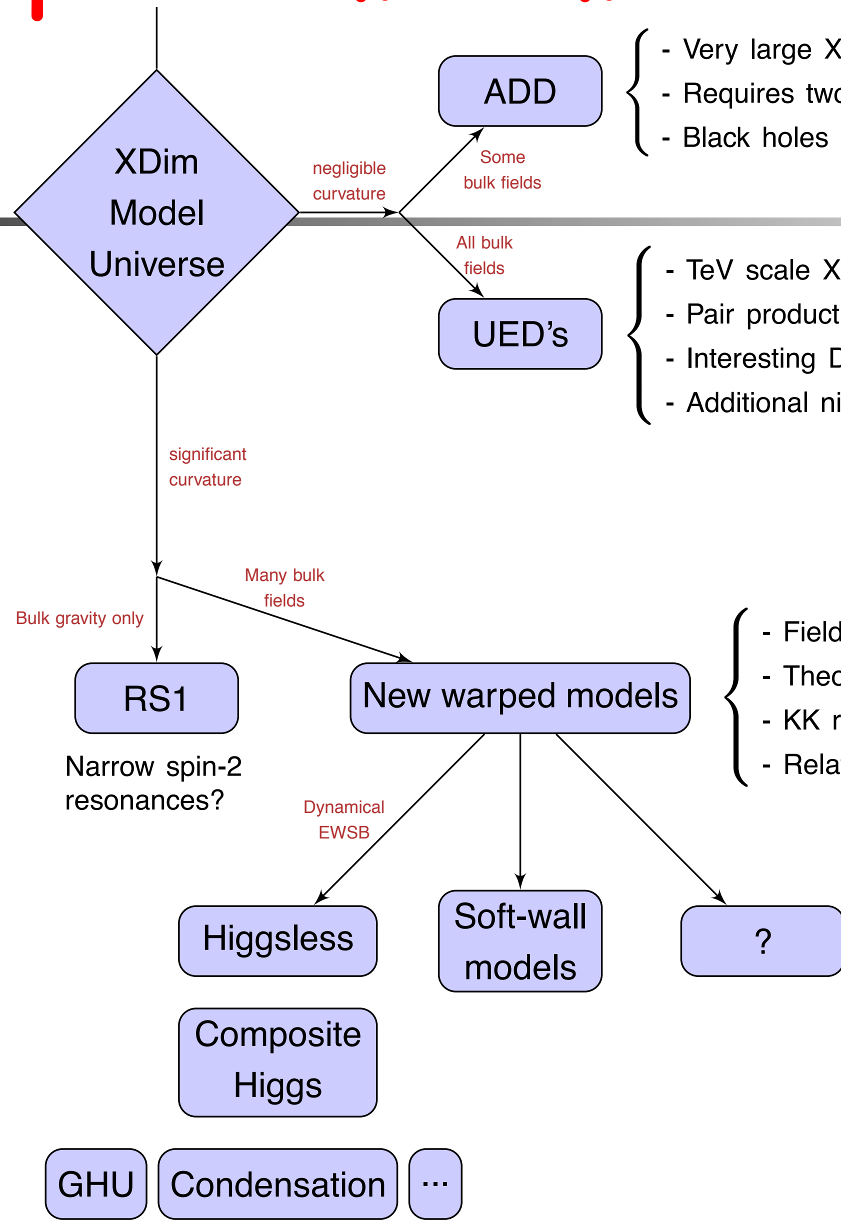

ADD:
- Very large XDim accesible only to gravity
- Requires two or more XDim
- Black holes at colliders?

UED's:
- TeV scale XDim (several hundred GeV?)
- Pair production, $\not{E}_T$ (SUSY-like)
- Interesting DM candidate (non SUSY-like)
- Additional nice features in 6D

New warped models:
- Field localization
- Theories of flavor?
- KK resonances at few TeV
- Relatively broad resonances

E.Pontón

Phenomenology of extra D

Accelerator signatures

- Gravitational radiation in the bulk => missing energy

Present LHC bounds $M_* \geq 3-5$ TeV

- Massive string vibrations => resonances in dijet distribution

$$M_j^2 = M_0^2 + M_s^2 j$$

- Higher spin excitations of quarks and gluons with strong interaction

present LHC limits $M_s \geq 5$ TeV

- Large TeV dimensions => KK resonances of SM gauge bosons

$$M_k = M_0^2 + r^2/R^2,\ k = 1, 2, \ldots$$

experimental limits

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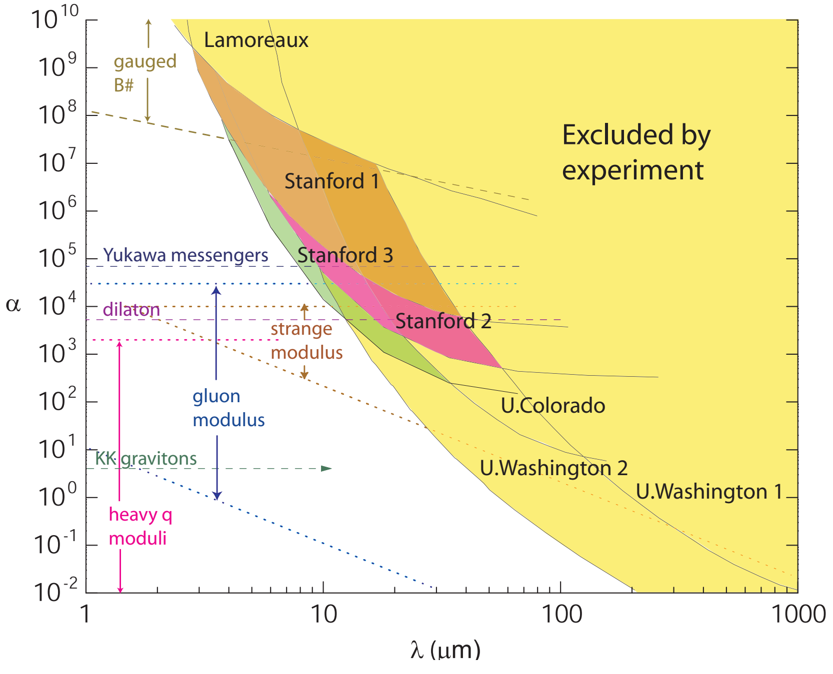
- change of Newton's law at short distances (detectable only in case of 2 large extra dim)
- new short range forces (light scalars and gauge fields)

$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Phenomenology of extra D

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Present LHC bounds $M_* \geq 3 -$ …

- Massive string vibration… resonances in dij…

$M_j^2 = M^2$ …

- Higher s… and glu… …n

pr… $\geq$ … 5 TeV

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M_k … $_0 + r^2/R^2,\ k = 1, 2, \ldots$

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Vast phenomenology but no indication so far

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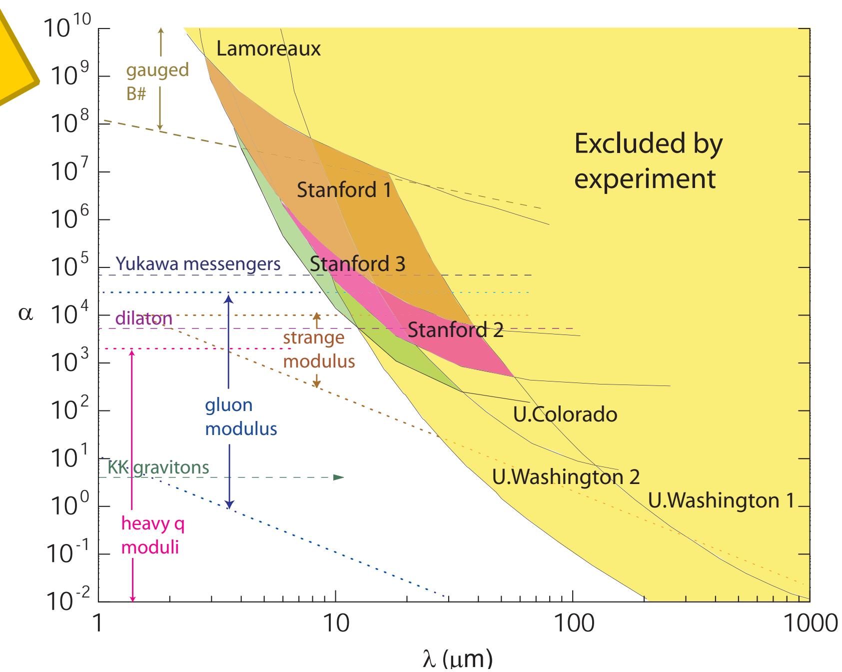
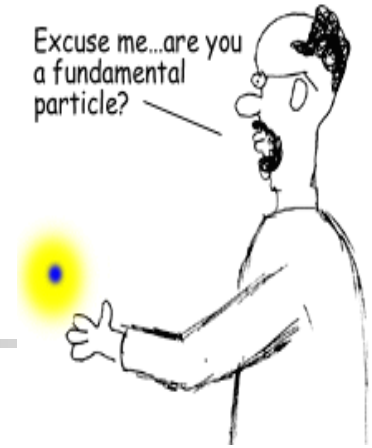


Compositeness



New level of fundamental particles

$$Higgs\ boson \Leftrightarrow \pi - meson$$
$$W, Z\ bosons \Leftrightarrow \rho - mesons$$

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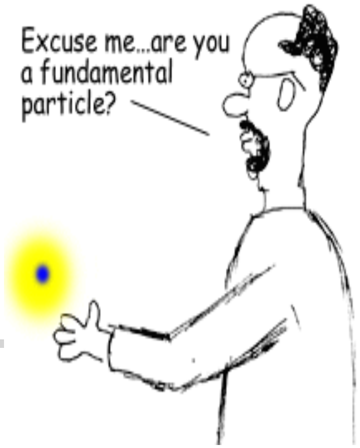

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Should be

$$\pi', \pi'', \rho', \rho'', ...$$

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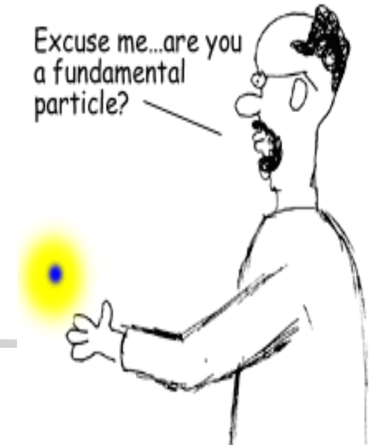

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Quarks and Leptons made of preons

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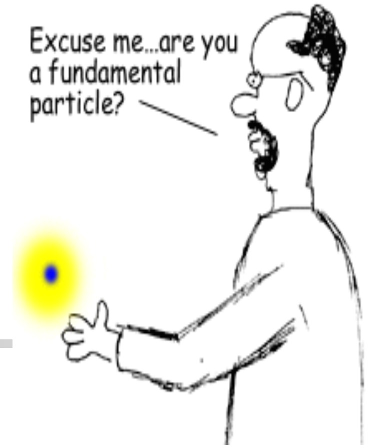

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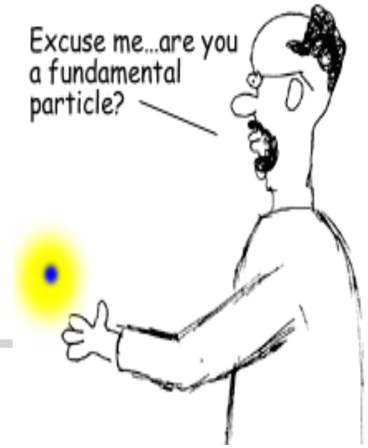
New strong confining forces

Compositeness



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Technicolor

Walking Technicolor

Extended Technicolor

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↓

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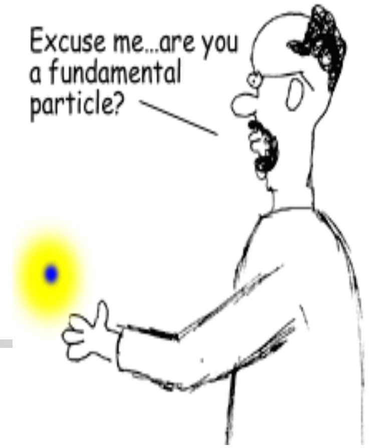

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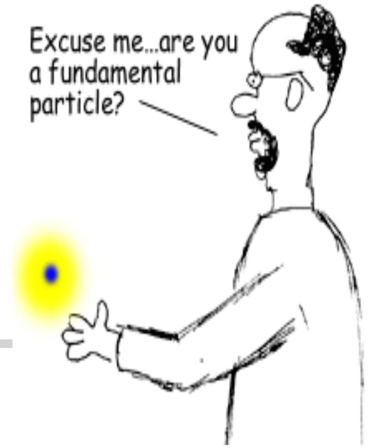
Quarks and Leptons made of preons

⇩

New strong confining forces

- No new excited states observed

Compositeness



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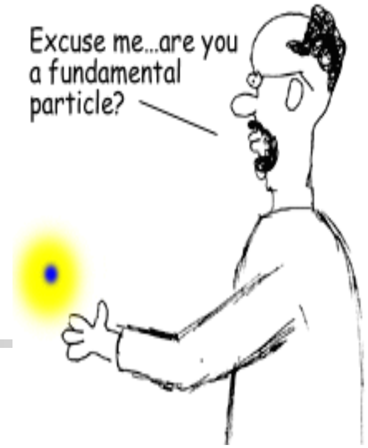
Walking Technicolor
Extended Technicolor

Quarks and Leptons made of preons

New strong confining forces

- No new excited states observed
- Problems with precision EW observables

Compositeness



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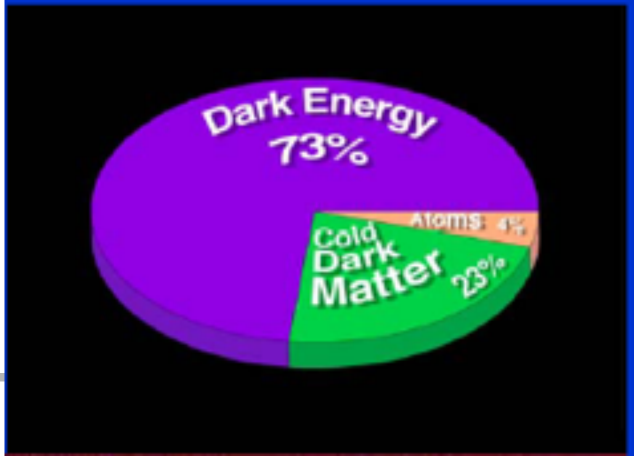
Quarks and Leptons made of preons

↓

New strong confining forces

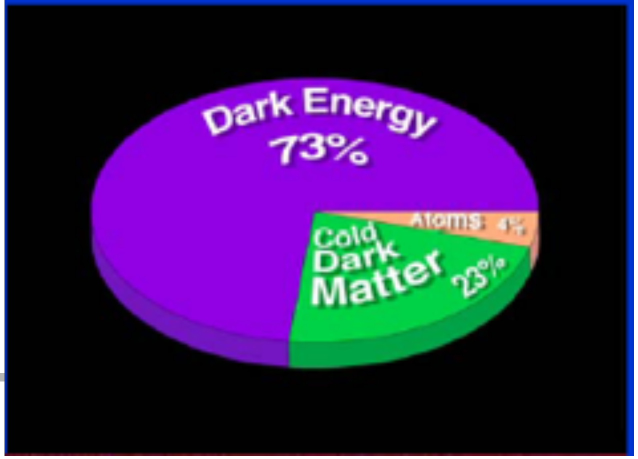
- No new excited states observed
- Problems with precision EW observables
- No viable simple scheme

Dark Matter



What is Dark Matter ?

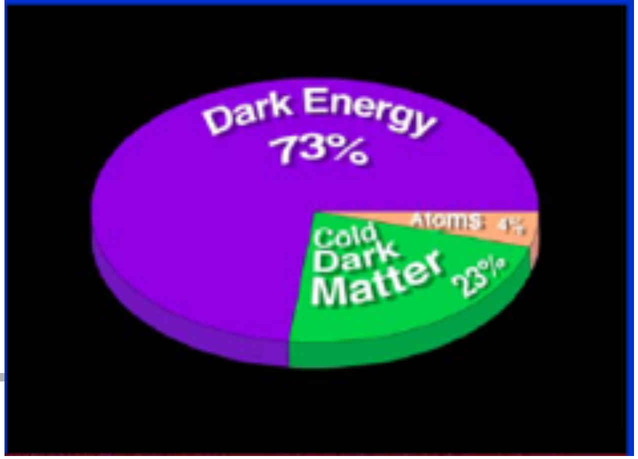
Dark Matter



What is Dark Matter ?

DARK

Dark Matter

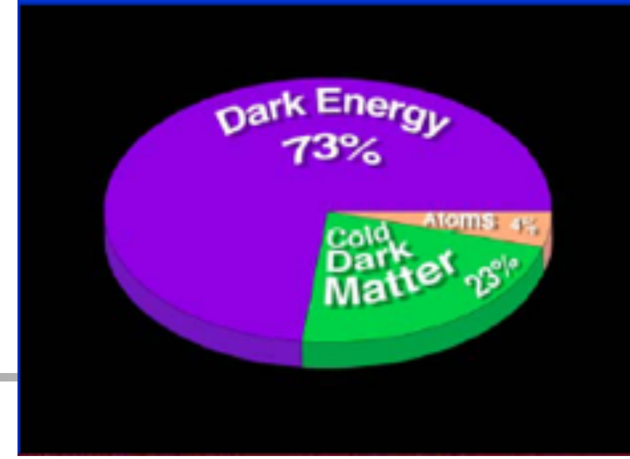


What is Dark Matter ?

DARK

WIMP

Dark Matter



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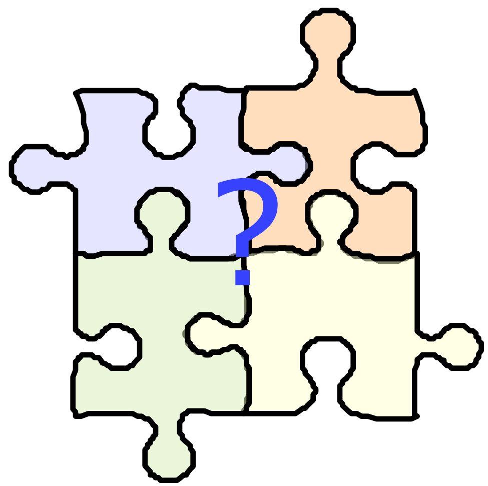
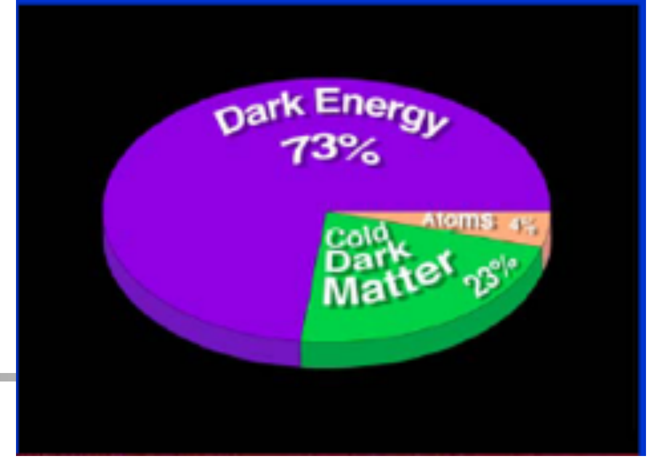


DARK

WIMP

TRANSPARENT

Dark Matter



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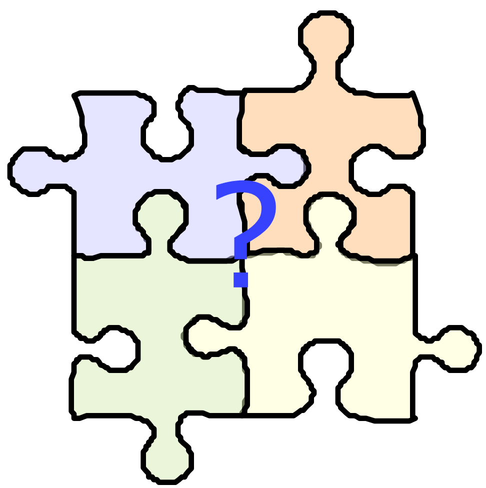
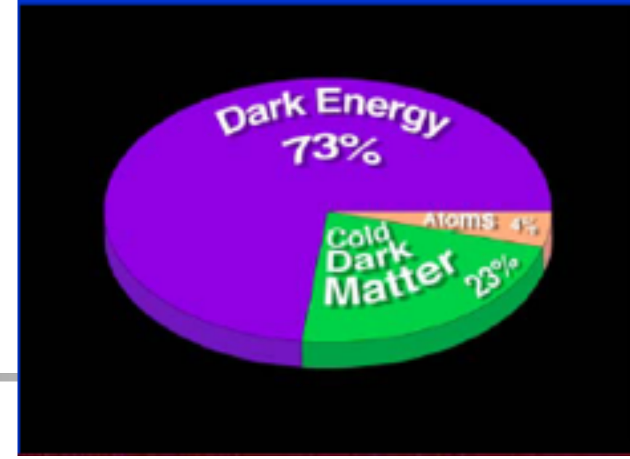


DARK	TRANSPARENT
WIMP	GRAVITINO

Dark Matter



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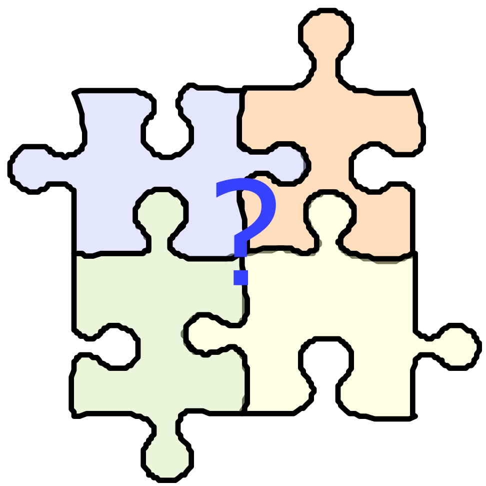
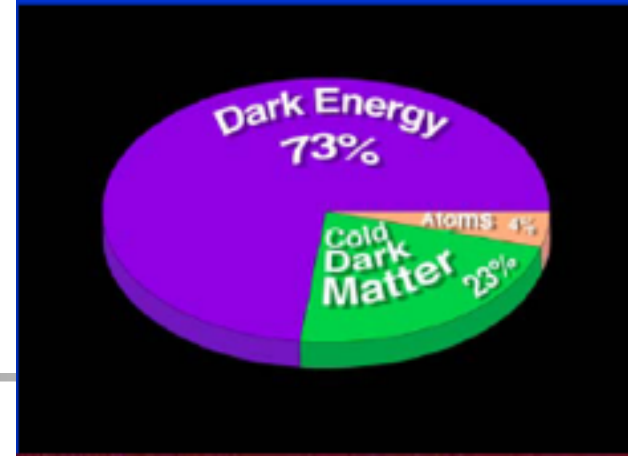


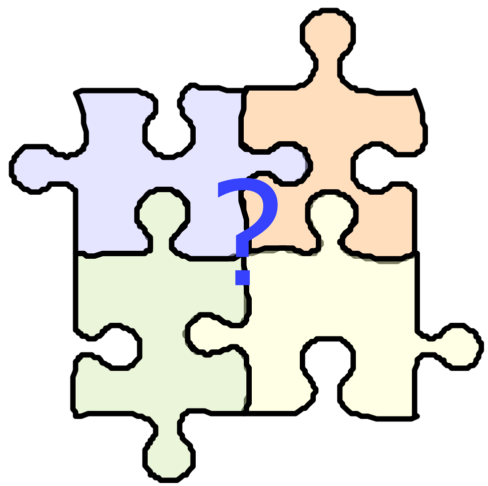
?

DARK	TRANSPARENT	INVISIBLE
WIMP	GRAVITINO	

Dark Matter



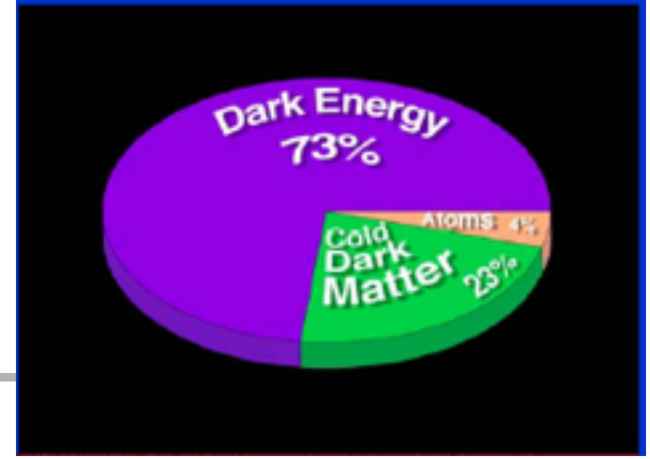
What is Dark Matter ?



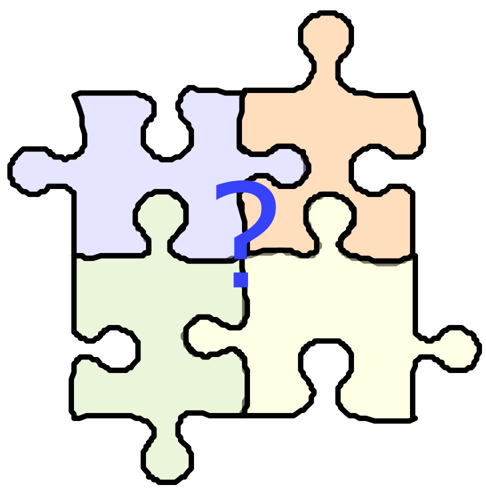
?

DARK	TRANSPARENT	INVISIBLE
WIMP	GRAVITINO	AXION

Dark Matter



What is Dark Matter ?



?

DARK	TRANSPARENT	INVISIBLE
WIMP	GRAVITINO	AXION

What is it made of ?

The Origin of Dark Matter

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right neutrino

Not from the SM:

- axion (axino)
- neutralino — mSUGRA
- sneutrino
- gravitino
- heavy photon
- heavy pseudo-goldstone
- light sterile higgs

The Origin of Dark Matter

The Dark Matter is made of:

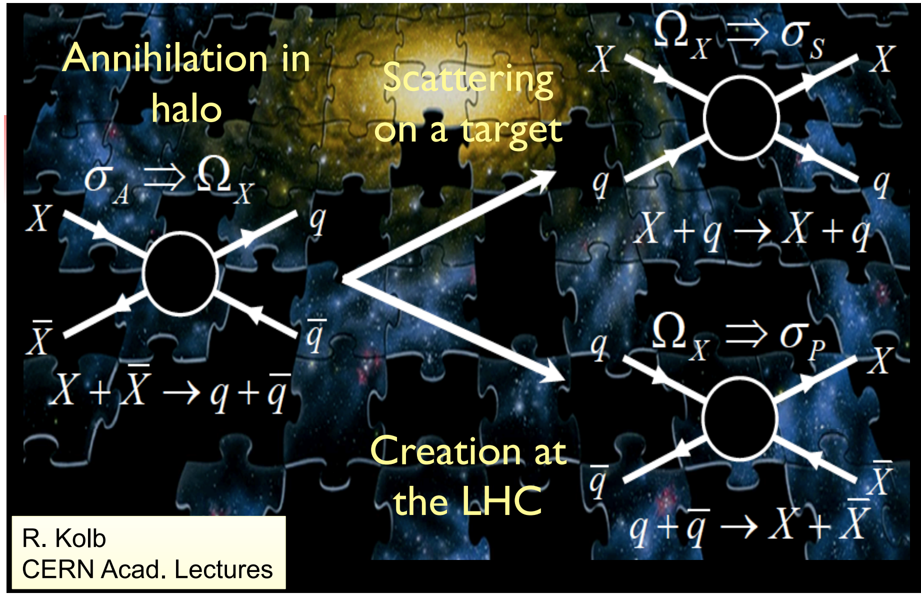
- Macro objects – Not seen
- New particles – right neutrino — not favorable but possible

Not from the SM:

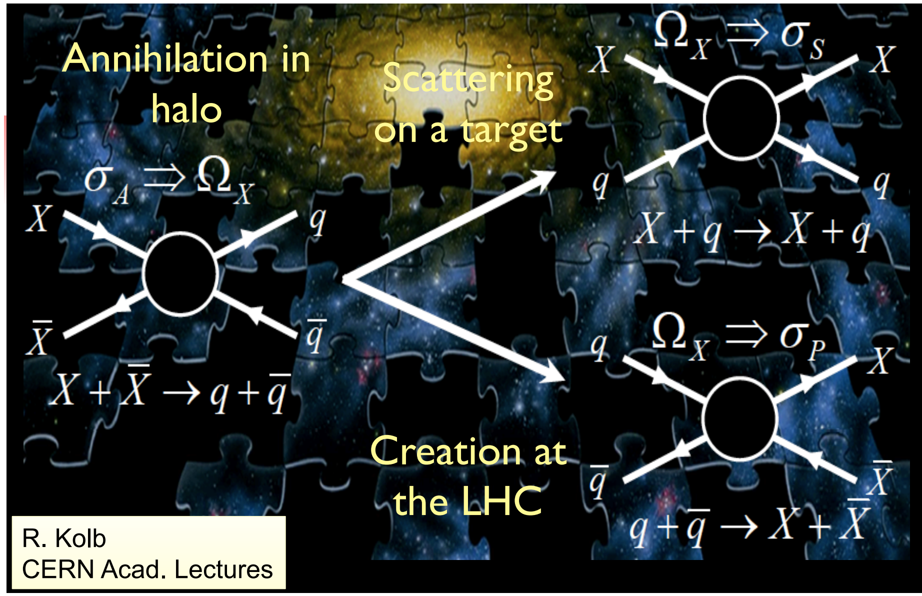
- axion (axino) — might be invisible (?)
- neutralino — mSUGRA — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon
- heavy pseudo-goldstone
- light sterile higgs

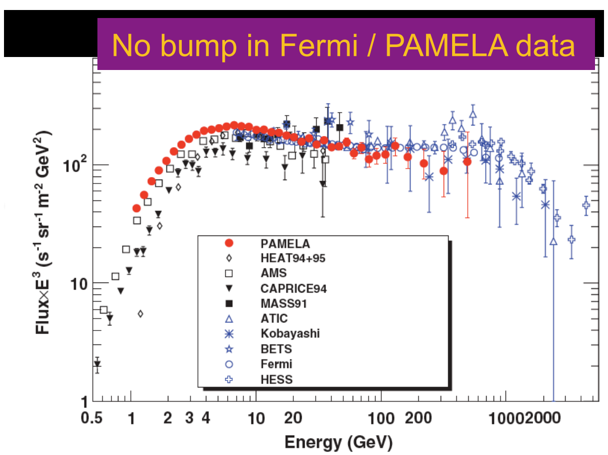
heavy photon, heavy pseudo-goldstone, light sterile higgs: possible, but not related to the other models

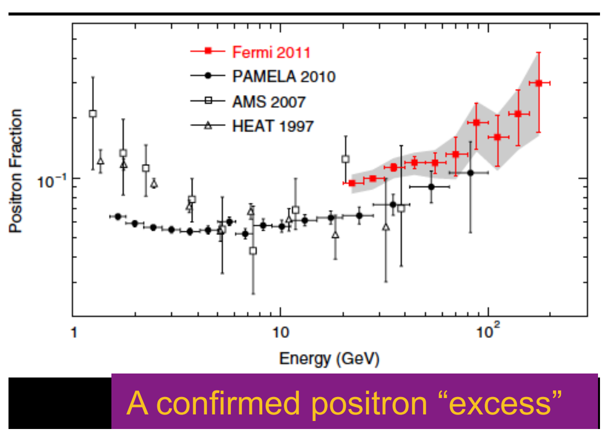
Search for the Dark Matter



Search for the Dark Matter

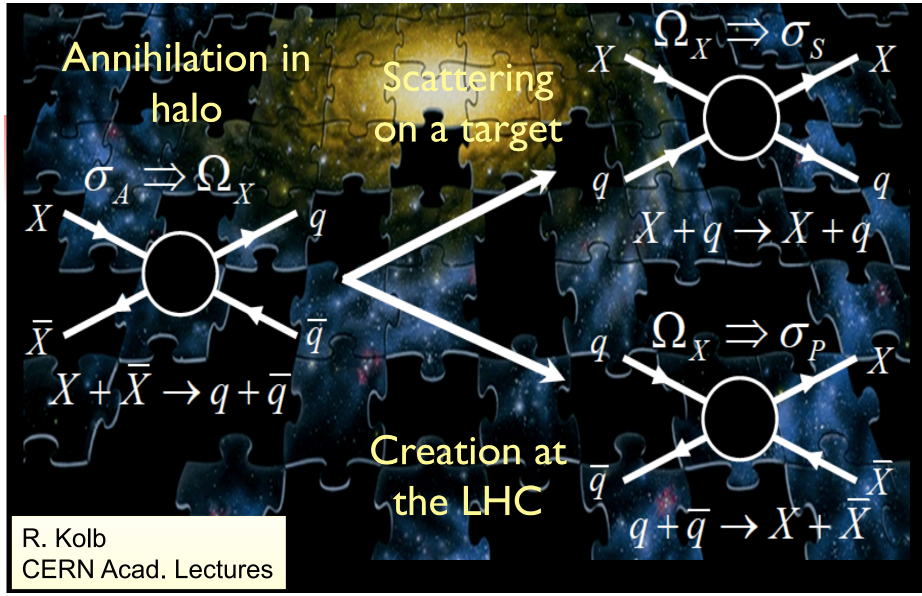


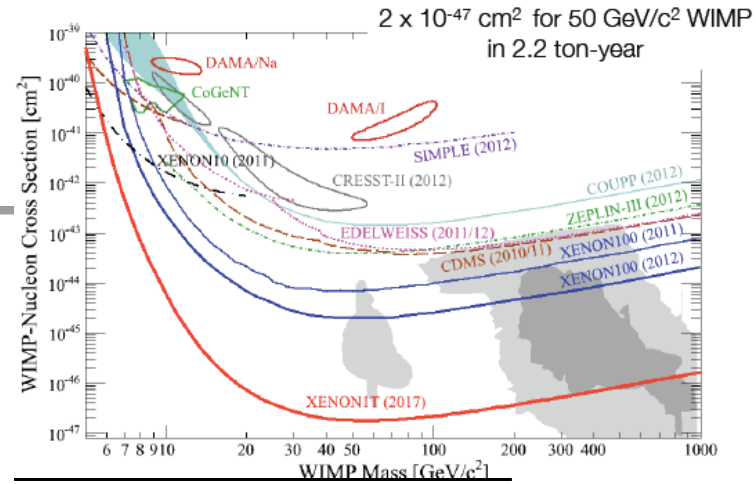




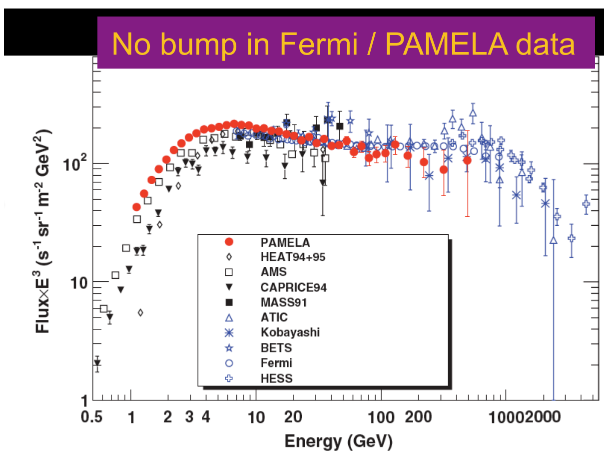
Annihilation in halo

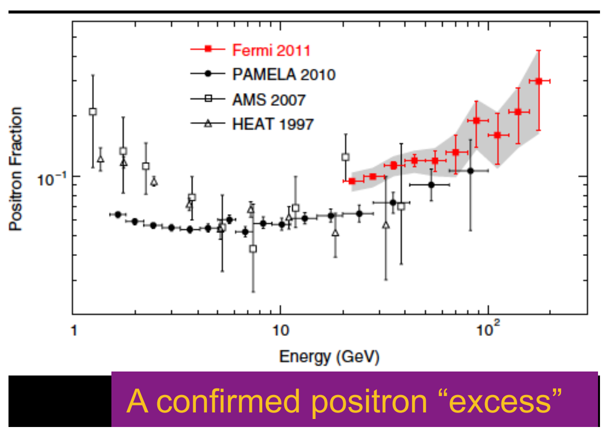
Search for the Dark Matter





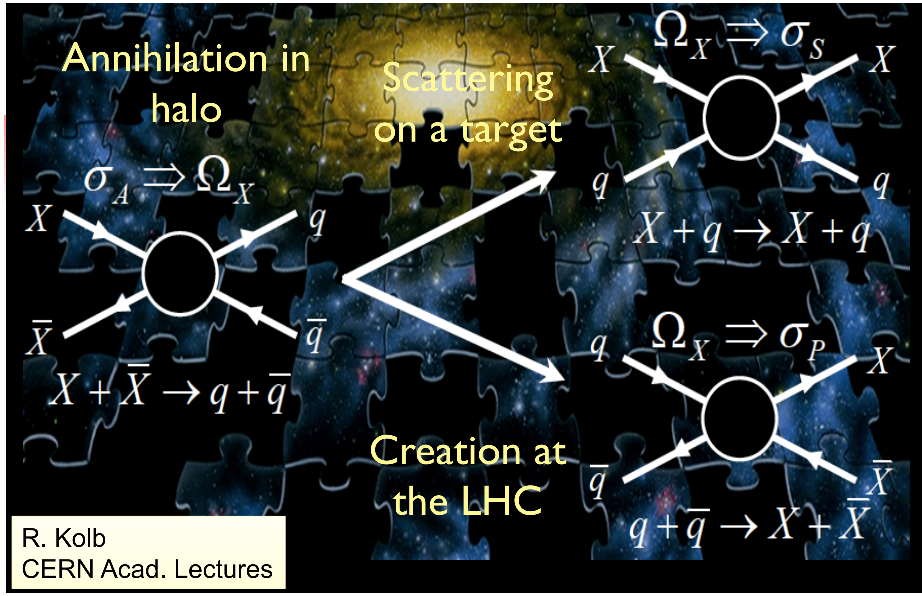
Scattering on a target

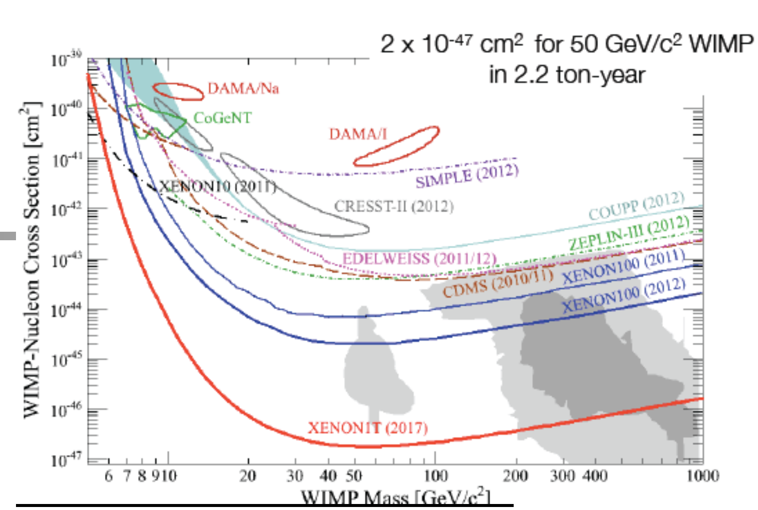




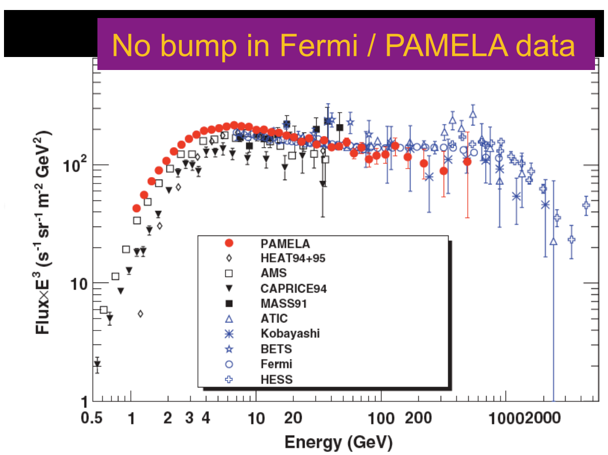
Annihilation in halo

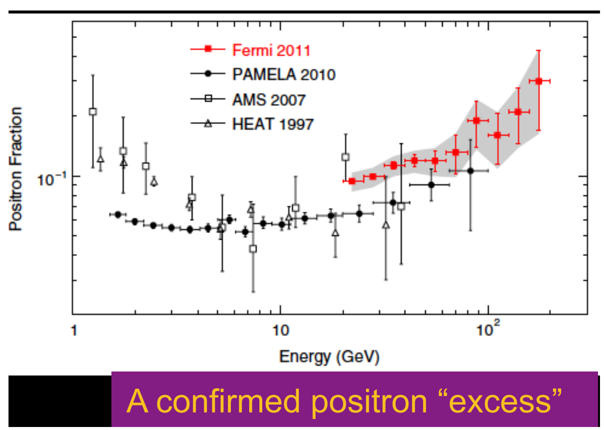
Search for the Dark Matter

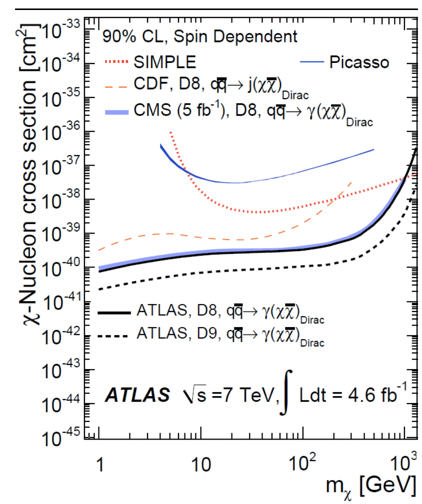




Scattering on a target



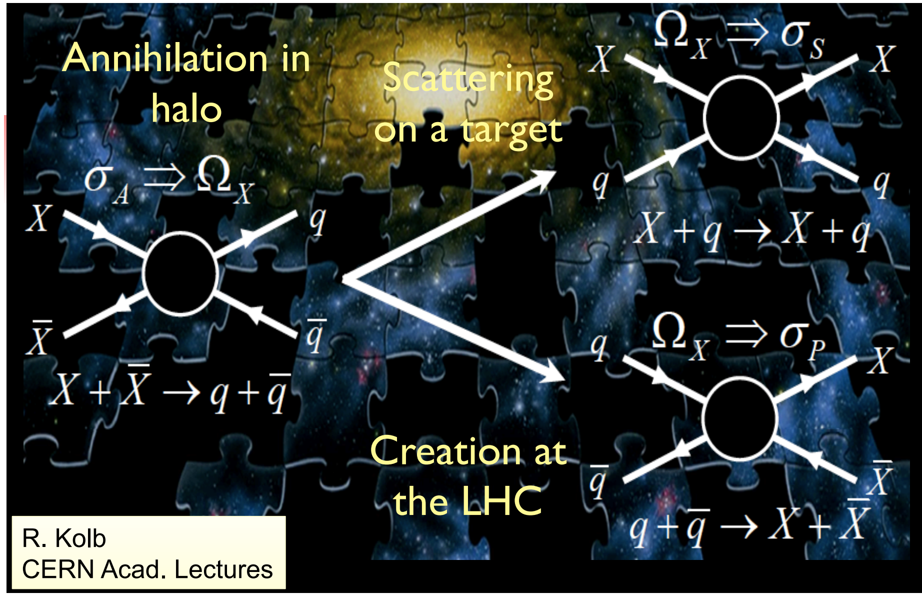


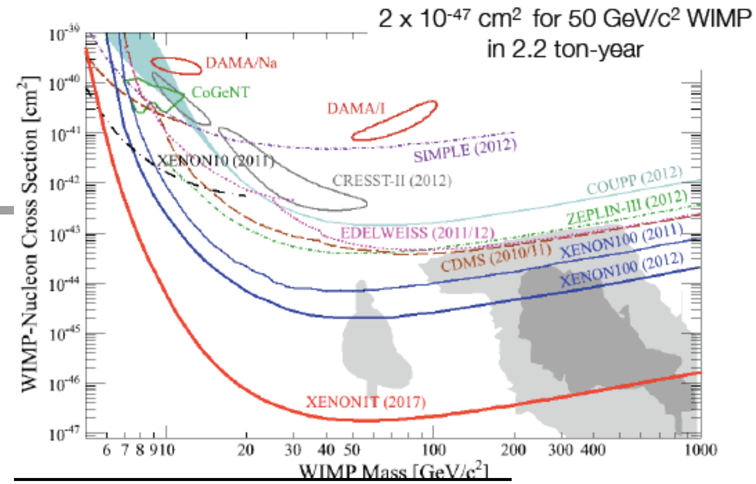


Creation at the LHC

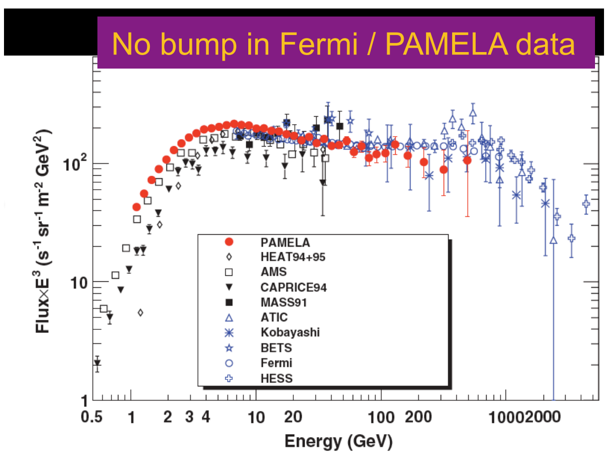
Annihilation in halo

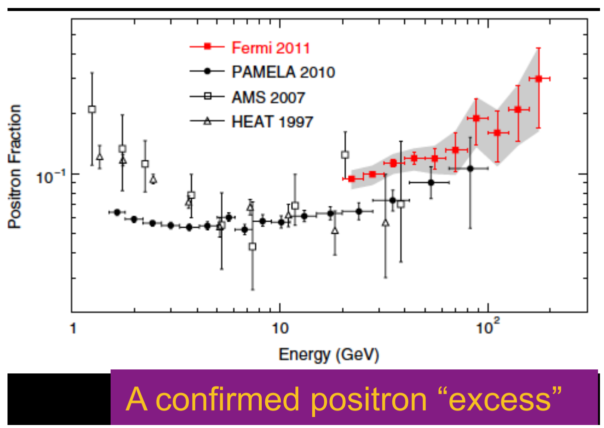
Search for the Dark Matter

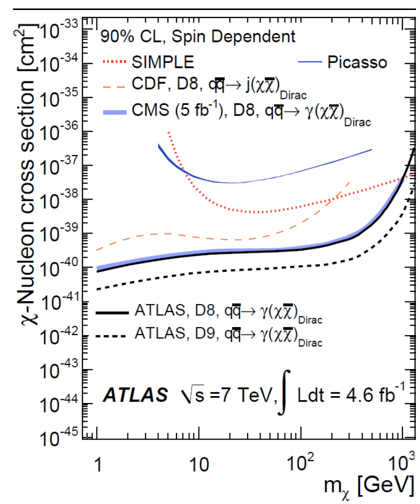




Scattering on a target





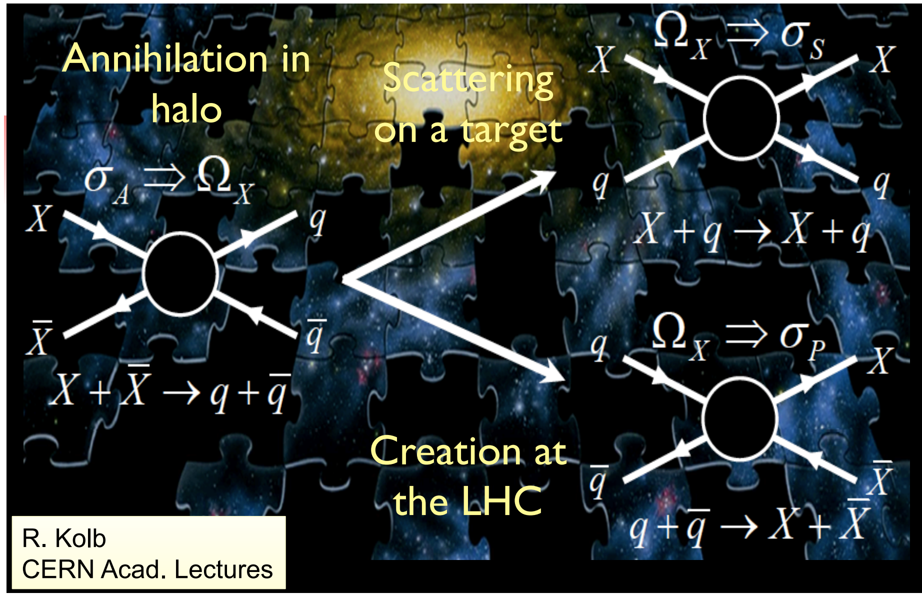


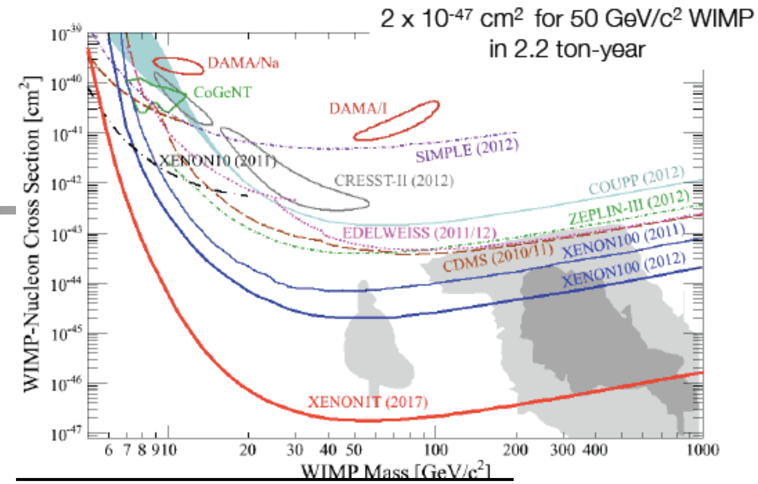
Creation at the LHC

Annihilation in halo

The signal in absent so far!

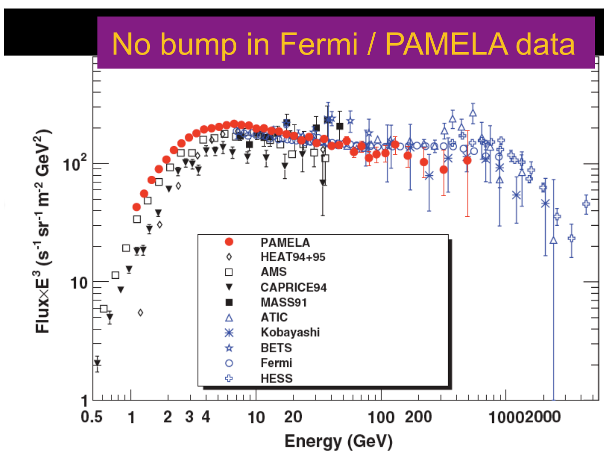
Search for the Dark Matter

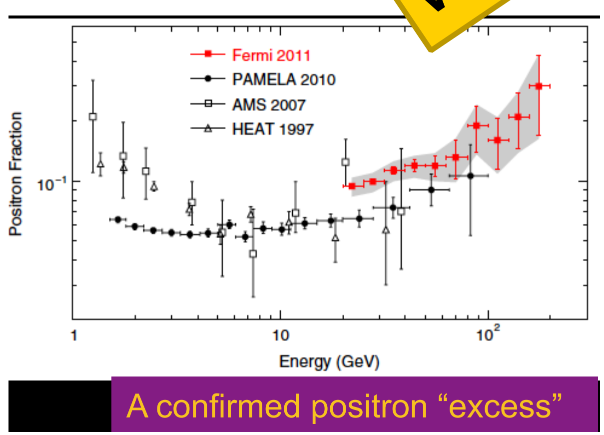


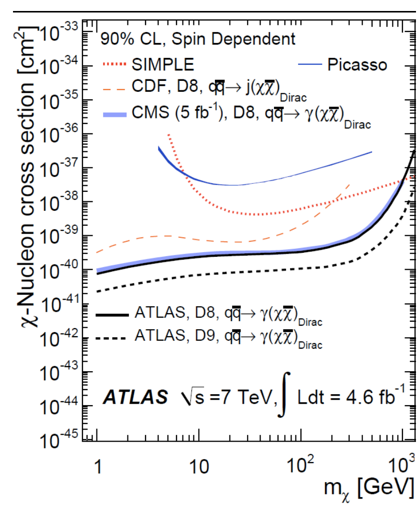


Scattering on a target

WIMP





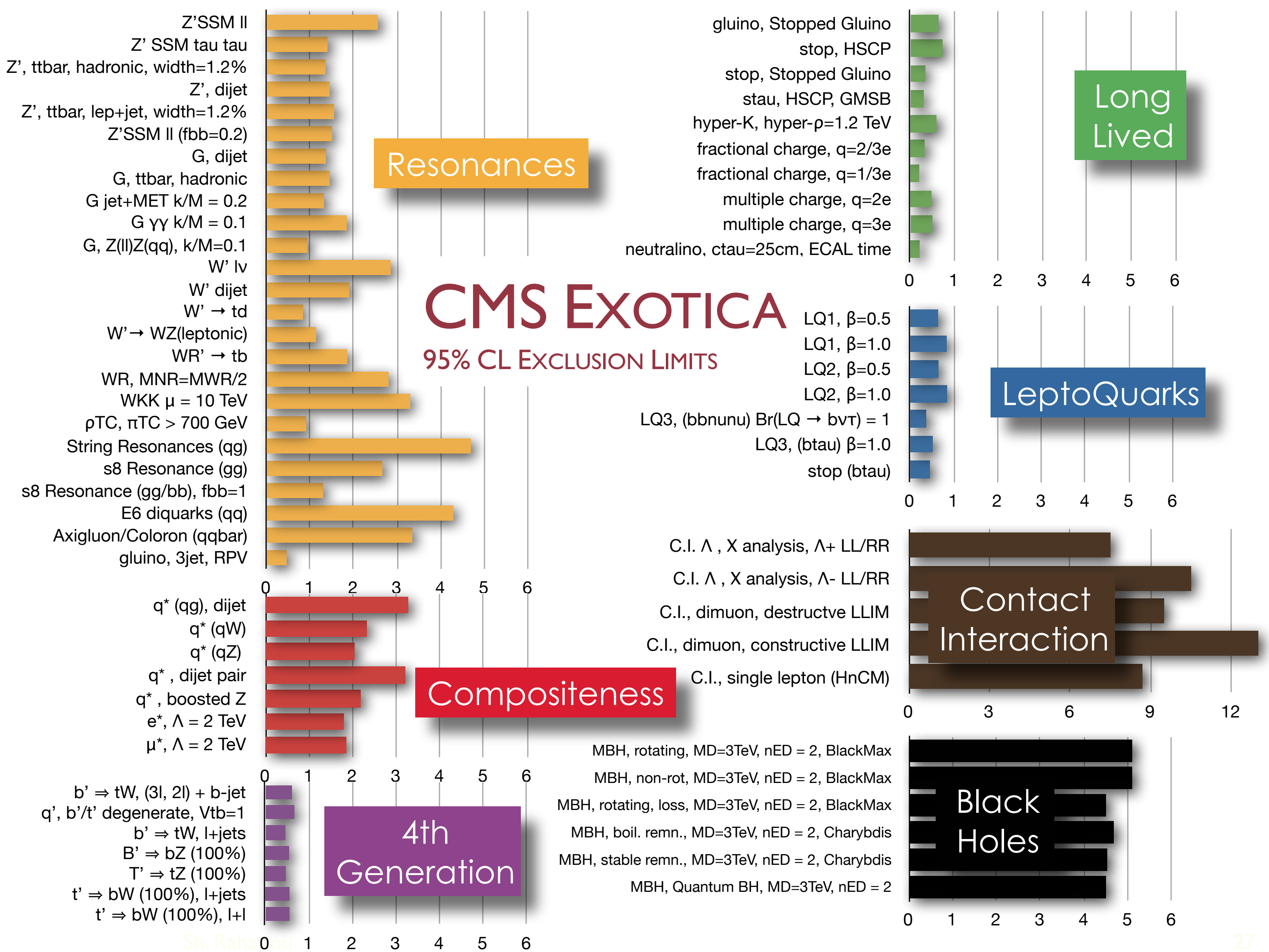


Creation at the LHC

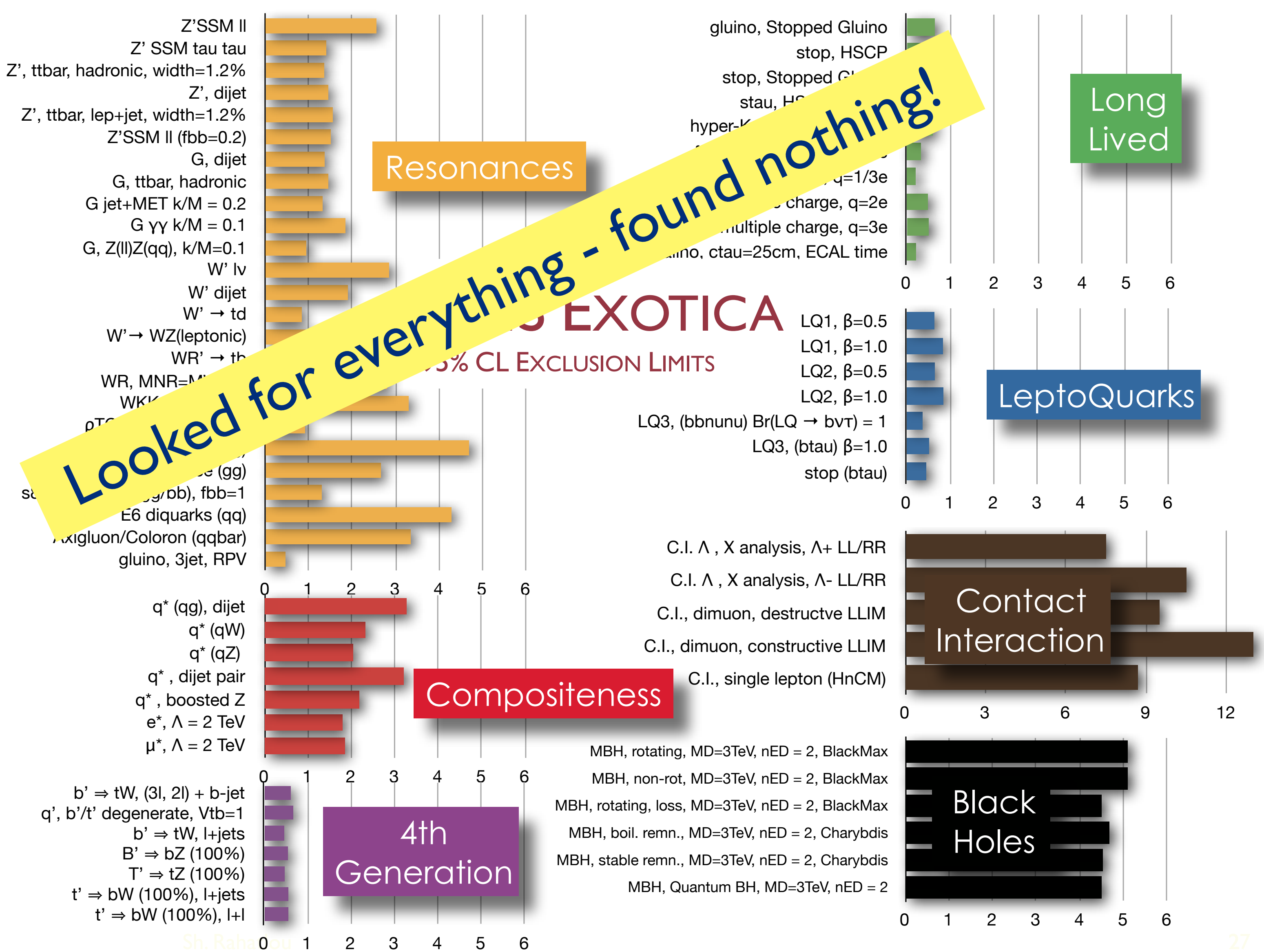
Annihilation in halo

The signal in absent so far!

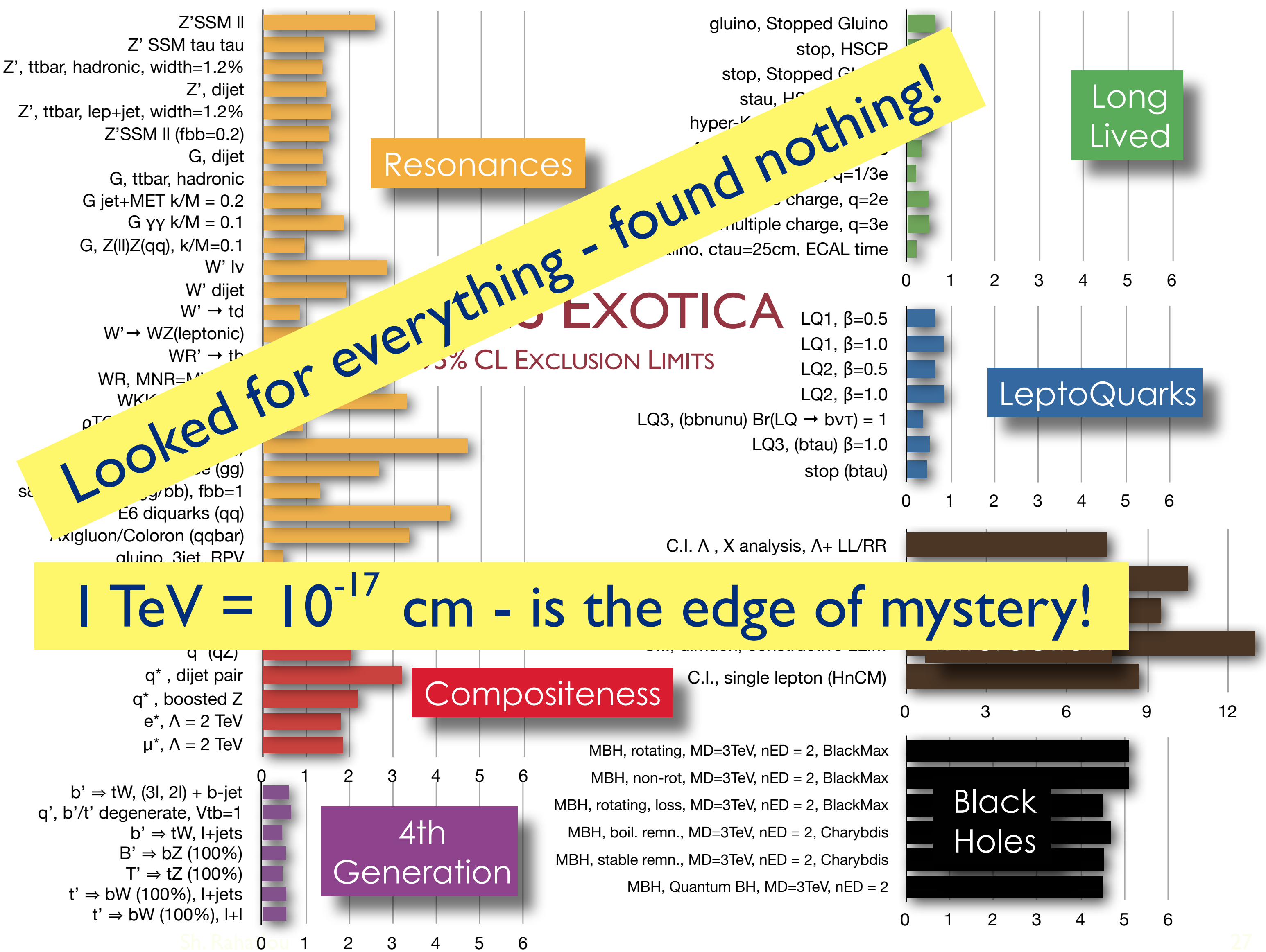
New particles and Interactions



New particles and Interactions



New particles and Interactions



Forward into the Future

Forward into the Future

We live in exciting time and have a chance to unveil the mystery!

Forward into the Future

We live in exciting time and have a chance to unveil the mystery!

Luck

Forward into the Future

We live in exciting time and have a chance to unveil the mystery!

Luck

Patience