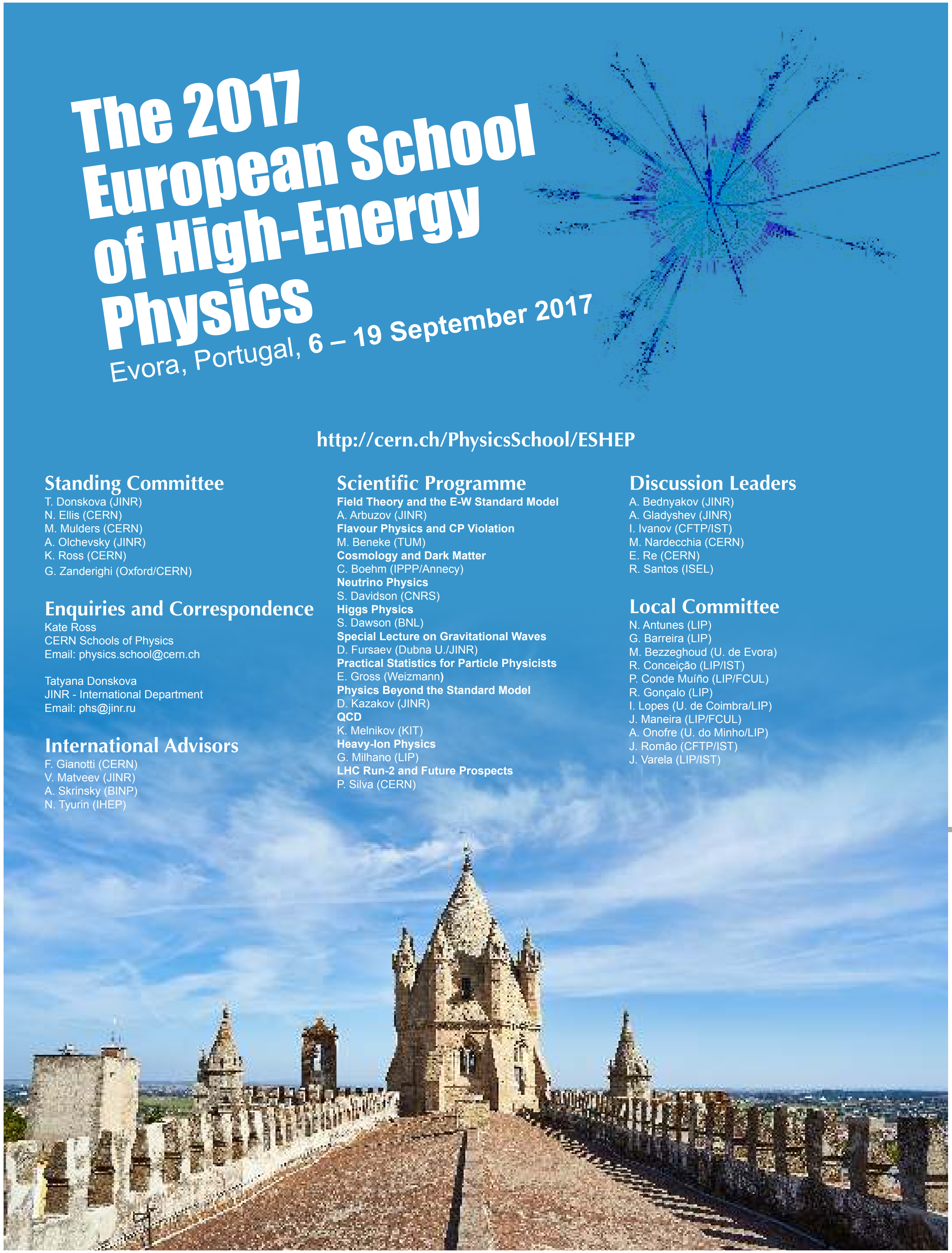

The 2017 European School of High-Energy Physics

Evora, Portugal, 6 – 19 September 2017

http://cern.ch/PhysicsSchool/ESHEP

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BEYOND THE STANDARD MODEL' 17

DMITRY KAZAKOV
JINR(DUBNA)

THE PRINCIPLES

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons $(\underline{3}\times\underline{2}, \underline{3}\times\underline{1}, \underline{1}\times\underline{2}, \underline{1}\times\underline{1})$
- Brout-Englert-Higgs mechanism of spontaneous EW symmetry breaking -> Higgs boson
- CKM and PMNS mixing of flavours
- CP violation via phase factors
- Confinement of quarks and gluons inside hadrons
- Baryon and lepton number conservation
- CPT invariance -> existence of antimatter

The ST principles allow:

- Extra families of quarks and leptons
- Presence or absence of right-handed neutrino
- Majorana or Dirac nature of neutrino
- Extra Higgs bosons

THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs},$$

$$\mathcal{L}_{gauge} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W^i_{\mu\nu} - \frac{1}{4} B_{\mu\nu} B_{\mu\nu}$$

$$+ i\overline{L}_\alpha \gamma^\mu D_\mu L_\alpha + i\overline{Q}_\alpha \gamma^\mu D_\mu Q_\alpha + i\overline{E}_\alpha \gamma^\mu D_\mu E_\alpha$$

$$+ i\overline{U}_\alpha \gamma^\mu D_\mu U_\alpha + i\overline{D}_\alpha \gamma^\mu D_\mu D_\alpha + (D_\mu H)^\dagger (D_\mu H),$$

$$\boxed{+ i\overline{N}_\alpha \gamma^\mu \partial_\mu N_\alpha}$$

possible right handed neutrino ?

$$\mathcal{L}_{Yukawa} = y^L_{\alpha\beta} \overline{L}_\alpha E_\beta H + y^D_{\alpha\beta} \overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta} \overline{Q}_\alpha U_\beta \tilde{H} + h.c.,$$

$$\boxed{+ y^N_{\alpha\beta} \overline{L}_\alpha N_\beta \tilde{H}}$$

$$\mathcal{L}_{Higgs} = -V = m^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2$$

All these parameters are not predicted by the SM and determined experimentally

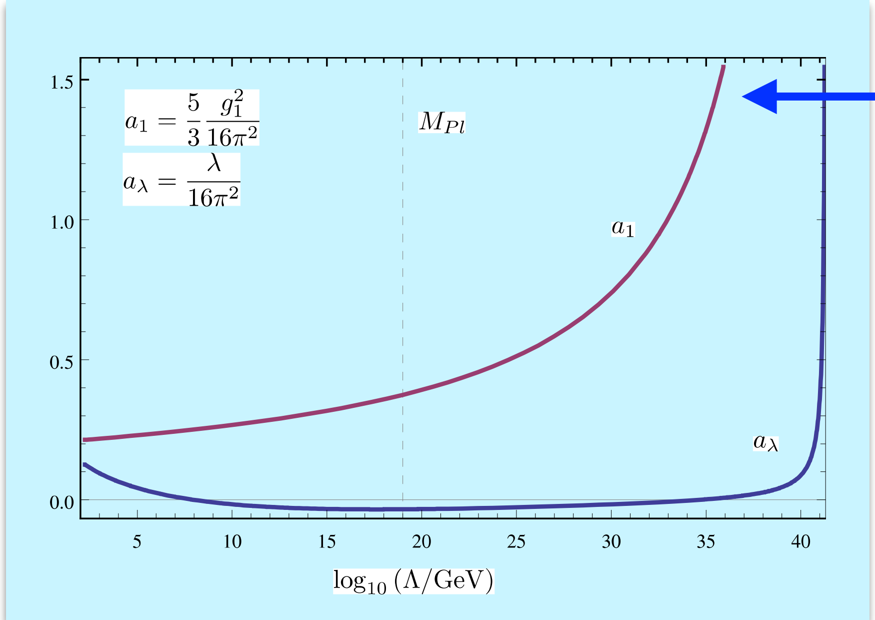
Three gauge couplings

Three or four Yukawa matrices

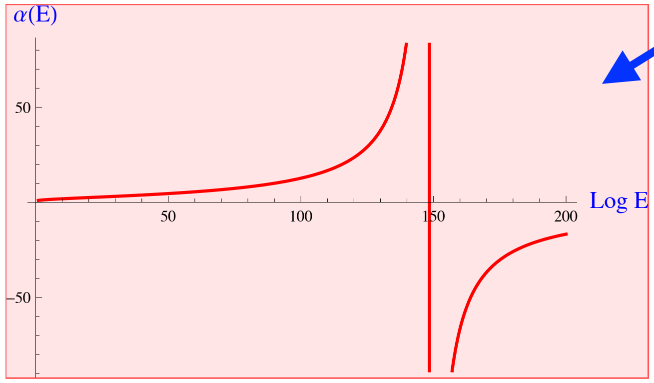
Two parameters

THE PROBLEMS

- The running couplings possess the Landau ghost poles at high energies



- The ghost pole exist for the U(1) coupling and for the Higgs coupling, but … beyond the Planck scale
- The Landau pole has a wrong sign residue that indicates the presence of unphysical ghost fields - intrinsic problem and inconsistency of a theory



This is the ghost pole

$$\alpha_1(Q^2) = \frac{\alpha_{10}}{1 - \frac{41}{10}\frac{\alpha_{10}}{4\pi}\log(Q^2/M_z^2)}$$

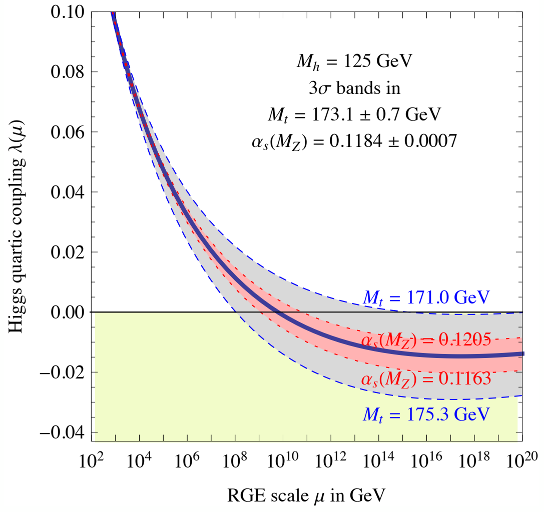
$$Q^* = M_Z e^{\frac{20\pi}{41\alpha_{10}}} \sim 10^{41}\ GeV$$

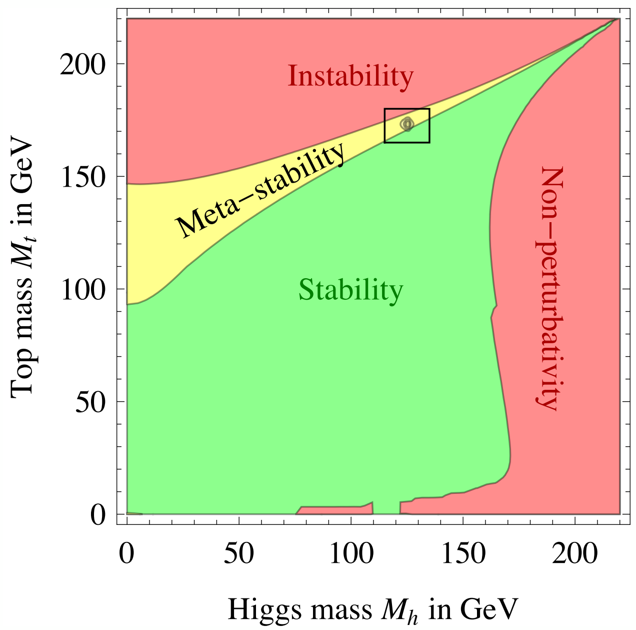
- The situation may change in GUTs due to new heavy fields @ the GUT scale
- requires modification of the SM at VERY high energies

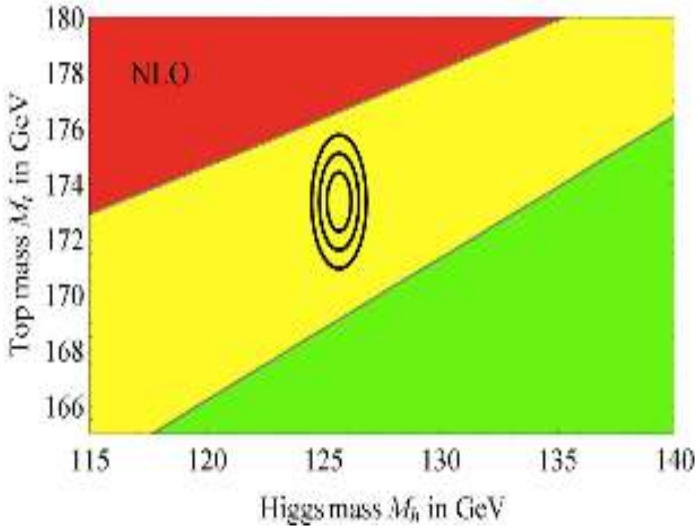
THE PROBLEMS

- Quantum corrections can make the vacuum unstable

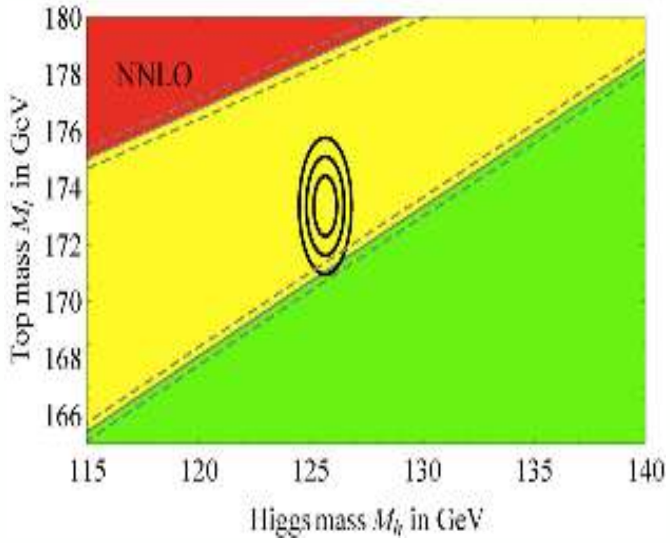
- the whole construction of the SM may be in trouble being metastable or even unstable
- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and accuracy







NLO



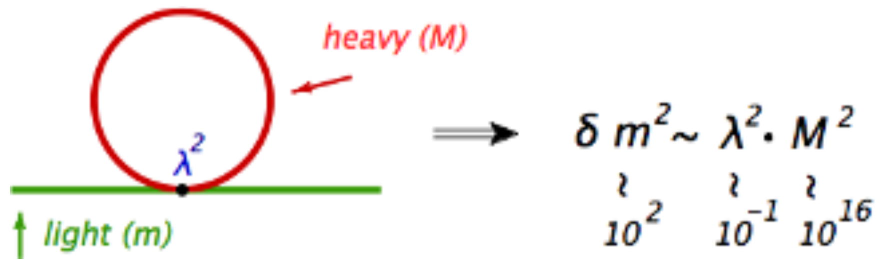
NNLO

The way out might be the new physics at higher scale

THE PROBLEMS

New physics at high scale may destroy the EW scale of the SM

- The Higgs sector is not protected by any symmetry
- This does not happen with the gauge bosons or fermions. Their masses are protected by gauge invariance and chiral nature of the EW sector
- Quantum corrections to the Higgs potential due to New physics



- creates the hierarchy problem
- requires modification of the SM

$$\frac{m_H}{m_{GUT}} \sim 10^{-14}$$

- This is not the problem of the SM itself (quadratic divergences are absorbed into the unobservable bare mass).
- This creates power law dependence of the low energy physics on unknown high energy physics that is not acceptable
- The way out might be the new physics at higher scale

THE OPEN QUESTIONS

Why's?

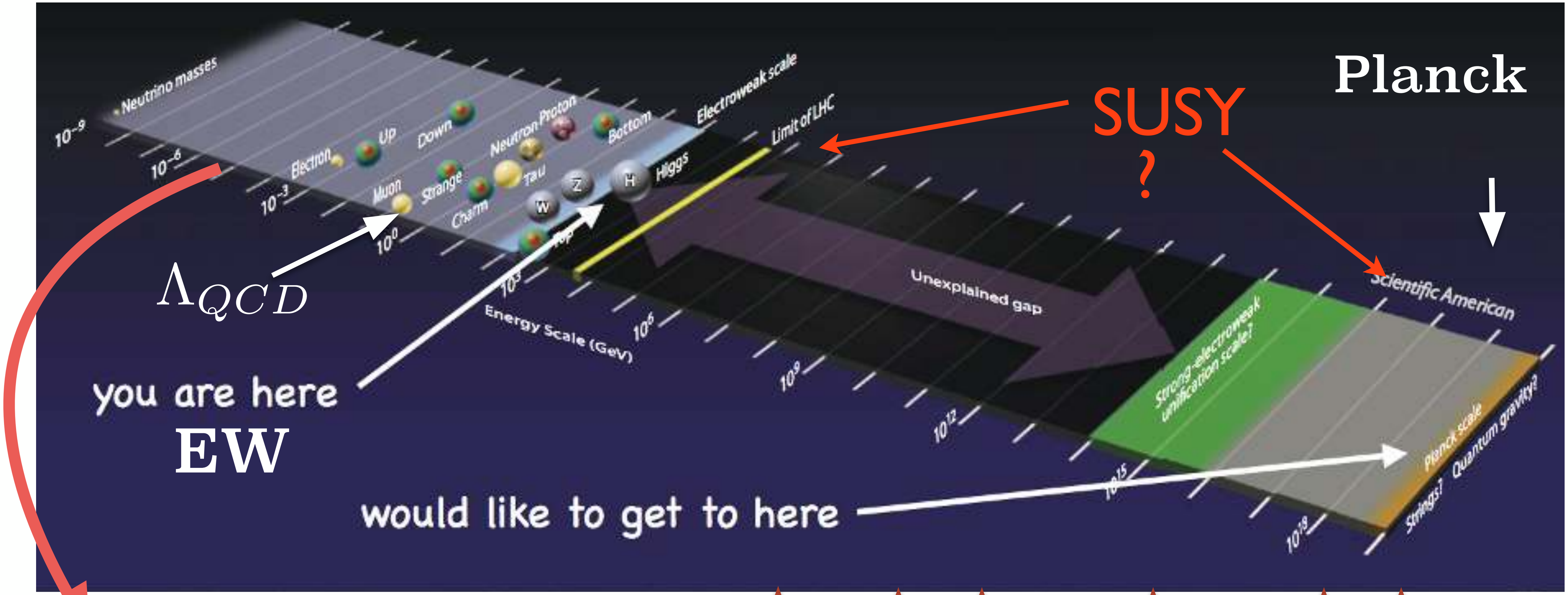
- why the SU(3)xSU(2)xU(1) ?
- why 3 generations ?
- why quark-lepton symmetry?
- why V-A weak interaction?
- why L-R asymmetry?
- why B & L conservation?
- etc

How's?

- how confinement actually works ?
- how the quark-hadron phase transition happens?
- how neutrinos get a mass?
- how CP violation occurs in the Universe?
- how to protect the SM from would be heavy scale physics?

- Is it self consistent ?
- Does it describe <u>all</u> experimental data?
- Are there <u>any</u> indications for physics beyond the SM?
- Is there another scale except for EW and Planck?
- Is it compatible with Cosmology? Where is dark matter?

IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?



Λ_{QCD}

you are here

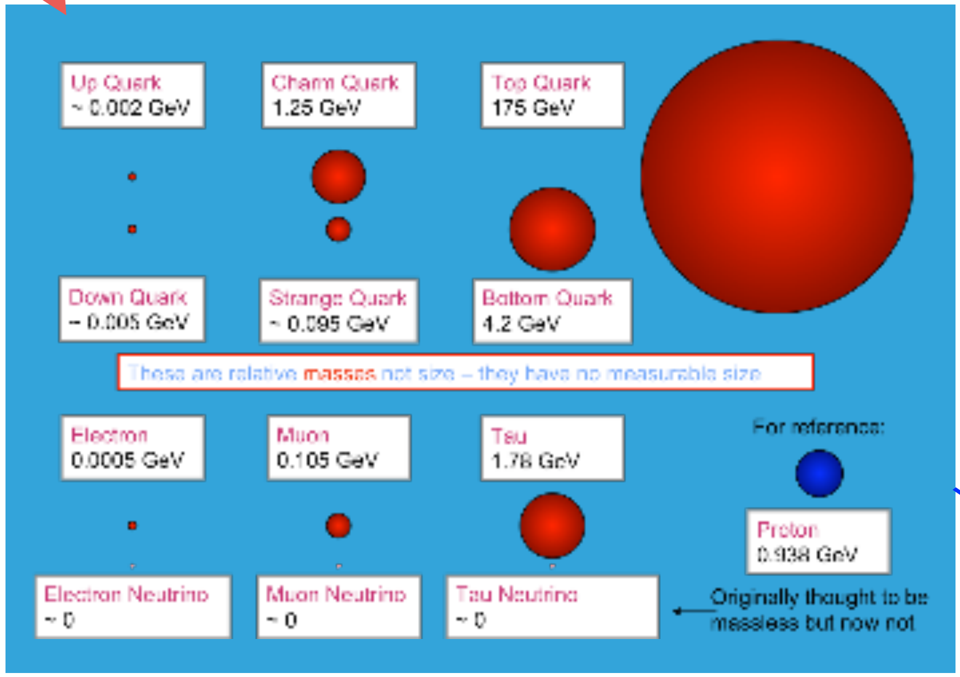
EW

would like to get to here

SUSY

?

Planck



?

Vacuum Stab ~ 10^{11} GeV

Majorana scale ~ 10^{12} GeV

GUT scale ~ 10^{16} GeV

String scale ~ 10^{18} GeV

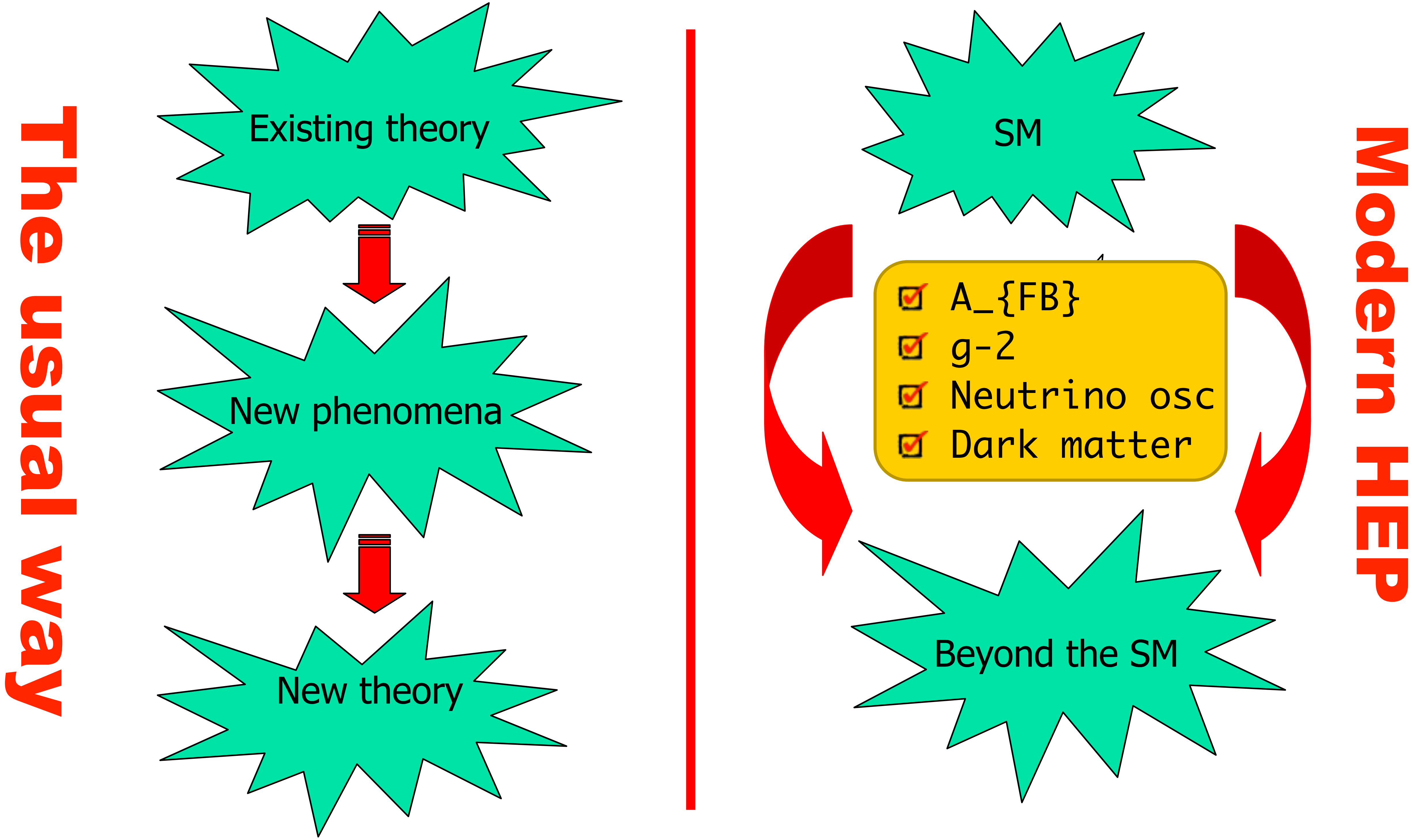
Planck scale ~ 10^{19} GeV

?

THE WAYS BEYOND

- Extension of symmetry group of the SM : SUSY, GUT, new U(1)'s
  -> may solve the problem of Landau pole, the problem of stability, the hierarchy problem, may give the DM particle
- Additional particles: Extra generations, extra gauge bosons, extra Higgs bosons, extra neutrinos, etc
  -> may solve the problem of stability, DM
- Extra dimensions: Compact or flat extra dim
  -> Opens a whole new world of possibilities, may solve the problem of stability and the hierarchy problem, gives new insight into gravity
- New paradigm beyond local QFT: string theory, brane world, etc
  -> main task is unification with gravity and construction of quantum gravity

HEP PARADOX



The usual way

Existing theory

New phenomena

New theory

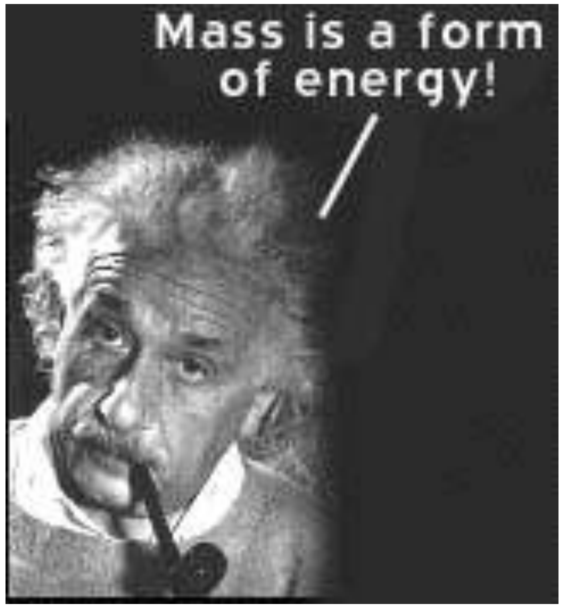
Modern HEP

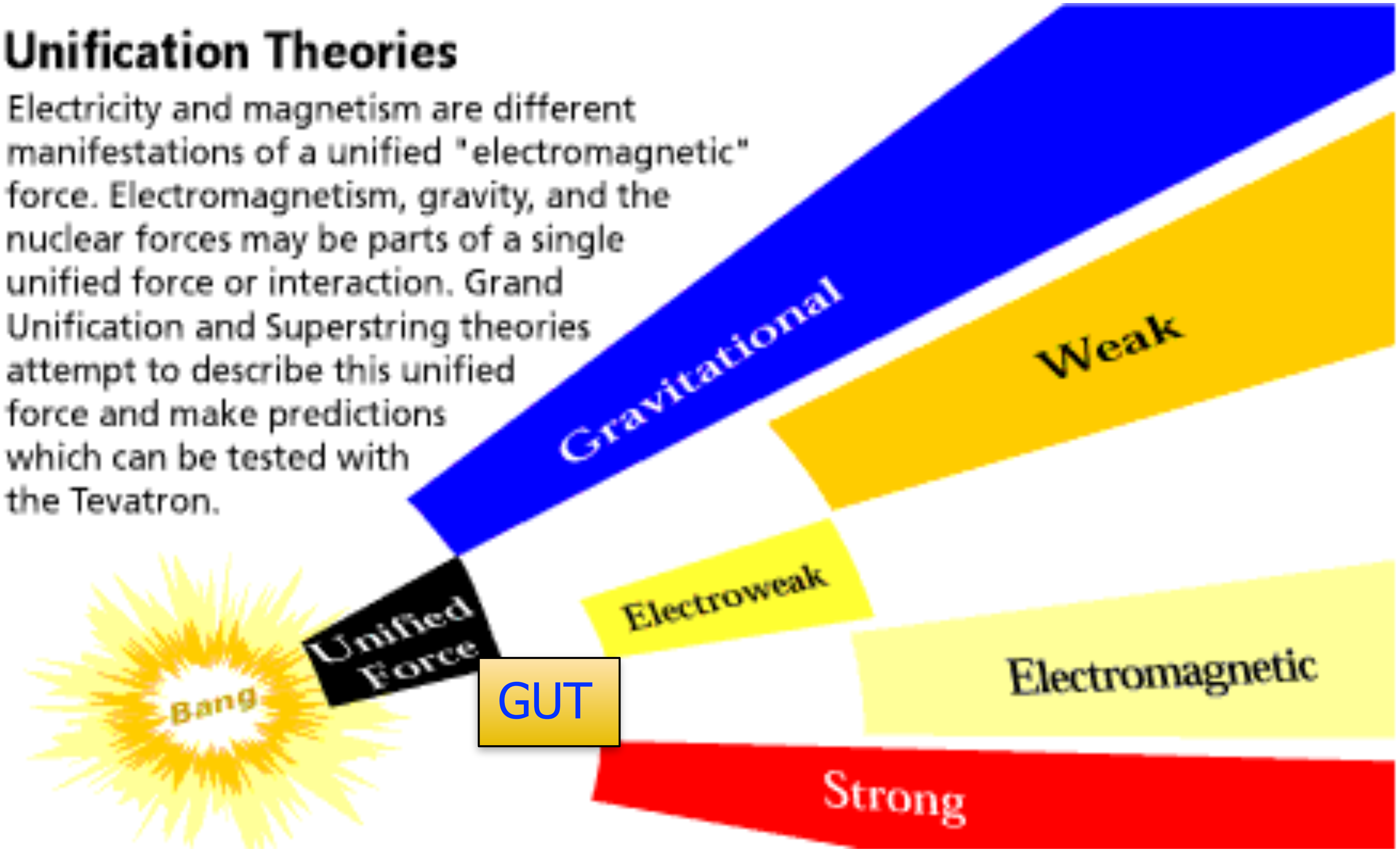
SM

- ☑ A_{FB}
- ☑ g-2
- ☑ Neutrino osc
- ☑ Dark matter

Beyond the SM

THE UNIFICATION PARADIGM





Unification Theories

Electricity and magnetism are different manifestations of a unified "electromagnetic" force. Electromagnetism, gravity, and the nuclear forces may be parts of a single unified force or interaction. Grand Unification and Superstring theories attempt to describe this unified force and make predictions which can be tested with the Tevatron.

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

NEW SYMMETRIES

SUPERSYMMETRY

Supersymmetry is an extension of the Poincare symmetry of the SM

Poincare Algebra

$$
\begin{aligned}
&[P_\mu, P_\nu] = 0,\\
&[P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),\\
&[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho})
\end{aligned}
$$

Super Poincare Algebra $Q_i,\ \bar{Q}_i$

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$

$$[Q^i_\alpha, M_{\mu\nu}] = \frac{1}{2}(\sigma_{\mu\nu})_\alpha^\beta Q^i_\beta, \qquad [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\frac{1}{2}\bar{Q}^i_{\dot\beta}(\bar{\sigma}_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta} P_\mu$$

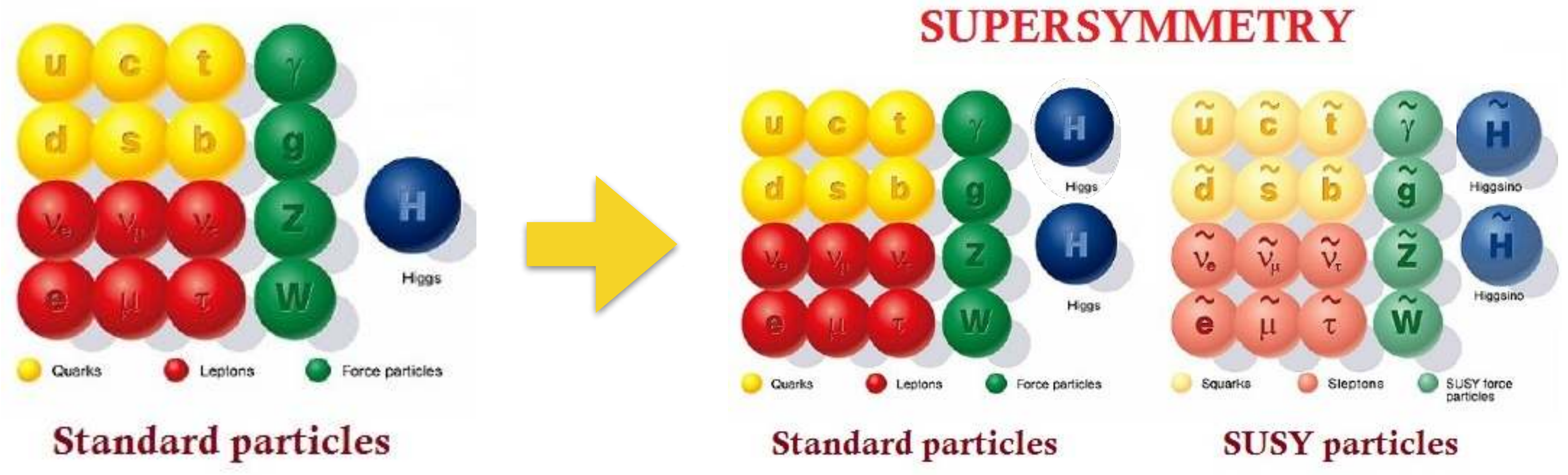
$$\{Q^i_\alpha, Q^j_\beta\} = 2\epsilon_{\alpha\beta}Z^{ij}, \qquad Z^{ij} = Z^+_{ij},$$

$$\{\bar{Q}^i_{\dot\alpha}, \bar{Q}^j_{\dot\beta}\} = -2\epsilon_{\dot\alpha\dot\beta}Z^{ij}, \qquad [Z_{ij}, anything] = 0,$$

$$\alpha, \dot\alpha = 1, 2 \qquad i, j = 1, 2, \ldots, N.$$

MOTIVATION FOR SUSY IN PARTICLE PHYSICS

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



Why SUSY?

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

- Unification with gravity!

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

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

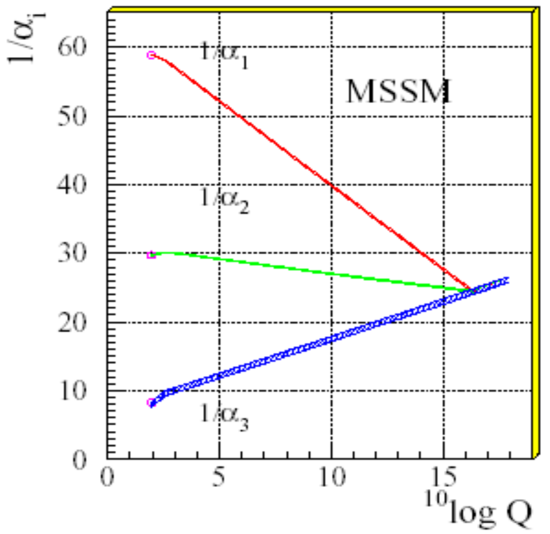
Local supersymmetry = general relativity !

MOTIVATION FOR SUSY IN PARTICLE PHYSICS

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

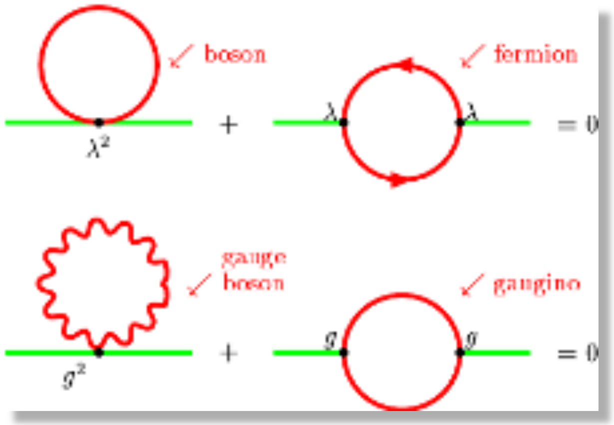
Why SUSY?

- Unification of the gauge couplings



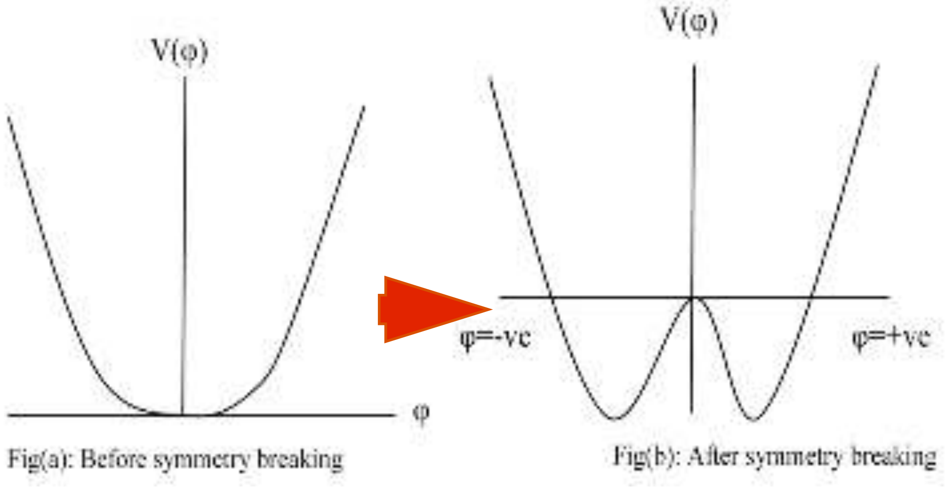
The basis of a grand Unified Theory

- Solution of the hierarchy problem



Cancellations of corrections and stabilization of the Higgs potential

- Explanation of the EW symmetry violation



Violation of symmetry comes from radiative corrections

- 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=DM

QUANTUM STATES

Quantum states: Vacuum = $|E,\lambda>$ $Q|E,\lambda>=0$

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0$$

Energy helicity

State	Expression	# of states
vacuum	$\|E,\lambda>$	1
1-particle	$\overline{Q_i}\,\|E,\lambda>=\|E,\lambda+1/2>$	$\begin{pmatrix} N \\ 1 \end{pmatrix} = N$
2-particle	$\overline{Q_i}\,\overline{Q_j}\,\|E,\lambda>=\|E,\lambda+1>$	$\begin{pmatrix} N \\ 2 \end{pmatrix} = \frac{N(N-1)}{2}$
…	…	…
N-particle	$\overline{Q_1}\,\overline{Q_2}...\overline{Q_N}\,\|E,\lambda>=\|E,\lambda+N/2>$	$\begin{pmatrix} N \\ N \end{pmatrix} = 1$

Total # of states: $\displaystyle\sum_{k=0}^{N} = 2^N = 2^{N-1}\ bosons + 2^{N-1}\ fermions$

SUSY MULTIPLETS

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

$$(\overset{\text{scalar}}{\varphi},\overset{\text{spinor}}{\psi})$$

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
# of states	1	1	1	1

$$(\underset{\text{spinor}}{\lambda}, \underset{\text{vector}}{A_\mu})$$

Members of a supermultiplet are called **superpartners**

Extended supersymmetry

N=4	SUSY YM	helicity	-1	–1/2	0	1/2	1				
	λ = -1	# of states	1	4	6	4	1				
N=8	SUGRA	helicity	-2	–3/2	–1	–1/2	0	1/2	1	3/2	2
	λ = -2	# of states	1	8	28	56	70	56	28	8	1

$\boxed{N \leq 4S}$ ← spin

$N \leq 4$ For renormalizable theories (YM)

$N \leq 8$ For (super)gravity

THE SIMPLEST (N=1) SUSY MULTIPLETS

Bosons and Fermions come in pairs

$$(\varphi, \psi) \qquad (\tilde{\lambda}, A_\mu) \qquad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

scalar

chiral fermion

majorana fermion

vector

gravitino

graviton

THE PARTICLE CONTENT OF THE MSSM

Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge							
$\mathbf{G^a}$	gluon	g^a	*gluino*	$\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak	W^k $(W^\pm, Z)$	*wino, zino*	$\tilde{w}^k$ $(\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge	B (γ)	*bino*	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
$\mathbf{N_i}$		$\tilde{N}_i = \tilde{\nu}_R$		$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	$1/3$
$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3^*	1	$-4/3$
$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3^*	1	$2/3$
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	-1
$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1
$\mathbf{S}$	Singlet	s	singlino	s	1	1	0

NMSSM

THE R-PARITY

$$R = (-)^{3(B-L)+2S}$$

The Usual Particle : R = + 1
SUSY Particle : R = - 1

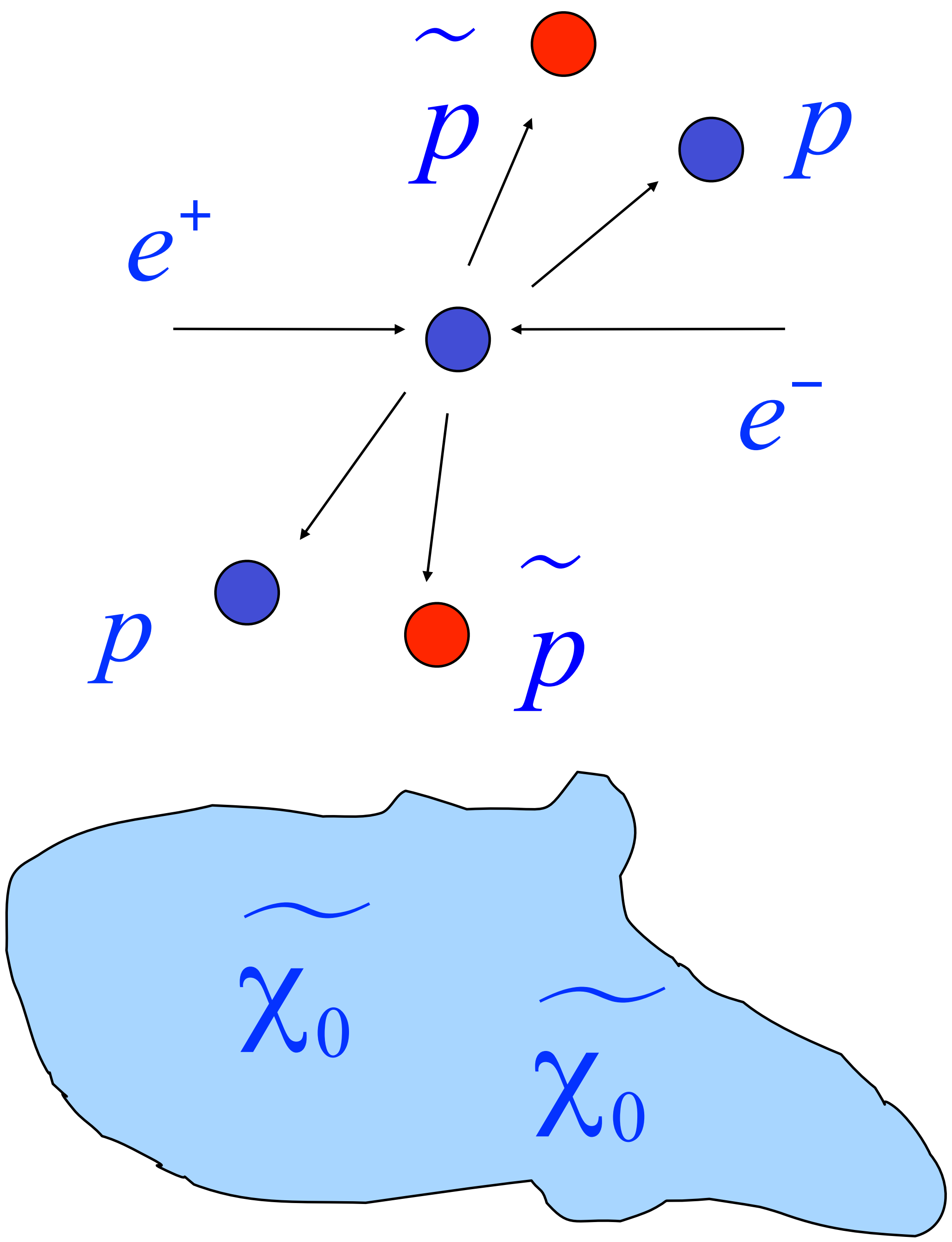
B - Baryon Number
L - Lepton Number
S - Spin

The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable

⬇

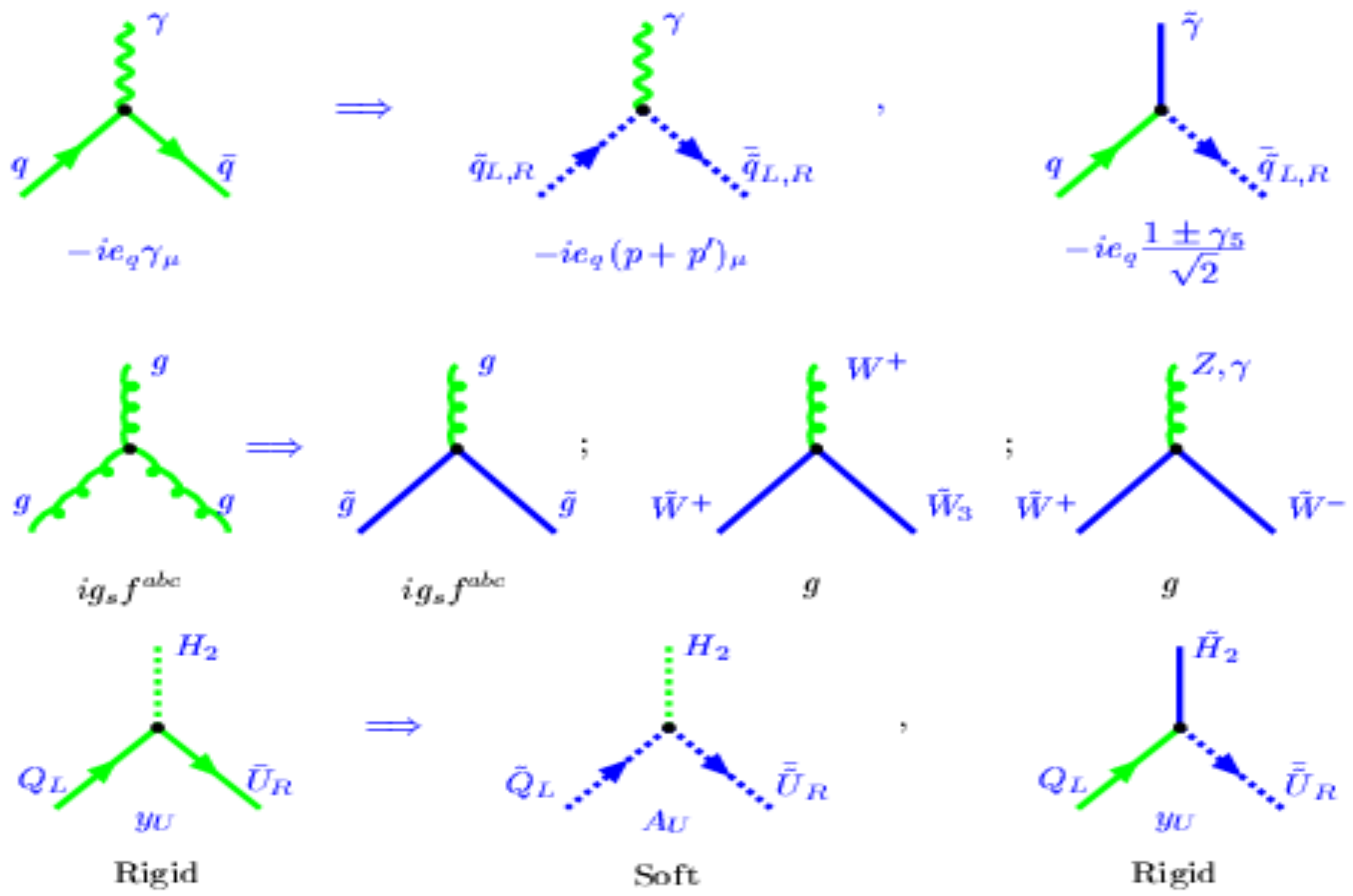
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe



THE INTERACTIONS IN THE MSSM

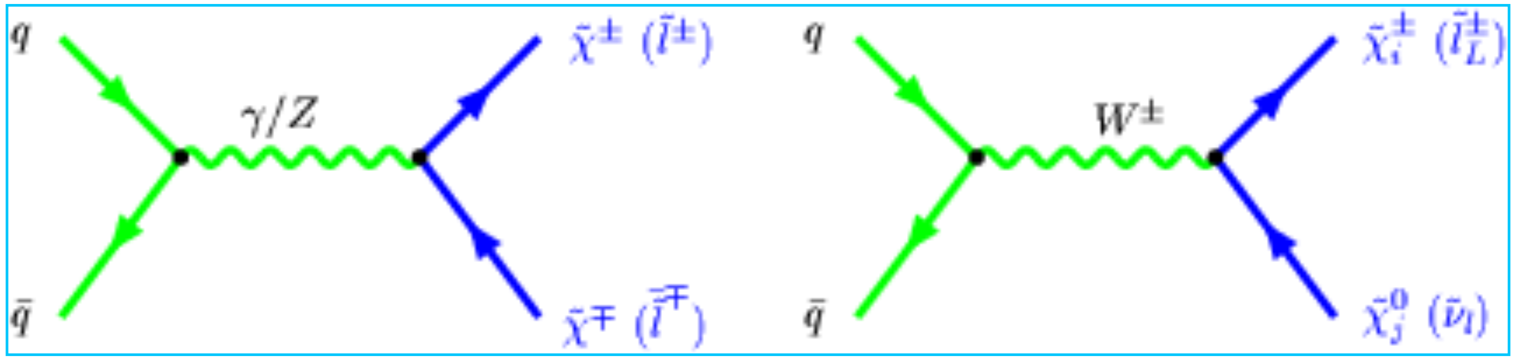
SM → **MSSM**

Vertices

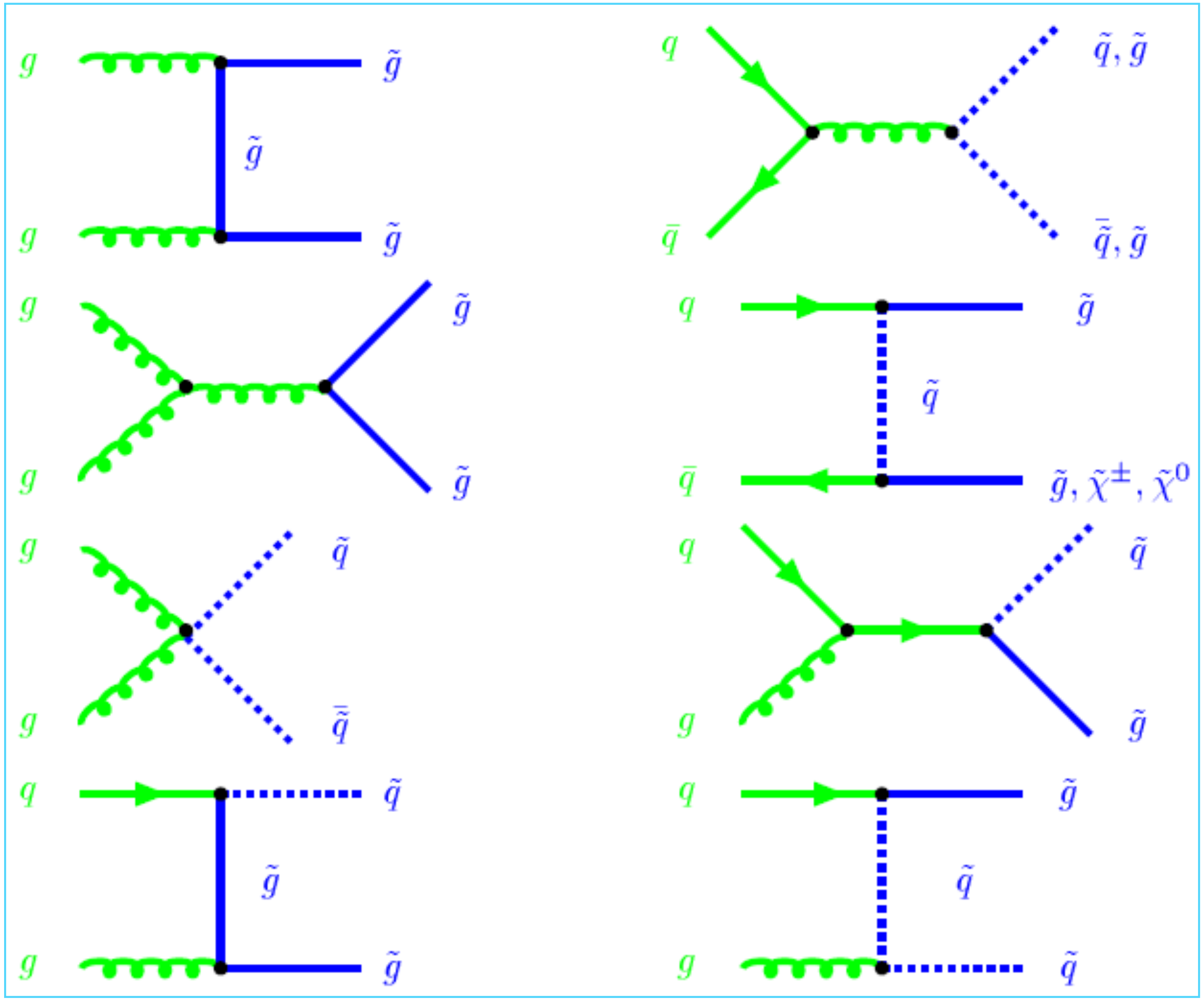


SUPERPARTNERS PRODUCTION AT THE LHC

Annihilation



Quark- gluon
Fusion



THE DECAY OF SUPERPARTNERS

squarks

$$\tilde{q}_{L,R} \to q + \tilde{\chi}_i^0$$

$$\tilde{q}_L \to q' + \tilde{\chi}_i^\pm$$

$$\tilde{q}_{L,R} \to q + \tilde{g}$$

sleptons

$$\tilde{l} \to l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \to \nu_l + \tilde{\chi}_i^\pm$$

chargino

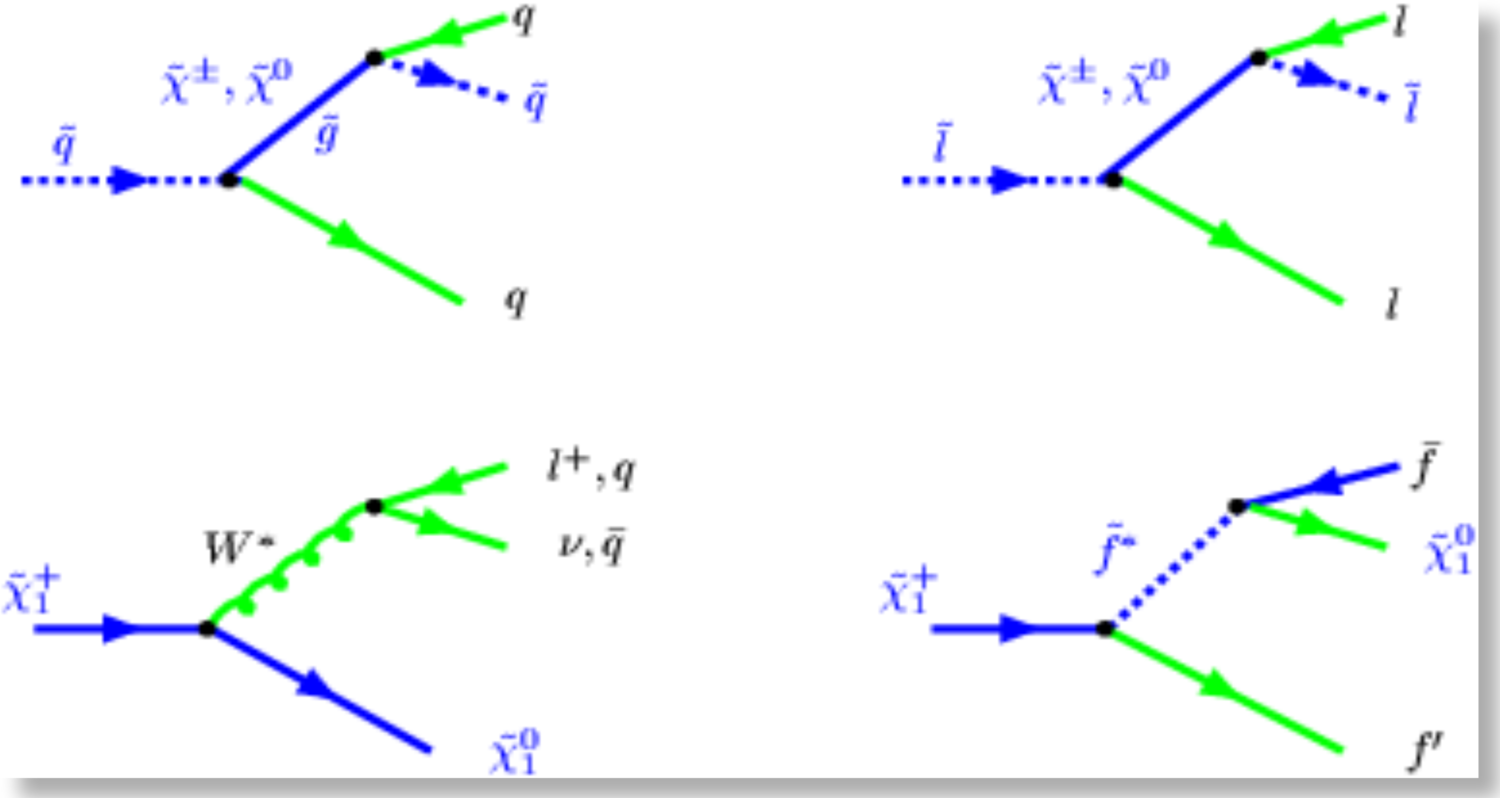
$$\tilde{\chi}_i^\pm \to e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^\pm \to q + \bar{q}' + \tilde{\chi}_i^0$$

gluino

$$\tilde{g} \to q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \to g + \tilde{\gamma}$$



neutralino

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + q + \bar{q}'$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^\pm + l^\pm + \nu_l$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final states

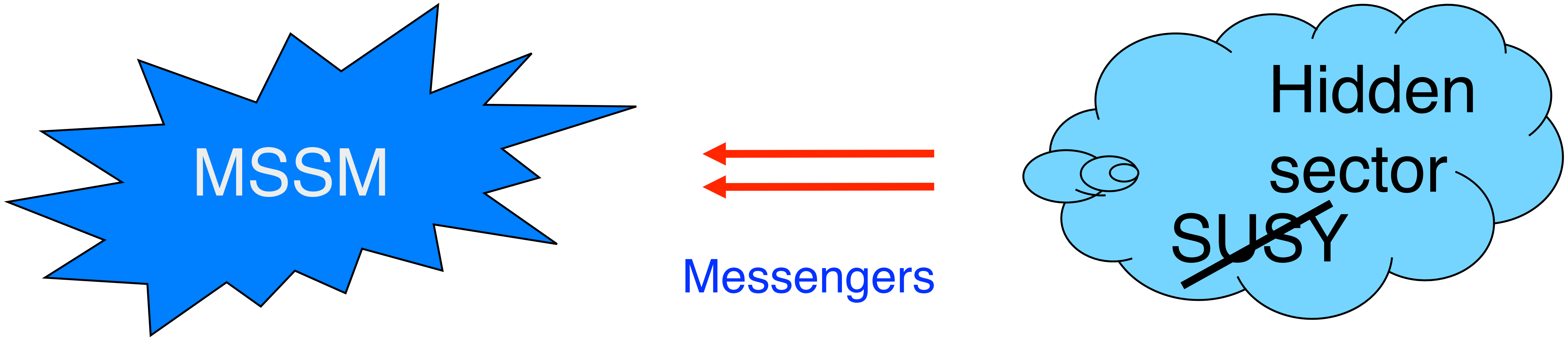
$l^+ l^- + \not{E}_T$

2 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

SOFT BUSY BREAKING



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \widetilde{\lambda}_i \widetilde{\lambda}_i + \sum_i m_{0i}^2 \, | A_i |^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{\mathrm{ij}} A_i A_j$$

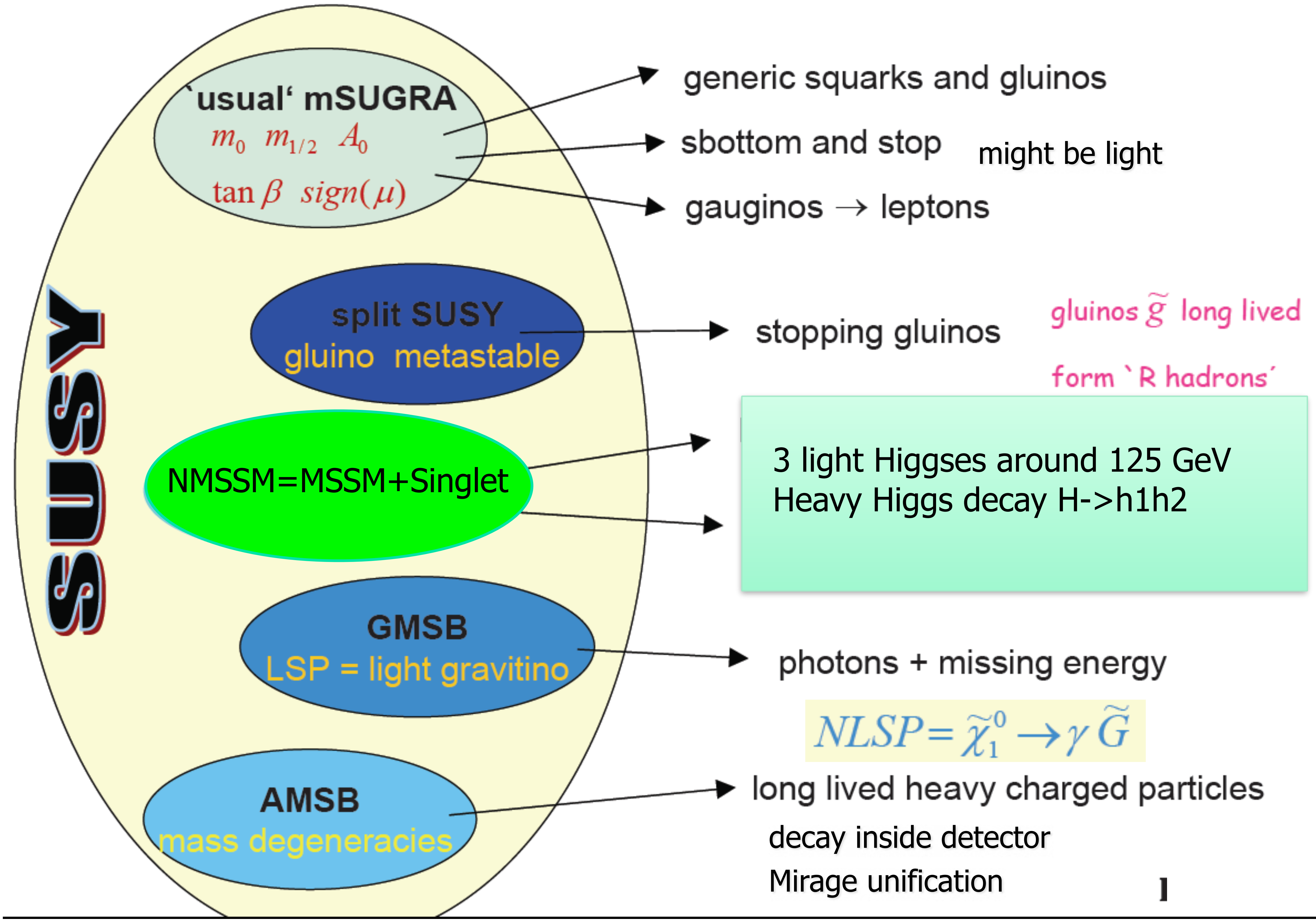
gauginos

scalar fields

Over 100 of free parameters !

SUSY Models and Signatures

T.Hebbeker



SUSY

`usual' mSUGRA

m_0 $m_{1/2}$ A_0

$\tan\beta$ $sign(\mu)$

- generic squarks and gluinos
- sbottom and stop — might be light
- gauginos → leptons

split SUSY
gluino metastable

- stopping gluinos — gluinos $\tilde{g}$ long lived, form `R hadrons´

NMSSM=MSSM+Singlet

- 3 light Higgses around 125 GeV
- Heavy Higgs decay H->h1h2

GMSB
LSP = light gravitino

- photons + missing energy

$$NLSP = \tilde{\chi}_1^0 \rightarrow \gamma\, \tilde{G}$$

AMSB
mass degeneracies

- long lived heavy charged particles

decay inside detector

Mirage unification

SEARCH FOR SUSY MANIFESTATION

Particle Phys

- Direct production at colliders at high energies
- Indirect manifestation at low energies
  Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)
  g-2 of the muon
- Search for long-lived SUSY particles

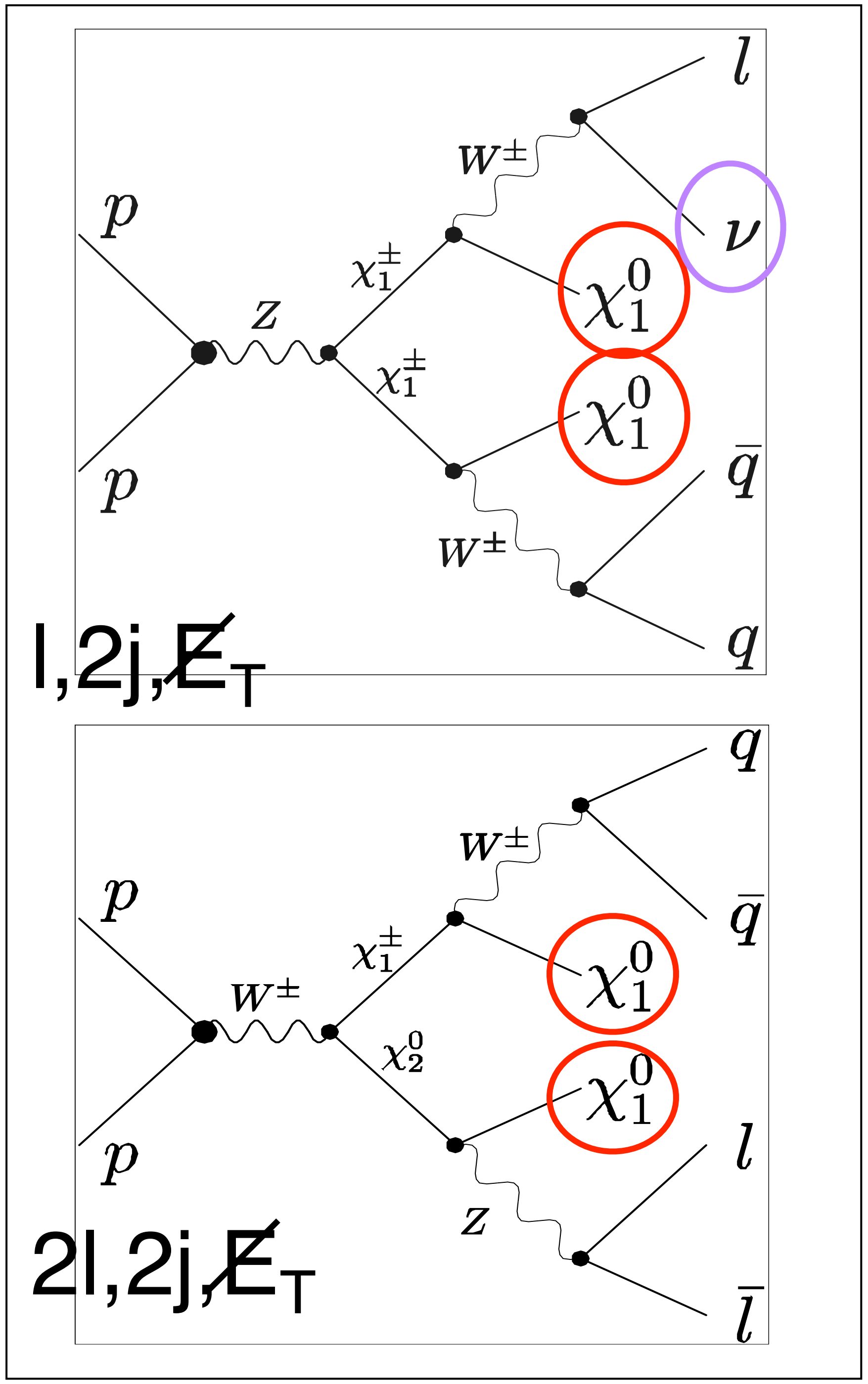
Astro Phys (if SUSY DM)

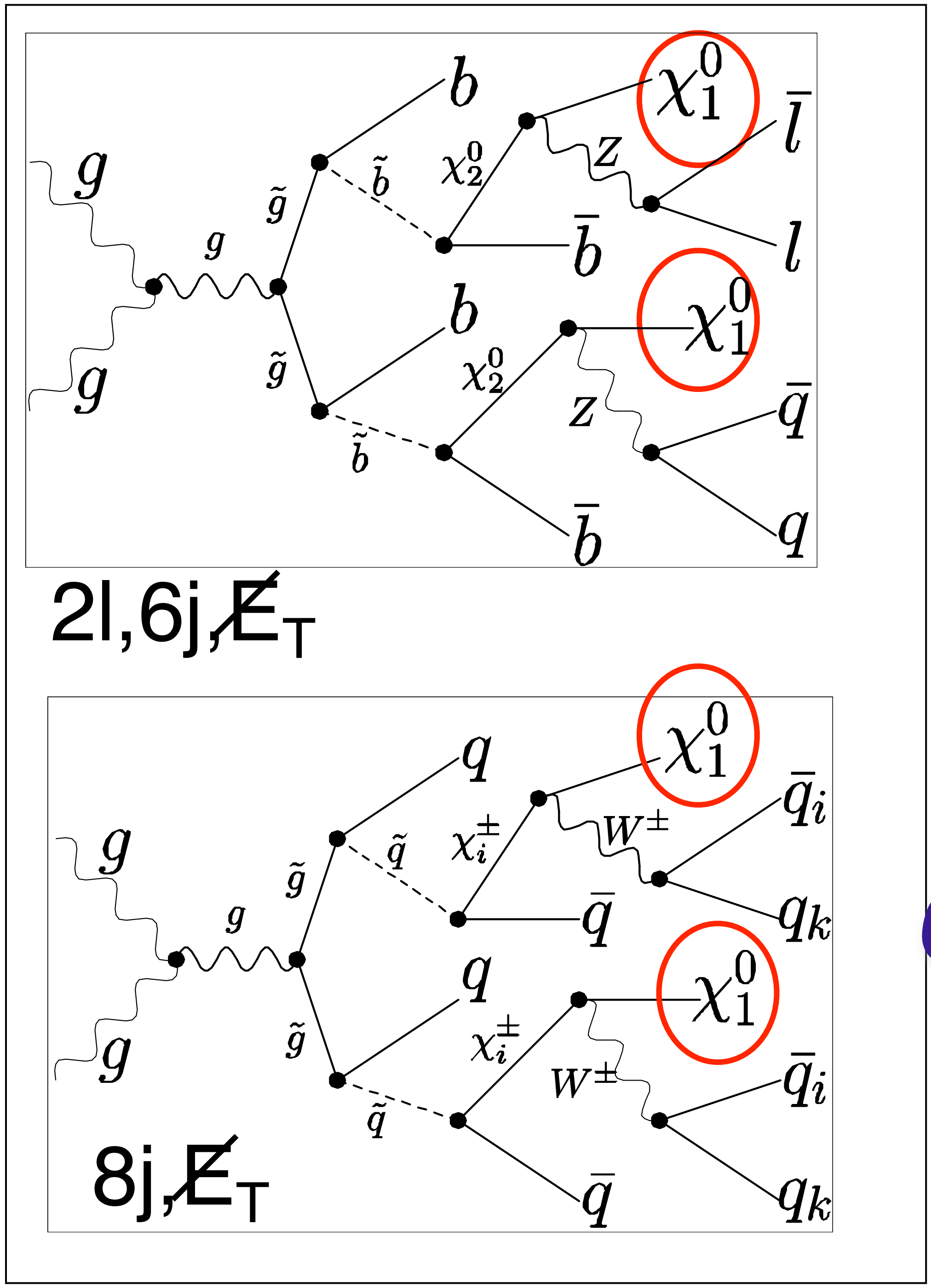
- Relic abundancy of Dark Matter in the Universe
- DM annihilation signal in cosmic rays
- Direct DM interaction with nucleons

Nothing so far ...

CREATION AND DECAY OF SUPERPARTNERS IN CASCADE PROCESSES @ LHC

weak int's





Strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

EXP AND THEOR FRAMEWORK

Two ways to present and analyse data:

1. High energy input:
introduce universal parameters at high energy scale (GUT)
Example $m_0,\ m_{1/2},\ A_0,\ \tan\beta$ of MSSM

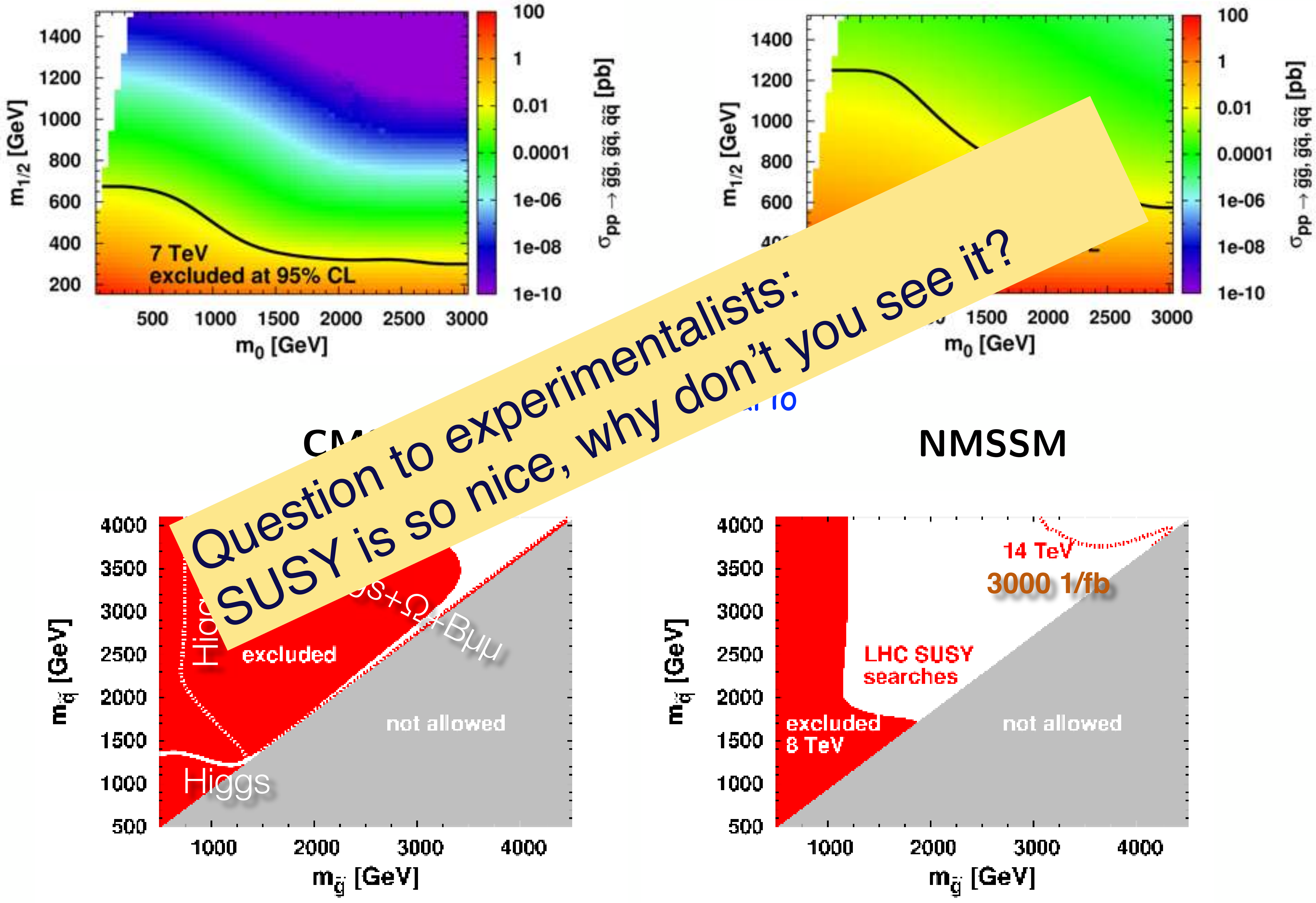
Advandage: small number of universal parameters for all masses
Disadvantage: strictly model dependent (MSSM, NMSSM, etc)

2. Low energy input:
use low energy parameters like masses of superpartners
Example $\tilde{m}_g,\ \tilde{m}_q,\ \tilde{m}_\chi$ or $m_A, \tan\beta$

Advandage: less model dependent
Disadvantage: many parameters, process dependent

Both approaches are used

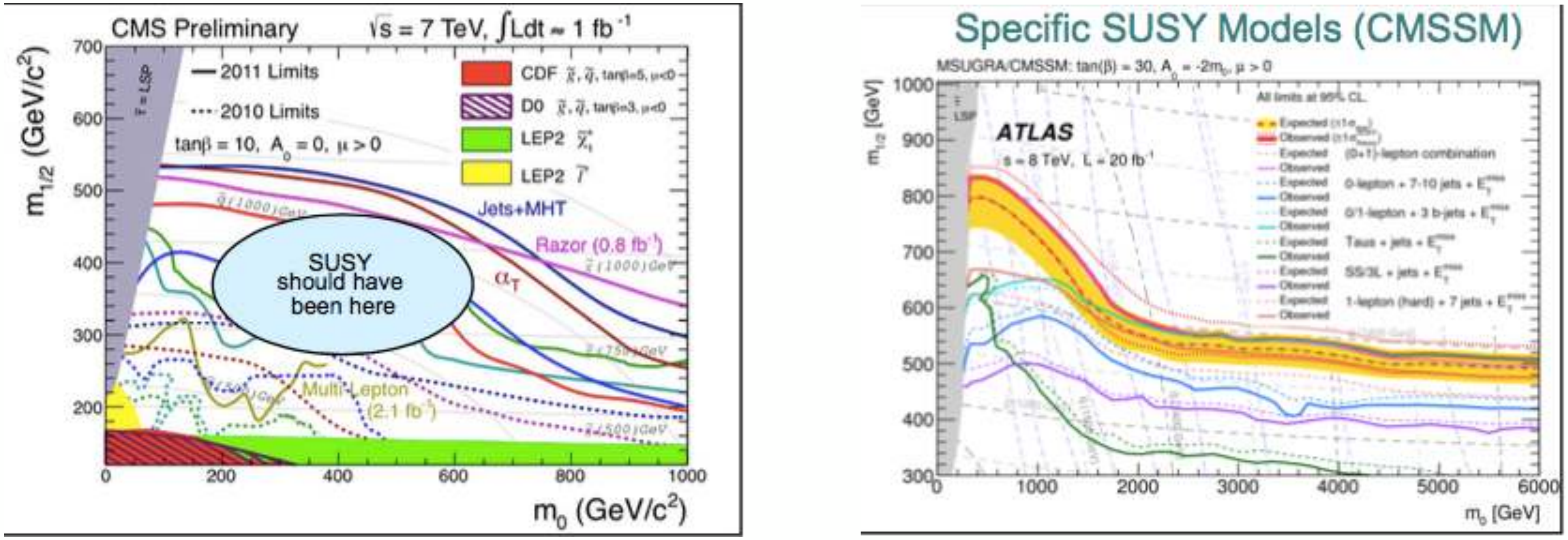
WHAT IS THE LHC REACH?



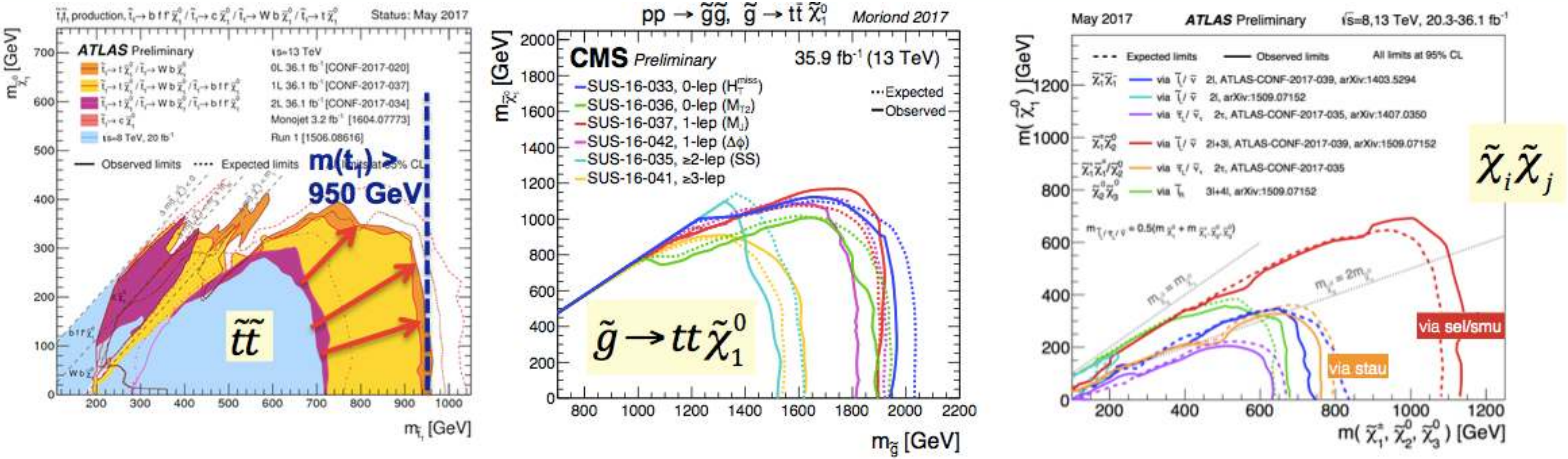
Question to experimentalists:
SUSY is so nice, why don't you see it?

Masses of superpartners

WHAT IS THE LHC REACH NOW?



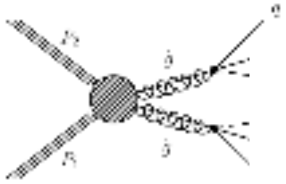
Universal parameters



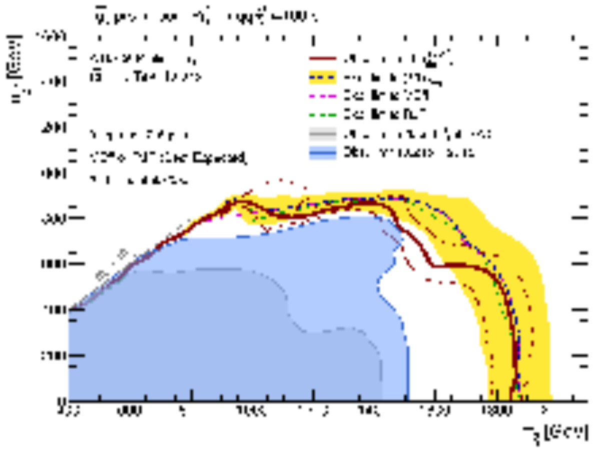
Masses of superpartners

SUPERSYMMETRY @ LHC

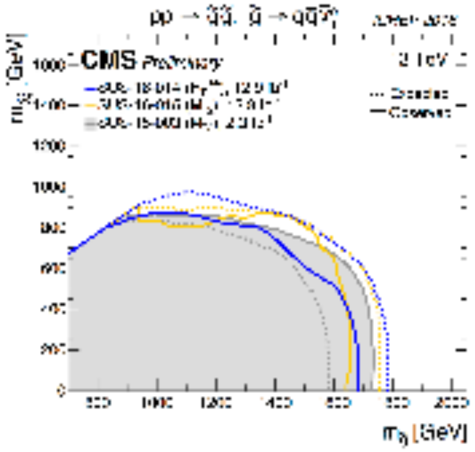
Gluino decays to qq+LSP



Summary of decays to light quarks + LSP

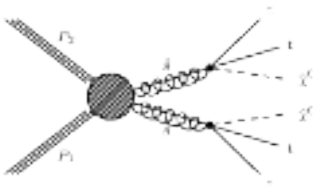


ATLAS-CONF-2016-078



CMS-SUS-16-014
CMS-SUS-16-015

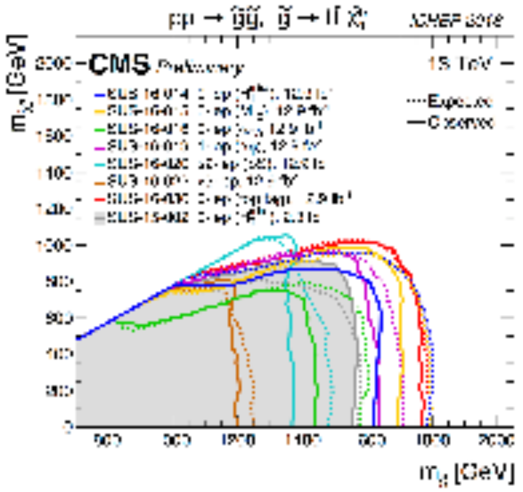
Gluino decays to tt+LSP

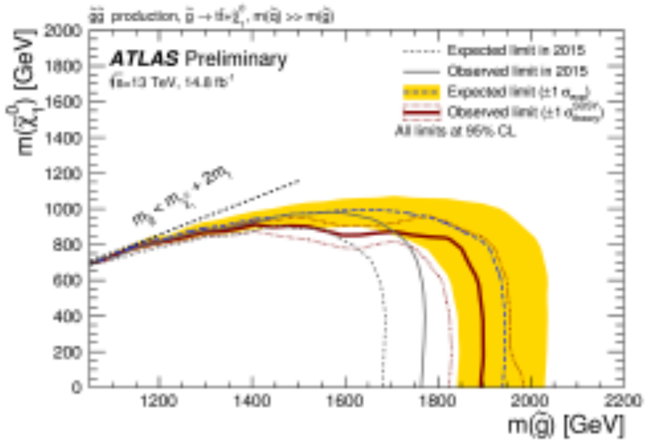


CMS summary

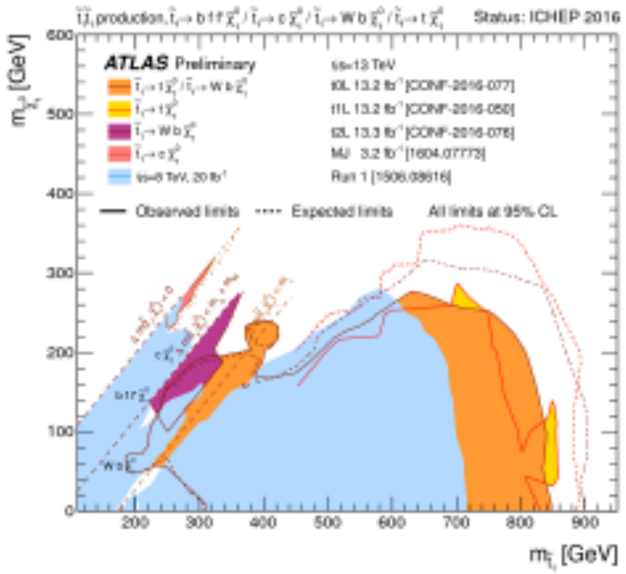
ATLAS multi-b

ATLAS-CONF-2016-052

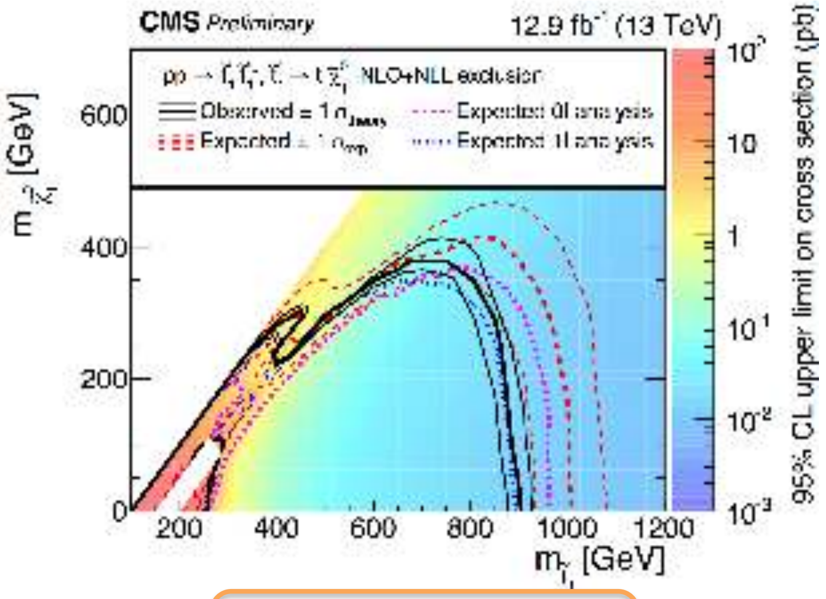




Top squarks - summaries



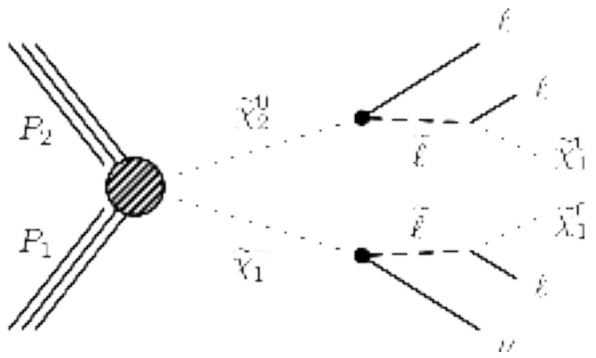
ATLAS summary



CMS 0l+1l combination
for 2-/3-body decay

- SUSY limits for strong int's are pushed above 1 TeV
- This already requires fine tuning - little hierarchy prob
- No guiding lines

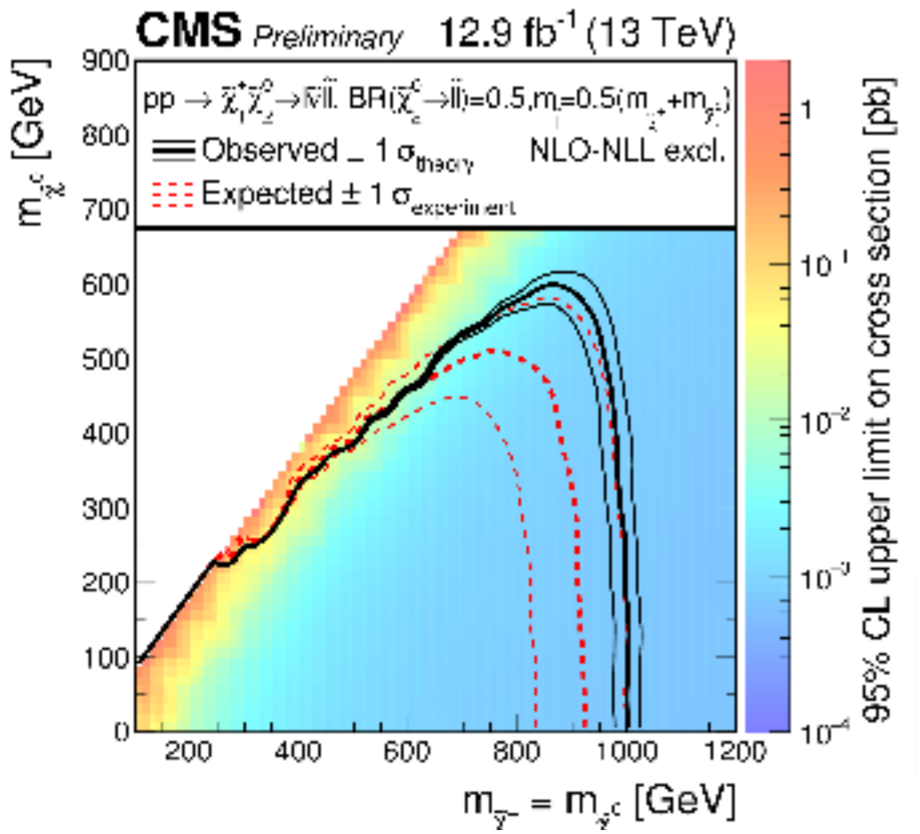
Chargino / neutralino production



Direct production of "electroweakino" pairs

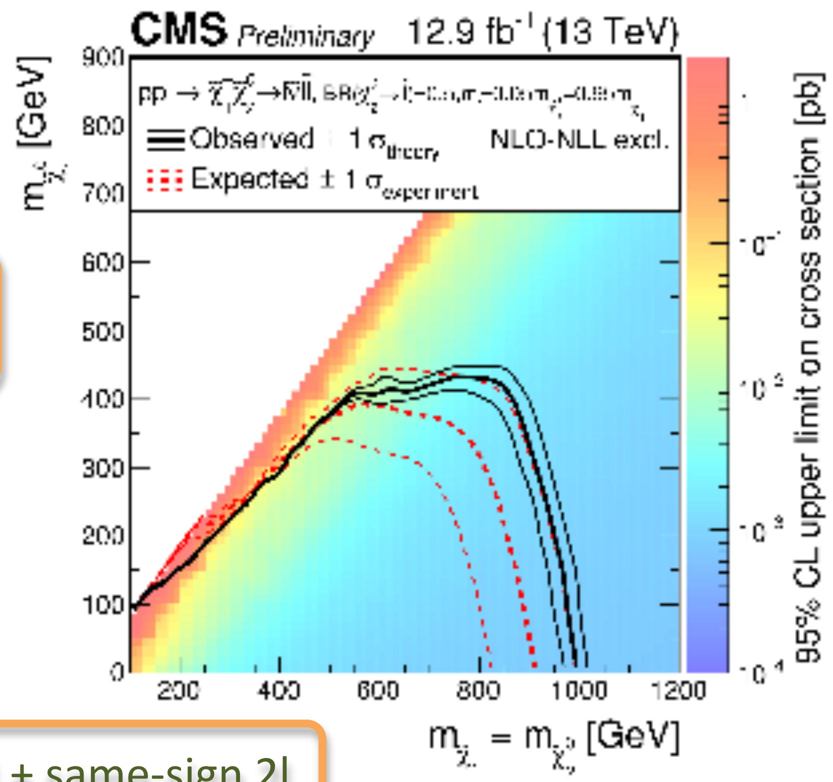
- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

No light EWkinos



Effect of change in inter-mediate slepton mass

↔

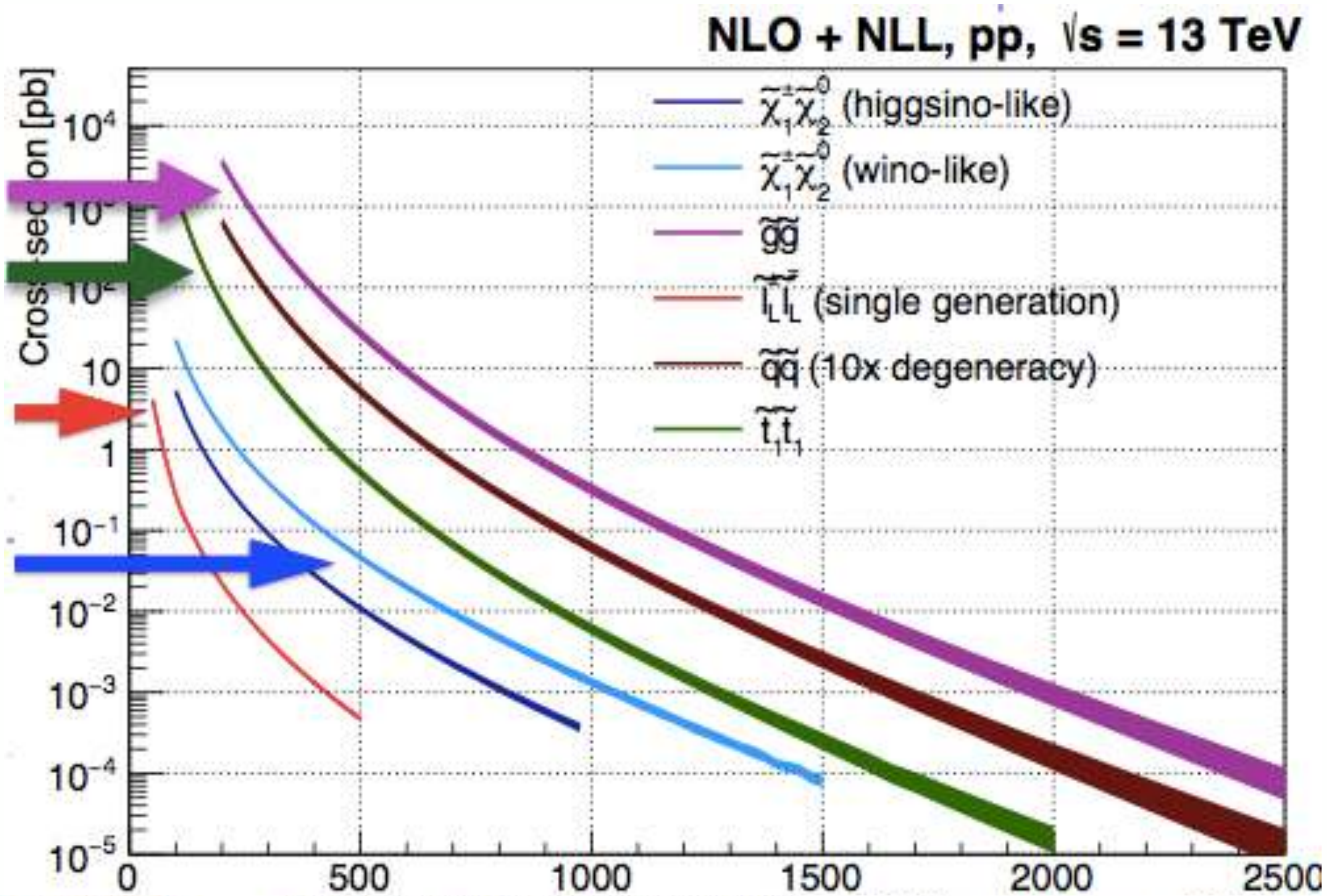


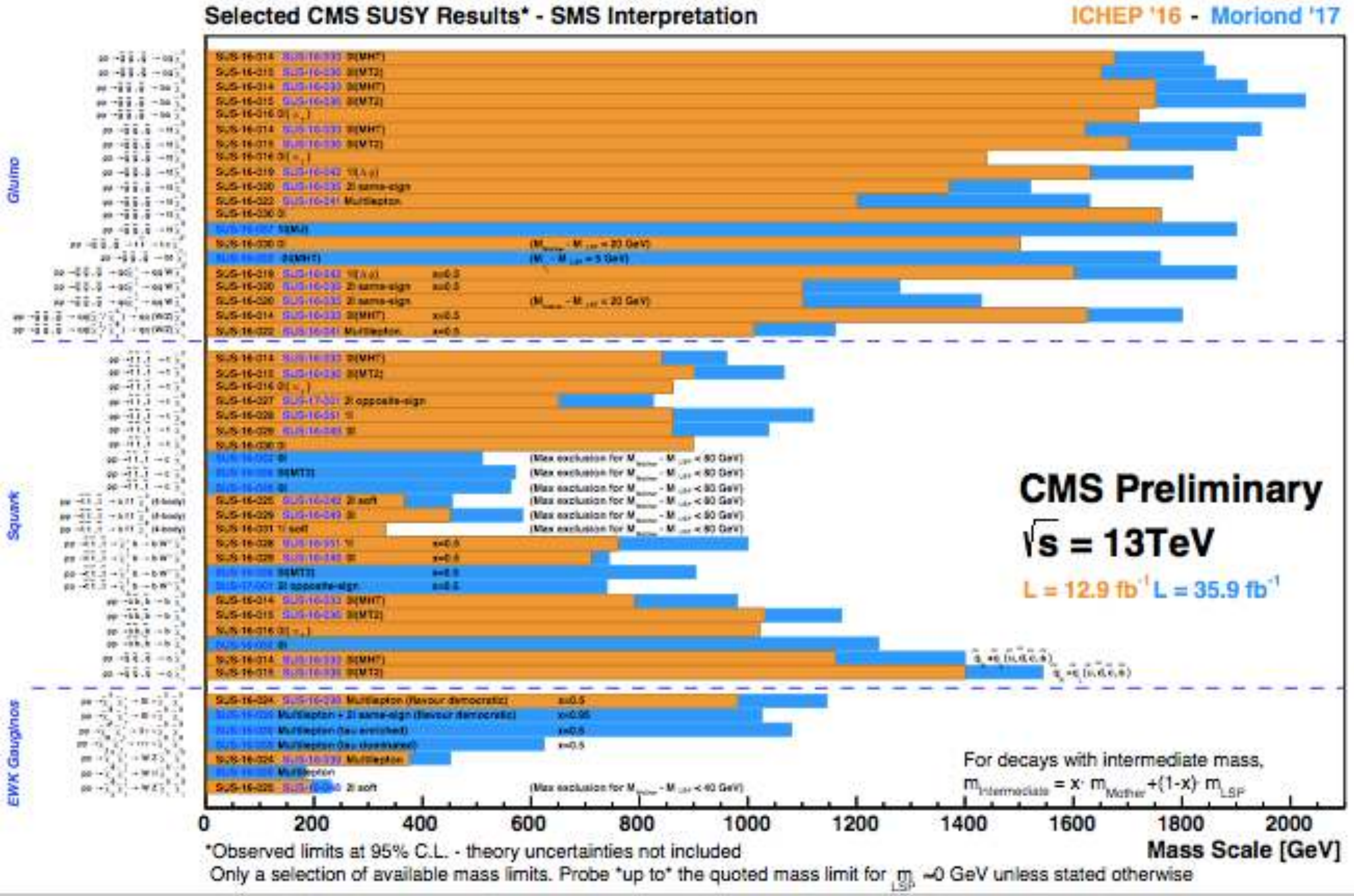
3l + same-sign 2l

WHERE ARE WE NOW?

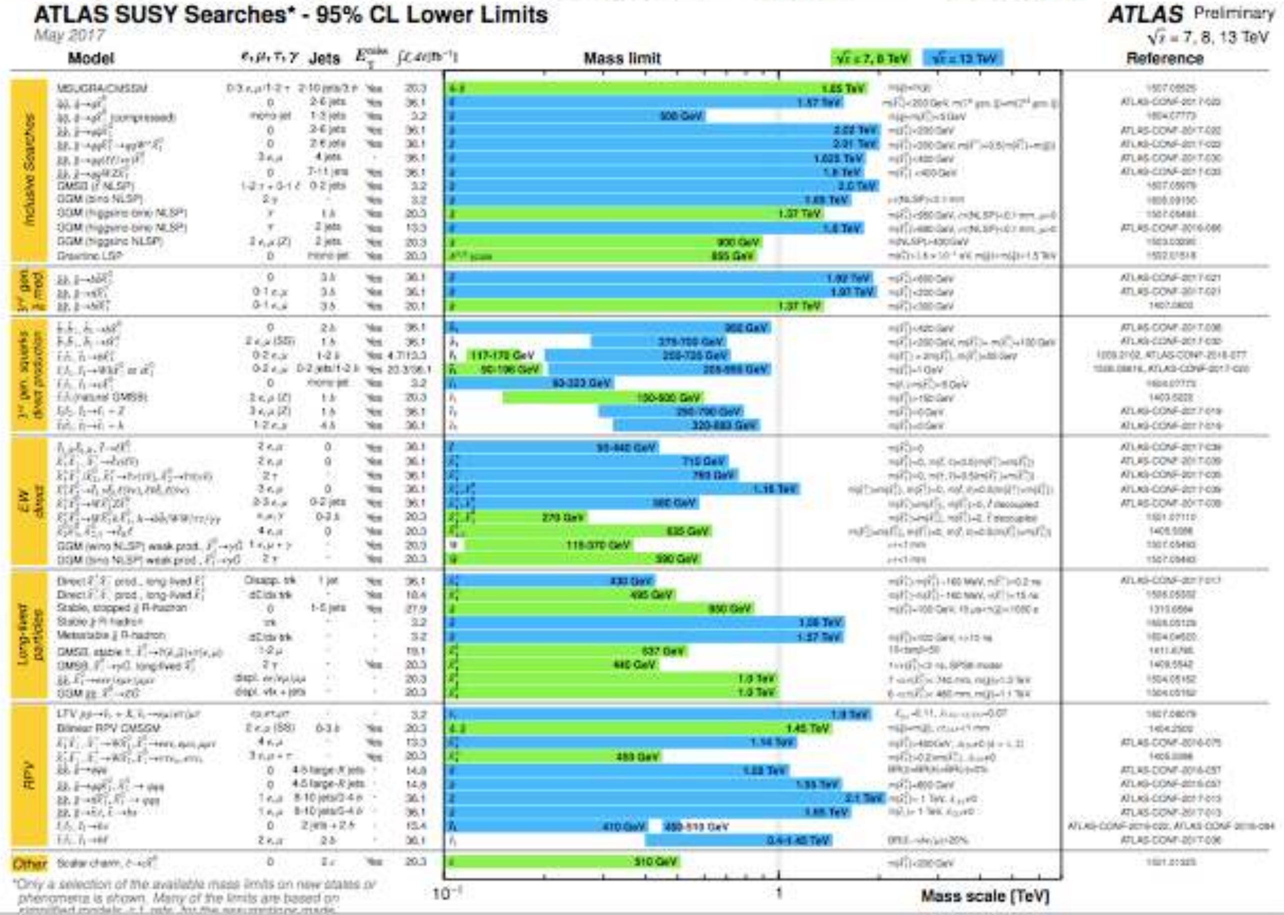
Strong production
(gluinos, squarks)

EWK production
(charginos, neutralinos, sleptons)





*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_{LSP} ~0 GeV unless stated otherwise



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models

FUTURE SUSY SEARCHES

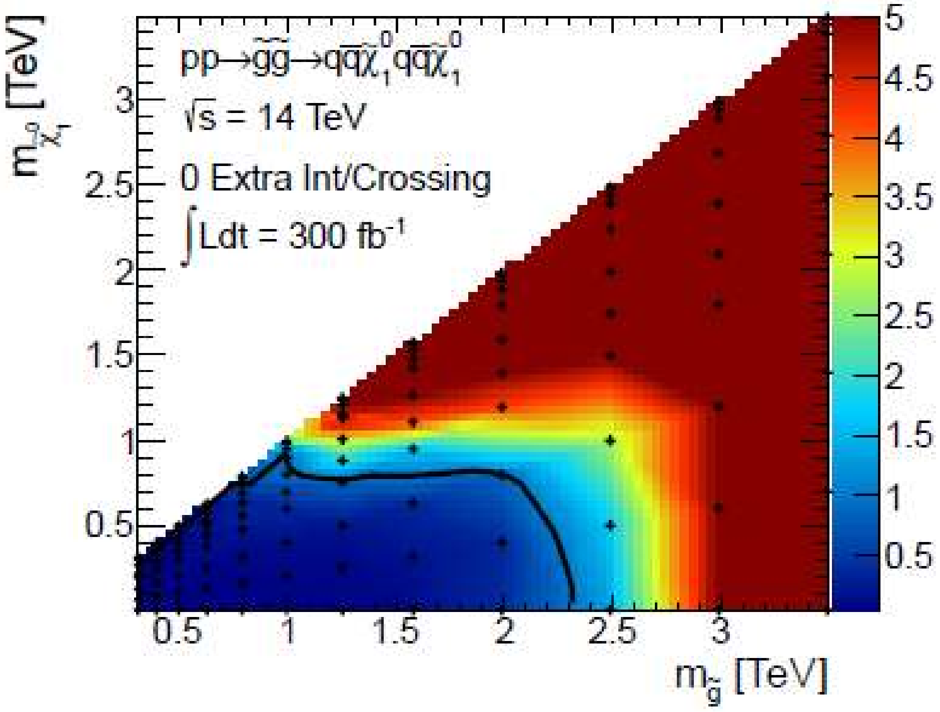
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

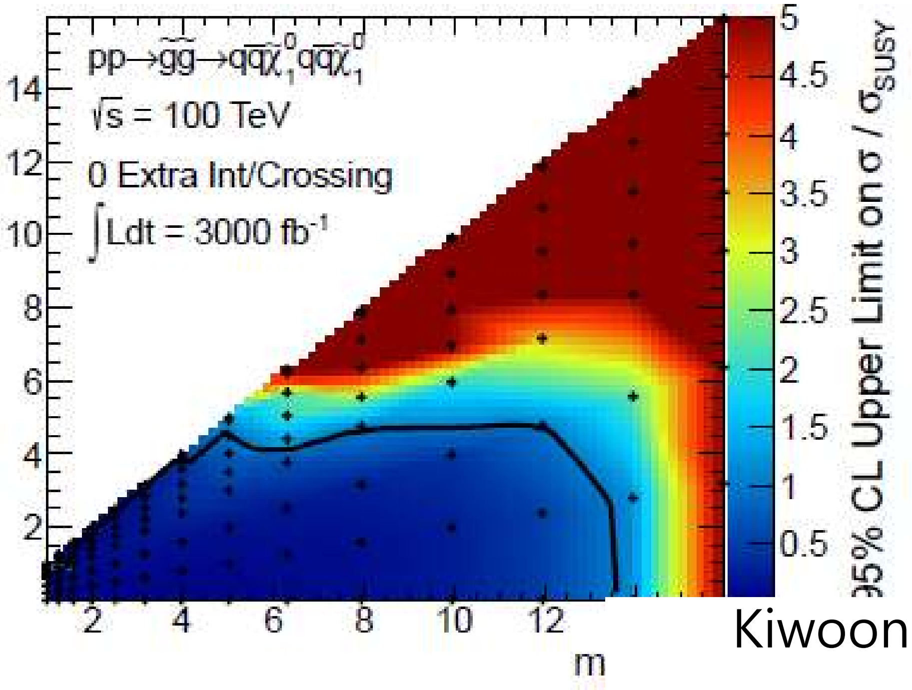
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, ‘13

100 TeV collider





Kiwoon Choi

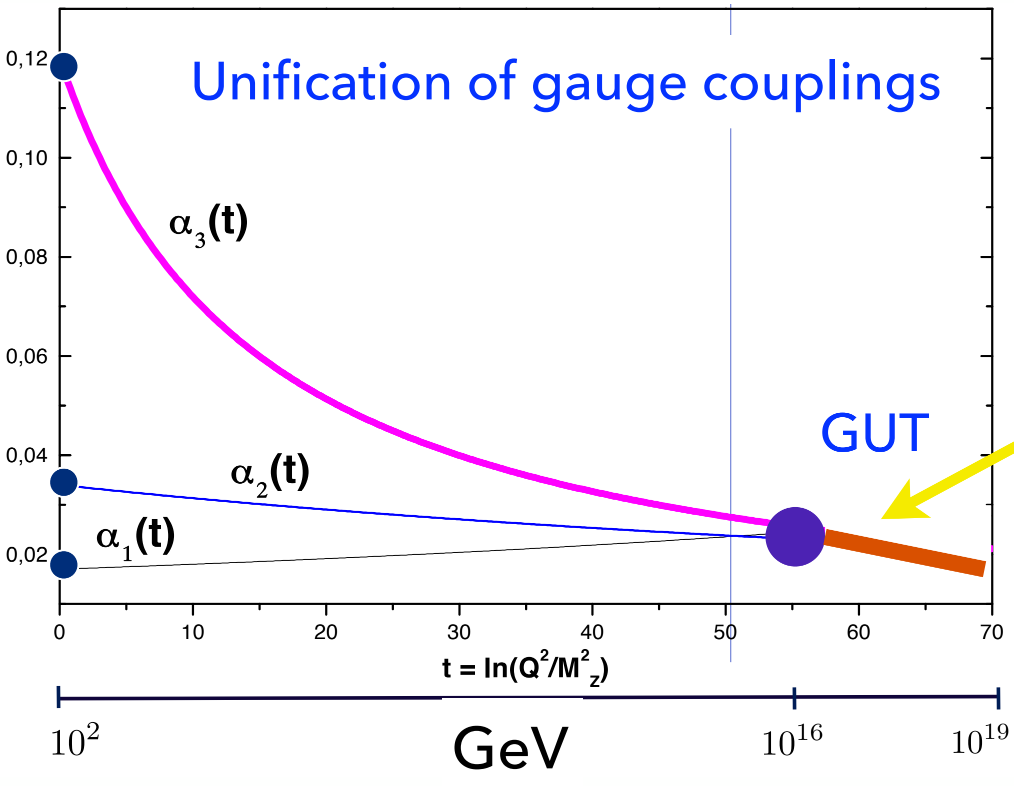
(ICHEP 2016, Chicago)

NEW SYMMETRIES

GRAND UNIFICATION

Grand Unification is an extension of the Gauge symmetry of the SM

$$
\begin{array}{ccccl}
 & \text{Low energy} & & \Rightarrow & \text{High energy} \\
SU_c(3)\otimes & SU_L(2)\otimes & U_Y(1) & \Rightarrow & G_{GUT} \quad (or\ G^n + \text{discrete symmetry}) \\
\text{gluons} & W, Z & \text{photon} & \Rightarrow & \text{gauge bosons} \\
\text{quarks} & \text{leptons} & & \Rightarrow & \text{fermions} \\
g_3 & g_2 & g_1 & \Rightarrow & g_{GUT}
\end{array}
$$



$$SU(3) \times SU(2) \times U(1) \subset G_{GUT}$$

$$Ex : SU(5), SO(10), E(6), SU(5) \times U(1),$$
$$SU(4) \times SU(2) \times SU(2), SO(10) \times U(1)$$

GUT MODELS

SU(5) - Minimal GUT

Gauge fields

$$\underline{24} = \underset{gluons}{(\underline{8},\underline{1})} \quad \underset{W\ and\ Z}{+(\underline{1},\underline{3})} \quad \underset{leptoquarks}{+(\underline{3},\underline{2}) + (\underline{3},\underline{2})}$$

$$\begin{pmatrix} & & & \vdots & X & Y \\ & SU_c(3) & & \vdots & X & Y \\ & & & \vdots & X & Y \\ \cdots & \cdots & \cdots & \vdots & \cdots & \cdots \\ X & X & X & \vdots & SU_L(2) & \\ Y & Y & Y & \vdots & & \end{pmatrix}$$

$$SU(5) : \bar{5} + 10 + 1$$

$$\underline{5}^* = (d_1^c, d_2^c, d_3^c, e^-, \nu_e)_{Left} \qquad \underline{10} = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & d_2 \\ & & 0 & u_3 & d_3 \\ & & & 0 & e^+ \\ & & & & 0 \end{pmatrix}_{Left} \qquad 1 = \nu_L^c$$

SO(10) - Optimal GUT

Matter fields - just one representation

$$\underline{16} = (u_1\ u_2\ u_3\ d_1\ d_2\ d_3\ \nu_e\ e^-\ u_1^c\ u_2^c\ u_3^c\ d_1^c\ d_2^c\ d_3^c\ \nu_e^c\ e^+)_{Left}$$

SU(5) decomposition

$$\underline{16} = \underline{5}^* + \underline{10} + \underline{1} \qquad fermions,$$

$$\underline{45} = \underline{24} + \underline{10} + \underline{10}^* + \underline{1} \qquad gauge\ bosons$$

GUT SYMMETRY BREAKING

GUT symmetry is broken spontaneously by Brout-Englert-Higgs Mechanism

SU(5)

Higgs Multiplets

$$SU(5) \xrightarrow{\Sigma} SU(3) \times SU(2) \times U(1) \xrightarrow{H} SU(3) \times U(1)$$

$$< \Sigma_{24} >= \begin{pmatrix} V & & & & \\ & V & & & \\ & & V & & \\ & & & -3/2\ V & \\ & & & & -3/2\ V \end{pmatrix} \qquad < H_5 >= \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$V \sim 10^{15}\ GeV \qquad v \sim 10^2\ GeV$$

SO(10)

Higgs Multiplets

$$16\ or\ 126;\ \ 45\ or\ 54\ or\ 210$$

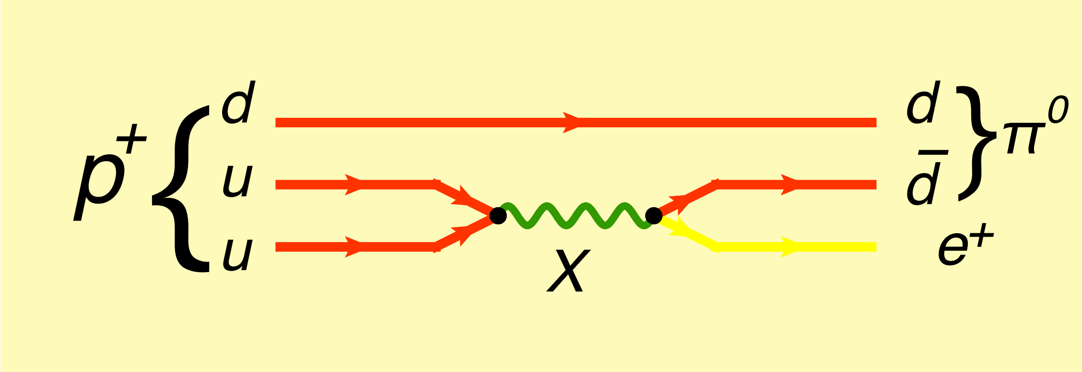
$$\begin{array}{lll} & \nearrow & SU(5) \overset{M_2}{\to} SU(3) \otimes SU(2) \otimes U(1) \overset{M_W}{\to} SU(3) \otimes U(1) \\ SO(10) & M_1 & \\ & \searrow & SO(6) \otimes SO(4) \sim SU(4) \otimes SU_L(2) \otimes SU_R(2) \end{array}$$

$$M_1 \gg M_2 \gg \cdots M_W$$

GRAND UNIFICATION

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



- Unification of the gauge couplings
- stabilization of the hierarchy

➡ Low energy SUSY

Creates new problems:

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

Crucial predictions:

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

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

$$\tau_{proton} \sim 10^{32} years$$

$$\tau_{Universe} \approx 14 \cdot 10^9 years$$

SUSY GUT

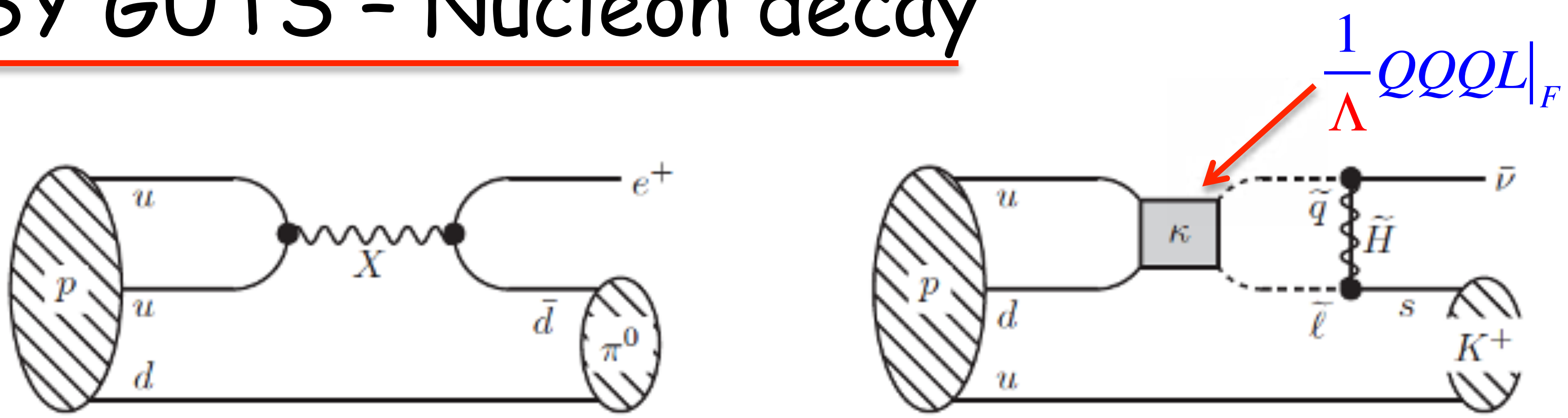
Crucial points:

- SUSY leads to unification
- SUSY solves the hierarchy problems for GUTs
- No GUT without SUSY

New properties:

- Later unification - higher GUT scale
- Longer proton life-time $\tau \sim M_{GUT}^4$
- New modes of proton decay

SUSY GUTS – Nucleon decay


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

(a) Dimension 6.

(b) Dimension 5.

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

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

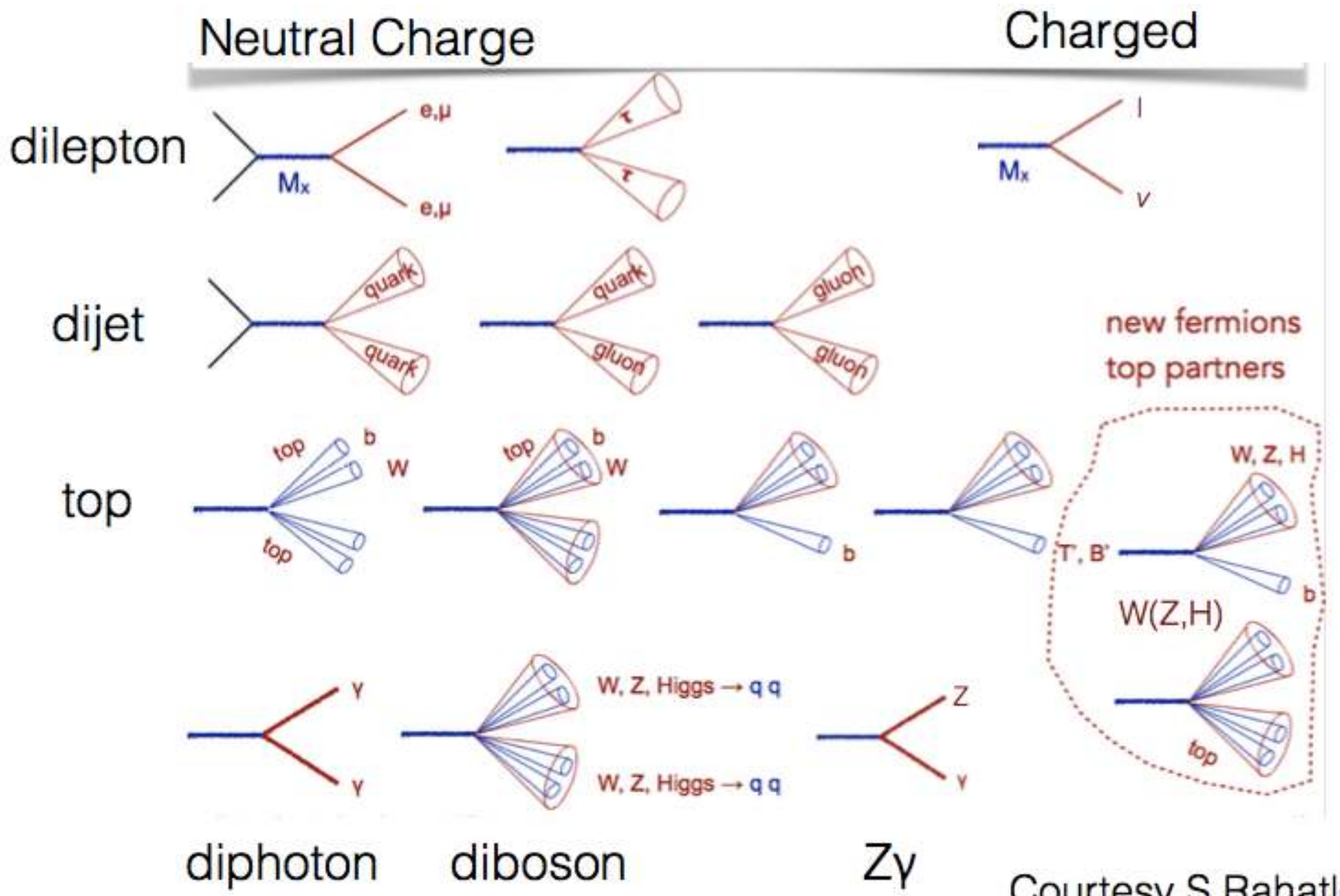
$p \to K^+ + \bar{\nu}$

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

NEW SYMMETRIES

- Appear in some GUT models
- Inspired by string models

Used as possible BSM signal with energetic single jet or diet events



Courtesy S.Rahatlou

EXTRA U(1)', SU(2)'

Used as possible Dark matter candidate - Dark photon

Mixture of a usual EM U(1) photon and a new U(1)' one

$$\mathcal{L} \sim F_{\mu\nu} F^{'\,\mu\nu}$$

Dedicated experiment to look for conversion of a usual photon into a dark one

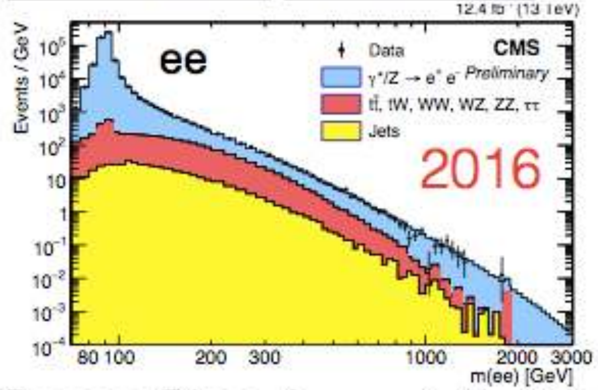
ADDITIONAL GAUGE BOSONS

Experiment

- Search for Z’ (Di-muon events)
- Search for W’ (single muon/ jets)
- Search for resonance decaying to t-tbar
- Search for diboson resonances
- Monojets + invisible

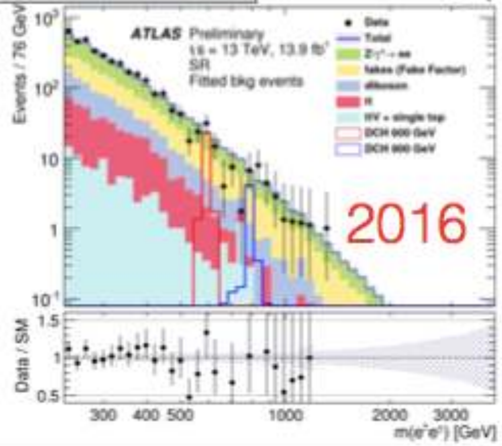
Same Flavor Opposite Sign (ee, μμ, ττ)

ATLAS-CONF-2016-045 CMS-PAS-EXO-16-031



Same Sign (ee, μμ) $Z'_{\rm SSM}$(3% width) >4 TeV

ATLAS-CONF-2016-051 Z'_{ψ} (0.5% width) >3.36 TeV

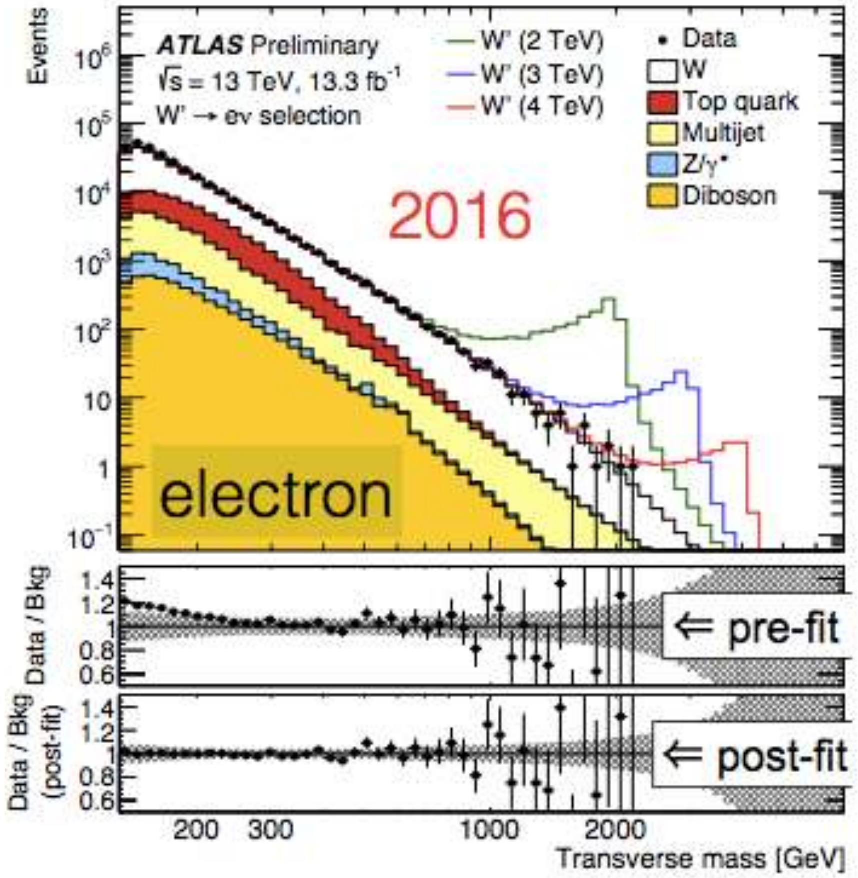


95% CL exclusion limit

$H_R^{\pm\pm}$ >420 GeV

$H_L^{\pm\pm}$ >570 GeV

ATLAS-CONF-2016-061 CMS-PAS-EXO-15-006



SSM W’ >4.74 TeV

No indication so far - experimental limits on Z’ and W’ masses around few TeV

NEW PARTICLES

EXTENDED HIGGS SECTOR

Is it the SM Higgs boson or not?

What are the alternatives?

A. Singlet extension
B. Higgs doublet extension
C. Higgs triplet extension

Custodial symmetry as guiding principle for extensions

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

indicates that an approximate global symmetry exists,
broken by the vev to the diagonal 'custodial' symmetry group

Thus the Higgs field transforms under

$$SU(2)_L \times SU(2)_R : \quad \Phi \to L\Phi R^\dagger$$

$$\rho = \frac{\sum_{i=1}^{n} [I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum_{i=1}^{n} \frac{1}{2}Y_i^2 v_i} \sim 1$$

For both SU(2)-singlet with Y=0

and SU(2) doublet with Y=+-1

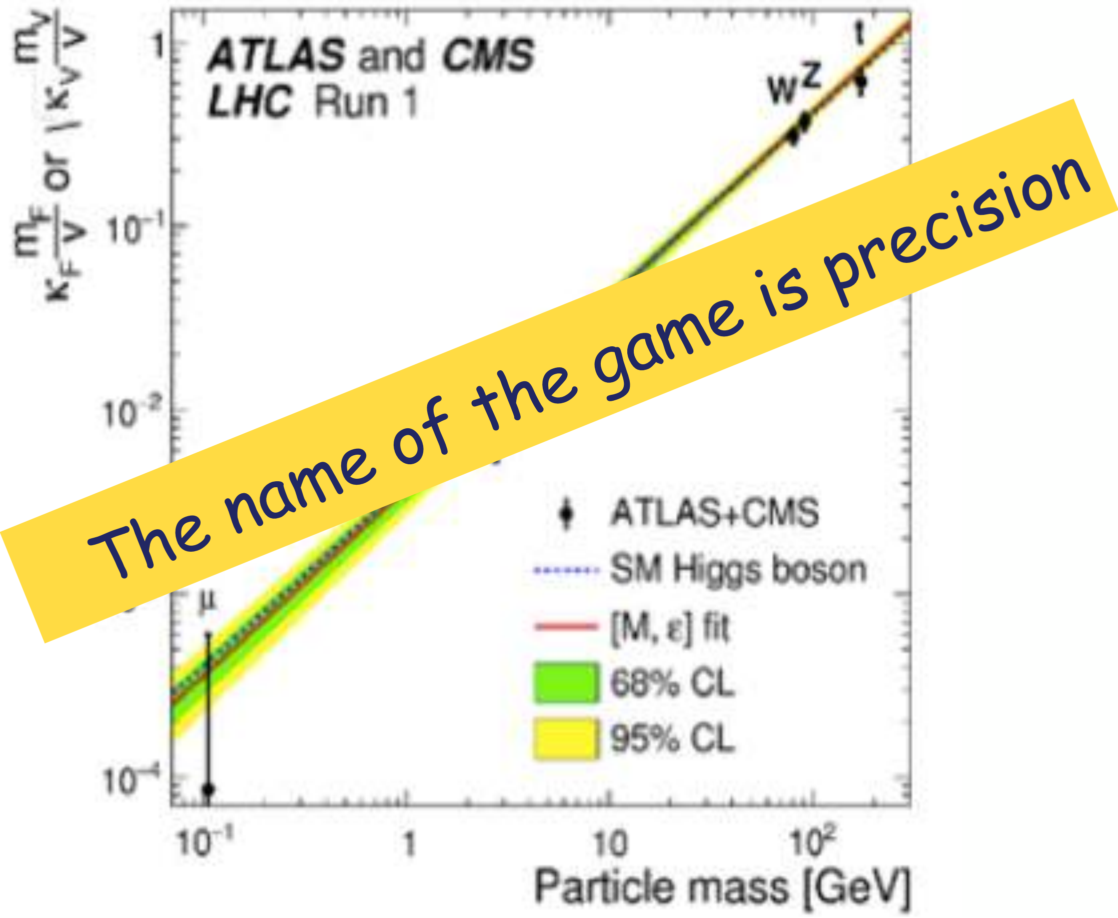
Any number of singlets and doublets respects custodial symmetry at tree level. Not so for arbitrary triplet models …

Model	Particle content
SM	h CP-even
2HDM/ MSSM	h,H CP-even A CP-odd H
NMSSM	H1,H2,H3 CP-even A1,A2 CP-odd
Composite	h CP-even + excited states

EXTENDED HIGGS SECTOR

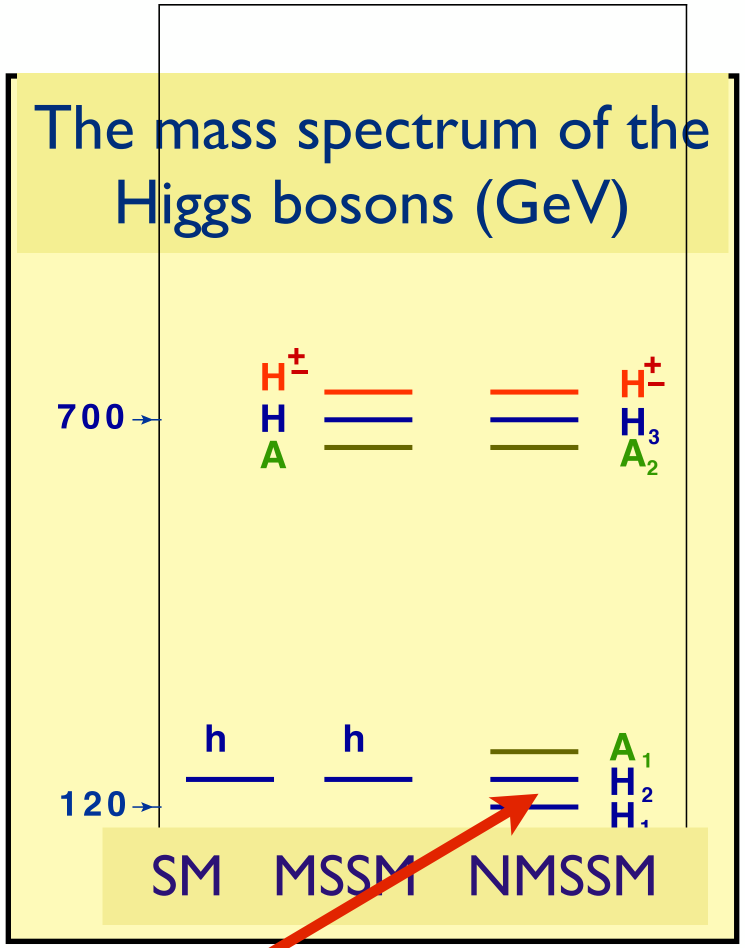
How to probe?

- Probe deviations from the SM Higgs couplings



The name of the game is precision

- Perform direct search for additional scalars

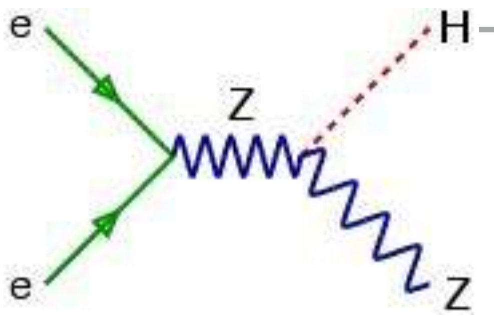


The mass spectrum of the Higgs bosons (GeV)

We may have found one of these states

One has to check the presence or absence of heavy Higgs bosons

PRECISION PHYSICS OF THE HIGGS BOSONS

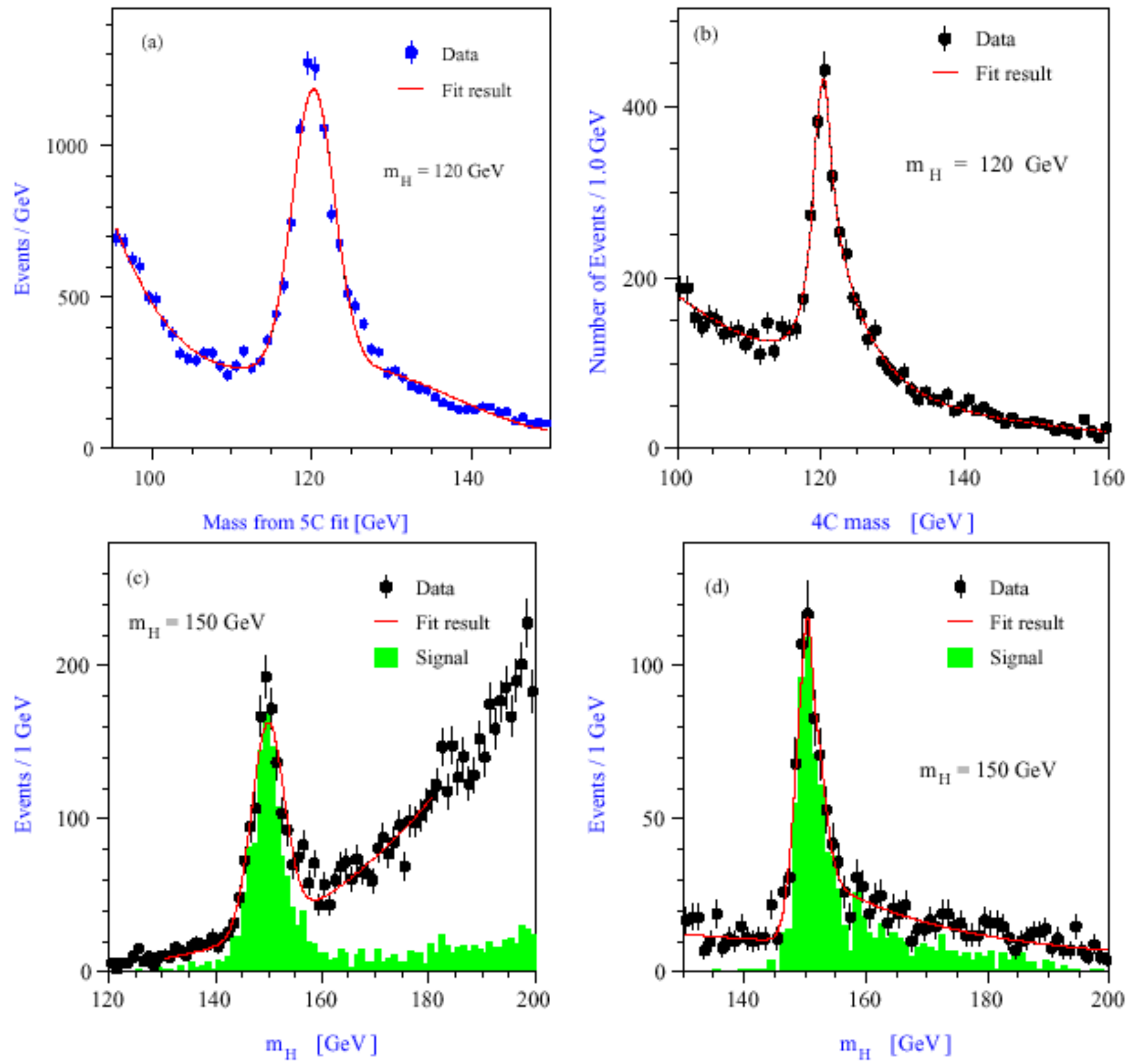


$\rightarrow b\bar{b}q\bar{q}$

ee -> HZ diff. decay channels

Int Linear Collider

$\rightarrow W^+W^-q\bar{q}$

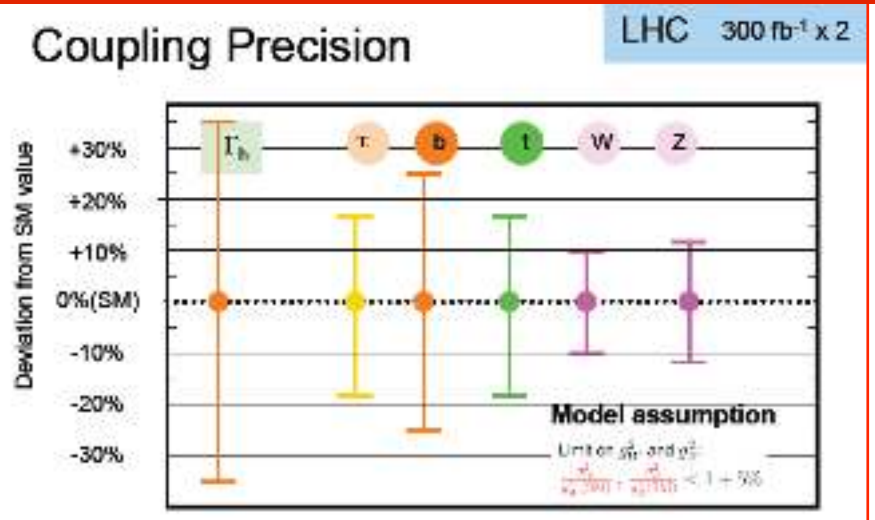


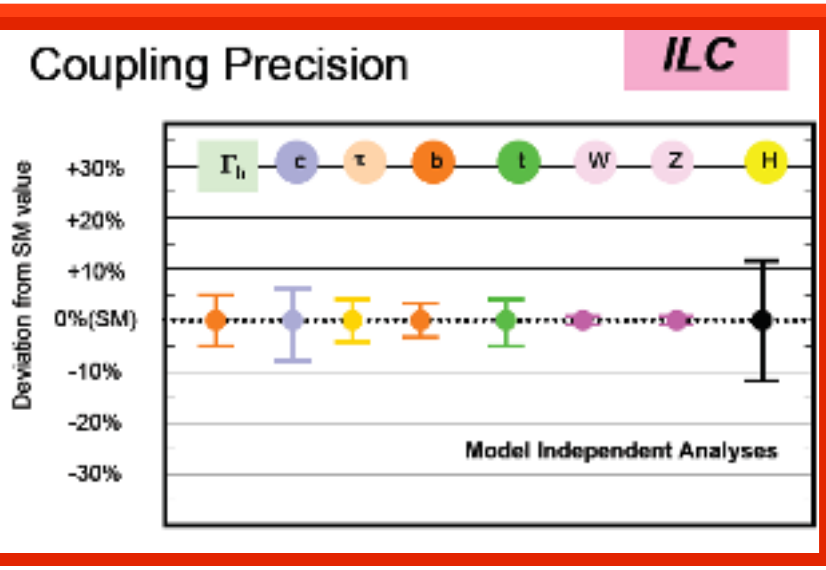
$\rightarrow q\bar{q}\ell^+\ell^-$

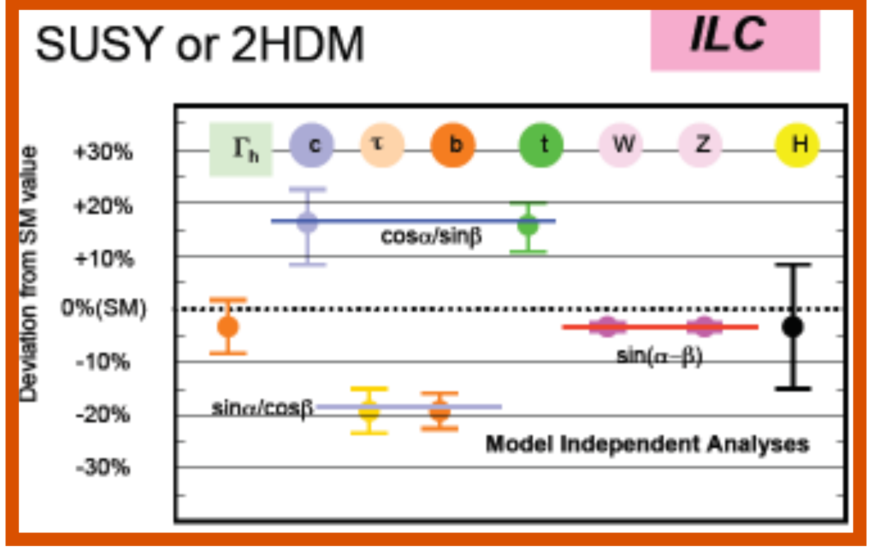
Δm_H = 40 MeV

$\rightarrow W^+W^-\ell^+\ell^-$

Δm_H = 70 MeV

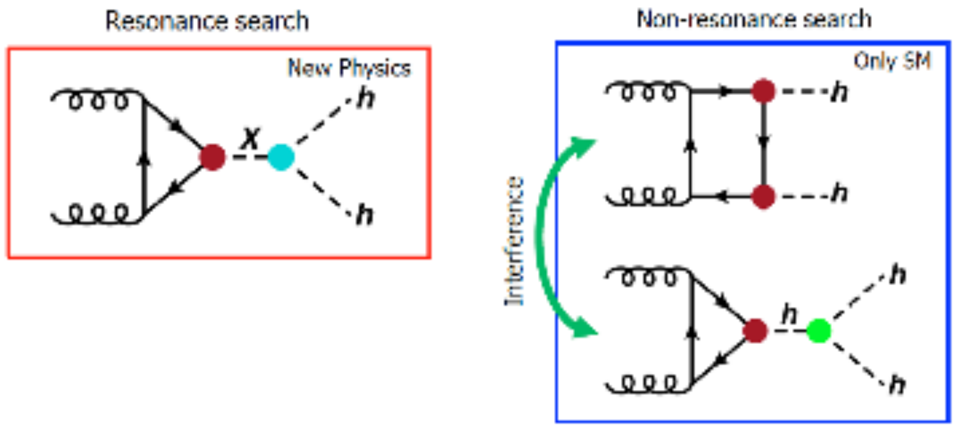




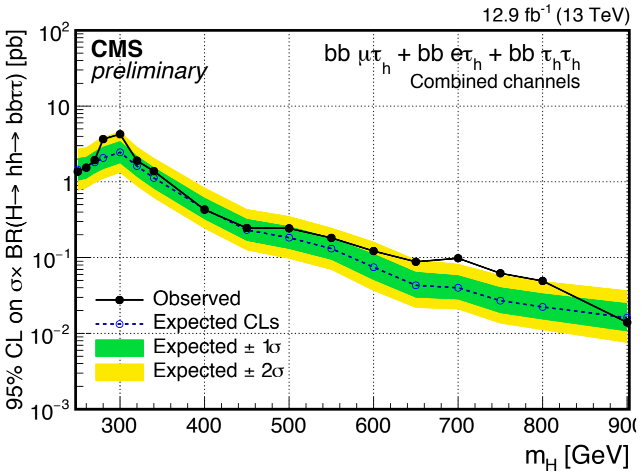


EXTRA HIGGS BOSONS

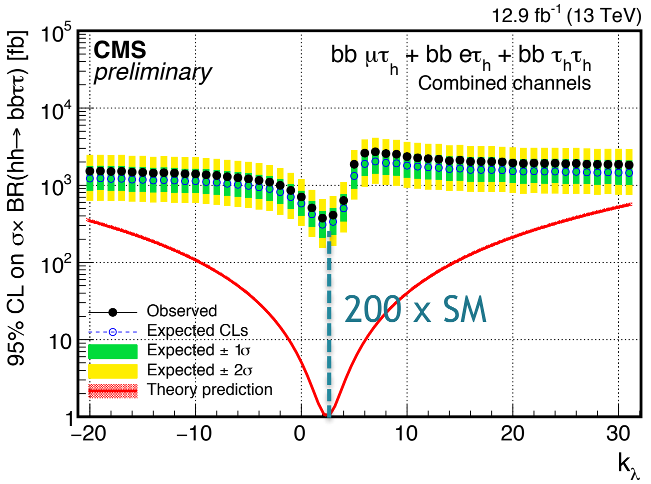
Higgs→hh→bbττ



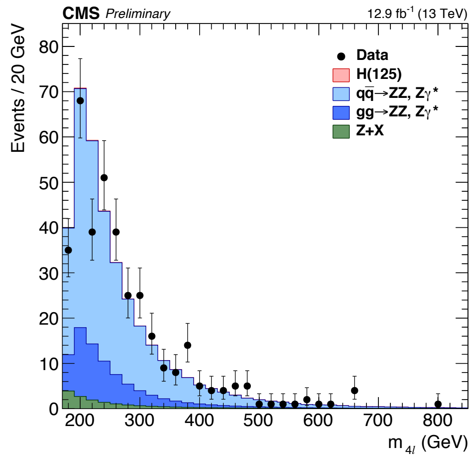
Resonant

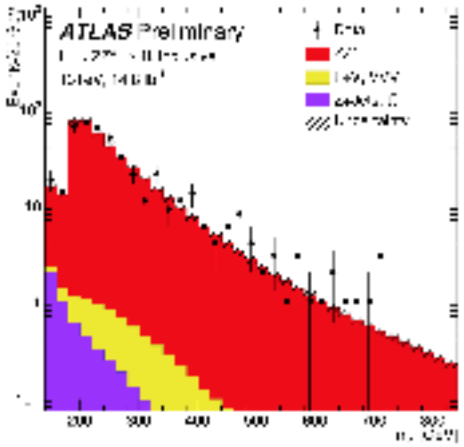


Non-Resonant

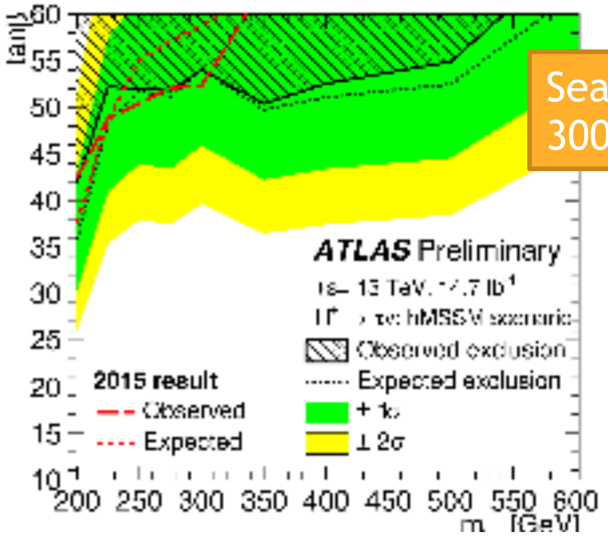


Heavy Higgs→ZZ→4l



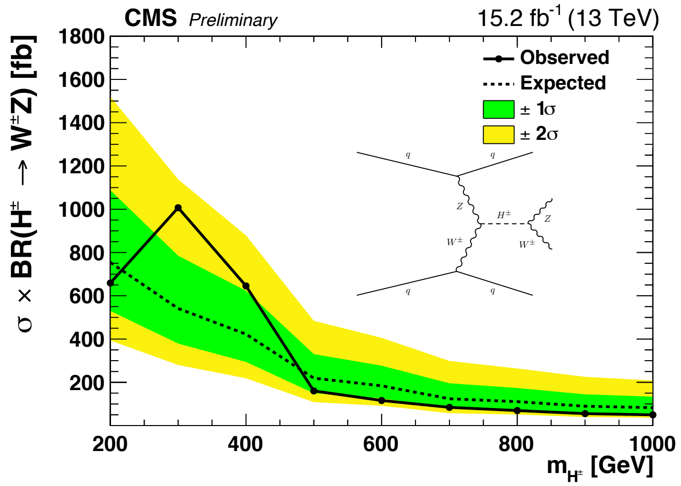


Charged Higgs

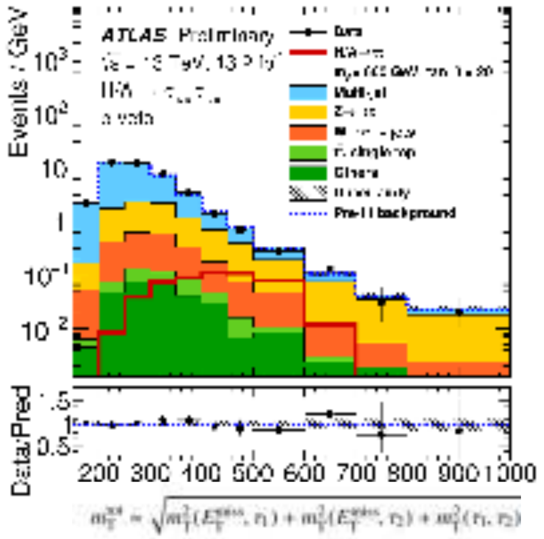


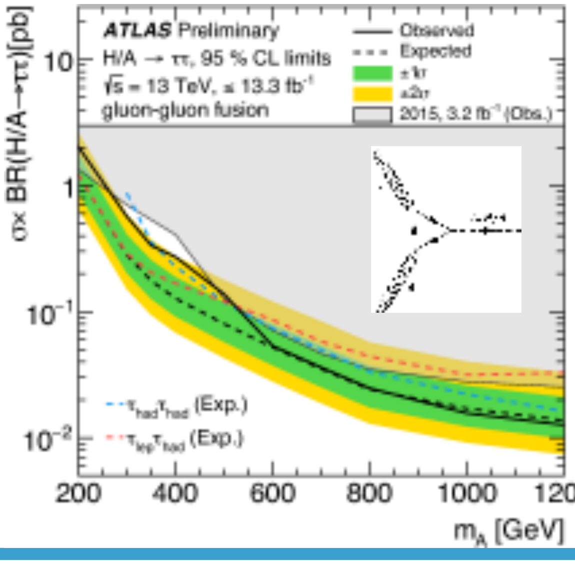
Search for H±→tb
$300<m_{H^{\pm}}<1000$ GeV

Search for H±WZ



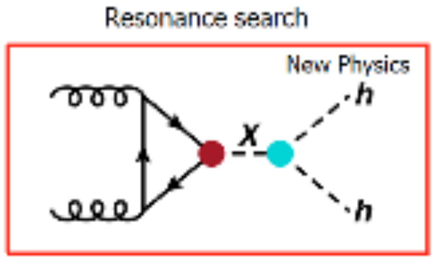
Heavy Higgs→ττ

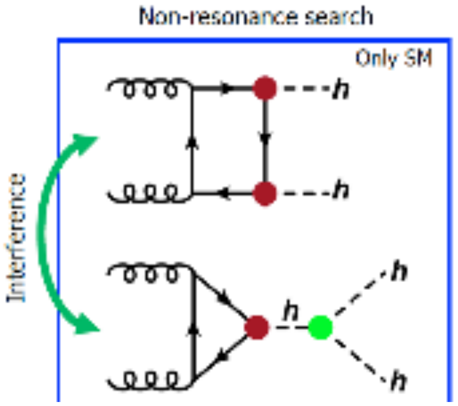




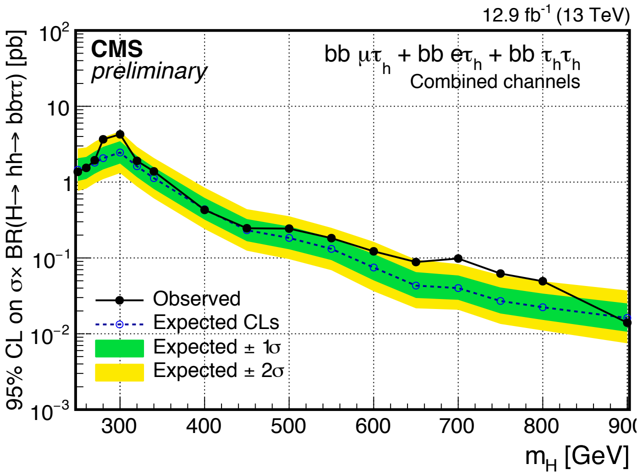
ТЕКСТ

Higgs→hh→bbττ

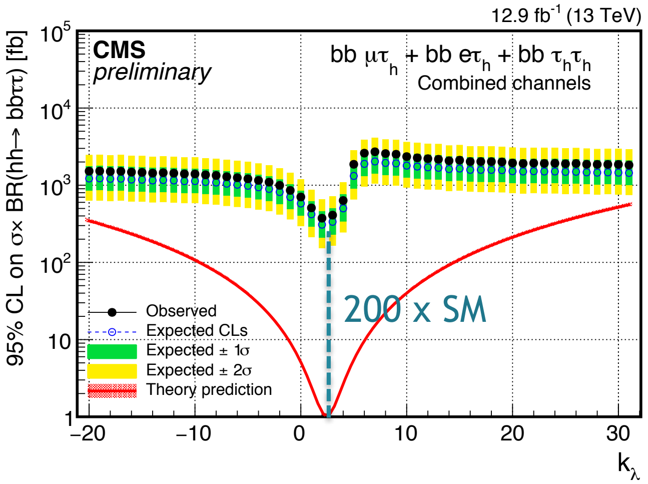




Resonant

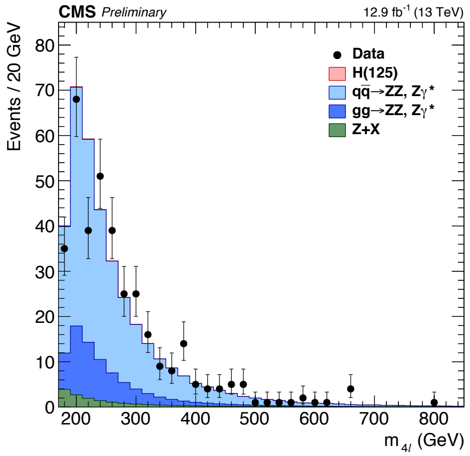


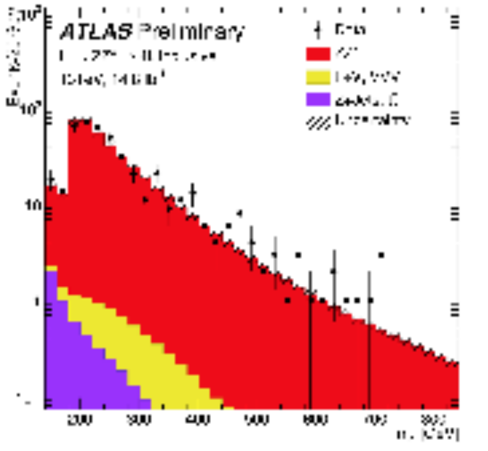
Non-Resonant



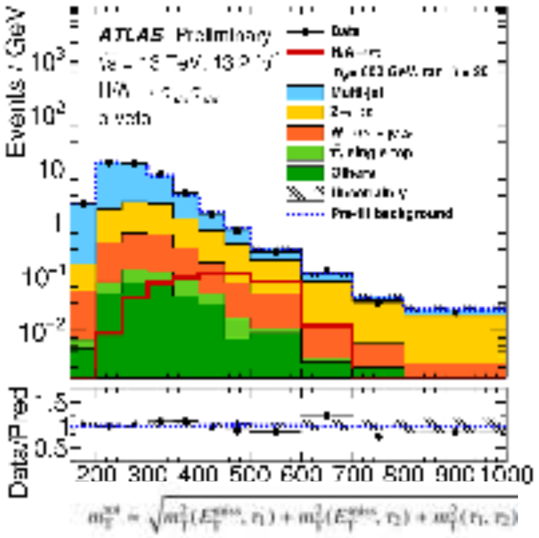
200 x SM

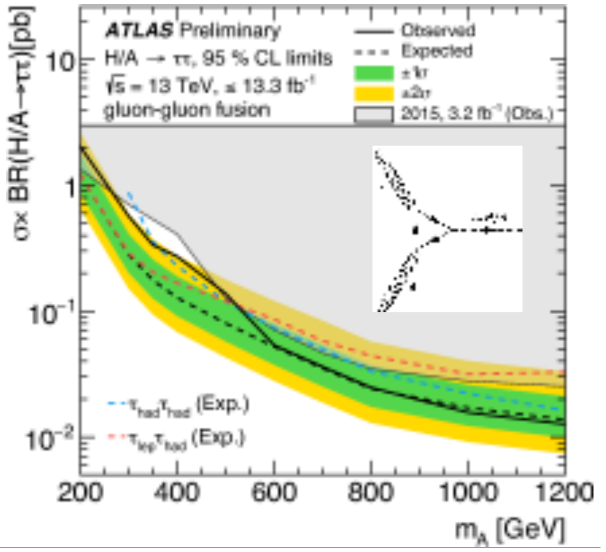
Heavy Higgs→ZZ→4l

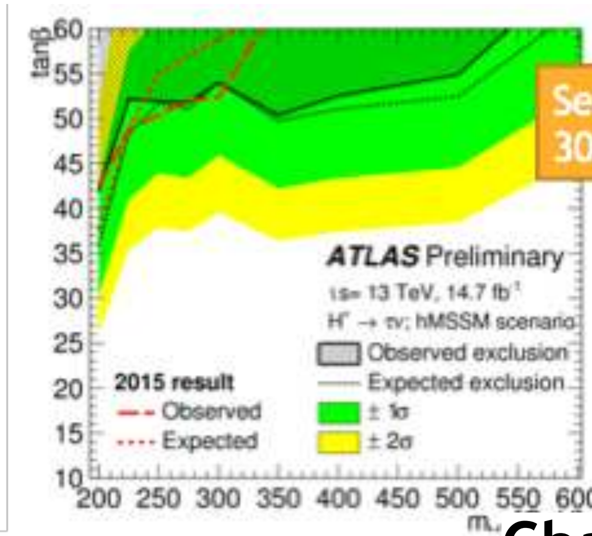




Heavy Higgs→ττ



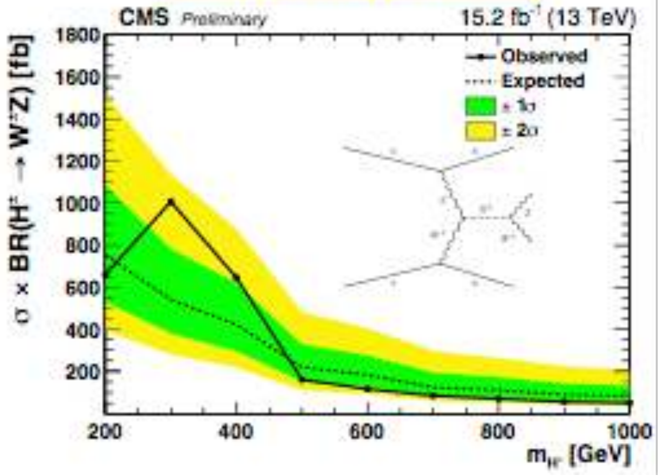




Search for H±→tb
300<m$_{H^\pm}$<1000 GeV

Charged Higgs

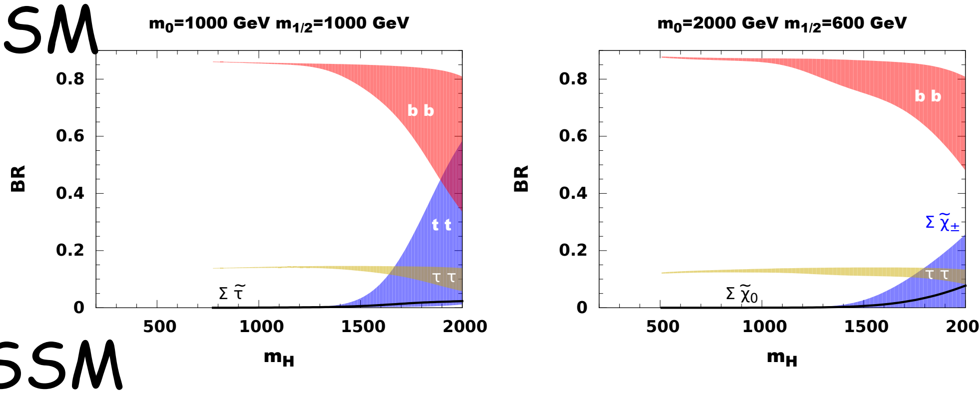
Search for H±WZ



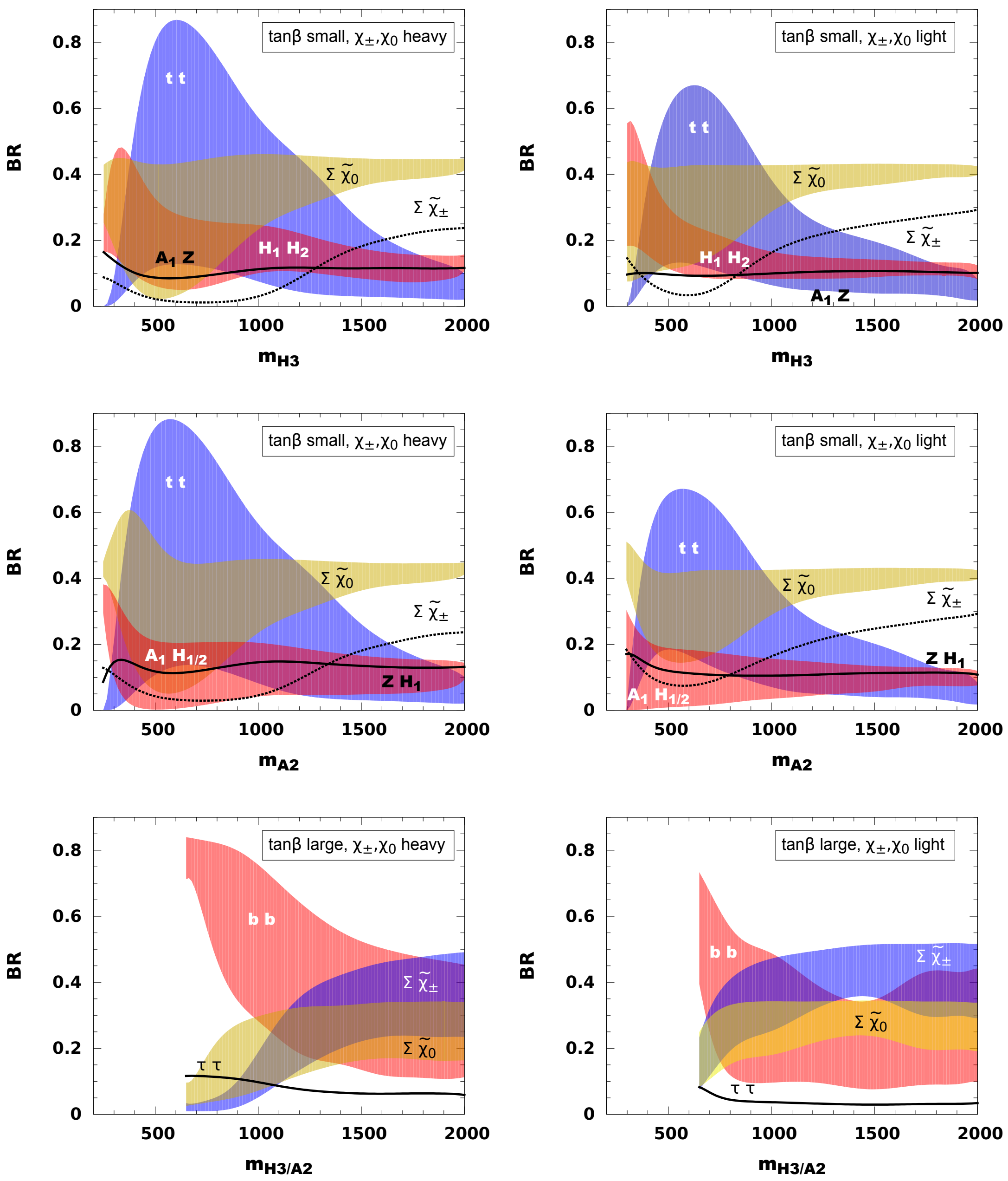
HEAVY HIGGS BOSON DECAYS

Branchings

MSSM

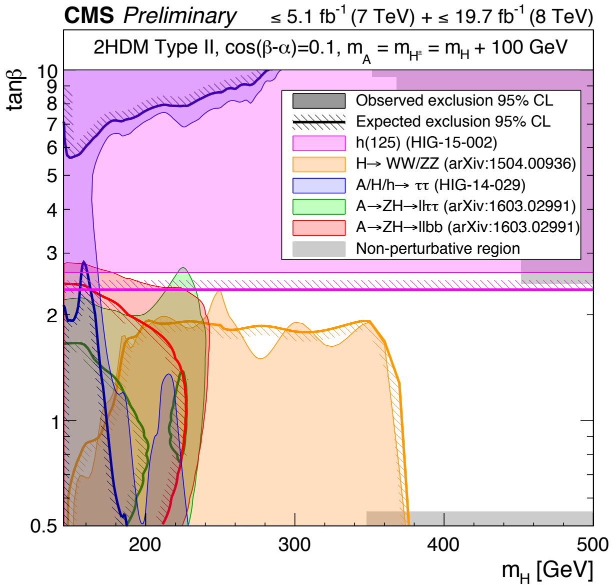


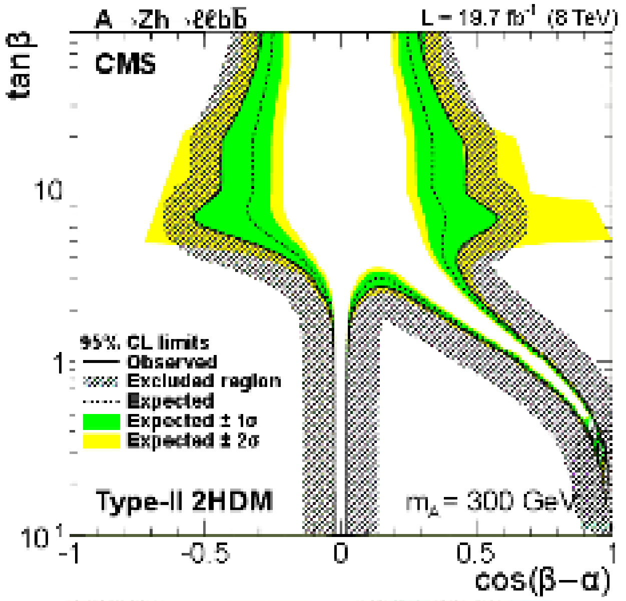
NMSSM

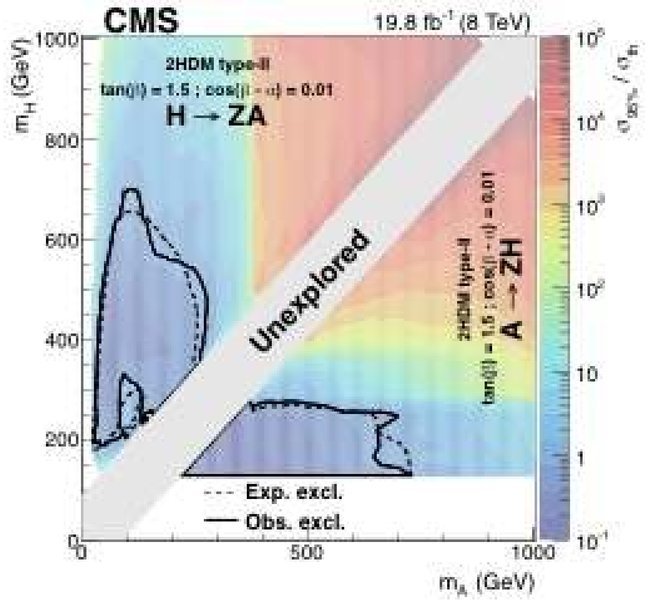


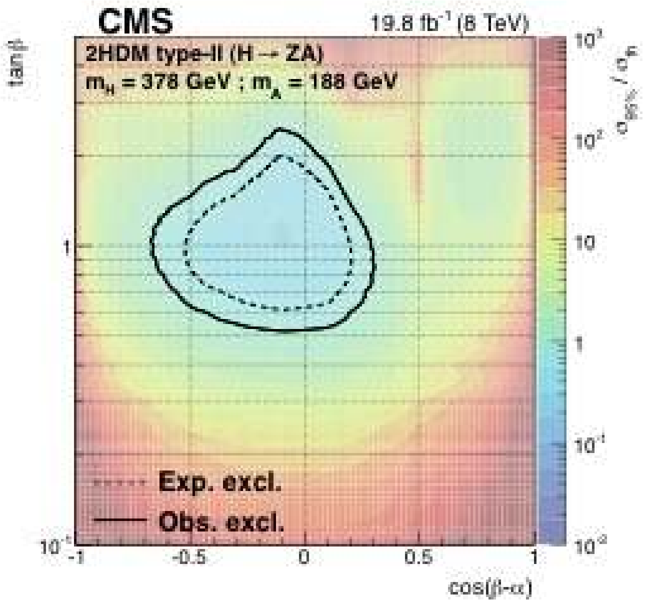
1) “Higgs to Higgs” decays

$A \to Zh$ and $A \to ZH$, $H \to ZA$









- The Higgs physics has already started
- This is the task of vital importance.
- May require the electron-positron collider

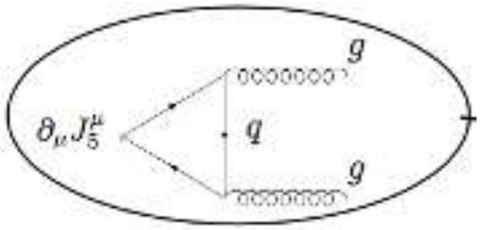
NEW PARTICLES AXION OR AXION-LIKE PARTICLES

Javier Redondo, EPS HEP 2017

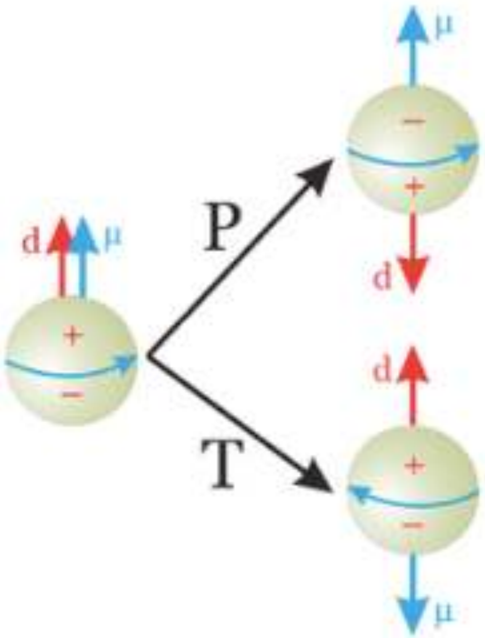
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\rm QCD} + N_f \delta$

$$\mathcal{L}_{\rm SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\rm QCD}$$

Axial anomaly



The θ-angle produces flavour-neutral CP violation like Electric Dipole Moments



- **Neutron EDM** **(Guo 1502.02295)**

$$d_n = -4 \times 10^{-3} \times \theta\,[\mathrm{e\,fm}]$$

- **Experimental upper limit** **(Grenoble hep-ex/0602020)**

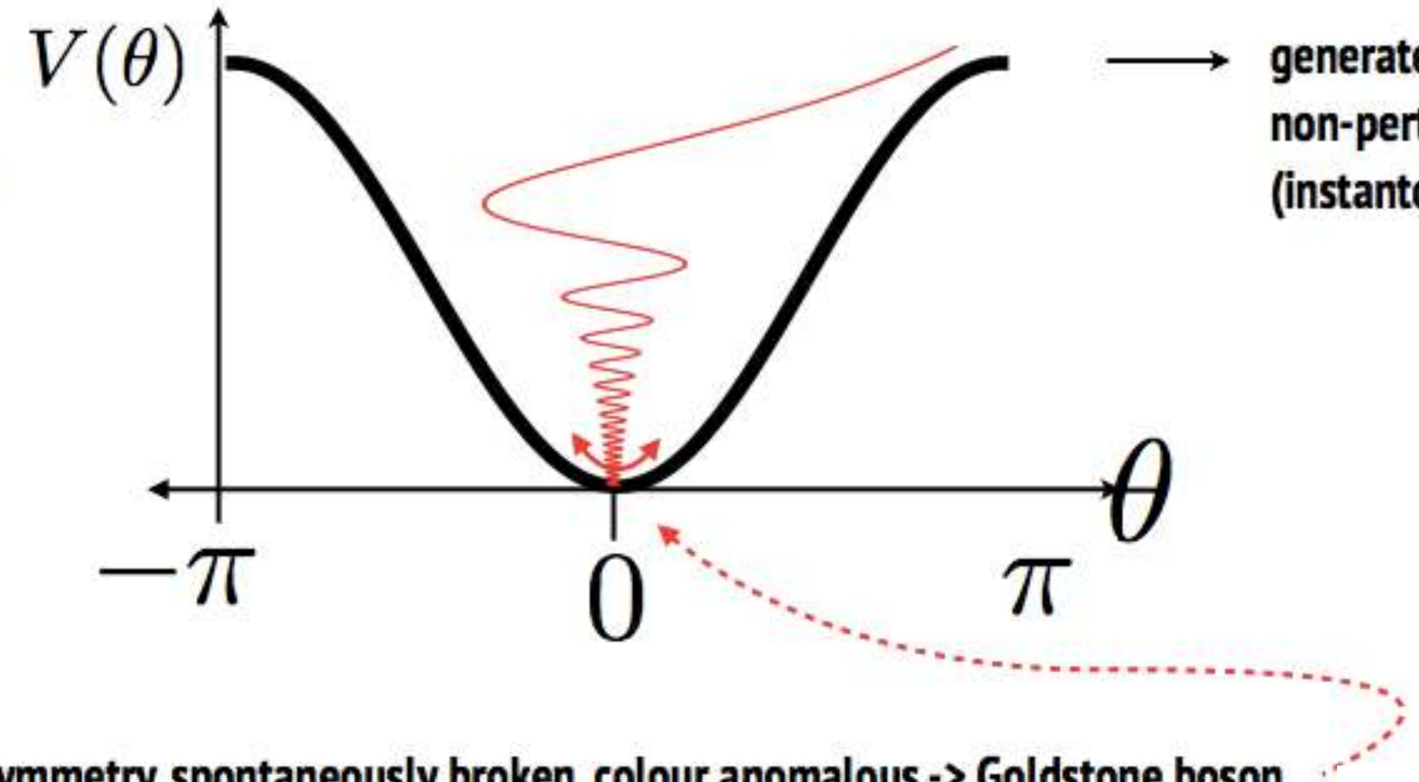
$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$

- **Why is** $\theta < 10^{-10}$**?**

PECCEI-QUINN MECHANISM - AXION

- Any theory promoting θ to a dynamical field, $\theta(t, \mathbf{x})$,will dynamically set $\theta \to 0$ after some time...

Potential energy density



generated by QCD
non-perturbative dynamics
(instantons)

- PQ Mechanism: Global U(1) axial symmetry, spontaneously broken, colour anomalous -> Goldstone boson

$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f_a^2 - \frac{\alpha_s}{8\pi}G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\theta$$

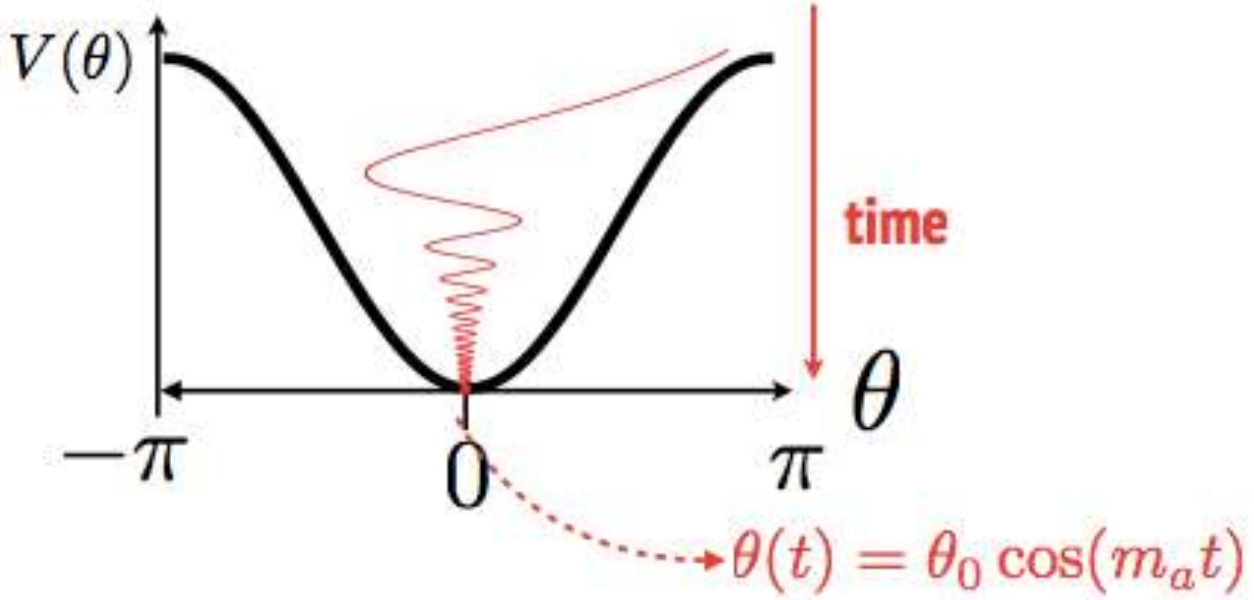
New Spontaneous symmetry breaking [energy] scale f_a

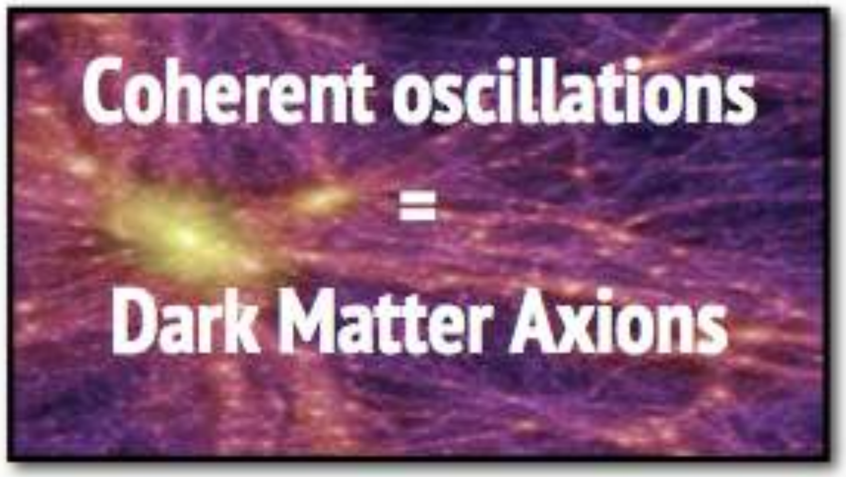
Canonically normalised θfield is the QCD AXION! $a(x) = \theta(x)f_a$

WW Axion

DARK MATTER AXION

- High T, no preference for Initial Conditions! At time $t \sim 1/m_a$ axion field seeks its minimum




Coherent oscillations

=

Dark Matter Axions

Oscillation frequency

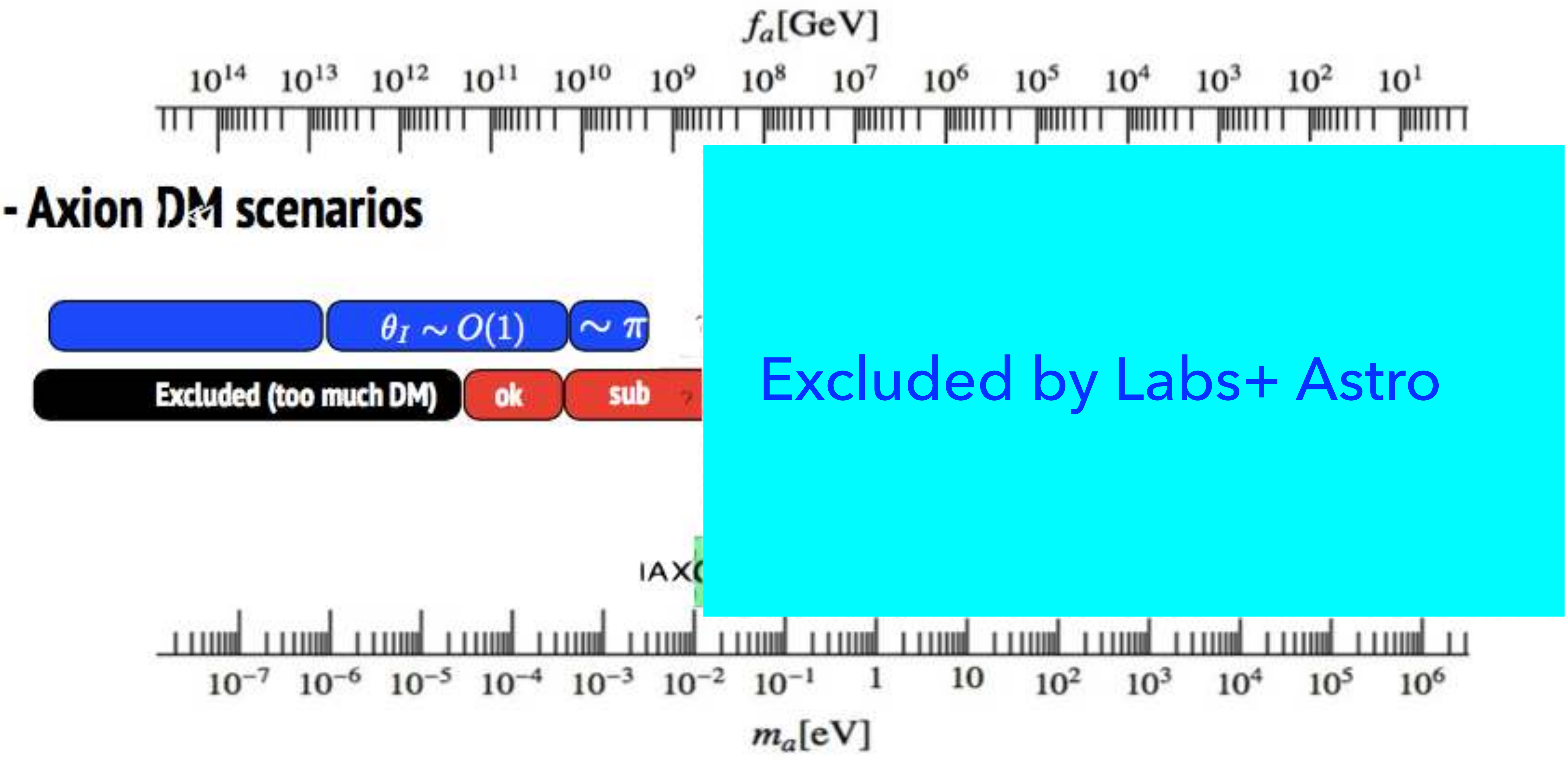
$$\omega = m_a$$

Energy density (harm. oscillator)

$$\rho_{\mathrm{aDM}} = \frac{1}{2} m_a^2 f_a^2 \theta_0^2 = \frac{1}{2} (75\mathrm{MeV})^4 \theta_0^2$$

- **Some amount of axion Dark matter is unavoidable!**

WHAT IS THE MASS TO GET $\Omega_{CDM}h^2 = 0.12$?



Excluded by Labs+ Astro

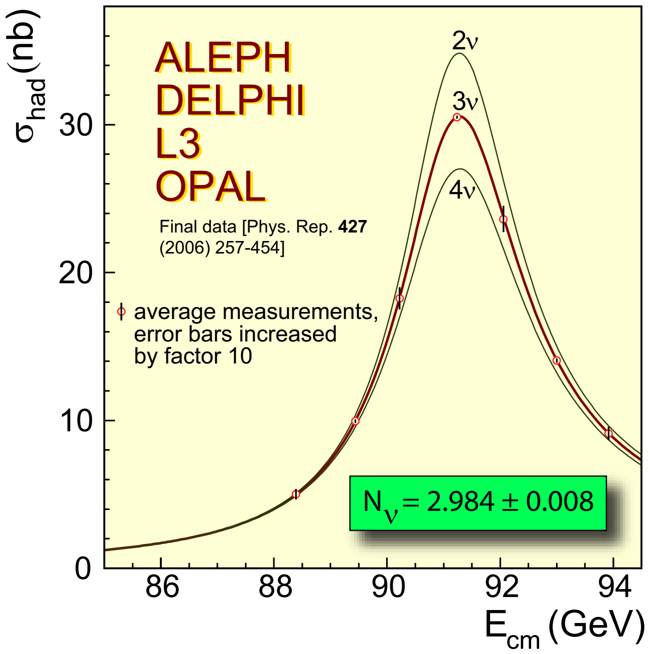
- Less minimal axion models have further possibilities ....

NEW PARTICLES

- Number of Generations=3?
  - Why 3 copies?

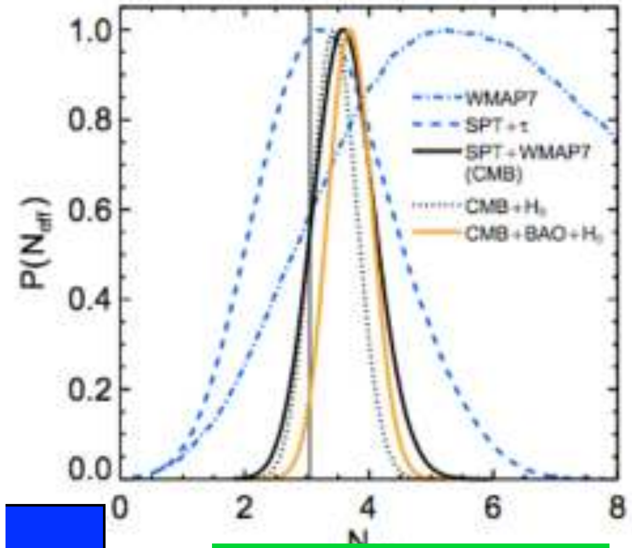
- The necessary condition for the baryon asymmetry of the Universe - CP violation
- CP in the SM comes from the non-zero phase in the quark (and lepton) mixing matrices
- Non-zero phase appears only if the number of generations N ≥ 3

- The width of the Z-boson (LEP)



NEUTRINOS

- The CMB spectrum (Planck)



$N_\nu^{eff} < 3.30 \pm 0.27$

- The fourth generation of quarks is excluded also by precision measurement of rare decays

- Do we see all neutrinos or there are heavy right-handed ones? (Majorana)

- Are there any new sterile neutrinos? (To release the constraints from LSND/ MiniBoone and reactor anomaly, etc)

DIRAC OR MAJORANA?

$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}$$

Mass martix

$$\mathcal{M} = \begin{array}{cc} \begin{array}{cc} L & R \end{array} & \\ \begin{pmatrix} 0 & m_D \\ m_D^* & M \end{pmatrix} & \begin{array}{c} L \\ R \end{array} \end{array}$$

Majorana term

Mass eigenvalues

$$m_1 \approx \frac{m_D^* m_D}{M} \qquad m_2 \approx M$$

Light

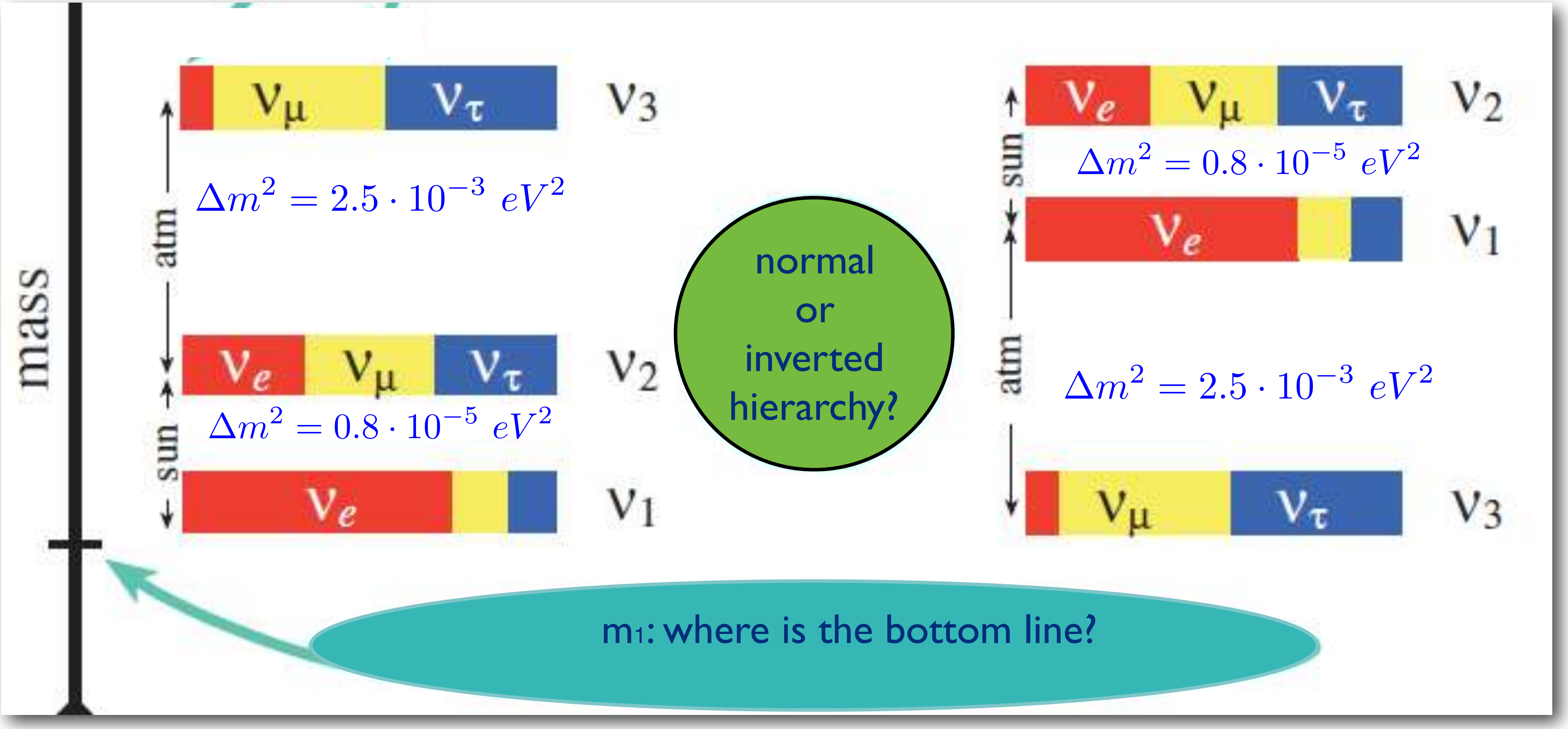
Heavy

$$\nu_D \neq \nu_D^*$$
$$m_{\nu_L} = m_{\nu_R}$$

?

$$\nu_M = \nu_M^*$$
$$m_{\nu_{M_1}} \neq m_{\nu_{M_2}}$$

NEUTRINO MASSES



$$\sum m_\nu < 0.23\ eV$$

cosmology: the CMB spectrum

Planck

$$m_{\nu_e} < 2\ eV$$

β-decay

Troitsk-Mainz

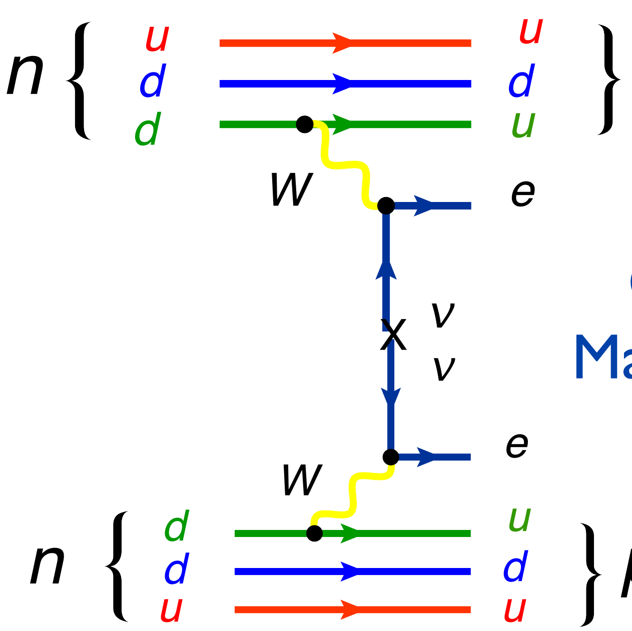
→

$$m_{\nu_e} < 0.2\ eV$$

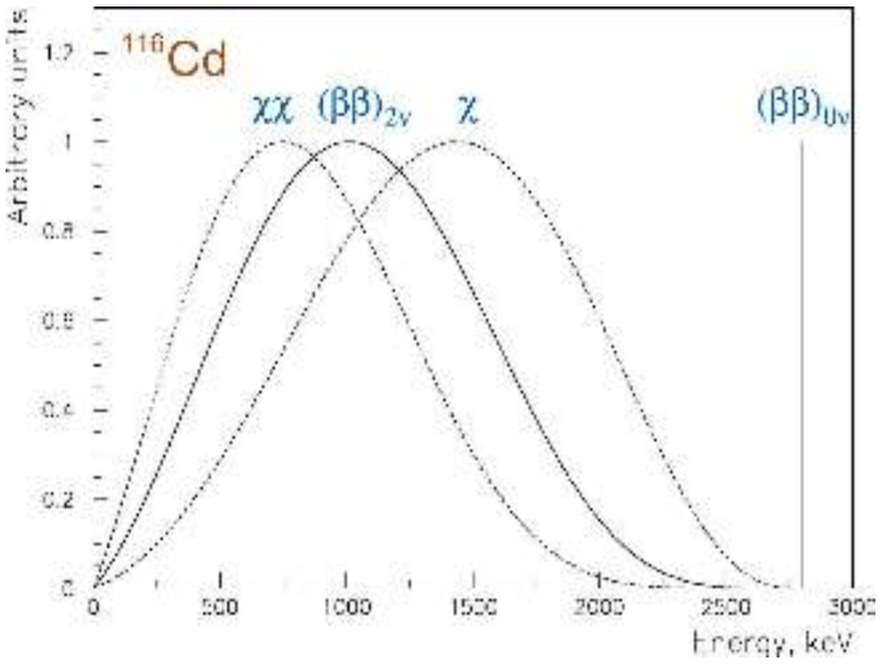
KATRIN

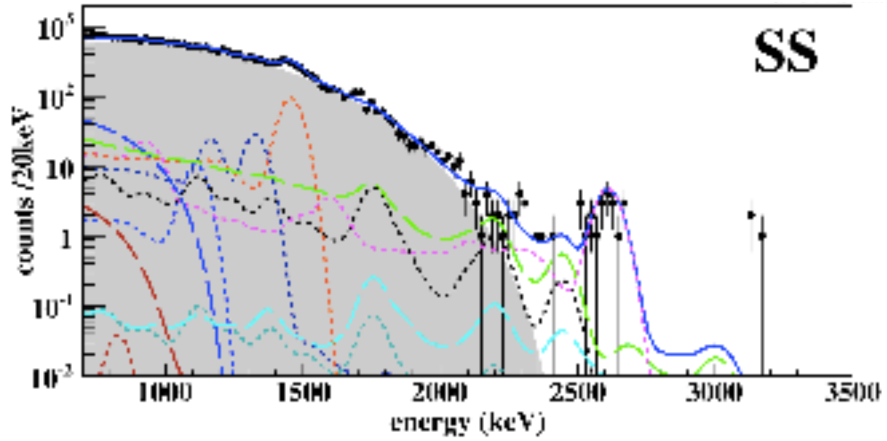
$0\beta\beta\nu$ NEUTRINOLESS DOUBLE BETA DECAY

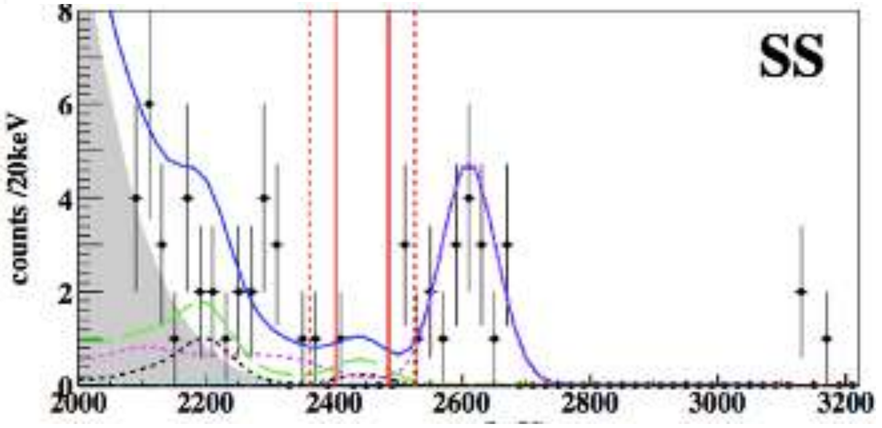
0νββ decay

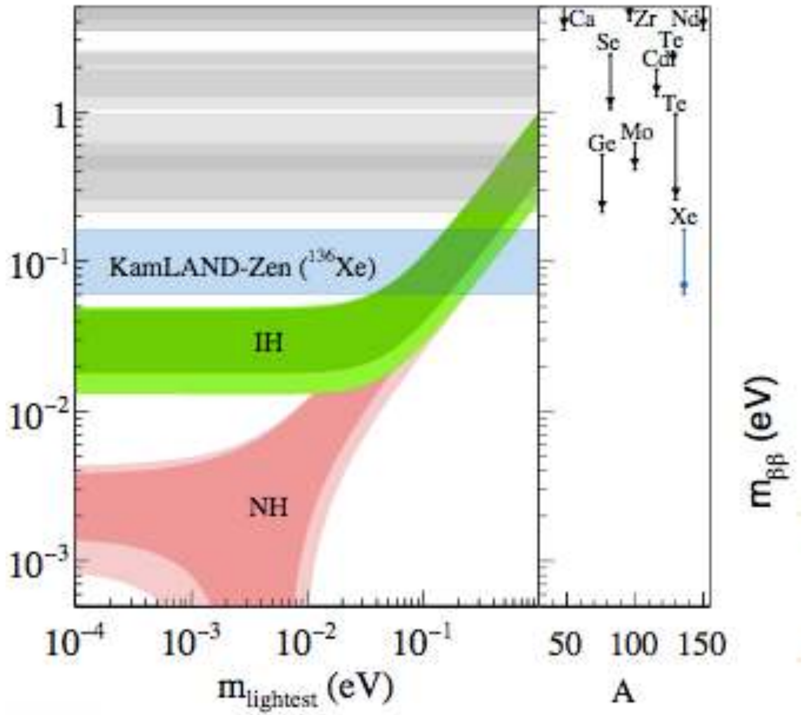


Only Majorana









Candidate Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	**Gerda**, Majorana
^{82}Se	SuperNemo,Lucifer
^{130}Te	**CUORE**
^{136}Xe	**EXO**, NEXT, **KamLAND-Zen**
^{150}Nd	SNO+

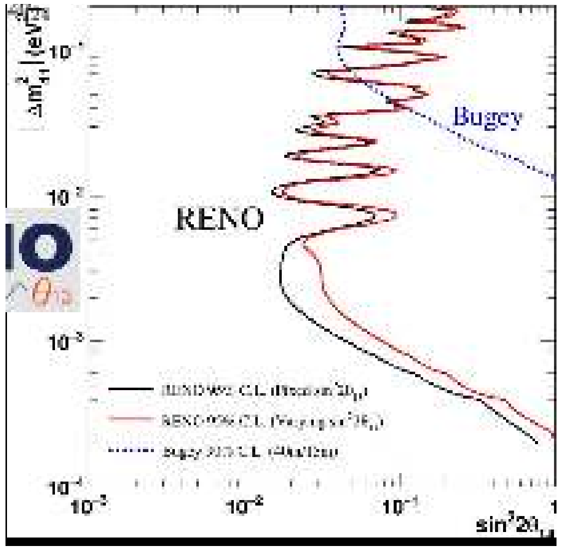
$T_{1/2}2\nu\beta\beta$ (^{136}Xe) x 10^{21} yr = 2.23 ± 0.017 stat ± 0.22 sys

$T_{1/2}0\nu\beta\beta$ (^{136}Xe) x 10^{25} yr > 1.6 (90% CL)

STERILE NEUTRINO

No evidence for sterile neutrinos

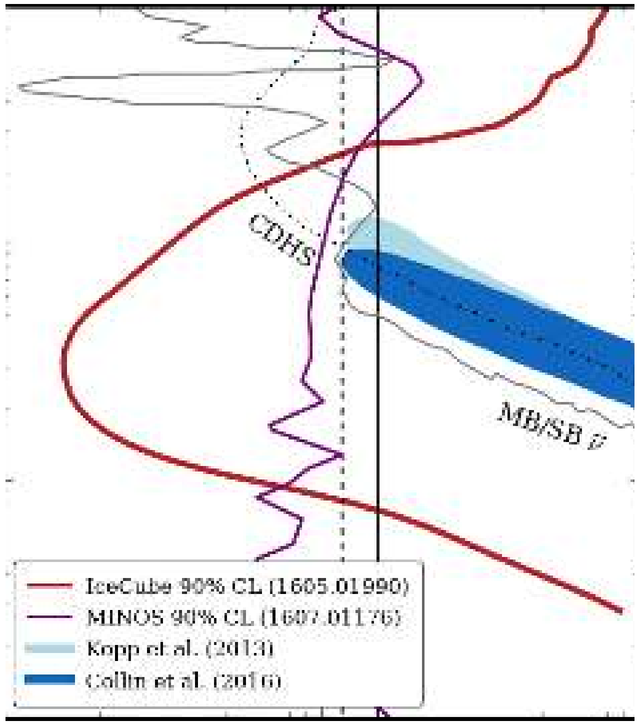
Various exps interpreted within 4 neutrino framework

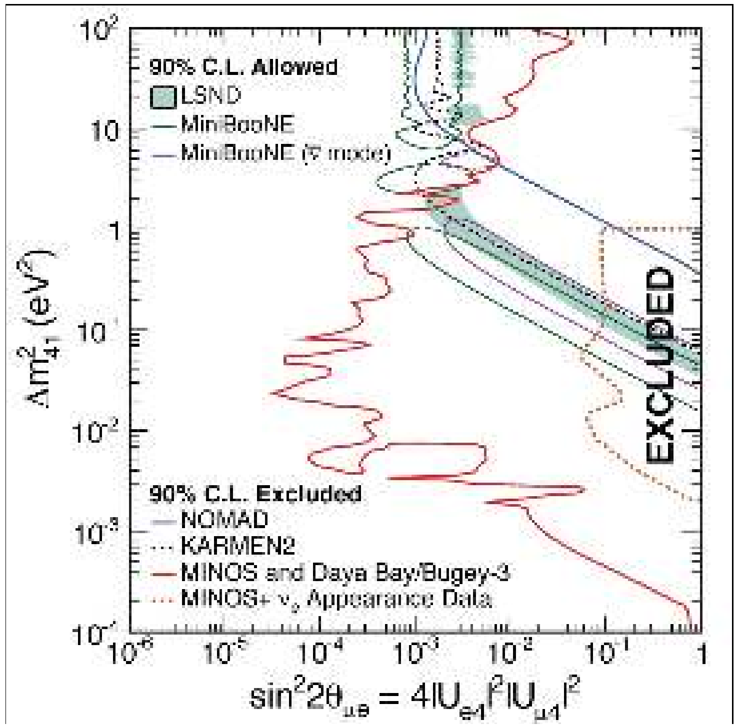


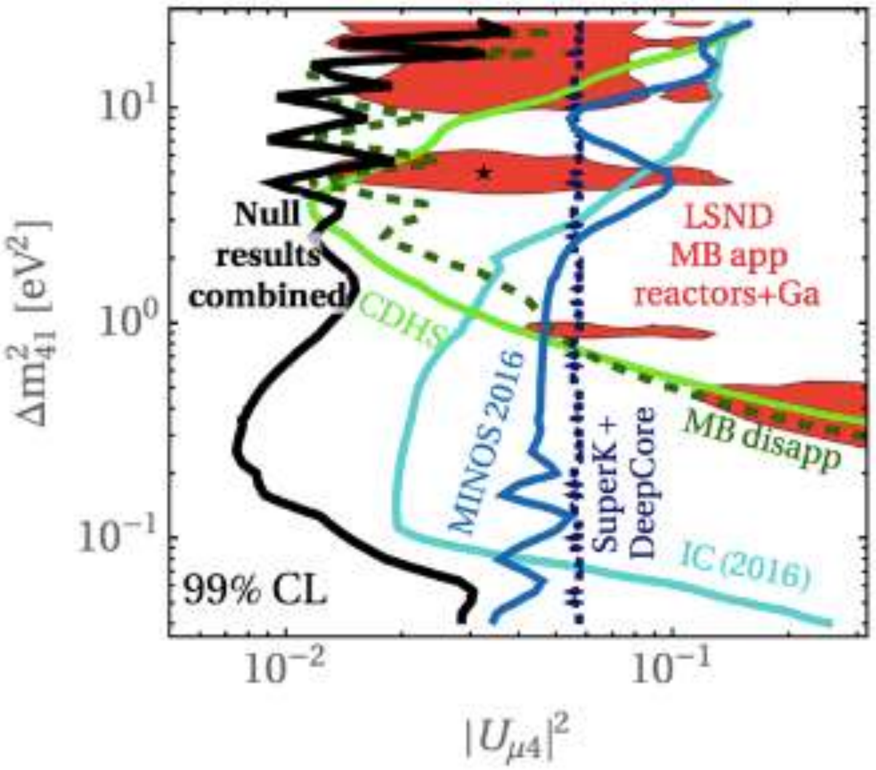
Oscillation channels are related:

$$P_{\nu_e\to\nu_e} \approx 1 - 2|U_{e4}|^2(1-|U_{e4}|^2)$$
$$P_{\nu_\mu\to\nu_\mu} \approx 1 - 2|U_{\mu4}|^2(1-|U_{\mu4}|^2)$$
$$P_{\nu_\mu\to\nu_e} \approx 2|U_{e4}|^2|U_{\mu4}|^2$$

for $4\pi E/\Delta m^2_{41} << L << 4\pi E/\Delta m^2_{31}$







NEW PARTICLES

DARK MATTER

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino
  - - axion (axino)
  - - neutralino
  - - sneutrino
  - - gravitino
  - - heavy photon
  - - heavy pseudo-goldstone
  - - light sterile higgs

Not from the SM

mSUGRA

might be invisible (?)

detectable in 3 spheres
less theory favorable

might be undetectable (?)

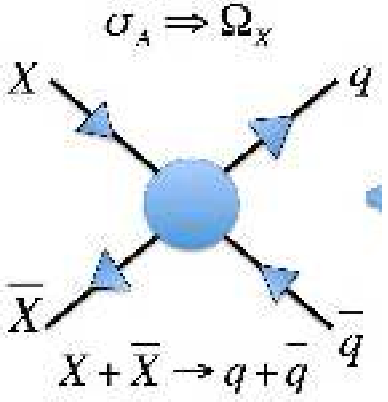
possible, but not
related to the other
models

WIMP is our chance !

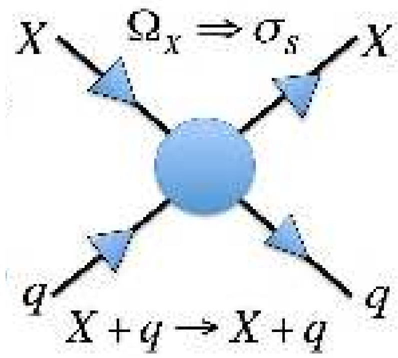
But we have to look elsewhere !

WIMP

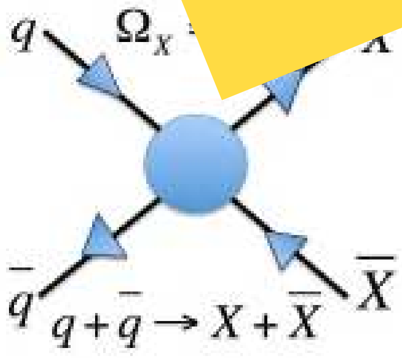
Annihilation
in the halo



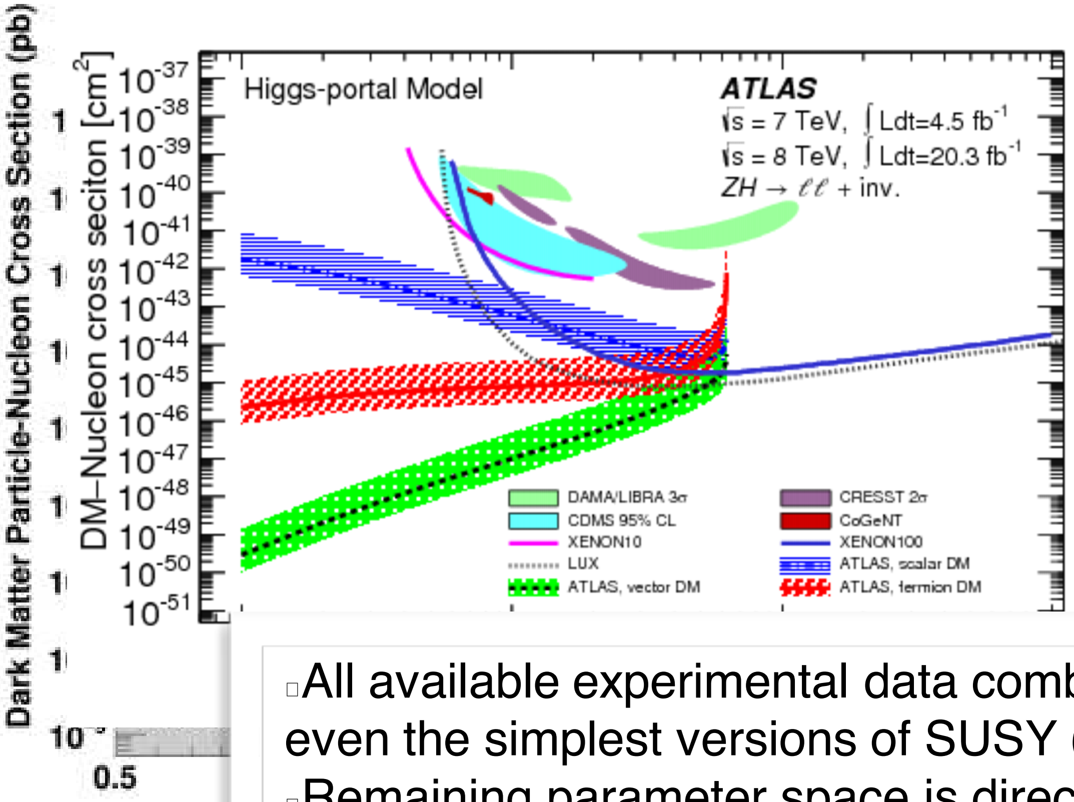
Scattering
on a target

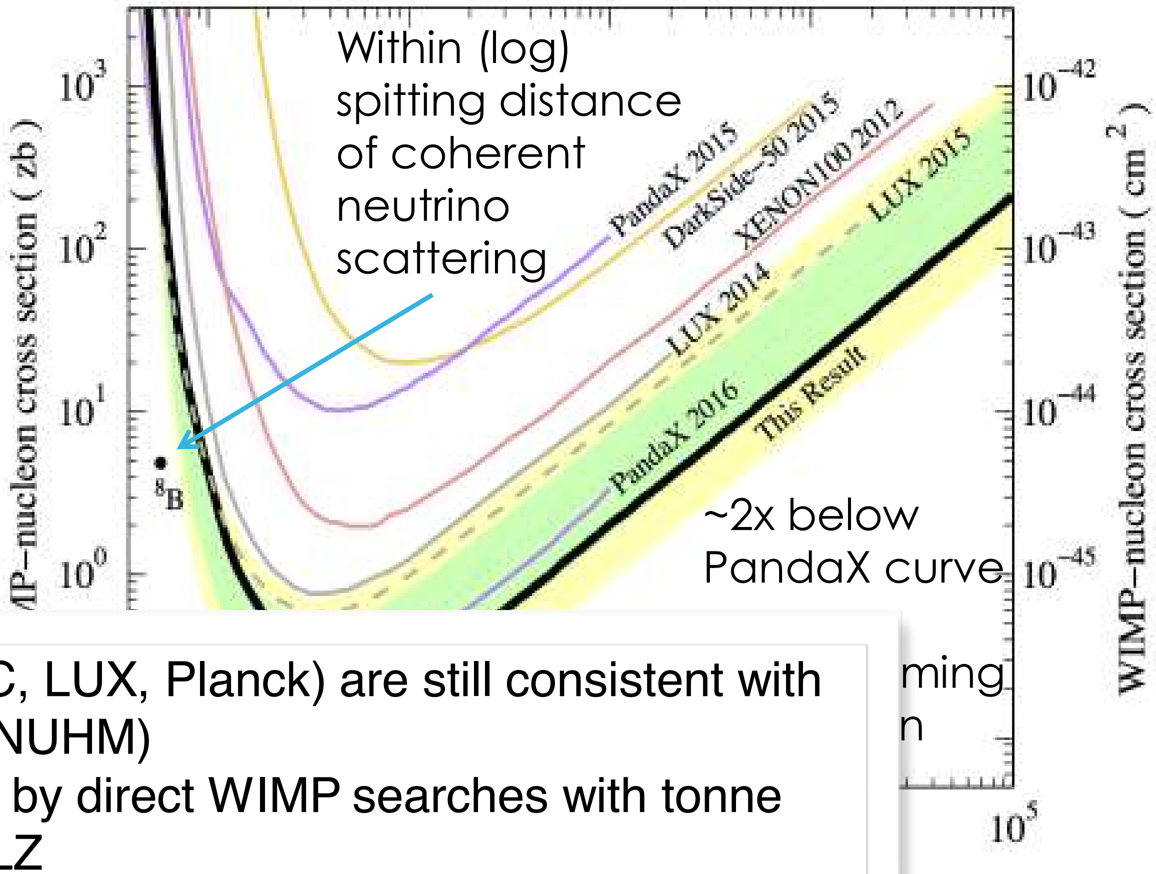


Creation at
the LHC



DARK MATTER: DIRECT DETECTION



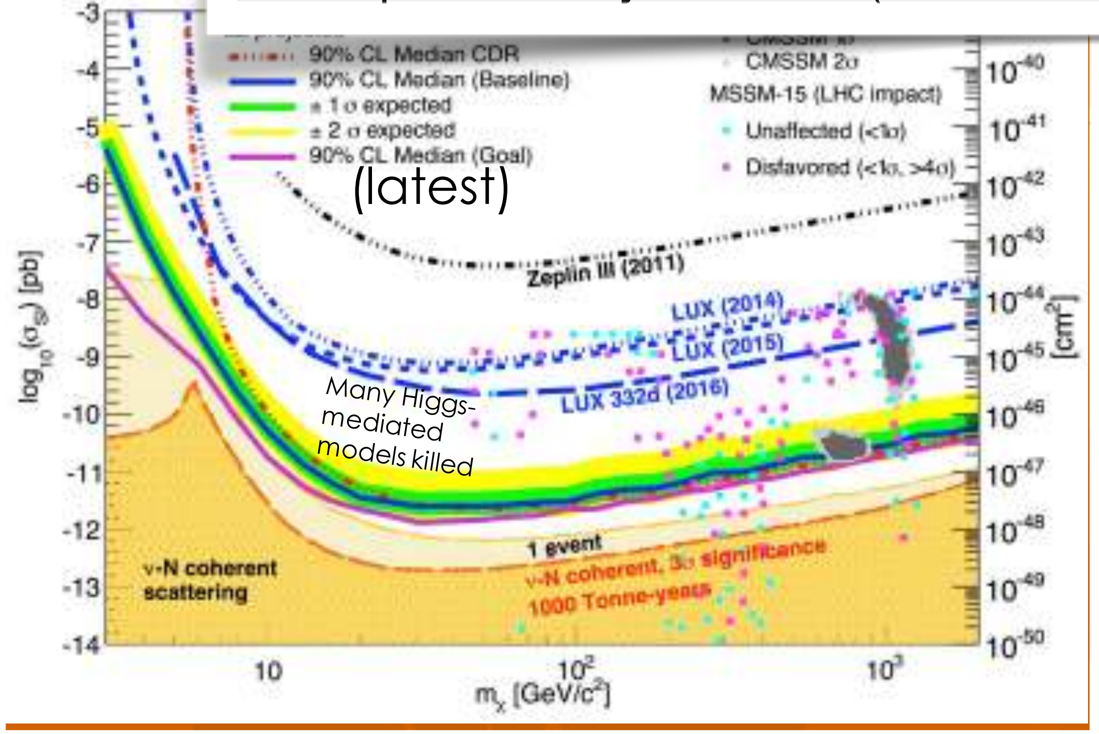


Within (log) spitting distance of coherent neutrino scattering

~2x below PandaX curve

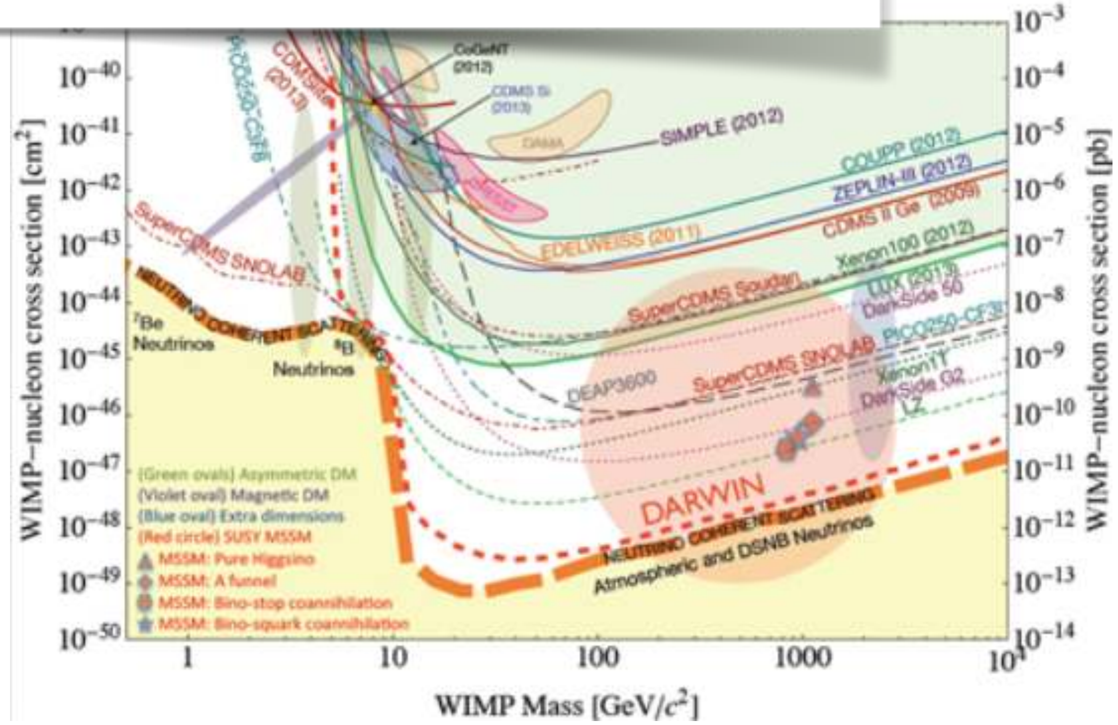
ming
n

- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)



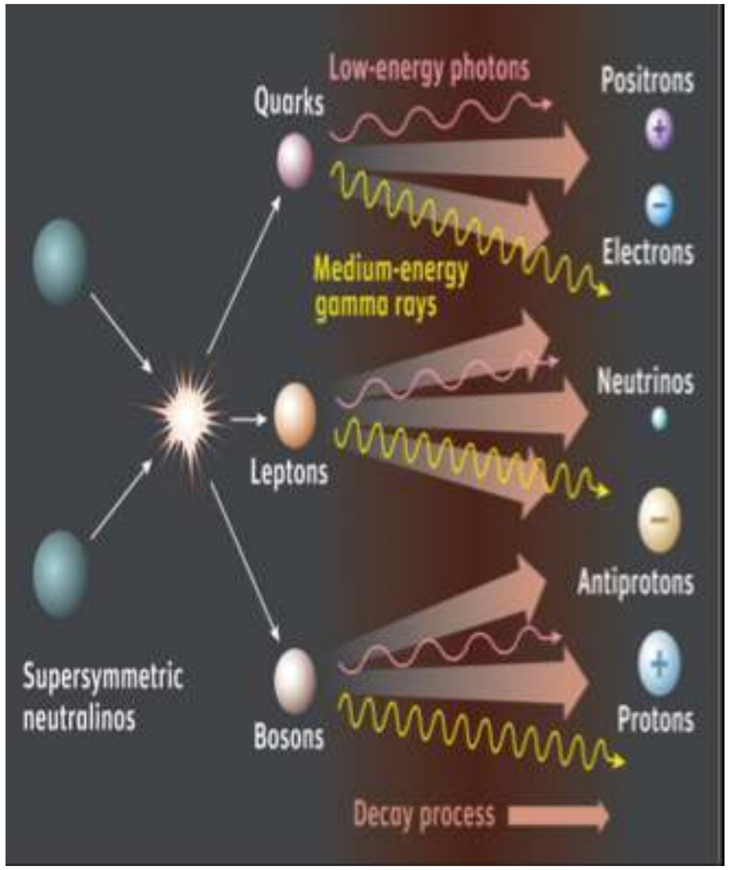
(latest)

Many Higgs-mediated models killed

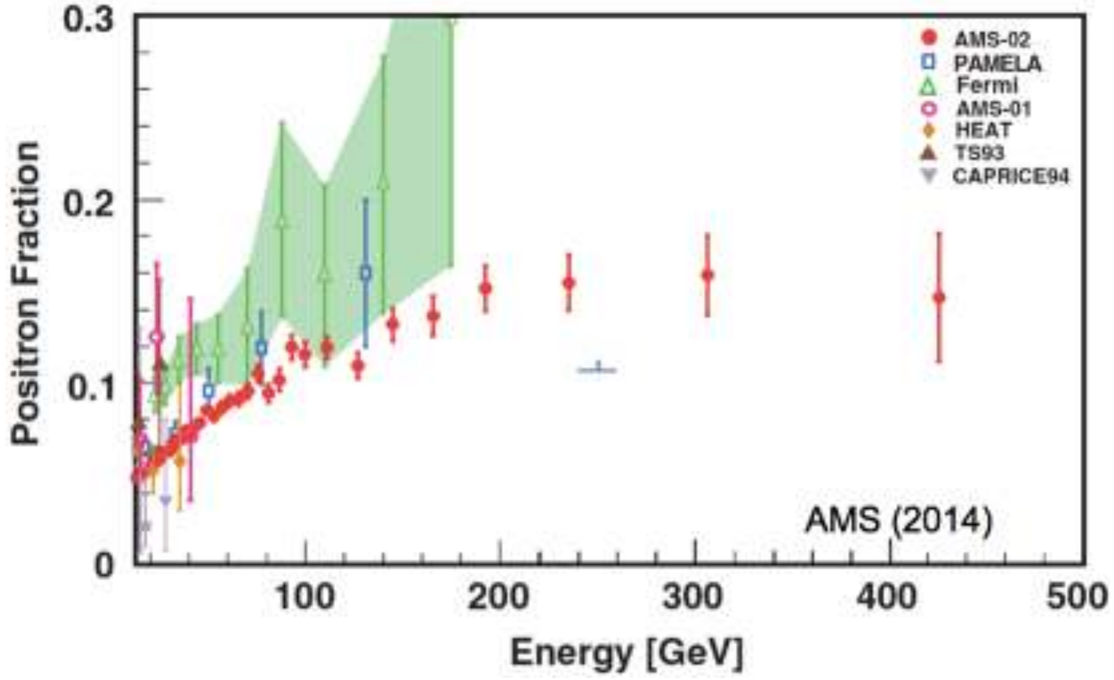


DARK MATTER: INDIRECT DETECTION

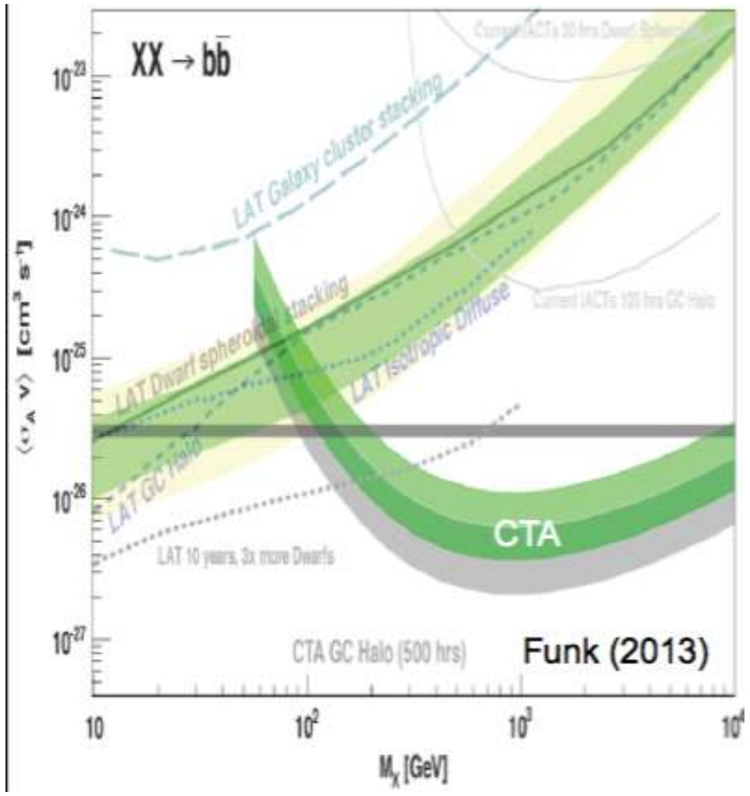
- Dark matter may pair annihilate or decay in our galactic neighborhood to:
- positrons
- high-energy photons
- neutrinos
- antiprotons
- antideutrons

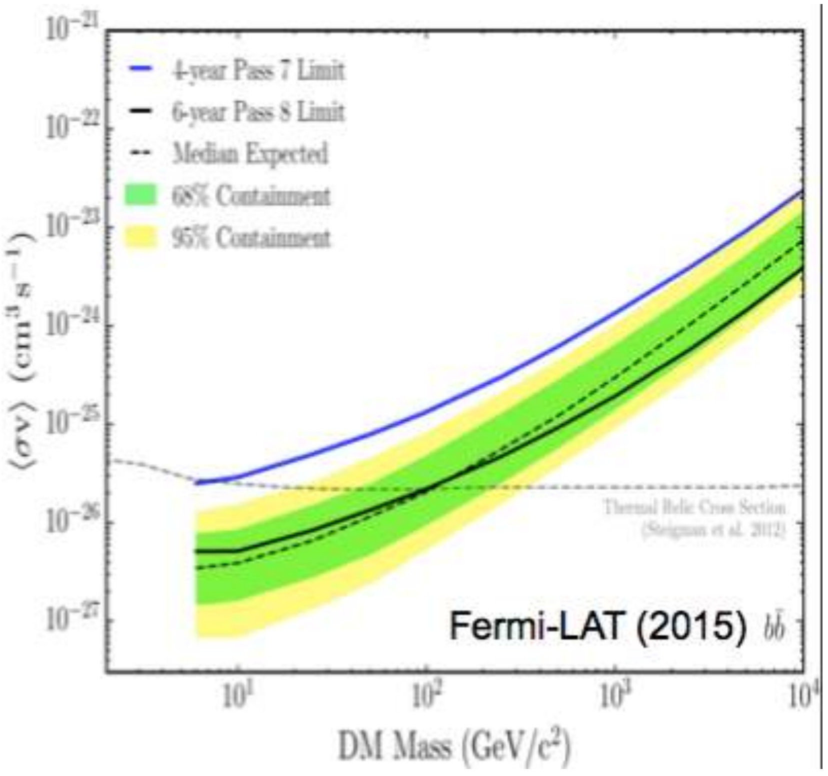


INDIRECT DM: POSITRON RESULTS



INDIRECT DM: PHOTON RESULTS





- Rapid improvements in recent years, Fermi-LAT now excludes WIMP makes up to ~100 GeV for certain annihilation channels
- The future is the Cherenkov Telescope Array, which will extend the reach by two orders in mass up to masses

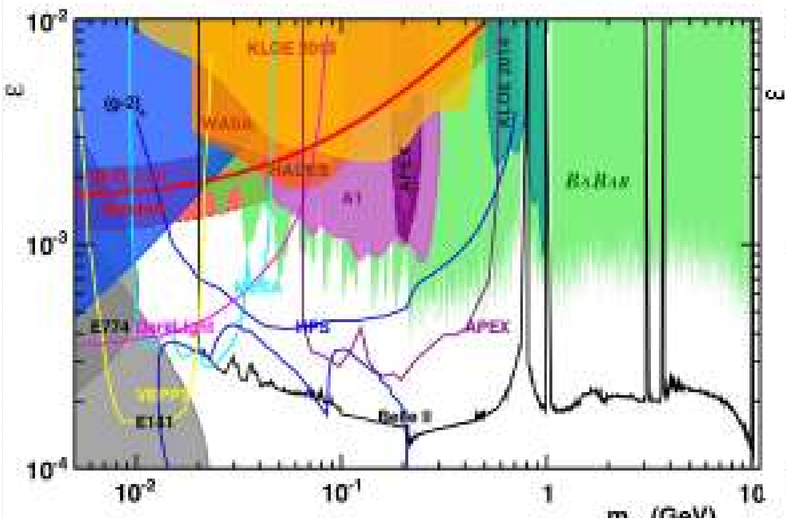
  ~ 10 TeV

DARK MATTER/NEW PHYSICS

SIMPs(strong interacting massive particle)

- dark matter is strongly interacting under the **other SU(N) gauge interactions.**
- DM may be pion/Baryon/gluball of the new strong interactions or couple to new scalar by large Yukawa coupling

$e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-,$ *prompt*

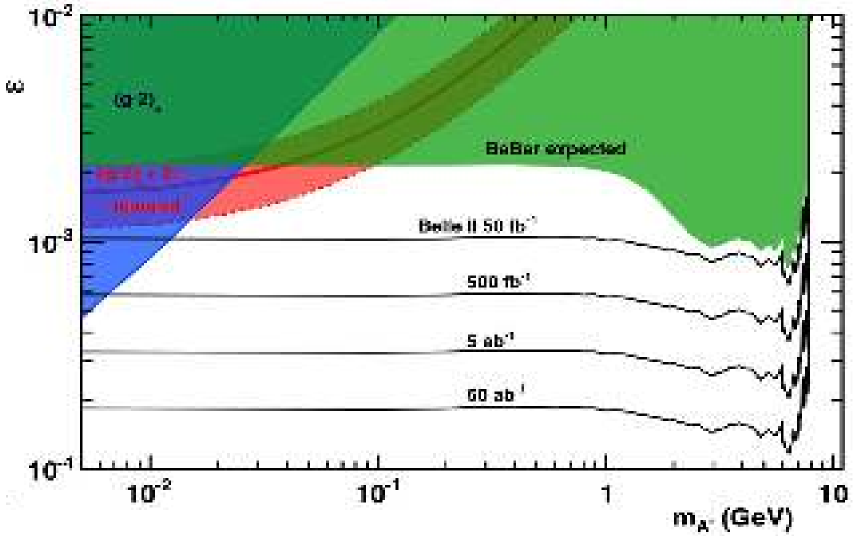


dark photon

- U(1) gauge boson is relatively easy going object "gauge invariant $F'_{\mu\nu}$"
- sequestering $U(1)_D$ dark sector from SM sector,
- Interaction with SM may arises from kinetic mixing $F_{\mu\nu}F'^{\mu\nu}$
- Dark matter couple to $U(1)_D$ can have very small coupling, and also Very light $U(1)_D$ $a' \rightarrow 3\gamma$ has very long lifetime. Both can be dark matter.

$e^+e^- \rightarrow \gamma A' \rightarrow \gamma \chi \bar{\chi}$

In



- **Nature of Dark matter** is one of the big questions that particle physics should answer.
- Success of LHC and dark matter searches and we are wondering over next steps to go.

NEW DIMENSIONS

EXTRA SPACE DIM

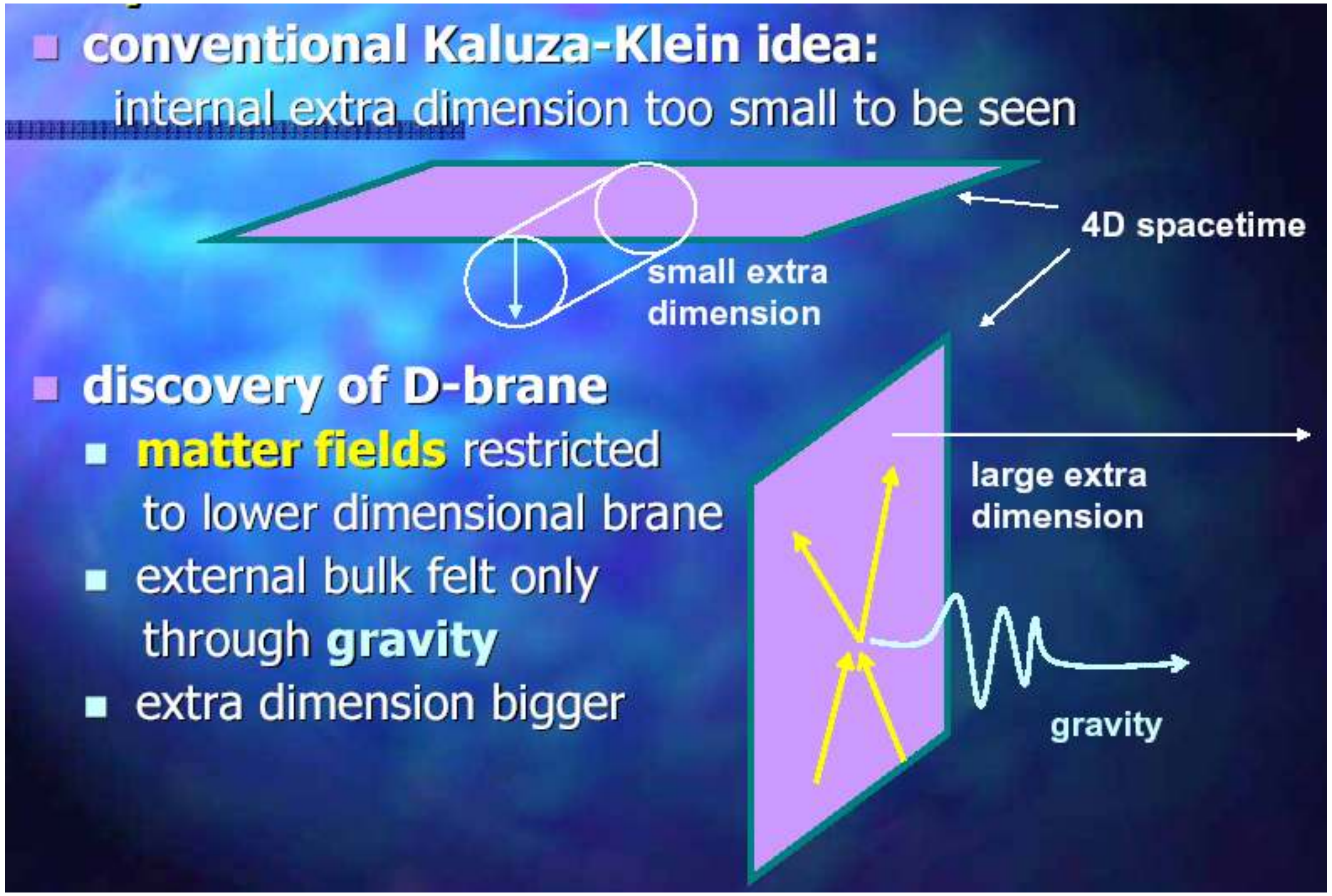
$$1 + 3 \to 1 + n, \;\; n > 3$$

Motivations

1. String theory
2. Interesting possibility that opens wide opportunities

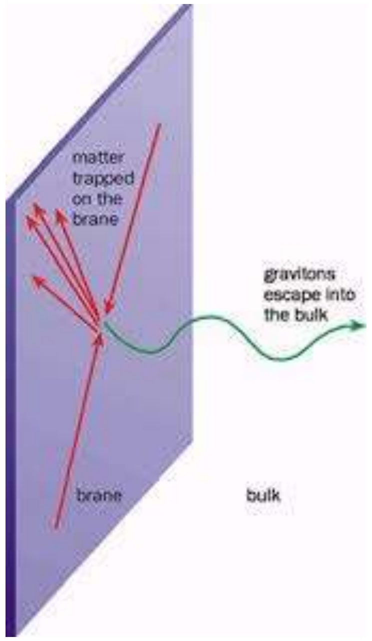
- String theory suffers conformal anomalies that make it inconsistent.
- Conformal anomaly cancels at D=26 for a bosonic string and D=10 for a fermionic string

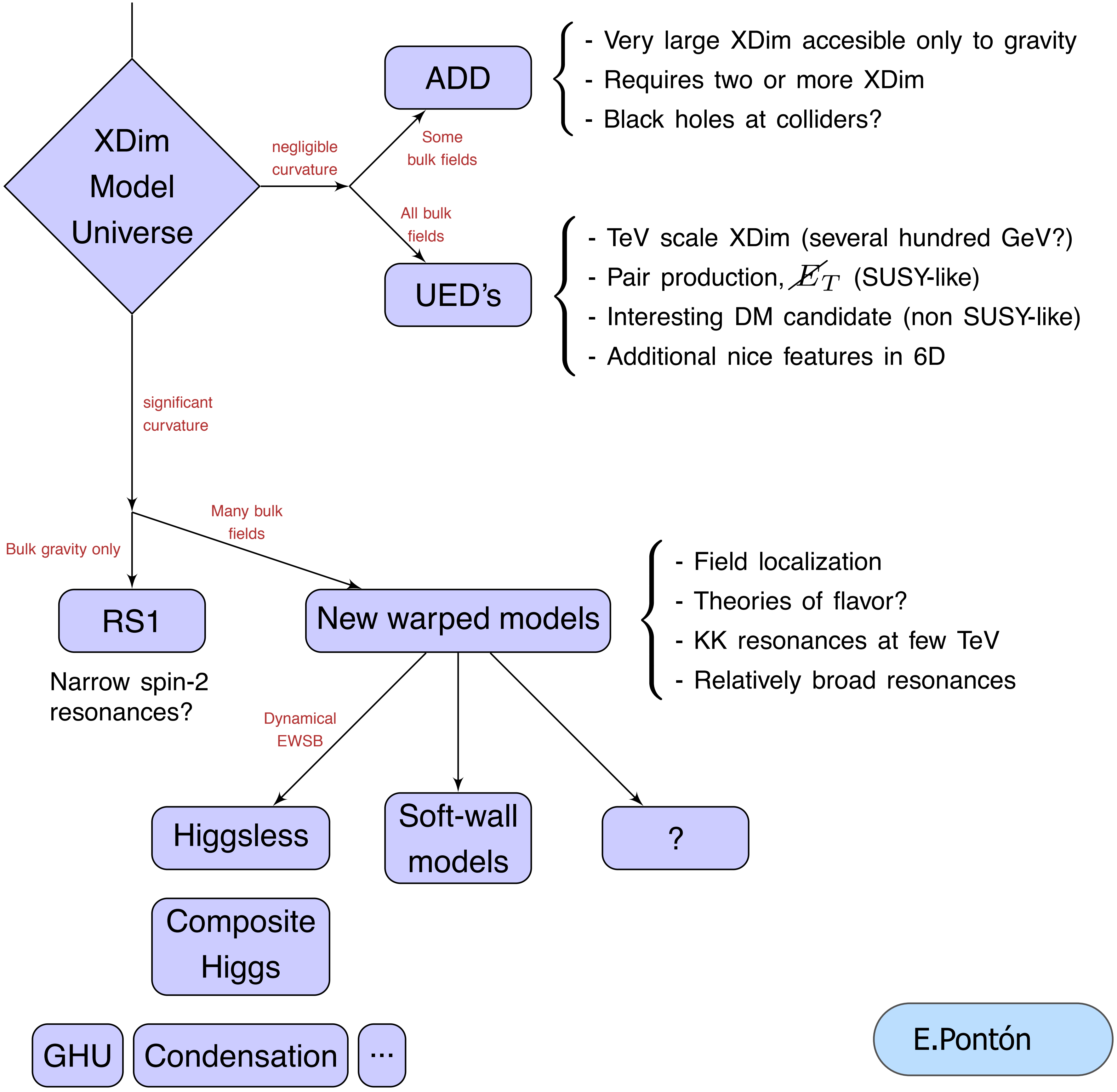
Why don’t we see extra dimensions



- **conventional Kaluza-Klein idea:**
  internal extra dimension too small to be seen
- **discovery of D-brane**
  - **matter fields** restricted to lower dimensional brane
  - external bulk felt only through **gravity**
  - extra dimension bigger

EXTRA SPACE-TIME DIMENSIONS





XDim Model Universe

negligible curvature

Some bulk fields

ADD

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

All bulk fields

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

significant curvature

Bulk gravity only

RS1

Narrow spin-2 resonances?

Many bulk fields

New warped models

- Field localization
- Theories of flavor?
- KK resonances at few TeV
- Relatively broad resonances

Dynamical EWSB

Higgsless

Composite Higgs

GHU

Condensation

...

Soft-wall models

?

E.Pontón

KALUZA-KLEIN APPROACH

Pseudo-Euclidean space

$$\boxed{E_{4+d} = M_4 \times K_d}$$

compact space

Minkowski space

Metrics

$$\boxed{ds^2 = G_{MN}(X)dX^M dX^N = g_{\mu\nu}dx^\mu dx^\nu + \gamma_{mn}(x,y)dy^m dy^n}$$

Fields

$$\boxed{\hat{\phi}(x,y) = \sum_n \phi^{(n)}(x) Y_n(y)}$$

Eigenfunctions of Laplace operator on internal space K_d

K-K modes

Masses

$$m_n^2 = m^2 + \frac{n_1^2 + n_2^2 + \cdots + n_d^2}{R^2}$$

Radius of the compact space

Couplings

$$\boxed{g_{(4)} = \frac{g_{(4+d)}}{V_{(d)}}}$$

$$V_{(d)} \propto R^d$$

MULTIDIMENSIONAL GRAVITY

Action

$$S_E = \int d^{4+d}\hat{x}\sqrt{-\hat{G}}\frac{1}{16\pi G_{N(4+d)}}\mathcal{R}^{(4+d)}[\hat{G}_{MN}],$$

K-K Expansion

$$S_E = \int d^4x\sqrt{-g}\left\{\frac{1}{16\pi G_{N(4)}}\mathcal{R}^{(4)}[g^{(0)}_{MN}] + \text{non-zero KK modes}\right\}$$

Newton constant

$$\boxed{G_{N(4)} = \frac{1}{V_{(d)}}G_{N(4+d)}}$$

$$V_{(d)} = R^d$$

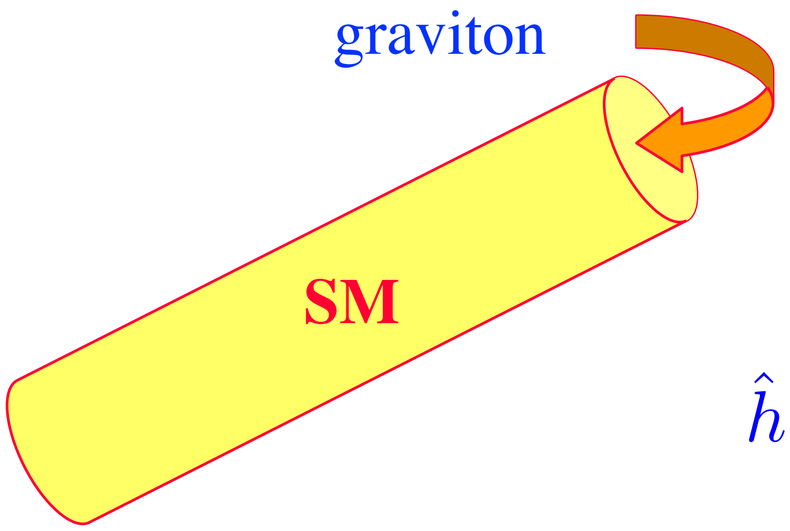
Plank Mass

$$M_{Pl} = (G_{N(4)})^{-1/2} \longleftrightarrow M \equiv (G_{N(4+d)})^{-\frac{1}{d+2}}$$

Reduction formula

$$\boxed{M^2_{Pl} = V_{(d)}M^{d+2}}$$

THE ADD MODEL



metric

$$\hat{G}_{MN}(x,y) = \eta_{MN} + \frac{2}{M^{1+d/2}} \hat{h}_{MN}(x,y)$$

$$\hat{h}_{MN}(x,y) = \sum_n h^{(n)}_{MN}(x) \frac{1}{\sqrt{V_{(d)}}} \exp(-i \frac{n_m y^m}{R})$$ K-K gravitons

Interactions with the fields on the brane

$$S_{int} = \int d^{4+d}\hat{x} \sqrt{-\hat{G}} \hat{T}_{MN} \hat{h}^{MN}(x,y) \quad \Rightarrow \sum_n \int d^4x \frac{1}{M_{Pl}} T^{\mu\nu}(x) h^{(n)}_{\mu\nu}(x)$$

The # of KK gravitons with masses $m_n \leq E < M$

$$\mathcal{N}(E) \sim \int_0^{ER} d\mathcal{N}(|n|) \sim S_{d-1} \frac{M^2_{Pl}}{M^{d+2}} \int_0^E m^{d-1} dm = \frac{S_{d-1}}{d} \frac{M^2_{Pl}}{M^{d+2}} E^d \sim R^d E^d$$

➡ Emission rate

$$\boxed{\sim \frac{1}{M^2_{Pl}} \mathcal{N}(E) \sim \frac{E^d}{M^{d+2}}.}$$

PARTICLE CONTENT OF THE ADD MODEL

(4+d)-dimensional picture:

- (4+d)-dimensional massless graviton + matter

4-dimensional picture

- 1 massless graviton $G^{(0)}$ (spin 2) + matter
- KK tower of massive gravitons $G^{(n)}$(spin 2)
- (d-1) KK spin 1 decoupling fields
- $(d^2 - d - 2)/2$ KK tower of real scalar decoupling fields $(d \geq 2)$
- KK tower of scalar fields (zero mode – radion)

The SM fields are localized on the brane,
while gravitons propagate in the bulk

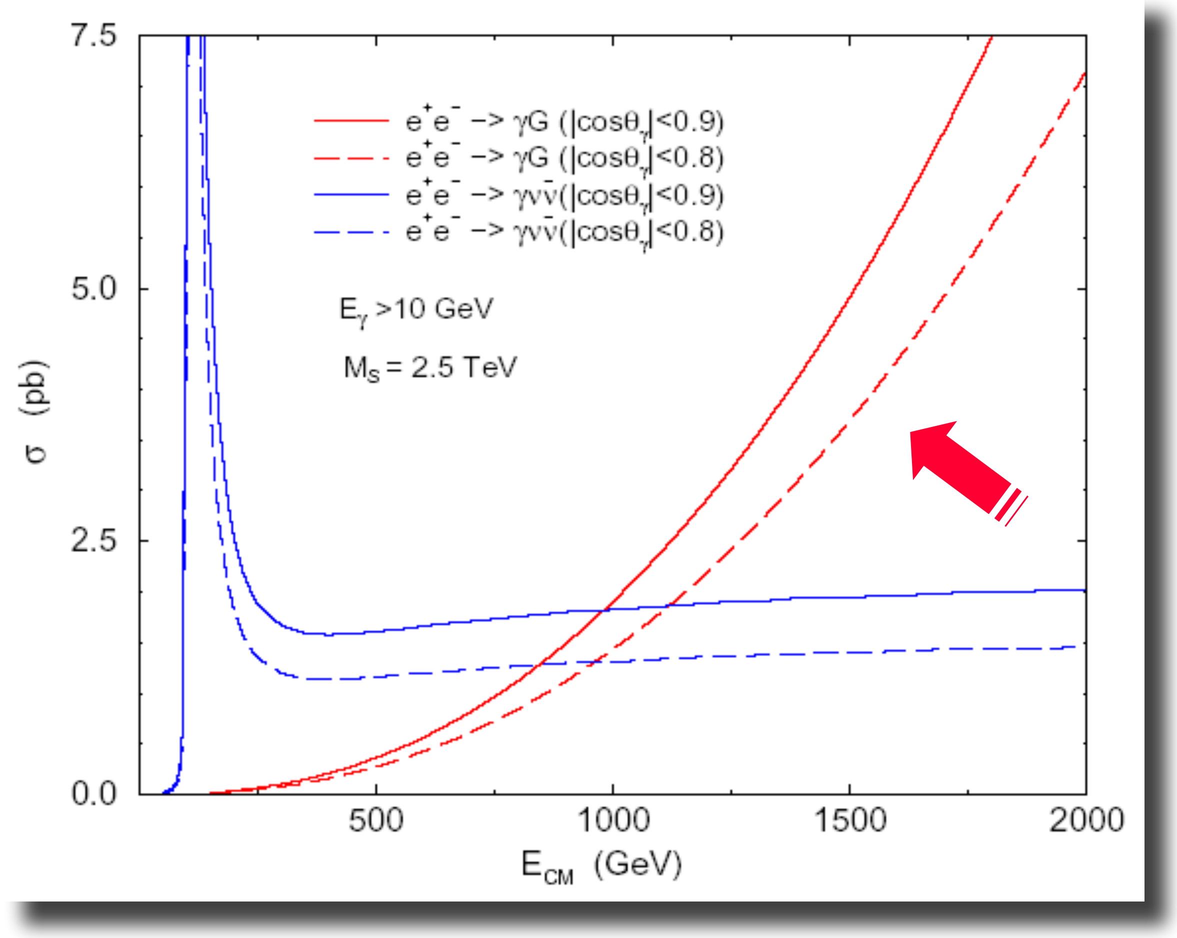
The “gravitational” coupling is $1/M^{1+d/2}$

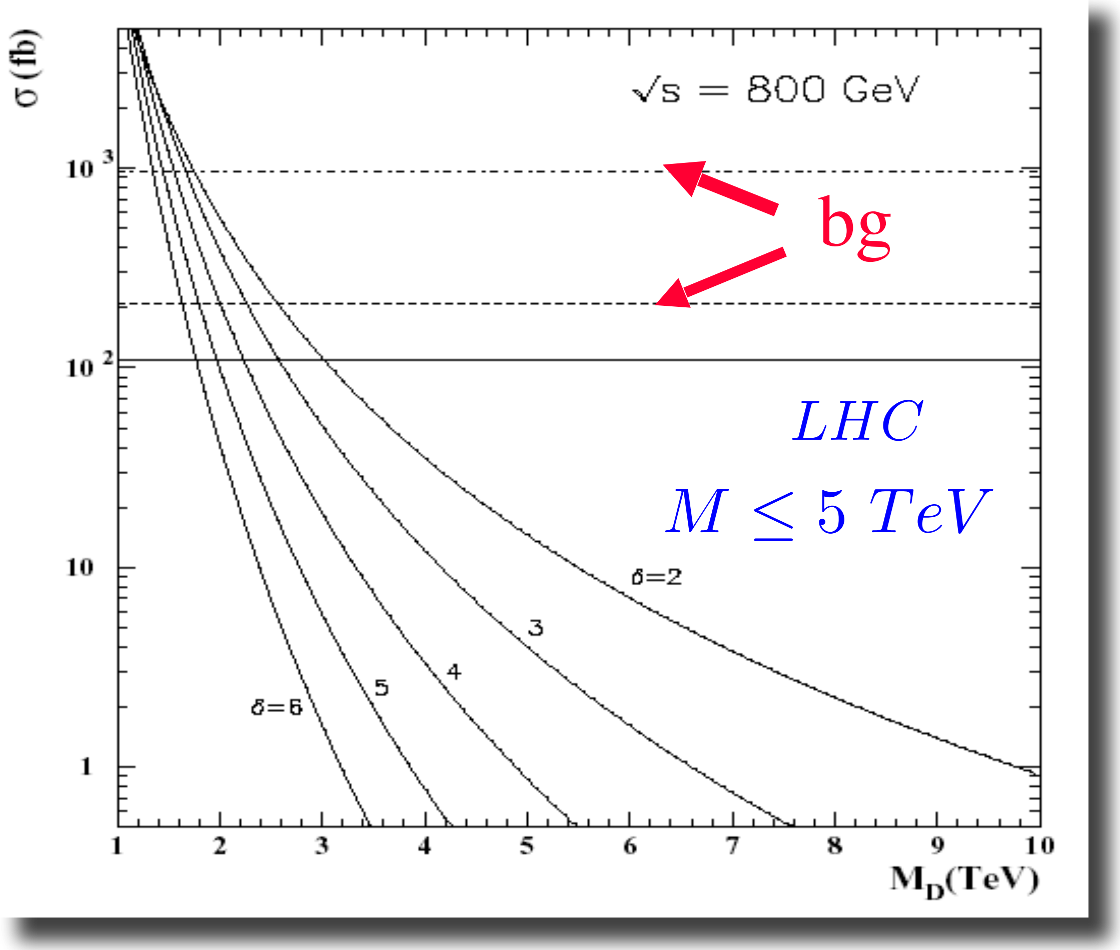
HEP PHENOMENOLOGY

New phenomena: graviton emission & virtual graviton exchange

- KK states production $e^+e^- \to \gamma G^{(n)}$ $e^+e^- \to \nu\bar{\nu}\gamma$

$$\boxed{\frac{d^2\sigma}{dtdm} \sim S_{d-1}\frac{M_{Pl}^2}{M^{d+2}}m^{d-1}\frac{d\sigma_m}{dt} \sim \frac{1}{M^{d+2}}}$$

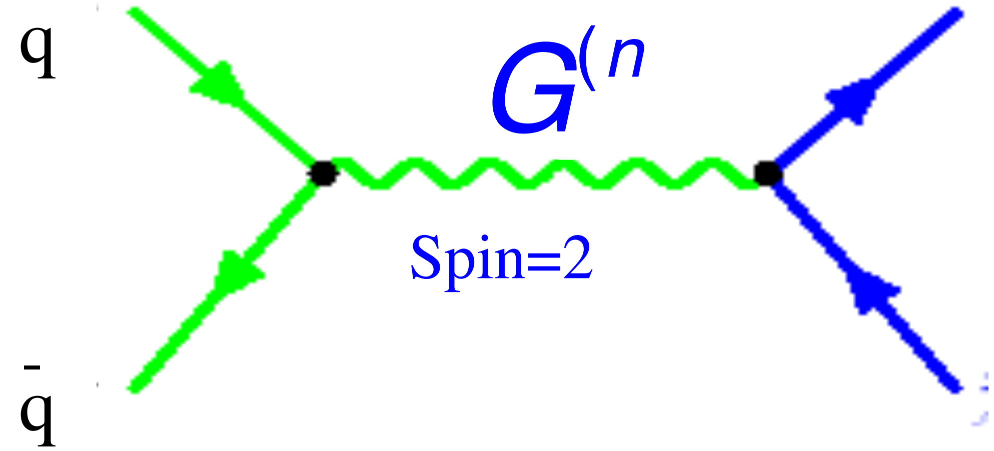




HEP PHENOMENOLOGY II

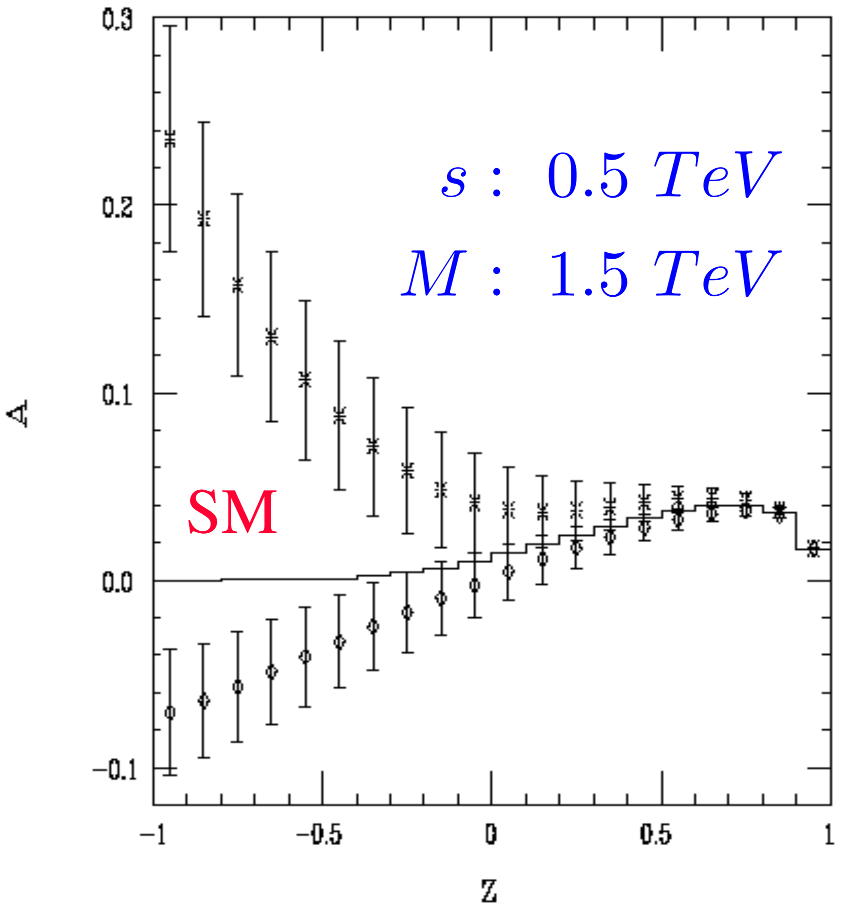
- Virtual graviton exchange $e^+e^- \to G^{(n)} \to f\bar{f}(HH, gg)$

$$\boxed{\mathcal{A} = \frac{1}{M_{Pl}^2}\sum_n \left\{ T_{\mu\nu}\frac{P^{\mu\nu}P^{\rho\sigma}}{s-m_n^2}T_{\rho\sigma} + \sqrt{\frac{3(d-1)}{d+2}}\,\frac{T_\mu^\mu T_\nu^\nu}{s-m_n^2}\right\}}$$



$$\mathcal{S} = \frac{1}{M_{Pl}^2}\sum_n \frac{1}{s-m_n^2} \approx \frac{1}{M_{Pl}^2} S_{d-1}\frac{M_{Pl}^2}{M^{d+2}}\int^\Lambda \frac{m^{d-1}dm}{s-m^2}$$

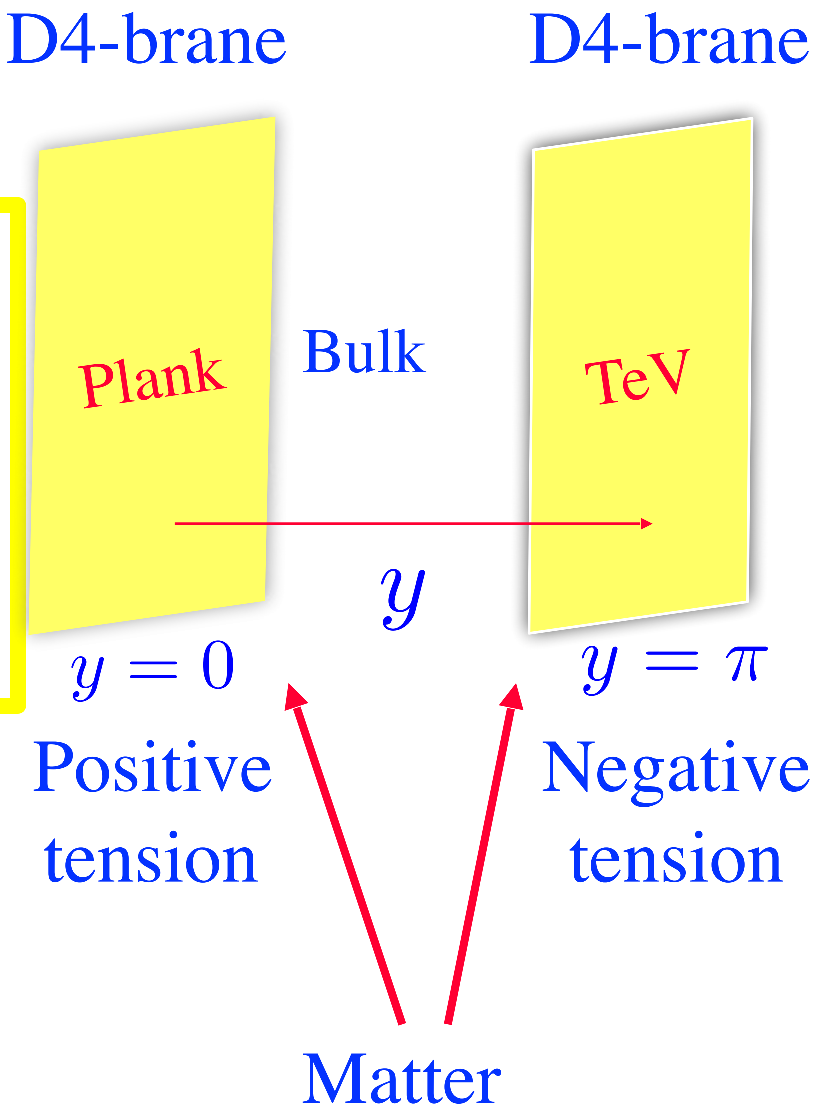
$$= \frac{S_{d-1}}{2M^4}\left\{ i\pi\left(\frac{s}{M^2}\right)^{d/2-1} + \sum_{k=1}^{[(d-1)/2]} c_k \left(\frac{s}{M^2}\right)^{k-1}\left(\frac{\Lambda}{M}\right)^{d-2k}\right\}$$



Angular distribution

RANDALL-SANDRUM MODELS

$$E_5 = M_4 \otimes S^1/Z_2$$



D4-brane

D4-brane

Plank

Bulk

TeV

y

$y = 0$

$y = \pi$

Positive tension

Negative tension

Matter

$$S = \int d^4x \int_{-\pi R}^{\pi R} dy \sqrt{-\hat{G}} \left\{ 2M^3 \mathcal{R}^{(5)} \left[\hat{G}_{MN} \right] + \Lambda \right\}$$
$$\int_{B_1} d^4x \sqrt{-g^{(1)}} \left(L_1 - \tau_1 \right) + \int_{B_2} d^4x \sqrt{-g^{(2)}} \left(L_2 - \tau_2 \right)$$

Metric $$ds^2 = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

$\sigma(y) = k|y|,$ warp factor

$$\tau_1 = -\tau_2 = 24M^3k, \quad \Lambda = 24M^3k^2$$

graviton

radion

Perturbed Metric $$ds^2 = e^{-2k|y|} \left(\eta_{\mu\nu} + \tilde{h}_{\mu\nu}(x,y) \right) dx^\mu dx^\nu + (1 + \phi(x)) dy^2$$

RANDALL-SANDRUM MODELS CONT'D

Brane 1

- Massless graviton
- massive K-K gravitons

$$m_n = \beta_n k e^{-\pi k R}$$

- massless radion

Brane 2

Wrap factor

$$\boxed{e^{-2\sigma(\pi R)}}$$

Hierarchy Problem !

$$\boxed{M_{Pl}^2 == \frac{M^3}{k}\left(e^{2k\pi R} - 1\right)}$$

$$S_{eff} = \frac{1}{2}\int_{B_2} d^4z \left[\frac{1}{M_{Pl}} h_{\mu\nu}^{(0)}(z) T^{\mu\nu} - \sum_{n=1}^{\infty} \frac{w_n}{\Lambda_\pi} h_{\mu\nu}^{(n)} T^{\mu\nu} - \frac{1}{\Lambda_\pi\sqrt{3}} T_\mu^{(2)\mu}\right]$$

$$\Lambda_\pi = M_{Pl} e^{-k\pi R} \approx \sqrt{M^3/k}$$

- Massless graviton $\longrightarrow \sim M_{Pl}$
- massive K-K gravitons $m_n = \beta_n k \longrightarrow \sim \Lambda_\pi$
- massless radion

HEP PHENOMENOLOGY

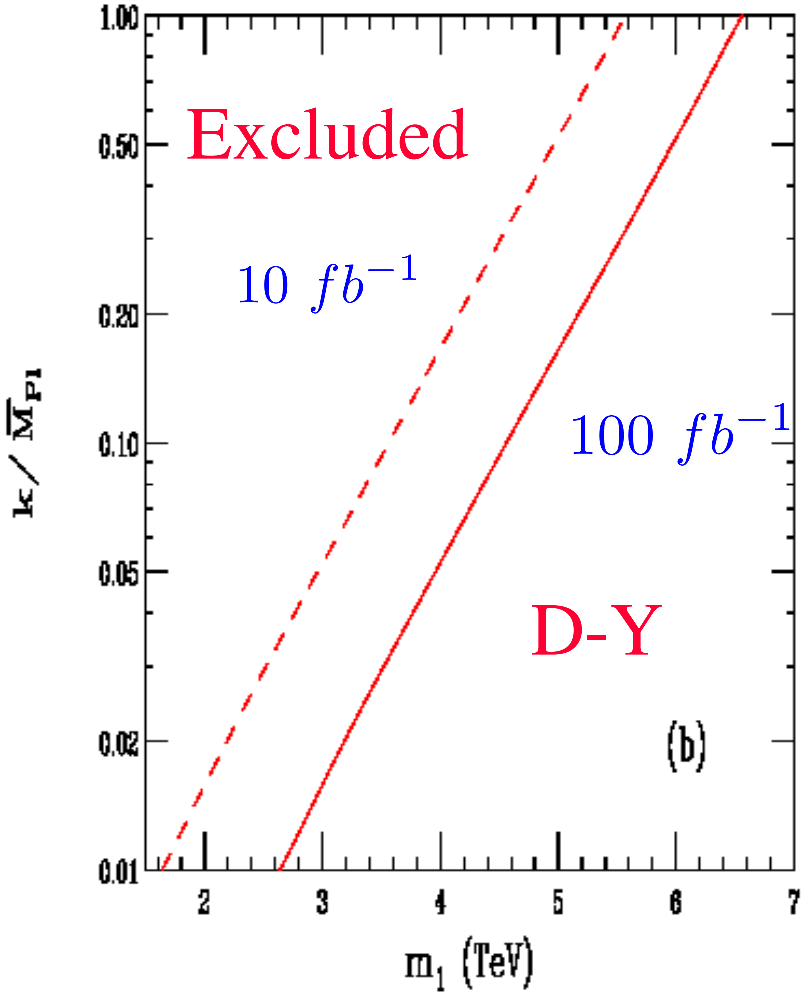
The first KK graviton mode M ~ 1 TeV

- Drell-Yan process
- Excess in dijet process

$$q\bar{q} \to h^{(1)} \to l^+l^-,$$
$$gg \to h^{(1)} \to l^+l^-$$

$$q\bar{q}, gg \to h^{(1)} \to q\bar{q}, gg$$

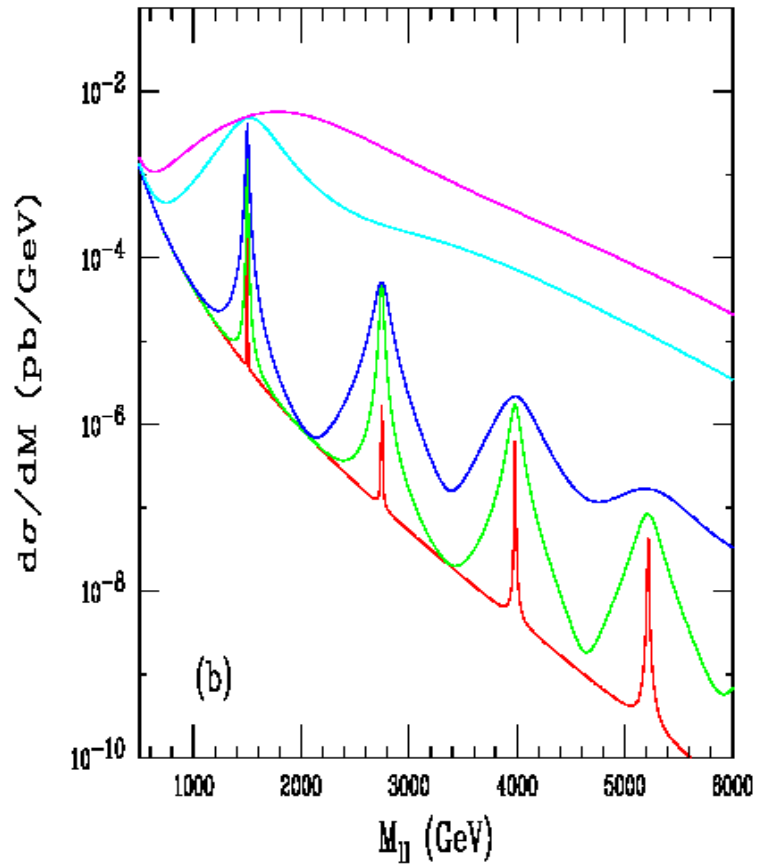
Exclusion plots for resonance production



LHC

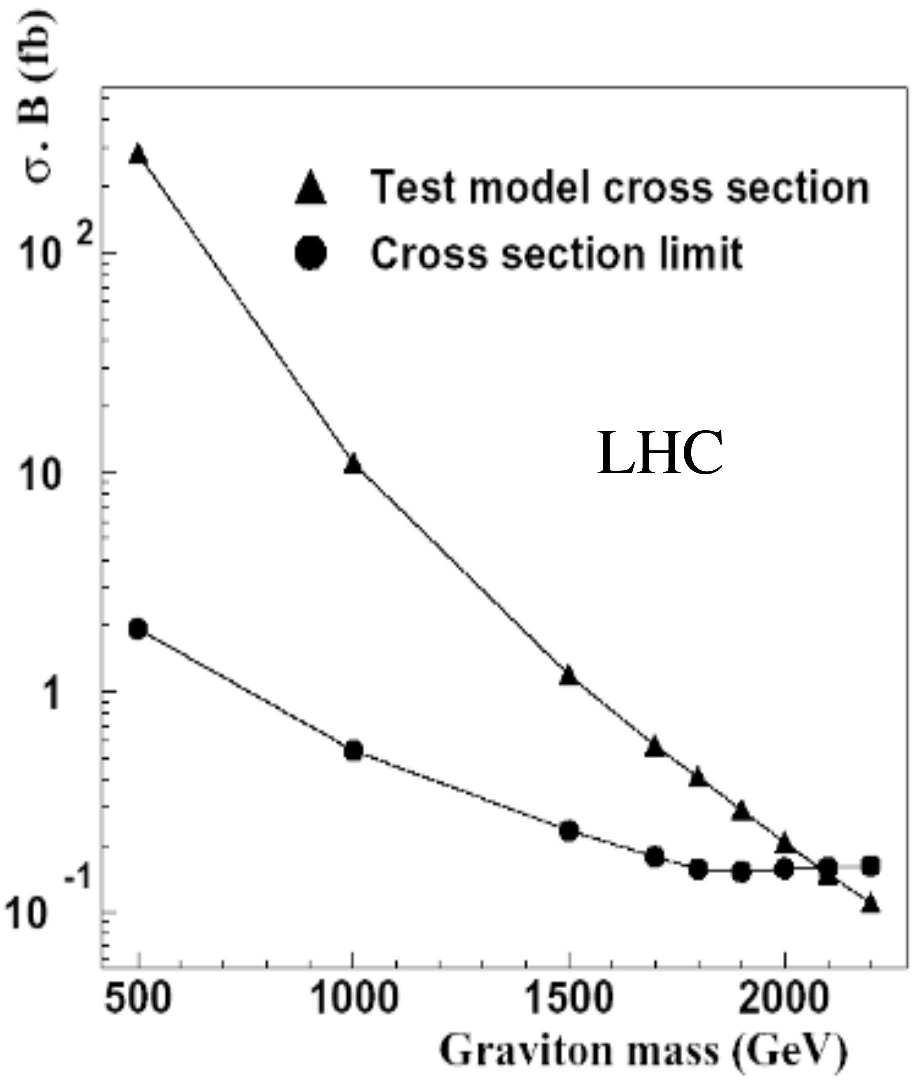
First and subsequent KK modes

The x-section of D-Y production



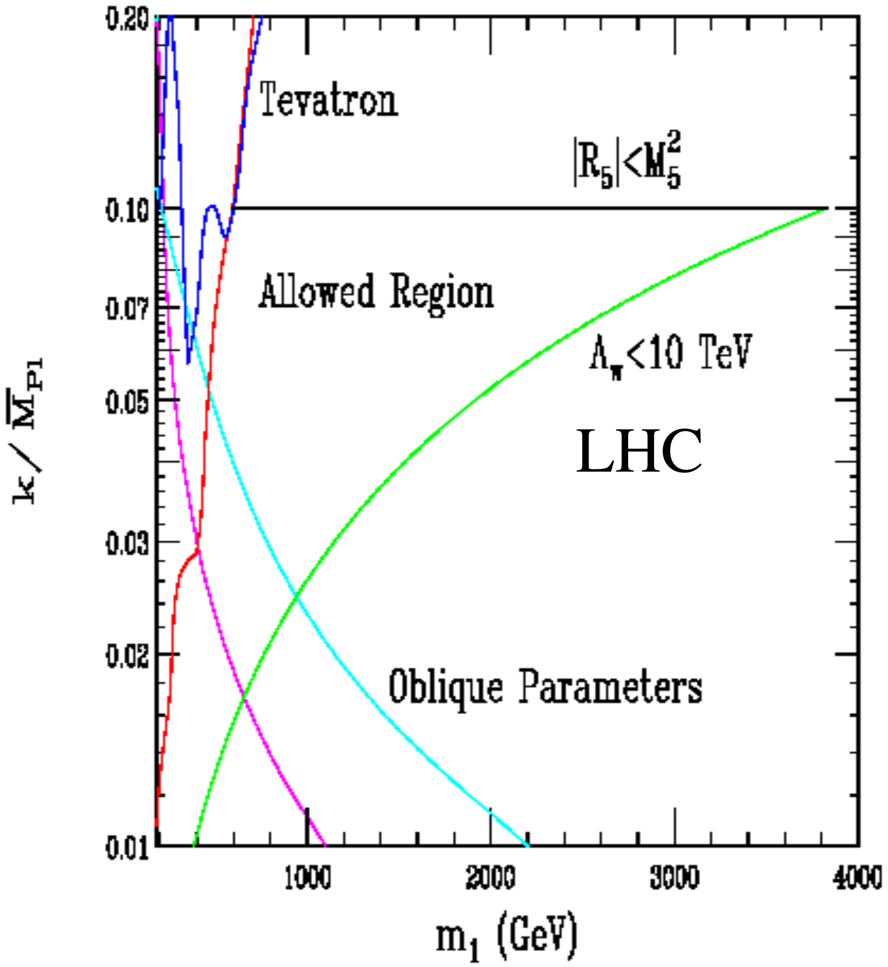
LHC (M ~ 1500 GeV)

$$pp \to h^{(1)} \to e^+e^-$$



Angular dependence

$$
\begin{aligned}
&Spin\ 0 => f(\theta) = 1,\\
&Spin\ 1 => f(\theta) = 1 + \cos^2\theta,\\
&Spin\ 2 => \begin{cases} q\bar{q} \to h^{(1)} \to e^+e^-,\\ f(\theta) = 1 - 3\cos^2\theta + 4\cos^4\theta,\\ gg \to h^{(1)} \to e^+e^-,\\ f(\theta) = 1 - \cos^4\theta. \end{cases}
\end{aligned}
$$



PHENOMENOLOGY OF EXTRA D

Accelerator signatures

- Gravitational radiation in the bulk => missing energy

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

- Massive string vibrations => resonances in dijet dist

$$M_j^2 = M_0^2 +$$

- Higher spin e gluons w

prese v

KK

auge bosons

$$/R^2, \; k = 1, 2, \ldots$$

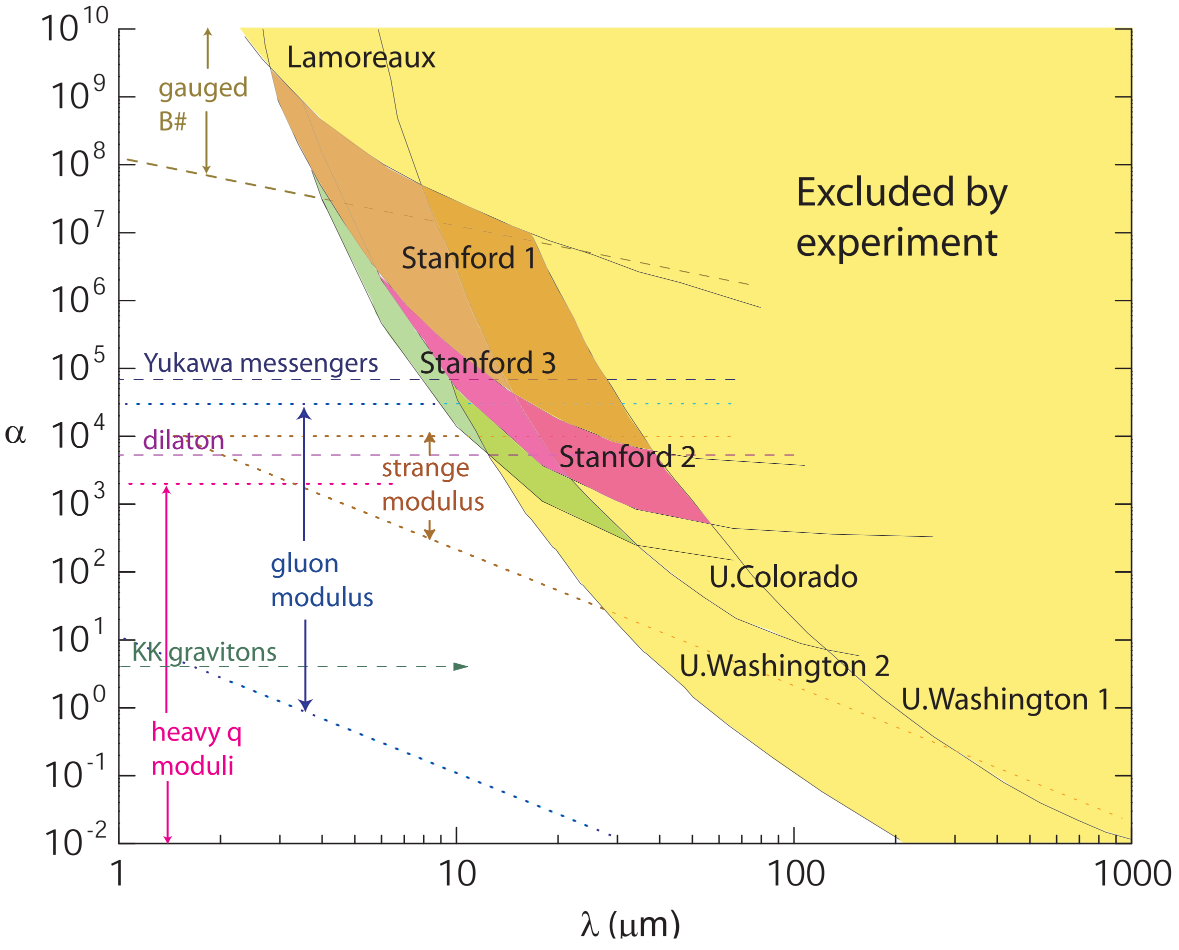
exp al limits

$$\geq 0.5 - 4 \;\; \text{TeV}$$

Vast phenomenology but no indication so far

- 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)

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



ED CONCLUSION

ADD Model

$$\frac{R^{-1}}{M} \sim \left(\frac{M}{M_{Pl}}\right)^{2/d} \sim 10^{-\frac{30}{d}}$$

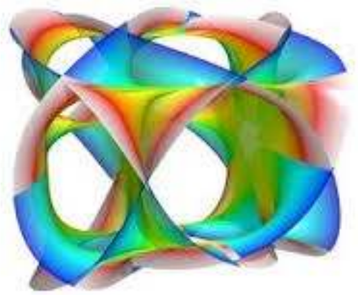
- The MEW/MPL hierarchy is replaced by
- For M small enough it can be checked at modern and future colliders
- For d=2 cosmological bounds on M are high (> 100 TeV), but for d>2 are mild
- Preictions of modification of the Newton's law may be checked

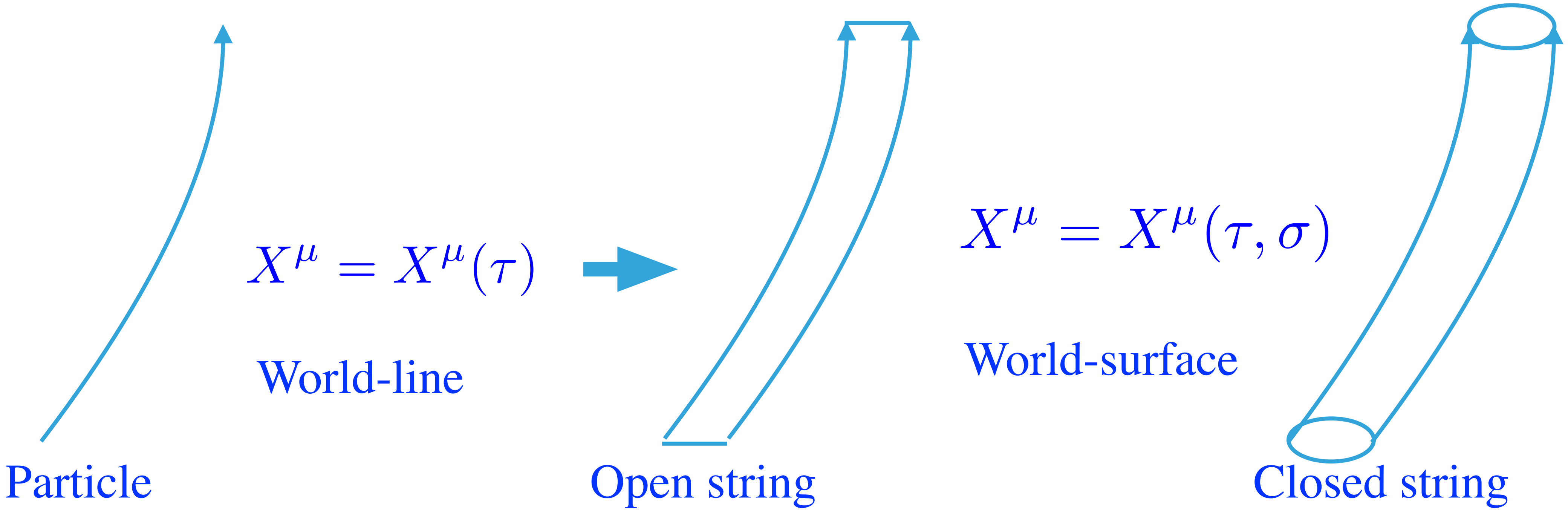
RS Model

- The MEW/MPL hierarchy is solved without new hierarchy
- A large part of parameter space will be studied in future collider experiments
- With the mechanism of radion stabilization the model is viable
- Cosmological scenarios are consistent (except the cosmological constant problem)

Drawback: No real motivation -> Unknown scale

NEW PARADIGM STRING THEORY





$X^\mu = X^\mu(\tau)$

World-line

Particle

Open string

$X^\mu = X^\mu(\tau, \sigma)$

World-surface

Closed string

World-line action:

$$S = -m \int d\tau \sqrt{-\frac{dX^\mu}{d\tau}\frac{dX^\nu}{d\tau}\eta_{\mu\nu}} \rightarrow \frac{d^2X^\mu}{d\tau^2} = 0$$

World-sheet action:

$$S = -\frac{1}{2\pi l_S^2}\int d^2\sigma \sqrt{-det\left(\frac{dX^\mu}{d\sigma^\alpha}\frac{dX^\nu}{d\sigma^\beta}\eta_{\mu\nu}\right)}$$

string tension

l_S string length

STRING THEORY

Spectrum

$$l_S^2 M = \sum_n \underbrace{\overset{\overset{\text{open}}{\downarrow}}{N_n}(+\bar{N}_n)}_{\text{closed}} \in Z, \quad N_n = \alpha^\mu_{-n}\alpha^\mu_n \qquad \begin{cases} n = 0, & \mathit{observed} \\ n \geq 1, & \mathit{massive} \end{cases}$$

Lowest string states

open string: $\alpha^\mu_{-1}|0> \rightarrow A^\mu \rightarrow \int d^D x\sqrt{-g}\, tr(F_{\mu\nu}F^{\mu\nu})$

Open strings lead to gauge fields (and matter)

closed string: $\alpha^\mu_{-1}\bar{\alpha}^\nu_{-1}|0> \rightarrow g^{\mu\nu}, \ldots \rightarrow \int d^D x\sqrt{-g}R + \cdots$

Closed strings lead to gravity (and gravity-like physics)

Modes of a string on a circle with radius R

momentum states: $M^2 = \dfrac{m^2}{R^2}$

winding states: $M^2 = \dfrac{w^2R^2}{l_S^4}$

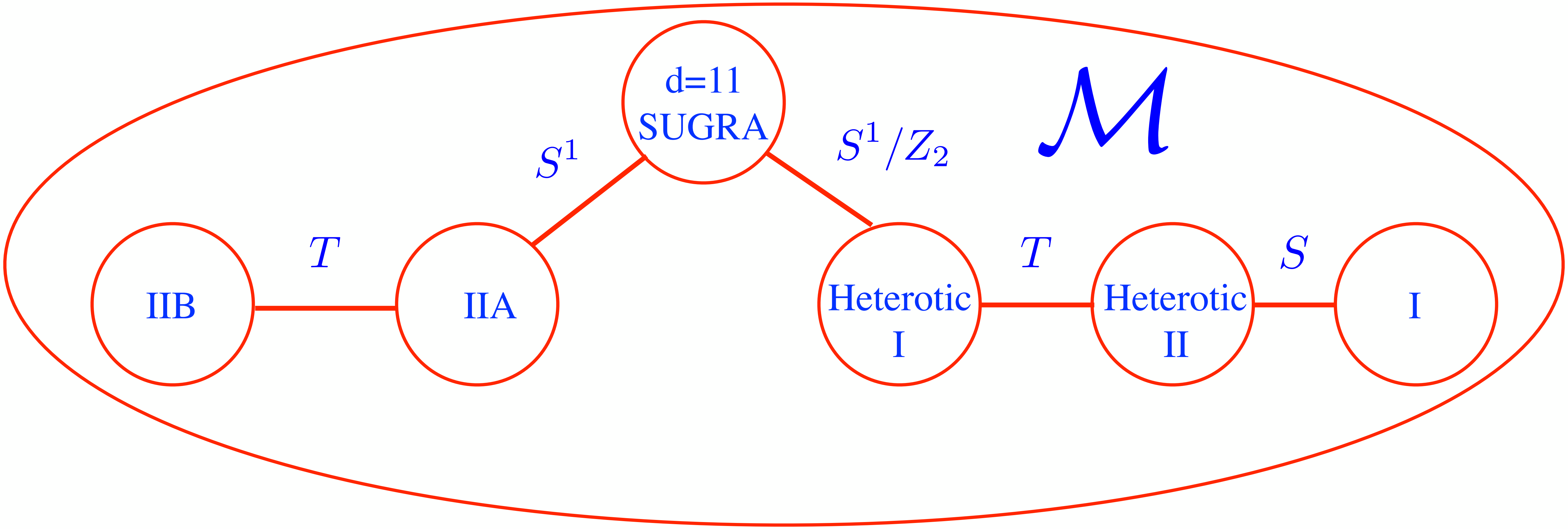
full spectrum: $M^2 = \dfrac{m^2}{R^2} + \dfrac{w^2R^2}{l_S^4}$

String theory has minimal length

$$l_S = \sqrt{\alpha'}$$

STRING THEORY

✳ There are five types of string theories (IIA, IIB, I, two Heterotic)
✳ All five string theories are only consistent in 10 space-time dimensions
✳ All five string theories have world-sheet supersymmetry and lead to space-time-supersymmetry in 10 dimensions
✳ All five string theories are related and part of a single ‘’theory”: M-theory

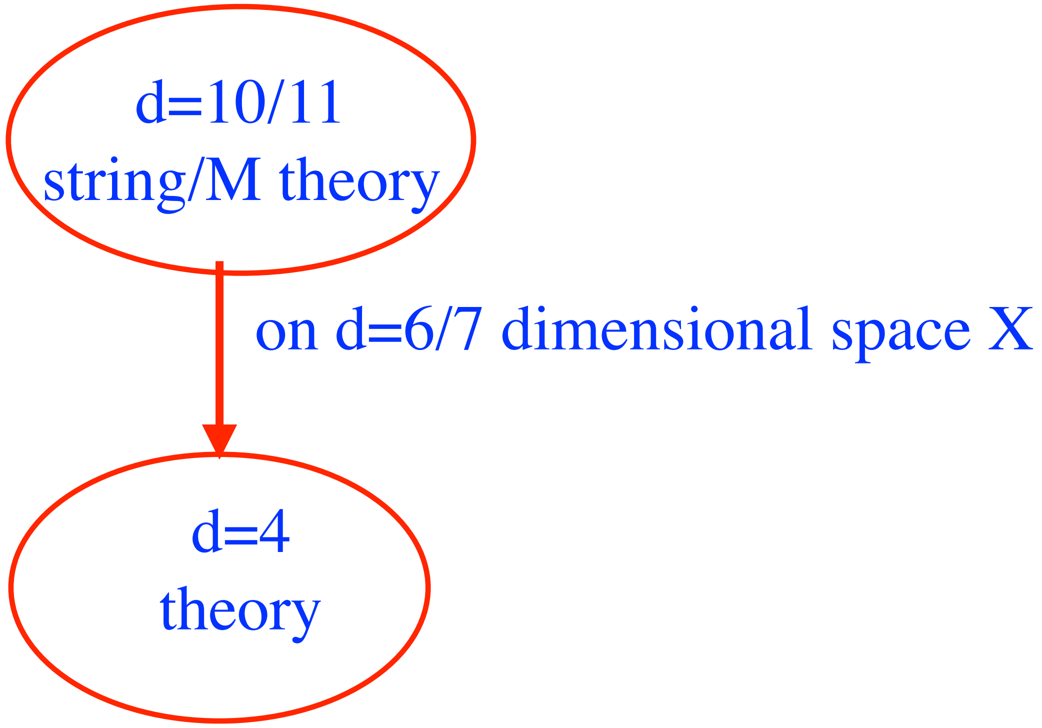


M-theory is a patchwork of the constituent theories plus many “rules”.

It seems unclear, at present, what its fundamental degrees of freedom are.

STRING THEORY AND THE "REAL" WORLD

Need to compactly six or seven dimensions to obtain d=4 theory



Two-fold degeneracy in space X: continuous one in size and shape (moduli) and discrete one topology

Topology determines the structure of d=4 theory

Moduli appearing as scalar fields determine values of couplings in d=4

in D=10/11: gravity… … and a p-brane

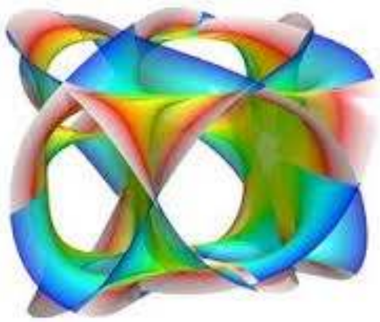
$$S_D = \frac{1}{l_S^{D-2}} \int d^D x \sqrt{-g} R + \cdots + \frac{1}{l_S^{p-3}} \int d^{p+1} x \sqrt{-\gamma}\, tr(F_{\alpha\beta} F^{\alpha\beta}) + \cdots$$

in D=4:

$$S_4 = \frac{V}{l_S^{D-2}} \int d^D x \sqrt{-g_4} R_4 + \cdots + \frac{v}{l_S^{p-3}} \int d^{p+1} x \sqrt{-g_4}\, tr(F_{\mu\nu} F^{\mu\nu}) + \cdots$$

$$\frac{1}{16\pi G_N} \qquad\qquad \frac{1}{16\pi g_{YM}^2}$$

STRING THEORY



Heterotic string

gravity $+$ gauge kinetic terms [47]

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

simplifi nits: $2 = \pi = 1$

Compactification in 4 dims on a 6-dim mani

$$\int [d^4x]\, \underbrace{\frac{V_6}{g_H^2} M_H^8}_{M_P^2} \,\mathcal{R}^{(4)} + \int [d^4x]\, V$$

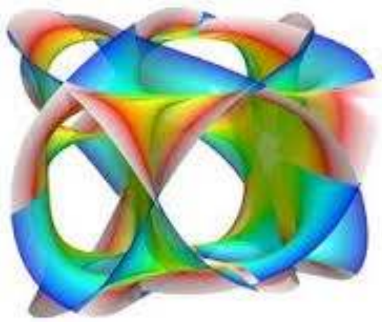
- Theoretically most attractive framework
- Part of the unification paradigm
- Main motivation for extra D

$\Rightarrow$

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

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

STRING THEORY PHENO



- 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 po nglet field

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

  A single anomalous $U(1) \Rrightarrow \langle \Phi \rangle \neq$ D-term

- R-neutrinos: natural f saw mechanism

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

- 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

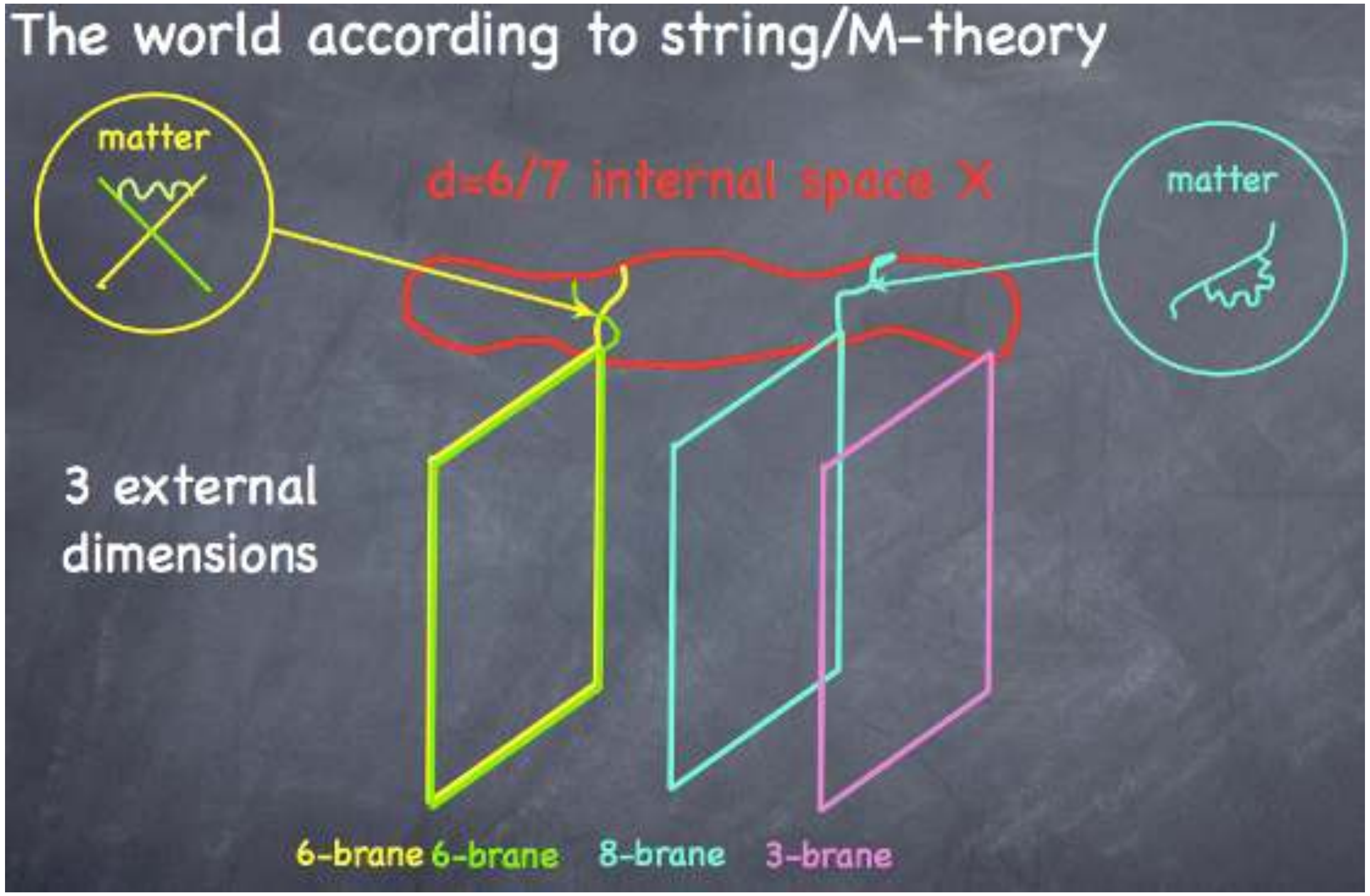
- Potentially answering many questions
- Requires SUSY for stabilization
- Difficult to get low-energy outputs

NEW PARADIGM

BRAIN WORLD

String theory contains not just strings but extended objects

- branes - of all dimensions



Q: Do we really live on a brane?
A: We have to check it
Q: Do we have good reasons to believe in it?
A: No, but it is appealing
Q: Why D>4?
A: String theory loves it
Q: Is it what we believe in?
A: We believe in BIG deal

CONCLUDING REMARKS

☑LHC experiments are at the front line of mystery land: be patient

☑Target #1: Higgs sector

☑Target #2: Dark Matter

☑ Target #3: Neutrino sector

☑Target #4: New physics (supersymmetry)

☑Future development of HEP crucially depends on LHC outcome

☑Complimentary searches for dark matter and insights in neutrino physics are of extreme importance

☑The areas that were left behind come to the front: confinement, exotic hadrons, dense hadron matter