Beyond the Standard Model and Supersymmetry

Alberto Mariotti

iihe BRUXELLES BRUSSEL

beh

HEP@VUB VRIJE UNIVERSITEIT BRUSSEL

HASCO Summer School 2019

21 -- 26 July 2019

Plan of the lectures

★***Introduction and motivation for Beyond Standard Model***

- ✳*Force Unification*
- ✳*Hierarchy Problem*
- ✳*Dark Matter*

★***Supersymmetry primer***

★***Properties of Supersymmetric extension of the SM***

★***SM Effective Field Theory (****if time permits****)***

★***Conclusions and references***

The Standard Model

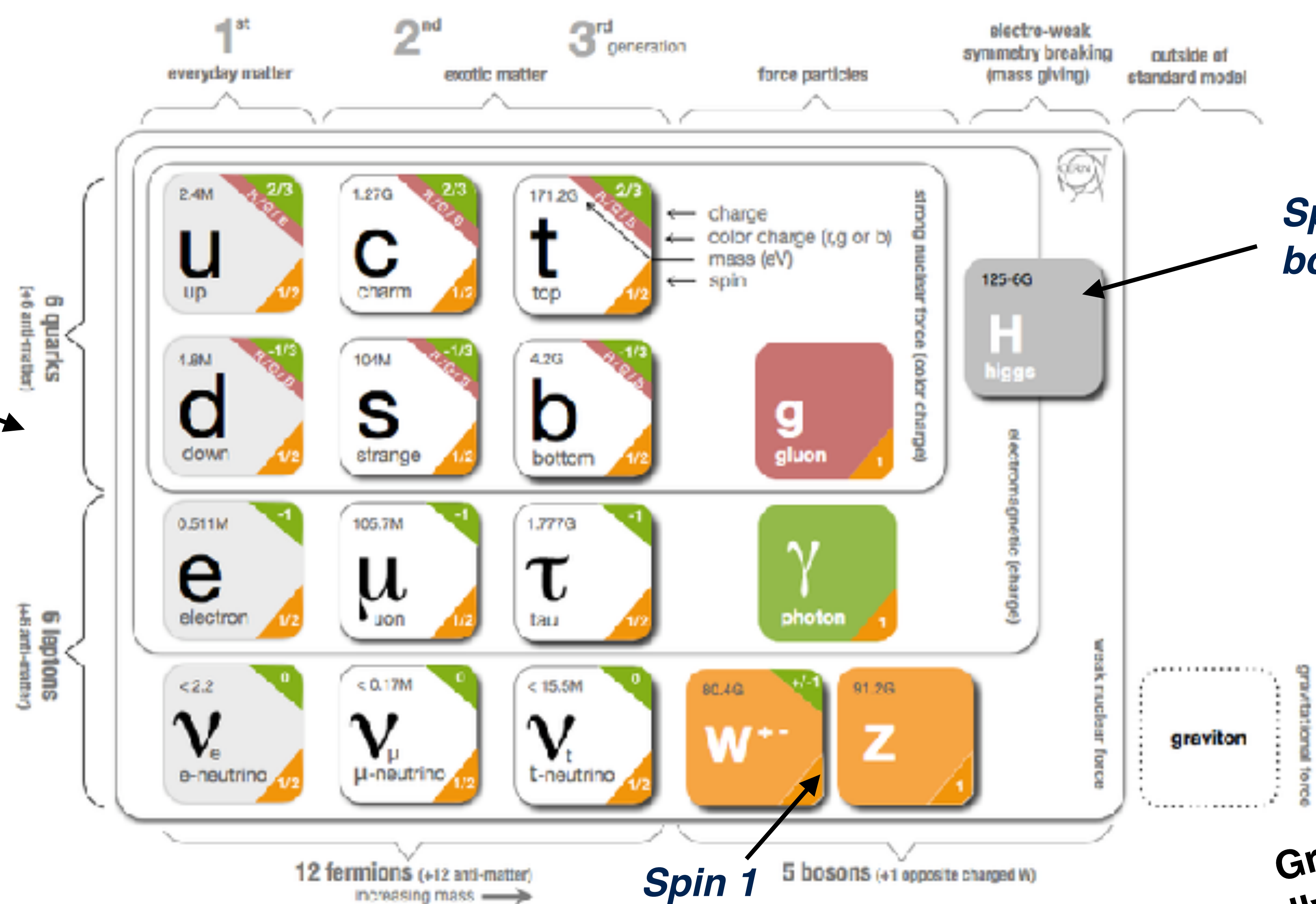
Describes fundamental particles and their interactions

Quantum field theory with gauge symmetries

$$SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$$

- ⋆ ***Elementary particles: fermions and bosons***
- ⋆ ***Fundamental interactions: strong, weak, electromagnetic***

Spin 1/2 fermions



Spin 0 boson

Spin 1 boson

Gravity not really included ...

Units and scales

Units of fundamental constants

$$[c] = LT^{-1}$$
$$[\hbar] = L^2 M T^{-1}$$
$$[G] = L^3 M^{-1} T^{-2}$$

Natural Units in Particle Physics

$$[M] = [E] = [L^{-1}] = [T^{-1}] \qquad c = \hbar = 1$$

Dimension is "mass dimension"

Examples: $[m^2] = 2$ $\quad [\tau] = -1$

$$[\hbar] = [c] = 0$$
$$[G_N] = -2$$

Fields: $[\psi] = \frac{3}{2} \quad [A_\mu] = [H] = 1$

$$[\mathcal{L}] = 4$$

Lagrangian density

Typical mass scales in the SM

Particle	Mass
neutrinos	$\sim 10^{-2}$ eV
electron	0.5 MeV
Muon	100 MeV
Pions	140 MeV
Proton, Neutron	1 GeV
Tau	2 GeV
W,Z Bosons	80-90 GeV
Higgs Boson	125 GeV
M_{Planck}	10^{19}GeV

couplings are dimensionless

$$\mathcal{L} \supset e A_\mu \bar{\psi} \gamma^\mu \psi$$

Electromagnetic coupling constant

$$\alpha_{EM} = \frac{e^2}{4\pi} \simeq \frac{1}{137}$$

SM shortcomings

SM is not explaining all ...

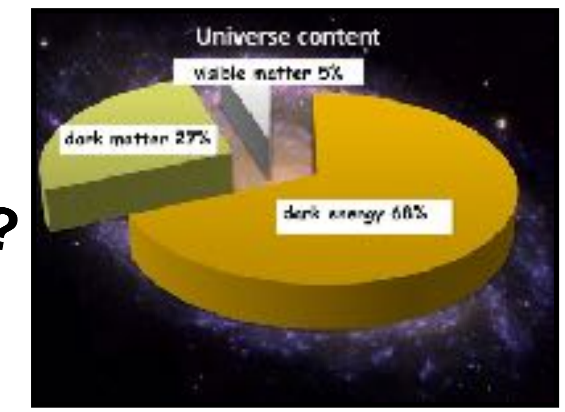
Many fundamental questions still open …

Hierarchy problem ?

Force Unification ?

Matter - Antimatter ?

Dark matter nature?



Flavour hierarchies ?

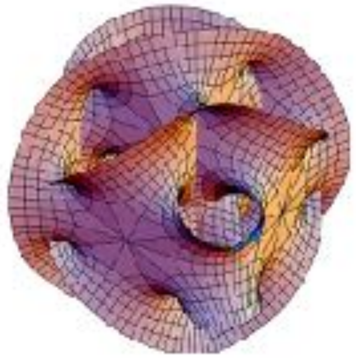
Neutrino masses ?

? Beyond Standard Model physics ?

Force Unification

Q: Can we provide a unique description of all fundamental forces?

★ ***Unification with gravity is hard ... String Theory***



★ ***SM unified framework for strong, weak, electromagnetic forces***

★ ***In SM Electroweak (EW) theory unifies weak and electromagnetism***

★ ***Can unify all forces in the SM?***

... first recap strength and force carriers properties ...

Interaction	Relative strength	Exchange	Mass (GeV)	Charge	Spin
Strong	1	Gluon	0	0	1
Electromagnetic	1/137	Photon	0	0	1
Weak	10^{-6}	W^+, W^-, Z^0	80.4, 91.2	+e,-e,0	1

Weak because of heavy force carriers

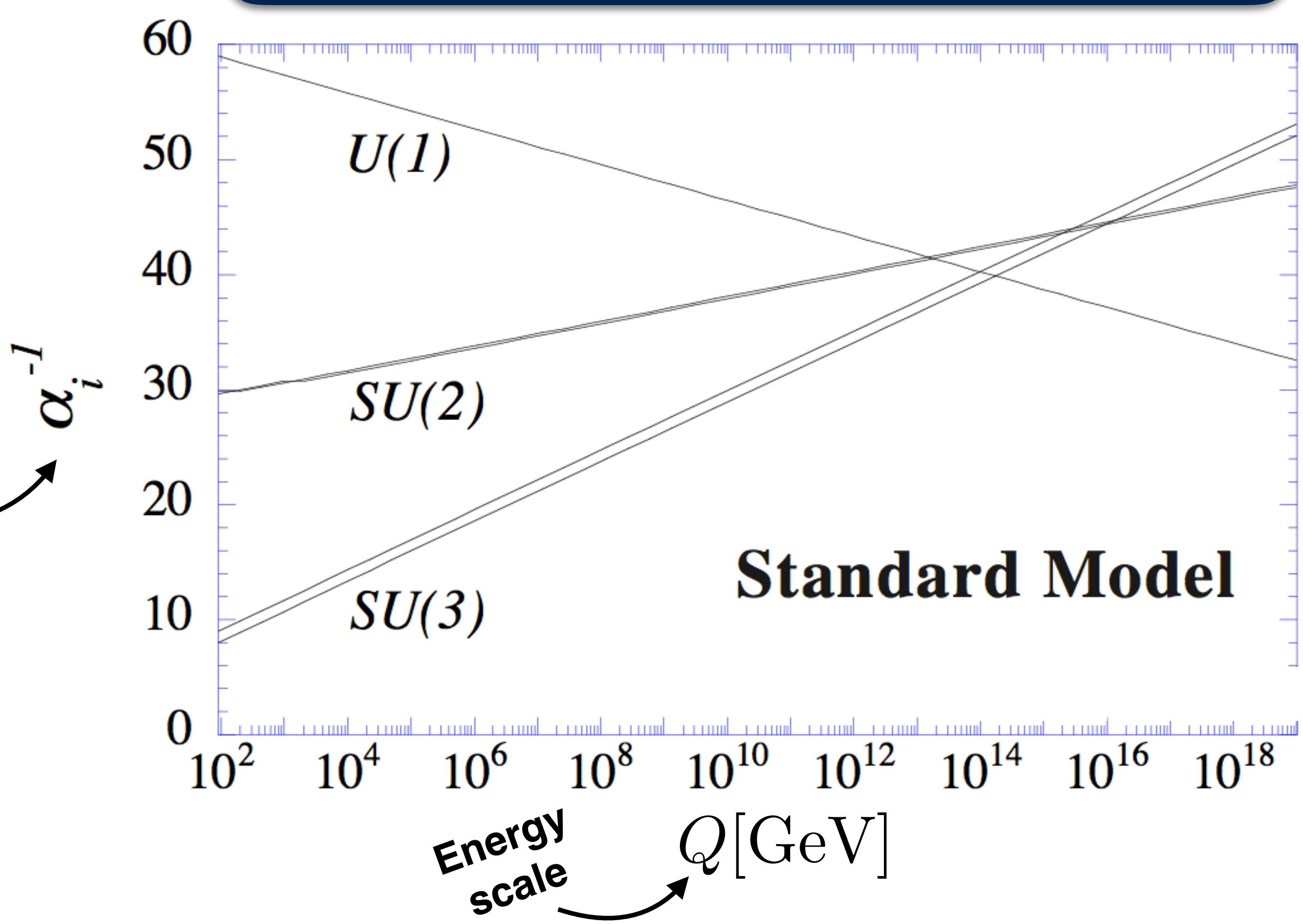
Running of couplings

- ★ *Coupling constants in QFT are functions of the probe energy*
- ★ *Variation with energy is "running of coupling"*
- ★ *Running depends on type of force and amount of matter*

Coupling $\alpha(Q^2)$ **Energy scale**

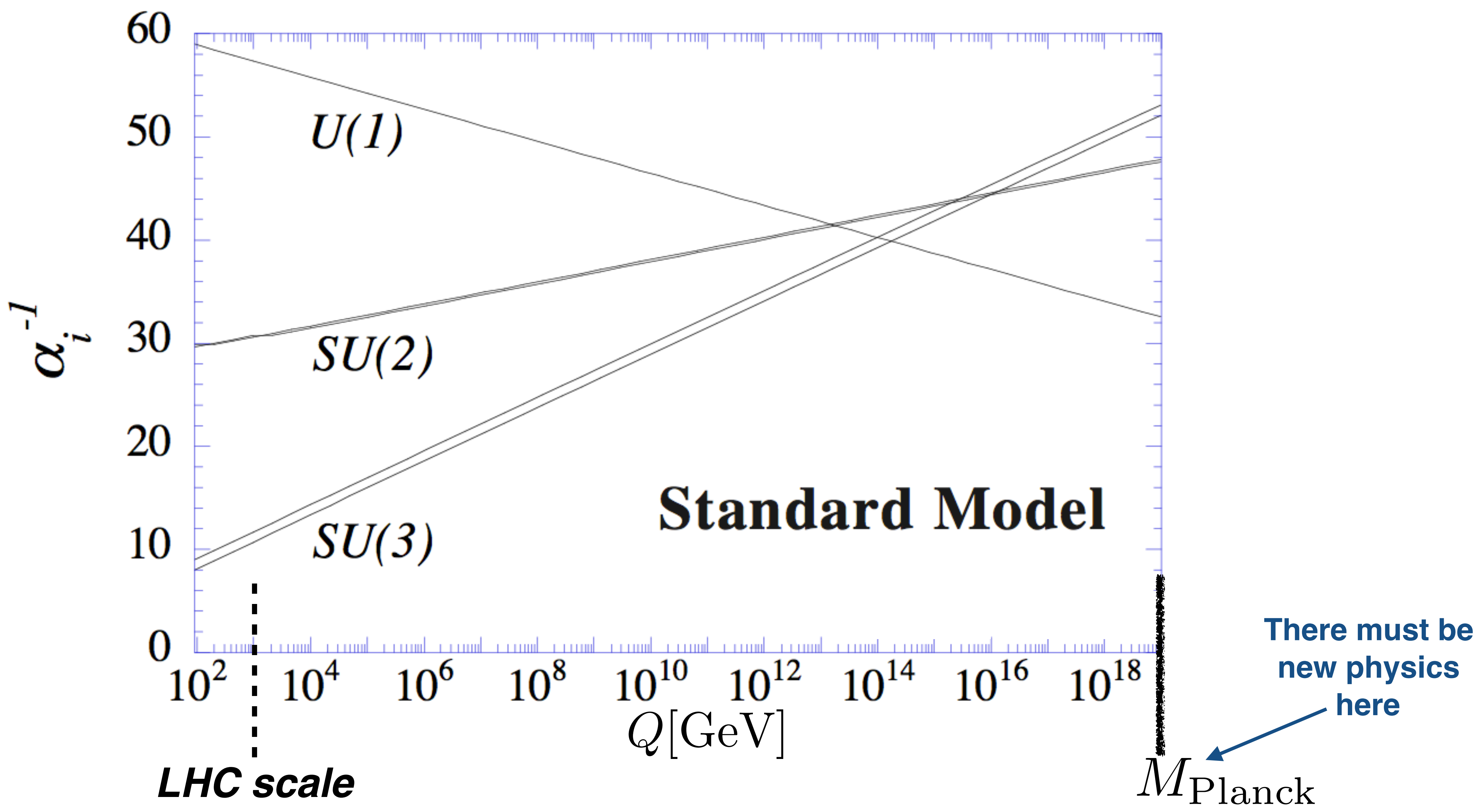
Running of SM couplings

Inverse of coupling constant
$\alpha_i = \frac{g_i^2}{4\pi}$

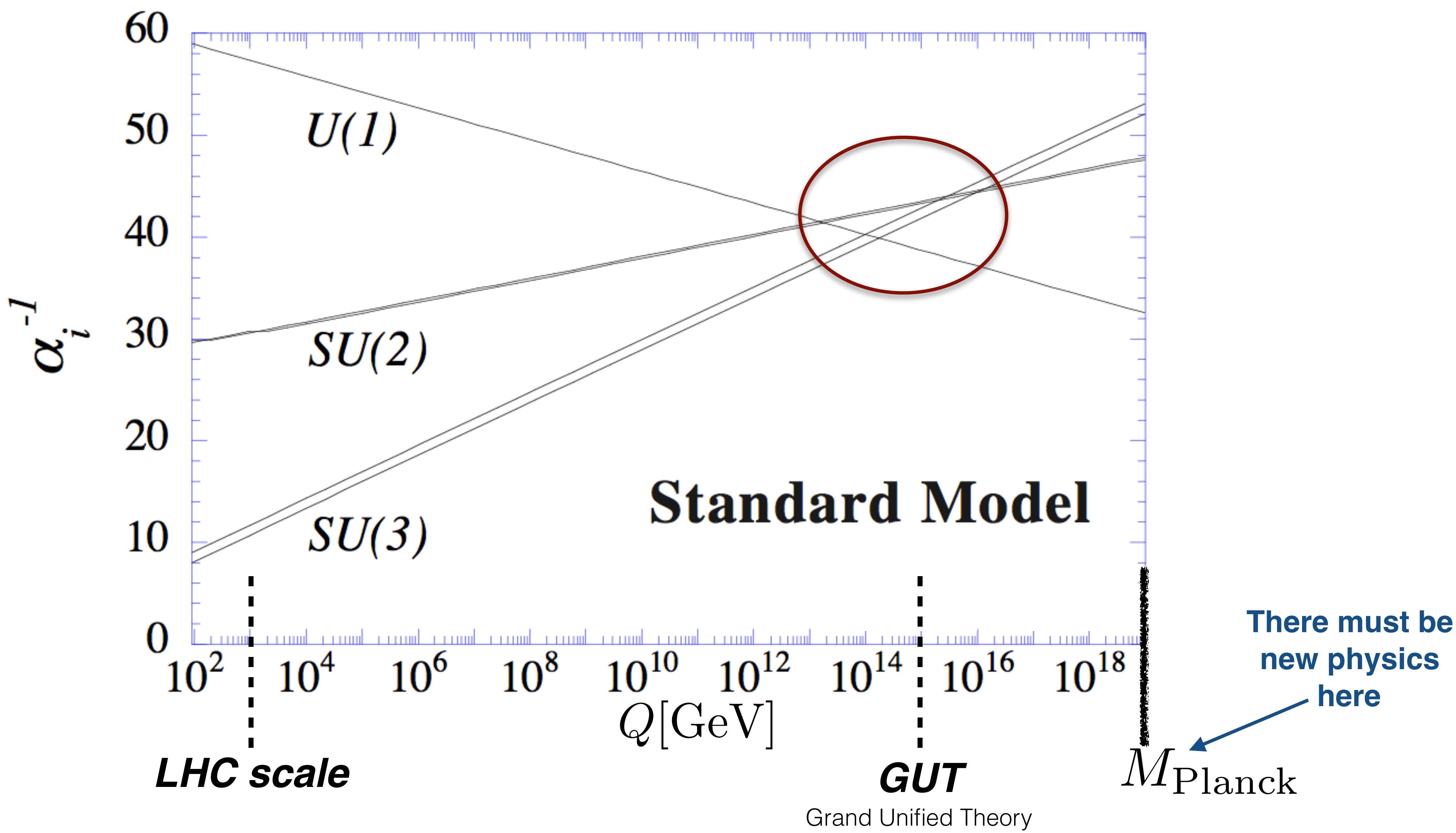


QCD asymptotic freedom

Running in the SM



Running in the SM



The coupling constants almost unify at GUT scale !!!

Q: Is there new physics to lead to precise unification?

Hierarchy problem

✳ ***Enormous hierarchy between EW scale and Planck scale***

$$m_h = 125 \text{ GeV} \ll M_{Planck} = 10^{19} \text{ GeV}$$

... nothing (= desert) in between ...

WHY?

✳ ***Can this be quantum mechanically stable?***

Assuming desert
$\Lambda_{UV} = M_{Planck}$

Quantum corrections

$$m_h^2 = m^2_{h(0)} \quad \delta m_h^2$$

Hierarchy problem

★*Standard Model Lagrangian*

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\gamma^{\mu}D_{\mu}\Psi + h.c. + \Psi_i Y_{ij}\Psi_j H + h.c. + |D_\mu H|^2 \underbrace{- \mu^2|H|^2 - \lambda|H|^4}$$

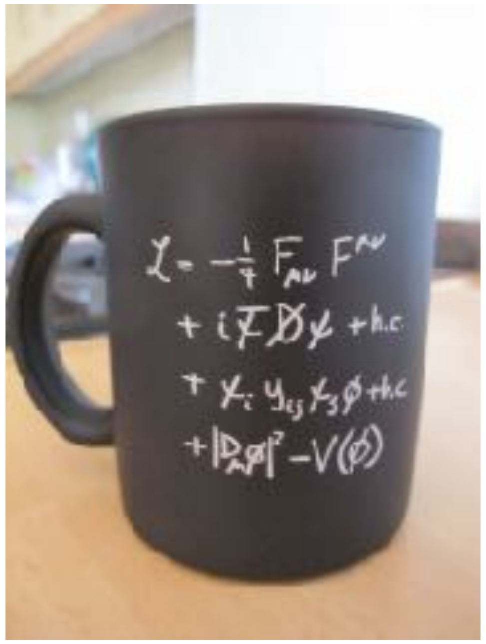
Gauge boson kinetic term

Matter kinetic term

Yukawa interactions

Higgs kinetic term

Higgs potential



★*Dimensions in natural units*

$$[\mathcal{L}_{SM}] = 4 \quad [F_{\mu\nu}] = 2 \quad [\Psi] = 3/2 \quad [H] = 1$$

!!! Higgs mass only dimensionfull parameter !!!

"Natural" size for Higgs mass is UV scale Λ_{UV} ***e.g.*** M_{Planck}

Dimensionful fundamental constant

HP: the pion example

... We already know a spin-0 particle (not fundamental) ...

★***Pion mesons Lagrangian***

$$\mathcal{L}_\pi = \frac{1}{2}(\partial_\mu \pi_0)^2 + |\,(\partial_\mu + ieA_\mu)\,\pi^+|^2 - \frac{1}{2}m_\pi^2\pi_0^2 - m_\pi^2\pi^+\pi^-$$

Neutral pion — *Charged pion* — *Mass terms*

★***Observed masses*** $m_{\pi_0} = 135 \text{ MeV}$ $m_{\pi^\pm} = 140 \text{ MeV}$

★***Quantum corrections assuming theory valid up to*** Λ_{UV}

$$\Delta m_{\pi^\pm}^2 \sim \frac{3e^2}{(4\pi)^2}\Lambda_{UV}^2 \qquad \Delta m_{\pi^0}^2 \sim 0$$

If $\Lambda_{UV} > 850 \text{ MeV}$ ***one would need fine tuning to get***

Nature: No Fine-tuning !!!

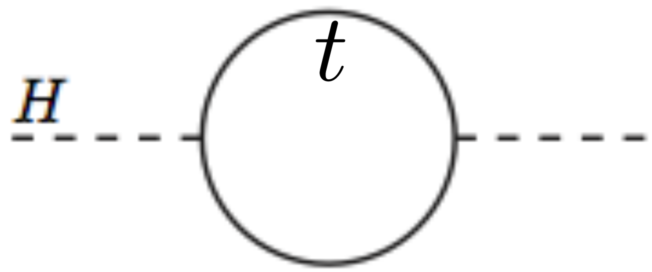
There is actually "new physics" lighter than 850 GeV: the rho meson etc... that stabilize the quantum corrections!

Hierarchy problem reload

Higgs mass gets quadratic divergent corrections

$$(125\text{GeV})^2 = m_h^2 = m_{h(0)}^2 + \delta m_h^2$$

Top loop



$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2$$

Scale where new physics kicks in !

* *Fine-tuned cancellation between* $m_{h(0)}^2$ *and* δm_h^2 *to get* $m_h \ll \Lambda_{UV}$

E.g. **Assuming desert** $\Lambda_{UV} = M_{Planck}$ → $\dfrac{\delta m_h^2}{(125\ \text{GeV})^2} \simeq 10^{32}$ **FINE-TUNING**

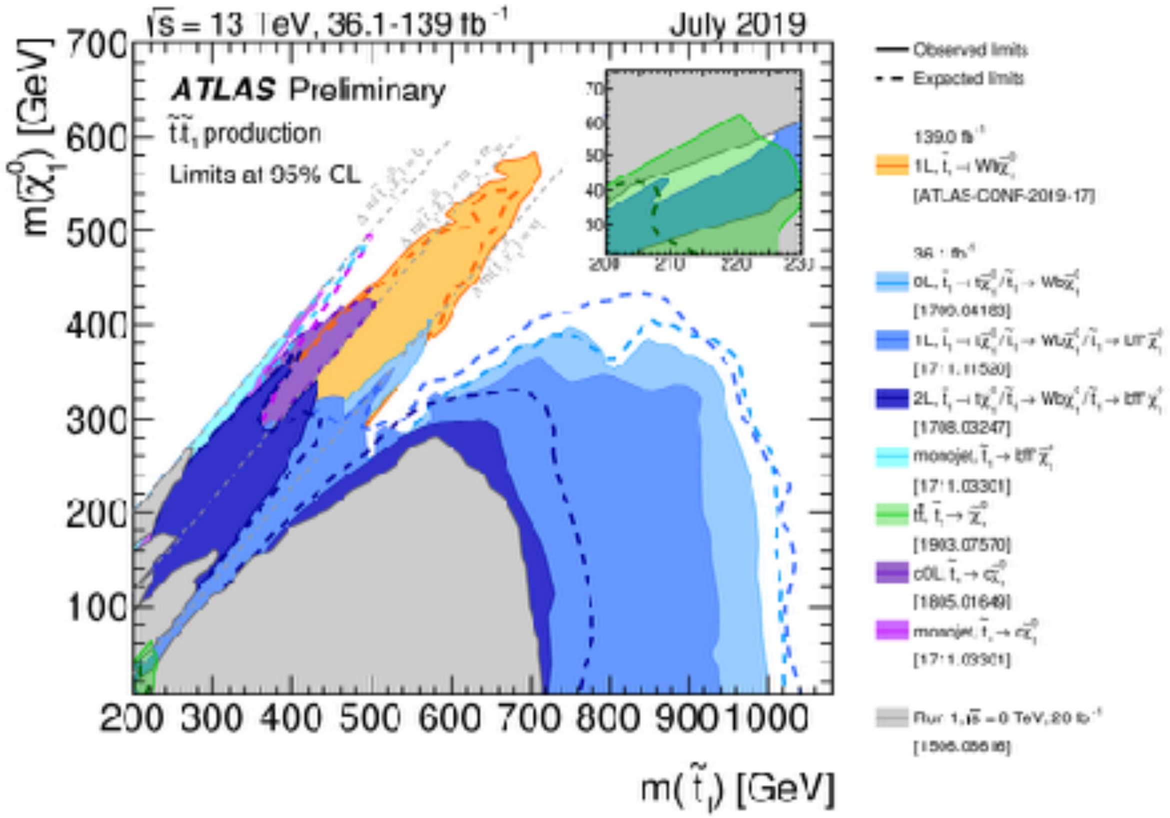
* *Demanding no fine-tuning predict scale of new physics*

$$\frac{\delta m_h^2}{(125\ \text{GeV})^2} \simeq 1 \rightarrow \Lambda_{UV} \simeq 650\ \text{GeV}$$

Supersymmetry
Composite Higgs
Extra Dimensions

Status of Hierarchy Problem

... Naturalness principle is already in tension with the LHC ...

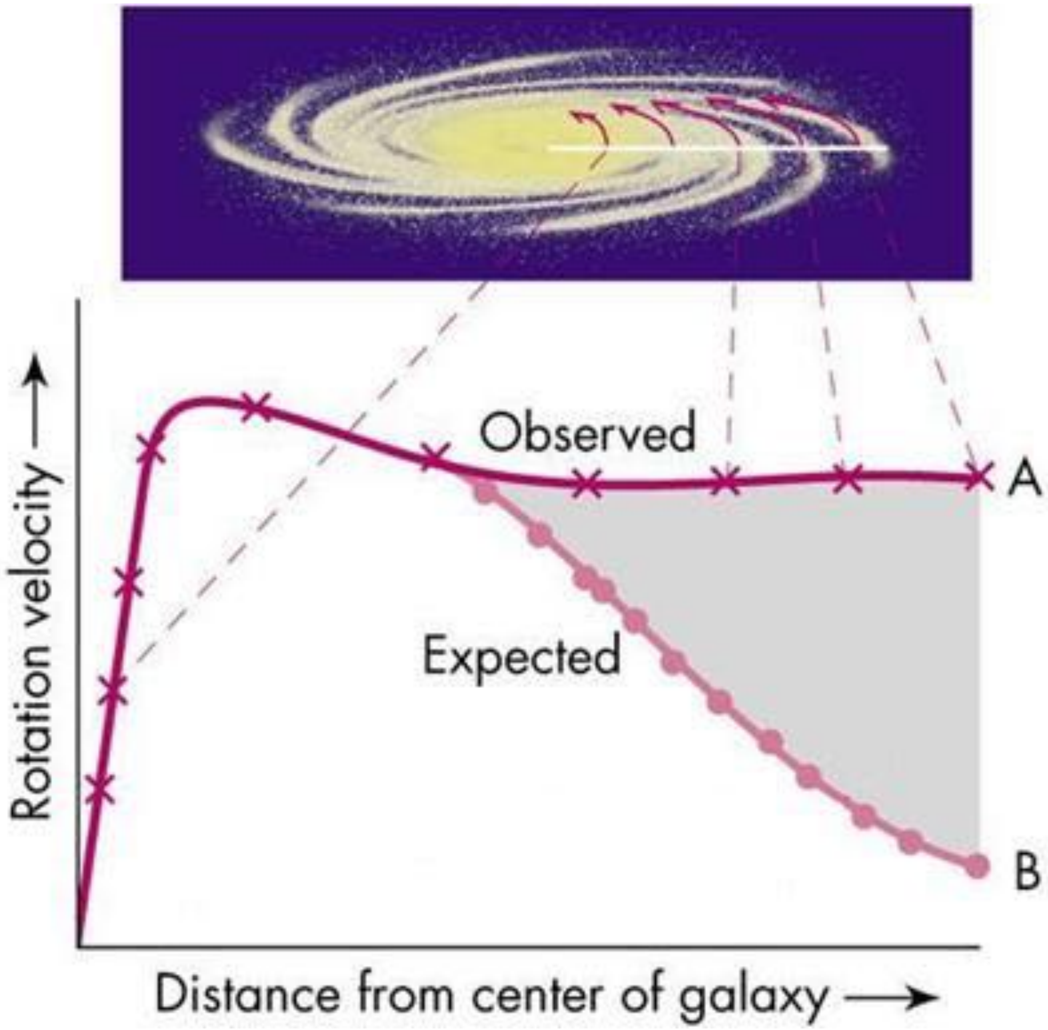


Open questions:

- ★*Maybe it is our bias?*
- ★*Do we understand fundamental scalars?*
- ★*Is there an unknown mechanism to make it "natural"?*
- ★*Is there an anthropic principle? What about c.c.?*

Dark Matter evidences

??? Why it should be there ???



★ ***Galaxy rotation curves (1970)***

- ***Gravitational force***

$$F_g = G\frac{Mm}{r^2}$$

- ***Centrifugal force***

$$F_c = m\frac{v^2}{r}$$

They should balance

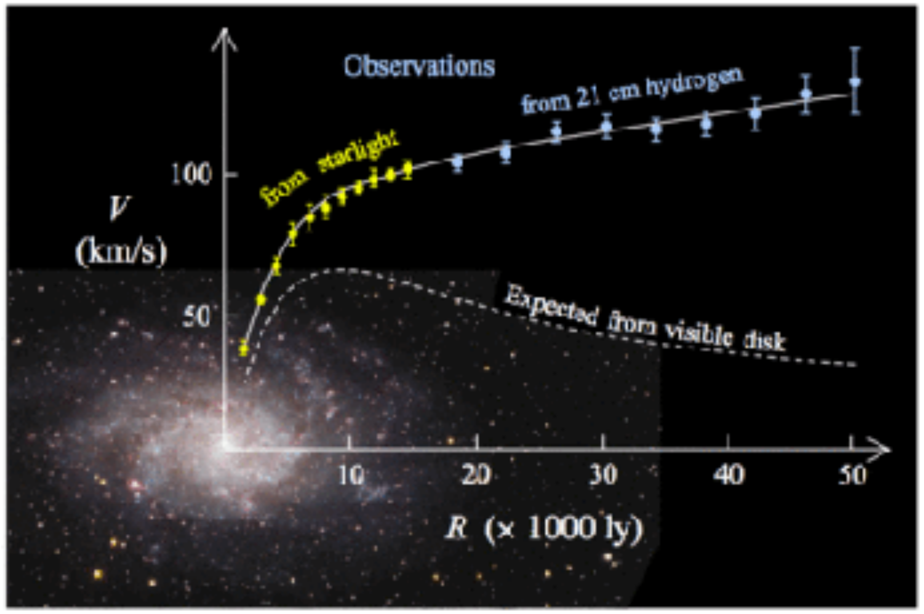
Not enough visible mass!!!

Attributed to invisible (hence dark) and unknown form of matter

Evidence for Dark Matter

★ ***Galaxy rotation curves***

★ ***...***



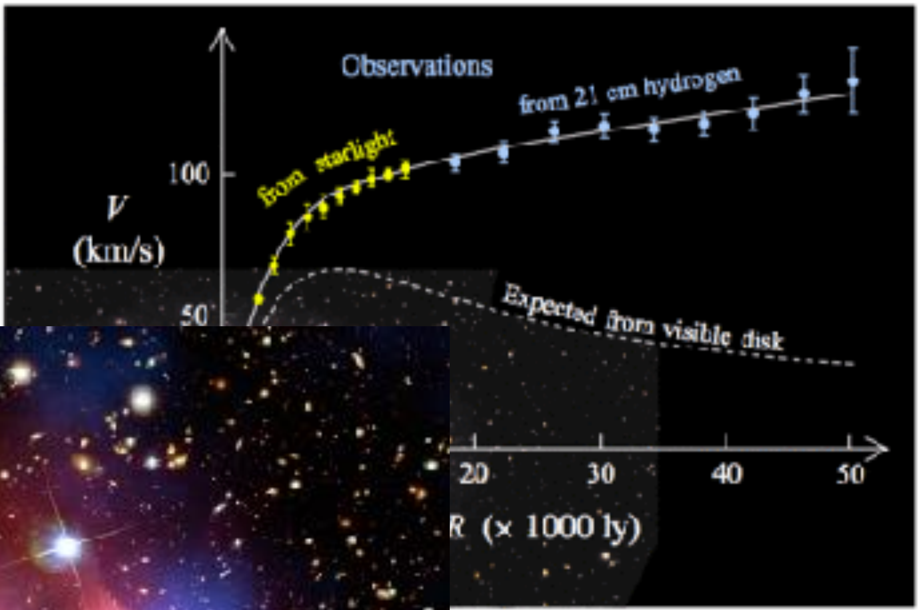
Evidence for Dark Matter

★ ***Galaxy rotation curves***

★ ***Gravitational lensing***

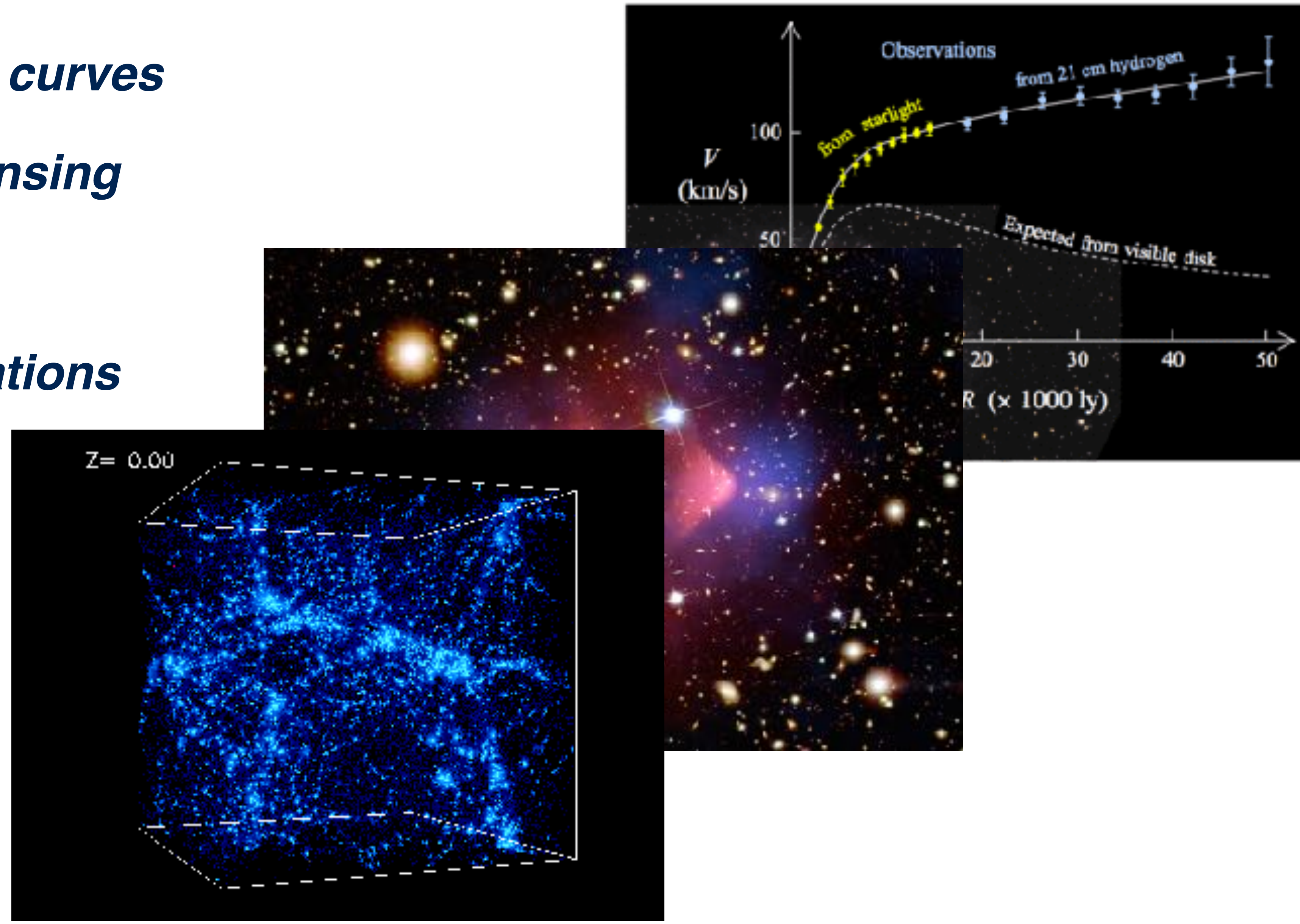
★ ***Bullet clusters***

★ ***...***



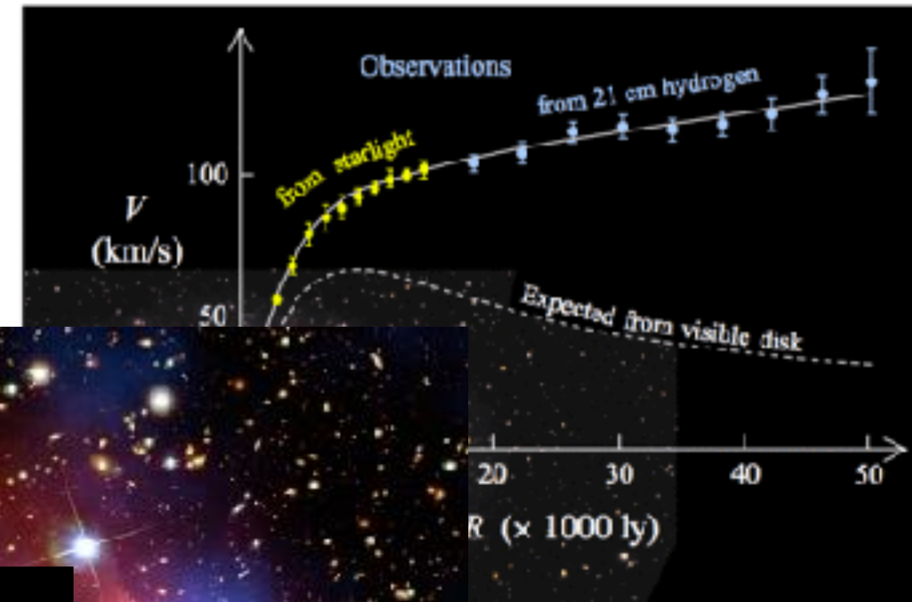
Evidence for Dark Matter

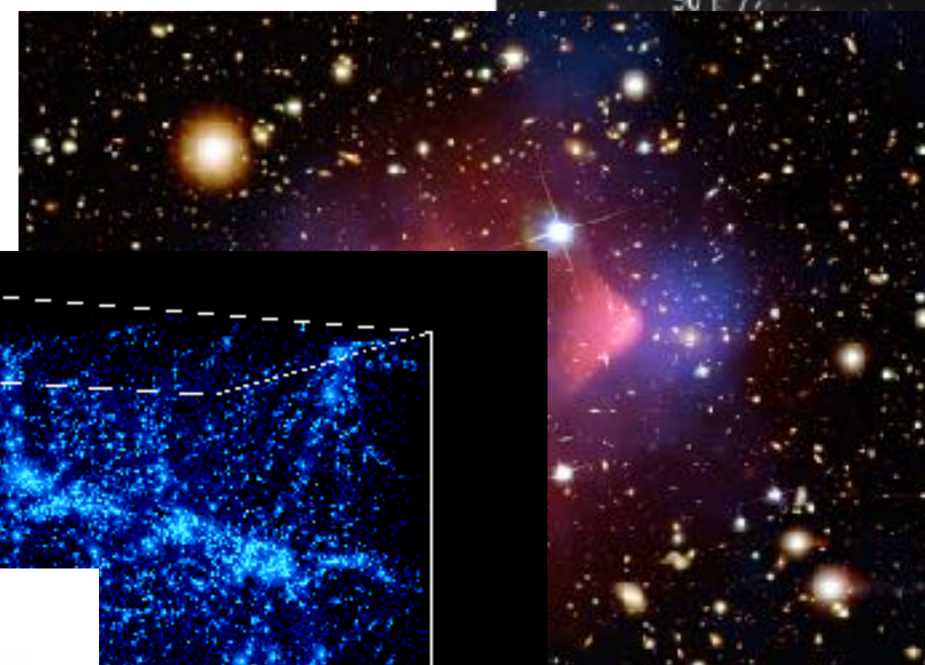
- ★ ***Galaxy rotation curves***
- ★ ***Gravitational lensing***
- ★ ***Bullet clusters***
- ★ ***Structure formations***
- ★ ***...***

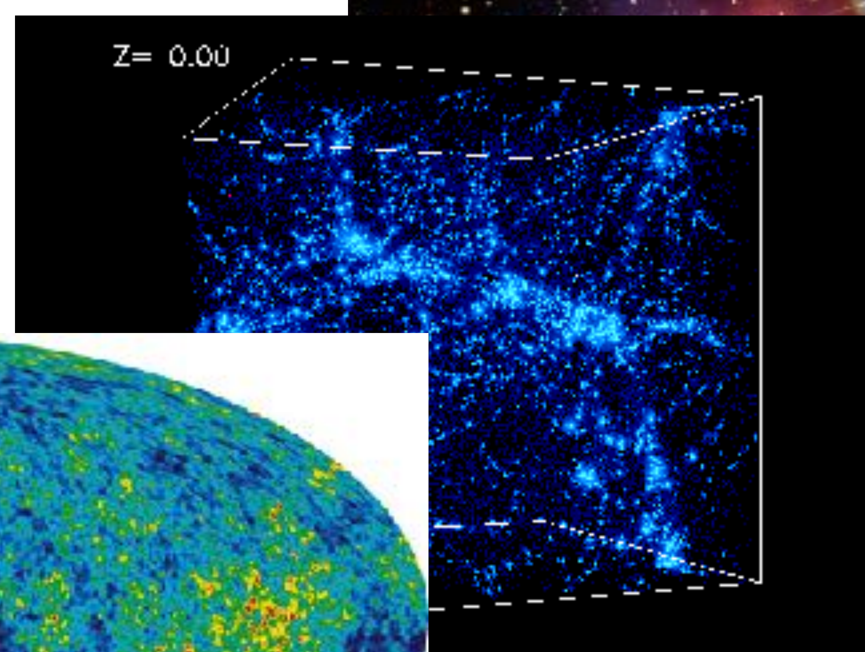


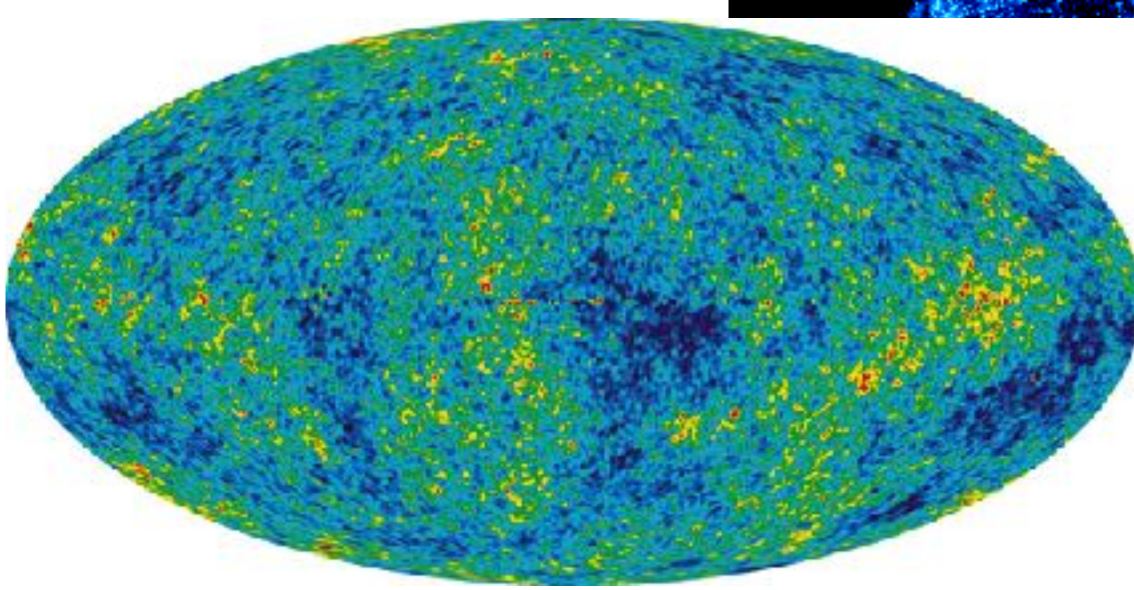
Evidence for Dark Matter

- ★ *Galaxy rotation curves*
- ★ *Gravitational lensing*
- ★ *Bullet clusters*
- ★ *Structure formations*
- ★ *CMB*
- ★ *...*









All related to gravity effects (on different scales)

Dark Matter?

? What can it be ?

New elementary particle

★ ***NOT ordinary (baryonic) matter*** ⟷ **including antimatter**

★ ***Dark (no absorption or emission of light)***

★ ***Neutral (no electric charge)***

★ ***Stable (no decay)***

★ ***Non relativistic (slow)***

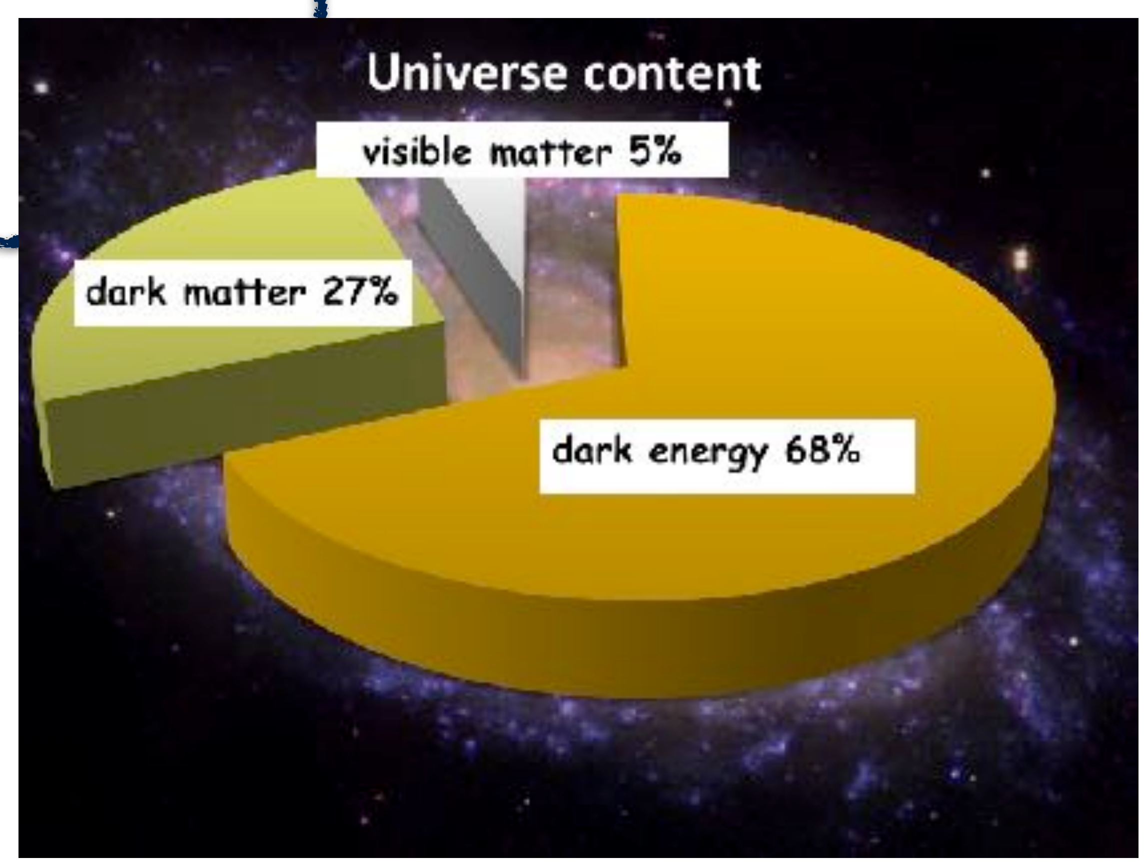
Dark Matter?

? What can it be ?

New elementary particle

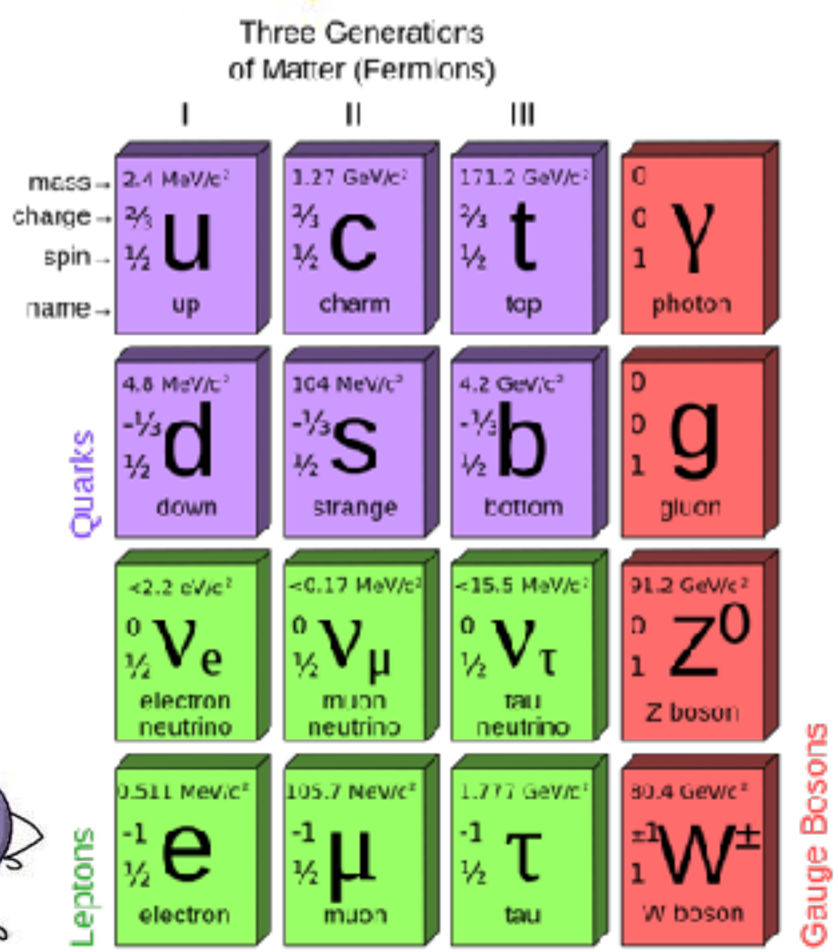
- ★ *NOT ordinary (baryonic) matter* ↔ *including antimatter*
- ★ *Dark (no absorption or emission of light)*
- ★ *Neutral (no electric charge)*
- ★ *Stable (no decay)*
- ★ *Non relativistic (slow)*

Very abundant in the Universe



Particle Dark Matter

Assume Dark Matter is a new elementary particle



Simplified models of Dark Matter

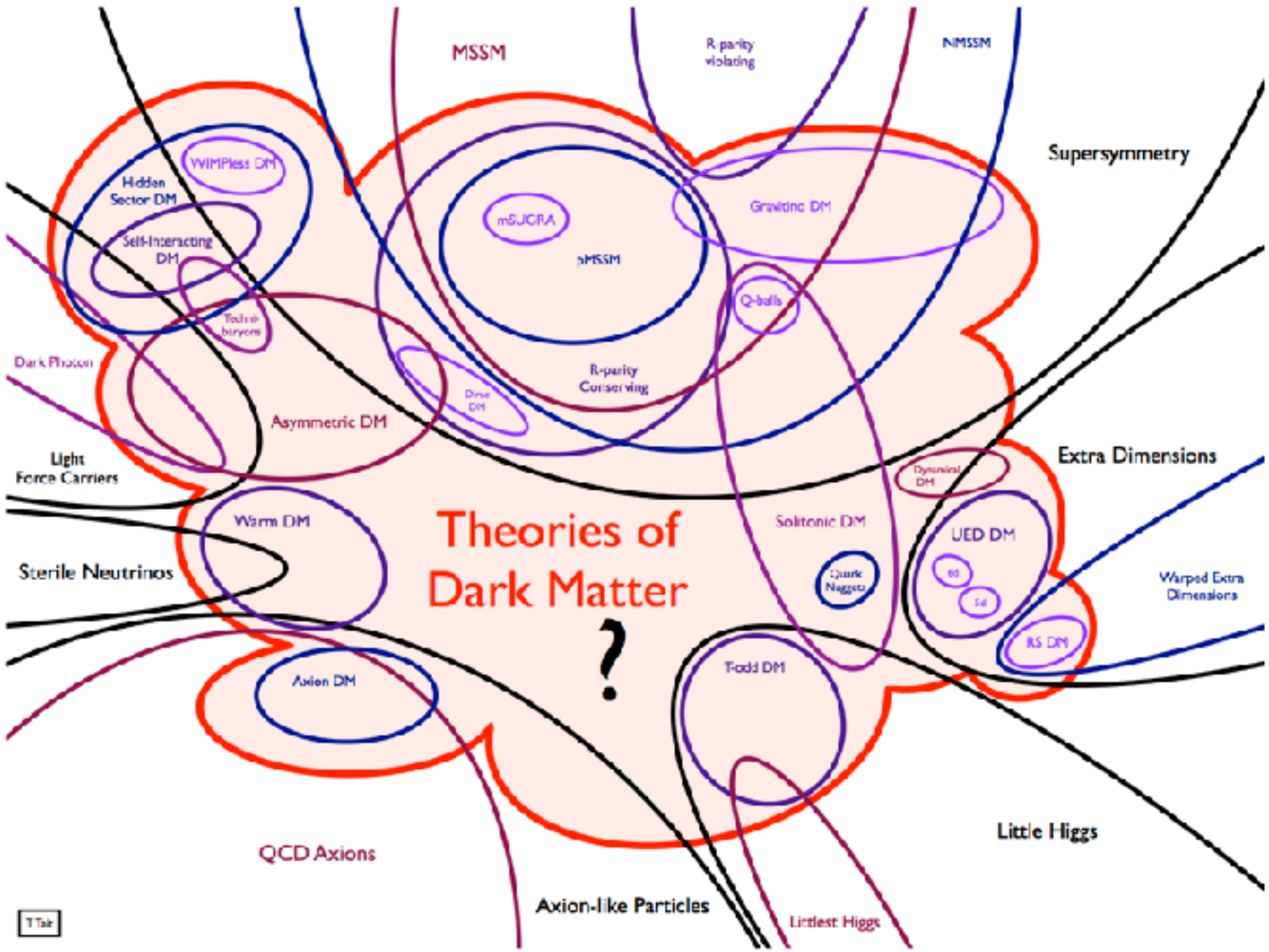
Inspired by UV complete models
e.g. Supersymmetry

Suitable for phenomenological analysis (e.g. collider signatures)

Portal

Dark Matter ZOO

Possibilities for Dark Matter are extremely vast



Q: what is the Dark Matter?

Beyond SM approaches

Many fundamental questions still open …

- ★ ***BSM proposals try to address some or few of these***
- ★ ***Falsify proposals with experiments (LHC etc …)***
- ★ ***But, no clear indication where BSM physics should be…***

Explore the unknown !!

Top Down

- ✳ ***Use guiding principle to formulate BSM theory***
- ✳ ***Derive phenomenology and experimental tests***

Bottom up

- ✳ ***Formulate BSM theory to explain specific observation***
- ✳ ***Derive other phenomenology and experimentally test it***

Symmetries

Symmetries plays central role in physics

- ✳ *Symmetries represented by groups*
- ✳ *Local action of a symmetry is described by generators*
- ✳ *Generators satisfy specific algebra*
- ✳ *Symmetry corresponds to conserved charge*

✦ ***Example: rotation in 3 dimensions***

$SO(3)$ ***group*** ***Algebra of generators:*** $[J_i, J_j] = i\epsilon_{ijk}J_k$

Conserved quantity: angular momentum

✦ ***Example: translation in 4d***

Generator: P_μ ***Satisfy:*** $[P_\mu, P_\nu] = 0$

Translations in orthogonal directions commute

Conserved quantity: energy and spatial momentum

Standard Model symmetries

Spacetime symmetries

- ★ *Spacetime translations*
- ★ *Rotations and boosts*

} *Poincare group*

Internal symmetries

- ★ *Gauge symmetries:* $SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$
- ★ *Global symmetries: isospin, baryon number, lepton number ....*

In the following I will denote with T^a *generator of internal symmetry*

Standard Model symmetries

Spacetime symmetries

- ★ *Spacetime translations*
- ★ *Rotations and boosts*

} **Poincare gro**

What can we add?

Int ymmetries

- ★ ***Ga ymmetries:*** $SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$
- ★ ***Global symmetries:*** *isospin, baryon number, lepton number ....*

In the following I will denote with T^a generator of internal symmetry

Supersymmetry (SUSY)

★*Only possible extension of Poincare algebra is SUSY*

Coleman, Mandula; Haag, Lopuszanski, Sohnius

★*SUSY is necessary ingredient in String Theory*

New symmetry relating fermions and bosons

Matter (fermions) — ***Forces and Higgs*** (bosons)

SUSY generator Q

Exchanges fermions with bosons

$$Q|\text{fermion}\rangle = |\text{boson}\rangle \qquad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

Q ***carries spinor index***

Theory should be invariant under exchange
fermion <--> boson

SUSY

SUSY algebra schematically

Please look the references for complete superalgebra

$$\{Q,Q^\dagger\} \sim P^\mu$$

$$\{Q,Q\} = \{Q^\dagger,Q^\dagger\} = 0$$

$$[P^\mu,Q] = [P^\mu,Q^\dagger] = 0 \quad [P^2,Q] = 0 = [P^2,Q^\dagger]$$

$$[T^a,Q] = [T^a,Q^\dagger] = 0$$

+ non trivial commutators with rotations and boosts

Representation of SUSY are "multiplets" of particles with:

$[M_{\mu\nu},Q] \neq 0$ → ***Different spin***

$[P^2,Q] = 0$ → ***Same mass***

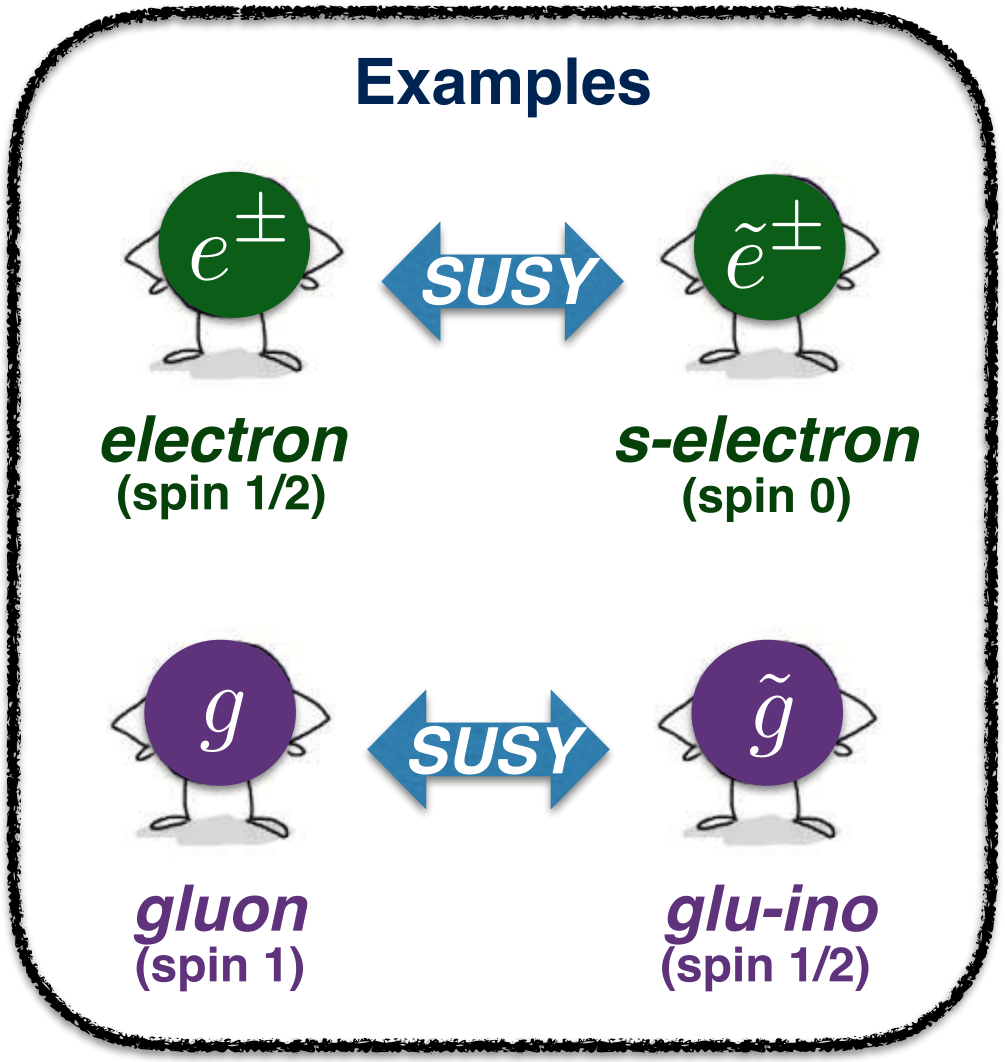
$[T^a,Q] = 0$ → ***Same quantum numbers***

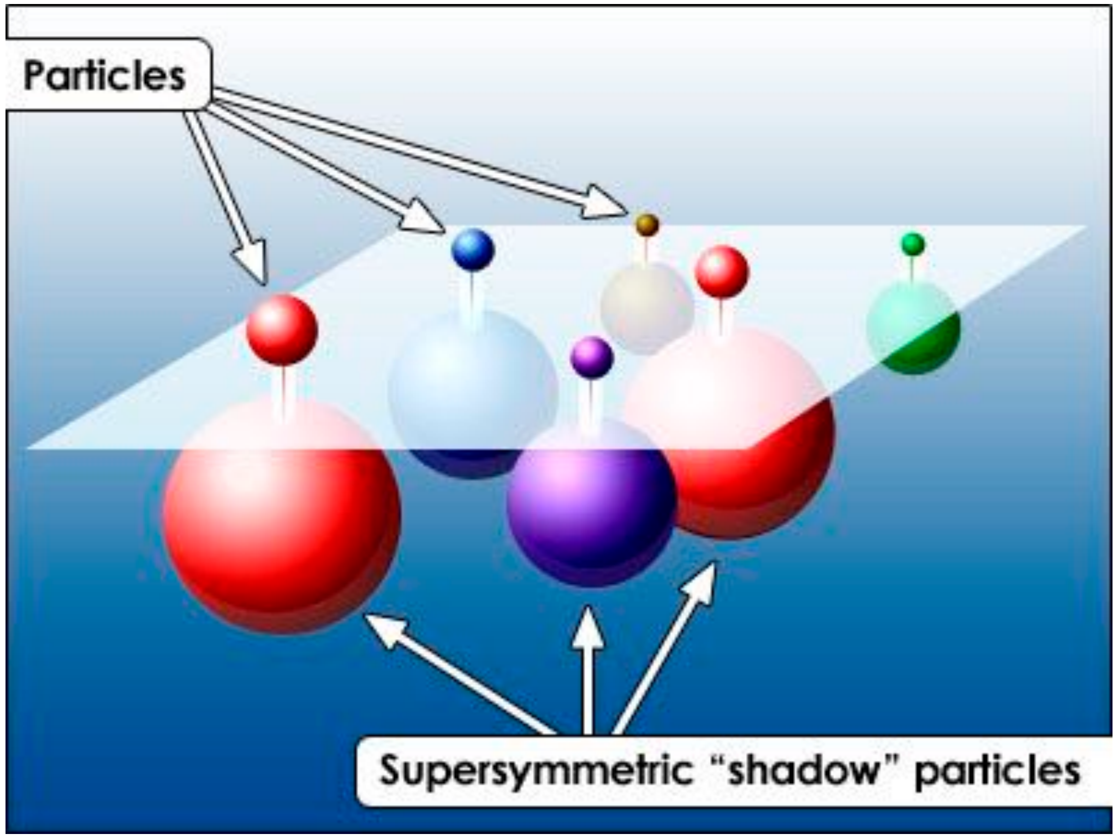
!!! We need to double the SM particle content !!!

SUSY

Every particle of SM has own supersymmetric partner

- **Fermions have partner with spin 0**
- **Bosons (gauge and Higgs) have partners with spin 1/2**





Superparticles typically denoted with tilde $\sim$ on top

Minimal SUSY SM (MSSM)

Quark and leptons multiplets

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$

Selectron, smuon, stau
stop, sbottom ...

- ***Supersymmetric partners indicated with s+SM_name***
- ***One spin-0 particle partner for each helicity state of SM fermion***

Two spin-0 superpartners for each of the SM fermion (except the neutrino)

But remind superpartners are spin-0, so no helicity

MSSM (2)

Gauge bosons multiplets

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\quad \widetilde{W}^{0}$	$W^{\pm}\quad W^{0}$	$(\mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^{0}$	B^{0}	$(\mathbf{1},\ \mathbf{1}\ ,\ 0)$

Higgs multiplets

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
Higgs, higgsinos	H_u	$(H_u^+\quad H_u^0)$	$(\widetilde{H}_u^+\quad \widetilde{H}_u^0)$	$(\mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\quad H_d^-)$	$(\widetilde{H}_d^0\quad \widetilde{H}_d^-)$	$(\mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

✳ ***Supersymmetric partners indicated with SM_name+ino***

Gluino, Wino, Bino
Higgsino

✓**Anomaly cancellation**
✓**Yukawa couplings**

✳ ***Need two Higgses*** ➡ ***In addition to superpartners, in SUSY there are total of 5 spin-0 particles in Higgs sector*** ⟷ **In SM just one Higgs**

SUSY breaking

Q: is SUSY an exact symmetry of nature?

... think about e.g. the s-electron mass and interactions ...

SUSY breaking

Q: is SUSY an exact symmetry of nature?

A: No, SUSY must be broken

★ *We add to the Lagrangian masses for superparticles*

Not yet observed because too heavy

★ *Masses constitute a SOFT breaking of SUSY*

Soft such that SUSY still address the hierarchy problem (see later)

★ *SUSY breaking terms introduce a lot of unknown parameter*

Study SUSY breaking and the way it is achieved to predict them

Topic for another lecture!!!

✳ *Remind: Broken symmetries are still very useful to describe physics*

SUSY spectrum

Mass eigenstates differ from gauge eigenstates

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

EW symmetry breaking and SUSY breaking

SUSY spectrum

Mass eigenstates differ from gauge eigenstates

EW symmetry breaking and SUSY breaking

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	(same) (same) $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	(same) (same) $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

Higgs sector

- ***States with same charge can mix***
- ***Physical states:*** $h^0\ H^0\ A^0\ H^\pm$

125 Higgs (h^0) ***Heavy Higgs*** (H^0) ***Pseudoscalar*** (A^0) ***Charged Higgs*** ($H^\pm$)

SUSY spectrum

Mass eigenstates differ from gauge eigenstates

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

EW symmetry breaking and SUSY breaking

Squark and sleptons

- *First and second generation assumed no mixing*
- *Third generations have R-L mixing*

To comply with flavour physics constraints

Listed from lighter to heavier

SUSY spectrum

Mass eigenstates differ from gauge eigenstates

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

EW symmetry breaking and SUSY breaking

Also denoted with $\tilde{\chi}^0_{1,2,3,4}$

Neutralinos and Charginos

- *Neutralinos are mixture of Bino, Neutral Wino and Higgsinos*
- *Chargino are mixture of charged Wino and Higgsino*

Listed from lighter to heavier

SUSY spectrum

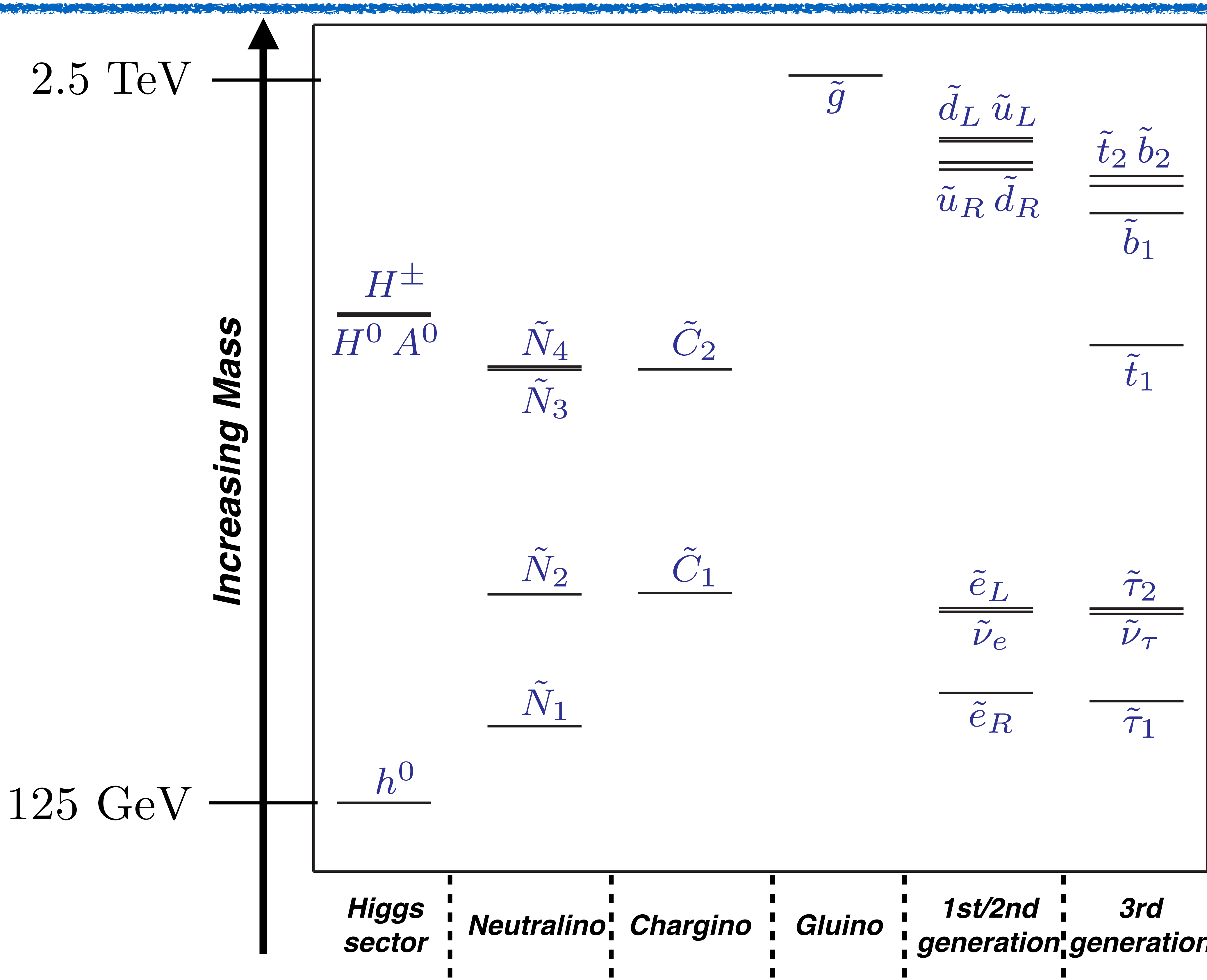
Mass eigenstates differ from gauge eigenstates

EW symmetry breaking and SUSY breaking

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

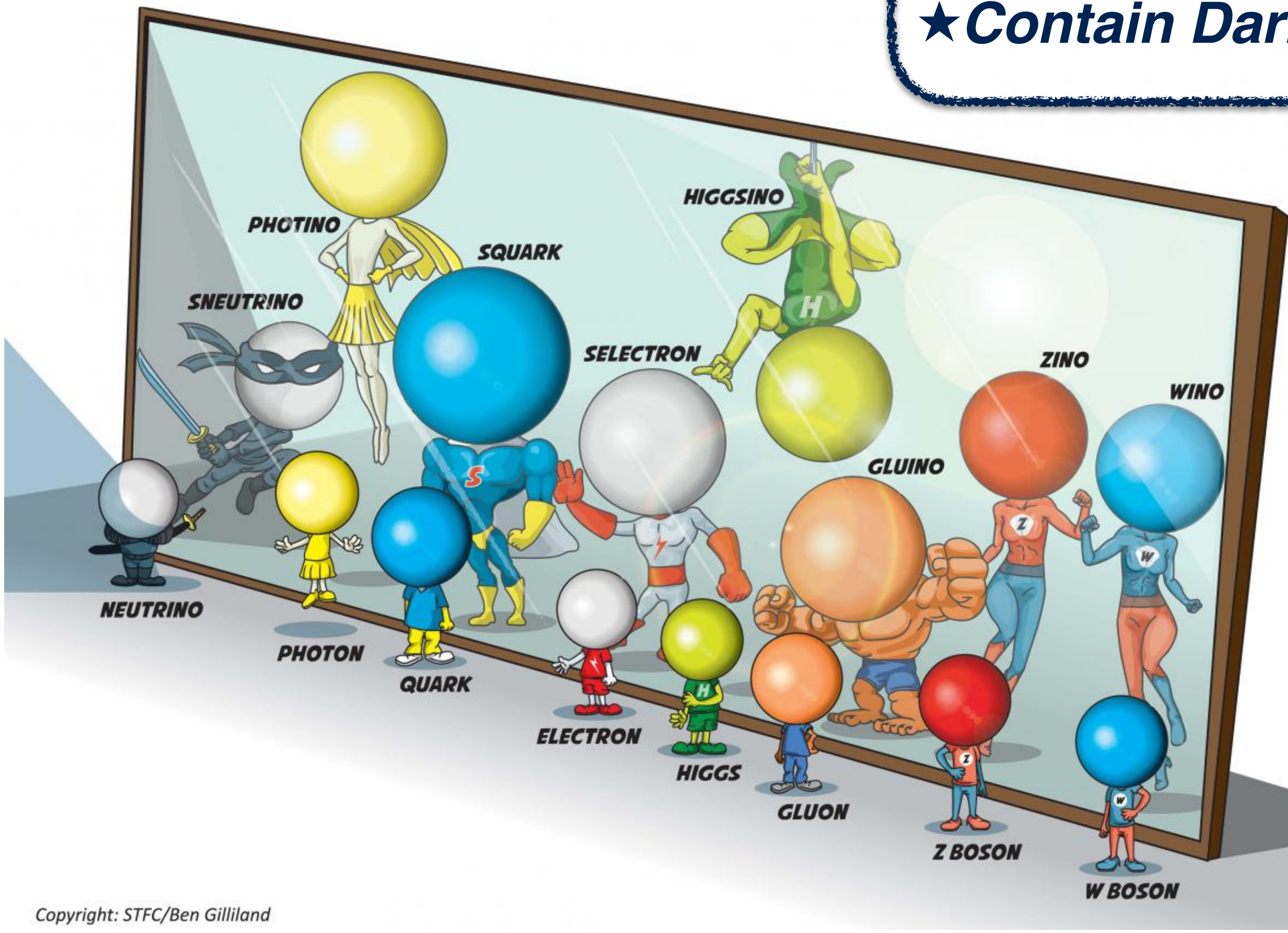
- **Gluinos**
  - *Octet of fermions (degenerate) charged under color (QCD)*

Example of SUSY spectrum



SUSY virtues

- ★ *Solve Hierarchy Problem*
- ★ *Lead to gauge coupling unification*
- ★ *Contain Dark Matter candidates*

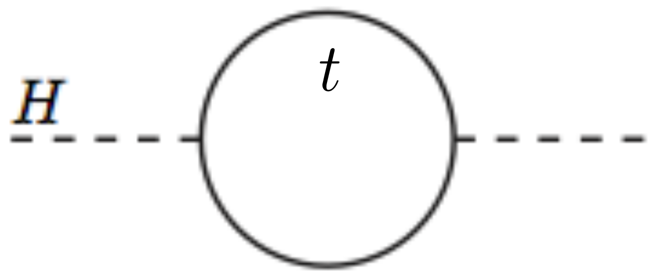


... and many others that I will not discuss ...

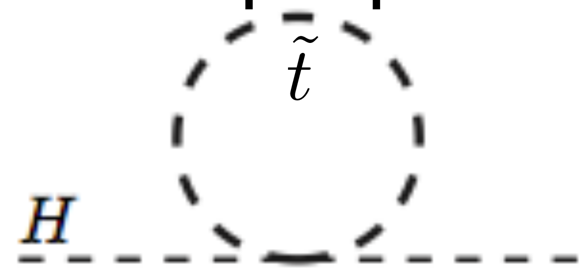
SUSY and hierarchy problem

Inspect Higgs mass quantum corrections in SUSY

Now there is also contribution from superpartners!



$+$



$$(\delta m_h^2)_{top} = -\frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2 + \ldots \qquad (\delta m_h^2)_{stop} = \frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2 + \ldots$$

★ ***Two contributions cancel because of SUSY (same coupling y_t)***

★ ***SUSY breaking effects lead to an extra term but NOT quadratically divergent with cutoff***

Soft Breaking

$$(\delta m_h^2)_{top} + (\delta m_h^2)_{stop} \simeq \frac{3y_t^2}{8\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}$$

Also Gluino, Higgsino enters significantly

Stop is main responsible for solving HP in SUSY !

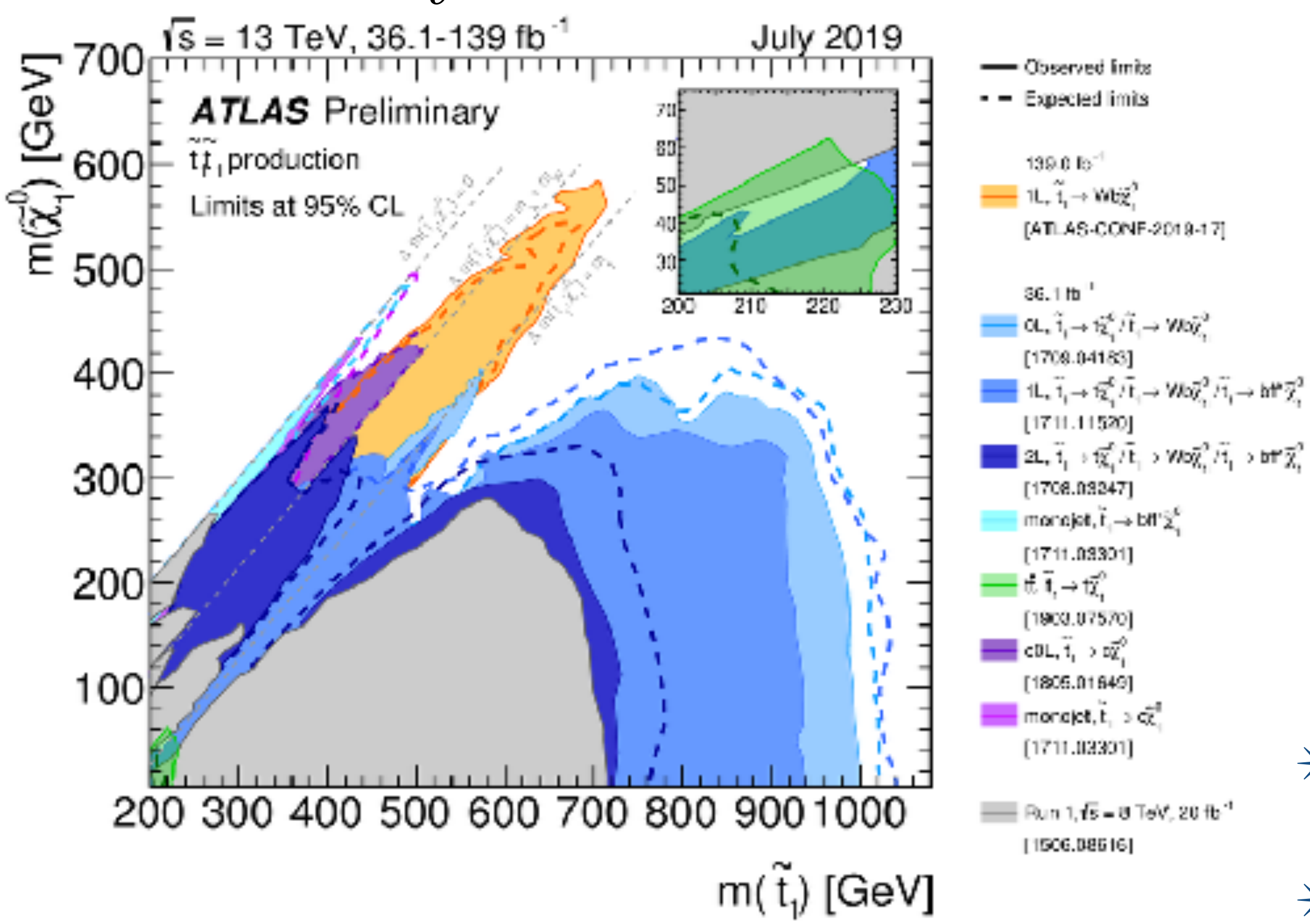
Little Hierarchy Problem

Also Gluino, Higgsino enters significantly

Stop is main responsible for solving HP in SUSY!

Q: Given bound of LHC, what is status?

$$m_{\tilde{t}} \geq 1 \text{ TeV}$$



SUSY Fine-Tuning

$$\frac{\delta m_h^2}{(125\ \mathrm{GeV})^2} \geq 25$$

Little Hierarchy Problem

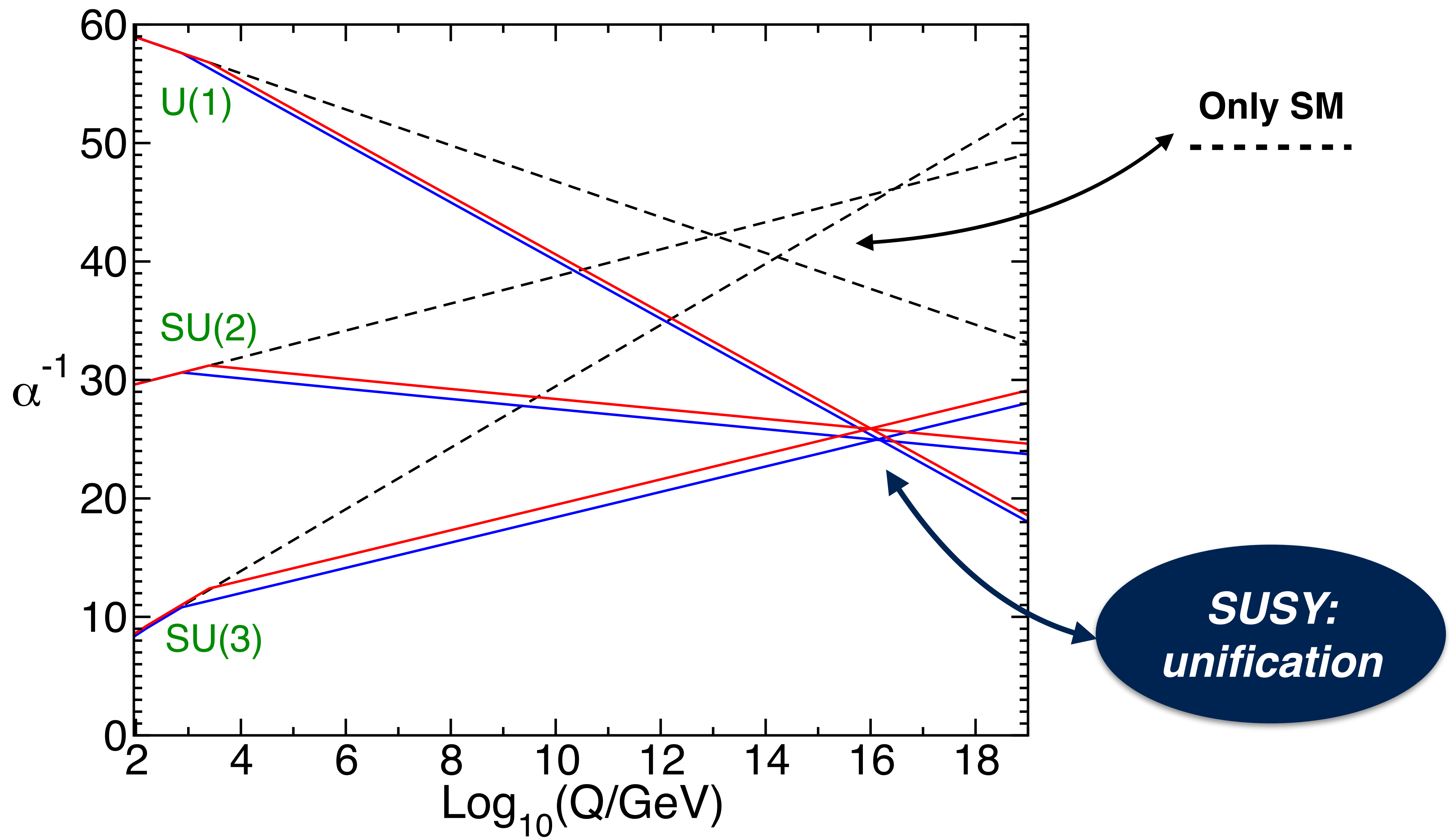
✳ ***Compare with Pion example ...***

✳ ***Compare with only SM up to M_Planck ...***

SUSY and gauge coupling unification

Superparticles modify running of gauge couplings in MSSM

➡ ***In MSSM gauge coupling unifies at ~MGUT***



R-parity

★ **SUSY interactions could have Baryon or Lepton number violation**

! Lead to Proton decay !

★ ***Impose symmetry to solve this issue***

R-parity

$$R = (-1)^{3(B-L)+2S}$$

$B =$ Baryon number

$L =$ Lepton number

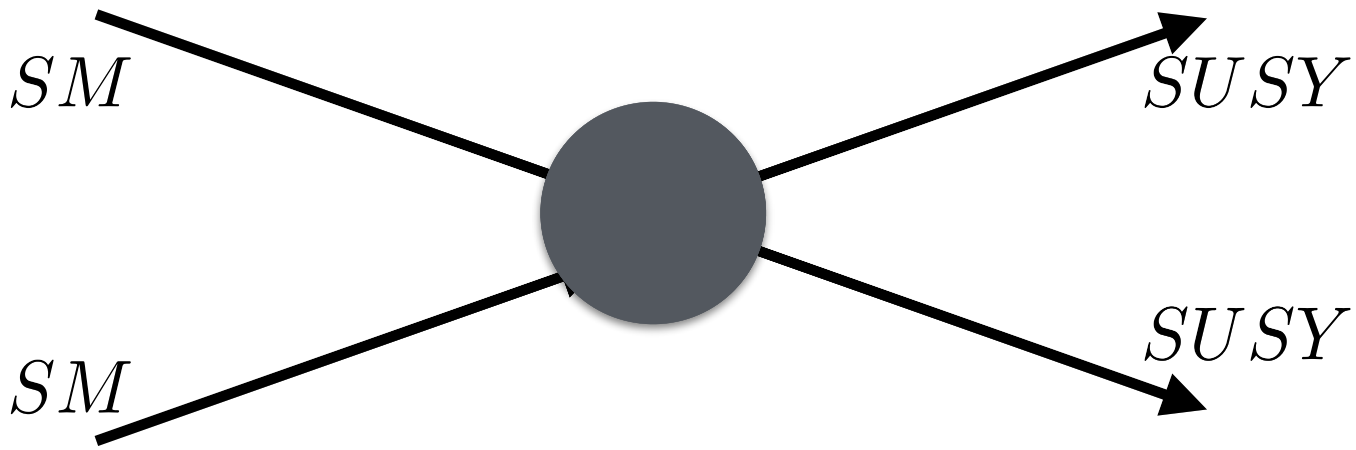
$S =$ Spin

Ordinary particles	***Supersymmetric partners***
$R = +1$	$R = -1$

Q: What are the consequences of R-parity?

Consequence of R-parity

★ ***Supersymmetric particles produced in pairs at colliders***



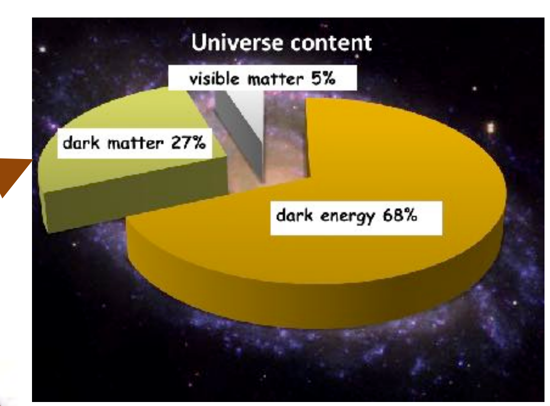
Initial state → ***Final state***

$R = (+1)(+1)$ → $R = (-1)(-1)$

★ ***Lightest SUSY particle (LSP) is stable***

→ ***If LSP is neutral, could be Dark Matter***

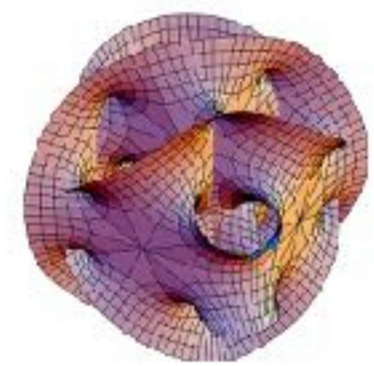
Typical example: lightest neutralino



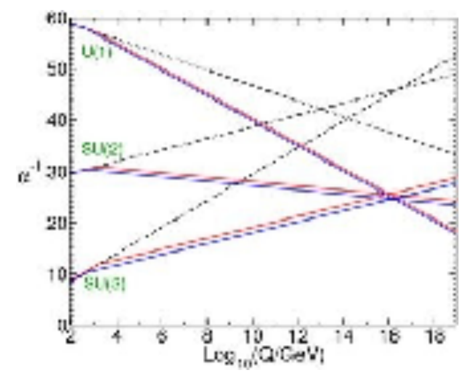
Why SUSY?

Pre LHC

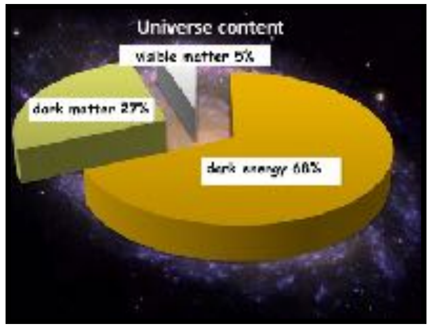
✳ Solve hierarchy problem and naturalness



✳ Necessary in unified description with gravity



✳ Gauge coupling unification



✳ Dark matter candidate (LSP)

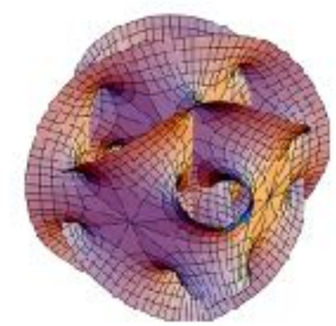
✳ Admit a low energy SM limit (including EWPT and flavour)

Why still SUSY?

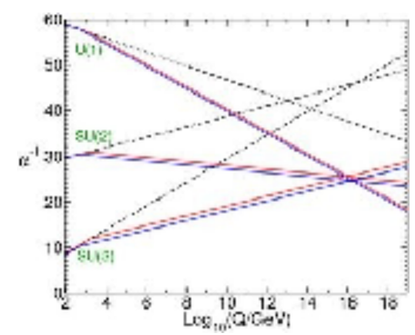
After/During LHC era

✴ ***Address*** hierarchy problem and naturalness (little fine-tuning)

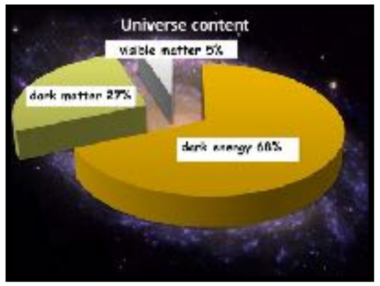
✴ Necessary in unified description with gravity



✴ Gauge coupling unification



✴ Dark matter candidate (LSP)

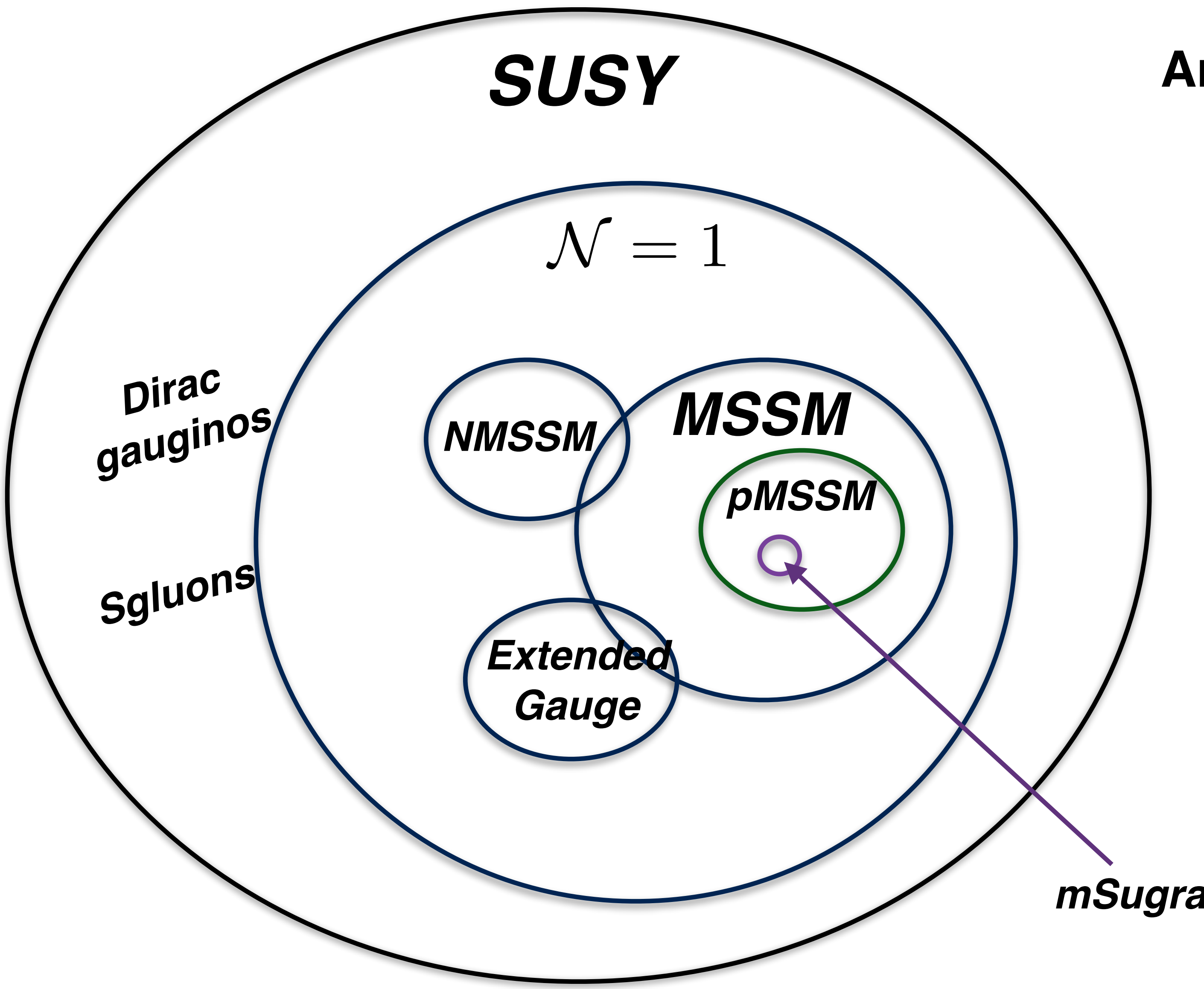


✴ Admit a low energy SM limit (including also ***SM-like H boson***)

SUSY is a broad framework

... We discussed only the *Minimal* SUSY SM (MSSM) ...

but SUSY provides a framework for more general/extended BSM proposals with different phenomenology



And also different scenarios for soft terms:
GMSB, AMSB, Split SUSY, ...

... but no sign of BSM physics ...

★*No new physics at the LHC*

★*No new physics at Dark Matter exp*

★*No new physics in rare processes*

... but no sign of BSM physics ...

★*No new physics at the LHC*

★*No new physics at Dark Matter exp*

★*No new physics in rare processes*

... but no sign of BSM physics ...

★*No new physics at the LHC*

★*No new physics at Dark Matter exp*

★*No new physics in rare processes*

★*No clear indications of where BSM physics should be*

★*We proceed exploring novel/unusual models/signatures!*

★*We look for deviations!*

Resonances

★ **Powerful probe for new physics:** *"look for a bump"*

★ ***Breit Wigner resonance***

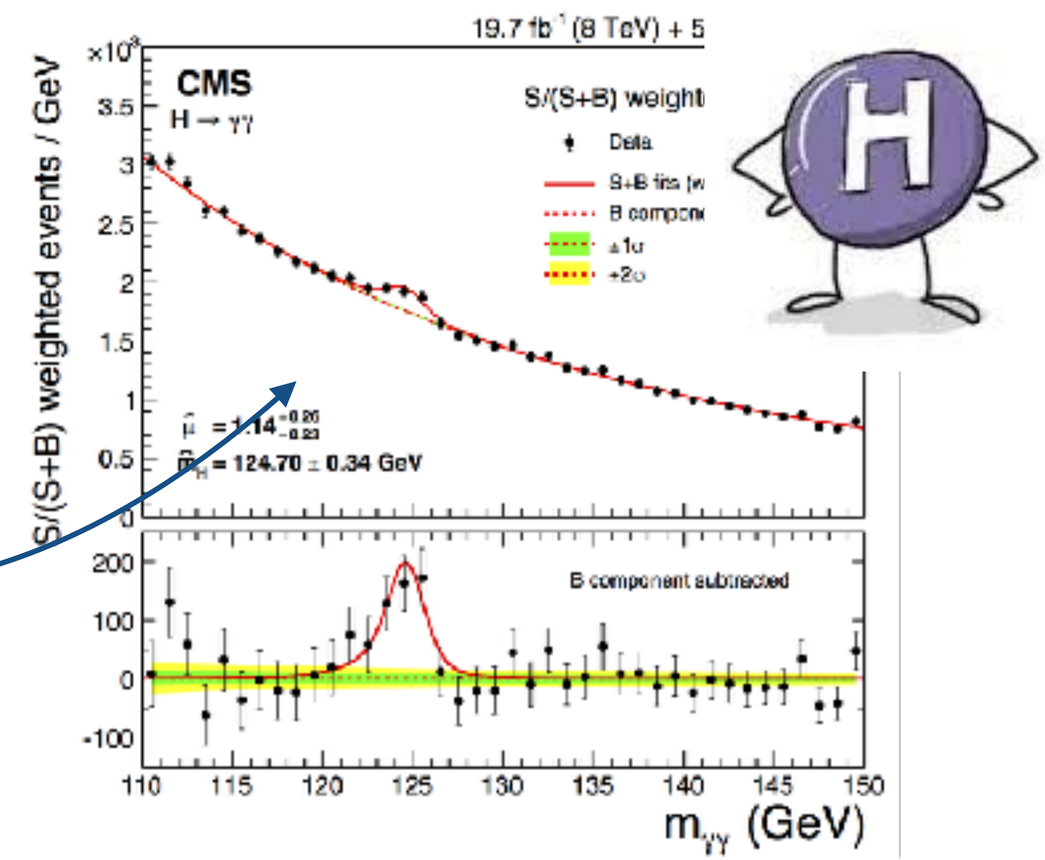
$$\sigma(e^+e^- \to Z) \sim \frac{1}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

Cross section maximum (peak) when c.o.m. energy is on Z mass

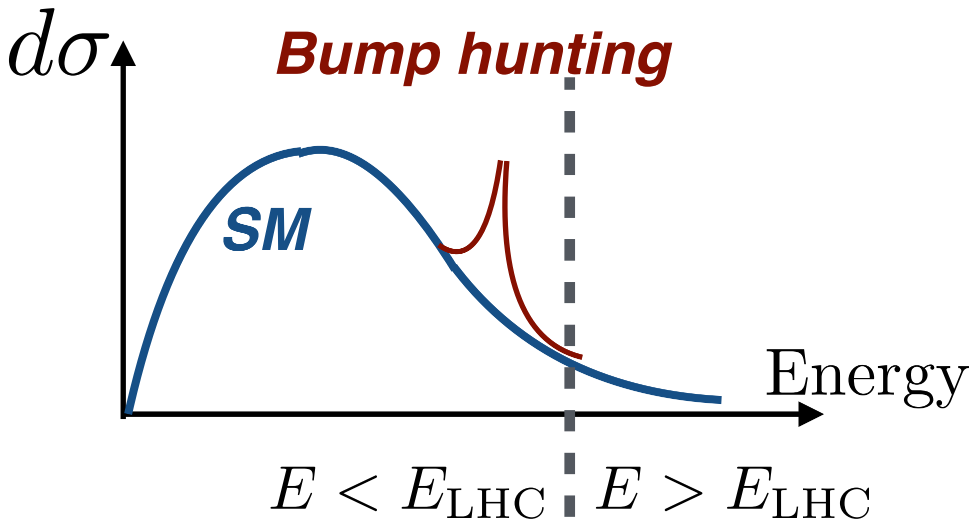
Width (inverse lifetime) of the resonance

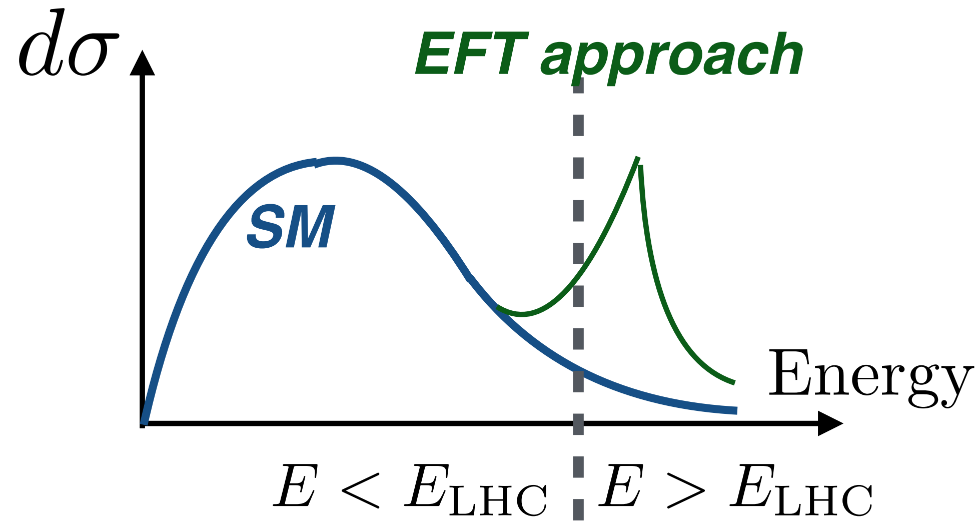
★ **Led to great discoveries**

$$J/\Psi, \Upsilon, Z, \text{BEH boson} \; ...$$



Resonances vs deviations





Maybe new physics is beyond the energy reach of the LHC

★**We can still capture deviations in *tail of distributions***

★**Need precise measurements of differential distributions** ← ***HL-LHC***

★**How do me parameterise possible new physics effects?**

➡ **With framework of EFT applied to SM (SMEFT)**

... let's review a familiar example of EFT ...

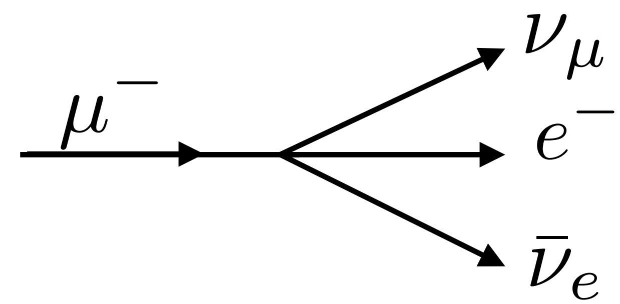
Fermi EFT

Fermi Theory is basic example of EFT

★**Four fermions interactions**

Dim 6 operator

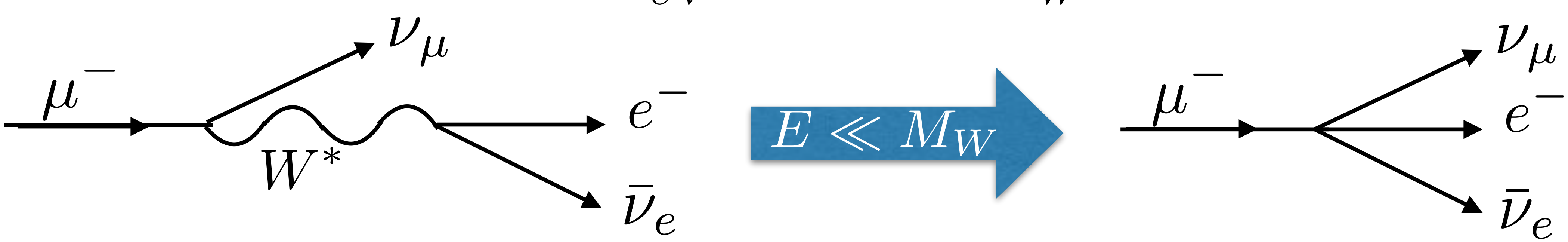
$$\mathcal{L} \supset \frac{1}{\Lambda_{UV}^2} \bar{\psi}_\mu \gamma^\rho \psi_{\nu_\mu} \bar{\psi}_e \gamma_\rho \psi_{\nu_e}$$



Explain muon decay

★**Not fundamental:** ***effective description*** **for exchange of W boson**

$$\frac{1}{\Lambda_{UV}^2} = G_{\rm F} = \frac{\sqrt{2}}{8} \frac{g^2}{M_W^2}$$



Parameterisation for new physics

★**Higher dimensional operator suppressed by** $1/M_W^2$

★**Valid description for** $E \ll M_W$

Describe well the physics

SMEFT @ LHC

Consider SM as EFT valid up to scale

★**Add to SM higher dimensional operators suppressed by** Λ

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)}$$

Wilson coefficients (dimensionless couplings)

Dim-6 operators (e.g. 4 fermions)

★**They affect distributions at** $E \lesssim \Lambda$

✳*Start with lowest dimension operators* — **Expansion in** E/Λ

✳*Dim5: one "Weinberg" operator (neutrino masses)*

✳*Dim6: basis of 59 operators (O(2000) without flavour assumptions)*

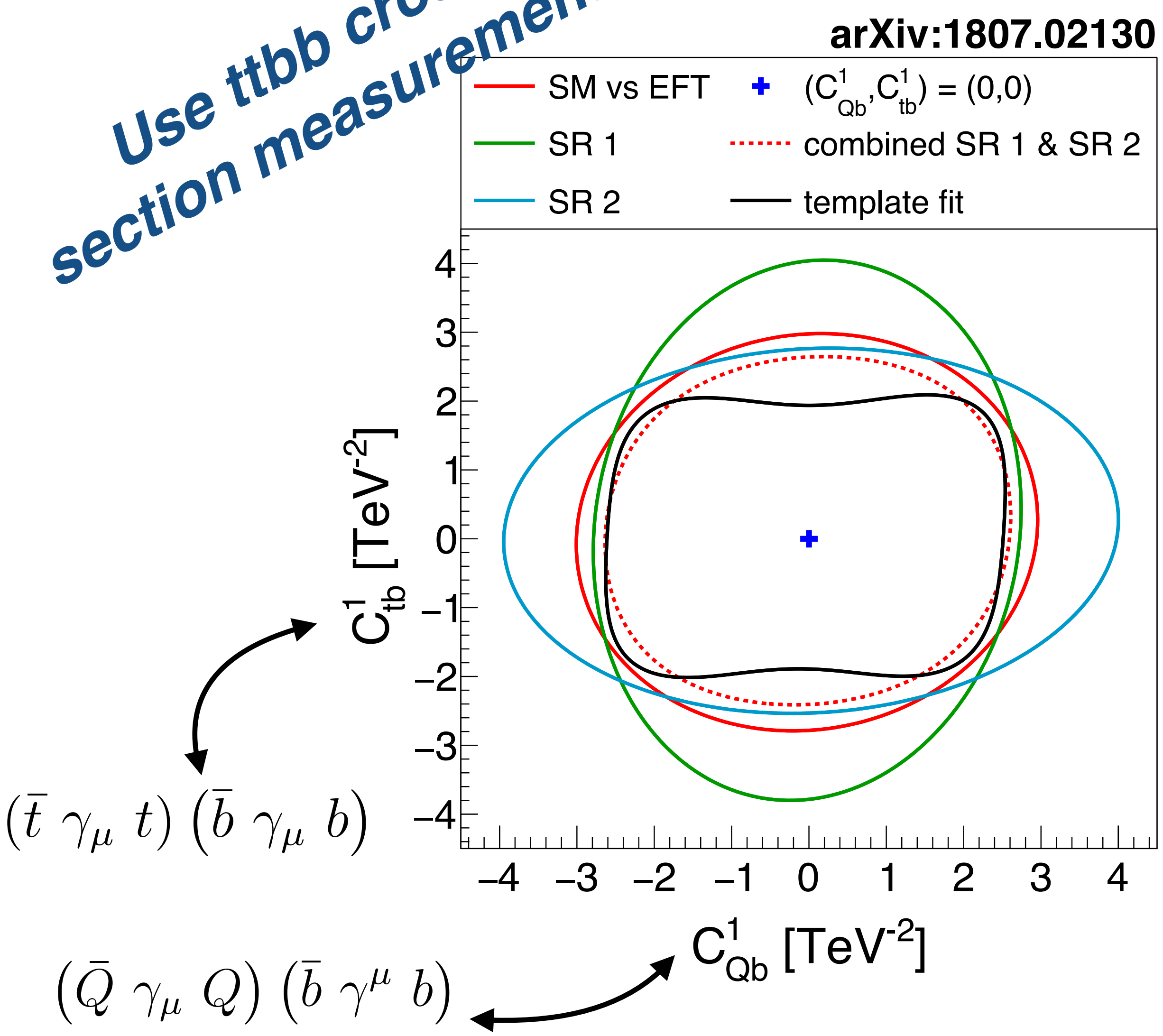
SMEFT program

Constrain the "size" of SMEFT operators by precise LHC measurements

SMEFT @ LHC

Example of two operator constraint at the LHC

Use ttbb cross section measurement!



- ✳ **Constraint combination of Wilson coefficient C and new scale Λ**
- ✳ **In interpretation often taken $\Lambda = 1\mathrm{TeV}$ for convenience, but careful with validity of EFT**

topic for another talk

★ ***Powerful strategy to look for new physics in a model-independent way***

★ ***Profit from large amount of data and precise measurements (HL-LHC)***

Take home messages

★*SM shortcomings need Beyond SM physics*

★*SUSY still well motivated BSM proposal*

★*SUSY addresses many open issues*

Dark Matter
Hierarchy problem
Inflation
Force unification
Matter-Antimatter
⋮

No sign of BSM at the LHC and in other Exp

✳*Where is SUSY? Where is BSM physics?*

✳New model building needed (also within SUSY)

✳New strategies to search for BSM (e.g. SMEFT)

... many options open ... search for the unknown !!!

References

★**For Supersymmetry:**

S.P.Martin, "A Supersymmetry primer,", hep-ph/9709356

H.Murayama, "Supersymmetry Phenomenology", arXiv:hep-ph/0002232

A.Bilal, "Introduction to supersymmetry," hep-th/0101055 (FORMAL)

★**For BSM and EFT**

M.McCullough, "Lectures on Physics Beyond the Standard Model"

W. Skiba, "TASI lectures on EFT", arXiv:1006.2142

★**For Quantum Field Theory**

M.E.Peskin and D.V.Schroeder, "An Introduction to quantum field theory," (BOOK)

D.Tong, "Lectures on Quantum Field Theory"

✳ *Credits to previous HASCO SUSY/BSM lecturers: C. Clément, T. Lari, F. Meloni*

I'm here until Thursday for questions !