Beyond the Standard Model

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Lecture 3

CERN Summer Student Programme 2013

Why is supersymmetry interesting?

Higgs field affected by quantum fluctuations of the vacuum

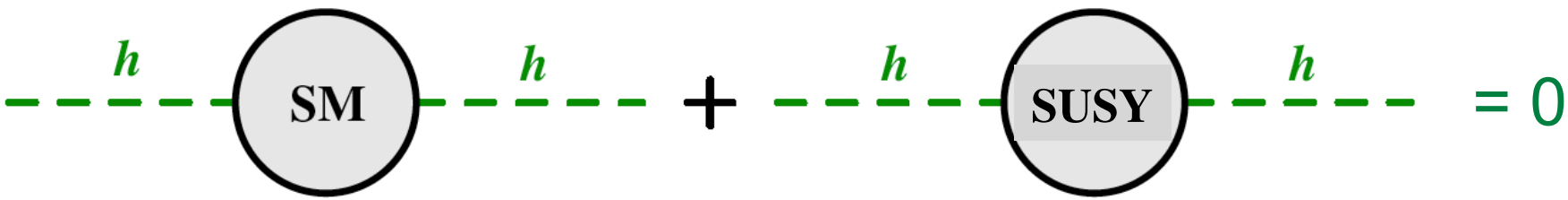
M_W , M_Z ➔ E_{max}

virtual particles increase the density of the Higgs field in the vacuum: M_W ↗

virtual sparticles decrease the density of the Higgs field in the vacuum: M_W ↘

total effect = 0

The magic of symmetry!

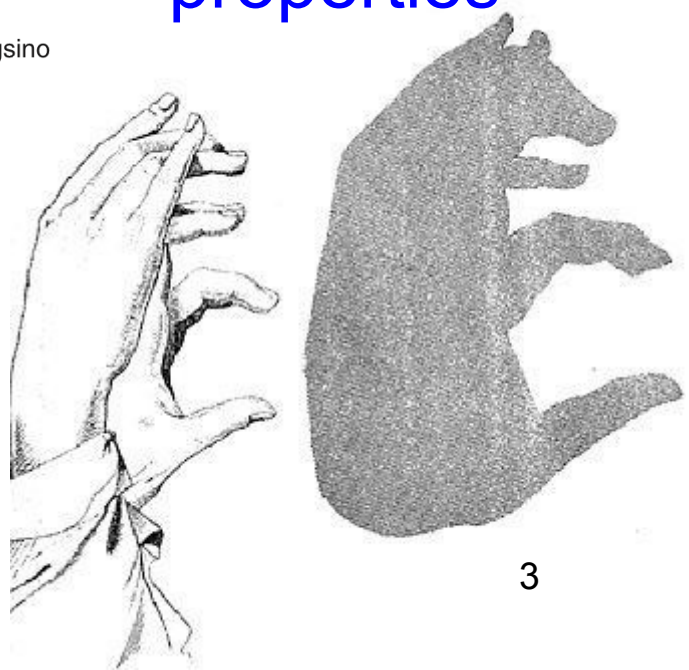


Supersymmetry gives the justification for an apparently miraculous coincidence

If the particle world took place in superspace…

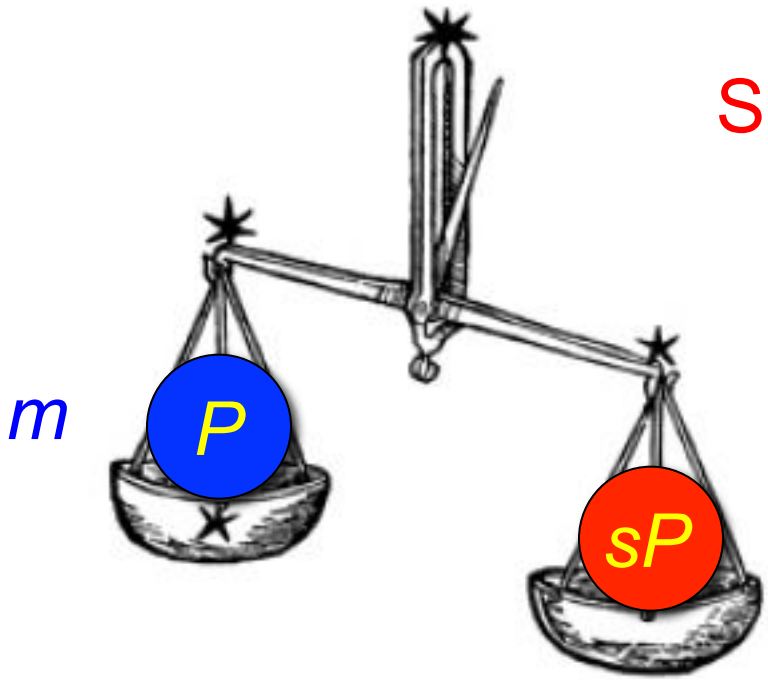
	The particle world			Spin		The sparticle world			
Quarks	Up	Charm	Top	$\frac{1}{2}$	0	Stop	Scharm	Sup	Squarks
	Down	Strange	Bottom	$\frac{1}{2}$	0	Sbottom	Sstrange	Sdown	
Leptons	Electron neutrino	Muon neutrino	Tau neutrino	$\frac{1}{2}$	0	Tau sneutrino	Muon sneutrino	Electron sneutrino	Sleptons
	Electron	Muon	Tau	$\frac{1}{2}$	0	Stau	Smuon	Selectron	
Gauge particles	Gluons			1	$\frac{1}{2}$	Gluinos			Gaugino & Higgsino sparticles
	W, Z			1	$\frac{1}{2}$	Neutralinos & Charginos			
	Photon			1	$\frac{1}{2}$				
Higgs particles	3 neutral & 1 charged Higgs bosons			0	$\frac{1}{2}$				

… lots of new particles, but the power of symmetry relates all their properties



Staring at shadows can be deceitful…

Supersymmetry cannot be an exact symmetry of our world (spin-0 electrons do not exist)



Supersymmetry breaking

$\tilde{m} >> m$

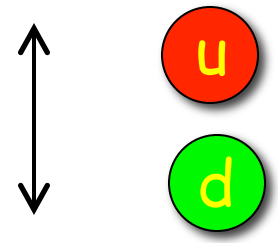
The dark side of the moon is hidden

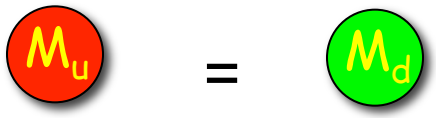
We need the LHC!

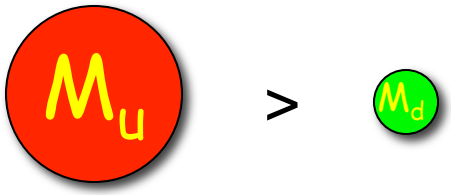
gauge symmetry ➔ $m = 0$
supersymmetry ➔ $\tilde{m} = 0$

With spontaneously broken symmetry, mass relations implied by exact symmetry can be modified

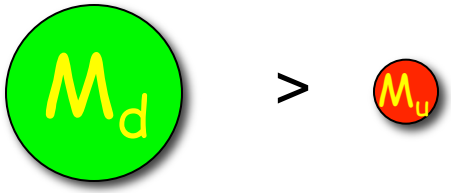
Equations invariant under exchange



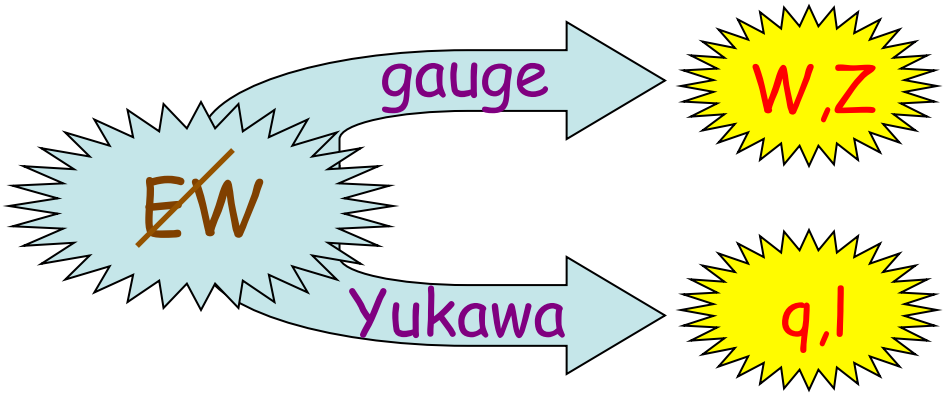
$\Rightarrow$ solutions with 

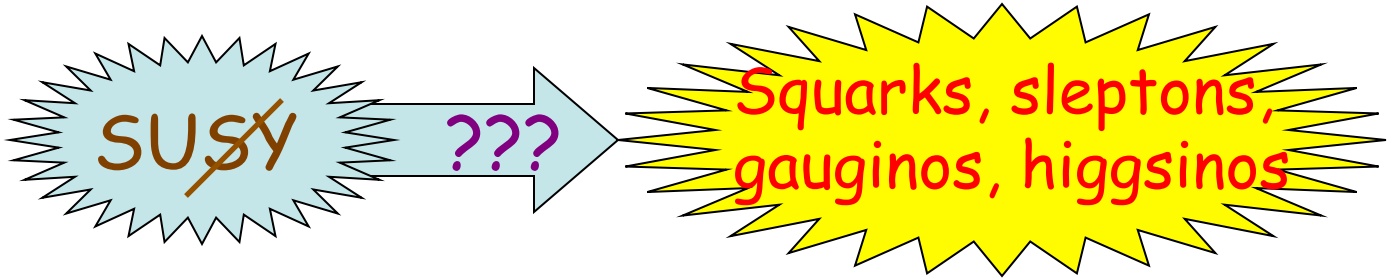
or solutions with 

possible,

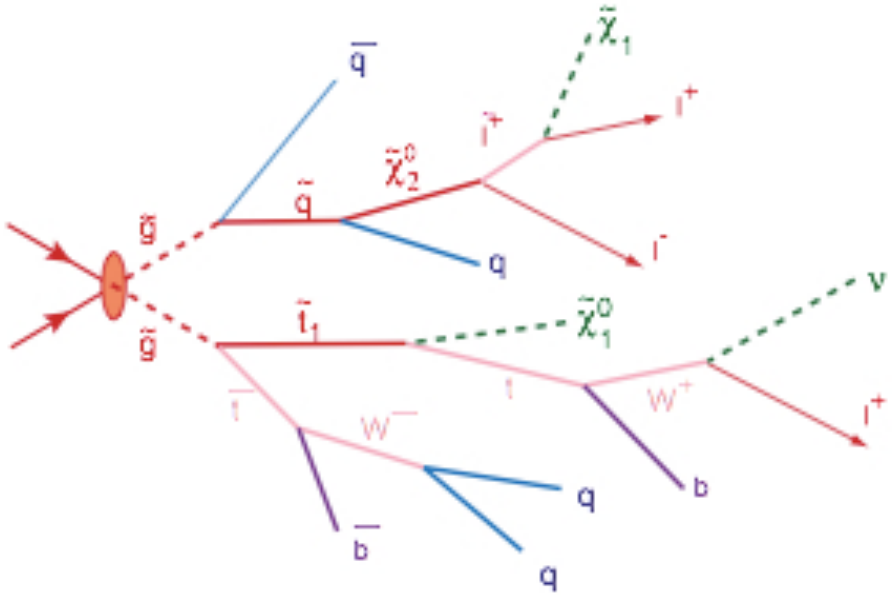
as long as 

also exists

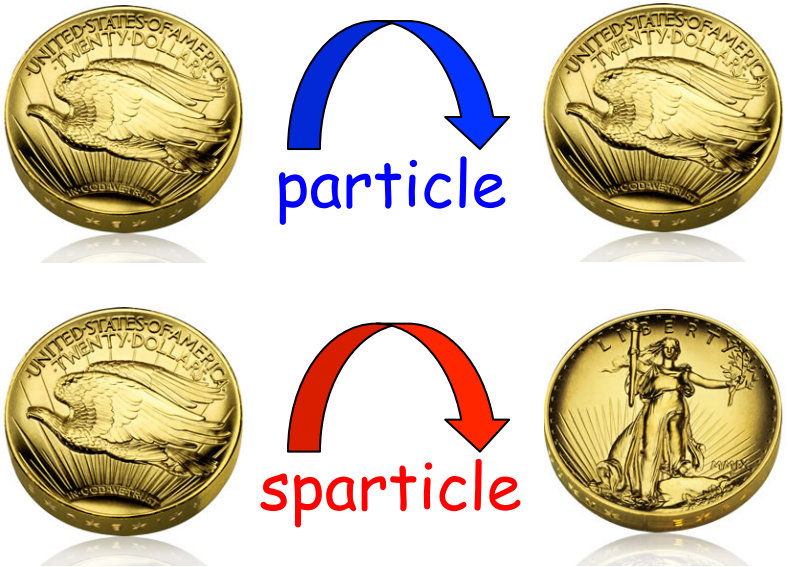

gauge
W,Z
EW
Yukawa
q,l


SUSY
???
Squarks, sleptons,
gauginos, higgsinos

How will the LHC detect supersymmetry?

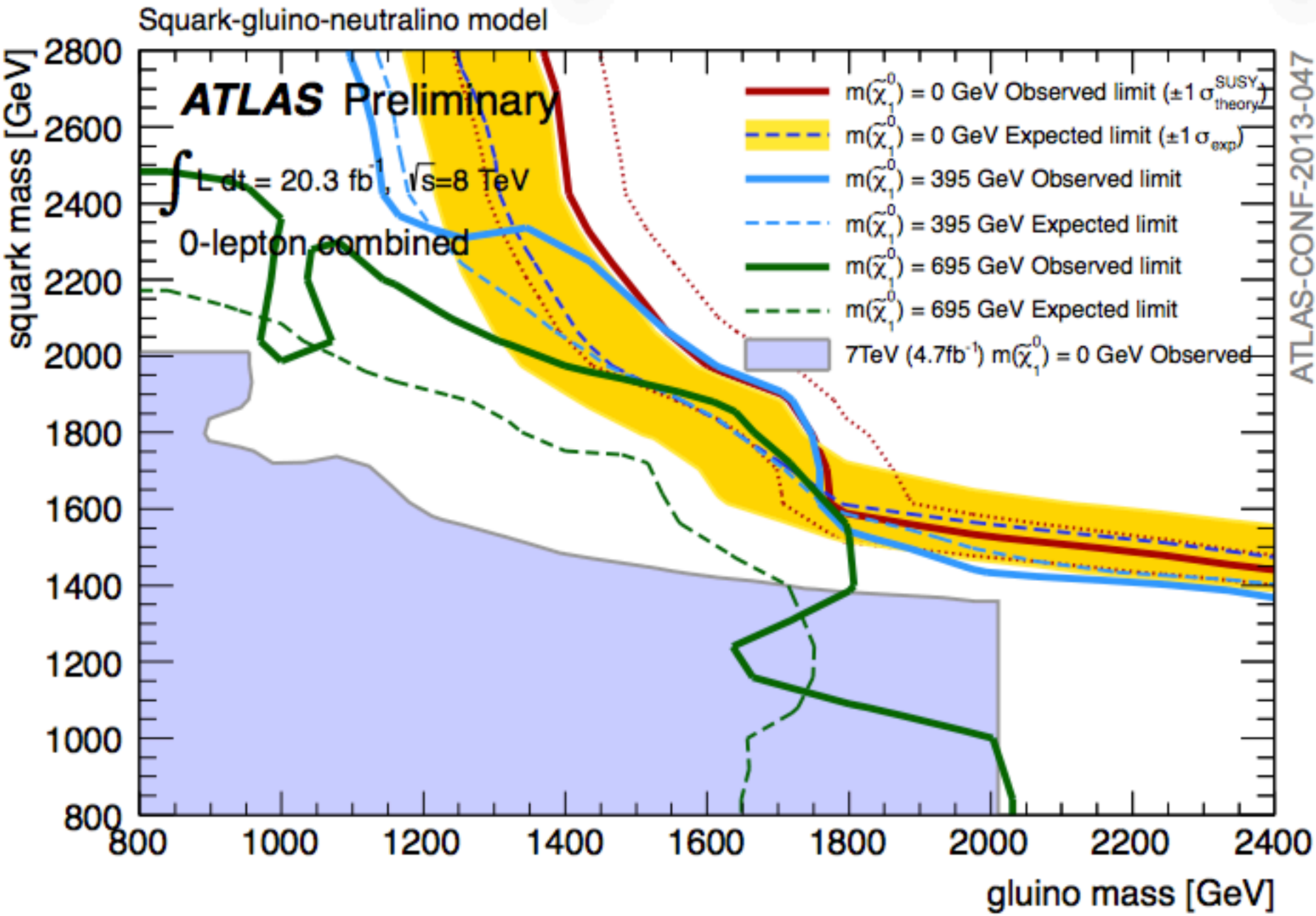


R-parity



LSP: neutralino ($\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}$)

➔ $\not{E}_T$


Squark-gluino-neutralino model
ATLAS Preliminary
∫ L dt = 20.3 fb⁻¹, √s=8 TeV
0-lepton combined
m(χ̃₁⁰) = 0 GeV Observed limit (±1 σ^SUSY_theory)
m(χ̃₁⁰) = 0 GeV Expected limit (±1 σ_exp)
m(χ̃₁⁰) = 395 GeV Observed limit
m(χ̃₁⁰) = 395 GeV Expected limit
m(χ̃₁⁰) = 695 GeV Observed limit
m(χ̃₁⁰) = 695 GeV Expected limit
7TeV (4.7fb⁻¹) m(χ̃₁⁰) = 0 GeV Observed
ATLAS-CONF-2013-047
squark mass [GeV]
gluino mass [GeV]
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}_1^0)$ <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}_1^{\pm})=2\, m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 150-440 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^{\pm})$=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0 Z^*\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^{\pm}$ 220 GeV	$1<\tau(\tilde{\chi}_1^{\pm})<10$ ns	1210.2852
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 385 GeV	$5<\tan\beta<50$	ATLAS-CONF-2013-058
	Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 395 GeV	$m(\tilde{\tau})=m(\tilde{\ell})$	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{g}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4<\tau(\tilde{\chi}_1^0)<2$ ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e + \mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

What about the Higgs boson in supersymmetry?

In SM: $H = \begin{pmatrix} h^0 + iG^0 \\ G^+ \end{pmatrix}$ $\quad V = \lambda\left(|H|^2 - v^2\right)^2$

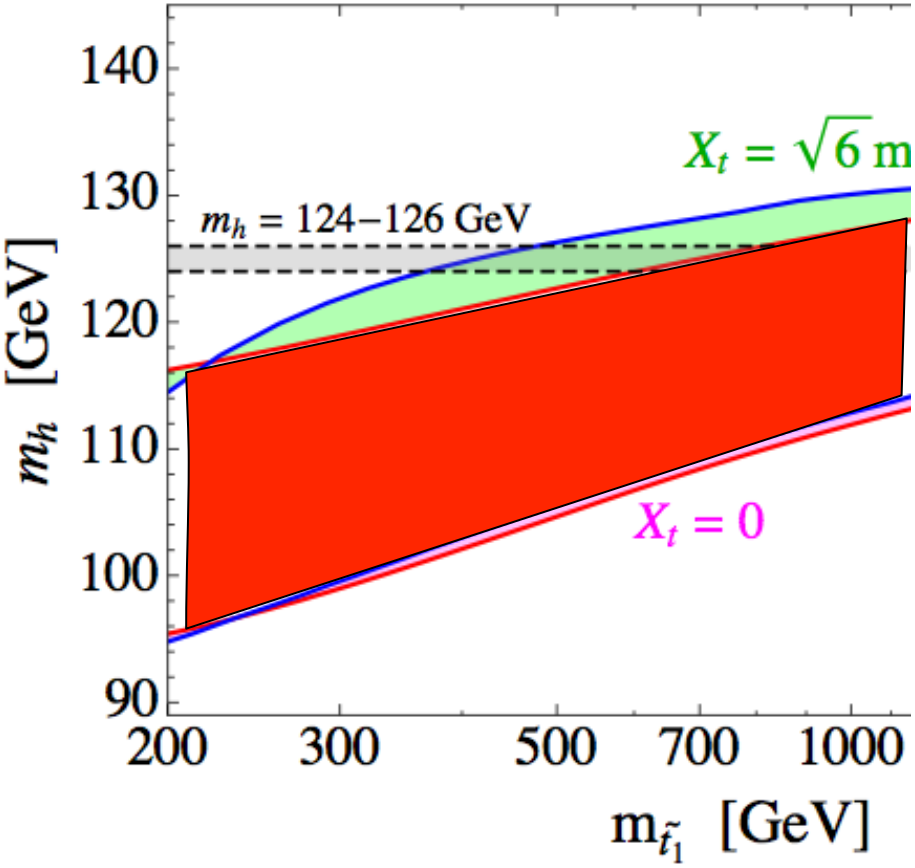
In SUSY: $H_1 = \begin{pmatrix} h^0 + iG^0 \\ G^+ \end{pmatrix}$ $\quad H_2 = \begin{pmatrix} H^0 + iA^0 \\ H^+ \end{pmatrix}$

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_3^2\left(H_1^0 H_2^0 + \text{h.c.}\right) + \frac{g_2^2 + g_Y^2}{8}\left(|H_1^0|^2 - |H_2^0|^2\right)^2$$

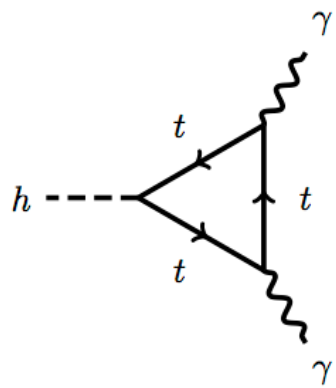
8 degrees of freedom - 3 Goldstones = 5 degrees of freedom

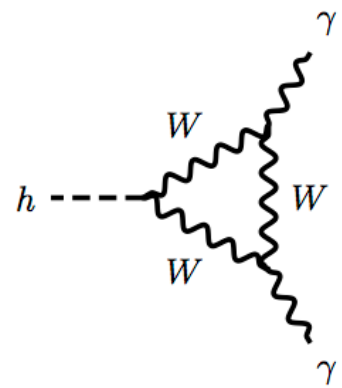
2 scalars (h^0,H^0), 1 pseudoscalar (A^0), 1 charged ($H^\pm$)

3 parameters ($m_{1,2,3}^2$) - M_Z = 2 free parameters

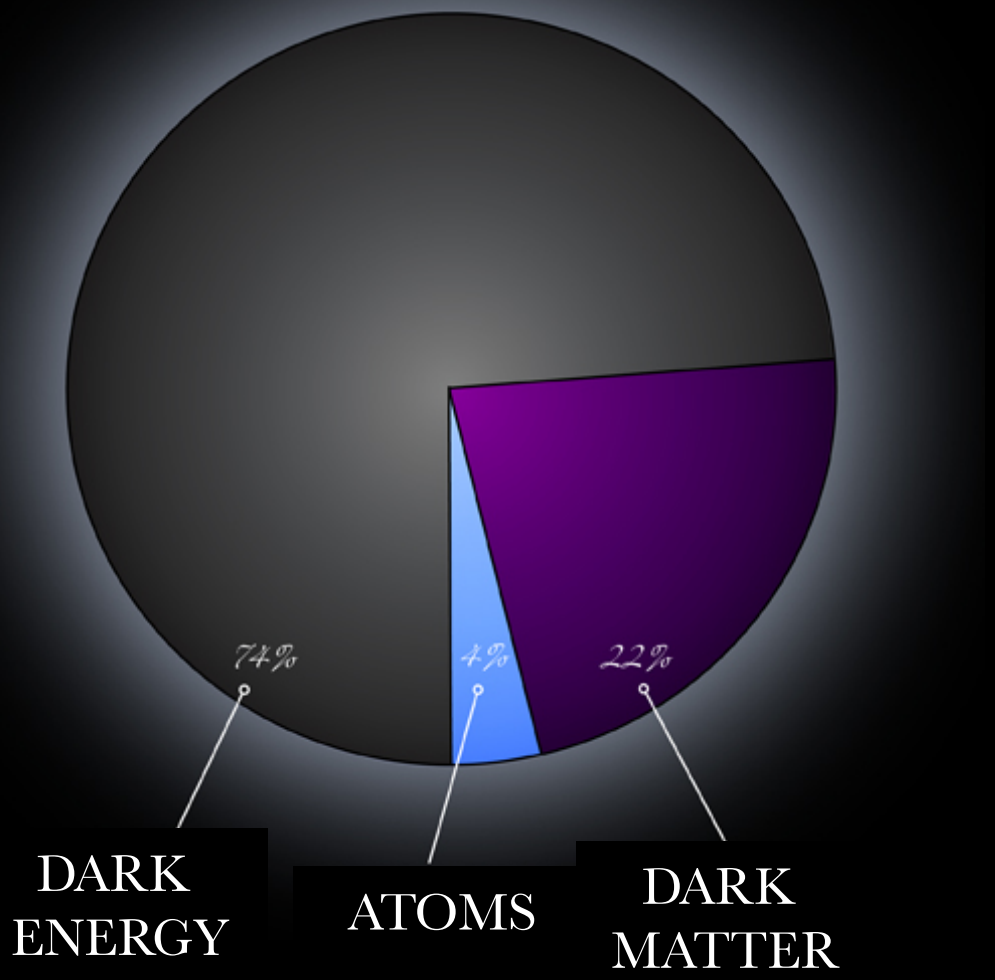


Susy Higgs couplings deviate from SM prediction





In spite of our successes, we are still in the dark...

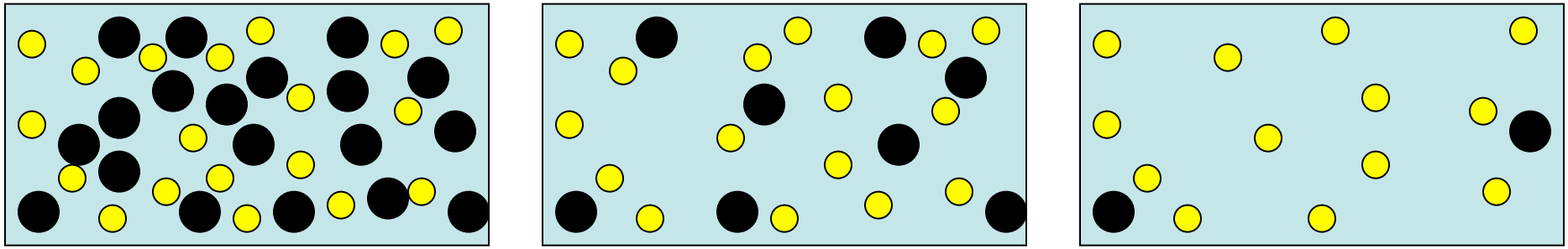


We still have to discover 96% of the universe!

Maybe supersymmetric particles are all around us at this very moment…

Link dark matter ←→ weak scale

If a stable massive particle is in thermal equilibrium in the early universe, its density today can be computed



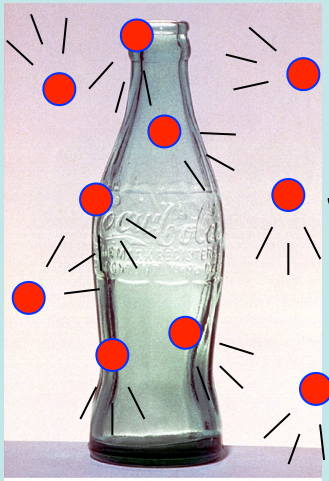
T >> M T ≈ M T << M

$$\sigma = \frac{k}{128\,\pi\, M^2} \quad \Rightarrow \quad \Omega_{DM} = 0.22 \left(\frac{M}{\sqrt{k}\ \mathrm{TeV}} \right)^2$$

Peculiar coincidence with the weak scale:

is dark matter made of supersymmetric particles?

Because of R-parity, LSP can behave as DM



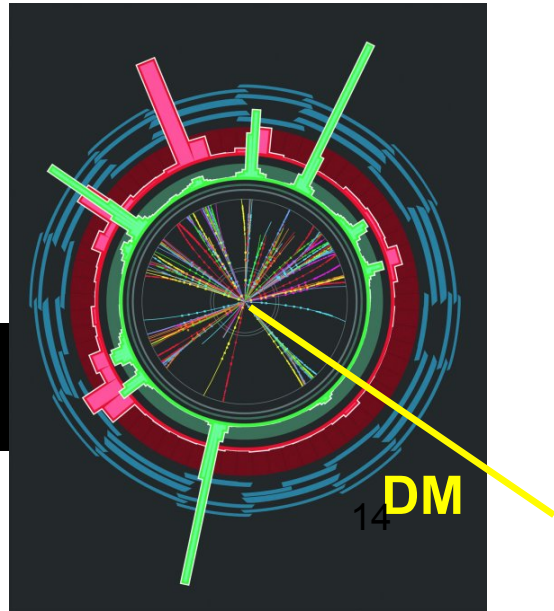
Several LSP per liter of space (moving at one million km/h)

Half a kg of them in the space occupied by the earth

matter: 6×10^{24} kg
dark matter: 0.6 kg

Power generated by DM on one kg of matter: 10^{-19} watts ➔ 1% of the moon for one light bulb

LHC could artificially produce DM

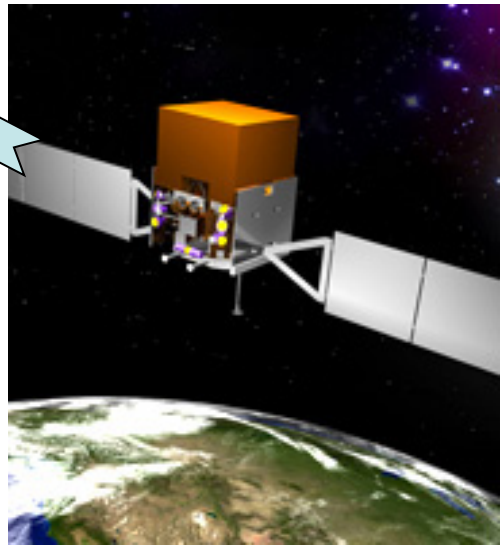


Complementarity of information

Direct detection

LHC

DM



Indirect detection

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Supersymmetry and unification

SM based on a symmetry principle:

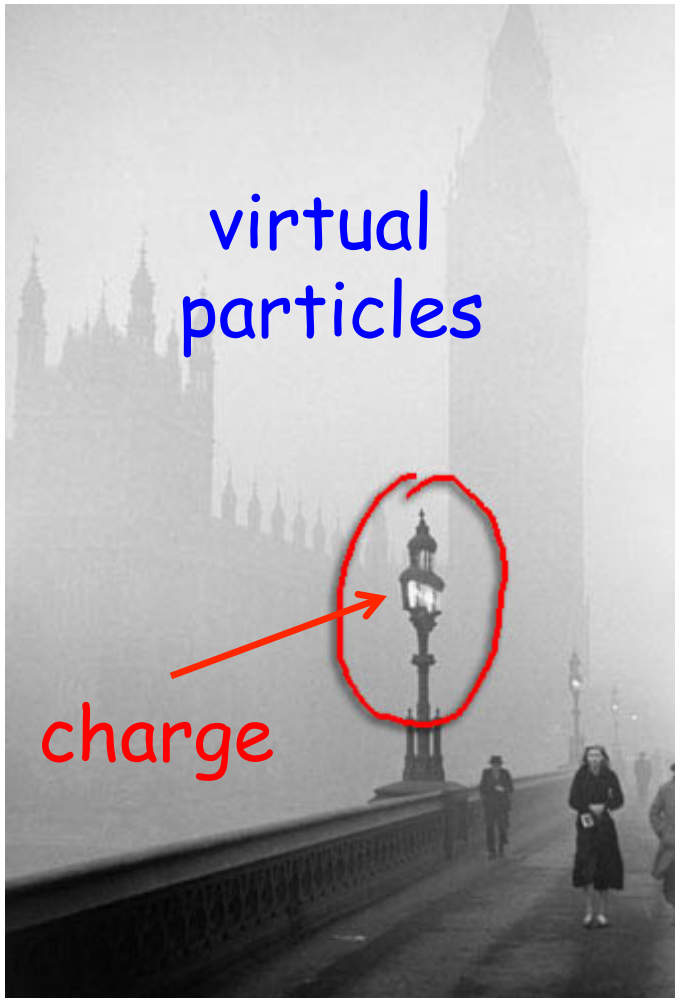
$$SU(3)\times SU(2)\times U(1)$$

strong: g_s

electroweak: $g,\ e$

Grand unification: single force ➔ single coupling

Classical physics: force depends on distance
Quantum physics: charge depends on distance



A strange phenomenon

QED: virtual particles screen the charge ➔ charge gets weaker as we move away

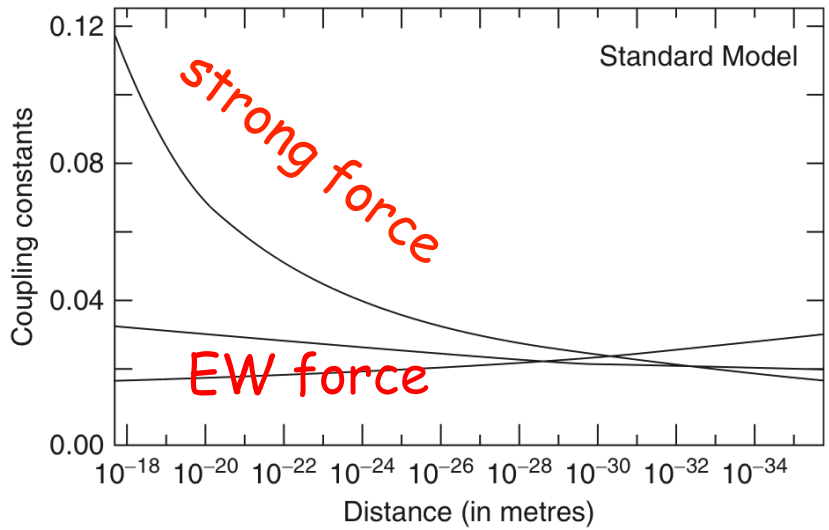
Even stranger

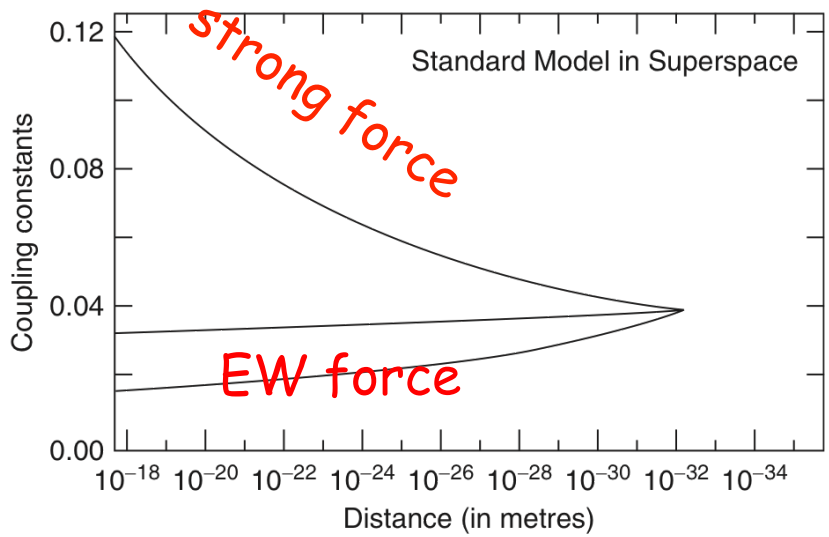
QCD: virtual particles antiscreen the charge ➔ charge gets stronger as we move away

$$\frac{d g_i^{-2}}{d \ln Q} = \frac{b_i}{4\pi}$$

SM $b_3=-7$, $b_2=-19/6$, $b_1=41/6$

susy $b_3=-3$, $b_2=1$, $b_1=11$





The screening (and antiscreening) depends on all species of existing particles

If supersymmetry is discovered, it could hint towards unification of forces at 10^{16} GeV

CONCLUSIONS

It is fascinating to speculate about the properties of matter and the physical laws at less than 10^{-19} m.

It is exciting to live in the age in which this unknown and strange space is explored by experiments.

If you have any questions:

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If you want to know more: