Theoretical overview for high energy physics

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ICPPA, Moscow, 22-26 October 2018

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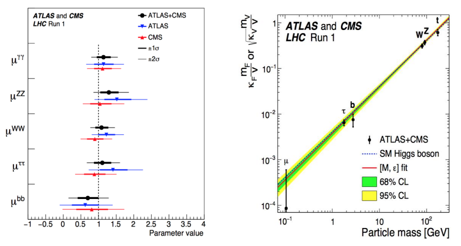
Standard Model of particle physics : accurate description of microphysics at present energies

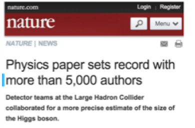
Higgs: ATLAS+CMS Combination

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

The Run-1 Higgs Legacy!

arXiv:1606.02266 /
JHEP 1608 (2016) 045
5153 authors!!





Physics paper sets record with more than 5,000 authors

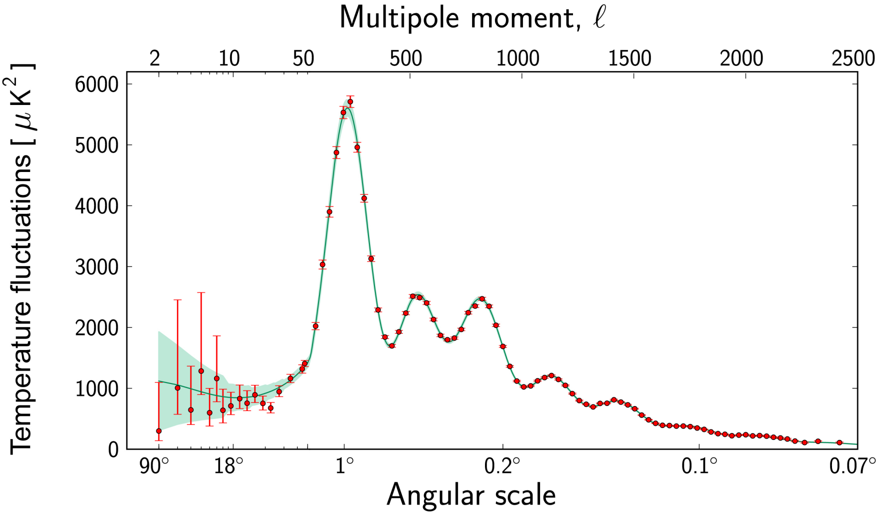
Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

The newly found boson has properties as expected for a Standard Model Higgs

Signal strength/SM:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

Standard Model of cosmology : ΛCDM



Beyond the Standard Model of PP : Why?

- to include gravity in a consistent quantum theory

  longstanding dream of unification of all fundamental forces of Nature

- hierarchy of masses and force intensities EW/gravity $\sim 10^{32}$

  stability at the quantum level $\Rightarrow$

  fine-tuning of parameters in 32 decimal places! [6]

- Neutrino masses and oscillations [7]

- origin of Dark Matter in the Universe [8]

Many theories have been proposed

Supersymmetry, new space dimensions, string theory, . . . [12]

Gravity : dominant force in astrophysics but irrelevant in particle physics

$m \bullet \longleftarrow r \longrightarrow \bullet\, m \qquad F_{\rm grav} = G_N \frac{m^2}{r^2} \qquad G_N^{-1/2} = M_{\rm Planck} = 10^{19}$ GeV

Compare with electric force: $F_{\rm el} = \frac{e^2}{r^2} \;\Rightarrow$

effective gravitational ‘charge’ $G_N m^2$ or in general $G_N E^2$ at energies E

$$E = m_{\rm proton} \;\Rightarrow\; \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m_{\rm proton}^2}{e^2} \simeq 10^{-40}$$

$\Rightarrow$ Gravity is very weak !

Beyond the Standard Theory of Particle Physics:
driven by the so-called mass hierarchy problem

Higgs mass: very sensitive to high energy physics

quantum corrections : $\delta m_H \sim$ scale of new physics/massive particles

stability requires adjustment of parameters at very high accuracy

to keep the physical mass $(m_H^{classical})^2 + \delta m_H^2$ at the weak scale

$\Rightarrow$ fine tuning up to 32 decimal places ! [4]

Neutrino masses and oscillations [4]

The Nobel Prize in Physics 2015

Takaaki Kajita

Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations, which shows that neutrinos have mass

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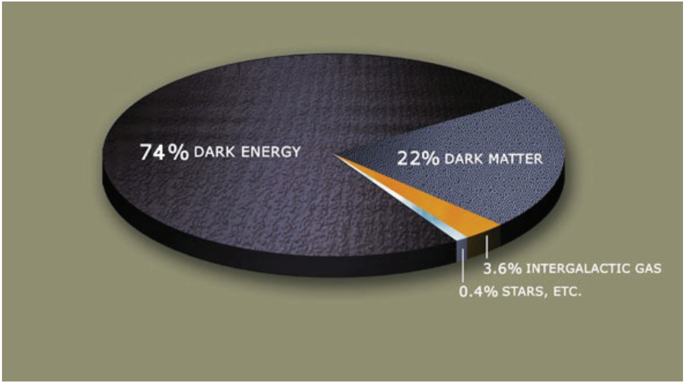
What our Universe is made of ?

- Ordinary matter: only a tiny fraction
- Non-luminous (dark) matter: $\sim 25\%$

  Natural explanation: new stable Weakly Interacting Massive Particle in the LHC energy region



Relativistic dark energy   70-75% of the observable universe

negative pressure: $p = -\rho \;\Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\Rightarrow\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

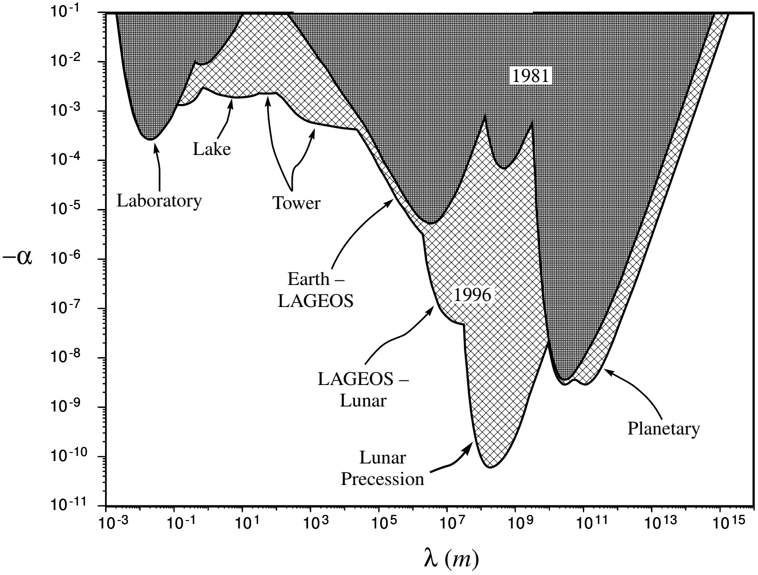
- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3 H_0^2 / c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  $\nwarrow$ Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

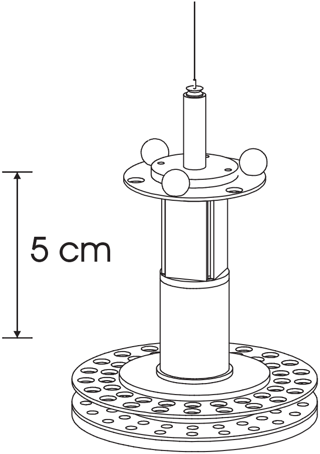
- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

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



Newton's law is valid down to distances 0.05 mm [4]

Adelberger et al. '06



Supersymmetry: every particle has a superpartner with spin differ by 1/2

Advantages:

- realize unification of the three Standard Model forces
- natural dark matter candidate (lightest supersymmetric particle)
- prediction of light Higgs ($\lesssim$ 130 GeV)
- rich spectrum of new particles within LHC reach

Problems:

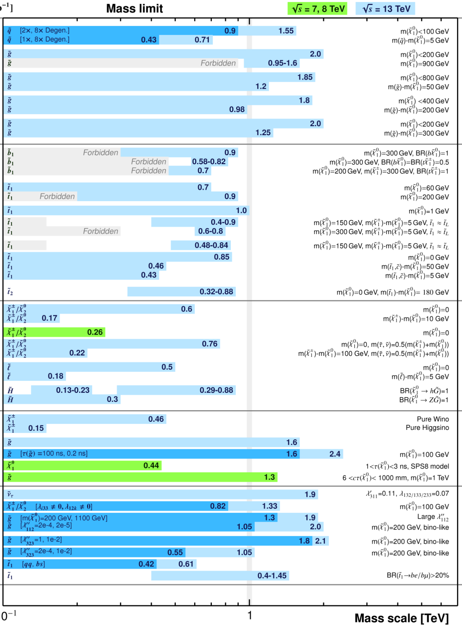
- too many parameters: soft breaking terms
- MSSM : already a % - ‰ fine-tuning 'little' hierarchy problem

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

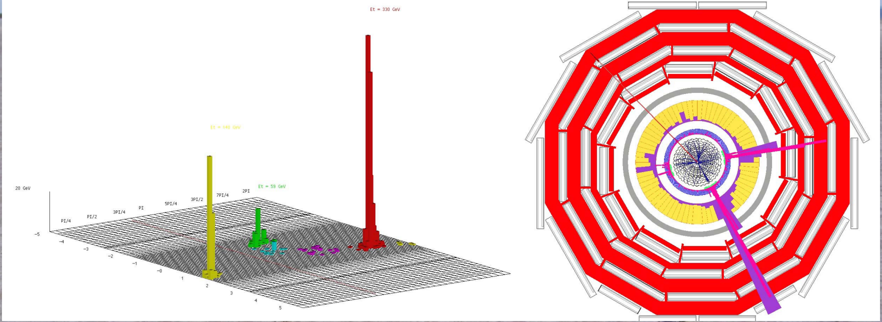
$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Classic Dark Matter Signature



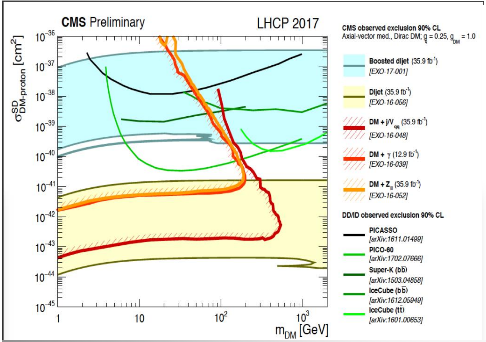
Missing transverse energy
carried away by dark matter particles

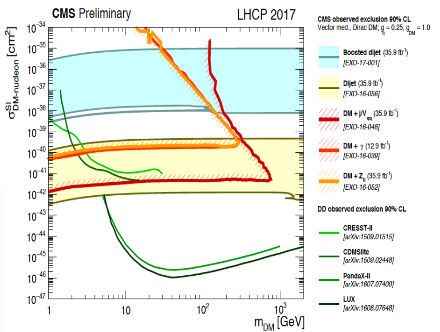
Comparison with Direct Detection

No signal seen in any of the “mono”-signals so far -> limits

Axial-vector mediator and
Spin-dependent direct limits

Vector mediator and
Spin-independent direct limits

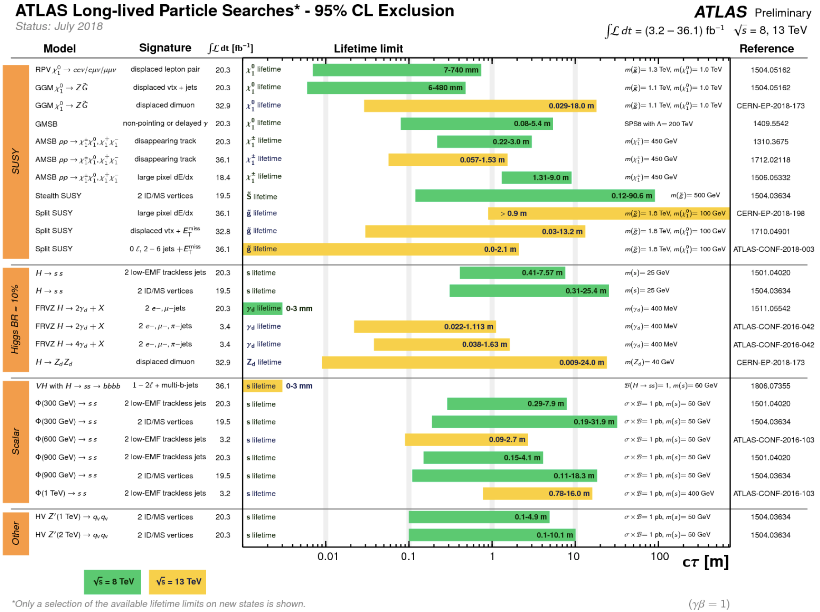




Mono-jet/V searches are typically the most sensitive ones

90% CL limits

Long Lived Particle Searches



ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2018

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 36.1)$ fb^{-1} $\sqrt{s} = 8, 13$ TeV

	Model	Signature	$\int\mathcal{L}\,dt$ [fb^{-1}]	Lifetime limit			Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime	7-740 mm	$m(\tilde{g})$= 1.3 TeV, $m(\chi_1^0)$= 1.0 TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime	6-480 mm	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced dimuon	32.9	χ_1^0 lifetime	0.029-18.0 m	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	CERN-EP-2018-173
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	0.08-5.4 m	SPS8 with Λ= 200 TeV	1409.5542
	AMSB $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^{\pm}$ lifetime	0.22-3.0 m	$m(\chi_1^{\pm})$= 450 GeV	1310.3675
	AMSB $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	36.1	$\chi_1^{\pm}$ lifetime	0.057-1.53 m	$m(\chi_1^{\pm})$= 450 GeV	1712.02118
	AMSB $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^{\pm}$ lifetime	1.31-9.0 m	$m(\chi_1^{\pm})$= 450 GeV	1506.05332
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime	0.12-90.6 m	$m(\tilde{g})$= 500 GeV	1504.03634
	Split SUSY	large pixel dE/dx	36.1	$\tilde{g}$ lifetime	> 0.9 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	CERN-EP-2018-198
	Split SUSY	displaced vtx + E_T^{miss}	32.8	$\tilde{g}$ lifetime	0.03-13.2 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1710.04901
	Split SUSY	$0\ \ell, 2-6$ jets $+E_T^{miss}$	36.1	$\tilde{g}$ lifetime	0.0-2.1 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \to s\,s$	2 low-EMF trackless jets	20.3	s lifetime	0.41-7.57 m	$m(s)$= 25 GeV	1501.04020
	$H \to s\,s$	2 ID/MS vertices	19.5	s lifetime	0.31-25.4 m	$m(s)$= 25 GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-$jets	20.3	γ_d lifetime	0-3 mm	$m(\gamma_d)$= 400 MeV	1511.05542
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	0.022-1.113 m	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2016-042
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	0.038-1.63 m	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2016-042
	$H \to Z_d Z_d$	displaced dimuon	32.9	Z_d lifetime	0.009-24.0 m	$m(Z_d)$= 40 GeV	CERN-EP-2018-173
Scalar	VH with $H \to ss \to bbbb$	$1-2\ell$ + multi-b-jets	36.1	s lifetime	0-3 mm	$\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV	1806.07355
	Φ(300 GeV) $\to s\,s$	2 low-EMF trackless jets	20.3	s lifetime	0.29-7.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1501.04020
	Φ(300 GeV) $\to s\,s$	2 ID/MS vertices	19.5	s lifetime	0.19-31.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	Φ(600 GeV) $\to s\,s$	2 low-EMF trackless jets	3.2	s lifetime	0.09-2.7 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	ATLAS-CONF-2016-103
	Φ(900 GeV) $\to s\,s$	2 low-EMF trackless jets	20.3	s lifetime	0.15-4.1 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1501.04020
	Φ(900 GeV) $\to s\,s$	2 ID/MS vertices	19.5	s lifetime	0.11-18.3 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	Φ(1 TeV) $\to s\,s$	2 low-EMF trackless jets	3.2	s lifetime	0.78-16.0 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 400 GeV	ATLAS-CONF-2016-103
Other	HV Z'(1 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	s lifetime	0.1-4.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	HV Z'(2 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	s lifetime	0.1-10.1 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634

**Only a selection of the available lifetime limits on new states is shown.*

String theory: Quantum Mechanics + General Relativity

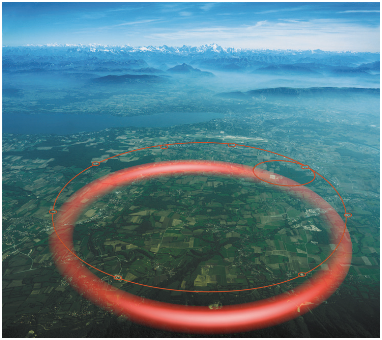
Main predictions → inspirations for BSM physics

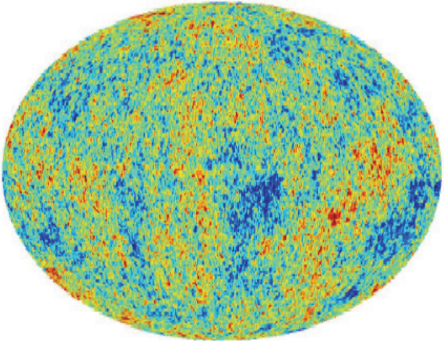
- Spacetime supersymmetry   but arbitrary breaking scale
- Extra dimensions of space   six or seven in M-theory
- Brane-world description of our Universe

  matter and gauge interactions may be localised in less dimensions
- Landscape of vacua
- $\cdots$

Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- If theory of Nature can it describe both particle physics and cosmology?





At what energies strings may be observed?

Very different answers depending mainly on the value of the string scale M_s

Before 1994: $M_s \simeq M_{\rm Planck} \sim 10^{18}$ GeV $\quad l_s \simeq 10^{-32}$ cm $\quad$ After 1994:

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV

- physical motivations $\Rightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$
- Intermediate : around 10^{11} GeV $(M_s^2/M_P \sim \text{TeV})$

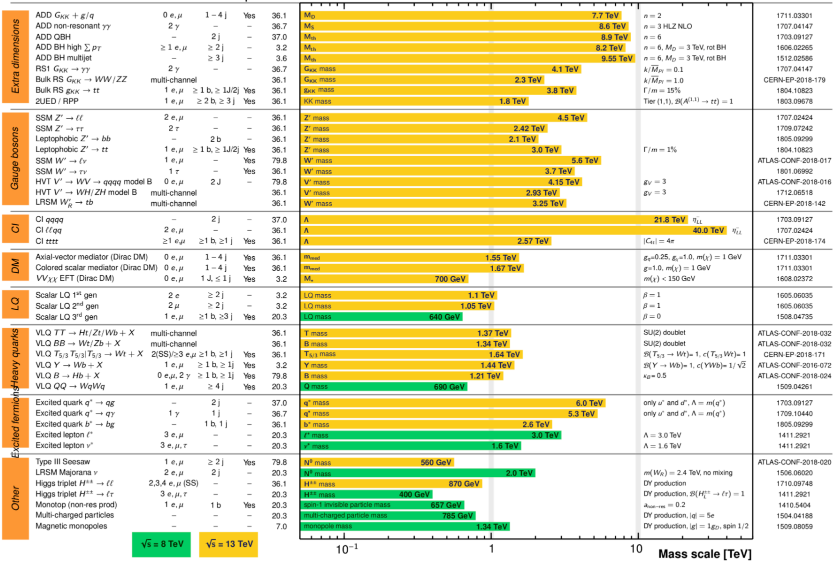
  SUSY breaking, strong CP axion, see-saw scale
- Low : TeV $\quad$ (hierarchy problem)

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

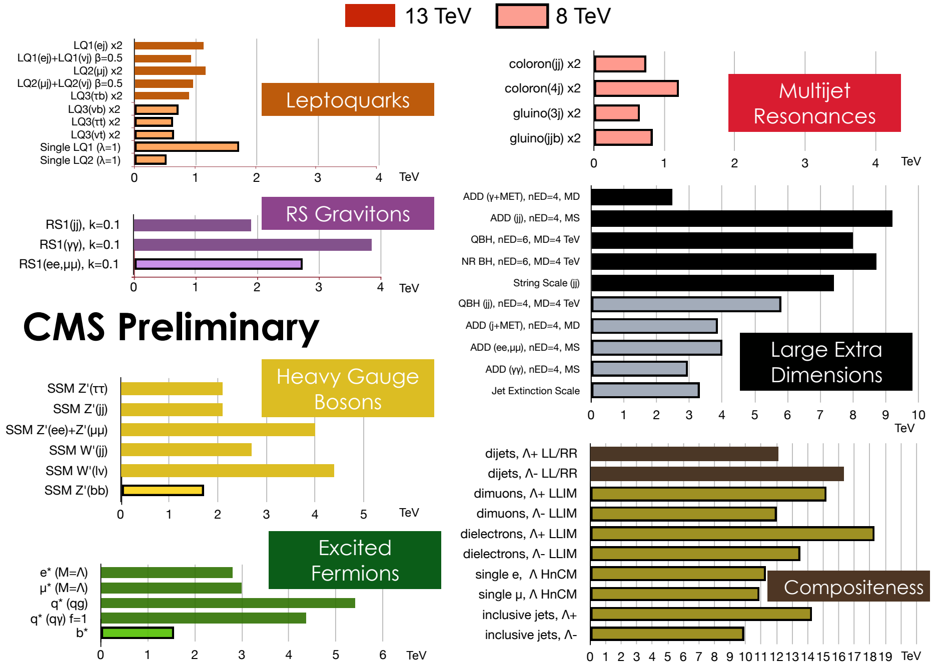
$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV η_{LL}^-		1707.02424
	CI $tttt$	≥ 1 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

**Only a selection of the available mass limits on new states or phenomena is shown.*

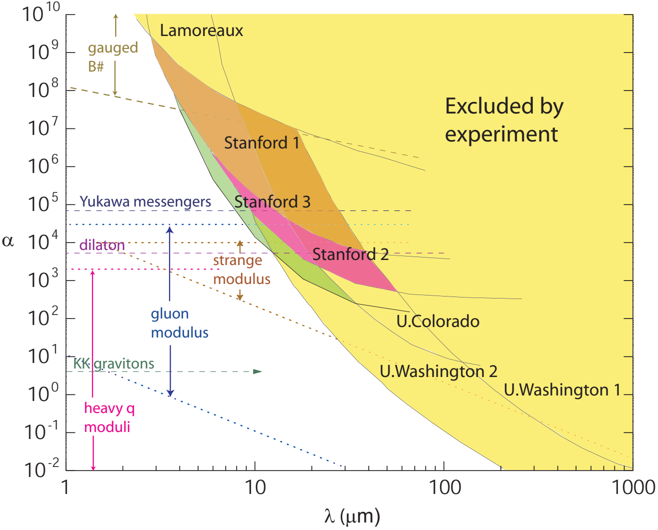
†Small-radius (large-radius) jets are denoted by the letter j (J).



CMS Exotica Physics Group Summary – ICHEP, 2016

Experimental limits on short distance forces

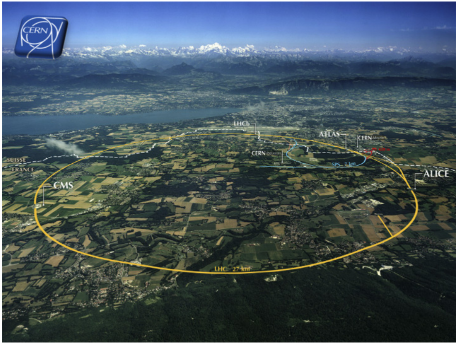
$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



What is next?

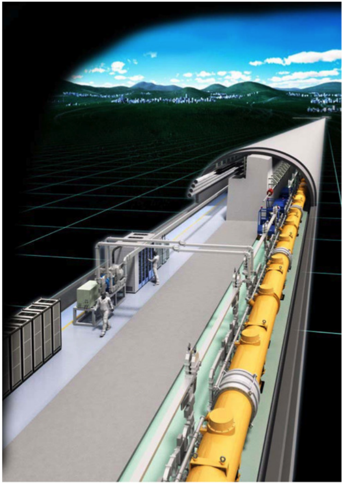
Physics is an experimental science

- Exploit the full potential of LHC
- Go on and explore the multi TeV energy range

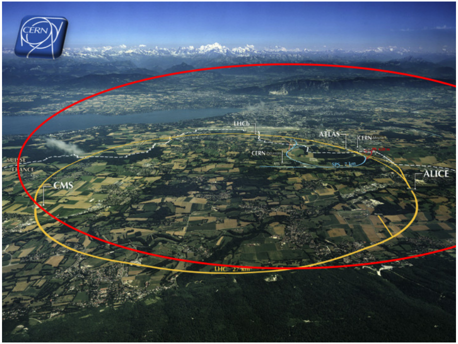


Explore the 10-100 TeV energy range

Linear Colliders - ILC project



Circular Colliders



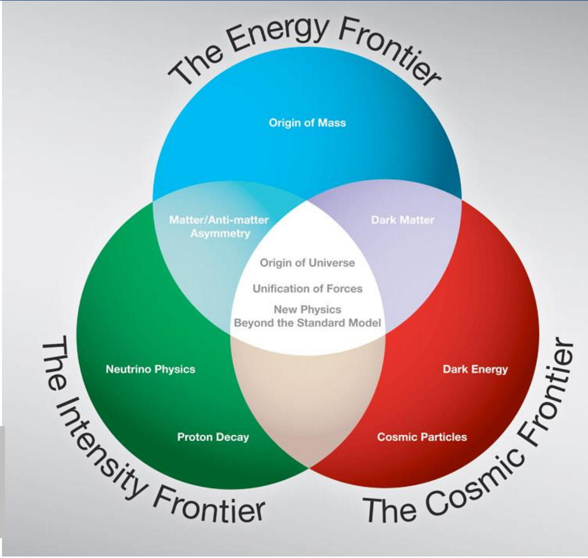
Future HEP: The Three Frontiers

After the Higgs discovery

2012-2014

Evaluation in all regions: Europe Asia, the Americas

- European strategy group
- Snowmass study and IP5
- Japan strategy group



Problem of scales

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

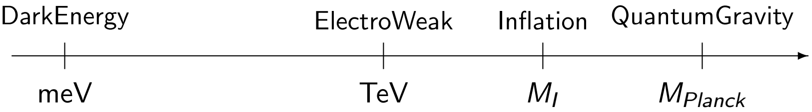
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

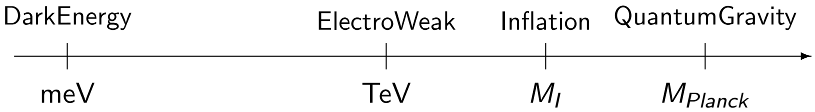
- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

⇒ 3 very different scales besides M_{Planck} :



Problem of scales


DarkEnergy ElectroWeak Inflation QuantumGravity

meV TeV M_I M_{Planck}

1. they are independent
2. possible connections
    - M_I could be near the EW scale, such as in Higgs inflation

      but large non minimal coupling to explain
    - M_{Planck} could be emergent from the EW scale

      in models of low-scale gravity and TeV strings
    - → connect inflation and SUSY breaking scales

      while accommodating observed vacuum energy

Inflation in supergravity: main problems

- slow-roll conditions: the eta problem $\Rightarrow$ fine-tuning of the potential

  $$\eta = V''/V \, , \quad V_F = e^K(|DW|^2 - 3|W|^2) \, , \quad DW = W' + K'W$$

  K: Kähler potential, W: superpotential

  canonically normalised field: $K = X\bar{X} \Rightarrow \eta = 1 + \dots$

- trans-Planckian initial conditions $\Rightarrow$ break validity of EFT

  no-scale type models that avoid the η-problem $\quad K = -3\ln(T + \bar{T})$

- stabilisation of the (pseudo) scalar companion of the inflaton

  chiral multiplets $\Rightarrow$ complex scalars

- moduli stabilisation, de Sitter vacuum, ...

Inflation from supersymmetry breaking

I.A.-Chatrabhuti-Isono-Knoops '16, '17, '18

Inflaton : goldstino superpartner in the presence of a gauged R-symmetry

- linear superpotential $W = f\,X \Rightarrow$ no η-problem

$$\begin{aligned} V_F &= e^K \left(|DW|^2 - 3|W|^2\right) \\ &= e^K \left(|1 + K_X X|^2 - 3|X|^2\right) |f|^2 \qquad K = X\bar{X} \\ &= e^{|X|^2} \left(1 - |X|^2 + \mathcal{O}(|X|^4\right) |f|^2 = \mathcal{O}(|X|^4) \quad \Rightarrow \eta = 0 + \dots \end{aligned}$$

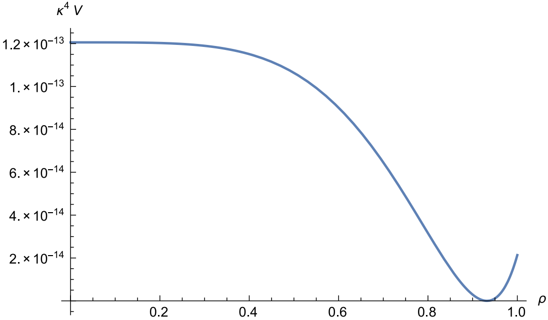
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  no large field initial conditions

- gauge R-symmetry: (pseudo) scalar absorbed by the $U(1)_R$
- vacuum energy at the minimum: tuning between V_F and V_D

Two classes of models

- Case 1: R-symmetry is restored during inflation (at the maximum)



- Case 2: R-symmetry is (spontaneously) broken everywhere

(and restored at infinity)

example: toy model of SUSY breaking

Case 1: predictions

slow-roll parameters

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = \text{naturally small parameter} + \mathcal{O}(\rho^2)$$

$$\epsilon = \frac{1}{2\kappa^2}\left(\frac{V'}{V}\right)^2 \simeq \eta^2\rho^2 + \mathcal{O}(\rho^4) << \eta \quad \Rightarrow$$

spectral index $n_s = 1 + 2\eta_* - 6\epsilon_* \simeq 1 + 2\eta_*$

number of e-folds $N = \int_{end}^{start} \frac{V}{V'} = \kappa \int \frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{|\eta_*|} \ln\left(\frac{\rho_{\rm end}}{\rho_*}\right)$

Planck '15 data : $\eta_* \simeq -0.02 \Rightarrow$ correct prediction for $N \gtrsim 50$

$\text{tensor} - \text{to} - \text{scalar ratio}\ r = 16\epsilon_*$ in general small

$r \lesssim 10^{-4}$, $H_* \lesssim 10^{12}$ GeV   assuming $\rho_{\rm end} \lesssim 1/2$

However a modified model with D-terms allow r as large as 0.015

Conclusions

The quest for new physics beyond the current standard models of particle physics and cosmology continues on several fronts

Awaiting for new discoveries

Challenge of scales: at least three very different (besides M_{Planck})

electroweak, dark energy, inflation, SUSY?

their origins may be connected or independent

General class of models with inflation from SUSY breaking:

identify inflaton with goldstino superpartner

small field, avoids the η-problem, no (pseudo) scalar companion