The Physics Landscape

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Open Symposium on European Strategy for Particle Physics

CERN Council Strategy Group

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The future of HEP hinges on the LHC

1st mission: look for the Higgs

$$A\left(W_L^+W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}\left(1 - \frac{E^2}{E^2 - m_H^2}\right)$$

Without Higgs ⇨ E < 1.2 TeV

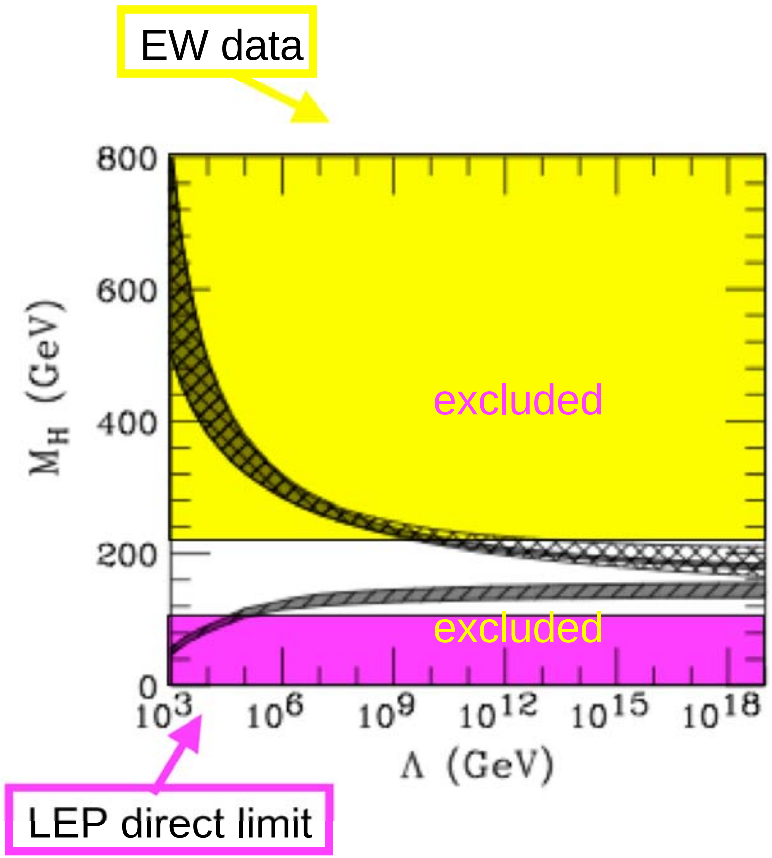
With Higgs ⇨ m_H < 780 GeV

LHC must discover Higgs or New Physics below TeV,

or else *unitarity* is violated

2^{nd} mission: search for New Physics

Extrapolate to high energies: $V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$



114 GeV < m_H < 130 GeV:
$V(H)$ unstable for $\Lambda < 10^7$ GeV

130 GeV < m_H < 180 GeV:
valid extrapolation to M_{GUT}

m_H > 219 GeV:
conflict with EW data

Extrapolate to high energies: $V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$

$\mu_H{}^2$ very sensitive to high-energy corrections

$$\delta\mu_H^2 = \frac{3G_F}{8\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 = -(0.2\,\Lambda)^2$$

$$\Lambda_{\max} = \mathrm{TeV}\left(\frac{m_H}{115\ \mathrm{GeV}}\right)\left(\frac{10\%}{\delta}\right)^{1/2}$$

No large tuning $\Rightarrow \Lambda <$ TeV

Can $m_H \sim$ 180–220 GeV reduce the tuning? NO!

Abuse of effective theories: finite (or log-div) corrections at Λ remain

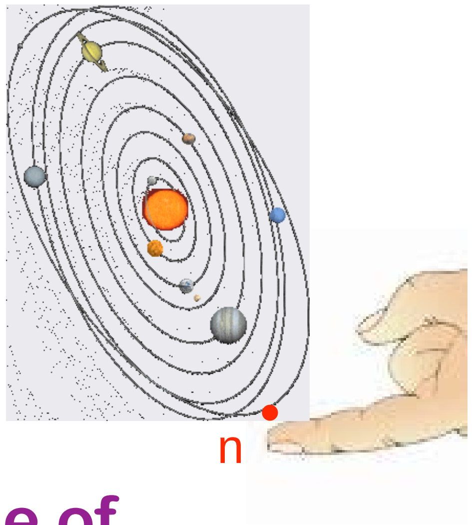
Ex.: in SUSY quadratic divergences cancel, but $\delta\mu_H^2 \approx \tilde{m}^2$

Consistency ⇒ $m_H < 780$ GeV or $\Lambda < 1.2$ TeV

⇒ discovery of Higgs, new dynamics, or strong WW scattering

Naturalness ⇒ $\Lambda < 1$ TeV

⇒ search for new physics



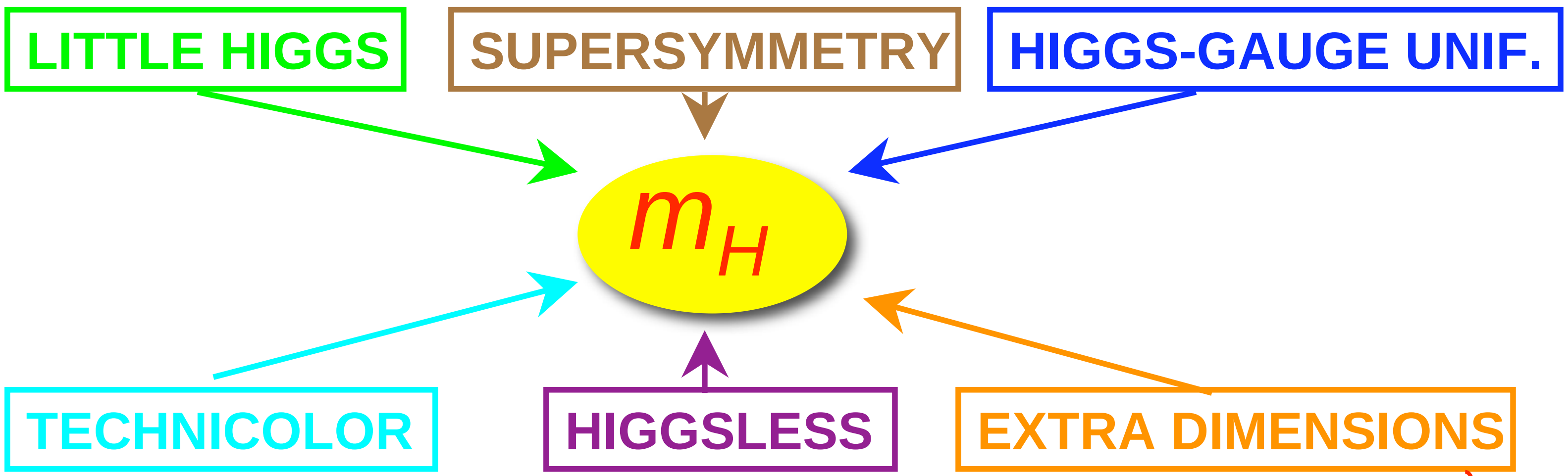
$$\text{Necessary tuning } \frac{M_Z^2}{\Lambda^2} \rightarrow \frac{M_Z^2}{M_{\text{GUT}}^2} \approx 10^{-28}$$

Cancellation of	Existence of
electron self-energy	positron
π^+-π^0 mass difference	ρ
K_L-K_S mass difference	charm
gauge anomaly	top
cosmological constant	10^{-3} eV??

CAVEAT EMPTOR

What screens the Higgs mass?

boson	fermion	vector	
$\phi \to \phi + a$	$\psi \to e^{ia\gamma_5}\psi$	$A_\mu \to A_\mu + \partial_\mu a$	
no $m^2\phi^2$	no $m\bar{\psi}\psi$	no $m^2 A_\mu A^\mu$	**Symmetry**
Spont. broken global symm.	Chiral symmetry	Gauge symmetry	



Dynamical EW breaking	Delayed unitarity violat.	Fundamental scale at TeV	**Dynamics**

- Very fertile field of research
- Different proposals not mutually excluded

Tense confrontation with data

Ex.: supersymmetry

$$\delta\mu_H^2 = \frac{3G_F m_t^2 \tilde{m}_t^2}{\sqrt{2}\pi^2} \log\frac{\Lambda}{\tilde{m}_t}$$

less than 10% tuning $\Rightarrow$ $\tilde{m}_t \lesssim 300\ \text{GeV}$

Higgs mass

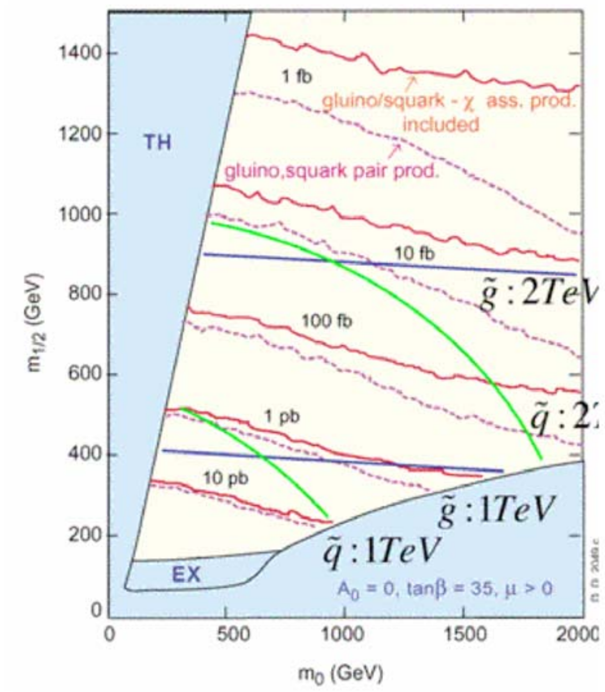
$$m_H^2 = M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log\frac{\tilde{m}_t^2}{m_t^2}$$

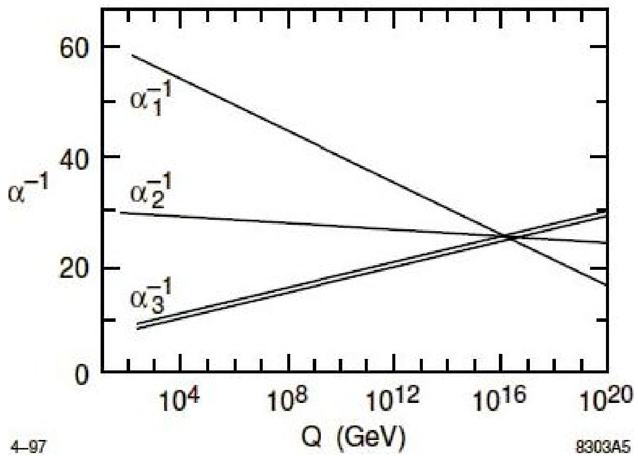
$$m_H > 114\ \text{GeV} \quad \Rightarrow \quad \tilde{m}_t \gtrsim 1\ \text{TeV}$$

Almost all BSM theories are tuned at few % or worse

(not much wrt $(M_W/M_{GUT})^2 \sim 10^{-28}$, but it bites into LHC territory)

The issue will be resolved at LHC





Clear signal: $\sigma(\text{TeV}\ \tilde{g}) \approx \text{pb}$

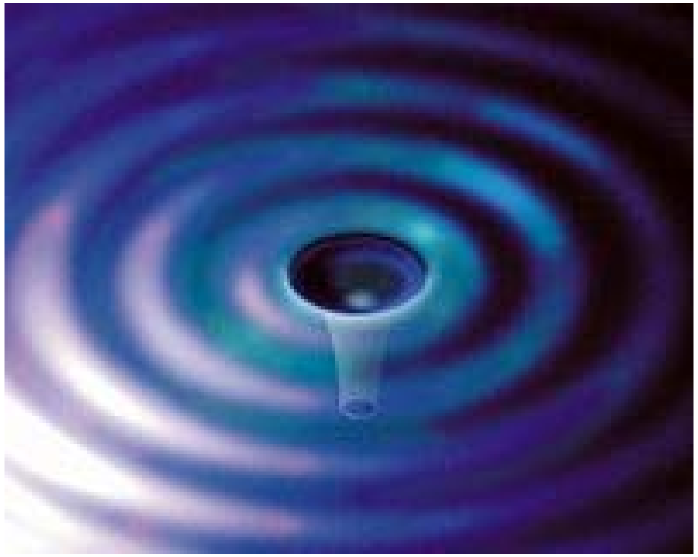
LHC with 100 $\text{fb}^{-1} \Rightarrow 10^4$ € / gluino

Supersymmetry: triumph of symmetry concept!

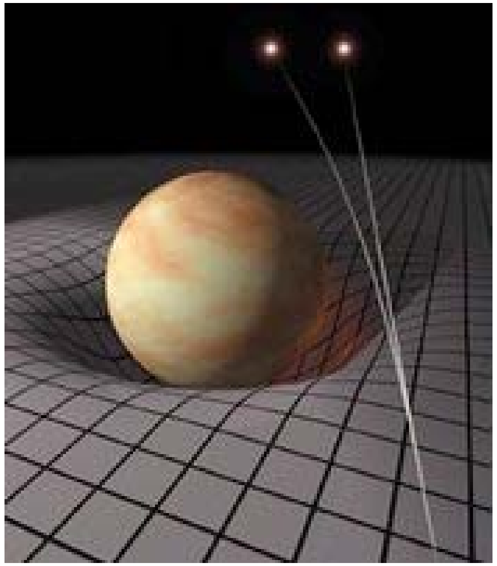
- Gauge-coupling unification
- Dark Matter
- Radiative EW breaking

Extra Dimensions

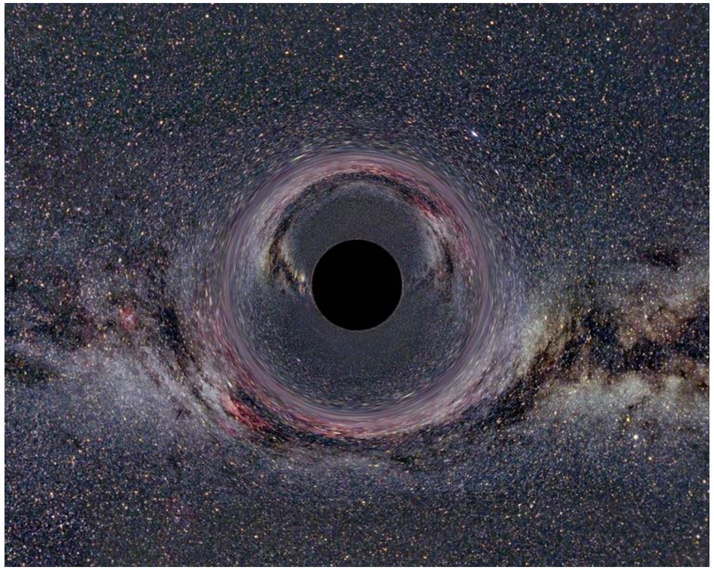
Gravity into collider arena



Gravitational wave
jet + $\not{E}_T$



Gravitational deflection
dijet



Black hole
multiparticle event

Discovery vs Interpretation

In susy: disantangle parameter space from data

- Vast parameter space
- Different exp strategies

$\not{E}_T$	sugra (χ^0), gauge med (χ^0)
$\not{E}_T\,\gamma$	gauge med (χ^0)
$\not{E}_T\,\tau$	sugra, gauge med ($\tilde{\tau}$)
$\not{E}_T$+ soft	anomaly med, well-tempered
long-lived charged	sugra ($\tilde{G}$), gauge med ($\tilde{\tau}$)
long-lived coloured	split
long-lived charged & coloured	5-d orbifold

LHC as a precision machine

Great progress made by
EXP and TH communities:

- Detector studies
- New techniques for analytic calculations
- MC tools
- NLO implementations

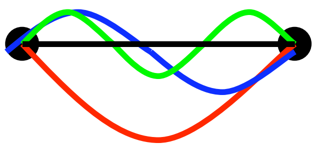
	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\ell}_L}$	5.0	0.2 (LC input)
Δm_{τ_1}	5-8	0.3 (LC input)
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

Discovery of supersymmetry ⇒ need for accuracy
LHC ⇒ SLHC, ILC, CLIC

- Confirm supersymmetry (partners with 1/2-spin diff.)
- Structure of supersymmetry breaking
- LSP relic abundance
- Unification of gaugino masses
- Radiative EW breaking

A different point of view

- "Collective breaking" $m_H^2 = \frac{\alpha_1}{4\pi}\frac{\alpha_2}{4\pi}\Lambda^2$ ⇒ Little Higgs
- AdS/CFT 5-D warped gravity ⇔ large-N technicolor ⇒ Composite Higgs
- New ways of symmetry breaking ⇒ Higgsless



no zero modes in restricted extra-D spaces
(Scherk-Schwarz mechanism)

Inspired by extra dimensions

Breakdown of unitarity: $4\,d \quad \Rightarrow \quad \Lambda \approx \frac{4\pi\, m_W}{g} \approx \text{TeV}$

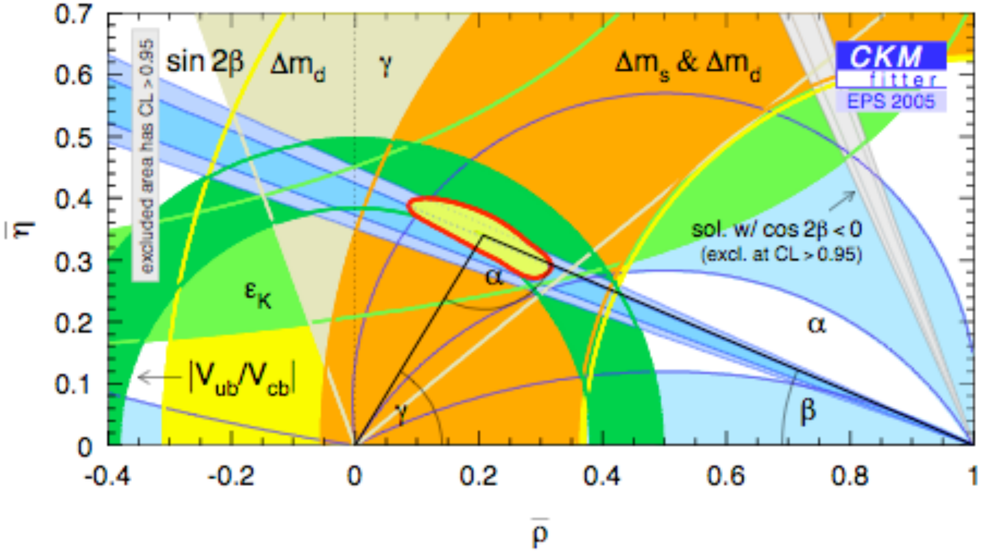
$$5\,d \quad \Rightarrow \quad \Lambda \approx \frac{24\pi^3}{g_5^2} \approx \frac{12\pi^2\, m_W}{g^2} \approx 10\ \text{TeV}$$

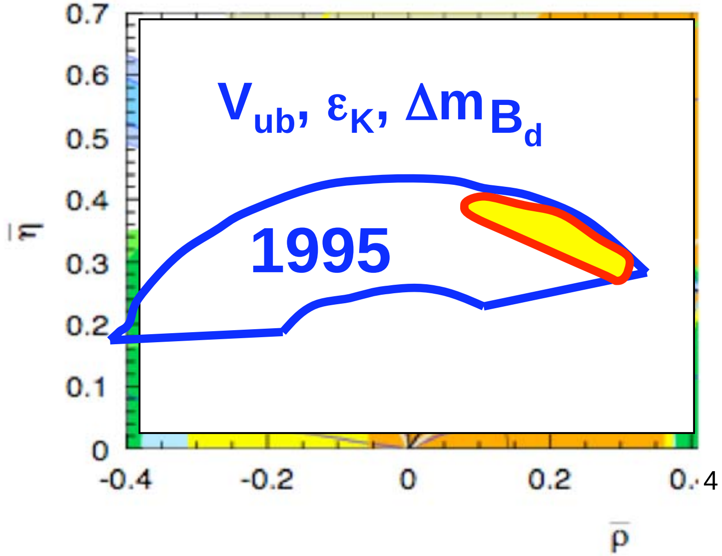
New states at TeV, cutoff at about 10 TeV

Besides accuracy, thirst for more energy ⇒
DLHC, VLHC, μ collider

- Evidence for new threshold
- Contact interactions
- Incomplete spectrum

Flavour Physics: precision era





CKM established as the leading mechanism
of flavour and CP violation

More to be explored: B_s mixing, ~~CP~~ in *b*-*s* transitions, rare decays

1 yr of LHCb, 5σ up to ΔM_s=68 ps^{-1}

Main goal: probe new physics

CKM $\Rightarrow$ Yukawa only source of flavour (SU_3^5) breaking

BSM $\Rightarrow$ new operators with Yukawa (MFV) or independent structure

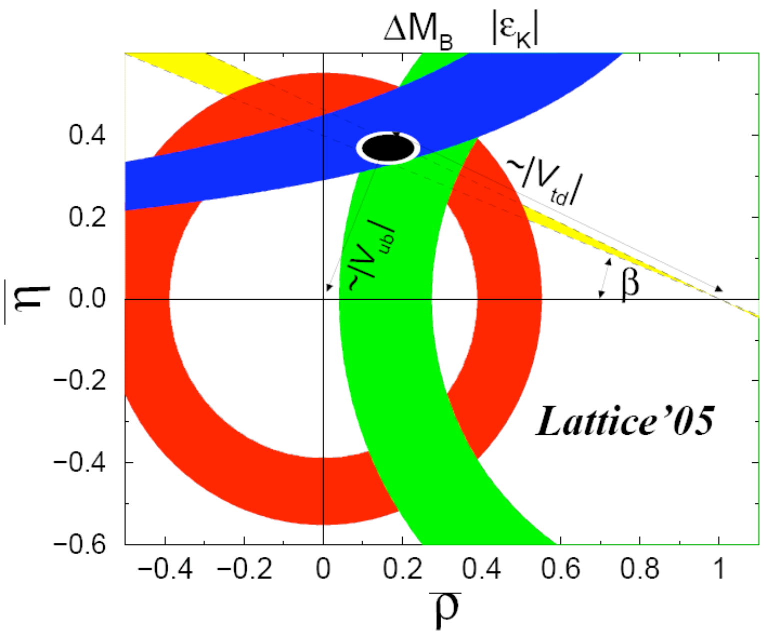
Need to satisfy expt'l constraints (the "flavour problem") has been a key element in construction of susy models (gauge mediation, anomaly mediation, gaugino mediation)

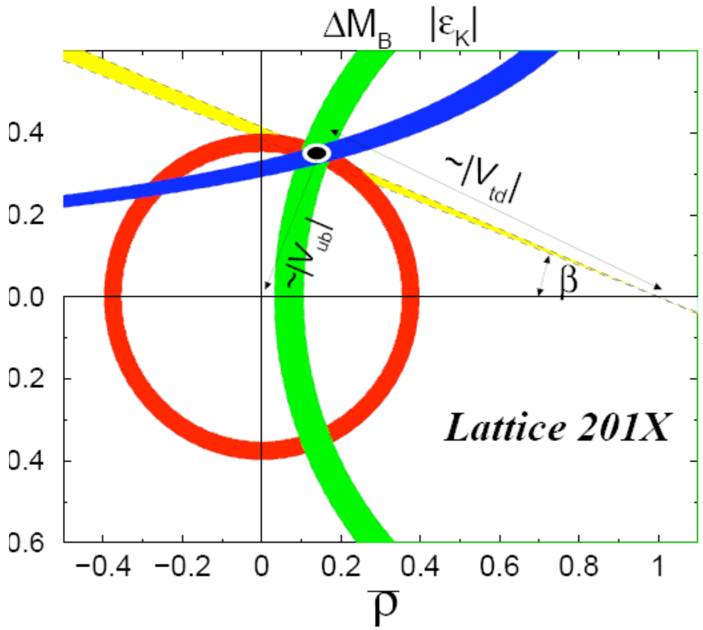
What is the necessary sensitivity?

To answer, we need to know
- theory of fermion masses → at which scale?
- new physics effects → indication from LHC?

Strategy: measure SM processes up to theoretical uncertainty

Hadronic matrix elements
- QCD approximate sym. (Isospin, $SU(3)_F$) → error assessment
- Expansions in small parameters (Op. product exp., Heavy-quark eff. th., Soft-collinear eff. th.) → applicability
- Lattice calculations → non-quenched (computational power)





Okamoto

Measurement (in SM)	Theoretical limit	Present error
$B \to \psi K_S\ (\beta)$	$\sim 0.2^\circ$	1.6°
$B \to \phi K_S,\ \eta^{(\prime)} K_S, \ldots\ (\beta)$	$\sim 2^\circ$	$\sim 10^\circ$
$B \to \pi\pi,\ \rho\rho,\ \rho\pi\ (\alpha)$	$\sim 1^\circ$	$\sim 15^\circ$
$B \to DK\ (\gamma)$	$\ll 1^\circ$	$\sim 25^\circ$
$B_s \to \psi\phi\ (\beta_s)$	$\sim 0.2^\circ$	—
$B_s \to D_s K\ (\gamma - 2\beta_s)$	$\ll 1^\circ$	—
$\lvert V_{cb}\rvert$	$\sim 1\%$	$\sim 3\%$
$\lvert V_{ub}\rvert$	$\sim 5\%$	$\sim 15\%$
$B \to X \ell^+ \ell^-$	$\sim 5\%$	$\sim 20\%$
$B \to K^{(*)} \nu \bar{\nu}$	$\sim 5\%$	—
$K^+ \to \pi^+ \nu \bar{\nu}$	$\sim 5\%$	$\sim 70\%$
$K_L \to \pi^0 \nu \bar{\nu}$	$< 1\%$	—

Ligeti

Post-LHC reasons for superfactories

α, β, γ, V_{ub}, V_{cb}, ΔM_d to limit of precision

CP in $b \to sss$, $b \to dss$, $b \to s\gamma$

A_{FB} in $b \to sll$ (location of zeros)

$B \to K\nu\nu$, $B \to \tau\nu$

$K \to \pi\nu\nu$

The landscape of flavour experiments and searches for rare or forbidden processes

B, *K*, τ, *c*, μ, EDM, *p*-decay, axion searches,
deviation of Newton's law

Examples:

$$\mathrm{BR}(\mu \to e\gamma) \quad 10^{-11} \to 10^{-13} - 10^{-14} \quad \vartheta_{\tilde{\ell}} \approx \left(\frac{\mathrm{BR}}{10^{-14}}\right)^{1/2} \left(\frac{\tilde{m}}{300\ \mathrm{GeV}}\right)^{2} 10^{-4} \Rightarrow \text{GUT}$$

PSI

$$\mathrm{EDM}\ d_e\ 10^{-27}\ \mathrm{e\ cm} \to 10^{-30}\ \mathrm{e\ cm?} \quad \phi_{CP} \approx \left(\frac{d_e}{10^{-27}\ \mathrm{e\ cm}}\right)\left(\frac{\tilde{m}}{300\ \mathrm{GeV}}\right)^{2} 10^{-2} \Rightarrow \text{~~SUSY~~}$$

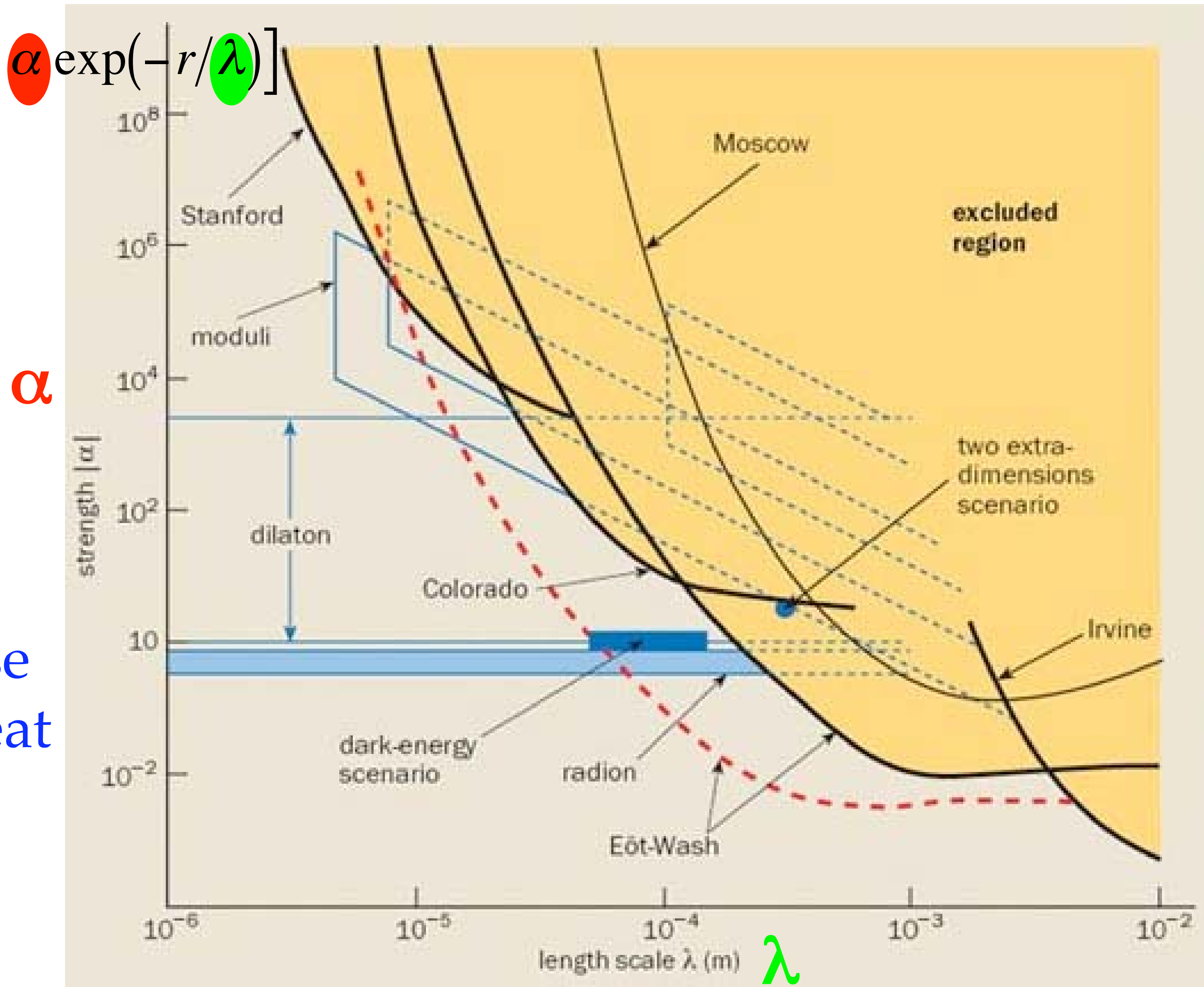
PSI, ILL Grenoble,
LANL, BNL

SUSY: $\phi_{CP} \sim \mathcal{O}(1)$?

With heavy scalars: $\phi_{CP} \sim \mathcal{O}(1/16\pi^2)$

Testing gravity at small distances

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 + \alpha \exp(-r/\lambda)\right]$$



No guaranteed signal but, in case of discovery, great impact

Flavour experiments and searches for rare or forbidden phenomena are complementary to high-energy searches and have great potential

Vital for fundamental research to have a diversified programme, esp. in the phase of discovery

Yet, in the US, many projects have been terminated

SuperBelle under discussion in Japan

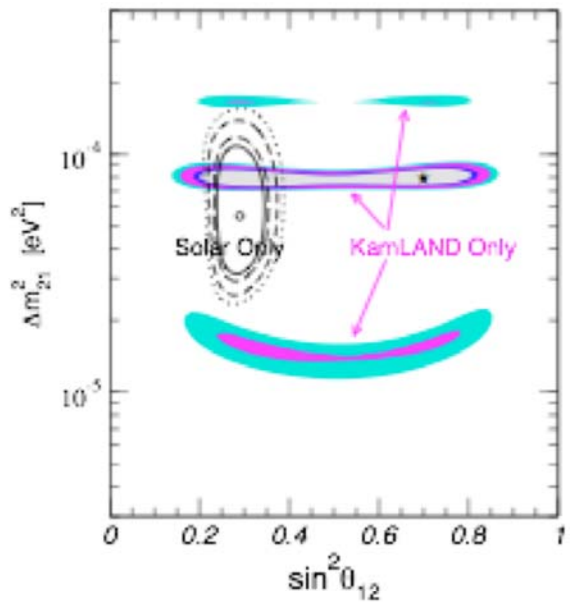
What will be Europe's role?

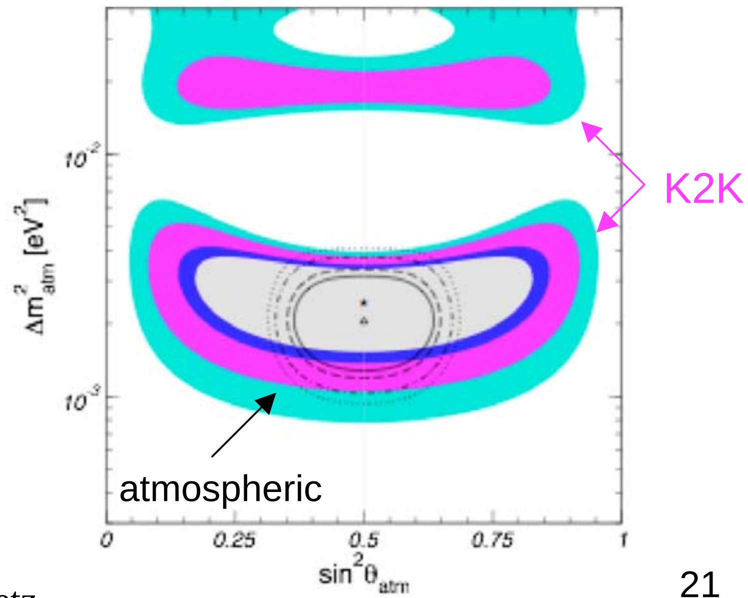
Neutrinos

Evidence of physics BSM

New mass scale $M = \frac{M_W^2}{m_\nu} \approx 10^{14}\ \text{GeV}$ close to M_{GUT}?

Striking confirmation between sol & atm oscillation and terrestrial experiments



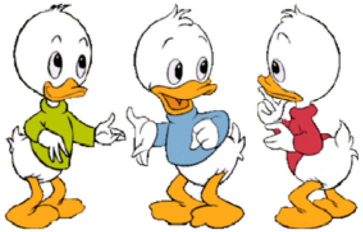


Schwetz

Issues to be resolved

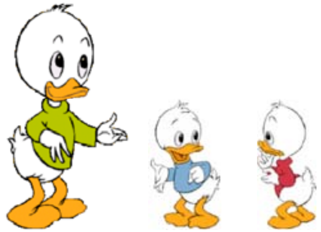
1. Absolute m_ν

- Degenerate



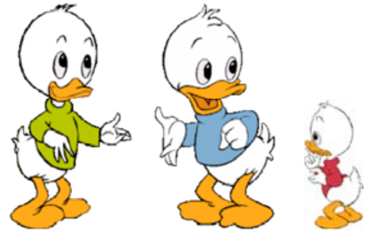
$m_1 \sim m_2 \sim m_3$

- Normal hierarchy

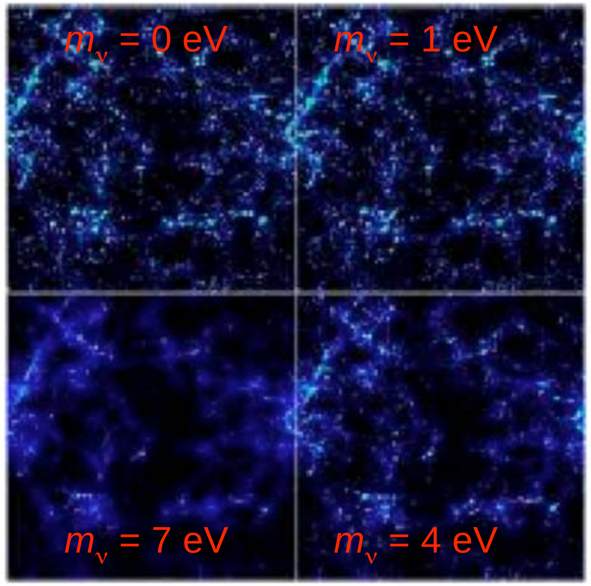


$m_3 >> m_2 \sim m_1$

- Inverse hierarchy



$m_1 \sim m_2 >> m_3$



CMB & LSS $\Sigma_\nu m_\nu < 0.4 – 2$ eV

weak lensing ⟶ $\Delta m_\nu = 0.05 – 0.1$ eV

νless ββ-decay $m_{ee} = \Sigma_i U_{ei}^2 m_{\nu_i} < 0.2$ eV

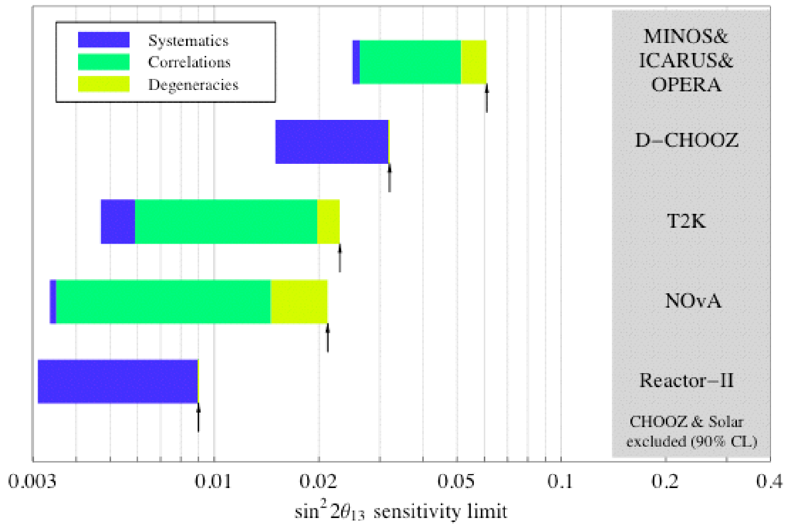
⟶ 0.1 eV

ultimate goal ⟶ 0.01 eV

Tritium β spectrum $m_\nu < 2$ eV ⟶ 0.2 eV

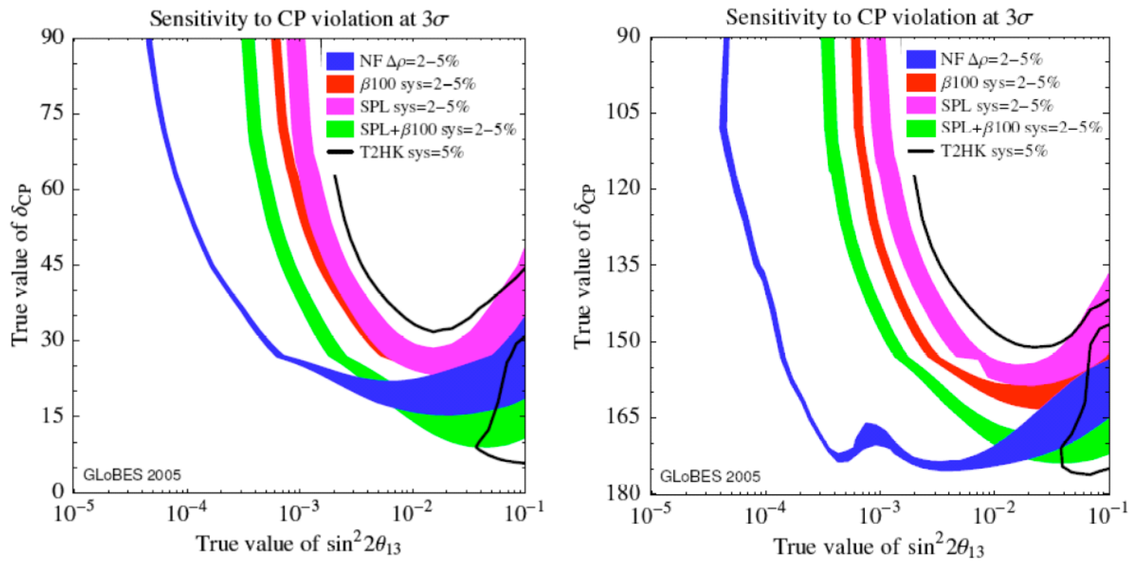
Mainz & Troitsk KATRIN

2. θ_{13}



Schwetz

3. CP violation



BENE report

4. Understanding ν mass matrix

- Origin of m_ν
- Sterile ν
- Flavour structure

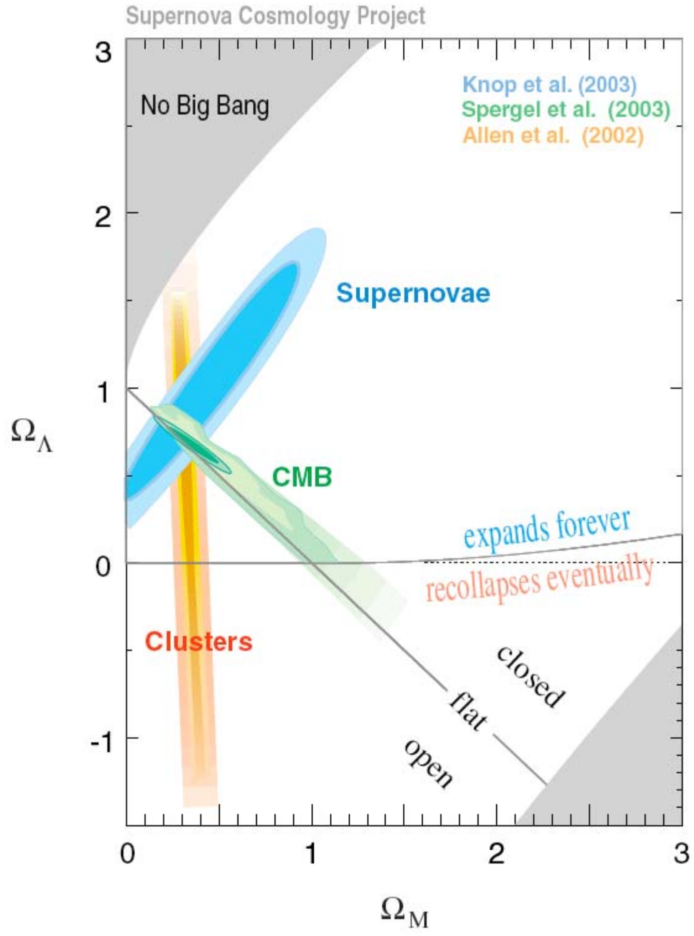
GUT, SUSY, Extra Dim

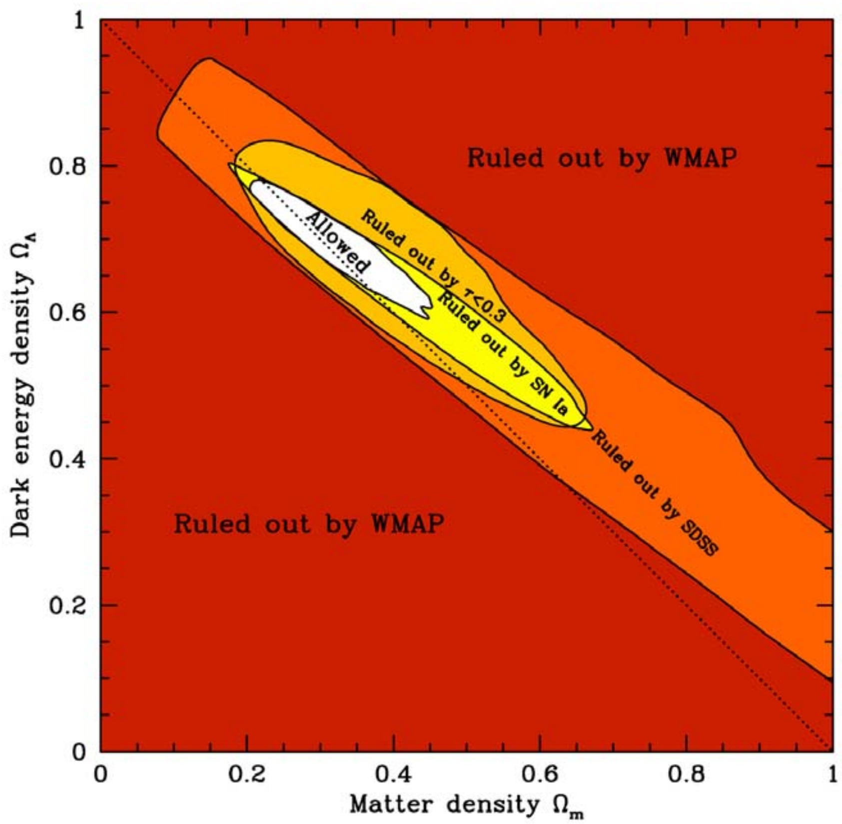
Theory of flavour

Leptogenesis

Observational cosmology

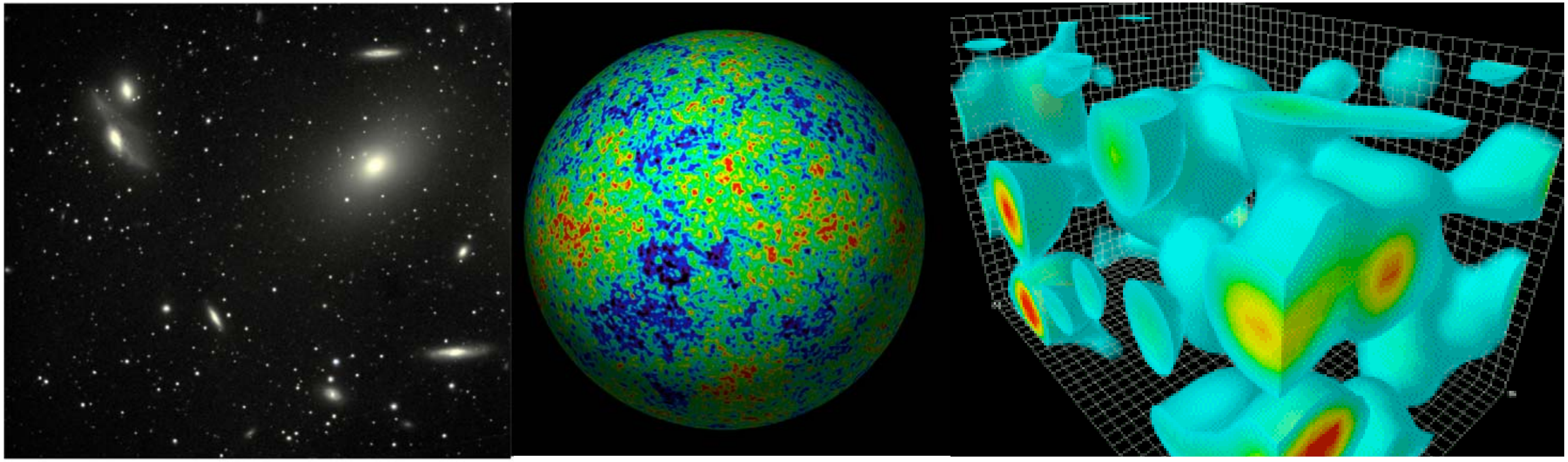
From discovery to precision: the composition of the Universe





SDSS Coll.

Prototype of cosmo-astro-particle connection



Galaxies | CMB | Quantum fluctuations

Astrophysics ⟷ Standard physics ⟷ New physics

For particle physics?

Ideas that require a NP implementation (inflation, baryogenesis, dark matter, dark energy)

1. Test of inflation

Tensor modes by CMB polarization

Non-gaussianity

(Only?) window to Planckian physics

2. $\Omega_b = 0.041 \pm 0.002$

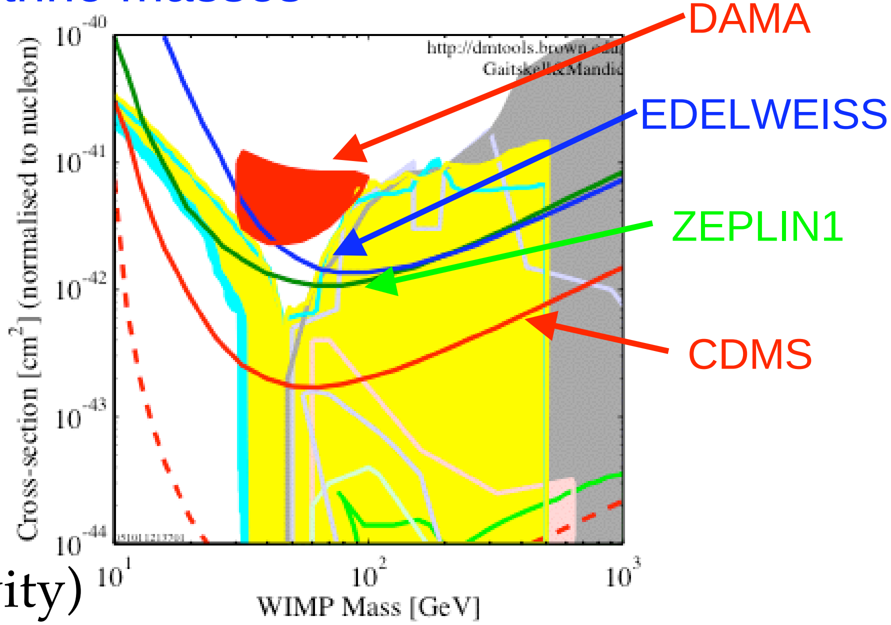
Nucleosynthesis
Baryogenesis

3. $\Omega_\nu / \Omega_{DM} < 0.105$ (95%CL) Neutrino masses

4. $\Omega_{DM} h^2 = 0.120 \pm 0.007$

Link to the weak scale?

$$\Omega_{DM} h^2 = 0.12 \frac{\text{TeV}^{-2}}{128\pi\sigma_{ann}}$$



5. $\Omega_\Lambda = 0.706 \pm 0.034$

New scale $\Lambda^{1/4} \sim 10^{-3}$ eV ?

(m_ν, M_W^2/M_{Pl}, modification of gravity)

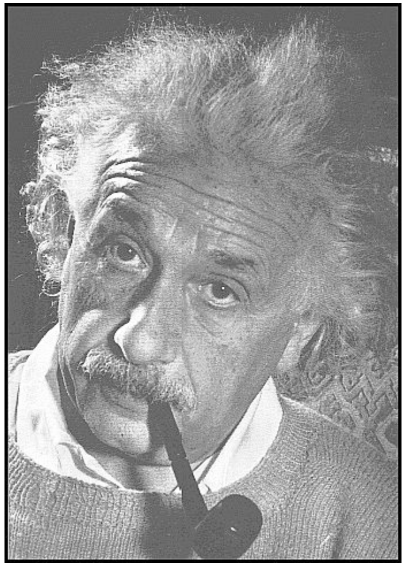
Failure of naturalness argument?

What determines the physical laws?

The reductionist's dream:

Unique consistent theory defined by symmetry properties

(no deformation allowed, no free parameters)

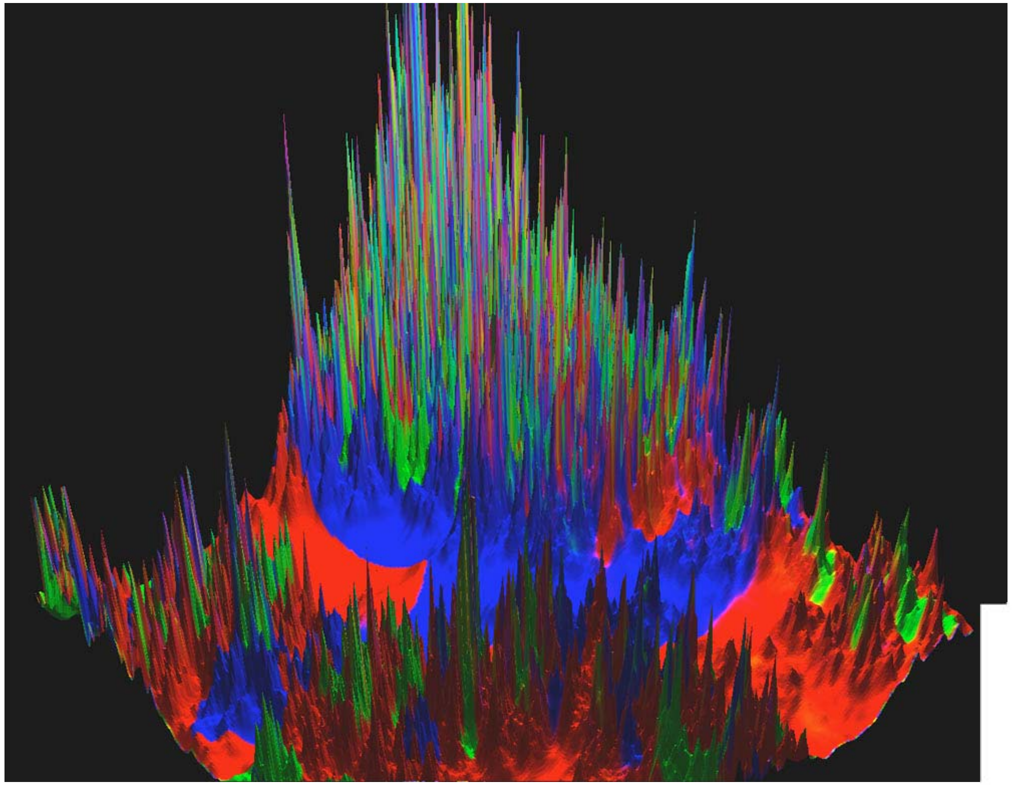


Could God have made the Universe in a different way? Does the necessity of logical simplicity leave any freedom at all?

- Monotheistic view → God
- M-theoristic view → 2nd string revolution

String theory ⇒ low-energy susy ⇒ SM

An unorthodox point of view

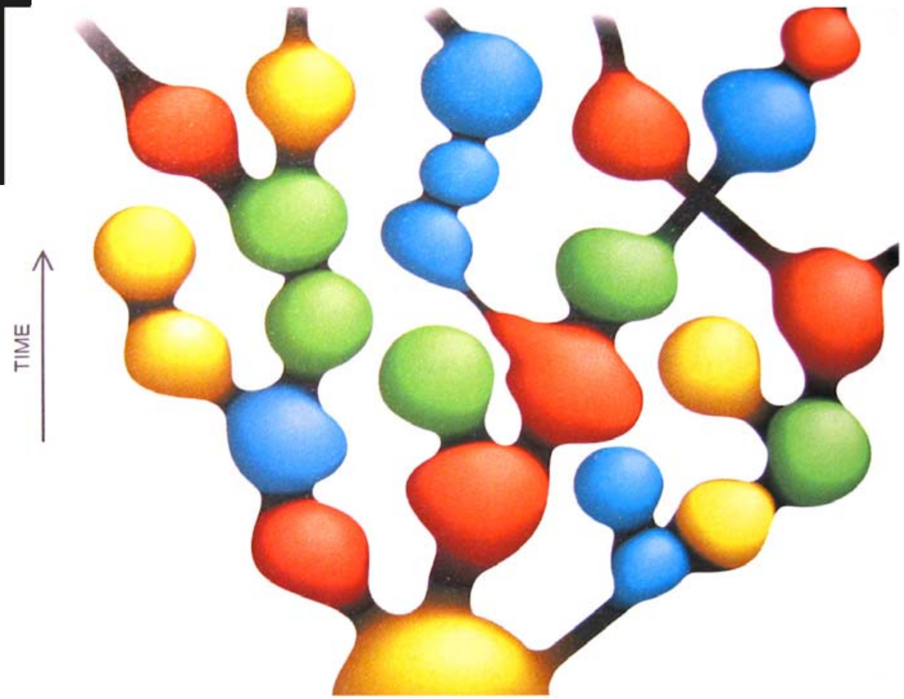


Vacuum structure of string theory

~ 10^{500} vacua

(N d.o.f in M config. make M^N)

Expansion faster than bubble propagation



Big bang ⇒ universe expanding like an inflating balloon

Unfolding picture of a fractal universe ⇒ **multiverse**

Not a unique "final" theory with
parameters = $\mathcal{O}(1)$ × allowed by symmetry
but a statistical distribution

In which vacuum do we live?

Determined by
"environmental selection"

Λ
- Large and positive ⇒ blows structures apart
- Large and negative ⇒ crunches the Universe too soon

Weinberg

Is the weak scale determined by "selection"? Are fermion masses determined by "selection"?

Will these ideas impact our approach to the final theory?

The LHC will address this question!

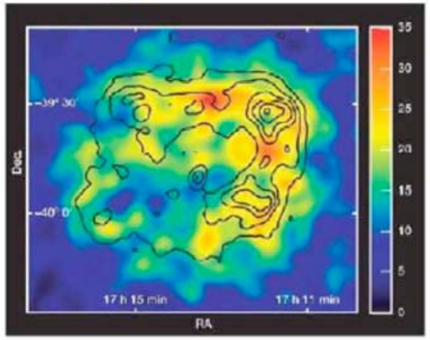
SPLIT SUPERSYMMETRY abandons the hierarchy problem, but uses unification & DM

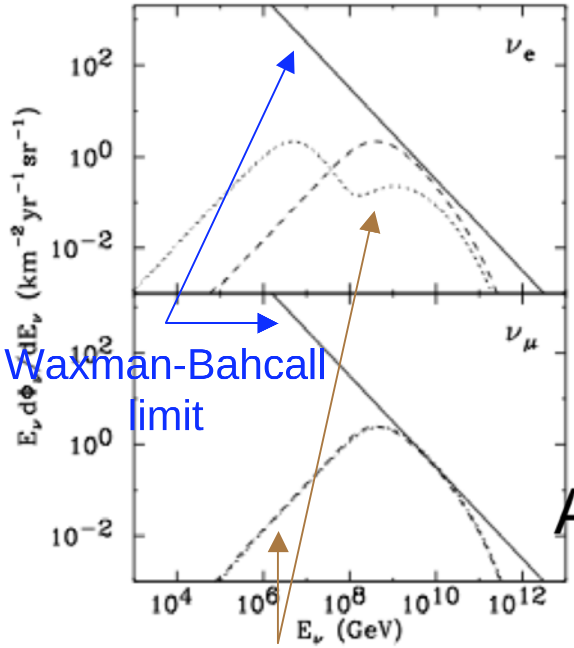
Cosmic Rays

We have explored the Universe from radiowave (10^4 cm) to GeV γ rays (10^{-14} cm)

Extend our exploration with different messengers

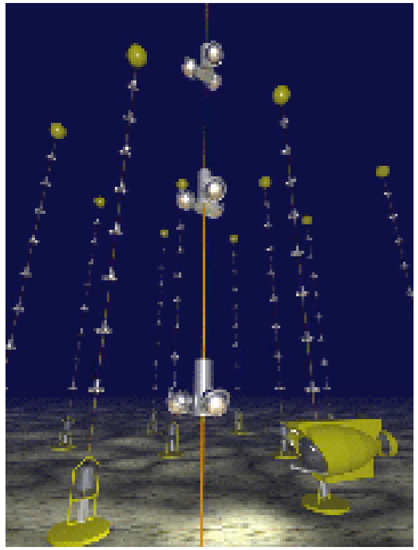
TeV γ rays: Whipple, Cangaroo, HESS





ν telescopes: Amanda, Icecube, Baikal, Antares, Nestor, Nemo

UHE cosmic rays: AGASA, HiRes, Yakutsk, AUGER



Antares

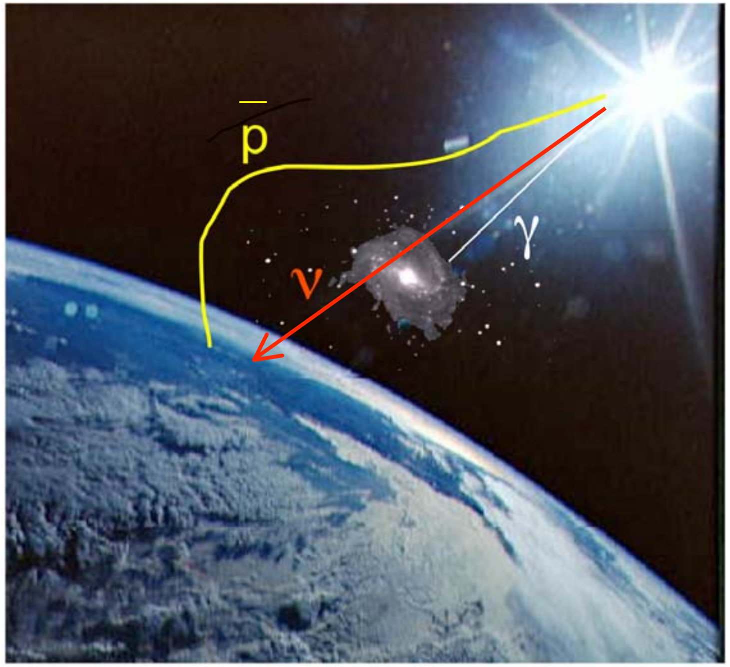
Gravitational waves: LIGO, VIRGO, LISA

Main goals in astrophysics and cosmic-ray origin & acceleration mechanism

For particle physics?

1. DM annihilation

- HE ν from centre of the Sun and Earth
- γ rays from galactic halo and centre
- Positrons, antiprotons, antideuterons

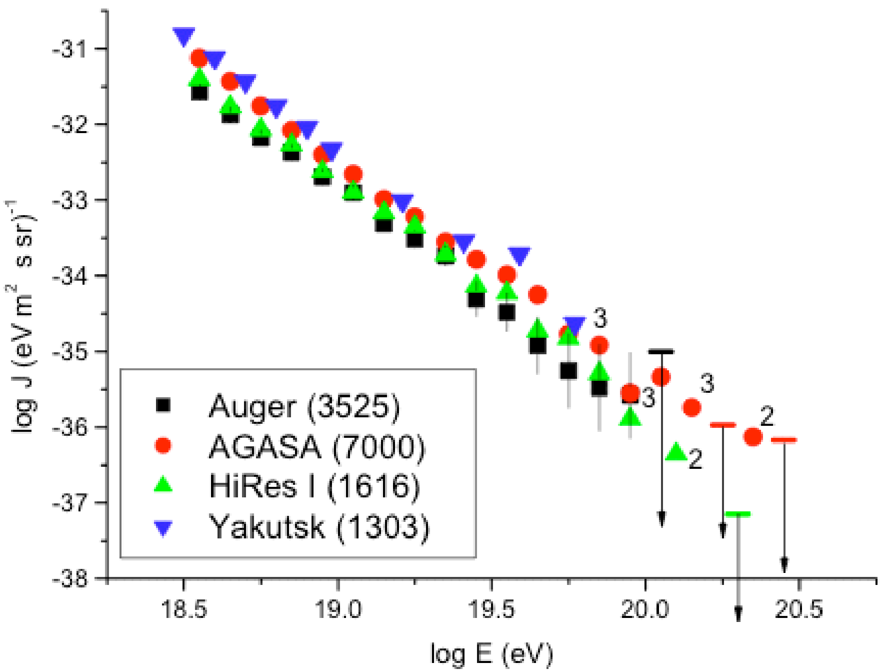


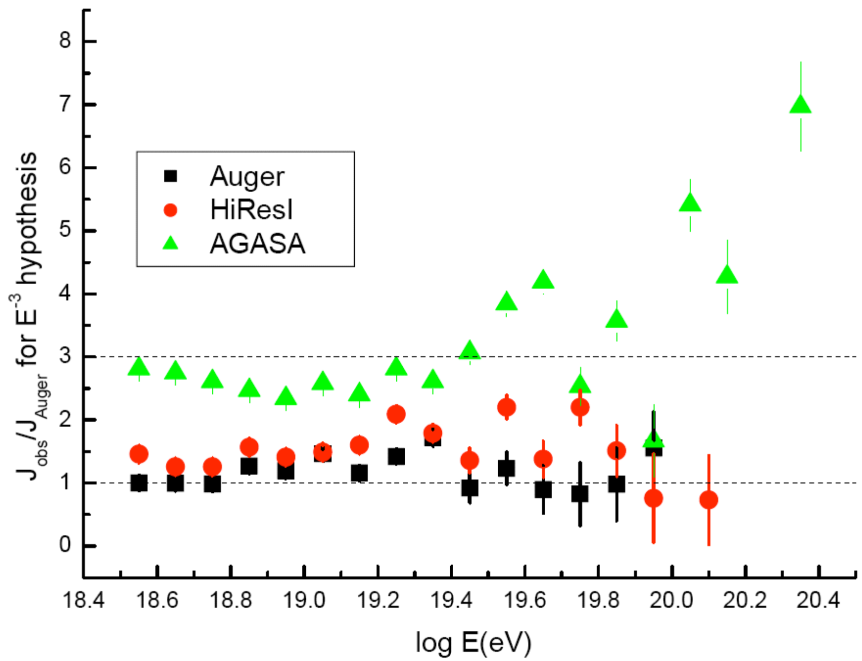
INTEGRAL (emission line from MW bulge) *m* = 1–10 MeV
HESS (γ rays from galactic centre) *m* = 10–30 TeV
EGRET (diffuse γ rays) *m* = 60 GeV & *m* = 500 GeV

2. GZK cutoff

(protons with E > 5×10^{19} eV cannot come from beyond 50 Mpc)

If no GZK cutoff ⇒ Metastable superheavy particle?
Violation of Lorentz invariance?





Watson

Correlation with BL Lacs ⇒

- evidence for extragalactic origin of UHECR
- indication for a new neutral particle?

3. High-energy ν interactions

ν–N scattering at $E_{CM} = \sqrt{\frac{E_\nu}{10^{15}\ \text{eV}}}\ \text{TeV}$

Test of new interactions at "LHC" energies:
extra dim, strings, black holes at TeV

More synergy between HEP & UHE cosmic rays in the future?

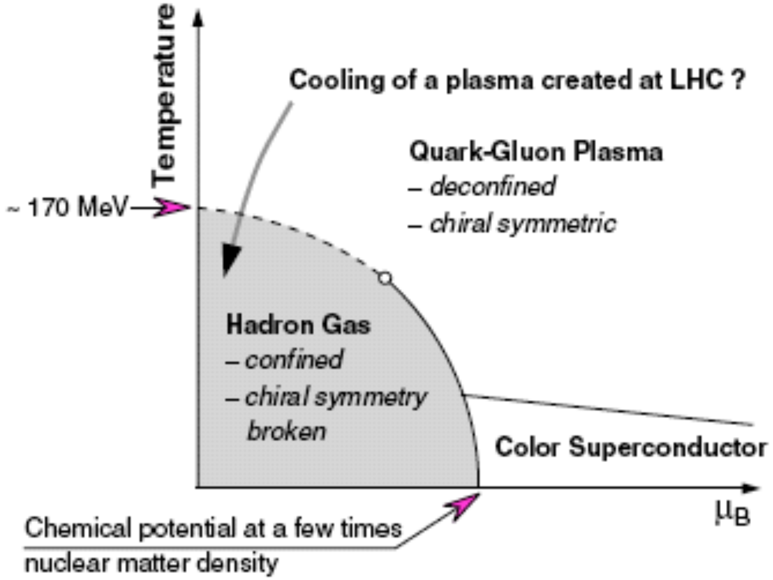
- Will LHC help reducing uncertainties in modelling hadronic showers?
- Will precise knowledge of cosmic fluxes allow particle-physics experiments? (see the cases of solar and atmospheric ν)

Heavy-ion collisions

Studying the QCD phase diagram

From RHIC indication for a strongly-interacting fluid with low viscosity/entropy

Although quarks are deconfined at $T>T_C$ (=173±15 MeV from lattice), energy separation still large just above T_C



Speculation from AdS/CFT ⇒ dual to rotating black hole?

Theoretical connections (from fluidodynamics to string theory)
Experimental implications (from QCD to pulsar & neutron stars)

Need for more EXP and TH work ⇒ LHC

Two phases in scientific progress

Experiment
- discovery (new phenomena found)
- precision (consolidation of measurement, precise parameter determination)

Theory
- how (consistent description of phenomenon)
- why (understanding, ability to compute parameters, predictions)

EXP		**TH**	
discovery	precision	how	why

gauge → $\delta M_Z = 0.0023\%$, $\delta \sin^2\theta = 0.069\%$

SM — GUT? Strings?

QCD in strong regime ⇒ lattice — confinement (strings, AdS/CFT?)

quarks → $\delta\bar{\rho} = 17\%$, $\delta\bar{\eta} = 6\%$ → superB, rare processes

CKM — Compute m_f, θ_{CKM}?

ℓ

ν — ν oscill. → $\delta\Delta m^2_{sol} = 4\%$, $\delta\Delta m^2_{atm} = 14\%$, $\delta\sin^2\theta_{12} = 9\%$, $\delta\sin^2\theta_{23} = 11\%$ → mass, θ_{13}, ~~CP~~

New mass scale → GUT?

Large θ (surprise, but compatible with GUT) — Same as flavour (+ M_R)

~~EW~~ — LHC → SLHC, ILC, CLIC, DLHC?

Higgs? — New physics?

↑

inflation, baryogenesis, dark matter, dark energy

Connection with cosmology/astrophysics/nuclear physics:

observational cosmology, high-energy cosmic rays, heavy ions

- Both discovery and precision phases are necessary for scientific progress
- Tevatron, Hera, LEP, B&K factories, ν expts have completed a very successful programme that had a dramatic impact on our understanding of the microworld
- Yet, the success of the LHC can only be justified by new discoveries
- Finding the Higgs is the beginning of the process of understanding EW breaking, not the end
- Future of HEP critically depends on LHC results
- R&D is necessary now ⇒ by the time LHC delivers data, future strategies will be determined by physics and not by limited technology

"When Alexander saw the breadth of his domain, he wept for there were no more worlds to conquer…"