The Quest for Unification

Alon E. Faraggi

- Understanding the universe and our place in it

- Unification of Matter and Interactions

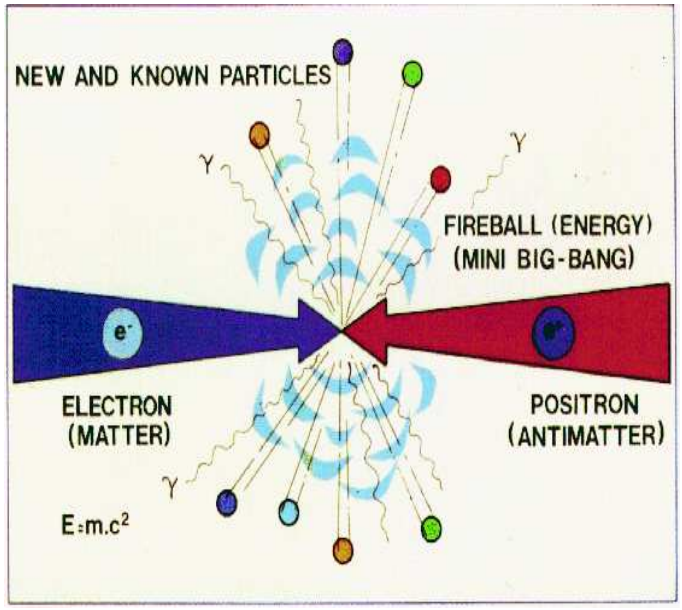
Astrophysics Research Institute, Birkenhead, 13 October 2010

Unification – a constant theme in science

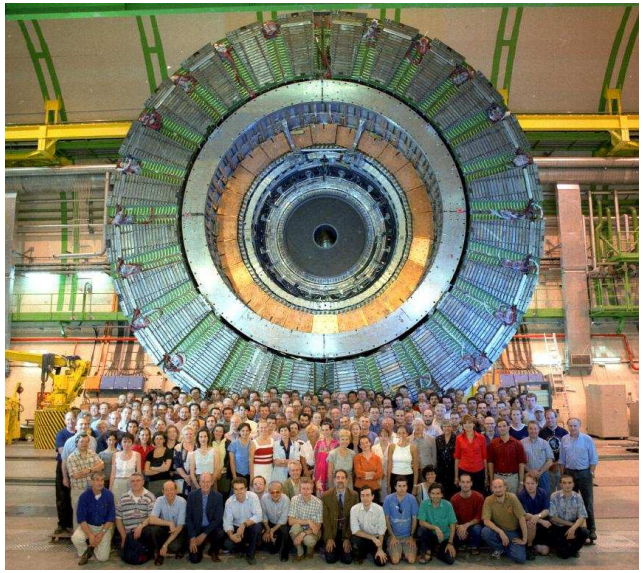
- 1600's – Newton: unification of terrestrial and celestial mechanics
- 1800's – Maxwell: unification of electric and magnetic forces
- 1960's – Glashow, Weinberg & Salam: eletroweak unification
- 1970's – GUTs: strong & electroweak unification
- 1980's – strings: Gauge & Gravity unification

A summer resort ...

LEP/LHC rings

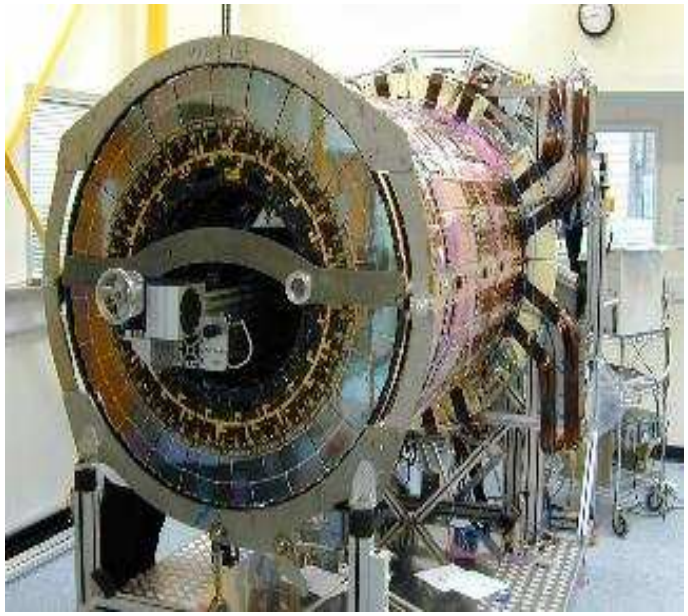


Sub−atomic collider



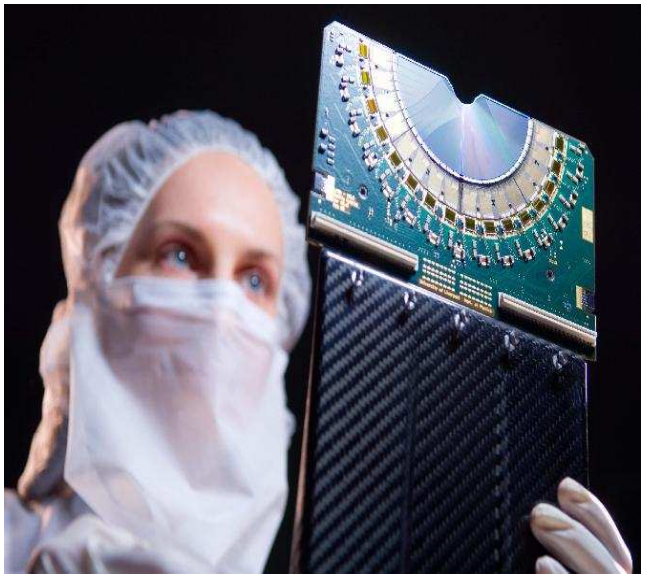
An older detector

Liverpool's contributions



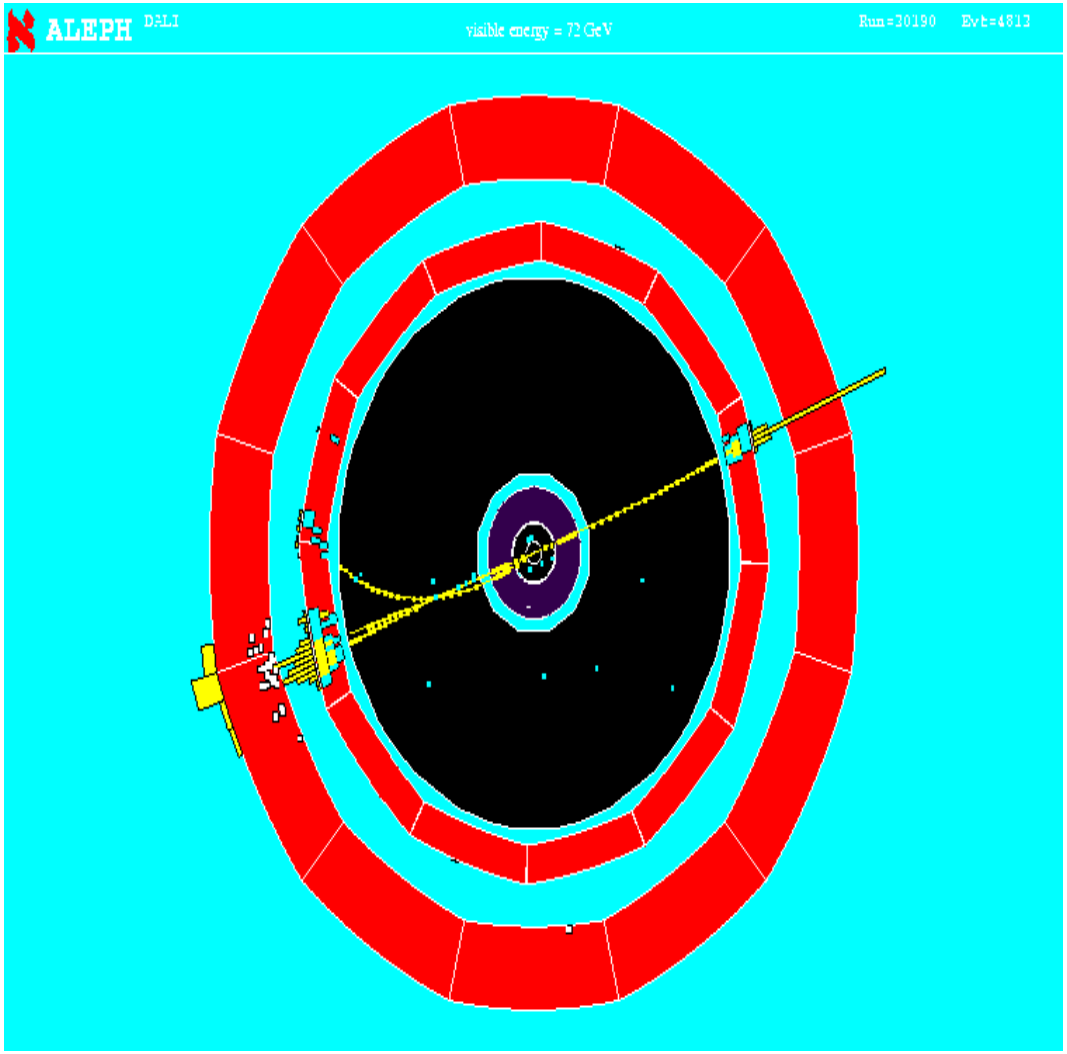
Silicon Central Tracker

ATLAS



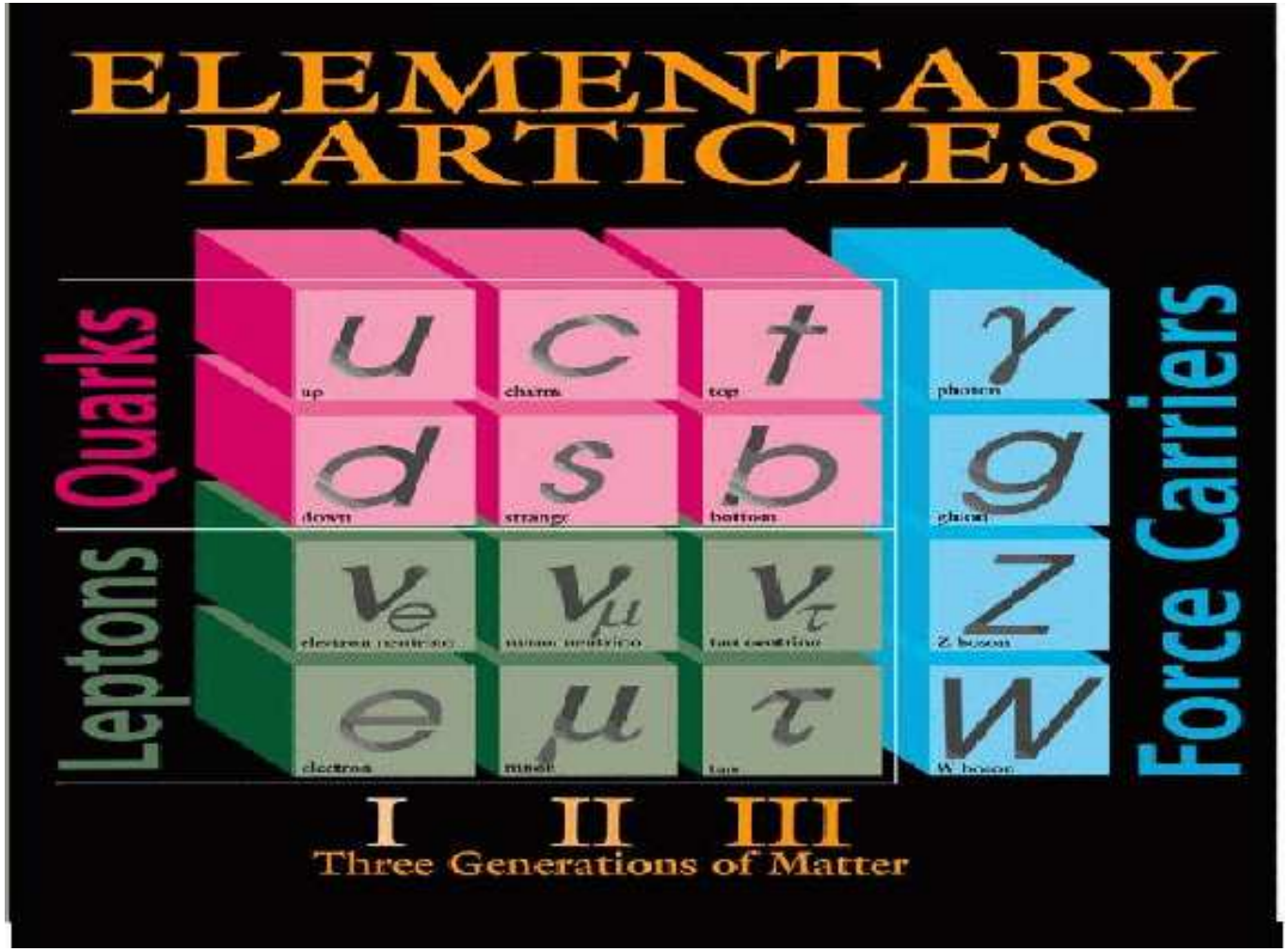
LHCb vertex detector

Makes nice pictures ...

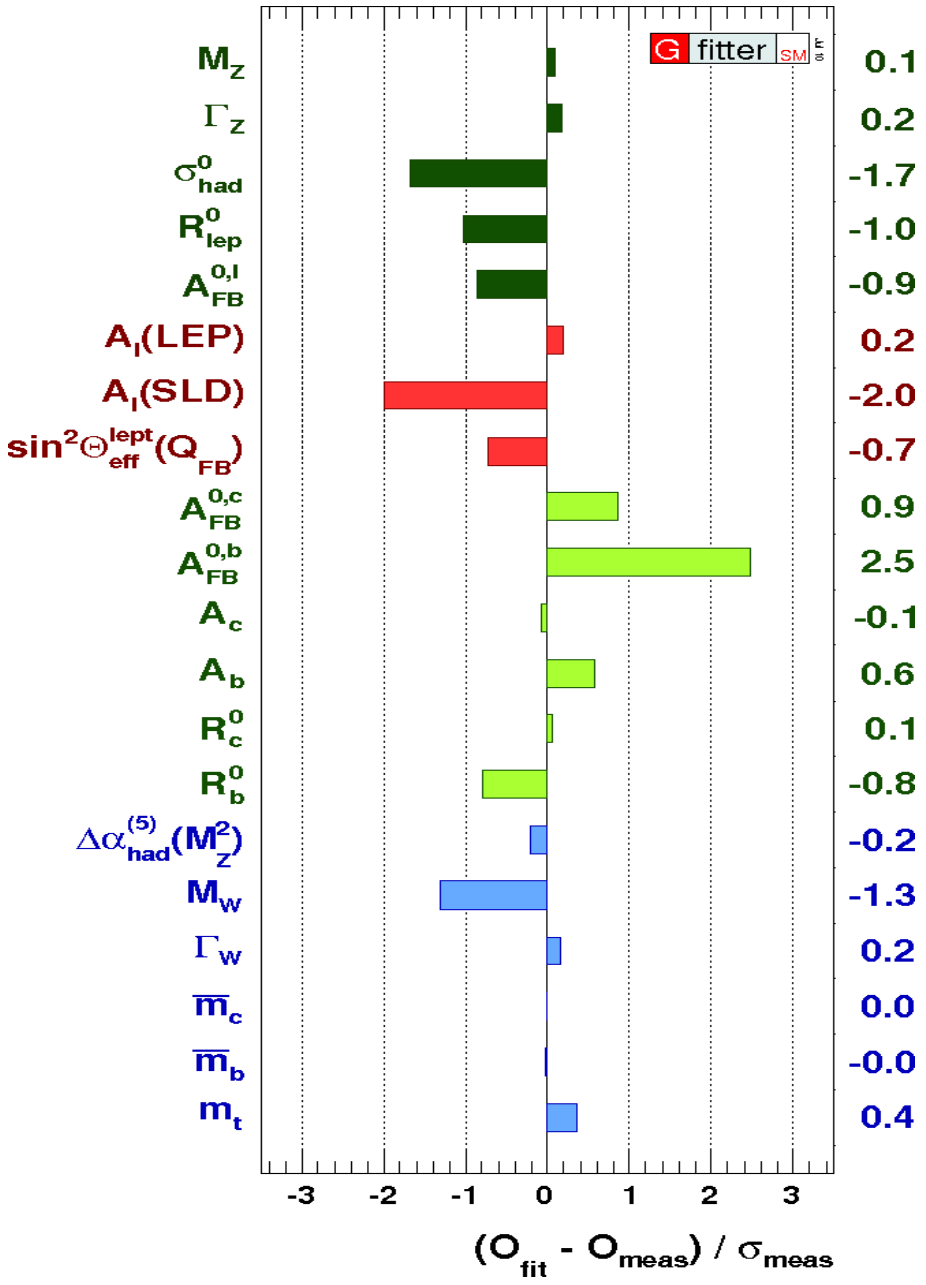


$$e^+e^- \longrightarrow \tau^+\tau^-$$

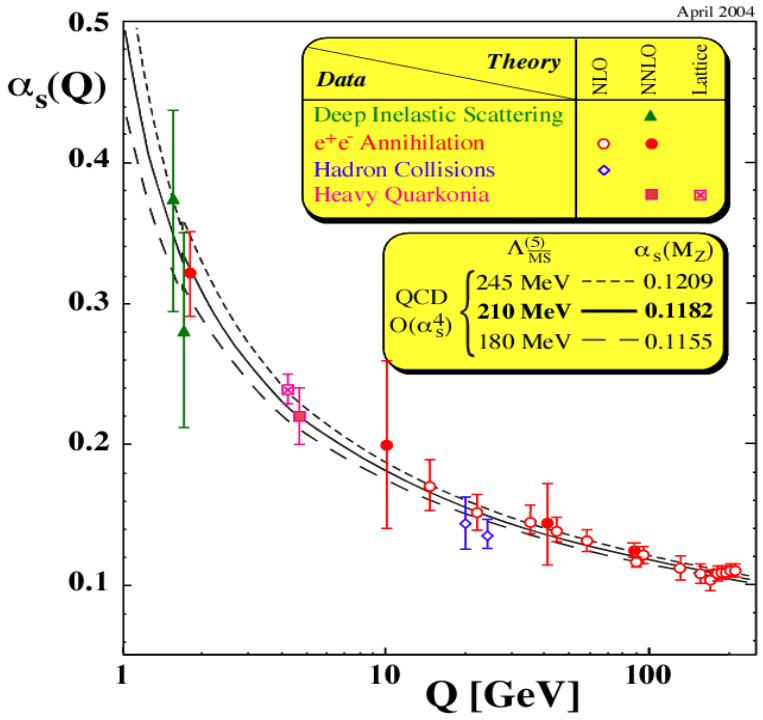
DATA –> STANDARD MODEL

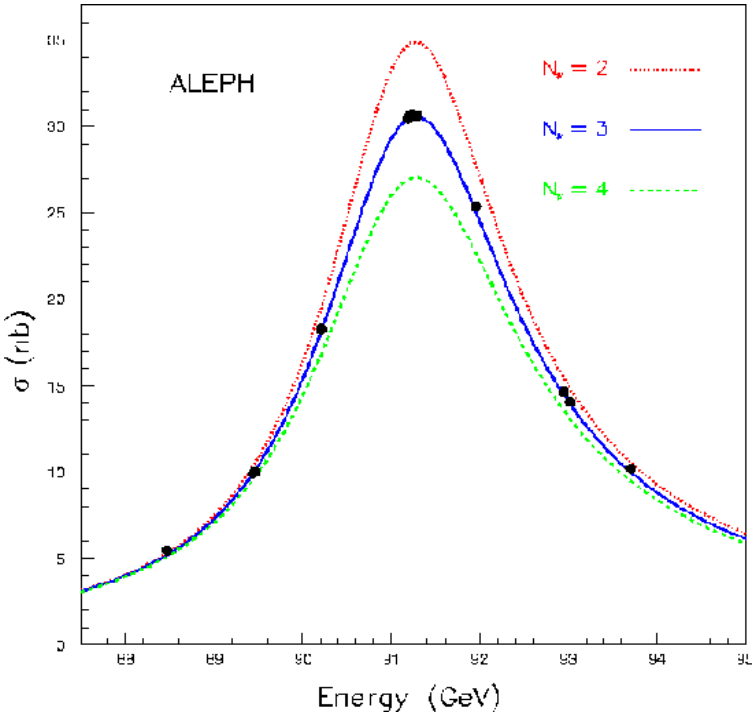


In agreement with all experimental DATA



More experimental DATA





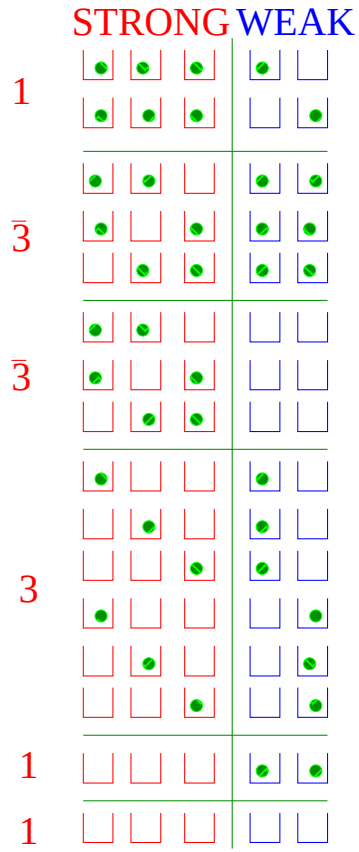
Logarithmic running of α_s the QCD gauge coupling

Invisible decay width of the Z gauge boson

DATA ⟶ STANDARD MODEL

STRONG WEAK ELECTROMAGNETIC ⟶ SO(10)

Put even # of coins in five slots 0 ; 2 ; 4



$\left(\begin{matrix}\nu\\ e\end{matrix}\right)$

D^c_L

U^c_L

$\left(\begin{matrix}u\\ d\end{matrix}\right)$

E^c_L

N^c_L

$\bar{5} = \binom{5}{4} = \frac{5!}{4!1!}$

$+$

$10 = \binom{5}{2}$

$+$

$1 = \binom{5}{0}$

16

STANDARD MODEL −> UNIFICATION

Addiotional evidence: Logarithmic running

Gauge

Matter

Higgs $\longrightarrow$ supersymmetry

Addiotional evidence: Proton stability, neutrino masses

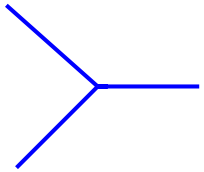
Primary guides:

3 generations

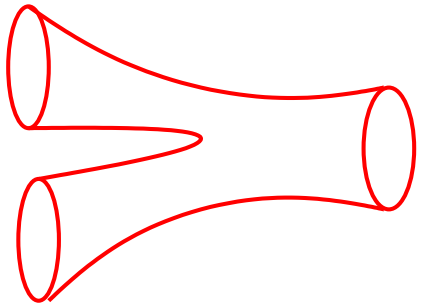
$SO(10)$ embedding

QUANTIZE GRAVITY?

QUANTUM MECHANICS ⊗ GRAVITY



STRING →

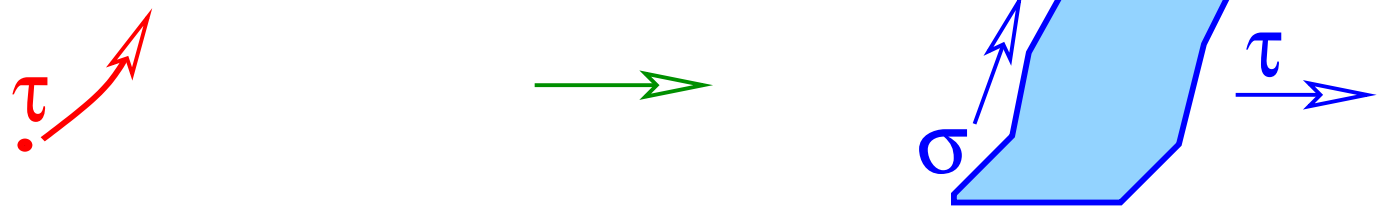


∞ finite

STRING THEORY

unification with flavour, hierarchy and gravity

ELEMENTS OF STRING THEORY



$X(\tau)$– World–line

$X(\tau,\sigma)$– World–sheet

$S = -T \bullet$ Area

Classically: $g^{\alpha\beta} \longrightarrow \eta^{\alpha\beta}$

Quantum : D=26

Eq. of motion: $\left(\partial_\sigma^2 - \partial_\tau^2\right) X^\mu(\sigma,\tau) = 0$

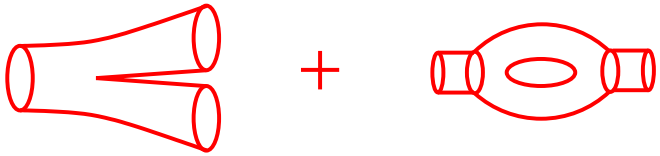
$X^\mu(\sigma,\tau) = X_L^\mu(\sigma-\tau) + X_R^\mu(\sigma+\tau)$

Mass levels :

$$M^2 = P^2 = -2 + 2\sum \alpha_{-n}\,\alpha_n \longrightarrow \text{tachyon}$$

−> Add World−sheet Fermions −> N=1 SUSY −> No tachyon

Perturbation Theory



−> Invariance under global reparameterizations

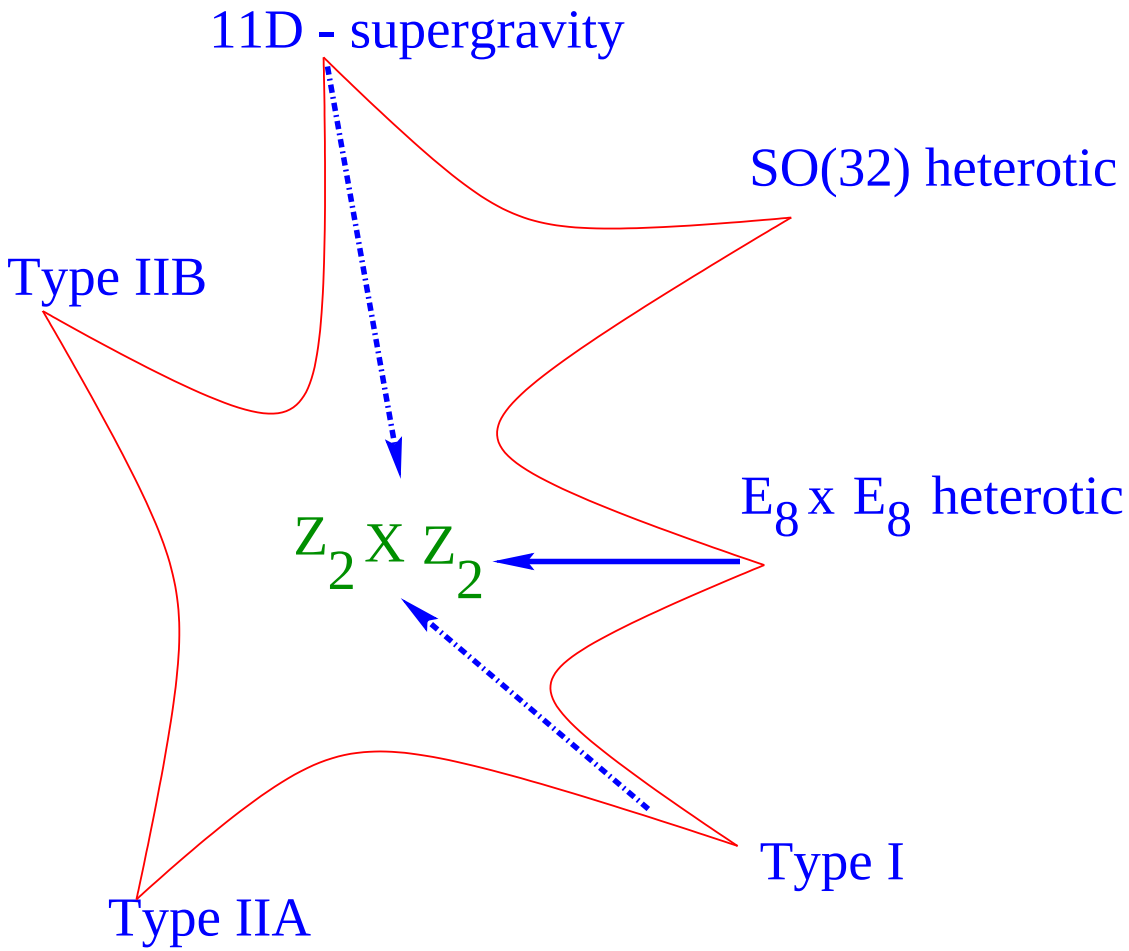
−> Consistency constraints

Heterotic string: $(X_L;\ \Psi_L)$ D=10

X_R D=26

Heterotic String: −> Chiral matter under SO(10)

Point, String, Membrane ....



REALISTIC STRING MODELS :

heterotic 10D −> heterotic 4D

6D compactifications $(T^2 \times T^2 \times T^2)$

Orbifold − twists of flat 6D torus

FREE FERMIONIC MODELS −

$Z_2 \times Z_2$ Orbifold −> $U(1)_Y \in SO(10)$

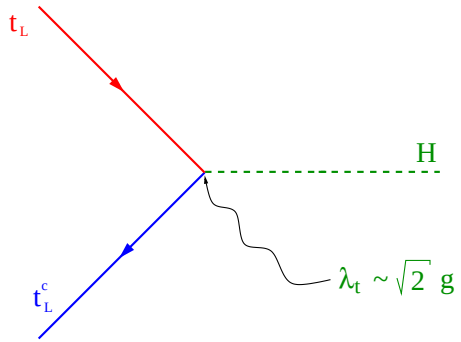
$$\frac{6}{2} = 1+1+1$$

Realistic free fermionic models

'Phenomenology of the Standard Model and string unification'

- Top quark mass $\sim$ 175–180GeV — PLB 274 (1992) 47
- Generation mass hierarchy — NPB 407 (1993) 57
- CKM mixing — NPB 416 (1994) 63 (with Halyo)
- Stringy seesaw mechanism — PLB 307 (1993) 311 (with Halyo)
- Gauge coupling unification — NPB 457 (1993) 409 (with Dienes)
- Proton stability — NPB 428 (1994) 111
- Squark degeneracy — NPB 526 (1998) 21 (with Pati)
- Minimal Superstring Standard Model — PLB 455 (1999) 135 (with Cleaver & Nanopoulos)
- Moduli fixing — NPB 728 (2005) 83
- Exophobia — PLB 683 (2010) 306 (with Assel, Christodoulides, Kounnas & Rizos)

Top Quark Mass Prediction



Only $\lambda_t = \langle Q t_L^c H \rangle = \sqrt{2} g$ at $N = 3$

mass of lighter quarks and leptons $\longrightarrow$ nonrenormalizable terms

$$\longrightarrow \qquad \lambda_b \;=\; \lambda_\tau \;=\; 0.35 g^3 \;\sim\; \frac{1}{8}\lambda_t$$

Evolve λ_t , λ_b to low energies

$$m_t \;=\; \lambda_t v_1 \;=\; \lambda_t \frac{v_0}{\sqrt{2}} \sin\beta \qquad m_b \;=\; \lambda_b v_2 \;=\; \lambda_b \frac{v_0}{\sqrt{2}} \cos\beta$$

where $v_0 = \dfrac{2 m_W}{g_2(M_Z)} = 246\mathrm{GeV}$ and $v_1^2 + v_2^2 = \dfrac{v_0^2}{2}$

$$m_t \;=\; \lambda_t(m_t)\, \frac{v_0}{\sqrt{2}}\, \frac{\tan\beta}{(1+\tan^2\beta)^{\frac{1}{2}}} \Longrightarrow$$

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PHYSICS LETTERS B

Hierarchical top–bottom mass relation in a superstring derived standard-like model

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Received 30 September 1991

I propose a mechanism in a class of superstring standard-like models which explains the mass hierarchy between the top and bottom quarks. At the trilinear level of the superpotential only the top quark gets a nonvanishing mass term while the bottom quarks and tau lepton mass terms are obtained from nonrenormalizable terms. I construct a model which realized this mechanism. In this model the bottom quark and tau lepton Yukawa couplings are obtained from quartic order terms. I show that $\lambda_b = \lambda_\tau = \frac{1}{2}\lambda$, at the unification scale. A naive estimate yields $m_t \sim 175$–180 GeV.

One of the unresolved puzzles of the standard model is the mass splitting between the top quark and the lighter quarks and leptons. Especially difficult to understand within the context of the standard model is the big splitting in the heaviest generation. Experimental limits [1] indicate the top mass to be above 80 GeV, while the bottom and tau lepton masses are found at 5 GeV and 1.78 GeV respectively. Possible extensions to the standard model are grand unified theories. Although the main prediction of GUTs, proton decay, has not yet been observed, calculations of $\sin^2\theta_w$ and of the mass ratio m_b/m_τ support their validity. Recent calculations seem to support supersymmetric GUTs versus nonsupersymmetric ones [2]. In spite of the success of SUSY GUTs in confronting LEP data [2], an understanding of the mass splitting between the top quark and the lighter quarks and leptons is still lacking. The next level in which such an understanding may be developed is in the context of superstring theory [3].

Towards String Predictions

1. Low energy supersymmetry

   Specific SUSY breaking patterns $\longrightarrow$ Collider implications

2. Additional (non–GUT) gauge bosons

   Proton Stability and low–scale Z' $\longrightarrow$ Collider signatures

3. Exotic matter

   In realistic string models

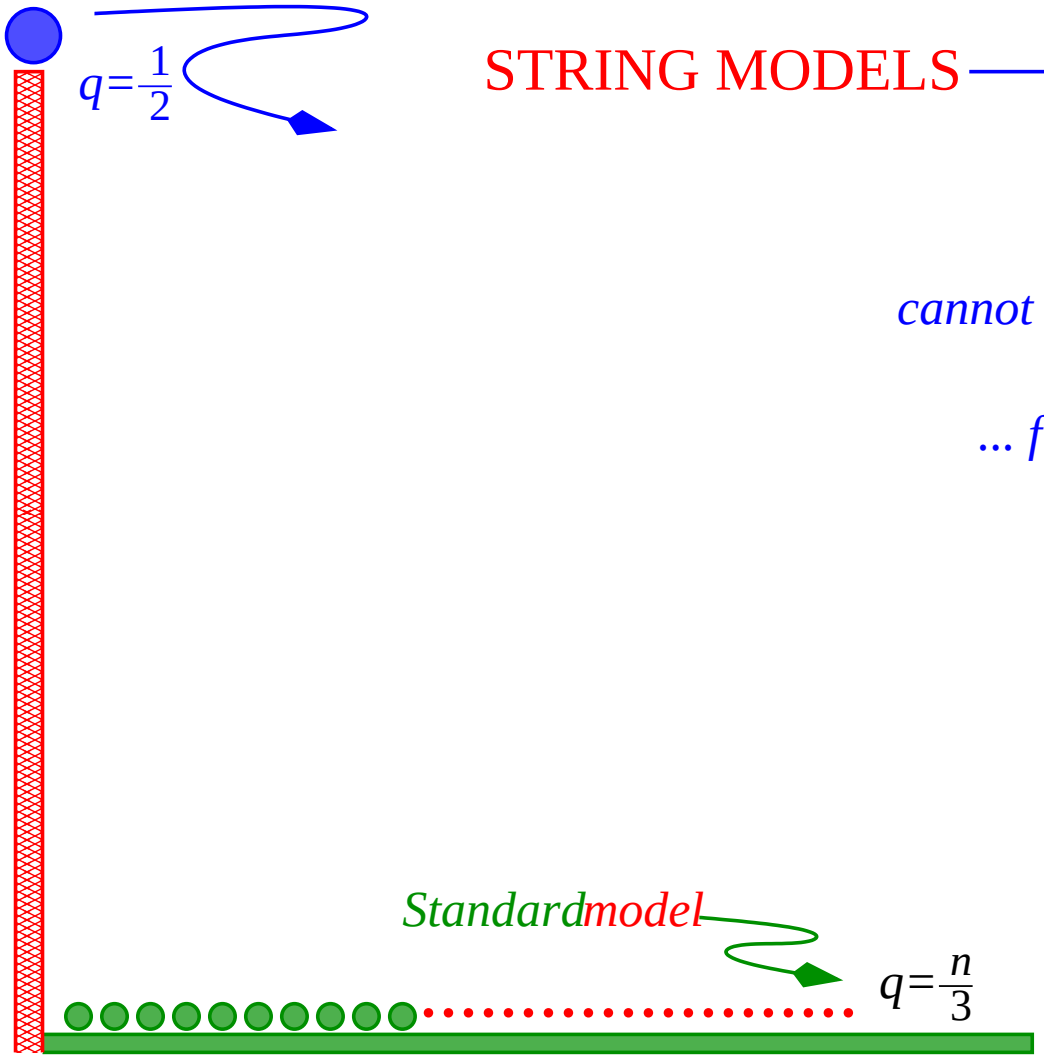
   Unifying gauge group $\Rightarrow$ broken by "Wilson lines".

   $\Rightarrow$ non–GUT physical states.

   $\Rightarrow$ Meta-stable heavy string relics

   $\longrightarrow$ Dark Mater ; UHECR candidates

EXPERIMENTAL PREDICTIONS?



STRING MODELS → SUPERHEAVY FRACTIONALLY CHARGED MATTER

cannot get down ...

... find another $\frac{1}{2}$ partner

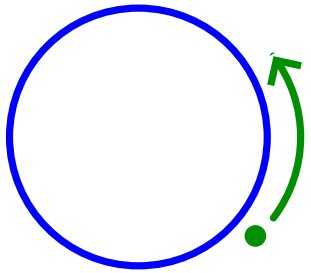
... but very rare ...

...and $E=MC^2$

THE PIERRE AUGER OBSERVATORY

T1 − COMPACTIFICATION

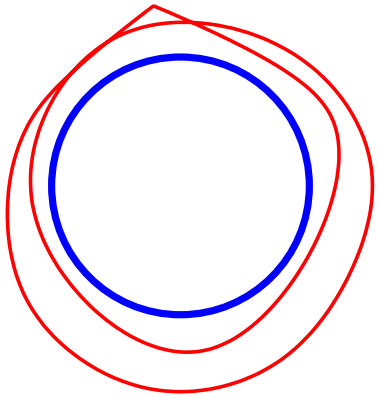
$X \longrightarrow X \sim X + 2\pi R\, m$



Point particle

$\Psi \sim \mathrm{Exp}(i P X) \quad \Rightarrow P = \frac{m}{R}$

String



$P_{L,R} = \frac{m}{R} \pm \frac{n R}{\alpha'}$

T − DUALITY

$$\text{mass}^2 = \left(\frac{n}{R}\right)^2 + \left(\frac{m\,R}{\alpha'}\right)^2$$

Invariant under

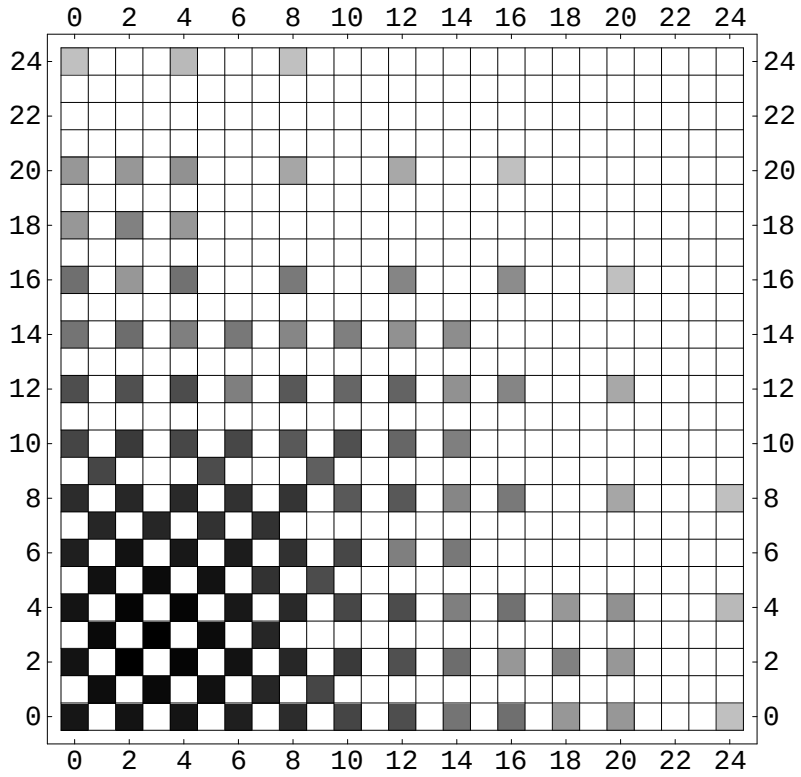
$$\frac{1}{R} \longleftrightarrow \frac{R}{\alpha'} \qquad \text{with} \qquad m \longleftrightarrow n$$

An exact symmetry in string perturbation theory!

Self−dual point $R = \dfrac{\alpha'}{R}$ = free fermionic point

Spinor–vector duality: $\longrightarrow$ A new duality!

Invariance under exchange of $\#(16+\overline{16}) \; <-> \; \#(10)$



Symmetric under exchange of rows and columns

Conclusions

- DATA $\longrightarrow$ UNIFICATION

- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION

- EXPERIMENTAL PREDICTIONS ?

- FUNDAMENTAL PRINCIPLES ?

  phase–space duality & the equivalence postulate of QM

  self–duality and dynamical vacuum selection

FUTURE: Study within string cosmology scenarios