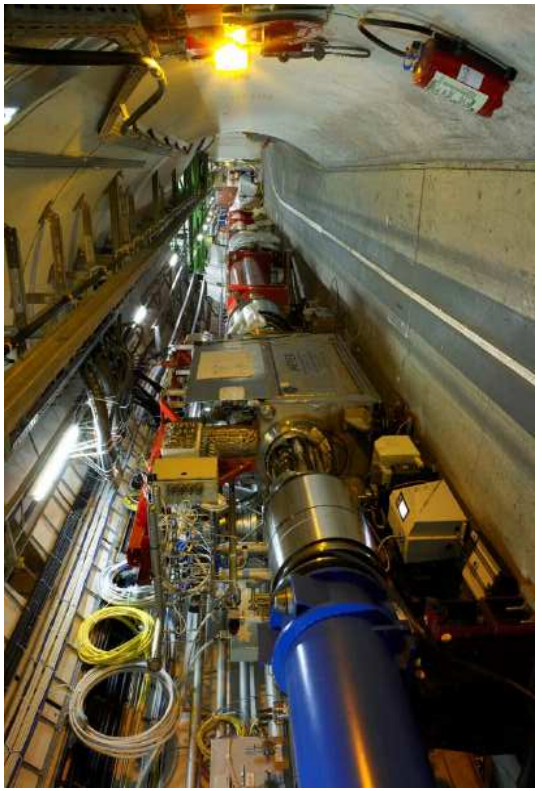
# HIGH ENERGY PHYSICS
# – TELESCOPING THE PLANCK SCALE –

- Target of High Energy Physics

  ⇒ Unraveling basic laws of physics : matter and forces

  ⇒ Platform for composition/evolution of Universe



Exp access : atomic/nuclear scale $\sim 10^{-8}/10^{-13}$ cm

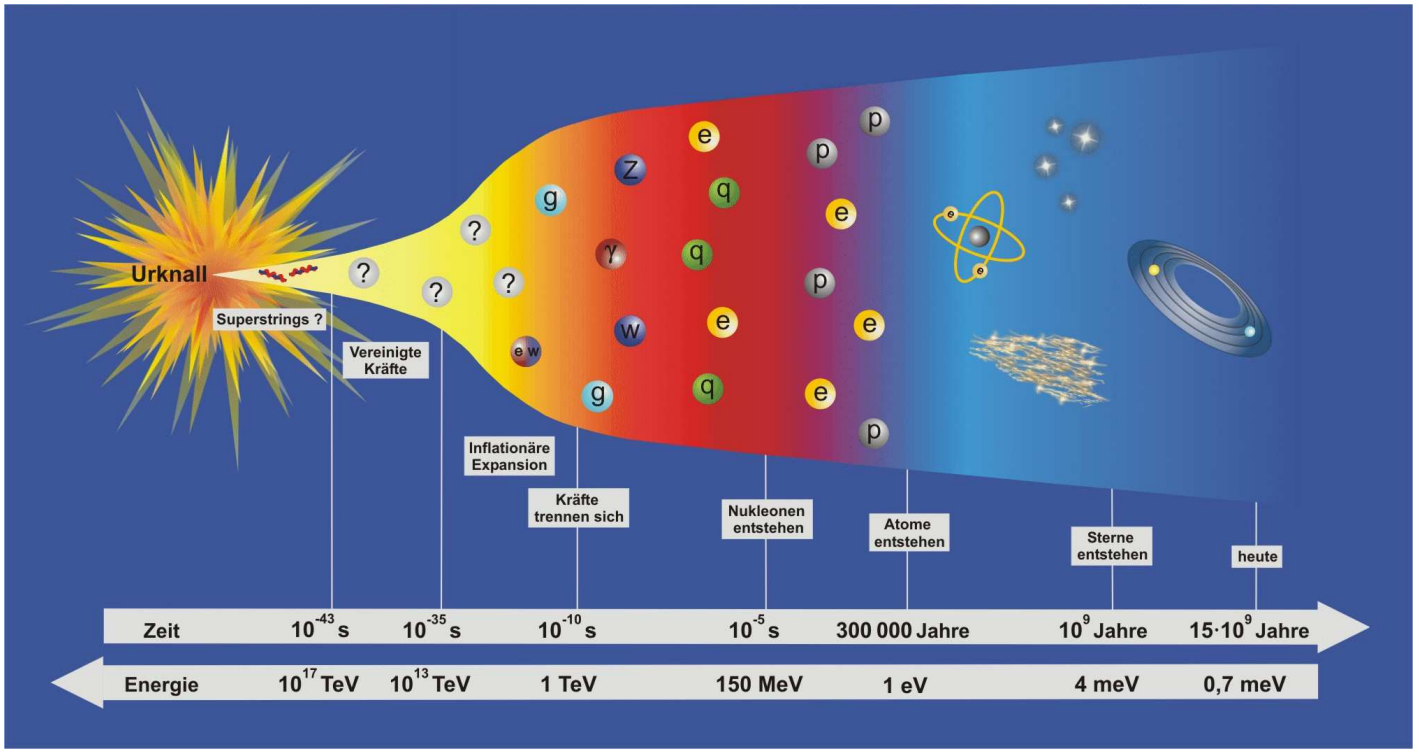
electroweak scale $\sim 10^{-14}/10^{-16}$ cm

⇒ Tera-scale $\sim 10^{-17}/10^{-18}$ cm

Accelerators : LHC / $pp$ : 14 TeV ⇒ *eff* $\sim$ 5 TeV

LC / $e^+e^-$ : ILC/CLIC ⇒ 0.5 to 3 TeV

- Window to composition/evolution of the Universe




# exploring composition of matter in Universe ⇒ Cold Dark Matter

# evolution studied directly for times $> 10^{-10}$ sec

[*QCD phase transition from quarks to hadrons*]

- Telescoping Planck scale

$$M_{PL} = 1/\sqrt{G_N} = 1.2 \cdot 10^{19} \text{ GeV}$$

corresponding to $10^{-33}$ cm $\sim 10^{-43}$ sec

# scale of ultimate unification: all forces, including gravity, of similar strength

seed area of matter and forces

:: canonically no direct experimentation at $M_{PL} \sim 10^{19}$ GeV /mod. $P$ decay

:: hope for theoretical set-up that allows telescoping the Planck scale scenario

experimentally from Tera scale : Supersymmetry $\Rightarrow$ GUT $\Rightarrow$ String theory

Extra space dimensions : $M_{PL} \Rightarrow 1$ TeV

$\Leftarrow$ How are the prospects?

# 1. STATUS OF PARTICLE PHYSICS / SM

Particle Physics has been tremendously successful in unraveling the fundamental laws of nature at subatomic scales:

*STANDARD MODEL OF PARTICLE PHYSICS*

Glashow, Salam, Weinberg

Fritzsch, Gell-Mann

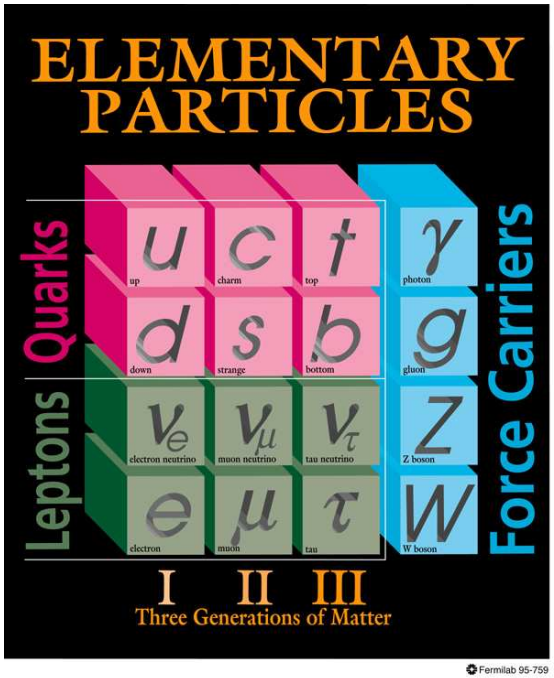
# Constituents of matter:

quarks/leptons in 3 families

with large spread of masses :
$\nu$'s $<$ eV $\Rightarrow$ *top* $\sim$ Au

– 1st family $\sim$ standard matter

– 3 families needed for asymmetry between matter and antimatter



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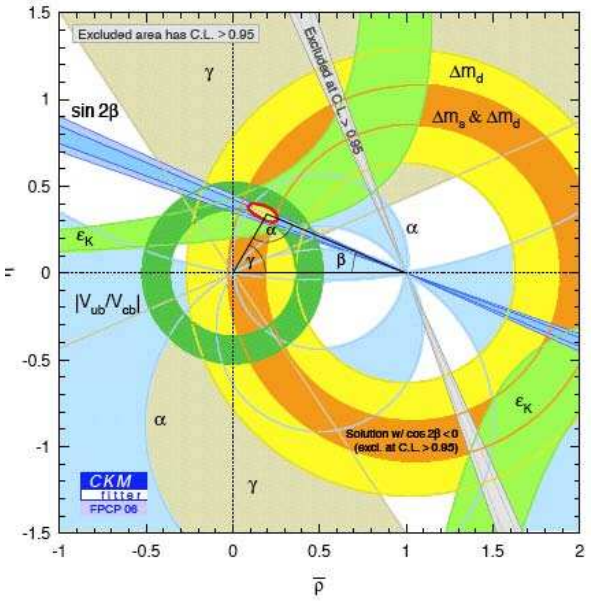


# Fundamental forces

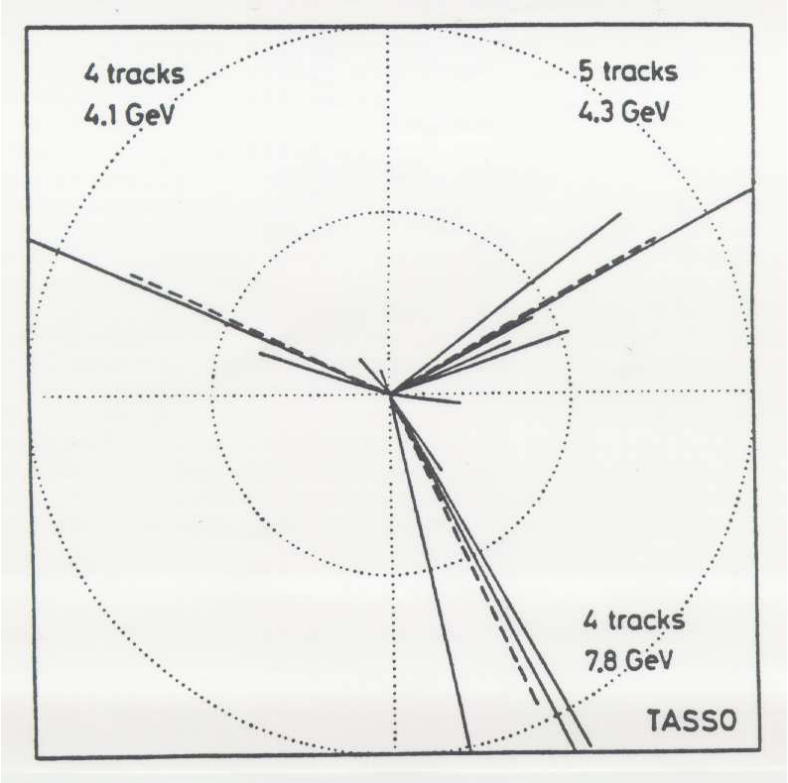
3 particle forces : electromagnetic | weak | strong

$\gamma$ Einstein | $W^{\pm}, Z$ CERN $Sp\bar{p}S$ | $g$ DESY $Petra$

spin $= 1$ : quantum theory

$\oplus$ gravity : classically attached ad-hoc

spin $= 2$



# Fundamental forces



3 particle forces : electromagnetic | weak | strong : SU(3)×SU(2)×U(1)

$\gamma$ Einstein | $W^{\pm}, Z$ CERN $Sp\bar{p}S$ | $g$ DESY $Petra$

spin = 1 : quantum theory

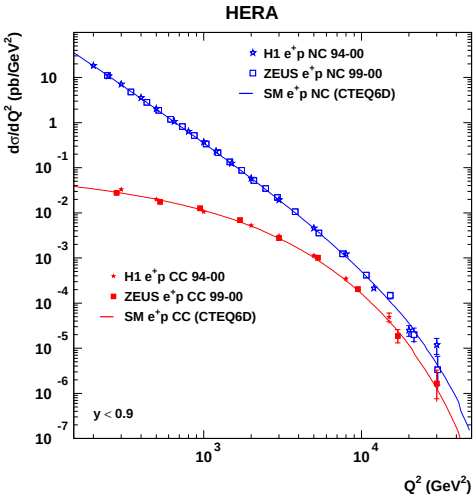
$\oplus$ gravity : classically attached ad-hoc

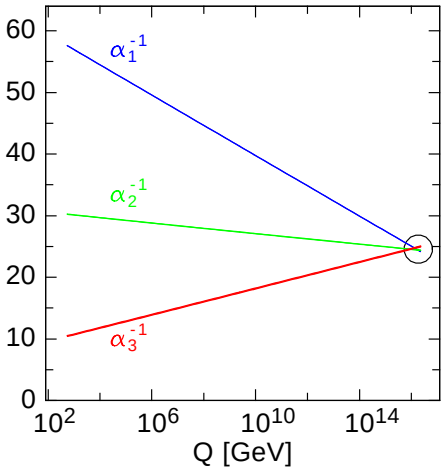
spin = 2

*Weyl, [Yang, Mills]* : Particle forces generated by invariance under gauge transformations

isomorphism $\Rightarrow$

El-weak / grand unification:



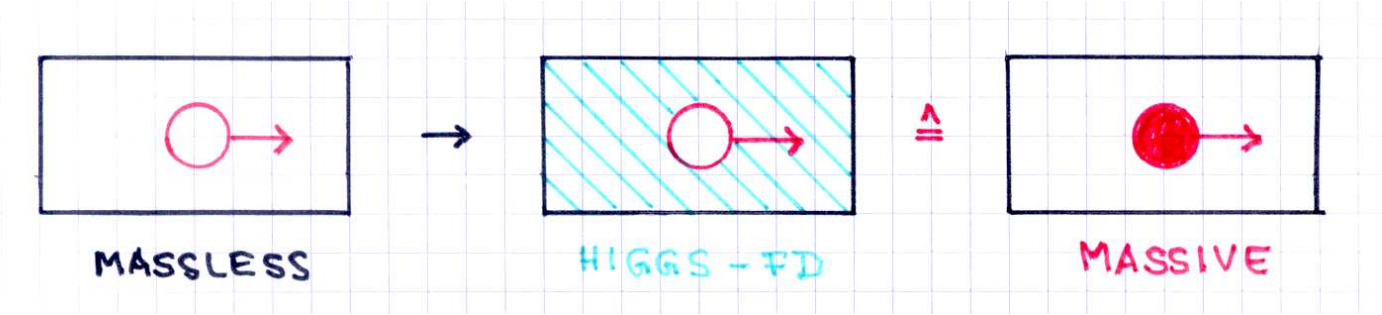



# [Brout-Englert-] Higgs Mechanism

Weyl symmetry destroyed by adding non-zero masses ad-hoc

$\Rightarrow$ theory physically not closed

preserved however if masses generated
by interaction with scalar vacuum field




Standard Model: without Higgs mechanism incomplete

$\Leftarrow$ open effective model

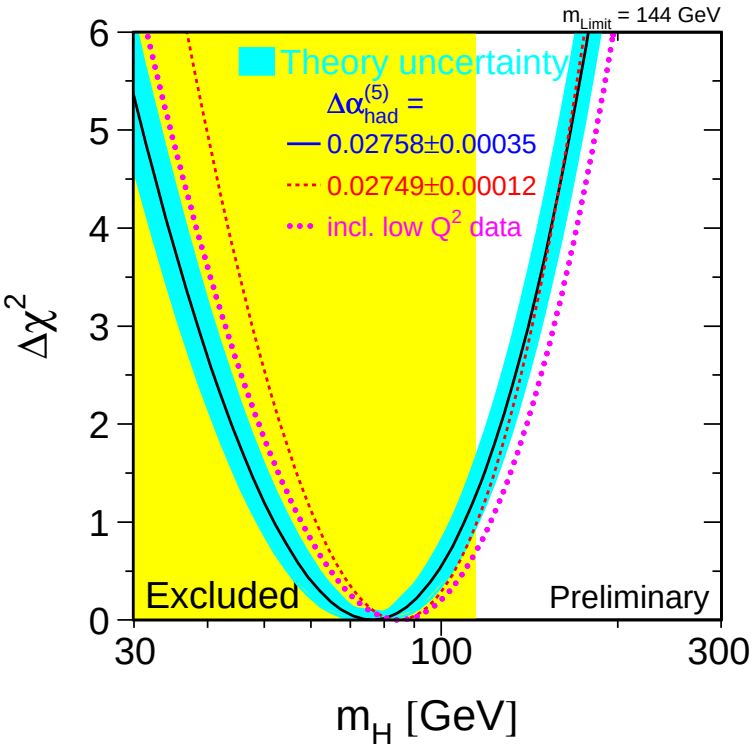
with Higgs mechanism : mathematically closed theory

## Higgs Rationale



– LEP *etc* : precision measurements $\Rightarrow$ $\boxed{M_H = 84^{+34}_{-26}\ \text{GeV}}$

– LEP : direct search $\Rightarrow$ $M_H > 114$ GeV



## Higgs Rationale



– LEP *etc* : precision measurements $\Rightarrow$ $\boxed{M_H = 84^{+34}_{-26}\ \text{GeV}}$

Light Higgs: particles remain weakly interacting up to Planck scale –
$\oplus$ grand unification $\Rightarrow$

*successful prediction of electroweak mixing:*

$\boxed{\sin^2\theta_W \simeq 0.2}$ $\Leftarrow$ first successful hep telescope operation

Alternatives: # Higgs bosons become strongly interacting at high energies

pointlike $\Rightarrow$ composite Higgs particles

*Technicolor, Little Higgs, ...*

# Higgs $\Leftarrow$ 5th gauge field in extra dimensional space

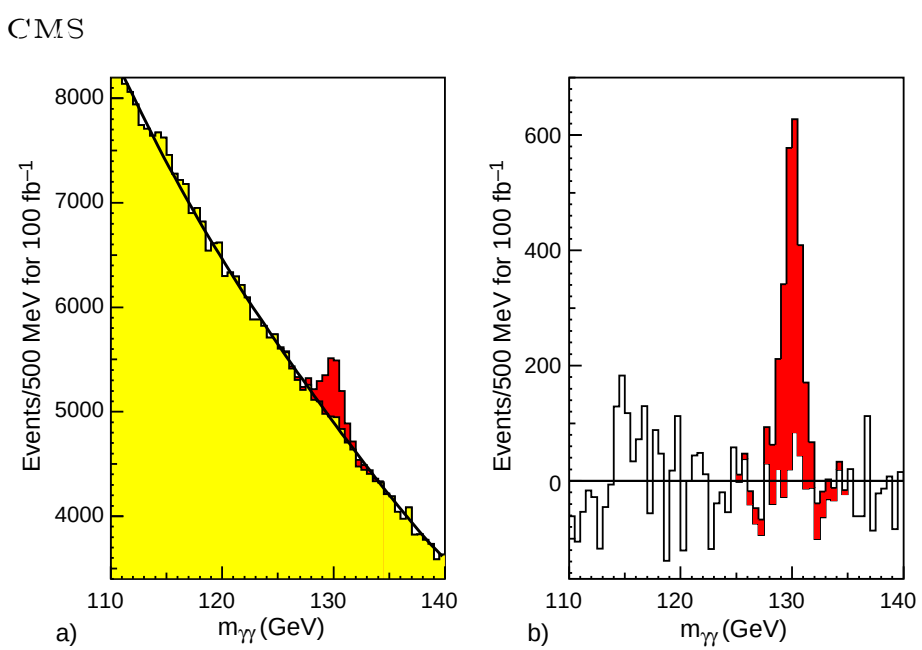
# no Higgs $\Rightarrow$ strong $WW$ interactions

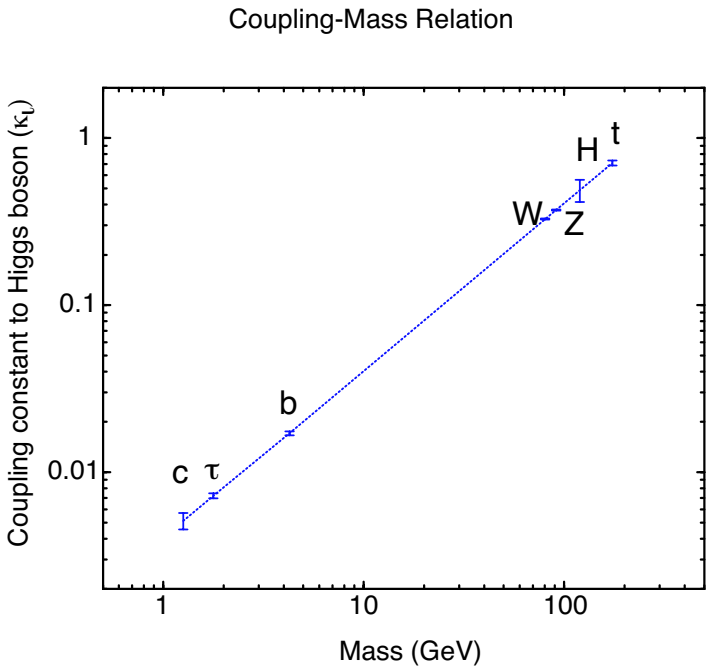
SM unitarity : either Higgs boson discovered with mass below 1 TeV

or theory modified fundamentally at energies $\sim$ 1 TeV

## Higgs Search

- LHC : SM Higgs particle will be discovered over entire mass range $< 1$ TeV
- LC : Higgs mechanism *sui generis* established in model-independent way



STANDARD MODEL: $\Rightarrow$ valid description of nature, formulated at Fermi electroweak scale $\langle H \rangle \simeq 174$ GeV

– but physically incomplete theory of nature

*Open questions*: FUNDAMENTAL LAWS OF PHYSICS

- grand unification of 3 particle forces $\oplus$ gravity / ultimate unification $\Leftarrow$
- Higgs / pattern of particle masses and mixings $[\Leftarrow$
- symmetry concepts for forces and matter

COSMOLOGY

- nature of Cold Dark Matter $\Leftarrow$
- baryon asymmetry in Universe
- cosmological constant / dark energy
- structure of space and time at small distance $\Leftarrow$

Comment: None of the open questions necessarily requires solution seeded at the Tera-scale

but

solutions at the Tera-scale are most suggestive to some

# SM FOREVER : light Higgs & nomore [other] new phenomena up to GUT/PL energies

$$CDM \sim cosmological\ axion > 10^{10}\ GeV$$

$\sin^2\theta_W \simeq 0.2$ : *further details by yet unknown GUT scale physics*

# SUPERSYMMETRY : stabilizing bridge from Fermi to Planck scale

$\sin^2\theta_W$ predicted accurately

offering natural candidate(s) for CDM

# EXTRA-SPACE DIMENSIONS : reducing $M_{PL}$ to Tera-scale

## 2. SUPERSYMMETRY

Attractive extension of SM : unifying bosons $\sim$ fermions

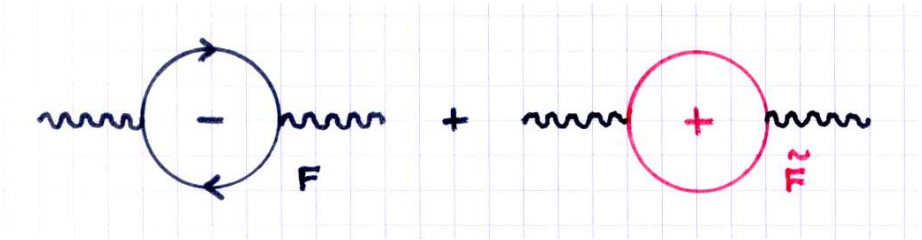
Golfand, Likhtman
Volkov, Akulov
Neveu, Schwarz, Thorn
Wess, Zumino

| | |
|---|---|
| leptons [1/2] | $\sim$ sleptons [0] |
| quarks [1/2] | $\sim$ squarks [0] |
| gluons [1] | $\sim$ gluinos [1/2] |
| photon, ... [1] | $\sim$ photino, ... [1/2] |
| Higgs$'$ [0] | $\sim$ higgsino$'$ [1/2] |
| graviton [2] | $\sim$ gravitino [3/2] |

$\Leftarrow$ solving key problems in a natural way :

stable bridge between Fermi electroweak and Planck scale :

*Higgs mass:*



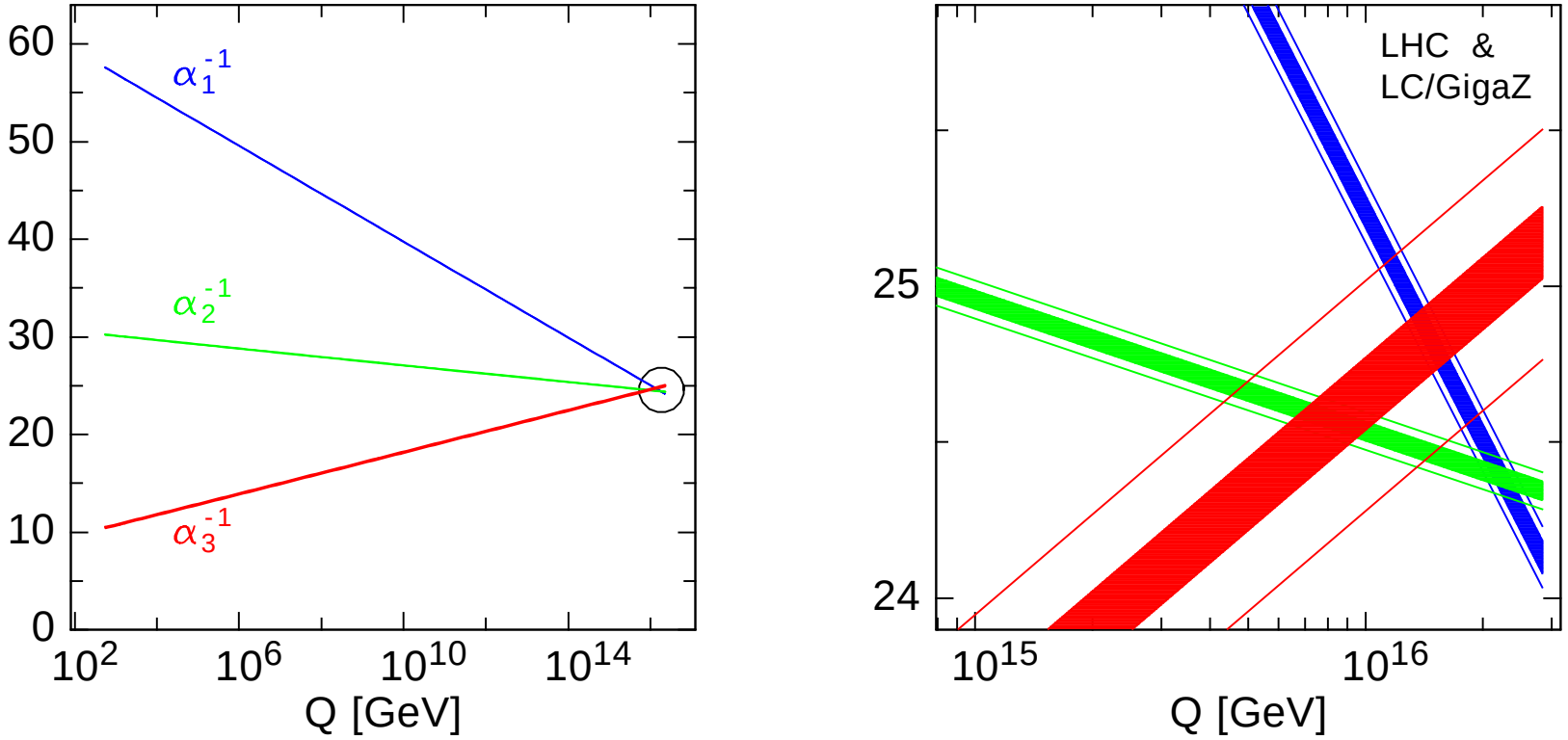

$$\simeq \frac{\alpha}{\pi}[m_{\tilde{F}}^2 - m_F^2]$$

$\Rightarrow$ low-energy supersymmetry:

$$m_{\tilde{F}} \sim \sqrt{\pi/\alpha}\, m_W \sim \mathcal{O}(1\text{TeV})$$

SUPERSYMMETRY $\Rightarrow$

grand unification of 3 particle forces at one per-cent level



## SUPERSYMMETRY $\Rightarrow$



– grand unification of 3 particle forces at one per-cent level

– Higgs mechanism $\Rightarrow$ spontaneous symmetry breaking predicted

– local supersymmetry $\Rightarrow$ gravity in analogy to
local gauge invariance $\Rightarrow$ electromagnetism

– natural candidate(s) for Cold Dark Matter $\sim$ 100 GeV :
# lightest neutralino — Weinberg
# gravitino — Primack

*Central problems:* breaking of supersymmetry ?

$m[\tilde{e}] \gg m[e]$

no phenomenological upper mass limit

[depending on controversial $\Delta[g-2]_\mu$ determination]

## SUPERSYMMETRY ⇒

– grand unification of 3 particle forces at one per-cent level

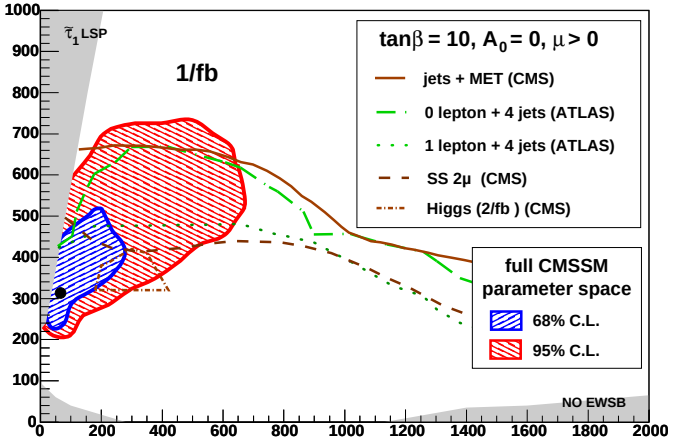
– Higgs mechanism ⇒ spontaneous symmetry breaking predicted

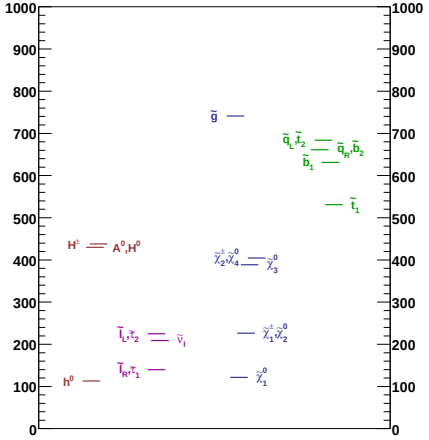
– local supersymmetry ⇒ gravity in analogy to
local gauge invariance ⇒ electromagnetism

– natural candidate(s) for Cold Dark Matter ∼ 100 GeV :
# lightest neutralino
# gravitino

*Estimates of masses:*

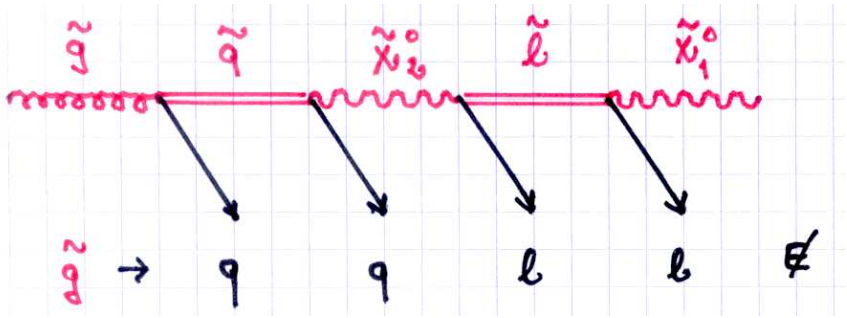
Buchmüller ea / SPS1a′



- LHC : $pp \to \tilde{q}\tilde{q}, \tilde{g}\tilde{g} \ldots$ : $\tilde{m}$ up to $\sim 3$ TeV

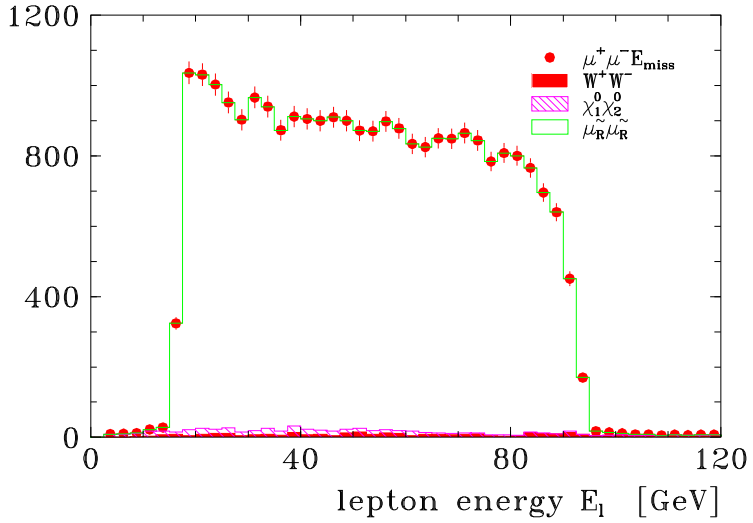
*cascades :*




allowing mass measurements $\sim$ per-cent level

- LC : high-resolution profile of susy particles [per-mille level]

Martyn : $\tilde{\ell} \to \ell\, \tilde{\chi}_1^0$

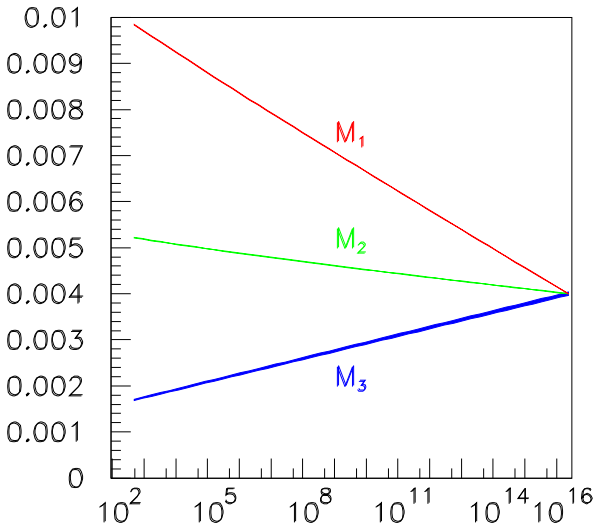


High-precision supersymmetry data allow extrapolation to

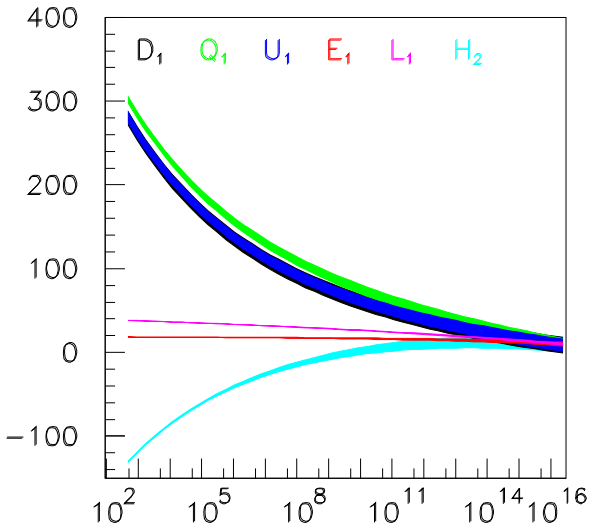
GUT/PL SCALE:

*RECONSTRUCTION OF SUPERSYMMETRIC THEORY / SUSY BREAKING*

*mass: gluino / photino / ...*




*mass: sleptons / squarks*




*masses in mSUGRA universal at GUT, in parallel to gauge couplings*

# INTERMEDIATE SCALES



suggested by : Seesaw mechanism in $\nu$ sector — Minkowski, Gell-Mann ea, Yanagida

Leptogenesis: matter-antimatter asymmetry in Universe through $\nu_R$ decay — Fukugita ea, Buchmüller ea

Seesaw mechanism:

$m_{up}/m_{down} \sim 1$ to 10

$m_\nu/m_\ell \sim 10^{-6}$

solution: coupling of heavy-mass particle to zero-mass particle generates non-zero mass but very light particle:

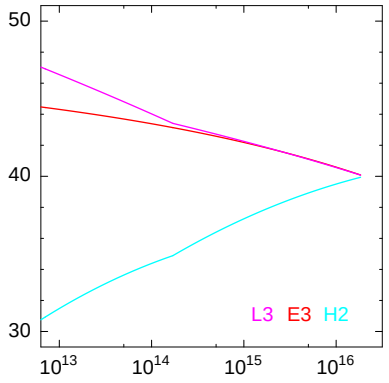
$m_\nu^{exp}[heavy] < M_{GUT} \sim 10^{16}$ GeV

$m_\nu^{exp}[light] \sim v^2/M_{GUT} <$ eV

Heavy $\nu_R$ in 3rd generation affects evolution of scalar susy masses :

universality $\oplus$ measured slepton masses at Tera-scale

$\Rightarrow$ estimate : $M_{\nu R} \sim 10^{14}$ GeV




Blair ea

## *COLD DARK MATTER*



observation: 24% of energy density in Universe appears to consist of invisible matter $\sim$ 5 times visible matter

nature not yet clarified : one component ?
many components ?

strategies: # study CDM interactions with matter in laboratory

# search for astrophysical signals [annihilation,..]

# determine properties of CDM candidates in collider experiments LHC/LC and predict relic density $\Leftarrow$

Supersymmetry: adopting discrete symmetry suppressing $\mathcal{P}$-decay:

$R_P$ : lightest supersymmetric particle stable

# 1 Lightest neutralino $\tilde{\chi}_1^0$ :

$\tilde{\chi}_1^0$ = complex mixture of photino, higgsino, etc $\Rightarrow$

precise measurements of masses and mixing needed

to predict relic density

$\Leftarrow$ Planck satellite : $\Delta\Omega/\Omega \sim 1\%$

$\tilde{\chi}_1^0$ LHC measurements |

ILC[1 TeV] measurements :

Baltz ea

| | low $\tilde{m}_0$ | high $\tilde{m}_0$ |
|---|---|---|
| LHC | 10% | 80% |
| ILC | 2% | 8% |

$\Leftarrow$ *difficult to match cosmological data when aiming at a high-resolution picture of CDM beyond qualitative comparison*

# 1 Lightest neutralino $\tilde{\chi}_1^0$ :

$\tilde{\chi}_1^0$ = complex mixture of photino, higgsino, etc $\Rightarrow$

precise measurements of masses and mixing needed
to predict relic density

# 2 Gravitino $\tilde{G}$ :

$\tilde{G}$ gravity coupling to matter very small $\Rightarrow$

standard lightest susy particle long-lived : $\tilde{\tau} \rightarrow \tau + \tilde{G}$, etc

metastable non-relativistic particles

# 3 Variants :

– schemes w $R_P$ slightly broken $\Rightarrow$ $e^+$, $\bar{p}$, $\gamma$, ... $\sim$ Pamela, AMS .. Buchmüller ea

– LSP in secluded light sector $\Rightarrow$ multi-lepton final states $\sim$ CDF ? Arkani-Hamed ea

## 3. EXTRA-SPACE DIMENSIONS

Hierarchy problem $v \ll M_{PL}$ : SM forever : *ignored*

Supersymmetry : *stability solved*

xtra space dimensions : *removed*

Antoniadis
Arkani-Hamed ea
Randall, Sundrum

*Basic ADD scenario* : Planck-scale reduced to Tera-scale

$\Leftarrow$ gravity strong in $D > 4$ dimensions

apparently weak only in projection to $D = 4$ dimensions

- higher dims wrapped up on small circles $\Rightarrow$ Kaluza-Klein $KK_G$ excitations

$pp/e^+e^- \to KK_G + X$ : escaping $KK_G$ $\Rightarrow$ $E_{miss}$ :

*new Planck scale* $M_{PL}$ *and dimension* $D$

## 3. EXTRA-SPACE DIMENSIONS

*Basic scenario* : Planck-scale reduced to Tera-scale

$\Leftarrow$ gravity strong in $D > 4$ dimensions

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- higher dims wrapped up on small circles $\Rightarrow$ Kaluza-Klein $KK_G$ excitations

  $pp/e^+e^- \to KK + X$ : escaping $KK$ $\Rightarrow$ $E_{miss}$

  measure $E_{miss}$ by varying total energy :

  new Planck scale $M_{PL}$ and dimension $D$

- Mini-black hole : mass $M_{BH} \sim M_{PL}/(M_{PL}R)^{D/(2+D)} \sim$ TeV

  lifetime $\tau_{BH} \sim G_N^2 M_{BH}^3 \sim 10^{-26}$ sec

[backed by astrophysical/cosmological observations]

# THEORETICAL ΤΕΛΟΣ

SUPERSYMMETRY : most attractive path to the Planck scale

but needs embedding in extended theory
for quantum gravity

SUPERSTRINGS : consistent theory of quantum gravity

$\Rightarrow$ landscape of some $10^{500}$ vacua

no principle known to single out one state

$\Rightarrow$ $10^{500}$ coexisting universes in a Megaverse ?

*"3rd Copernican Revolution!"*

# SUMMARY

# 1 : Standard Model must be completed by Higgs or modified at Tera-scale :

– light Higgs discovered as suggested by precision data

– elw gauge bosons strongly interacting at Tera-scale,
xtra dimensions and new $KK$ states
...

# 2 : If Higgs light, fields weakly interacting up to Planck-scale

but gap between Fermi and Planck-scale unstable :

⇒ Supersymmetry most natural solution
*smooth path to Planck scale*

⇒ completed by superstring /w fascinating new cosmology ?

# 3 : Extra-space dimensions ?

gravity strong nearby and Planck-scale at Tera-scale ?

LHC : opening window to the microscopic world of matter and forces at Tera-scale :

– solving problem of mass and

building platform for telescoping Planck scenario with unification of matter and forces

– connecting particle physics with cosmology in clarifying nature of Cold Dark Matter

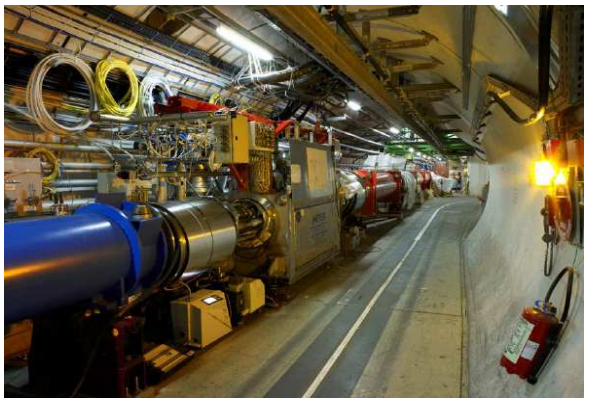
LC : picture after LHC remains coarse without high-precision lepton collider ILC/CLIC,

sharpening telescope resolution by order of magnitude $\Rightarrow$

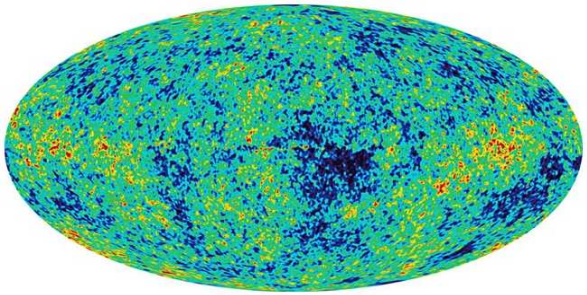
TERA-SCALE EXPERIMENTS ESSENTIAL IN SHAPING THE FUNDAMENTAL PICTURE OF OUR WORLD

Rolf returning back to Hamburg in 5 ... years :

– hopefully not without a bag filled with



a few Higgs bosons
and many supersymmetric particles?
– or mini-Black holes?
– or something Unexpected?



Viel Erfolg mit LHC !