BSM Physics Vol. 1: Models and Motivations

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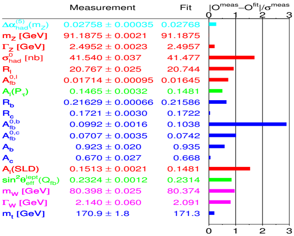
The Standard Model of Particle Physics – Doubts



– describes microcosm (too well?)

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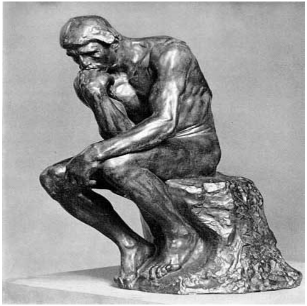
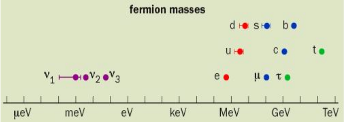
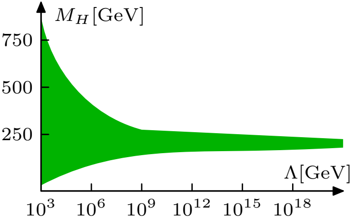


- describes microcosm (too well?)
- 28 free parameters



- form of Higgs potential ?



Hierarchy Problem

chirale Symmetrie: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry for quantum corrections to the Higgs mass

$$\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2\ \text{GeV}^2$$

20000 GeV^2 = (100000000000000000000000000000000020000 –

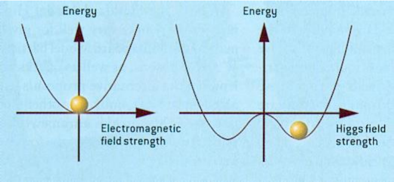
1000000000000000000000000000000000000000) GeV^2

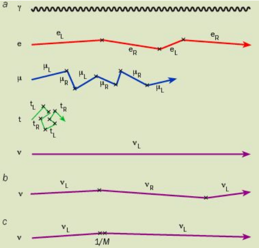
The Higgs Boson – A Long Expected Party

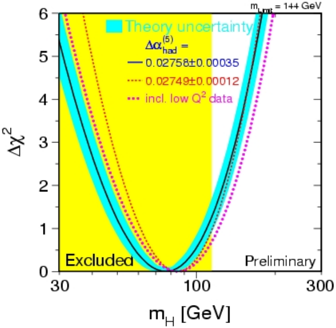
- Higgs: fundamental scalar field

  Brout, Englert, Higgs, 1964

- Vacuum expectat. value $v = 246\,\text{GeV}$
- breaks electroweak symmetry to electromagnetism
- gives elementary particles mass
- couples proportional to its mass

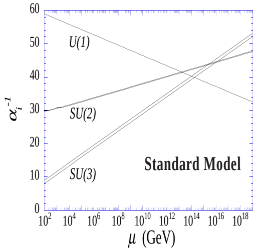




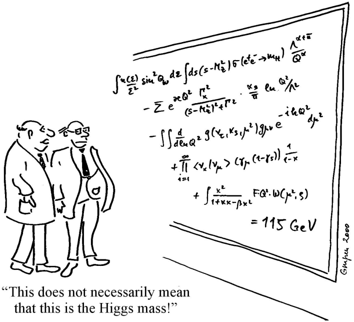


40 years search in vain

Open questions



- Unification of all interactions (?)
- Baryon asymmetry $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$
  missing CP violation
- Flavour: three generations
- Tiny neutrino masses: $m_\nu \sim \frac{v^2}{M}$
- Dark Matter:
  - stable
  - weakly interacting
  - $m_{DM} \sim 100\,$GeV
- Quantum theory of gravity
- Cosmis inflation
- Cosmological constant



"This does not necessarily mean that this is the Higgs mass!"


bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
MSSM +νR
unnified SM
axigluon
sterile ν
6th gen
5th gen
4th gen
lepto quark
heavy Majorana ν
vector-like family
fractionally charged
milli-charged
mono-pole
S, T, U
NOT YET THOUGHT OF
shadow matter
mirror symmetry
NOT YET THOUGHT OF
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
saxion
axino
N=2
N=4
N=8
string
hetero-tic
matrix
M
IIB
IIA
F
I
contact int.
quintessence
k-essence
composite W, Z
Extra dim
worm-hole

Ideas for New Physics since 1970

(1) **Symmetry for elimination of quantum corrections**

- Supersymmetry: Spin statistics $\Rightarrow$ corrections from bosons and fermions cancel each other
- Little Higgs Models: Global symmetries $\Rightarrow$ corrections from particles of like statistics cancel each other

(2) **New Building Blocks, Substructure**

- Technicolor/Topcolor: Higgs bound state of strongly interacting particles

(3) **Nontrivial Space-time structure eliminates Hierarchy**

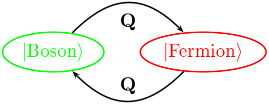
- Extra Space Dimensions: Gravitation appears only weak
- Noncommutative Space-time: space-time coarse-grained

(4) **Ignoring the Hierarchy**

- Anthropic Principle: Parameters are as we observe them, since we observe them

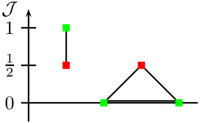
Supersymmetry (SUSY)

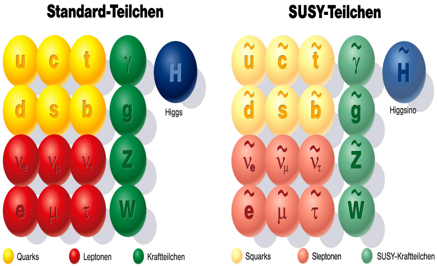
Gelfand/Likhtman, 1971; Akulov/Volkov, 1973; Wess/Zumino, 1974



- connects gauge and space-time symmetries
- Multiplets with equal-mass fermions and bosons

⇒ SUSY broken in Nature





- Every particle gets a superpartner
- Minimal Supersymmetric Standard Model (MSSM)
- Mass eigenstates:
  Charginos: $\tilde{\chi}^{\pm} = \tilde{H}^{\pm}, \tilde{W}^{\pm}$
  Neutralinos: $\tilde{\chi}^0 = \tilde{H}, \tilde{Z}, \tilde{\gamma}$

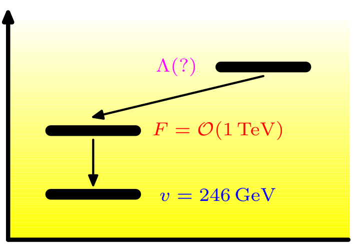
SUSY: Success and Side-Effects

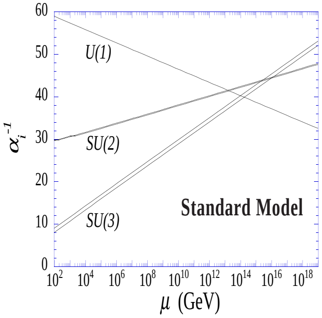
MSSM: spontaneous SUSY breaking ⚡ (SUSY partners in MeV range)

Breaking in "hidden sector"

Breaking mechanism induces 100 free parameters

solves hierarchy problem:
$\delta M_H \propto F \log(\Lambda^2)$





- Existence of fundamental scalars
- Form of Higgs potential
- light Higgs ($M_H = 90 \pm 50$ GeV)
- discrete R parity
  - SM particles even, SUSY partners odd
  - prevents a proton decay too rapid
  - lightest SUSY partner (LSP) stable
    Dark Matter $\tilde{\chi}_1^0$
- Unification of coupling constants

SUSY: Success and Side-Effects

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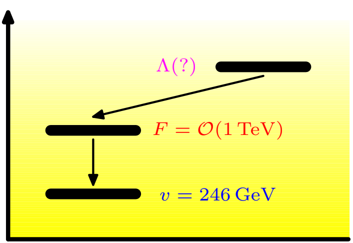

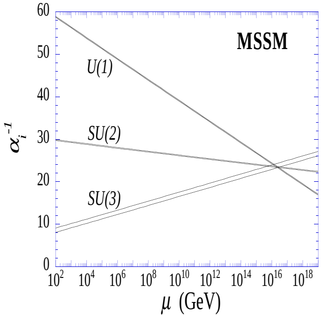

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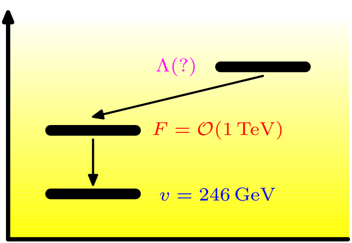

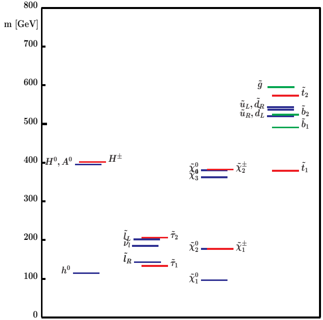

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"SUSY will be discovered, even if non-existent"

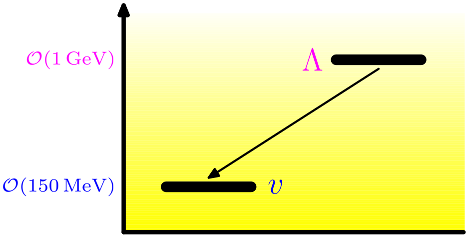
What, if not SUSY?

Higgs as Pseudo-Goldstone boson: Technicolor

Nambu-Goldstone Theorem: Spontaneous breaking of a global symmetrie: spectrum contains massless (Goldstone) bosons 1960/61

Color: Adler/Weisberger, 1965; Weinberg, 1966-69

Light pions as (Pseudo-)Goldstone bosons of spontaneously broken chiral symmetry



Skala Λ: chiral symmetry breaking,
Quarks, $SU(3)_C$

Scale v: pions, kaons, ...

Higgs as Pseudo-Goldstone boson: Technicolor

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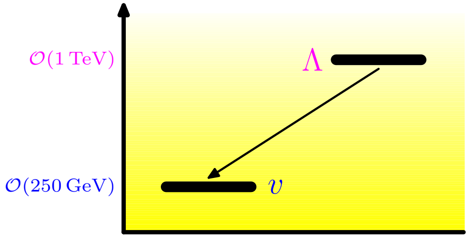
Technicolor: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

Light Higgs as (Pseudo)-Goldstone boson of a new spontaneously broken chiral symmetry

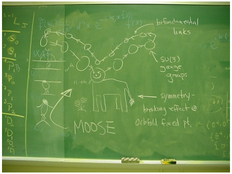


Skala Λ: chiral symmetry breaking, techni-quarks, $SU(N)_{TC}$

Skala v: Higgs, techni-pions

experimentally constrained, but not ruled out

Collective Symmetry Breaking, Moose Models



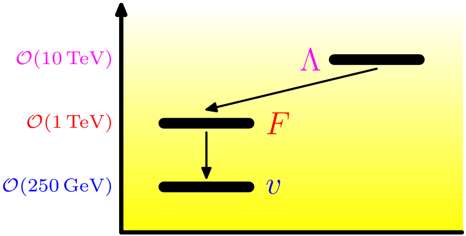
Collective Symmetry Breaking:

Arkani-Hamed/Cohen/Georgi/Nelson/..., 2001

> 2 different global symmetries; if one were unbroken
> $\Rightarrow$ Higgs exact Goldstone boson

Higgs mass only by quantum corrections of 2. order:

$$M_H \sim (0.1)^2 \times \Lambda$$

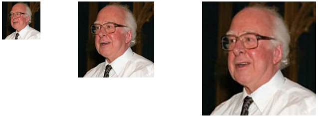


Scale Λ: chiral SB, strong interaction

Scale F: Pseudo-Goldstone bosons, new gauge bosons

Scale v: Higgs

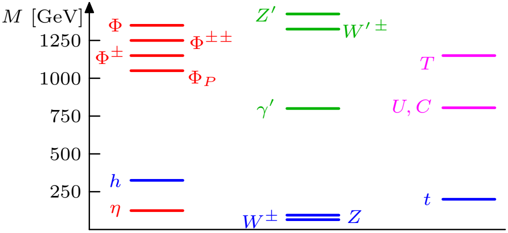
Little-Higgs Models



– Economic implementation of collective symmetry breaking

– New Particles:
  - Gauge bosons: $\gamma', Z', W'^{\pm}$
  - Heavy Fermions: $T, U, C, \ldots$
  - Quantum corrections to M_H cancelled by particles of like statistics

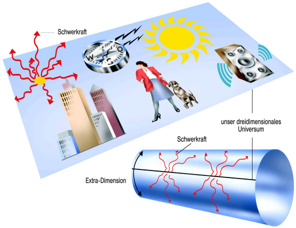
Littlest Higgs Arkani-Hamed/Cohen/Katz/Nelson, 2002



– "Little Big Higgs": Higgs heavy $(300 - 500\,\text{GeV})$

– discrete T-(TeV scale) parity:
  - allows for new light particles
  - Dark matter: LTOP (lightest T-odd), often γ'

Extra Dimensions & Higgsless Models



Motivation: String theory

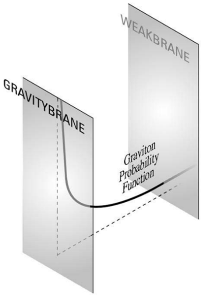
$3+n$ Space dimensions: Radius $R \sim 10^{\frac{30}{n}-17}$ cm   Antoniadis, 1990; Arkani-Hamed/Dimopoulos/Dvali, 1998

Gravitation strong in higher dimensions

Particles in quantum well: Kaluza-Klein tower

Production of mini Black Holes at LHC

- "Higgsless Models": Higgs component of higher-dim. gauge field
- "Large Extra Dimensions": continuum of states
- "Warped Extra Dimensions": discrete, resolvable resonances   Randall/Sundrum, 1999
- "Universal Extra Dimensions": also fermions/gauge bosons in higher dimensions



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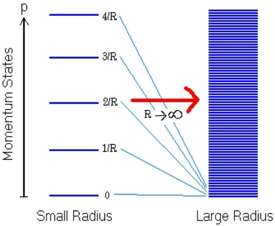

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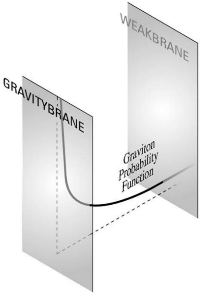
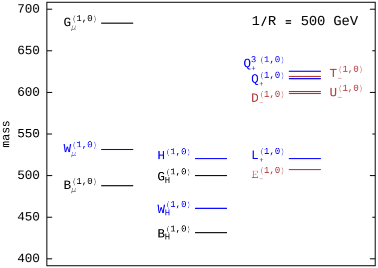
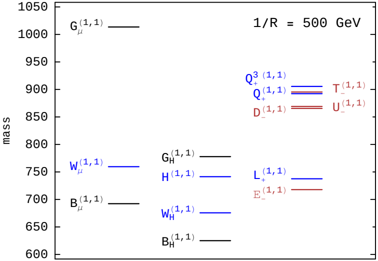


KK parity and Dark Matter

- typical Kaluza-Klein spectra





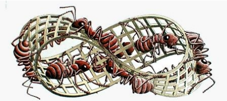
- Spectrum structure similar to SUSY, but shifted in spin

- Dark matter: lightest KK-odd particle (LKP)
  Photon resonance γ' (in 5D vector, in 6D scalar)

- Quote from SUSY orthodoxy:
  “This is a strawman’s model invented with the only purpose to be inflamed to shed light on the beauty of supersymmetry!”

Noncommutative Space-time

Wess et al., 2000



– Assumption: non-commuting Space-time coordinates $[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu}$

– Classical analogue: charged particle in lowest Landau level: $\{x_i, x_j\}_P = 2c(B^{-1})_{ij}/e$

– Low energy limit of string theory

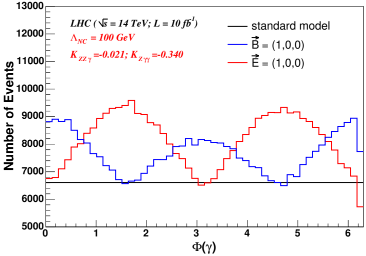
Seiberg/Witten, 1999

– Yang-Landau-Theorem violated: $Z \to \gamma\gamma, gg$ possible

– Special direction in the Universe: broken rotational invariance

– Cross sections depend on azimuth

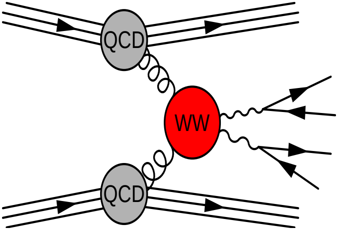
$\Rightarrow$ Varying signals as Earth rotates



– Dark Matter, cosmology, theoretical problems ↯

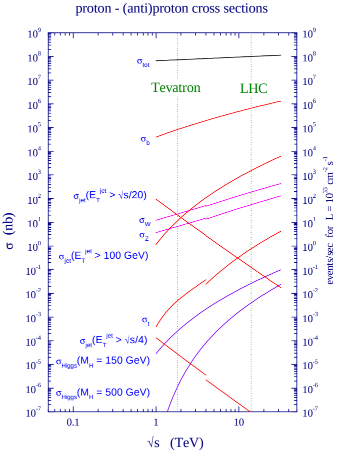
Which model? A Conspiracy Unmasked

The Challenge of the LHC



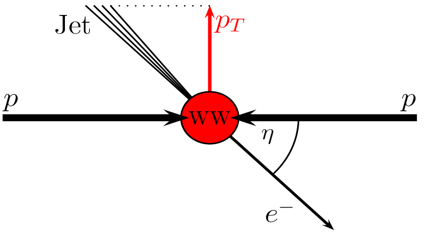
Partonic subprocesses: qq, qg, gg

No fixed partonic energy



$R = \sigma\mathcal{L} \qquad \mathcal{L} = 10^{34}\,\text{cm}^{-1}\text{s}^{-1}$

High rates for t, W/Z, H, $\Rightarrow$ **hugh backgrounds**



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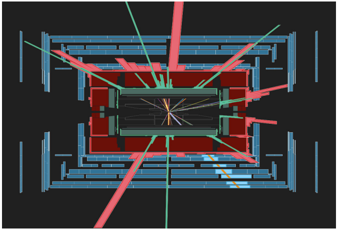

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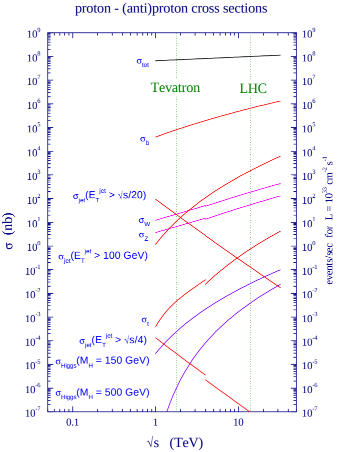

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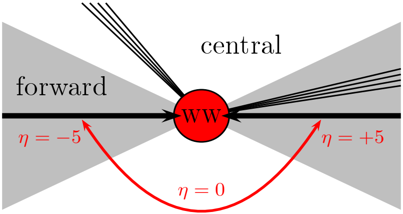
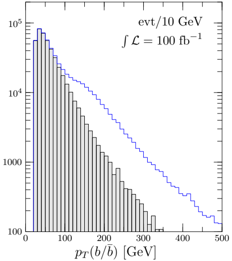


Search for New Particles



Decay products of heavy particles:

- high-p_T Jets
- many hard leptons

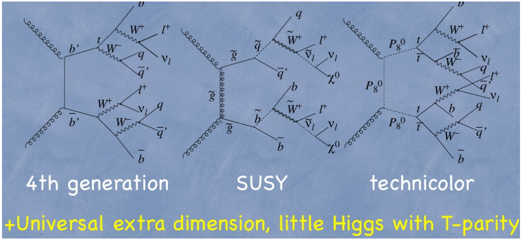
Production of coloured particles

weakly interacting particles only in decays

Dark Matter $\Leftrightarrow$ discrete parity (R, T, KK)

- only pairs of new particles $\Rightarrow$ high energies, long decay chains
- Dark Matter $\Rightarrow$ large missing energy in detector ($\not{E}_T$)

Different Models/Decay Chains — same signatures



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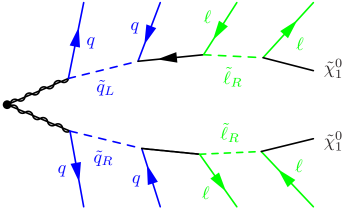

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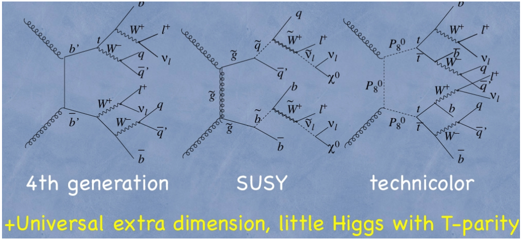
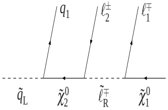
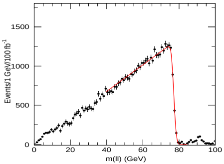
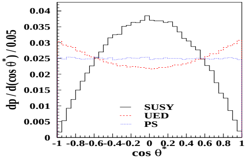


Model Discrimination – A Journey to Cross-Roads

- Mass of new particles: end points of decay spectra







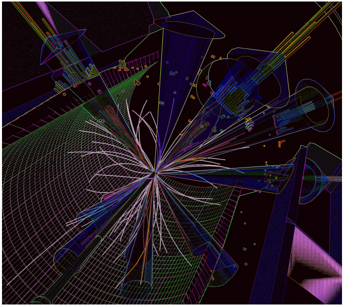
- Spin of new particles: Spin of new particles: angular correlations, . . .
- Model determination: measuring coupling constants

$\Rightarrow$ Precise predictions for signals and backgrounds

- kinematic cuts
- Exclusive multi particle final states $2 \to 4$ up to $2 \to 10$
- Quantum corrections: real and virtual corrections

Outlook

- LHC: new era of physics
- New Particles, new symmetries, new interactions
- Dark Matter
- Interesting times!



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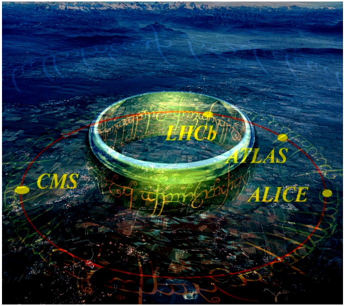
- Dark Matter
- Interesting times!



"Will man nun annehmen, dass das abstrakte Denken das Höchste ist, so folgt daraus, dass die Wissenschaft und die Denker stolz die Existenz verlassen und es uns anderen Menschen überlassen, das Schlimmste zu erdulden. Ja es folgt daraus zugleich etwas für den abstrakten Denker selbst, dass er nämlich, da er ja doch selbst auch ein Existierender ist, in irgendeiner Weise distrait sein muss."

Søren Kierkegaard