Lecture : Physics Beyond the SM

2019 , 3+1 h/week , 14 weeks

Intented audience : master theory
masters particle physics (both theory and expt.)
master/PhD students in particle physics

Content : Why BSM ?
How to search for BSM (which observables)? which experiments?
Overview of theo. approaches and models
Detailed discussion of specific models and relevant expt. constraints:
susy , neutrino masses , 2HDM

Note : in parallel : Lecture SM Theory

Foreword : - very active and vast field of ongoing research
- can only provide introduction and have to skip alot
- aim : provide a fairly complete picture of BSM "landscape" i.e. which expts are done why , which models are considered and how do they differ , which ideas for BSM exist
- provide technical details for repres. examples which are also of interest in Dresden.

1. First survey of BSM physics

- Why BSM?
- Which directions of searches? Constraints on BSM?
- Overview of models / strategies

1.1 Why BSM physics?

1.1.1 Successes of the SM

SM of particle physics:

- excellent achievement of humanity
- complete, math. consistent and precise description of vast range of phenomena: chemistry .... Higgs
- theory based on deep and rigid structure: gauge symmetry + spont. sym. breaking
- $\mathcal{L}$ very compact: gauge terms, + kinetic, Yukawa, Higgs self interact.
- $\mathcal{L}$ contains QED, nonrel. QM as limits

Particles:

quarks $\begin{cases} u & c & t \\ d & s & b \end{cases}$

leptons $\begin{cases} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{cases}$

3 generations

, gauge bosons: 8 gluons $\Leftrightarrow SU(3)_{col}$

$W^\pm$, Z, photon $\Leftrightarrow SU(2)_L \times U(1)_Y$

Higgs boson h

note: quarks, gluons do not exist as free, observable particles

Masses:

$M_Z \approx 91\ GeV$ $M_W \approx 80\ GeV$ $M_h \approx 125\ GeV$

$\rightarrow$ "EW scale $\approx 100\ GeV$"

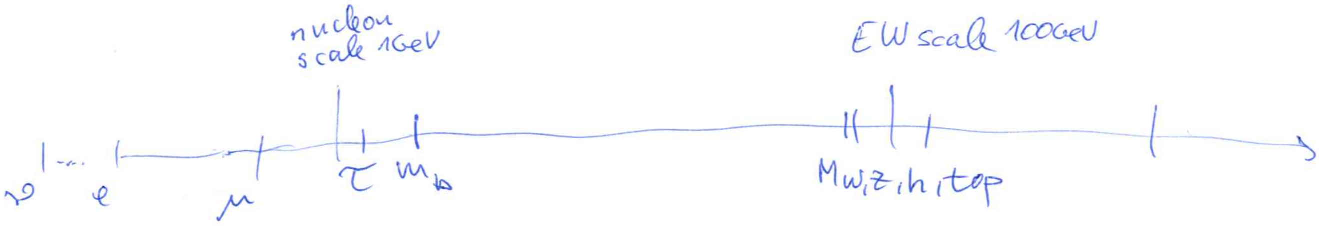
$m_e = 511\ keV$, $m_\mu \approx 100\ MeV$, $m_\tau \approx 1{,}7\ GeV$

$m_{u,d,s} \ll 100\ MeV$, difficult to define

$m_b^{\overline{MS}}(\mu = m_b^{\overline{MS}}) \approx 4{,}2\ GeV$, $m_t^{pole} \approx 172\ GeV$

$m_\nu \lesssim 1\ eV$

~~$\Rightarrow$ vast differences~~
~~SM: all masses $\sim v \ast$ (coupling to Higgs)~~
~~(except m_ν - undefined)~~



note: new physics could be anywhere!

- vast differences
- SM: all masses $\sim v \ast$ (coupling to Higgs)
  $\rightsquigarrow$ so far exp. confirmed!
- ν-masses in SM: undefined / zero

1.1.2 Reasons for BSM physics: observations

observations $\Longrightarrow$ there must be BSM

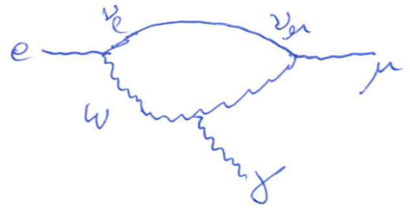
theoretical speculations/arguments/prejudice $\Longrightarrow$ there should be BSM

Observational reasons:

① **Neutrino masses $\neq 0$, neutrino mixing**

oscillation:
- only possible if masses $\neq 0$
- $\sim |m_1^2 - m_2^2|$ can be determined
- implies non-conservation of lepton generation number, even charged lepton flavour violation $\neq 0$ $\Rightarrow$ process $\mu \to e\gamma$ should happen

$\Rightarrow$ also:



but: don't know whether

Majorana masses ($\to$ new type of masses)

or Dirac masses ($\to$ similar to lept./qu. masses)

Q. $\Rightarrow$ no "SM of neutrino masses" so far!

(2) Dark matter := matter, non-relativistic, not interact with γ, gluons

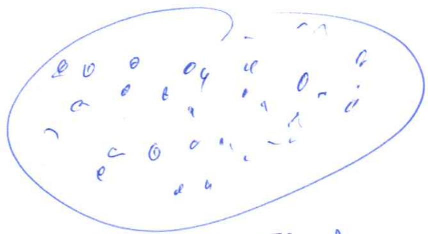
evidence:

energy density of Universe today:

$$\rho_{total} = \rho_{Baryon} + \rho_{dark\ matter} + \rho_{dark\ energy} + \rho_{Photons,\ Neutrinos,\ rest}$$

ρ_{Baryon}	$\rho_{dark\ matter}$	$\rho_{dark\ energy}$	$\rho_{Photons,\ Neutrinos,\ rest}$
~4 %	~26 %	~70 %	~0 %

from fluctuations of cosmic microwave background



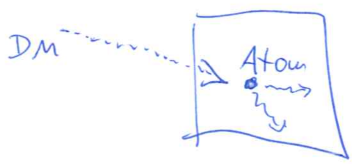
WMAP or Planck satellites

further evidence from gravity measurements:
- rotation velocities in galaxies, galaxy clusters
- grav. lensing (→ "bullet cluster")

knowledge:

a) D.M. property relevant for evolution of galaxies, clusters

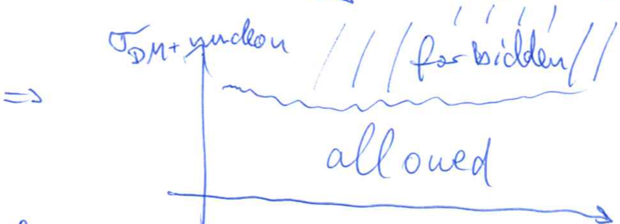
b) many searches, e.g. like for ν's



~~$\sigma_{DM+nucleus}$ is constrain~~

not found

⇒



⇒ only SM candidates: Neutrinos ⇝ excluded by (a, b)

⇒ must be BSM particle: stable, neutral, spin = 0, ½, 1, ?

(3) Baryon Asymmetry of the Universe

- today $\eta :\simeq \frac{\#(\text{baryons} - \text{antibaryons})}{\#\text{ photons in C.M.B.}} \approx 10^{-9}$

why not $\eta = 0$?

- assume initial condition (~ big bang) has $n_B - n_{\bar{B}} = 0$
- Sakharov conditions for developing $n_B > n_{\bar{B}}$:
  a) Baryon number violating processes
  b) C, CP violating processes
     (otherwise $X \to B$ and $\bar{X} \to \bar{B}$ at same rate)
  c) nonthermal equilibrium
     (otherwise $X \to B$ and $B \to X$ at same rate)

- In SM : B-number indeed violated by non-perturbative effects ($\neq$ Feynman diag.)
  C, CP violated
  non-th. equil. at Higgs phase transition

$\Rightarrow$ however effect is too weak !

$\Rightarrow$ need new sources of CP violation and stronger non-equil. processes

1st lect.

2nd lect.

(1), (2), (3) are unavoidable. In addition there are small deviations between SM predictions and measurements:

- muon anomalous magn. moment: $\Delta a_\mu^{EXP-SM} \approx (27 \pm 8) \cdot 10^{-10}$
- few observables in $b \to s$ and $b \to c$ decays
- however, not conclusive (yet)

1.1.3 Reasons for BSM physics: conceptual

(1) Too many free parameters
3 gauge couplings, 3 · 3x3 complex Yuk. matrices
2 H-pot. parameters

hope ⇝ fundamental theory with fewer (0 or 1) param.?
can predict values of these param.

(2) Why:

why $SU(3)_c \times SU(2)_L \times U(1)_Y$?

hope / guess: bigger group: SU(5), SO(10) (unified)
or $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)$
↑ ↗
⇒ study generic consequences of GUTs / LR-symmetric
~~extra light gauge~~ proton decay, Z'? W'?
~~prediction~~ g. coupling unification

why three generations?
why such diff. masses / ~~small~~ mixings?

hope: explanation, e.g. family symmetry
or localization / ~~topology~~ of extra dimension

⇒ study flavour physics!

(3) electroweak symmetry breaking (EWSB)
too ad hoc / simplistic in SM
(compare to superconductor: e^--phonon dynamics ⇒
cooper pairs ⇒ condense at low T ⇒ SSB;
Ginzburg Landau ≙ effective macroscopic theory)

- ~~no explanation~~ existence of scalar field?
- reason for mexican hat potential?
- if scalar, why only one?
- naturalness / hierarchy problem:
  SM + heavy d.o.f. (eg GUT, Planck scale)
  ⇝ contrib. $\sim M^2_{heavy}$ to M^2_H ⇝ why so small?

hope/guess : $\exists$ dynamical origin :
explains existence of scalar, mexican hat,
lightness compared to M_{cut}

⇝ **expect new physics associated with Higgs**

(4) Why charge quantization (all electric charges = $\frac{n}{3}$,
hypercharges = $\frac{n}{6}$, $Q_{proton} + Q_{electron} = 0$)?

note: $U(1)_Y$ charges could be arbitr. real numbers

hope/guess: explained by unified gauge group —
non-abelian qu. numbers always quantized!

(5) Why nature of spacetime = 3+1-dim
(bosonic, commuting dimensions)?

⇝ spacetime might be dynamic (gravity, string th.)
⇝ susy

(6) Strong CP problem:

SM in principle contains non-pert. effect
⇝ $\mathcal{L}_\theta = \theta_{QCD} F_a^{\mu\nu} F_a^{\rho\sigma} \varepsilon_{\mu\nu\rho\sigma}$
⇝ breaks CP ⇝ would lead to
observable electric dipole moment of neutron
⇝ not observed

$\Rightarrow |\theta_{QCD}| < 10^{-9}$ → Why?
→ finetuning/naturalness problem

hope/guess: dynamical explanation for smallness
e.g. "axion" particle whose potential
drives θ_{QCD} to zero

⇝ axion = very light, neutral, weakly interacting particle

(7) Gravity : not unified / quantized with SM

→ need at least SM + quantum gravity

→ then, problem :

why cosmological constant / dark energy so small : $\Lambda \sim 10^{-120} M_{Planck}^4$

$\sim 10^{-40} (1 GeV)^4$

↑ typical contrib. expected by SM

→ finetuning / naturalness problem

(8) Cosmological questions : flatness, horizon problems etc.

⇝ inflation : period of exponentially fast expansion!

⇝ could be triggered by scalar field ⟹ need appropriate scalar (can it be the SM Higgs ?)

Assessment :

very diverse reasons

strongest ones from neutrinos / cosmo

might lead to BSM with very diverse properties

BSM observable soon ? ~~motivated by D.M., Higgs naturalness, but also by the fact that most extensions of SM~~

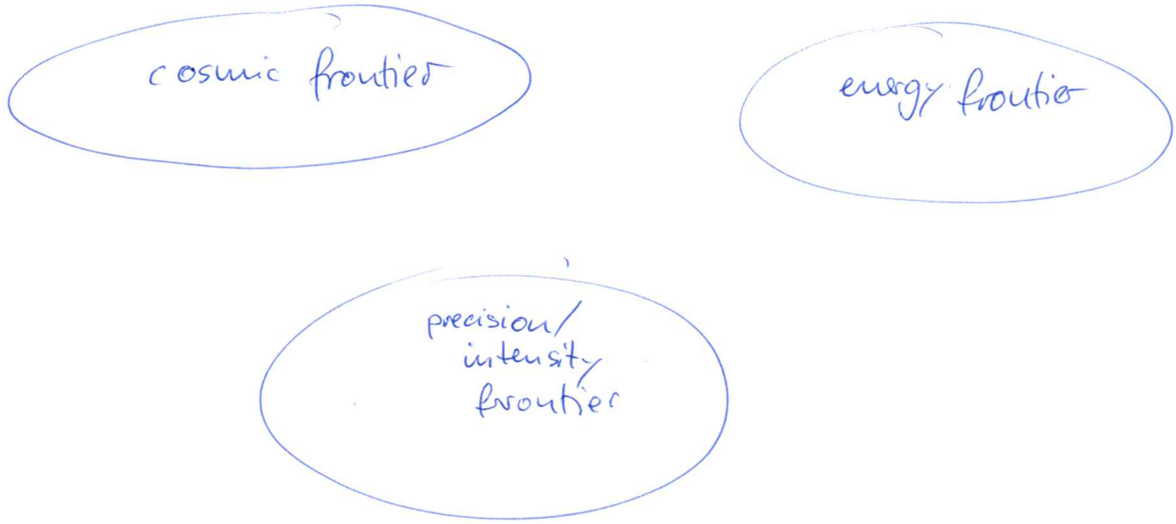
- D.M. , Higgs naturalness → point towards TeV-sc.
- a_μ , b - decays "
- most concrete solutions for any of the puzzles lead to observ. consequences

→ next : observables / tests

1.2 Directions in BSM physics

- where to focus theory attention?
- spend money on which experiments?

1.2.1 The "frontiers" of physics



Selected obvious open Q.: - dark matter, baryogenesis

- EWSB/Higgs, towards GUT, susy, higher sym.

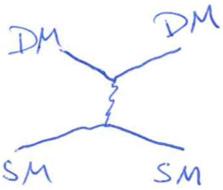
- neutrinos, flavour

However, lot of overlap in theory! Mainly useful for classifying/optimizing experiments

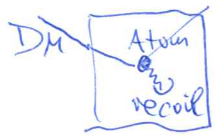
⇝ which observables/measurements/expt.s are useful to make progress?

cosmic frontier:

direct DM searches:

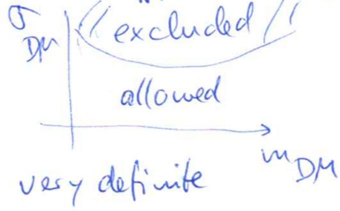


e.g.

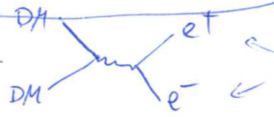


very low-background exp. (similar to neutrino searches

XENON, LUX, ... =>



indirect DM searches: eg.



← with very definite energy

=> search for such monoenergetic electrons

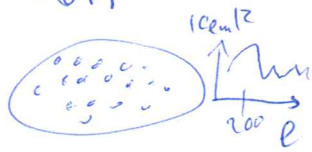
⇝ many other ideas, many experiments

CMB measurements (WMAP, Planck), in particular of polarization

⇝ further tests of cosmol. stand. model, ρ_{DM}

⇝ potential tests of inflation

=>



grav. wave experiments:

⇝ clues on black holes, neutron stars

⇝ clues on inflation? ⇝ info on scalar fields

on phase transitions ⇝ baryogenesis?

energy frontier:

LHC → searches for SUSY particles, Z', W', leptoquarks, extra Higgs (TUD), etc.

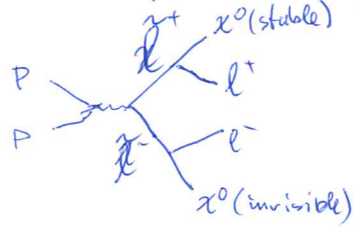
LHC → SM-Higgs measurements

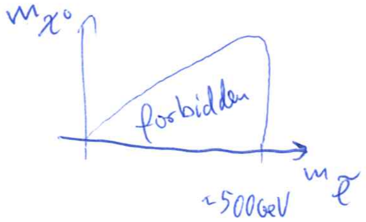
LHC → other SM measurements

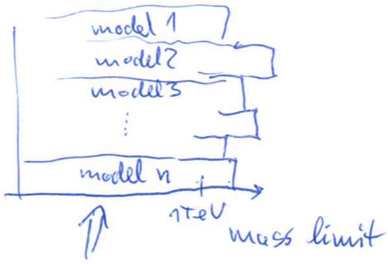
searches for SUSY particles, Z', W', leptoquarks, extra Higgs (TUD), etc.

⇒ limits on masses, depending on assumptions!

e.g.



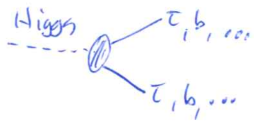




each time different important <u>assumptions</u>!

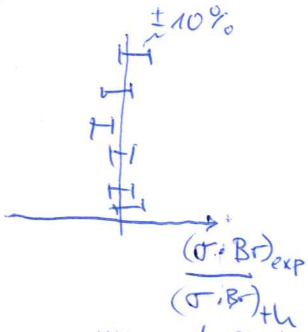
SM-Higgs measurements

$\Rightarrow \sigma_{pp \to Higgs}$



~~Br~~ $(H \to ii)$

⇒



many observables ⇝ perfect agreement

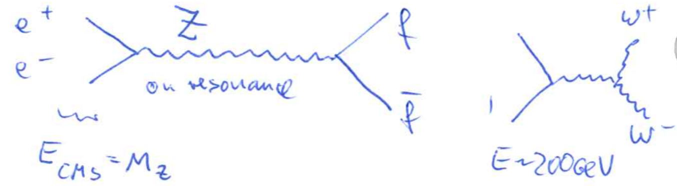
uncertainty ~10%

other SM measurements

- top: heaviest particle, large top-Higgs coupling
  ⇝ interesting probe of EWSB?
  ⇝ top mass: <u>precision crucial!</u>
- ~~...~~ WW → WW (TUD): sensitive to Higgs,
  ⇝ deviations from elementary Higgs?
- ...

⇒ hierarchy problem / EWSB: very likely to find something new! Maybe need higher energy (→ 100 TeV collider) or less QCD "dirt" (→ e^+e^- collider) (→ $\mu^+\mu^-$-collider?)

LEP
(was energy frontier, now precision)



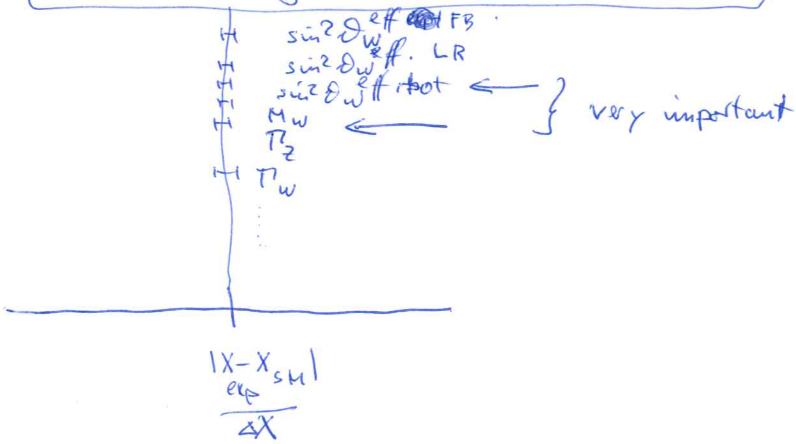
EWPO
(el. weak precision obs.)

very precise Z-couplings, masses $M_{Z,W}$

→ test of EWSM gauge structure at 0,1% -level!

(⟺ 1-Loop + 2-Loop calculations)

→ very strong constraints on BSM!



precision / intensity / low energy:

auxiliary $\Delta\alpha$, a_μ^{had} $\Leftrightarrow$ $e^+e^- \to had$
μ-lifetime
meson properties

quark flavour

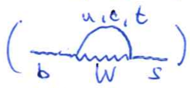
conserving
- EDMs neutron

flavour transitions
- $s \to u$, $b \to c$, ...

()

exist at tree-level
$\Rightarrow$ robust SM-pred.

- $s \to d$, $b \to s$, ...

()

SM $\Rightarrow$ loop-level
"FCNC"
$\Rightarrow$ very small in SM
$\Rightarrow$ sensitive to BSM flavour structure

observables:

measured at
B-factories
Babar, Belle (past)
Belle II (soon)
LHCb

observables:
- rare decays $b \to s\gamma$,
  $B_s \to \mu^+\mu^-$
  $B \to s\mu^+\mu^-$ etc.
- oscillation
  $B_s \leftrightarrow \bar{B}_s$
  $(\bar{b}s)$ $(b\bar{s})$
  $K^0 \leftrightarrow \bar{K}^0$
  $(\bar{s}d)$ $(s\bar{d})$

lepton flavour

conserving:
- a_μ, a_e

very important
- EDMs, CPV
- τ-decays

CLFV:
$\mu \to e\gamma$
$\mu \to e e^+ e^-$
$\mu \to e$ Atom
TUD
COMET, Mu2E

neutrino

1. ν-less double β
(Majorana-mass?)
TUD
GERDA, ...

2. direct mass measurem.
KATRIN

3. oscillation
long: sun $\to$ earth
short: atmosph. $\to$ earth
reactor or accelerator $\to$ detector
T2K, DayaBay, ...

future:
DUNE / Fermilab

new light particles

axion, axion-like particles
$(A \cdots \gamma\gamma,\ A \cdots g g)$
$\Rightarrow$ dedicated searches
e.g. DESY

light new Z' ("dark photon / dark Z")

e.g. Mainz

future: SHIP at CERN

1.2.2 Overview of BSM scenarios

Motivated by fundamental theory/conceptual problems of SM: (not necessarily easy to observe in any given expt.)

- Susy
- GUT ($SU(5)$, $SO(10)$, E_6, $SU(2)_L \times SU(2)_R$, ...)
- Composite Higgs, Technicolor (≈ excluded)
- extra dimensions "warped extra dimensions" (Randall Sundrum)
- seesaw mechanism for ν masses
- axions (⇒ strong CP problem)
- flavour symmetries
- scale invariant QFTs

Motivated as simplistic extensions of SM with observable effects: (might originate from some of the above)

- SM + Higgs singlet/doublet/triplet etc
- SM + new gauge boson Z' or W' (might couple to quarks or/and leptons or subset, couplings could depend on generation)
- SM + 4th generation of qu., leptons ("chiral" fermions: left and right-handed different)
- SM + "leptoquarks" ∈ vertex

, coupling might depend on generation,
- SM + "vector like" quarks or leptons (left, right-handed q., l.-type have equal gauge couplings ⇒ mass term is gauge invariant, independent of Higgs)
- SM + any combination of a few of such new particles
- SM + "dark matter" particles (= stable, neutral fermions or bosons)

Motivated by exp. hints:

- many of the above might explain dark matter or a_μ, models with CP-violation have a chance to explain baryogenesis
- other ν-mass models
- models with very light new particles