Particle physics for pedestrian

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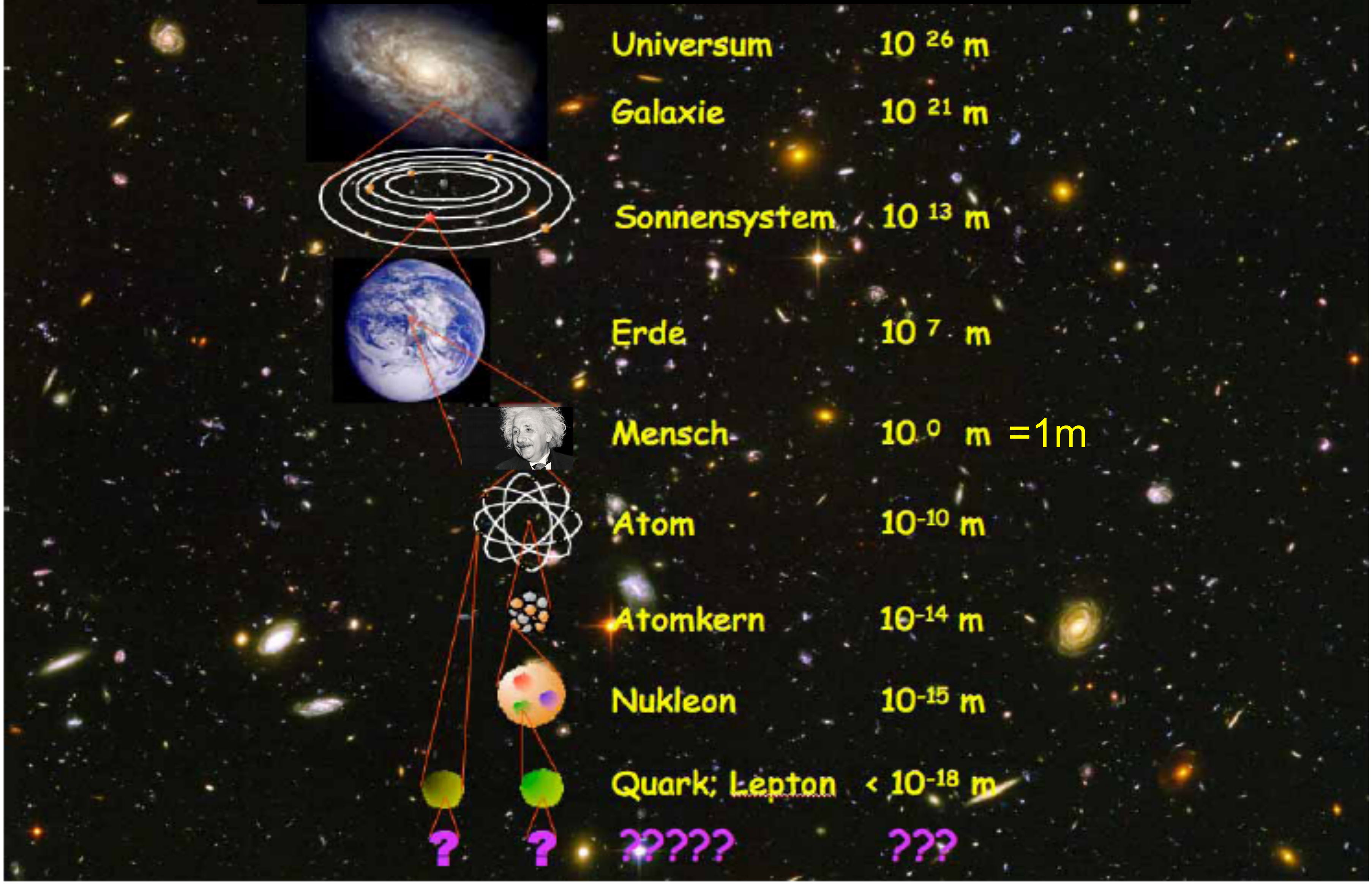
- Introduction
- The Standard Model
  - Construction Principle
  - Particle Content

Dimensions and Structure of Matter



Probing the fundamental of nature

Particle accelerators (Large Hadron Collider (LHC), . . .)

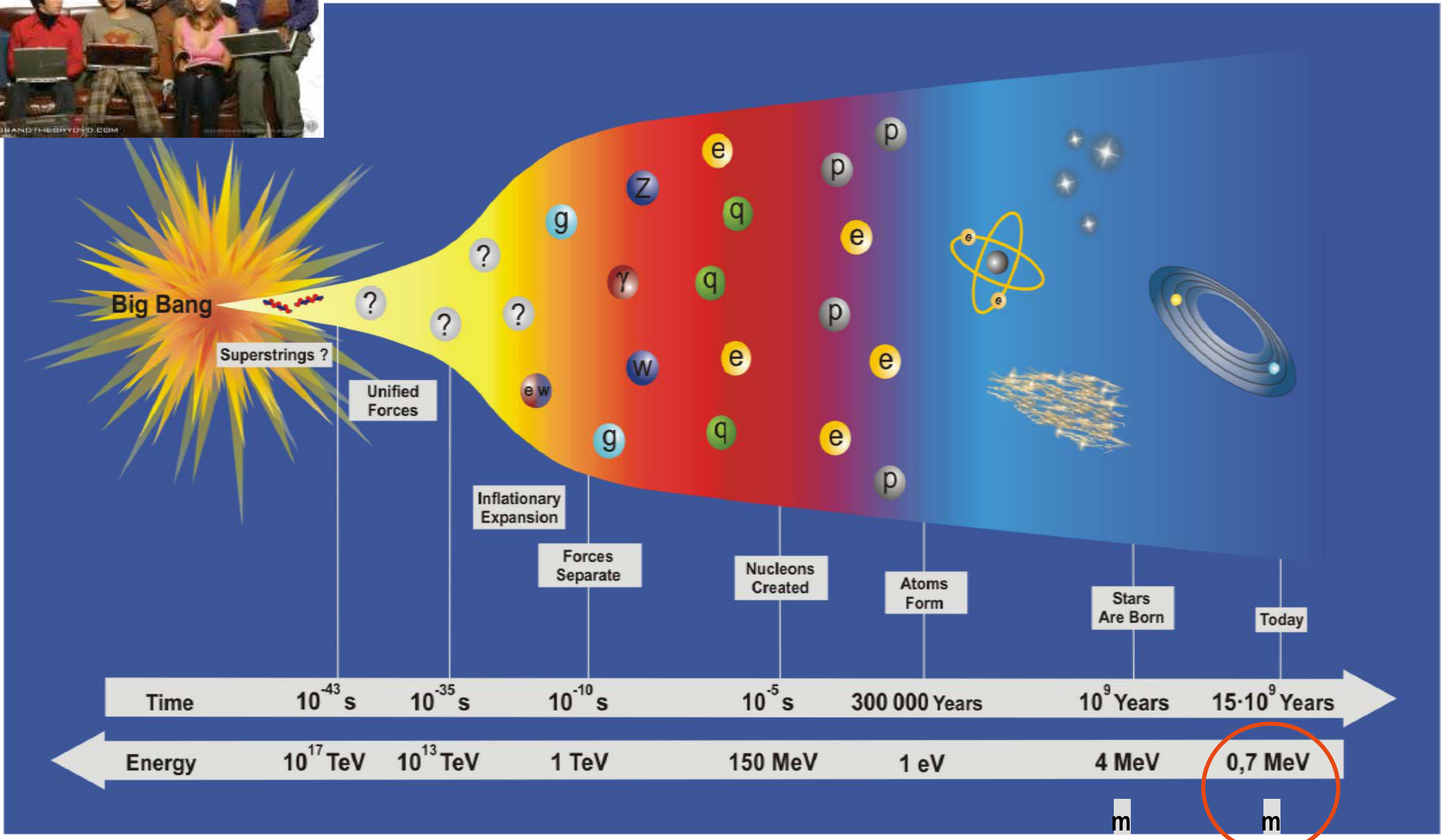
$\Rightarrow$ probe the TeV scale (Terascale)

What are the fundamental laws of nature?

$\Rightarrow$ Study the fundamental forces (“interactions”) and the fundamental building blocks of matter (“elementary particles”)

Probing high energies and short distances $\Leftrightarrow$ viewing the early Universe

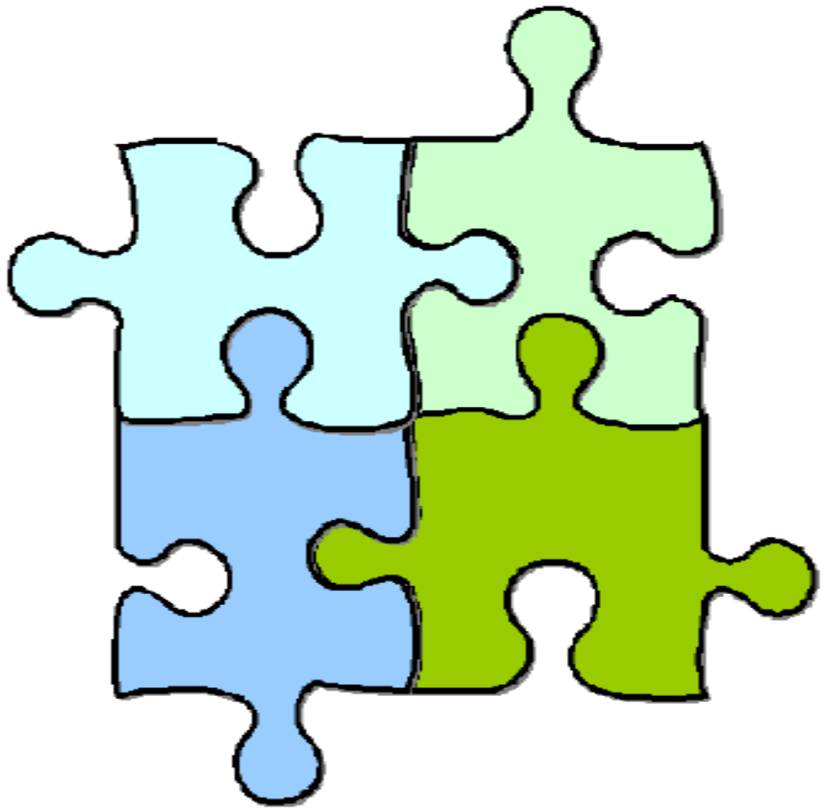
Once upon the time….



Quantum-Universe

Particle
Physics
Experiments
Accelerators
Underground

Quantum
Field
Theory
(Standard
Model)



Astronomy
Experiments
Telescopes
Satellites

Standard
Cosmology
Model

10^{-18} m

10^{26} m

Fundamental Interactions

- Electromagnetism (electricity + magnetism)
- Strong interaction (binds quarks within the proton and protons and neutrons within nuclei)
- Weak interaction (radioactivity, difference between matter and anti-matter, . . .)
- Gravity (solar system, . . .)

Interaction between two particles is mediated by a field

E.g.: atom, interaction between proton and electron: electromagnetic field

The Universe is a quantum world

The fields are quantised

Particles are quanta of fields

The photon is the quantum of the electromagnetic field

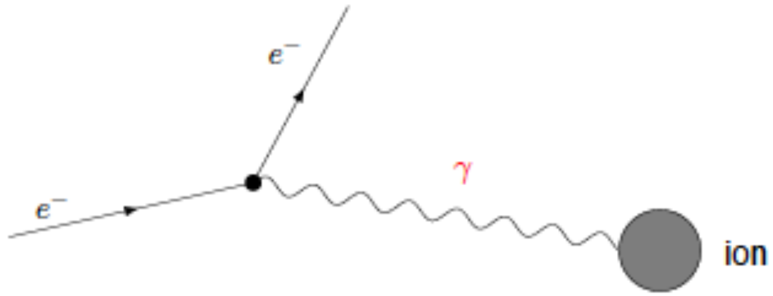
Fundamental interactions are mediated by the exchange of field quanta, i.e. particles

- Electromagnetic interaction: photon, γ
- Weak interaction: W, Z
- Strong interaction: gluon, g
- Gravity: graviton, G

Description of fundamental interactions with quantum field theories

Classical field theory (e.g. classical electrodynamics):

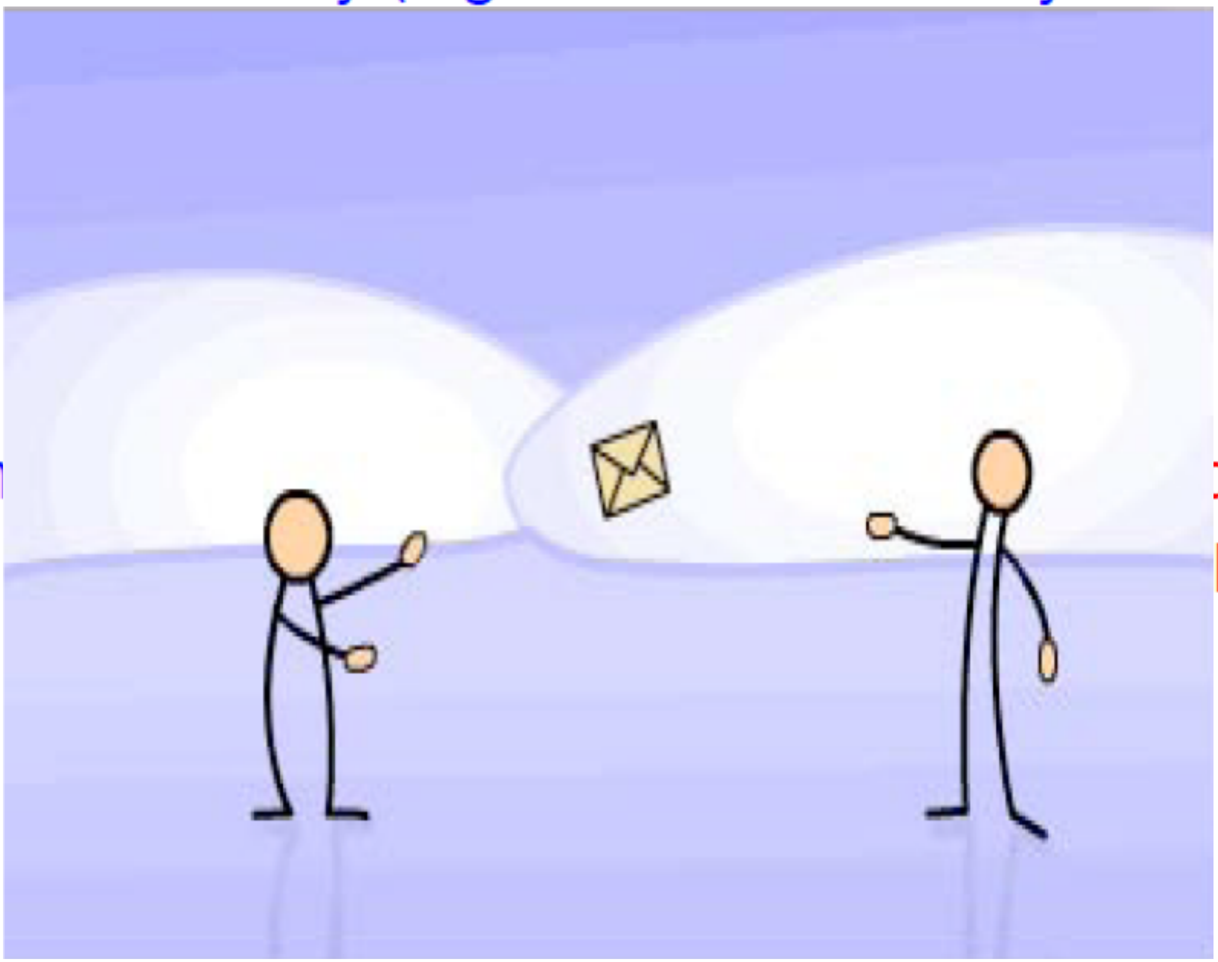
Quantum field theory (e.g. QED): field is quantised,
field quantum: photon



Interaction: exchange of field quanta

Description of fundamental interactions with quantum field theories

Classical field theory (e.g. classical electrodynamics):



Quantur

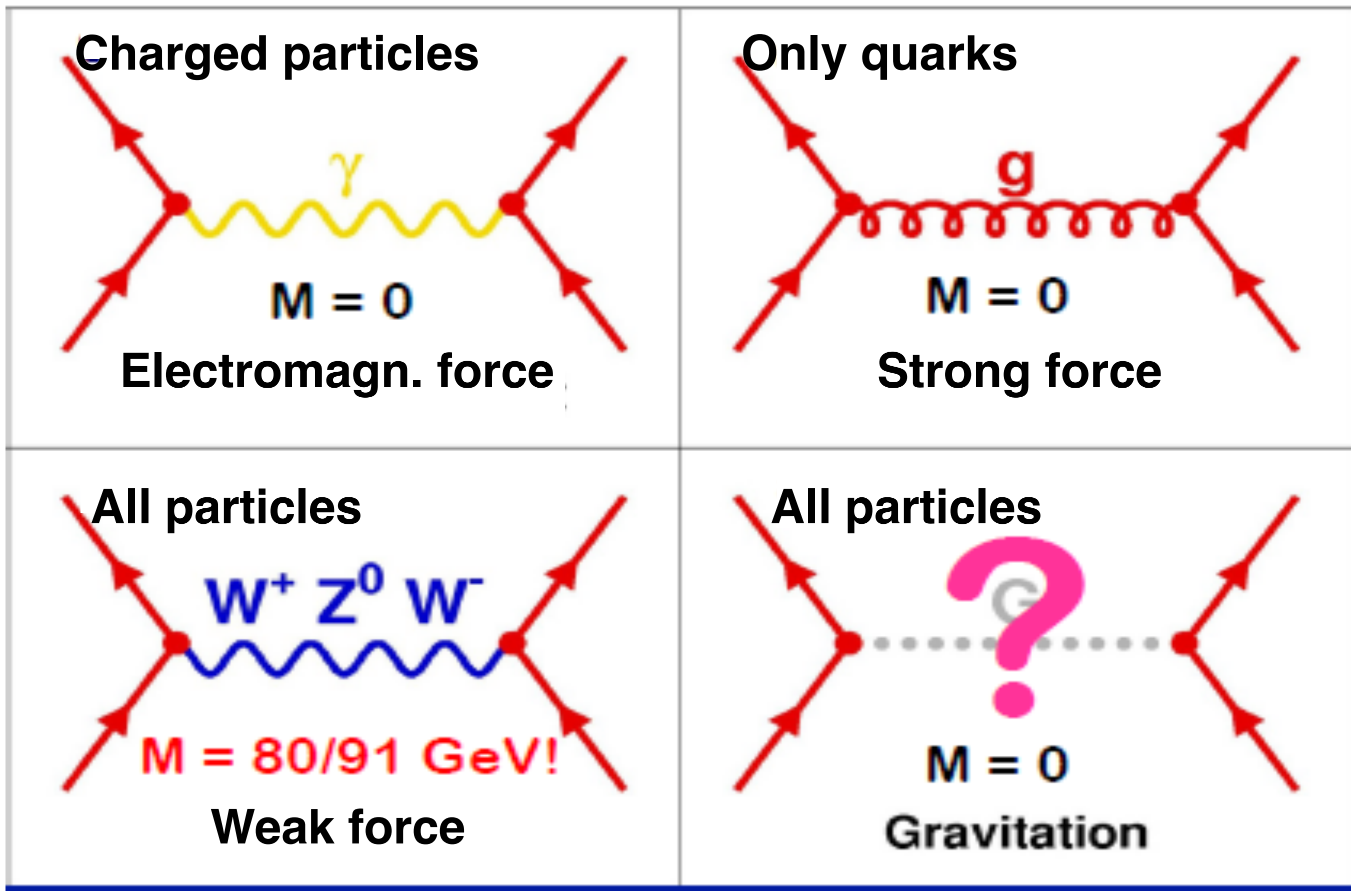
d,

hoton

Interaction: exchange of field quanta

Elementary forces

unified:
electroweak forces

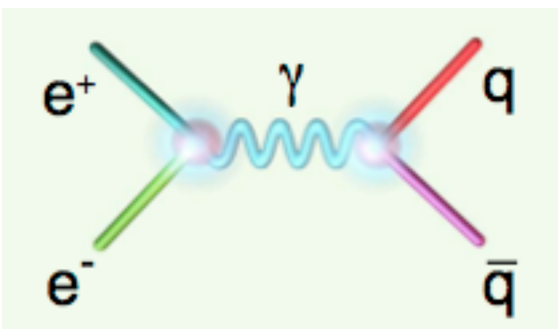


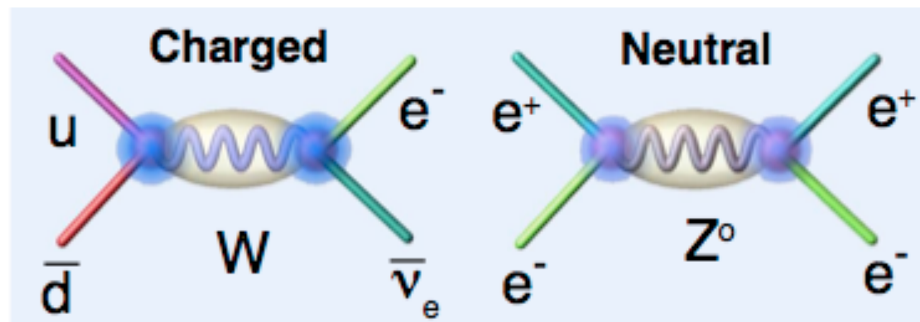
Exchange particles: "bosons"
Only bosons of the weak force carry (a lot of) mass!

Force Carrying Quanta

Photon (electromagnetic)
- verified 1922
- mass of photon = 0

W,Z bosons (weak force)
- verified 1983
- m_W, m_Z: 80 GeV/c^2, 91 GeV/c^2





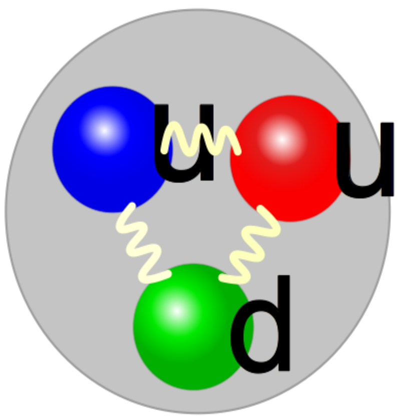
Mass of gluon = 0

Fundamental interactions of elementary particles are described by Quantum Field Theories

Overview :`Forces' + `Matter'

- Four 'different' kinds of forces:
  - Ellectromagnetic: 'The current in the cables'
  - Strong force: 'Nucleus of the hydrogen atom'
  - Weak force: 'Radioactivity'
  - Gravitation: 'weakest force'
- Three families of matter:
  - 1. family:
    - Hydrogen atom: proton (u,d quarks)
      e- in atomic shell
    - plus massless campanions: neutrinos
  - 2. and 3. family: same as before but he

Proton

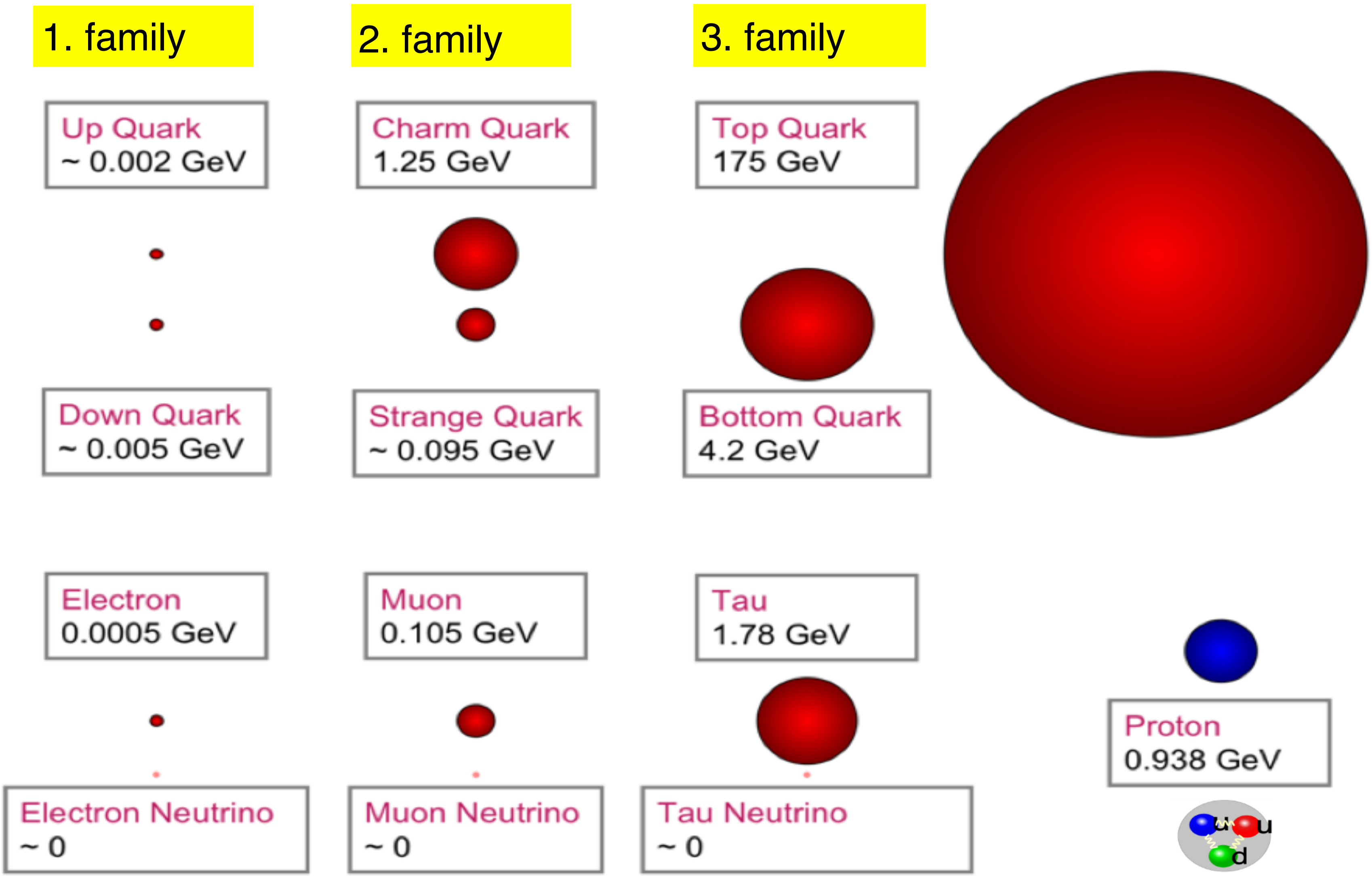


Where is the problem?

- **Fundamental quantum symmetry principle:** ***gauge symmetry***
- **Problem:** ***This fundamental principle requires that all 'matter' and 'force' particles are massless!***
- **Contradiction?**
  - **Most of the discovered elementary particles do have mass!!**

➢ ***How to integrate 'mass' in the theory without giving up the beautiful symmetry concept?***

Mass of the matter particles



The Standard Model (SM): electroweak and strong interactions

Electroweak interaction:

Fermion fields: quarks: $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R,$ leptons: $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$

3 generations: $u, d, \quad s, c \quad t, b$

$\nu_e, e \quad \nu_\mu, \mu \quad \nu_\tau, \tau$

gauge bosons: γ, Z, W^+, W^-

Gauge group: $\mathrm{SU}(2)_\mathrm{I} \times \mathrm{U}(1)_\mathrm{Y} \supset \mathrm{U}(1)_\mathrm{em}$

Strong interaction: QCD

quarks: q_r, q_g, q_b, gauge bosons: $g_1, \ldots g_8$: gluons, $\mathrm{SU}(3)_\mathrm{C}$

All postulated fermions and gauge bosons experimentally verified

Understanding mass for runners

The Standard Model
  - Local gauge invariance
  - Higgs particle
  - Brout-Englert-Higgs mechanism
- Interlude symmetries
  - symmetries in physics
  - broken symmetries
- Masses of gauge bosons & fermions

Construction principle of the SM: gauge invariance

Example:

Quantum electrodynamics (QED)

free electron field: $\mathcal{L}_{\rm Dirac} = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi - m\overline{\Psi}\Psi$

invariant under global gauge transformation: $\Psi \to e^{i\theta}\Psi$

Requirement of local gauge invariance:

gauge field A_μ introduced, $\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$

gauge transformation: $\Psi \to e^{ie\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

Construction of the QED Lagangian

$\Rightarrow$ Lagrangian with interaction term:

$$\mathcal{L}_{\mathrm{QED}} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{free photon field}} + \underbrace{\overline{\Psi}(i\gamma_\mu\partial^\mu - m)\Psi}_{\text{free electron field}} + \underbrace{\mathrm{e}\overline{\Psi}\gamma_\mu\Psi A^\mu}_{\text{interaction}}$$

invariant under local gauge transformations

mass term, $m^2 A^\mu A_\mu$: not gauge-invariant

$\Rightarrow$ A_μ: massless gauge field

How do elementary particles get mass?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle: "gauge invariance"

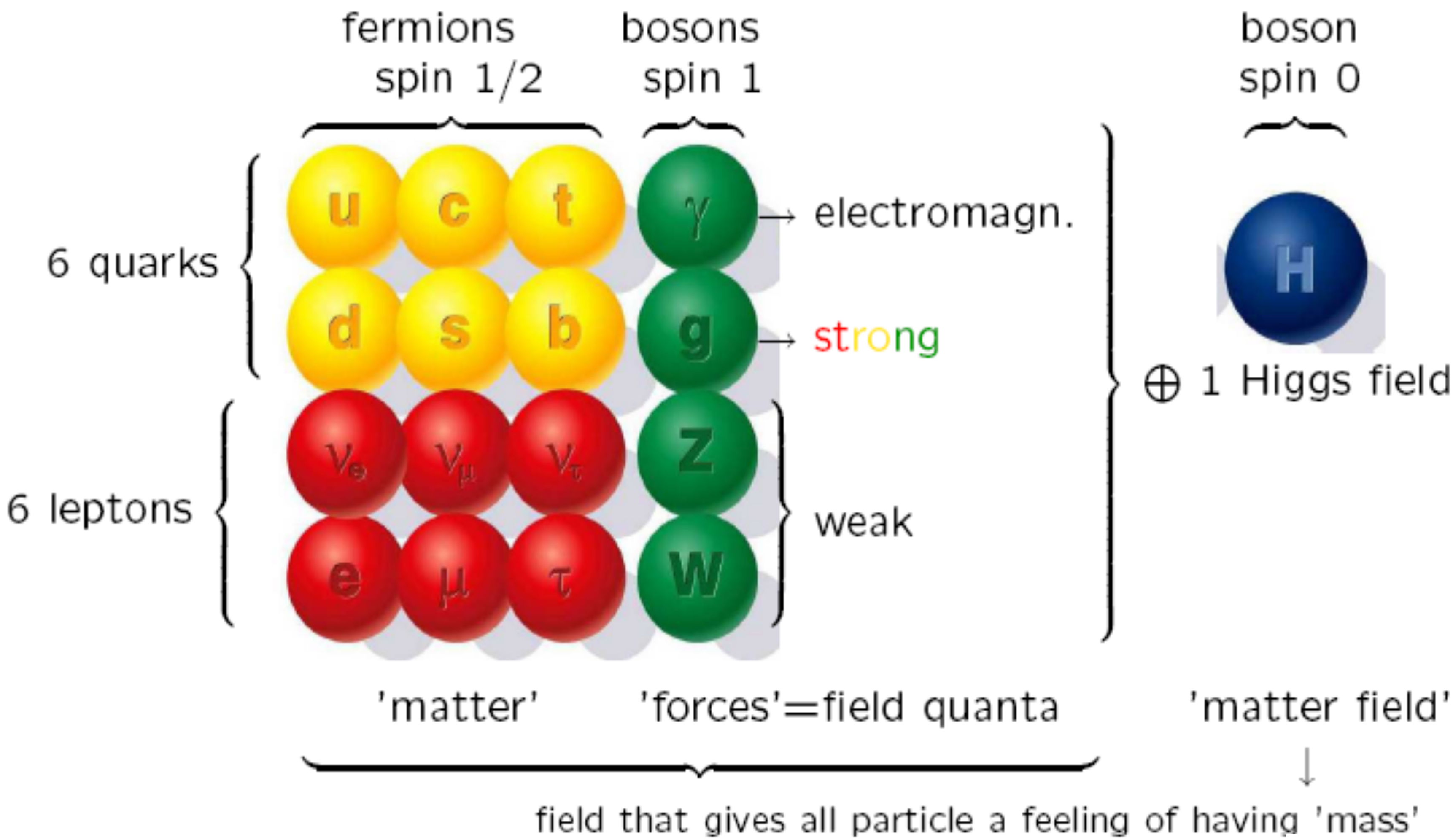
- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless

- However: W, Z, top, bottom, . . . , electron are massive, have widely differing masses

  explicit mass terms $\Leftrightarrow$ breaking of gauge invariance

How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?

Standard Model of particle physics

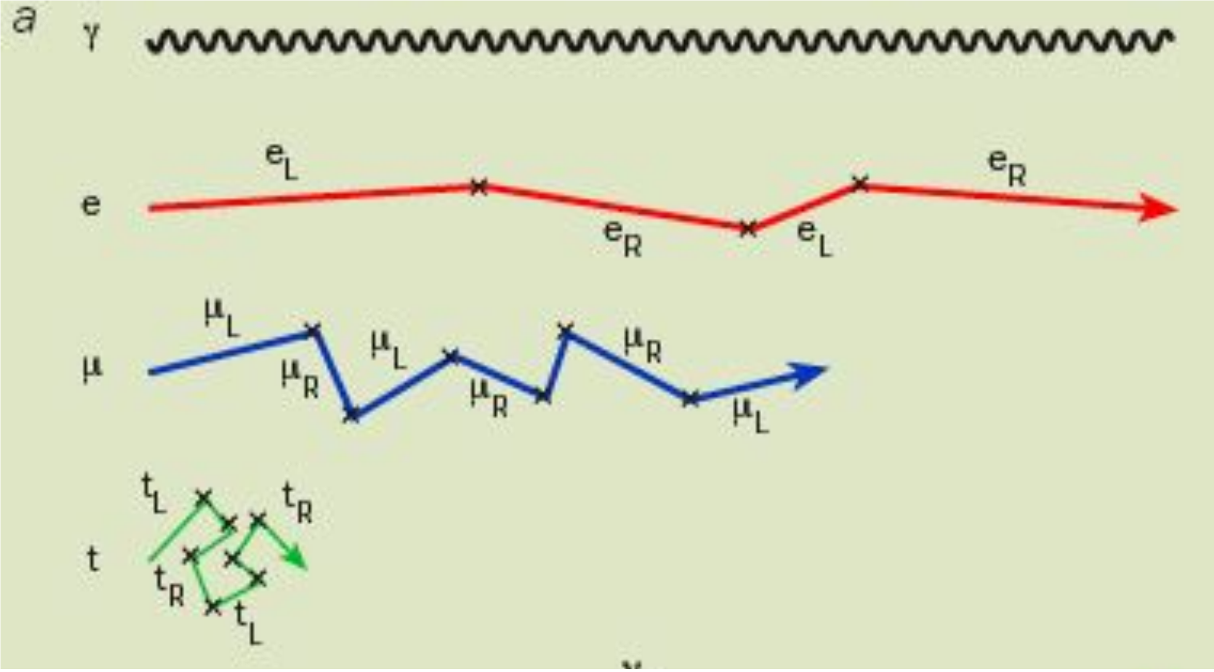


In experiment: o.k. o.k. **4.7.2012 !**

What was the idea 50 years ago?

Peter Higgs, Francois Englert and others (1964!)

„All particles are massless …
...only, if one removes the permanent Higgs field
(But it exists always and everywhere !)



Massless particles move with velocity of light

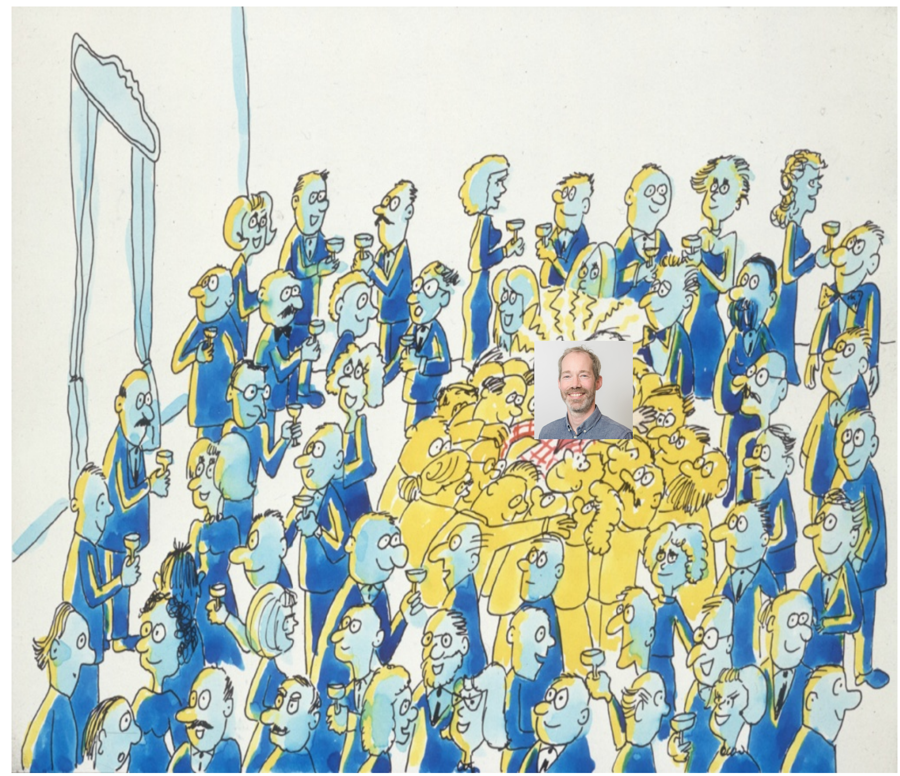
Massive particles are slower

Higgs: it seems that „massive“ particles get slowed down via the Higgs field

What`does' the Higgs?

Room full of people=

Higgs field



Famous person=

`massive' movement

What is the 'Higgs' field?

What is the 'Higgs' field?

That's a Snowfield:

What does the 'Higgs'-field ?

That's a Snowfield:

Photon: massless

small interaction with the Higgs field: quick move

What does the 'Higgs'-field ?

That's a Snowfield:

electron: light

stronger interaction with the Higgs field: moderate velocity

What does the 'Higgs'-field ?

That's a Snowfield:

W/Z boson: heavy

strong interaction with the Higgs field: slow move

Possible consequences of this idea

2 possibilities:

A)(Almost) all particles carry mass

or

B) All particles are massless, but there exists a Higgs field, everywhere and permanent, unremovable = property of the vacuum !

Crucial criterium:

If B) is correct, then it is possible to excite the Higgs field (more power) and for a short time to `materialise‘ a Higgs `particle‘

The existence or non-existence of a Higgs particle decides whether A) or B) might be correct!

What is so spectacular at the Higgs?

- H is neither „matter“ (spin1/2) nor „;force“ (spin 1) but „spin 0“

- H interacts directly with <u>all</u> particles, that (seems to) carry mass (more strongly if more mass)

- Therefore this particle can only be produced if enough energy is provided

- H is rather short living (10^{-22} s) – it decays fast in pairs of almost all massive particles of the Standard Model.

➢ **The Higgs particle is not only „yet another particle“ but a fundamental new building block of the nature !**

Higgs ‘field ‘ and Higgs ‘boson’

- **Higgs mechanism:** ***particles get their masses via the interaction with the Higgs field***

- **Higgs boson(s):** ***quanta of the Higgs field (analogue photon = quantum of the electromagnetic field)***

- **Decisive:** ***Coupling between Higgs and the particle is proportional to their mass***

- **Spin:** ***postulated Higgs is a scalar particle, i.e. spin 0 !***
  - ***before 4/7/2012 there has never been observed a fundamental scalar particle !***

The Higgs field and the Higgs boson

Higgs mechanism: fundamental particles obtain their masses from interacting with the Higgs field

Higgs boson(s): field quantum of the Higgs field

SM Higgs field: scalar SU(2) doublet, complex $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

$\Rightarrow$ 4 degrees of freedom

3 components of the Higgs doublet $\longrightarrow$ longitudinal components of W^+, W^-, Z

4th component: H: elementary scalar field, Higgs boson

Models with two Higgs doublets (e.g. MSSM)

$\Rightarrow$ prediction: 5 physical Higgses

The Brout-Englert-Higgs mechanism

$\Rightarrow$ Need additional concept:

Higgs mechanism, spontaneous electroweak symmetry breaking:

New field postulated that fills all of the space: the Higgs field

Higgs potential

$\Rightarrow$ non-trivial structure of the vacuum postulated!

Gauge-invariant mass terms from interaction with Higgs field

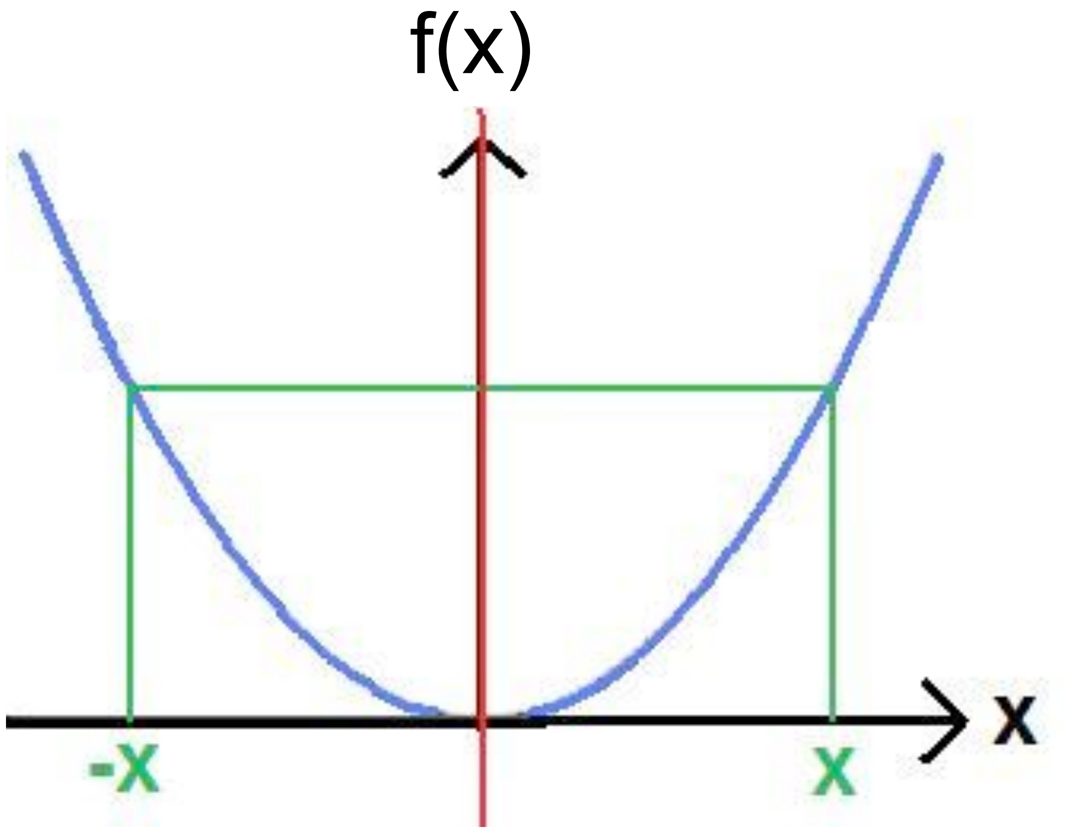
Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

Very common in nature, e.g. ferromagnet

Interlude Symmetries

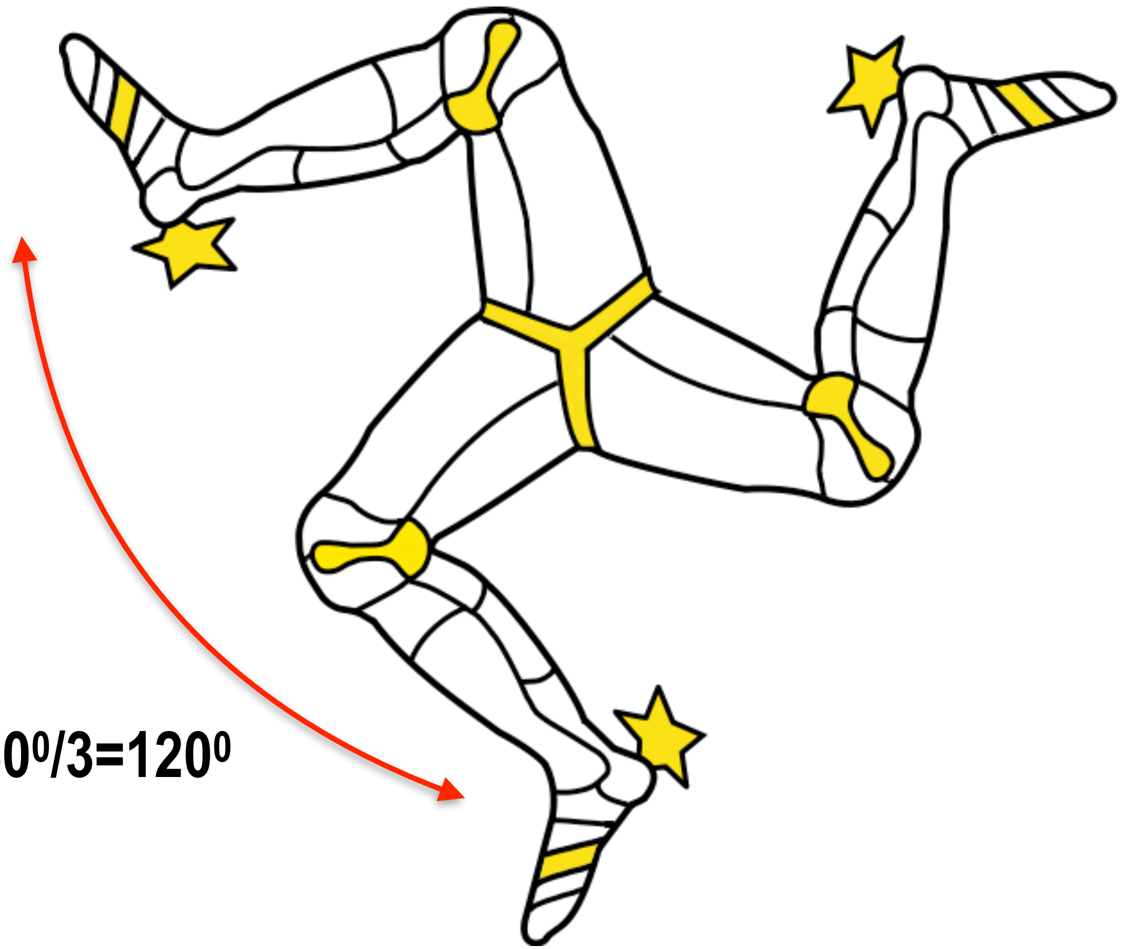
- **Axial symmetry:**

f(x)=f(-x)



Interlude Symmetries

- **Rotational symmetry:**



rotation via $360^0/3=120^0$

Why are symmetries important?

The Noether theorem:

Emmy Noether

- Symmetries induce conserved quantities:

  for each (continuous) symmetry,
  there is a conserved quantity:

  - Translationsymmetry → Momentum cons.
  - Rotationsymmetry → Conservation of Ang. Momentum
  - Time symmetry → Energy conservation

- Conservation important: *With conserved quantities, one can reliably describe quantities and simplify calculations*
- Assumption of the theorem: *Everywhere in the Universe, there are the same physical laws!*

Why are symmetries important?

- **Parity:**
  - all space coordinates are reflected: 'P'

    (t,x,y,z) ⟶ (t,-x,-y,z)

Wolfgang Pauli

- **Matter and Antimatter exchange:** 'C'

  electron ⟶ positron

- **Time symmetrie: exchange of future and past:** 'T'

  independent in which direction 'time' runs

physics is exact symmetric if simultaneous exchange of CxPxT Vertauschung !

conserves Lorentz invariance! (Einsteins theory of relativity)

Summary: why are symmetries important?

- **Symmetries crucial for description of nature**
- **Simplification of calculations**
- **Allow classification**
- **Ordering character**

Symmetries enable the description of the 'Universe'……..

What are broken symmetries?

- **In nature:**

symmetric

'beauty'

But if you look in detail:

asymmetric

i.e. the symmetries are broken.

Are these faces symmetric?

This face would be symmetric

What are broken symmetries?

- **in nature represented:**

symmetric
regarded as 'being beautiful'
in nature: broken!

- **Symmetries simplifies the description**

→ **Symmetries in physics:**
are these also broken? Yes, ….some are broken……

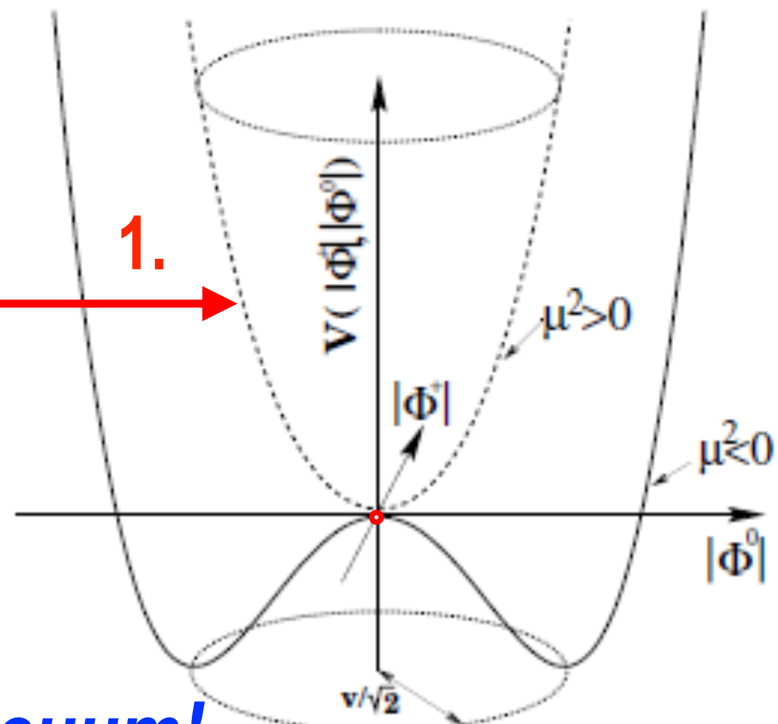
Which structure generates the Higgs field?

- The `Higgs' is a 'field', generates 'field lines':
  - Fills the complete space/universe
  - With such a potential:

    at higher energy:

    potential: parabel-shape

Symmetry principle fulfilled!



Provides a structure for the vacuum!

The Brout-Englert-Higgs mechanism

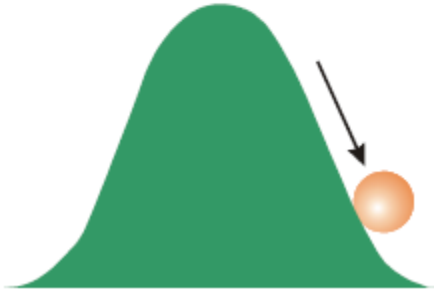
- **Requires a new concept:**
  - **Principle of 'spontaneous symmetry breaking':**

    The interactions respect the symmetry, but not the ground state!

- **Example:**

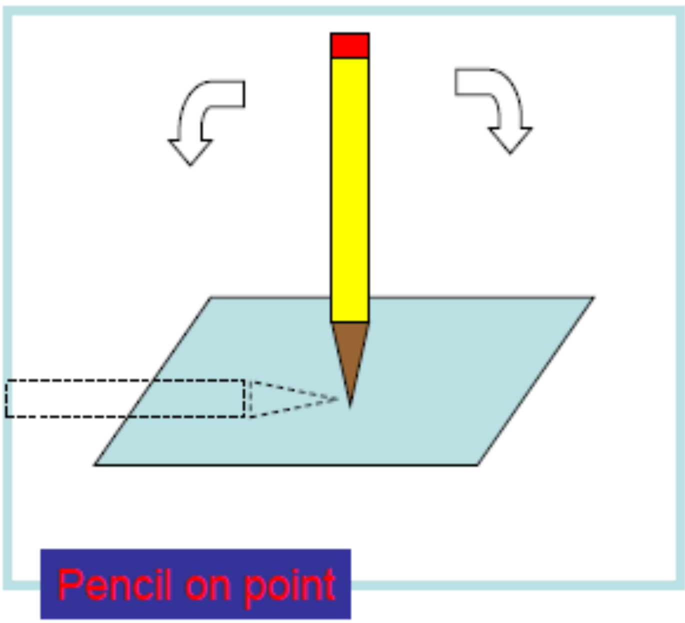
Ball on summit: respects left-right symmetry

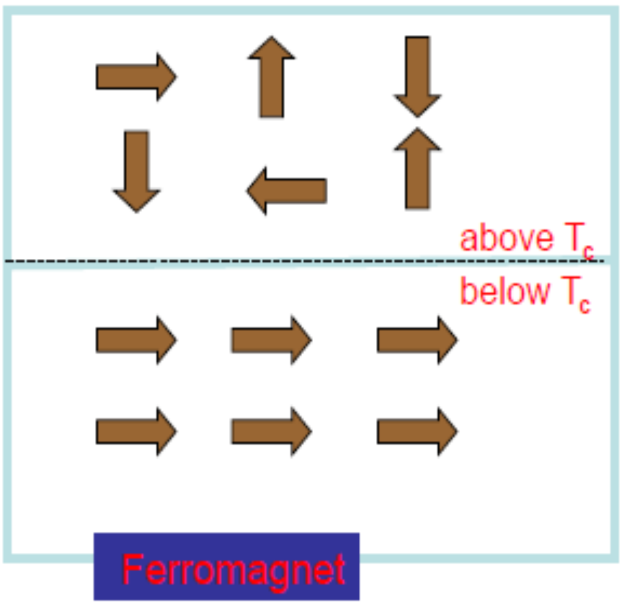
Ball can roll down only left OR right: Ground states breaks the symmetry



Further examples of spontaneous symmetry breaking

- **System is rotation invariant (left), or ‘uncharged’(right), but not the ground state:**





What is superconductivity?

- **Phenomenon: electric currents**
  - Ohm's law:
    U = I x R, R = resistance

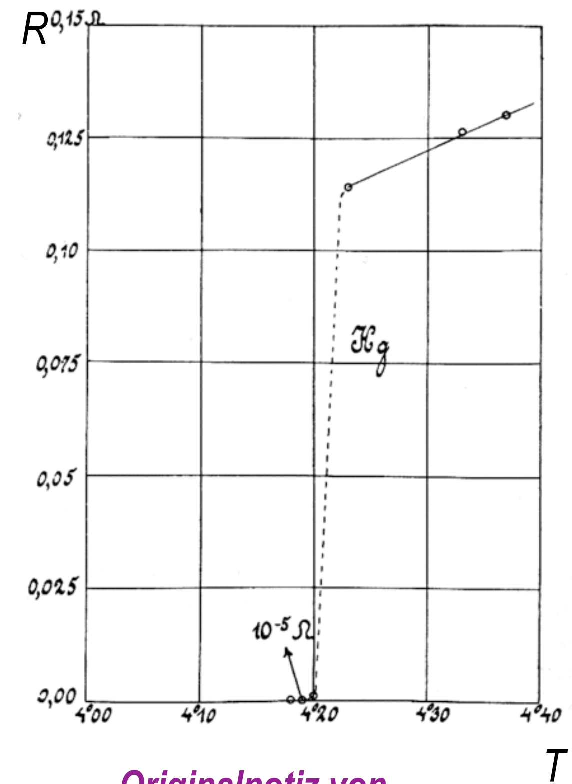
  `Friction of electrons among each other within wire'
  - From transition temperature: R=0 !

  `Electrons compose couples, move ordered'
  - *Example*:

    Mercury from T< 4.2 Kelvin~ -269^0 Celsius

    Niobium from T< 9.3 Kelvin~ -264^0 Celsius

April 1911



Originalnotiz von Heike Kamerlingh Onnes

- **'Macroscopic Quantum effect'**
  - how to explain this phenomenon?
  - again with spontaneous symmetry breaking?

What is common in superconductivity and Higgs?

- **Ginsburg-Landau-Theory:** *also a gauge theory!*
  phenomenological, macroscopic description:
  - Transition from normal- to supraconductivity: 'ordering parameter' Ψ
  - Normal conductivity: Ψ = 0   above transition temperature
  - Supra conductivity: Ψ ≠ 0   below transition temperature

    similar as in Higgs mechansim:

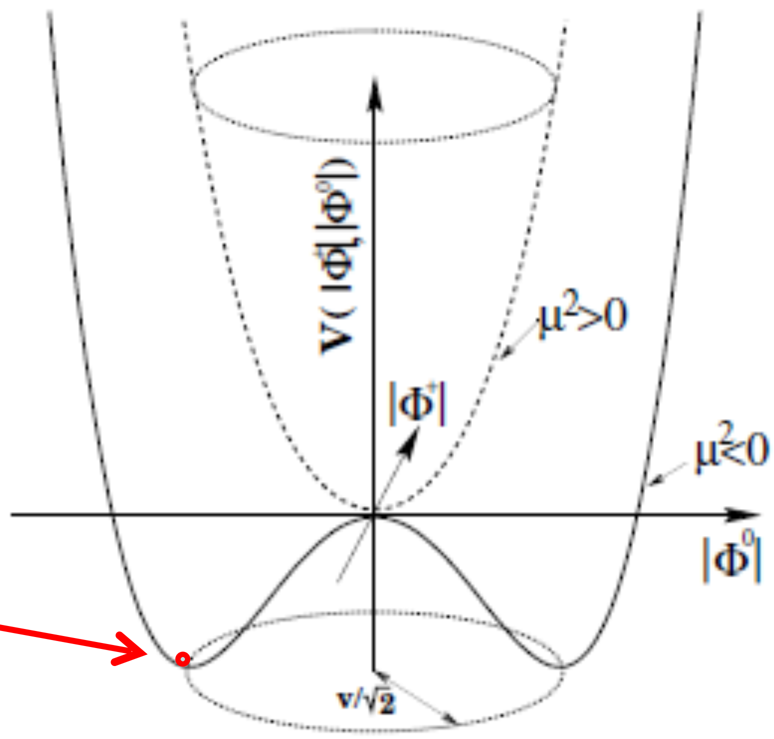
    'Free Energy corresponds to potential of Higgs mechanism'
  - again spontaneous symmetry breaking!

- **Microscopic description: BCS-Theory**
  - quantum mechanical multi-particle theory
  - Cooper-pairs: 'bosonic' wave function

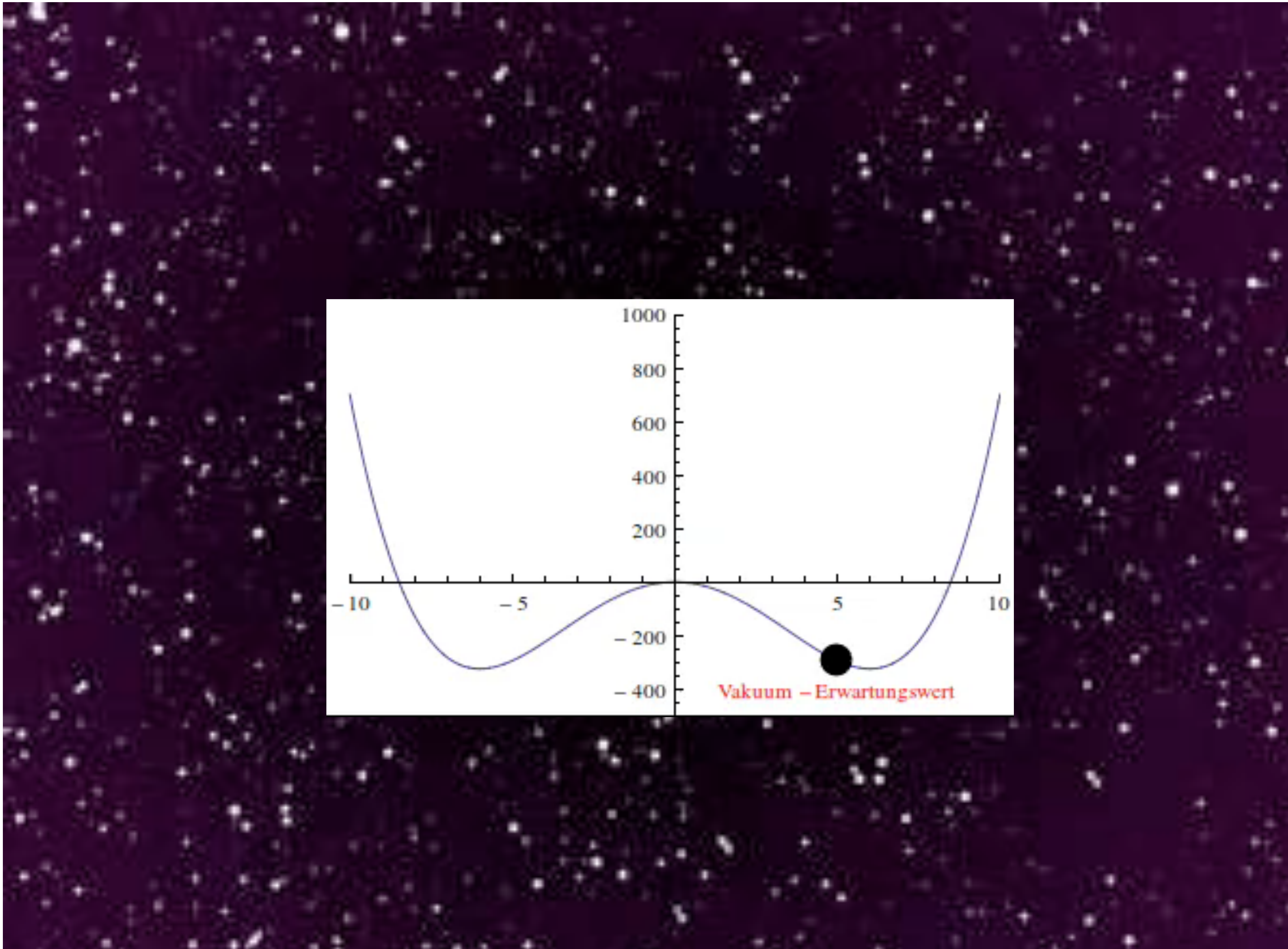
Back to the Brout-Englert-Higgs mechanism

- **The 'Higgs' is a 'field':**
  - **Fills the whole space: 'structure'**
  - **With such a potential:**
    ground state (state of the vacuum) does not respect the symmetry! (gauge symmetry)

➢ ***Spontaneous symmetry breaking !***



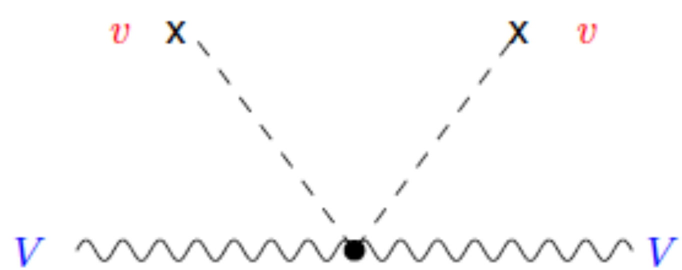
$$V(\Phi) = \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \mu^2\left(\Phi^\dagger\Phi\right), \quad \lambda > 0$$


1000
800
600
400
200
– 200
– 400
– 10
– 5
5
10
Vakuum – Erwartungswert

Gauge-invariant interaction with gauge fields

$\mathcal{L}_{\mathrm{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi);$ unitary gauge: $\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

$VV\Phi\Phi$ coupling:



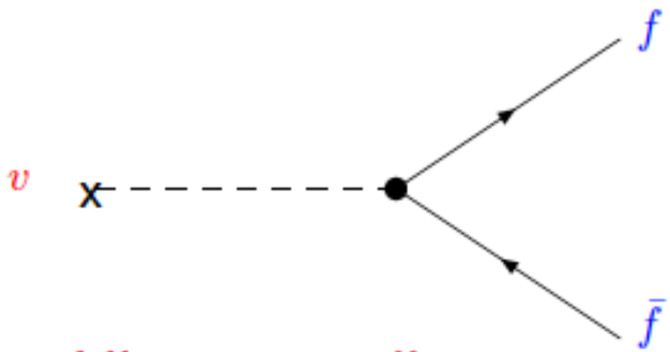
$\Rightarrow$ VV mass terms: $\frac{1}{2} g_2^2 v^2 \equiv M_{\mathrm{W}}^2, \quad \frac{1}{2}(g_1^2 + g_2^2) v^2 \equiv M_{\mathrm{Z}}^2$

WWH coupling: $g_{WWH} = g_2 \, M_{\mathrm{W}}$

$\Rightarrow$ Higgs coupling to W bosons is proportional to the W mass

Fermion masses, Higgs mass

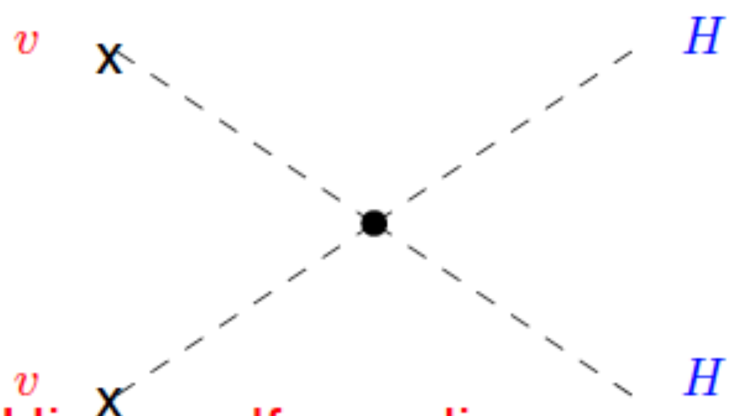
Fermion mass terms: Yukawa couplings



$m_f = v\, g_f$ free parameters

⇒ Higgs couplings are proportional to masses of the particles

Mass of the Higgs boson: self-interaction



$M_{\mathrm{H}} = v\sqrt{\lambda}$ free parameter

Higgs self-coupling ⇔ access to Higgs potential

Fermion masses in the SM

Fermion mass terms in SM Lagrangian:

$$\mathcal{L}_{\mathrm{SM}} = \underbrace{m_d \bar{Q}_L H d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \tilde{H} u_R}_{\text{u-quark mass}}, \quad Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$\Rightarrow$ Would at first sight expect that two doublets are needed

"Trick" used in the SM:

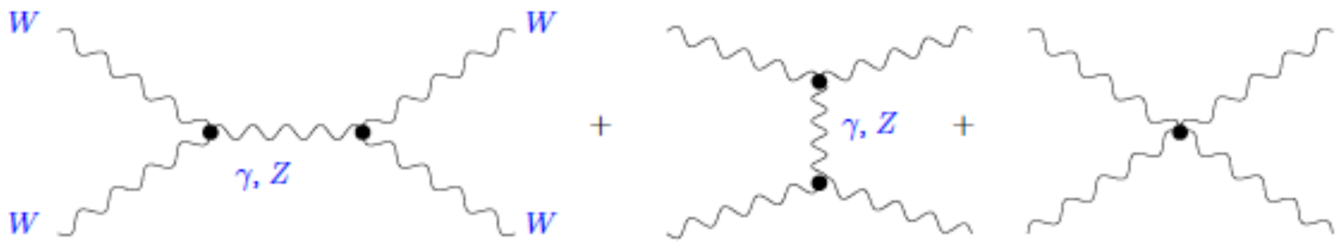
$$\tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$\Rightarrow$ One Higgs doublet sufficient to give mass to both up-type and down-type fermions

Unitarity cancellation in longitudinal gauge boson scattering

E.g.: WW scattering, longitudinally polarised: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$

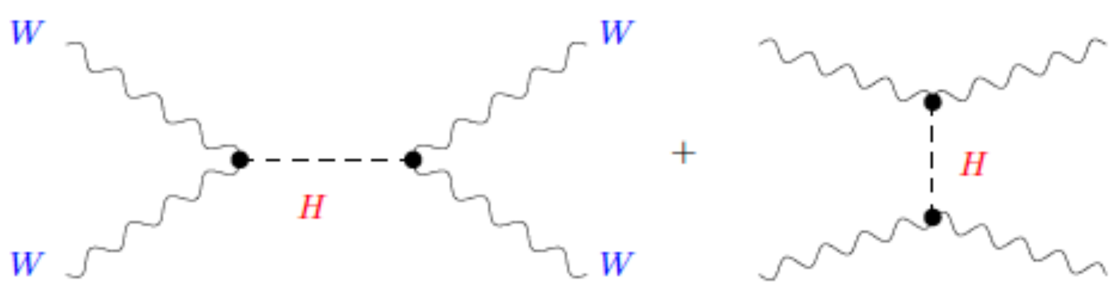


$= -g^2 \frac{E^2}{M_{\mathrm{W}}^2} + \mathcal{O}(1)$ for $E \gg M_{\mathrm{W}}$

$\Rightarrow$ violation of probability conservation

Compensated by Higgs contribution:

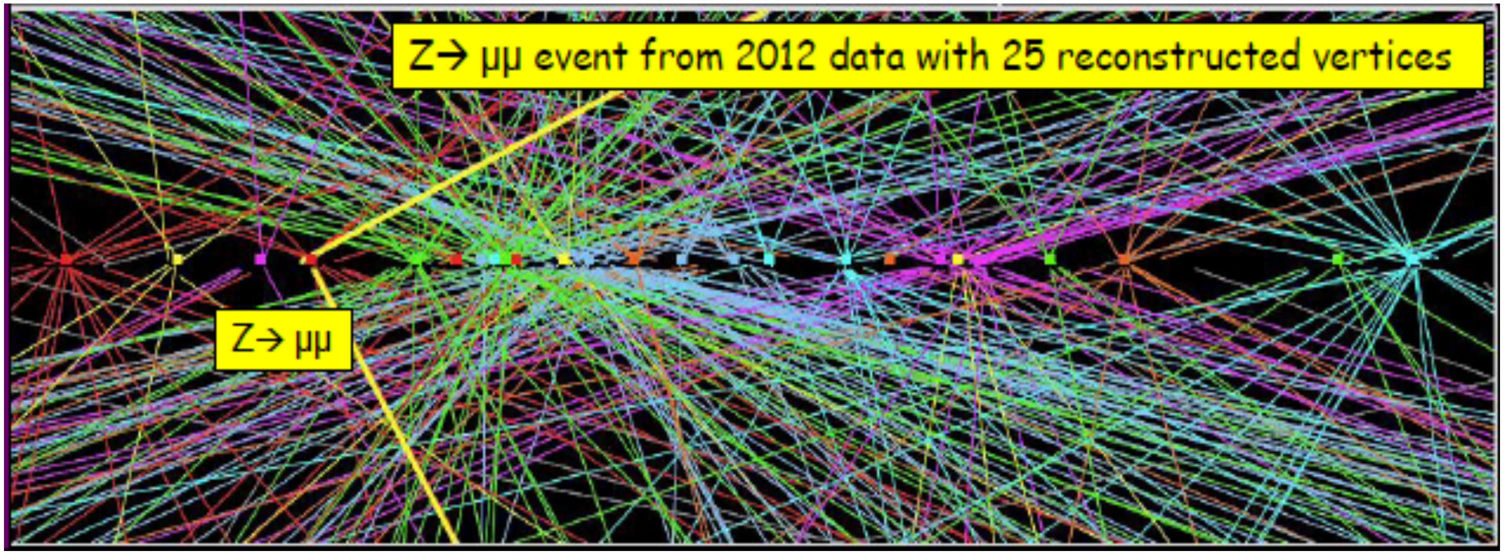
$\mathcal{M}_S =$



$= g_{WWH}^2 \frac{E^2}{M_{\mathrm{W}}^4} + \mathcal{O}(1)$ for $E \gg M_{\mathrm{W}}$, $g_{WWH} = g_2 M_{\mathrm{W}}$

Huge amount of data @ LHC

- LHC delivers annually about 15 Petabytes
- Reconstruction of these events is highly non-trivial!

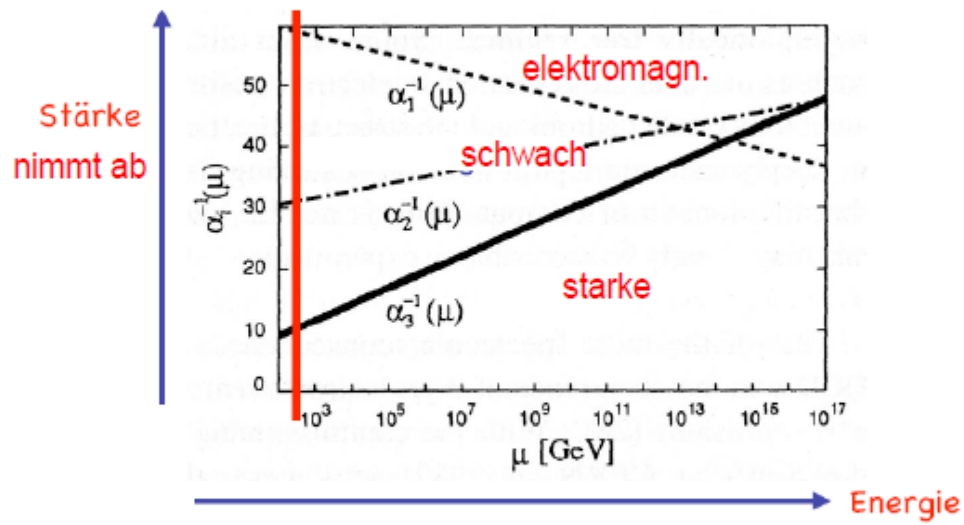


Open questions of the SM

- **Particle discovered with m_H=125.5 GeV – Higgs@SM?**
  - **The discovered signal is so far compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics**
  - **Bur we still need spin, couplings, potential, CP properties**
- **In addition**

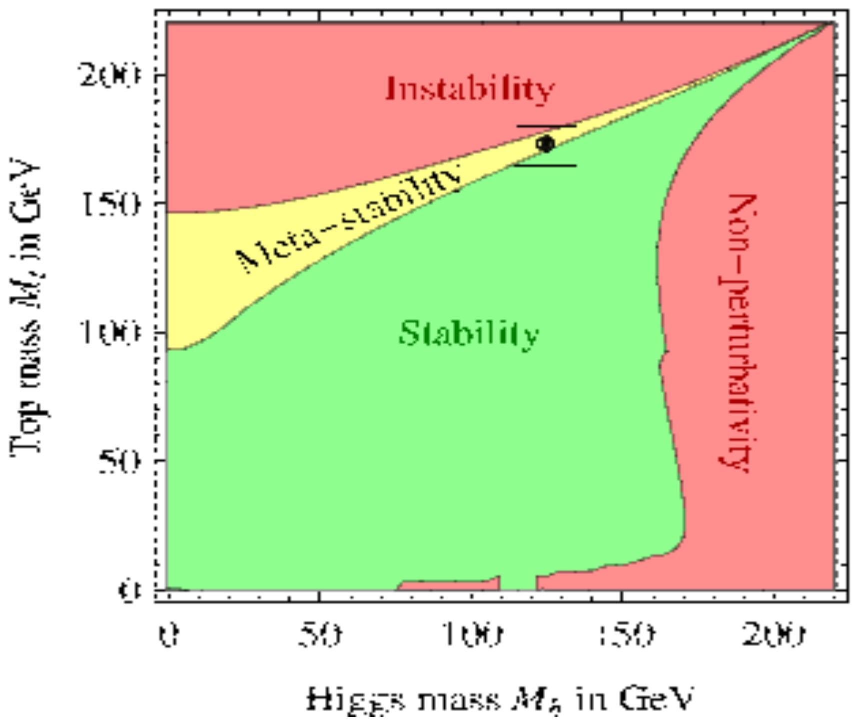
  The SM does not contain
  - **Unification**
  - **Dark matter**

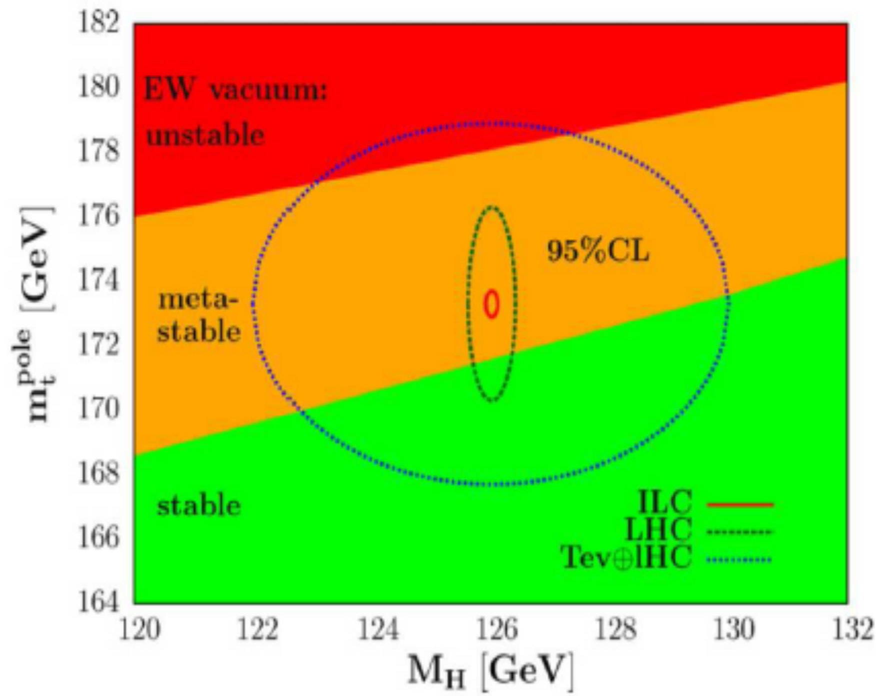
  Cosmological constant
  - **Extreme fine tuning**



- **Solutions via `Beyond Standard Model' Physics?**

Open question: `stable' Universe?





- **Strong relation between Higgs boson and top quark: m_t~173.3±0.8GeV**
  - **If Higgs boson is too 'light': Universe could be unstable**

    (don't panic:... only under the assumption of the pure Standard Model….)
- **Precise measurements of m $_t$ and m_H mandatory!**

Higgs mass: the need for high precision

- **Measuring the mass of the discovered signal with high precision is of interest in its own right !**
  - **Currently m_H~ 125.1±0.2 GeV**
- **But a high-precision measurement has also direct implications for probing Higgs physics**

➢ ***M_H: crucial input parameter for Higgs physics***

- **BR(H → ZZ*), BR(H → WW*): highly sensitive to precise numerical value of M_H**
- **A change in M_H of 0.2 GeV shifts BR(H → ZZ*) by 2.5%!**

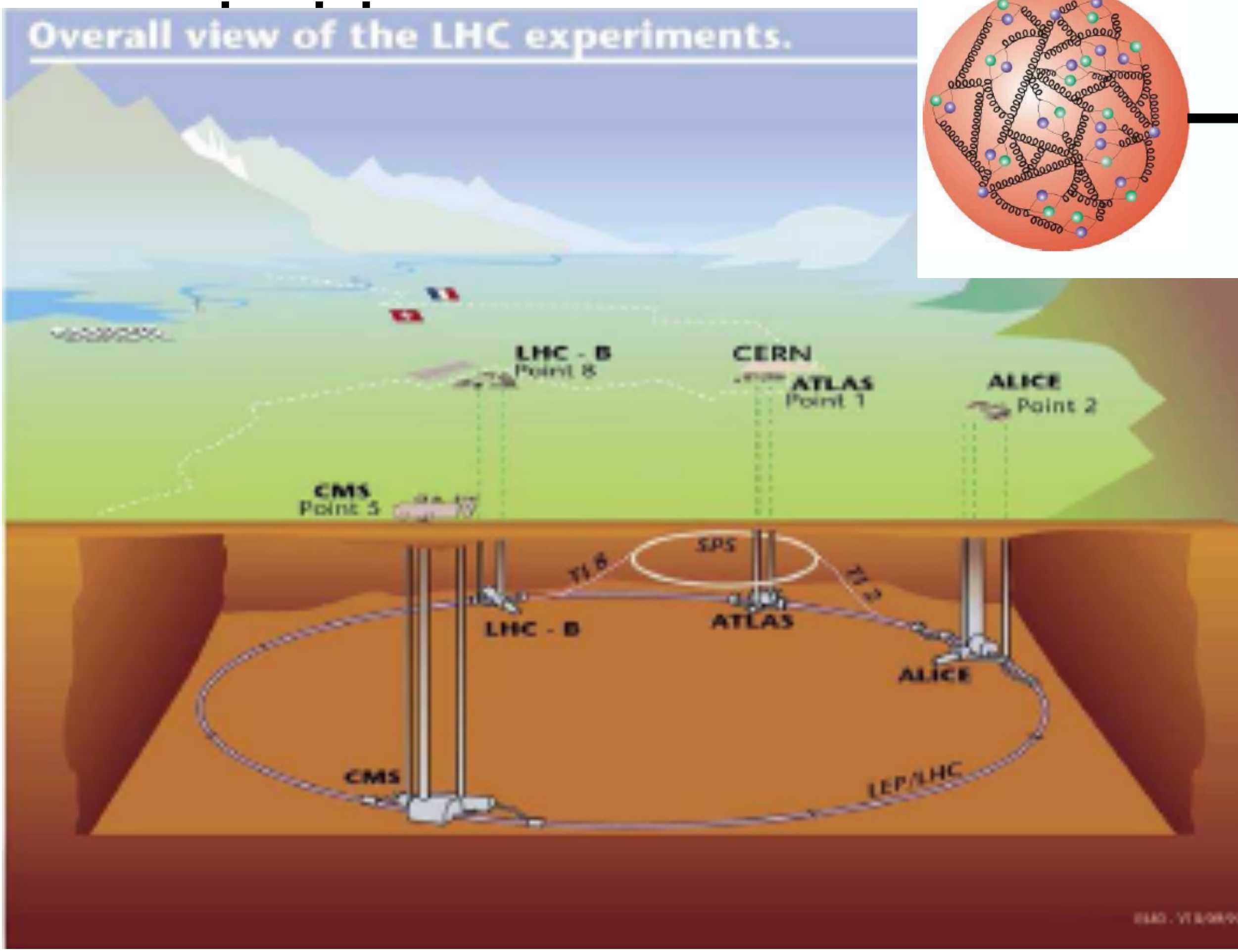
➢ **Need high-precision determination of M_H to exploit the sensitivity of BR(H → ZZ*), .etc.. to test BSM physics !**

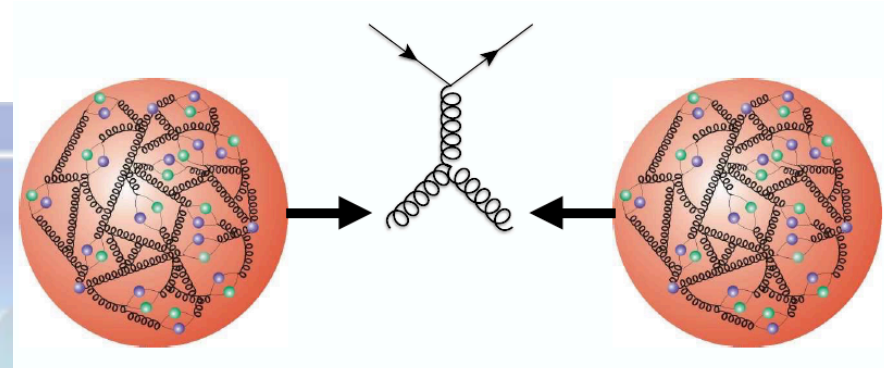
Accelerator and Experiments Decathlon

Collider experiments and physics potential

- LHC: circular proton-proton
- ILC: linear e+e-
- FCC: circular pp
- Further discussed options

LHC: proton-proton, $\sqrt{s}$=13 TeV, 27km



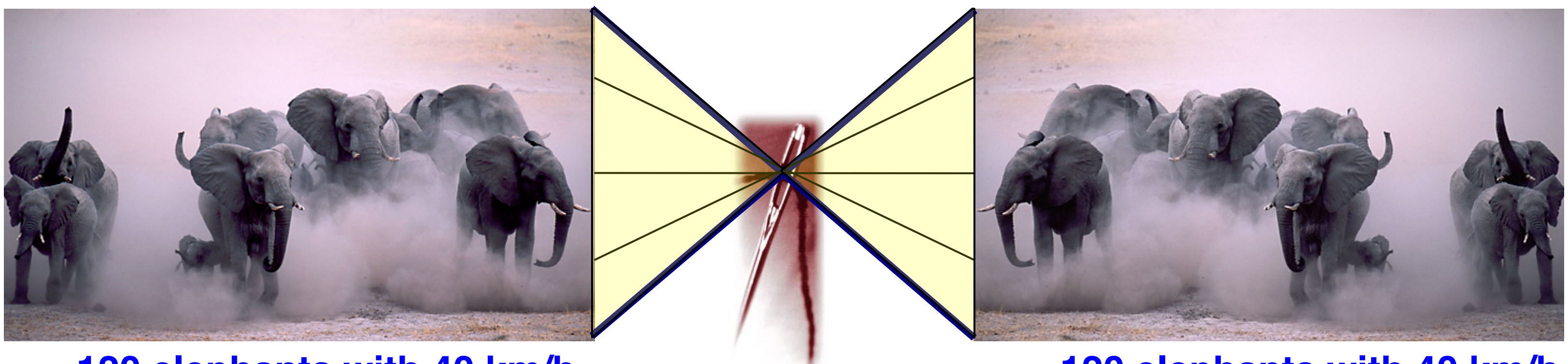


Energy stored in the LHC beams

2808 bunches, 1.1 x 10^{11} protons/bunch @ 7 TeV

350 MJ stored energy per proton beam

Same as colliding 2 x 120 elephants...



120 elephants with 40 km/h **120 elephants with 40 km/h**

The energy of a single 7 TeV proton is equivalent to a flying mosquito (1 μJ)

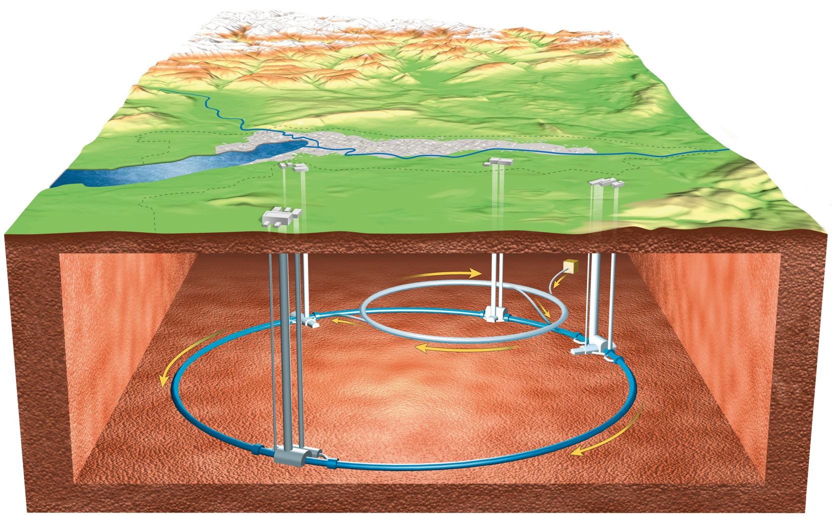
eye of a needle:
0.3 mm diameter

proton beams at interaction point are 10x smaller:
0.03 mm diameter

Acceleration cavities

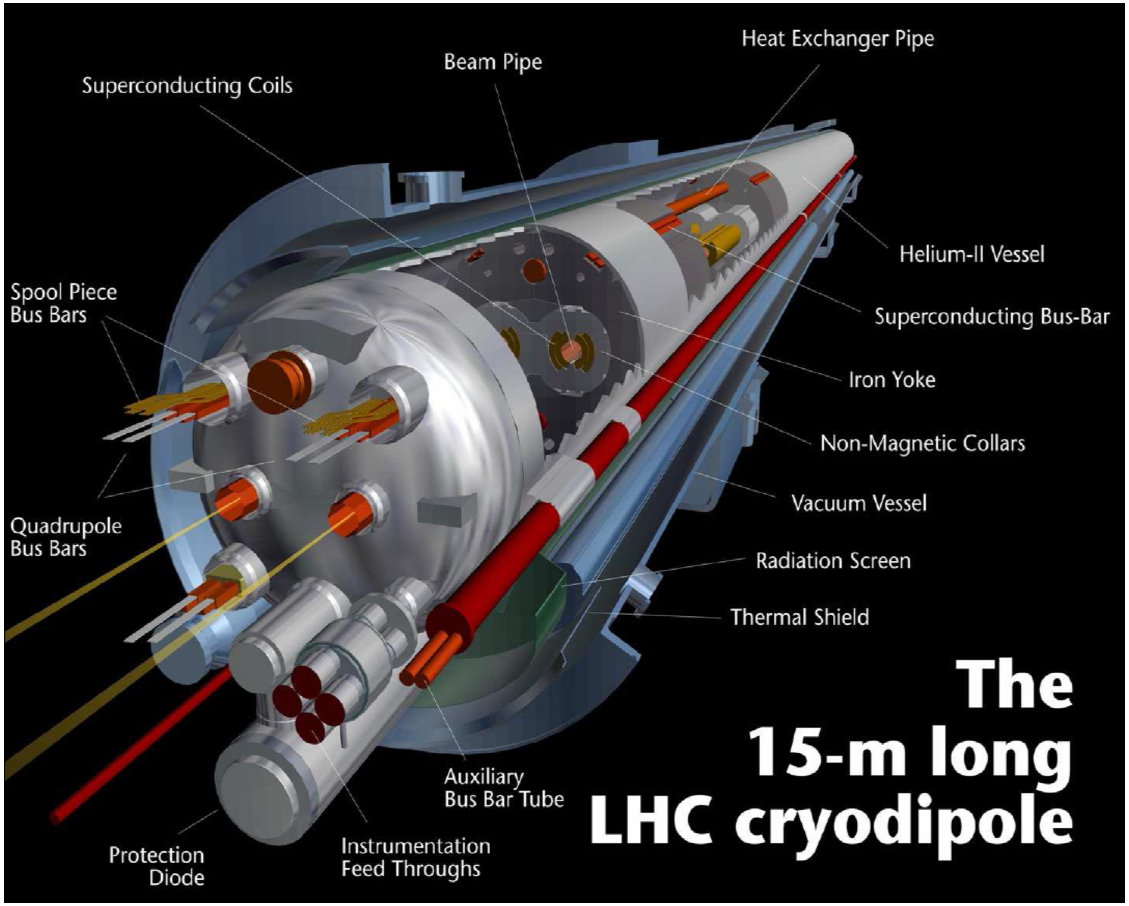
- Voltage 2 MV
- 8 resonators per beam, voltage adjusted such that protons are always accelerated
- Protons make more than 11,000 orbits per second

The LHC: circular accelerator



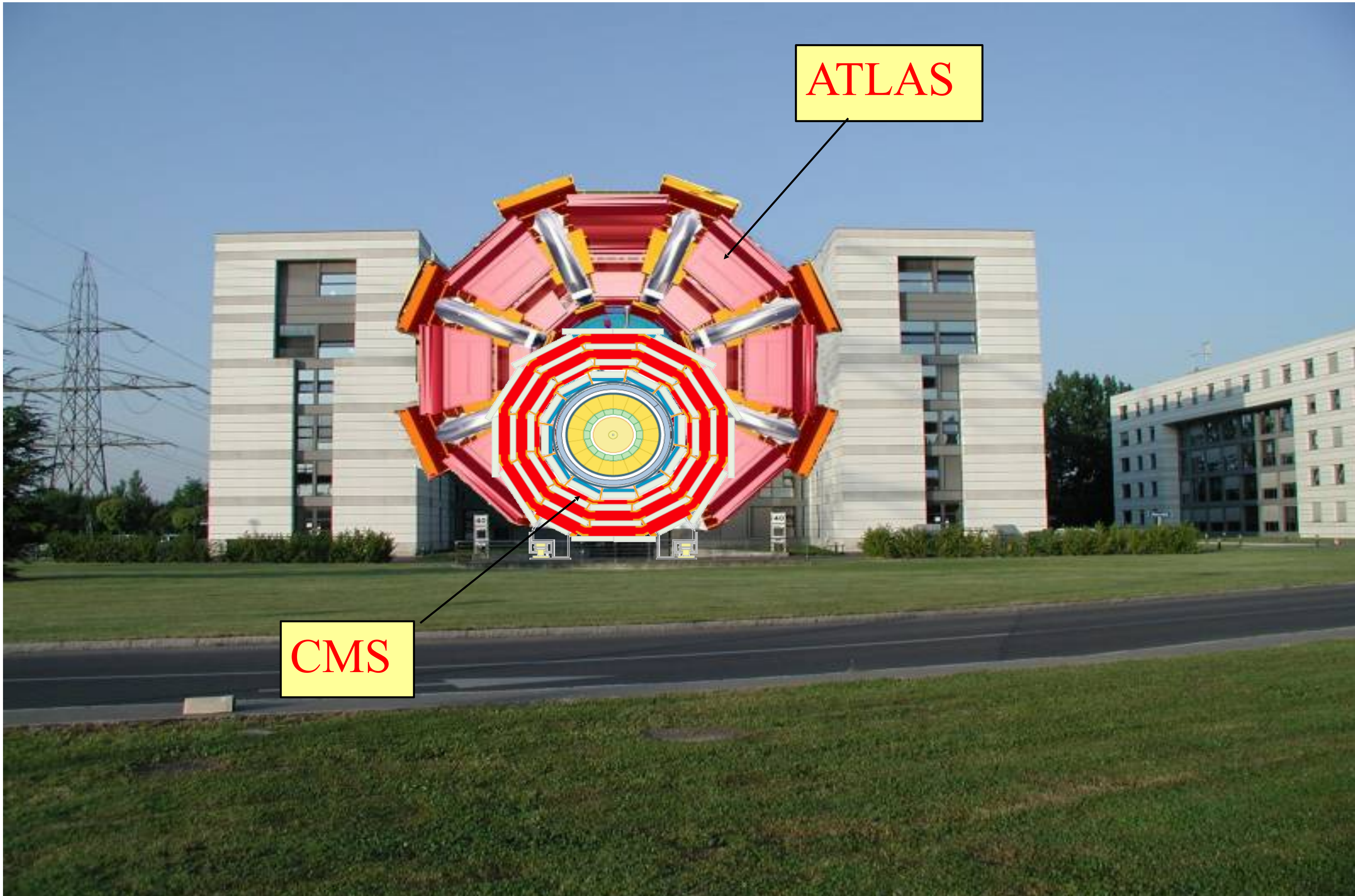
- Circular orbits: proton beams can be brought to collision many times
- Beams intersect inside 4 enormous detectors
- Need very powerful magnets to keep protons on circular orbit

The LHC dipole magnets

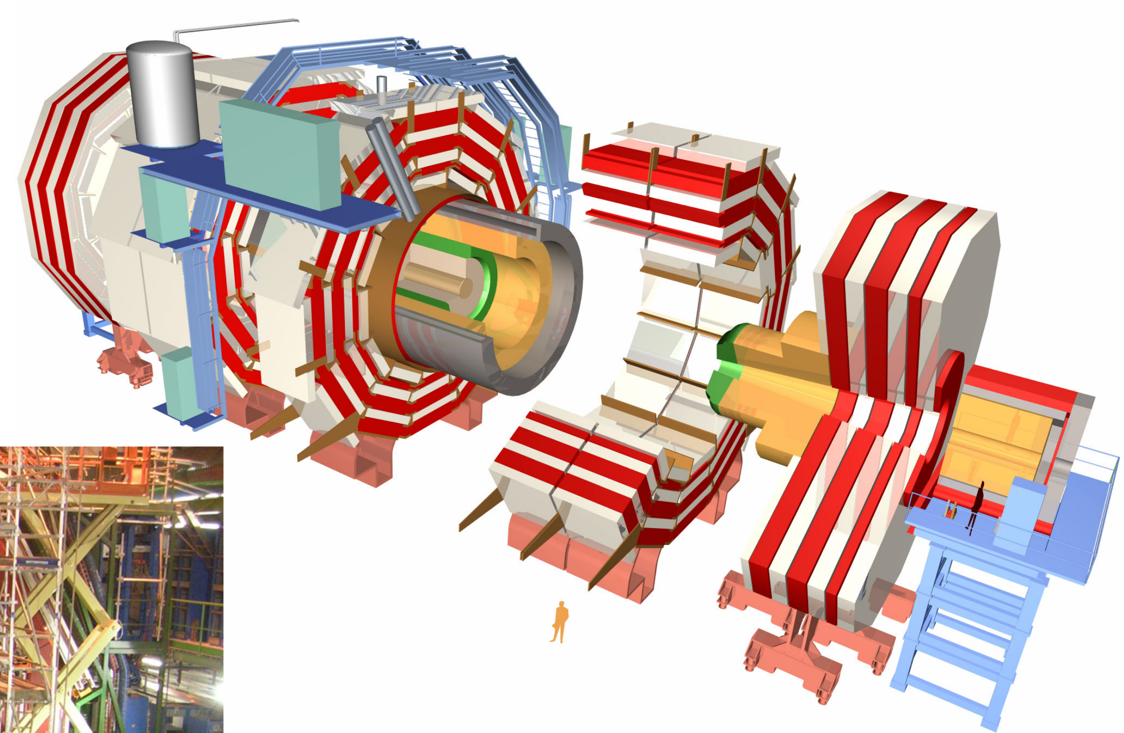


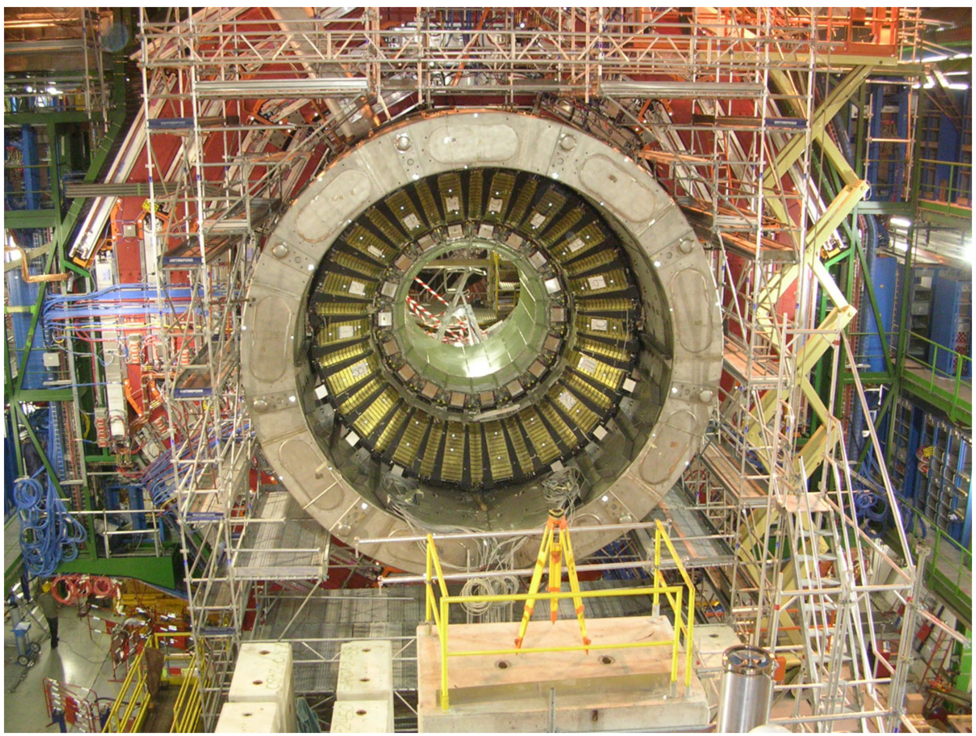
- Length: 15 m, weight: 35 tons, magnetic field: 8.3 Tesla
- Need current of 11,700 Ampere
- Superconducting magnets, have zero electrical resistance
- Operated at 1.9 K, i.e. just above absolute zero

Two LHC detectors: ATLAS and CMS



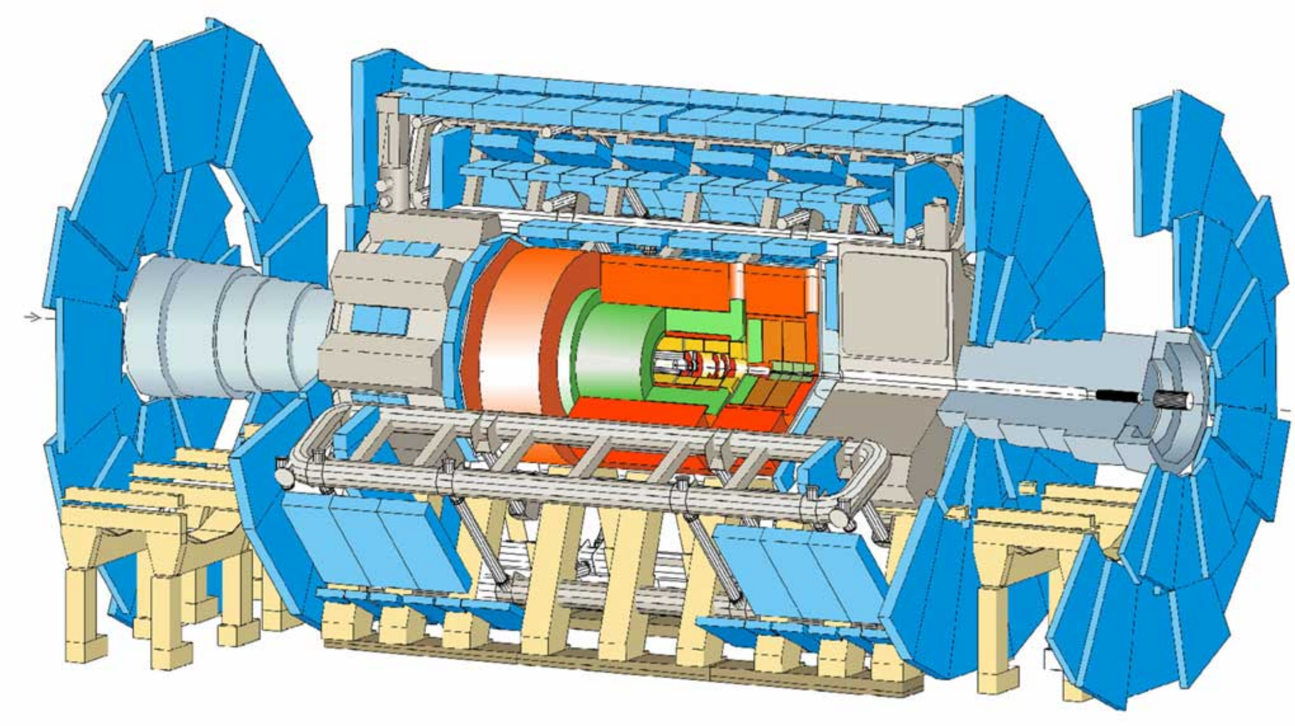
CMS – an LHC Detector





2000 tonnes
15m diameter
100m underground

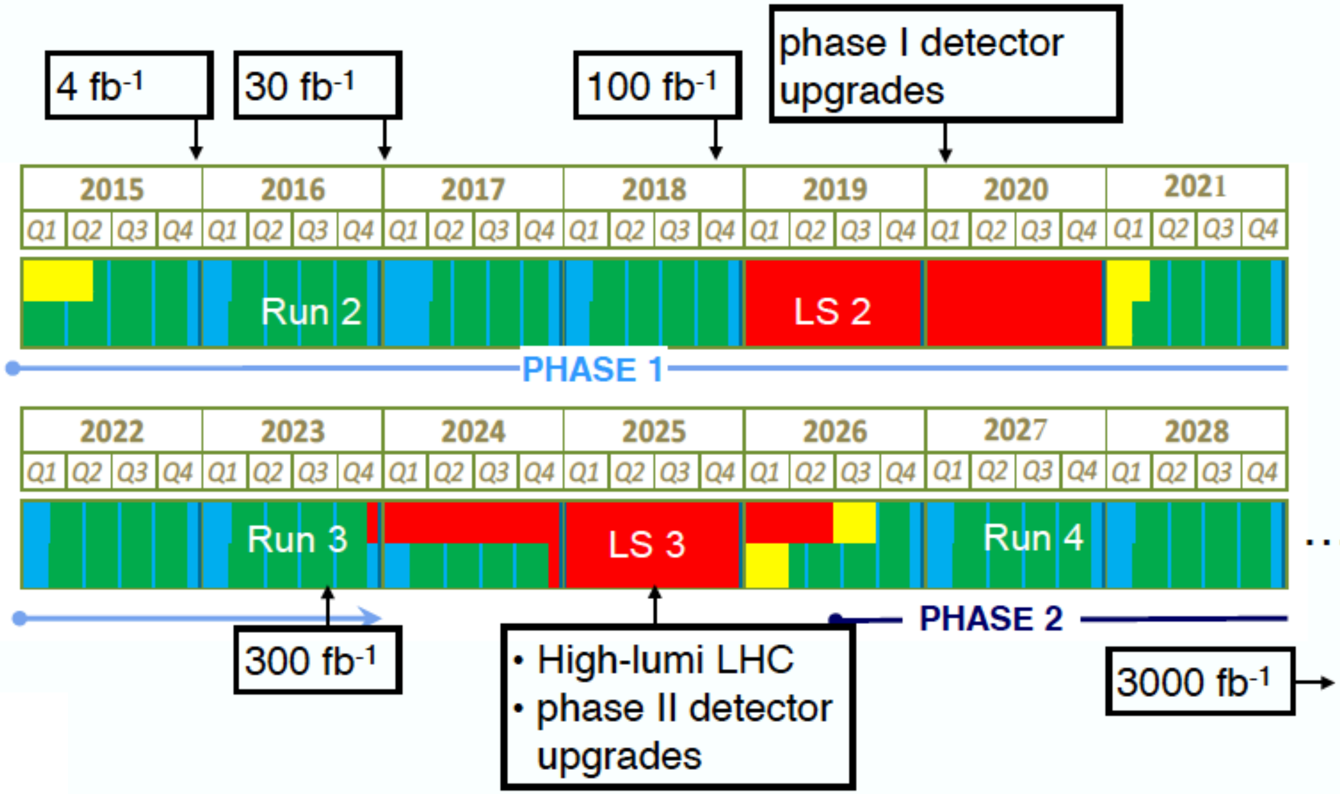
ATLAS – an LHC Detector



The ATLAS experiment:
7,000 tonnes 42m long 22m wide 22m high
2,000 Physicists 150 Institutes 34 Countries

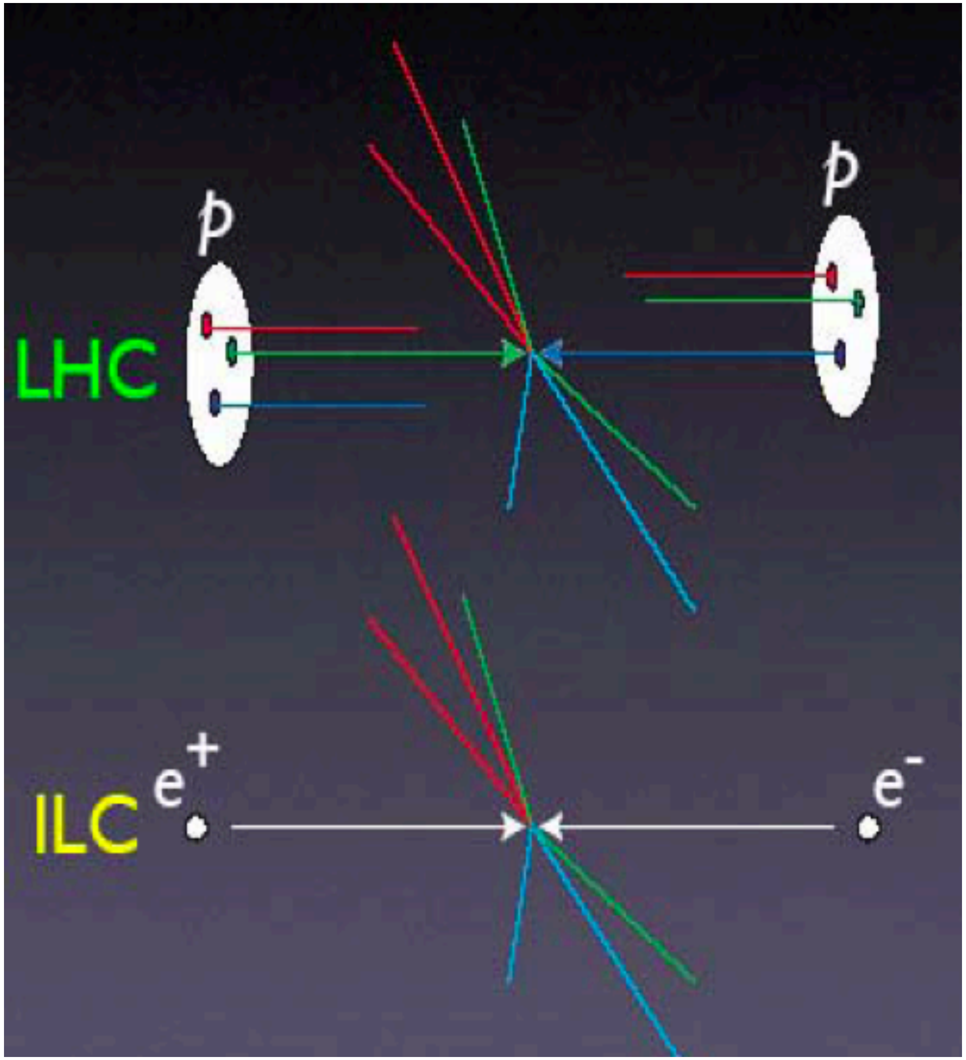
Future of LHC

- "Europe's top priority should be the exploitation of the full potential of the LHC" (aus der Europäischen Strategie für Teilchenphysik)

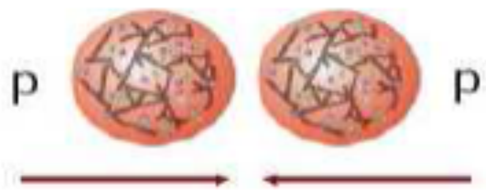


e^+e^- versus pp

- Simple particles
- Well defined:
  energy, angular mom.
- E can be scanned precisely
- Particles produced ~ democratically
- Final states generally fully reconstructable



Comparison: LHC and ILC

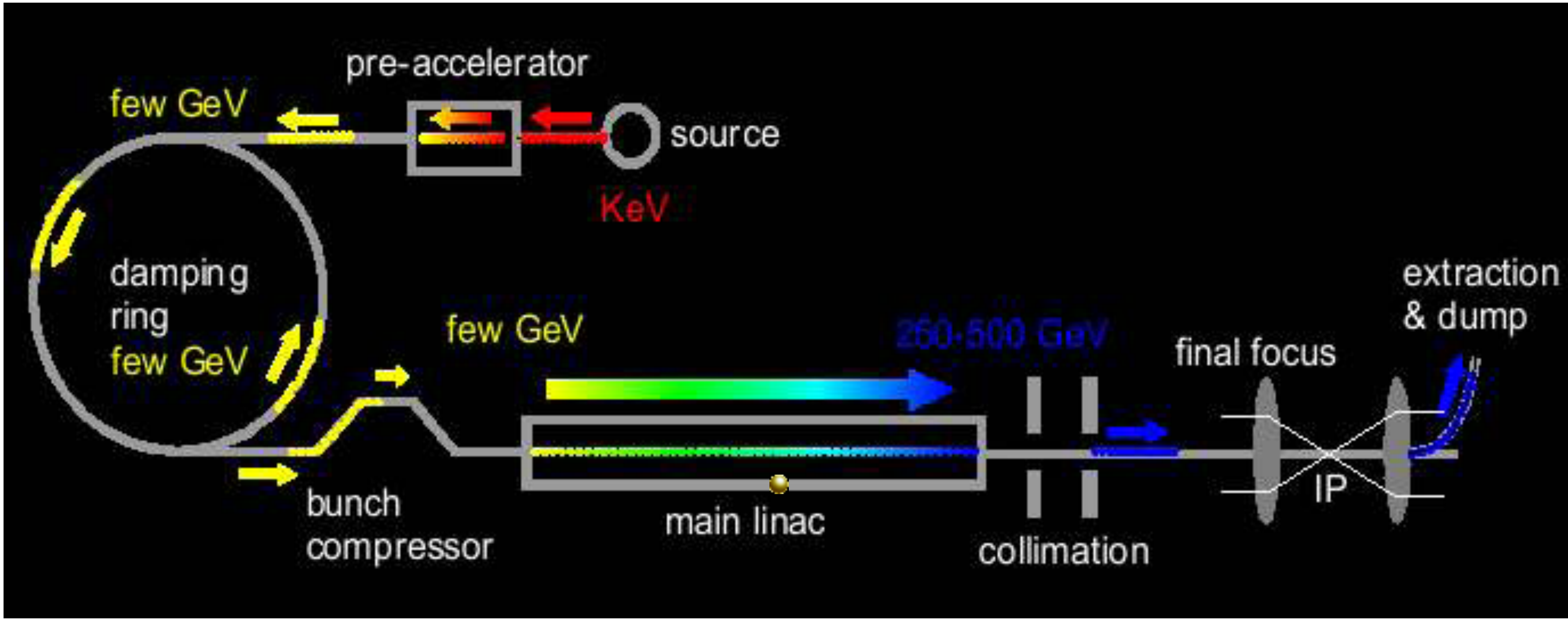


Characteristics of pp collider	and of the e^+e^-(γe, $\gamma\gamma$) collider
composite particles collide	Pointlike particles collide
E(CM) < 2 E(beam)	Known E(CM) = 2 E(beam)
strong interaction in initial state	well defined initial state
\`no' polarization applicable	polarized initial e- and e+ beams
LHC: $\sqrt{s}$ = 14TeV,	ILC: $\sqrt{s}$ = 500 GeV -- 1 TeV, tunable
used $\hat{s} = x_1 x_2 s$ few TeV	
small fraction of events analyzed	most events in detector analyzed
multiple triggers	no triggers required
superposition with spectator jets	clean +fully reconstructable events

Large potential for direct discovery

Large potential for discovery also via high precision

Generic Linear Collider



- ***High luminosity:*** **ILC beam structure = 3000 bunches per pulse, pulse every 5 Hz and each bunch contains about 10^{10} particles !**

- ***Challenge:*** **number of $e^{\pm}$ / pulse = factor 1000 higher than at SLC ('88-98) !   (but luminosity even factor 10000!)**

SCRF Linac Technology

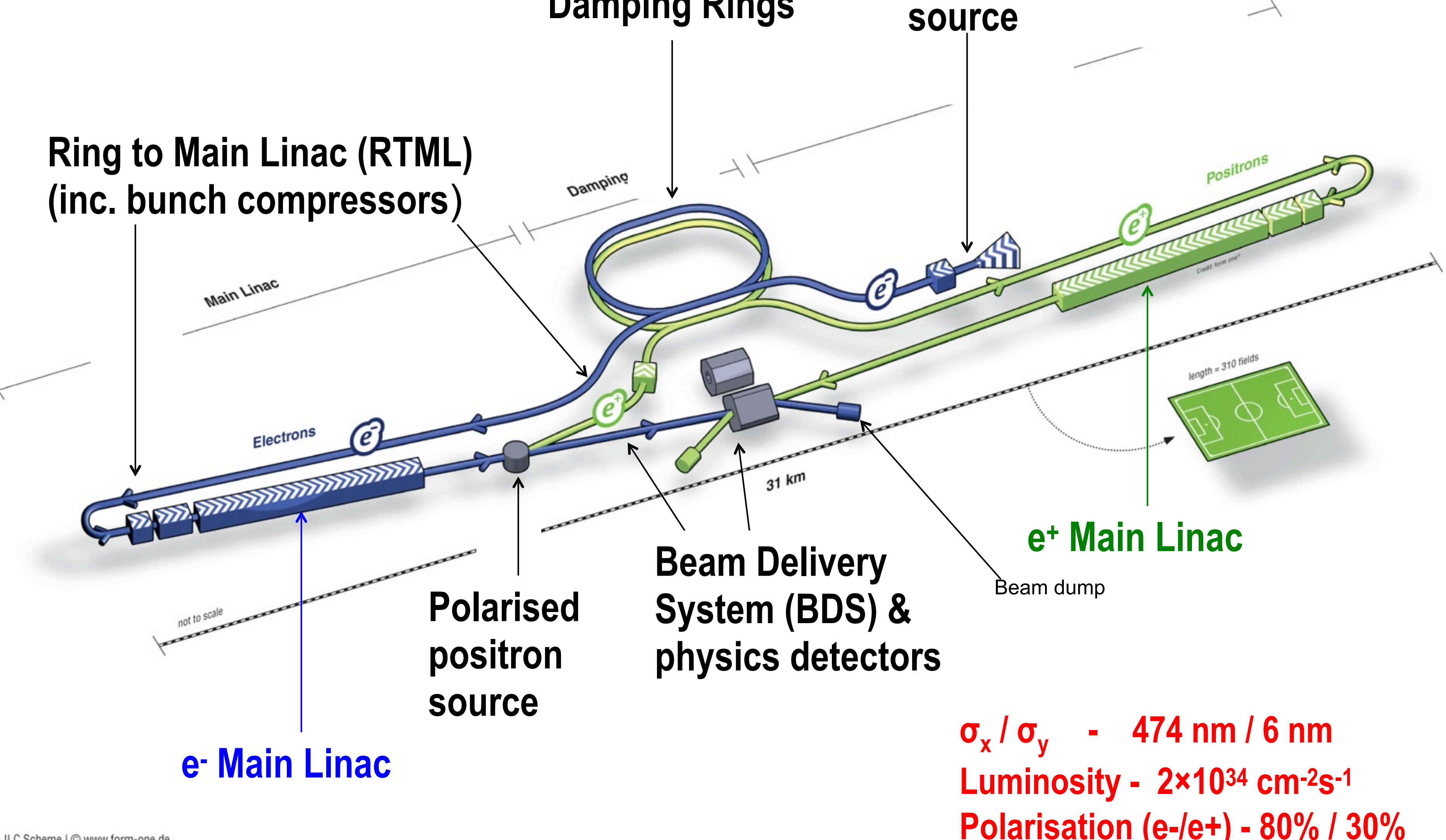
- solid niobium
- standing wave
- 9 cells
- operated at 2K (Lqd. He)
- 35 MV/m
- $Q_0 \geq 10^{10}$

1.3 GHz Nb 9-cell Cavities	16,024
Cryomodules	1,855
SC quadrupole package	673
10 MW MB Klystrons & modulators	436 / 471*

* site dependent

Approximately 20 years of R&D Worldwide → Mature technology

ILC Machine Overview



Ring to Main Linac (RTML) (inc. bunch compressors)

Damping Rings

Polarised electron source

Polarised positron source

Beam Delivery System (BDS) & physics detectors

Beam dump

e^+ Main Linac

e^- Main Linac

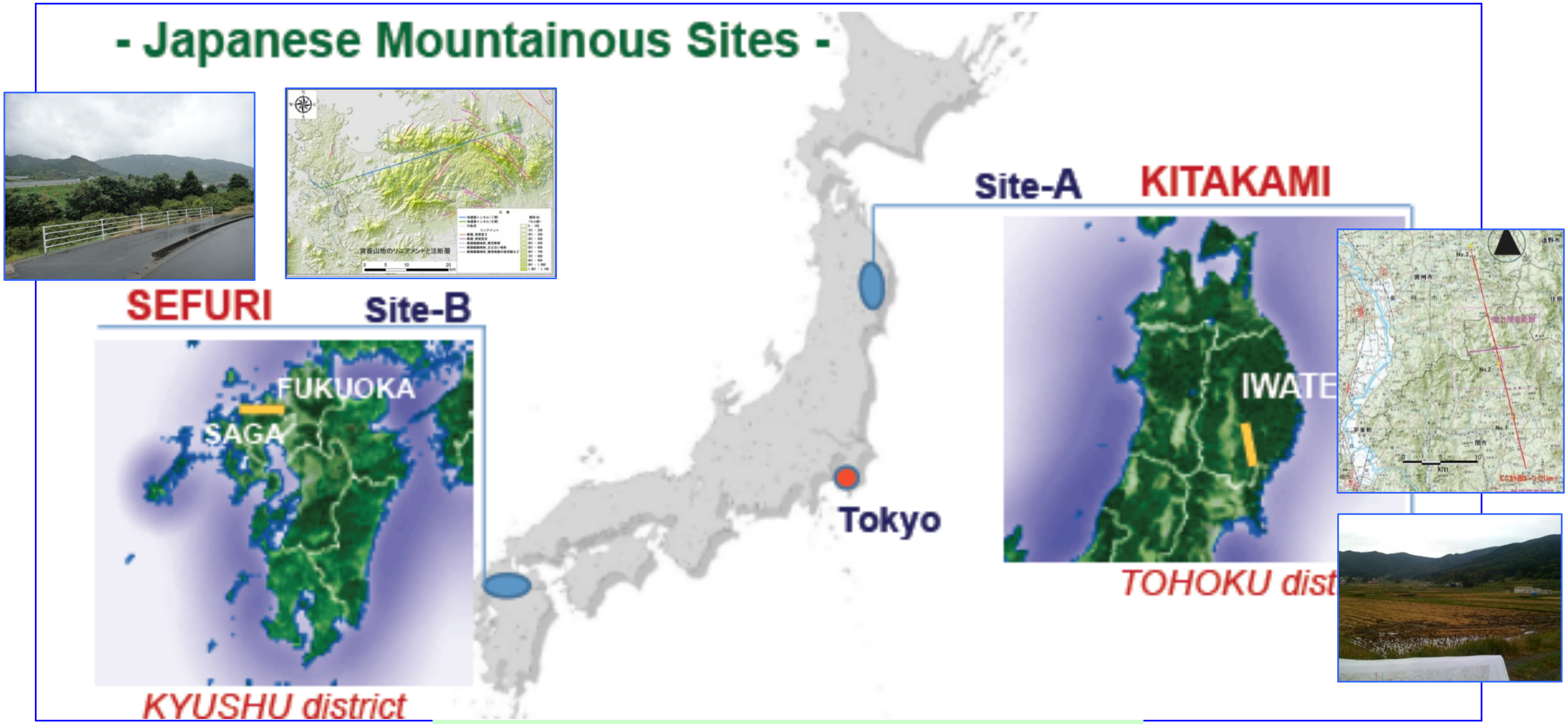
σ_x / σ_y - 474 nm / 6 nm

Luminosity - 2×10^{34} cm^{-2}s^{-1}

Polarisation (e-/e+) - 80% / 30%

Japanese Site(s) for the ILC

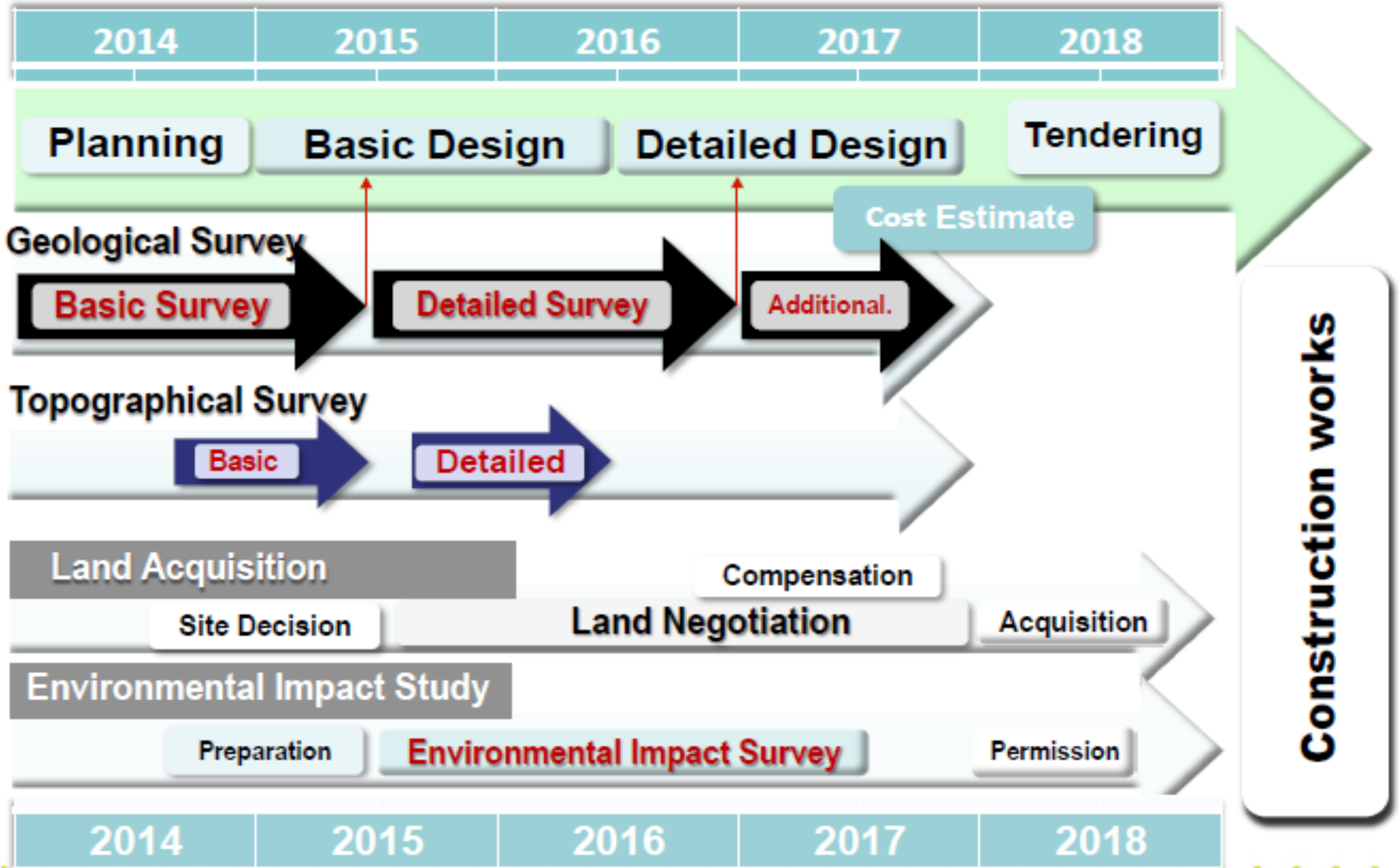
Brian Foster



- GDE-CFS group visited two sites, Oct., 2011.
- GDE EC visit in Jan. 2012.

Site specific schedule

Brian Foster



Beam polarization at HEP colliders

- *Polarization* = ensemble of particles with definite helicity λ = -½ left- or +½ right-handed :

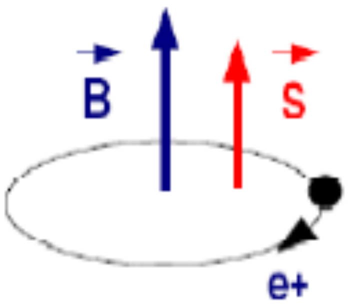
$$\boxed{\mathcal{P} = \frac{\#N_R - \#N_L}{\#N_R + \#N_L}}$$

→ beam polarization gives access to the couplings and unravels the structure of interactions

★ <u>Polarized beams at circular e^-e^+ colliders:</u>

- Polarization of both beams via Sokolov-Ternov effect

  (= spin-flip effect due to synchrotron radiation)



- At LEP (e+e-): massive depolarization effects; low polarization; not used for physics
- At HERA (ep): excellent e^- / e^+ polarization reached, ~50%-70%; spin rotators used to produce longitudinally polarized beams for physics studies

Beam Polarization at the LC

Polarized beams at linear e^-e^+ colliders:

- synchrotron radiation due to longitudinal acceleration negligible
- beams have to be polarized at the source !

Polarized e^- source:

- at the SLAC Linear Collider (SLC): excellent e^- polarization of about 78%
- led to precision measurement of the weak mixing angle:

$\sin\theta_{eff}=0.23098\pm0.00026$ (SLD) (LEP: 0.23221 ± 0.00029)

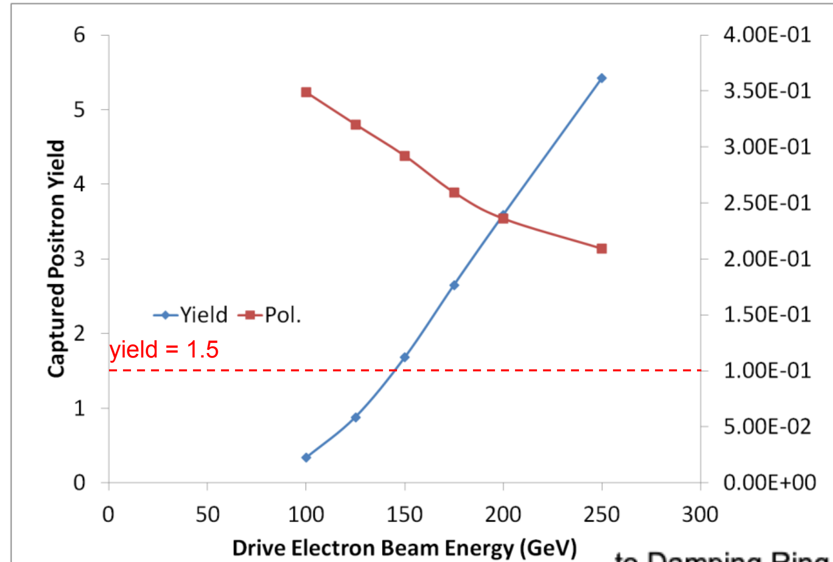
Polarized sources at the ILC/CLIC:

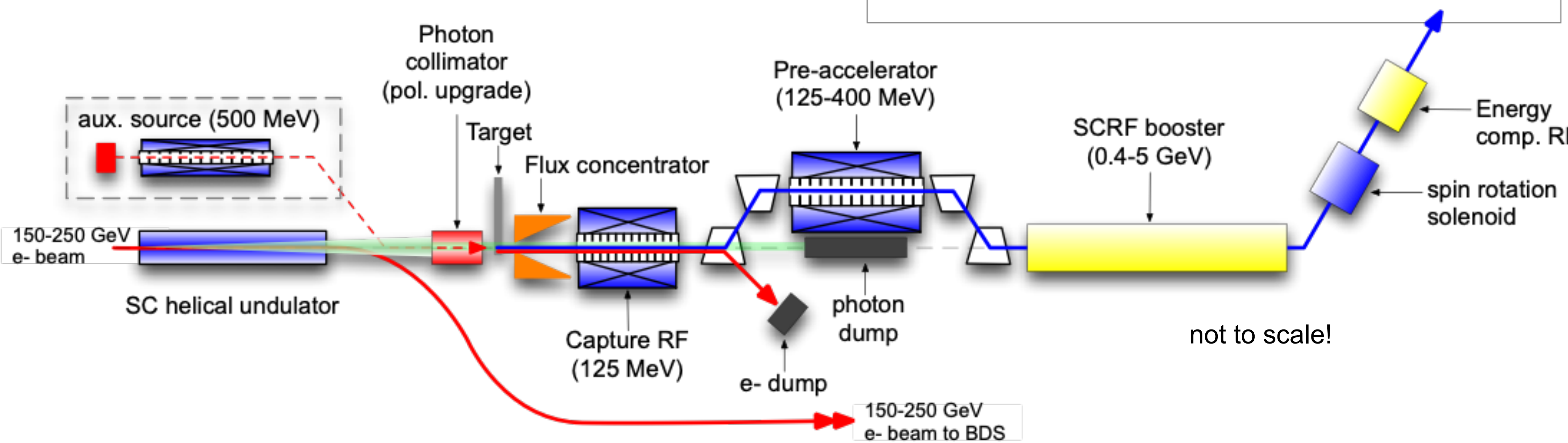
- expected e^- polarization between 80% and 90%

- Polarized e+ source designed, absolute tech. novelty!

Positron source: challenge for all LC!

- located at exit of electron Main Linac
- 147m (up 231m) SC helical undulator
- driven by primary electron beam (150-250 GeV)
- produces ~30 MeV photons
- converted in thin target into e^+e^- pairs





P_{eff} and L_{eff} for the staged approach

- With the listed parameters:

$\sqrt{s}$	$P(e^-)$	$P(e^+)$	$P_{\rm eff}$	$\mathcal{L}_{\rm eff}/\mathcal{L}$	$\frac{1}{x}\Delta P_{\rm eff}/P_{\rm eff}$
total range	$\mp 80\%$	0%	$\mp 80\%$	1	1
250 GeV	$\mp 80\%$	$\pm 40\%$	$\mp 91\%$	1.3	0.43
$\geq$350 GeV	$\mp 80\%$	$\pm 55\%$	$\mp 94\%$	1.4	0.30
total range	$\mp 90\%$	0%	$\mp 90\%$	1	1
250 GeV	$\mp 90\%$	$\pm 40\%$	$\mp 96\%$	1.4	0.43
$\geq$350 GeV	$\mp 90\%$	$\pm 55\%$	$\mp 97\%$	1.5	0.29

← No gain!

← No gain!

Gain in polarization! (Almost 100%)

Gain in number of interactions!

Gain in precision by more then a factor 3! (large N)

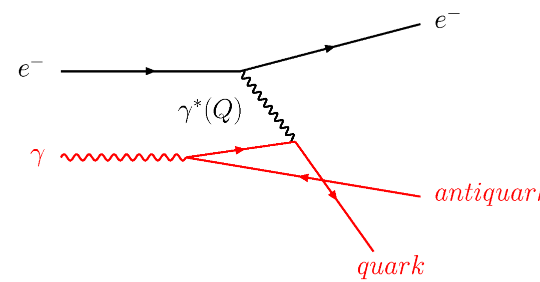
- Just by switching on P(e+)!

The LC offers and challenges

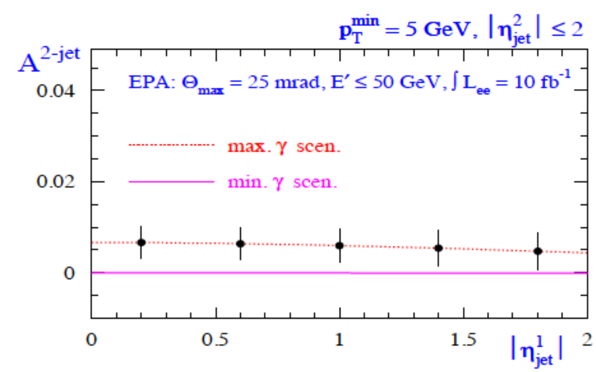
- **Staged energy approach:**
  - $\sqrt{s}$~240 GeV, `Higgs frontier‘
  - $\sqrt{s}$~350 GeV, `Top threshold‘
  - $\sqrt{s}$~500 GeV, `Top Yukawa‘
  - ($\sqrt{s}$=91 GeV, `EW Precision frontier‘)
  - $\sqrt{s}$~1000 GeV, `Higgs potential‘
- **Polarized beams and threshold scans:**
  - impact on ‘quality’ (and quantity)
  - Something ‘new’ comp. to LHC analyses
- **Highest precision measurements !**

Determining the γ structure

- **Quark content of a photon**
  - quark content of the photon: number and energy spectrum
  - conversion of photon energy in fermions
  - defined via e + $\gamma \rightarrow$ e + hadrons



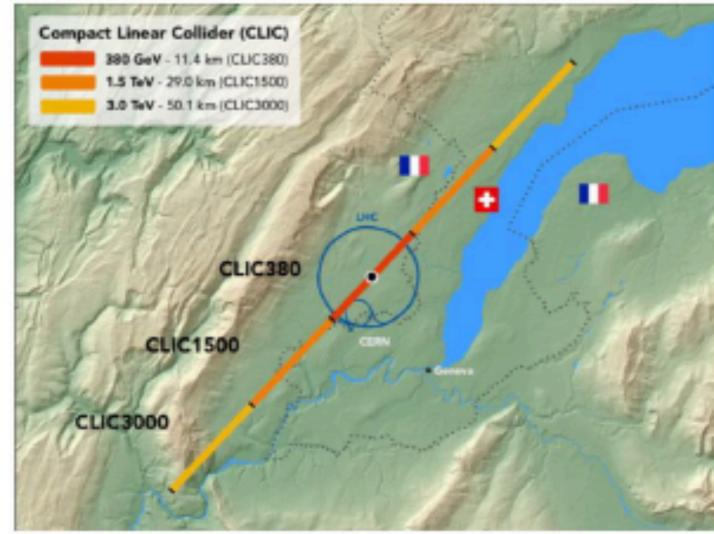
  - detectable via measuring small asymmetries



  - different from gluon content, testable in photon-proton scattering

CLIC: multi-TeV e^+e^- linear collider

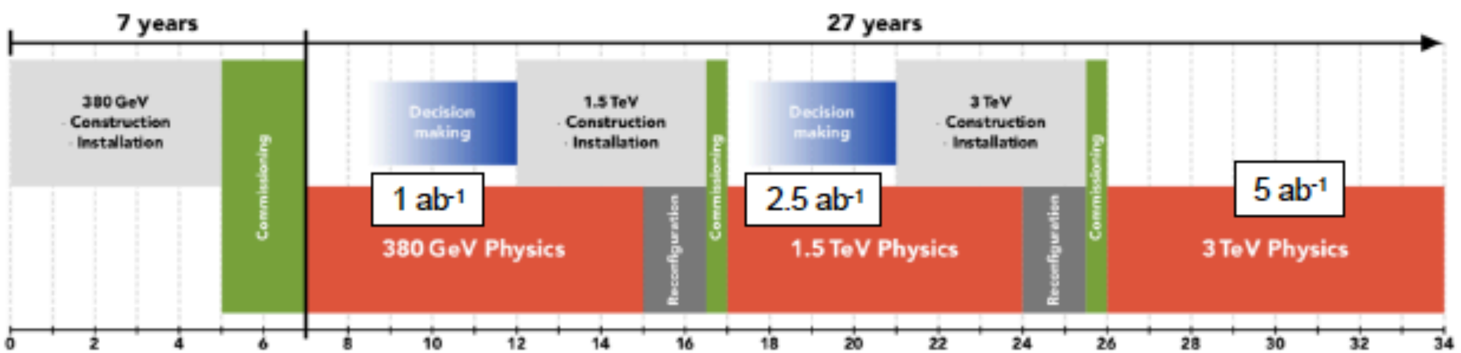
Parameter	Unit	Stage 1	Stage 2	Stage 3
$\sqrt{s}$	GeV	380	1500	3000
Tunnel length	km	11	29	50
Gradient	MV/m	72	72/100	72/100
Luminosity (above 99% of $\sqrt{s}$)	10^{34} $cm^{-2}s^{-1}$	1.5 0.9	3.7 1.4	5.9 2
Beam size at IP (σ_y/σ_x)	nm	2.9/149	1.5/60	1/40
Annual energy consumption CERN today: 1.2 TWh	TWh	0.8	1.7	2.8
Power consumption	MW	170	370	590
Construction cost	BCH	5.9	+5.1	+7.3



Since last ESPP: development of key technologies, progress towards demonstration of design parameters:

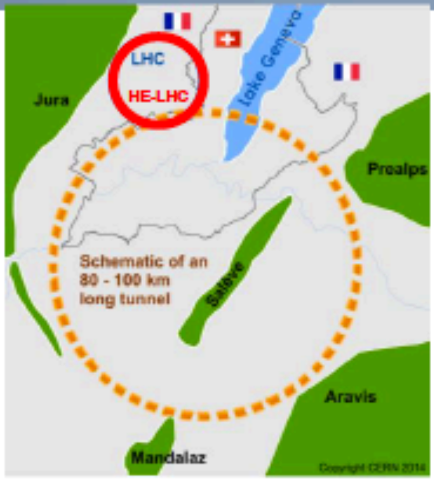
- ❑ 100 MV/m accelerating structures with low breakdown rate
- ❑ two-beam acceleration scheme demonstrated (CTF3) up to 145 MV/m
- ❑ R&D on alignment and vibration stabilization systems
- ❑ reduction of energy consumption (optimisation ongoing for 1.5 and 3 TeV) and cost

Technically:
construction could start in ~2026 (TDR in 2025)
→ start operation at $\sqrt{s}$=380 GeV in ~2035



FCC: Future Circular Collider

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230×10^{34} 28 8.5 1.5	75 ab^{-1} 5 2.5 0.8	2 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5×10^{34} 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39 TeV	3×10^{29}	65 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb



Also studied: HE-LHC: $\sqrt{s}$=27 TeV using FCC-hh 16 T magnets in LHC tunnel; L~1.6×10^{35} → 15 ab^{-1} for 20 years operation

Parameter	Unit	FCC-ee	FCC-hh
Annual energy consumption CERN today: 1.2 TWh	TWh	1.9	4
Power consumption	MW	~300	550
Construction cost (tunnel included)	BCH	11.6	17 if after FCC-ee; otherwise 24

<u>**Preliminary, purely technical**</u> schedule for integrated programme (FCC-ee followed by FCC-hh), assuming green light to preparation work in 2020.

8 years preparation	10 years tunnel and FCC-ee construction	**15 years FCC-ee operation**	11 years preparation for FCC-hh and installation	**25 years FCC-hh operation pp/PbPb/eh**
2020-2028		**2038-2053**		**2064-2090**

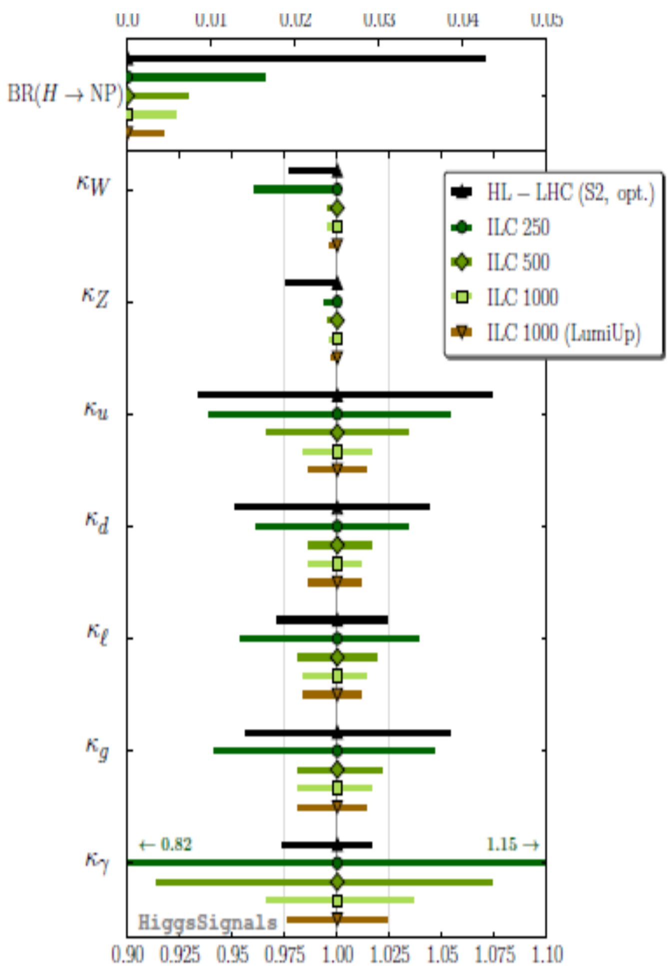
Olympics at High-Precision- and High-Energy-Frontier

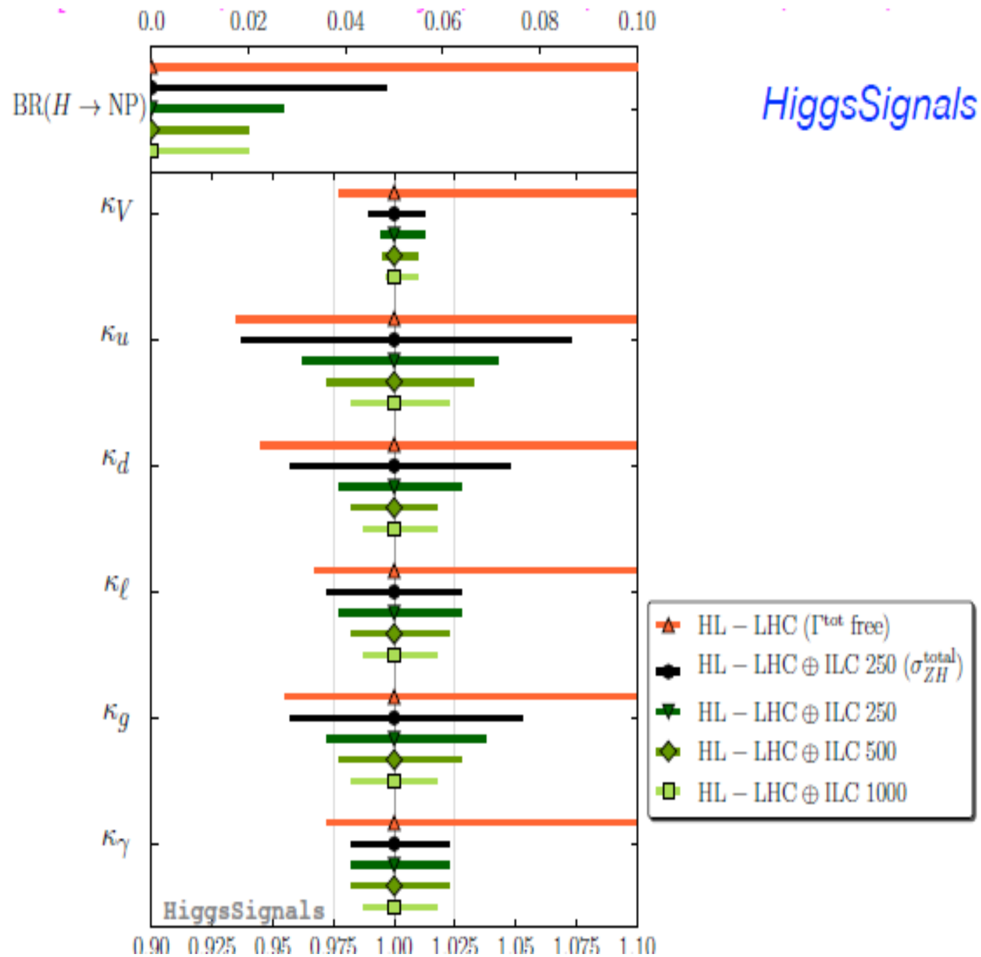
- Precision Higgs physics
- GigaZ
- Supersymmetry
- Dark Matter
- Inflation

Great thanks to LHC+ILC

Somewhen in ~2050 ?!

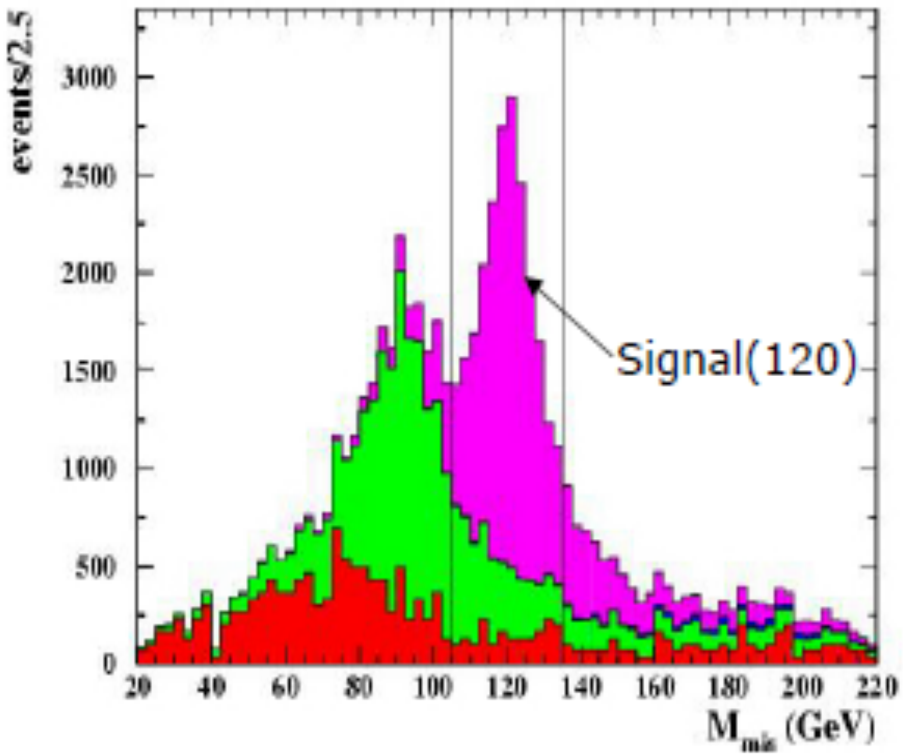
Assumed: $\kappa_V \leq 1$

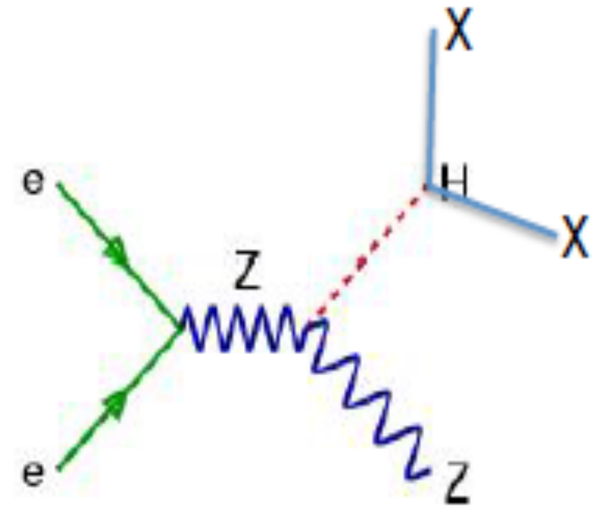




HiggsSignals

Unique sensitivity at a LC: H →invisible





- ***Only measure Z production and decay***
- ***Precise initial state: Higgs reconstruction independ. of decay***
- ***Sensitive to invisible decays: New Physics!***

Unique sensitivity at a LC: H $\rightarrow$ invisible

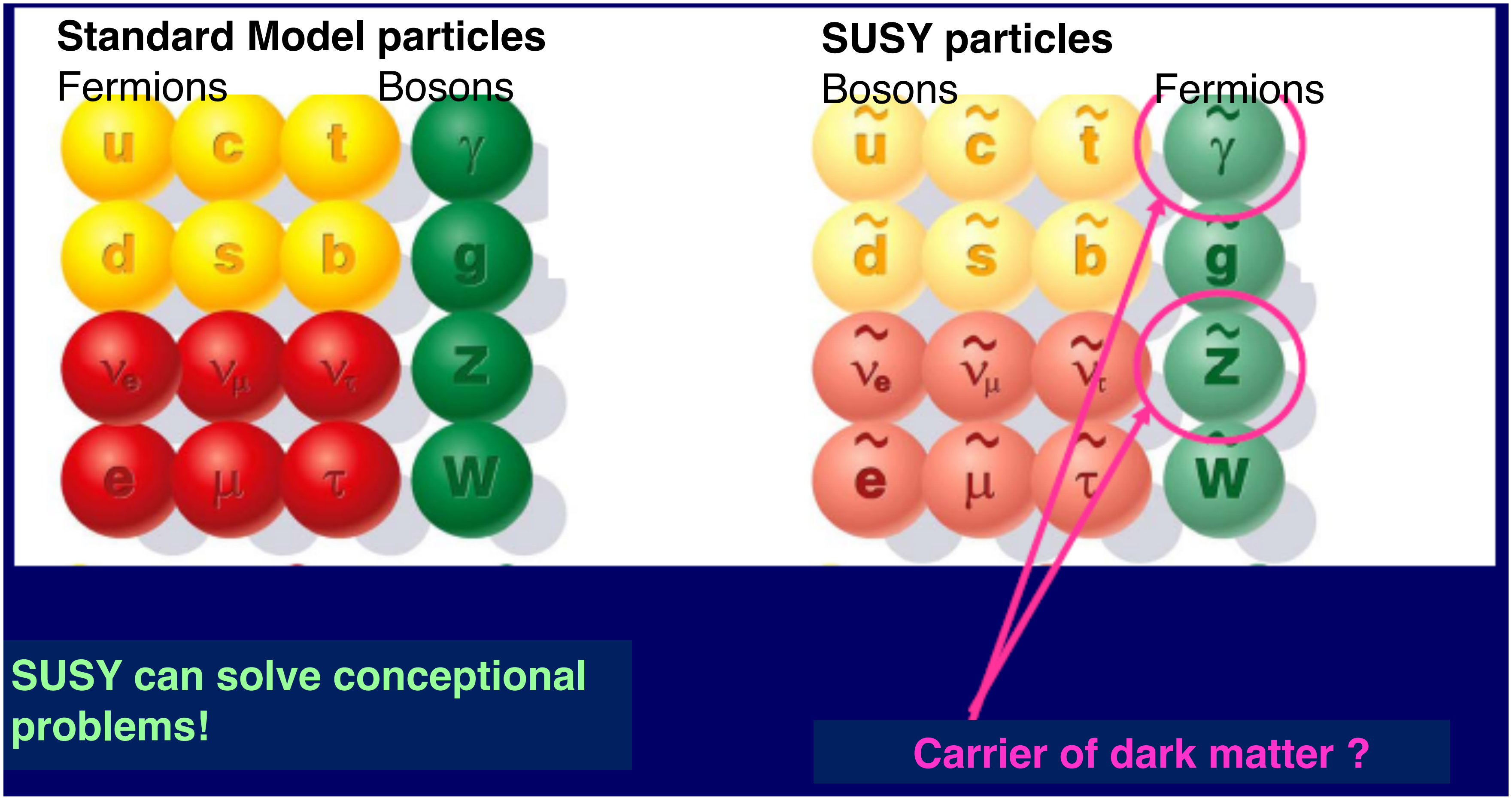
- **Dark matter: sizeable deviation to SM predictions possible, even if couplings to gauge bosons and SM fermions are very close to SM**
  - If dark matter consists of one or more particles with a mass below ~63 GeV, then the decay of the state at 125 GeV into a dark matter pair is kinematically open!

- **Crucial: detection of an invisible decay mode of the 125 GeV-state could be manifestation of BSM physics**
  - Direct search for H $\rightarrow$ invisible
  - Suppression of all other branching ratios

➢ ***Unique potential: high precision recoil method !***

Prospects for Beyond Standard Model

- **Postulate new kind of symmetry:Supersymmetry**
  - **Symmetry between force and matter particles**



What does a SUSY transformation?

- **Provides each particle a superpartner**
- **Superpartner has same properties with exactly one exception: Spin changes by 1/2 unit $\longrightarrow$ *SUSY QU-number***

Matter⇔ Force Symmetry !

- **But same gauge group as the Standard Model!**

Consequences:

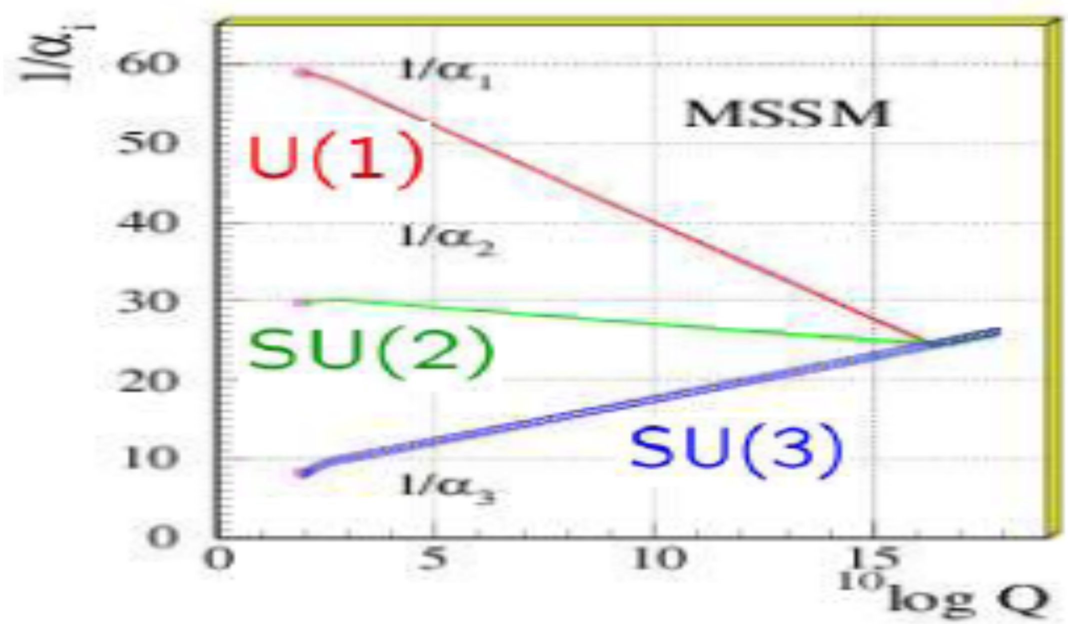
- **SUSY-partner couples identically as their SM-partner**
- **Same quantum numbers, only spin different**
- **I.e. masses should be equal………*???***

similar as for Higgs!

➤ ***Since no SUSY partners found: symmetry has to be broken!***

SUSY and unification

- **Idea:**
  - New SUSY particles change energy dependence of forces



- Unification possible!
- SUSY provides candidate for dark matter (see later)
- SUSY predicts even 5 Higgs particles ……

What if nothing else than H is found now?

The exciting Higgs story has just started….

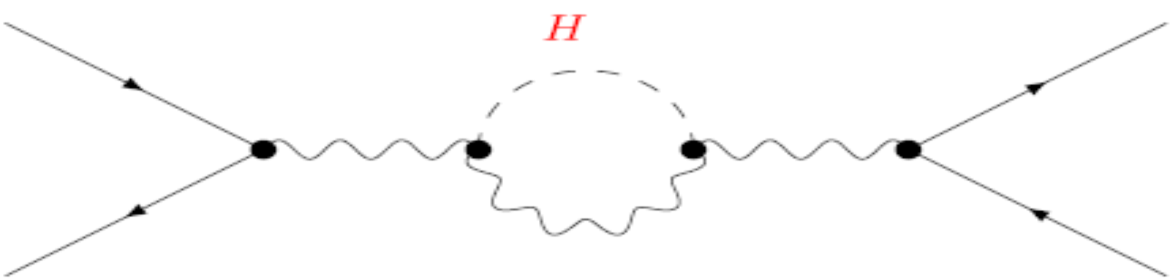
- Since m_H is free parameter in SM at tree level
  - Crucial relations exist, however, between m_{top}, m_W and $\sin^2\theta_{eff}$
  - If nothing else appears in the electroweak sector, these relations have to be urgently checked
- Which strategy should one aim?
  - exploit precision observables and check whether the measured values fit together at quantum level
  - m_Z ,m_W,α_{had}, $\sin^2\theta_{eff}$ und m_{top}
- Exploit \`GigaZ' @ILC: high lumi run at $\sqrt{s}$ = 91 GeV
  - closes open question of the SM
  - sensitive to new physics even beyond LHC reach

One more window to new physics

EW precision data:	Theory:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$	SM, MSSM, ...

$\Downarrow$

Test of the theory at Quantum Level



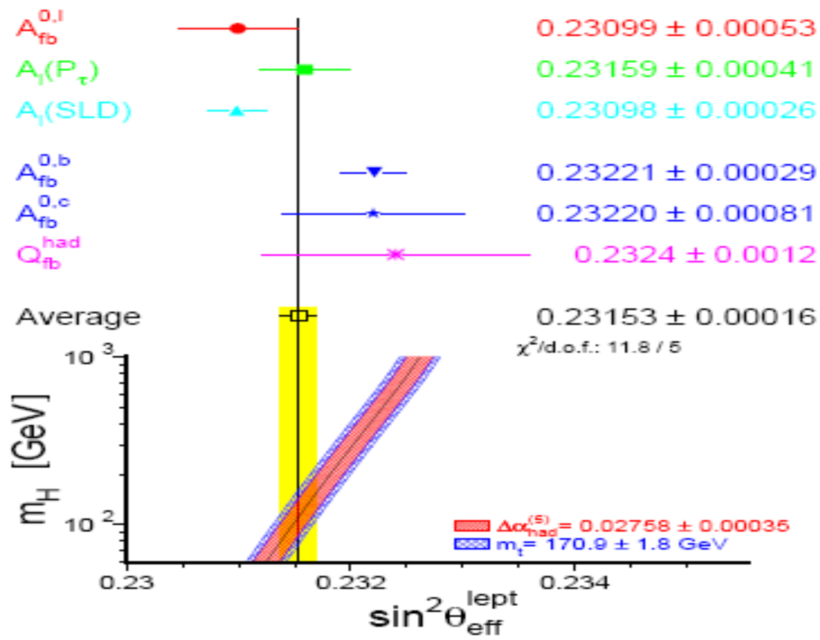
$\Downarrow$

Sensitive to parameters of new physics: Higgs mass etc.

➢ Window opens to 'new Physics'!

Higgs story has just started …

$\sqrt{s}$=91 GeV



LEP:

$\sin^2\theta_{eff}(A_{FB}{}^b)$= 0.23221±0.00029

SLC:

$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

World average:

$\sin^2\theta_{eff}$ = 0.23153±0.00016

Goal GigaZ: $\Delta\sin\theta$=1.3 x 10^{-5}

- **Uncertainties from input parameters: Δm_Z, m_{top}, etc. …**
  - Δm_Z=2.1 MeV: $\Delta\sin^2\theta_{eff}^{para}$~1.4x$10^{-5}$
  - Δm_{top}~1 GeV (Tevatron/LHC): $\Delta\sin^2\theta_{eff}^{para}$~3x$10^{-5}$
  - Δm_{top}~0.1 GeV (ILC): $\Delta\sin^2\theta_{eff}^{para}$~0.3x$10^{-5}$

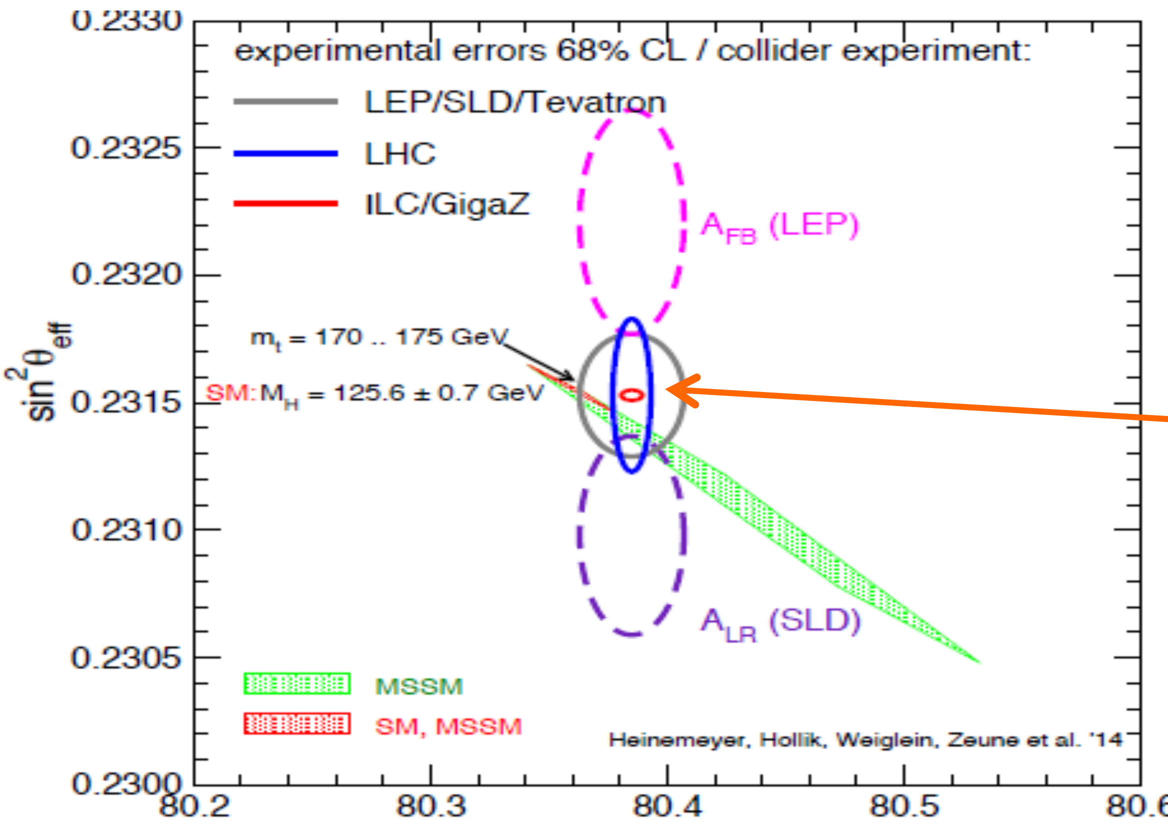
To close the story… GigaZ

$\sqrt{s}$=91 GeV

- **Measure $\sin^2\theta_{eff}$ via A_{LR} with high precision: $\Delta\sin\theta$=1.3 10^{-5}**

World average → happy with both!

Central value has large impact !!!



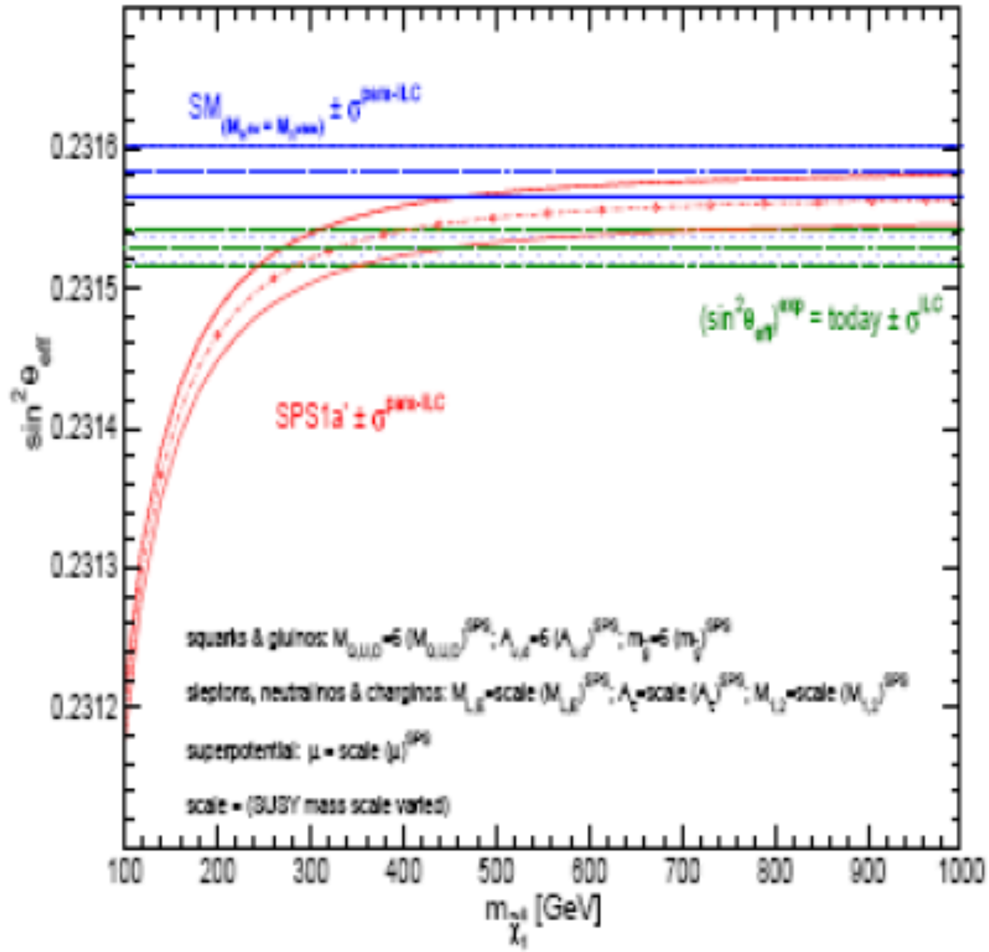
← LEP value disfavours both, SM+MSSM

GigaZ precision!

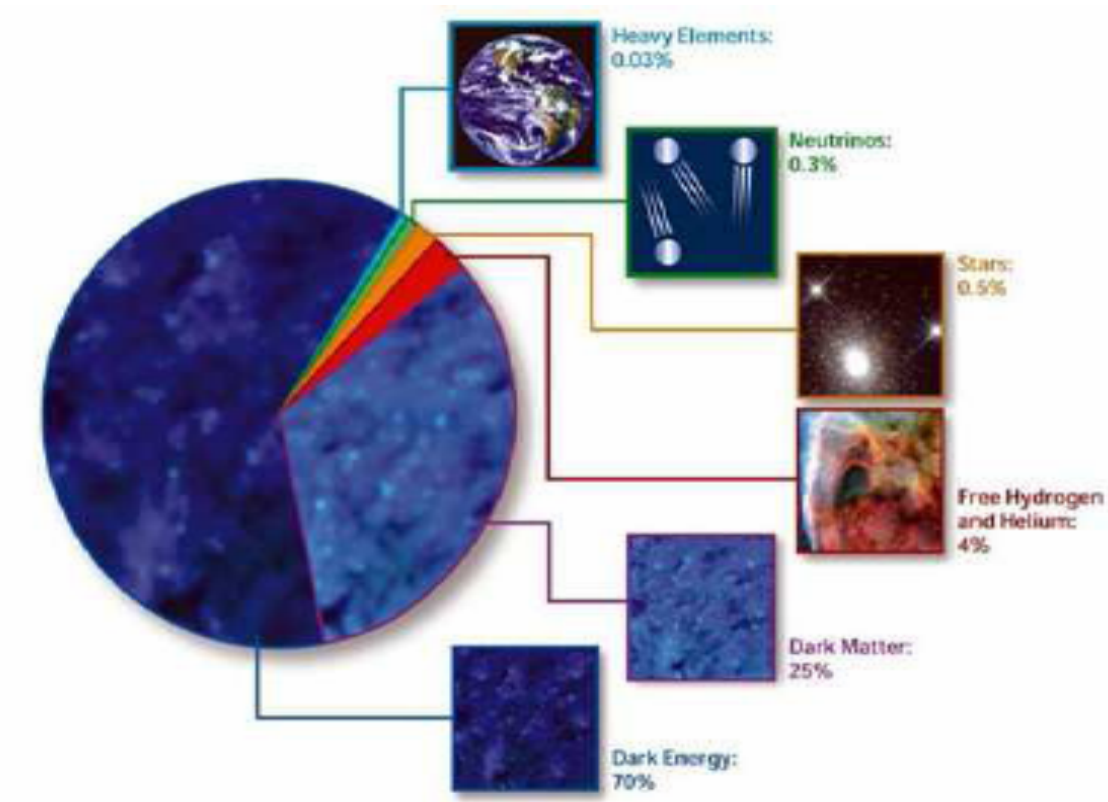
↑ SLD value disfavours SM

What else could we learn @GigaZ $\sqrt{s}$=91 GeV

- **Assume only Higgs@LHC but no hints for SUSY:**
  - Really SM?
  - Help from $\sin^2\theta_{eff}$?
- **If GigaZ precision:**
  - i.e. Δm_{top}=0.1 GeV…
  - Deviations measurable
- **$\sin^2\theta_{eff}$ can be the crucial quantity to reveal effects of NP!**



What is the Universe be made of?

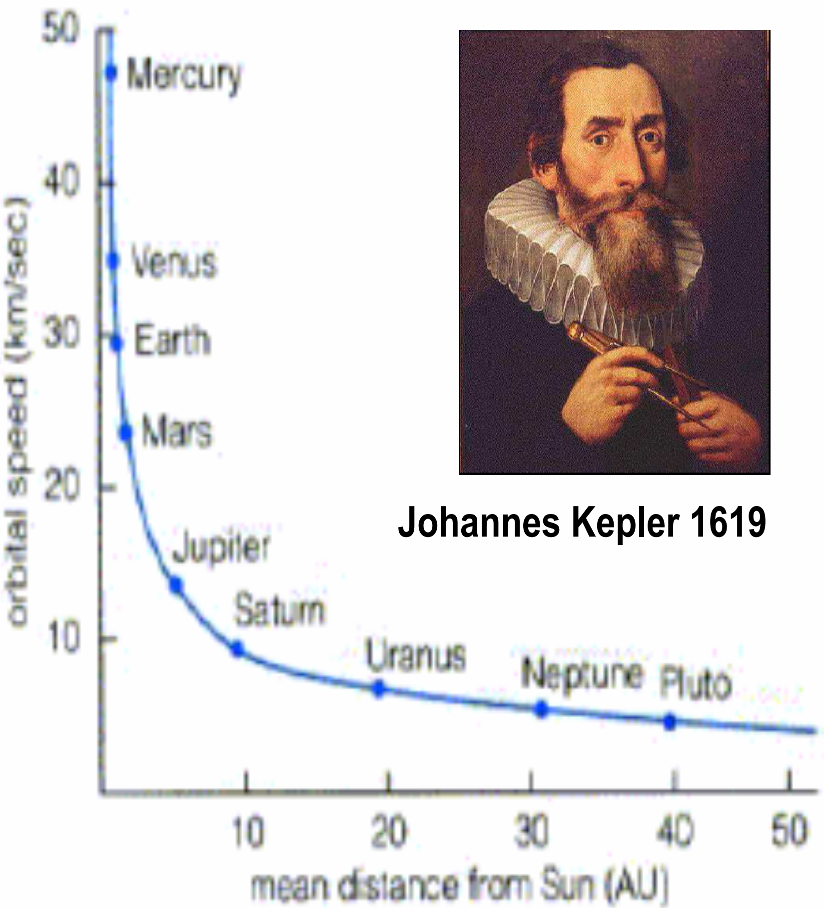


- **We only know about 4% of the Universe**

- ***Dark matter and dark Energy build about 96% of the Universe***

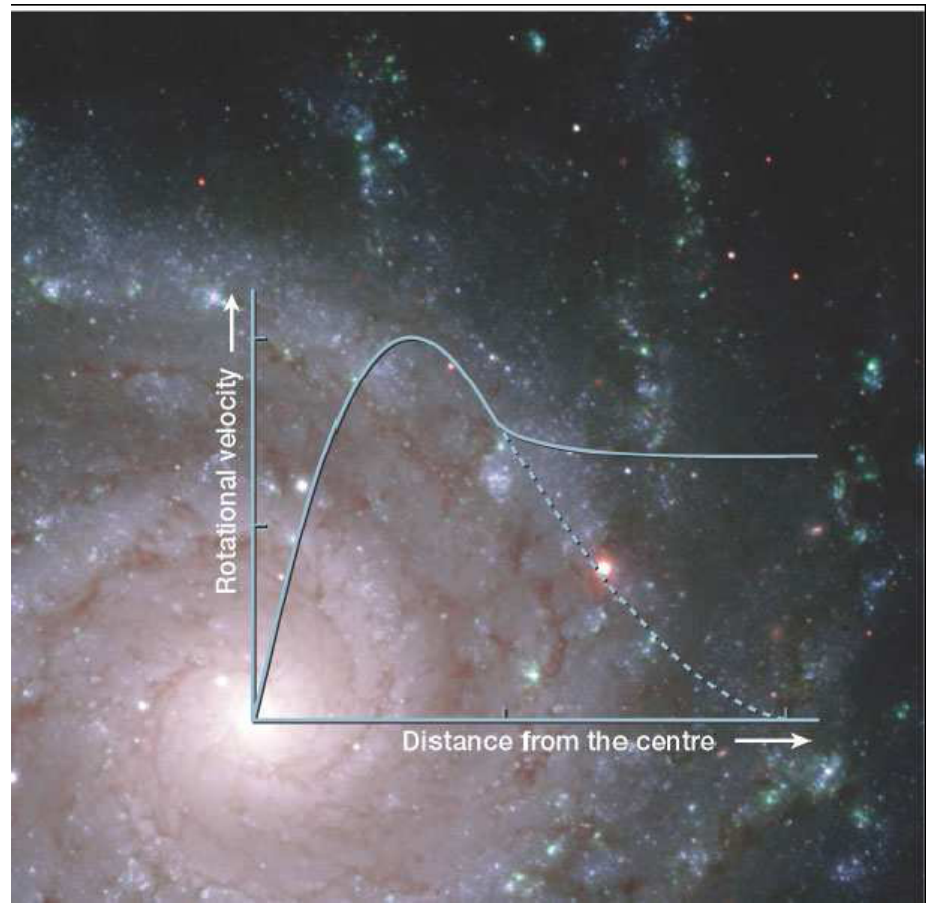
Hint for dark matter

Planets around the sun



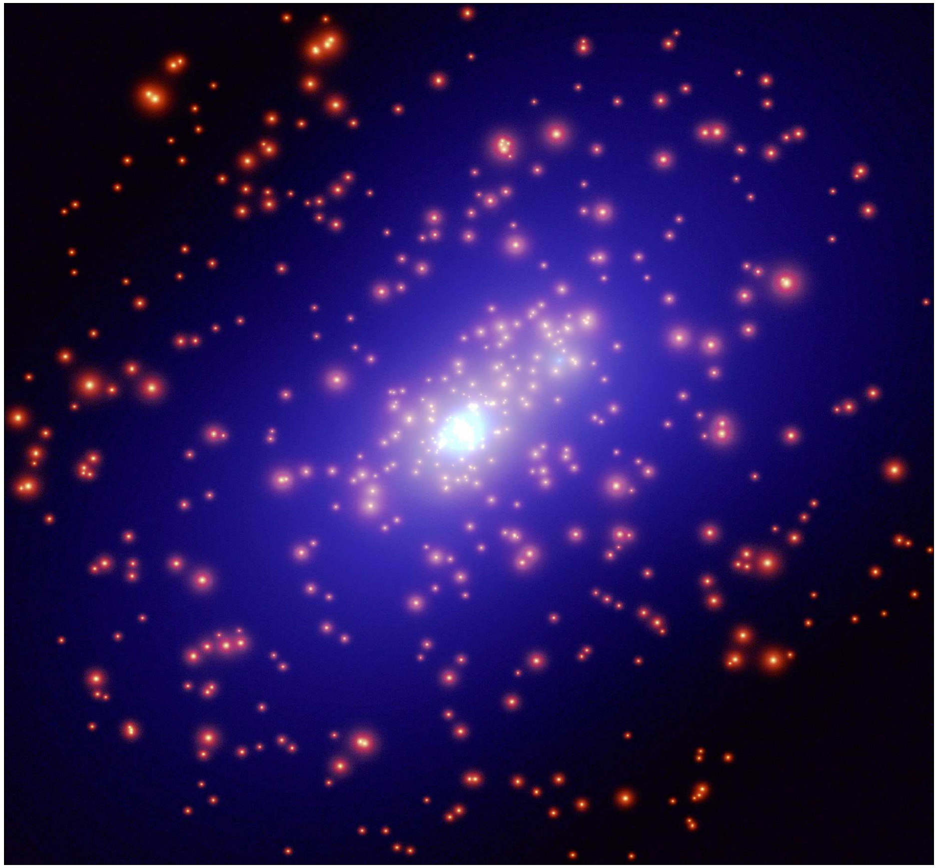
Johannes Kepler 1619

Stars around the galactic centre



Additional dark matter keeps the stars at their orbit, inducing high rotational velocity

Distribution of the dark matter

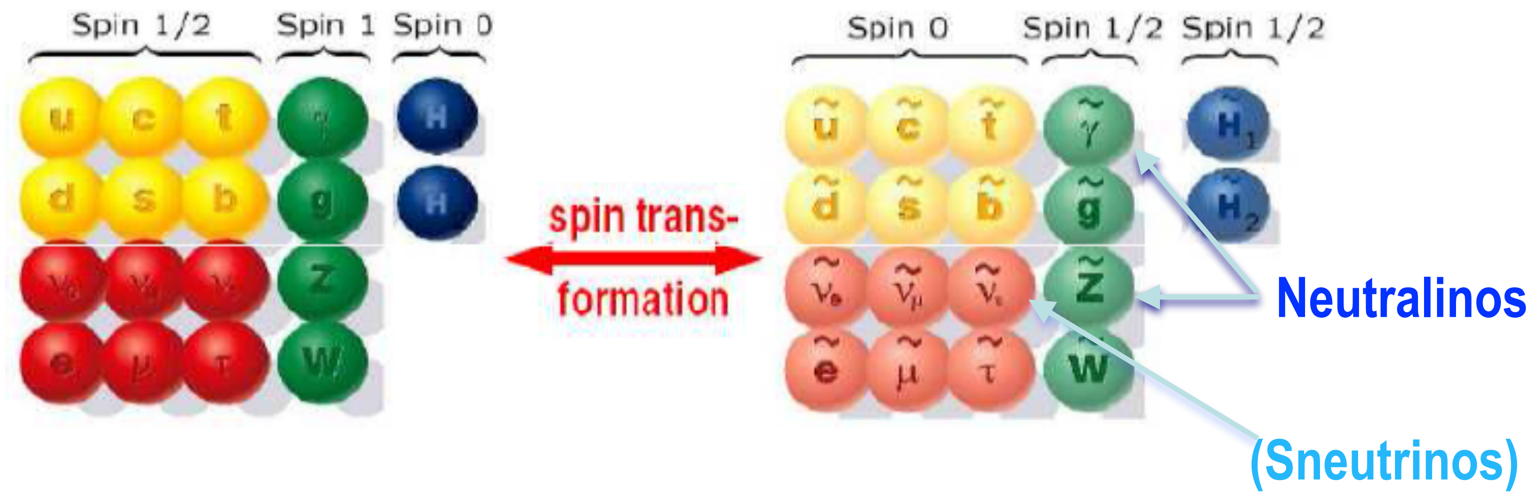


- Galaxy Cluster (Hubble telescope)
- Red: visible matter
- Blue: dark matter via gravitational lensing

➢ **not possible in the Standard Model ….. new physics?**

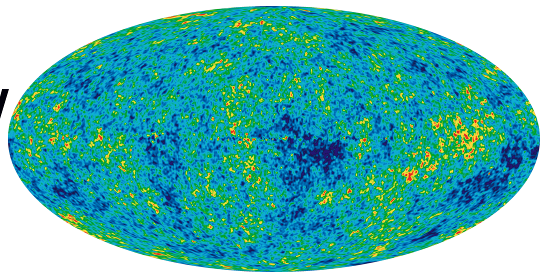
SUSY and dark matter

- **SUSY offers promising candidates:**



- **Conditions?**

  ➢**has to fulfill constraints from energy density of the cosmic *background radiation***

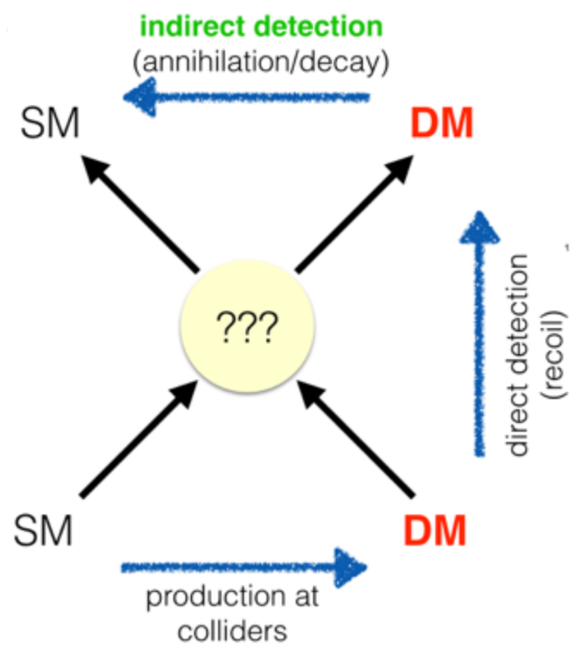


$\Omega h^2 = 0.1196 \pm 0.0031$

Detection of dark matter (DM)

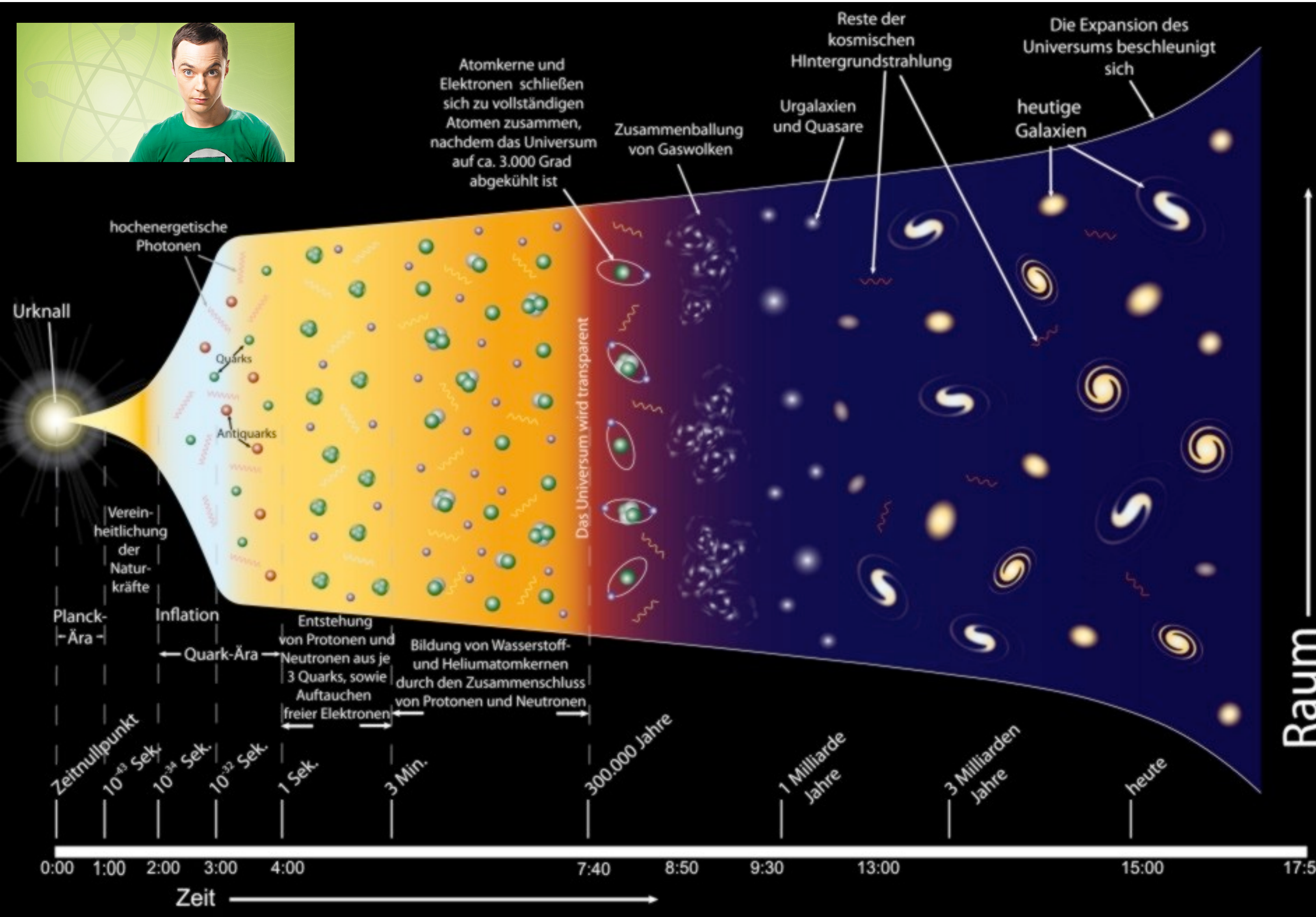
- **Many possibilities in astro- and particle physics experiments:**

  a) direct and b) indirect detection and c) production via colliders



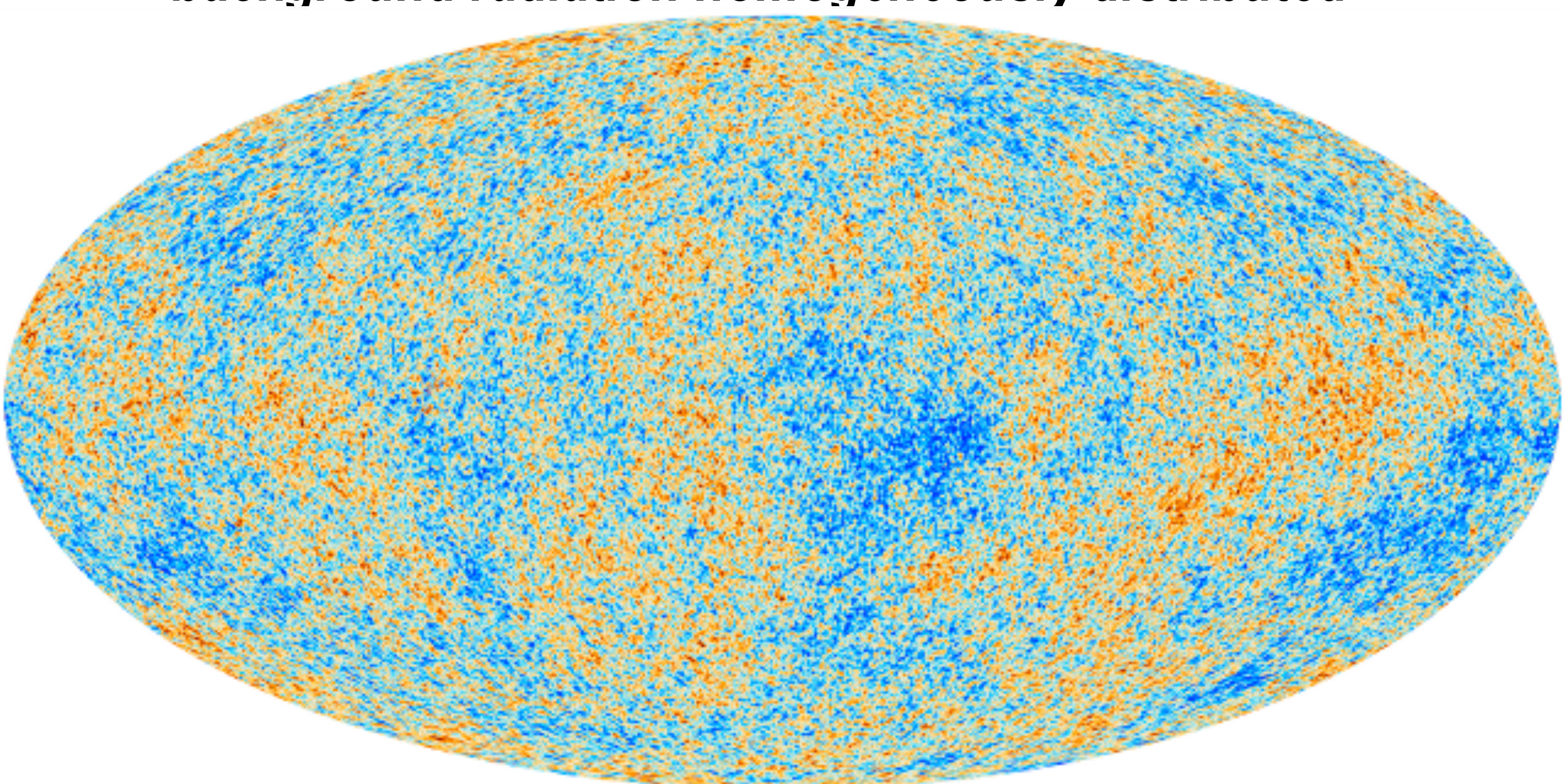
- **At colliders: e.g. $e^+e^- \to$ DM+DM .....Detection of 'nothing'?**

  $\to$ yes, via the process $e^+e^- \to$ DM+DM+γ i.e. photon ist indicator!


Urknall
hochenergetische Photonen
Quarks
Antiquarks
Atomkerne und Elektronen schließen sich zu vollständigen Atomen zusammen, nachdem das Universum auf ca. 3.000 Grad abgekühlt ist
Zusammenballung von Gaswolken
Urgalaxien und Quasare
Reste der kosmischen HIntergrundstrahlung
heutige Galaxien
Die Expansion des Universums beschleunigt sich
Das Universum wird transparent
Verein-heitlichung der Natur-kräfte
Planck-Ära
Inflation
Quark-Ära
Entstehung von Protonen und Neutronen aus je 3 Quarks, sowie Auftauchen freier Elektronen
Bildung von Wasserstoff- und Heliumatomkernen durch den Zusammenschluss von Protonen und Neutronen
Zeitnullpunkt
10^-43 Sek.
10^-34 Sek.
10^-32 Sek.
1 Sek.
3 Min.
300.000 Jahre
1 Milliarde Jahre
3 Milliarden Jahre
heute
0:00
1:00
2:00
3:00
4:00
7:40
8:50
9:30
13:00
15:00
17:50
Zeit
Raum

Why explains cosmic inflation?

- **2 phenomena** can only be explained via inflation
  - **horizon problem:** Universe looks similar everywhere…..
    - *background radiation homogeneously distributed*



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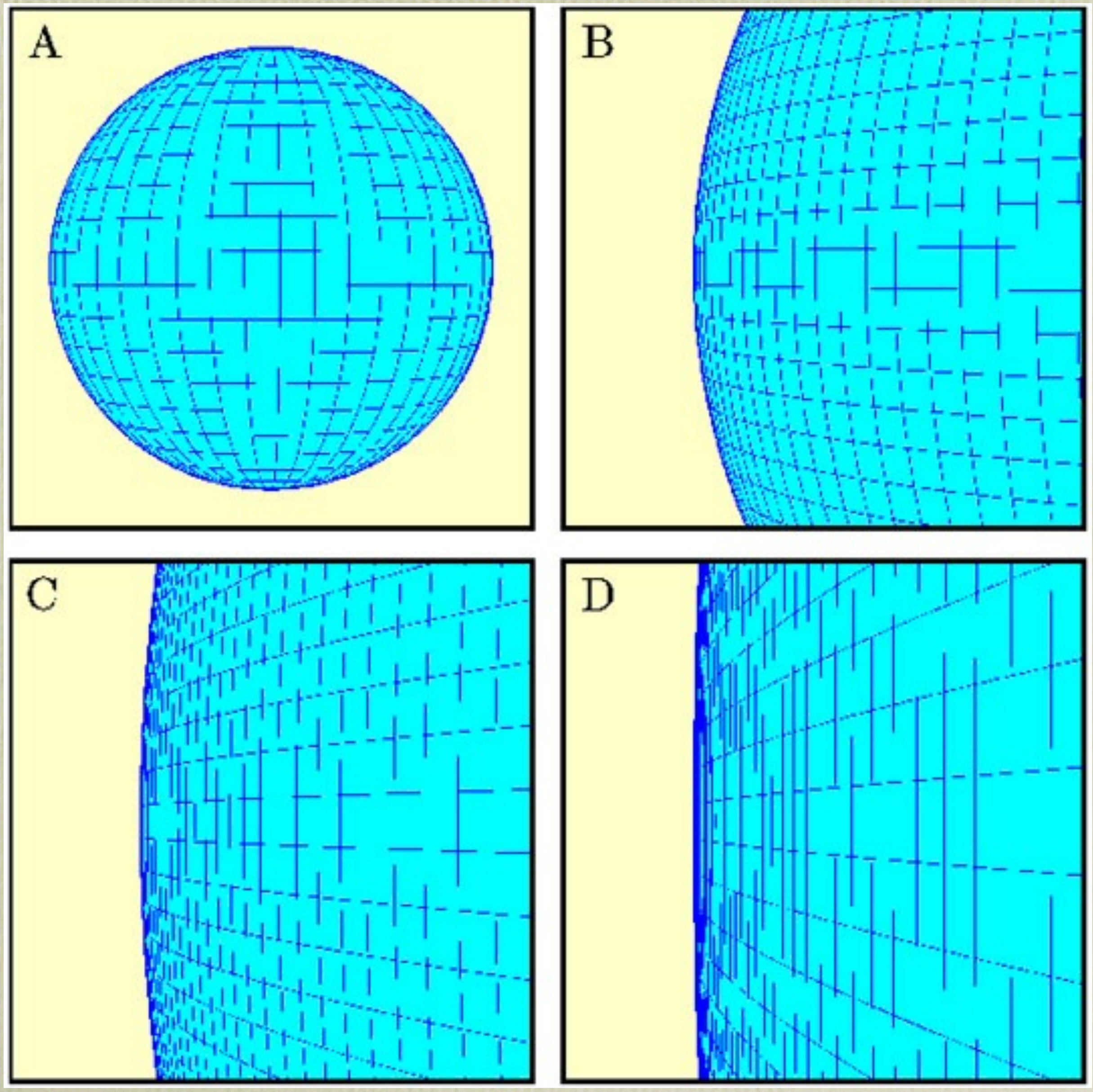
Why explains cosmic inflation?

- **2 phenomena can only be explained via inflation**
  - **horizon problem: Universe looks similar everywhere…..**
    - ***background radiation homogeneously distributed***
    - ***even at opposite sites: inaccessible for light***
    - ***cannot have causal relation***
  - **'Flat' Universe: we are on the path between eternal expansion and collapse**
    - ***in other words: the energy density of the Universe has just the 'critical' value Ω=1***
- **Scalar fields can be trigger of the inflationary phase:**

  from *[10^{-35} -10^{-32}]s after the big bang: the Universe grows by a factor >10^{26}!*

Inflation smothes everything ...

A. Westphal
Ringvorlesung, 11/2016



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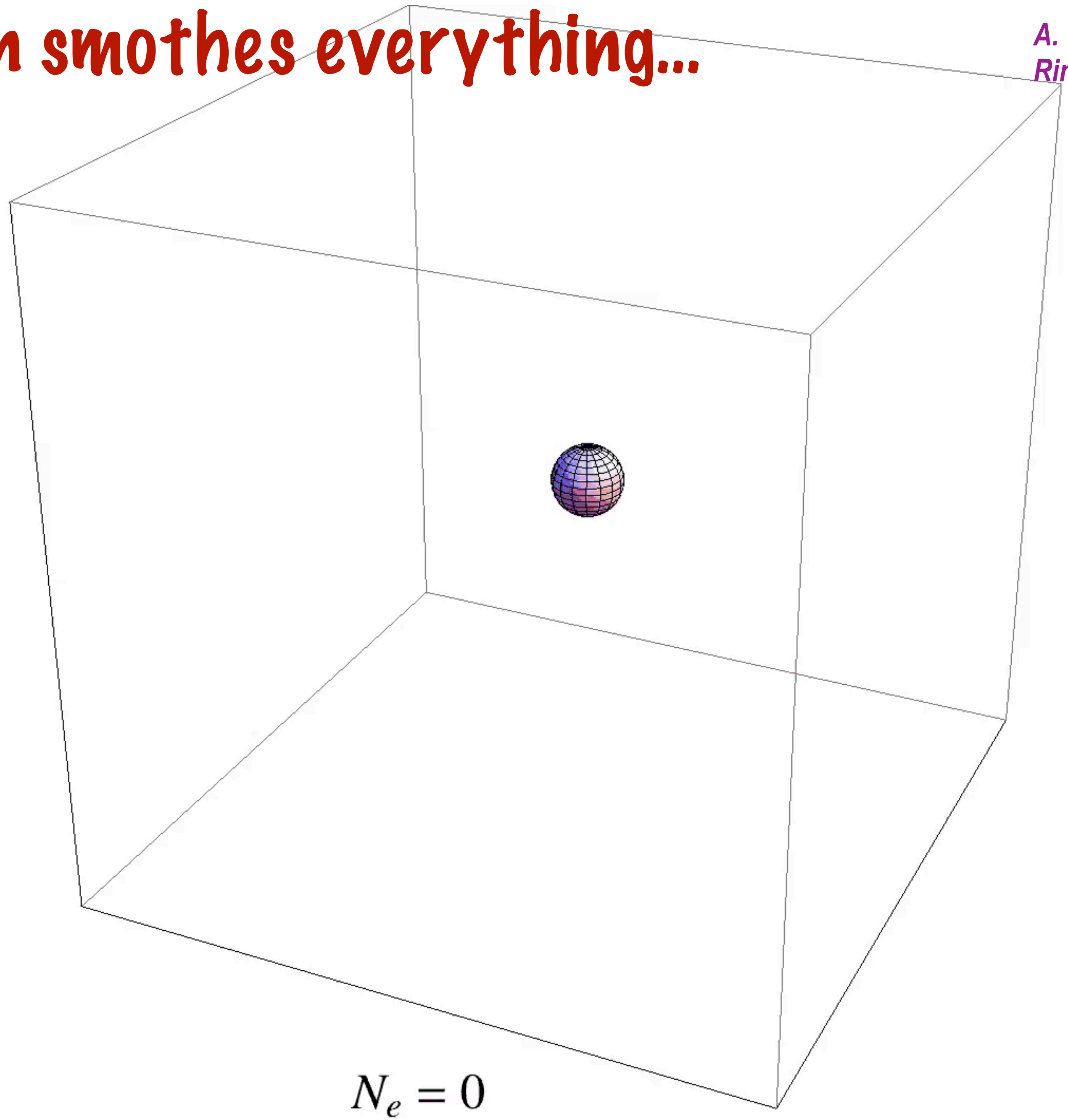

Einstein & Universe

- **Einstein's theories: description of both, gravity and quantum physics**
  - **Curved space time**
  - **Hints for dark matter**
- **Higgs boson**
  - **responsible for the 'mass' of all particles**
  - **measurement of the Higgs potential crucial**
- **'Higgs-like' particle: trigger for inflation**
  - **Inflation explains 'horizon'- and 'flatness'-problems**
  - **Galaxy formation via Quantum fluctuations**
- **SUSY models can embed inflation, dark matter, gauge unification and baryon asymmetry,……..**

➔ ***testable at colliders…..exciting times ahead!***

Conclusions

The Standard Model of particle physics

- **mathematical framework: gauge symmetry**
- **matter and force particle**
- **mass explained via Higgs mechanism**
- **needs spont. symmetry breaking**

SM is not complete, can not embed:

- **dark matter**
- **gauge unification**
- **inflation**

SUSY could embed all these features

- **new symmetry**
- **testable at colliders**
- **either directly or via precision**
- **LHC+LC (tuneable energy, polarized beams)**

➔ ***perfectly well suited to detect BSM…..exciting times ahead!***

Be prepared for the ‘Unexpected’…

- ➢ the LC +LHC are mandatory………!