Experimental Particle Physics in Austria

TWEPP 2011
Vienna, September 26, 2011

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ÖAW und TU Wien

…Major Open Questions in Particle Physics

- **How do leptons and quarks acquire their masses ? -> LHC**
- **A more complex World: are there higher symmetries ? -> LHC; Astroparticle Physics; Precision Experiments**
- **What is the nature of 'Dark Matter' ? -> LHC; Astroparticle Physics; Precision Experiments**
- **What are the properties of the 'Primordial Matter' ? -> LHC; FAIR**
- **Matter-Antimatter Asymmetry-> Belle; LHC; FAIR; Astroparticle Physics; Precision experiments**
- **Are there extra spatial dimensions ? -> LHC; Precision Experiments**
- **Are the Natural Constants constant ? -> Precision experiments**
- **The Unexpected -> Accelerators; Astroparticle Physics; Precision Experiments**

The Experimental Strategy

- This is a vast program for (more than) the next ten years
- This program needs a multi-prong approach because
  - certain questions need to be viewed from different perspectives
  - certain questions need to be addressed in different energy regions
  - no single approach is adequate to answer all these questions
- Plan to show examples of the synergy and complementarity which can be achieved with these diverse approaches
  - Will emphasize Austrian programmes and the role of electronics

The Fourfold Way of Experimental Particle Physics

New physics signals from Cosmic Accelerators: Astro-particle physics
Land- and satellite-based observation

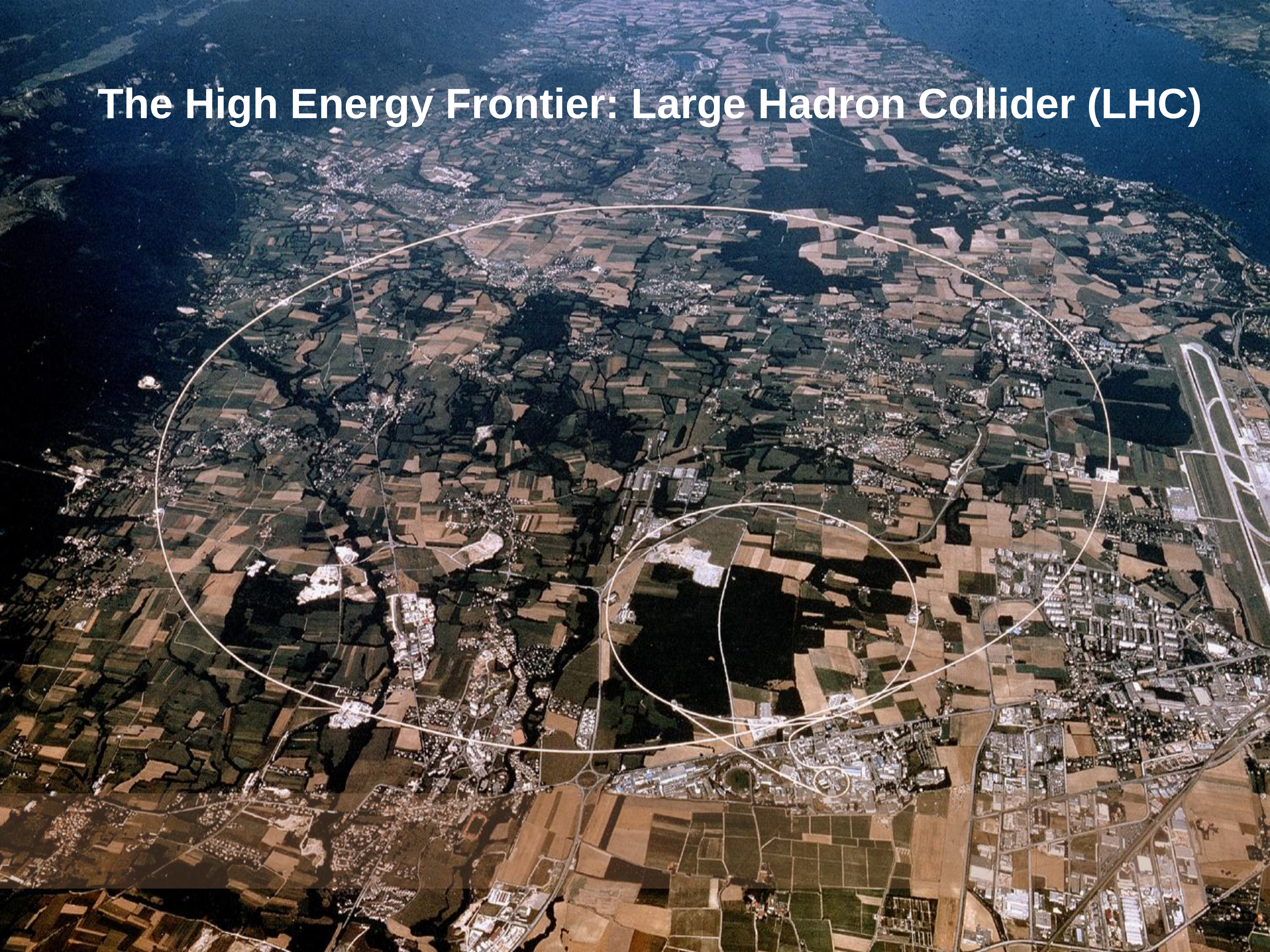
Ultra-precision experiments in ‘laboratory’
Direct and indirect observations

Fundamental topics in Particle physics

Experimentation at High Energy Colliders (LHC, BELLE, FAIR)
New physics in energy range of accelerators

Precision tests at ‘Low Energy’ Accelerators (AD, JPARC, FAIR)
New physics through virtual phenomena

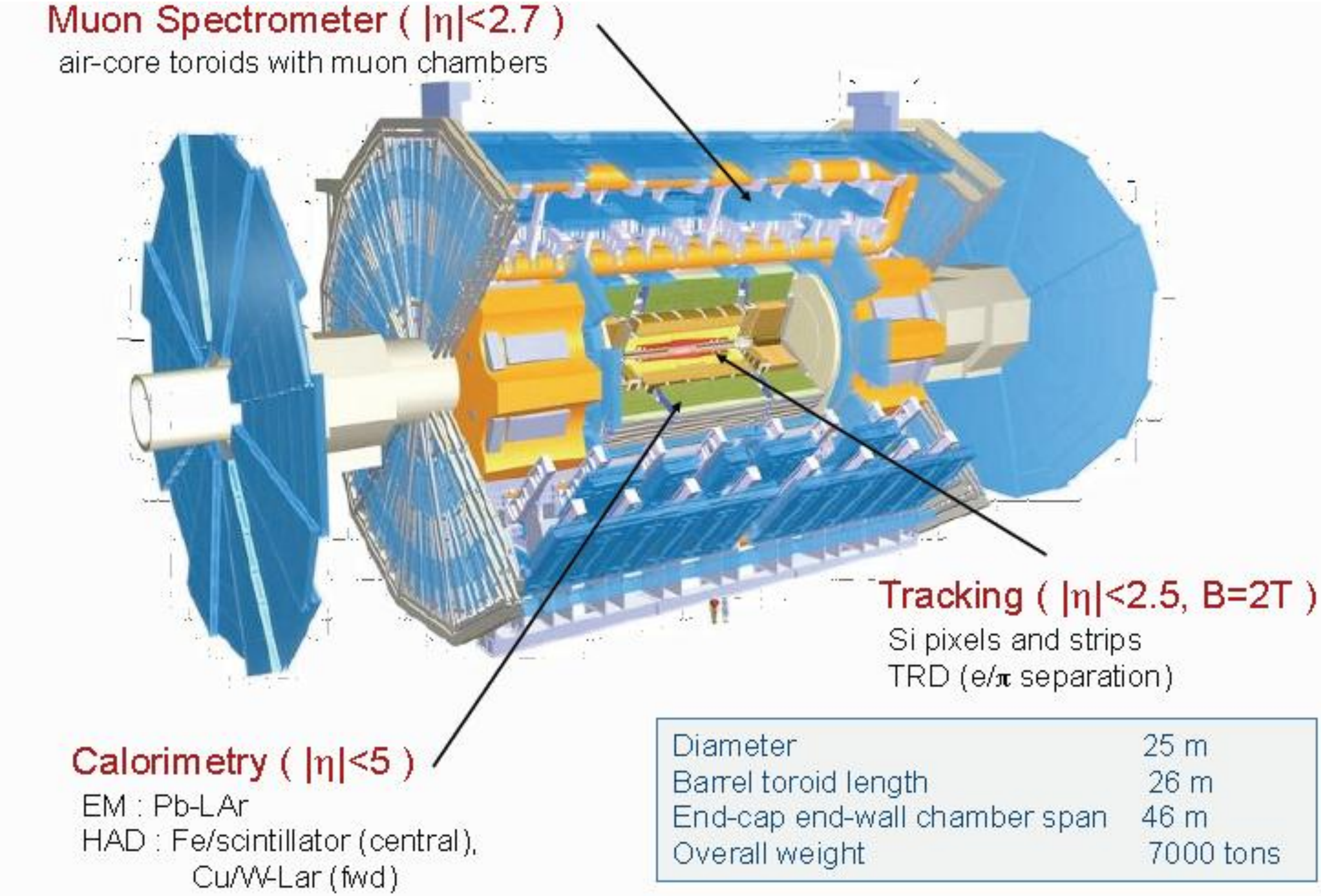
The High Energy Frontier: Large Hadron Collider (LHC)



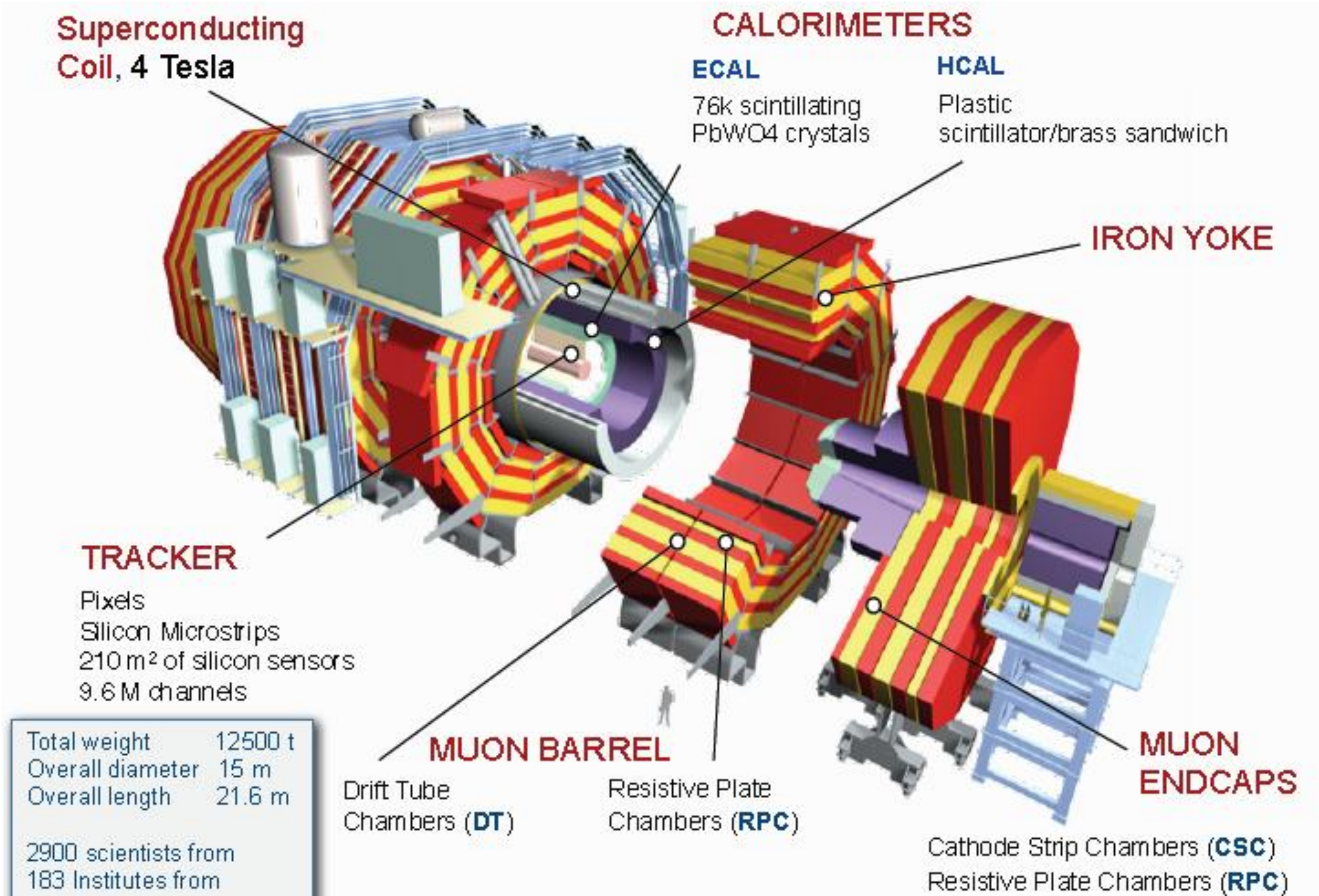
The new High Energy Frontier: Large Hadron Collider (LHC)

- LHC has started $\sqrt{s}$ = 7 TeV operation in March 2010
- Remarkable performance of experiments with first physics publications within days
- Spectacular increase in collision rate (luminosity) of LHC
- Peak luminosity is now exceeding $3 * 10^{33}$ cm^{-2} sec^{-1} (three times design luminosity for 7 TeV operation), corresponding to ca. $2 * 10^{8}$ collisions per sec
- A great tribute to the machine, the experiments and the whole engineering community
- Biggest experimental challenge: **electronics**; mastered exceedingly well (with a bit of luck)

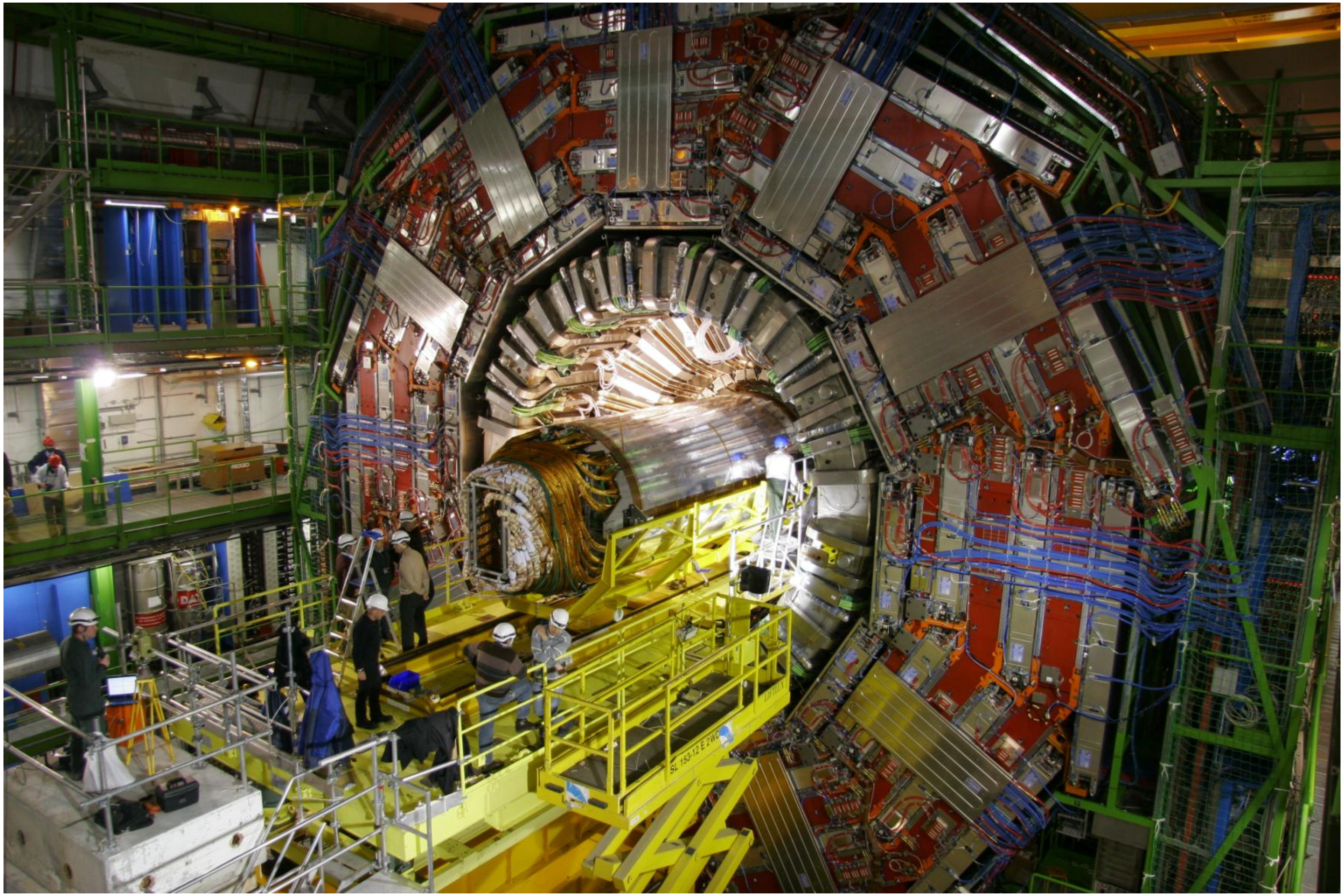
ATLAS: with Innsbruck participation in QCD and Beauty physics studies



CMS: major Austrian participation (HEPHY)
~20 % of world's largest Silicon Tracker
Responsibility for Event Selection ('Trigger')



The world's largest Si-Tracker during installation in CMS: big, beautiful, complex with 80 000 000 detection channels: made possible through new approaches in electronics



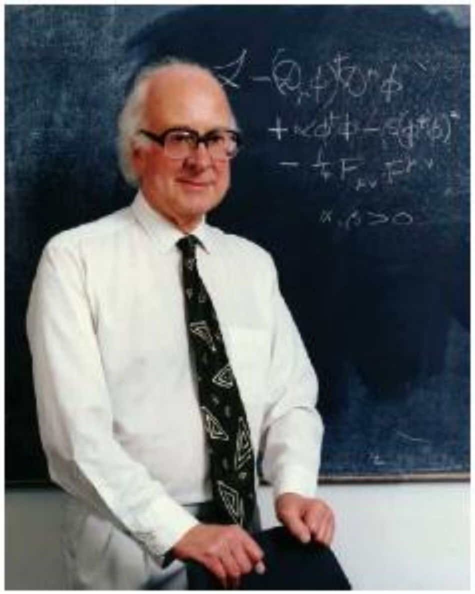
HEPHY Activities

- Research with CMS
  - SM Physics (Quarkonia): precision tests of QCD; benchmarks for Quark-Gluon Plasma studies
  - Central Topic: SUSY Physics; in collaboration with HEPHY SUSY Phenomenologists
- Research with BELLE and BELLE II
  - Precision measurements of CKM Matrix Elements
  - Leadership of Belle CKM Analysis group
  - Global responsibility for Si-Tracker for BelleII
  - Participation in Detector Group for International Linear Collider
- Algorithm Group: development of new analysis algorithms
  - Responsible for Vertex, Tracking, Alignment algorithms in CMS
  - Development of new vertexing and tracking algorithm for Belle2

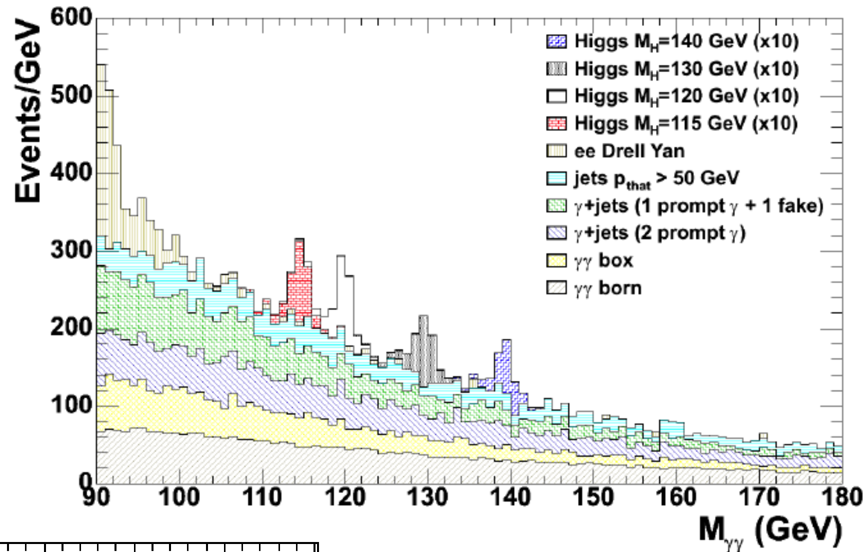
HEPHY Activities

- Semiconductor Detector and Electronics
  - Majot contributions (~ 20%) to CMS Tracker
  - Global responsibility for CMS Trigger (development, construction, operation)
  - Global respobsibility for Belle2 Tracker and readout electronics
- SUSY and QCD Phenomenology
- GRID-Rechenzentrum ‘Tier 2’:
  - Developed together with Uni Innsbruck
  - Responsibility of operation; contractual obligation to CMS collaboration
  - Contribution to Organisation and Implementation of Austrian National GRID Organisation
  - Collaboration with other research units
    - Medizin-Universität (Optimisation of cancer therapy radiation protocols using simulations programs developed for particle physics

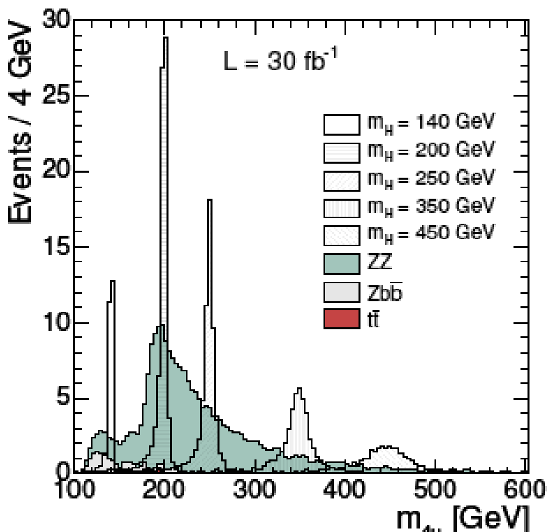
Priority 1A:find the Higgs



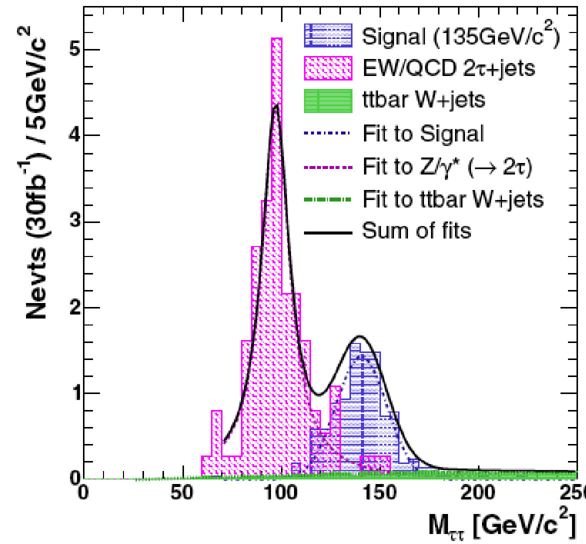
γγ



Higgs -> ZZ*
-> 4 leptons

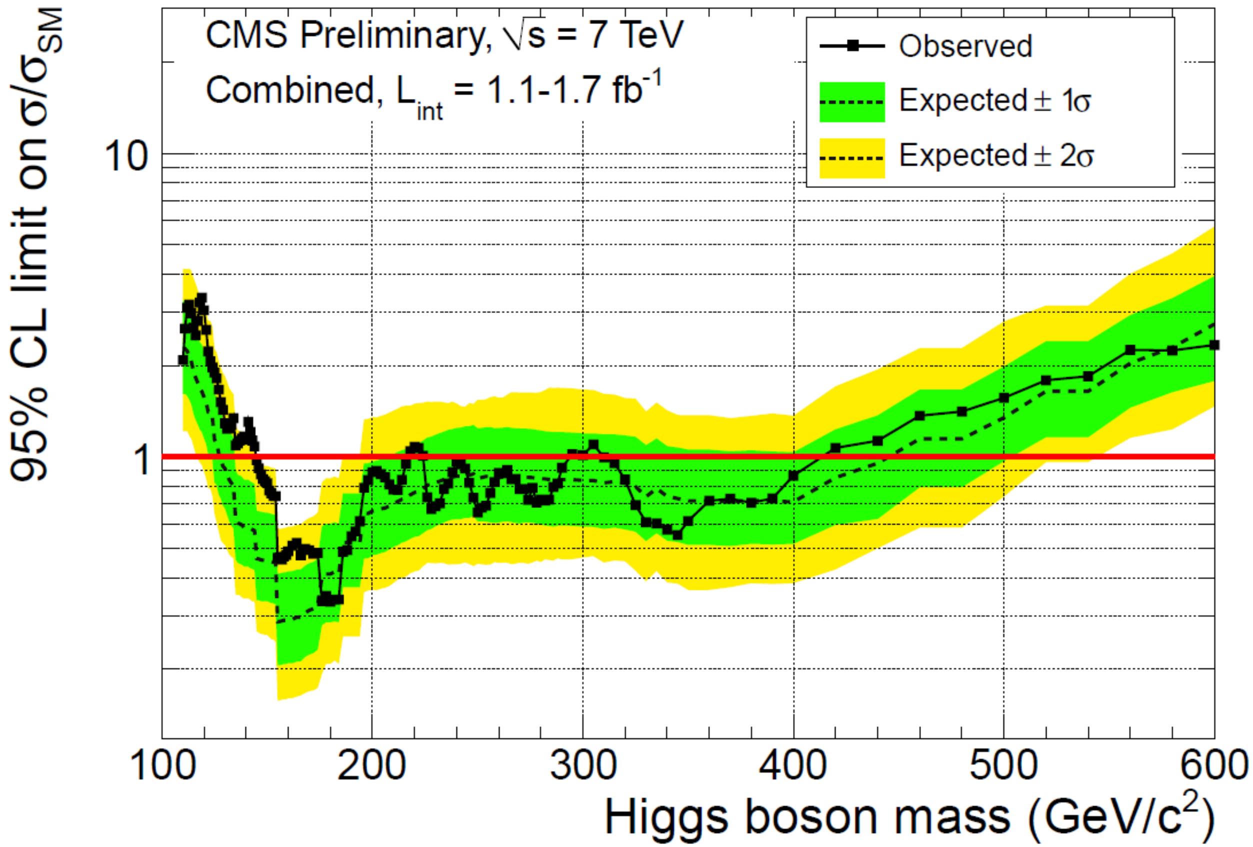


ττ



one Higgs in 10^{14} to 10^{15} collisions…

LHC Priority 1A: find the Higgs Particle present status: closing in



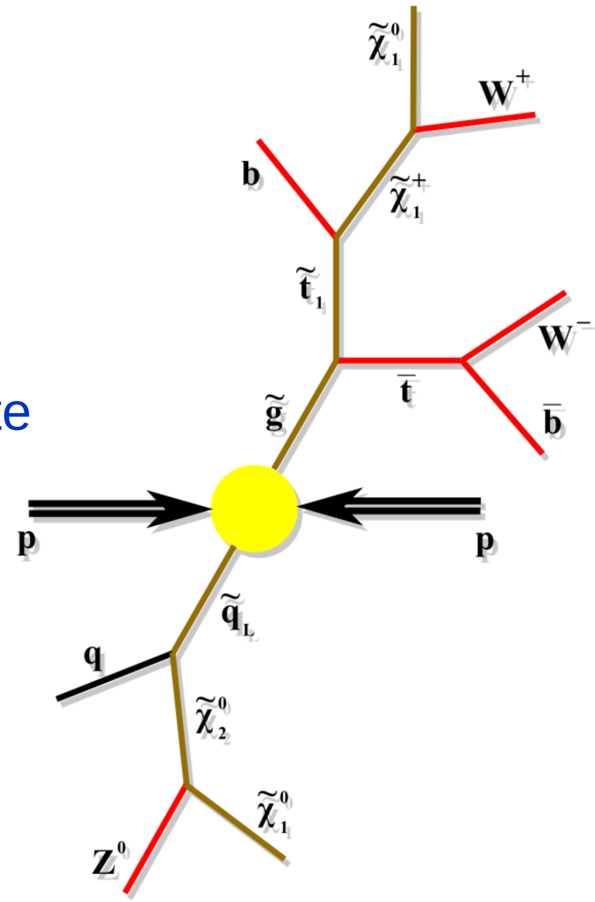
- Note: at present not enough sensitivity for favored mass region 110 to 140 GeV: will be settled in approximately one year

Priority 1B: look for new Symmetries: Is our world more complex, ‘supersymmetric’?

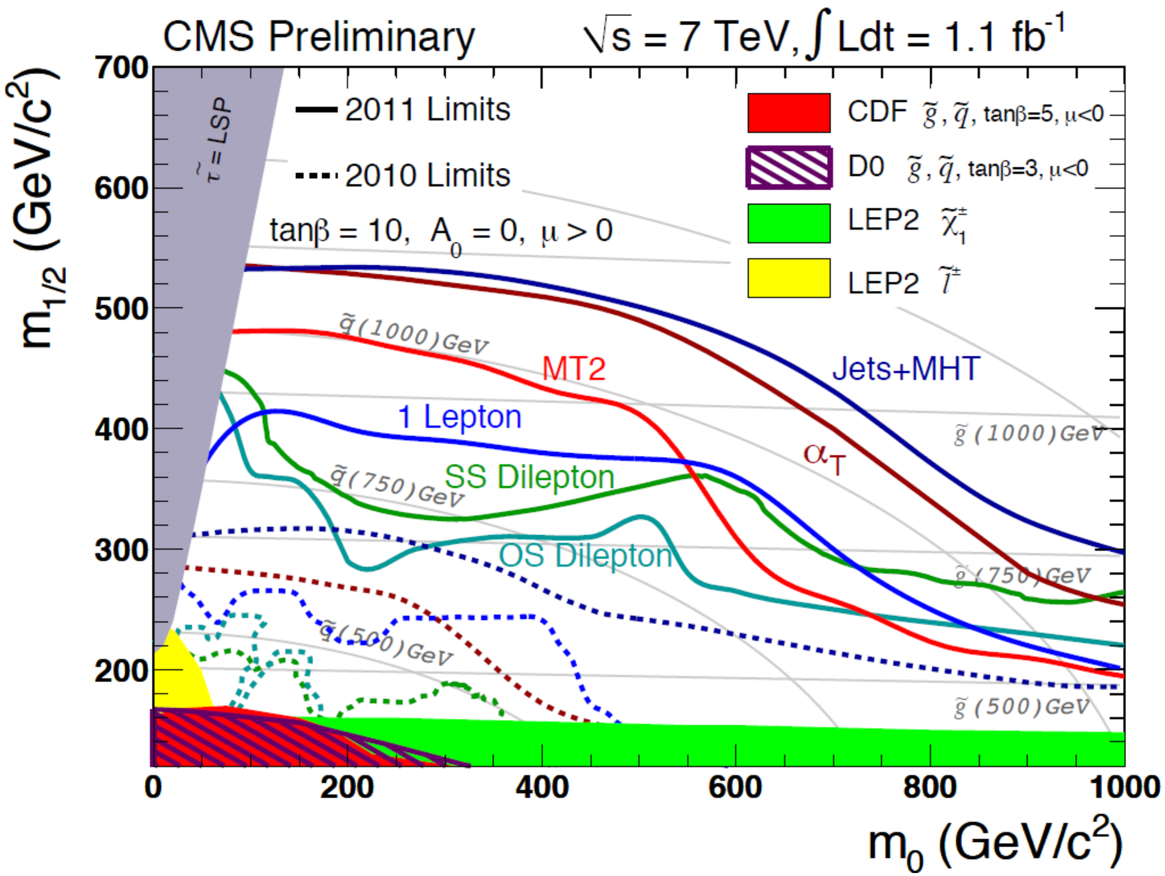
- Such a world would solve several problems...
- New world is related to the rotation properties (‘spin’) of the known particles
  - 0 ½ ½ 1 1
  - Higgs Lepton Quark Gluon Gauge Bosons
  - plus supersymmetric partners
  - ½ 0 0 ½ ½
  - Chargino Slepton Squark Gluino Neutralinos
- Why all this trouble ? Many good reasons…three of them
  - Would solve the of fine-tuning of higher order contributions to Higgs mass
  - Would possibly provide unification of the fundamental forces
  - Would possibly solve a ‚massive‘ problem: the lightest supersymmetric particle would be a good candidate for dark matter
- Austrian physicist Julius Wess was one of the fathers of SUSY

Looking for Supersymmetry (SUSY): the Vienna/ HEPHY approach

- Problem: an unknown parameter space to be explored -> HEPHY is developing model-independent analysis strategy
- Ultimate aim is to reconstruct these complex decay chains
- Lightest SUSY particle: dark matter candidate but would need independent confirmation from direct and indirect observation
- If SUSY exists, it will show up in many different ways: decay of particles, e.g. neutron, B- mesons -> need to look in many different systems



Present limits on Supersymmetry



- Note: Exclusion limits with HEPHY participation; refer to simplest manifestations of Supersymmetry; Nature may be more inventive: need to work harder

Snapshot status of LHC frontier

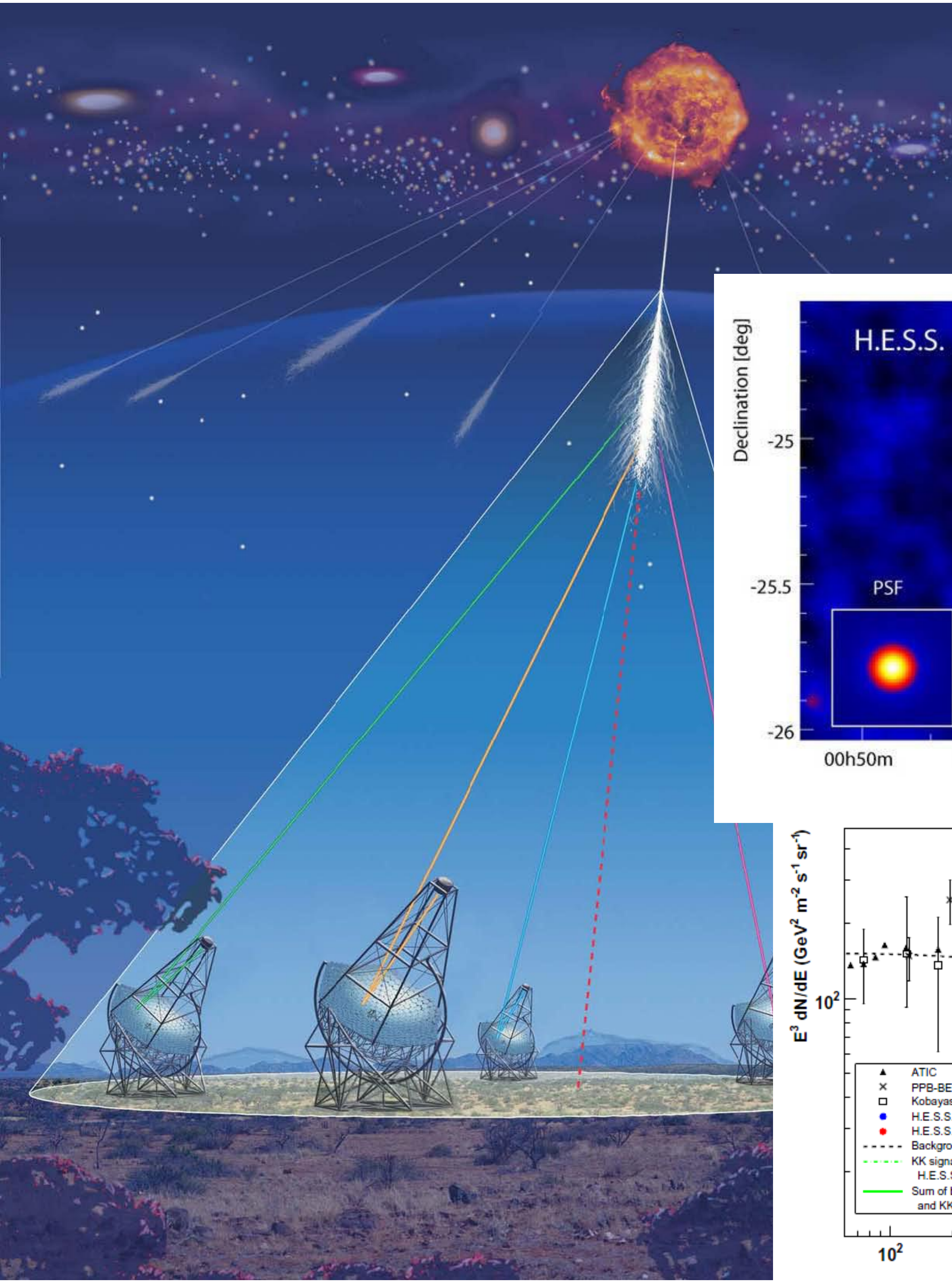
- Impressive list of publications (close to 200) confirming with new precision the validity of the Standard Model of Particle Physics: this gives a solid base for searching for deviations from SM
- Status of Higgs search: mass regions, which are disfavored for the Higgs have been excluded at the 95% probability…not enough: need to go for a minimum of 5 σ exclusion

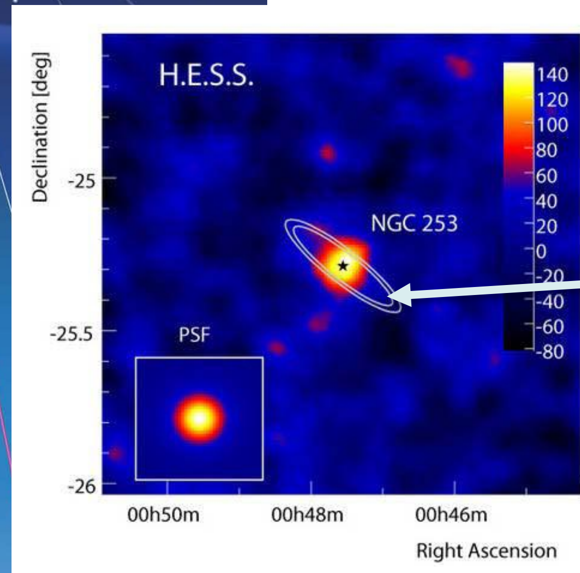
  Mass region favored for Higgs (110 to 150 GeV): sensitivity as of yet insufficient : significant statement will require 3 to 4 times present data sample. Question should be settled before the end of 2012 (two years ahead of schedule compared to expectations by LHC start)
- Status of Supersymmetry: minimal scenarios are starting to be ruled out. But: we know that Nature is inventive and there is still an enormous parameter space to be explored within the 'Concept of SUSY'.
- Needed: Lots more of LHC collisions and patience! →TWEPP2012

The Cosmic Ray Frontier

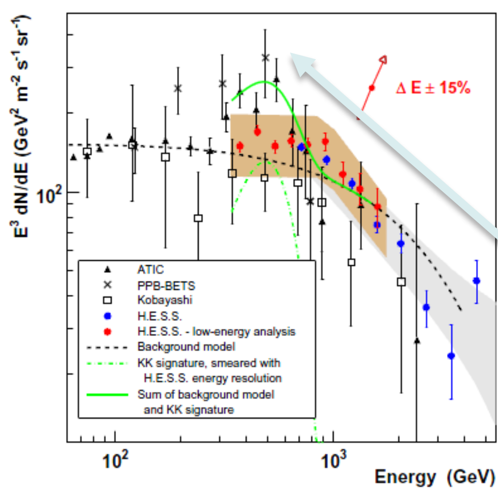
- Astroparticle Physics: domain of the Univ. of Innsbruck, where a dedicated chair was established in 2008.
- Innsbruck particpates in frontier programmes
  - HESS: ground-based observation of cosmic phenomena
  - FERMI: Satellite-based obeservation of a range of signatures with vast potential for ‚New Physics'
  - Participaion in the next round of ground-based observatories:
    - CTA (Cherenkov Telescope Array)
- Instrumentation for these Experiments (particularly for satellite based experiments) is a very active, innovative area of R&D; electronics is a major factor in performance

HESS: High Energy Spectroscopic System with Innsbruck participation





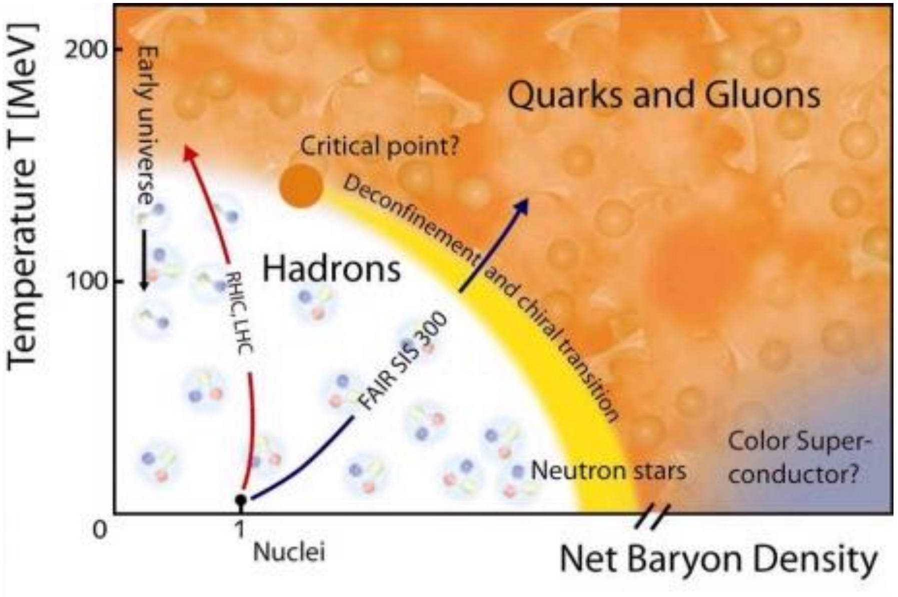
1st observation of CR interactions due to high matter density from a supoernova outside our Galaxy



Novel analysis technique Allows improved e/γ Separation -> severe constraints on intensely discussed excess of electrons, reported by ATIC collaboration and interpreted as Dark Matter annihilation

New forms of Matter; virtual effects

- In the 1st microsecond after Big Bang
  - All matter as fre quarks and gluons
  - ‘Quark Gluon Plasma (QGP)
- Will be studied at LHC with lead-lead collisions
- Will be studied at new facility GSI-FAIR with participation of Stefan-Meyer-Institute Vienna (SMI)
- Exotic forms of atoms and matter with the aim to study fundamental interactions under special conditions is also pursued by SMI at Frascati, JPARC (Japan)



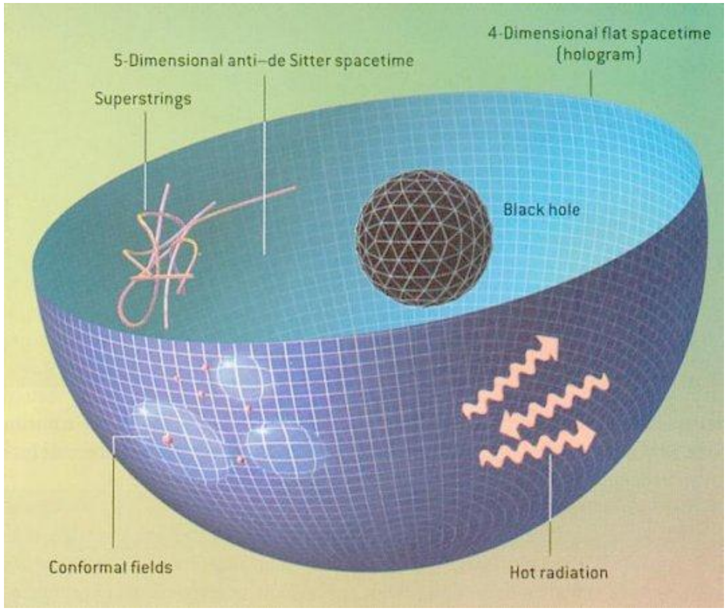
Gravity: a fundamental correspondence

- Most-cited theoretical development of last decade

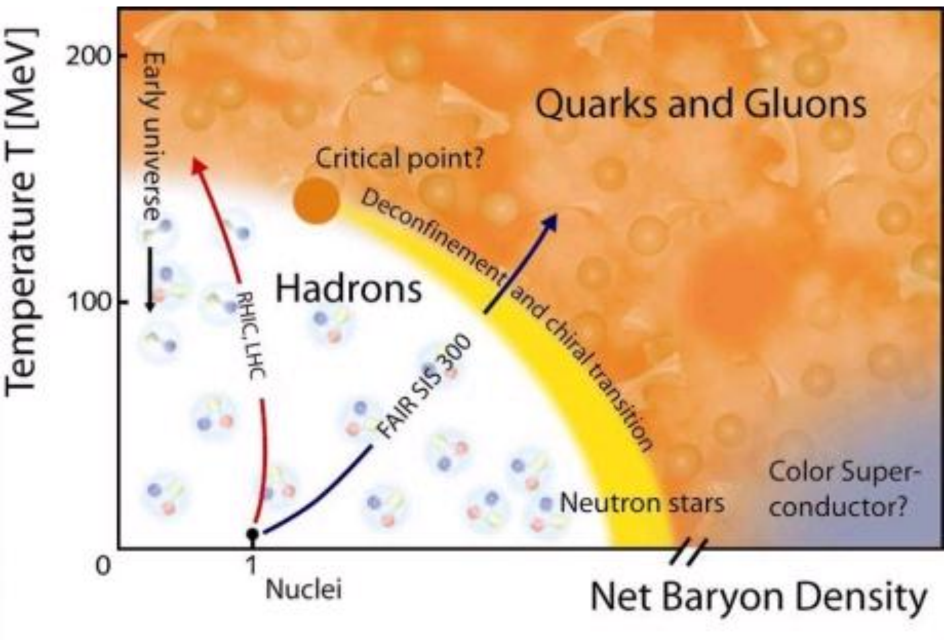
  Correspondence between anti-deSitter Gravity and conformal Quantum Field-Theories: AdS/CFT

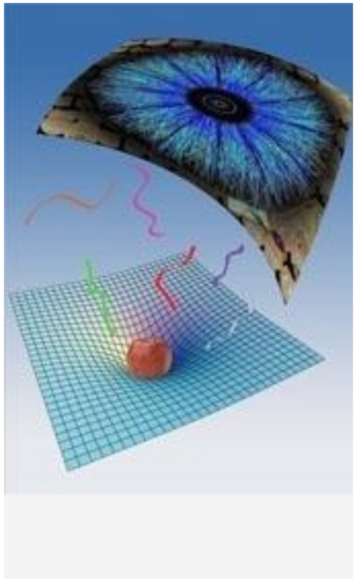
  - Discovery within frame of Superstring-Theory
  - Strongly interacting Quantum Fieldtheorie (z.B. QCD) in 3 space and 1 time dimension →

    equivalently described with 5-dimensional Gravity theory



Applying the AdS/CFT correspondence: Black Holes <-> Quark-Gluon Plasma





- Spectacular application: strongly coupled Quark-Gluon Plasma is described with the physics of black holes in 5 dimensionen (and vice-versa)
- Successful prediction: viscosity of Quark-Gluon Plasma
- Quark-Gluon Plasma is being studied at LHC

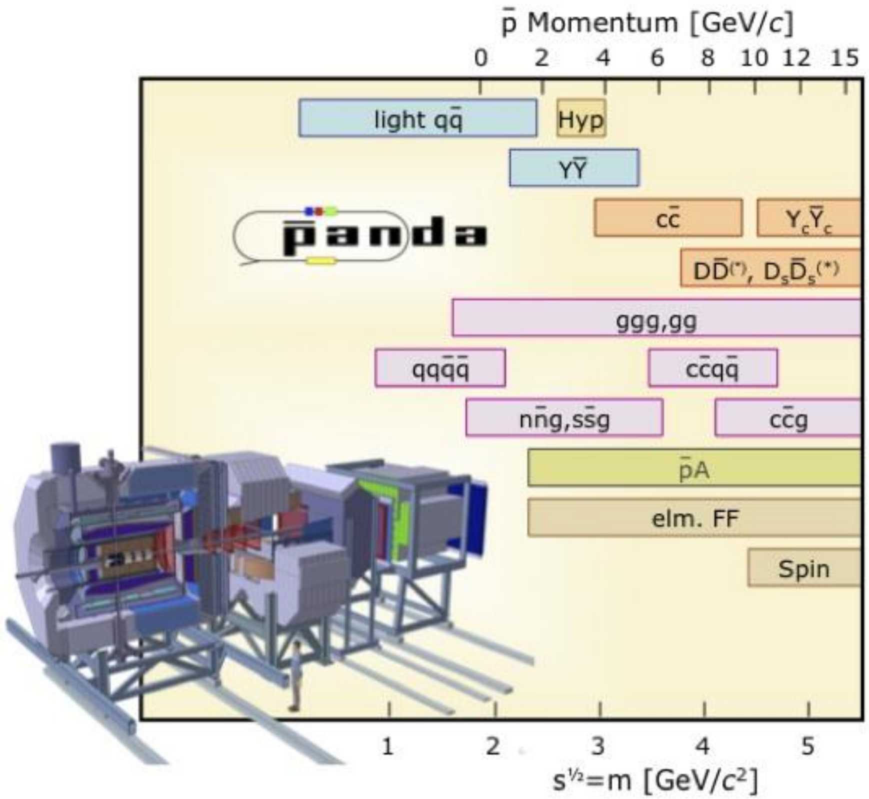
International Laboratory: under construction at GSI, Darmstadt during coming decade

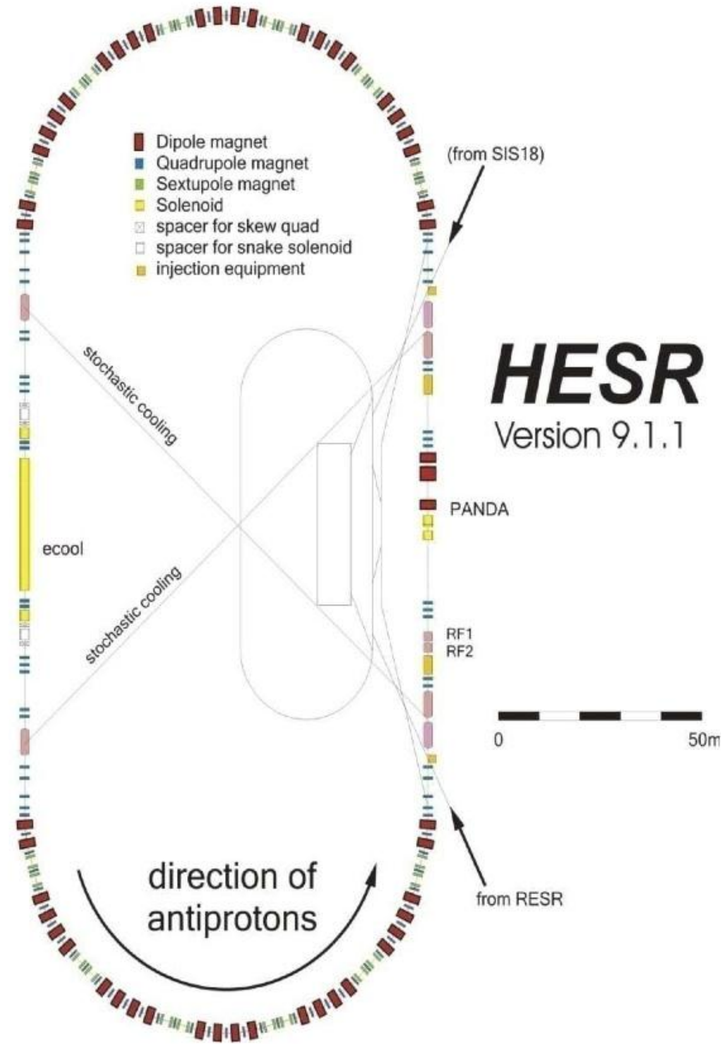
Complex of several accelerators and storage rings

Panda @ FAIR

PANDA physics program with SMI Participation:

- **Charmonium Spectroscopy**
- **QCD Exotics**
- **Hypernuclear physics**
- **Charm in nuclear matter**

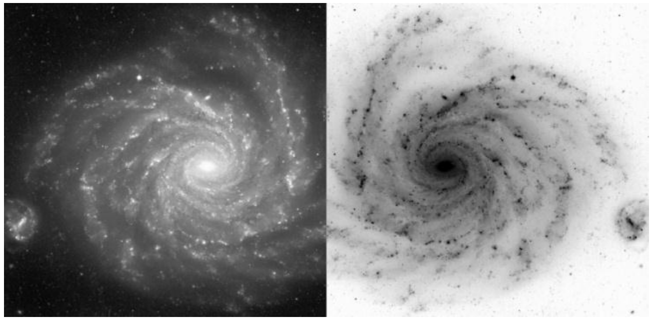




The Precision Frontier

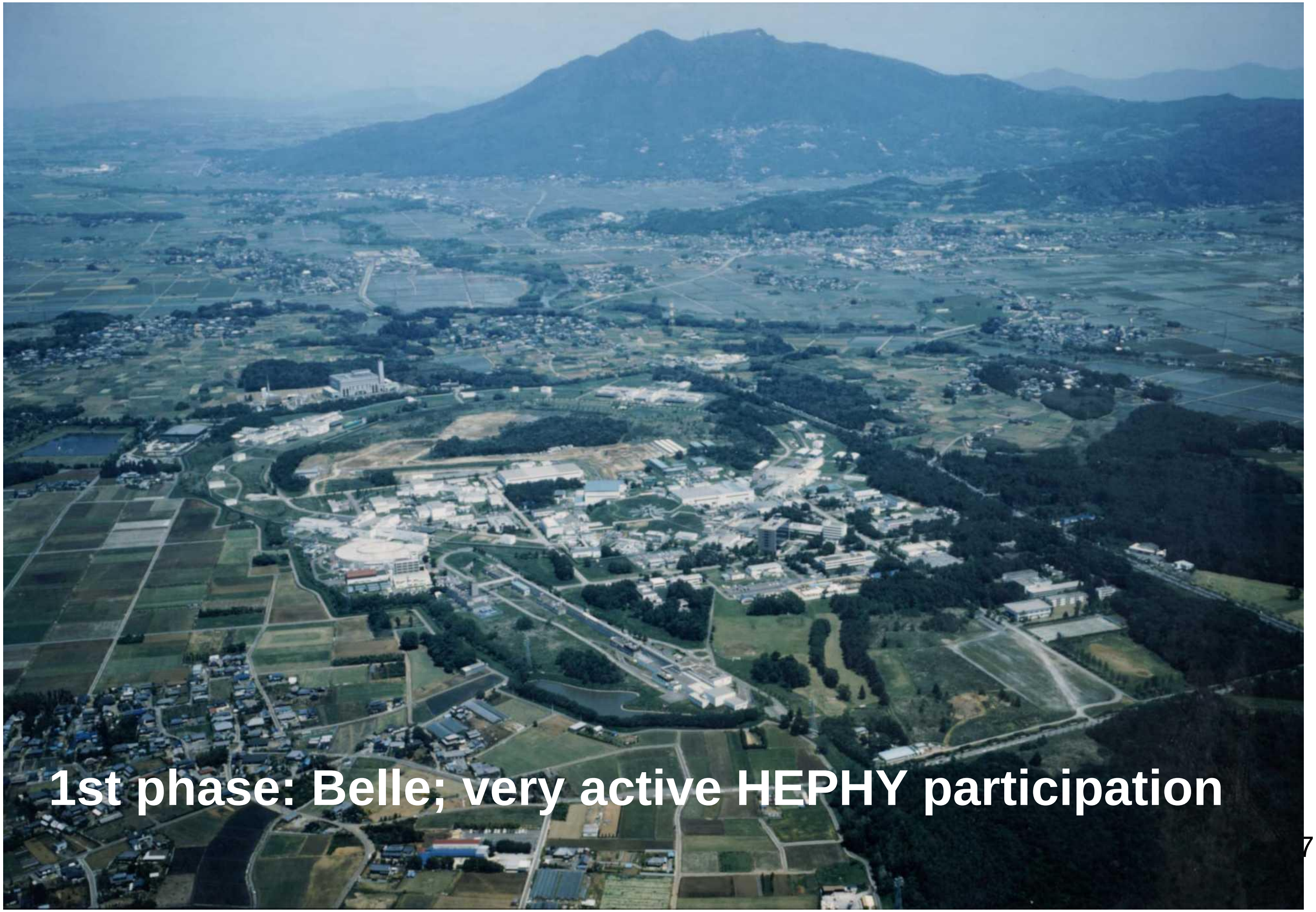
- Measurements with very hgh precision may reveal deviations from known (Standar Model) physics
- Attractive, because with this approach one may probe energy regimes not attainable with earth-based accelerators
- Two avenues are being pursued
  - Precision measurements at accelerators ; will be pursued at LHC and at KEK Beauty factory with BelleII
    - Strategy pursued by HEPHY
  - Precision measurements at very low energy
    - Strategy pursued by SMI and Groups at Institute of Atomc and Suibatomic Physics of the University of Technology, Vienna

Mystery of Matter-Antimatter Asymmetry

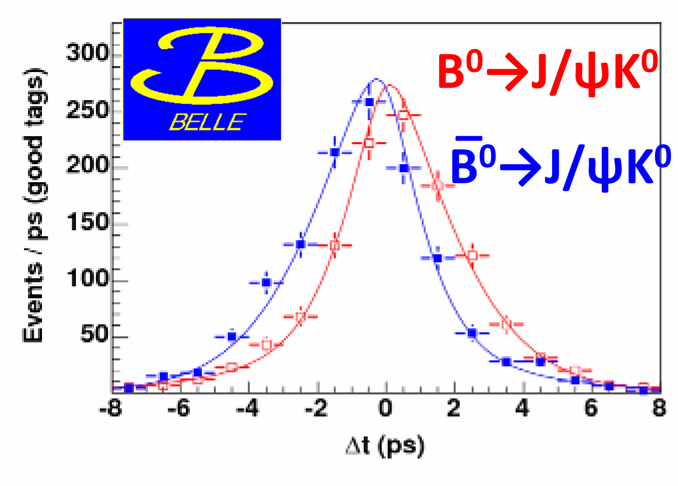


- As far as we know, there was Matter and Antimatter in symmetric amounts in the very early Universe
- This symmetry was broken: fortunately!
- Most matter annihilated with antimatter, BUT
  - Approximately one matter particle out of 10^9 survived
  - All other matter and antimatter particles annihilated into photons
- All visible matter of our Universe is made from these remnants
- The study of this symmetry breaking between matter and antimatter (CP-violation) is a very active area of research
- At present: we have only a very incomplete understanding of this live-saving symmetry breaking mechanism

The dedicated Matter-Antimatter 'Factory' (B- and Anti- B mesons) at KEK, Japan



CP – Violation in the B- antiB- system



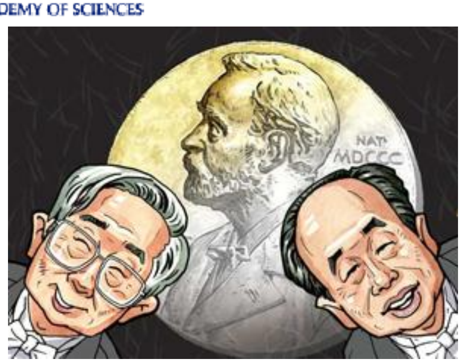
One example: B^0 and to $\bar{B}^0$ have slightly different masses and lifetimes

Very successful program to test our present theory of CP Violation;
Theory developed in the early 70's
by Cabbibo, Kobayashi, Maskawa

The Nobel Prize in Physics 2008

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

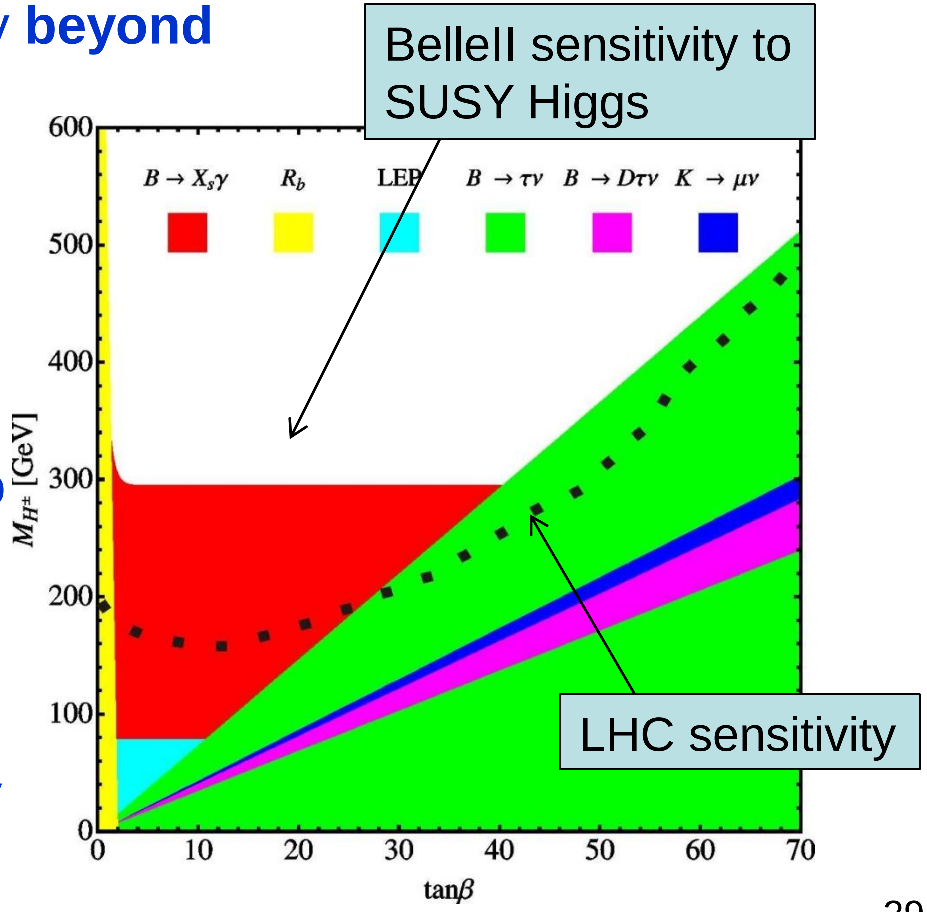
Press Release
7 October 2008



"... As late as 2001, the two particle detectors
BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier."

Success breeds success: BelleII in construction stage

- BelleII with 10 times higher collision rate
- Precision tests with sensitivity **beyond** Standard Model
- Alternative way to access TeV scale
- Example: SUSY Higgs: may exceed LHC sensitivity!
- In Europe: LN Frascati is also planning a similar project
- Key to high rate: novel electronics with fast shaping and intrinsic timing capability



Extra Spatial Dimensions Revealed at Ultra-Low Energies ?

- String Theories: explored with the motivation to provide a unified description of the four forces

- In many versions of these String Theories: additional (‘extra’) spatial dimensions (e.g. 3+1 dimensions ⇒ 11 D), which are not (yet) observed, because extra dimensions extend only over very small distance (d << 1 mm) -> possibility of mini-black holes at the LHC
- Extra dimensions ⇒ modify gravitational potentials

$$\phi_{\text{gravity}} \sim \frac{G_n}{r^{n-2}}$$ n …. total number of dimension

or

$$\phi(r) = -G_4 \frac{m}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

α … measures strength; λ … characteristic range

- Experiments have checked and are checking for such modifications

Probing with ultra-cold (< 300 neV) neutrons in the earth's gravitational field (International 'Forschungsschwerpunkt' under Atominstitut co-leadership)

Schrödinger equation:

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}+mgz\right)\varphi_n(z)=E_n\varphi_n(z)$$

	E_n	E_n
1st state	1.41peV	1.41peV
2nd state	2.46peV	2.56peV
3rd state	3.32peV	3.97peV

boundary conditions:

$\varphi_n(0)=0$

with 2nd mirror at height l

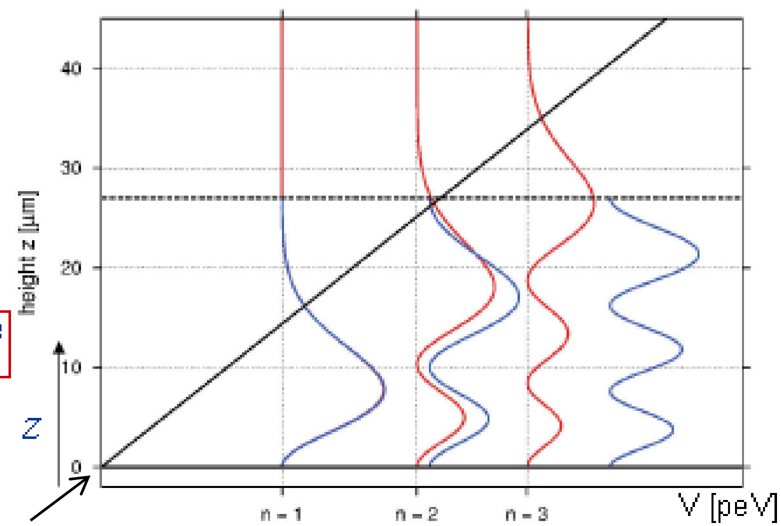
$\varphi_n(l)=0$

solutions: Airy-functions

scales: energies: peV

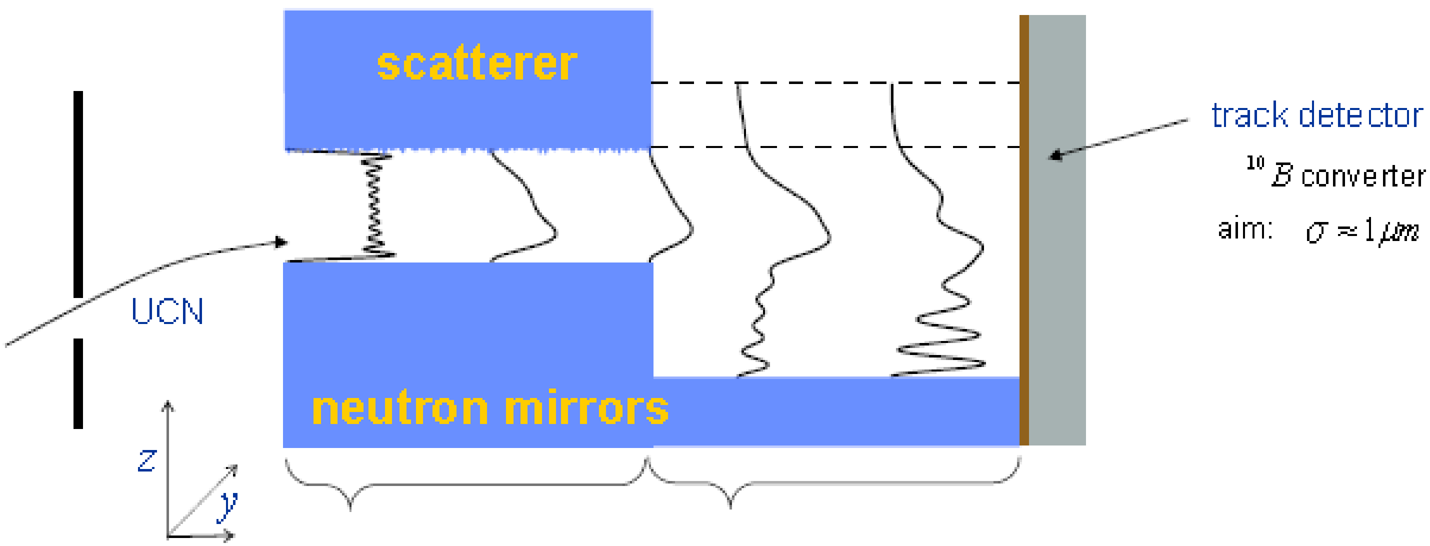
$$1peV=0.000000\,000\,000\,000\,002\,m_{electron}c^2$$

length: μm



neutron mirror

Quantum Bouncing Ball: study time evolution of quantum mechanical neutron position



Preparation:

$$\sum_n \left| c_n \varphi_n e^{-iE_n t/\hbar} \right|^2$$

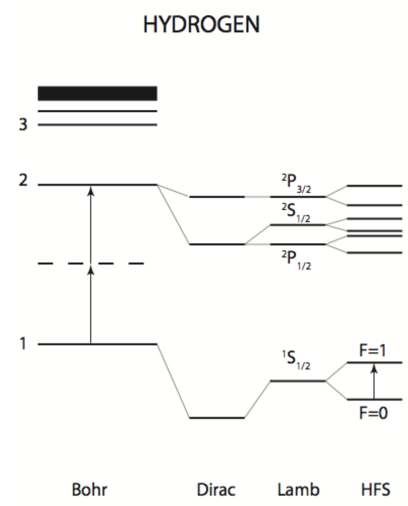
Time evolution:

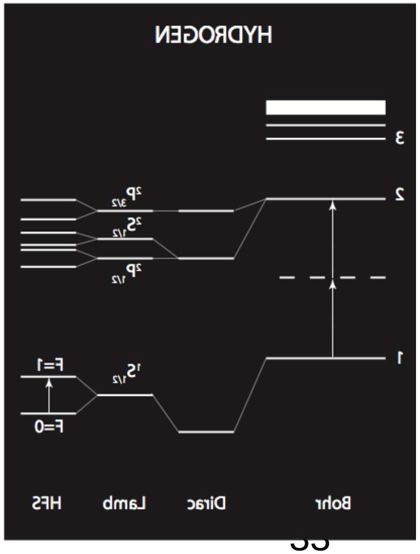
$$\left| \sum_m d_m \phi_m e^{-iE_m (t-t_0)/\hbar} \right|^2$$

This quantum behaviour has been observed!
Next step: increase sensitivity to probe deviations from Newton’s law of gravity

Testing Gravity and CTP with Antihydrogen

- AEgIS: Antimatter Experiment, Gravity, Interferometry, Spectroscopy
  - Main goal: measurement of earth gravitational accleration on antihydrogen
  - High precision spectroscopy of antihydrogen (CPT)
- ATRAP, ALPHA, ASACUSA (with SMI participation)
  - 2-photon optical transition 1s-2s
    $\Delta f/f = 10^{-14}$
  - Ground state hyperfine splitting
  - f = 1.4 Ghz; $\Delta f/f = 10^{-12}$
- SMI plans to continued the program at the FAIR facility





Are Natural Constants constant?

- Very active field, theoretically and experimentally
- New concept by START Prize winner T. Schumm at Atominstitut
- Principle
  - Build a new Frequency Standar by using a very narrow, very low-energy transition in Thorium ^{229}Th nucleus
  - This transition is very sensitive to fine structure constant α

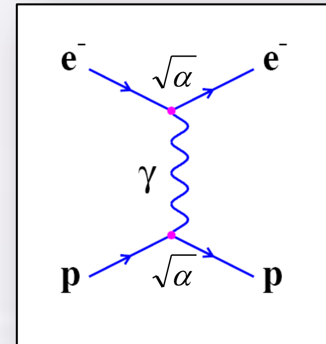
Fundamental physics with a *nuclear clock*: Shifts of fundamental constants?

Fine structure constant:

$$\alpha = \frac{1}{2c_0\varepsilon_0}\frac{e^2}{h} \approx \frac{1}{137}$$

with

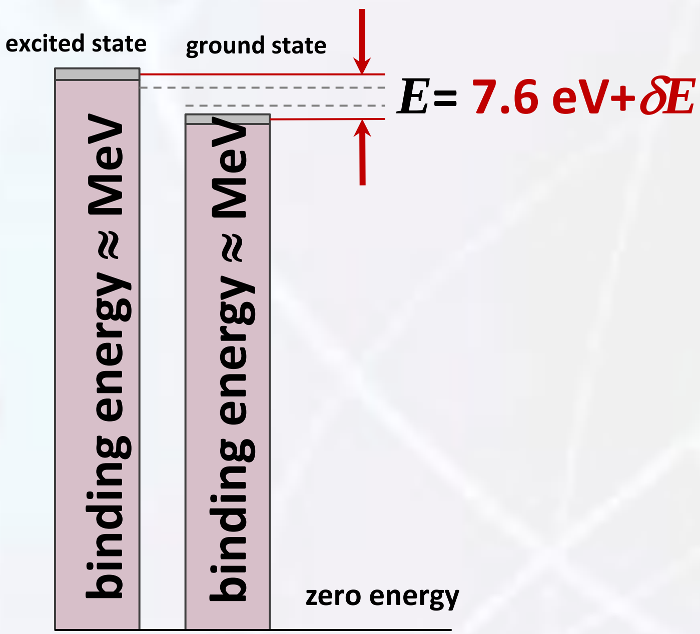
- c_0 : vacuum speed of light (defined)
- ε_0 : permittivity of vacuum (defined)
- h : Plancks constant („nature“)
- e : electron charge („nature“)



electromagnetic interaction

describes the strength of the electromagnetic interaction

^{229}Th transition is extremely sensitive to changes in α



$$\frac{\delta E}{E} \approx 10^5\left(4\frac{\delta\alpha}{\alpha} + \frac{\delta X_q}{X_q} - 10\frac{\delta X_s}{X_s}\right)$$

V. V. Flambaum, Phys. Rev. Lett 97, 092502 (2006)

with $X_q = \frac{m_q}{\Lambda_{QCD}}$ $\quad X_s = \frac{m_s}{\Lambda_{QCD}}$

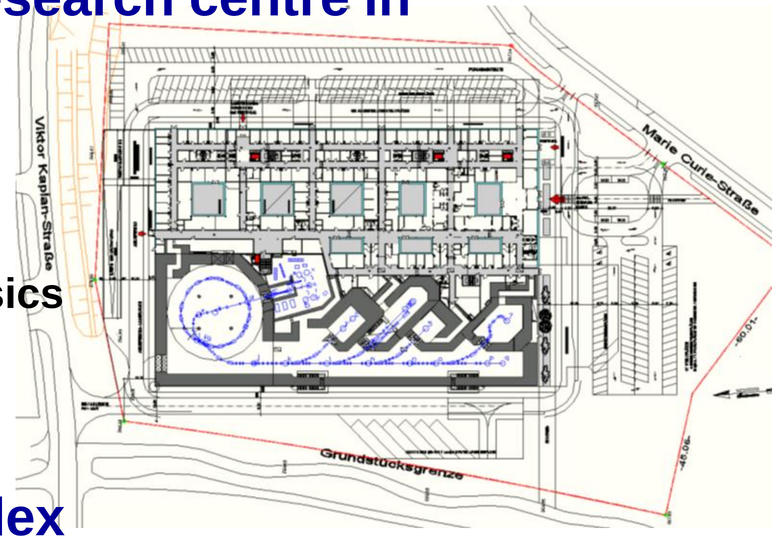
the nuclear atomic clock will be a factor 100.000 more sensitive to variations of the fine structure constant than atomic clocks

Spin-Offs

- Particle physics has always contributed in significant ways to tranferring particle physics concepts to applications for Society
- Best-know example is WWW
- Instrumentation for Medical Imaging, such as Positron Emission Tomography (PET) is another, very active area of Technology Transfer
  - Present developments towards multi-modality, combining two or more different schemes in one instrument
    - Requires light sensores insensitive to magnetic fields
    - High-speed, low-noise electronics insensitve to radiofrequency
    - Extremly tight integration of sensors and electronics
  - In other words: LHC technology
- Accelerators for Society: Tumor facilityt MedAustron beeing built near Vienna

The MedAustron Project

- **Construction of an ion-therapy and research centre in Wiener Neustadt, Austria**
  - Proton and carbon ion therapy
  - Related research in radio-biology and medical radiation physics
  - **Non-clinical research in expt. Particle Physics**
  - **Excellent training facility for students**

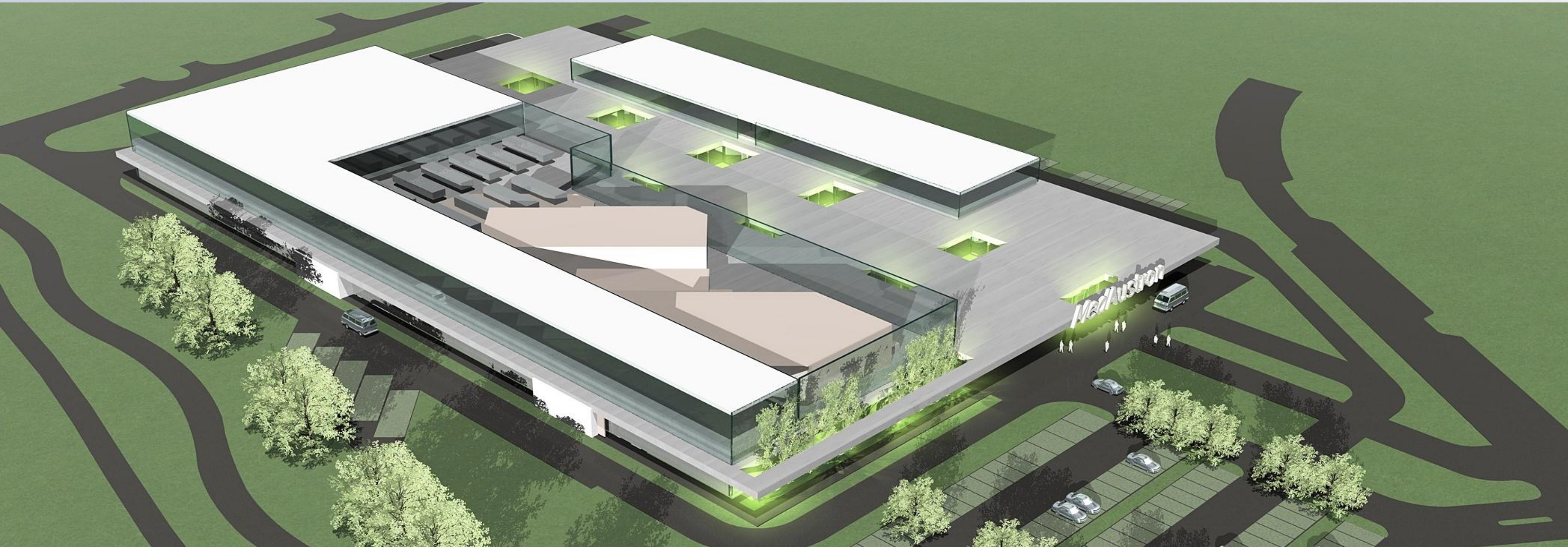


- **Synchrotron based accelerator complex**
  - Protons: 60-800 MeV, C-ions ($^{12}C^{6+}$): 120-400 MeV/n, ppm

- **Very fruitful collaboration with CERN**
  - Large (35 FTE) Austrian design team at CERN
  - Personnel costs of participating CERN experts covered by Austria

Overall project timeline

Summer 2008	**Start of project planning and team build-up**
March 16, 2011	**Ground breaking, Civil Engineering starts**
September 2012	**Start of accelerator installation (sequential)**
March 2013	**Start of accelerator commissioning (sequential)**
Mid 2014	**Start of medical commissioning (sequential)**
2015	**First patient treatment**



Future of Particle Physics in Austria

It is planned to create a new Institute of Particle Physics through the merging of HEPHY and SMI

- Three major research lines are planned to be pursued
  - Accelerator-based particle physics with CMS at LHC and Belle II at KEKB
  - Physics of non-perturbative QCD (exotic nuclear matter) at DAΦNE, JPARC and FAIR
  - Development of novel precision experiments relevant to particle physics; this line is expected to be developed together with ATI
- A section of 'Experimental methods' will provide the experimental basis for this ambitious programme
- The merger of the two Institutes necessarily requires a new building to be sited next to the Atominstitut
- These two entities will form a center for the study of fundamental particles and interactions

Outlook: Exciting times!

- During the next decade a number of major new facilities will be operational
  - LHC: long, rich program ahead
  - FAIR construction has been started ; operational towards the end of the decade
  - BelleII is in construction
  - Satellite-based FERMI scheduled to operate for the next decade
  - CTA: new Cherenkov Array Facility very actively discussed
  - A very diverse program of low energy; ultra-low energy; precision and ultra-precision experiments is in the construction phase: necessary, crucial, frequently unique approach to some of the most fundamental physics questions
- Austrian scientists are strongly involved in all these programs, frequently in leadership positions