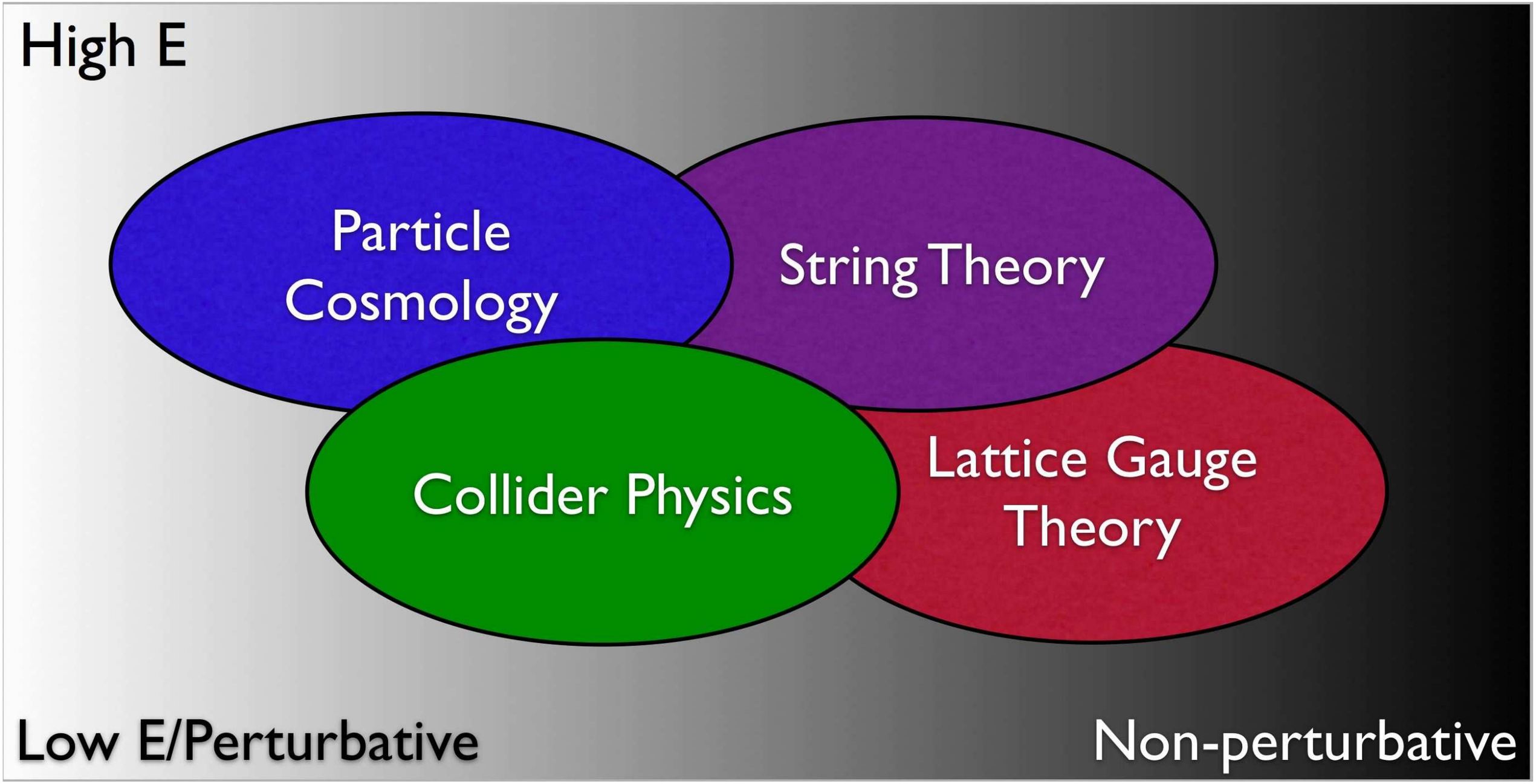
Theory

Georg Weiglein, DESY

POF III Evaluation

Karlsruhe, 02 / 2013

Particle physics theory



⇒ Close interaction with experimental programme: predictions, interpretation, tools

Development of improved understanding of the fabric of matter, space and time

Particle physics theory

- DESY (Collider phenomenology, Particle cosmology, Lattice field theory, String theory) + KIT (Collider phenomenology)

- Challenges:

  - Identify the underlying physics of the signal at 126 GeV

  - Improve the understanding of the physics of the early universe

  - Explore theory space for advancing the understanding of nature

  - Provide precise predictions that can be confronted with present or future data

  - Develop new methods, algorithms and concepts

Particle physics theory

- DESY (Collider phenomenology, Particle cosmology, Lattice field theory, String theory) + KIT (Collider phenomenology)

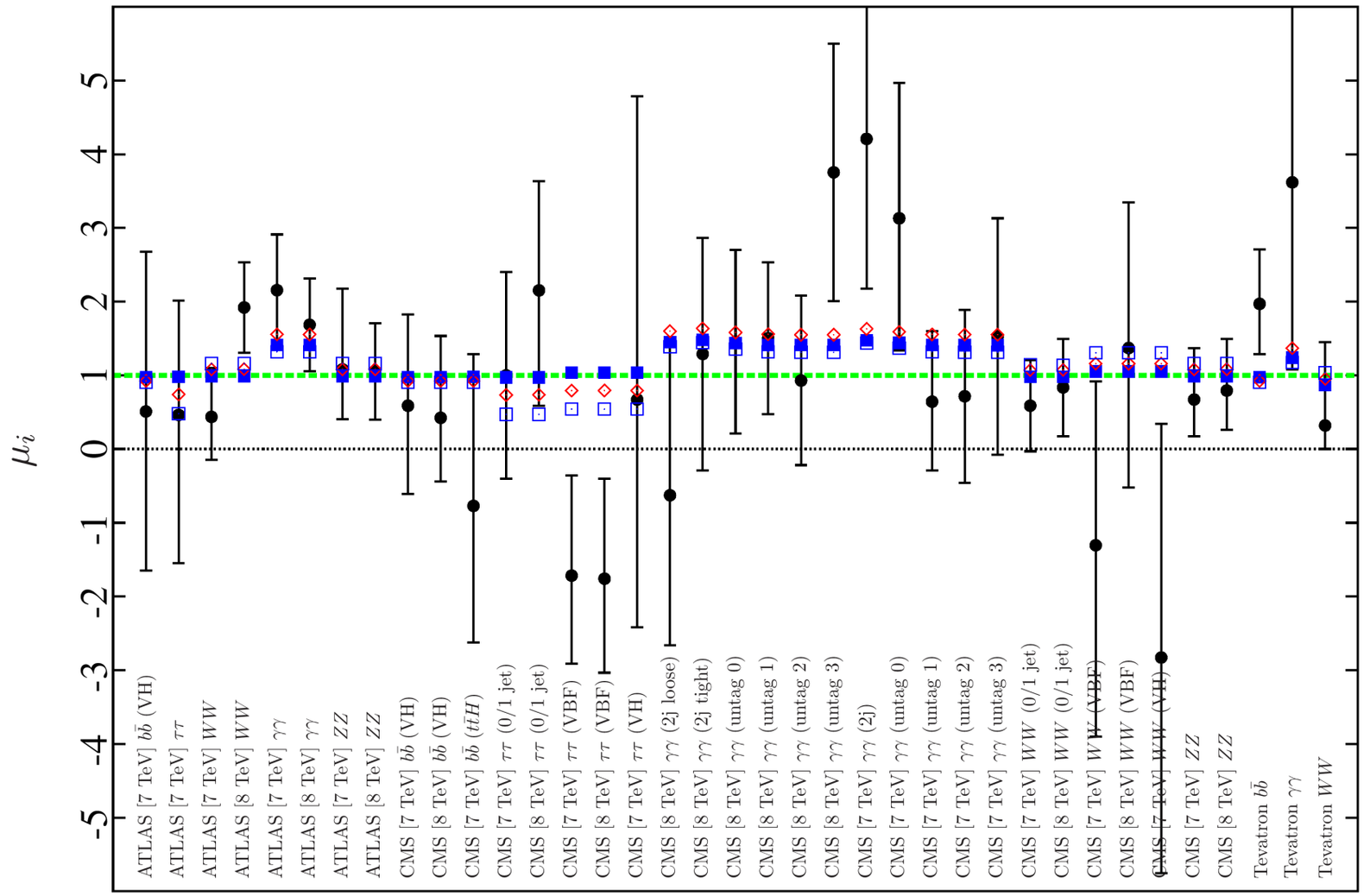
- Challenges:

- Identify the underlying physics of the signal at 126 GeV
- Improve the understanding of the physics of the early universe
- Explore theory space for advancing the understanding of nature
- Provide precise predictions that can be confronted with present or future data
- Develop new methods, algorithms and concepts

Collider phenomenology (DESY + KIT)

SUSY interpretation of the observed Higgs signal?

- LHC / TeV. data, ■ full fit, ⊡ without TeV., ◇ without low. en. obs.

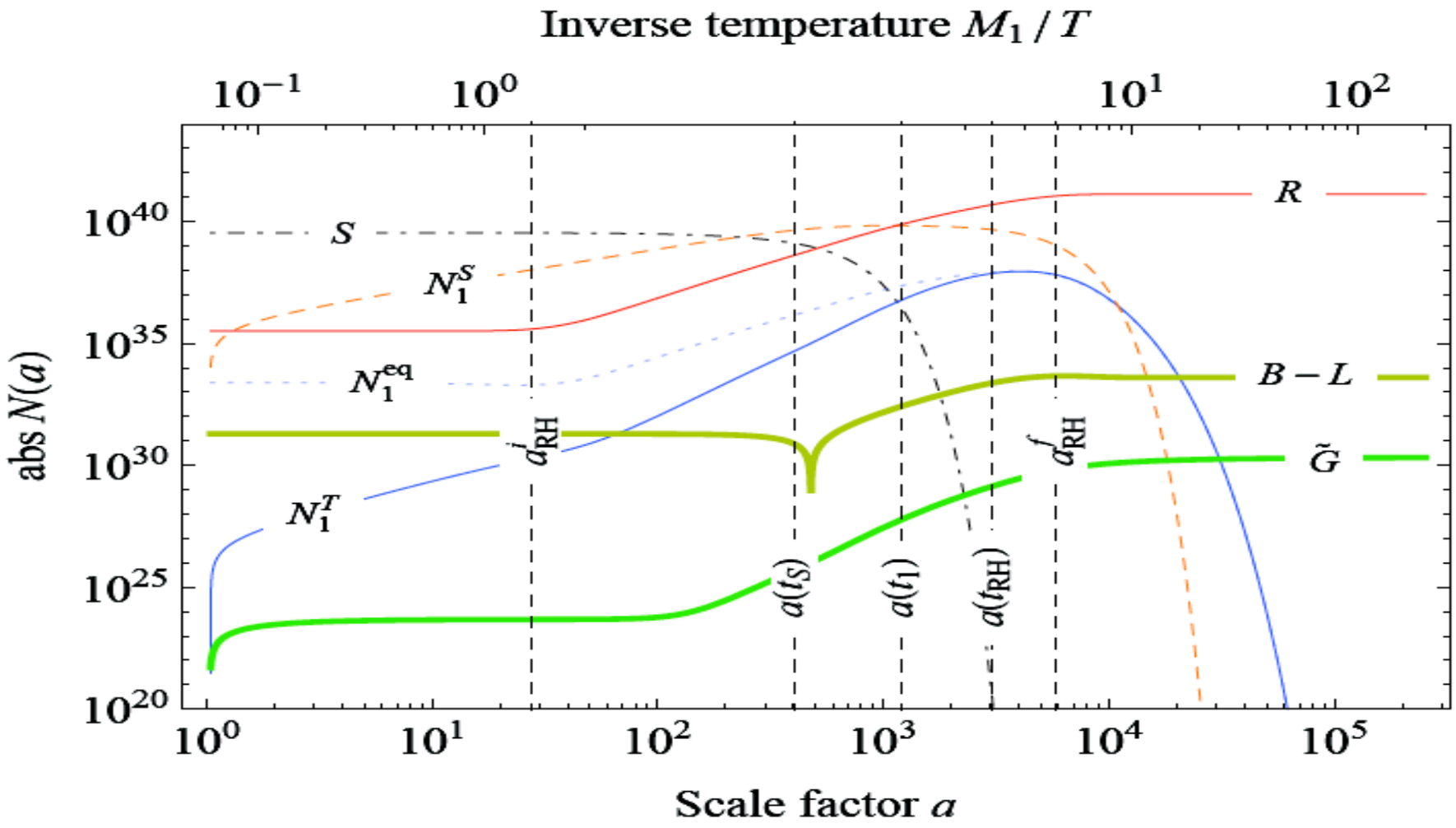


$\Rightarrow \chi^2$ reduced compared to SM case, better fit probability

Higgs as a portal to physics beyond the Standard Model, dark matter, ...?

Particle cosmology

Explanation of the initial conditions of the hot early universe from a phase transition at the end of inflation:



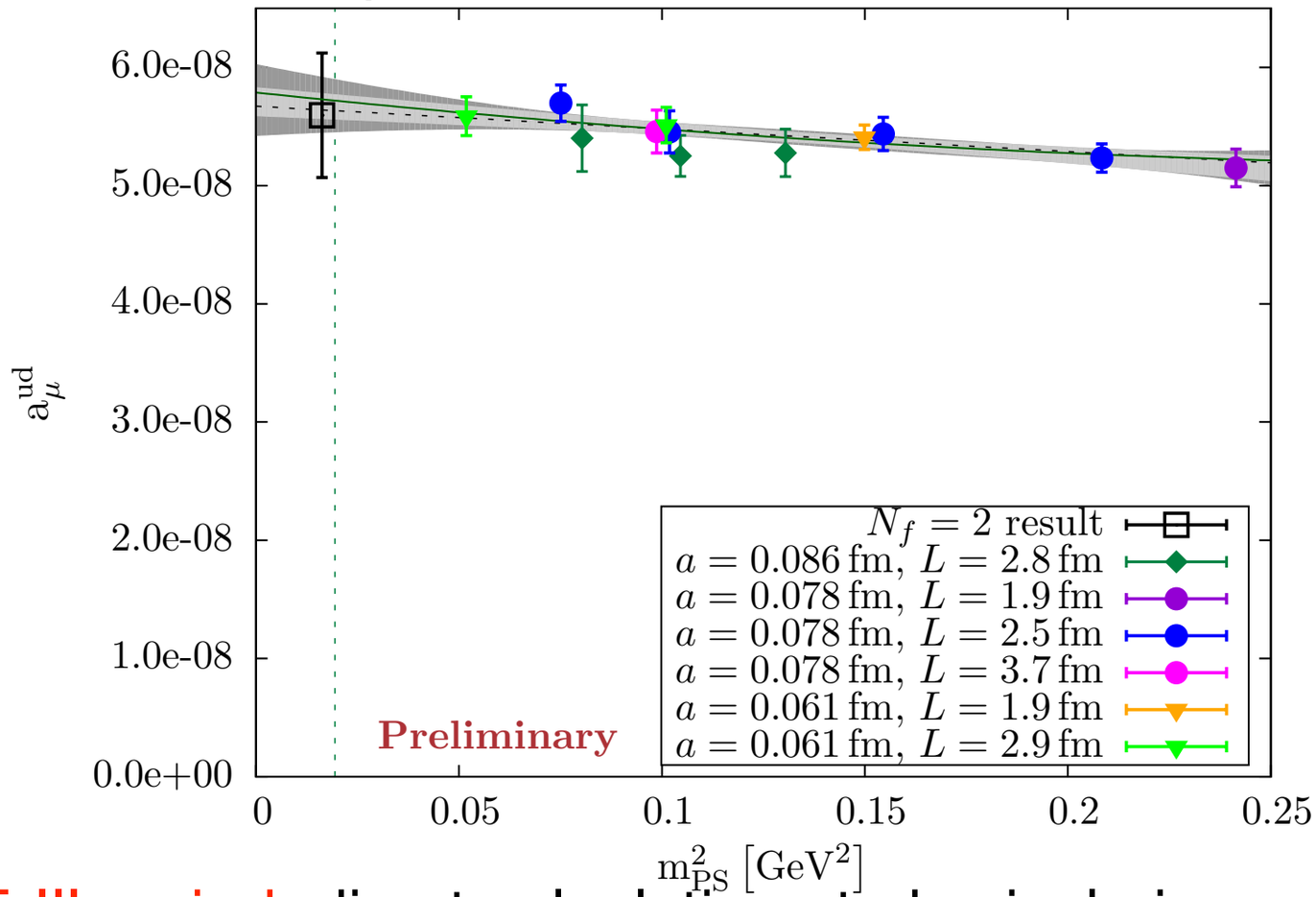
[Generation of entropy (R), matter-antimatter asymmetry (B-L) and dark matter (G) after inflation]

Inflation models in light of Planck results? Dark matter candidates that are consistent with all cosmological, astrophysical collider constraints?

Lattice field theory

2-flavour leading order hadronic contribution to the anomalous magnetic moment of the muon:

POF-II period: chiral extrapolation



Goal for POF-III period: direct calculation at physical pion mass

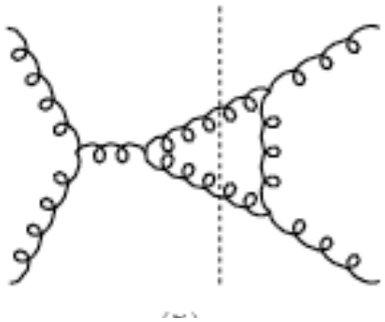
Precision computation of hadronic contributions, simulation laboratory

String Theory

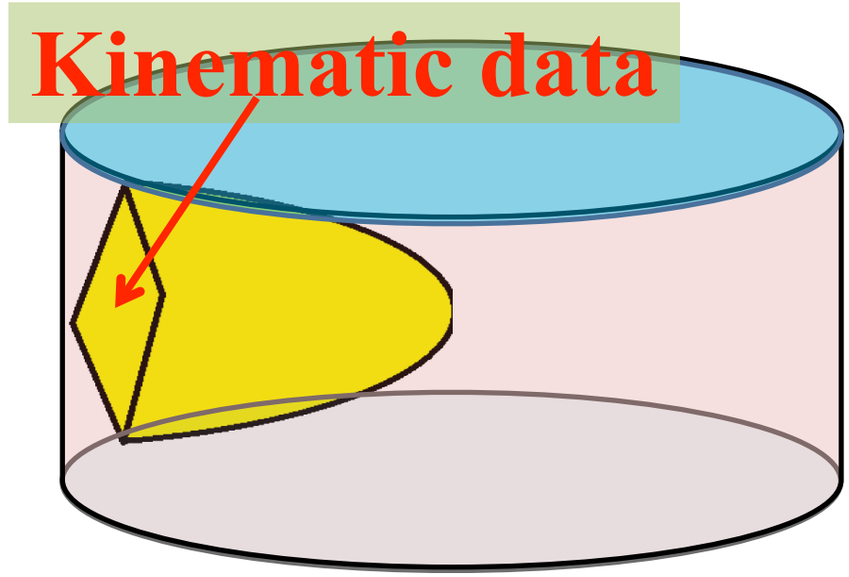
Development of string theory tools for computation of gauge theory quantities [mostly w. SUSY]

- to high/all loop order
- non-perturbative ⇒ probe dualities

e.g. gluon scattering amplitudes



interpolation



Applications of string theory methods to strongly coupled quantum systems [QGP and cond-mat]

Wider impact of the theory activities

- The DESY theory group plays a special role in DESY's strong partnerships with the local universities at Hamburg and in the Berlin area

- DESY and KIT groups are well connected in numerous national and international cooperations, e.g. Helmholtz Alliance ``Physics at the Terascale"; novel activity of KIT in POF III fosters collaboration of different HGF centres

- Synergies between widely different areas of theoretical particle physics allow efficient transfer of latest developments

- Theory plays a pivotal role in the scientific exchange with the different experiments.

- Theory is instrumental in the context of DESY's role as a national laboratory (more than 50% of the permanent staff in particle theory at German universities had been employed at DESY before, etc.)

Supporting material

Elementary particle physics 2015 - 19

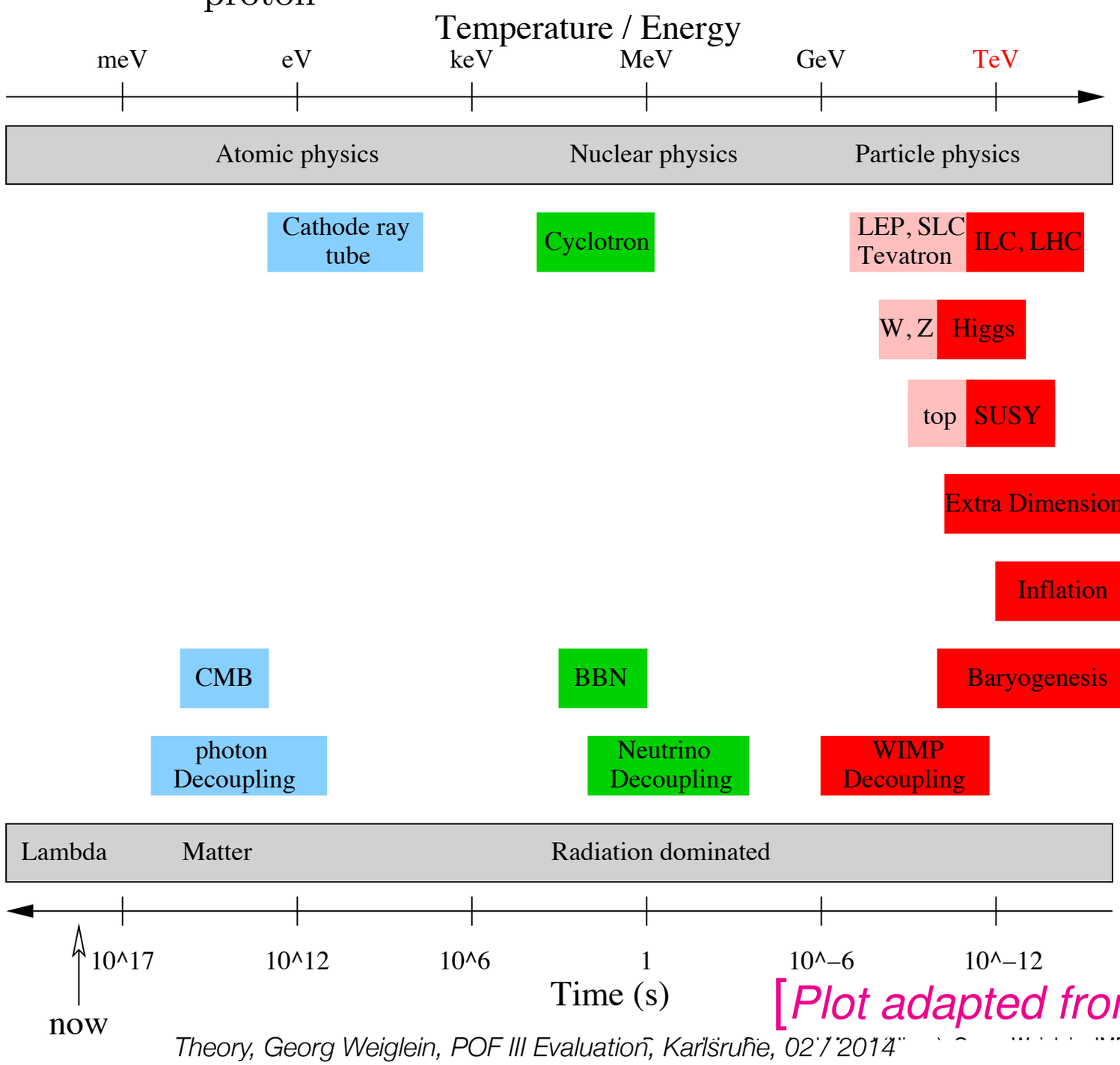
- Particle physics programme for next funding period 2015-19, Three <u>main</u> research topics:

1. Proton-proton physics: ATLAS and CMS
   - Significant contributions to operation, analysis, development and upgrade
   - DESY is one of few places worldwide with contributions to ATLAS & CMS!
2. e^+e^- physics: Belle (I/II) and ILC
   - Belle II: Germany is second-largest group after Japan
   - ILC: Commitment to international project in Japan, DESY is important contributor to machine, detector, physics
3. Theory
   - Particle phenomenology, cosmology, lattice field theory, string theory
   - Support of experimental community with tools and data interpretation
   - Development of new methods and concepts

- In-line with German Roadmap and Update of European Strategy

LHC and ILC: exploring the Terascale

$$1\ \mathrm{TeV} \approx 1000 \times m_{\mathrm{proton}} \Leftrightarrow 2 \times 10^{-19}\,\mathrm{m}$$



[*Plot adapted from J. Feng '05*]

Particle accelerators: viewing the early Universe

Today's universe is cold and empty: only the stable relics and leftovers of the big bang remain

The unstable particles have decayed away with time, and the symmetries that shaped the early Universe have been broken as it has cooled

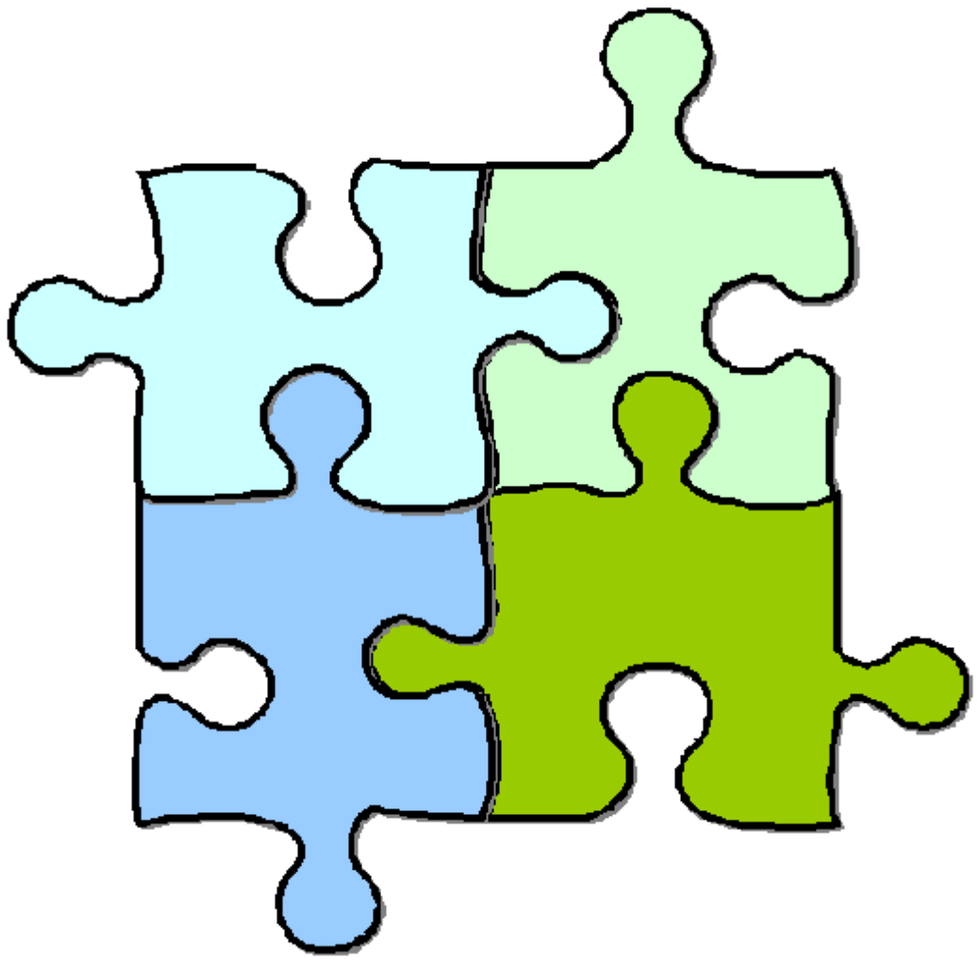
$\Rightarrow$ Use particle accelerators to pump sufficient energy into a point in space to re-create the short-lived particles and uncover the forces and symmetries that existed in the earliest Universe

$\Rightarrow$ Accelerators probe not only the structure of matter but also the structure of space-time, i.e. the fabric of the Universe itself

The 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

What can we learn from exploring the Terascale?

- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking? What is the role of the discovered particle at $\sim 126\ \mathrm{GeV}$ in this context?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- What is dark matter? Can it be produced in the laboratory?
- Are there new sources of $\mathcal{CP}$-violation?
  Can they explain the asymmetry between matter and anti-matter in the Universe?

Collider phenomenology: highlights from the POF-II period

- Significant strengthening of collider phenomenology at DESY: new appointments, three additional staff members compared to previous funding period (2 permanent + 1 Emmy Noether group leader (tenure track))

- Important input for Higgs searches and the determination of the properties of the observed signal, strong involvement in LHC Higgs Cross Section WG

- Interpretation of observed signal, exclusion of different scenarios (SM with a fourth fermion generation, etc.)

- Interpretation of limits from new physics searches at the LHC

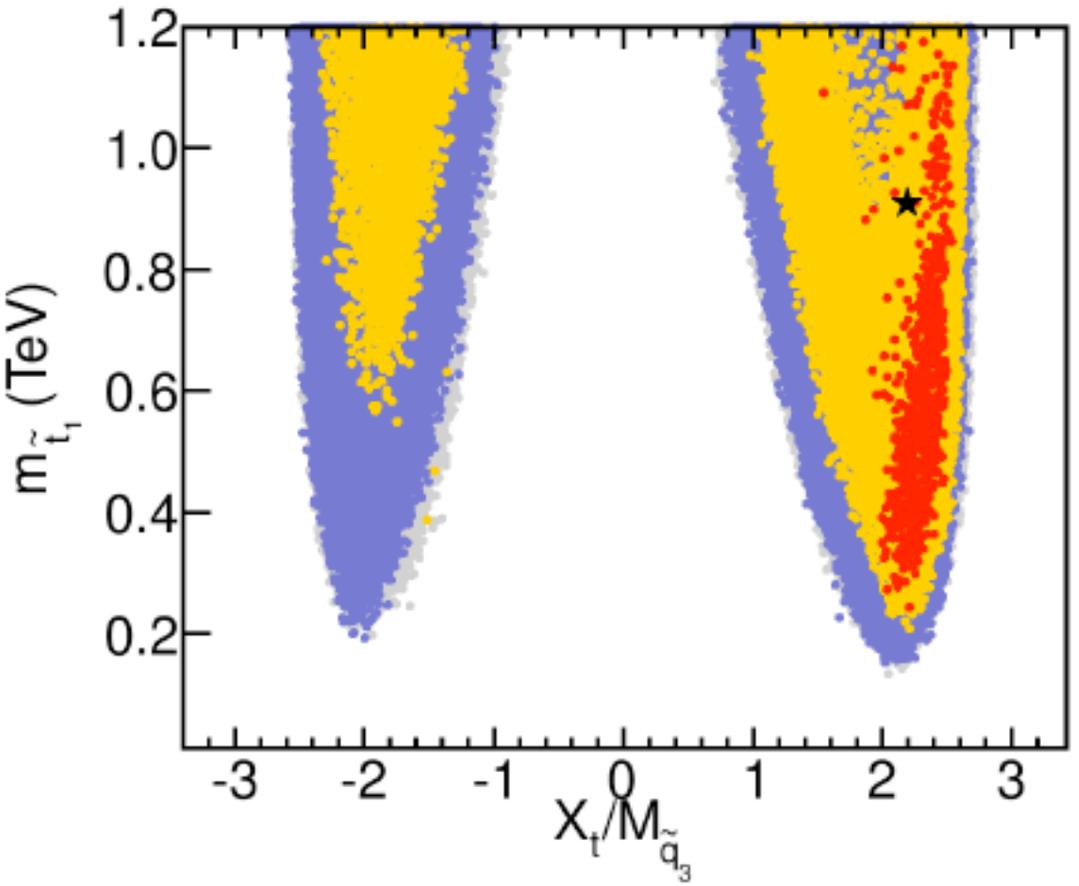
- Precise predictions for signal and background processes at the LHC, provision of tools that are used by experimentalists for the data analysis (parton shower for Monte Carlo event generators, etc.)

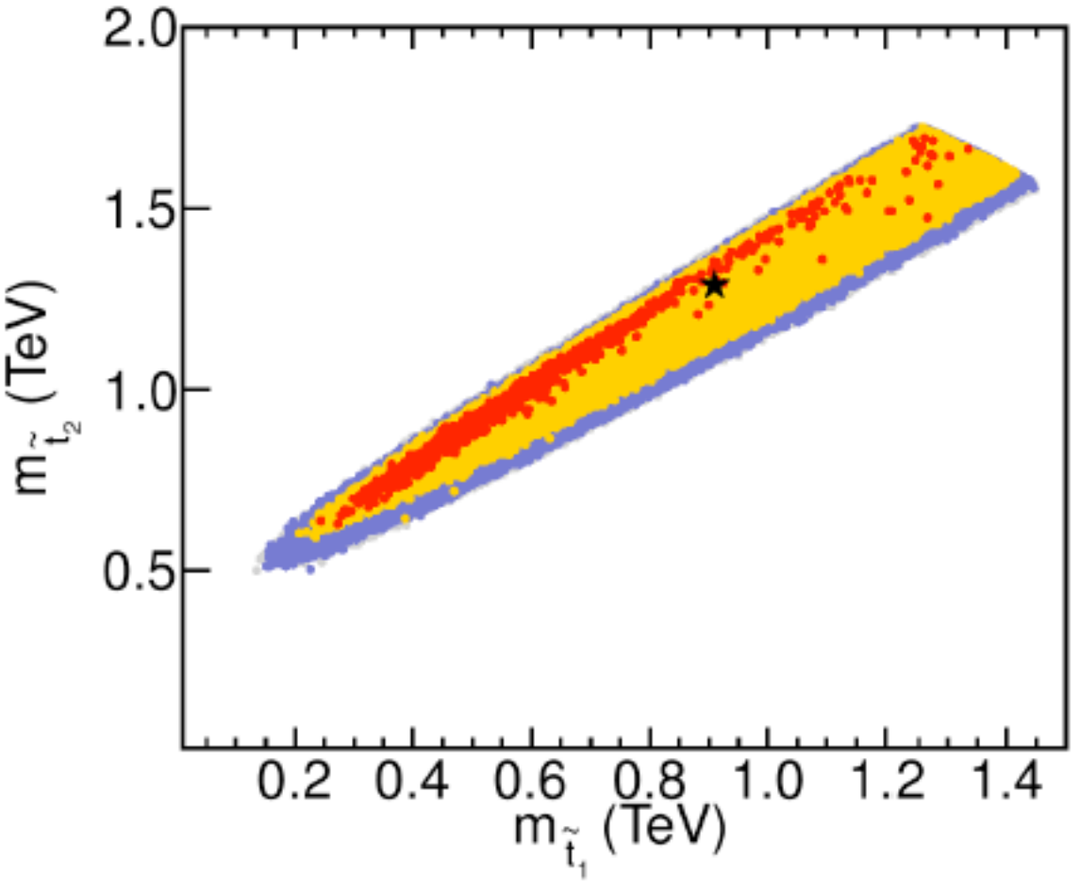
- Precise determination of parton distributions, α_s, charm and bottom masses

MSSM interpretation of the signal at 126 GeV in terms of the light Higgs h of the MSSM

MSSM fit, preferred values for the stop masses:

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]





$\Rightarrow M_{\rm h} \sim 126$ GeV requires large stop mixing,
but stop masses can still be light

Collider phenomenology: plans for the POF-III period

- Exploration of the physics of the signal at 126 GeV, discrimination between different theoretical interpretations

- Global fits of different models (initiative of DESY theory group led to formation of dedicated SUSY/BSM Fit Working Group within Helmholtz Alliance during POF II period)

- Investigation how different scenarios can be probed in the future, exploration of ILC physics potential in view of the LHC results

- High-precision predictions for LHC physics using improved perturbative methods (extension of classes of mathematical functions, etc.), computer algebra tools, all-order summations, generalised unitarity approach and new developments on non-perturbative methods

- Development of new generation of event generators

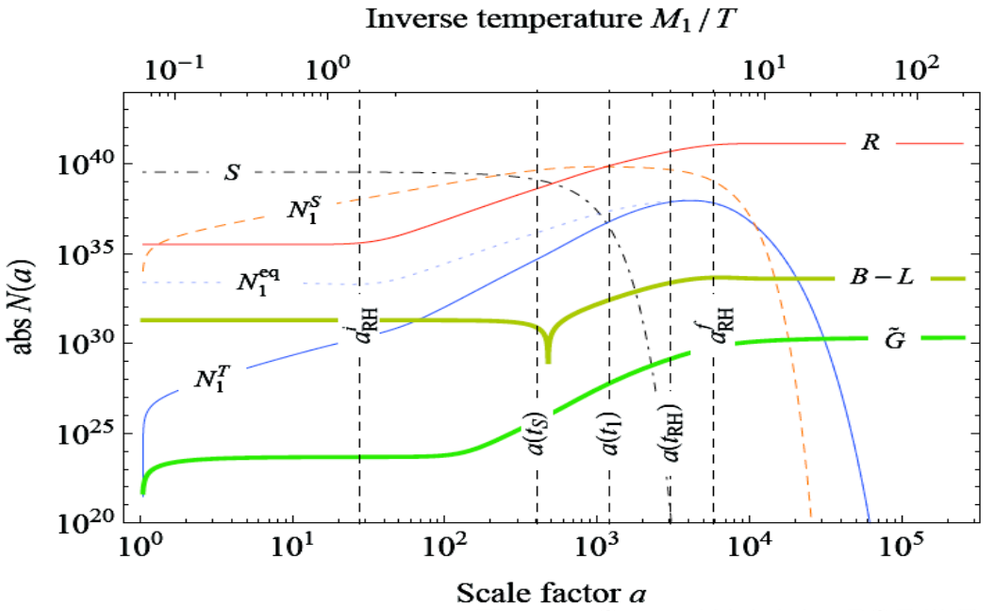
Synergies DESY - KIT

KIT brings synergies

- with the theory groups at DESY-H and DESY-Z in collider physics
  - HERWIG++ Monte-Carlo simulations
  - QCD corrections to LHC collider processes
  - probing new physics with collider data
- with the theory group at DESY-Z in precision calculations
  - precise determination of fundamental parameters of the Standard Model (α_s, m_c, m_b)
  - N^{3}LO corrections to top-quark threshold production at ILC
- with the Belle II group at DESY-H in flavour physics
  - NLO and NNLO corrections to flavour-changing processes
  - probing new physics with B and D meson decays

Particle cosmology: significant achievements in POF-II

- Central questions: cosmic microwave background and inflation, dark energy, matter-antimatter asymmetry, dark matter. Specific results:
- Axions and axion-like particles (alps) are interesting dark matter candidates, which can be searched for at DESY
- Signatures of WIMPs and gravitinos have been compared with a tentative gamma-ray line in the FERMI-LAT data.
- De Sitter vacua could be explicitly constructed in type IIB string theory
- The initial conditions of the hot early universe can be explained as result of a phase transition at the end of inflation



[Generation of entropy (R), matter-antimatter asymmetry (B-L) and dark matter (G) after inflation]

Particle Cosmology: goals for POF-III

Recent results from Planck satellite and the discovery of the signal at 126 GeV will have major impact on theoretical activities.

Specific goals:

- Construction of unified theory with extra dimensions and low-scale supersymmetry consistent with LHC results
- Identification of dark matter candidates consistent with all cosmological, astrophysical and collider constraints (e.g. axions, non-thermal WIMPs, gravitinos): cosmology, collider phenomenology, lattice field theory
- Detailed study of inflation models in light of Planck results
- Embedding of inflation models in extensions of Standard Model consistent with LHC results

Lattice field theory: highlights from the POF-II period

- Fundamental QCD parameters: α_s, quark masses

- Flavour Physics: Theory and strategy for non-perturbative HQET, B-meson decay constants, b-quark mass

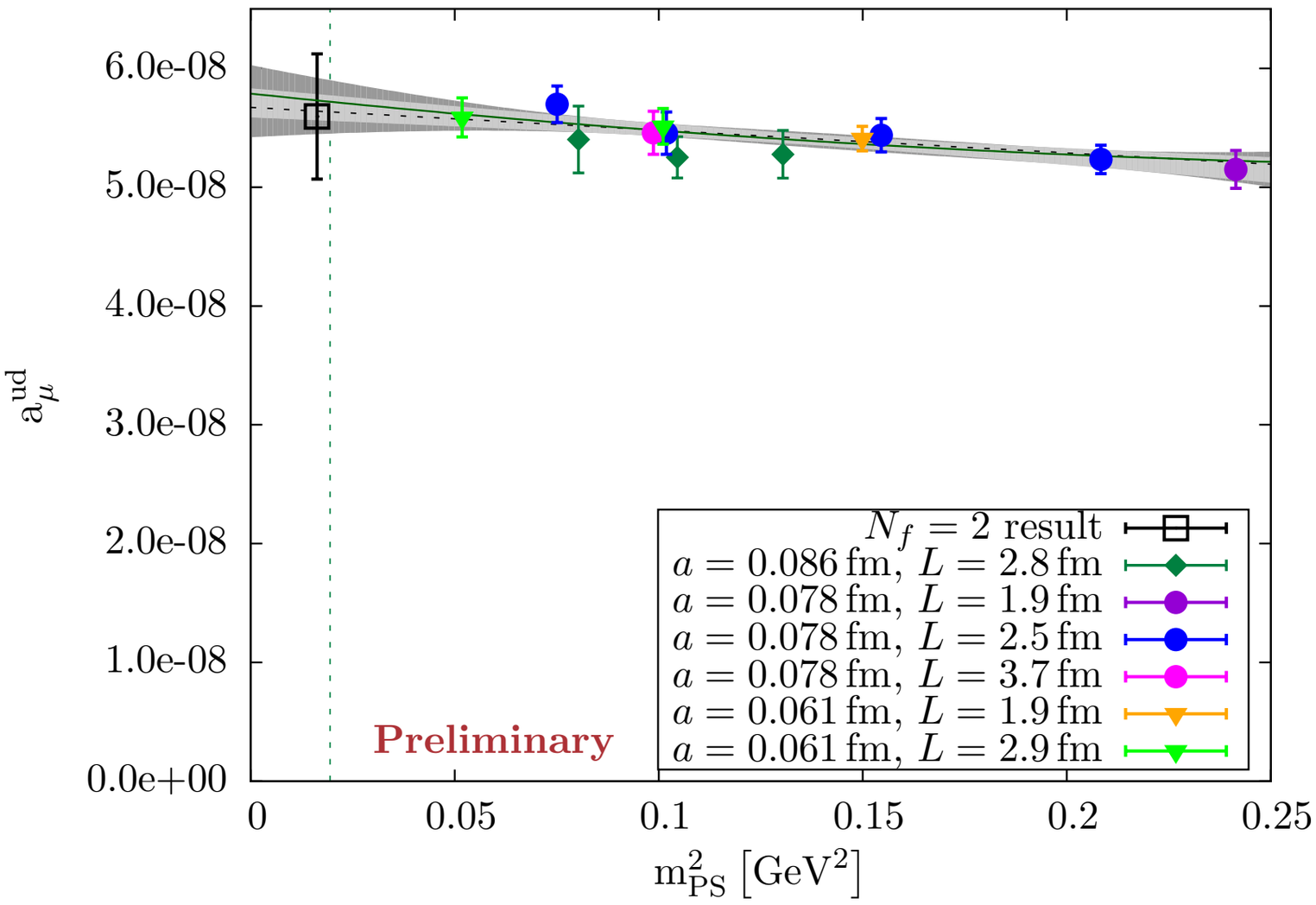
- Hadronic contributions to electroweak observables: muon anomalous magnetic moment

- Hadron structure: moments of PDFs, nucleon-WIMP cross-section

- Higgs physics: upper and lower Higgs boson mass bounds

Example: 2-flavour leading order hadronic contribution to the anomalous magnetic moment of the muon

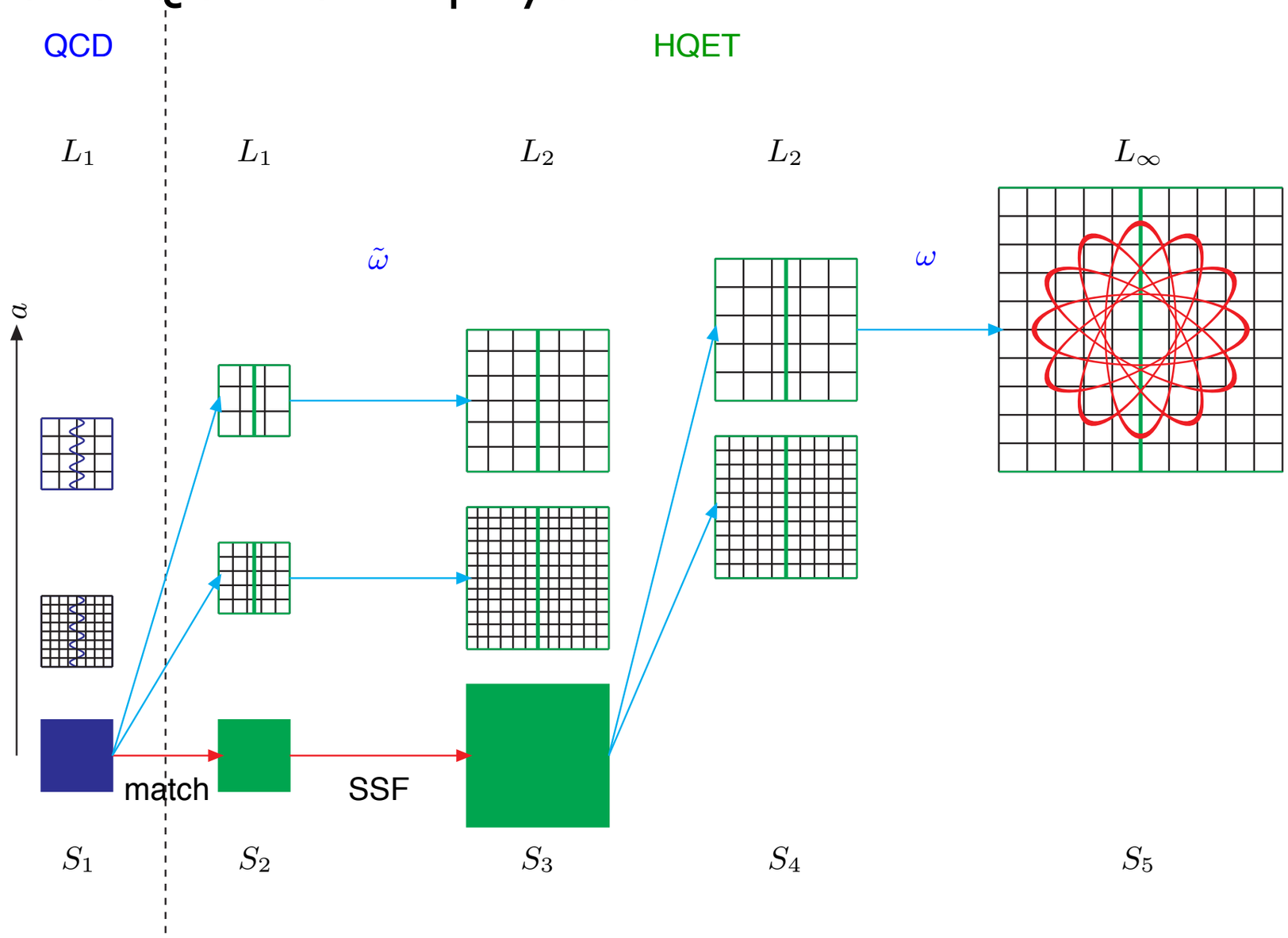
- POF-II period: chiral extrapolation



- Goal for POF-III period: direct calculation at physical pion mass

Lattice

- Establishing the strategy for relating Heavy Quark Effective Theory and QCD for B-physics



Lattice field theory: goals for POF-III period

- Simulations at or close to physical quark masses
- Comprehensive investigation of B-meson system
- Leptonic decays and form factors for semi-leptonic decays
- High precision calculation of strong coupling constant, α_s
- Precision computation of hadronic contributions to
  - Muon anomalous magnetic moment, at LO and NLO
  - Moments of PDFs, nucleon form factors, coupling of the nucleon to a Higgs boson
- Establishing a simulation laboratory (with JSC Jülich and the Cyprus Institute)

String theory: Highlights from PoF-II Period

DFG-funded Graduate school ``Mathematics inspired by String Theory and Quantum Field Theory"

All loop computation of scaling weights in several QFTs, including 4D N=4 supersymmetric QCD, through string theory techniques.

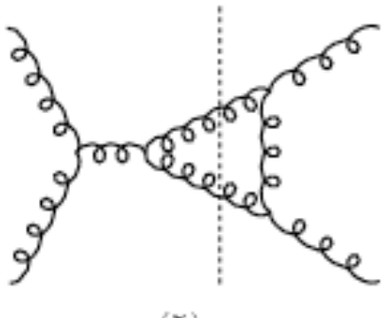
Computation of transport properties in strongly coupled plasma through AdS/CFT (in particular CME)

String Theory: Goals for PoF-III Period

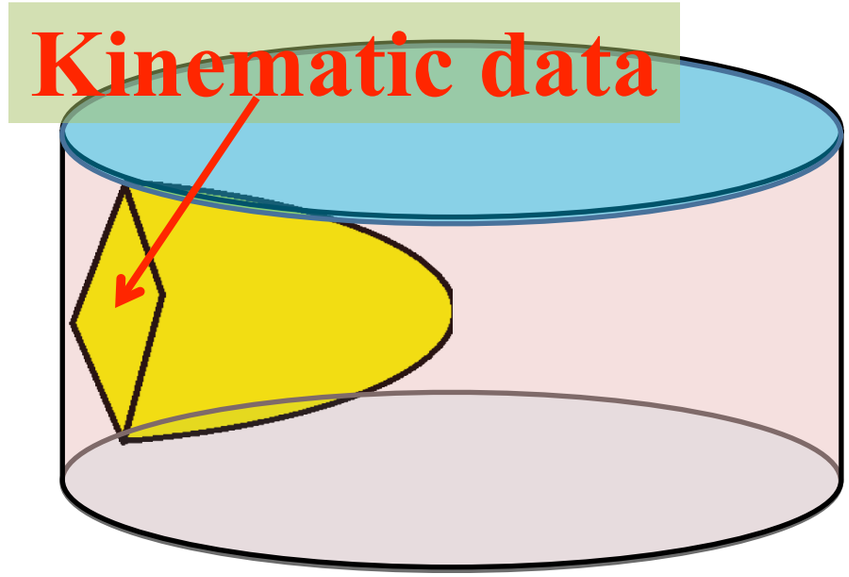
Development of string theory tools for computation of gauge theory quantities [mostly w. SUSY]

- to high/all loop order
- non-perturbative ⇒ probe dualities

e.g. gluon scattering amplitudes

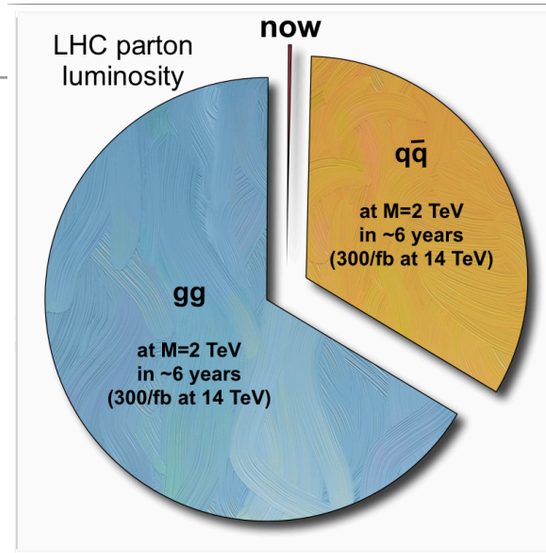


interpolation



Applications of string theory methods to strongly coupled quantum systems [QGP and cond-mat]

Conclusions



- Extremely exciting times for particle physics!
- LHC:
  - Spectacular discovery of a signal in the Higgs searches
  - Exploration of the underlying physics will be a prime goal for the next years
    - A lot more to expect from the LHC; we have just scratched the surface
- Belle II: physics is complementary to direct searches at the LHC
- ILC: strong physics case, encouraging developments in Japan
- Theory: great opportunities for a major progress in understanding the fundamental laws of nature