USQCD at Oak Ridge
April 29, 2013

USQCD and the Energy Frontier

Julius Kuti

University of California, San Diego

Lattice QCD Computational Science Workshop

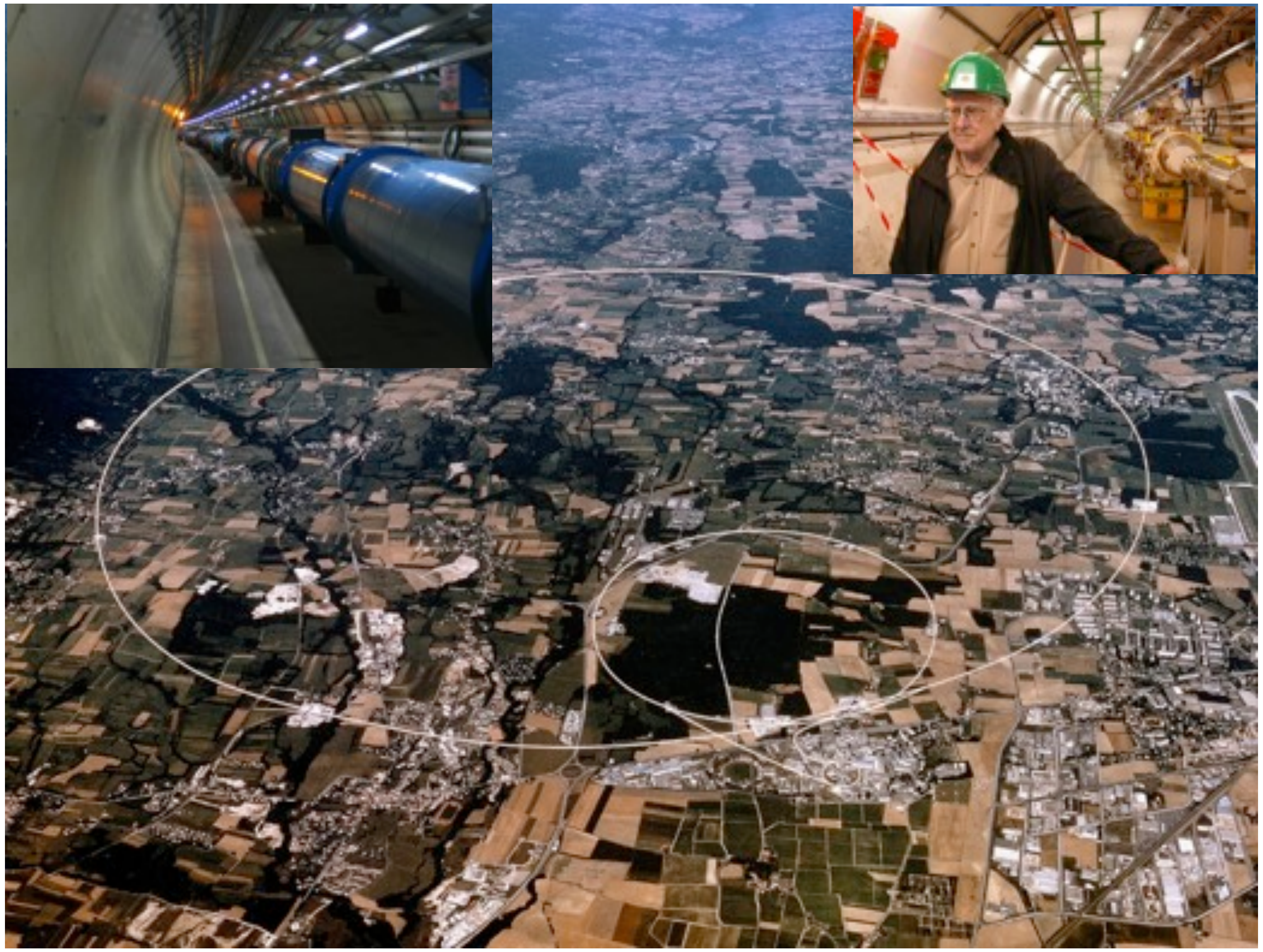
Oak Ridge National Lab, April 29-30, 2013

Large Hadron Collider - CERN

primary mission:

- *Search for Higgs particle*

- *Origin of Electroweak symmetry breaking*



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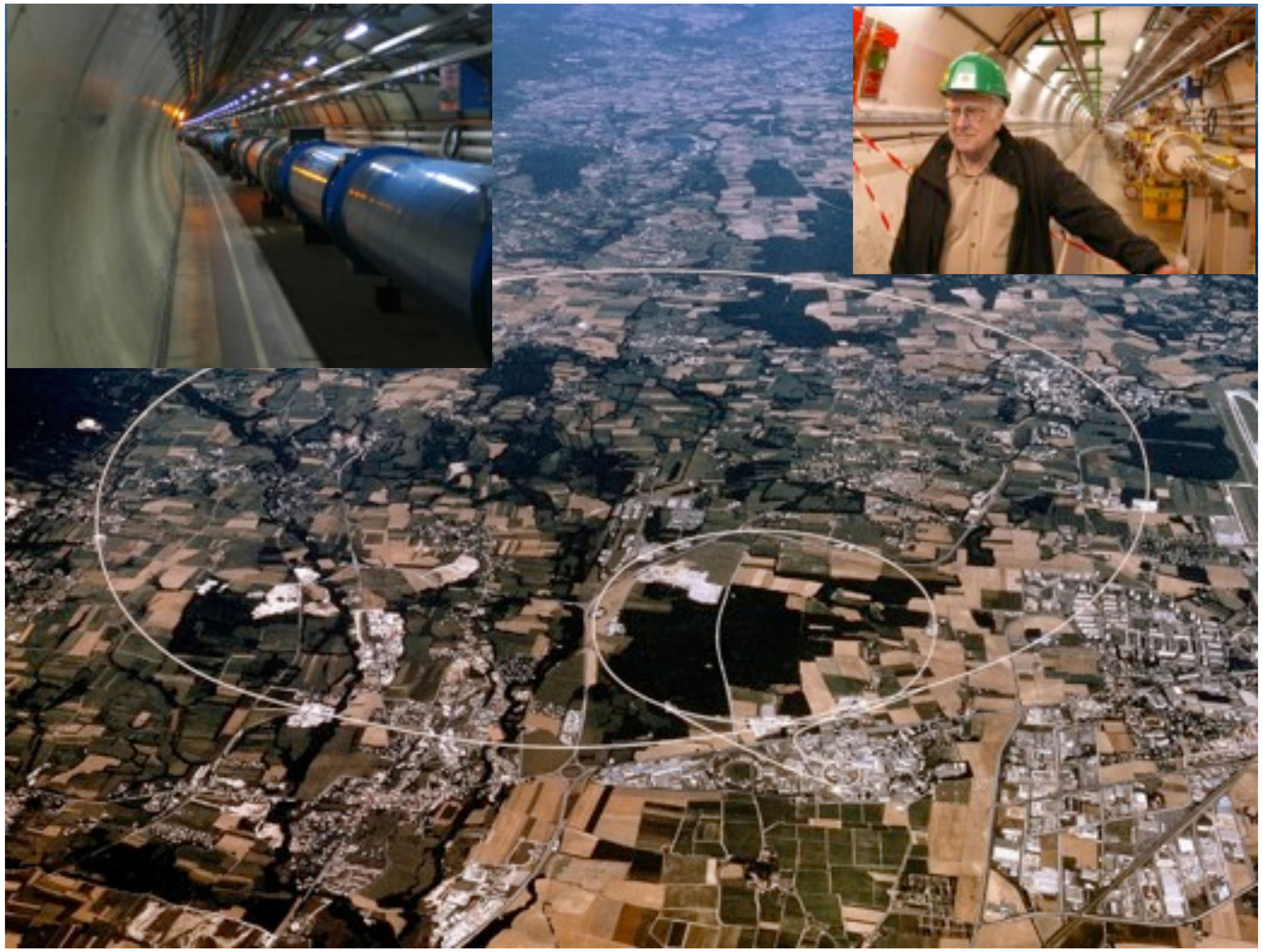

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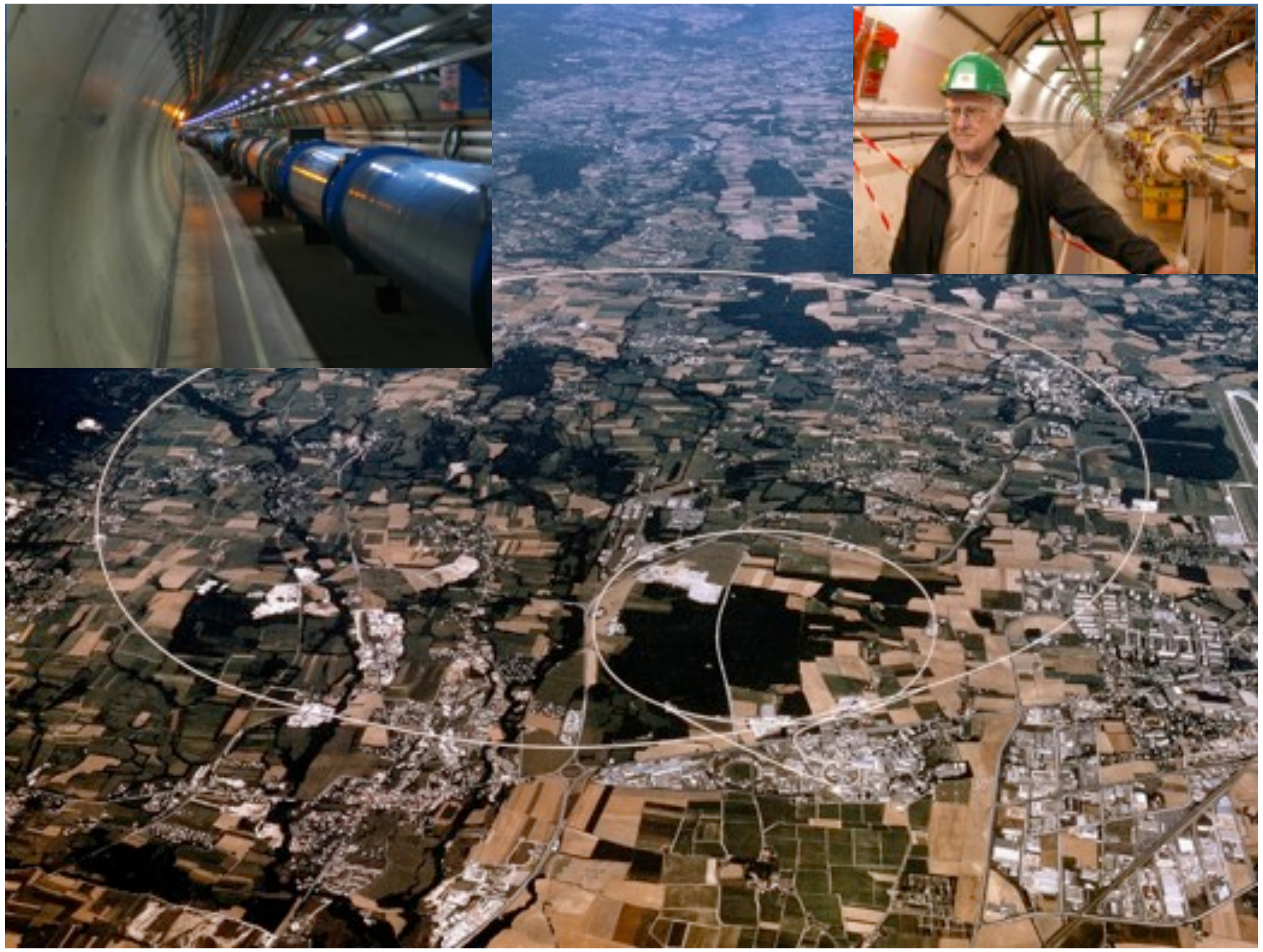

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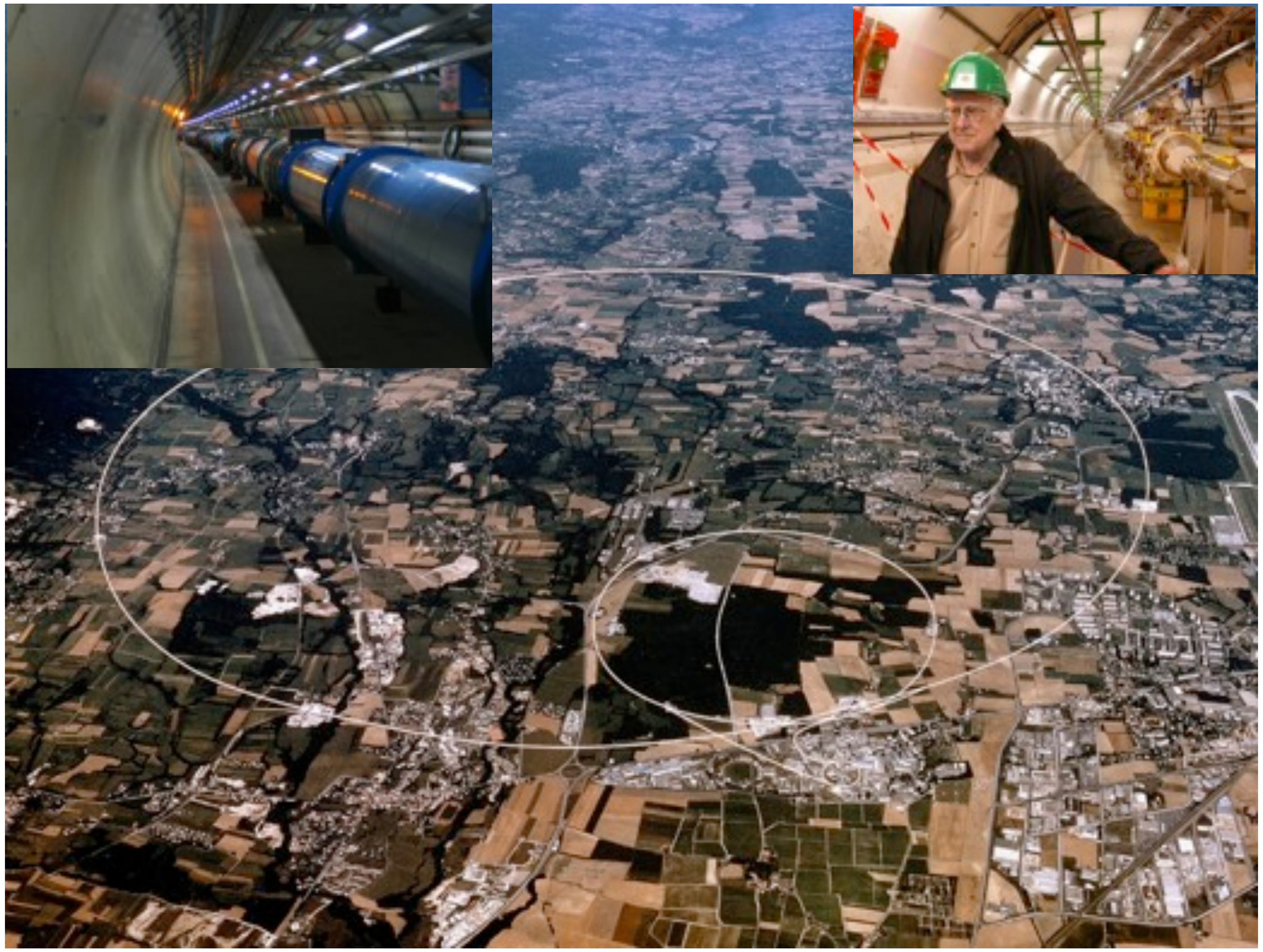

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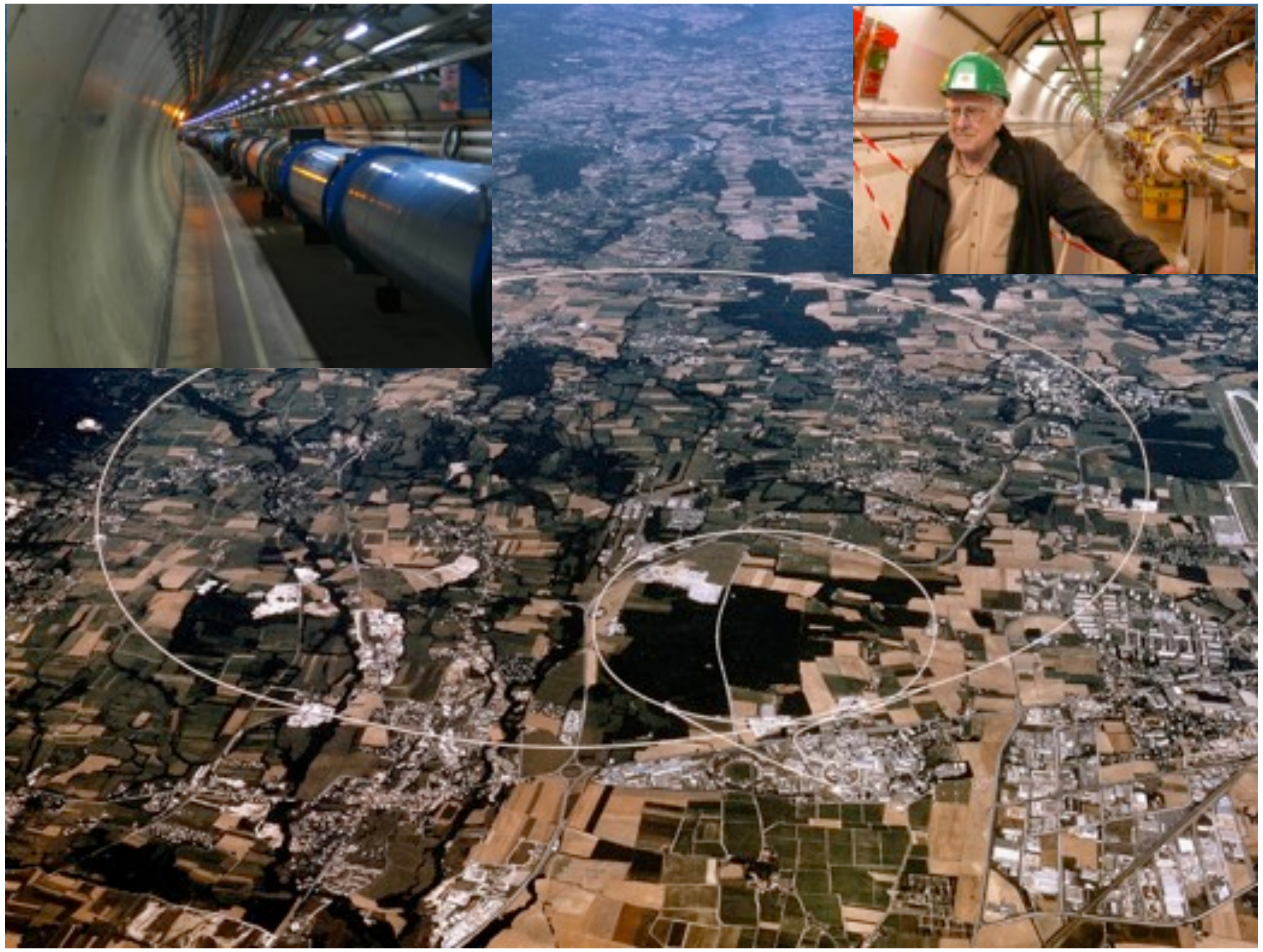
- Composite Higgs mechanism?



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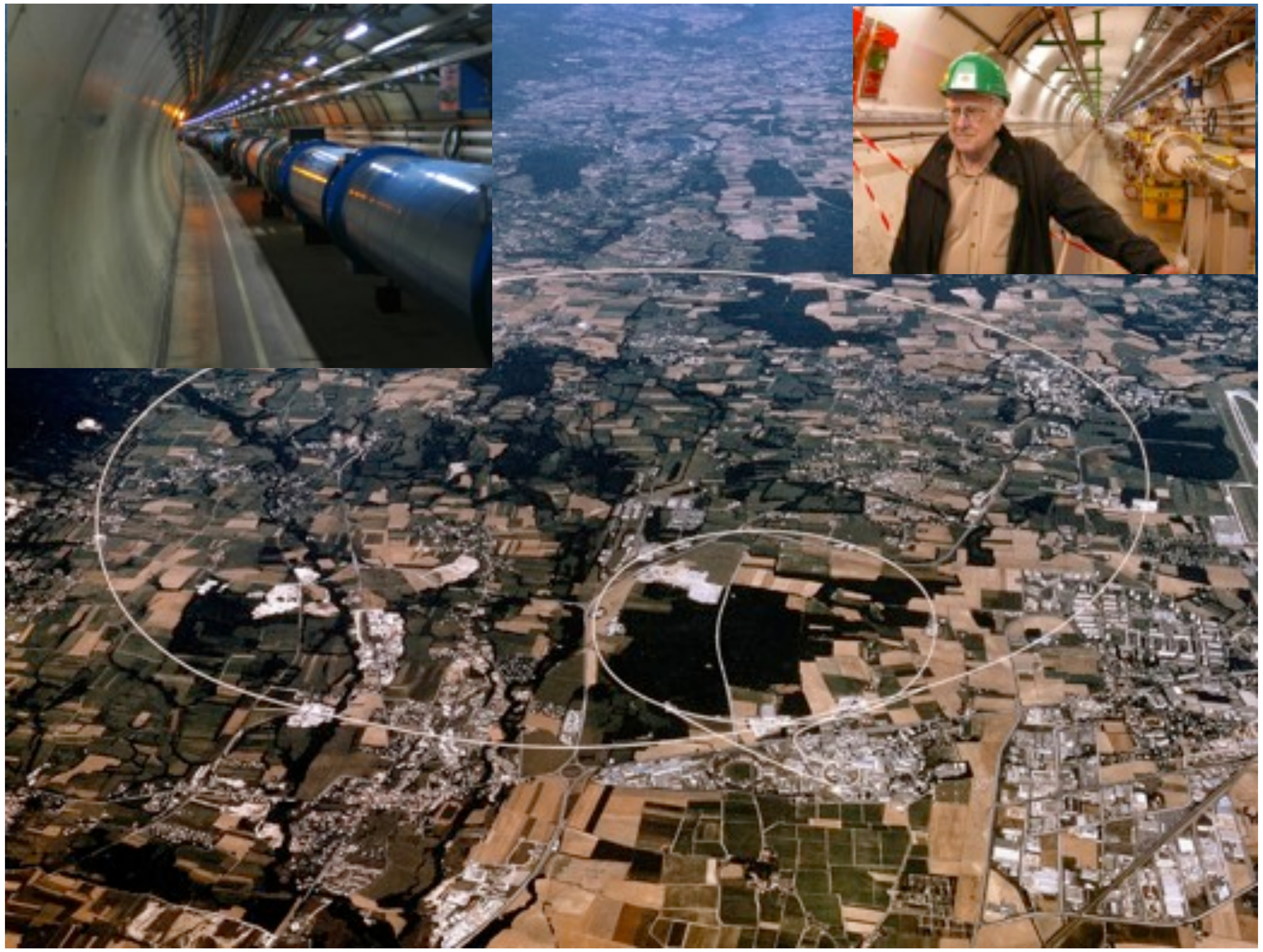

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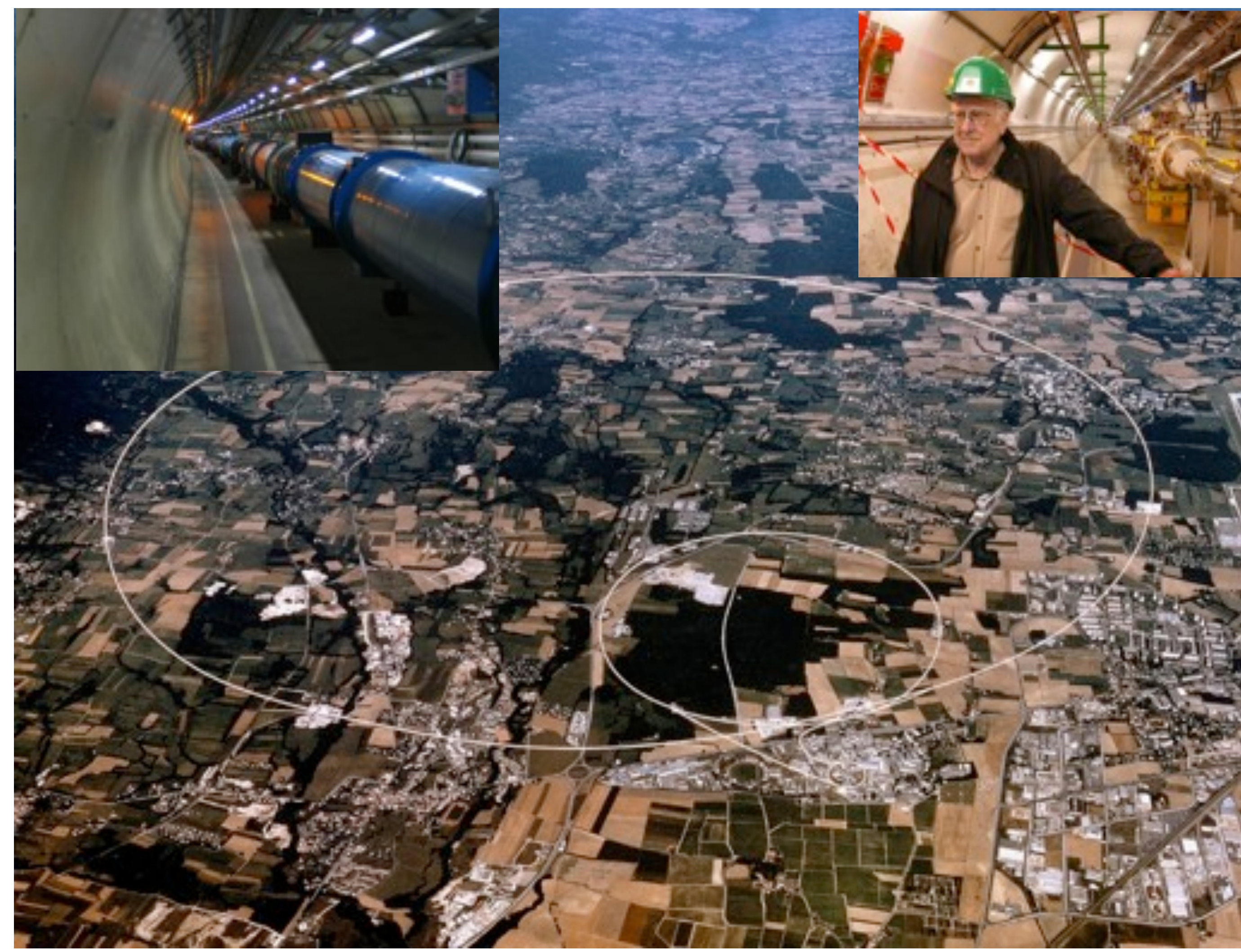
Primary focus of USQCD BSM effort and this talk



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

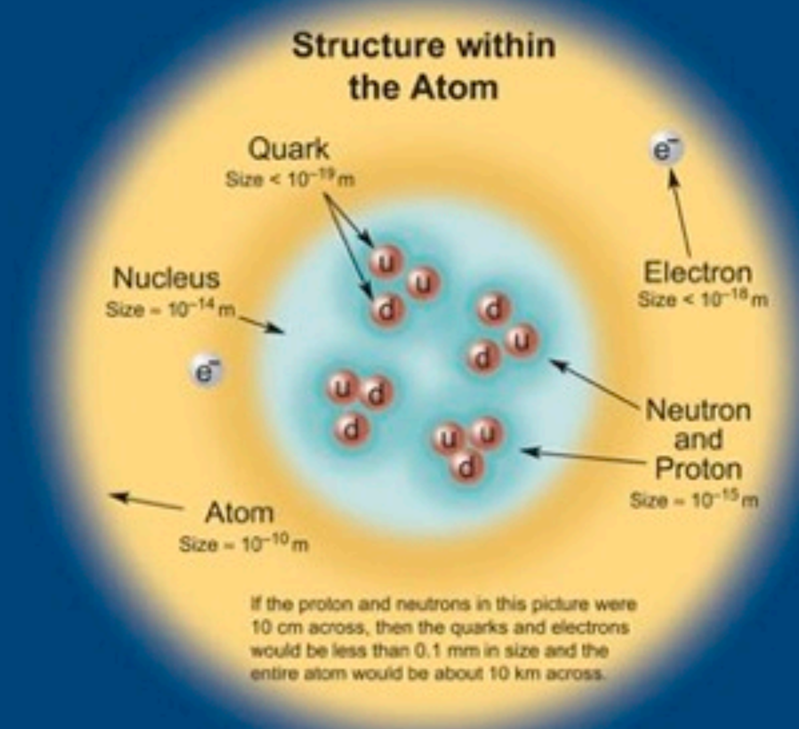
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² $= 1.67\times10^{-27}$ kg.

Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, −1, 0, 0 respectively.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Visit the award-winning web feature *The Particle Adventure* at

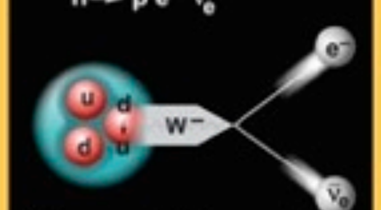
ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory

Particle Processes

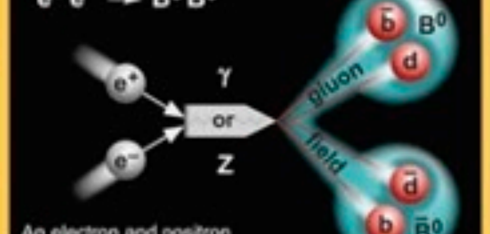
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^- \bar{\nu}_e$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

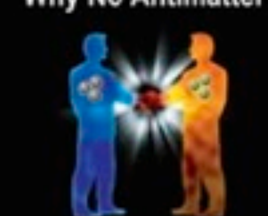
Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

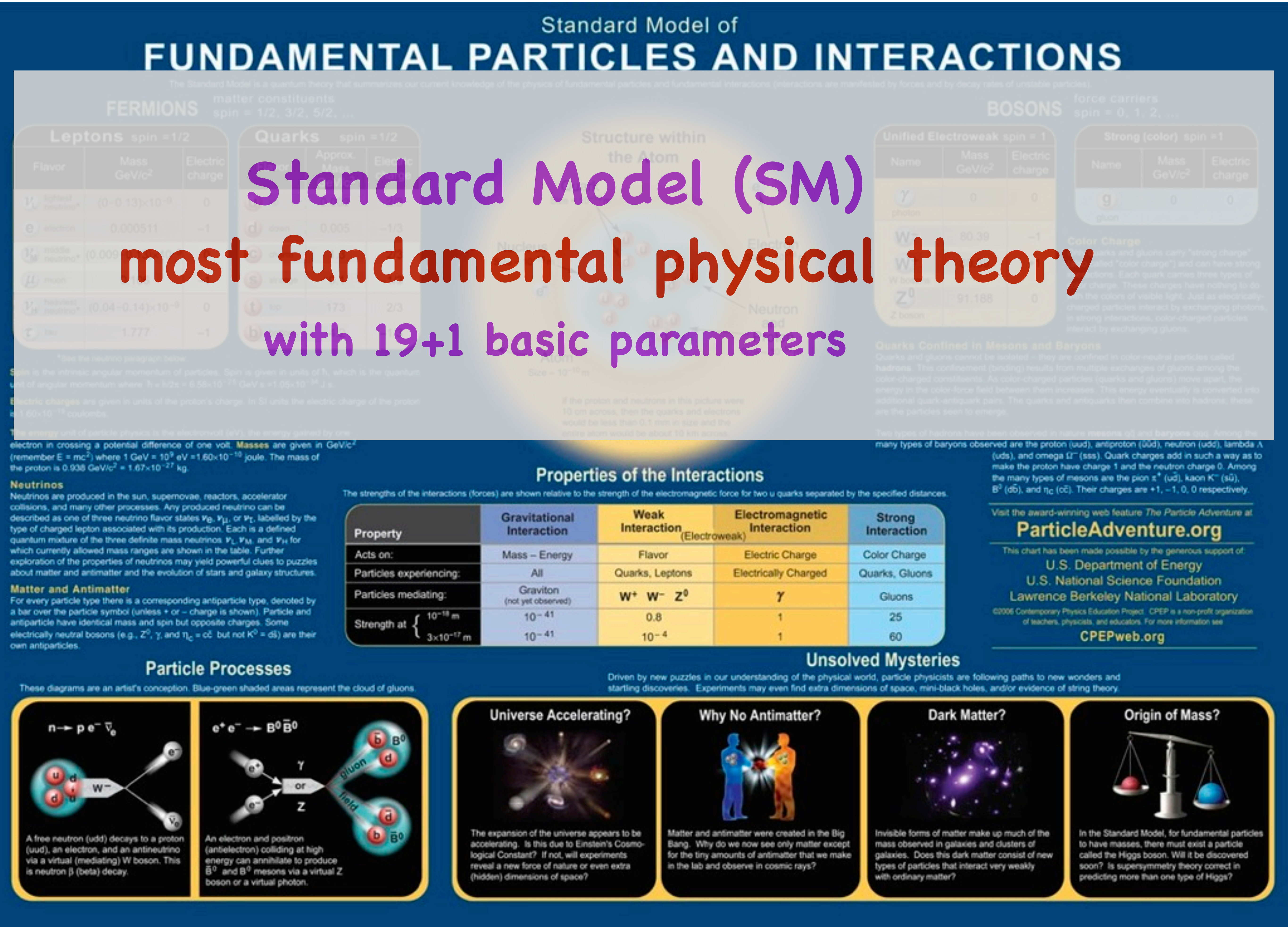
Origin of Mass?

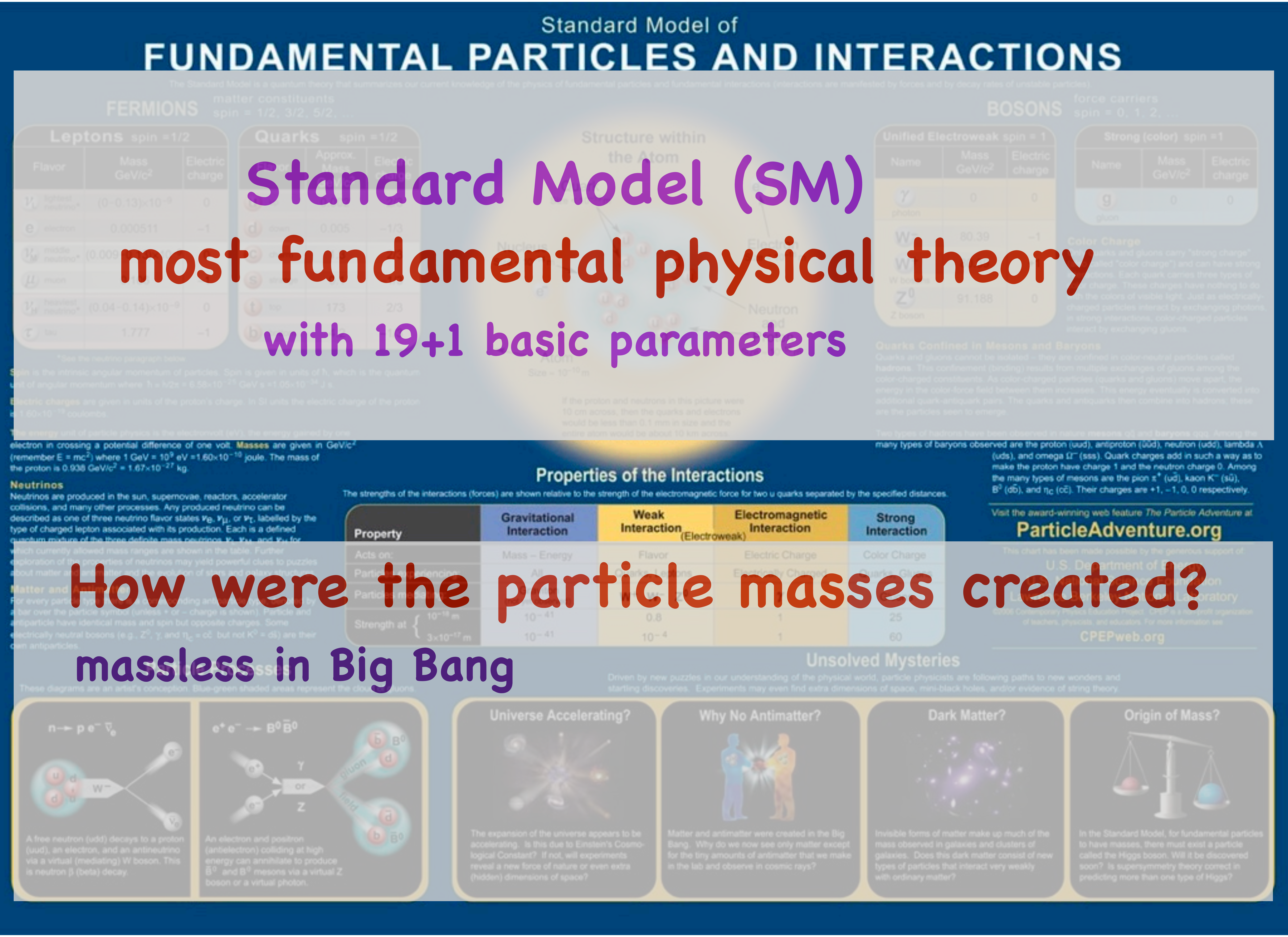
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

Standard Model (SM)

most fundamental physical theory

with 19+1 basic parameters





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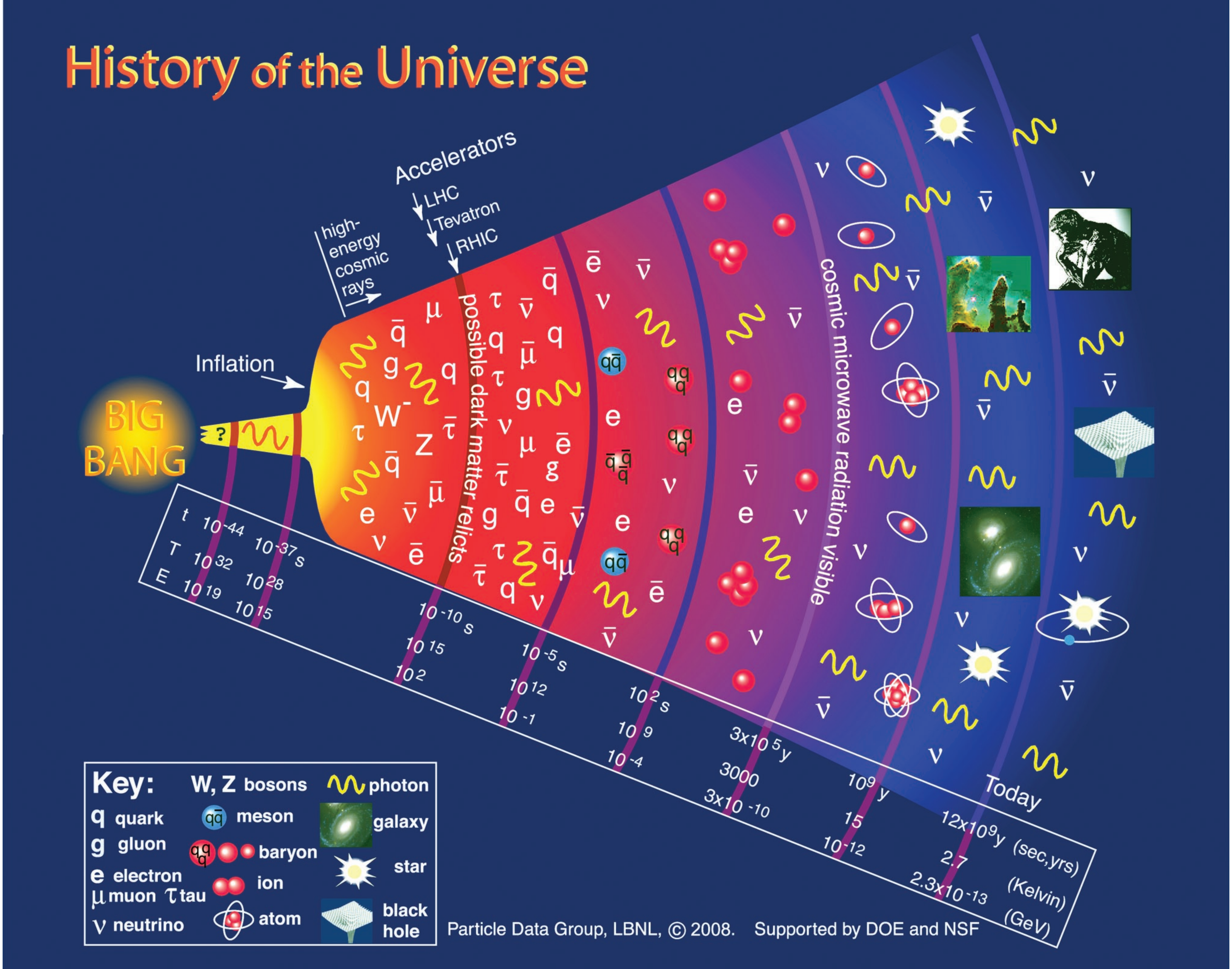
How were the particle masses created?

massless in Big Bang


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
3×10^{5} y
3000
3×10^{-10}
10^{9} y
15
10^{-12}
Today
12×10^{9} y (sec,yrs)
2.7 (Kelvin)
2.3×10^{-13} (GeV)
Key:
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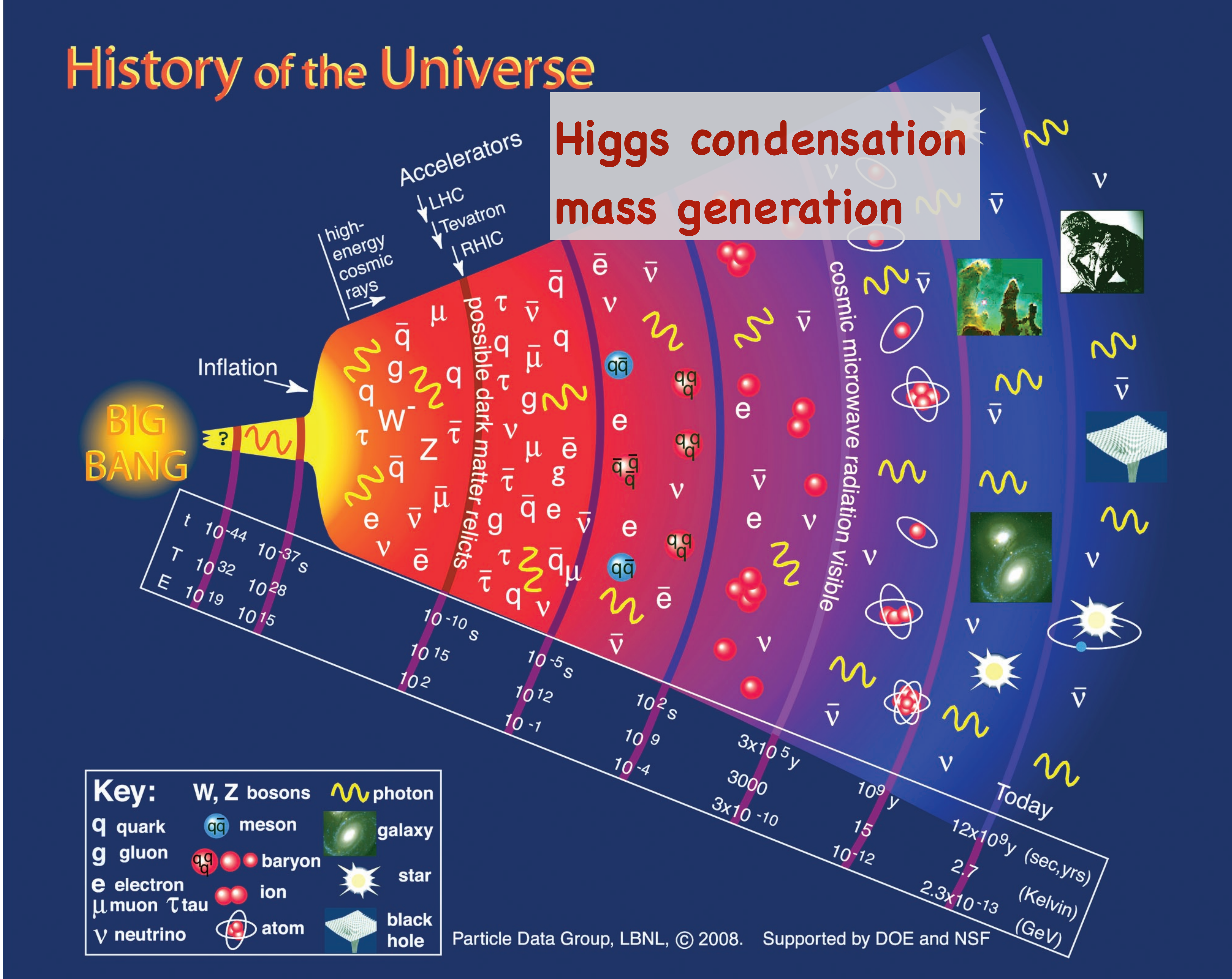
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF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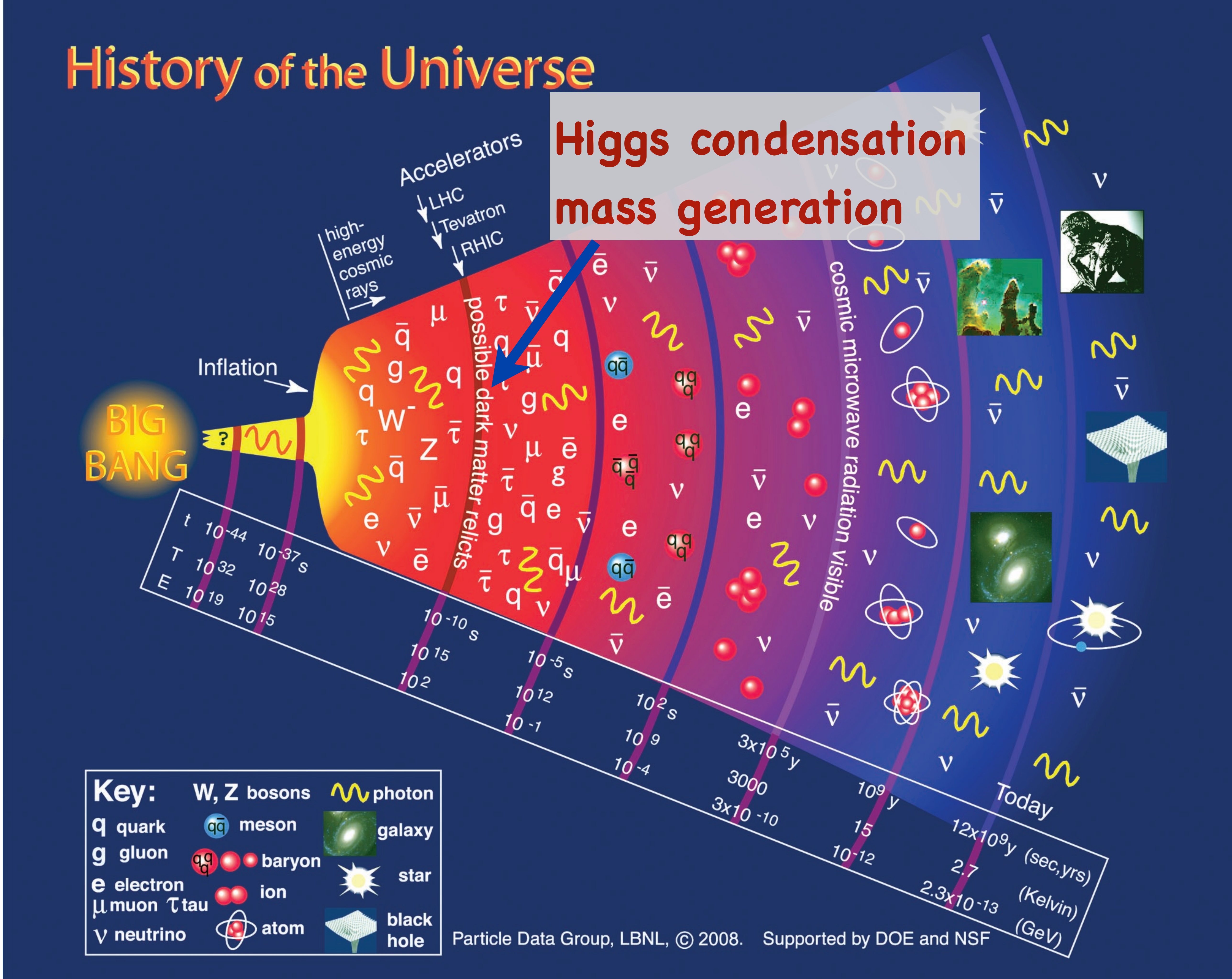

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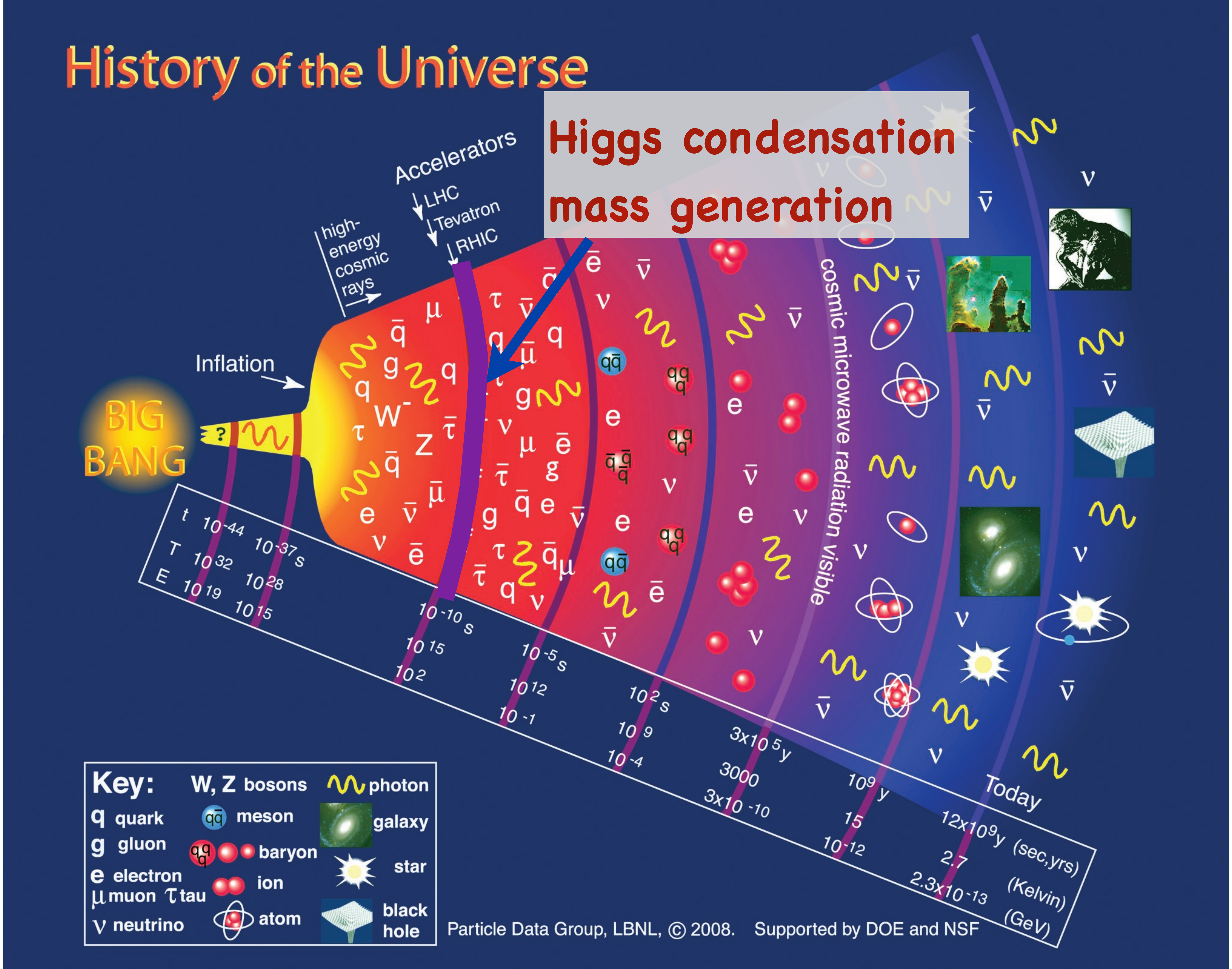

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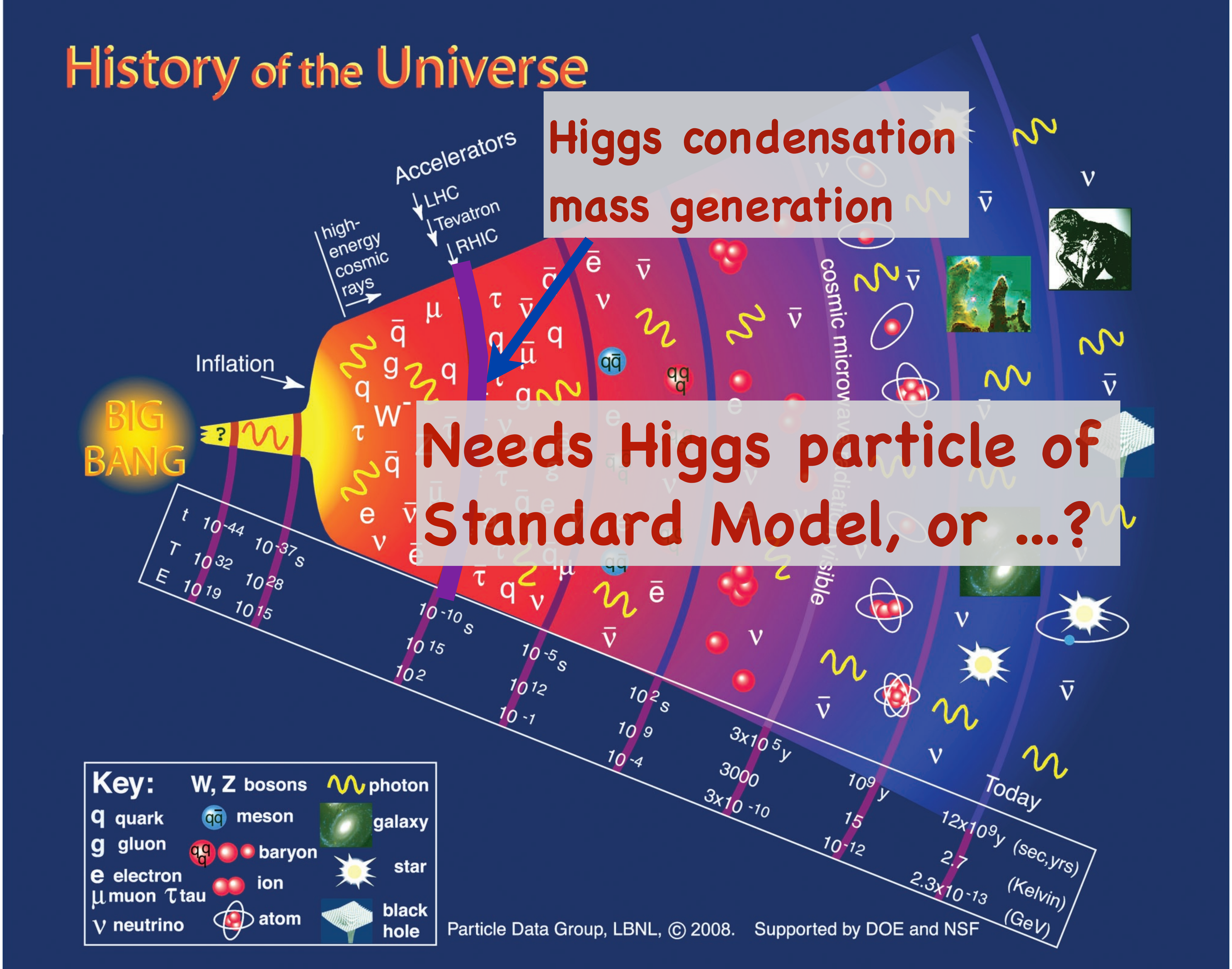


Higgs condensation
mass generation

Needs Higgs particle of
Standard Model, or ...?

Higgs-like boson discovered

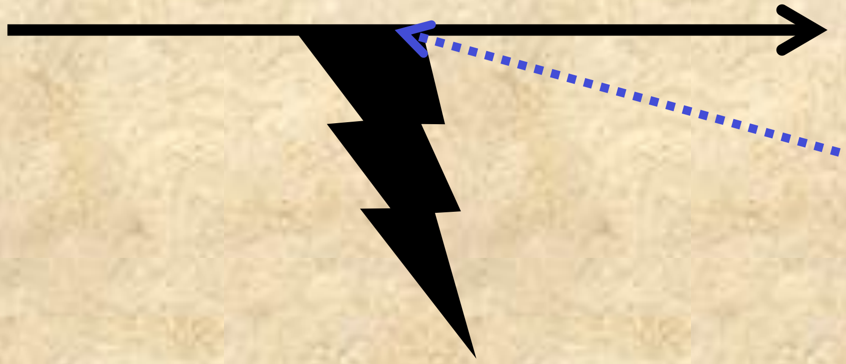
represents two of the 19+1 parameters
(Higgs mass and vacuum condensate)

vacuum condensate is characterized

by strength v = 250 GeV

massless particle moves with 'friction' in Higgs field condensate

Generates mass (origin of all masses !)



Higgs mass ~ 125 GeV

strength of 'friction' is Yukawa coupling g

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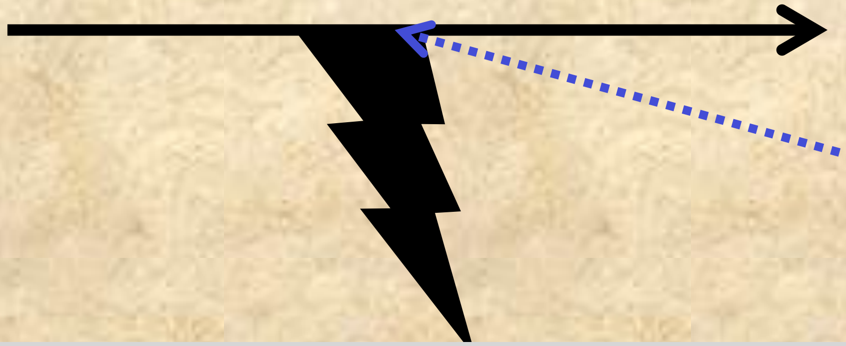

strength of 'friction' is Yukawa coupling g

Excitation of the condensate is the Higgs particle

Higgs-like boson discovered

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Higgs theory makes very accurate predictions -->

massless particle moves with 'friction' in Higgs field condensate

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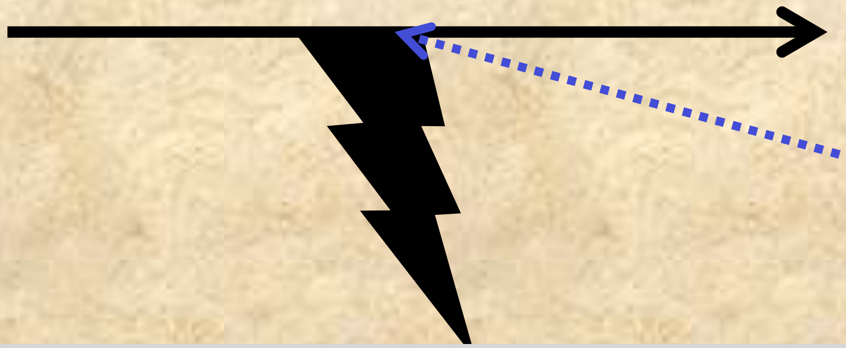
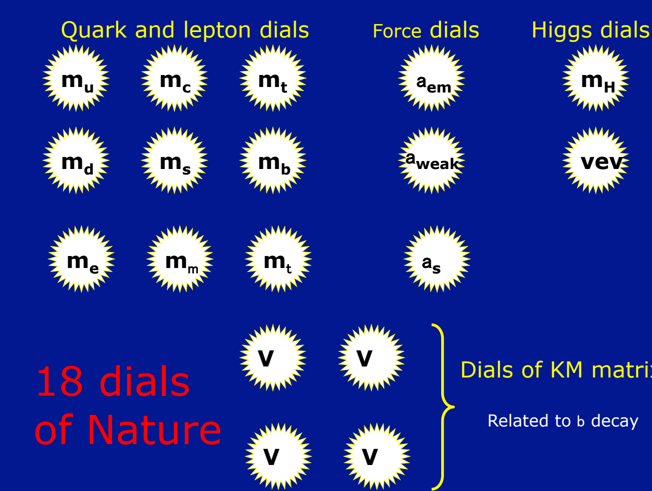


strength of 'friction' is Yukawa coupling g

Excitation of the condensate is the Higgs particle

Fusion process p+p -> de$^+$n begins pp cycle which fuels the Sun

If value of Higgs condensate v=250 GeV were doubled, the fusion reaction inside sun would slow down. Sun would shrink by about 22% (Jackson), it would also appear brighter with higher surface temperature.



Our everyday world would change dramatically by dialing the 19+1 parameters !

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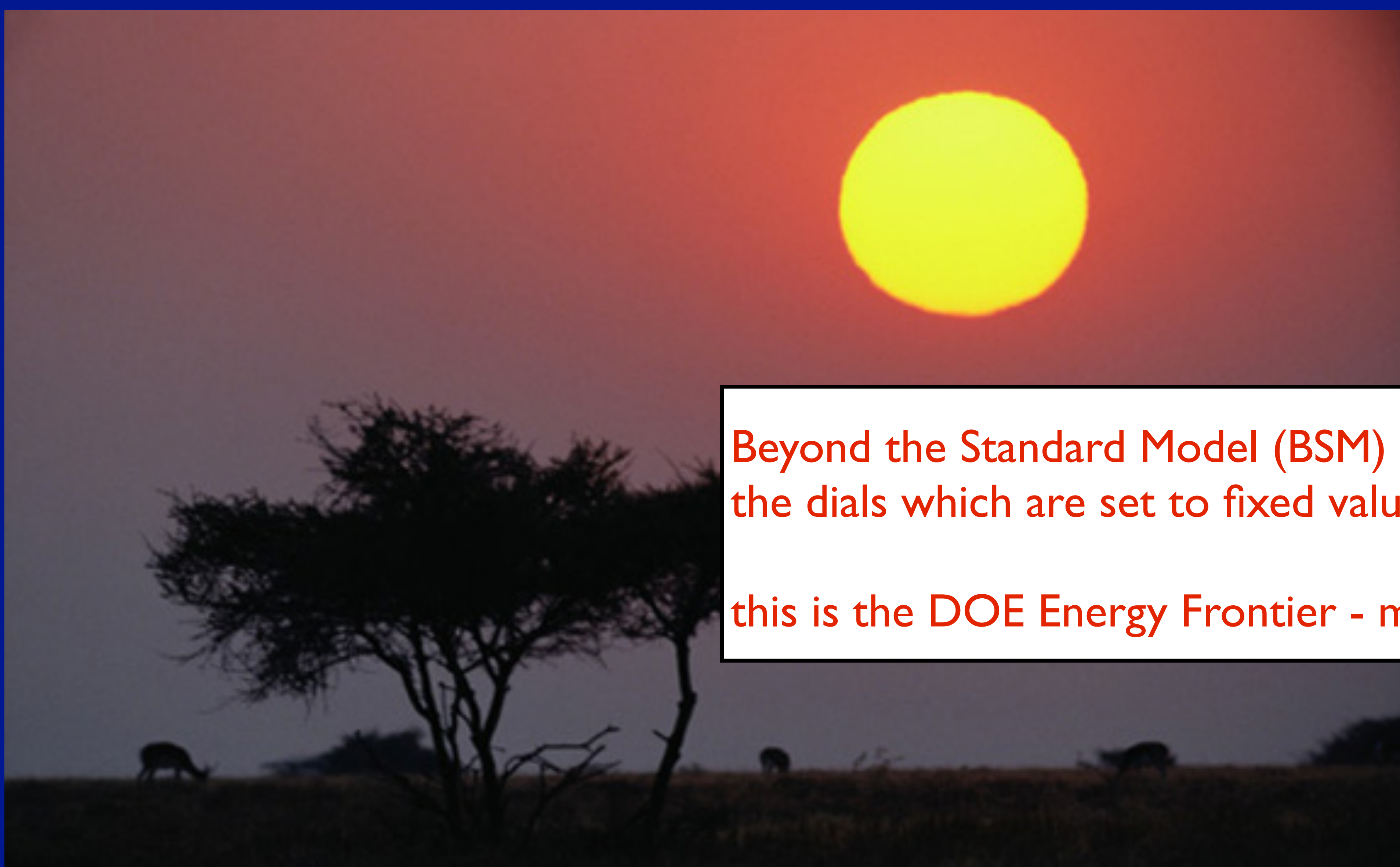
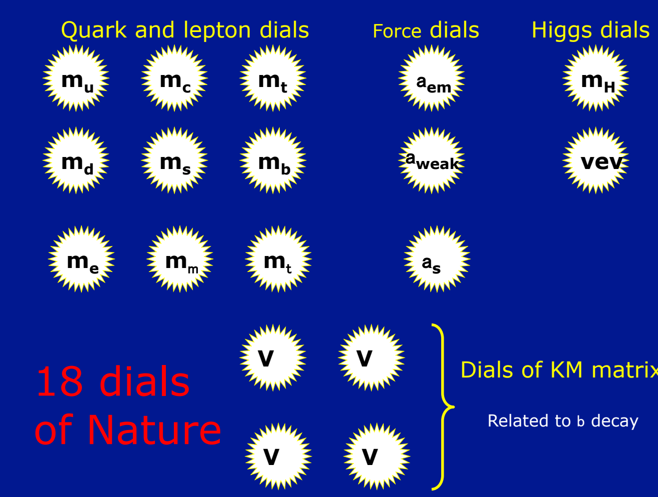




Beyond the Standard Model (BSM) tries to explain the origin of the dials which are set to fixed values in Standard Model (SM)

this is the DOE Energy Frontier - major USQCD effort

LATTICE GAUGE THEORIES AT THE ENERGY FRONTIER

Thomas Appelquist, Richard Brower, Simon Catterall, George Fleming,
Joel Giedt, Anna Hasenfratz, Julius Kuti, Ethan Neil, and David Schaich

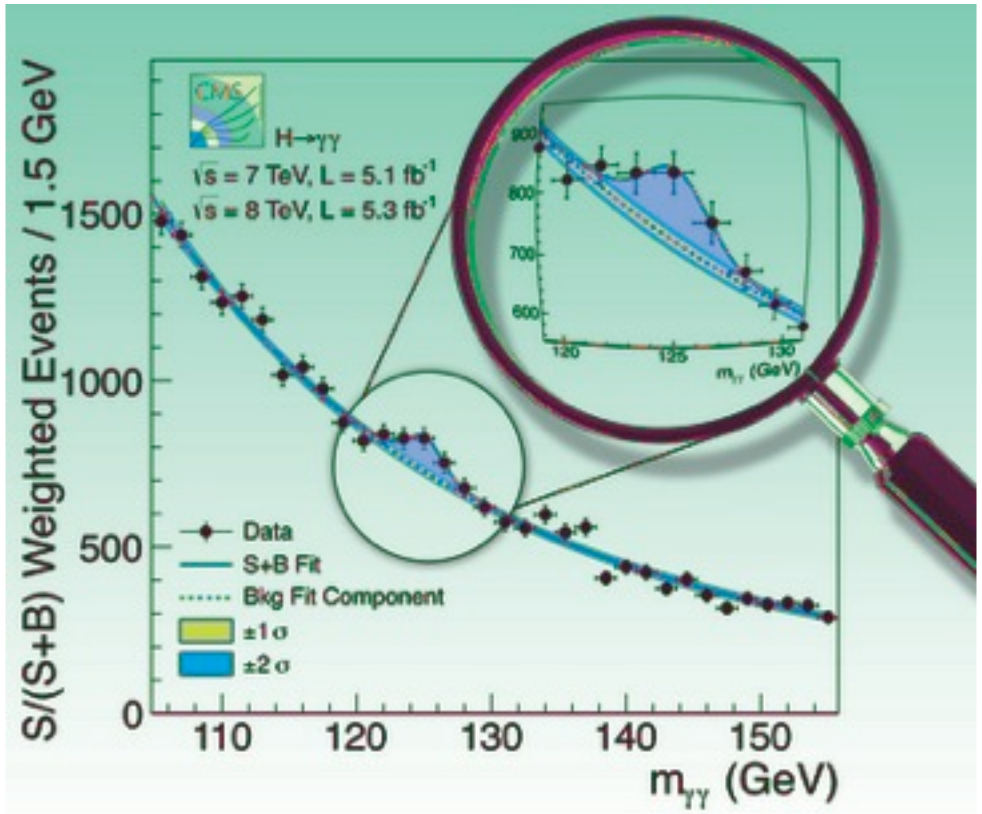
(USQCD Collaboration)

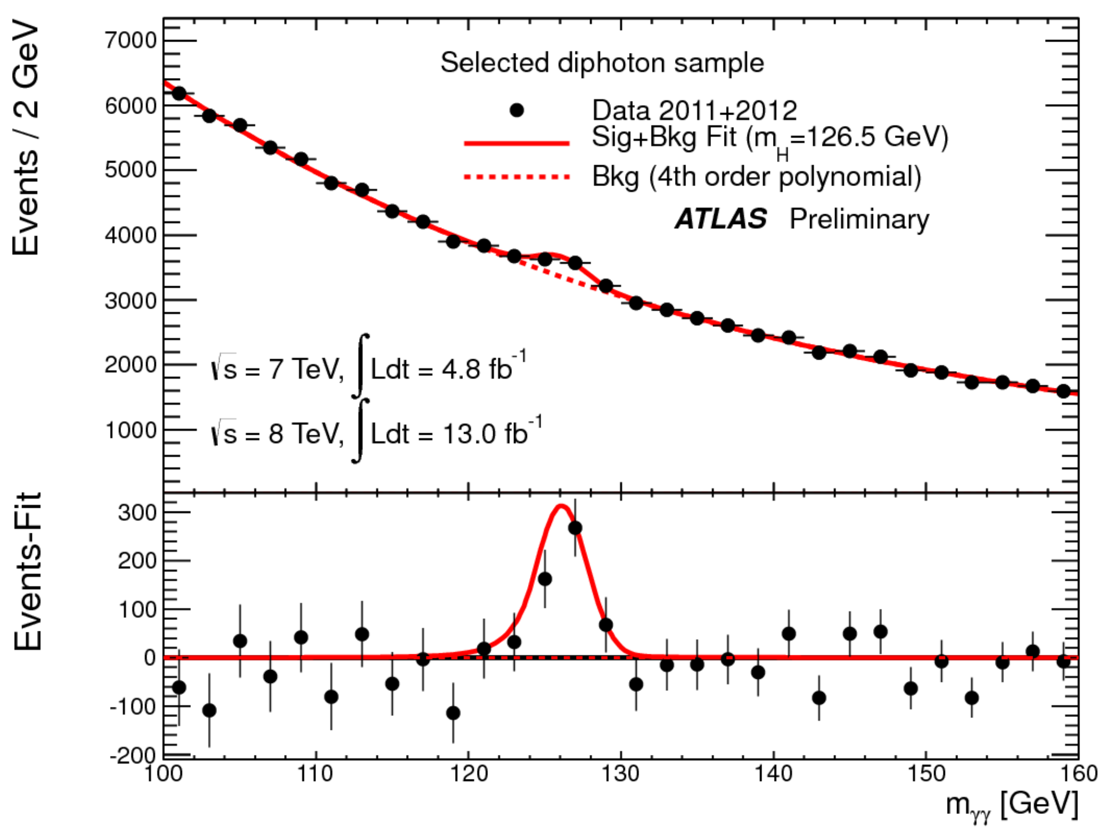
(Dated: March 10, 2013)

White paper - BSM community based effort to:

- identify most significant accomplishments of last few years
- identify our three major research directions for planning
- describe the toolset and its phenomenological applications
- estimate resources needed for the plan

New hardware proposal of USQCD just submitted to DOE



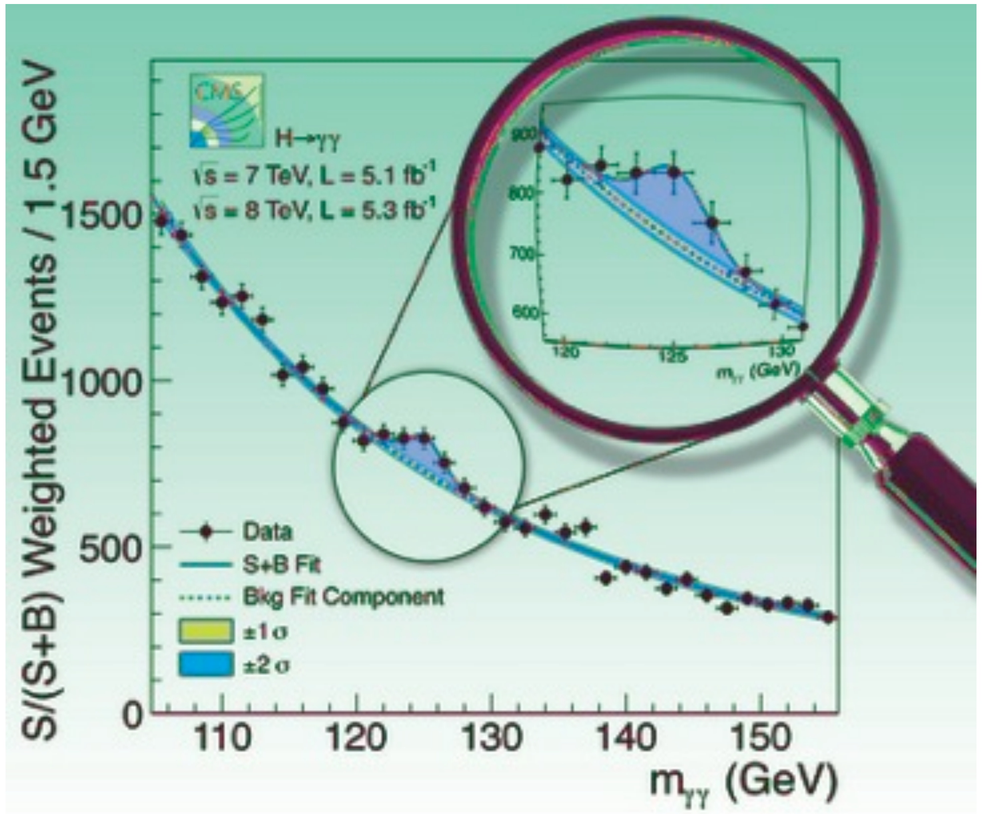


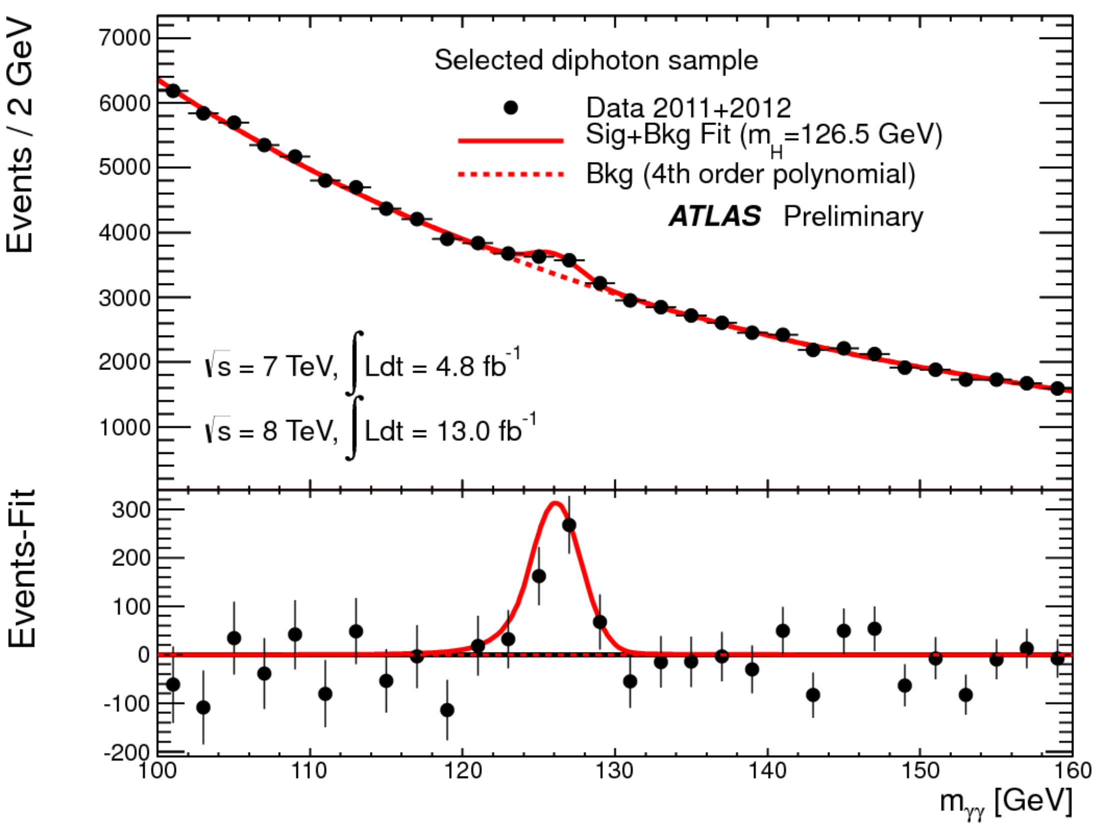
- two plots on left drives our planning

where is the Higgs?	no more asked
what is it made of?	asked now all the time

- “Mexican hat” solution is parametrization rather than dynamical explanation **(not gauge force!)**

- has fine tuning and hierarchy problems





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- three BSM directions to do better:

  - strongly coupled near-conformal gauge theories

  - light pseudo-Goldstone boson (like little Higgs)

  - SUSY

- new physics without tuning, within LHC14 reach? Or hiding just above LHC14 reach?

Highlights of accomplishments:

- Investigations of strongly coupled BSM gauge theories identified conformal or near conformal behavior, demonstrating that the anomalous mass dimensions and chiral condensates are enhanced near conformality, with interesting implications for model building.
- Electroweak precision experimental constraints were compared with numerical estimates of the S-parameter, W-W scattering, and the composite spectra. In particular in contrast with naive estimates, these studies demonstrate that the S-paramenter in near-conformal theories may be reduced in better agreement with experimental constraints.
- Investigations of $\mathcal{N} = 1$ supersymmetric Yang Mills theory (gauge bosons and gauginos) produced estimates of the gluino condensate and string tension in these theories.

Calculational goals identified in the white paper:

- To determine whether a composite dilaton-like particle or light Higgs can emerge in near-conformal quantum field theories.
- To investigate strongly coupled theories with a composite Higgs as a pseudo-Goldstone boson.
- To investigate the nature of $\mathcal{N} = 1$ SUSY breaking with matter multiplets and $\mathcal{N} = 4$ conformal SUSY as a test bed for AdS/CFT theoretical conjectures.

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all three directions break away from QCD paradigm

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new fields and field theories on the lattice (compute intensive)

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feedback to Intensity Frontier ?

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feedback to Intensity Frontier ?

muon g-2 experiment is an interesting example

The light Higgs and the dilaton near conformality

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\left[\Theta_\mu^\mu(0)\right]_{NP}|0\rangle$$

Partially Conserved Dilatation Current (PCDC)

there are two different expectations when conformal window is approached: $g(\mu=\Lambda)=g_c$

1. dilaton mass parametrically vanishes $m_\sigma^2 \simeq (N_f^c - N_f)\cdot\Lambda^2$ $\quad \frac{m_\sigma}{f_\sigma}\to 0$

2. dilaton mass finite in the limit $f_\sigma \simeq \Lambda$ $\quad \frac{m_\sigma}{f_\sigma}\to const$

important role of $\frac{f_\pi}{f_\sigma}$ in electroweak phenomenology

both scenarios expect light Higgs-like dilaton

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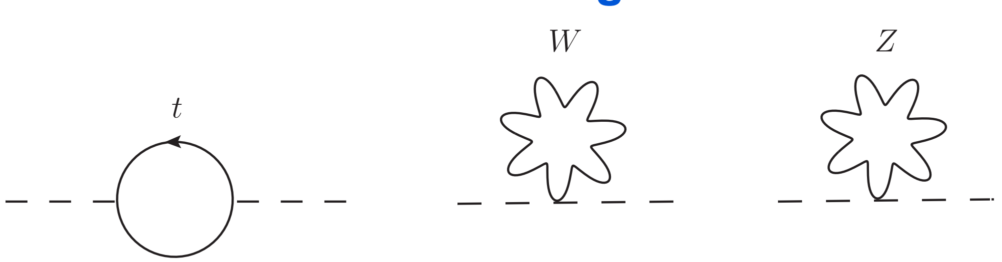

$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\mathrm{GeV})^2$$

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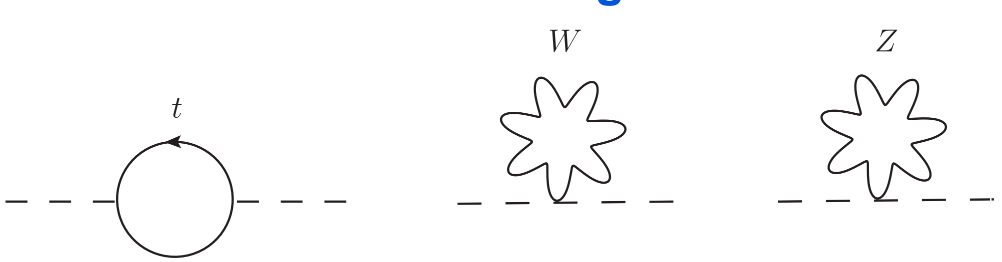

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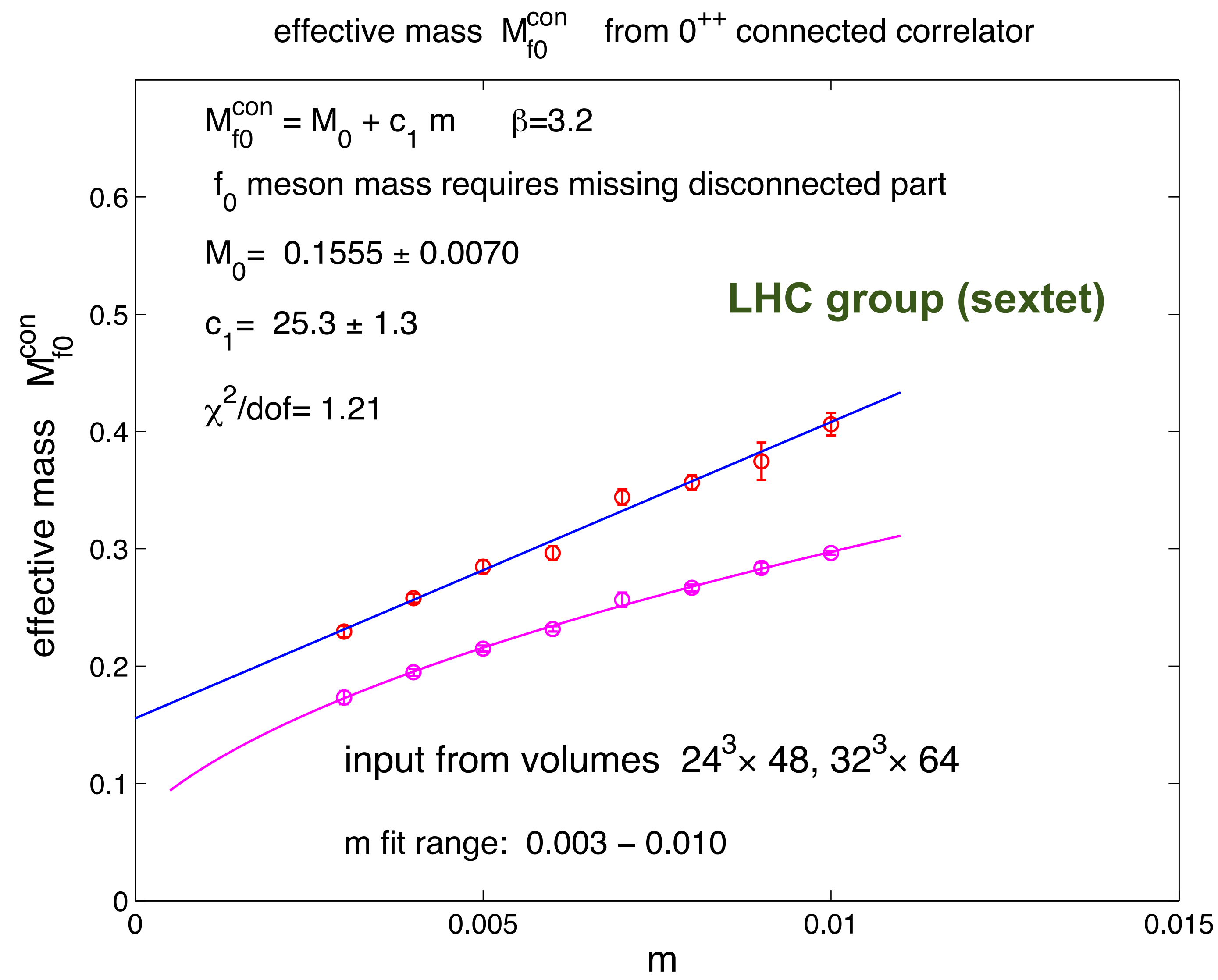

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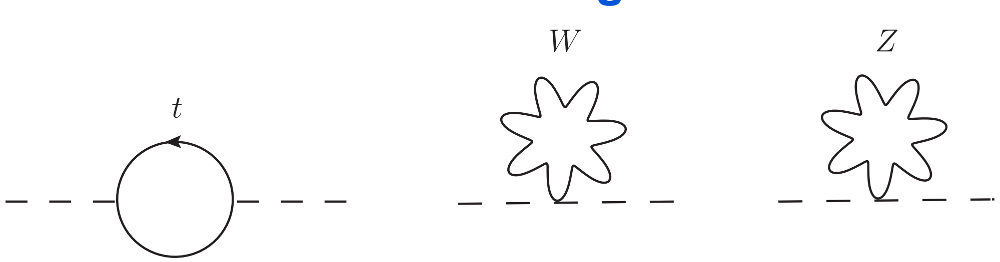

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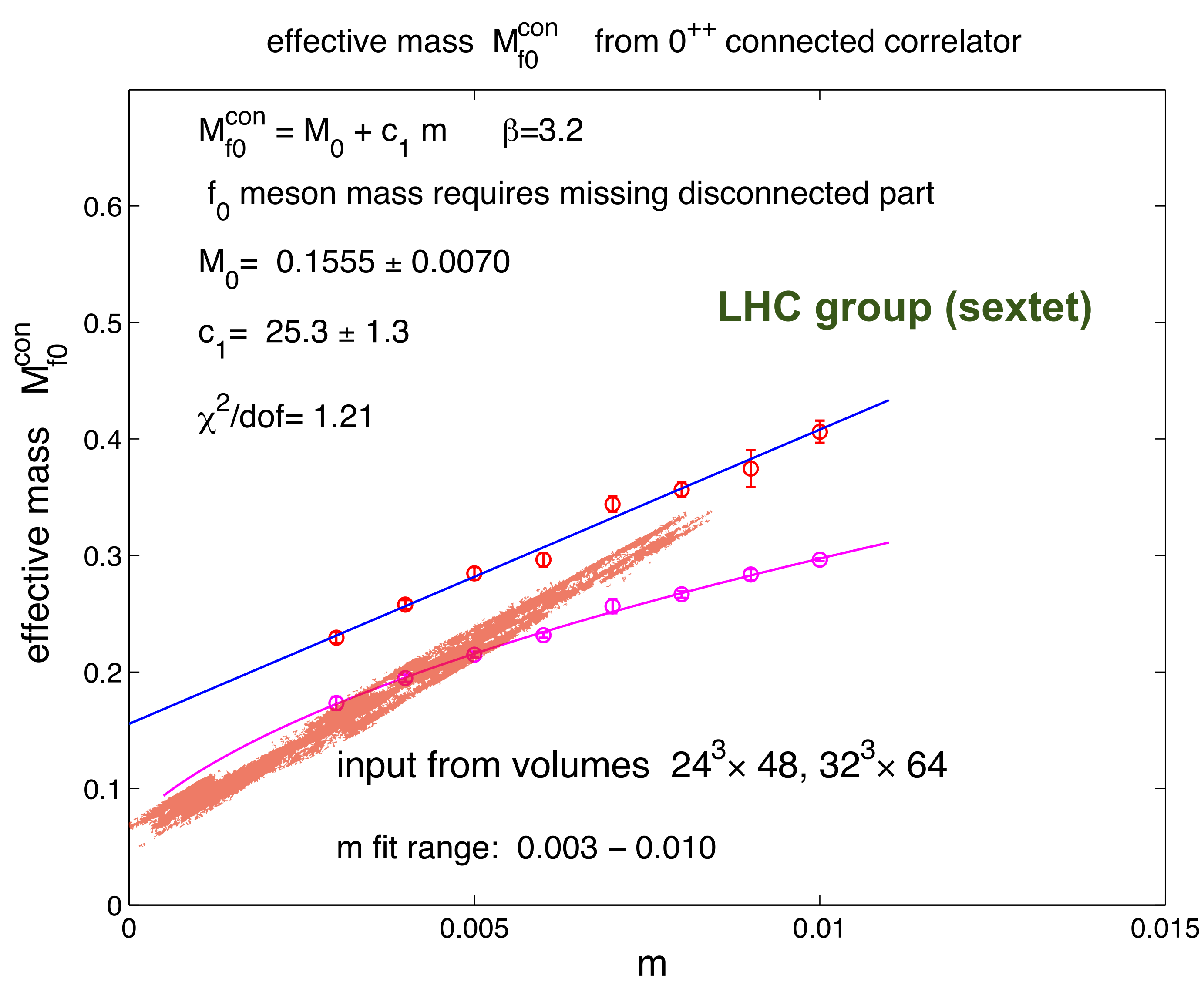
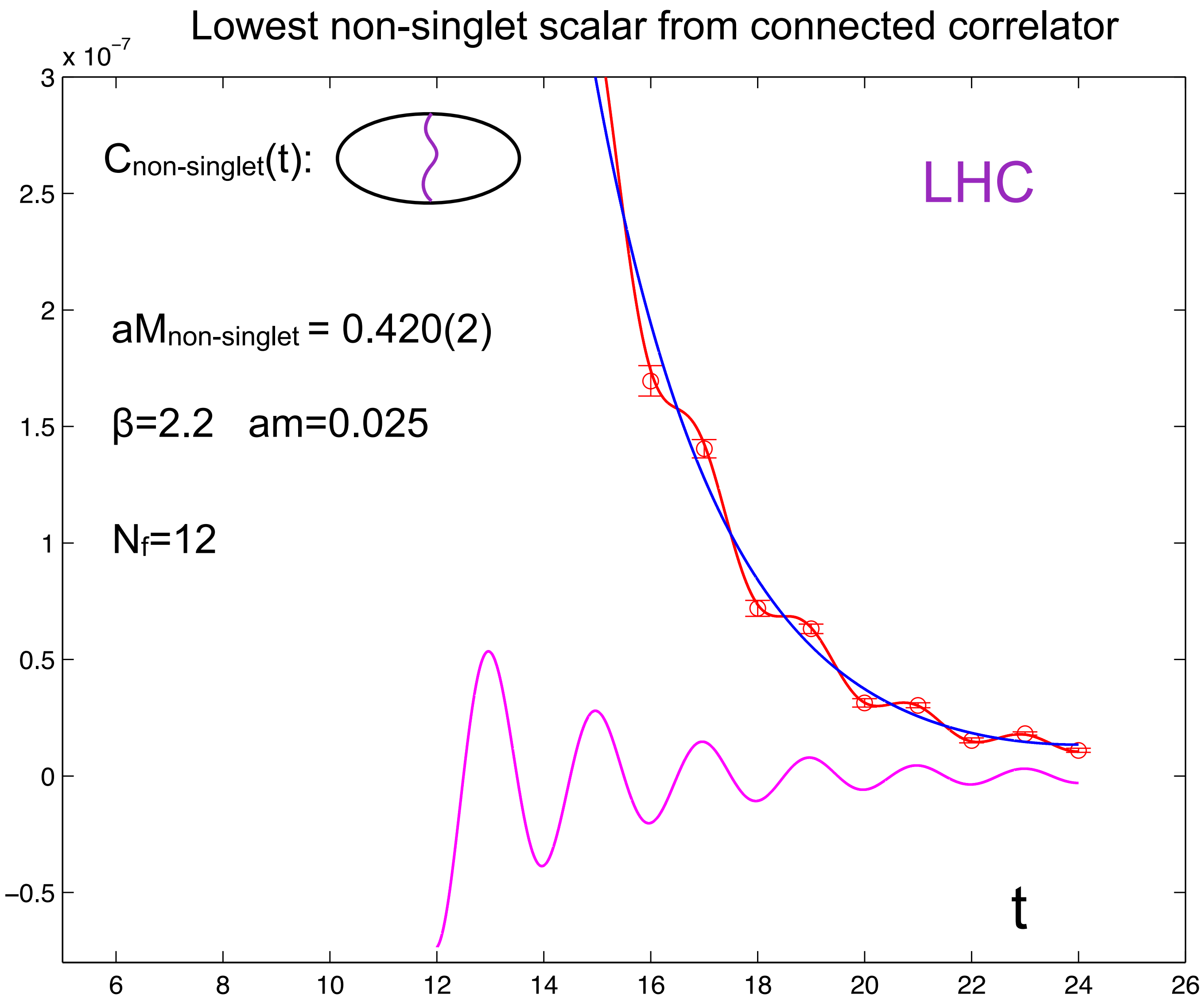
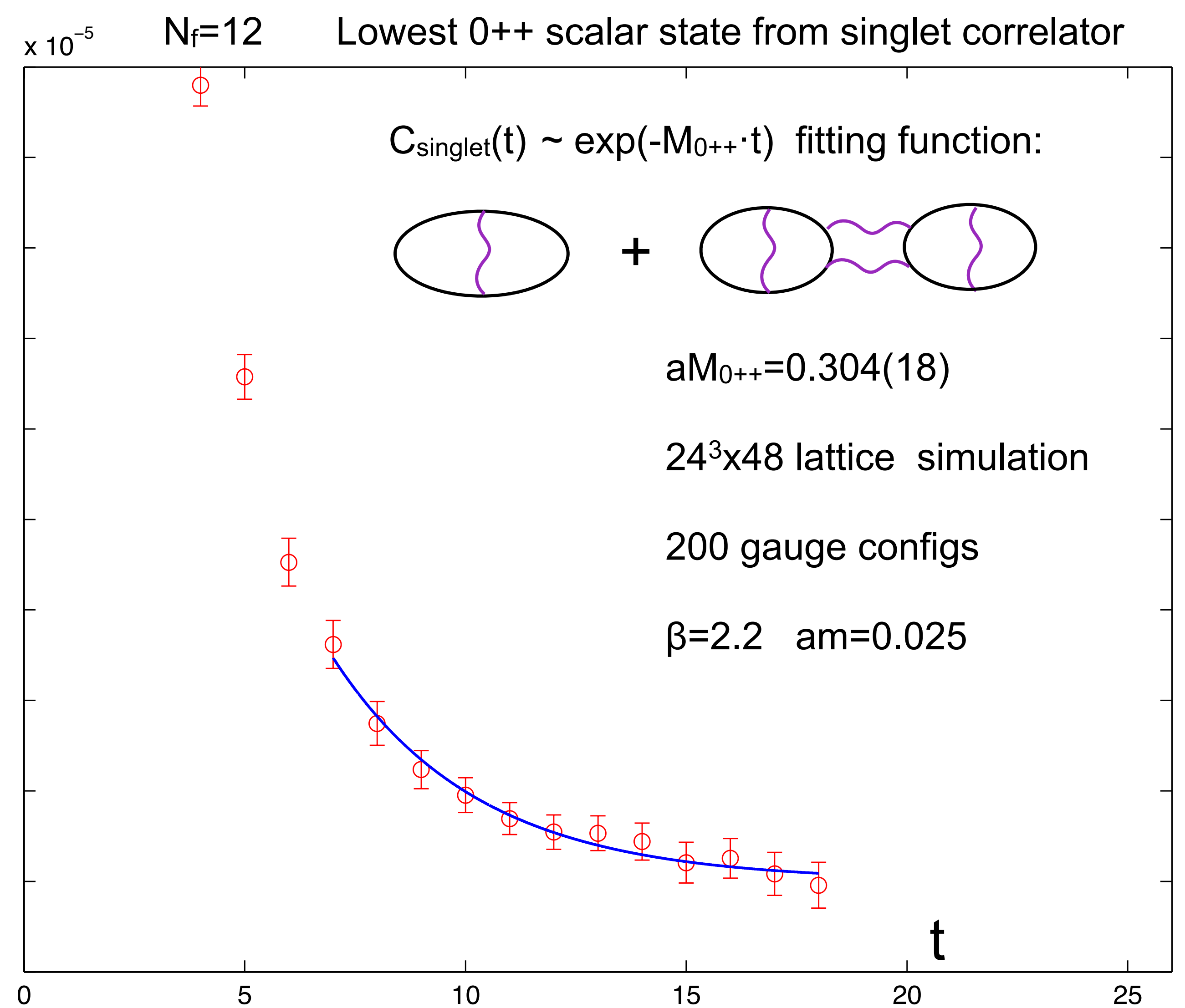


The light Higgs and the dilaton near conformality

proof of life:





$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S \otimes \gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

similar test results were performed in sextet model with Nf=2

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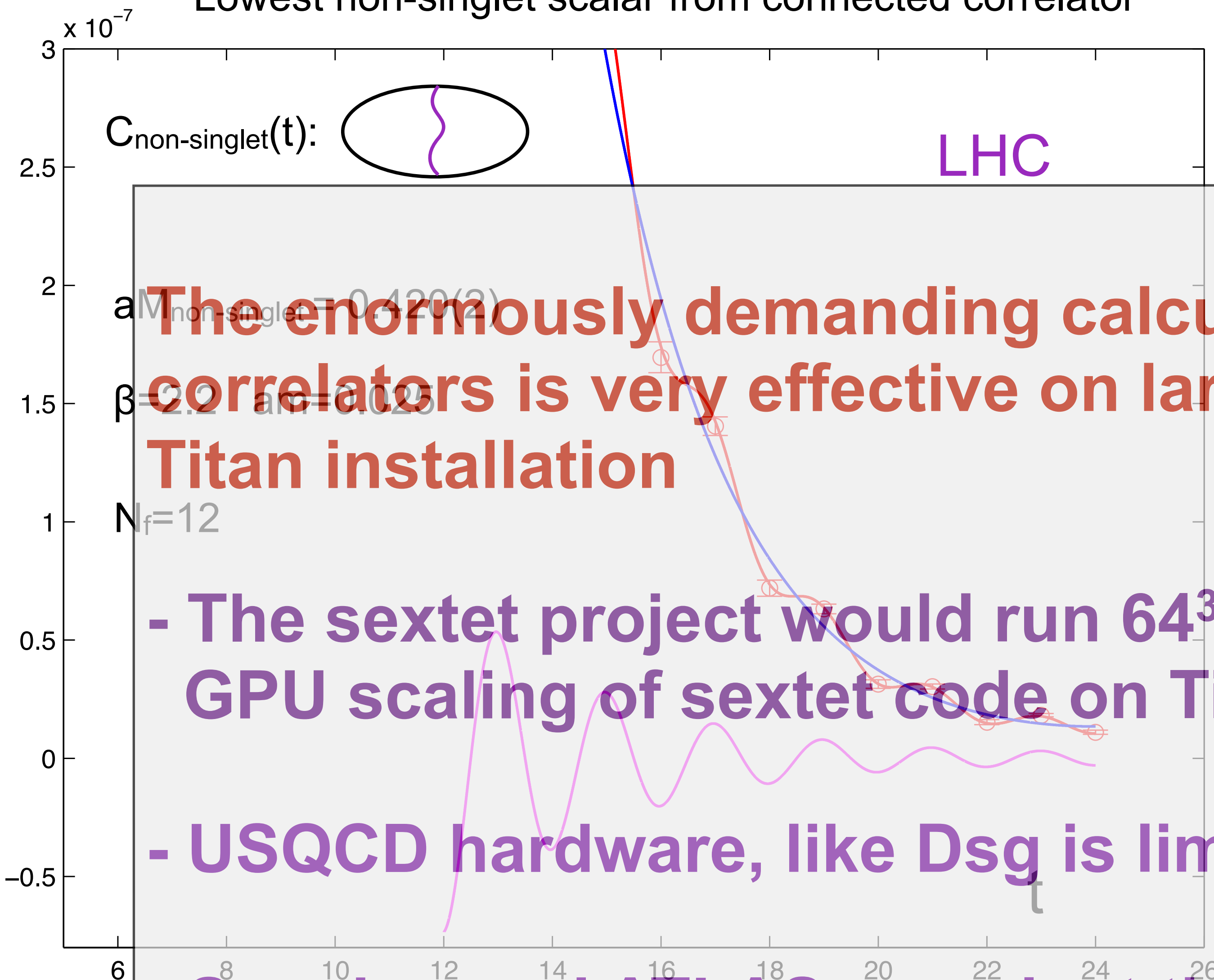

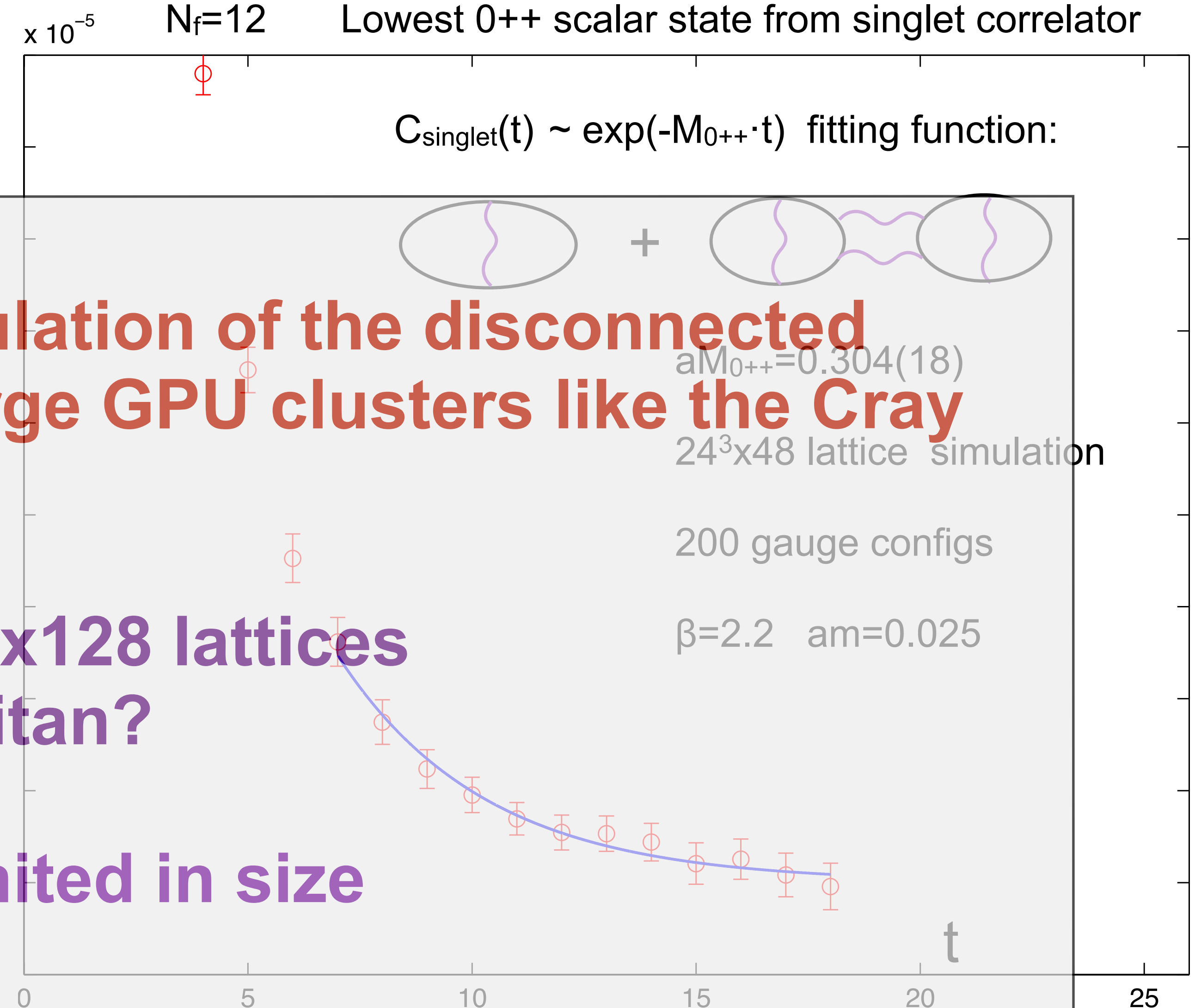

The enormously demanding calculation of the disconnected correlators is very effective on large GPU clusters like the Cray Titan installation

- **The sextet project would run 64^3x128 lattices GPU scaling of sextet code on Titan?**

- **USQCD hardware, like Dsg is limited in size**

- **Sannino and ATLAS search at the LHC**

$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S\otimes\Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S\otimes\gamma_4\gamma_5\Gamma_T)t}\right]$$

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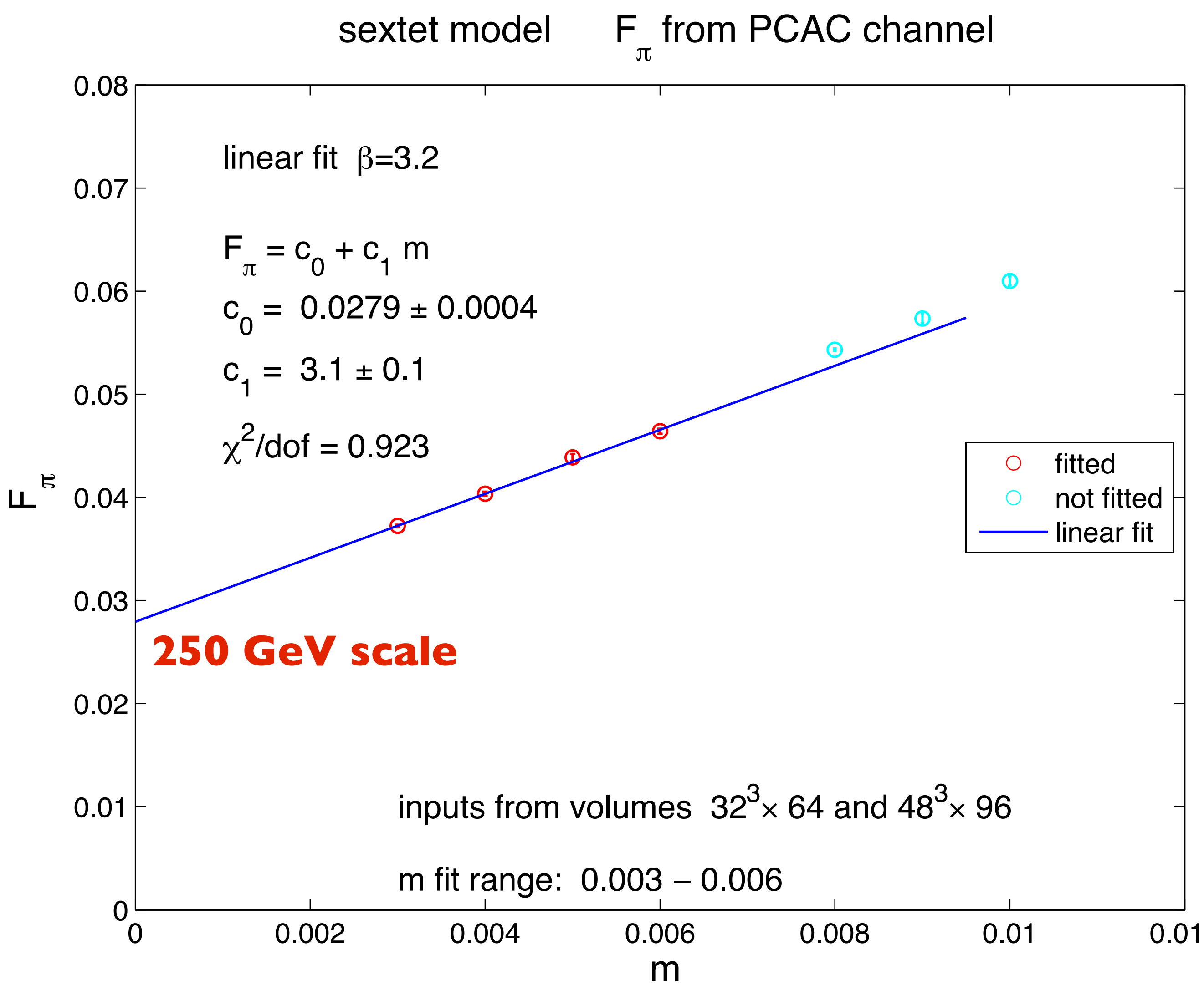
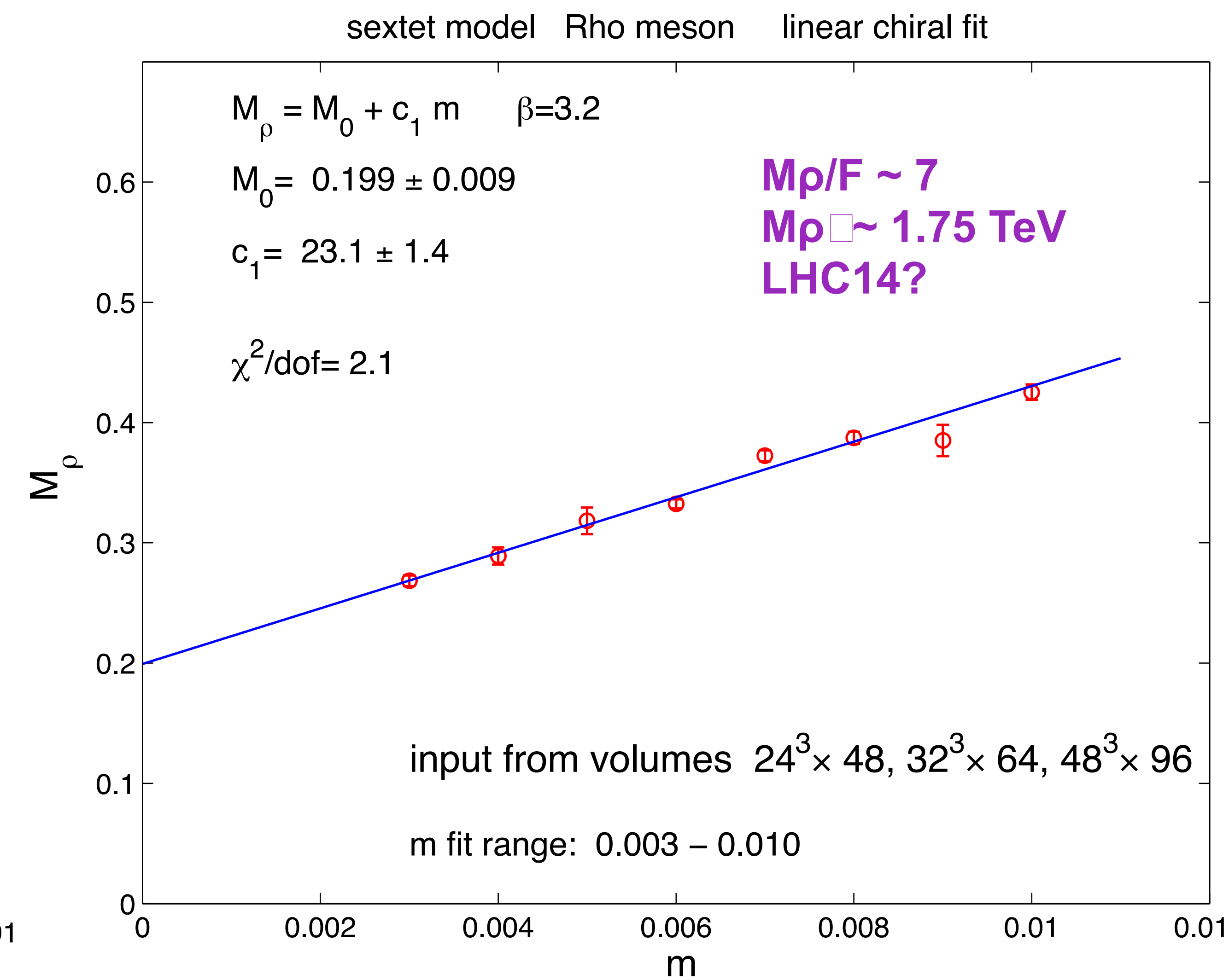
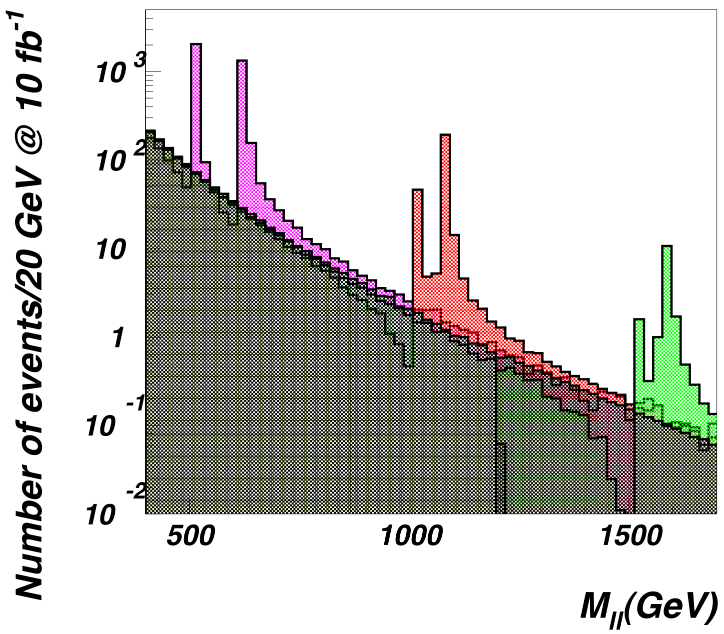
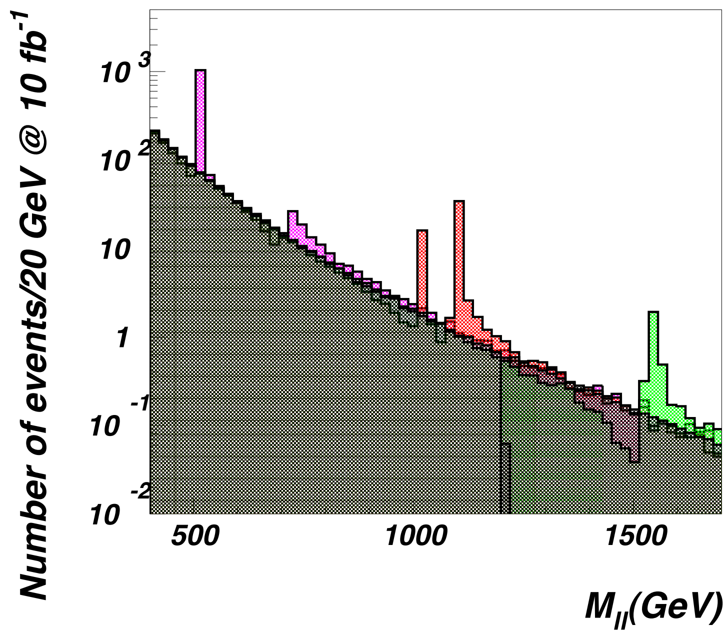

sextet model F π from PCAC channel
linear fit β=3.2
F π = c 0 + c 1 m
c 0 = 0.0279 ± 0.0004
c 1 = 3.1 ± 0.1
χ2/dof = 0.923
fitted
not fitted
linear fit
250 GeV scale
inputs from volumes 323× 64 and 483× 96
m fit range: 0.003 – 0.006
F π
m
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.002
0.004
0.006
0.008
0.01


sextet model Rho meson linear chiral fit
M ρ = M 0 + c 1 m β=3.2
M 0= 0.199 ± 0.009
c 1= 23.1 ± 1.4
χ2/dof= 2.1
Mρ/F ~ 7
Mρ ~ 1.75 TeV
LHC14?
input from volumes 243× 48, 323× 64, 483× 96
m fit range: 0.003 – 0.010
M ρ
m
0.6
0.5
0.4
0.3
0.2
0.1
0
0.002
0.004
0.006
0.008
0.01
0.012

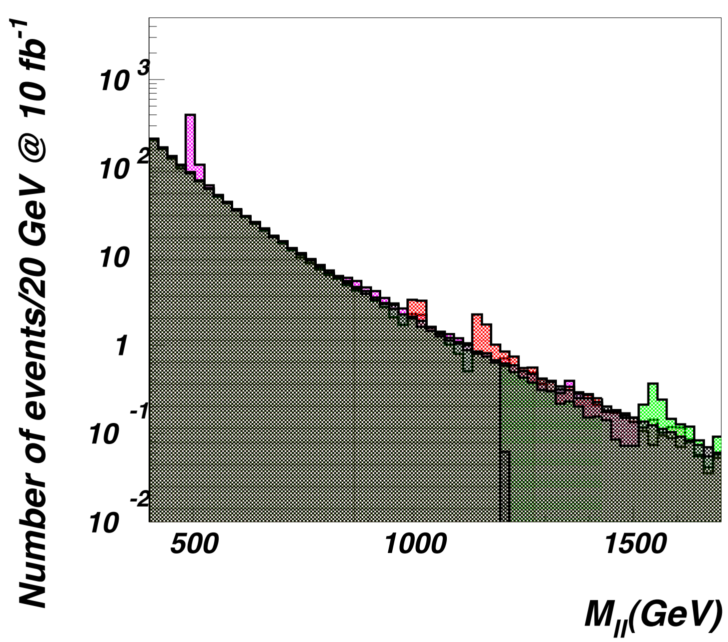
- neraly-conformal BSM physics is represented by the sextet model
- Highly compute intensive (required flop rate ~ 5x-6x of lattice QCD
- Atlas is looking for predictions of the model

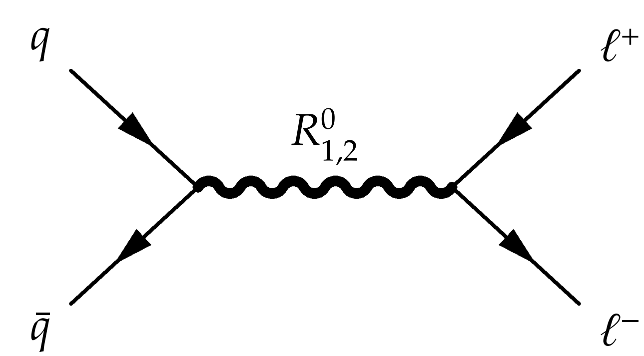




Drell-Yen production of composite vector bosons on the TeV scale

from Sannino et al.





Feynman diagram of TeV scale new vector meson production

Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R_{1,2} \to \ell^+\ell^-$ signal

Higgs as a pseudo-Goldstone boson

- strong dynamics identifying the Higgs as a **scalar** pseudo-Nambu-Goldstone boson (PNGB)

- in strongly coupled gauge theories with fermions in real or pseudo-real reps of the gauge group Goldstone scalars emerge

- this PNGB Higgs mechanism plays a critical role in **little Higgs** models

- (also in minimal technicolor models)

- in little Higgs models global symmetries and their symmetry breaking patterns cancel the quadratic divergences of the Higgs mass with little fine tuning to ~ 10 TeV

- this provides phenomenologically interesting models with weakly coupled extensions of the SM with PNGB Higgs scalars

- project to demonstrate that viable UV complete theories exist with strong gauge sector replacing the weakly coupled elementary (mexican hat) Higgs.

Higgs as a pseudo-Goldstone boson

Minimal PNGB model:

- SU(2) color gauge group with Nf=2 fundamental massless fermions

- additional steril flavors with Nf > 2 can be added to drive the theory close to or into the conformal window (?)

- pseudo-real SU(2) color group enlarges SU(Nf)xSU(Nf) vector-axial vector symmetry to SU(2Nf) flavor symmetry combining 1Nf left/right 2-component chiral spinors

- most attractive channel breaks SU(2Nf) to Sp(2Nf). If explicit masses are given to Nf-2 flavors the remaining 2 massless flavors yield SU(4)/Sp(4) coset with 5 Goldstone bosons:

- isotriplet pseudo-scalars (techni-pions) and two isosinglet scalars

- top quark loop breaks symmetry explicitly and lifts the massas of the two scalars

- the lighter is the Higgs impostor and the heavier is dark matter candidate

Studies of supersymmetric theories on the lattice

- New theoretical formulations
- improved algorithms
- increased computer power

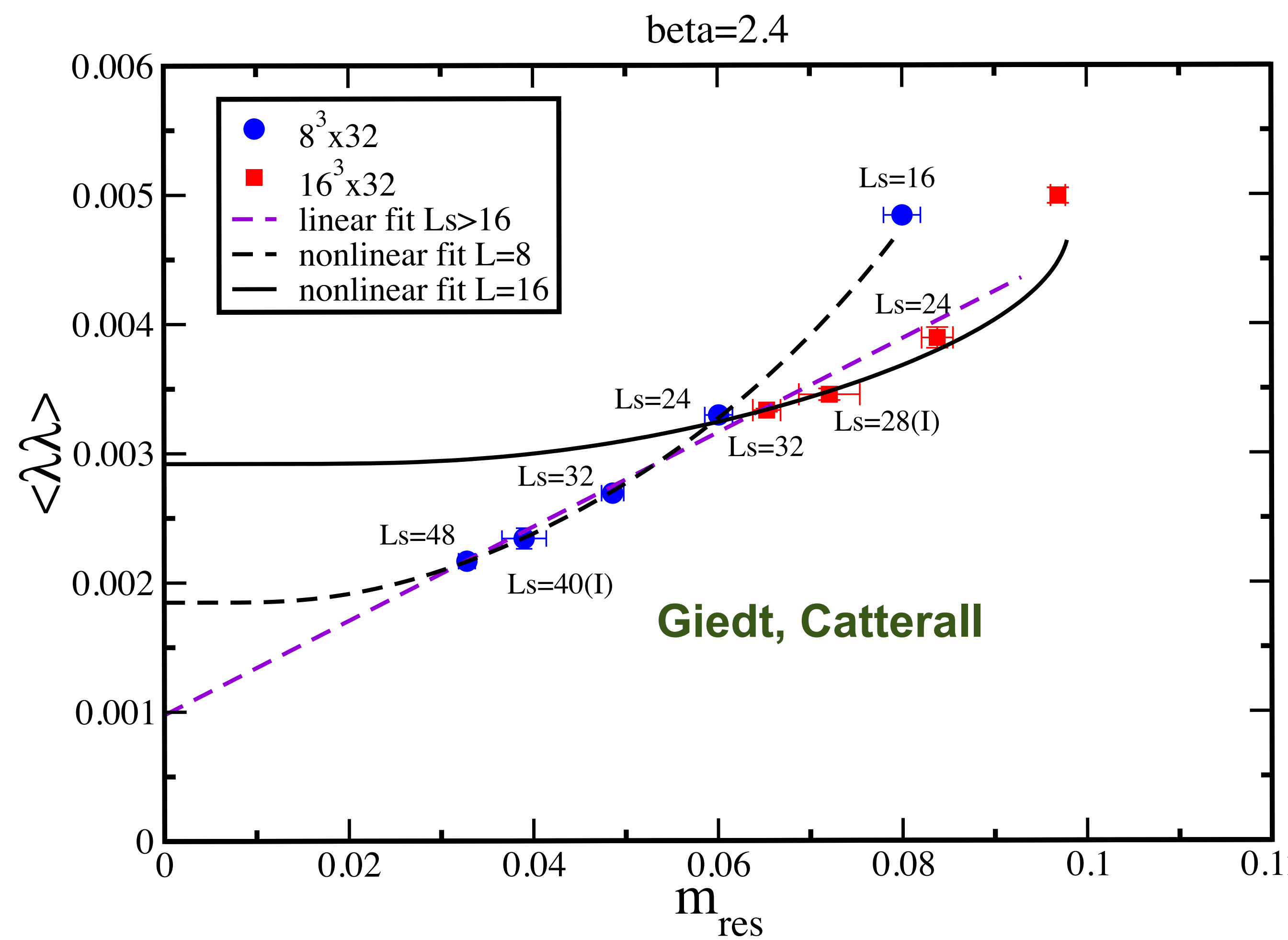
pioneering studies of N=1 and N=4 super Yang-Mills

N=1 super Yang-Mills is supersymmetric pure gauge QCD

first step to super QCD can play the role of non-perturbative SUSY breaking in high scale hidden sector

Gaugino condensate vs residual mass
SU(2) N=1 super Yang-Mills
DW fermions

next goal is super QCD investigating the simplest system with metastable vacua (four colors and five flavors)



Studies of supersymmetric theories on the lattice

Non-perturbative N=4 super Yang-Mills program

- with topologically twisted form of the action

- possesses a single exact supersymmetry at finite lattice spacing

- exploring holographic connections between gauge theories and string/gravity theories

- holographic techni-dilaton connection?

  - dilaton is simple to realize (translations along flat directions)

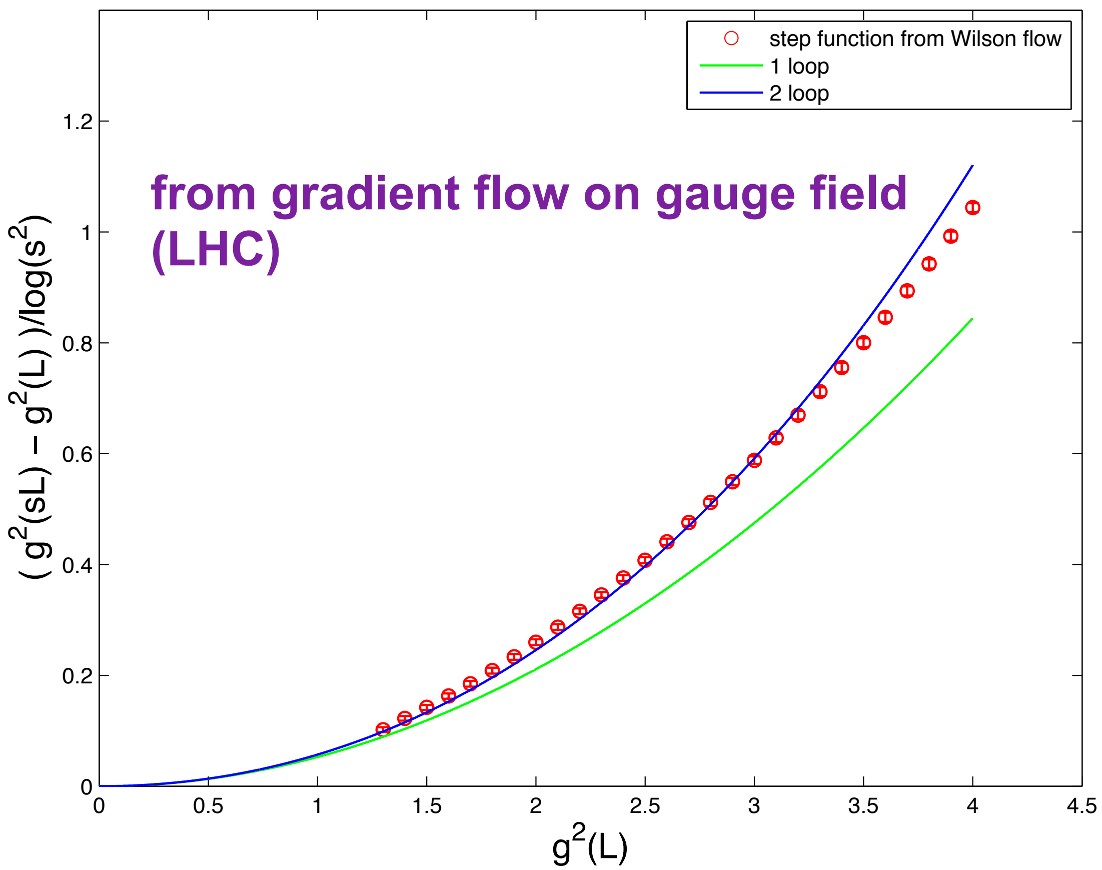
  - N=4 lattice action has flat directions (protected by exact lattice supersymmetry)

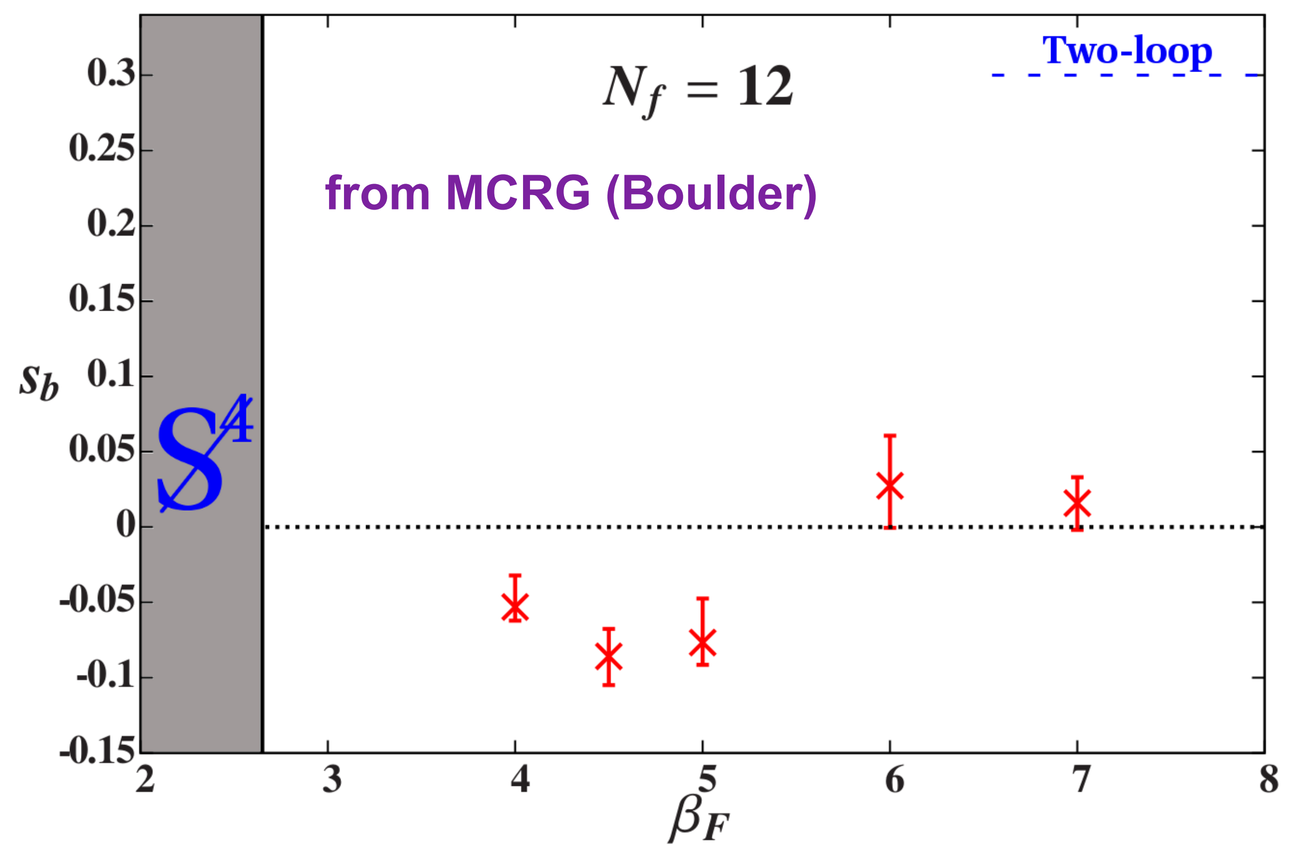
- fermion Pfaffian presents algorithmic challenge with complex phases in determinant

Toolset and its phenomenological applications

Running coupling and beta-function

(to understand the force triggering the vacuum condensate)





gradient flow on gauge field id beautiful realization of Wilson's exact RG with continuous momentum integration - Luscher

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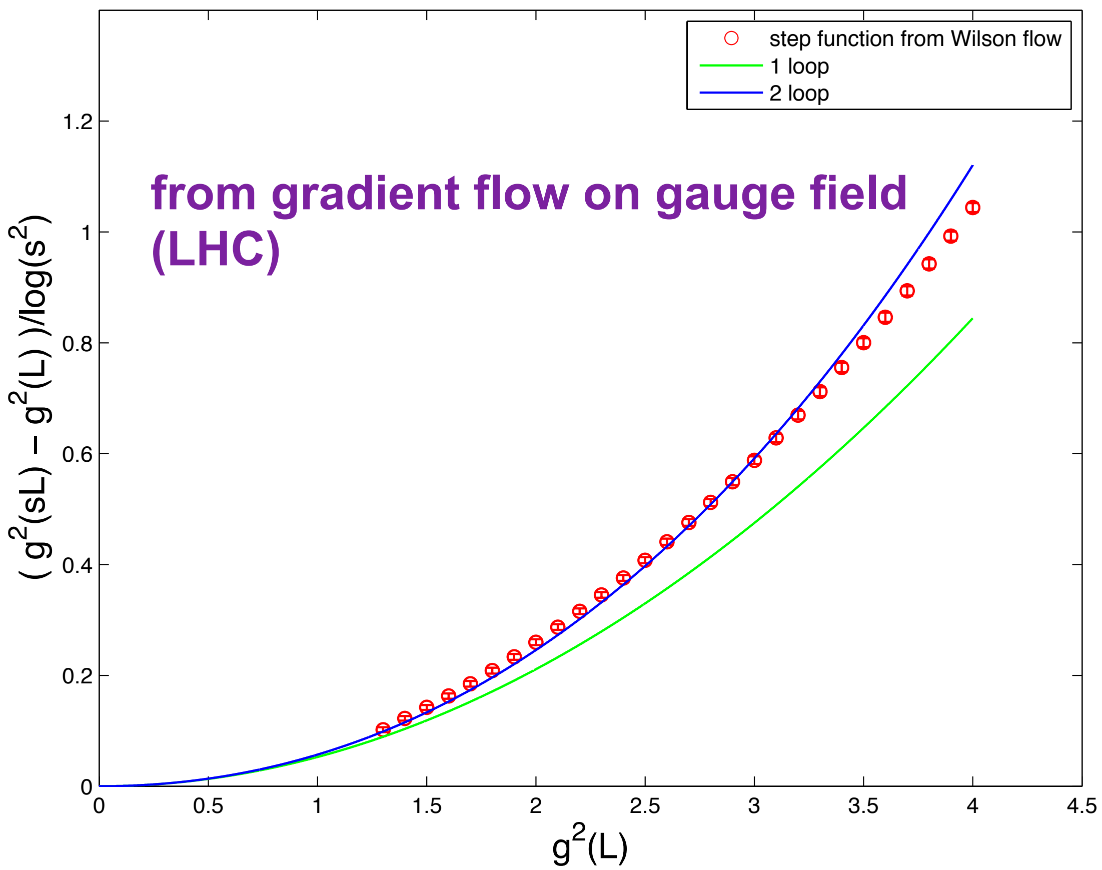
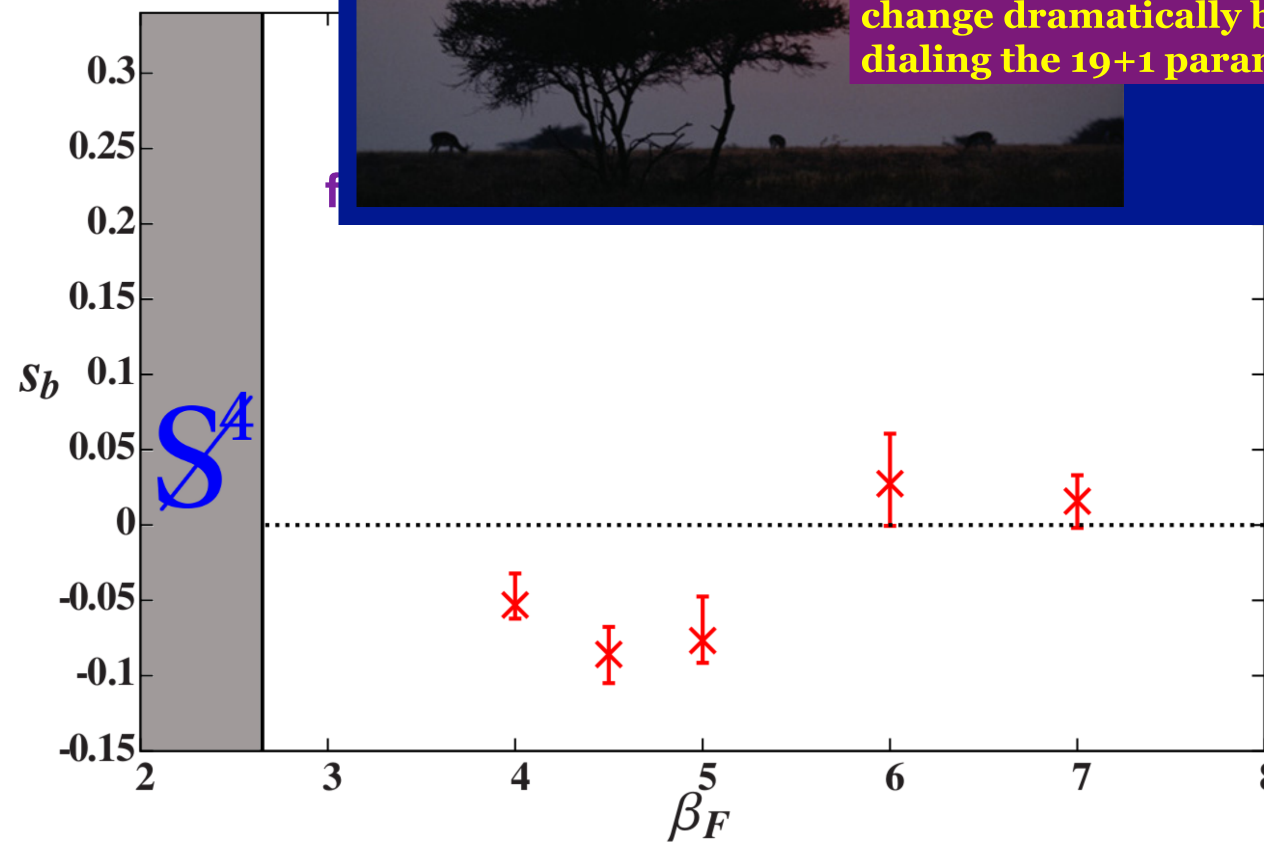
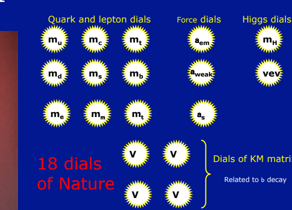




Fusion process p+p -> de⁺n begins pp cycle which fuels the Sun

If value of Higgs condensate v=250 GeV were doubled,
the fusion reaction inside sun would slow down.
Sun would shrink by about 22% (Jackson), it would
also appear brighter with higher surface temperature.



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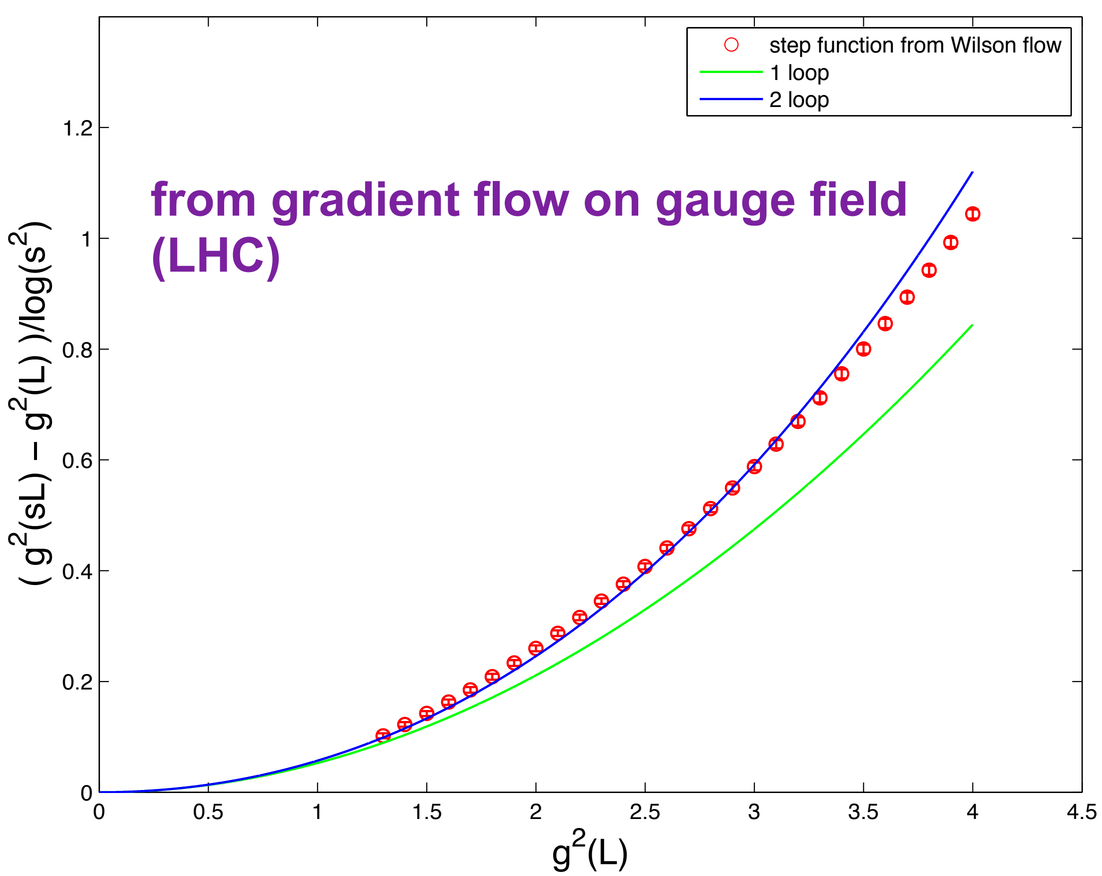

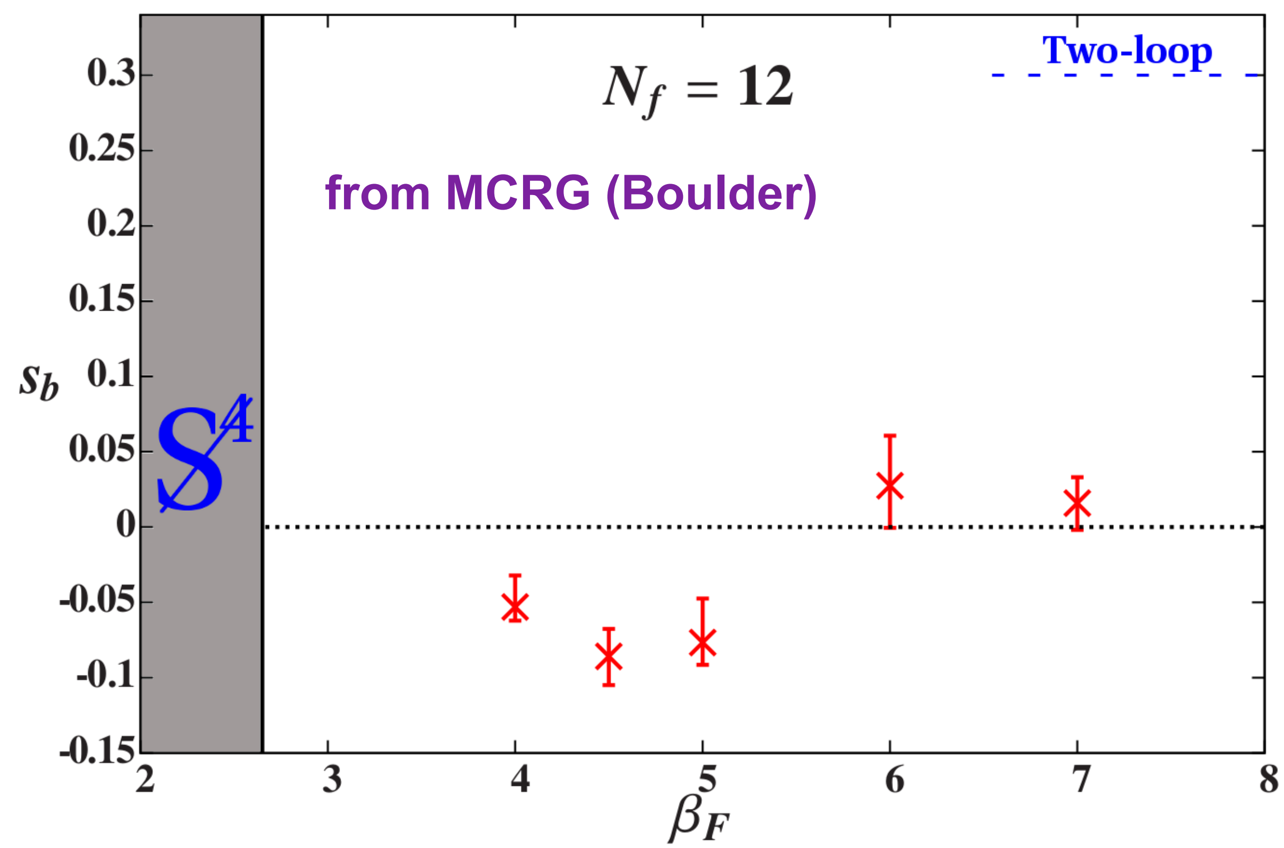

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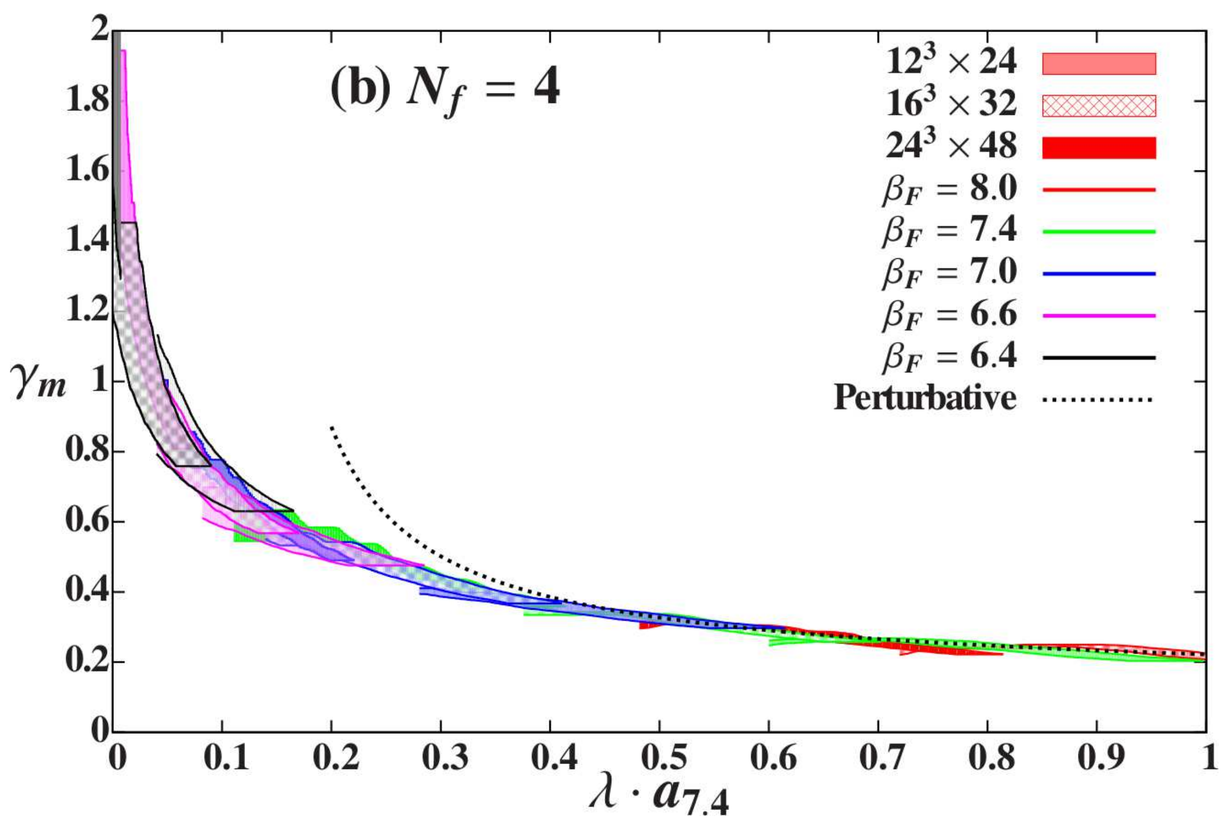
chiSB, Dirac spectrum, Anomalous dimension

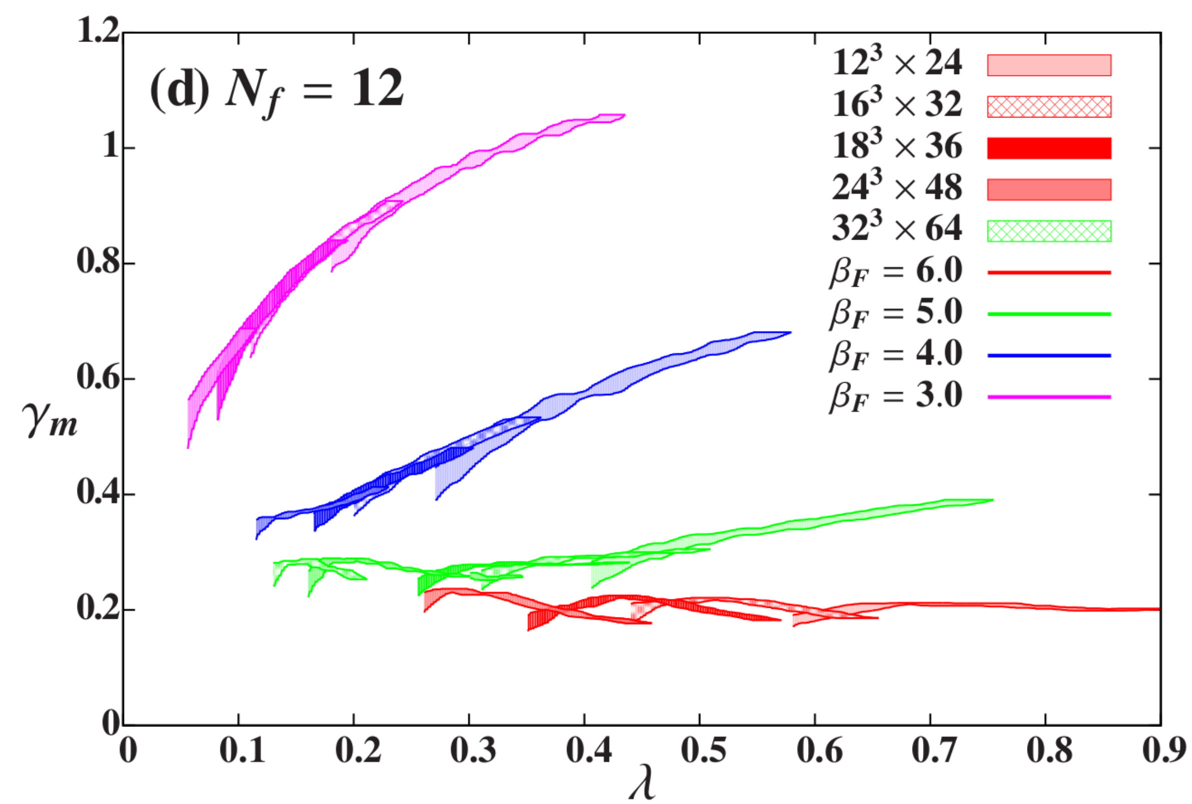
$$\lim_{\lambda\to 0}\lim_{m\to 0}\lim_{V\to\infty}\rho(\lambda,m)=\frac{\Sigma}{\pi}$$ spectral density

$$\nu(M,m)=V\int_{-\Lambda}^{\Lambda}\mathrm{d}\lambda\,\rho(\lambda,m),\qquad \Lambda=\sqrt{M^2-m^2}$$ mode number density complete UV control

$$\nu_{\mathrm{R}}(M_{\mathrm{R}},m_{\mathrm{R}})=\nu(M,m_{\mathrm{q}})$$ renormalized and RG invariant

Boulder group initiative:





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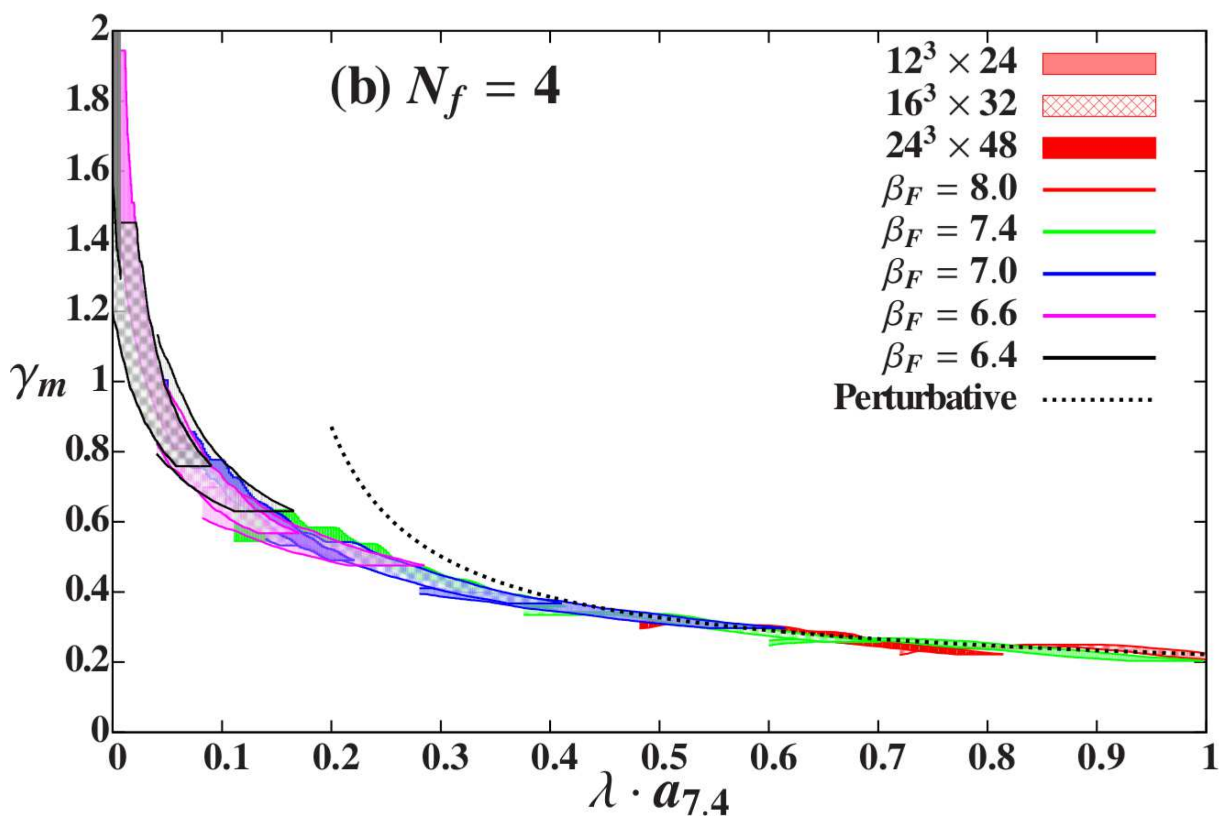

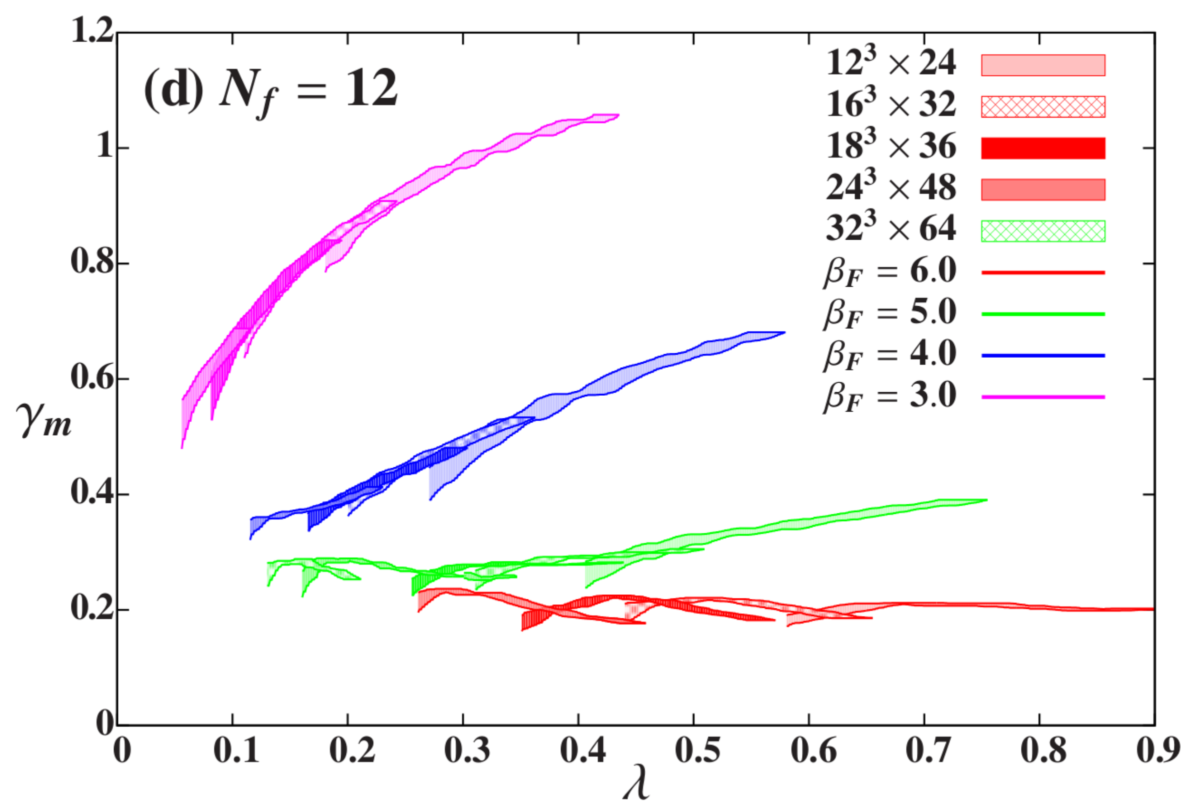

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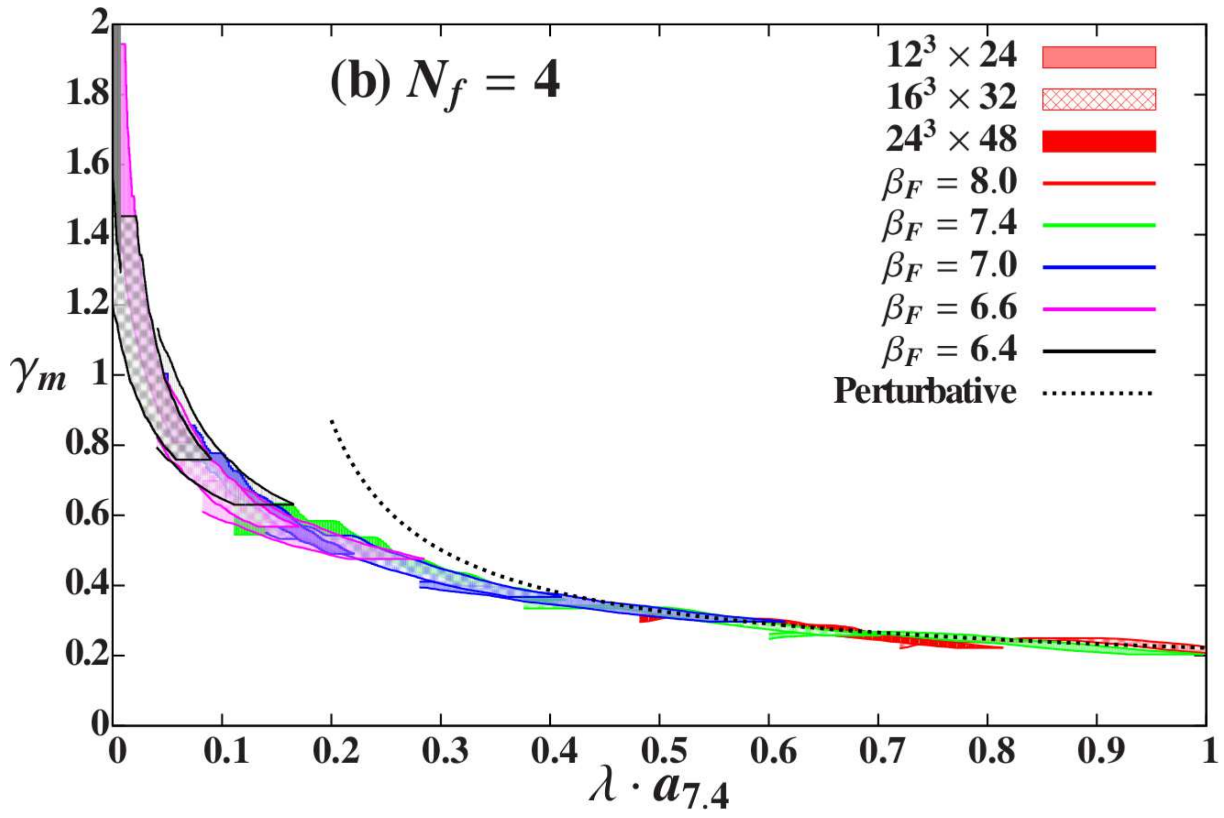
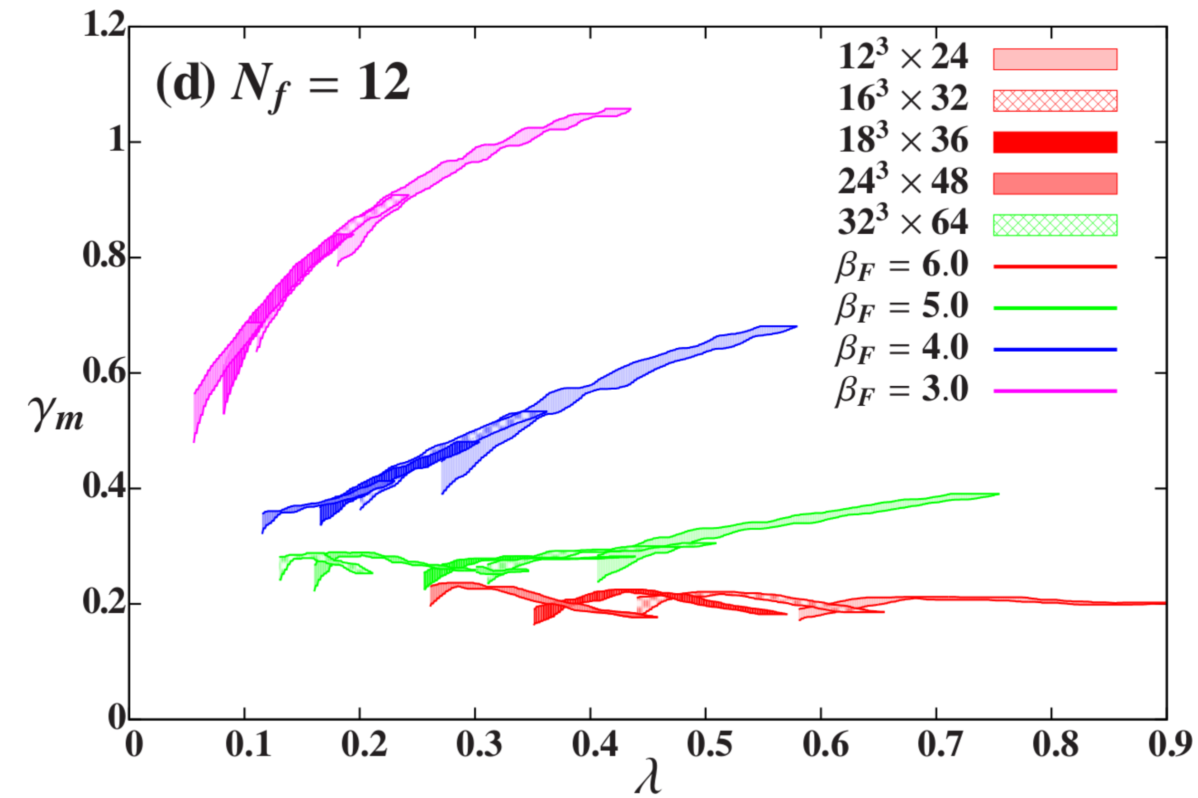
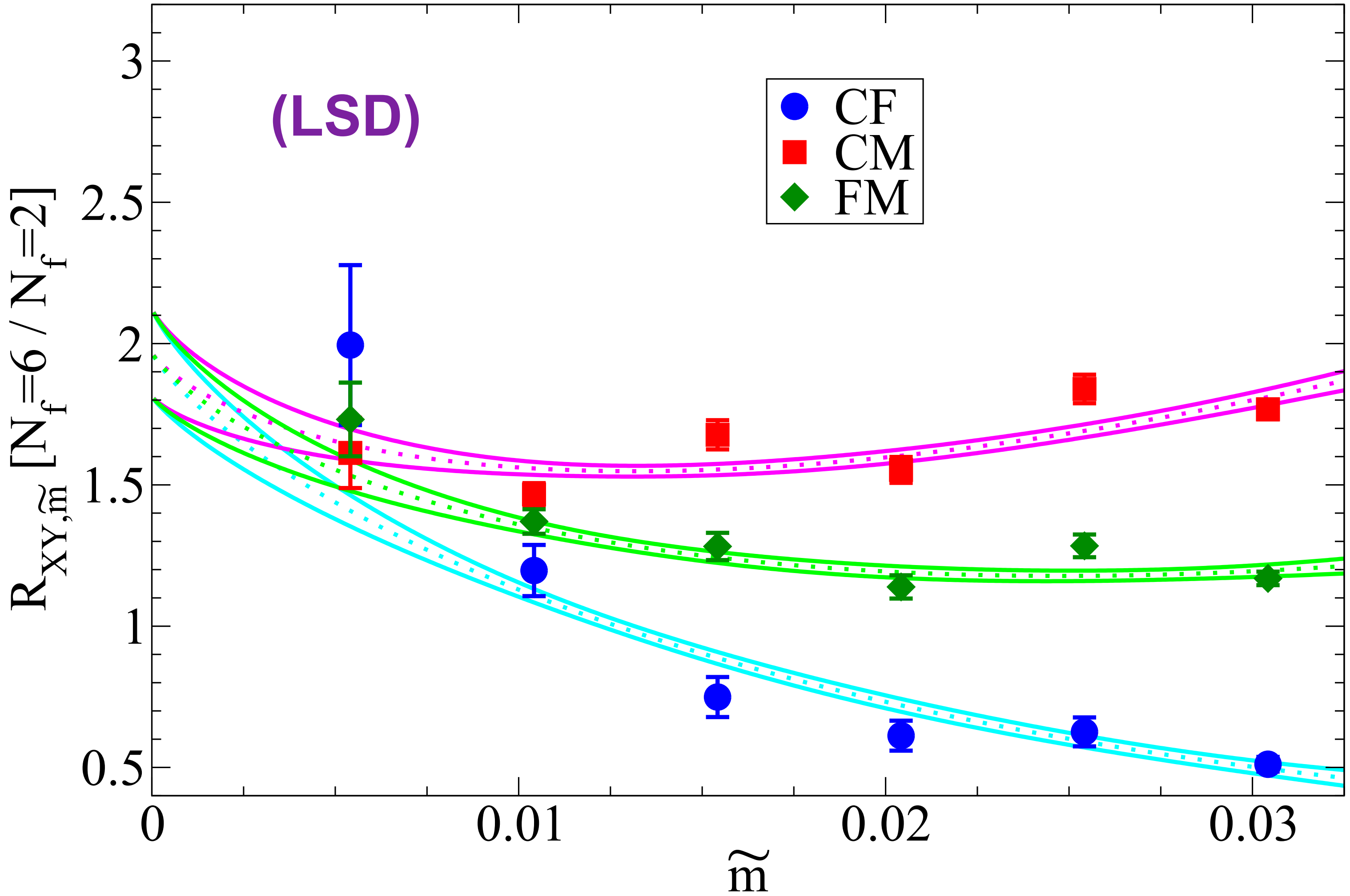




chiral condensate enhancement



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- there is fast growth in B/F as the conformal window is approached
- parity split is decreasing in the spectrum as CW is approached

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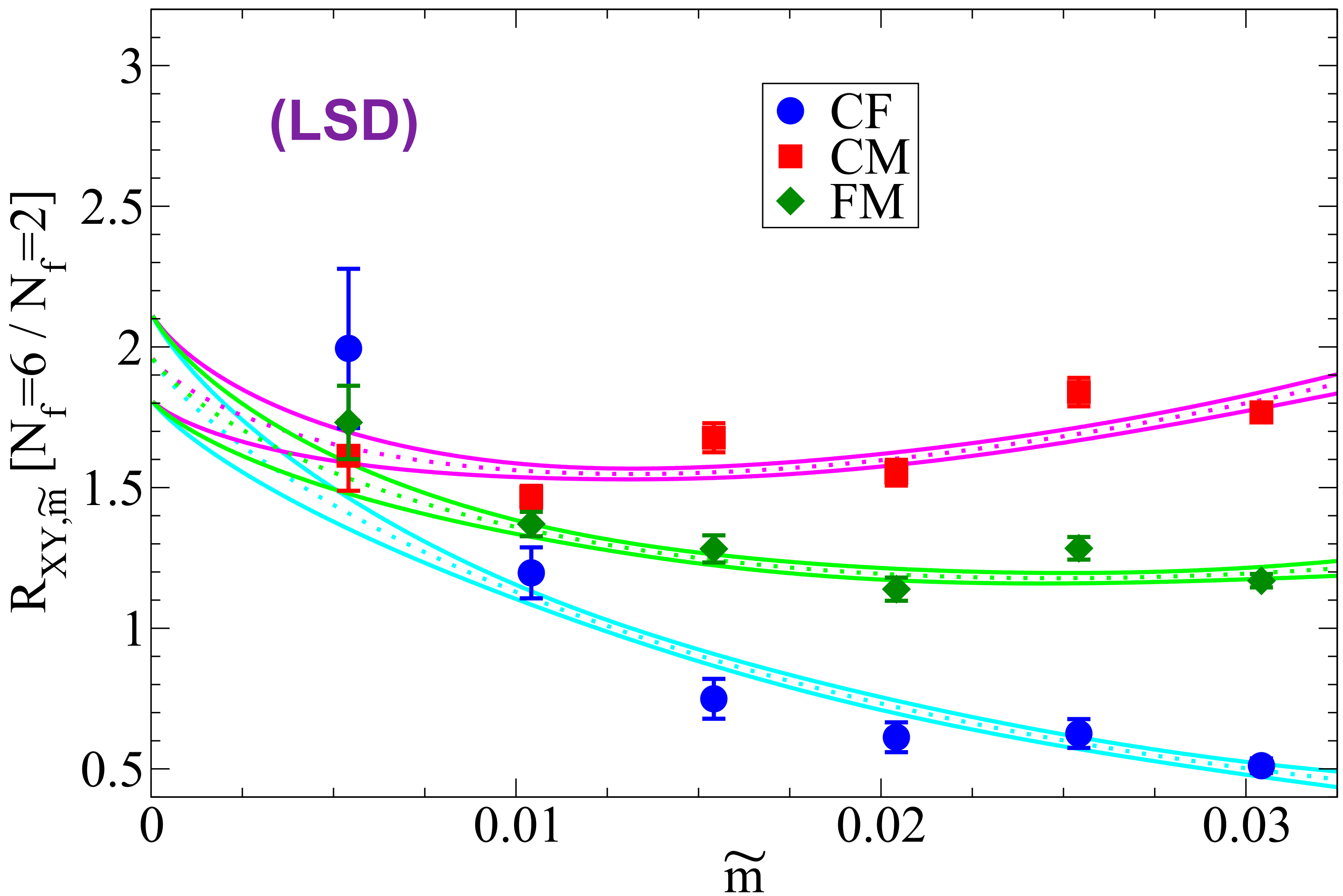

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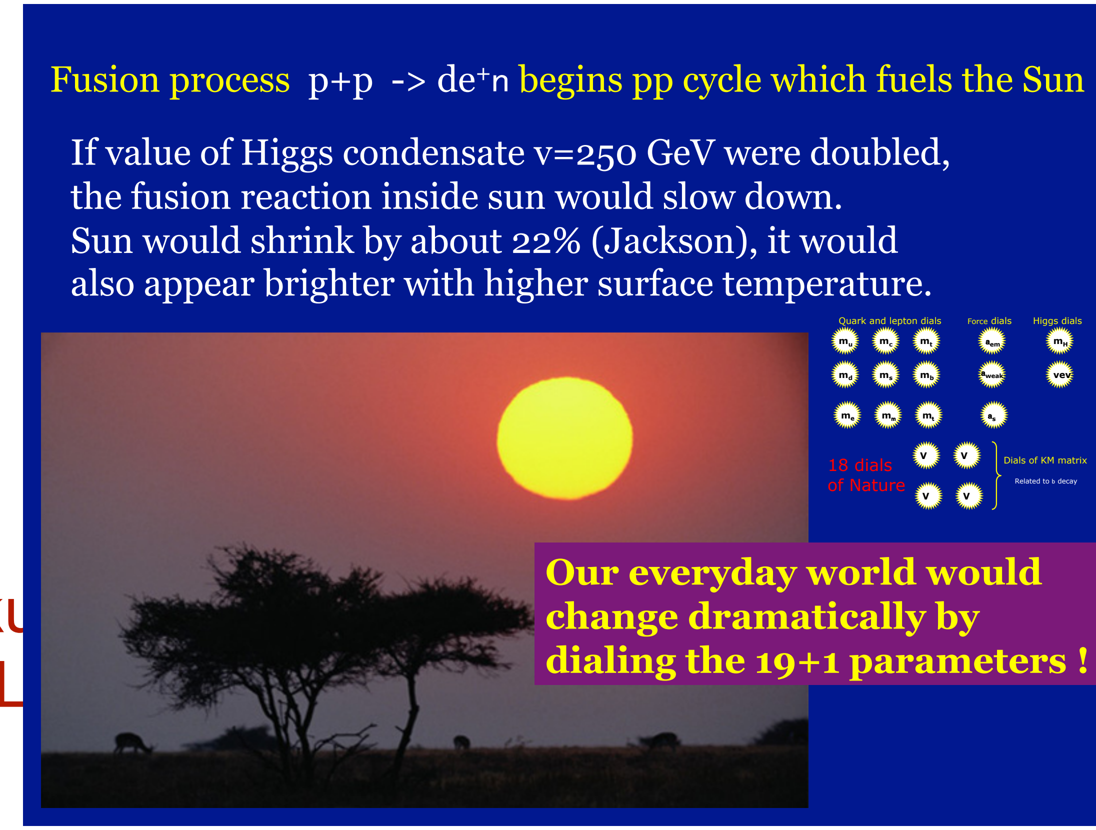

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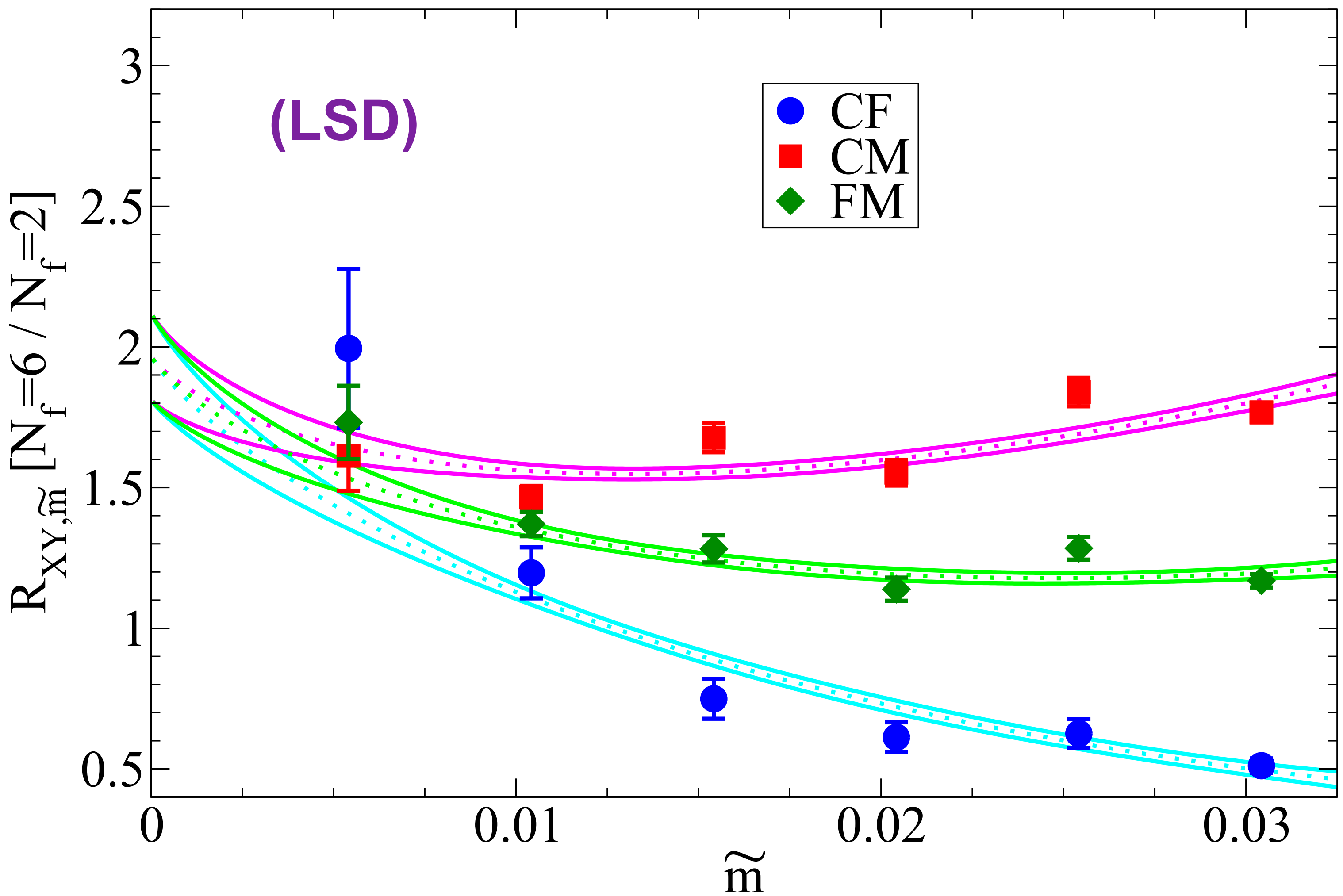

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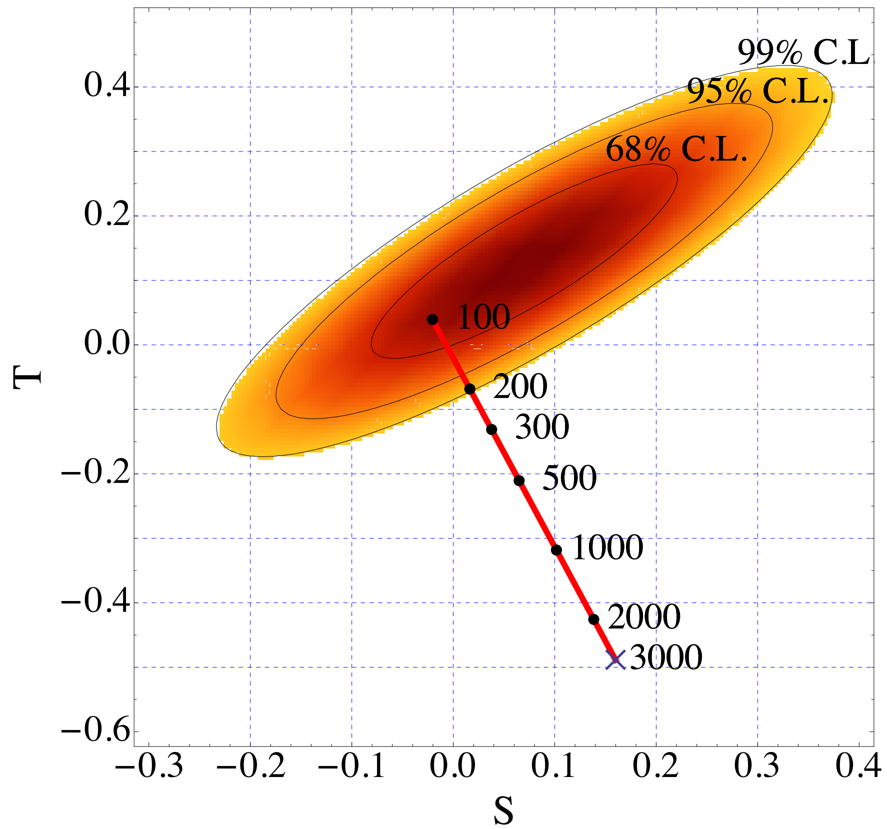
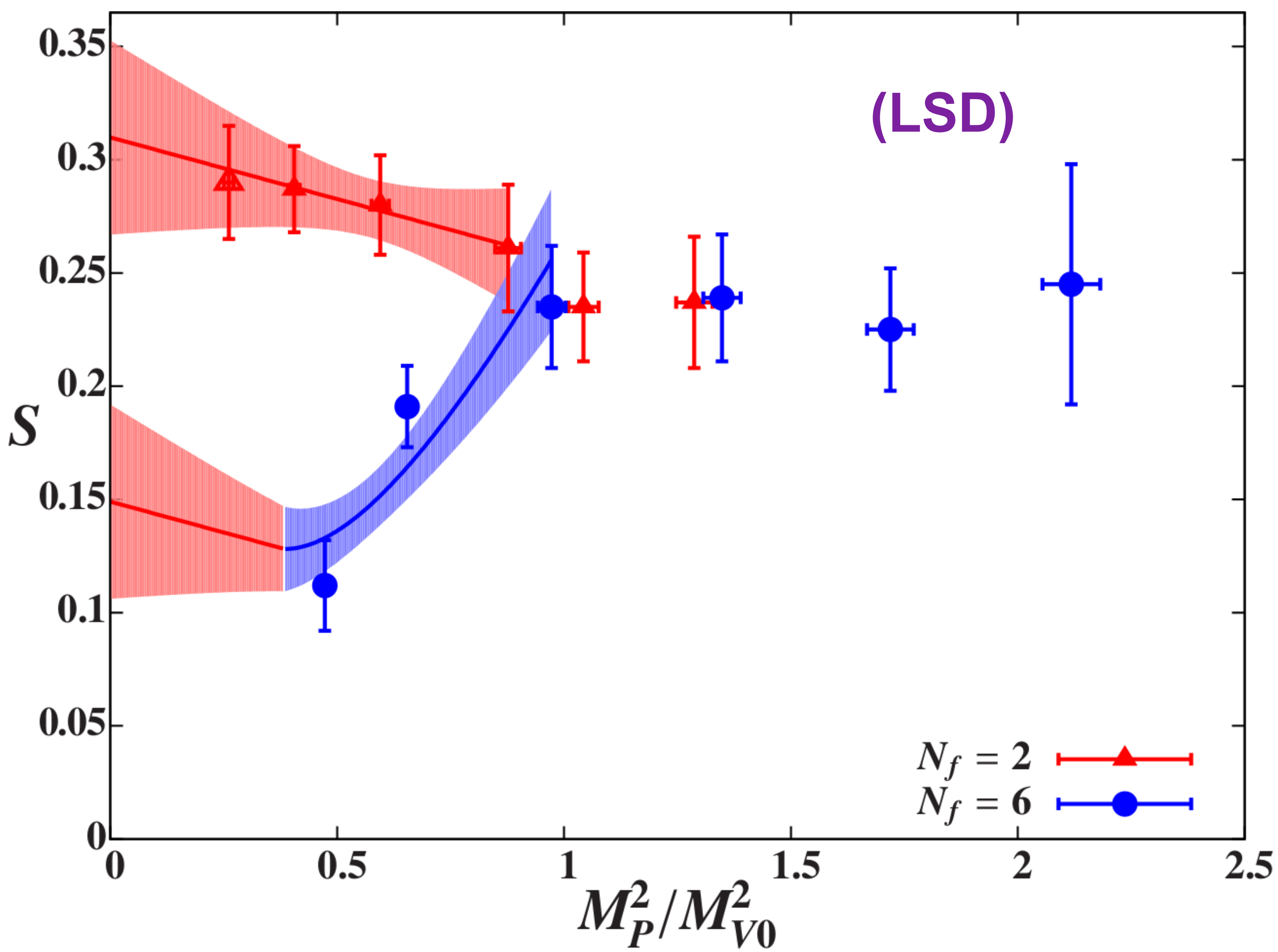


S-parameter

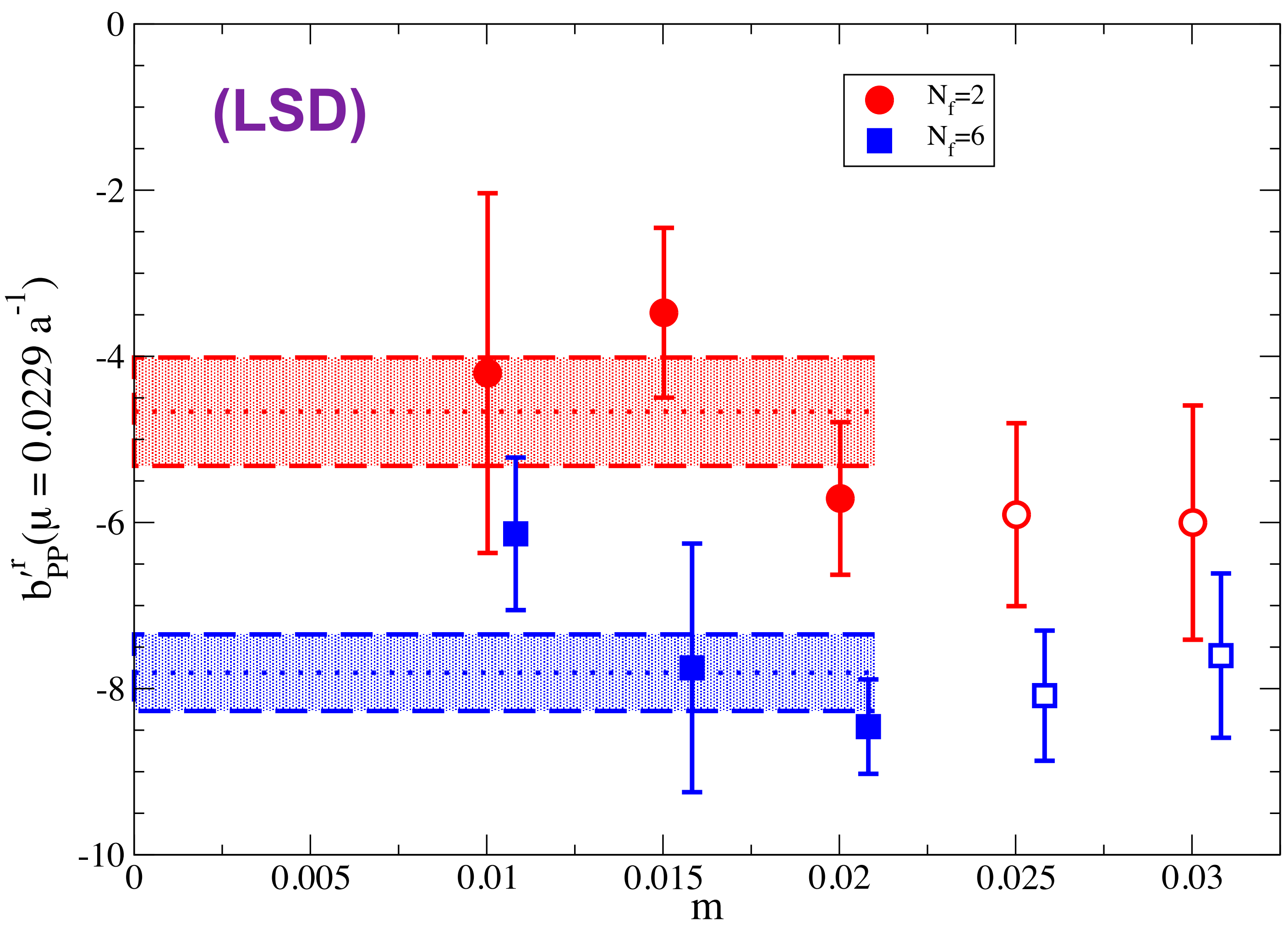


kudos to LSD group

- S-parameter is not increasing according to the naive scaling based on QCD and expected by phenomenologists

- without non-perturbative lattice work phenomenology is way off

W-W scattering



LSD group

- potentially important for LHC14 machine upgrade
- based on equivalence theorem

Dark matter

The Total Energy of the Universe:

Vacuum Energy (Dark Energy)	~	67 %
NonBaryonic Dark Matter	~	29 %
Visible Baryonic Matter	~	4 %

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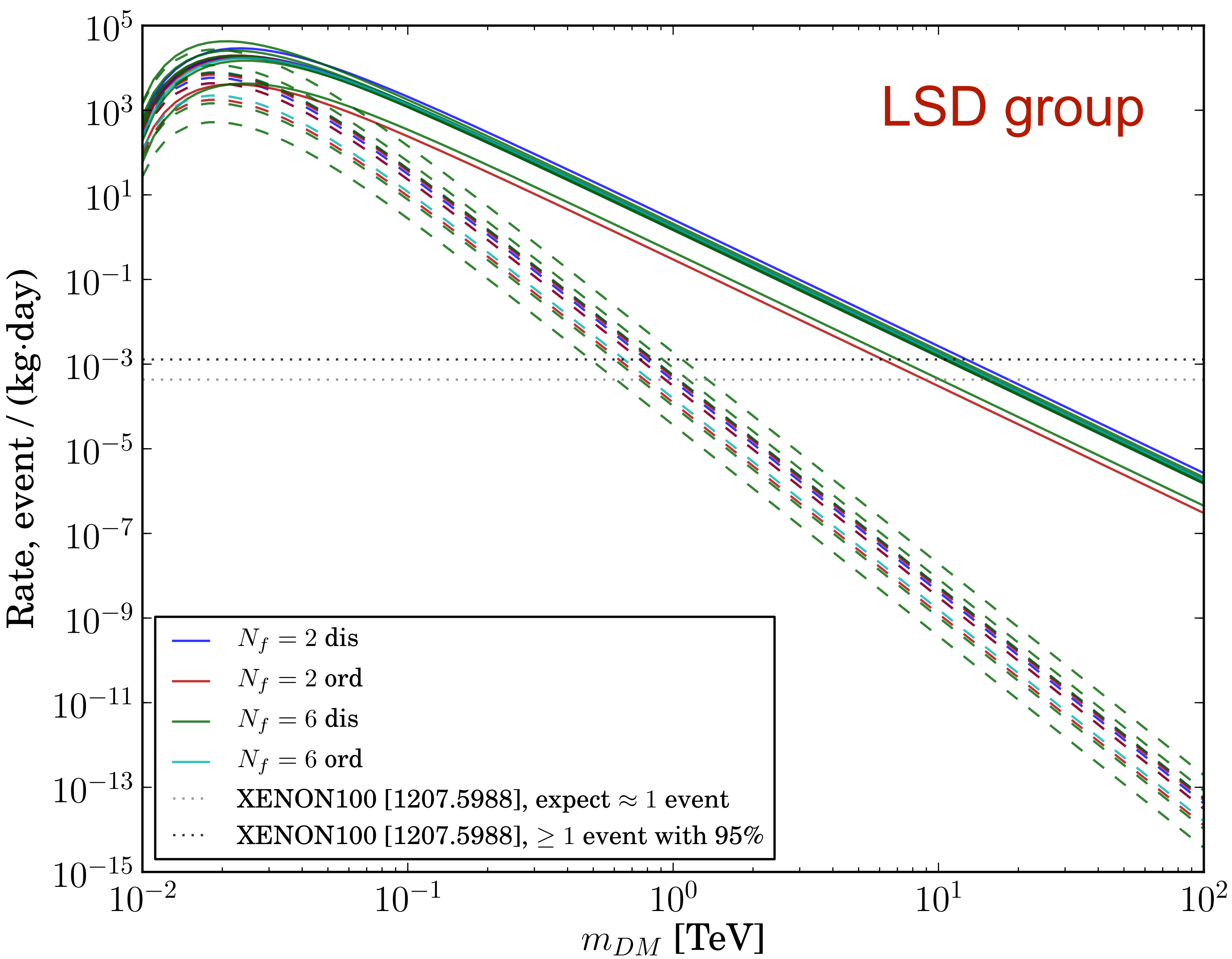


- dark matter candidates electroweak active in the application
- there is room for electroweak singlet dark matter particles

Resource estimates

(A) Resource estimates of the near-conformal BSM project				
lattice spacing a (in fermi)	fermion mass (in a units)	lattice volume $V \times T$	config generation (TF-Years)	measurements (TF-Years)
2.25×10^{-5}	0.003	$64^3 \times 128$	24	72
2.25×10^{-5}	0.004	$64^3 \times 128$	20	60
2.25×10^{-5}	0.005	$64^3 \times 128$	18	54
1.75×10^{-5}	0.0023	$96^3 \times 192$	100	300
1.75×10^{-5}	0.0030	$96^3 \times 192$	90	270
1.75×10^{-5}	0.0035	$96^3 \times 192$	80	240

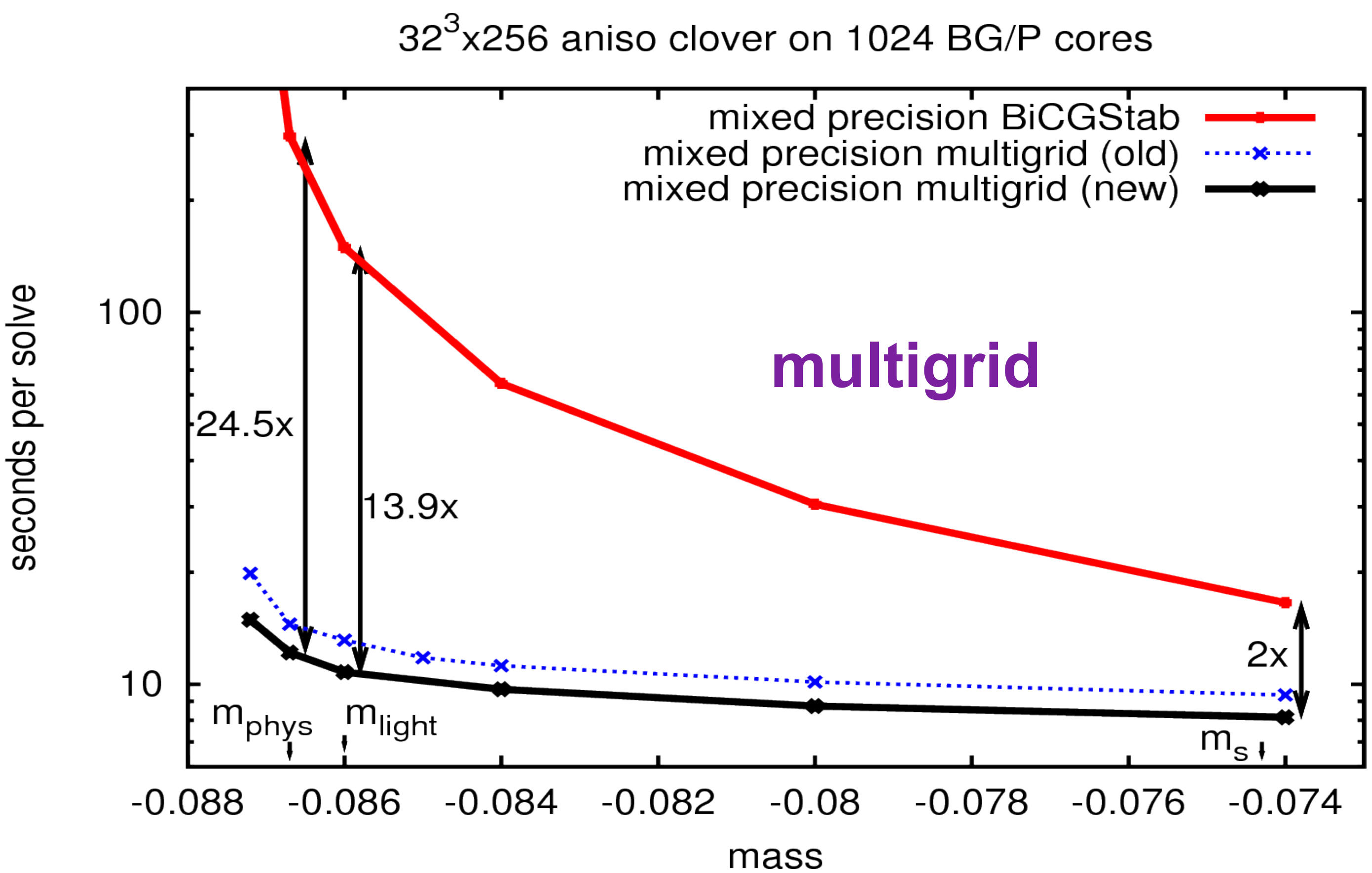
(B) Resource estimates of the PNGB project				
min. M_H (GeV)	lattice volume $V \times T$	MD trajectory (time units)	config generation (TF-Years)	measurements (TF-Years)
650	$32^3 \times 64$	10000	1	2
520	$40^3 \times 80$	10000	9	12
433	$48^3 \times 96$	10000	44	60
371	$56^3 \times 112$	10000	180	270

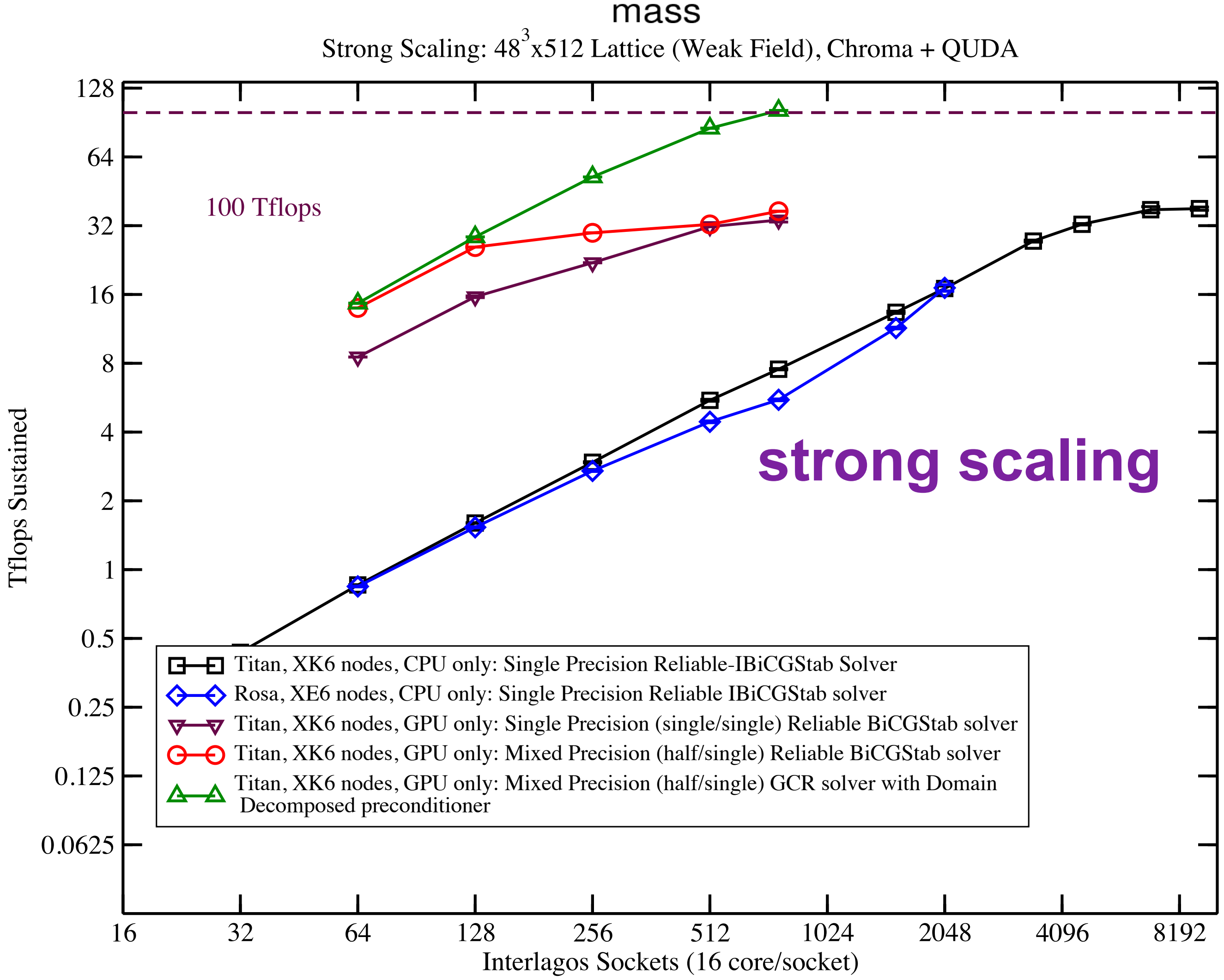
(C) Resource estimates of the SUSY project				
lattice volume $V \times T$	wall separation L_s	bare coupling $\beta = 4/g_0^2$	trajectory. (time units)	config generation (TF-Years)
$16^3 \times 32$	24	2.4	10000	5
$16^3 \times 32$	48	2.4	10000	11
$24^3 \times 48$	24	2.4	10000	42
$24^3 \times 48$	48	2.4	10000	84
$32^3 \times 64$	24	2.4	10000	171
$32^3 \times 64$	24	2.45	10000	342
$32^3 \times 64$	48	2.45	10000	380
Total BSM resource estimate				2,941

TABLE VI: **(A)** Requested resources for the SU(3) two flavor sextet project. The fourth column shows the resources needed to generate 2,000 configurations from 20,000 MD time units. The fifth column shows the required resources for all the physics measurements. **(B)** Resources to generate gauge configuration ensembles in SU(2) gauge theory with $N_f = 2$ fermions in the fundamental representation. The inverse lattice spacing is held fixed at $a^{-1} = 5$ TeV. The first column gives the minimum Higgs mass that can fit in the volume assuming $LM_H \geq 4$ and the second column gives the corresponding lattice volume. The fourth column gives the resources in teraflop/s-years (TF-Years) needed to generate 10,000 molecular dynamics time units (1,000 equilibrated gauge configurations) for each ensemble for the Wilson fermions. **(C)** Resources needed for DWF simulation of $SU(2)$ $\mathcal{N} = 1$ Yang-Mills theory are estimated. As in previous studies, we set the bare fermion mass $m_f = 0$ for these estimates. Residual masses fall in the range 0.02-0.1 for these values of the parameters using Shamir (non-Möbius) domain wall fermions. Using three lattice volumes, two lattice spacings and two values of L_s should allow for careful extrapolation to the chiral continuum limit while maintaining control over finite volume effects.

- three projects use three different fermions: staggered, Wilson, DW
- estimates in Table are expected to change dynamically
- resources for The BSM program are shared equally with the other three USQCD programs
- part (A) in the table is based on sextet model estimates as a stake holder close to the CW
- all three parts are open for adjustments and competition to advance the three major directions as defined in the white paper

BSM algorithmic developments





- resource estimates and strategic deployments of fermion method will be dynamical adjusted based on code and algorithm developments
- kudos to the software group and to RCB holding it together!