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Beyond the Standard Model

Guido Altarelli

Universita' di Roma Tre
CERN

Plan of the lectures

- Experimental Status of the SM
- Problems of the SM (conceptual and empirical)
- Overview of EW symmetry breaking and BSM
  - Supersymmetry
  - Little Higgs Models
  - Extra Dimensions
  - Composite Higgs
  - The anthropic alternative
- The most accepted BSM: GUT's
- The most established BSM: Neutrino masses

My purpose: give basic facts, describe ideas with a minimum of technicalities, expand on the most realistic avenues (proceed from real to imaginary)

By "Beyond the SM" I actually mean "Beyond what we know" in particle physics.

Since most we know is extremely well described by the SM this is mostly "Beyond the SM"

But we must not forget that a main part of the SM, the Higgs sector, is so far not tested and its explicit form and content is still essentially a conjecture.

Thus an important part of this course is devoted to the open problem of the EW symmetry breaking sector.

The Standard Model

$$\underbrace{SU}(3) \otimes SU(2) \underbrace{\otimes} U(1)$$

Strong

Electroweak

add classical gravity (general relativity) to describe 99% of measurable phenomena

SU(3) colour symmetry is exact!

The EW symmetry is spont. broken down to $U(1)_Q$

Higgs sector (???)

Gauge Bosons

8 gluons g^A

$W^{\pm}$, Z, γ

Matter fields: 3 generations of quarks (coloured) and leptons

$$\begin{bmatrix} u & u & u & \nu \\ d & d & d & e \end{bmatrix}$$

+ 2 more replicas (???)

Particle physics at a glance

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable and highly predictive.
And is (too) well supported by the data.

But even just as a low energy effective theory
the SM is not satisfactory:

QCD + the gauge part of the EW theory are fine, but the
Higgs sector is so far only a conjecture and is problematic

and we expect New Physics at higher energies

not only from the GUT or Planck scales
but also from the TeV scale (LHC!)
hierarchy, dark matter...

QCD

QCD stands as a very solid building block of the SM

No essential problems of principle in its foundations
Comparison with experiment is excellent

A complex theory and it is difficult to make its content explicit

Marvelous progress in techniques to extract precise predictions (higher order perturbative, resummation, event simulation, non perturbative techniques e.g. lattice.....)

Very important for the LHC preparation: understanding QCD processes is a prerequisite for all possible discoveries

QCD is a "simple" theory

$$L = -\frac{1}{4}\sum_{A=1}^{8} F^{A\mu\nu}F^{A}_{\mu\nu} + \sum_{j=1}^{n_f} \bar{q}_j(i\widehat{D} - m_j)q_j$$

but with an extremely rich dynamical content:

- Confinement
- Complex hadron spectrum (light and heavy quarks)
- Spontaneous breaking of (approx.) chiral symm.
- Phase transitions

  [Deconfinement (q-g plasma), chiral symmetry restauration,……]
- Highly non trivial vacuum topology

  [Instantons, $U(1)_A$ symm. breaking, strong CP violation (???)]
- Asymptotic freedom
- • • •

QCD is an unbroken SU(3) gauge theory with triplet quarks

$$L = -\frac{1}{4}\sum_{A=1}^{8} F^{A\mu\nu}F_{\mu\nu}^{A} + \sum_{j=1}^{n_f} \bar{q}_j(i\widehat{D} - m_j)q_j$$

Defs: $[t^A, t^B] = iC^{ABC}t^C$ $\quad Tr[t^A t^B] = \frac{1}{2}\delta^{AB}$

(C_{ABC}: SU(3) struture constants, t^A: generator representation)

$$g_\mu = \sum_{A=1}^{8} g_\mu^A t^A$$ (g^A_μ is a gluon field)

$\widehat{D} = D_\mu \gamma^\mu$; $D_\mu = \partial_\mu + ie_s g_\mu$ (D: covariant derivative)

$$\alpha_s = \frac{e_s^{\ 2}}{4\pi}$$ (e_s: SU(3) gauge coupling)

$$F_{\mu\nu}^A = \partial_\mu g_\nu^A - \partial_\nu g_\mu^A - e_s C_{ABC} g_\mu^B g_\nu^C$$

How do we get predictions from QCD?

- Non perturbative methods

•Lattice simulations (great continuous progress)

•Effective lagrangians

* Chiral lagrangians
* Heavy quark effective theories

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•QCD sum rules

•Potential models (quarkonium)

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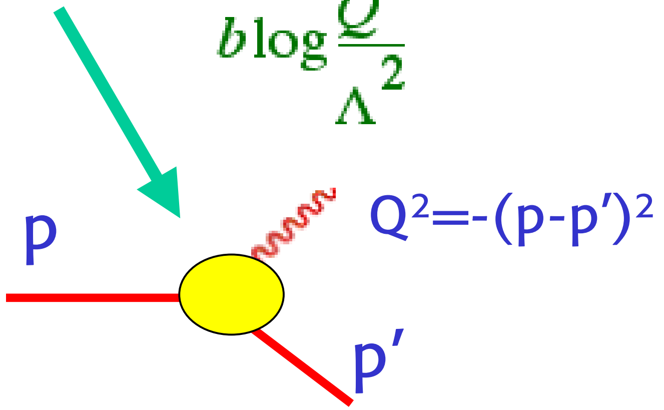
- Perturbative approach

Based on asymptotic freedom.

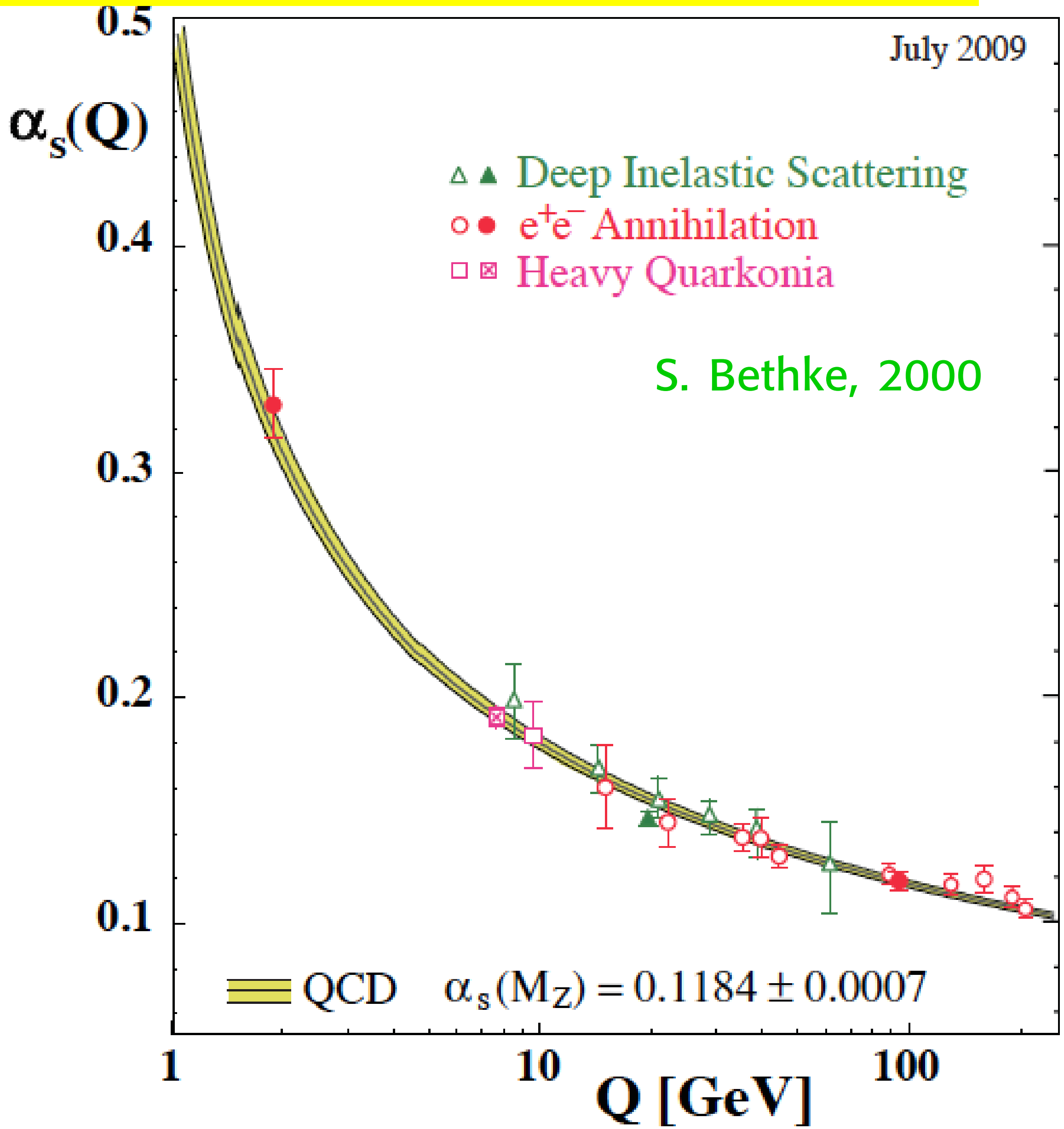
It still remains the main quantitative connection to experiment. Also difficult: α_s relatively large

Asymptotic freedom: due to quantum corrections the effective coupling decreases with Q, the momentum transfer

$$\alpha(Q^2) \cong \frac{1}{b \log \frac{Q^2}{\Lambda^2}}(1 + ...)$$

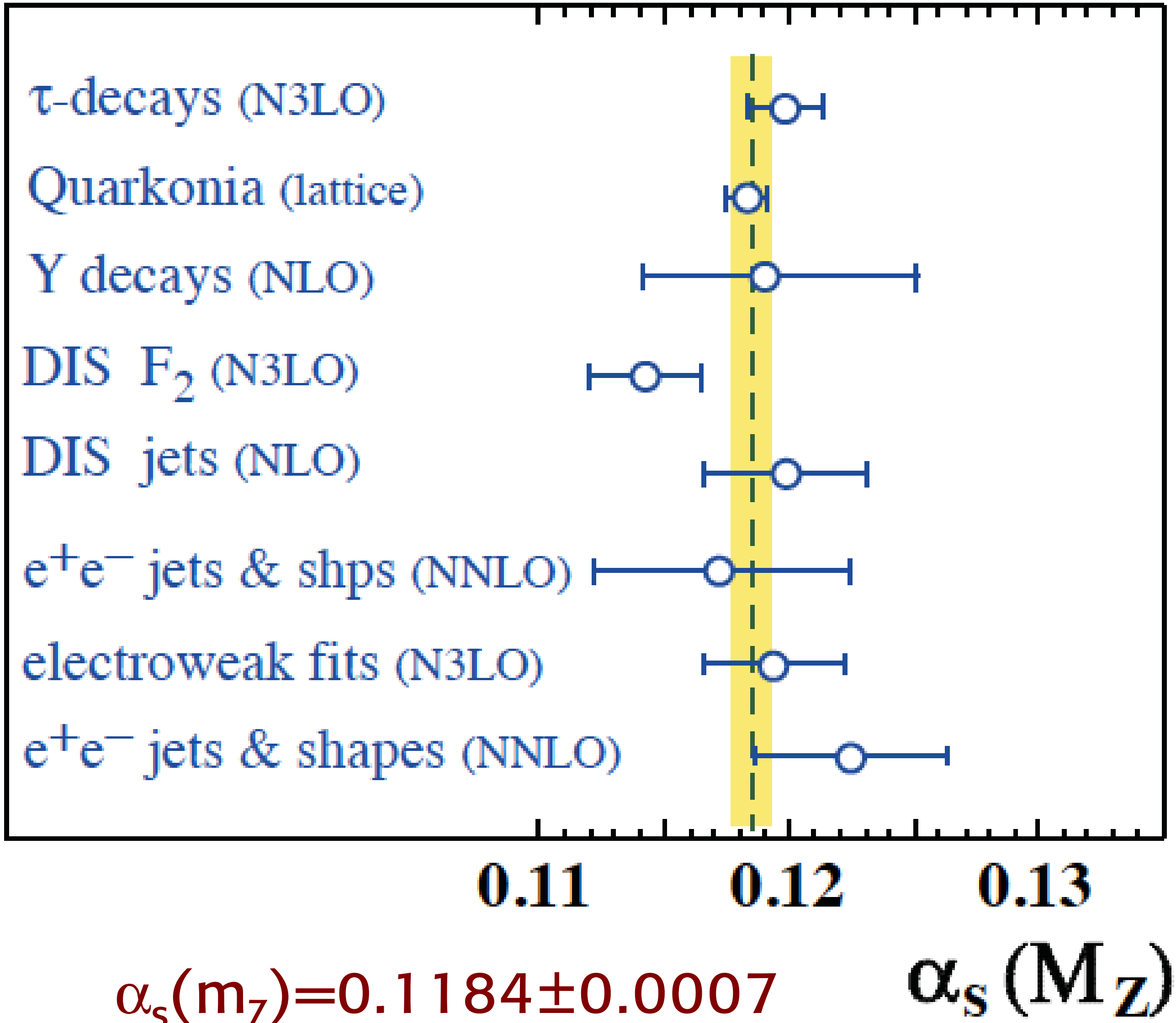


Measuring $\alpha_s(Q)$ at different scales clearly shows the running of the QCD coupling



Measurements of $\alpha_s(m_Z)$

Bethke'09



The agreement among many different ways of measuring α_s is a strong quantitative test of QCD

$\alpha_s(m_Z)=0.1184\pm0.0007$

Too small error! ±0.002 more plausible

In recent years a large amount of QCD theoretical work was directed to prepare the LHC experiments

- New and improved generators for event simulation
- Advanced QCD and EW calculations
- Study of signals and background

In this class one can also include

- QCD lattice calculations for flavour physics
  and heavy ion experiments

QCD for LHC: very difficult calculations needed

New powerful techniques for loop calculations

Basic idea: Loops can be fully reconstructed from their unitarity cuts

First proposed by Bern, Dixon, Kosower ‘93-‘97
Revived by Britto, Cachazo, Feng ’04
Perfected by Ossola, Papadopoulos, Pittau ’06

Generalized d-dimension unitarity
K. Ellis, Giele, Kunszt, Melnikov ‘08-’09

Examples of recent NLO calculations in pp collisions

[The first NLO pp calculation was done for Drell-Yan processes in 1978 by myself, K. Ellis and Martinelli]

ttbb Bredenstein et al '09-'10, Bevilacqua et al '09

W+3jets Berger et al '09, R.K.Ellis , Melnikov, Zanderighi '09,

Z,γ^* +3jets Berger et al '10

WW+2jets Melia et al '10-'11

WWbb Denner et al '10

tt+2jets Bevilacqua et al '10-'11

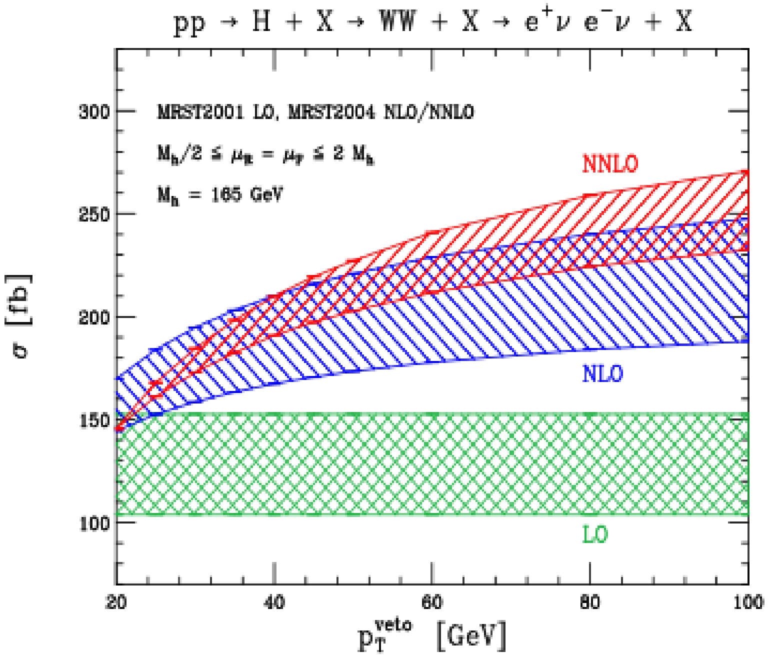
bbbb Greiner et al '11

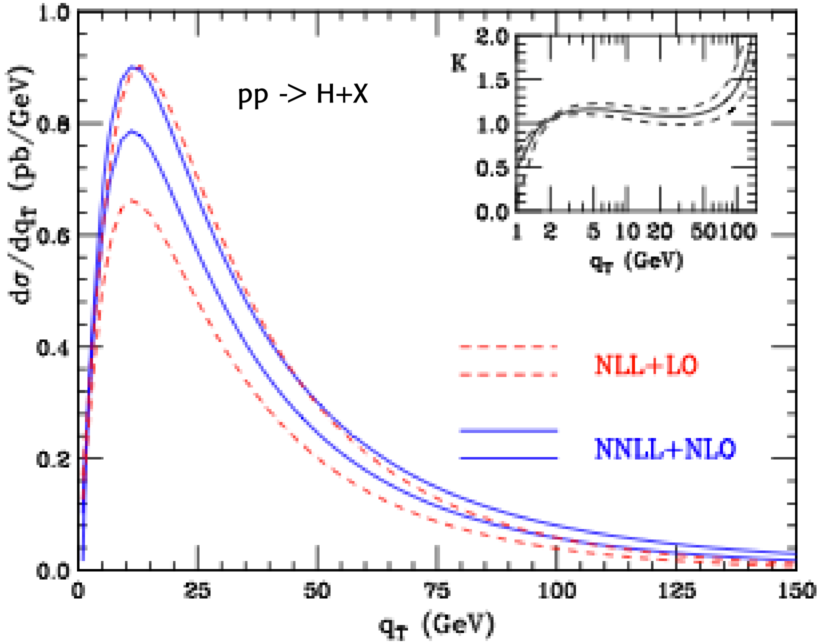
W+4jets Berger et al '11

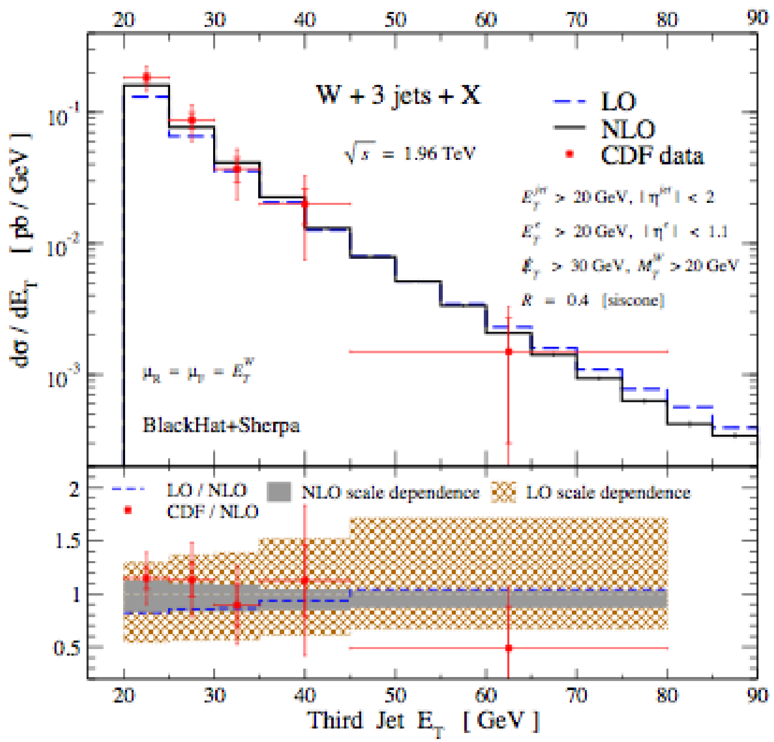
And the Higgs cross section and distributions are known to NNLO Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran et al '03; Anastasiou, Melnikov, Petriello '04, Bozzi et al '07

A terrific amount of work by QCD theorists for LHC

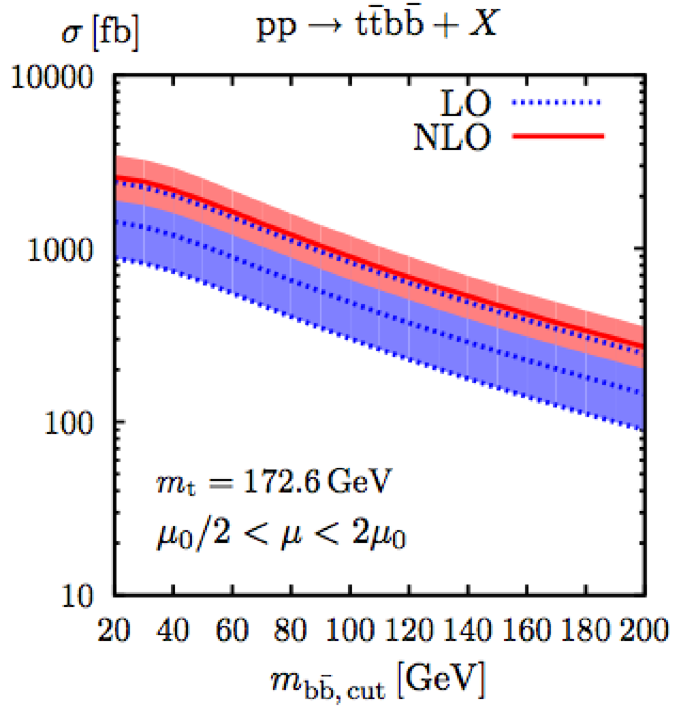
Complete Z width at $o(\alpha_s{}^4)$ here in Karlsruhe! Balkov et al' 12





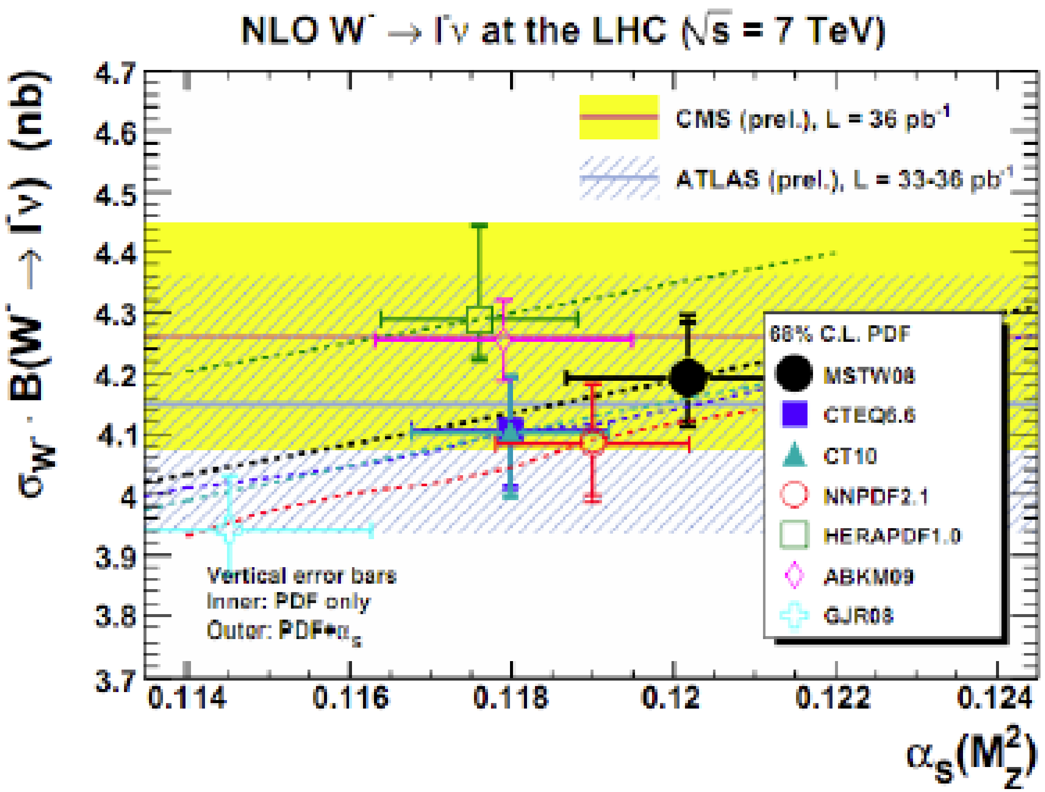


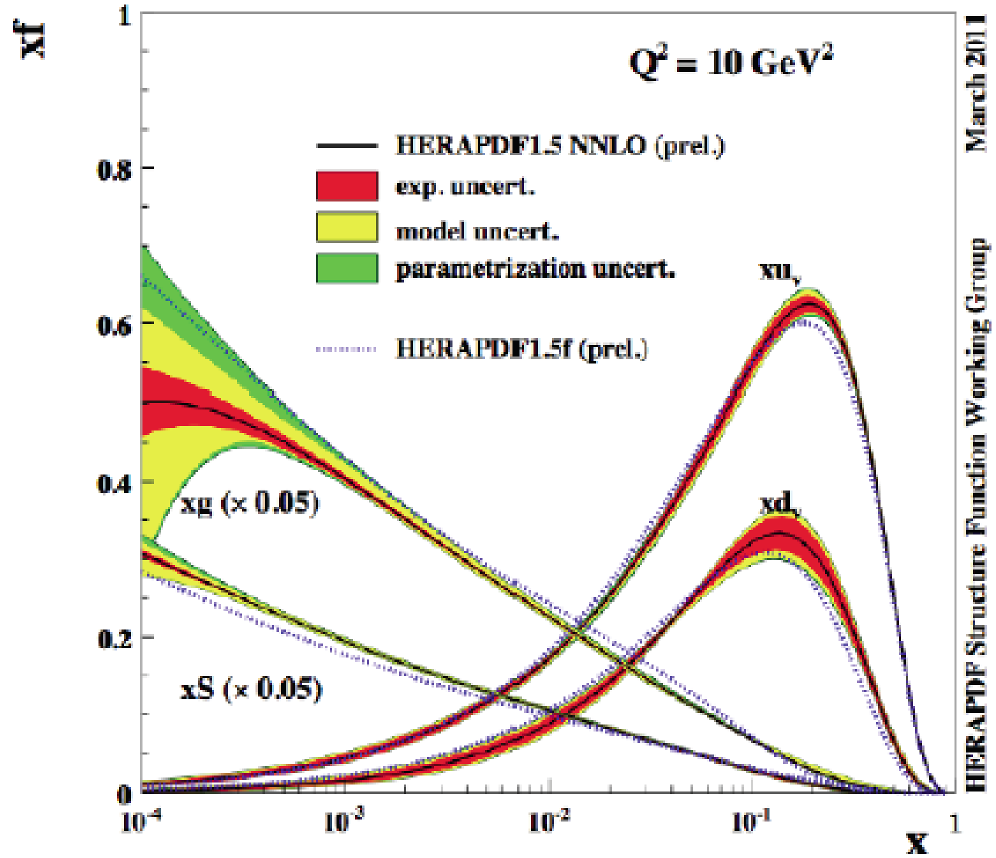
Fantastic technical skill!!



Essential for the LHC

An important task: preparing the optimal pdf's for the LHC





Dedicated groups

MSTW, CTEQ, NNPDF, HERAPDF,.....

QCD event simulation A big boost in view of the LHC

General algorithms for computer NLO calculations

the dipole Catani, Seymour,..... FKS formalisms Frixione, Kunszt, Signer

the antenna pattern Kosower....

Beyond general purpose HERWIG PYTHIA, SHERPA

Matching matrix elements and parton showers

LO ME: ALPGEN, MadGraph, MLM, (L)-CKKW Mangano.....

NLO ME: MC@NLO Frixione, Webber.....

POWHEG, MENLOPS Frixione, Nason, Oleari.....

Hamilton, Nason

Perturbative (+ resumm.s)

$$d\sigma = A\alpha_S^N [\, 1 + (c_{1,1}L + c_{1,0})\alpha_S + (c_{2,2}L^2 + c_{2,1}L + +c_{2,0})\alpha_S^2 + \ldots \,]$$

L= large log eg L=log(p_T/m)

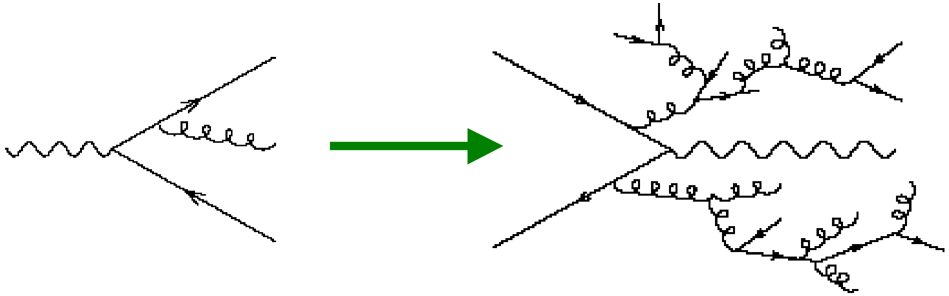
Complementary virtues:
the hard skeleton plus
the shower development
and hadronization

Parton showers

collinear emissions factorize

$$d\sigma_{q\bar{q}g} = d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi}$$

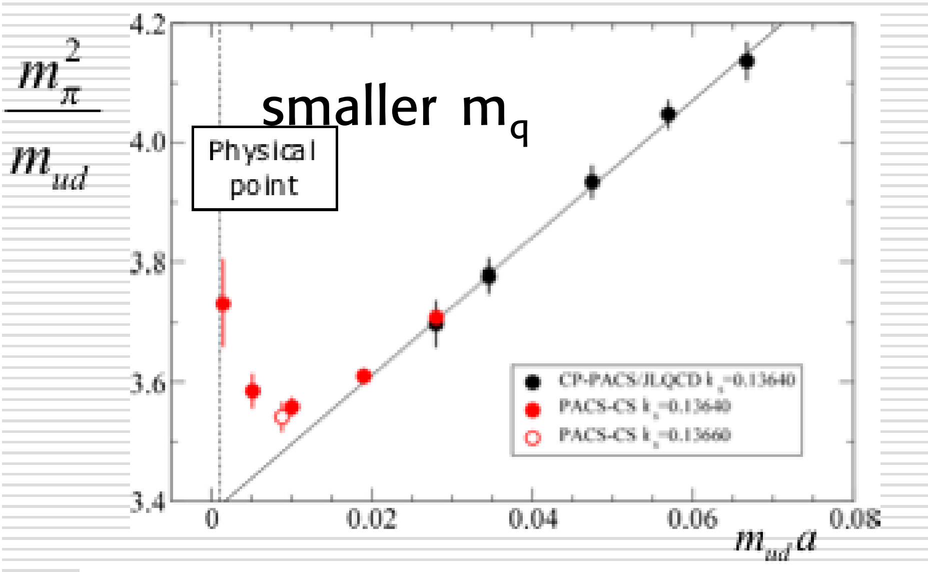
$$t = (p_q + p_g)^2 \longrightarrow 0$$



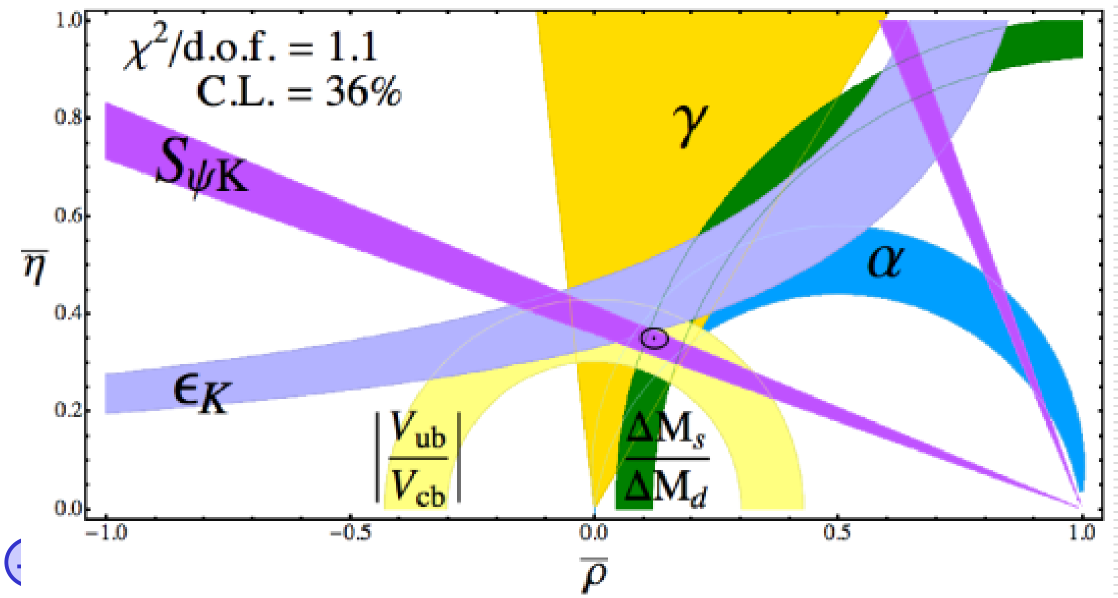
hadronization added

On going progress in automatisation

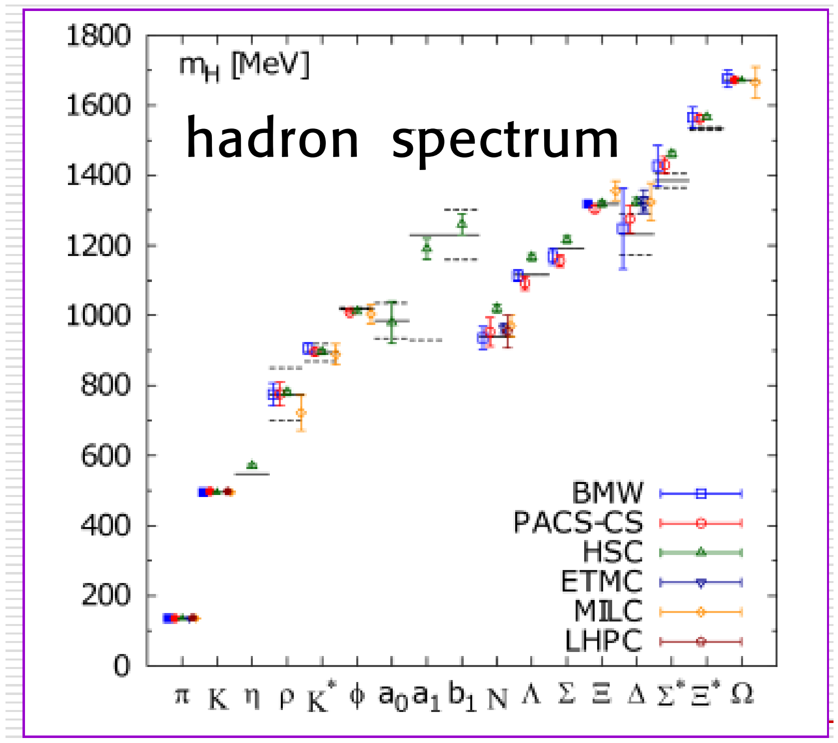
Great progress in lattice QCD



A crucial role in flavour physics



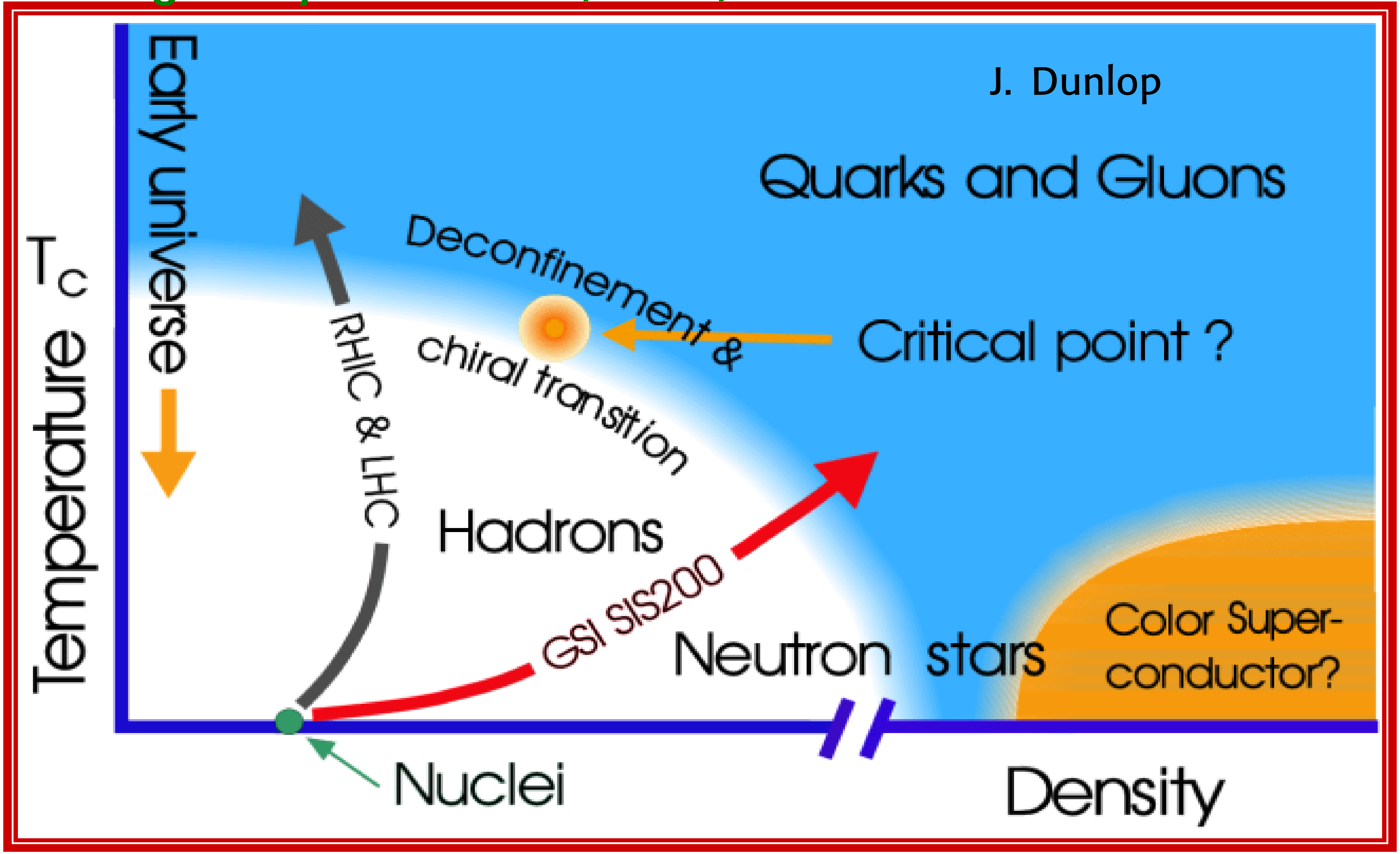
From postdiction to prediction



Unquenching
a -> smaller
L -> larger
m_q -> 0

The QCD phase diagram

Studied on the lattice and probed by colliding heavy ions at SPS, RHIC, LHC

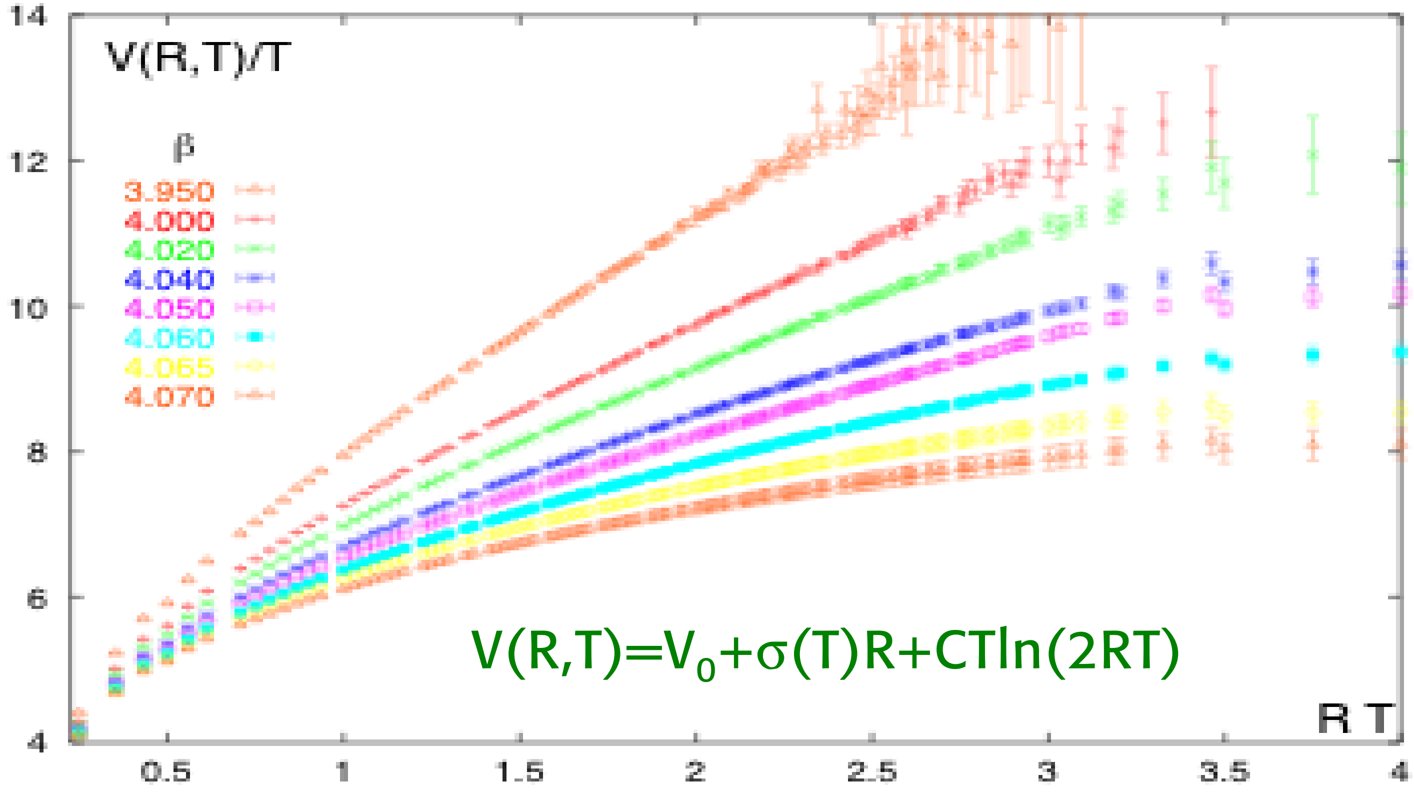


Confinement on the lattice

Potential between static quarks on the lattice

Kaczmarek, Karsch, Laermann, Lutgemeier '00

quenched approx.

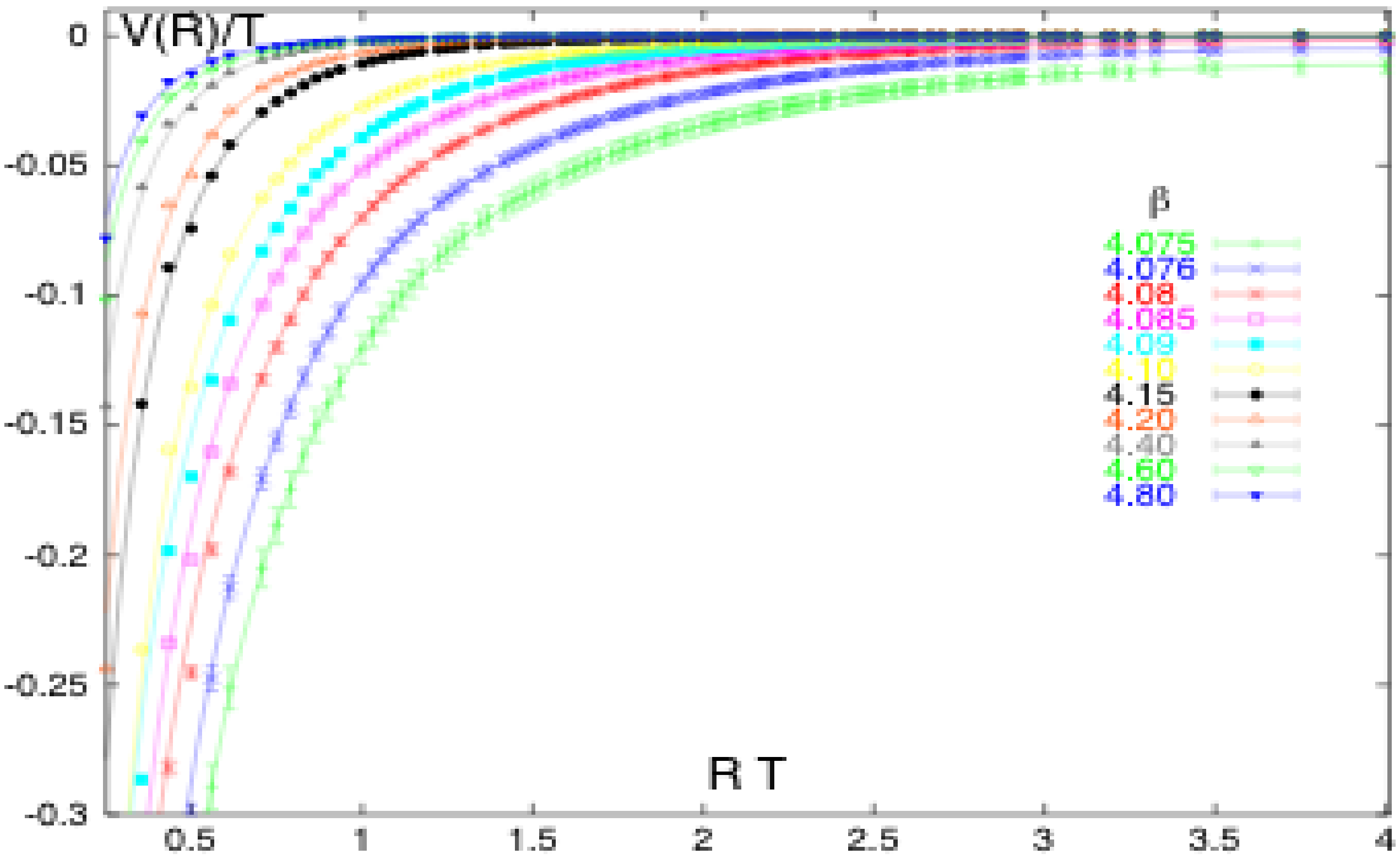


$V(R,T)=V_0+\sigma(T)R+CT\ln(2RT)$

Potential in units of kT (k=1) as function of R in units 1/T, for different $\beta=1/T$

The linearly rising term slope vanishes at T_C

At $T > T_C$ the slope at large R remains zero

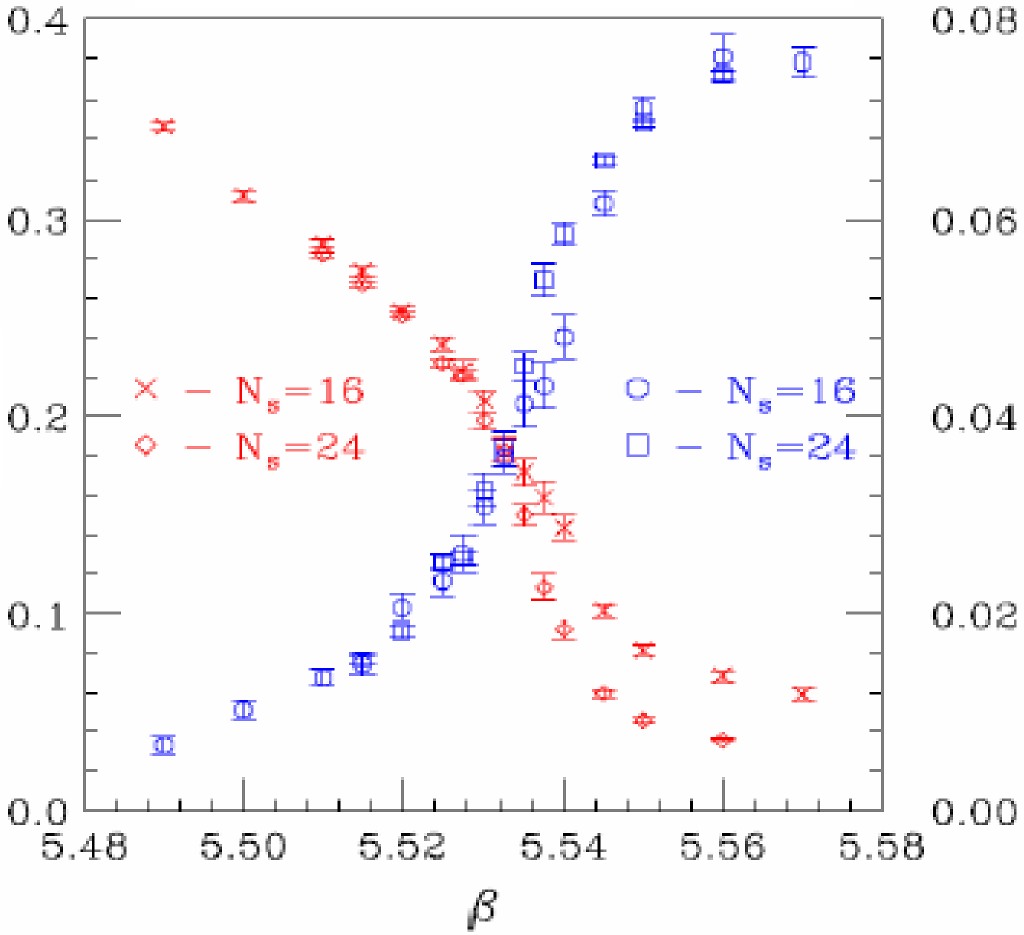


T_C depends on the number of quark flavours

$T_C \sim 175$ MeV

Lattice QCD predicts a rapid transition, with correlated deconfinement and chiral restauration

$\langle \bar{q} q \rangle$



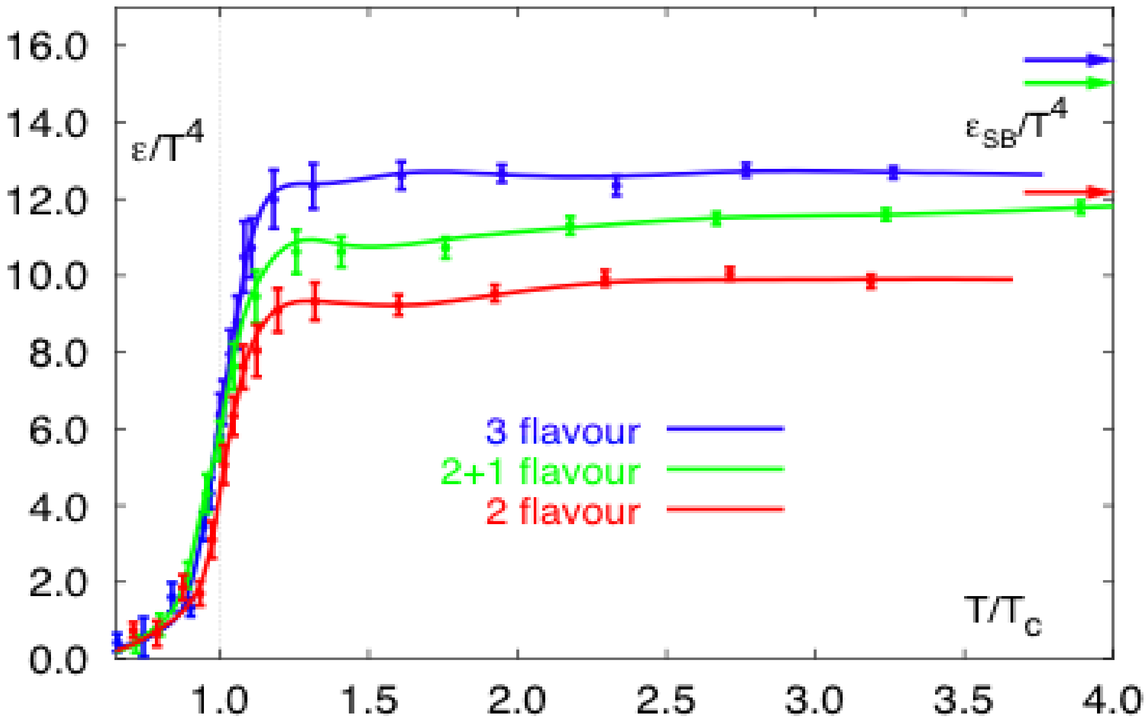
$$\langle L \rangle = \left\langle \mathrm{tr}\, \exp(i \int_0^{1/T} A_4\, d\tau) \right\rangle$$

$$\sim \exp(-F_Q / T)$$

N_f=2, χQCD

Kogut and Sinclair, hep-lat/0408003

- **energy density increases sharply by the latent heat of deconfinement**



For $N_f = 2, 2+1$:

$$T_c \simeq \ 175 \text{ MeV}$$
$$\epsilon(T_c) \simeq 0.5 - 1.0 \text{ GeV/fm}^3$$

An open question: the strong CP violation problem

The axial anomaly breaks the singlet axial current
in the massless theory (also broken by quark masses)

$$\partial_\mu j_5{}^\mu = \frac{\alpha_s}{2\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta}) \qquad \tilde{F}^{\alpha\beta} = \frac{1}{2}\varepsilon^{\alpha\beta\gamma\delta}F_{\gamma\delta}$$

for $N_f = 1$ quark flavours

A CP violating term should be added to the lagrangian

$$\Delta L = \theta \frac{\alpha_s}{2\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})$$

for m=0 it is a 4-divergence but θ arises from the topology of the vacuum in non abelian gauge theories (instantons):

$\theta = \theta_{instantons}$ + Arg Det m

m quark mass matrix

θ is expected to be o(1). But it would contribute to the neutron electric dipole moment:

$$d_n(e \cdot cm) \simeq 3 \cdot 10^{-16}\theta$$

[CKM phase: d_n ~ 10^{-32} e cm]

From experiment: $|\theta| \leq 10^{-10}$

The "strong CP problem" consists in finding an explanation:

- Non rinormalisation theorem in SUSY
- An ad hoc symmetry (Peccei-Quinn) spont. broken --> axion (could contribute to dark matter)
- Something not understood on vacuum topology?

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d_n violates P and T

$$\vec{d}_n = d\vec{\sigma} \qquad \vec{m}_n = \mu\vec{\sigma}$$

$$H \sim -(\vec{d}_n \cdot \vec{E} + \vec{m}_n \cdot \vec{B}) = -(d\vec{E} + \mu\vec{B}) \cdot \vec{\sigma}$$

E and B have opposite behaviour under P and T

CPT is conserved, so
T violation implies CP violation

Recent limit on d_n from Grenoble

$|d_n| < 2.9\ 10^{-26}$ e cm (90%cl)