Summary of ICHEP04

Theory

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DESY Zeuthen

– Colloquium, DESY, Zeuthen, Sep 08, 2004 –

Plan

Plan

- QCD
  - perturbative
  - lattice
  - hadron spectroscopy

Plan

- QCD
- Electroweak physics
  - precision
  - NuTeV
  - $g_\mu - 2$

Plan

- QCD
- Electroweak physics
- Flavour physics
  - Quark mixing and CKM
  - CP violation
  - B-decays

Plan

- QCD
- Electroweak physics
- Flavour physics
- Beyond Standard Model physics
  - electroweak symmetry breaking
  - neutrino physics

Plan

- QCD
- Electroweak physics
- Flavour physics
- Beyond Standard Model physics

My comments in red boxes

Disclaimer No Quark-Gluon-Plasma, particle astrophysics, cosmology and strings

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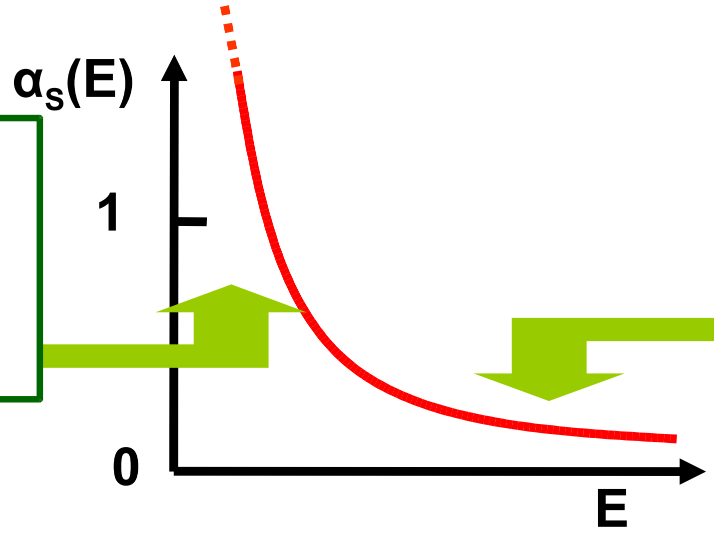
QCD in 2004

non-perturbative approaches:
lattice, Regge theory, skyrmions, large-N_c,...



perturbative field theory calculations

for semi-hard, exclusive and soft processes, we need to *extend* and test calculational techniques

$\Rightarrow$ experiment and theory working together

for 'hard' processes (i.e. suitably inclusive, with at least one large momentum transfer scale), QCD is a *precision tool* – calculations and phenomenology aiming at the per-cent level

compare $\sigma_{tot}(pp)$ and $\sigma_{tot}(e^+e^- \rightarrow \text{hadrons})$

examples of 'precision' phenomenology

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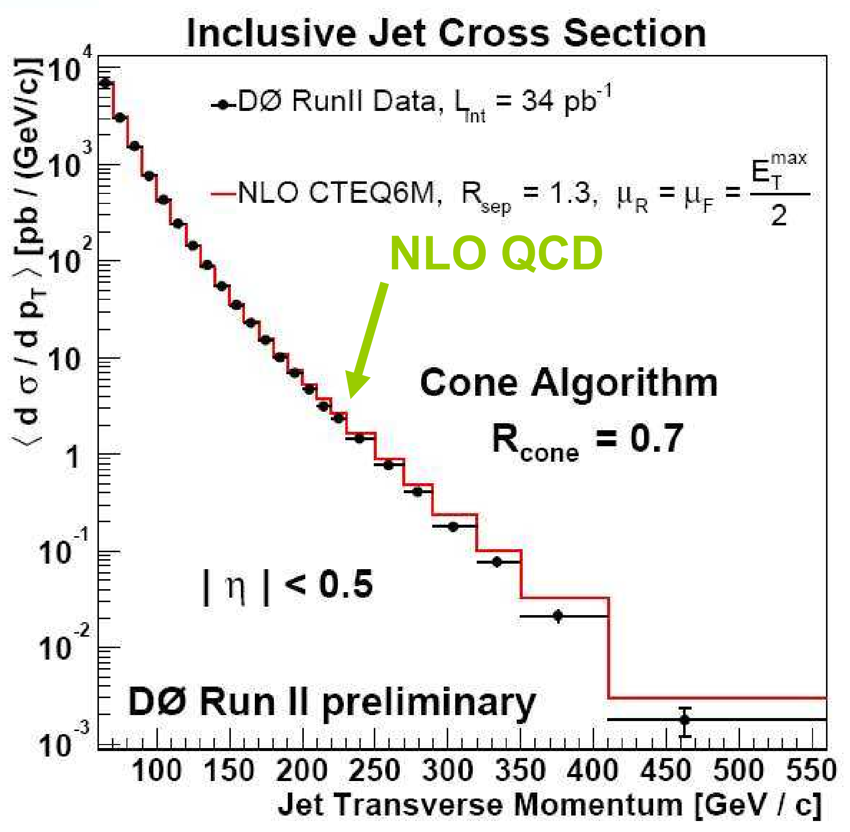
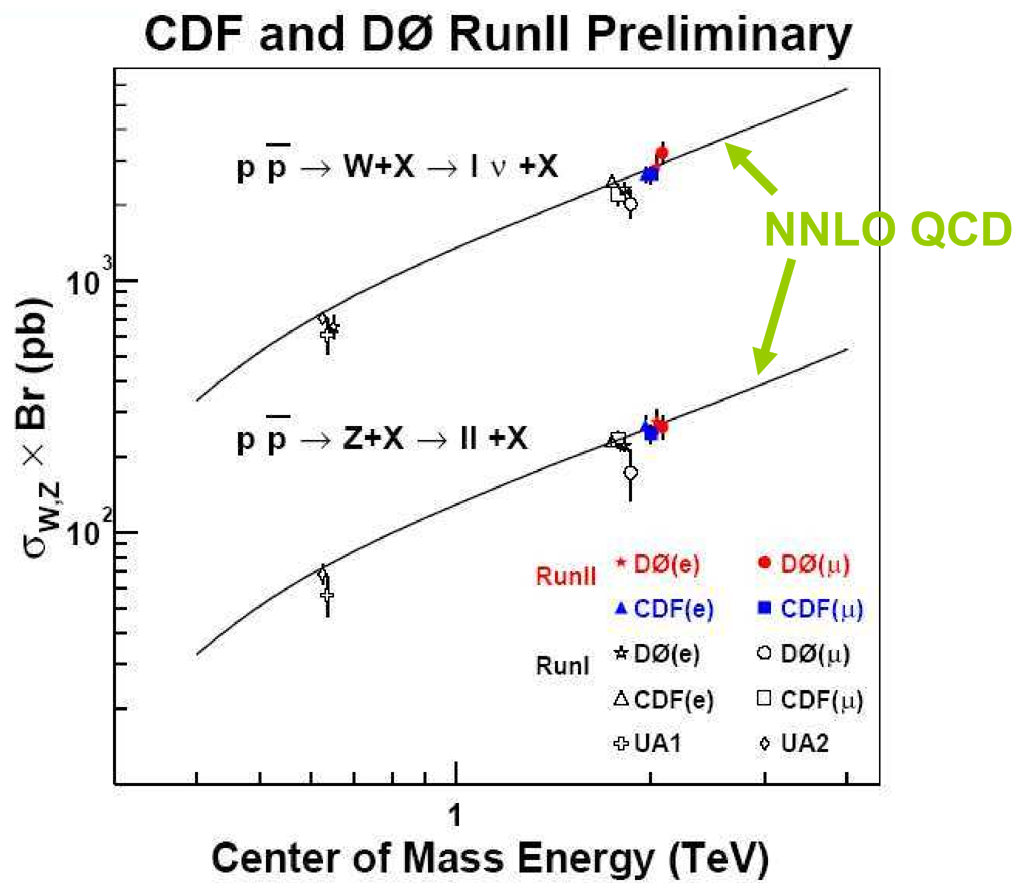
jet production

W, Z production





… and many other examples presented at this Conference

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status of pQCD calculations

fixed order: $d\sigma = A\,\alpha_S^N\,[\,1 + C_1\,\alpha_S + C_2\,\alpha_S^2 + \ldots\,]$

thus LO, NLO, NNLO, etc, or resummed to all orders using a leading log approximation, e.g.

current frontier

$$d\sigma = A\,\alpha_S^N\,[\,1 + (c_{11}\,L + c_{10})\,\alpha_S + (c_{22}\,L^2 + c_{21}\,L + c_{20})\,\alpha_S^2 + \ldots\,]$$

where $L = \log(M/q_T), \log(1/x), \log(1\text{-}T), \ldots >> 1$ thus LL, NLL, NNLL, etc.

LO

- automated codes for arbitrary matrix element generation (MADGRAPH, COMPHEP, HELAC, …)
- jet = parton, but 'easy' to interface to hadronisation MCs
- large scale dependence $\alpha_S(\mu)^N$ therefore not good for precision analyses

NLO

- now known for 'most' processes of interest
- $d\sigma_V^{(N)} + d\sigma_R^{(N+1)}$
- reduced scale dependence (but can still dominate α_S measurement)
- jet structure begins to emerge
- no automation yet, but many ideas
- now can interface with PS

NLO QCD Calculations Needed for Extracting BSM signals

Ellis

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

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summary of NNLO calculations (~1990 $\rightarrow$)

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ep

- DIS pol. and unpol. structure function coefficient functions
- Sum Rules (GLS, Bj, …)
- DGLAP splitting functions Moch Vermaseren Vogt (2004)

e^+e^-

- total hadronic cross section, and $Z \rightarrow$ hadrons, $\tau \rightarrow \nu$ + hadrons
- heavy quark pair production near threshold
- C_F^3 part of σ(3 jet) Gehrmann-De Ridder, Gehrmann, Glover(2004)

pp

- inclusive W,Z,γ^* van Neerven et al, Harlander and Kilgore corrected (2002)
- inclusive γ^* polarised Ravindran, Smith, Van Neerven (2003)
- W,Z,γ^* differential rapidity dis^n Anastasiou, Dixon, Melnikov, Petriello (2003)
- H^0, A^0 Harlander and Kilgore; Anastasiou and Melnikov; Ravindran, Smith, Van Neerven (2002-3)
- WH, ZH Brein, Djouadi, Harlander (2003)

HQ

- QQ onium and Qq meson decay rates

+ other partial/approximate results (e.g. soft, collinear) and NNLL improvements

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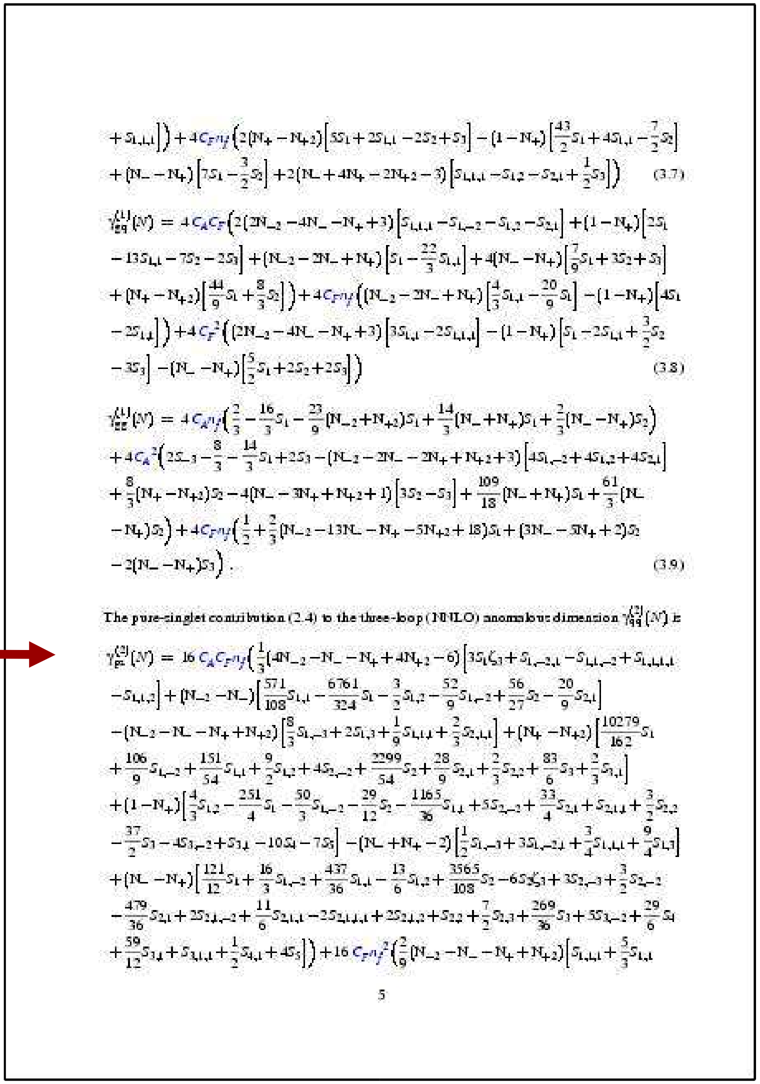
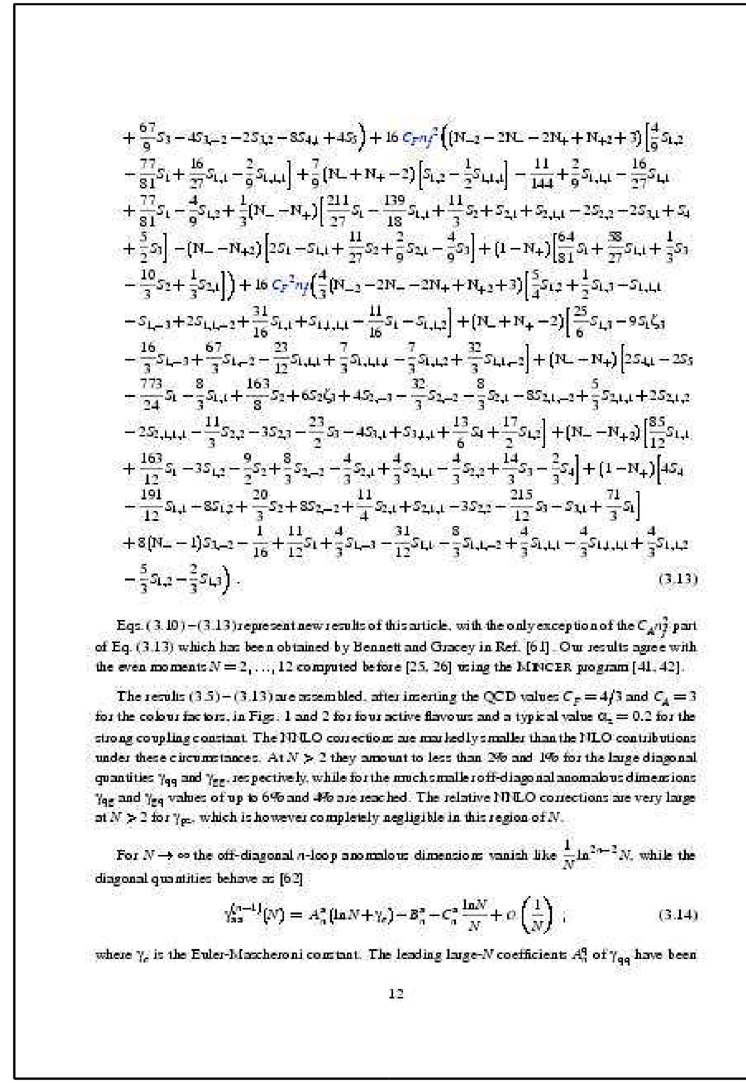
Moch, Vermaseren and Vogt,
hep-ph/0403192, hep-ph/0404111



The pure-singlet contribution (2.4) to the three-loop (NNLO) anomalous dimension $\gamma_{qq}^{(2)}(N)$ is

5

7 pages later…



Eqs. (3.10)–(3.13) represent new results of this article, with the only exception of the $C_A n_f^2$ part of Eq. (3.13) which has been obtained by Bennett and Gracey in Ref. [61]. Our results agree with the even moments $N = 2, \ldots, 12$ computed before [25, 26] using the MINCER program [41, 42].

The results (3.5)–(3.13) are assembled, after inserting the QCD values $C_F = 4/3$ and $C_A = 3$ for the colour factors, in Figs. 1 and 2 for four active flavours and a typical value $\alpha_s = 0.2$ for the strong coupling constant. The NNLO corrections are markedly smaller than the NLO contributions under these circumstances. At $N > 2$ they amount to less than 2% and 1% for the large diagonal quantities γ_{qq} and γ_{gg}, respectively, while for the much smaller off-diagonal anomalous dimensions γ_{qg} and γ_{gq} values of up to 6% and 4% are reached. The relative NNLO corrections are very large at $N > 2$ for γ_{gq}, which is however completely negligible in this region of N.

For $N \to \infty$ the off-diagonal n-loop anomalous dimensions vanish like $\frac{1}{N} \ln^{2n-2} N$, while the diagonal quantities behave as [62]

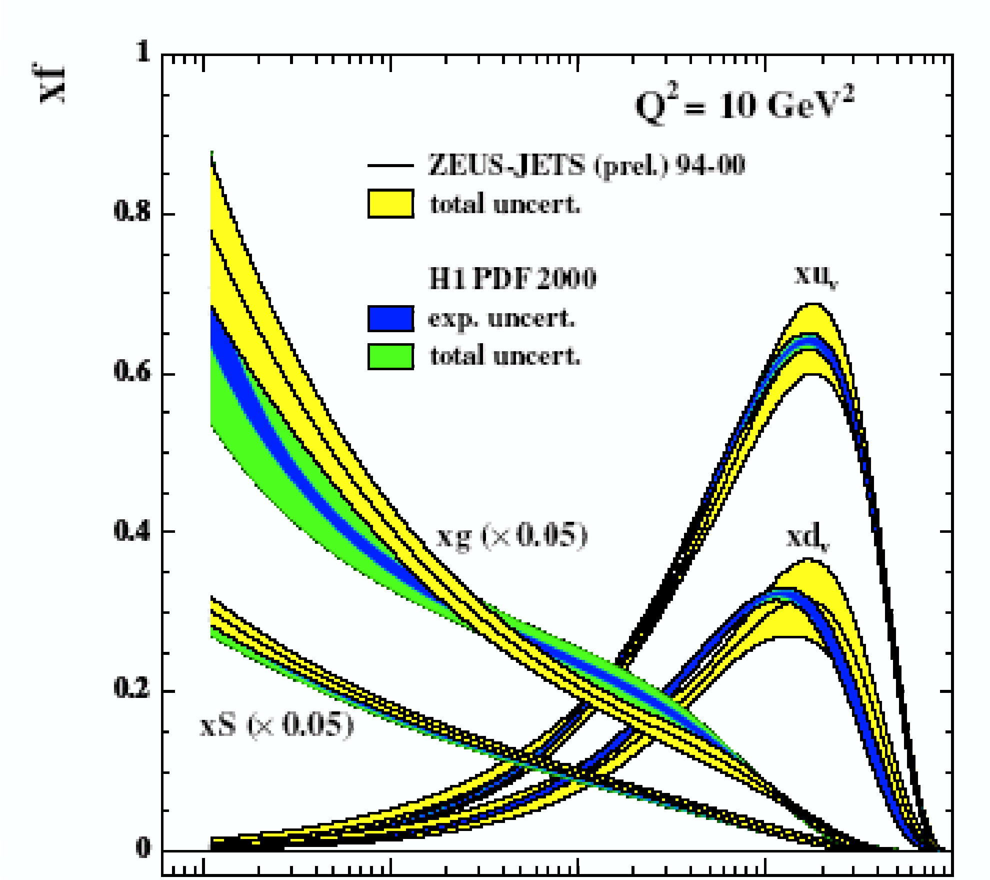
$$\gamma_{aa}^{(n-1)}(N) = A_n^a (\ln N + \gamma_e) - B_n^a - C_n^a \frac{\ln N}{N} + O\left(\frac{1}{N}\right) \; ; \qquad (3.14)$$

where γ_e is the Euler-Mascheroni constant. The leading large-N coefficients A_n^q of γ_{qq} have been

12

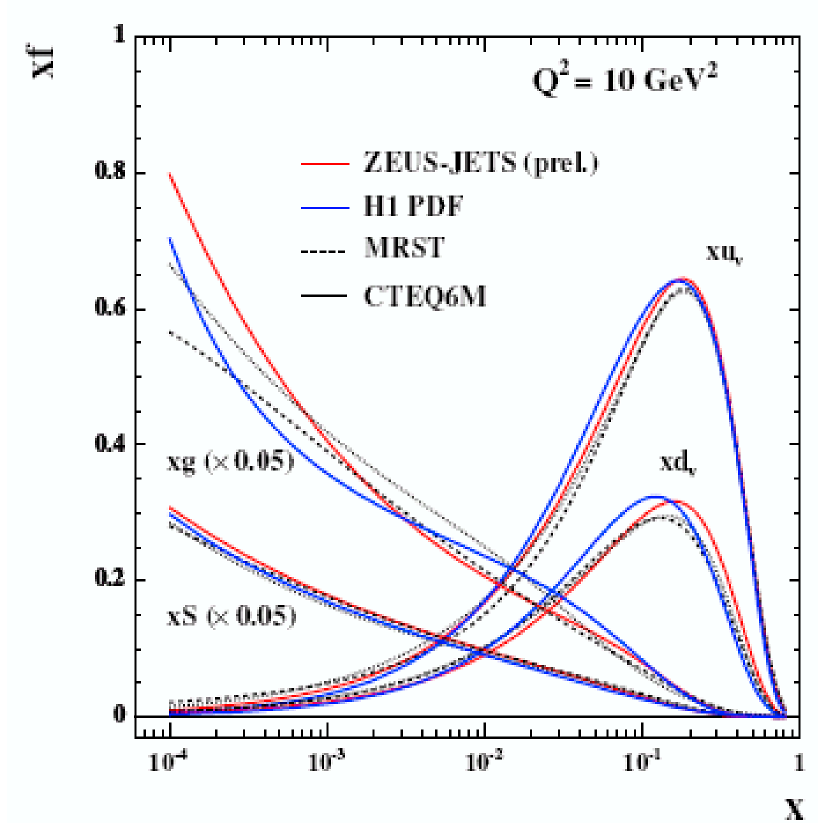
…then 8 pages of the same quantities expressed in x-space!

Parton distributions unfolded with H1 data and with ZEUS data only



Klein

comparison to global fits



- H1 and ZEUS parton distributions are in agreement
- HERA experiment's fits agree with global fits
- Gluon at low x and Q^2 not well constrained
- Treatment of systematic, model and theoretical errors subject to conventions

QCD fits parameterise initial PDFs

H1 $U, \bar{U}, D, \bar{D}, xg \leftrightarrow V, A, xg - \alpha_s$

ZEUS $u_v, d_v, \bar{u} \pm \bar{d}, xg - \alpha_s$

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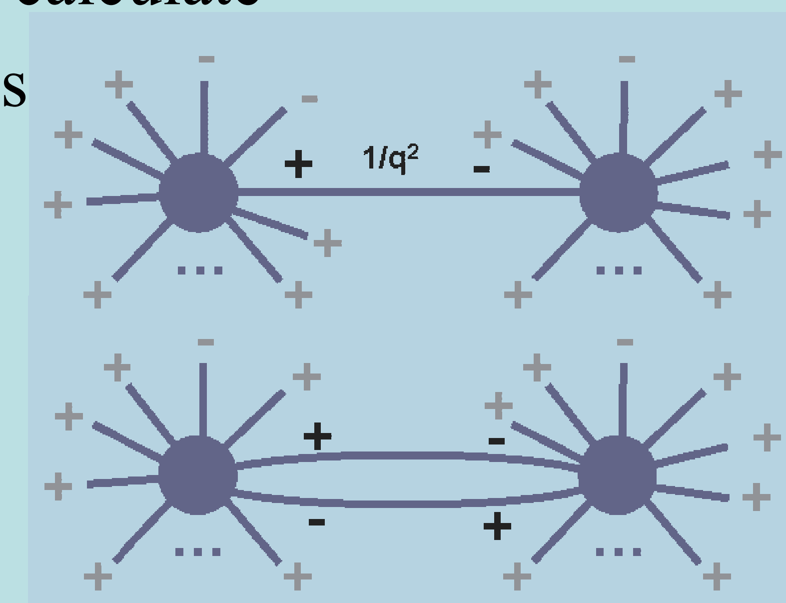
QCD Calculations in String Approach

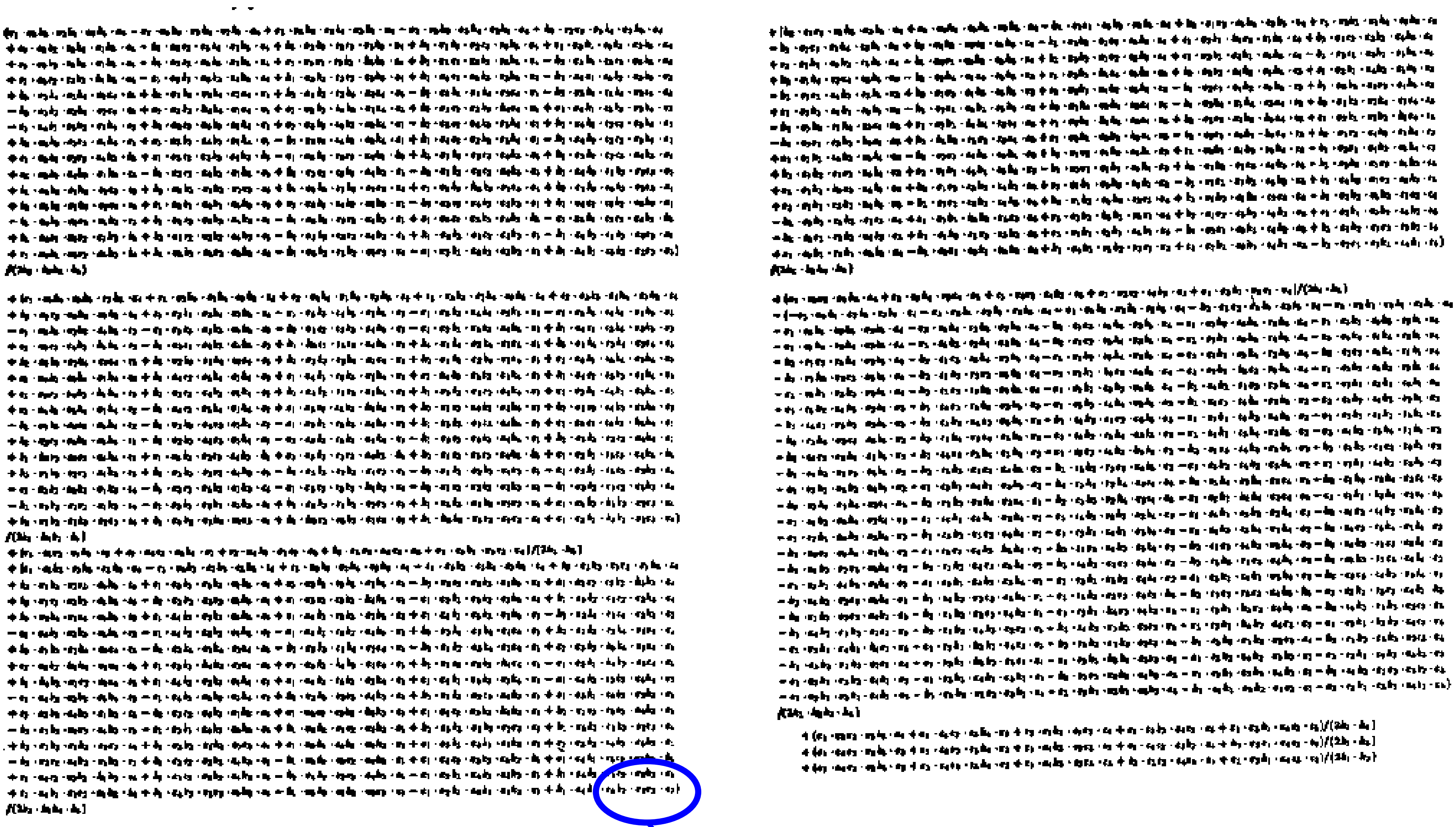
Cachazo, Svrcek & Witten

- Maximal helicity-violating (MHV) amplitudes as effective vertices in a new scalar graph approach
- use them with scalar propagators to calculate
  - — tree-level non-MHV amplitudes
  - — with both quarks and gluons
  - — … and loop diagrams!



- dramatic simplification: compact output in terms of familiar spinor products
- phenomenology? multijet cross sections at LHC, etc. underway

Result of a brute force calculation (actually only a small part of it):



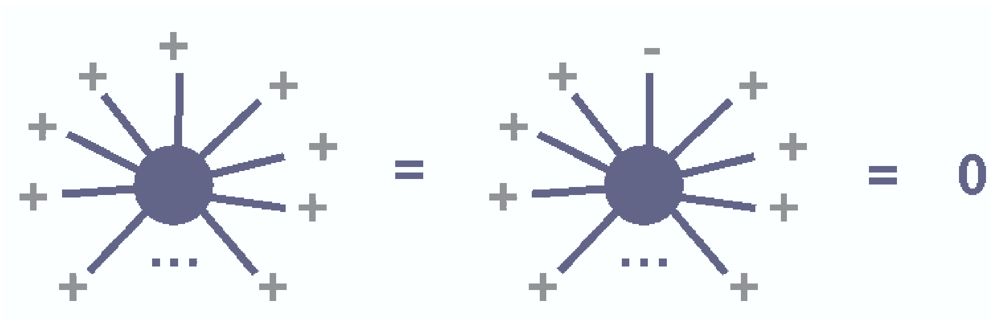
Bern

$k_1 \cdot k_4 \, \varepsilon_2 \cdot k_1 \, \varepsilon_1 \cdot \varepsilon_3 \, \varepsilon_4 \cdot \varepsilon_5$

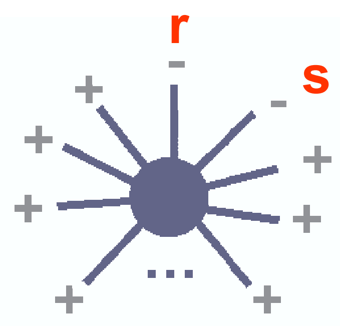
$gg \to ggg$ amplitude by conventional means (2 out of 25 pages)

the Parke-Taylor amplitude mystery

- consider a n-gluon scattering amplitude with ± helicity labels



Maximum
Helicity
Violating



$$= \; i\, g_S^{n-2} \frac{\langle r,s\rangle^4}{\prod_{j=1}^{n}\langle j, j+1\rangle} \qquad \begin{cases} \langle i,j\rangle = u_-(p_i)\bar{u}_+(p_j) \\ |\langle i,j\rangle| = \sqrt{2p_i\cdot p_j} \end{cases}$$

(colour factors suppressed)

- Parke and Taylor (PRL 56 (1986) 2459):

“this result is an educated guess”
“we do not expect such a simple expression for the other helicity amplitudes”
“we challenge the string theorists to prove more rigorously that [it] is correct”

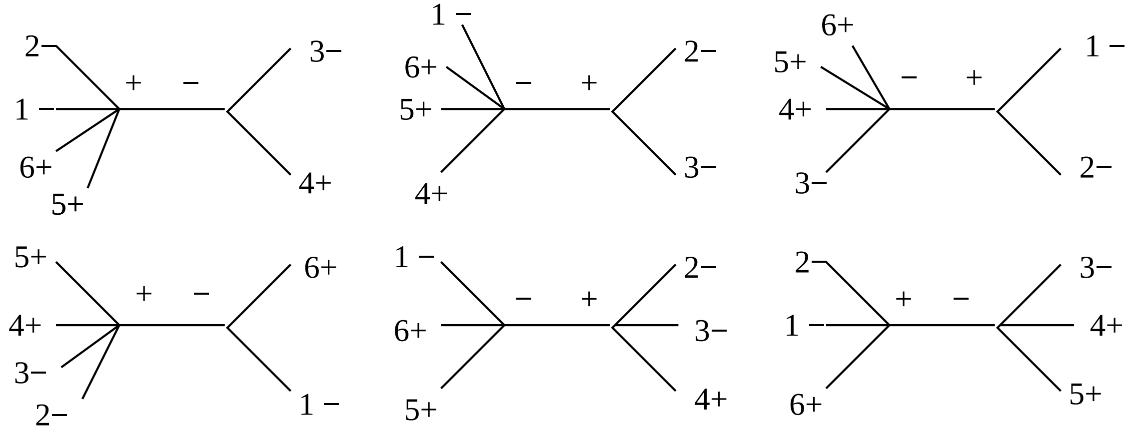
true!

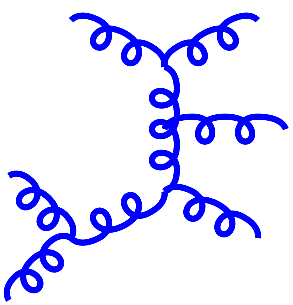
- Witten, December 2003 (hep-th/0312171)
“P*erturbative gauge theory as a string theory in twistor space”*

Bern

QCD gluon scattering amplitude

$- \; - \; - \; + \; + \; +$





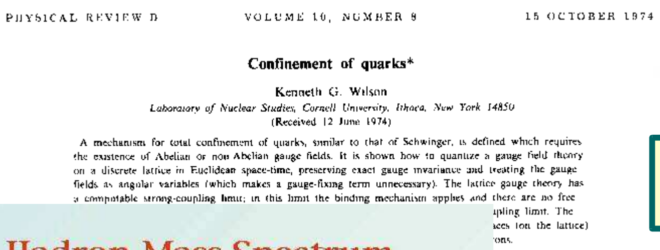
$$
\begin{aligned}
A_6(1^-,2^-,3^-,4^+,5^+,6^+) = {} & \frac{\langle 1\,2\rangle^3}{\langle 5\,6\rangle\,\langle 6\,1\rangle\,\langle 2|\,5+6+1\,|q\rangle\,\langle 5|\,6+1+2\,|q\rangle} \times \frac{1}{s_{34}} \times \frac{\langle 3|\,4\,|q\rangle^3}{\langle 3\,4\rangle\,\langle 4|\,3\,|q\rangle} \\
& + \frac{\langle 1|\,4+5+6\,|q\rangle^3}{\langle 4\,5\rangle\,\langle 5\,6\rangle\,\langle 6\,1\rangle\,\langle 4|\,5+6+1\,|q\rangle} \times \frac{1}{s_{23}} \times \frac{\langle 2\,3\rangle^3}{\langle 3|\,2\,|q\rangle\,\langle 2|\,3\,|q\rangle} \\
& + \frac{\langle 3|\,4+5+6\,|q\rangle^3}{\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,\langle 6|\,3+4+5\,|q\rangle} \times \frac{1}{s_{12}} \times \frac{\langle 1\,2\rangle^3}{\langle 2|\,1\,|q\rangle\,\langle 1|\,2\,|q\rangle} \\
& + \frac{\langle 2\,3\rangle^3}{\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5|\,2+3+4\,|q\rangle\,\langle 2|\,3+4+5\,|q\rangle} \times \frac{1}{s_{61}} \times \frac{\langle 1|\,6\,|q\rangle^3}{\langle 6\,1\rangle\,\langle 6|\,1\,|q\rangle} \\
& + \frac{\langle 1|\,5+6\,|q\rangle^3}{\langle 5\,6\rangle\,\langle 6\,1\rangle\,\langle 5|\,6+1\,|q\rangle} \times \frac{1}{s_{561}} \times \frac{\langle 2\,3\rangle^3}{\langle 3\,4\rangle\,\langle 4|\,2+3\,|q\rangle\,\langle 2|\,3+4\,|q\rangle} \\
& + \frac{\langle 1\,2\rangle^3}{\langle 6\,1\rangle\,\langle 2|\,6+1\,|q\rangle\,\langle 6|\,1+2\,|q\rangle} \times \frac{1}{s_{612}} \times \frac{\langle 3|\,4+5\,|q\rangle^3}{\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5|\,3+4\,|q\rangle}
\end{aligned}
$$

Indepent checks on amplitudes from soft and collinear limits

Hashimoto

30 years of lattice QCD

K. Wilson (1974)


PHYSICAL REVIEW D VOLUME 10, NUMBER 8 15 OCTOBER 1974

Confinement of quarks*

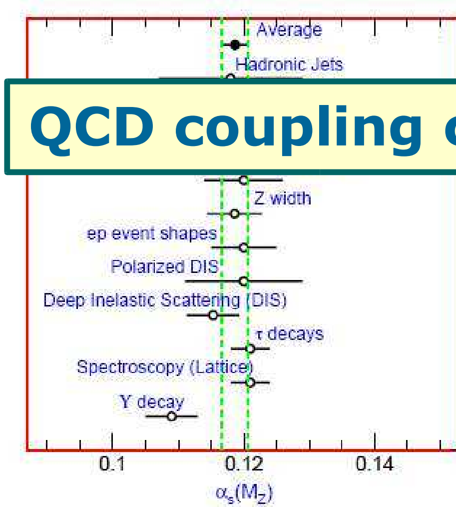
Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

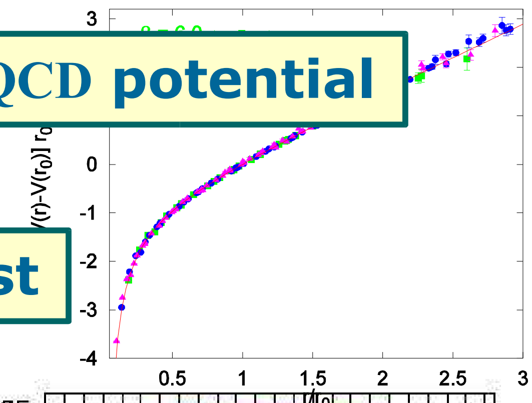
(Received 12 June 1974)

A mechanism for total confinement of quarks, similar to that of Schwinger, is defined which requires the existence of Abelian or non-Abelian gauge fields. It is shown how to quantize a gauge field theory on a discrete lattice in Euclidean space-time, preserving exact gauge invariance and treating the gauge fields as angular variables (which makes a gauge-fixing term unnecessary). The lattice gauge theory has a computable strong-coupling limit; in this limit the binding mechanism applies and there are no free ...

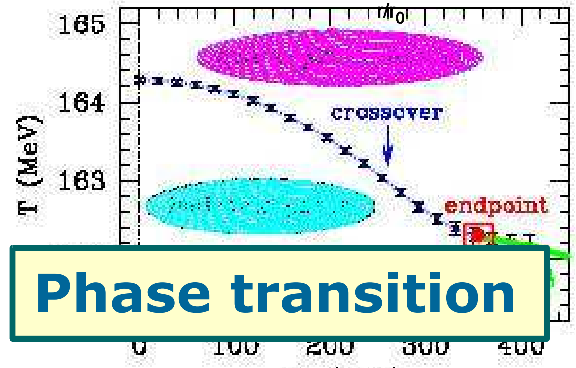
Hadron spectrum



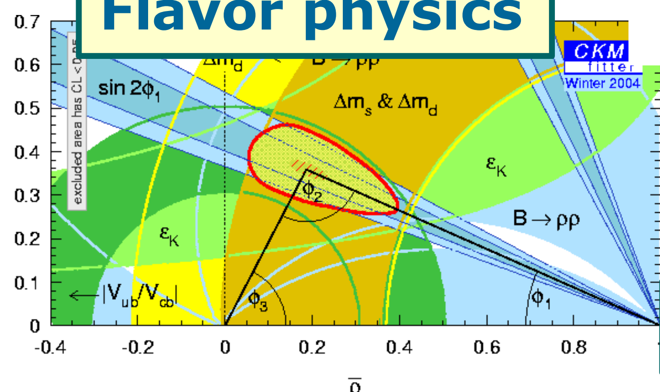
QCD coupling const



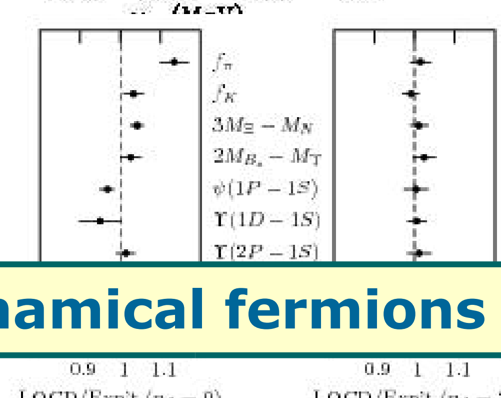
QCD potential



Phase transition



Flavor physics



Dynamical fermions

Sven-Olaf Moch

Hashimoto

Dynamical fermions

- Calculating the fermion determinant = numerically very hard.

$$\int d\psi d\bar{\psi}\, e^{\int d^4x \bar{\psi}(\not{D}+m)\psi} = \det(\not{D}+m)$$

Quenched: neglect it
Unquenched: include it

- How hard it is depends on the fermion formulation on the lattice.

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Fast simulations at low quark masses

Lattice fermions

	chiral symmetry	flavor symmetry	numerical simulation
Wilson / $O(a)$-improved Wilson	*violated*; will recover in the continuum	okay	*expensive*; harder at small quark masses
twisted mass	violated	2 flavors; a flavor mixing mass term	less expensive at small quark masses
staggered (Kogut-Susskind)	exact U(1) out of U(4)	*4 tastes*; non-trivial mixing	*fast*
Ginsparg-Wilson (domain-wall, overlap)	exact at finite a	okay	most expensive; still exploratory

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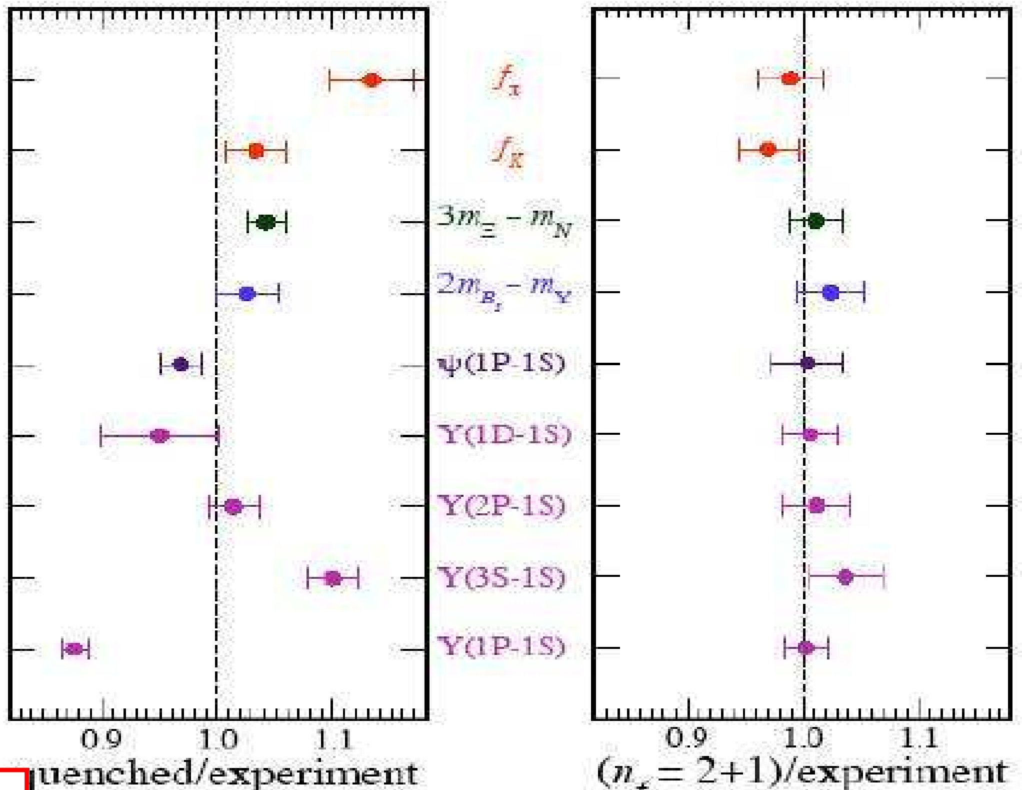
"Lattice QCD confronts experiment"

HPQCD, MILC, UKQCD, Fermilab (2003)

"Gold-plated lattice observables agree with experiments within a few %."

"Only with 2+1 flavors."

PRL92, 022001 (2004)



Simulation with dynamical fermions give control of lattice systematics

“Lattice QCD confronts experiment”

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HPQCD, MILC, UKQCD, Fermilab (2003)

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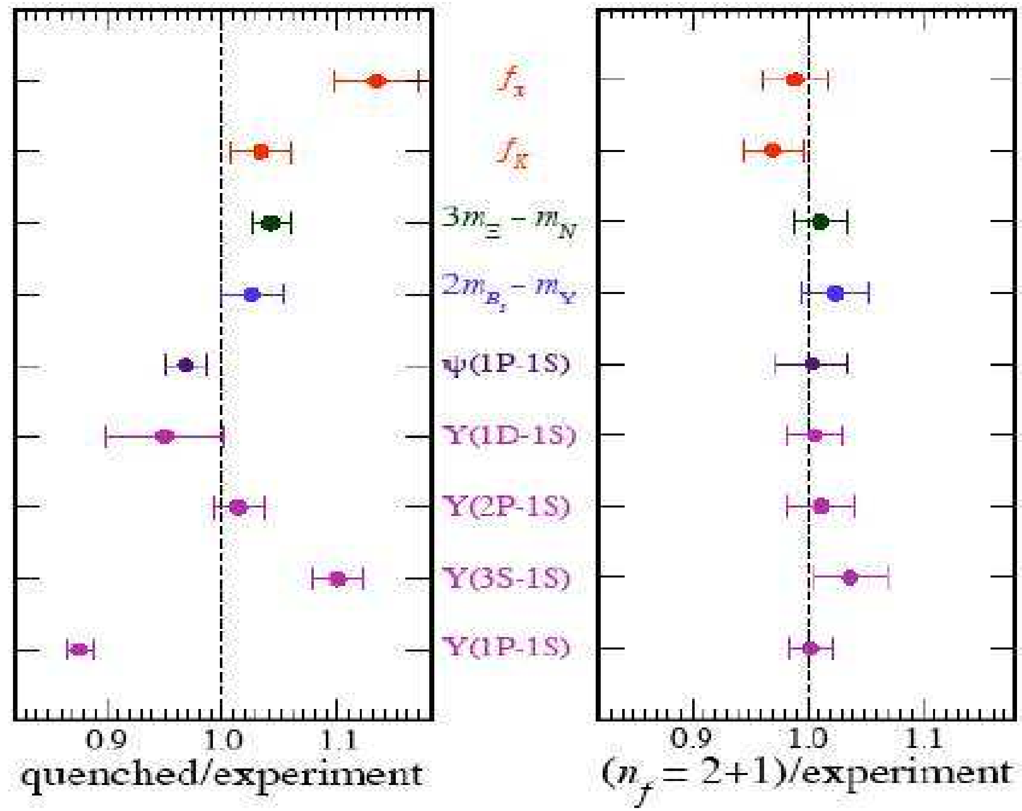

Is everything okay?

Locality/Universality

Fourth-root trick:

$\det D^{\text{stag}}$ 4 tastes (unwanted)

↓

$(\det D^{\text{stag}})^{1/4}$ no doubling

Can it be written as a local field theory?

$$(\det D^{\text{stag}})^{1/4} \quad =? \quad \int d\psi d\bar{\psi}\, e^{\int d^4x \bar{\psi} M^{local} \psi}$$

Otherwise, there is no guarantee that the theory is renormalizable as a quantum field theory, i.e. continuum limit is *the* QCD.

$(D^{\text{stag}})^{1/2}$ is non-local: Bunk et al, hep-lat/0403022; Hart, Muller, hep-lat/0406030.

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Issue still controversial; Open question = project out single taste from staggered operator (possible?) and check locality

Locality/Universality

Fourth-root trick:

$\det D^{\rm stag}$ 4 tastes (unwanted)

$(\det D^{\rm stag})^{1/4}$ no doubling

Can it be written as a local field theory?

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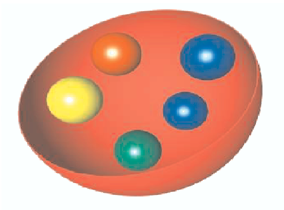
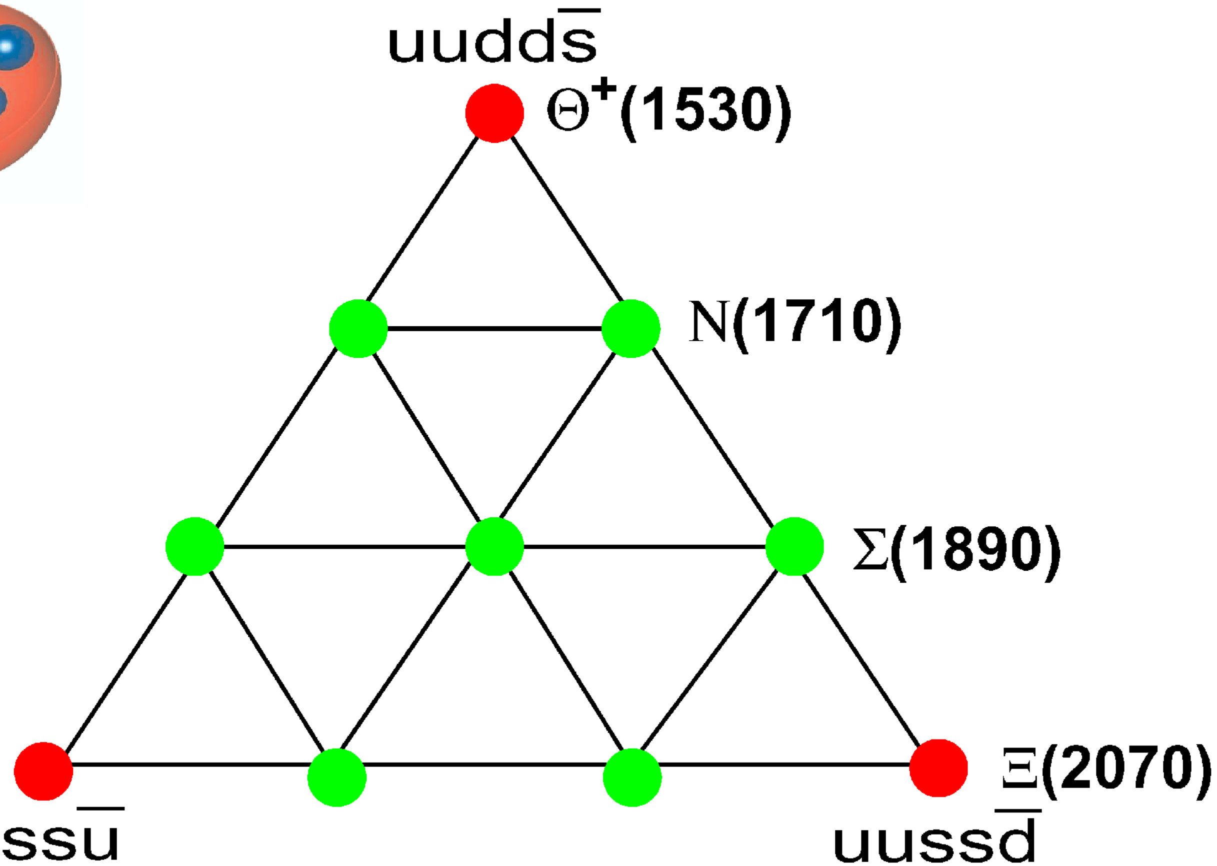
Pentaquark States from Theory:

anti-decuplet in chiral soliton models-1st version





½+ Strangeness +1 baryon mass 1540MeV narrow width

Close

Predicted!!! DPP

In chiral soliton model with unusual assumptions

Narrow width an enigma
Mass a problem
Production mechanism unknown

n.b. expt has not established ½+
It might not exist!

Ma

Theories of positive parity for

- Chiral Soliton Models (old version)

  Diakonov-Petrov-Polyakov, ZPA359(1997)305
- Analysis in Quark Model

  Stancu-Riska, PLB575(2003)242
- Diquark Cluster Model

  Jaffe-Wilczek, PRL91(2003)232003
- Diquark-Triquark Model

  Karliner-Lipkin, PLB575(2003)249
- Inherent Nodal Structure Analysis

  Y.-x.Liu, J.-s.Li, and C.-g. Bao, hep-ph/0401197

Ma

Theories of negative parity for

- **Naive Quark Model**

  Jaffe (1976)

- **Some Quark Models**

  Capstick-Page-Roberts, PLB570(2003)185

  Huang-Zhang-Yu-Zhou, hep-ph/0310040 PLB586(04)69.

- **QCD Sum Rules**

  Zhu, PRL91(2003)232002, Sugiyama-Doi-Oka, hep-ph/0309271

- **Lattice QCD**

  Sasaki, hep-ph/0310014, Csikor et al, hep-ph/0309090,

  but we heard difference voices recently

Close

Ellis

Interpretations of $\theta^+(1530)$ – if it exists

- Naïve non-relativistic quark model would need epicycles:

  di/triquarks, P-wave ground state

- Predicted in chiral soliton model:

  fits data, predicts other exotic states

← Based on idea that quarks weigh << Λ_{QCD}

- Existence requires confirmation:

  a high-statistics, -significance experiment

- If it exists, θ^+ spin & parity distinguish models

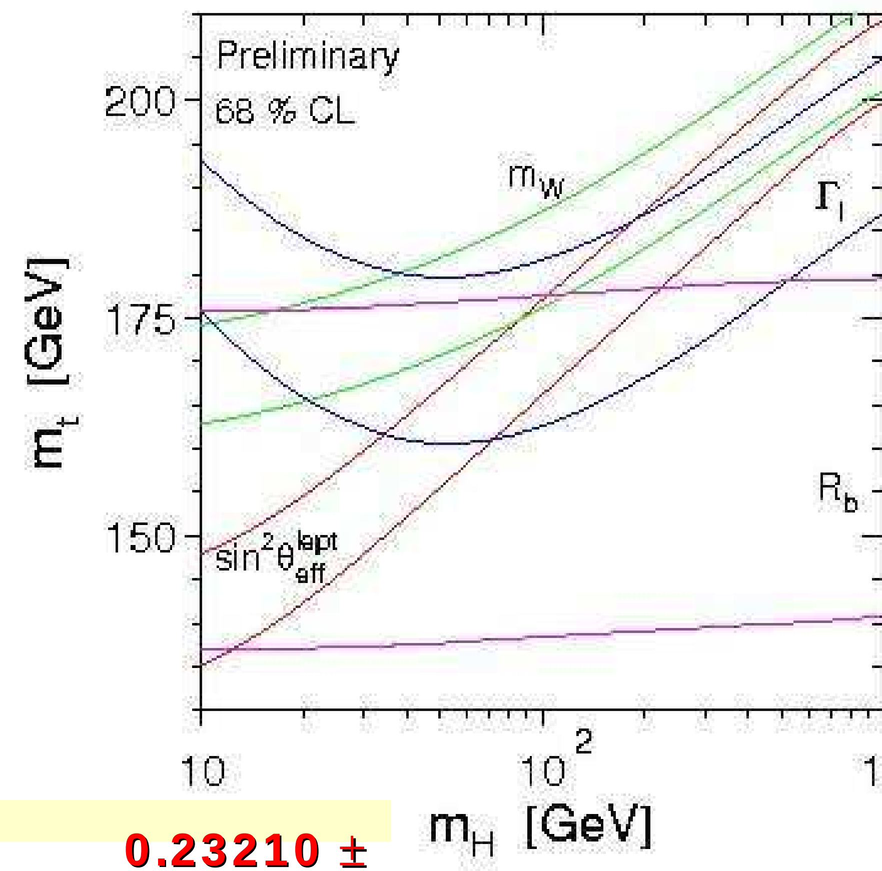
The stakes are high:
the $\theta^+(\Xi^{--}, \theta_c)$ may take us beyond the naïve quark model

Teubert

Consistency with the SM

All the high Q^2 measurements are fitted as a function of:

$O(\alpha, G_\mu, m_Z, \alpha_s, m_{Higgs}, m_{top})$



Changes w.r.t. summer 03:

-New measurement of m_{top} at TeVatron:

m_{top} = 174±5.1 GeV → 178.0 ± 4.3 GeV

-New HF average from LEP:

$\sin^2\theta_{eff}$ (b-asym) = 0.23212±0.00029 → 0.23210 ± 0.00030

-New version of ZFITTER v6.4 with two loop corrections to Mw and $\sin^2\theta_{eff}$

New version of ZFITTER with important theory improvements

Recent EW calculations

Muon decay:

fermionic: A.Freitas, W.Hollik, W.Walter, G.Weiglein 2000; M.Awramik, M.Czakon, 2003;

bosonic: M.Awramik, M.Czakon, 2002; A.Onishchenko, O.Veretin, 2002;

New M_W prediction: M.Awramik, M.Czakon, A.Freitas, G.Weiglein 2003;

$\sin^2\theta_{\text{eff}}^{\text{lept}}$:

fermionic: M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Aug 2004;

Recent EW calculations

Muon decay:

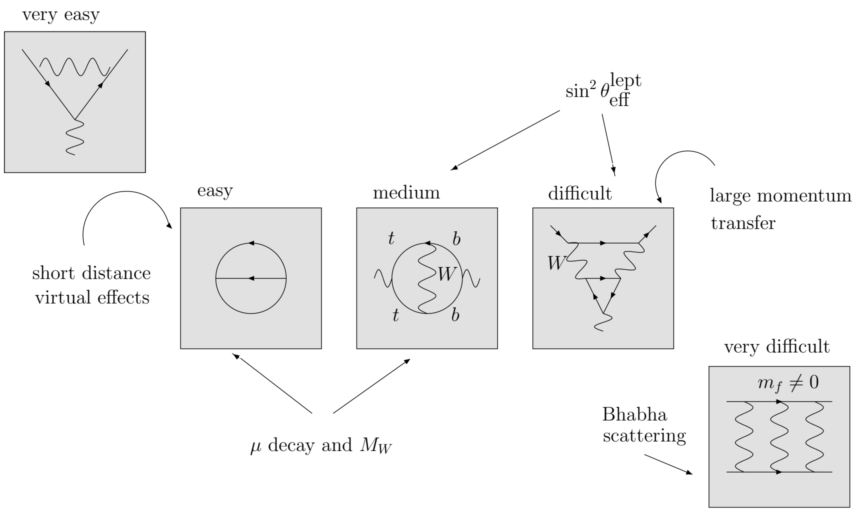
fermionic: A.Freitas, W.Hollik, W.Walter, G.Weiglein 2000; M.Awramik, M.Czakon, 2003;

bosonic: M.Awramik, M.Czakon, 2002; A.Onishchenko, O.Veretin, 2002;

New M_W prediction: M.Awramik, M.Czakon, A.Freitas, G.Weiglein 2003;

$\sin^2\theta_{\text{eff}}^{\text{lept}}$:

fermionic: M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Aug 2004;



80ties → present → future

Recent EW calculations

Shift in M_H due to new calculations is almost as large as shift due to new m_t

Muon decay:

fermionic: A.Freitas, W.Hollik, W.Walter, G.Weiglein 2000; M.Awramik, M.Czakon, 2003;

bosonic: M.Awramik, M.Czakon, 2002; A.Onishchenko, O.Veretin, 2002;

New M_W prediction: M.Awramik, M.Czakon, A.Freitas, G.Weiglein 2003;

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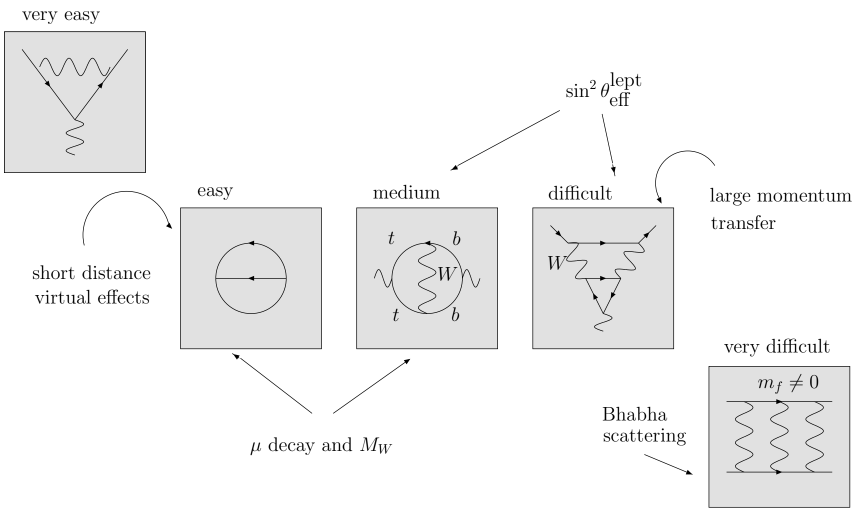
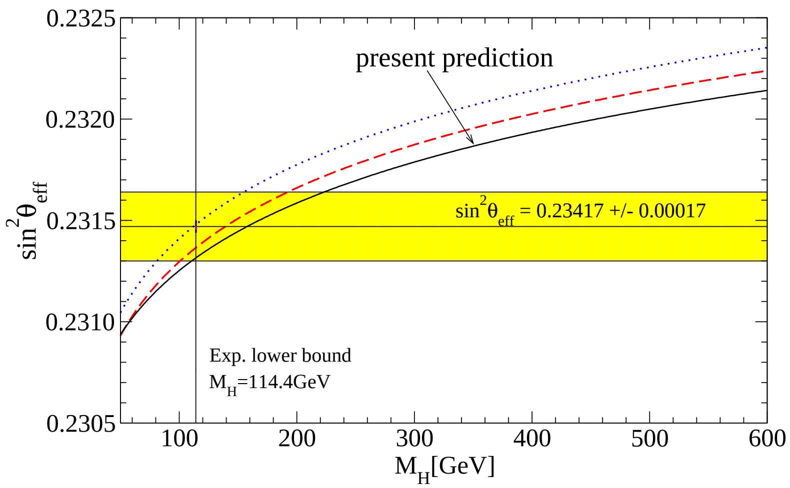


80ties → present → future

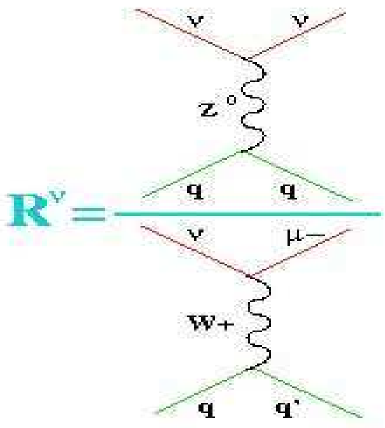


Teubert

$\sin^2\theta_{eff}$ at low Q^2 (NuTeV)

$$R^{\nu} = \frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu^- X)} \quad \text{and/or} \quad R^{\bar\nu} = \frac{\sigma(\bar\nu N \to \bar\nu X)}{\sigma(\bar\nu N \to \mu^+ X)}$$

$$R^{\nu} = \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}(1 + r)\sin^2\theta_W^4\right) \text{ with } r = \frac{\sigma(\nu N \to \mu^- X)}{\sigma(\bar\nu N \to \mu^+ X)} \sim \frac{1}{2}$$

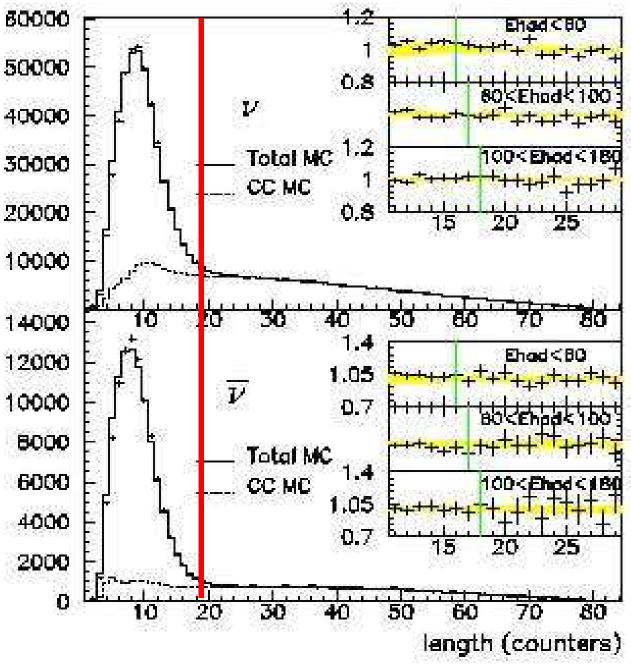


Uncertainties from modelling such as charm mass and strange sea… alternatively, measure CC and NC in both neutrinos and anti-neutrinos: Paschos-Wolfenstein method

$$R^{-} = \frac{\sigma(\nu N \to \nu X) - \sigma(\bar\nu N \to \bar\nu X)}{\sigma(\nu N \to \mu^- X) - \sigma(\bar\nu N \to \mu^+ X)}$$

$$R^{-} = \frac{R^{\nu} - rR^{\bar\nu}}{1 - r}$$

Large cancellation of uncertainties !



R^{ν} = 0.3916 ± (0.0007 stat. ⊕ 0.0011 syst.)

SM: 0.3950 (-2.6 σ)

R^{ν} = 0.4050 ± (0.0016 stat. ⊕ 0.0022 syst.)

SM: 0.4066 (-0.6 σ)

Teubert

$\sin^2\theta_{eff}$ at low Q^2 (NuTeV)

Stirling, Ma, De Florian

Possible sources of discrepancy

Electroweak corrections:

New calculations: K.Diener et al. hep-ph/0310364, hep-ph/0311122
Kretzer, hep-ph/0405221, Arbuzov et al., hep-ph/0407203

Improved treatment of initial state mass singularities

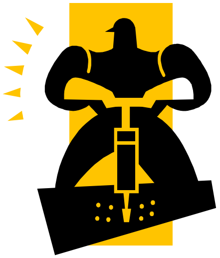
Could reduce the discrepancy by about 1σ

The Strange Sea:

The computation assumes that the strange sea is symmetric.

New CTEQ analysis including the NuTeV dimuon data gives,

$$-0.001 < \int x s^-(x) dx < +0.004$$



while to explain the whole effect would require +0.006

Isospin Violation:

Could $u^p(x) \neq d^n(x)$?

Can account for about 1σ of the effect.

$$R^- = \frac{1}{2} + \sin^2\theta_W + \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{[\delta U_v] - [\delta D_v]}{2V^-}$$

$$[\delta U_v] - [\delta D_v] = \int_0^1 x(u_v^p(x) - d_v^n(x)) - \int_0^1 x(d_v^p(x) - u_v^n(x$$

Best fit gives $[\delta U_v] = -[\delta D_v] = 0.002$

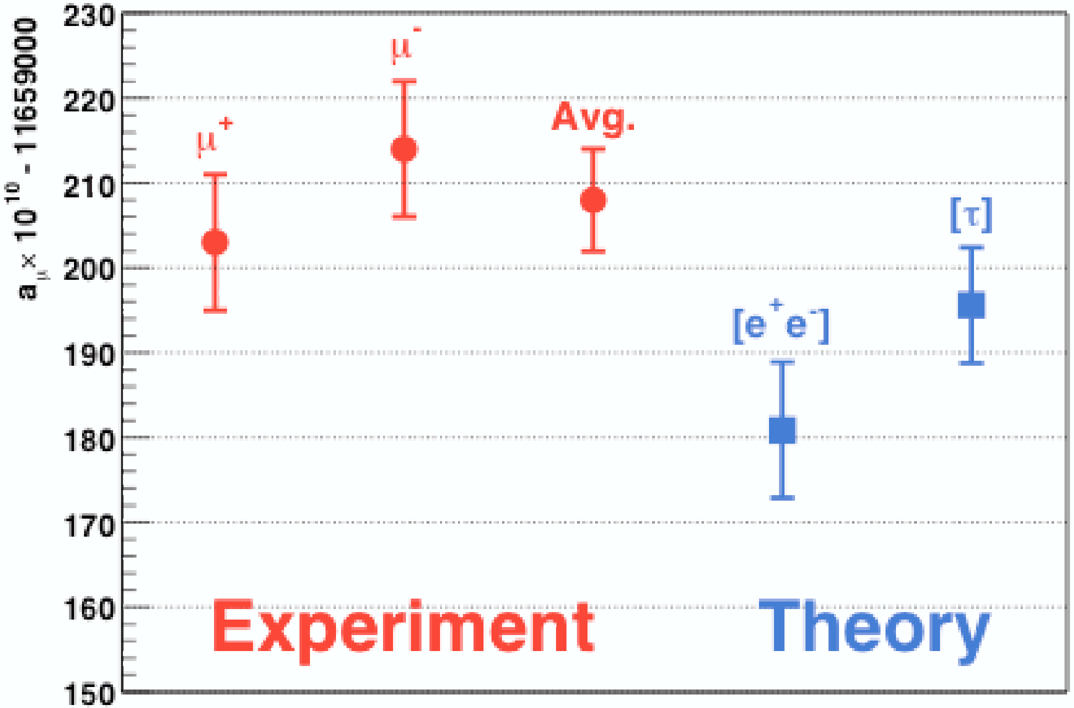
$\downarrow$

$\Delta \sin^2\theta_W \sim -0.0018$ or -0.0015 including sea quarks.

Before a careful re-assessment of all theoretical uncertainties, the 3σ discrepancy with the SM cannot be taken at face value.

$g_\mu - 2$: deviations theory/experiment

Langacker



$$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10}$$ 2.4 s.d.

$$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10}$$ 0.9 s.d.

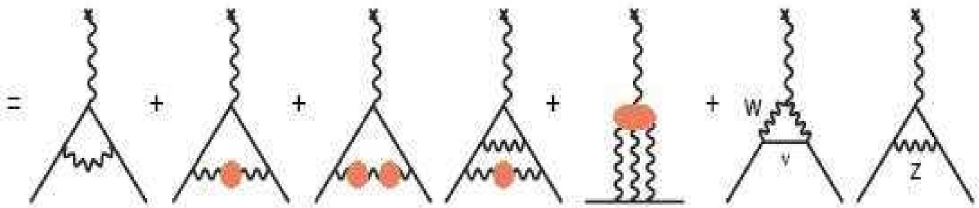
New physics?
Precision calculation of Standard Model value!

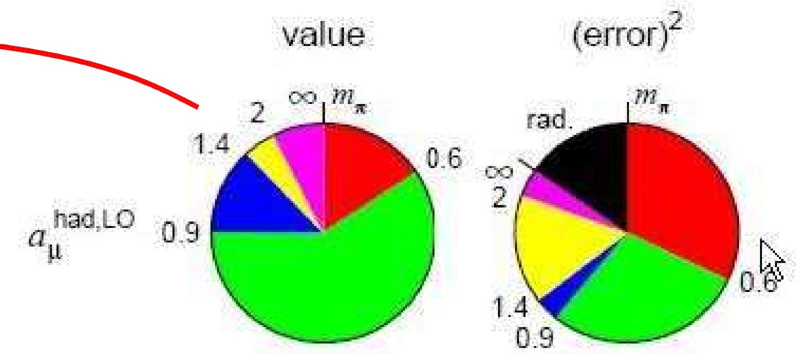
FNAL *James Miller* - The Muon Magnetic Moment Anomaly: Experiment

Teubert

Parameters of the SM: $\alpha(\sim M_\mu^2)$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had,LO} + a_\mu^{had,HO} + a_\mu^{had,LBL} + a_\mu^{weak}$$





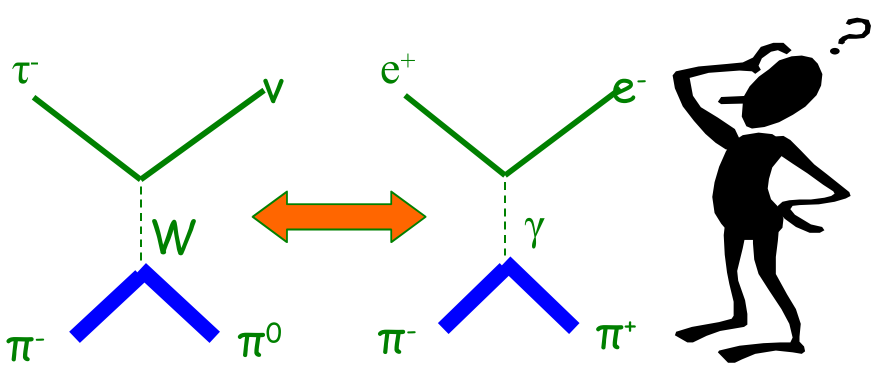
= (QED) $(11\,658\,470.35 \pm 0.28)10^{-10}$ (5-loop!) **$(11658472.07 \pm 0.11)10^{-10}$**

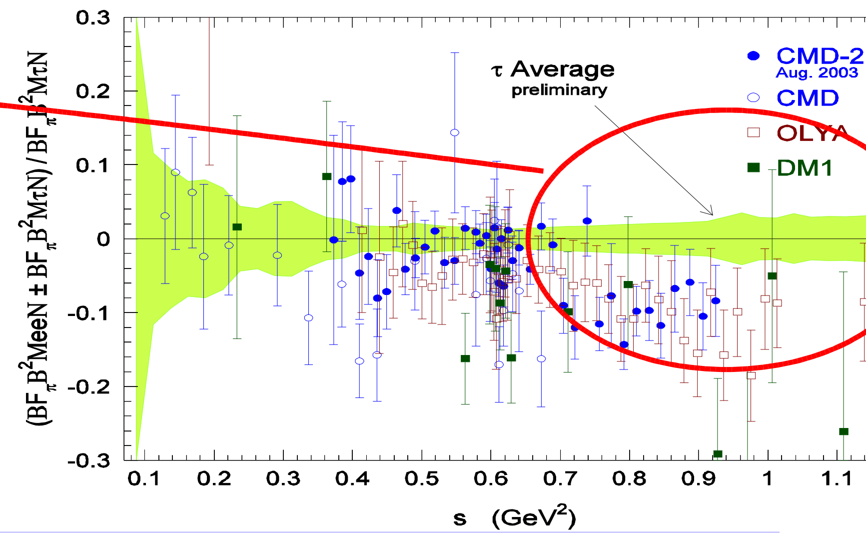
+ (had,LO) $(684.7$ to $709.0 \pm 6)10^{-10}$ (Big spread, largest error) **$(692.4$ to $694.4 \pm 7)10^{-10}$ [e^+e^- -based 04]**

+ (had,HO) $(-10.0 \pm 0.6)10^{-10}$

+ (had,LBL) $(8.0 \pm 4.0)10^{-10}$ **$(12.0 \pm 3.5)10^{-10}$ [Melnikov & Vainshtein 03]**

+ (weak) $(15.4 \pm 0.2)10^{-10}$ (2-loop)

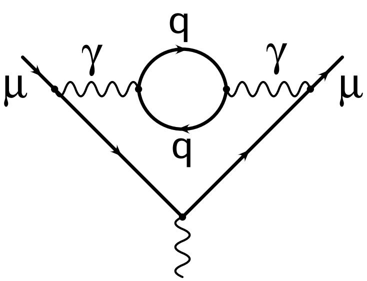


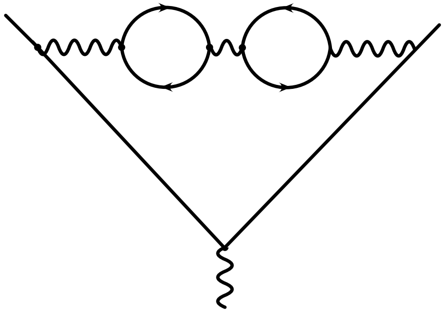


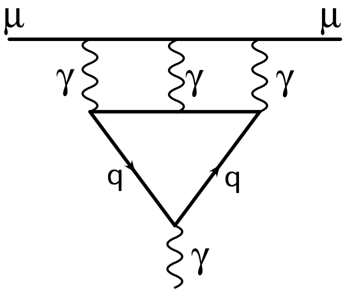
Hadronic contributions

Vainshtein

$$a_\mu^{\text{had}} = a_\mu^{\text{had,LO}} + a_\mu^{\text{had,HO}} + a_\mu^{\text{LBL}}$$







Lowest order hadronic contribution represented by a quark loop

An example of higher order hadronic contribution $a_\mu^{\text{h,HO}} = -100(6) \times 10^{-11}$

Light-by-light scattering contribution $a_\mu^{\text{LbL}} = 86(35) \times 10^{-11}$

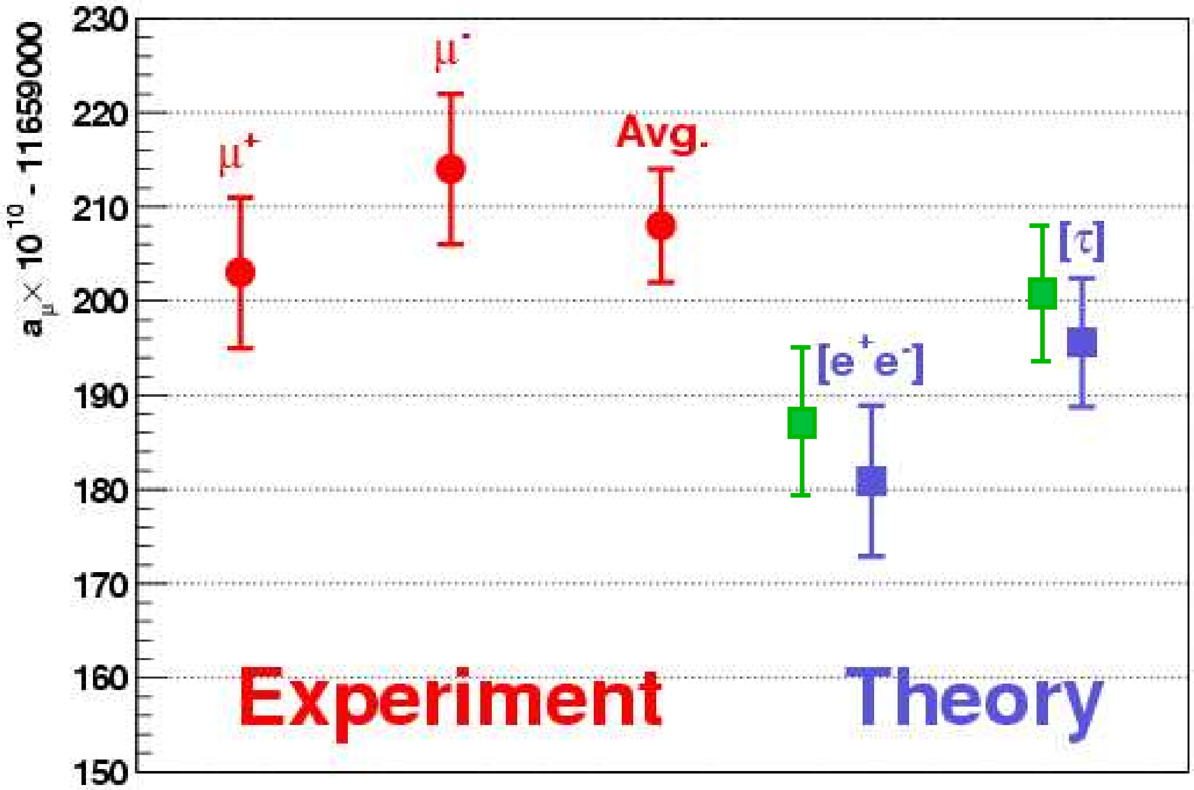
$$a_\mu^{\text{had,LO}} = \begin{cases} 6963(62)(36) \times 10^{-11} & e^+e^- \text{ based} \\ 7110(50)(8)(28) \times 10^{-11} & \tau \text{ based} \end{cases}$$

Davier, Eidelman, Höcker, Zhang ’03

New evaluation of light-by-light contribution with OPE constraints in QCD from short-distances

Vainshtein

Sizeable effect of light-by-light contribution
Further improvement of theory error?



Experimental values and theoretical predictions. The green bars are due to the shift in the hadronic light-by-light contribution.

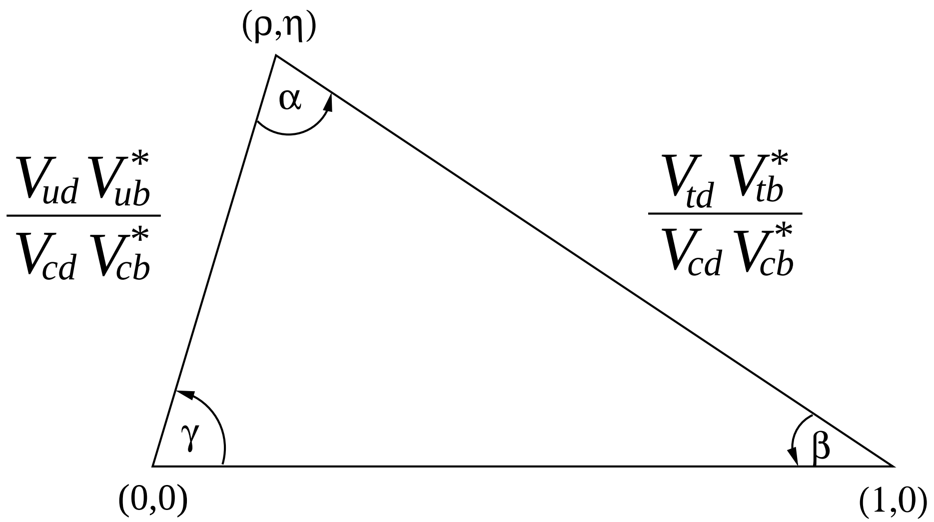
A convenient parametrization of CKM matrix

Ligeti

- Exhibit hierarchical structure by expanding in $\lambda = \sin\theta_C \simeq 0.22$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Measurements often plotted in the (ρ, η) plane (a "language" to compare data)



Main uncertainties of two sides:

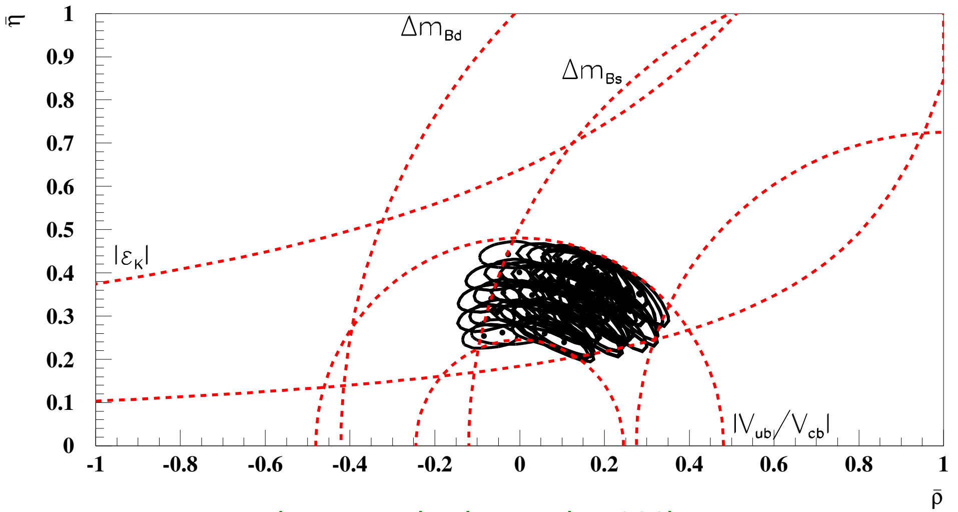
V_{ub}/V_{cb}: $B \to X_u \ell\bar{\nu}$ and $B \to X_c \ell\bar{\nu}$

V_{td}: B_d and B_s mixing

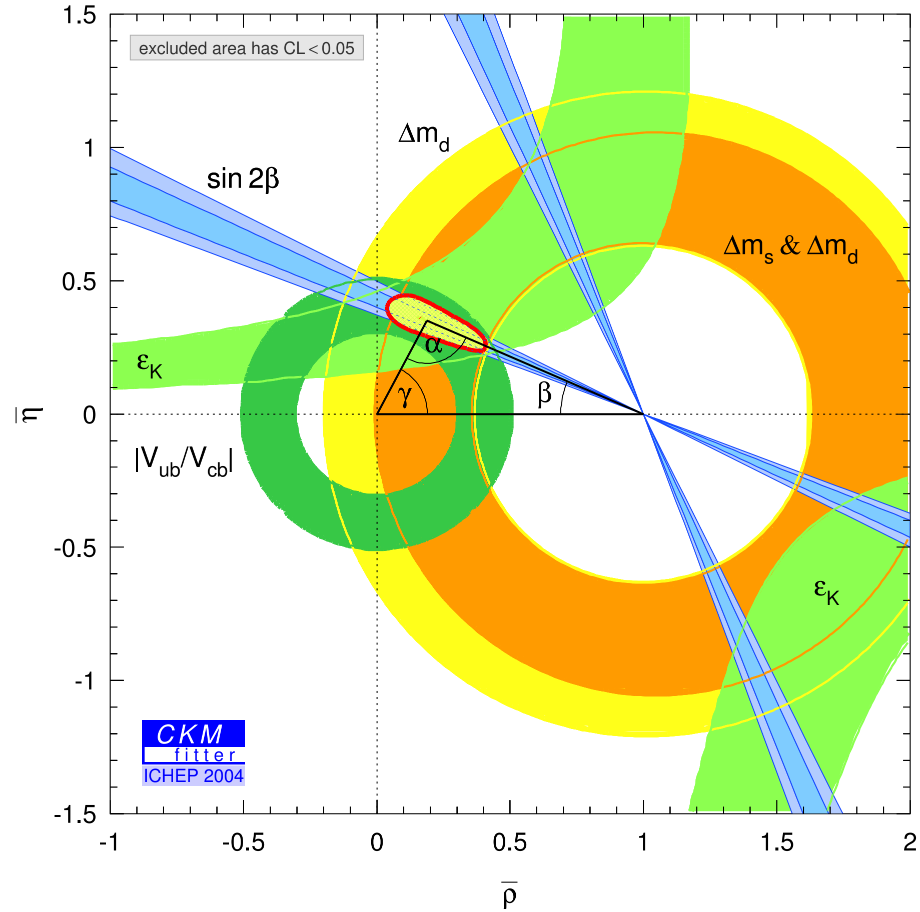
Ligeti

Testing the flavor sector

- For 35 years, untill 1999, the only unambiguous measurement of CPV was ϵ_K



(BABAR Physics Book, 1998)



$\sin 2\beta = 0.726 \pm 0.037$, order of magnitude smaller error than first measurements

Ligeti

SM tests with K and D mesons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)
- $K \to \pi\nu\bar\nu$: Theoretically clean, but rates small $\mathcal{B} \sim 10^{-10}(K^\pm)$, $10^{-11}(K_L)$

  By now 3 events observed: $\mathcal{B}(K^+ \to \pi^+\nu\bar\nu) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [BNL E949]

  Need higher statistics to make definitive tests

- D system complementary to K, B: CPV, FCNC both GIM and CKM suppressed $\Rightarrow$ tiny in SM and not yet observed

  Only meson where mixing is generated by down type quarks (SUSY: up squarks)

$$y_{CP} = \frac{\Gamma(CP\ \text{even}) - \Gamma(CP\ \text{odd})}{\Gamma(CP\ \text{even}) + \Gamma(CP\ \text{odd})} = (0.9 \pm 0.4)\%$$

[See Shipsey's talk this afternoon]

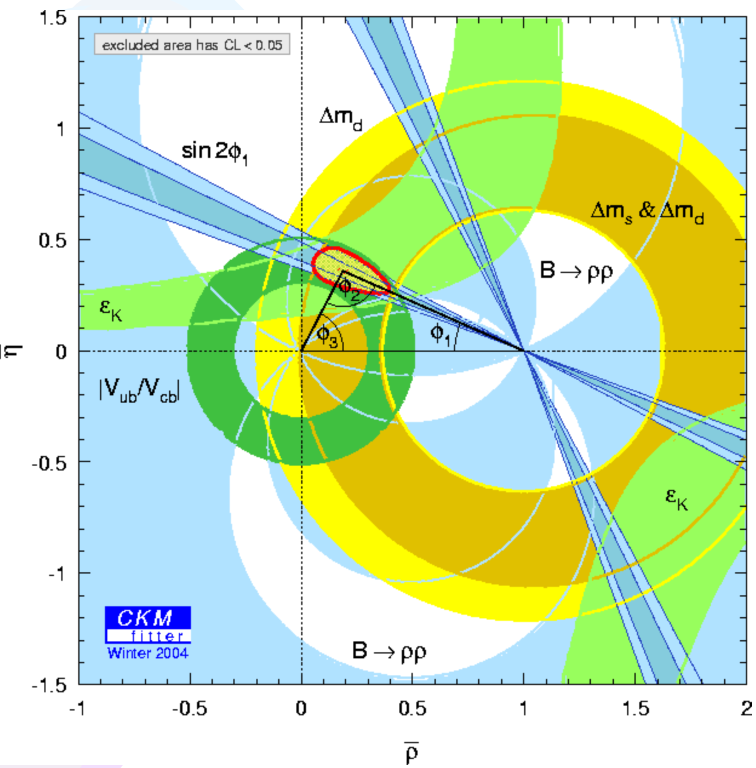
At present level of sensitivity, CPV would be the only clean signal of NP

Gold-plated quantity for lattice QCD

Kaon B parameter

$$\varepsilon_K \propto B_K \eta \left[(1-\rho) + \text{const} \right]$$

$$B_K = \frac{\langle \bar{K} | (\bar{s}d)_{V-A} (\bar{s}d)_{V-A} | K \rangle}{\frac{8}{3} f_K^2 m_K^2}$$



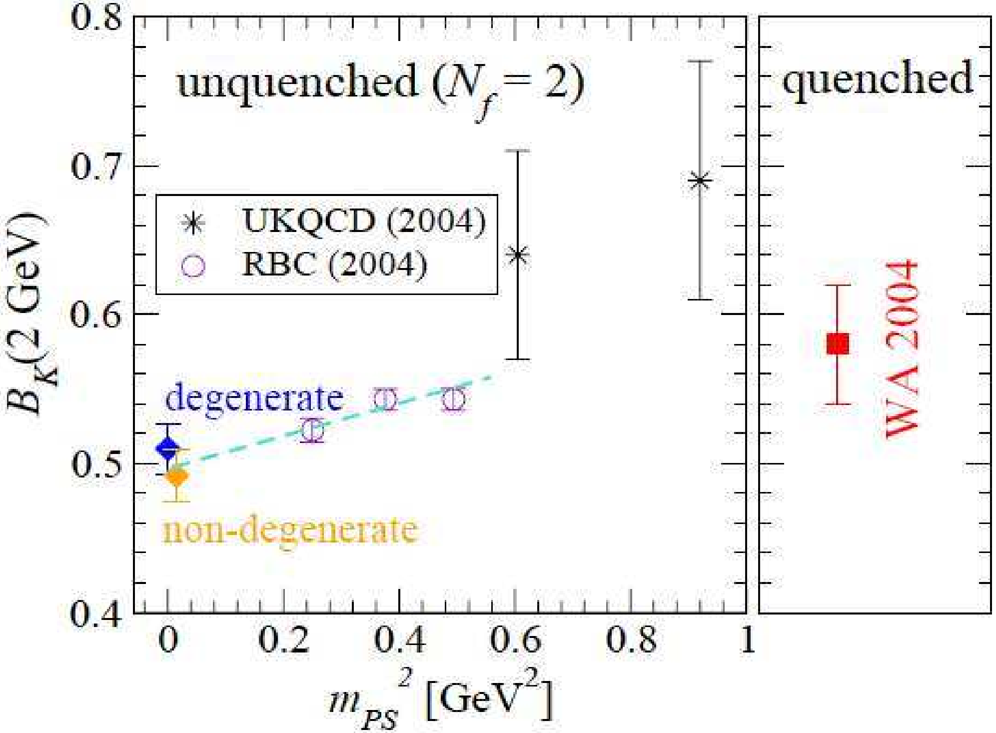
- Need chiral symmetry to avoid mixing of wrong chirality operators.
- Previous world average:

$$B_K(2\ \text{GeV}) = 0.63(4)(9)$$

- Unchanged since 1997 (central value from JLQCD staggered)
- 2nd error from quenching ~ 15% (Sharpe 1996)

Hashimoto

Unquenched B_K



RBC (2004), *preliminary*

- Sea quark mass dependence is seen.
- B_K is lower in the chiral limit.
- SU(3) breaking ($m_d \neq m_s$) effect -3%.

My average: $B_K(2\,\mathrm{GeV}) = 0.58(4)(^{+0}_{-9})$

- Central value is from quenched, as the RBC work is still preliminary; second error represents quenching effect
- cf. the previous number 0.63(4)(9)

Rare B decays

Ali

Two inclusive rare B-decays of current experimental interest

$$\bar{B} \to X_s \gamma \quad \text{and} \quad \bar{B} \to X_s l^+ l^-$$

$X_s =$ any hadronic state with $S = -1$, containing no charmed particles

Theoretical Interest:

- Accurate measurements anticipated in near future
- Non-perturbative effects under control
- Sensitivity to new physics

Status of the NNLO perturbative calculations:

- $\bar{B} \to X_s l^+ l^-$: completed
- $\bar{B} \to X_s \gamma$: $\sim \frac{1}{3}$ way through [Misiak, Steinhauser, Greub, Haisch, Gorbahn, Schröder, Czakon,...]

Ali

The effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{QCD\times QED}(q,l) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i$$

$(q = u, d, s, c, b, \;\; l = e, \mu)$

$$O_i = \begin{cases} (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b), & i = 1,2, & |C_i(m_b)| \sim 1 \\ (\bar{s}\Gamma_i b)\Sigma_q(\bar{q}\Gamma_i' q), & i = 3,4,5,6, & |C_i(m_b)| < 0.07 \\ \frac{e m_b}{16\pi^2}\bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}, & i = 7, & C_7(m_b) \sim -0.3 \\ \frac{g m_b}{16\pi^2}\bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}, & i = 8, & C_8(m_b) \sim -0.15 \\ \frac{e^2}{16\pi^2}(\bar{s}_L\gamma_\mu b_L)(\bar{l}\gamma^\mu \gamma_5 l), & i = 9, \mathbf{10} & |C_i(m_b)| \sim 4 \end{cases}$$

Three steps of the calculation:

Matching: Evaluating $C_i(\mu_0)$ at $\mu_0 \sim M_W$ by requiring equality of the SM and the effective theory Green functions

Mixing: Deriving the effective theory RGE and evolving $C_i(\mu)$ from μ_0 to $\mu_b \sim m_b$

Matrix elements: Evaluating the on-shell amplitudes at $\mu_b \sim m_b$

Status of the SM calculations for $\bar{B} \to X_s \gamma$ (Courtesy: M. Misiak)

Ali

Matching $(\mu_0 \sim M_W, m_t)$:

$$C_i(\mu_0) = C_i^{(0)}(\mu_0) + \frac{\alpha_s(\mu_0)}{4\pi} C_i^{(1)}(\mu_0) + \left(\frac{\alpha_s(\mu_0)}{4\pi}\right)^2 C_i^{(2)}(\mu_0)$$

$i = 1, ..., 6$: tree | 1-loop | 2-loop | [Bobeth, Misiak, Urban, NPB 574 (2000) 291]

$i = 7, 8$: 1-loop | 2-loop | 3-loop | [Steinhauser, Misiak, hep-ph/0401041]

The 3-loop matching has less than 2% effect on BR$(\bar{B} \to X_s \gamma)$

Mixing:

$$\hat{\gamma} = \frac{\alpha_s}{4\pi} \begin{pmatrix} 1L & 2L \\ 0 & 1L \end{pmatrix} + \left(\frac{\alpha_s}{4\pi}\right)^2 \begin{pmatrix} 2L & 3L \\ 0 & 2L \end{pmatrix} + \left(\frac{\alpha_s}{4\pi}\right)^3 \begin{pmatrix} 3L & 4L \\ 0 & 3L \end{pmatrix}$$

Haisch, Gorbahn, Gambino, Schröder, Czakon

Matrix elements $(\mu_b \sim m_b)$:

$$\langle O_i \rangle(\mu_b) = \langle O_i \rangle^{(0)}(\mu_b) + \frac{\alpha_s(\mu_b)}{4\pi} \langle O_i \rangle^{(1)}(\mu_b) + \left(\frac{\alpha_s(\mu_b)}{4\pi}\right)^2 \langle O_i \rangle^{(2)}(\mu_b)$$

$i = 1, ..., 6$: 1-loop | 2-loop | 3-loop [Bieri, Greub, Steinhauser, hep-ph/0302051]

$\mathcal{O}(\alpha_s^2 n_f)$, Steinhauser, Misiak

$i = 7, 8$: tree | 1-loop | 2-loop [Greub, Hurth, Asatrian]

SM predictions at NNLO accuracy & Comparison with data

Ali

Expt. [HFAG]; SM: [AA, Greub, Lunghi, Hiller]

(in units of 10^{-6})

	Decay Mode	Theory (SM)	Expt. (BELLE & BABAR)
	$B \to K\ell^+\ell^-$	0.35 ± 0.12	$0.55\ ^{+0.09}_{-0.08}$
	$B \to K^* e^+ e^-$	1.58 ± 0.52	$1.25\ ^{+0.37}_{-0.33}$
	$B \to K^* \mu^+\mu^-$	1.2 ± 0.4	$1.19\ ^{+0.34}_{-0.29}$
$\longrightarrow$	$B \to X_s \mu^+\mu^-$	4.2 ± 0.7	4.8 ± 1.0
		4.6 ± 0.8 [1)]	$4.13 \pm 1.05^{+0.73}_{-0.69}$ [3)]
		4.6 ± 0.7 [2)]	
$\longrightarrow$	$B \to X_s e^+ e^-$	4.2 ± 0.7	5.0 ± 1.3
			$4.04 \pm 1.03^{+0.80}_{-0.76}$ [3)]
$\longrightarrow$	$B \to X_s \ell^+\ell^-$	4.18 ± 0.7	4.8 ± 1.0
			$4.11 \pm 0.83^{+0.74}_{-0.70}$ [3)]

[1)] Ghinculov et al. [2)] Bobeth et al. [3)] BELLE [ICHEP '04]

- Inclusive measurements and the SM rates include a cut $M_{\ell^+\ell^-} > 0.2$ GeV

$B \to M_1 M_2$ Decays

Non-leptonic B-decays

Ali

Theoretical Approaches

1. SU(2)/SU(3) Symmetries, supplemented with phenomenological Ansaetze
   [Lipkin; Gronau, London; Grossman, Quinn; Charles; Gronau, London, Sinha, Sinha; Fleischer, Mannel; Neubert, Rosner; Buras, Fleischer; Gronau, Rosner; Grossman, Ligeti, Nir; Buchalla, Safir; Botella, Silva; Lavoura; Fleischer et al., Buras et al., Soni et al.; Hou et al.; Lunghi, Parkhomenko, AA; ...]
2. QCD Factorization
   [Beneke, Buchalla, Neubert, Sachrajda (BBNS); Large following with strong local activity: Su, Zhu, Du; Du, Sun, Yang, Zhu; Du, Gong, Sun, Yang, Zhu; ...]
3. pQCD
   [Keum, Li, Sanda; Large following with strong local activity: Cai-Dian Lu, Ukai; Lu, Yang,; Li, Lu; Song, Lu; Li, Lu, Xiao, Yu; ...]
4. Charming-Penguins [Ciuchini et al.] using the Ren. Group Invariant Topological Approach [Buras, Silvestrini]
5. SCET
   [Bauer et al., Beneke et al., Neubert et al.; Lunghi et al.; ...]

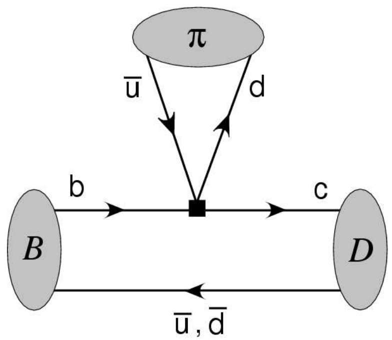
$B \to \pi\pi$-decays role model for applications of QCD factorization approach

Ligeti

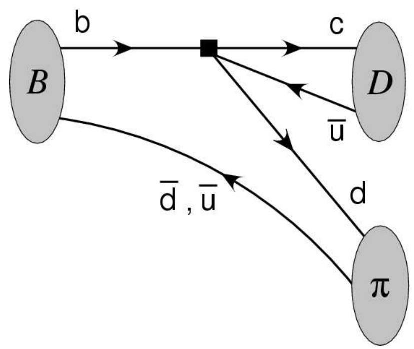
$B \to D^{(*)}\pi$ decay and SCET

- “Naive” factorization: $A(\overline{B}^0 \to D^+\pi^-) \propto \mathcal{F}^{B\to D} f_\pi$, works at $\mathcal{O}(5\text{–}10\%)$ level
  Factorization also in large N_c limit $(1/N_c^2)$ — need precise data to test mechanism

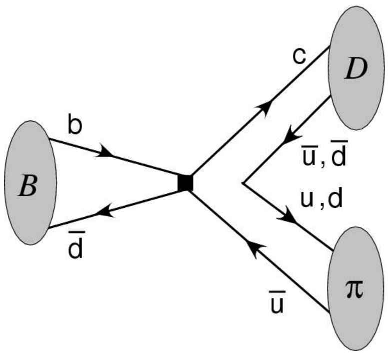
$\overline{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$



$B^- \to D^0\pi^-$
$\overline{B}^0 \to D^0\pi^0$



$\overline{B}^0 \to D^+\pi^-$
$\overline{B}^0 \to D^0\pi^0$



SCET: $\mathcal{O}(1)$ $\quad \mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\quad \mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\quad Q = \{E_\pi, m_{b,c}\}$

- Predictions: $$\frac{\mathcal{B}(B^- \to D^{(*)0}\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\pi^-)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

data: $\sim 1.8 \pm 0.2$ (also for ρ)
$\Rightarrow$ $\mathcal{O}(35\%)$ power corrections

$$\frac{\mathcal{B}(\overline{B}^0 \to D^0\pi^0)}{\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

data: $\sim 1.1 \pm 0.25$

Totally unexpected before SCET

[Mantry, Pirjol, Stewart]

Z. Ligeti — p. xi

Ligeti

Ellis

Still Room for Future Progress

- Many interesting decay modes will not be theory limited for a long time

Measurement (in SM)	Theoretical limit	Present error
$B \to \psi K_S\ (\beta)$	$\sim 0.2^\circ$	1.6°
$B \to \phi K_S,\ \eta^{(\prime)} K_S, \ldots (\beta)$	$\sim 2^\circ$	$\sim 10^\circ$
$B \to \pi\pi,\ \rho\rho,\ \rho\pi\ (\alpha)$	$\sim 1^\circ$	$\sim 15^\circ$
$B \to DK\ (\gamma)$	$\ll 1^\circ$	$\sim 25^\circ$
$B_s \to \psi\phi\ (\beta_s)$	$\sim 0.2^\circ$	—
$B_s \to D_s K\ (\gamma - 2\beta_s)$	$\ll 1^\circ$	—
$\lvert V_{cb}\rvert$	$\sim 1\%$	$\sim 3\%$
$\lvert V_{ub}\rvert$	$\sim 5\%$	$\sim 15\%$
$B \to X \ell^+ \ell^-$	$\sim 5\%$	$\sim 25\%$
$B \to K^{(*)} \nu\bar{\nu}$	$\sim 5\%$	—
$K^+ \to \pi^+ \nu\bar{\nu}$	$\sim 5\%$	$\sim 70\%$
$K_L \to \pi^0 \nu\bar{\nu}$	$< 1\%$	—

It would require breakthroughs to go significantly below these theory limits

Ellis

Breaking Electroweak Symmetry

- Calculability principle:

  EW scale should be calculable in terms of other mass scale

- No quadratic divergences:

  supersymmetry ?

  or Higgs as pseudo-Goldstone boson ?

- Supersymmetry:

  also gauge unification and dark matter

- LEP data:

  some fine-tuning needed

Barbieri

A road map to the discovery/test of EWSB physics *(cum grano salis, please)*

Barbieri

	MSSM NMSSM	5D-Susy	Split-Susy∗	Higgs as PGB
LHC	√ ∼	√ ∼	√ ∼	√ ∼
LC(500 GeV)	√ √	— ∼	√ √	— ∼
LHC LC	very significant	add indirect evidence	crucial for test	add indirect evidence

∗under favorable parameter conditions

√ = likely

∼ = incomplete

— = unlikely

RED = Discovery

BLU = Test

naturalness assumed

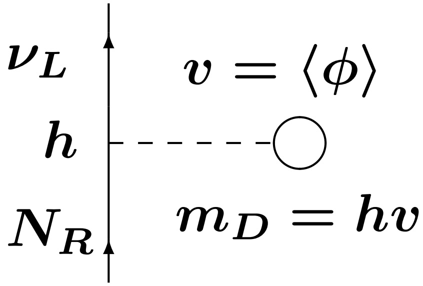
Langacker

Models and spectra

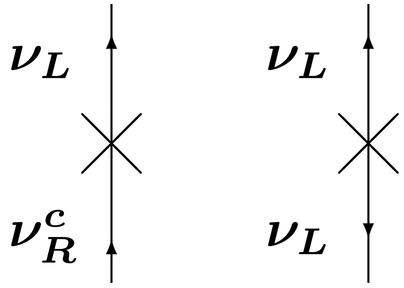
- Weyl fermion
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$ by CPT
- Active Neutrino (a.k.a. ordinary, doublet)
  - in $SU(2)$ doublet with charged lepton $\rightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CPT
- Sterile Neutrino (a.k.a. singlet, right-handed)
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N_L^c$ by CPT
  - Almost always present: Are they light? Do they mix?

Langacker

- Dirac Mass
  - Connects distinct Weyl spinors (usually active to sterile): $(m_D \bar{\nu}_L N_R + h.c.)$
  - 4 components, $\Delta L = 0$
  - $\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet
  - Why small? LED? HDO?
  - Variant: couple active to anti-active, e.g., $m_D \bar{\nu}_{eL} \nu^c_{\mu R} \Rightarrow L_e - L_\mu$ conserved; $\Delta I = 1$



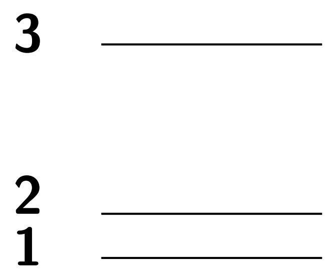
- Majorana Mass
  - Connects Weyl spinor with itself: $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ (active); $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ (sterile)
  - 2 components, $\Delta L = \pm 2$
  - Active: $\Delta I = 1 \rightarrow$ triplet or seesaw
  - Sterile: $\Delta I = 0 \rightarrow$ singlet or bare mass

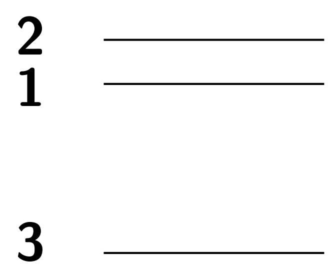


- Mixed Masses
  - Majorana and Dirac mass terms
  - Seesaw for $m_S \gg m_D$
  - Ordinary-sterile mixing for m_S and m_D both small and comparable (or $m_S \ll m_d$ (pseudo-Dirac))

– Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:

$$\begin{aligned} \nu_3 &\sim \nu_+ \\ \nu_2 &\sim \cos\theta_\odot\ \nu_- - \sin\theta_\odot\ \nu_e \\ \nu_1 &\sim \sin\theta_\odot\ \nu_- + \cos\theta_\odot\ \nu_e \end{aligned}$$





– Hierarchical pattern

* Analogous to quarks, charged leptons
* $\beta\beta_{0\nu}$ rate very small

– Inverted quasi-degenerate pattern

* $\beta\beta_{0\nu}$ if Majorana
* SN1987A energetics (if $U_{e3} \neq 0$)?
* May be radiative unstable

Summary of the Summary

Summary of the Summary

- QCD
  - essential and established part of the toolkit for discovering new physics (e.g. Tevatron and LHC)
  - close collaboration with experiment is important
  - major advances in past year, promise of more to come . . .

Summary of the Summary

- QCD
- Electroweak physics
  - precision data/theory indicate new physics at $\mathcal{O}(1\text{TeV})$
  - biggest discrepancy: NuTeV measurement of $\sin^2\theta_{\text{eff}}$
    $\longrightarrow$ theory uncertainties must be reevaluated
  - biggest challenge: deviation of $g_\mu - 2$

Summary of the Summary

- QCD
- Electroweak physics
- Flavour physics
  - Paradigm change:
    look for corrections rather than alternatives to CKM
  - Strong constraints on new physics:
    rare B-decays, $B - \bar{B}$-mixing
  - Soft-collinear effective theory:
    QCD technology for non-leptonic B-decays

Summary of the Summary

- QCD
- Electroweak physics
- Flavour physics
- Beyond Standard Model physics
  - address electroweak symmetry breaking at future colliders
  - neutrino masses

Summary of the Summary

- QCD
- Electroweak physics
- Flavour physics
- Beyond Standard Model physics

Bright future for particle theory and phenomenology
in close collaboration with experiments