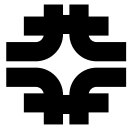
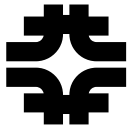


Theoretical Physics in Four-Part Harmony

C. Hill, K. Ellis, P. Fox & A. Kronfeld

FRA Visiting Committee

April 25-26, 2008



Theoretical Physics Department

Chris Hill

Who are we?

- Scientists I-III
  - William Bardeen
  - Marcela Carena
  - Bogdan Dobrescu
  - Estia Eichten
  - R. Keith Ellis
  - Walter Giele
  - Christopher Hill
  - Boris Kayser
  - Andreas Kronfeld
  - Joseph Lykken
  - Paul Mackenzie
  - Stephen Parke
  - Chris Quigg

- Associate Scientists
  - Thomas Becher (9/2004)
    - -> Scientist I
  - Peter Skands (2/2007)
  - Patrick Fox (10/2007)

- Research Associates
  - Anupama Atre ('07)
  - Yang Bai ('07)
  - Jon Bailey ('07)
  - Richard Hill ('05)
  - Kyoungchul Kong ('06)
  - Enrico Lunghi ('05)
  - Rakhi Mahbubani ('06)
  - Ruth Van de Water ('05)
  - Jan Winter ('07)

Theoretical Physics Group

- Shuffle ('07):
  - Hubisz -> Argonne
  - Laiho -> Washington U.
  - Santiago -> ETH Zürich
  - Skands -> Assoc. Scientist
- Shuffle ('08):
  - R. Hill -> jr. faculty
  - Lunghi -> jr. faculty
  - Van de Water -> BNL
    - Goldhaber Fellow
- Incoming postdocs ('07):
  - Anupama Atre <- Wisconsin
  - Yang Bai <- Yale
  - Jon Bailey <- Wash. U.
  - Jan Winter <- Dresden
- Associated colleagues:
  - Carl Albright (ex-NIU)
  - André de Gouvea (NU)
  - Elizabeth Freeland (SAIC)
  - Jeff Harvey (UoC)
  - Wai-Yee Keung (UIC)
  - Stephen Martin (NIU)
  - Stephen Mrenna (CD)
  - Jim Simone (CD)
  - Tim Tait (ANL)
- Incoming postdocs ('08):
  - Enno Scholz <- BNL
  - Ruth Britto <- Amsterdam
    - Taking tenured position at Saclay.

Where are they now?

- Postdocs
  - http://theory.fnal.gov/people/ellis/alumni.html
- Associate Scientists
  - http://theory.fnal.gov/people/ellis/Assoc.html
- Frontier Fellows
  - http://theory.fnal.gov/people/ellis/frontier.html

Our Core Strengths

- Perturbative QCD
  - Tevatron, LHC (both CMS & ATLAS), ILC, MC
    - Becher, Ellis, Giele, Parke, Skands
- Lattice QCD
  - B and D factories, CDF & D0, LHCb, Project X, computing
    - Bardeen, Eichten, Kronfeld, Mackenzie
- Neutrinos
  - MINOS, MiniBooNE, Nova, Project X, DUSEL
    - Hill, Kayser, Parke, Quigg
- Electroweak (SM & BSM)
  - Tevatron, LHC, ILC, MC, Project X, Cosmology,…
    - Bardeen, Carena, Dobrescu, Eichten, Fox, Hill, Lykken, Quigg, Skands

Major Questions in Particle Physics

- What causes electroweak symmetry breaking?
  - Bardeen, Carena, Dobrescu, Eichten, Fox, Hill, Lykken, Quigg
- Is supersymmetry associated with EWSB?
  - Bardeen, Carena, Dobrescu, Eichten, Fox, Hill, Lykken
- Are extra dimensions at the EW scale?
  - Carena, Dobrescu, Fox, Hill, Lykken
- What causes neutrino mass and mixing?
  - Hill, Kayser, Parke, Quigg
- What are indirect signals of flavor physics?
  - Bardeen, Becher, Eichten, Hill, Kronfeld, Mackenzie, Quigg
- How do we extract new physics within QCD?
  - Becher, Ellis, Giele, Skands
  - Bardeen, Eichten, Kronfeld, Mackenzie
- How do particles influence cosmology & astrophysics?
  - Carena, Fox, Hill, Lykken, Quigg

Publications, Conf. Proceedings, Reports

	'07-'08 ('06-'07)
Senior Staff Scientific Publications:	34 (32)
Senior Staff Conf. Proceedings, Reports, etc.:	30 (24)
Research Associate Scientific Publications:*	17 (26)
Research Associate Conference Proceedings:	21 (8)
Total	102 (90)

* not counting newly arrived Research Associates, or papers coauthored and counted for senior members

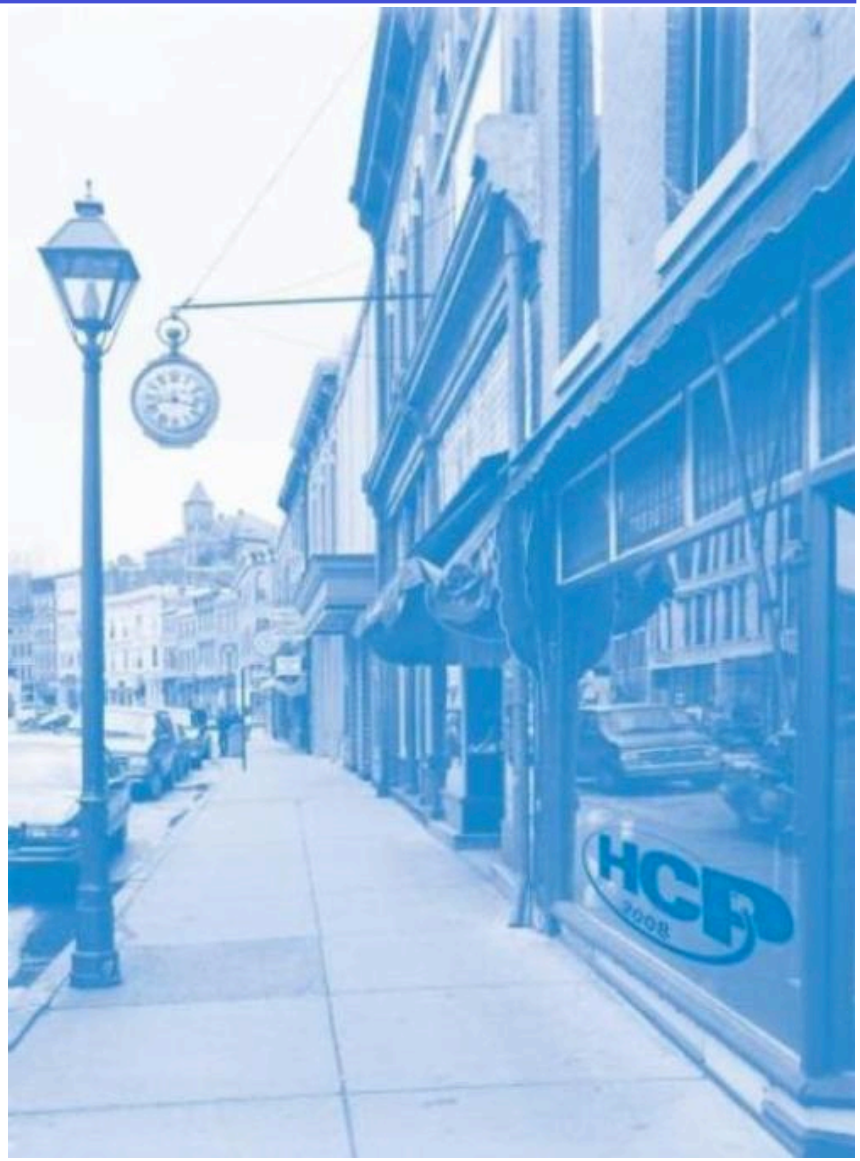
Conferences and Workshops

- Hadron Collider Physics Conference (Ellis)
  - May 2008, Galena, Illinois
- Aspen Center for Physics (Fox)
  - Summer 2008, Aspen, BSM Signals in a QCD Environment
- Joint Fermilab-CERN Hadron Collider Physics Summer School (Carena)
  - Summer 2008, Fermilab
- USQCD: Lattice Meets Experiment (Mackenzie)
  - December 2007, Fermilab
- Monte Carlo Tools for Beyond the Standard Model (Skands)
  - March 2008, CERN
- LoopFest VI: Radiative Corr'ns for LHC and ILC (Ellis, Giele)
  - April 2007, Fermilab
- Neutrino Physics Summer School (Kayser)
  - Summer 2007, Fermilab
- The LHC Early Phase for the ILC (Carena)
  - April 2007, Fermilab

HCP2008
19th Hadron Collider Physics Symposium 2008

May 27-31 2008

Meeting Location:
Eagle Ridge Resort near the Mississippi River
Galena, Illinois, USA



Theorists' Community Service

- American Physical Society
  - DPF: Kayser (Vice-Chair), Kronfeld (ExecCom), Carena (NomCom, Outreach)
  - APS: Quigg (candidate for APS presidency), Carena (CISA)
- Agency advisory committees
  - HEPAP: Lykken
  - P5: Carena, Kayser; Lykken
  - Other subpanels: Carena, Kayser, Lykken, …
- Institutional advisory committees
  - Aspen Center for Physics: Carena, Lykken
  - KITP Board: Lykken
  - Fermilab PAC: Kayser
- Fermilab-CERN Hadron Collider Physics Summer School
  - Carena

Community Service (2)

- ILC Policy
  - Kronfeld (WWS-OC, …)
- Neutrino Physics Policy
  - Kayser (all possible panels), Parke
- Lattice QCD Policy
  - USQCD: Mackenzie (ExecCom), Kronfeld (SPC Chair)
  - DOE SciDAC, US NSF, KEK (Japan): Mackenzie
- Education
  - IMSA Board: Quigg
- Editorial
  - Annual Review of Nuclear and Particle Science: Kayser
- International conference advising and convening duties
  - All & too numerous to mention

Theorists' Laboratory Service

- Project X (physics groups, workshops, reports)
  - Carena, Eichten, Hill, Kayser, Kronfeld, Lykken, Parke, Quigg
- Colloquium Committee
  - Dobrescu (w/ many others)
- Scientific Committees at Fermilab
  - FCSA: Eichten
  - Scientist III committee: Bardeen
  - Wilson Fellows: Kronfeld
  - URA thesis award: Dobrescu
  - Awards (e.g., APS Fellowship): Quigg

Seminar Series

- Theoretical Physics Seminar (R. Hill, Kronfeld)
  - 43 seminars in 2007
  - http://theory.fnal.gov/seminars/
  - Incorporates new semiannual Joint Theory-CMS Seminar
- Joint Experimental-Theoretical Seminar (Becher, Giele)
  - The "Wine and Cheese" Seminar
  - 52 speakers in 2007
  - http://theory.fnal.gov/jetp/
- Academic Lectures (Carena, Becher, Kronfeld, Quigg)
  - Two series in 2007
    - 12 lectures on flavor physics by Lunghi, Berryhill, Herndon, Becher, and Kronfeld (SM & BSM, e^+e^-, Tevatron, QCD, and lattice)
    - 5 lectures on extra dimensions by Dobrescu and Landsberg (theory and collider signatures)

Visitors Program

- Frontier Fellows
  - Sabbatical leave for distinguished scientists
    - Matthias Neubert, August–November 2007
    - Mariano Quiros, September–December 2007
  - New name: Ben Lee Fellows

- Summer Visitors
  - Several weeks for from May to September
    - Fermilab pays local expenses
    - Often, but not limited to, collaborators
  - Suspended in 2008 because of budget constraints

- Beyond the SM: from the Tevatron to the LHC
  - Funded by URA, organized by Fox & G. Kribs (Oregon)

Benjamin W. Lee

Widely regarded as one of the world's leading physicists working on the theory of elementary particles, Benjamin W. Lee led the Theoretical Physics Department at Fermilab from 1973 until his tragic death in an automobile accident in 1977. In the last six months of life, Lee was in the midst of a period of enormous creativity. He explored the problems of CP violation, of lepton-number nonconservation, and of the high-energy limit of weak interactions in gauge theories, formulated a theory based on the enlarged gauge group SU(3)⊗U(1), and was just beginning a program of research on cosmology.

continued at: https://imapserver1.fnal.gov/attach/BWLProfile.html

Staff Research Highlights (2007-08)

Bill Bardeen - Studying AdS/CFT models relevant for a dual description of QCD. Continued the development of a phenomenological chiral string model for heavy-light mesons. Studied the Gasser-Leutwlyer operator structure of Little Higgs models (with Buras).

Thomas Becher - Obtained a precise determination of α_s from an improved calculation of thrust. Derived the two loop QED corrections to massive Bhabha scattering for luminosity measurement at ILC. Resummed the Drell-Yan rapidity distribution to next-to-next-to-next-to-leading logarithmic accuracy. Evaluated (with E. Lunghi) the kinetic corrections to $B \to X_c l \nu$ at one loop.

Marcela Carena - Explored the relevant connections between the supersymmetric Higgs sector and B physics observables on the light of ongoing searches at the Tevatron and the prospective reach of the imminent LHC. Explored possibility of generating the baryon asymmetry and Dark Matter and its complementarity to astrophysical experiments . Showed the potential of a lepton collider to probe the SUSY parameter space. Constructed novel models of warped extra dimensions, compatible with present electroweak precision measurements, including loop effects that can significantly modify Higgs and new physics searches at the Tevatron and the LHC. Possibility of detecting new Higgs physics signals in the context of the Minimal SUSY extension of the SM and other SUSY models.

Bogdan Dobrescu – Explored the phenomenology of two universal extra dimensions, e.g.dark matter. Identified important signature in the multi-jet final states at Tevatron and the LHC due to color octet bosons. With Kronfeld have observed that 4 sigma discrepancy with SM in leptonic decays of the D_s mesons may be accounted for by a either a leptoquark or a charged Higgs boson. With P. Fox attempting to explain the pattern of quark and lepton masses in a top quark mass model. Studied structure of six dimensional gauge theories compactified on the chiral square, high mass ttbar resonances can appear at the LHC, and potentially at the Tevatron. Explored types of new macroscopic spin-dependent forces that may be discovered in laboratory experiments and studied implications for Z' searches.

Staff Research Highlights (2007-08)

Estia Eichten - Continuing studies in heavy quark physics focused on quarkonium physics. Involved in a review of quarkonia and their transitions including the phenomenology of the new charmonium-like states discovered at the various B-factories (BELLE, BaBar, and CLEO). Studying the nature of the X(3872) and Y(4260) states. Examined signals for new strong dynamics at the Tevatron and LHC[2]. Presently, looking at the physics potential of a multi-TeV Muon Collider.

Keith Ellis - Research in has focused on the problem of making prediction at the 10-20% level for hard processes at the Tevatron and the LHC. On the one hand there has been further development of the NLO Monte Carlo program MCFM. New processes include the production of WW pairs in association with 1 jet and the production of W bosons with b-jet tags. On the other hand there has been progress toward a systematic calculation of one-loop diagrams. Elements of the latter progress include a complete calculation of one-loop integrals which contain propagators with some massless internal lines, setting up a web-site qcdloop.fnal.gov to document these results and a proof of principle that unitarity based methods can be used to calculate one loop diagrams efficiently.

Patrick Fox – Developed model of fermion mass hierarchies generating masses through loop effects (with B. Dobrescu). SUSY breaking which has metastable minimum but non-zero gaugino masses, a problem in the original models (with E. Poppitz). Studied light Higgses with non-standard decays as a way of increasing the order of SM phase transition, with applications to baryogenesis and astrophysical signatures (with N. Weiner and A. Kumar).

Walter Giele – developing techniques to numerically calculate high multiplicity one-loop scattering amplitudes. We are currently at the point where we can realistically start the construction of NLO parton level Monte Carlo's for such processes as PP -> V+3, 4 jets, PP->ttbar+2 jets. The second area is the development of a parton shower constructed on the premise of matching to fixed order matrix elements. This is still developing quickly and lots of interesting progress is being made. This effort will lead to interesting results in the coming year.

Staff Research Highlights (2007-08)

Christopher Hill – Discovered new aspects Standard Model anomalies with J. Harvey and R. Hill. This likely explains the MiniBooNE low energy excess, and also leads to new effects in neutrino physics at finite baryon density, eg in neutron stars and supernovae. Showed (with R. Hill) that T-parity is generally broken by anomalies in Little Higgs theories

Boris Kayser – Exploring the possibility that the leptonic mixing matrix is not unitary. Impact on oscillation of the flavor-summed charged-current neutrino and neutral-current event rate. Near-future experiments that could seek some of these phenomena. N. Bell, and S. Law, and I have developed an electromagnetic alternative to leptogenesis.. With Langacker, and de Gouvea studying the connections between neutrino mass and the character of the universe, e.g. leptogenesis could not have led to the baryon asymmetry of the universe if today's light neutrinos had been massless.

Andreas Kronfeld – Continued focus on lattice QCD, as part of the Fermilab Lattice Collaboration. Recently constructed a new lattice action for heavy quarks to reduce cutoff effects, clarifying conceptual issues, such as the power counting in the framework of Symanzik's effective field theories. The Fermilab Lattice Collaboration completed the first determination with an unquenched lattice QCD calculation of the CKM matrix element V_{cb} via the exclusive decay (analysis by Laiho with supervision from Kronfeld). With Dobrescu noticed that leptonic D_s decay is 4 sigma discrepant with the SM, and sought explanations in new physics. Continues as Chair of USQCD Scientific Program Committee. Invited to present plenary review on staggered sea quarks at Lattice 2004.

Joe Lykken - joined the CMS Collaboration in July 2007. From that time he is working 80% on CMS. He is developing new analysis techniques to discriminate between different theoretical models for a missing energy signal at CMS, focusing on the early running with 100 to 1000 pb-1 of data. This project also involves extensive cross-validation of simulation software (MadEvent, Pythia, CMSSW, PGS, Suspect, SUSY-HIT, Isajet, SoftSusy).

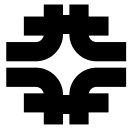
Staff Research Highlights (2007-08)

Paul Mackenzie - Continued study of charm meson decay constants in lattice QCD. Continued work on B meson decay constants and B and D meson semileptonic decays. New results for semileptonic weak decays using method of Becher and Hill. Continued my work on the Executive Committee of USQCD. This year, we have been particularly active presenting our plans for continued work in the period 2010-2014. Our plans received a spectacularly successful review in Germantown, and we received a very friendly reception when we reviewed our plans for HEPAP.

Stephen Parke – Neutrino research has focused on different ways to determine the neutrino mass hierarchy. Have explored how one can use mono-chromatic nu_e beams and CPT conjugate channels to determine the mass hierarchy. Has written an expensive review of CP violation in the neutrino sector. For Collider physics, has discovered a new way to deal with the spin correlations in massive particle production.

Chris Quigg – Continued to consider electroweak symmetry breaking. Wrote and lectured extensively on the physics opportunities of the LHC. Pursued ongoing work on ultrahigh-energy neutrinos and cosmic neutrinos, and investigated the gravitational interactions of neutrinos. Preparing a new edition of *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions.*

Peter Skands– On leave at CERN. Working on tools for understanding collider physics, such as PYTHIA (collaboration with Mrenna) and VINCIA (collaboration with Giele).



Perturbative QCD

Keith Ellis

Menu

Personnel: Thomas Becher, Keith Ellis, Walter Giele, Peter Skands, Jan Winter

- New SCET results for α_s
- Necessity of NLO and loop corrections.
- Progress with calculation of one loop diagrams.
- Results for parton showers
- The plan for the future.

Long tradition: Bardeen and $\overline{\text{MS}}$ scheme; Parke-Taylor amplitudes; …

α_S from jet shape measurements

LEP event shapes 91.2-206. NLO+NLLA

α_S=0.1202 ±0.0005(stat) ±0.0008(exp) ±0.0019(had) ±0.0049(pert)

Theoretical errors dominate the total error.
Therefore an improved theoretical calculation is required.

S Kluth hep-ex/0609020

New NNLO and N^{3}LL results for thrust

The thrust is defined as the maximum of directed momentum $T = \max_{\mathbf{n}} \frac{\sum_i \mathbf{p}_i \cdot \mathbf{n}}{\sum_i |\mathbf{p}_i|}$

Defining τ=1-T, perturbative expansion of thrust is

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = \delta(\tau) + \frac{\alpha_S}{2\pi}A(\tau) + \left(\frac{\alpha_S}{2\pi}\right)^2 B(\tau) + \left(\frac{\alpha_S}{2\pi}\right)^3 C(\tau)$$

A=LO, Farhi, 1977

B=NLO, ERT, 1981

C=NNLO, Gehrmann-De Ridder, Gehrmann, Glover, Heinrich 2007

Expression for thrust contains large logarithms for small τ which need to be resummed.

$$R(\tau) = \int_0^\tau d\tau' \frac{1}{\sigma_0}\frac{d\sigma}{d\tau'} \lim_{\tau\to 0} 1 + \frac{2\alpha_S}{3\pi}\left[-2\ln^2\tau - 3\ln\tau\right] + \ldots$$

$\alpha_S^n \ln^{2n}\tau$: LL

$\alpha_S^n \ln^{2n-1}\tau$: NLL — Catani et al 1993

$\alpha_S^n \ln^{2n-3}\tau$: N^{2}LL

$\alpha_S^n \ln^{2n-5}\tau$: N^{3}LL — Becher, Schwartz, 2008

New method applicable to many other quantities

NNLO+N^{3}LL result for α_S

Becher and Schwartz arXiv 0803.0342v1 have a new NNLO+N^{3}LL result using Aleph & Opal data

$$\alpha_s = 0.1172 + 0.0010(\text{stat}) + 0.0008(\text{sys}) + 0.0012(\text{had}) + 0.0012(\text{pert})$$

Perturbative error is for the first time smaller than the other uncertainties at each energy. Result is in agreement with the world average.
α_S is now known to about 2% from a single measurement.

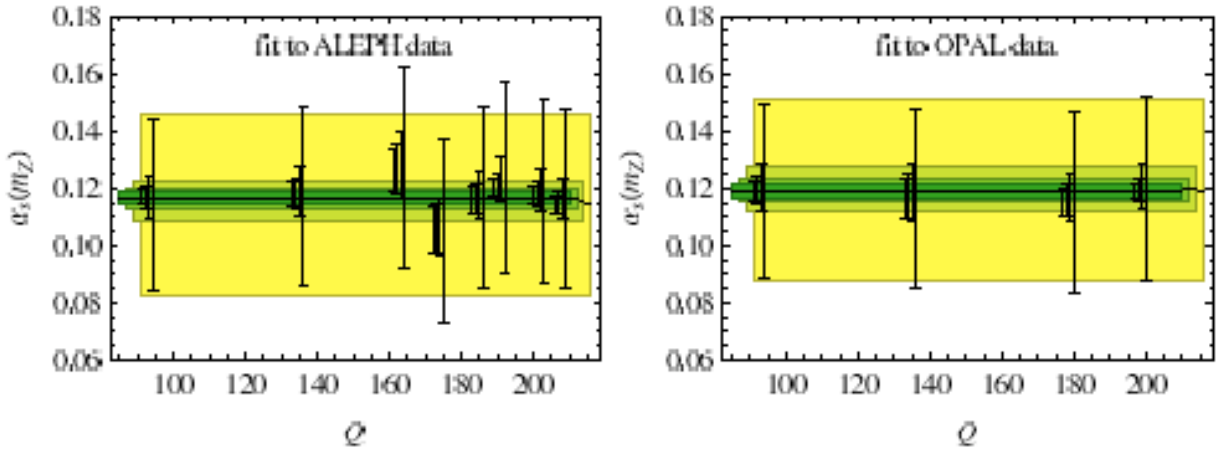
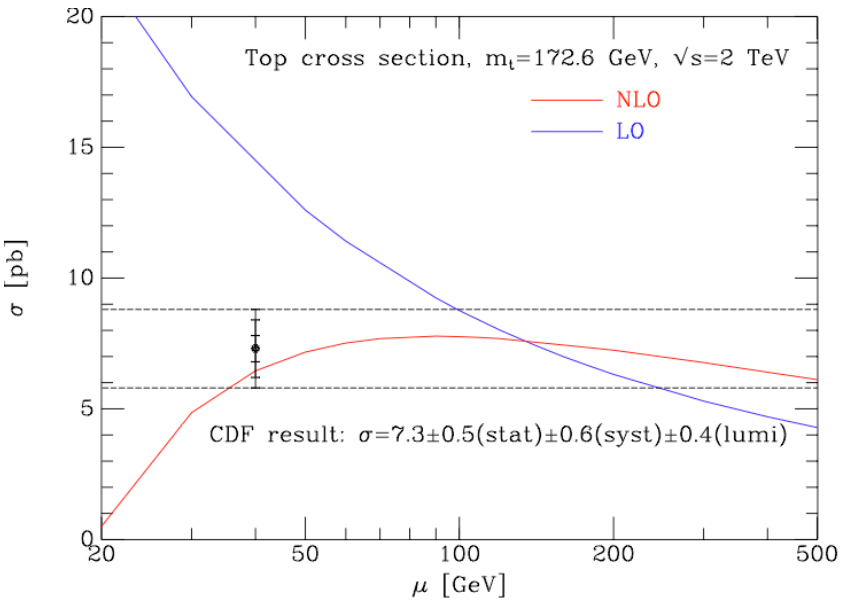


Figure 10: Best fit values for $\alpha_s(m_Z)$. From right to left the lines are the total error bars at each energy for first order, second order, third order and fourth order, as defined in the text. The bands are weighted averages with errors combined from all energies.

Why NLO?



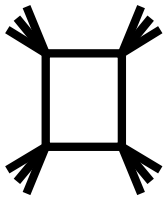
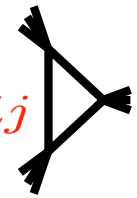
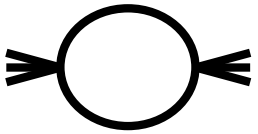
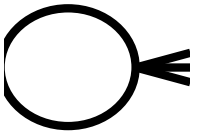
- Less sensitivity to unphysical input scales, (eg. renormalization and factorization scales)
- NLO first approximation in QCD which gives an idea of suitable choice for μ.
- NLO has more physics, parton merging to give structure in jets, initial state radiation, more species of incoming partons enter at NLO.
- A necessary prerequisite for more sophisticated techniques which match NLO with parton showering.

In order to get ~10% accuracy we need to include NLO.

NLO requires the general calculation of one-loop amplitudes

Basis set of scalar integrals

Any one-loop amplitude can be written as a linear sum of boxes, triangles, bubbles and tadpoles

$$\mathcal{A}_N(\{p_i\}) = \sum d_{ijk}$$  $$+ \sum c_{ij}$$  $$+ \sum b_i$$  $$+ \sum_i a_i$$ 

In the context of NLO calculations, scalar higher point functions, can always be expressed as sums of box integrals.
Passarino, Veltman - Melrose ('65)

Finite one-loop integrals addressed in 1979 'tHooft and Veltman

Scalar one-loop integrals

- 't Hooft and Veltman's integrals contain internal masses; however in QCD many lines are (approximately) massless. The consequent soft and collinear divergences are regulated by dimensional regularization.
- So we need general expressions for boxes, triangles, bubbles and tadpoles, including the cases with one or more vanishing internal masses.
- We have identified a basis set of sixteen divergent box integrals, and six divergent triangles.

QCDLoop

- Analytic results are given for the complete set of divergent box integrals at http://qcdloop.fnal.gov
- Fortran 77 code is provided which calculates an arbitrary scalar box, triangle, bubble or tadpole integral.
- Finite integrals are calculated using the ff library of Van Oldenborgh. (Used also by Looptools)
- For divergent integrals the code returns the coefficients of the Laurent series $1/\varepsilon^2$, $1/\varepsilon$ and finite.
- Problem of one-loop scalar integrals is completely solved numerically and analytically

Ellis, Zanderighi, arXiv:0712.1851

Determination of coefficients of scalar integrals

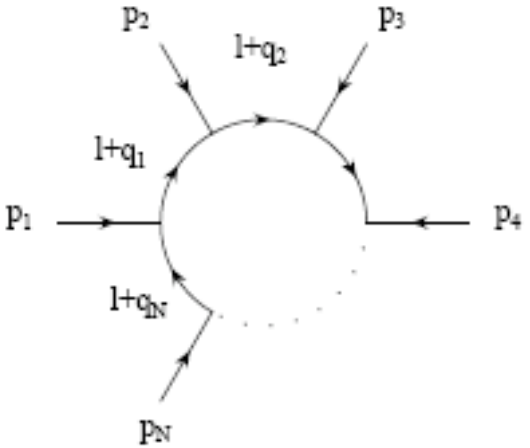
Feynman diagrams + Passarino-Veltman reduction cannot be the answer as the number of legs increases. There are too many diagrams with cancellations between them.

Process	Amplitude	# of diagrams at 1 loop
$t\bar{t}$	$t\bar{t}gg$	30
$t\bar{t}$+1 jet	$t\bar{t}ggg$	341
$t\bar{t}$+2 jets	$t\bar{t}gggg$	4341
$t\bar{t}$+3 jets	$t\bar{t}ggggg$	63800

Semi-numerical methods based on unitarity may be the answer. Note however that the majority of complete n-leg calculations for n>4 are currently based on Passarino-Veltman.

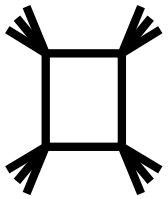
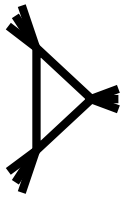
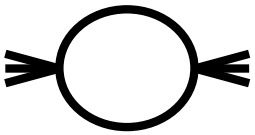
Decomposing in terms of master integrals

$$\mathcal{A}_N(p_1, p_2, \ldots, p_N) = \int [d\,l]\ \mathcal{A}(p_1, p_2, \ldots, p_N; l)$$



$$\mathcal{A}_N(p_1, p_2, \ldots, p_N; l) = \frac{\mathcal{N}(p_1, p_2, \ldots, p_N; l)}{d_1 d_2 \cdots d_N}$$

$$d_i = (l + q_i)^2 - m_i^2 = (l - q_0 + \sum_{j=1}^{i} p_i)^2 - m_i^2$$

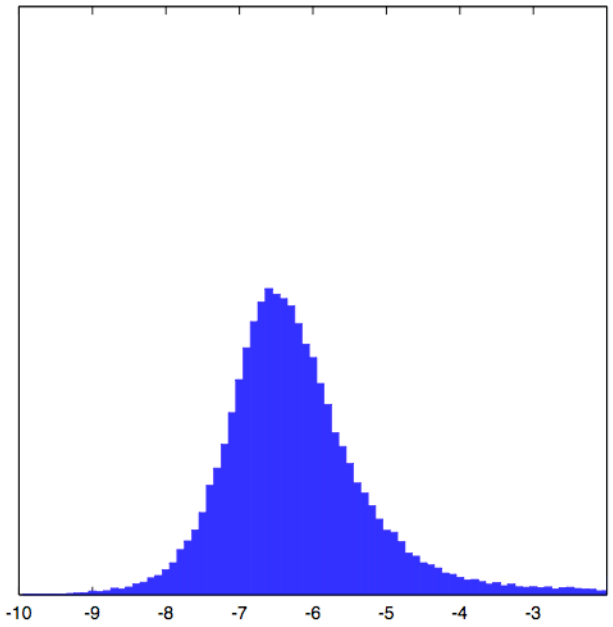
$$\mathcal{A}_N(\{p_i\}) = \sum d_{ijk}$$  $$+ \sum c_{ij}$$  $$+ \sum b_i$$ 

If it were not for the integral sign the identification of coefficients would be simply multi-pole expansion of rational function. There is a systematic way of calculating the coefficients by also identifying the spurious terms which vanish under integration. Ossola et al,hep-ph/0609007

Result for six gluon amplitude

Ellis, Giele, Kunszt,arXiv:0708.2398

- Results shown here for the cut-constructible part
- The relative error for the finite part of the 6-gluon amplitude compared to the analytic result, for the (+ + - - - -) helicity choice. The horizontal axis is the log of the relative error, the vertical axis is the number of events in arbitrary linear units.
- For most events the error is less than $10^{-6,}$ although there is a tail extending to higher error.



Extension to full amplitude

Giele, Kunszt,Melnikov, arXiv 0801.2237

- Keep dimensions of virtual unobserved particles integer and perform calculations in more than one dimension.
- Arrive at non-integer values D=4-2ε by polynomial interpolation.
- Results for six-gluon amplitudes agree with original Feynman diagram calculation of Ellis, Giele, Zanderighi.

$\lambda_1, \lambda_2, \ldots, \lambda_6$	$\Delta^{\rm cut}$	$\Delta^{\rm rat}$	Δ
- - + + + +	-19.481065+78.147162 i	28.508591-74.507275 i	9.027526+3.639887 i
- + - + + +	-241.10930+27.176200 i	250.27357-25.695269 i	9.164272+1.480930 i
- + + - + +	5.4801516-12.433657 i	0.19703574+0.25452928 i	5.677187-12.179127 i
- - - + + +	15.478408-2.7380153 i	2.2486654+1.0766607 i	17.727073-1.661354 i
- - + - + +	-339.15056-328.58047 i	348.65907+336.44983 i	9.508509+7.869351 i
- + - + - +	31.947346+507.44665 i	-17.430910-510.42171 i	14.516436-2.975062 i

MCFM: a NLO parton level generator

- pp → W/Z
- pp → W+Z, WW, ZZ
- pp → W/Z + 1 jet
- pp → W/Z +2 jets
- pp → t W
- pp → tX (s&t channel)
- pp → tt

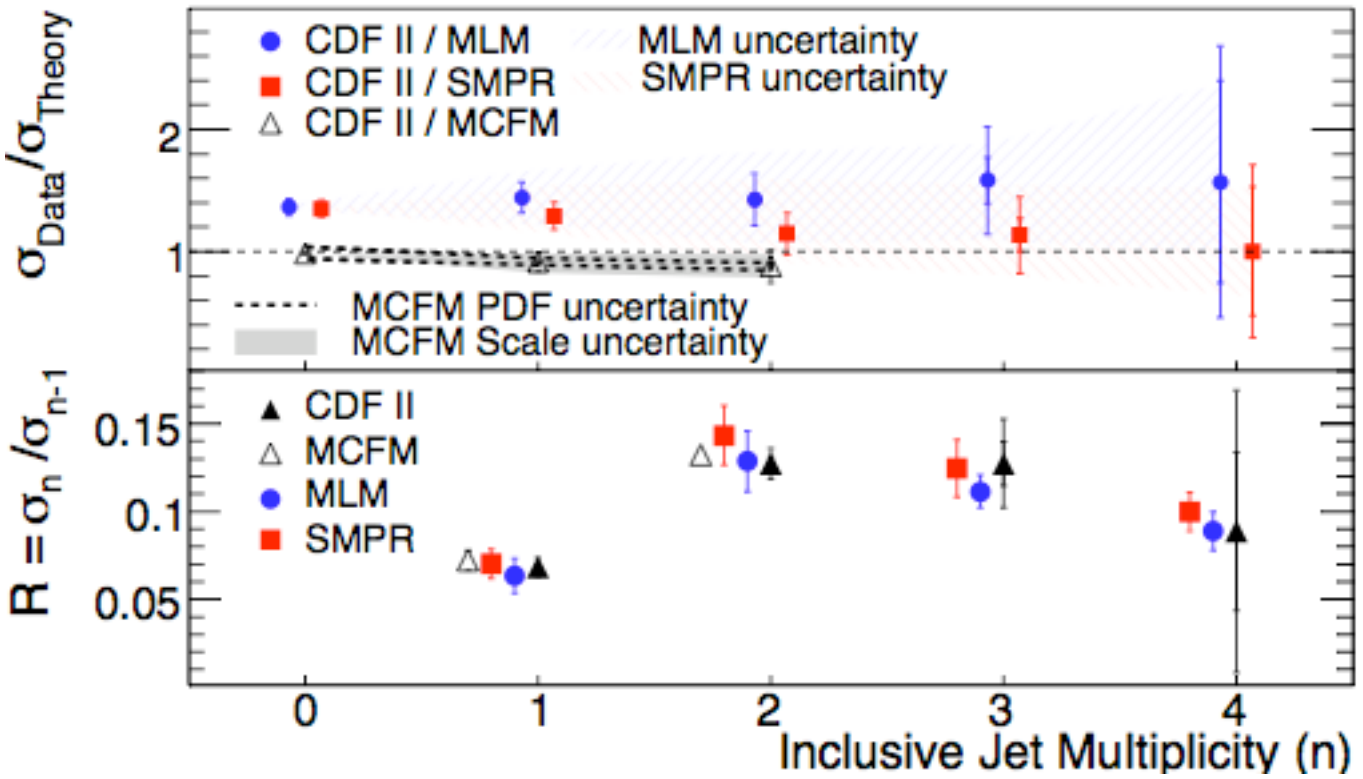
- pp → W/Z+H
- pp (gg) → H
- pp→(gg) → H + 1 jet
- pp→(gg) → H + 2 jets
- pp(VV) → H +2 jets
- pp → W/Z +b , W+c
- pp → W/Z +bb

Ellis, Campbell ..

Processes calculated at NLO, but no automatic procedure for including new processes.

Code available at http://mcfm.fnal.gov (used for many Tevatron analyses and LHC prognostications).

W+n jet rates from CDF



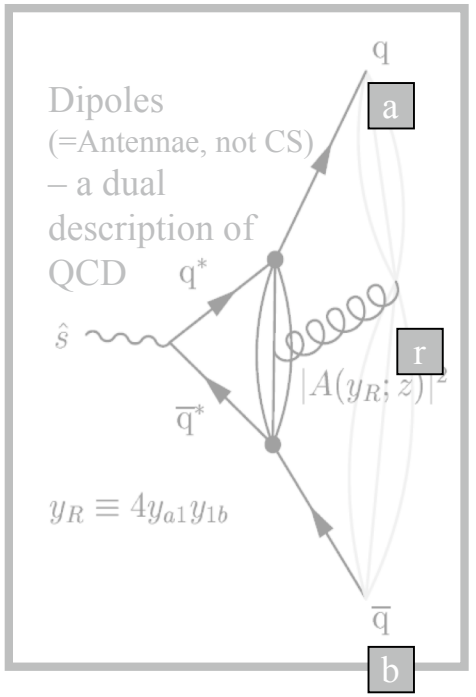
As expected NLO calculation gives Data/Theory ratio closer to 1 than tree level.
"Berends" ratio agrees well for all calculations but only available for n=2 from MCFM.

Giele, Kosower,Skands, arXiv:0707.3652

- Based on Dipole-Antennae
  - Shower off color-connected pairs of partons
  - Plug-in to PYTHIA 8.1 (C++)
  - Emphasis on general treatment of matching which provides a generalization of the methods of CKKW and MC@NLO

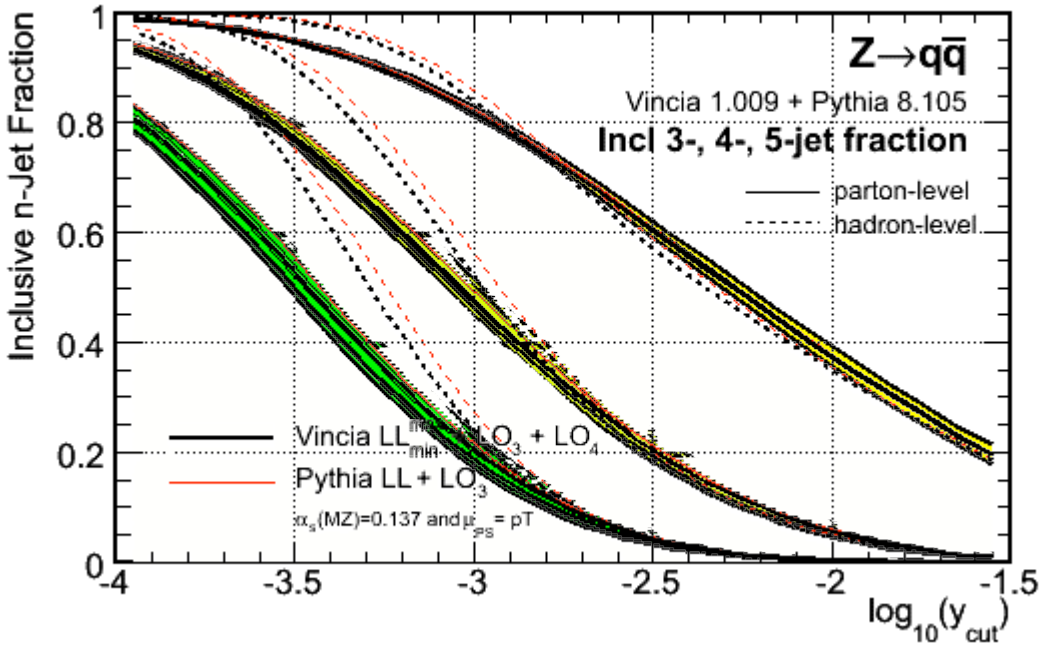
  ➢ 3 different shower evolution variables:
    - p_T-ordering (= ARIADNE ~ PYTHIA 8)
    - Dipole-mass-ordering (~ but not = PYTHIA6, SHERPA)
    - Thrust-ordering (3-parton Thrust)

  ➢ For each: an infinite family of antenna functions
    - Laurent series in branching invariants with arbitrary finite terms



Tree-level 2→3 + 2→4 in Action

- The unknown finite terms are a major source of uncertainty
  - They are arbitrary (and in general process-dependent)



← Varying finite terms only

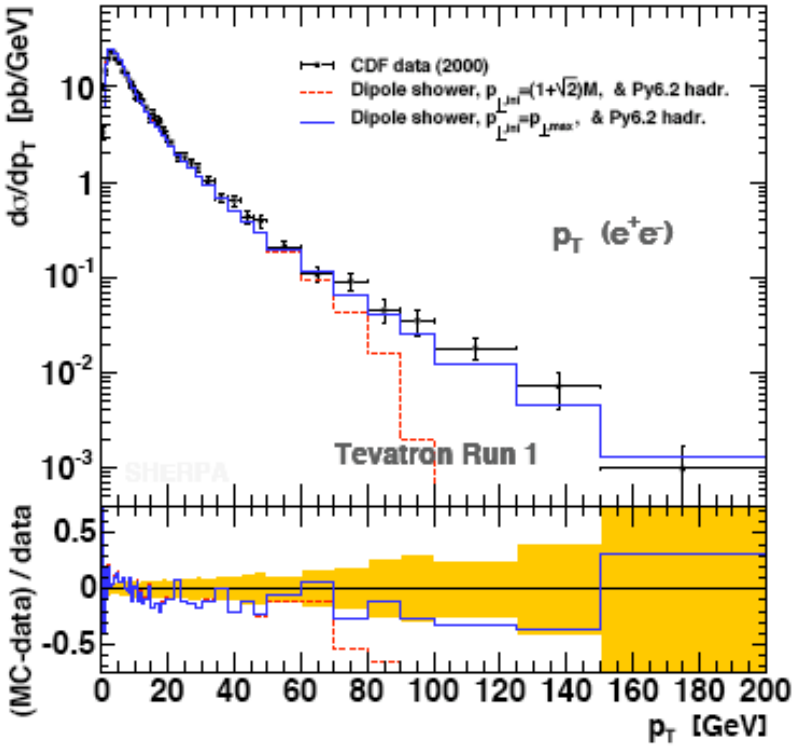
with $\alpha_s(M_Z)=0.137$,

$\mu_R=p_T$,

$p_{Thad} = 0.5$ GeV

Color dipole shower for hadronic collisions

Winter, Krauss, arXiv:0712.3913



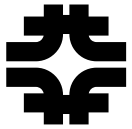
Radiation is associated with pairs of partons, initial-initial, initial-final and final-final color lines, using dipole phase-space and matrix element factorization and invariant evolution variables

Hadron remnant does not participate in shower.

Applied also to jet production scattering.

The plan for the future

- Work on innovative techniques for QCD calculations (similar to semi-numerical reduction, further development of unitarity-based numerical methods, renormalization group methods). (Becher, Ellis, Giele, Skands)
- Effective field-theory methods for multi-scale problems, and resummation (Becher)
- Development of an automatic tools for one-loop QCD (Ellis, Giele, Winter).
- Further development of the Pythia (Skands, Mrenna)
- Extension of Vincia style matching program to initial state and inclusion of massive particles (Skands, Giele)
- Distribution and maintenance of computing tools of use to the whole community (MCFM,QCDLoop etc) (Ellis)



Beyond the Standard Model

Patrick Fox

Theoretical Physics Group

- BSM'ers (of one type or another)

- Scientists (of one type or another)
  - William Bardeen
  - Marcela Carena
  - Bogdan Dobrescu
  - Estia Eichten
  - Patrick Fox
  - Christopher Hill
  - Boris Kayser
  - Joseph Lykken
  - Stephen Parke
  - Chris Quigg

- Postdocs
  - Anupama Atre
  - Yang Bai
  - Richard Hill
  - Jay Hubisz (now ANL)
  - Kyounghul Kong
  - Rakhi Mahbubani
  - Jose Santiago (now ETH, Zurich)

Dobrescu and Fox

- Source of fermion mass hierarchies unknown

➢ Propose new mechanism where fermion masses are generated through loops

➢ Top is massive at tree level, interactions with new scalars break chiral symmetries

➢ Light fermions have their mass generated through loops involving top

➢ Introduce leptoquark in representation (3,2,+7/6)

➢ All couplings allowed by symmetry

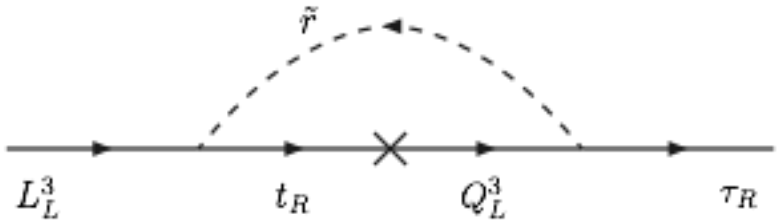
➢ All couplings are of order 1

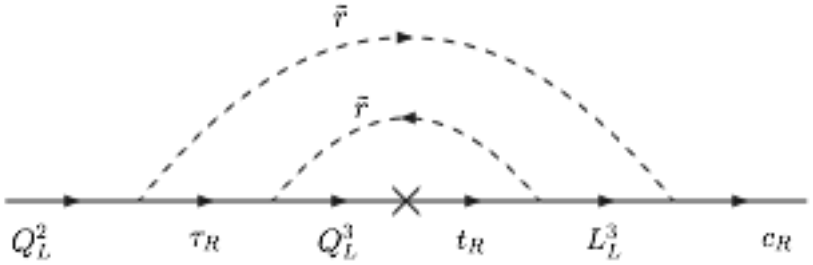
$$\lambda_{ij}\, r\, \overline{u}_R^i L_L^j + \lambda'_{ij}\, r\, \overline{Q}_L^i e_R^j + \text{H.c.}$$

- Leads to interesting pattern of masses w/o treating SM fermions separately

➢ Domino mechanism

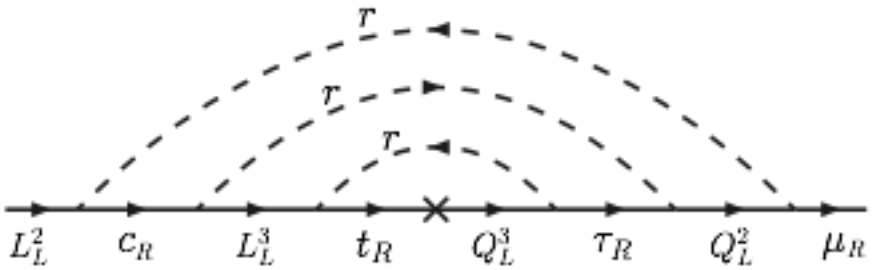
Dobrescu and Fox





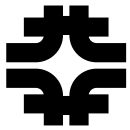
$$m_\tau \simeq \lambda_{33}\lambda'_{33}\, m_t \frac{N_c}{16\pi^2} \ln\left(\frac{\Lambda^2}{M^2_{\tilde{\tau}}}\right)$$

$$m_c = \lambda'_{23}\lambda_{23} m_\tau \frac{1}{16\pi^2} \log\frac{\Lambda^2}{M^2_{\tilde{\tau}}}$$



. . .

$$m_\mu \approx \lambda'_{22}\lambda_{22}\, m_c \frac{N_c}{16\pi^2} \log\frac{\Lambda^2}{M_r^2}$$



Dobrescu and Fox

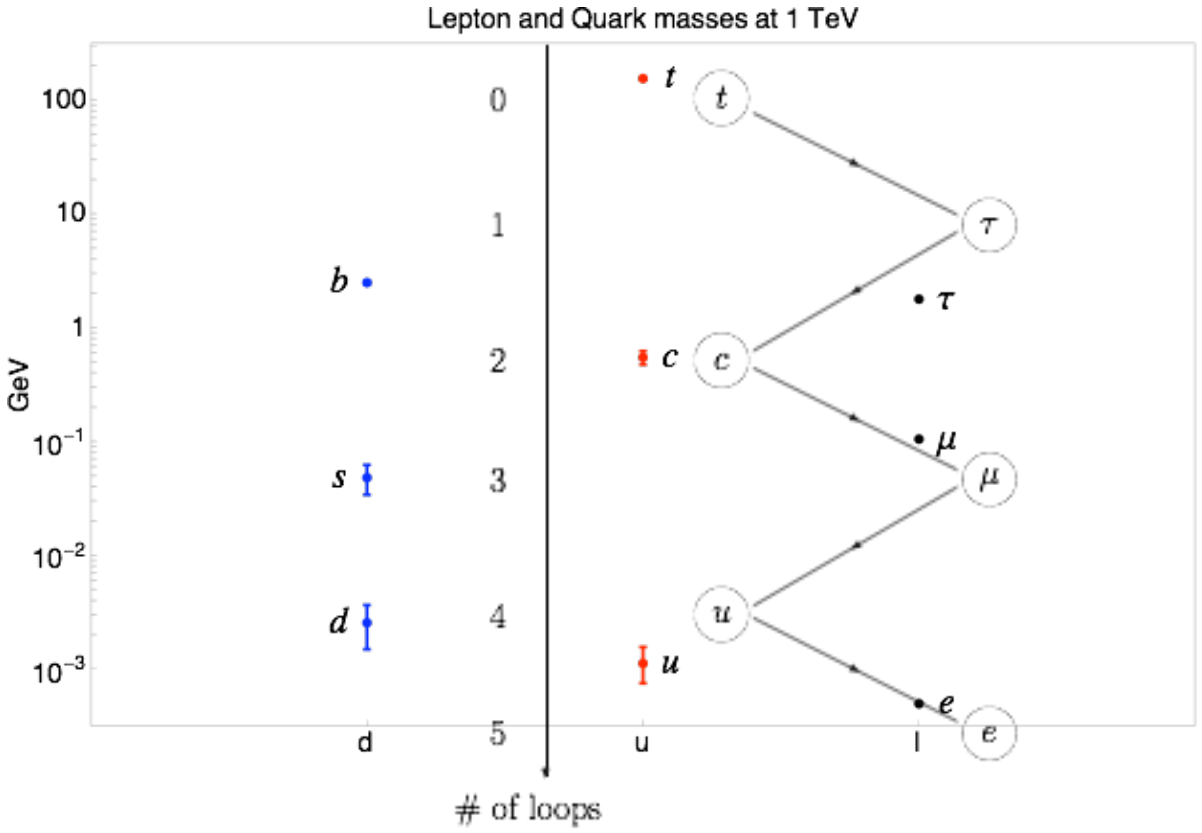
- Similar for the up quark sector
- Down sector requires introduction of scalars: $(8, 2, \pm 1/2)_{+1}$
- All masses generated after 4 loops
- Get correct CKM matrix

➢ Search for new states at LHC

➢ Look for their effects in precision flavour tests

- eg mu-e conversion
- rare meson decays

Dobrescu and Fox



Kayser and Parke

- Leptogenesis and neutrino CP violation
  - Heavy N made in early universe, decay out of equilibrium
  - If CP violated in decays, net lepton number produced

$$N \to l^+ + \ldots \quad \neq \quad N \to l^- + \ldots$$

  - Lepton number processed by SM sphalerons
  - Nonzero baryon number produced
    - Requires CP violation in N decays
    - CP violation in neutrino oscillations has same origin - Yukawa matrices
    - How to establish CP violation in neutrino oscillations?

- A key goal of Project X

Kayser and Parke

$$P\left[\nu_\mu \rightarrow \nu_e\right] \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx 1/30 \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2\left[(1-x)\Delta\right]}{(1-x)^2}, \quad T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)},$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)}, \quad T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$P\left[\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right] = P\left[\nu_\mu \rightarrow \nu_e\right] \text{ with } \delta \rightarrow -\delta \text{ and } x \rightarrow -x.$$

Kayser and Parke

If $E \rightarrow E/3$ at fixed L, we go from the 1st atmospheric oscillation peak to the 2nd one.

When $E \rightarrow E/3$ at fixed L, ~~*CP*~~ *is tripled*, *but the matter effect is reduced by a factor of 3*.

Carena and collaborators

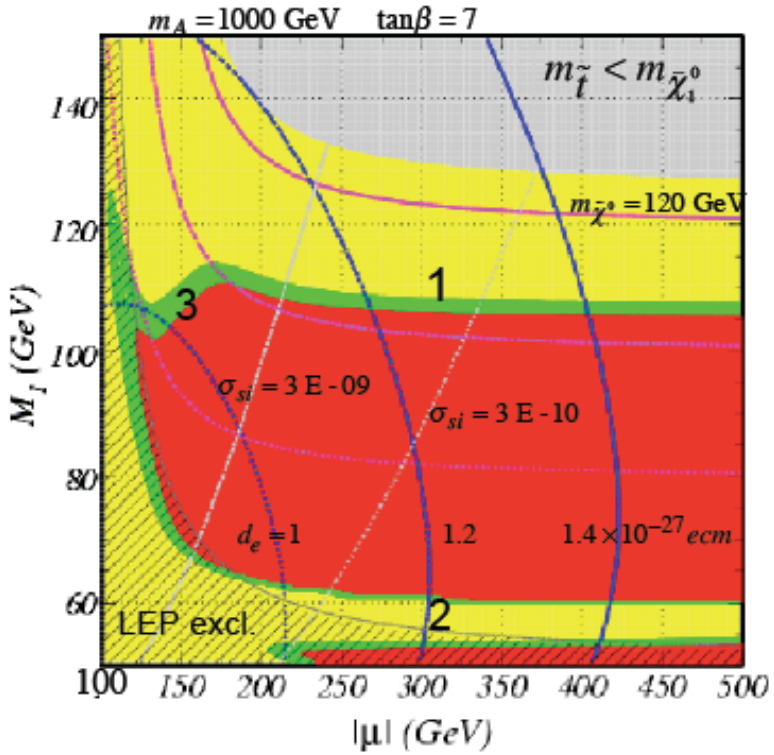
- SM contains all ingredients necessary to generate baryon asymmetry
  - Numbers don't work out
    - Need new physics, associated with EWSB
    - Dark matter is also indication of new physics
    - Can SUSY do both?
      - SUSY with R-parity has a DM candidate - neutralino LSP
      - SUSY breaking may introduce new phases
        - CP violation increases - helps
      - New light (bosonic) states coupled to the Higgs
        - $E_{SUSY} \approx 8E_{SM}$
      - Lightest stop is below 130 GeV
      - Higgs now above LEP bound (<120GeV)
      - All other squarks heavy

Carena and collaborators

$$d_e < 1.6\ 10^{-27}\ \text{e cm} \quad \Rightarrow \quad 5 \le \tan\beta \le 10$$

$$M_A \ge 200\ \text{GeV}$$

$$110\ \text{GeV} \le |\mu| \le 550\ \text{GeV}$$



- 1: neutralino-stop co-annihilation, mass splitting 20-30 GeV
- 2: Higgs pole
- 3: Z pole

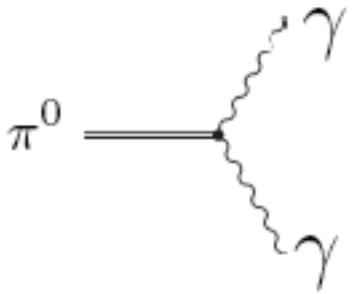
$$m_{\tilde{\chi}^0} \cong m_h/2$$

Carena and collaborators

- Collider tests of SUSY EWBG
  - Light Higgs
    - $h \to b\bar{b}$ may achieve 3 sigma evidence after 4-6 fb^{-1} at Tevatron
    - $h \to \tau\tau$ or $\gamma\gamma$ well tested at LHC after 10 fb^{-1}
  - Light Stops
    - Stop dominant decay is $\tilde{t} \to c\tilde{\chi}_0$, jet and missing energy
    - In region 1 (co-annihilation) small stop-neutralino mass splitting makes this challenging

Hill and Hill

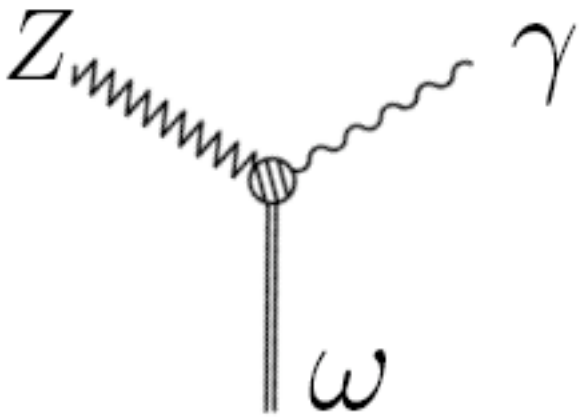
- (Breaking T-parity in) Little Higgs
  - Higgs is pNGB a la pions in QCD
  - Just as chiral Lagrangian contains WZW term effective theory of Higgs should include anomaly term
    - Unless UV theory predicts coefficient 0, places constraints on UV theory
  - Neutral pion decay due to anomaly (WZW term)
  - In Little Higgs WZW term breaks T-parity - far reaching implications
    - No missing energy signatures
    - No DM candidate

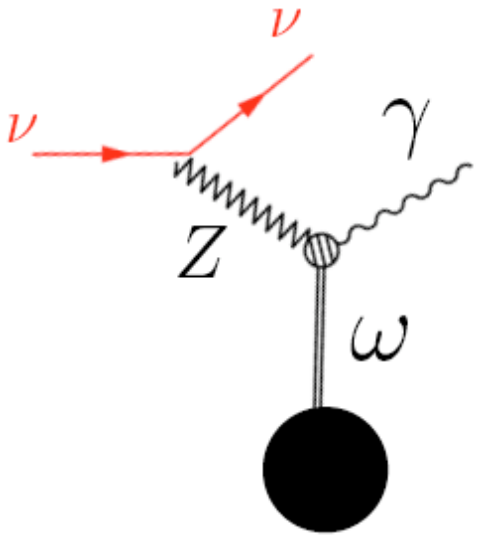


Harvey, Hill and Hill

- Revisited the anomaly term in the SM
  - SM is not a vector like gauging of SU(2)xU(1)
  - Careful analysis of anomalous transformations and counterterms leads to new class of SM interactions

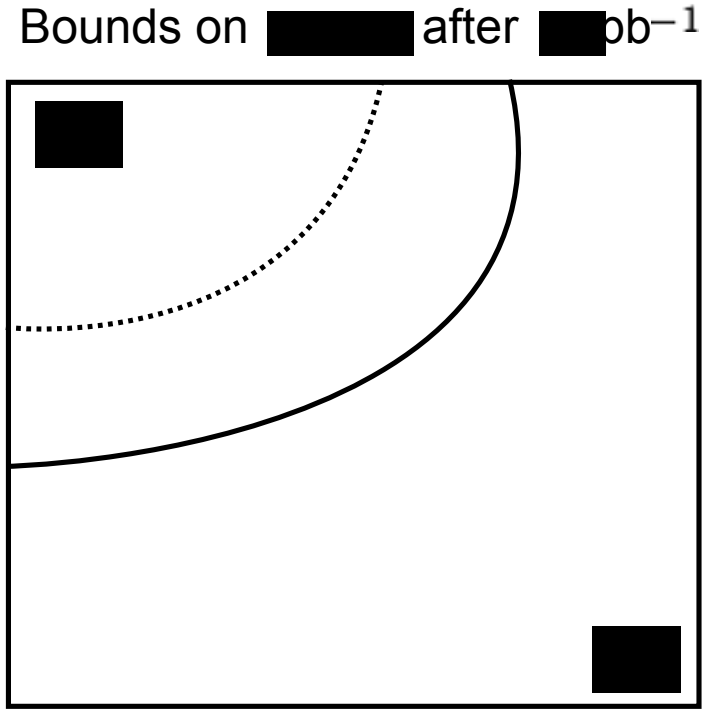
$$\mathcal{L} = \frac{N_c}{48\pi^2}\frac{e g_\omega g_2}{\cos\theta_W}\epsilon^{\mu\nu\rho\sigma}\omega_\mu Z_\nu F_{\rho\sigma}$$

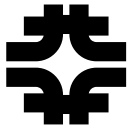




Joe Lykken (CMS)

- Recently Joe has been working with CMS on
  - Analyses of [redacted] using CMSSW with [redacted] and a new [redacted]
    - They have new results on the search reach for [redacted]





Lattice QCD

Andreas Kronfeld

Lattice QCD

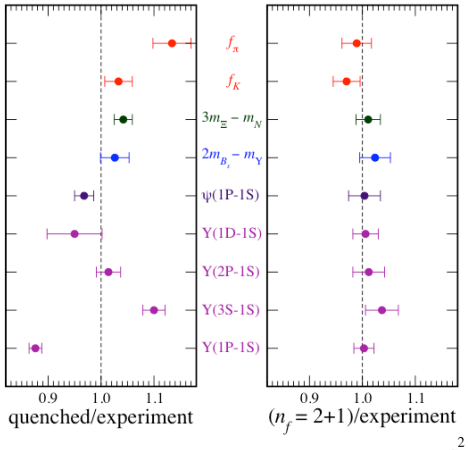
- Major theoretical and computational effort
  - Three senior scientists: Kronfeld, Mackenzie, Simone (CD); computing support from Holmgren, Singh, …
  - Typically two postdocs: Van de Water and Laiho -> Bailey.
  - Fermilab Lattice Collaboration at Fermilab, UIUC, DePaul, SAIC
    - Collaboration of Collaborations with MILC Collaboration
    - Cooperation with HPQCD Collaboration

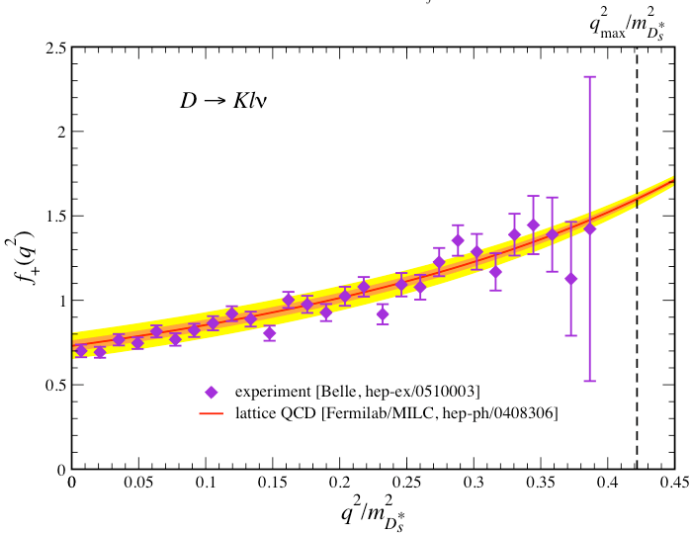
- USQCD Collaboration / LQCD hardware Project
  - PC clusters, funded by DOE-HEP and DOE-NP
    - $9.2 M over FYs '06-'09.
  - Earlier DOE-funded QCDOC (FYs '04, '05; HEP, NP, SciDAC, ASCR).
  - Lab infrastructure from Fermilab, JLab, BNL.
  - Software support from SciDAC.
  - Fermilab physics projects within USQCD:
    - B and D Meson Decays: 10% -> 13% -> 9.5 % of USQCD resources
    - Quarkonium Physics: 3.2% -> 4.5% -> 2.9%
    - B_K with Mixed Action (Laiho, Van de Water): 2.9% -> 6.0% -> 4.5%

Lattice Status

- Nine 1–3% postdictions (March 2003, HPQCD, MILC, and Fermilab Lattice Collab'ns). PRL.

- Predictions (all PRL):
  - D meson semileptonic decays (August 2004)
  - Mass of B_c meson (November 2004)
  - D meson leptonic decays (June 2005)
  - Verified by FOCUS, Belle, CLEO; CDF; CLEO, BaBar….

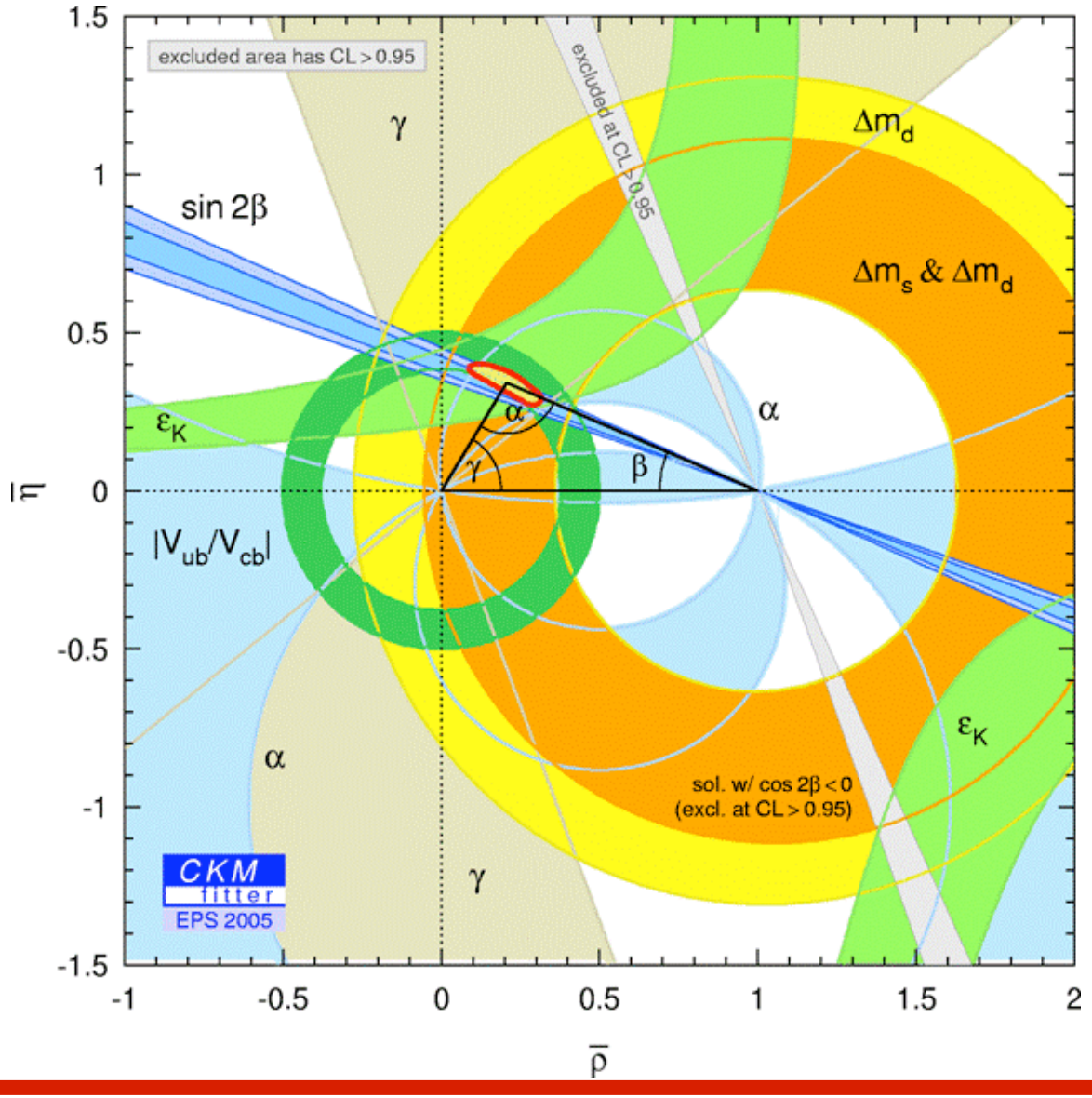




- Hardest part: sea quarks
  - Successful post- and predictions with fastest approach to sea quarks; other (theoretically cleaner) methods making strides.

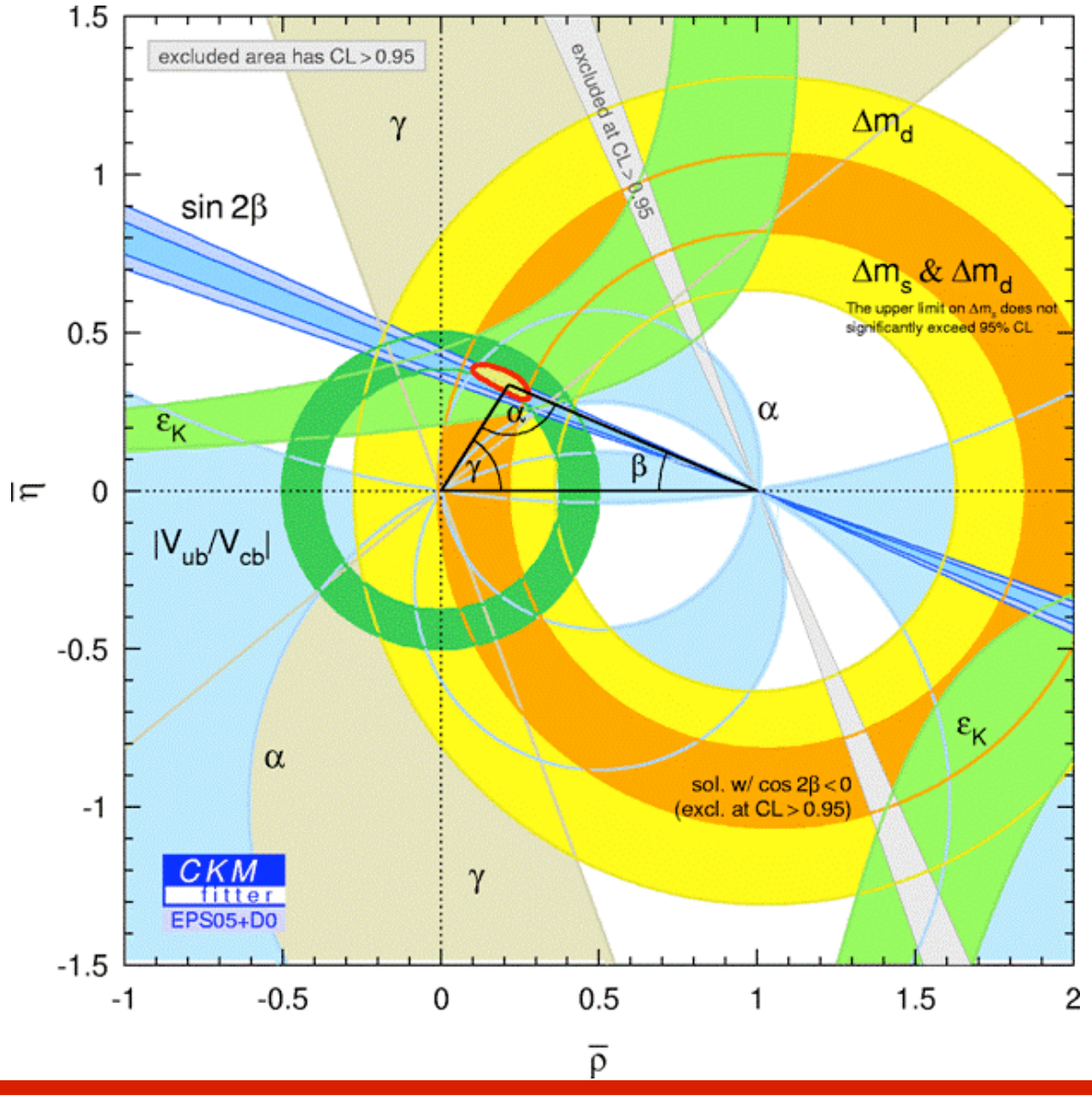
Lattice Flavor Physics

pre-Tevatron



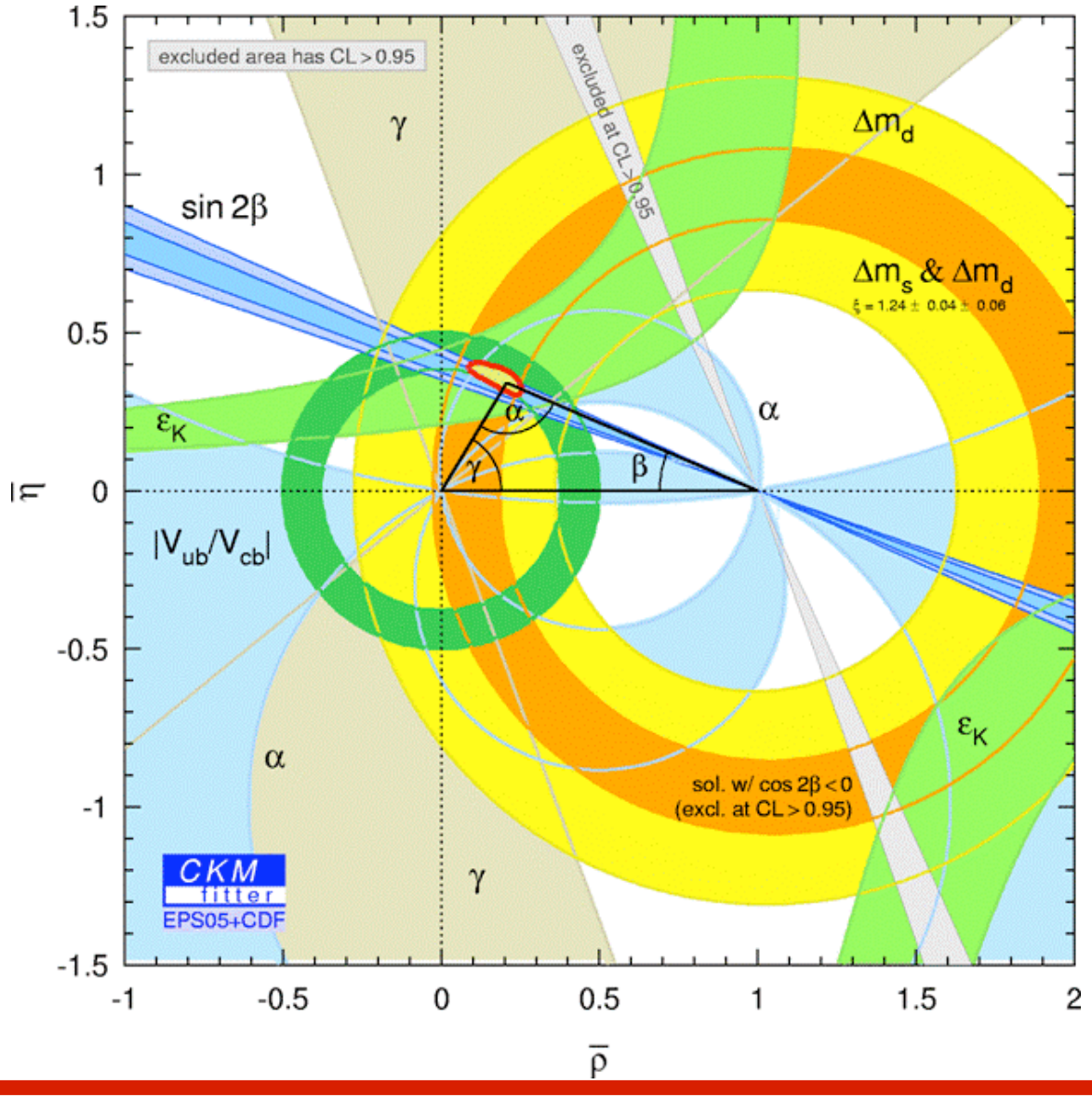
Lattice Flavor Physics

D0
10%



Lattice Flavor Physics

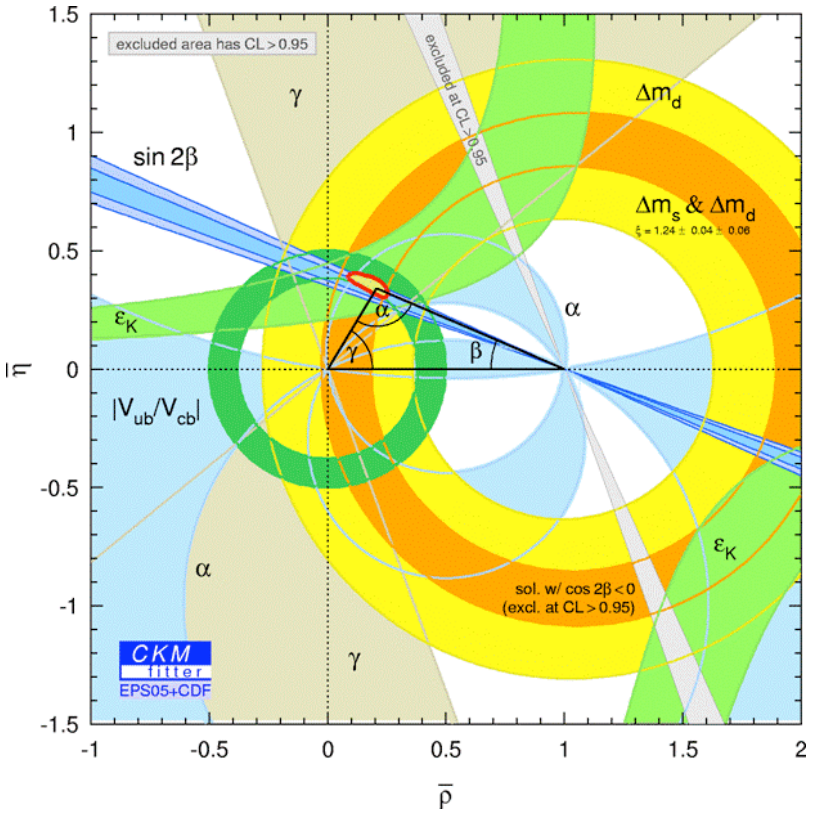
CDF
1%



Okamoto
Average ξ

Fermilab Lattice Flavor Physics

- Unitarity triangle
  - V_{cb} units
  - B decays, K & B mixing
- After success with D mesons, we simply change the quark mass.
- $B \to D^{(*)}l\nu$ yields V_{cb}
  - Laiho, Kronfeld
- $B \to \pi l\nu$ yields V_{ub}
  - Van de Water, Mackenzie
- SM B mixing yields V_{td}
  - Simone, UIUC, DePaul
- SM K mixing constrains apex
  - Laiho, Van de Water

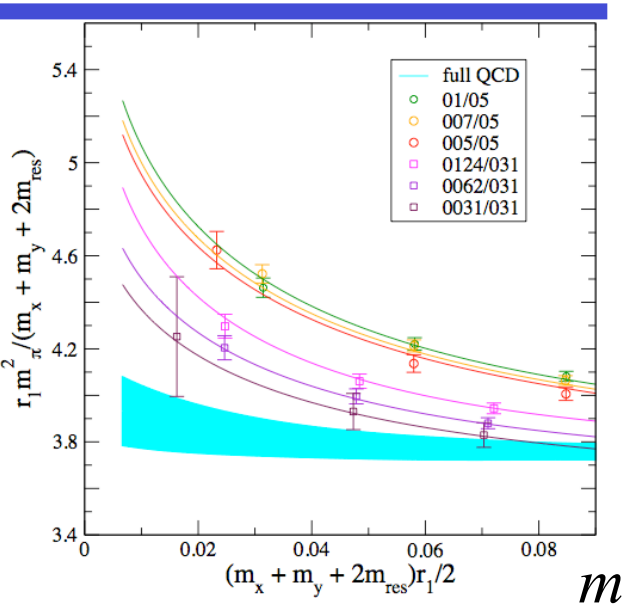


- Leptonic and semileptonic $D_{(s)}$ meson decays:
  - Bailey, Kronfeld, Simone, Mackenzie, Van de Water

Aubin, Laiho, Van de Water

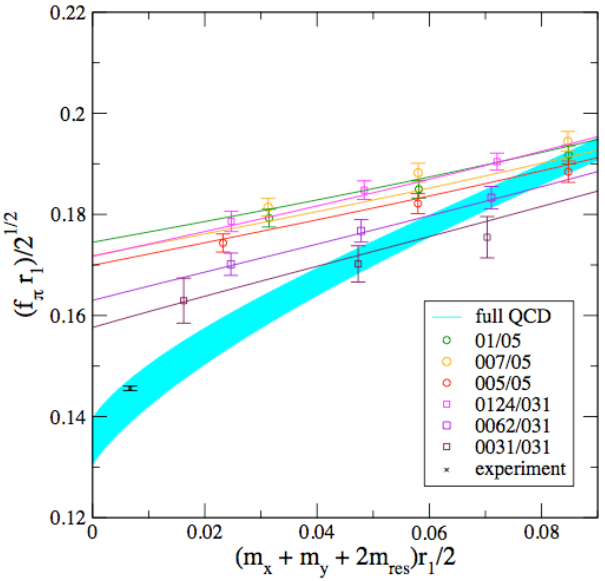
- Neutral kaon mixing
  - Measure ε_K
  - Calculate B_K
- Staggered sea ready to go
- Chiral valence simpler (theoretically)
- "Mixed" action needs one new (unphysical) parameter
  - ChPT [hep-lat/0609009]
  - Numerical demo: **arXiv:0803.0129** [hep-lat]
- Will yield one of best calculations of B_K: target 3–4% uncertainty

m_π^2

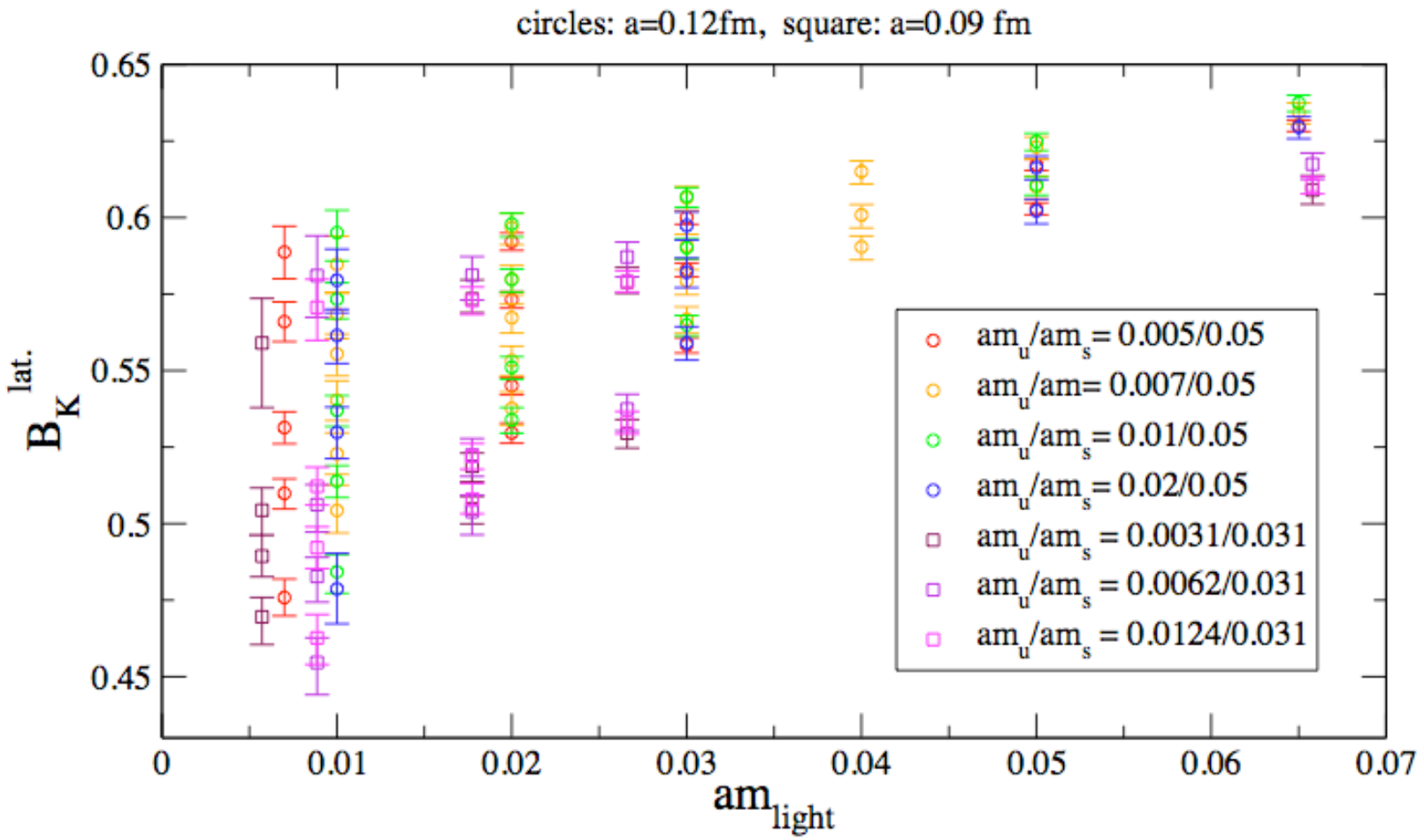


m_q

f_π

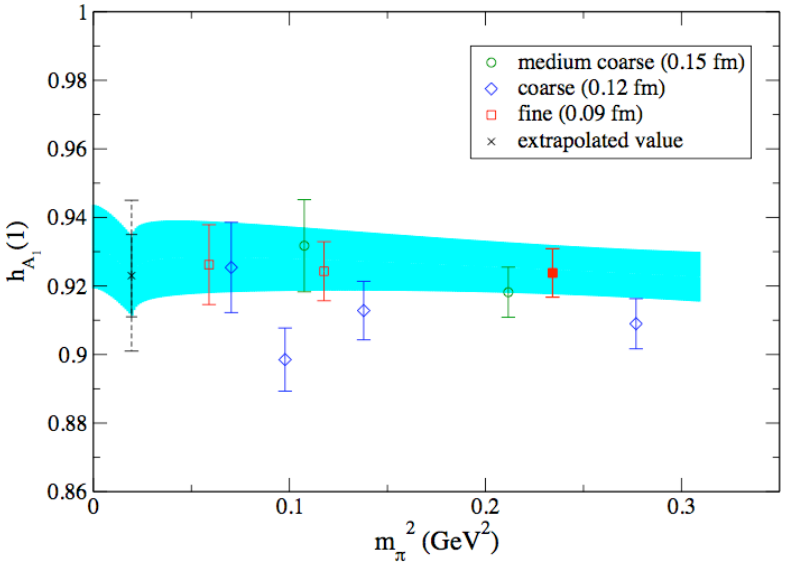


B_K Data


circles: a=0.12fm, square: a=0.09 fm
0.65
0.6
0.55
0.5
0.45
$B_K^{lat.}$
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
am_{light}
$am_u/am_s = 0.005/0.05$
$am_u/am = 0.007/0.05$
$am_u/am_s = 0.01/0.05$
$am_u/am_s = 0.02/0.05$
$am_u/am_s = 0.0031/0.031$
$am_u/am_s = 0.0062/0.031$
$am_u/am_s = 0.0124/0.031$

V_{cb} from B -> D*lν

- V_{cb} enters in every side of the unitarity triangle.
- Determined with 1-2% error from inclusive b -> clν decays.
- Exclusive decay as a cross-check and (long term) way to reduce error further.
- Need F(1) = $h_{A1}(1)$—first and only quenched calc. from us in 2001.
- Now: first calculation with 2+1 sea quarks.



- Also improved chiral extrapolation.
- Paper in near-final form.
- Lat '07: arXiv:0710.1111 [hep-lat]

$$|V_{cb}| = \begin{cases} (38.7 \pm 0.7 \pm 0.9) \times 10^{-3} & \text{exclusive} \\ (41.9 \pm 0.6 \pm 0.3) \times 10^{-3} & \text{inclusive} \end{cases}$$

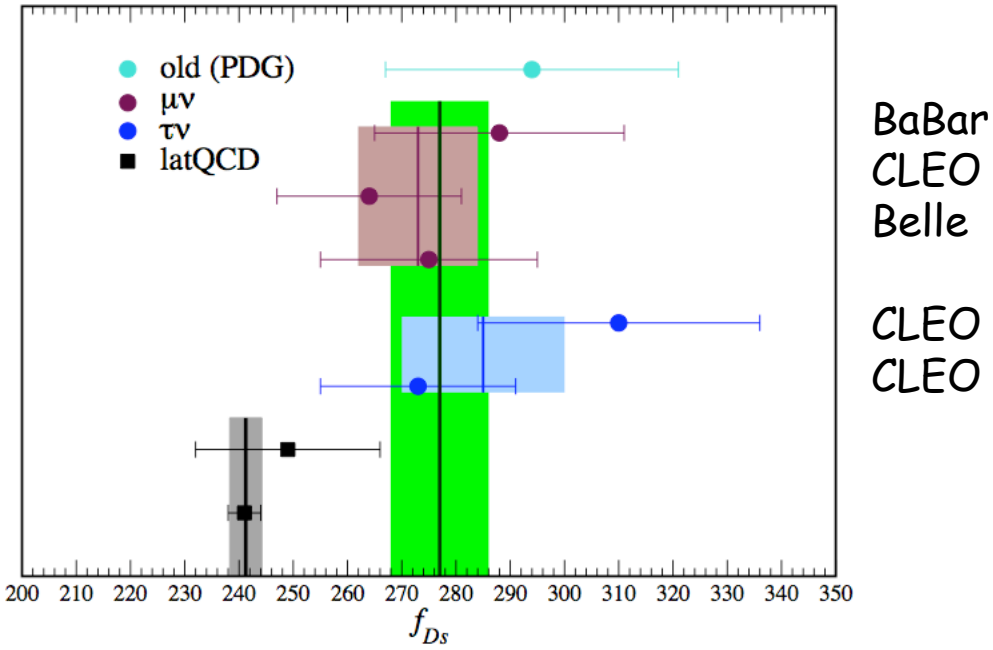
D_s Puzzle

- A recent calculation by HPQCD (*i.e.*, not by us) finds the leptonic decay of the Ds meson to be slower than measured (assuming SM only).
- Usually reported by comparing calculation and "measurement " of f_{D_s}.

- 3.8σ

Fermilab/MILC 2004

HPQCD 2006



BaBar
CLEO
Belle

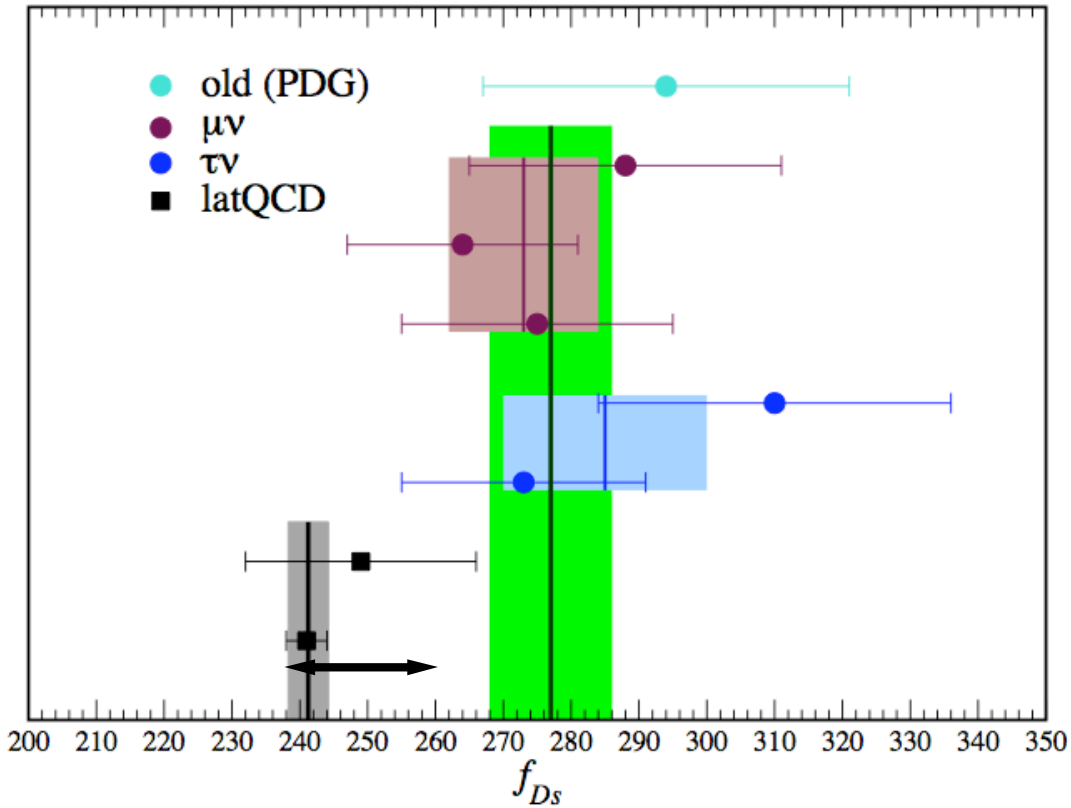
CLEO
CLEO

Dobrescu and Kronfeld

- Discrepancy unlikely from
  - Experimental effects
  - Radiative corrections
- HPQCD's error bar is aggressive, but unlikely to be underestimated by a factor of 5
  - Double their error bar -> 3.3σ
  - Triple their error bar (and include our 2005 value) -> 3.1σ
  - Sigmatology works this way because experimental error is three times larger than HPQCD's
- Could be explained by new physics
  - Charged Higgs (in a *new* 2HDM)
  - Leptoquarks (of two ilks)

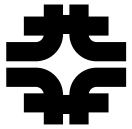
Fermilab Lattice & MILC Collabs.

- We are a few months away from finishing a paper updating our 2005 results:
  - More lattice spacings
  - More extensive chiral extrapolation



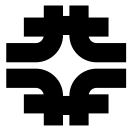
Future Plans

- Near term: projects mentioned, plus B meson mixing, semileptonic *B* -> $\pi l\nu$, *Kll*,….
- Longer term: flavor physics will remain important
  - LHCb, upgrades to KEKB & Belle
  - Super B factory
  - Project X: kaon experiments can constrain new physics if CKM is determined better (and here lattice QCD is key)
- EWSB may be strongly coupled
  - Local expertise in LHC signal interpretation, model building, and lattice gauge theories strong at Fermilab
    - It is not stronger anywhere else
- Plan to continue leading role in national scientific and computing landscape of lattice gauge theory.



Summary and Future Plans

Theoretical Physics Department



Summary

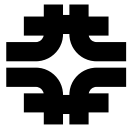
- Fermilab's Theoretical Physics Department
  - Produces exciting results across theoretical elementary particle physics
  - Mentors excellent postdocs who go on to tenure-track and tenured positions in the US and abroad
  - Assists the Directorate and experimenters in shaping the HEP program
    - especially in these challenging times

Future Plans

- Maintain and build on current core strengths
  - Perturbative QCD
  - Lattice gauge theory
  - Neutrinos
  - SM and BSM

} Postdocs are key

- Restore and reinvigorate visitor programs
  - Summer Visitors' Program for 2009
  - Wider base of US university and other lab physicists
  - Include bright young experimenters



Backup

Chris Hill

Frontier Fellows & Academic Visitors

Vernon Barger (10-12/98)

Howard Haber (9-12/98)

Stuart Raby (2-6/99)

Wu-Ki Tung (2-6/00)

Stefan Pokorski (9-12/00)

Jo Anne Hewett (9-12/00)

Steve Gottlieb (9-6/02)

Ulrich Baur (2-4/02)

Scott Willenbrock (7-12/02)

Peter Zerwas (9-11/04)

Manny Paschos (10/04 –12/04)

Sherwin Love (1/05 –04/05)

Frank Petriello (spring 2006)

Matthias Neubert (8/07 – 11/07)

Thomas Appelquist (10-12/98)

Pierre Ramond (6/99; 5/00)

Steve Ellis (3-6/00)

Moshe Moshe (3-9/00)

Mariano Quiros (9-12/00)

Alexei Yu. Smirnov (4/01)

Ken Lane (9-2/02)

Eric Braaten (10-12/02)

Aida El-Khadra (7-12/02)

Tao Han (10/04 –12/04)

Edward Boos (10/04 –12/04)

Paul Langacker (9/05 – 2/06)

Mariano Quiros (9/07 – 12/07

Summer Visitors (2007)

Paschos, Manny	Univ. of Dortmund	5/21/07	6/4/07
Minakata, Hisakazu	Tokyo	7/19/07	8/11/07
Uchiyama, Shoichi	Tokyo	7/22/07	8/8/07
Gamiz, Elvira	UIUC	7/23/07	7/25/07
Evans, Richard Todd	UIUC	7/23/07	7/25/07
Gallichio, Jason		8/2/07	8/6/07
Mann, Ady	Technion	8/3/07	8/13/07
Ponton, Eduardo	Columbia Univ.	8/15/07	8/21/07
Nierste, Ulrich	Univ. Karlsruhe	9/10/07	9/19/07
Rückl, Reinhold	Univ. Würzburg	9/10/07	10/5/07
Ahrens, Valentin	Univ. of Mainz	9/17/07	10/1/07

Academic Visitors (2007-2008)

Serone, Marco	SISSA Trieste, Italy	1/27/07	2/3/07
Delgado, Antonio	CERN	2/3/07	2/7/07
Stephens, Philip	ITJ, Poland	2/7/07	2/8/07
Freitas, Ayres	Univ. of Zurich	2/12/07	3/2/07
Hewett, JoAnn	SLAC	2/26/07	4/17/07
Chen, Mu-Chen	UC, Irvine	4/1/07	7/31/07
Racker, Juan	Centro Atomico Bariloche	4/1/07	9/29/07
Panes, Boris	Univ. Catolica de Chile	4/1/07	9/29/07
Kosower, David	CEA, France	4/8/07	4/15/07
Kunst, Zoltan	ETH, Zurich	4/12/07	4/27/07
Hoang, Andre	Max-Planck Inst.	4/19/07	4/20/07
Moshe, Moshe	Technion	5/1/07	9/1/07
Sim, Usha	Univ. of Delhi	5/5/07	5/13/07
Kulshreshtha, Daya	Univ. of Delhi	5/5/07	5/13/07
Kittel, Olaf	Univ. of Bonn	5/9/07	5/12/07

Nierste, Ulrich	Karlsruhe	1/23/08	1/24/08
Kunszt, Zoltan	Zurich	1/28/08	2/5/08
Mena, Olga	Rome	2/4/08	2/22/08
Menon, Arjun	U. Michigan	2/5/08	2/8/08
Fukano, Hidenori	Nagoya Univ.	2/5/07	3/5/07
Ponton, Eduardo	Columbia Univ.	3/19/08	3/21/08
Kozlov, Gennady	JINR	3/30/08	4/29/08
Zurita, Jose	UBA	4/5/08	9/30/08
Jin Chun, Eung	KIAS	4/22/08	4/27/08
Nandi, Satyi	Oklahoma State	5/15/08	7/15/08
Yamawaki, Koichi	Nagoya Univ.	5/16/08	8/15/08
Reiter, Thomas	Univ. of Edinburgh	5/17/08	5/24/08
Gavela, Belen	Univ. Auto. Madrid	6/1/08	6/20/08

"Renowned" Papers, 500+ citations

For this list we follow the SLAC/Spires "Topcited Theorist" guidelines: subtract the "Reviews of Particle Properties" cites and any articles with > 5 authors; This includes only papers written by authors active now on the Fermilab staff and only at the time they were affiliated with Fermilab.

Cited > 500 times: Since 1990

On Kaluza-Klein states from large extra dimensions.
Tao Han, Joseph D. Lykken, Ren-Jie Zhang, Phys.Rev.D59:105006,1999. Cited 550 times

Weak scale superstrings.
Joseph D. Lykken Phys.Rev.D54:3693-3697,1996. Cited 582 times

On the viability of lattice perturbation theory.
G.Peter Lepage, Paul B. Mackenzie. Phys.Rev.D48:2250-2264,1993. Cited 810 times

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William A. Bardeen, Christopher T. Hill, Manfred Lindner
Published in Phys.Rev.D41:1647,1990. Cited 792 times

An Effective Field Theory for the Calculation of Matrix Elements Involving Heavy Quarks.
Estia Eichten, Brian R. Hill; Phys.Lett.B234:511,1990. Cited 769 times

"Famous" papers, 250+ citations

b --> s gamma and supersymmetry with large tan Beta.
Marcela Carena, David Garcia, Ulrich Nierste, Carlos E.M. Wagner, Phys.Lett.B499:141-146,2001. Cited 257 times

Effective potential methods and the Higgs mass spectrum in the MSSM.
Marcela Carena, M. Quiros, C.E.M. Wagner Nucl.Phys.B461:407-436,1996 Cited 451 times

Analytical expressions for radiatively corrected Higgs masses and couplings in the MSSM.
Marcela Carena , J.R. Espinosa, M. Quiros, C.E.M. Wagner. Phys.Lett.B355:209-221,1995, Cited 406 times

Electroweak symmetry breaking and bottom - top Yukawa unification.
Marcela Carena, M. Olechowski, S. Pokorski, C.E.M. Wagner . Nucl.Phys.B426:269-300,1994. Cited 459 times

On the unification of couplings in the minimal supersymmetric Standard Model.
Marcela Carena, S. Pokorski, C.E.M. Wagner .Nucl.Phys.B406:59-89,1993 Cited 269 times

Bounds on universal extra dimensions.
Thomas Appelquist , Hsin-Chia Cheng, Bogdan A. Dobrescu , Phys.Rev.D64:035002,2001.; Cited 426 times

Heavy quark production in very high-energy hadron collisions.
John C. Collins, R.Keith Ellis . Nucl.Phys.B360:3-30,1991. Cited 400 times

Cosmology with ultralight pseudo Nambu-Goldstone bosons.
Joshua A. Frieman, Christopher T. Hill, Albert Stebbins, Ioav Waga .
Phys.Rev.Lett.75:2077-2080,1995. Cited 390 times

Topcolor assisted technicolor.
Christopher T. Hill . Phys.Lett.B345:483-489,1995.Cited 438 times

Topcolor: Top quark condensation in a gauge extension of the standard model.
Christopher T. Hill , Phys.Lett.B266:419-424,1991. Cited 325 times

More "Famous" papers, 250+ citations

Massive fermions in lattice gauge theory.
Aida El-Khadra, Andreas Kronfeld, Paul Mackenzie, Phys.Rev.D55:3933,1997. Cited 258 times

Neutrino interactions at ultrahigh-energies.
Raj Gandhi, Chris Quigg, Mary Hall Reno, Ina Sarcevic, Phys.Rev.D58:3009,1996, Cited 349 times

Ultrahigh-energy neutrino interactions.
Raj Gandhi, Chris Quigg, Mary Hall Reno, Ina Sarcevic Astropart.Phys.5:81,1996. Cited 367 times

Mesons with beauty and charm: Spectroscopy.
Estia J. Eichten, Chris Quigg, Phys.Rev.D49:5845,1994. Cited 256 times

Multiparton amplitudes in gauge theories.
Michelangelo L. Mangano, Stephen J. Parke, Phys.Rept.200:301,1991. Cited 344 times

Higher order corrections to jet cross-sections in hadron colliders.
W.T. Giele, E.W.Nigel Glover, David A. Kosower Nucl.Phys.B403:633-670,1993. Cited 443 times

Higher order corrections to jet cross-sections in e+ e- annihilation.
W.T. Giele, E.W.Nigel Glover . Phys.Rev.D46:1980-2010,1992. Cited 289 times

On the production of a W and jets at hadron colliders.
Frits A. Berends, H. Kuijf, B. Tausk, W.T. Giele. Nucl.Phys.B357:32-64,1991. Cited 324 times