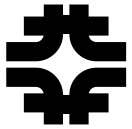


Theoretical Physics: Directions

Andreas Kronfeld

FRA Visiting Committee

April 20–21 2007

Theoretical Physics Group

- 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)
  - Peter Skands (2/2007)
  - Patrick Fox (10/2007)
- Research Associates
  - Richard Hill ('05)
  - Jay Hubisz ('05)
  - Kyoungchul Kong ('06)
  - Jack Laiho ('04)
  - Enrico Lunghi ('05)
  - Rakhi Mahbubani ('06)
  - José Santiago ('04)
  - Ruth Van de Water ('05)
  - (Skands)

Theoretical Physics Group

- Associated colleagues:
  - Carl Albright (ex-NIU)
  - André de Gouvea (NU)
  - Elizabeth Freeland (SAIC)
  - Wai-Yee Keung (UIC)
  - Stephen Martin (NIU)
  - Stephen Mrenna (CD)
  - Jim Simone (CD)
  - Tim Tait (ANL)
  - …
- Visitors:
  - Frank Petriello (1-5/06)
  - JoAnne Hewett (3-4/07)
  - Matthias Neubert (7-9/07)
  - Mariano Quirós (10-11/07)
- Alumni:
  - Mu-Chun Chen -> UC Irvine
  - Olga Mena -> Roma I
- Upcoming departures:
  - Laiho -> Washington U.
  - Santiago -> ETH Zürich
- Incoming postdocs:
  - Yang Bai <- Yale
  - Jon Bailey <- Wash. U.
  - Jan Winter <- Dresden
- Latin American Students:
  - Boris Panes (Chile)
  - Juan Racker (Argentina)

Community Service

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

Community Service (2)

- ILC Policy
  - Kronfeld (WWS-OC, Fermilab ILC Task Force, …)
- Neutrino Physics Policy
  - Kayser (all possible panels), Parke, Mena
- 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

Laboratory Service

- Academic Lectures (to educate on-site grad students)
  - Organization: Carena, Becher, Kronfeld, Quigg, …
  - Lectures: Quigg, Kayser, Parke, Ellis, Giele, Lunghi, Becher, Kronfeld; Langacker, Plunkett, Dodelson, Cabrera, Green, Berryhill, Herndon
- Fermilab Seminars
  - Colloquium: Dobrescu (w/ many others)
  - Joint Experimental-Theoretical Physics: Becher, Giele
  - Theoretical Physics: Kronfeld, Skands
- Scientific Committees at Fermilab
  - FCSA: Eichten
  - Scientist III committee: Bardeen
  - Wilson Fellows: Quigg -> Kronfeld
  - URA (now FRA?) thesis award: Dobrescu
  - Awards: Quigg
  - Joint Appointments with nearby universities
    - Lab policy: Hill
    - Search with University of Chicago: Bardeen, Ellis, Kronfeld

Conferences and Workshops (@ Fermilab)

- Monte Carlo Tools for Beyond-the-Standard Model Physics
  - Skands
- USQCD Collaboration Meeting
  - Kronfeld
- Joint Fermilab-CERN Hadron Collider Physics Summer School
  - Dobrescu
- The LHC Early Phase for the ILC Workshop
  - Carena
- LoopFest VI: Radiative Corrections for the LHC and ILC
  - Ellis, Giele
- Neutrino Physics Summer School (2007)
  - Kayser

Cosmological Connections

- Scientific collaboration with colleagues in the Theoretical Astrophysics Group has always been healthy:
  - Classic papers: Hill & Schramm; Frieman, Hill, Stebbins, Waga
  - Neutrino cosmology: Barenboim, Mena, Quigg
  - Modified gravity: Mena, Santiago, and Weller (2005)
  - WIMPs at colliders: Carena, Hooper, Skands (2006)

- Pizza nights

- Grudge matches
  - Soccer
  - (American) football
  - Softball
  - Basketball (Bardeen was unavailable)

- Computational Cosmology Task Force
  - Includes lattice theorist and lattice computing experts

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 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.
  - Fermilab physics projects within USQCD:
    - B and D Meson Decays: 10% -> 13% of USQCD resources
    - Quarkonium Physics: 3.2% -> 4.5%
    - B_K with mixed action (Laiho, Van de Water): 2.9% -> 6.0%

Lattice Status

- Benjamín Grinstein at CKM 2006 (December in Nagoya):
  - "I'll believe a 3% lattice [QCD] theory error when the lattice has produced one successful **pre**diction and several 3% **post**dictions."

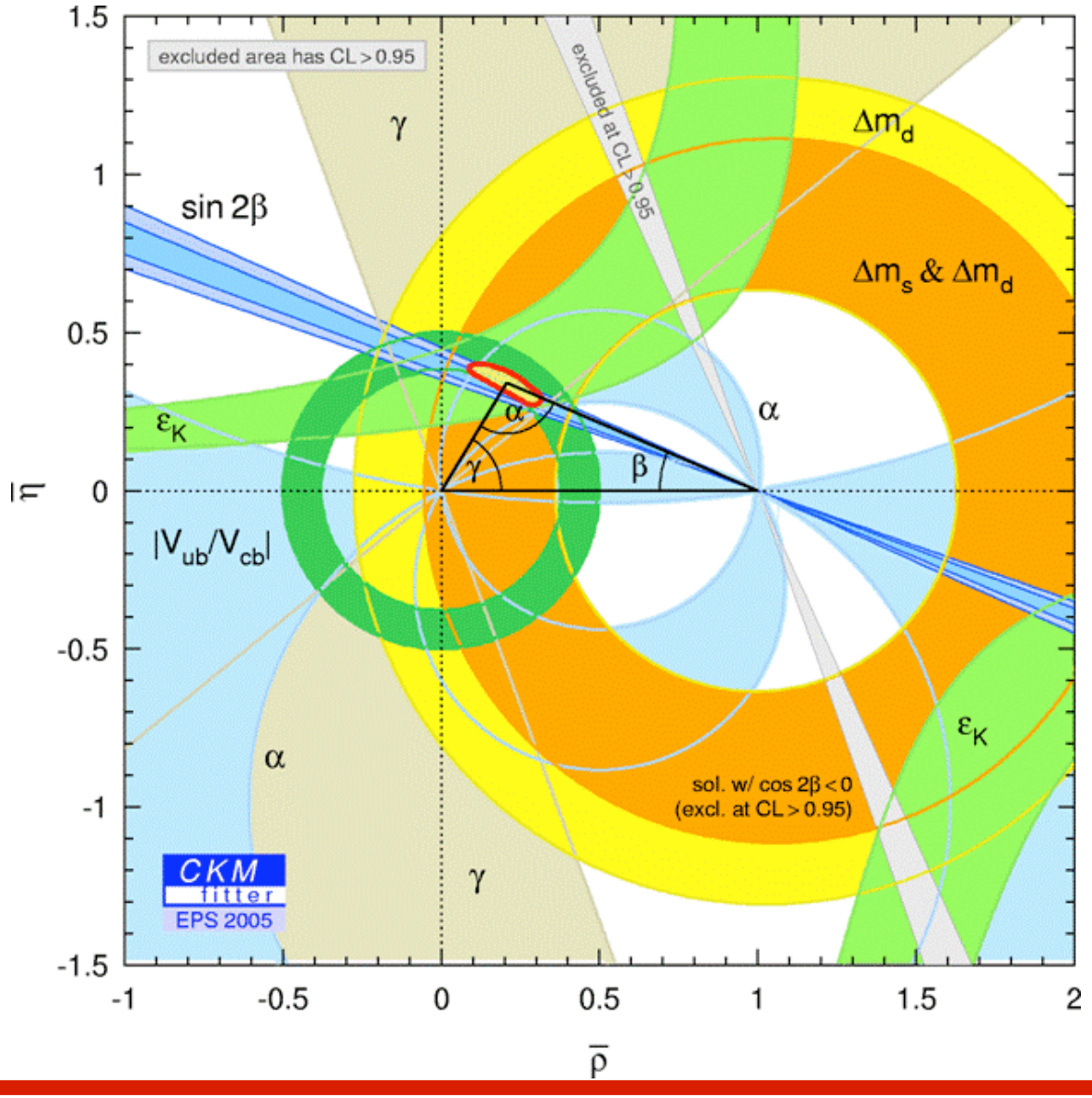
- Nine 1–3% postdictions in March 2003 from HPQCD, MILC, and Fermilab Lattice Collaborations. PRL.

- Predictions of D meson semileptonic decays in August 2004; mass of B_c meson in November 2004; and D meson leptonic decay in June 2005. (All PRL.) 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.

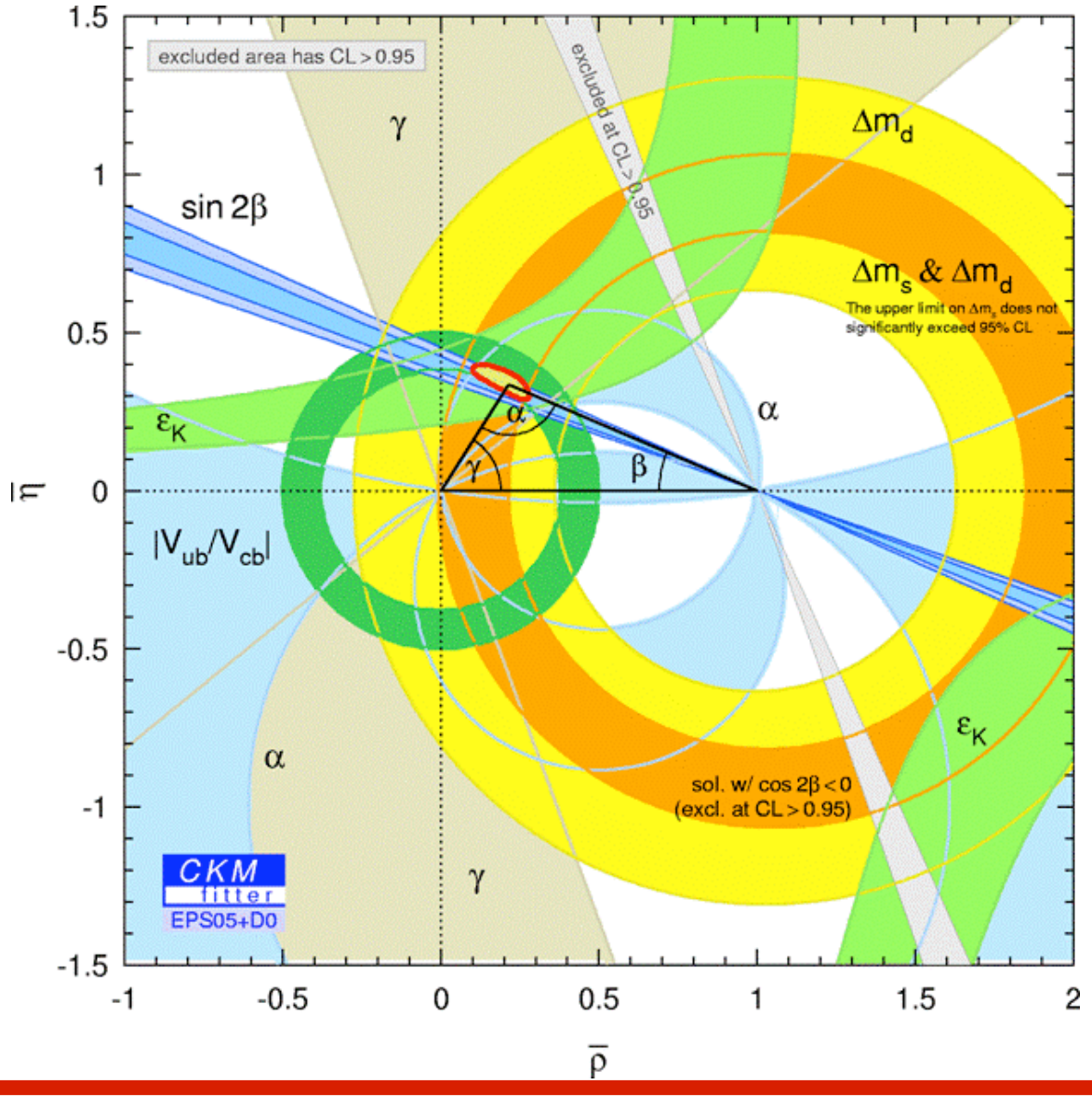
Lattice Flavor Physics

pre-Tevatron



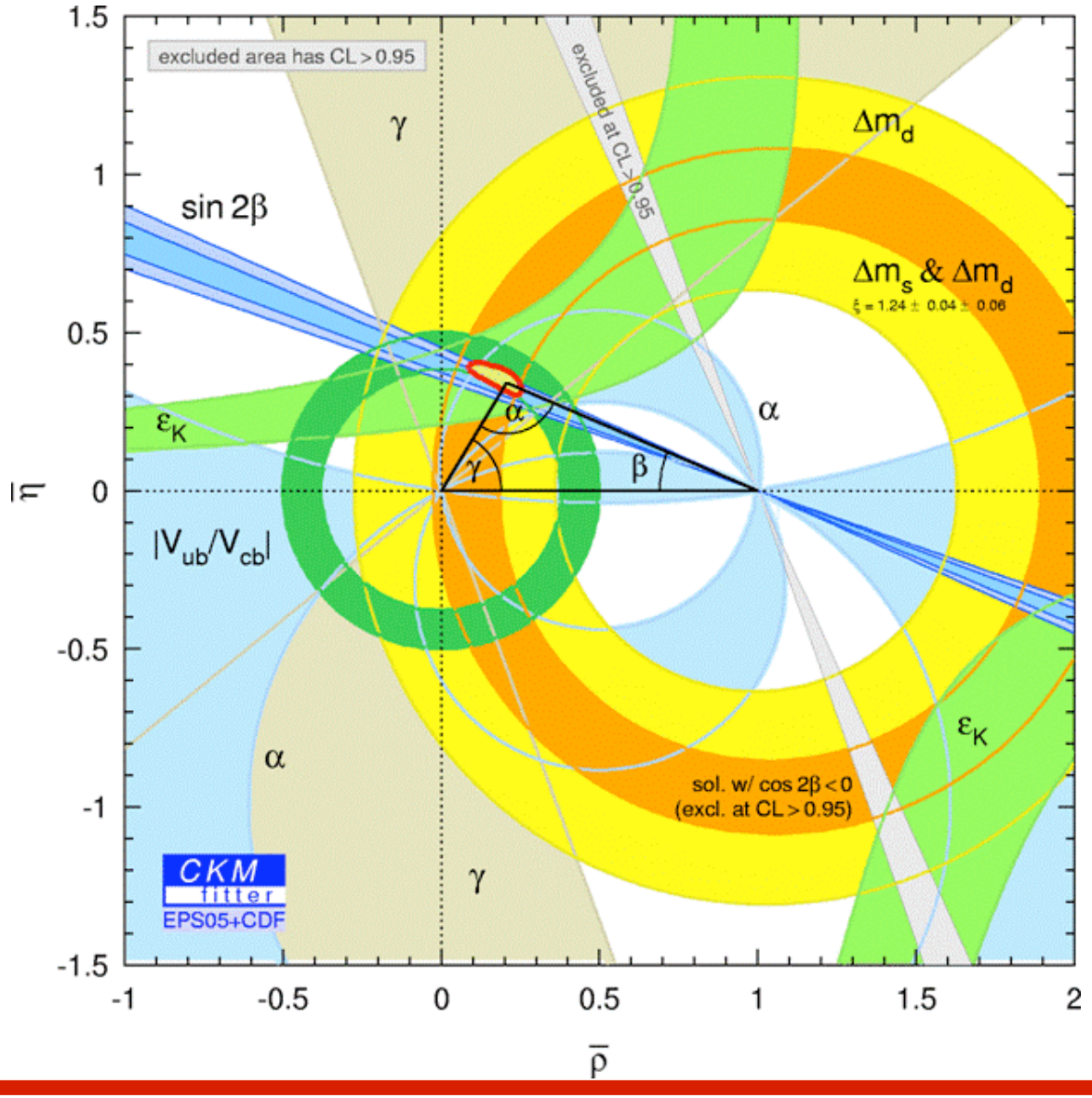
Lattice Flavor Physics

D0
10%



Lattice Flavor Physics

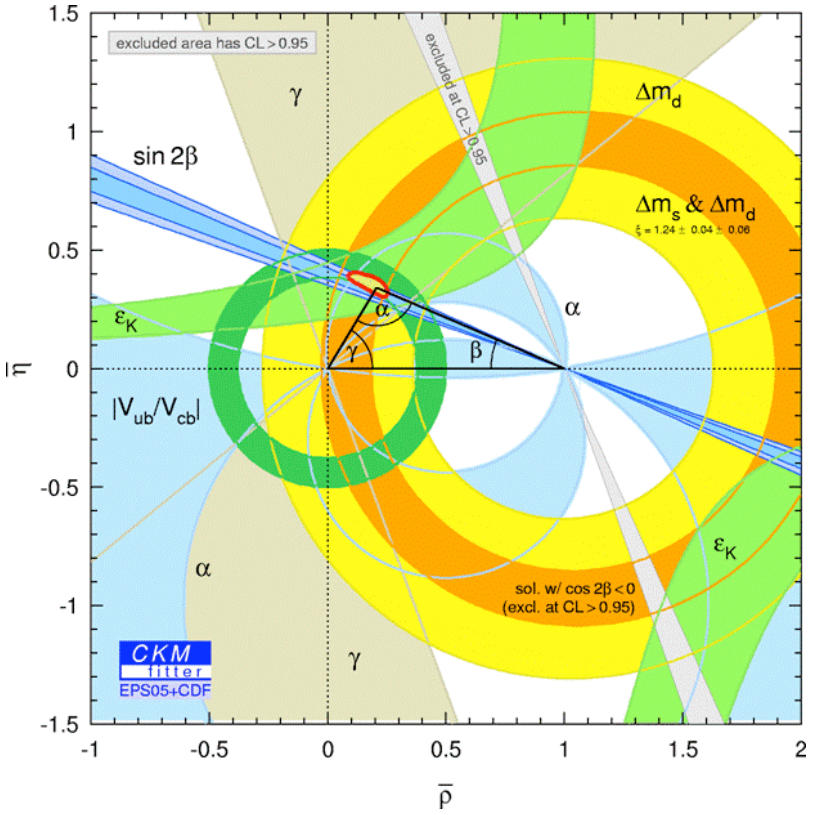
CDF
1%



Okamoto
Average ξ

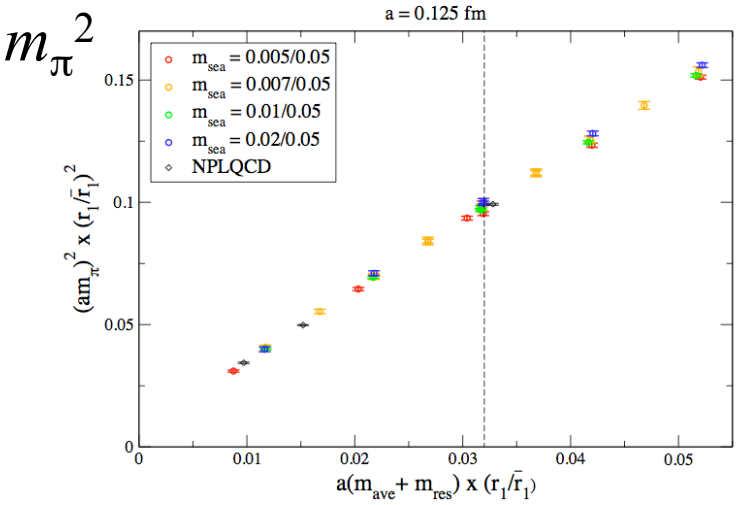
Fermilab Lattice Flavor Physics

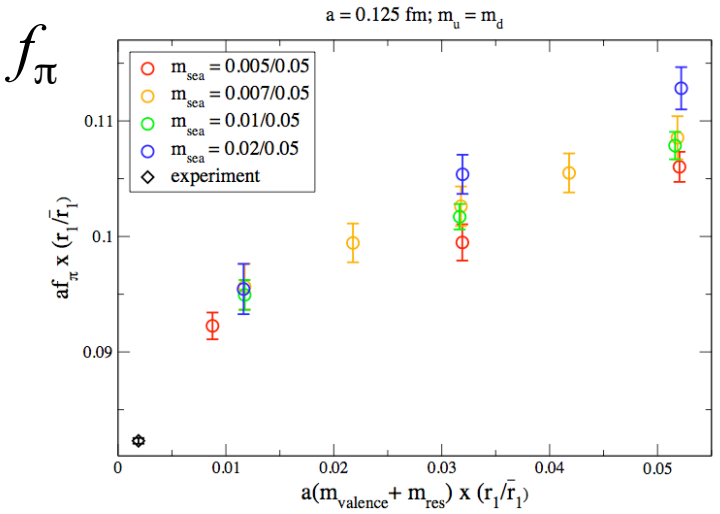
- Unitarity triangle
  - V_{cb} units
  - B decays, K & B mixing
- After success with D mesons, we simply change the quark mass.
- $B \to D^{(*)}l\nu$ yields V_{cb}
  - Laiho, Kronfeld
- $B \to \pi l\nu$ yields V_{ub}
  - Van de Water, Mackenzie
- SM B mixing yields V_{td}
  - Simone, UIUC, DePaul
-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



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: straightforward
- Will yield one of best calculations of B_K: target 5% uncertainty





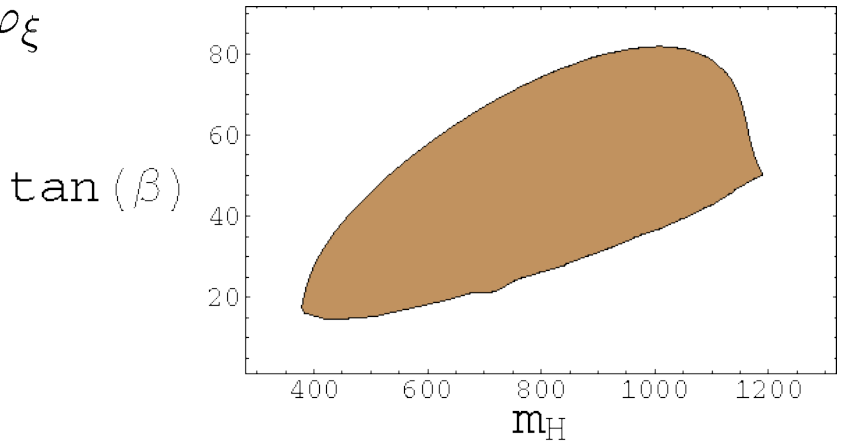
Lunghi & Soni

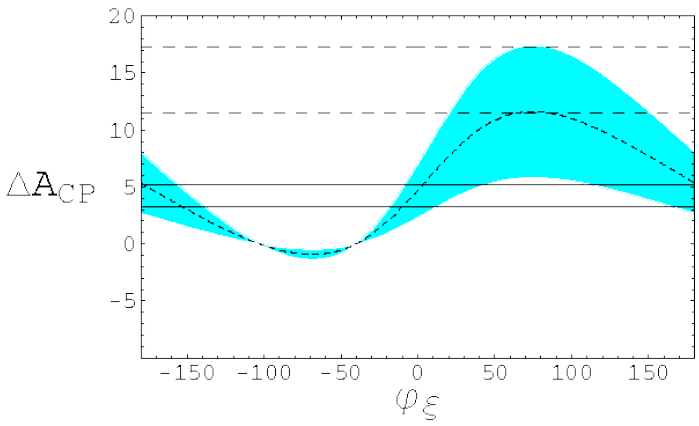
- Type III 2-Higgs Doublet Model in B Physics
  - One doublet for top quark; another for the rest.
  - New parameters: $m_{H^\pm}$, m_{H^0}, m_{A^0}, α, $\tan\beta$, $|\xi|e^{i\varphi_\xi}$, $|\xi'|e^{i\varphi_{\xi'}}$
  - Last two induce FC and CP violation in 23 & 13 processes
  - Sensitive to
    - Asymmetry in $B \to \psi K_S$, $a_{\psi K}$
    - Neutral kaon mixing, ε_K
    - Rare decay $B \to X_s\gamma$
    - $|V_{ub}/V_{cb}|$
    - Asymmetries in $K\pi$:

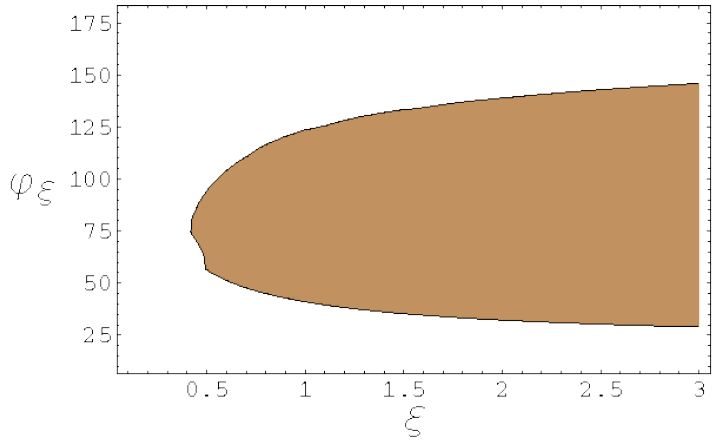
$$\Delta A_{CP} = A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+)$$

Lunghi & Soni (2)

- Constraints from B Physics
  - Look at $m_{H^\pm}$, $\tan\beta$, $|\xi|$, φ_ξ
  - UT fit B -> $X_s\gamma$, B -> $\tau\nu$
  - ε_K and $a_{\psi K}$ depend strongly on φ_ξ
  - Fix φ_ξ to accommodate $a_{\psi K}$ we have no freedom left to adjust ε_K.
  - Same region improves fit to $K\pi$ asymmetries.





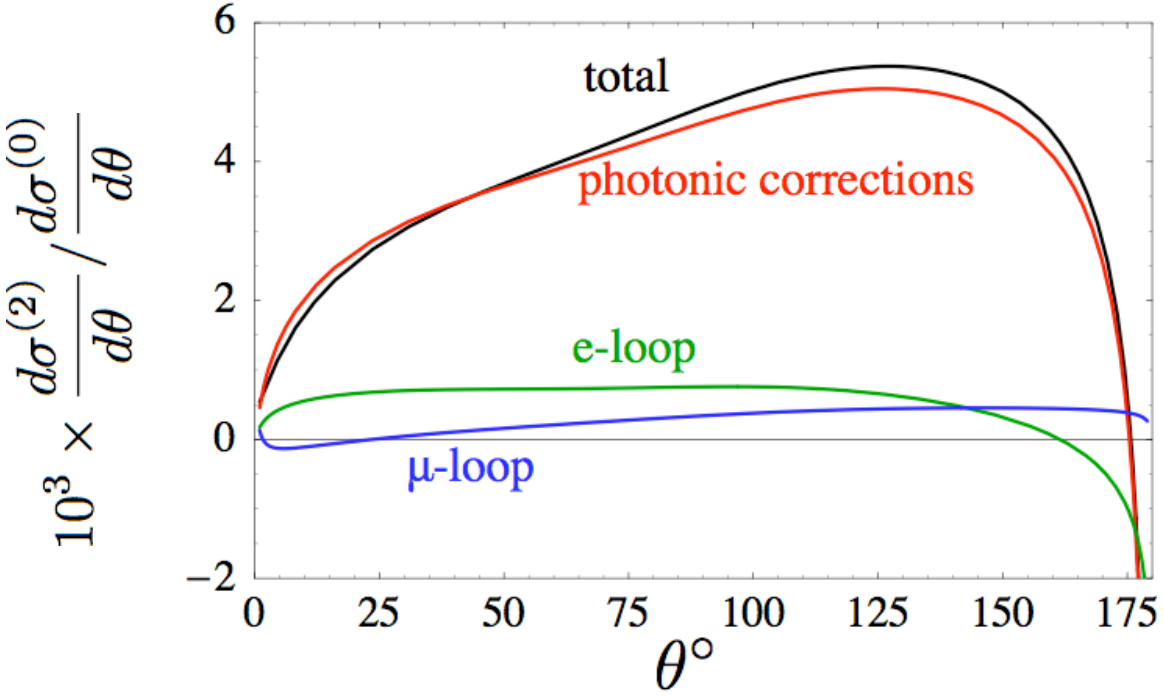


Becher and Melnikov

- Two-loop QED corrections to Bhabha scattering.
  - Used to measure luminosity at lepton colliders.
    - At present and past e^+e^- machines luminosity uncertainty is theory dominated.
  - Simple relation between massive and massless gauge theory amplitudes at large momentum transfers.
    - Massless loop amplitudes are much easier to evaluate.
  - Obtain the result for massive Bhabha scattering using known results for the massless case and for the massive form factor.
    - First independent check of
      - two-loop photonic corrections calculated by Penin '05.
      - electron loop contributions by Bonciani et al. '04.
    - New result for muon loop contribution.
- Same method is applicable to QCD, for example to heavy quark production at large energies.
- Paper to appear; see Becher's talk at Loopfest VI.

Becher and Melnikov (2)

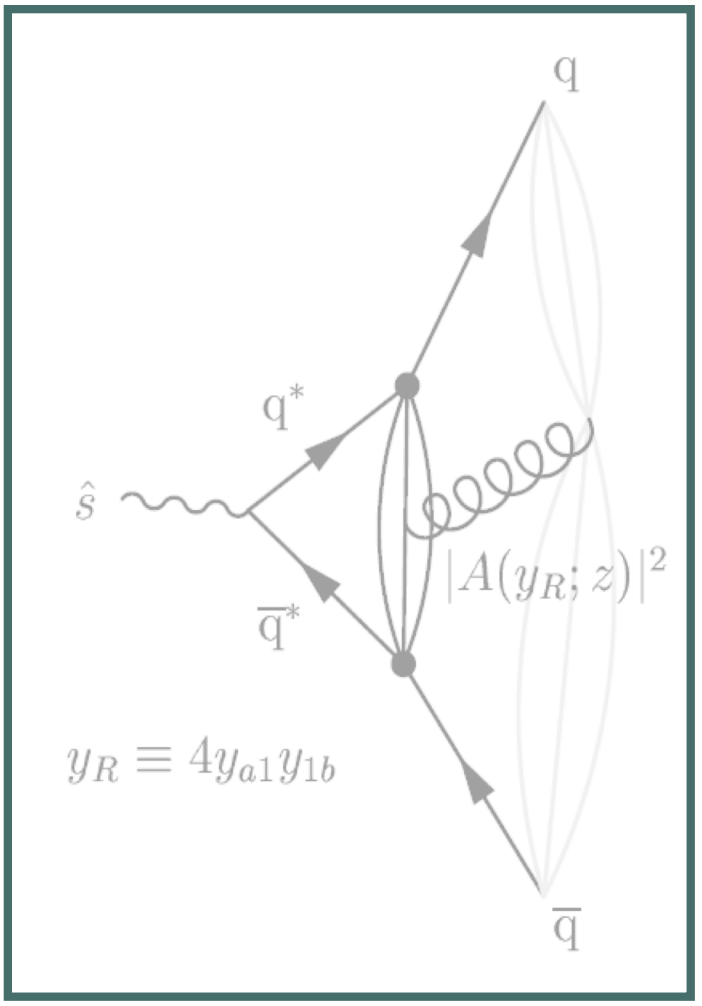
- Size of the two-loop corrections in units of the tree-level cross section ($s = 1\ \mathrm{GeV}^2$).



- Plot assumes that MC generates soft radiation (have set all soft logarithms $\ln(E_\gamma)$ to zero).
- Corrections need to be implemented into MC program.

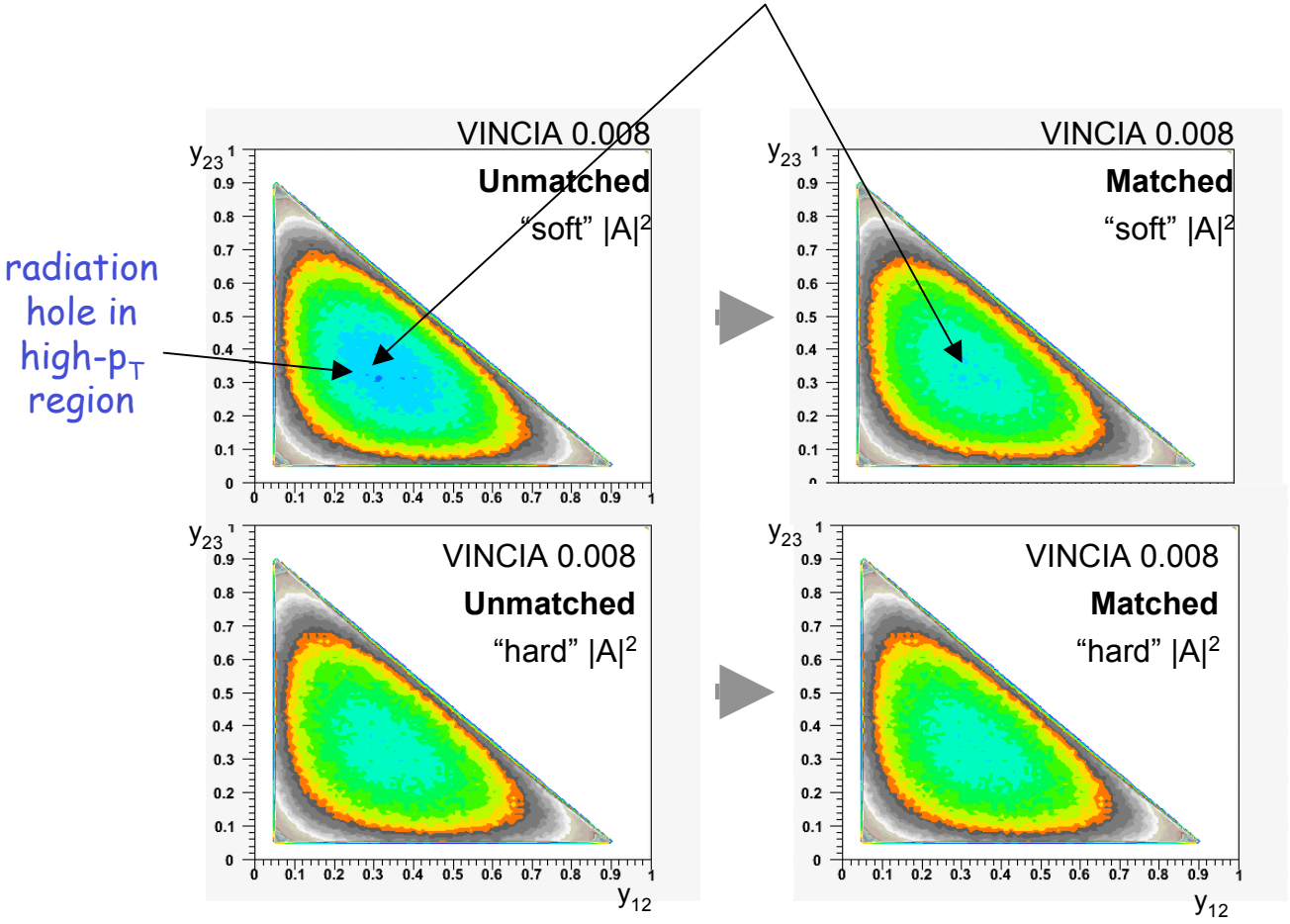
Giele, Kosower, Skands

- VINCIA Parton Showers
  - Antenna functions
  - Exact expansions
  - C++ code
    - Standalone version
    - PYTHIA plug-in version
- Matching at LO, NLO (and framework for N^nLO).
- Numerical implementation
  - General purpose
    - Overhead at startup
    - Fast event generation
  - Flexible



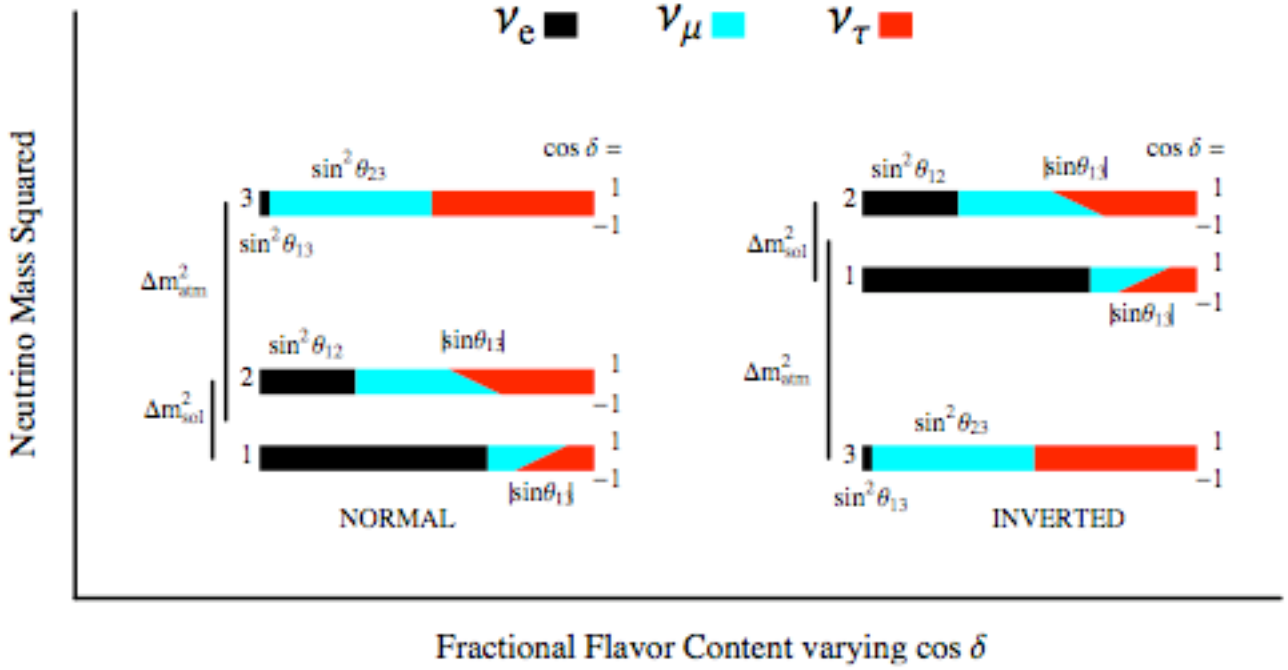
Giele, Kosower, Skands (2)

- Example: $H \rightarrow gg \rightarrow ggg$
  - Unmatched shower varied from "soft" to "hard" : soft shower has "radiation hole". Filled in by matching.



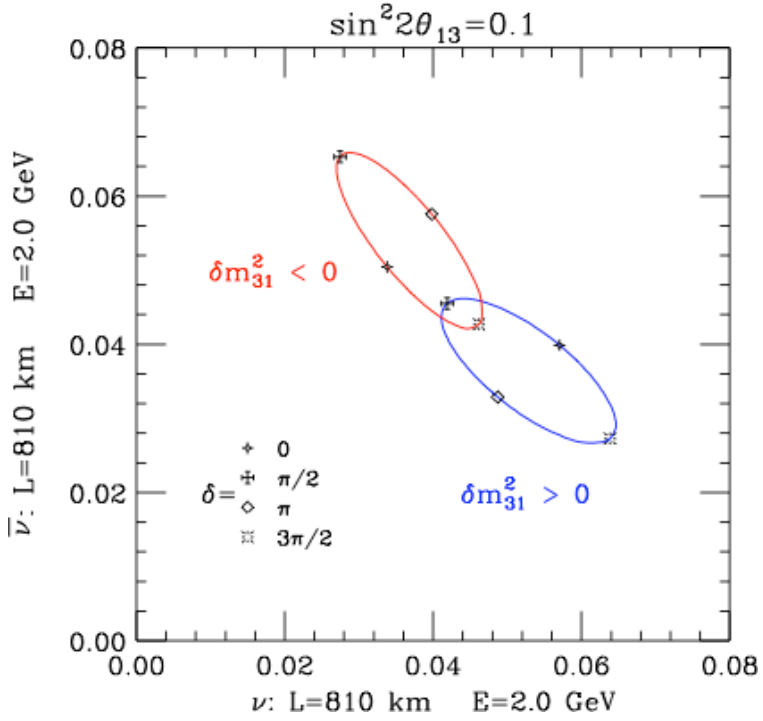
Mena, Nunokawa, Parke

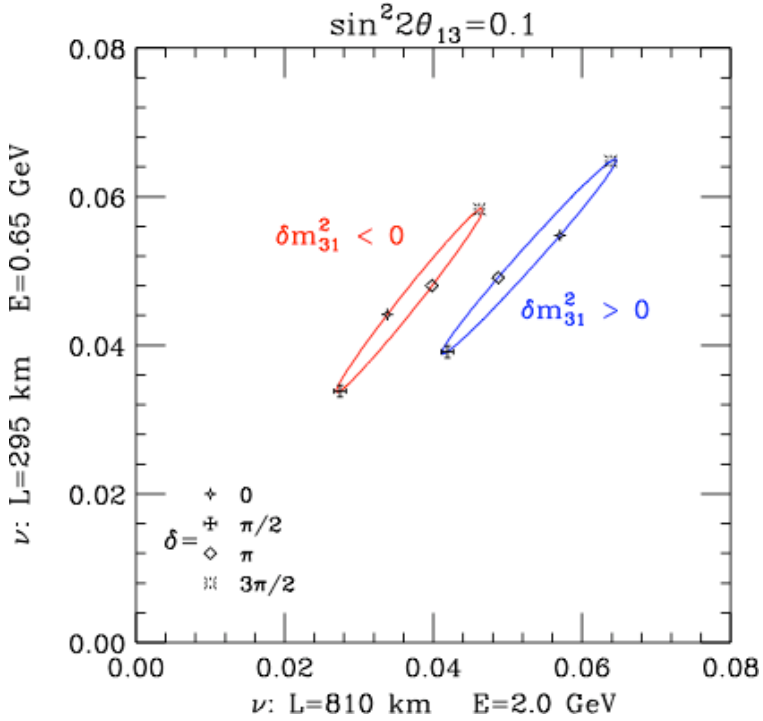
- NOνA and T2K: the Race for the Neutrino Mass Hierarchy [hep-ph/0609011]



- Examine by combining experiments at different *L* but same *E*/*L*, such as NOνA and T2K.

Mena, Nunokawa, Parke (2)





- Left: $P_{810}(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs. $P_{810}(\nu_\mu \to \nu_e)$
- Right: $P_{295}(\nu_\mu \to \nu_e)$ vs. $P_{810}(\nu_\mu \to \nu_e)$
- Cf. talk by N. Saoulidou.

Chen, de Gouvea, Dobrescu

- TeV Scale Seesaw [Phys. Rev. D75 (2007) 055009]
  - Conventional wisdom: small neutrino masses ⇒ GUT-scale physics

$$m \sim \frac{HHLL}{\Lambda} \Rightarrow \Lambda \sim 10^{14}\ \text{GeV}$$

  - Small neutrino mass can also arise from TeV-scale physics
    - SM + non-anomalous U(1)' + 3 ν_R
    - All particles charged under U(1)'
    - U(1)' forbids usual dim-4, dim-5 operators
    - Neutrino mass generated by operators of much higher dimension

$$m \sim \left(\frac{\langle\phi\rangle}{\Lambda}\right)^p \frac{HHLL}{\Lambda} \Rightarrow \text{for large } p: \ \Lambda \sim \text{TeV}, \ \frac{\langle\phi\rangle}{\Lambda} \sim \text{not too small}$$

    - Anomaly cancellations relate U(1)' charges of different particles ⇒ predict flavor mixing
    - Through coupling to Z': can probe neutrino sector at colliders

Chen, de Gouvea, Dobrescu (2)

- Anomaly cancellation condition generally hard to solve: finding rational solutions to cubic equation ⇒ Fermat's last theorem

- "Leptocratic" model with 3 ν_R:
  - Solutions exist for flavor-blind U(1)' charges for quarks & generation dependent charges for leptons
  - Only 2 parameters (a,b) in lepton sector; they describe charge diff
  - Bi-large mixing can arise for some (a,b)
  - Three active neutrinos can either be Dirac or Majorana
  - Three light sterile neutrinos:
    - Two heavier ones: 1 keV ~ 1 MeV
    - One ultra-light one: 10^{-9} eV
    - Active-sterile mixing ≤ 10^{-3} ⇒ may have interesting cosmological and astrophysical implications (pulsar kicks, … etc)

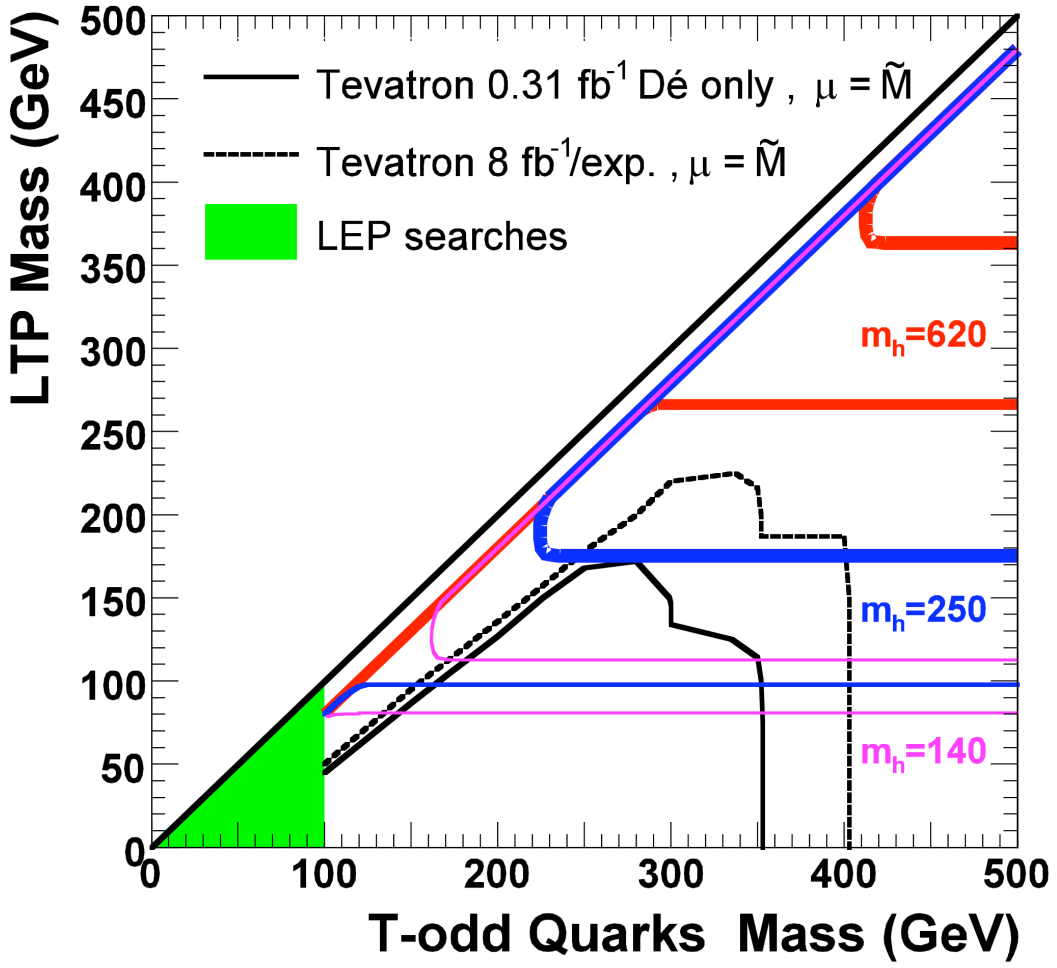
- $M_{Z'}$ < 1 TeV : can be produced at LHC
  - Most models predict 1 for the ratio of BF's; in leptocratic model can differ from 1 (depend on a, which also govern neutrino mixing)

$$\frac{B(Z' \to e^+e^-)}{B(Z' \to \mu^+\mu^-)} = \left(\frac{1+2az}{1-az}\right), \quad z = -\frac{3(a+b)}{a^2+ab+b^2}$$

Carena, Hubisz, Perelstein, Verdier

- T-odd quark pair production in Little Higgs models with T-parity
  - New parity odd vector-like color triplet states
    - pair produced
    - decay to 2j + MET
    - MET is lightest T-parity odd particle (massive neutral gauge boson)
- Implemented in MadGraph, preserving spin correlations
- Calculated production cross sections, studied distributions
- Used full DØ background analysis
  - Realistic study of Tevatron discovery potential
- Placed limit of ~350GeV on new states
- Reach is ~400GeV with $8fb^{-1}$
- Take into account dark matter constraints

Carena, Hubisz, Perelstein, Verdier (3)



Carena, Pontón, Santiago, Wagner

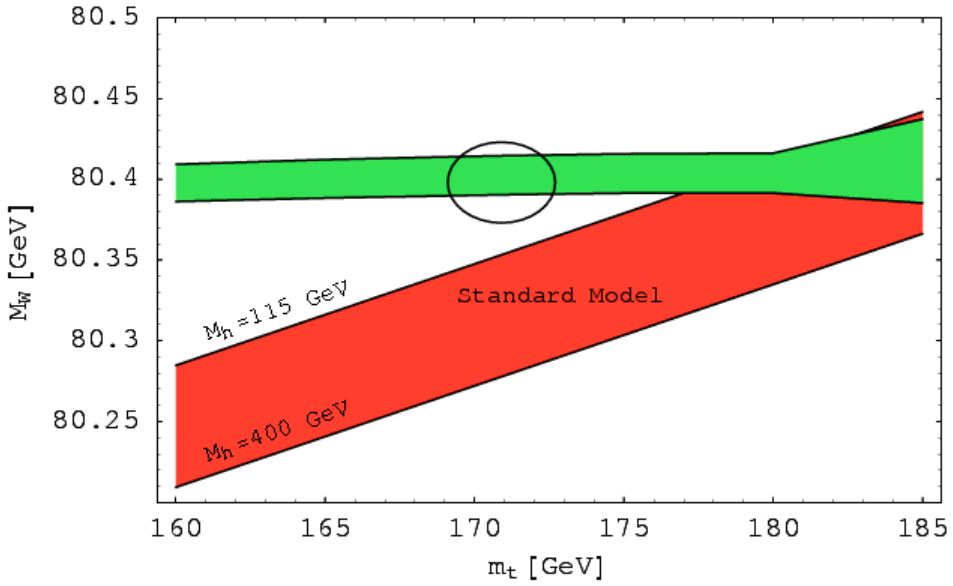
- New Signatures from Warped Extra Dimensions

- Original model (Randall-Sundrum)
  - Solves hierarchy problem
  - Suggests theory of flavor
  - Towers of copies of SM particles
  - Out of LHC reach

- New ideas
  - Compatible with current data
  - Accessible at Tevatron and LHC

- Symmetries: custodial and LR
  - Custodial protects m_W/m_Z
  - Both together protect Zbb coupling

Carena, Pontón, Santiago, Wagner (2)



- Model agrees with recent measurements of m_t, m_W
- Masses:

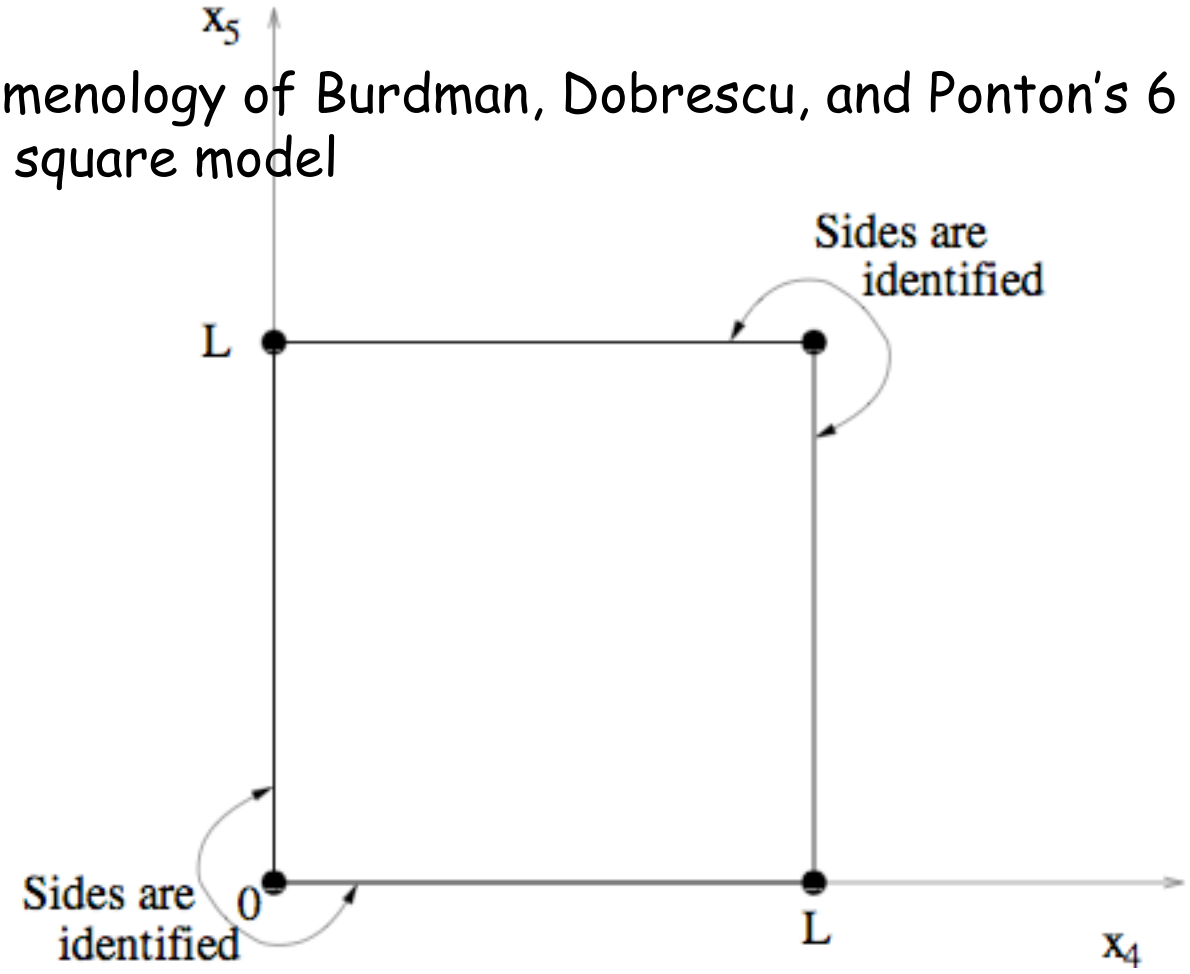
$$M_{KK}^{gauge} \sim 2.5 - 3.5\ \text{TeV}$$

$$M_{KK}^{fermions} \geq 300\ \text{GeV}$$

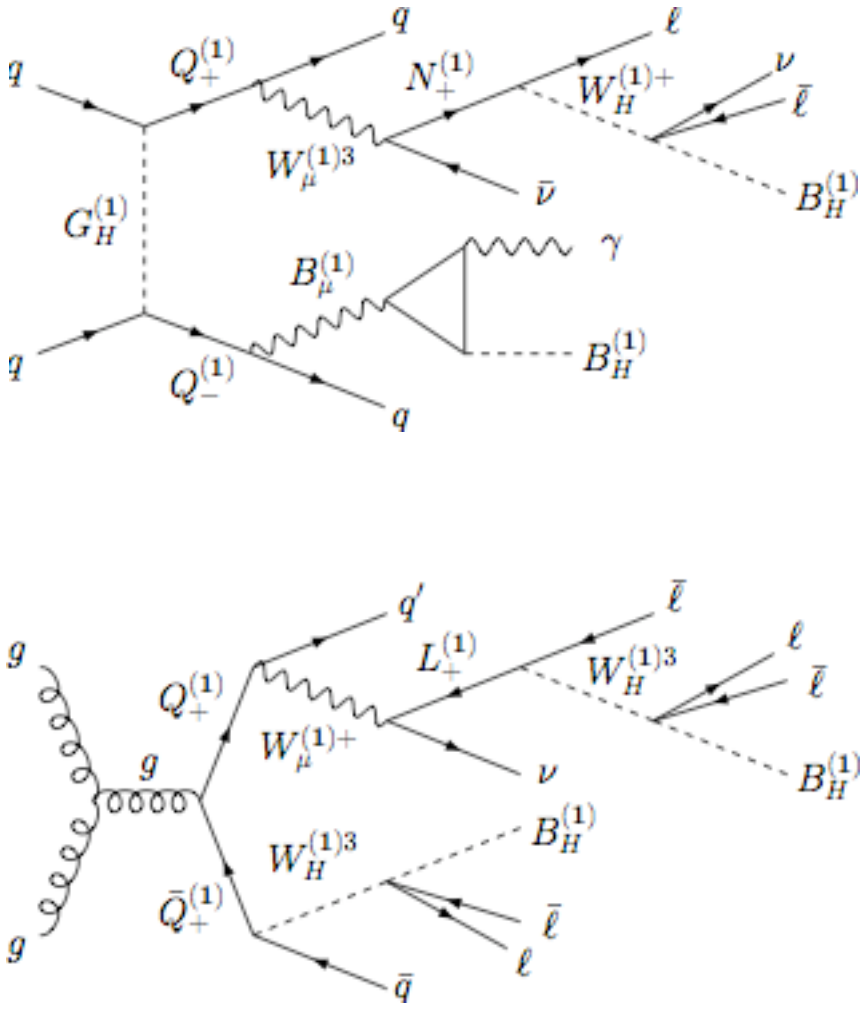
- Exotically charged quarks, $Q_{5/3}$ -> $W^+W^+b_{-1/3}$

Dobrescu, Kong, Mahbubani

- Leptons and photons at the LHC: Cascades through spinless adjoints [hep-ph/0703231]
- Phenomenology of Burdman, Dobrescu, and Ponton's 6 UED chiral square model



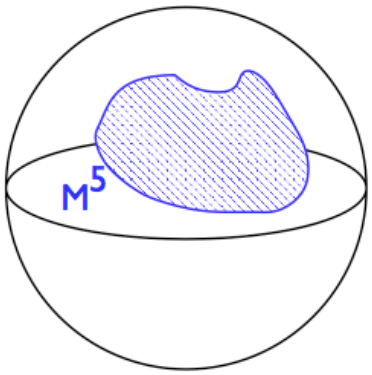
Dobrescu, Kong, Mahbubani (2)



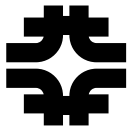
Hill & Hill

- Topological Interactions of Higgs Bosons [hep-ph/07010444]
  - Consideration of composite Higgs models leads to questions
    - What is the most general 4-d Lagrangian for Goldstone bosons?
    - What is the most general low-energy description of (bound states of) strongly-coupled fermions?

- Constraints of topology and symmetry constrain former: index p (cf. N_c in WZW for pions).

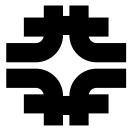


- Topological action for bosons ⇔ chiral fermion interpretation.



Hill & Hill (2)

- Physical implications
  - "Little Higgs" and "composite Higgs" are points of view
    - Interaction induced by anomalies always there
  - Identity of (putative) Higgs bosons tied up in these interactions.
  - Unless $p = 0$, T parity merges with spatial inversion to form "the" parity. Analogous to pion parity in QCD.



Conclusions

- Service
  - Theorists at Fermilab are actively engaged in many activities sustaining and planning the future of particle physics.
- Research
  - The senior theorists at Fermilab are acknowledged experts in many subfields of particle physics.
- Education
  - Fermilab's Theoretical Physics Department is a training ground for many of the best young theorists in the world, focusing on those with a keen interest in experimental and observational results, aka physics!