# Argonne National Laboratory
# HEP Theory Group

## Overview of the Group Activities

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KICP and EFI, University of Chicago

DOE Site Visit, Argonne, September 23, 2009

# Composition of the Group

- Theory Group has five staff members:

  E. Berger (Collider physics, QCD, BSM)
  G. Bodwin (QCD, Quarkonium physics)
  I. Low (Collider Physics, BSM, Cosmology)
  C. Zachos (Abstract Physics)
  C. Wagner (Collider Physics, BSM, Cosmology)

- The group also includes a few postdoctoral fellows and students.

# Activities

- Theory group has been very strong in the areas related to phenomenology of particle physics, which are our main research priority : Collider physics, QCD, Higgs physics, heavy quarkonia and beyond the standard model phenomenology.

- The group has also produced relevant articles in the areas of cosmology and astroparticle physics, in particular on the questions of dark-matter and baryogenesis.

- The group has also contributed to fundamental physics and to non-perturbative field theory.

# New Appointments

- The most important recent news, since the Theory review last summer, has been the departure of Tim Tait.
- Even before Tim's decision to leave, we had already inquired a well established young physicist, about his possible interest in joining the group, and received a positive response. The DOE was informed of this development. This person is planning to spend six months at Argonne in the coming year, starting in January,
- At the same time, we plan to conduct an open search for a new joint faculty (replacement for Tim Tait).
- Bringing additional theorists, with broad phenomenological background, who can interact efficiently with experimentalists and make an impact in the LHC era is our highest priority.

# Postdocs

- The HEP Theory Group has been very successful in the supervision of postdocs.
- Most of the recent Argonne postdocs have found excellent positions and carried successful careers after their stay at Argonne
- Notable recent cases are Csaba Balazs, Puneet Batra, John Campbell, Cheng-Wei Chiang, Ayres Freitas, Xavier Garcia i Tormo, Jay Hubisz, David E. Kaplan, Michael Klasen, Jungil Lee, Irina Mocioiu, Pavel Nadolsky, Geraldine Servant, Zack Sullivan, Tim Tait and Alexander Velytsky.

- Two postdocs supported by base funding this year (Chris Jackson and Seth Quakenbush). Two additional postdocs, who hold joint positions with Northwestern, supported by ALD start up packages, (Jamie Gainer and Gabe Shaughnessy) and one who holds a joint position with the University of Chicago, supported by JTI funds, (Qing-Hong Cao).
- All current postdocs work on issues of hadron collider physics and/or beyond the SM phenomenology.

# Students

Carlos Wagner, holds a joint tenured position with the University of Chicago. Ian Low holds a joint position with Northwestern.

Graduate students from the UofC have been working regularly with members of the Theory Group. They all carried research careers in HEP physics after graduation :

David Morrissey, Ph.D. 2005, (tenure-track position at TRIUMF),
Arjun Menon, Ph.D. 2007 (postdoc at IIT),
Anibal Medina, Ph. D. 2008 (postdoc at UC Davis)
Jing Shu, Ph.D. 2008 (postdoc at IPMU, Tokyo)
Nausheen Shah, Ph.D. 2009 (postdoc at Fermilab).

PhD students Kunal Kumar, Shashank Shalgar, and Roberto Vega-Morales, from NWU have been involved in theory research, and have been supported by laboratory funds provided by the ALD as part of a start-up agreement. Kumar and Vega-Morales have been working on manifestation of top compositeness at colliders and Shalgar on Higgs physics.

Patrick Draper, a UofC graduate student, is now working at Argonne and at UofC, and will be supported in the coming year by an University of Chicago Fellowship. He has been concentrating his research on Higgs Physics searches at the Tevatron and at the LHC.

# Organization of Workshops and Conferences

- The group has organized seven international workshops at the Argonne HEP Division in the last five years. Subjects included

- Higgs, Supersymmetry, extra dimensions, 2004 and 2005 (E. Berger and C. Wagner)
- QCD in extreme environments, 2004, (D.K. Sinclair)
- Symmetry Breaking Dynamics, 2007 and 2009, (jointly with Chicago) (C. Zachos)
- Collider Physics, 2006 and 2009, (jointly with IIT) (E. Berger, I. Low and C. Wagner)
- Quarkonia, planned for 2010, (G. Bodwin)

- Apart from these local workshops, members of the group has help in the organization of numerous workshops and conferences worldwide and has participated in several national DOE and NSF committees.
- All these activities have greatly enhanced the visibility of the Theory group and of the HEP Division at Argonne.

# Research Activities

# *Ed Berger*

Hadron Collider Phenomenology (Tevatron, LHC, RHIC) with emphasis on quantitative QCD predictions of signals and standard model backgrounds – Recent Examples:

1. Trileptons and the Search for Supersymmetry

   with Zack Sullivan, Phys Rev. D78:034030, 2008 and e-Print: arXiv:0909.2131

   - $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ ( "Golden" SUSY channel) vs. leptons from SM Sources. Emphasis on the importance of isolated leptons from heavy flavor decays, $b \to lX$

2. NLO Cross Sections for New Heavy Quark and Lepton Production at three LHC Energies

   with Qing-Hong Cao, ANL-HEP-PR-09-93, e-Print: arXiv:0909.

3. Longitudinal Parity-Violating Asymmetry in Hadronic Decays of $W$'s in Polarized Proton Collisions at RHIC

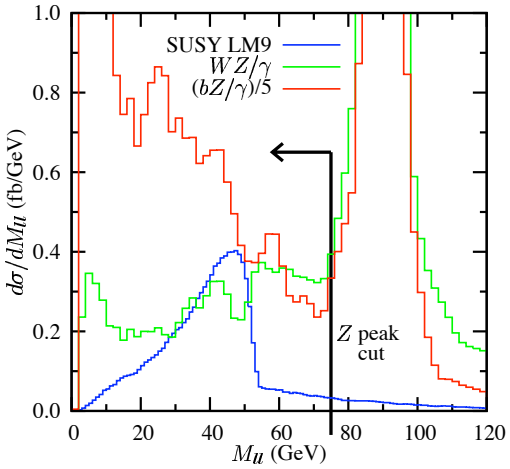
   with Pavel Nadolsky, Phys.Rev. D78:114010, 2008

# Trileptons: SUSY & SM at CMS w/ 30 fb$^{-1}$

| Channel | $N^l = 3$, NoJets | $M_{ll}^{\rm OSSF} < 75$ GeV |
|---|---|---|
| LM9 | 248 | 243 |
| LM7 | 126 | 123 |
| LM1 | 46 | 44 |
| $WZ/\gamma$ | 1880 | 538 |
| $t\bar{t}$ | 1540 | 814 |
| $tW$ | 273 | 146 |
| $t\bar{b}$ | 1.1 | 1.0 |
| $bZ/\gamma$ | 14000 | 6870 |
| $cZ/\gamma$ | 3450 | 1400 |
| $b\bar{b}Z/\gamma$ | 8990 | 2220 |
| $c\bar{c}Z/\gamma$ | 4680 | 1830 |
| $b\bar{b}W$ | 9.1 | 7.6 |
| $c\bar{c}W$ | 0.19 | 0.15 |

Analysis cuts:

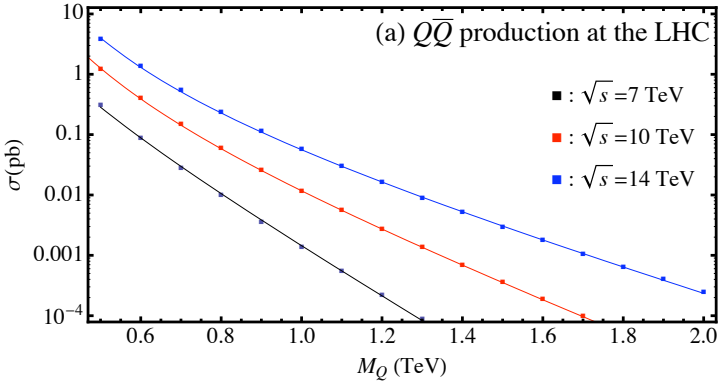
- 3 leptons
- No jets ($E_{Tj} > 30$ GeV)
- Remove $Z$ peak (demand $M_{ll}^{\rm OSSF}) < 75$ GeV

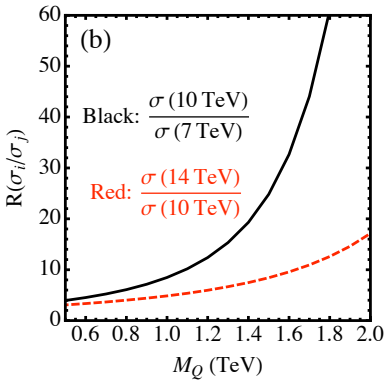


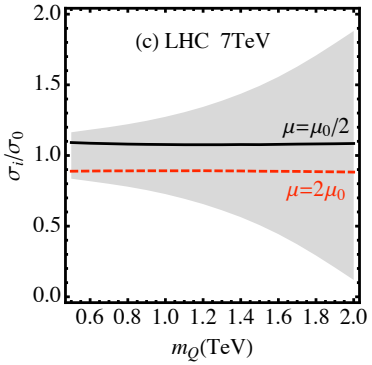

$Z$+heavy flavor decays are $10\times$ $WZ/\gamma + t\bar{t}$!

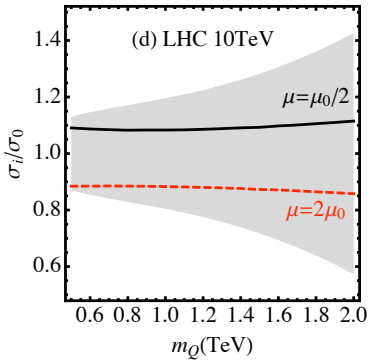
# NLO $Q\bar{Q}$, Single Q, and Exotic Lepton Cross Sections at LHC

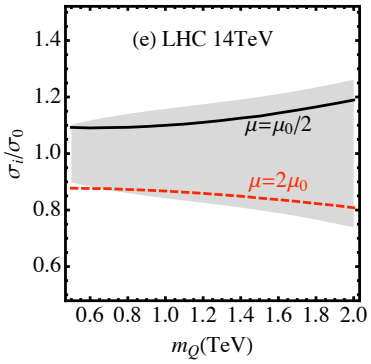
- Heavy quarks and leptons expected in various models of New Physics
- NLO $Q\bar{Q}$ cross sections vs $m_Q$ at 3 LHC energies plus full exploration of PDF uncertainties (shaded bands)




- NL predictions also for production of a single heavy (T) quark, and for exotic heavy leptons

# New Method for Computing NLO Quarkonium Rates to All Orders in $v$

G.T. Bodwin (ANL), H.S. Chung (Korea U.), J. Lee (Korea U.), C. Yu (Korea U.)

Phys. Rev. D **79**, 014007 (2009)

- Computation of quarkonium decay and production rates requires matching of amplitudes between full QCD and Nonrelativistic QCD (NRQCD).
- At one-loop level, the matching calculation at all orders in the heavy-quark velocity $v$ is daunting.
  - Requires operators and coefficients of all orders in $v$.
  - Requires one-loop renormalizations of operators by interactions of all orders in $v$.
- Instead, compute the NRQCD part of the matching by starting with full QCD.
  - Carry out integrations over the time component of the loop momentum by the contour method.
  - Expand integrands in powers of momenta divided by $m_c$.
  - Discard scaleless integrals in dimensional regularization.
  - Sum the resulting expression to all orders in $v$.
- Application to the heavy-quark electromagnetic current
  - Important for decay and production of quarkonium through a virtual photon ($e^+e^-$ colliders).
  - The resulting one-loop expression for the EM current to all orders in $v$ is very compact.
  - The method recovers all of the known fixed-order results.

# Factorization Theorems for QCD

- Factorization theorems are the cornerstone of all perturbative calculations of hard-scattering cross sections and decay rates in QCD.
- They separate high-momentum, perturbative processes (parton scattering) from low-momentum, nonperturbative processes (parton distributions).

## Factorization Theorems for Exclusive Quarkonium Production

G.T. Bodwin (ANL), J. Lee (Korea U.), X. Garcia i Tormo (ANL)
Phys. Rev. Lett. **101**, 102002 (2008)

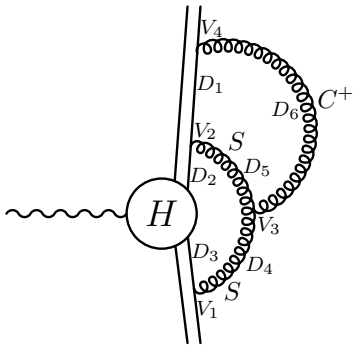
- Bodwin and collaborators established factorization theorems for
  - $e^+e^- \to$ charmonium $+$ charmonium,
  - $B \to$ light meson $+$ charmonium.
- Hold to all orders in $\alpha_s$ up to corrections of order
  - $(m_c v^2)^2/s$ for $e^+e^-$ annihilation to two $S$-wave charmonium,
  - $m_c v^2/m_b$ for $B$-meson decays to an $S$-wave charmonium.
- These are the first factorization theorems to be proven for quarkonium production.

# Closing a Loop-Hole in Proofs of Factorization Theorems

G.T. Bodwin (ANL), J. Lee (Korea U.), X. Garcia i Tormo (ANL)

arXiv:0903.0569 [hep-ph]

- Existing proofs of factorization theorems, both traditional graphical proofs and proofs in soft-collinear effective theory (SCET), overlook a crucial fact of QCD:
  Low-energy collinear gluons can couple to soft gluons.




| | | |
|---|---|---|
| volume of integration | $\sim$ | $Q^8\epsilon_S^4(\epsilon^+)^4(\eta^+)^4$ |
| $V_1\cdot V_2$ | $\sim$ | $Q^2$ |
| $V_3\cdot V_4$ | $\sim$ | $\epsilon_S Q^2$ |
| $D_1$ | $\sim$ | $1/[Q^2\epsilon^+(\eta^+)^2]$ |
| $D_2$ | $\sim$ | $1/(Q^2\epsilon_S)$ |
| $D_3$ | $\sim$ | $1/(Q^2\epsilon_S)$ |
| $D_4$ | $\sim$ | $1/(Q^2\epsilon_S^2)$ |
| $D_5$ | $\sim$ | $1/[Q^2(\epsilon_S^2+\epsilon_S\epsilon^+)]$ |
| $D_6$ | $\sim$ | $1/[Q^2(\epsilon^+)^2(\eta^+)^2]$ |

- Bodwin and collaborators pointed out this fact and devised new all-orders methods to deal with it in factorization proofs.
- They demonstrated the new methods by proving to all orders in $\alpha_s$ that the traditional factorization formula holds for $e^+e^- \to$ light meson $+$ light meson.
- This new understanding of the nature of factorization may be important in removing singularities from calculations in QCD at NNLO and higher.

# Ian Low's activities since the last review:

- "*Implications of the Higgs Discovery in the MSSM Golden Region*" [arXiv:0901.0266] **JHEP 0904:091,2009**

  Work with Shashank Shalgar (graduate student at NU).

- "*Model Independent Constraints Among the Wtb, Zbb, and Ztt Couplings*" [arXiv:0907.2191]

  Work with E. Berger (ANL) and Q.-H. Cao (postdoc at ANL/Chicago).

- "*Theoretical Constraints on the Higgs Effective Couplings*" [arXiv:0907.5413]

  Work with R. Rattazzi (EPFL, Lausanne) and A. Vichi (graduate student at EPFL).

"*Model Independent Constraints Among the Wtb, Zbb, and Ztt Couplings*"
[arXiv:0907.2191]

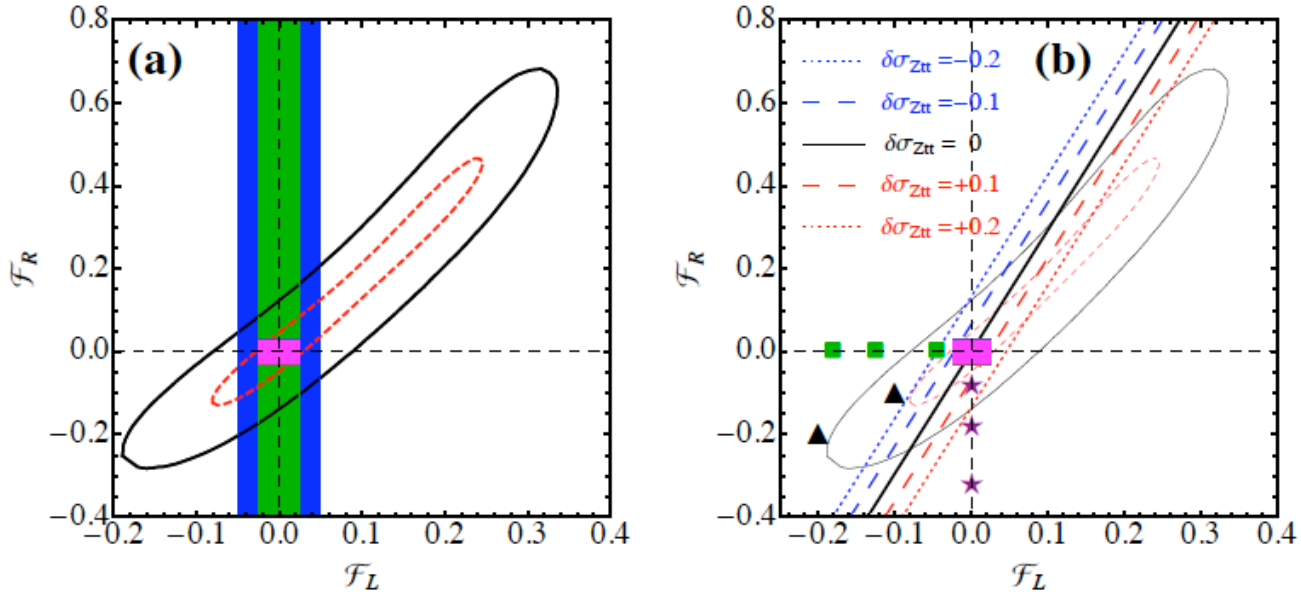



FIG. 7: (a): Projected 68.3% C.L. bounds on the anomalous $Zt\bar{t}$ coupling from the LHC with an integrated luminosity of 300 $\text{fb}^{-1}$(solid) and 3000 $\text{fb}^{-1}$(dashed) and from a LC ($\sqrt{s} = 500\,\text{GeV}$) with an integrated luminosity of 100 $\text{fb}^{-1}$ (magenta area). The expected accuracy of the single top quark production cross section is represented by vertical bands, green (blue) for $\delta\sigma_t < \pm 5(\pm 10)\%$. (b): Various NP model predictions, where box (star, triangle) denotes the left-handed $t'$ (right-handed $t'$, sequential fourth generation) model, respectively. See text for details.

## CHERN SIMONS TOPOLOGICAL INTERACTIONS ACROSS DIMENSIONS

▶ Chern-Simons interactions in 5d

$$\mathcal{L}_{CS} = \frac{N_c\ \epsilon^{ABCDE}}{24\pi^2}\,\mathrm{Tr}\Big(A_A\partial_B A_C\partial_D A_E - \frac{3i}{2}A_A A_B A_C\partial_D A_E - \frac{3}{5}A_A A_B A_C A_D A_E\Big)$$

encode holographically physical (safe, flavor-chiral) anomalies of our familiar world: the 4d Standard Model and its effective gauged chiral models [C T Hill & Zachos, Ann Phys **323** (2008) 3065-3073]. May also lead to new dimensional deconstruction-based phenomena accessible at colliders.

⊛ However, they **also** model, in a remarkable **3d superconformal** lagrangian model (Bagger-Lambert-Gustavsson) with a finite number of fields, the dual to two M2 branes superposed on an orbifold $R^8/Z_2$ in M-theory—the strong-coupling limit of quantum gravity.

⫛ **This CS interaction is predicated on Ternary algebraic structures**, Nambu Brackets under a very stringent condition (FI). Finite-dimensional exemplars of such algebras satisfying FI are provably **few** (essentially **one**).

★ Still, a **New infinite dimensional ternary algebra** was discovered, based on the Witt algebra, in [Curtright, Fairlie, & Zachos, Phys Lett **B666** (2008) 386-390],

$$[Q_k, Q_m, Q_n] = (k-m)\,(m-n)\,(k-n)\;\; R_{k+m+n}\;\;,$$

$$[Q_p, Q_q, R_k] = (p-q)\;\; \Big(Q_{k+p+q} + s\;\, k\;\, R_{k+p+q}\Big)\;\;,$$

$$[Q_p, R_q, R_k] = (k-q)\;\; R_{k+p+q}\;\;, \qquad [R_p, R_q, R_k] = 0\;\;,$$

with $s$ a parameter. Only for $s = \pm 2i$ is the FI satisfied.

↻ This intriguing compliance with FI was finally **fully understood** in an unexpected isomorphic correspondence with Nambu's Classical Brackets (**unrelated**, in principle!) in [Curtright, Jin, Mezincescu, Fairlie, & Zachos, Phys Lett **B675** (2009) 387-392].

■ These results were further extended, heuristically, to cover several other concrete cases: in fact, **all known** FI-compliant Ternary Algebras.
$\rightsquigarrow$ Applications to new lagrangian M2-model building, and consistency checks?

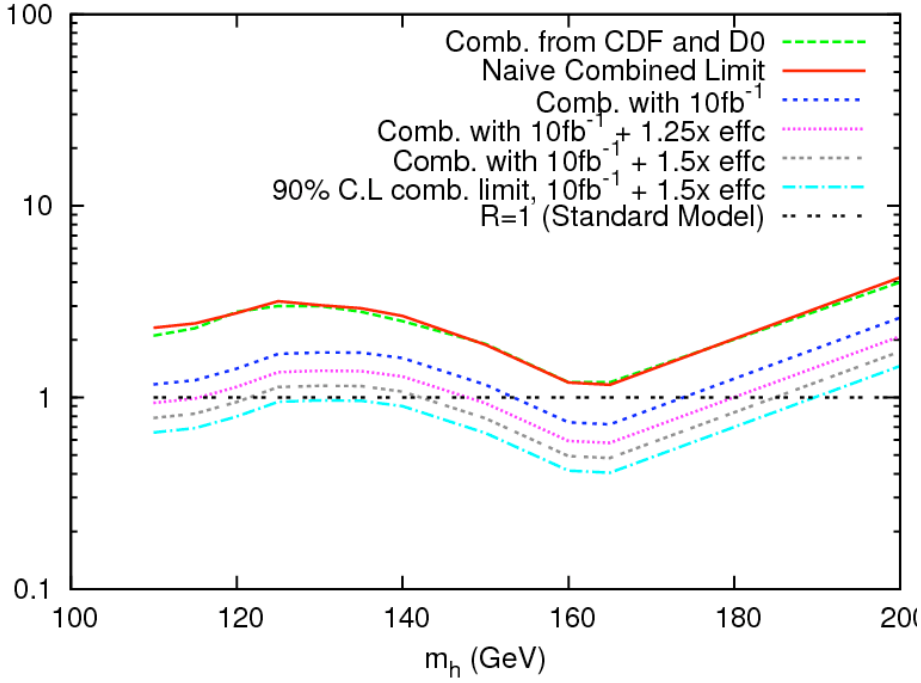
# C. Wagner articles since last Theory Review

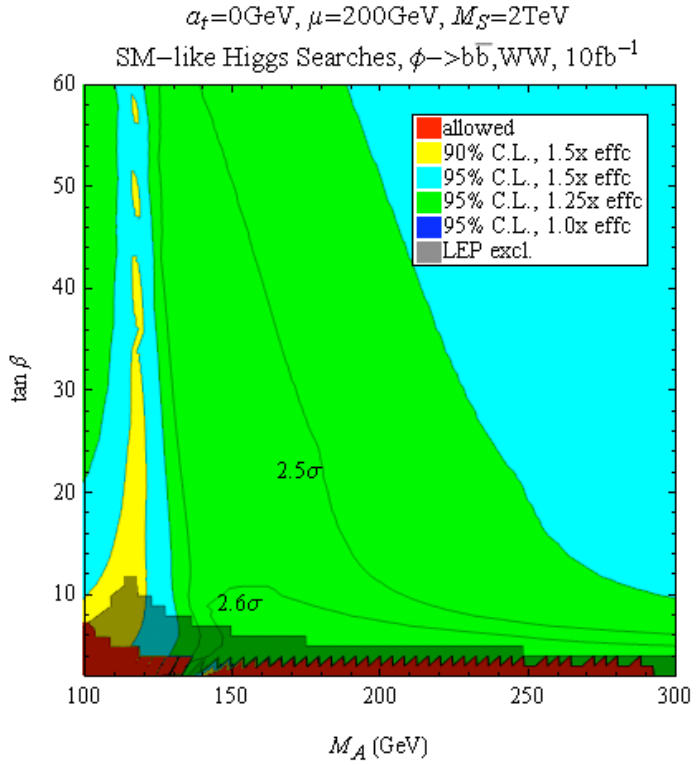
- Light stop Searches at the LHC in events with one hard jet and Missing Energy, with M. Carena and A. Freitas, JHEP, 0810:109, 2008
- Baryogenesis window in the MSSM, with M. Carena, M. Quiros and G. Nardini, Nucl.Phys.B812:243-263,2009
- Minimal Flavor Violation and the scale of Supersymmetry Breaking, with M. Carena and A. Menon, Phys. Rev. D79:075025, 2009
- Gauge-Higgs Unification, Neutrino Masses and Dark Matter in Warped Extra Dimensions, with M. Carena, A. Medina and N. Shah, Phys. Rev. D79:096010, 2009
- Family Non-Universal Z' and b to s transitions, with V. Barger, J. Jiang, P. Langacker, L. Everett and T. Liu, Phys. Rev. D80:055008, 2009 and arXiv: 0906.3745
- Heavy Higgs and Light Sneutrino in the MSSM with enhance SU(2) D-terms, with A. Medina and N. Shah, Phys. Rev. D80: 015001, 2009
- Prospects for MSSM Higgs Searches at the Tevatron Collider, with P. Draper and T. Liu, Phys. Rev. D80:035025, 2009.

# Prospects for Higgs Searches at the Tevatron in the SM and in the MSSM

T. Liu, P. Draper and C.W.'09

Each Tevatron experiment is expeted to obtain about $10\ \mathrm{fb}^{-1}$ of good quality data.
Improvements in efficiencies in all channels are expected.




With modest increases in efficiencies, most of the Higgs range consistent with precision measurements can be probed.
Similarly, the minimal mixing scenario of the MSSM may be probed.
Other benchmark scenarios, and impact of non-SM Higgs searches also studied.

# Conclusions

- Theory Group has been productive in a very broad range of subjects, including collider, quarkonia and beyond the standard model physics, as well as more formal subjects.
- The group has close ties with most nearby Universities as well as other research institutions in the Chicago area, including Univ. of Chicago, Northwestern, UIC, IIT and Fermilab.
- It has been extremely successful in the supervision of postdocs and students and has organized several well attended workshops and conferences locally and worldwide.
- We seek to strengthen our collider physics activities. Our goal is to attract broad particle physics phenomenologists with expertise in collider physics, who can make an impact in the coming LHC era.
- An open search for a joint faculty with NWU will be conducted.