
CMS: Theory efforts & synergies

CMS theory overview

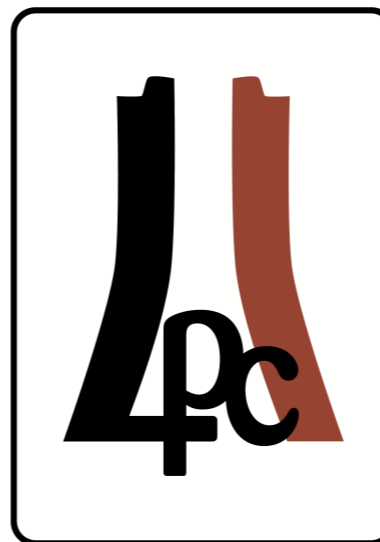
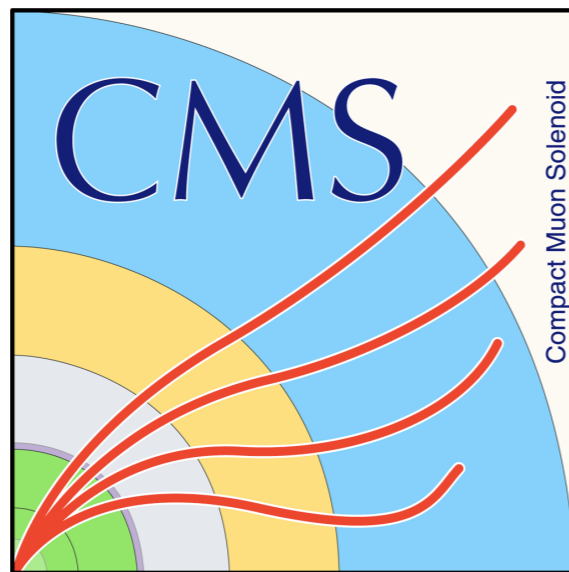
- Theory groups have core strengths in several areas directed towards LHC physics
- Strong record in marking the path for experimental studies, generating exciting theoretical ideas, and confronting them to LHC data
- Nurture productive collaborations and discussions with LPC members & visitors
- Provide exciting venue for postdocs, students & visitors

perturbativ
e QCD

Standard-Model
phenomenology

BSM model
building

lattice QCD



Laboratory activities

- Theoretical Physics Department organizes and hosts weekly Joint Experimental Theoretical Physics (“Wine & Cheese”) seminar
 - Lab tradition provides important avenue for communication between experimenters and theorists.
- Fermilab Theorists regular participants in the LPC physics Forum
 - Informal gathering in which one theorist and one experimentalist give blackboard presentations to members of both groups.
- **Dobrescu & Harnik** co-organizers of LPC’s Topic of the Week seminar.
 - Brings regular stream of theory speakers to the LPC, and has become a de-facto joint Theory–CMS seminar.
- Fermilab theorists are regular consultants to experimenters, both lab scientists and users, in all cross-cut areas including LHC physics.
- **Campbell & Ellis** regularly present their work at CMS meetings.

Community leadership

- **Fermilab theorists authors on 18 Snowmass reports.** In particular:
 - **Campbell** co-convenor of Snowmass QCD WG.
 - **Van de Water** co-convenor of Lattice Field Theory/Computing Frontier WG, and co-convenor of Lattice QCD task force of the Quark Flavor/Intensity Frontier WG
- **Fermilab theorists active in several LHC physics working groups.** In particular:
 - **Campbell, Carena & Ellis** co-authored 3rd Yellow Report of Higgs X-section WG
 - **Carena** involved in LHC HXS BSM Higgs WG
- **Fermilab theorists serve on numerous domestic and international scientific councils and advisory boards.** In particular:
 - **Carena** serves on Physics Research Committee at DESY
 - **Ellis** served on CERN Scientific Policy Committee.
- **Eichten & Kronfeld** Quarkonium WG conveners.
- **Campbell & Ellis** co-authored review papers on perturbative QCD and have multiple contributions to Les Houches WG reports.
- **Carena & Dobrescu** authors of PDG Higgs, W' , and Z' -boson chapters.

Workshops and schools

- Fermilab theorists organized numerous conferences and workshops related to LHC physics including:
 - Campbell co-organizer of QCD@LHC in 2012.
 - Campbell, Fox & Harnik organized a Chicago 2012 Workshop on LHC Physics
 - Carena co-organized Chicago 2012 workshop series on LHC; 2013 Aspen workshop on “Dark Matter in Galaxies, the LHC and Direct and Indirect Searches”; 2013 KITP conference on “LHC: the first part of the Journey” and workshop “Exploring TEV Scale New Physics with LHC data.”
 - Harnik (+ LPC experimentalists + university theorists) organizing 2015 Fermilab workshop “MC4BSM”
 - Kronfeld, Mackenzie (chair), & Van de Water co-organized the 2014 “Lattice Meets Experiment” workshop. Topics included heavy-quark masses & strong coupling for precision Higgs measurements.
 - Kronfeld organizing 2015 KITP workshop on connection between lattice gauge theories and physics beyond the standard model.
 - RA Neil organized “Lattice QCD Meets Experiment 2013: Beyond the Standard Model” on lattice-gauge-theory calculations for nonperturbative BSM physics.
- Fox (2012) and Campbell (2014) chairs of Fermilab–CERN Hadron Collider Physics Summer School. Dobrescu, Carena, & Kronfeld chairs in previous years.
 - Provide training in theoretical and experimental aspects and draw students from both areas. Recent lecturers include Campbell (2010/12, QCD/MC generators), Kronfeld (2012, LQCD), Quigg (2014, SM), Van de Water (2014, LQCD).
- Dobrescu Program Director of the 2013 TASI summer school.

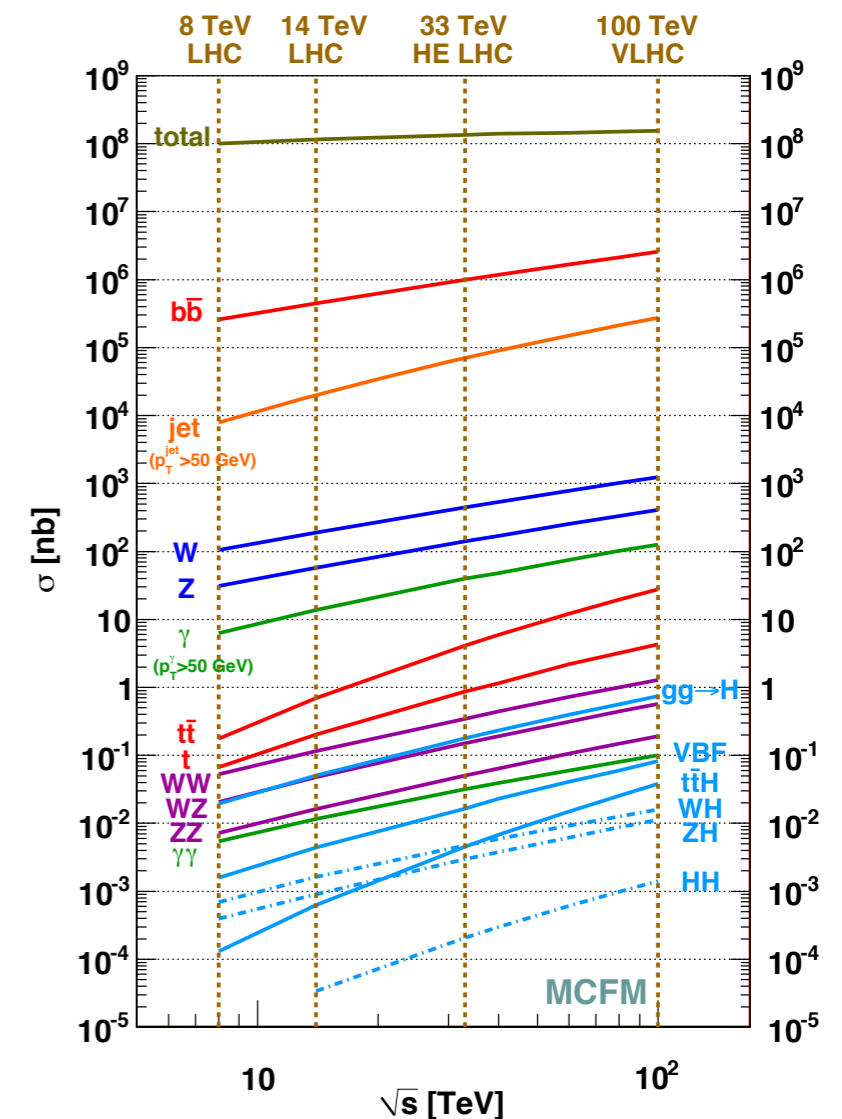
QCD tools and calculations for the LHC

Perturbative QCD

- Main focus on the formulation and execution of practical calculations in perturbative QCD [Campbell, Ellis, Giele + RAs].
 - Theoretical calculations at next-to-leading order (NLO), that enable tests of Standard Model cross sections, confidence in background predictions and precision measurements.
 - Systematic improvement of parton shower predictions.
 - Particular interest in calculations that aid the ATLAS and CMS experimental programs, especially the identification and characterization of the Higgs boson.
 - Development and distribution of tools for precision phenomenology.
- Diverse other areas in QCD:
 - Strong dynamics of quarkonium systems [Eichten], hadron spectroscopy [Quigg], top-quark spin correlations and constraints on stop quarks [Parke].

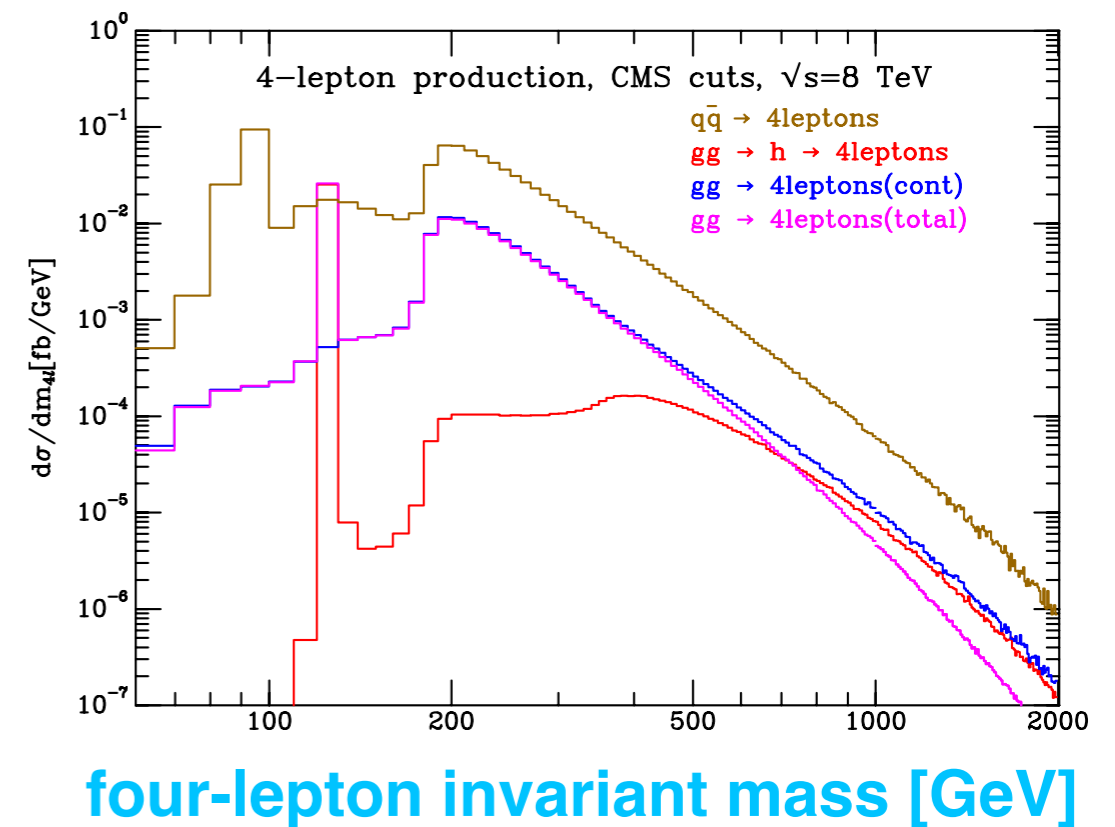
Recent scientific highlights: *tools for the LHC*

- **Campbell & Ellis** develop next-to-leading order parton level code MCFM that is widely used both by the LHC experiments and as a catalyst for other developments in the theoretical community.
 - Provides analytic expressions for matrix elements that enable fast and efficient evaluation.
 - Directly incorporated by CMS into Matrix Element Method algorithms for distinguishing Higgs-boson events from SM background.
- **Giele** contributes to development of Monte Carlo program VINCIA that is the long-term successor to Pythia. Provides systematic improvements to parton-shower description of collider processes.
- **RA efforts also strongly aligned with local CMS expertise:** NLO predictions for dark matter mono-jet or mono-photon production [Fox,Williams], first direct limits on anomalous top-Z couplings from CMS ttZ data [Röntsch], calculation of threshold production of the Higgs boson at N³LO [Furlan et al].



Recent scientific highlights: *Higgs properties*

- **Fermilab theorists contributed significantly to the 2012 Higgs boson discovery**, with multiple papers from the theory group cited throughout the ATLAS and CMS searches and in the discovery paper.
- Recently, **Campbell & Ellis** performed precision studies of the production of Higgs boson decays into Z and W boson pairs far above the resonance region.
 - Provided code used by ATLAS and CMS to (with assumptions) directly bound the width of the Higgs boson, improving previous limits by more than two orders of magnitude.
 - Will reduce theoretical uncertainties and bias in these analyses by extending calculations to higher orders and exploiting complementarity of vector-boson-fusion channels.

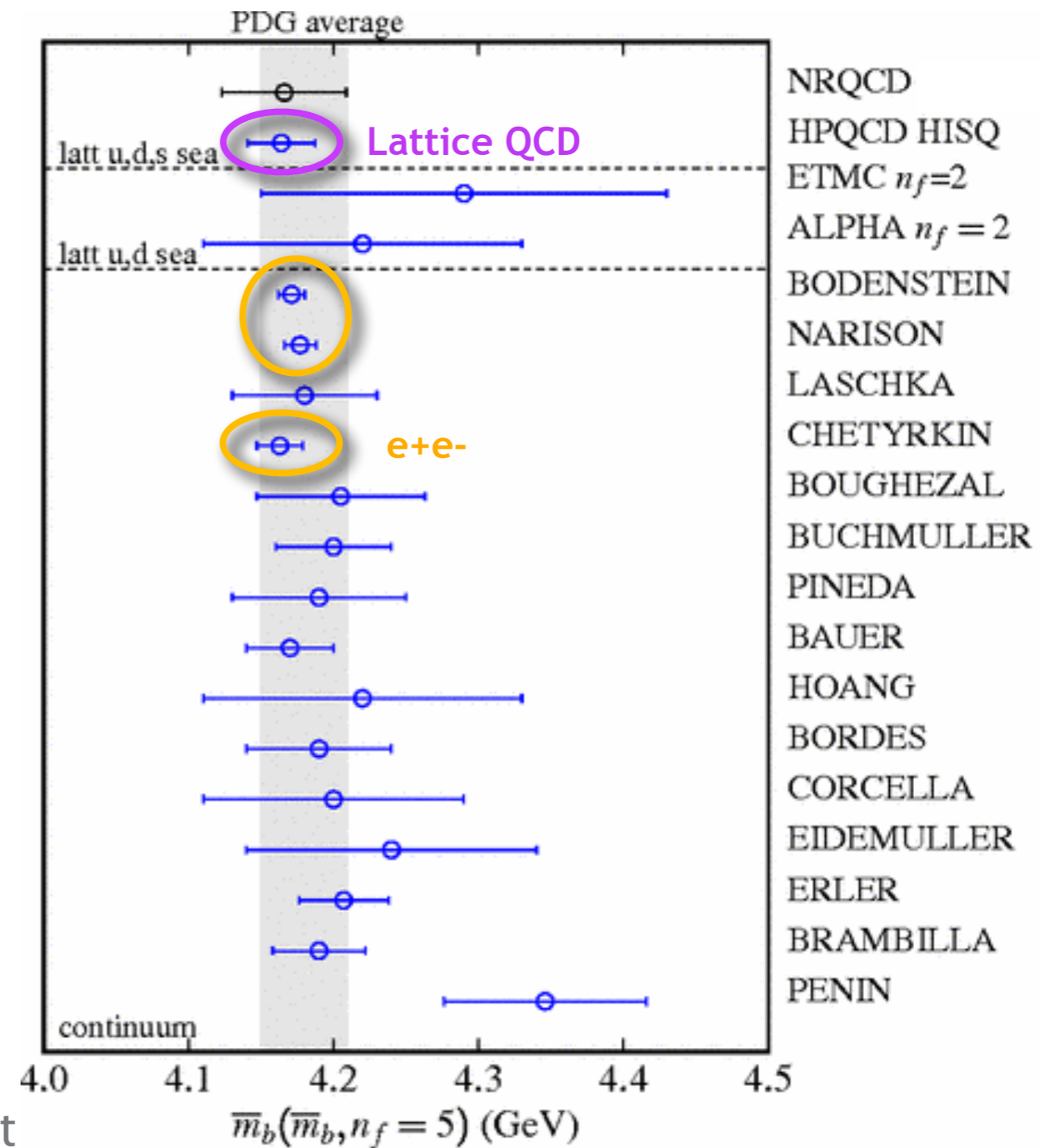


pQCD future plans

- Continued support of LHC program through a coherent plan to be pursued jointly by **Campbell, Ellis, Giele** together with RAs.
 - Improve tools that can be used to simulate and analyze LHC data.
- Planned improvements to MCFM will include the addition of electroweak corrections for select processes, evaluation of tree-level matrix elements using Berends-Giele recursion for access to high-multiplicity final states, optional multi-threading for improved speed.
- Aspire to NNLO precision in a similar, flexible Monte Carlo program.
- Will explore the possibility of combining MCFM framework with VINCIA, more directly than existing combination with POWHEG-BOX. Matrix element method formalism can be adapted to a unit-weight NLO generator, providing a new way of matching with a shower.
- Lab environment crucial due to programmatic nature and ability to exploit presence of broad local expertise.

Heavy-quark masses and strong coupling from lattice QCD

- Parametric errors from m_c , m_b , & α_s largest sources of uncertainty in SM width predictions for $H \rightarrow bb$, many other Higgs decay channels, & total width
- HPQCD obtained m_c , m_b , & α_s to $\sim 0.5\%$ from lattice QCD, but uncertainties limited by discretization & perturbative truncation errors
- Lepage, Mackenzie, Peskin [1404.0319] studied how precision must **and can** improve to meet needs of future high-luminosity colliders
- Mackenzie and Van de Water[★] leading effort to reach these targets with new, finer ensembles being generated
 - As first step, now analyzing existing Fermilab/MILC data to obtain independent determinations of m_c & α_s



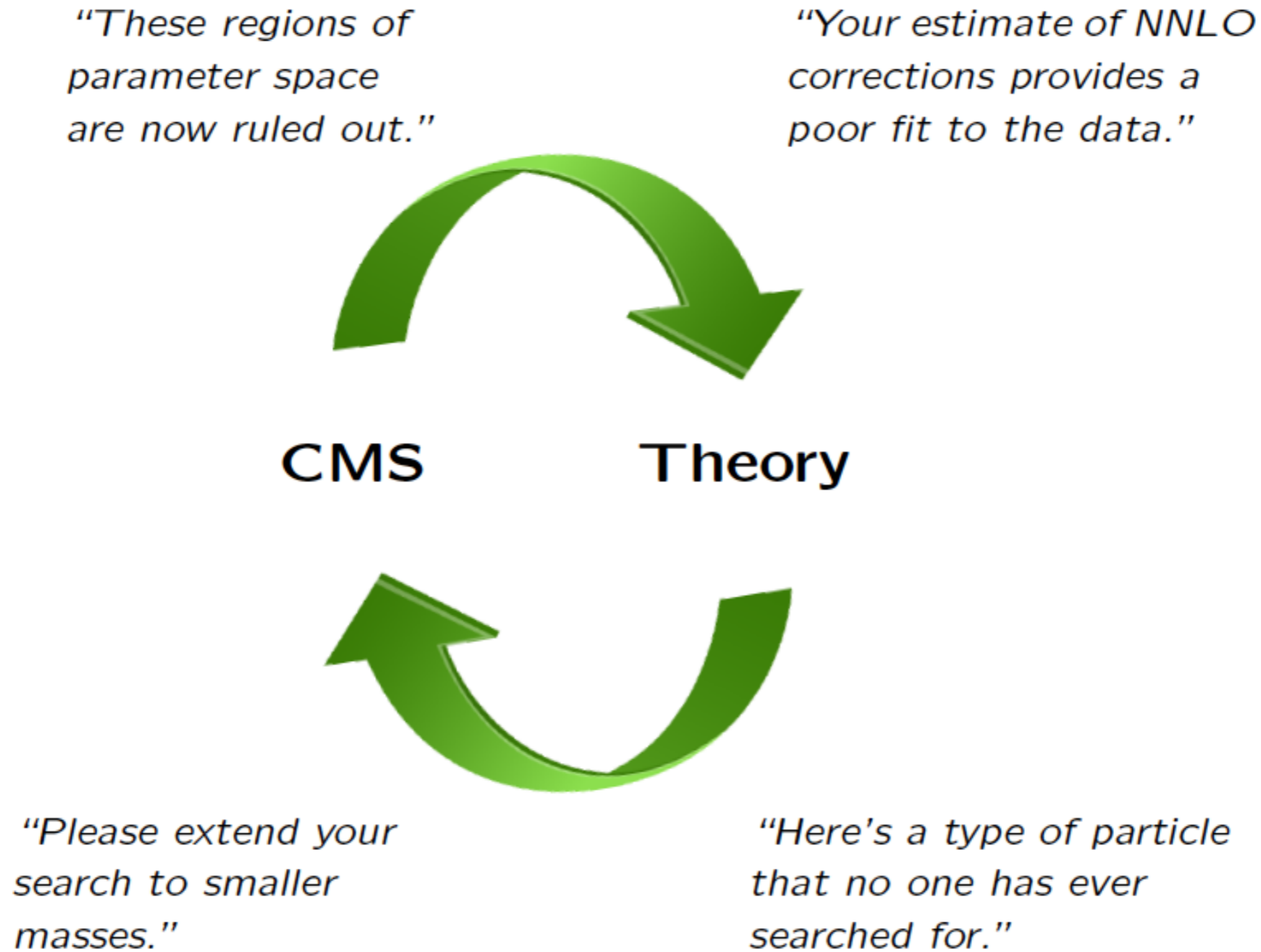
★ Submitted DOE Early Career Award to work on this + $(g-2)_\mu$

Phenomenology and model building for the LHC

Phenomenology and model-building

- Fermilab theorists contribute to LHC analyses in multiple ways including:
 - Discussing new ideas/new models and confronting their predictions with LHC data.
 - Helping in the interpretation of LHC analyses in Higgs models.
 - Developing new techniques to determine Higgs properties.
 - Proposing new search strategies for BSM particles and working with local LPC groups.
 - Defining benchmark scenarios for additional Higgs searches.
 - Providing analytic formulae necessary to perform the likelihood fits.
 - Writing MadGraph files used by CMS for the signal simulation in BSM scenarios.
- Substantial input to wide range of CMS publications including:
 - Higgs to four leptons [CMS HIG-14-018].
 - Higgs to tau mu [CMS HIG-14-007].
 - Search for pair-produced resonances decaying to jet pairs [CMS EXO-12-052].
 - Search for neutral color-octet weak-triplet scalar particles [CMS EXO-12-007].
 - Search for Heavy Resonances Decaying into bb and bg Final States [EXO-12-023].
 - Dark matter mono-jet [CMS EXO-12-048].
 - Dark matter mono-photon [CMS EXO-12-047].

Theory-CMS interactions



Getting the most out of $H \rightarrow 4$ leptons

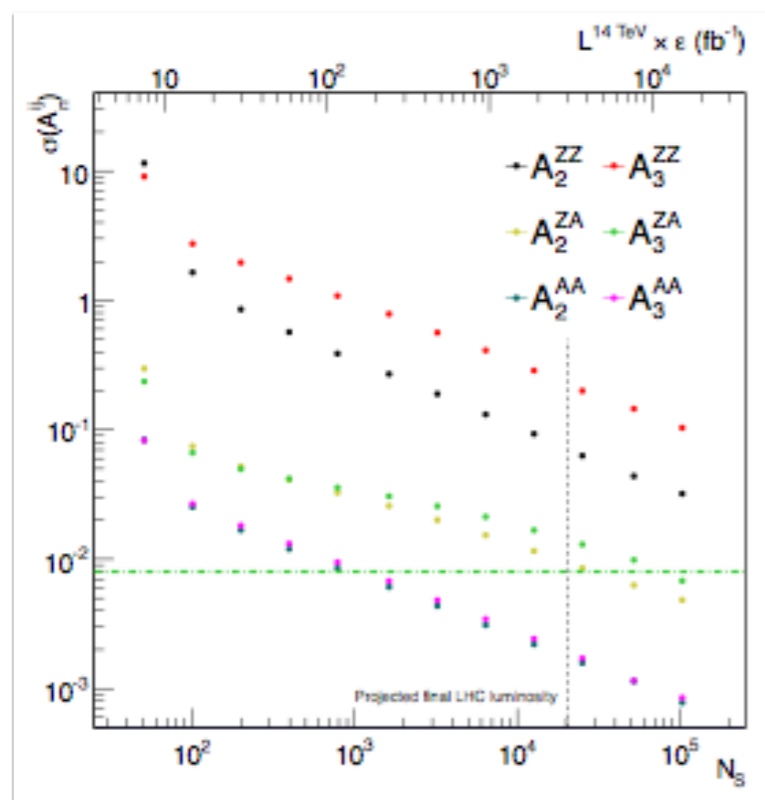
- Direct hands on the discovery.
 - Ground breaking work by **Lykken and Vega-Morales + LPC experimenters** to characterize Higgs properties from kinematic distributions; performed likelihood analysis based on an analytic fully-differential cross section.
 - Allows extraction of Higgs coupling to gauge bosons.

Milestone

Roberto Vega-Morales earns Sakurai Dissertation Award



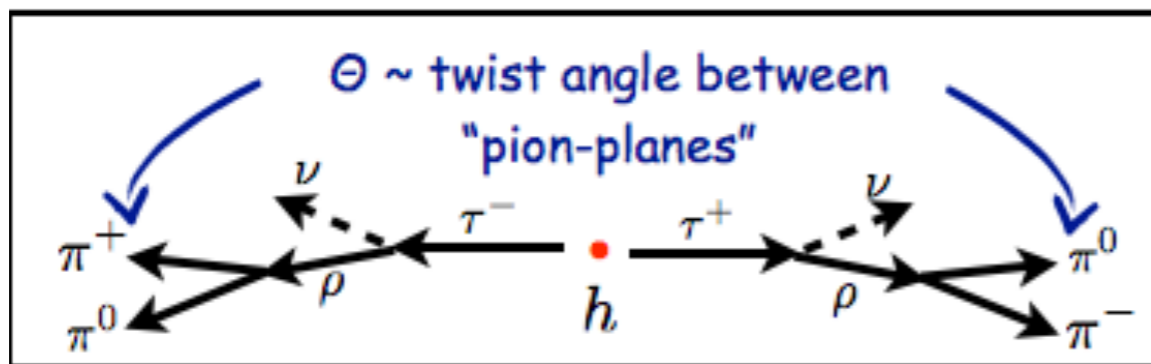
Earlier this month, the American Physical Society awarded Roberto Vega-Morales the 2014 [J.J. and Noriko Sakurai Dissertation Award](#) in theoretical particle physics.



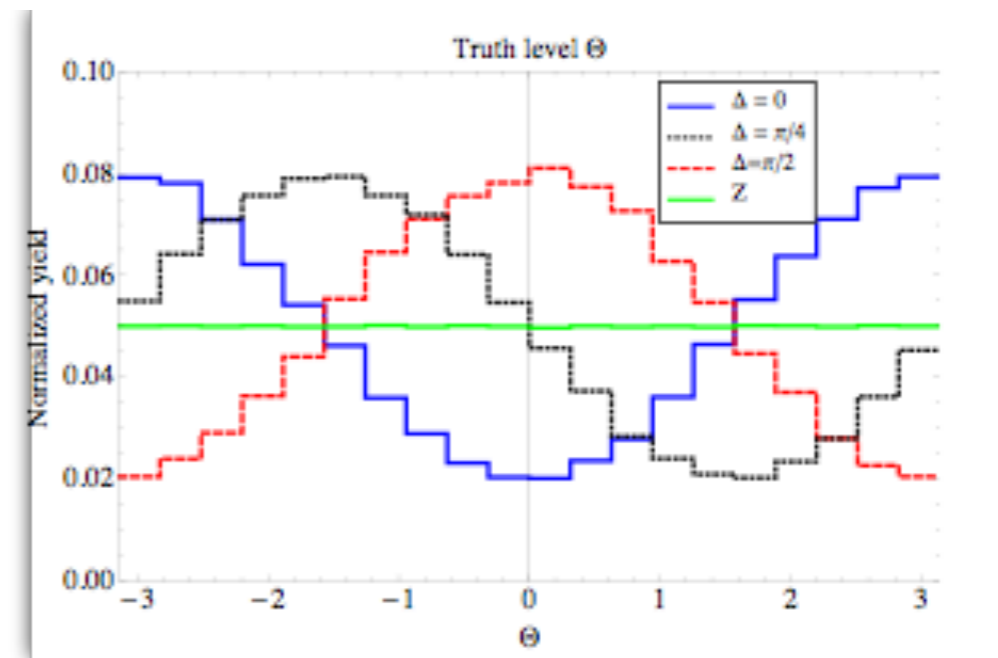
- Analytic framework allows analysis of Higgs coupling to photons in $H \rightarrow 4\ell$ [Harnik, V.-M.]
 - Fit simultaneously for ZZ, $Z\gamma$, $\gamma\gamma$ couplings; of dim-5 ops, $h \rightarrow 4\ell$ most sensitive to $\gamma\gamma$!
 - Important to include all couplings in future searches (HL-LHC sensitive to SM $h\gamma\gamma$).
 - Adopted in CMS-PAS-HIG-14-005.

Tests of CP violation in the Higgs sector

- CPV in Higgs couplings to τ 's is unconstrained.
 - Fermilab theorists proposed first LHC search [Harnik, Martin, Yu, et al].
 - Members of CMS exploring feasibility of measurement. [1501.03156]



measure momentum of charged and neutral pions separately to resolve the sub-structure of hadronic τ 's.

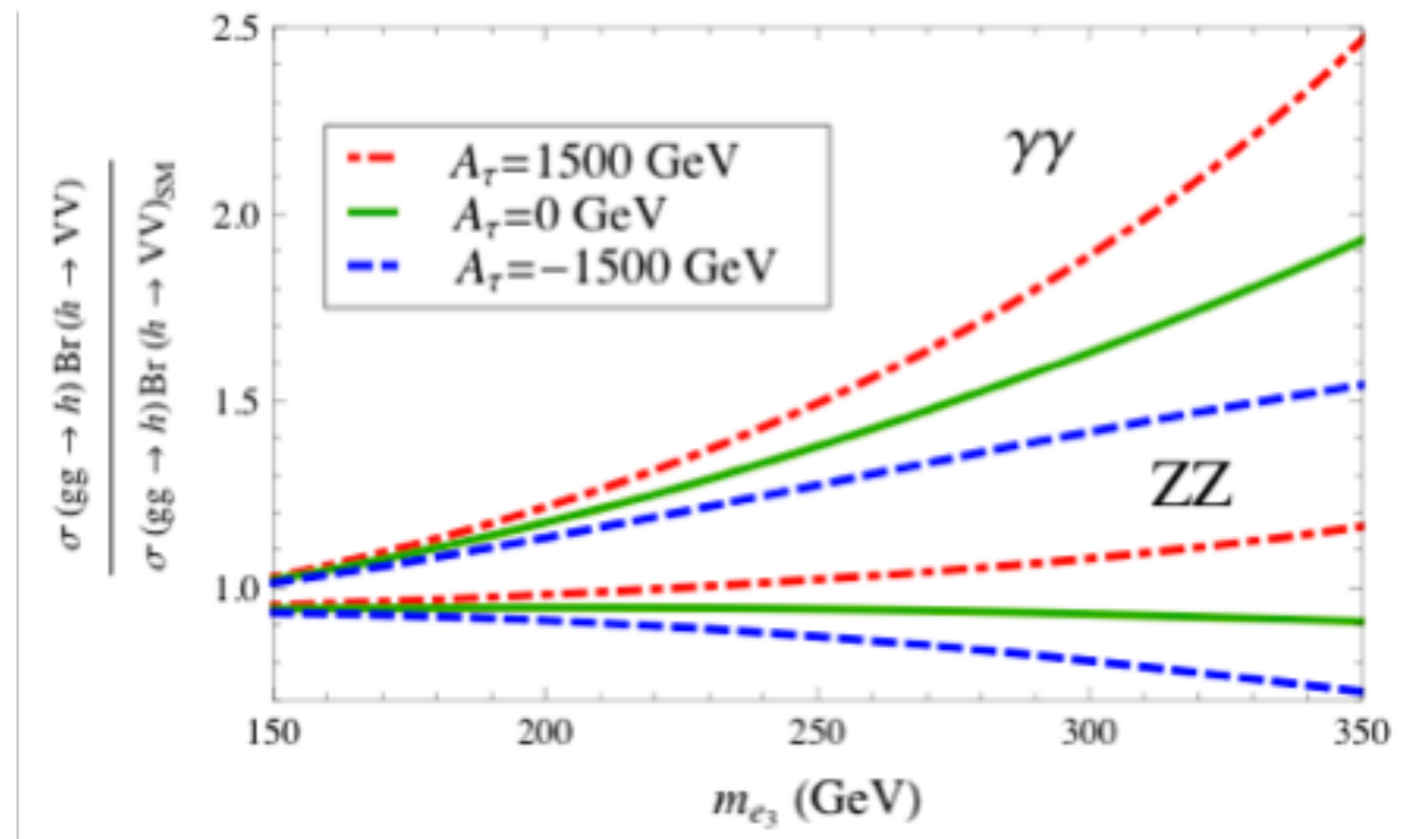
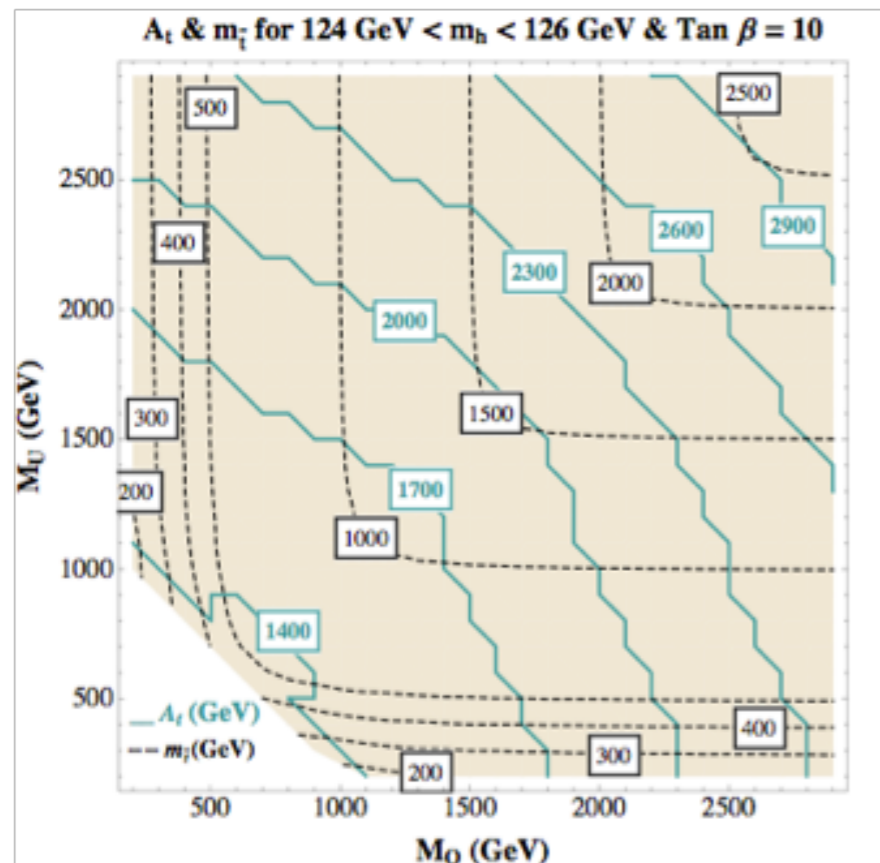


- Future LHC sensitivity to $H \rightarrow \gamma\gamma$ can prove CPV in this channel.
 - Interference effects in the golden channel [Harnik, Vega-Morales et al].
 - Models with vector like fermions [Altmannshofer, Bauer, Carena'13].

Higgs and SUSY: *MSSM, NMSSM and beyond*

- First detailed study showing constraints on stop spectrum from Higgs data in the MSSM for most general case of stop parameters [Carena, Shah].
 - Triggered interest in search for light staus within LPC SUSY subgroup: CMS results in single and di-tau channels + discussions with Eva Halkiadakis (LPC).

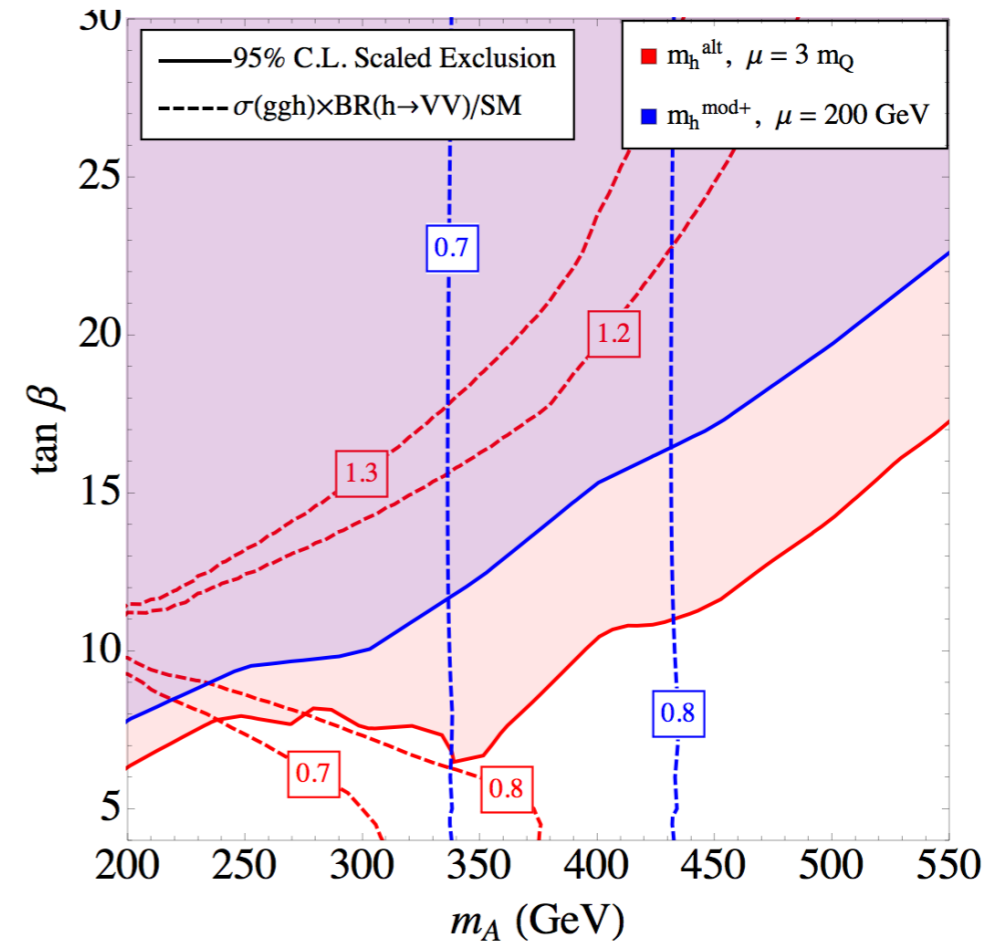
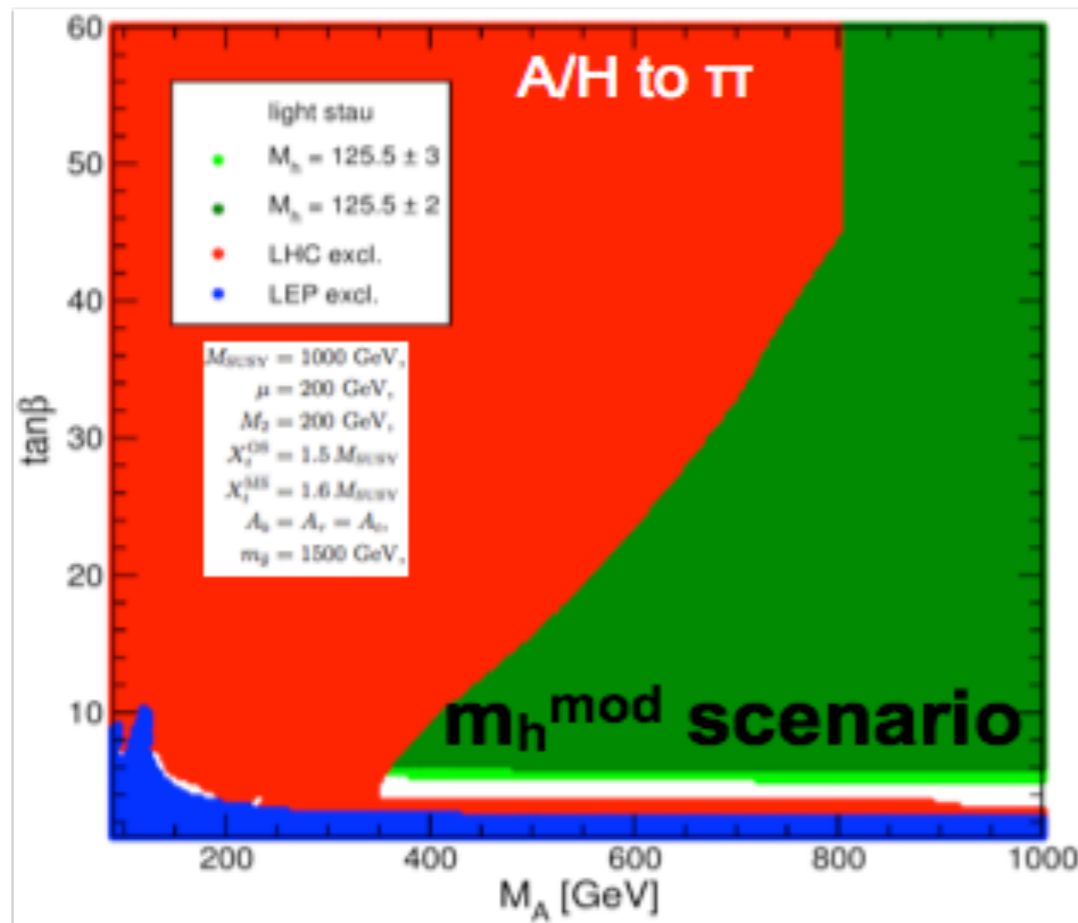
Large mixing in the stop sector to obtain $m_H \sim 125$ GeV \rightarrow only mild modification of the gluon fusion rate



Light staus modify tree-level coupling due to Higgs mixing effects

Higgs and SUSY: *MSSM, NMSSM benchmarks*

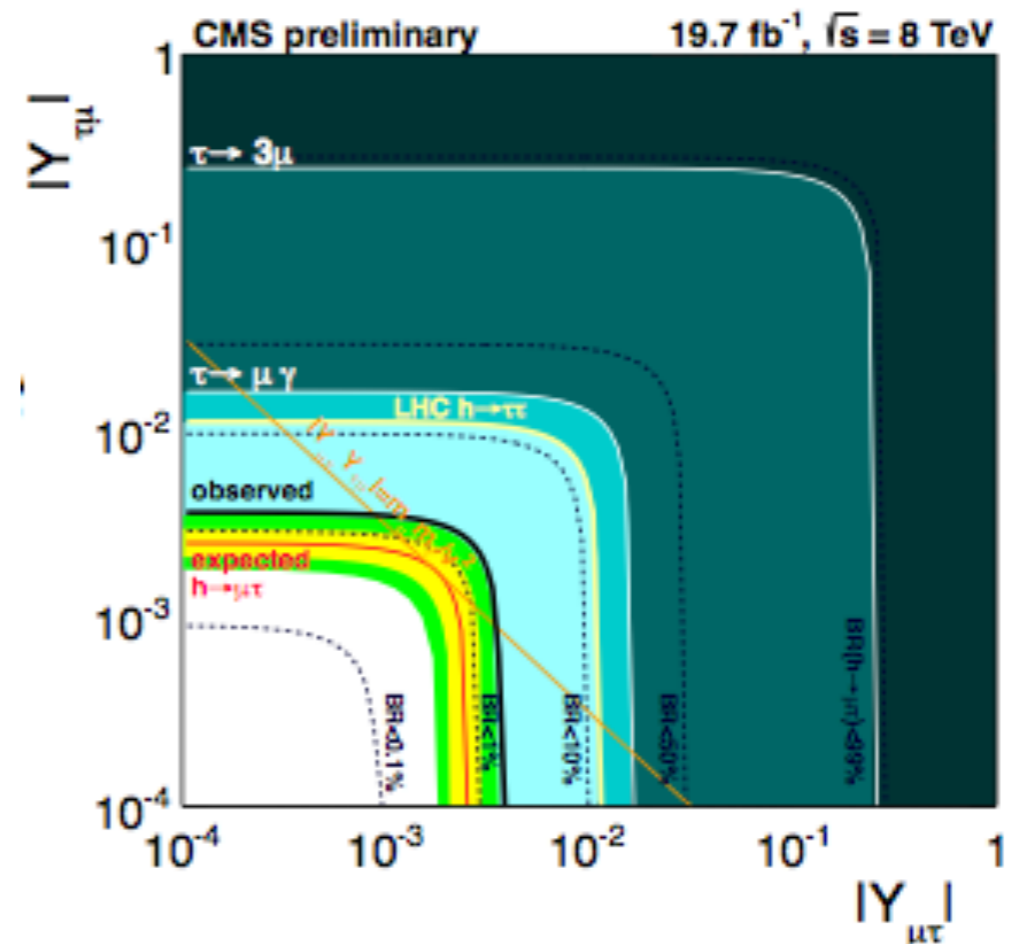
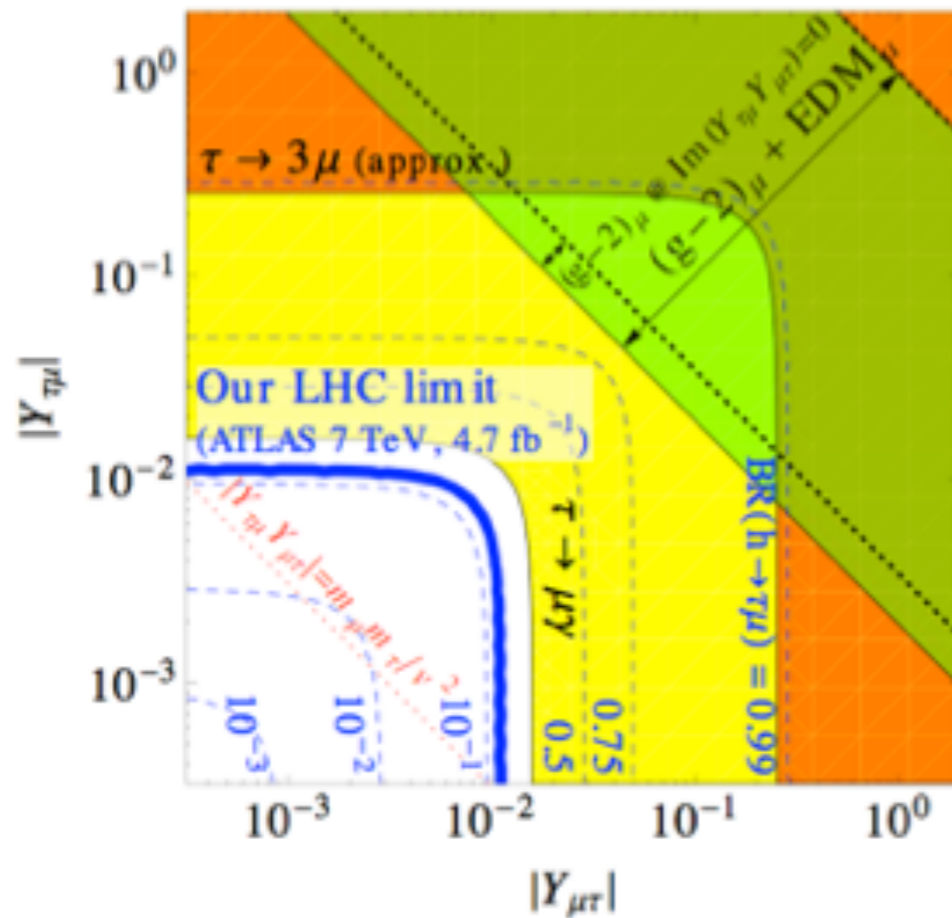
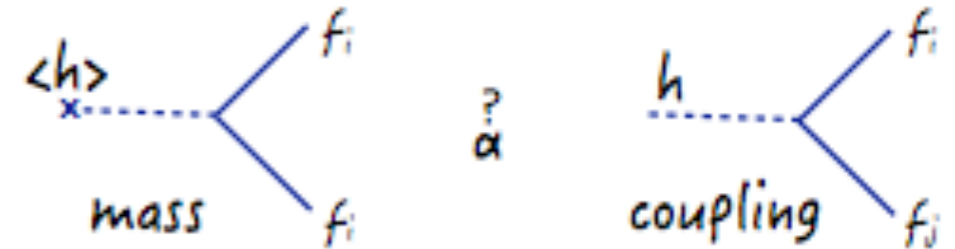
- Benchmark scenarios used by CMS, ATLAS and the LHC Higgs X-section WG to present their interpretation of additional Higgs bosons searches.
- Complementarity between non-standard Higgs searches & Higgs data [Carena].



- Opportunity to search for non-SM Higgs decays, e.g. $A \rightarrow Zh$, $A \rightarrow tt$, $A/H \rightarrow \chi\chi$.
- Many discussions with CMS/LPC members to help define SUSY Higgs searches.

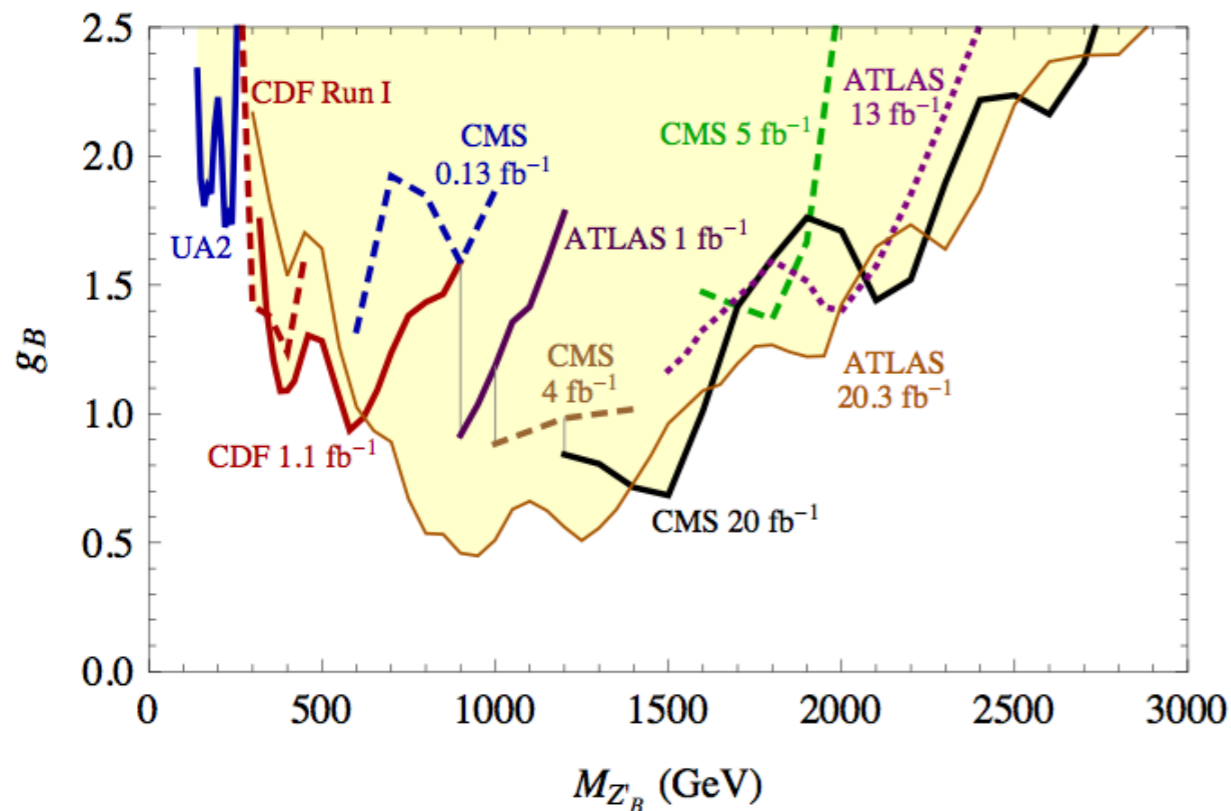
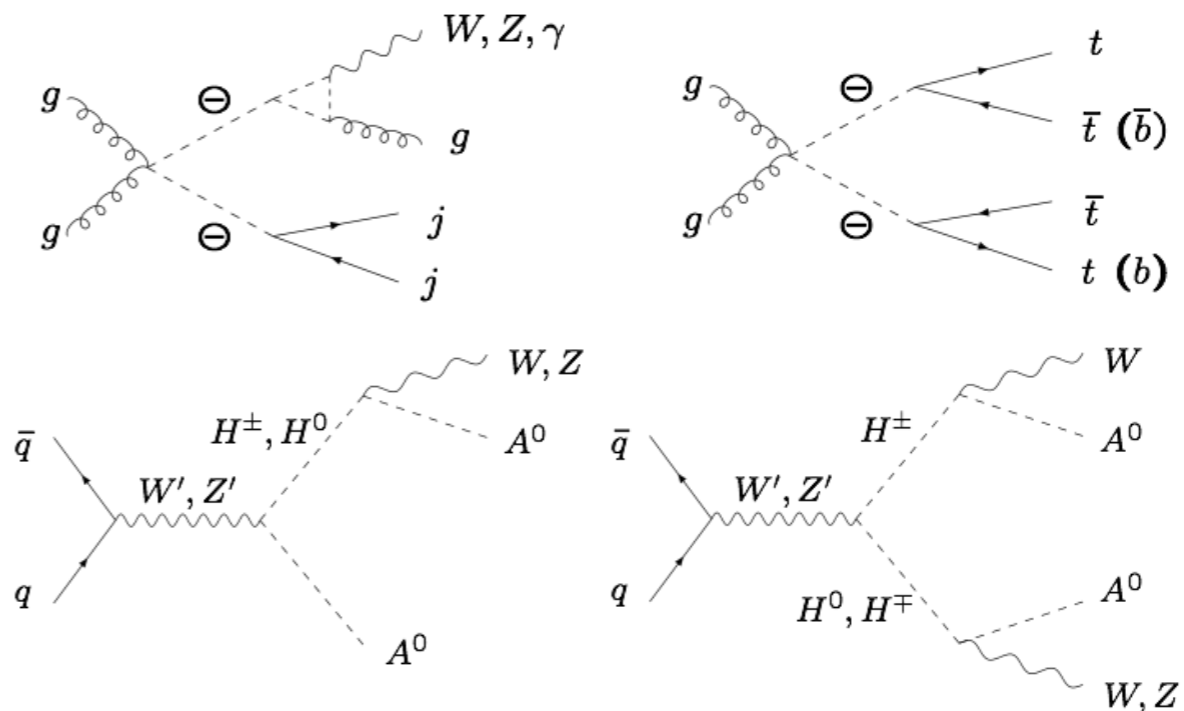
Higgs and flavor

- Do Higgs couplings violate flavor?
Systematic analysis of FV Higgs [Harnik, Kopp].
- Followed by recent CMS dedicated search.
- Conclusion: for flavor violation in τ - μ , LHC dominates.



New particle searches for the LHC

- Colour–octet, weak–triplet scalar [Dobrescu, Krnjaic].
- Meta–sequential W' decays into heavy Higgs particles [Dobrescu, Peterson].



- Comparison at different CM energies and at different colliders (translation of $\sigma \times B \times A$ limits) [Dobrescu, Yu].
 - Baryonic Z' (same coupling to all quark flavors).
- Refocus on unconstrained regions for dijet resonance searches.

Wjj at the Tevatron

- Illustrates tight experiment–theory coupling at Fermilab [Eichten, Martin].
 - Sizeable excess (4.1 σ at CDF) \rightarrow build technicolor–motivated models to explain.
 - Involved (at director’s request) in task force set up to resolve origin of the excess e.g. correlated channels, predictions at the LHC, new kinematic distributions that would enhance the signal.

