CMS: Past, Present and Future

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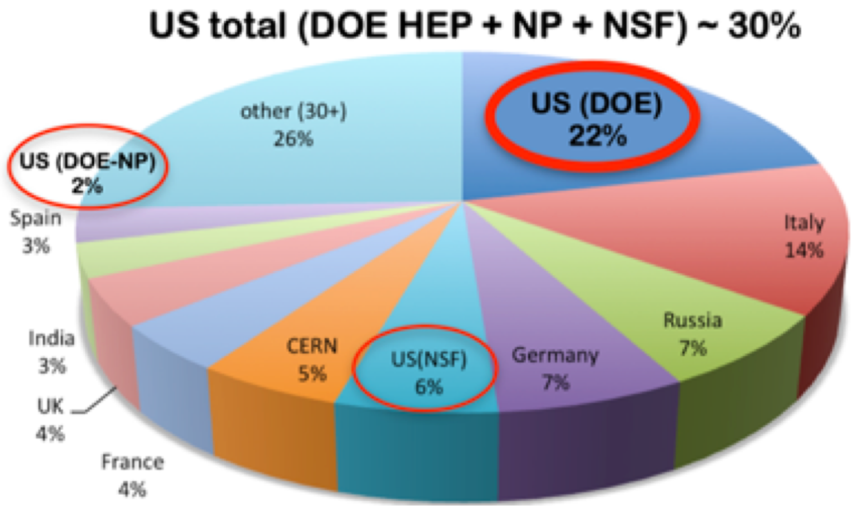
THE UNIVERSITY OF ILLINOIS AT CHICAGO

Introduction & Outline

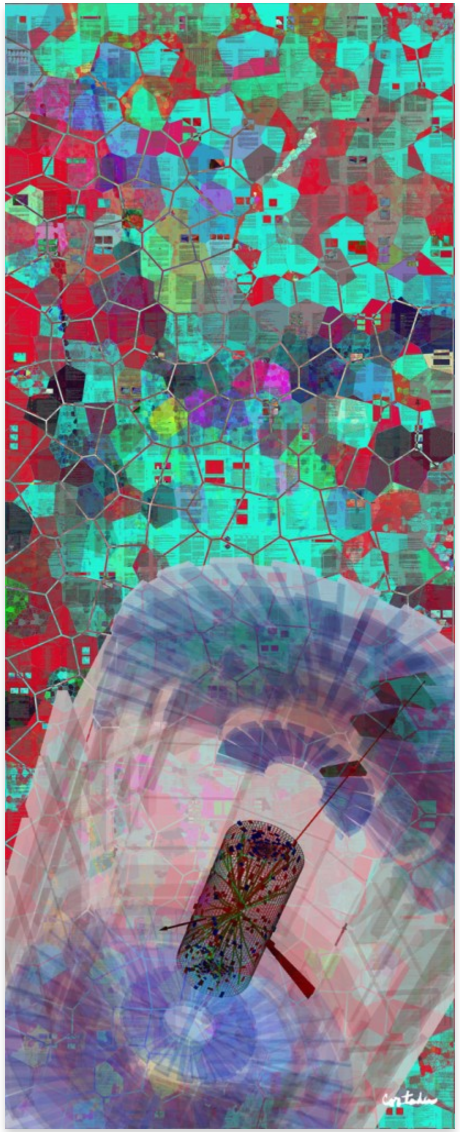
- The Compact Muon Solenoid (CMS) collaboration involves more than 3500 scientists, engineers, and students from 198 institutes in 46 countries.
- The US CMS members make up about 30% of the international CMS collaboration
- Fermilab is the sole host laboratory in the US for the CMS collaboration
- The Large Hadron Collider Physics Center (LPC), located on the 10th and 11th floor of Wilson Hall, is a is a powerhouse of talent, experience and resources, that acts as a catalyst for contributions of US and international collaborators to CMS
- Vibrant intellectual community with educational opportunities and workshops and seminar series open to the wider Fermilab community (Topic of the Week, Physics Forum, etc.)



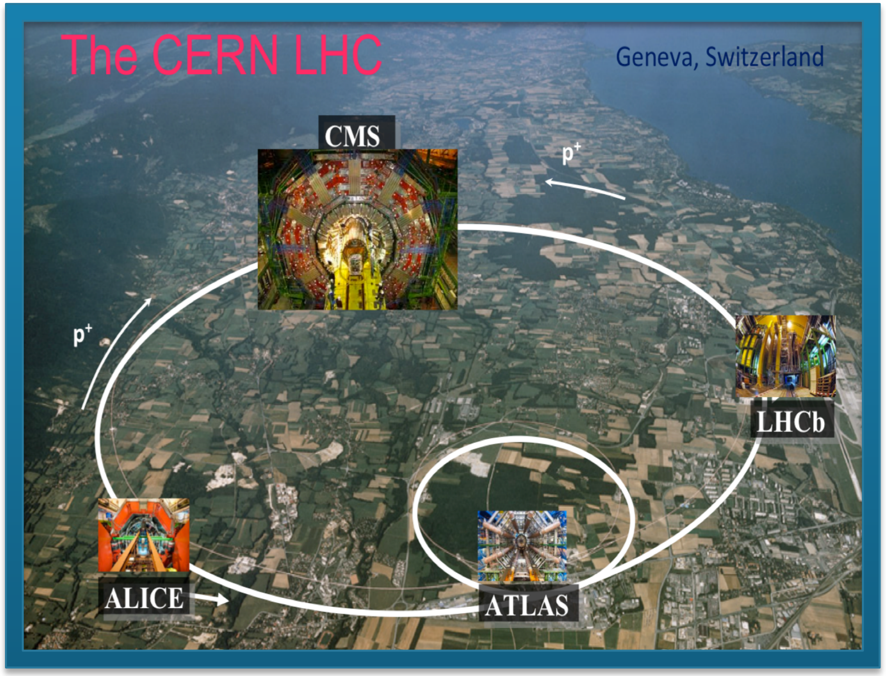
IN THIS TALK

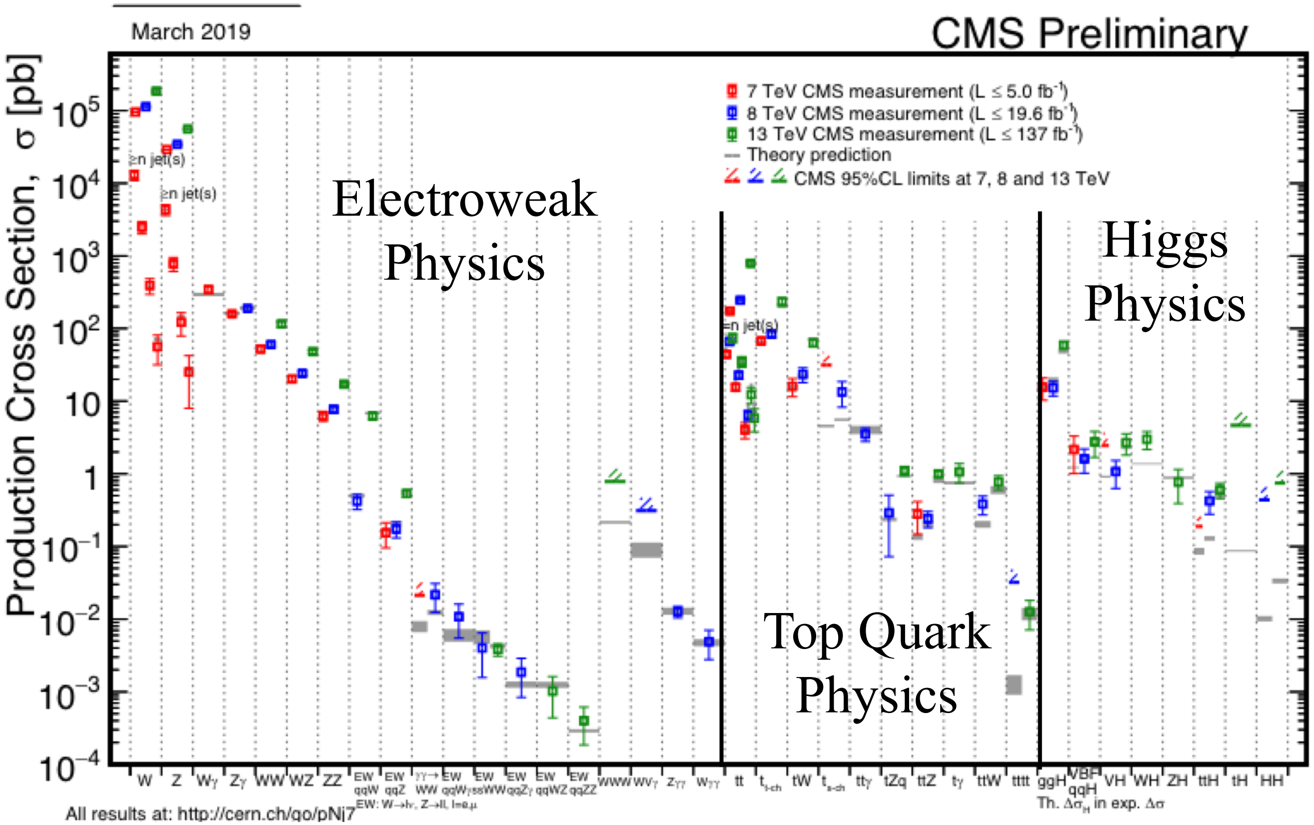
- LHC & the CMS Detector
- Physics Highlights
  - Higgs, Rare SM Processes, Searches
  - The next few years
  - Planning the energy frontier future
- See also talk by Zoltan Gecse on US contributions to the CMS upgrade

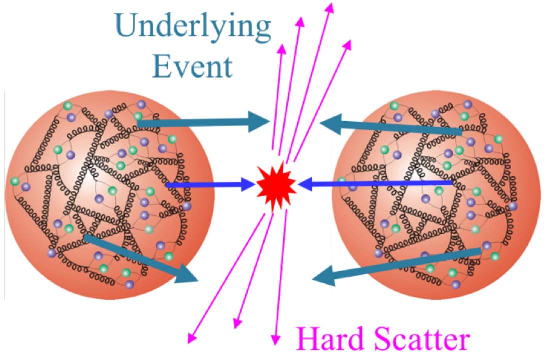
CMS AND THE LHC

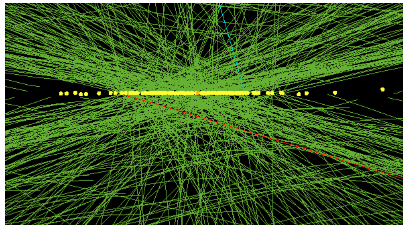


Hadron Collisions at the LHC



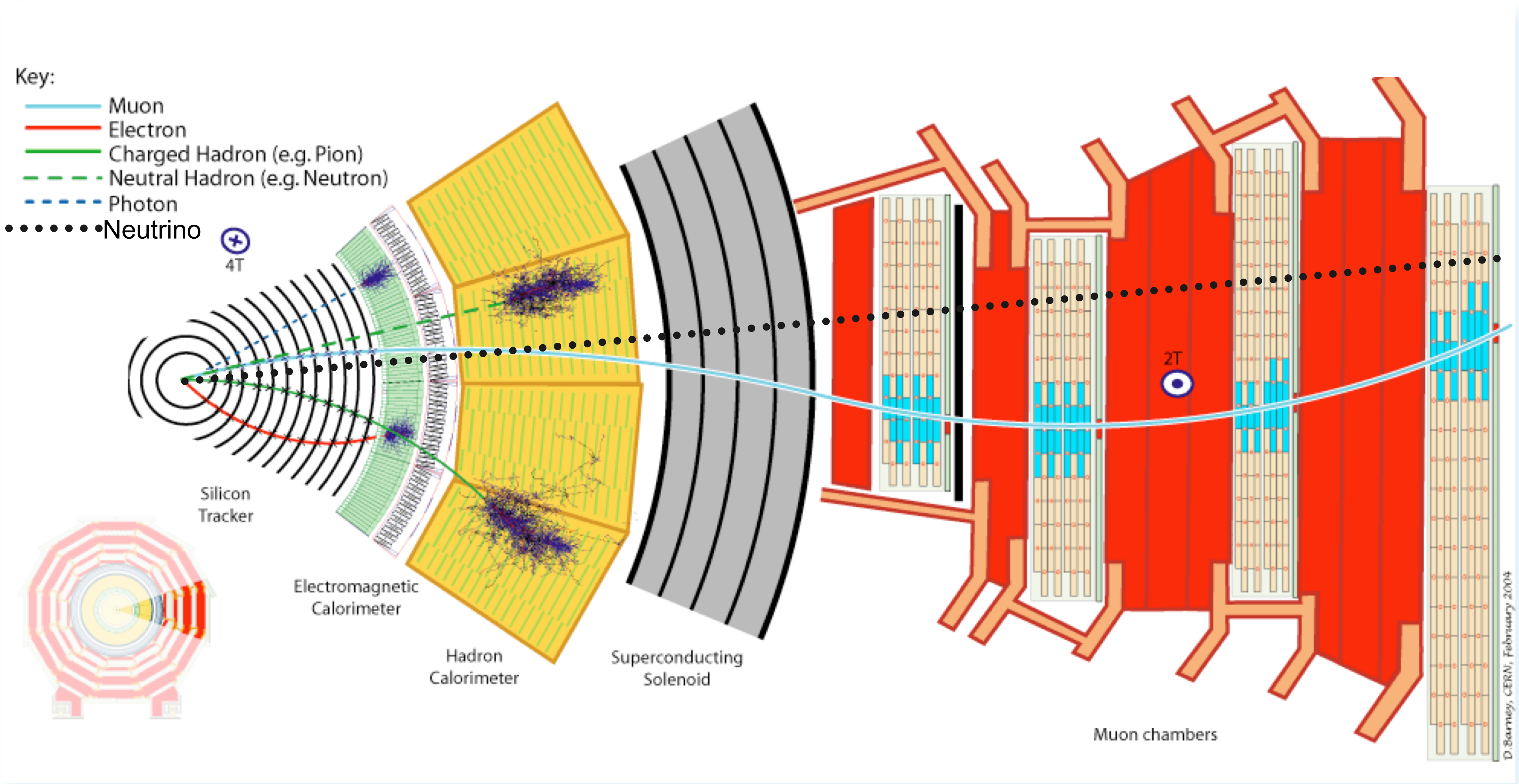






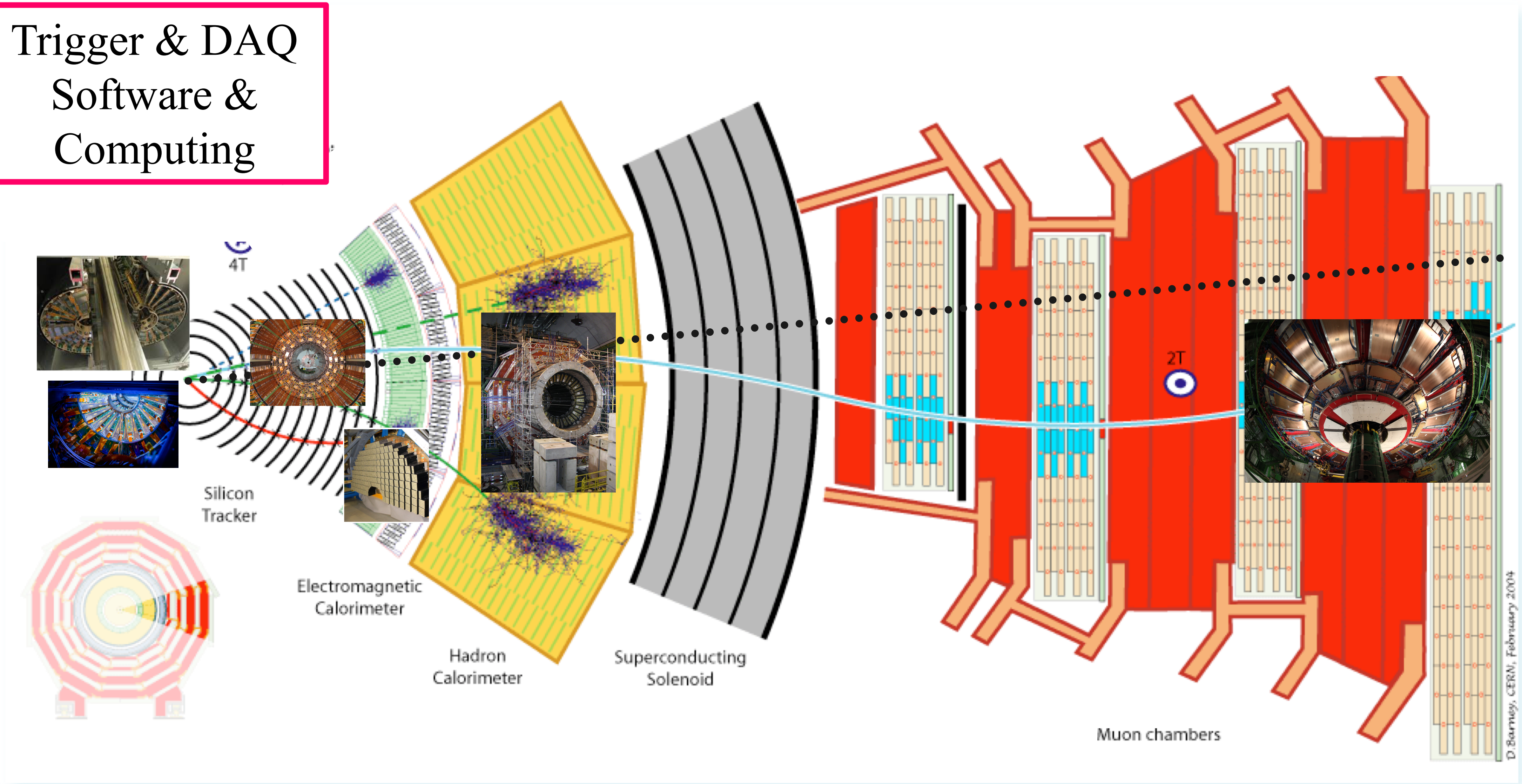
An extremely rich program, allowing to probe processes spanning 9 orders of magnitude in production cross-section

CMS Detector Cross Section



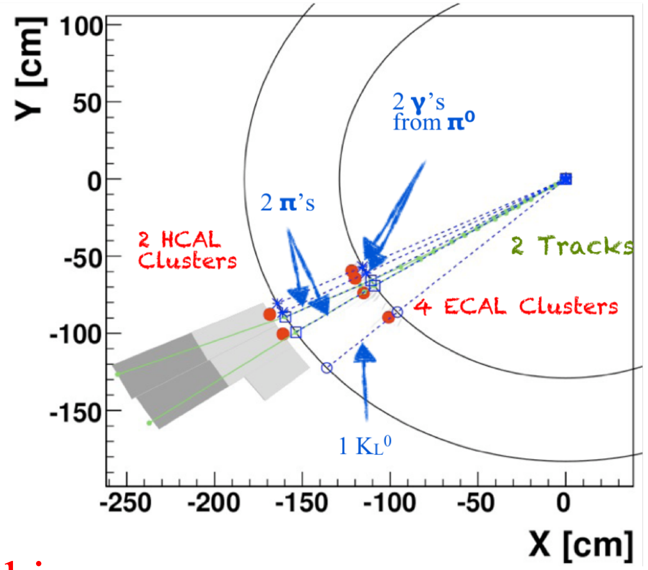
US Contributions to CMS Detector Components

Trigger & DAQ
Software &
Computing

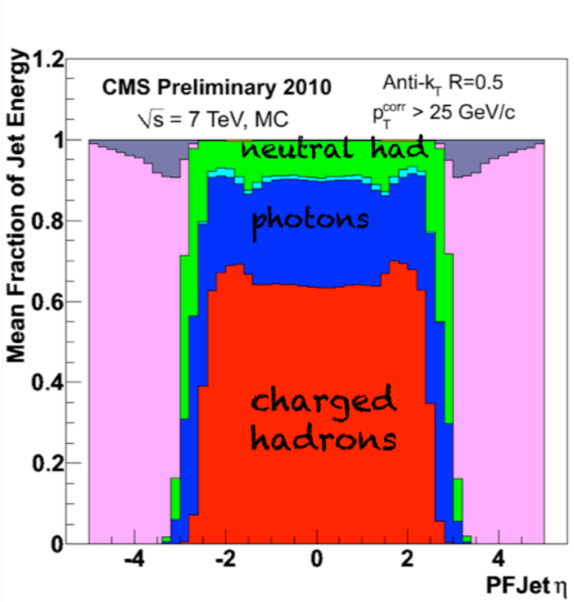


Particle Flow Algorithm

- CMS is ideally suited to exploit the PF event reconstruction
  - Large volume tracker, high magnetic field, high granularity calorimeter
  - Use the best available measurement of the energy
    - calorimeter resolution overcomes the tracker resolution at ≈ 500GeV

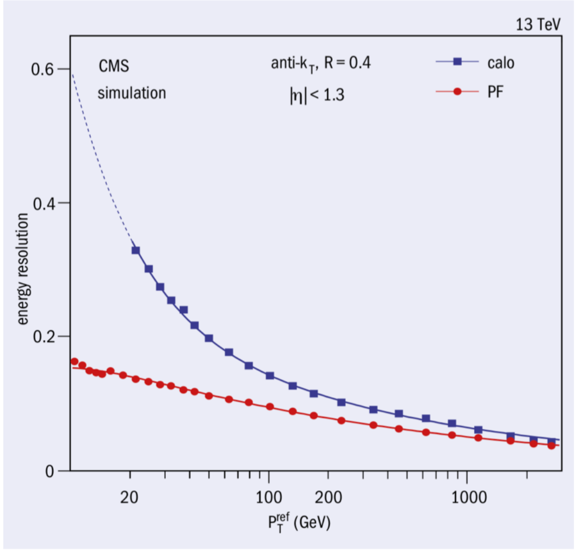


Link across detectors to create list of <u>individual particles</u> that describe the entire event

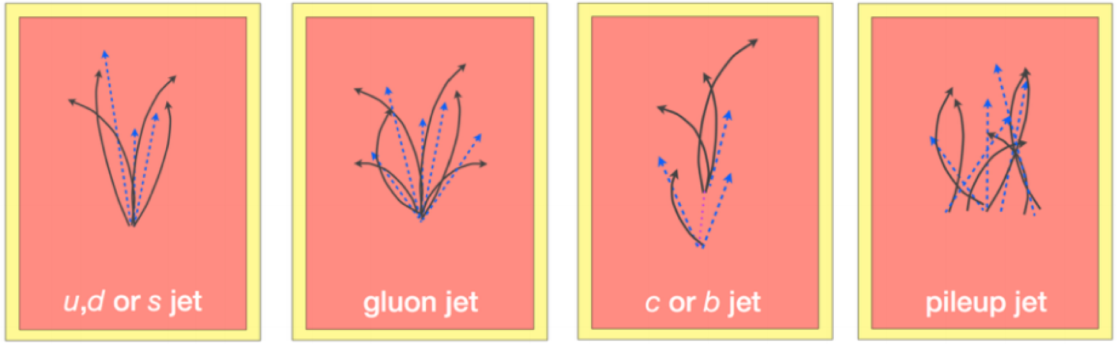


- Charged particles : ~60% Tracking
- Photons : ~25% ECAL
- Long-lived neutral hadrons : ~10% HCAL
- Short-lived neutral hadrons : ~5% Tracking

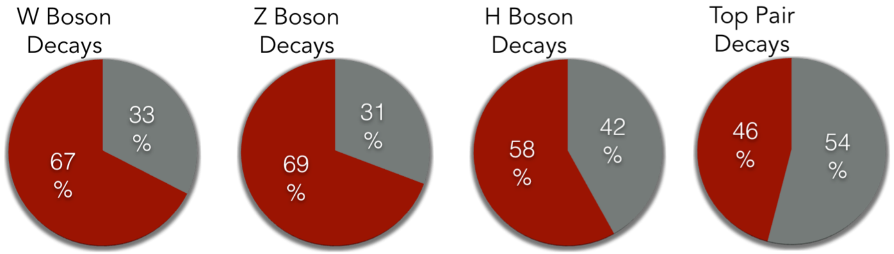
Full use of Detector Information significantly improves resolution & helps to mitigate the effects from pileup



New Field: Jet Substructure Techniques

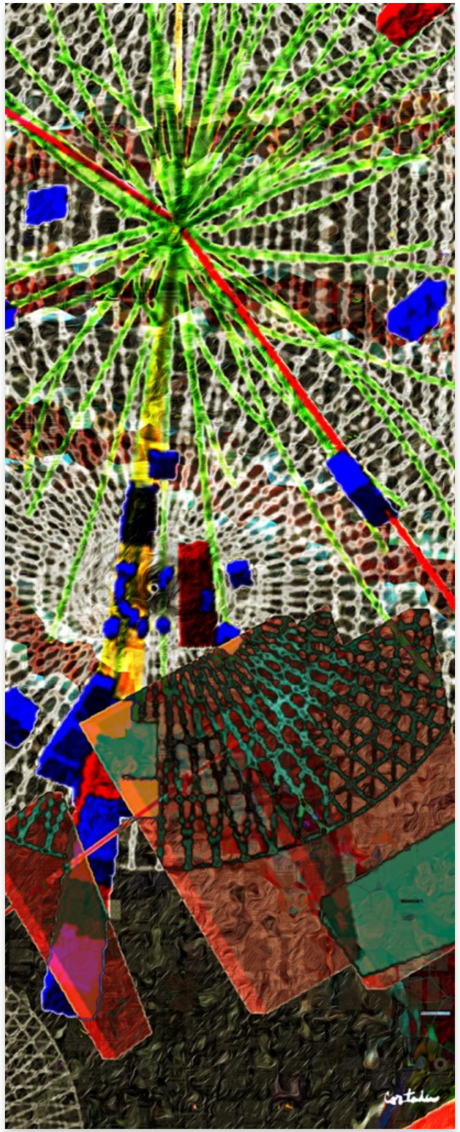


- Qualitatively different quarks/gluons produce different jet topologies
  - Different radiation patterns & lifetimes
  - Can use topologies to discriminate
- Jets can also form from hadronic decays of high-p_T heavy particles
  - $W/Z \to qq$, $H \to bb$, $t \to Wb \to qqb$
  - By looking at these patterns we can gain useful information about the process in the event



Large amount of acceptance can be gained from hadronic channels

CMS PHYSICS HIGHLIGHTS



CMS Publications

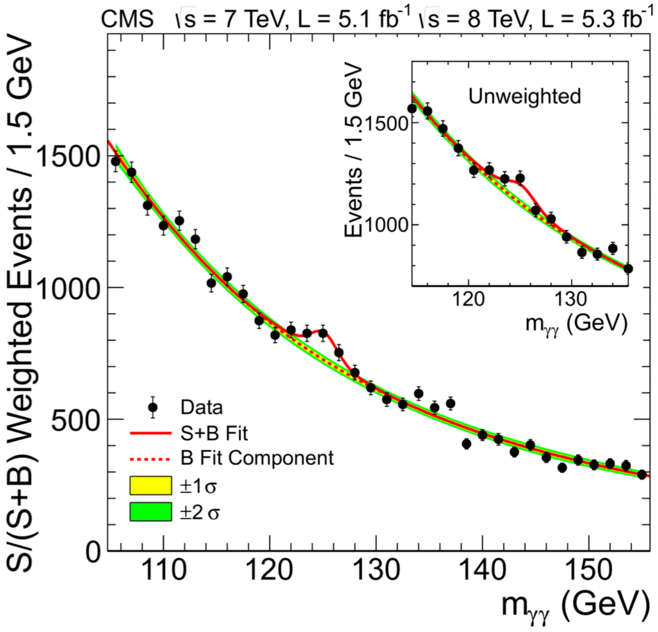
- 900th paper submitted end of May
  - Average of 3 papers per week
    - 200 (3) papers with more than 100 (1000) citations
    - 5 papers highlighted as PRL Editor's suggestions since Sep 2017
- US CMS & the LPC are major contributors to the majority of them
  - 27% of the papers published in the last two years have majority (> 50%) of authors affiliated with the Fermilab LPC

- Read more about this in the May 29th Fermilab at work https://news.fnal.gov/2019/05/cms-publication-count-climbs-to-900/

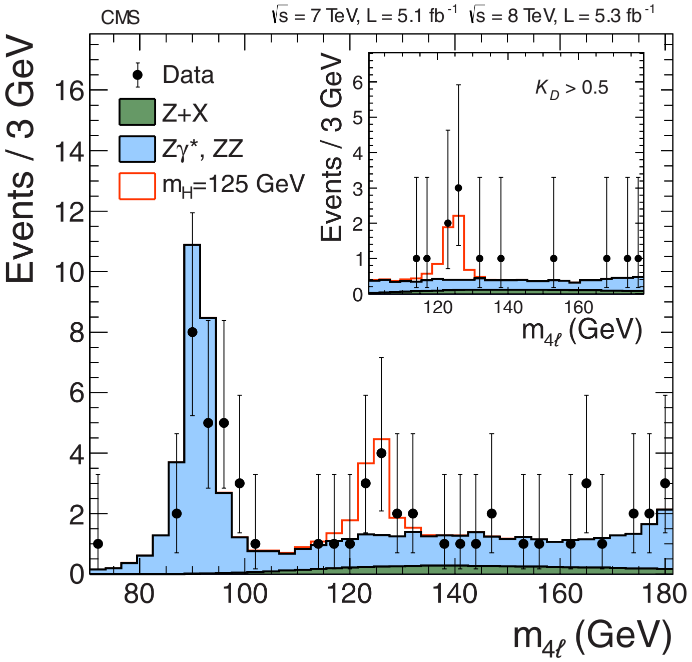
More than 90% of USCMS institutions have members affiliated with the LPC

July 4th, 2012: Higgs boson discovery

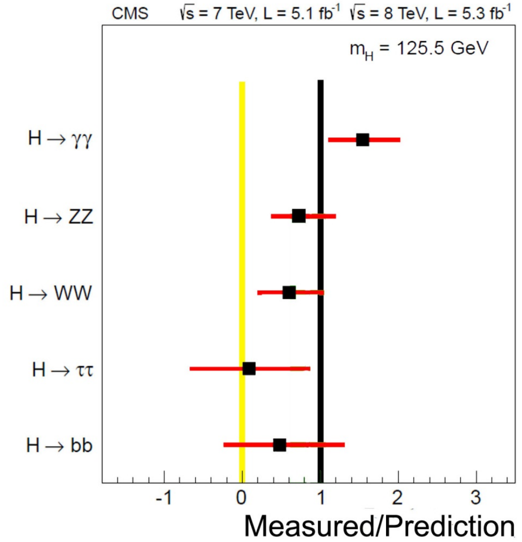
- Fully reconstructed Higgs boson decay channels with excellent mass resolution drove the discovery
- Peter Higgs and François Englert won the 2013 Nobel Prize in physics



Di-photon channel

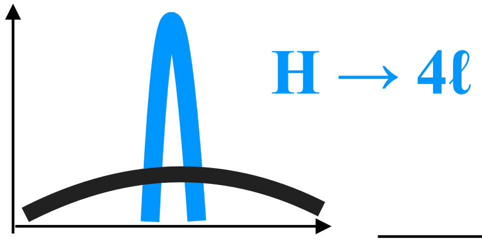


Four lepton channel

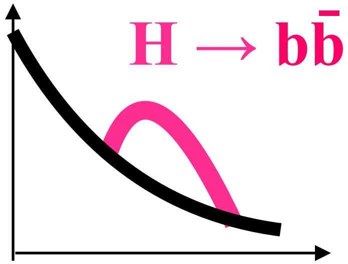


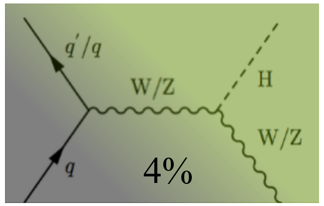
H→bb (H→ $\tau\tau$) not observed at the time

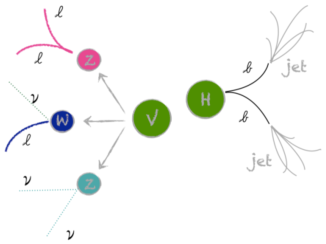
Six years in the making: VH(bb)

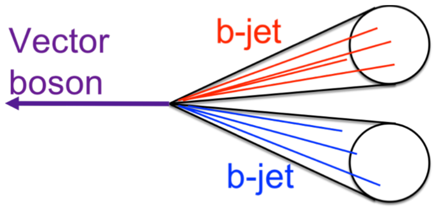


	H → 4ℓ	H → $b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05

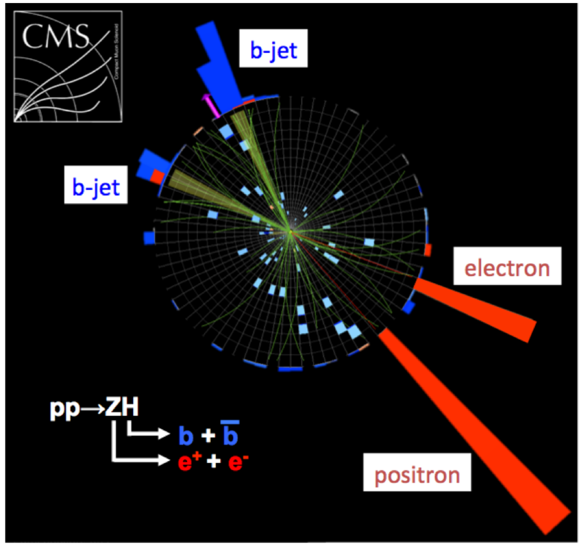




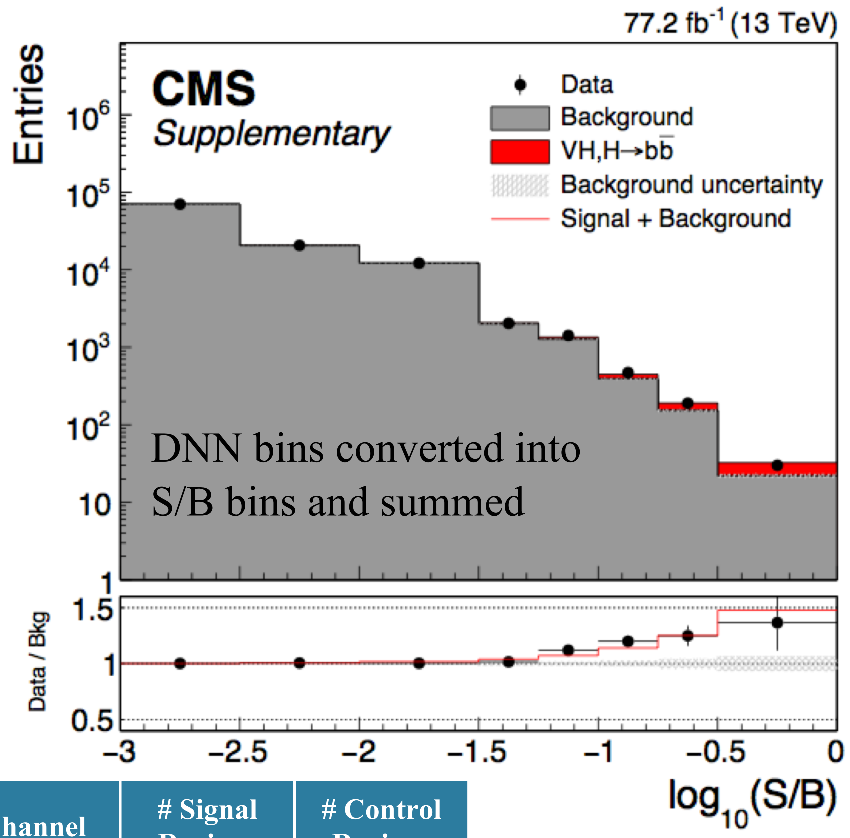




- Require W/Z to have large boost (~150 GeV)
  - multi-jet QCD background is highly suppressed
- b-jet energy specific corrections (regression)
- DNN classifier used to separate signal and background(s)
- Extract normalization for the dominant backgrounds from the data
  - 0, 1 and 2 leptons +0b/1b/2b define signal and control regions



VH(bb) Observation

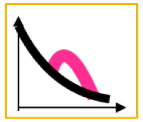


DNN bins converted into S/B bins and summed

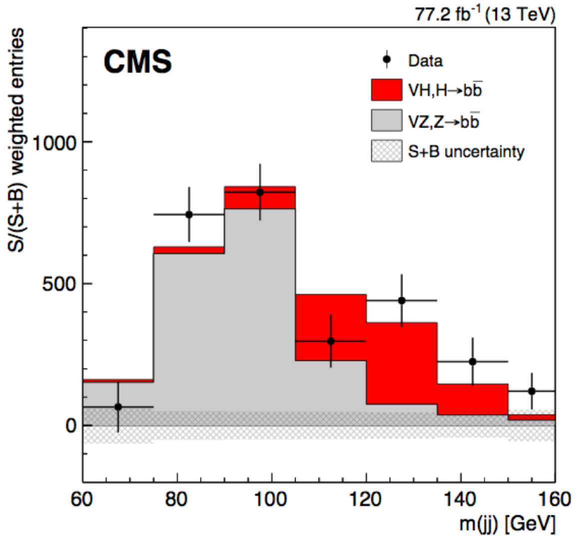
Channel	# Signal Regions	# Control Regions
0-lep	1	3
1-lep	2	6
2-lep	4	12
Total	7	21

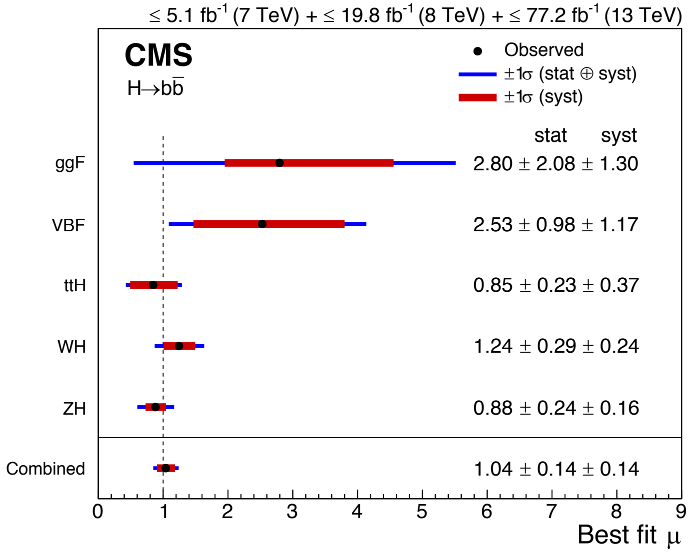
4.8σ
$\mu = 1.01 \pm 0.23$

Overall compatible with S+B hypothesis



Dijet invariant mass distribution for events weighted by S/S+B





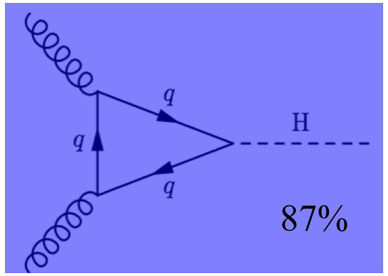
Phys. Rev. Lett. 121, 121801 (2018)

5.6σ (5.5σ)
$\mu = 1.04 \pm 0.20$

Combination with Run 1 data led to observation of the the H→bb decay

https://www.energy.gov/science/hep/articles/beautiful-higgs-decays
https://news.fnal.gov/2018/08/lhc-scientists-detect-most-favored-higgs-decay/

Gluon Fusion H to bb

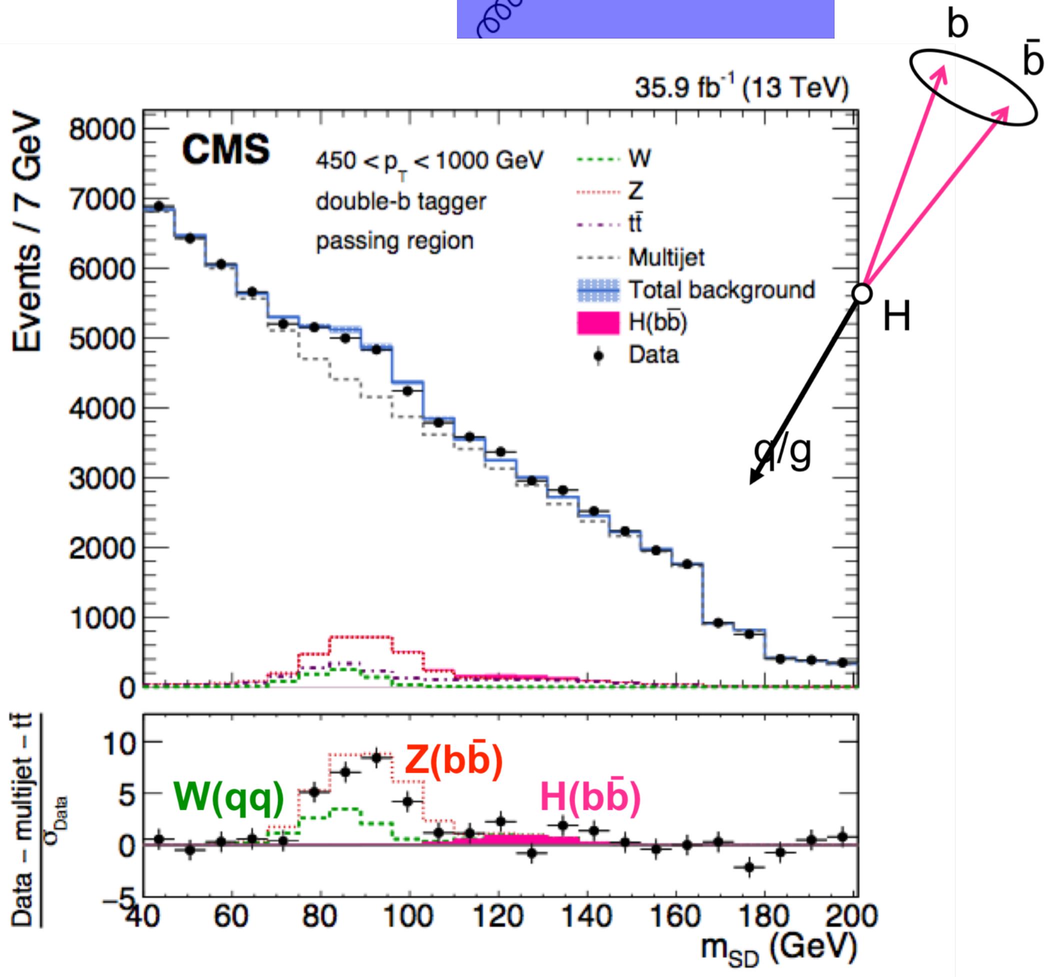


- Require Higgs boson to be very boosted
  - two b-jets are merged into a fat jet
  - identified using dedicated BDT double-b tagger

The Z → bb process is observed for the first time in the single-jet topology with a local significance of 5.1 standard deviations (5.8 expected).

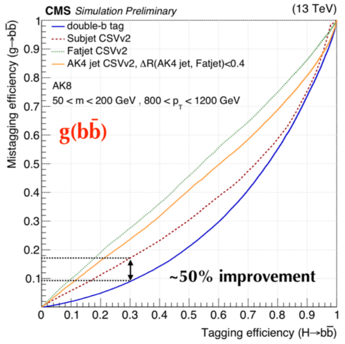
Excess of 125GeV Higgs above the expected background is observed (expected) with a local significance of 1.5 (0.7) standard deviations

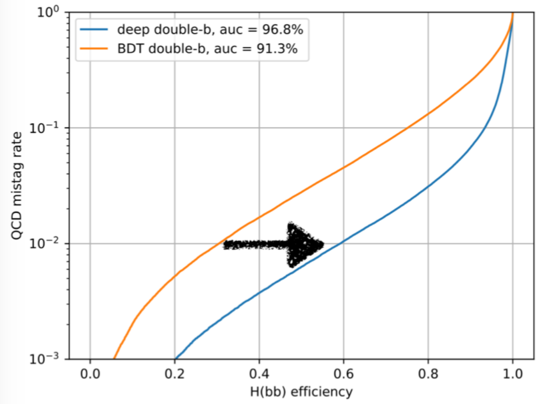
X-sec consistent with SM expectations



Phys. Rev. Lett. 120, 071802 (2018)

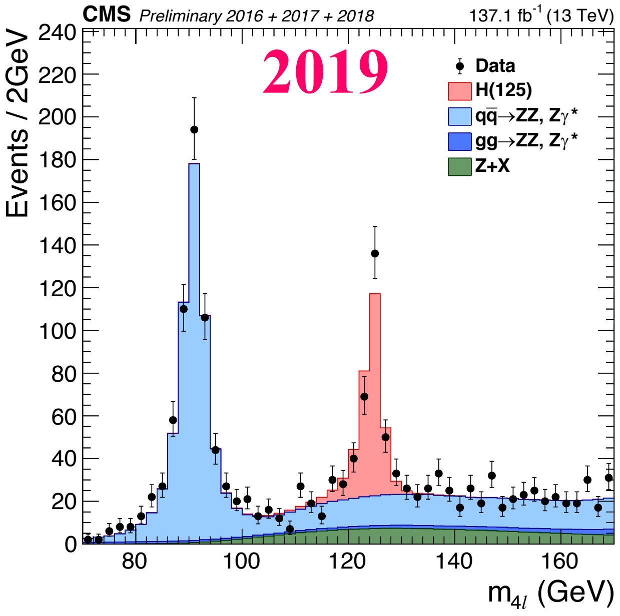
DNN double-b tagger in the works

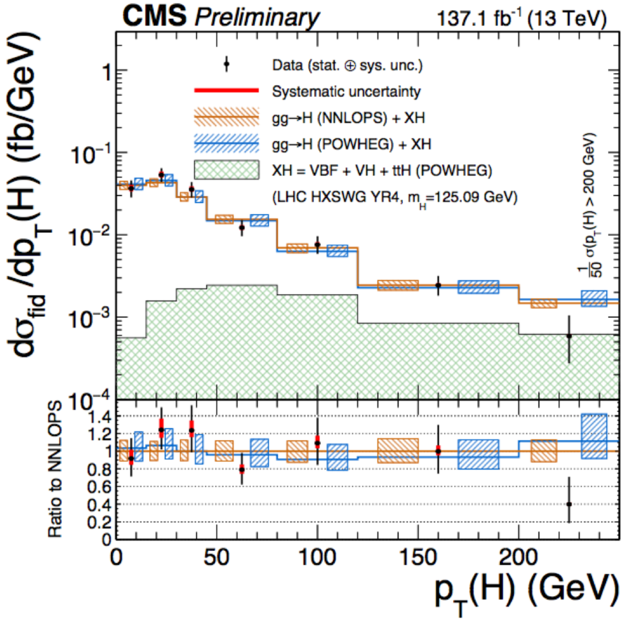


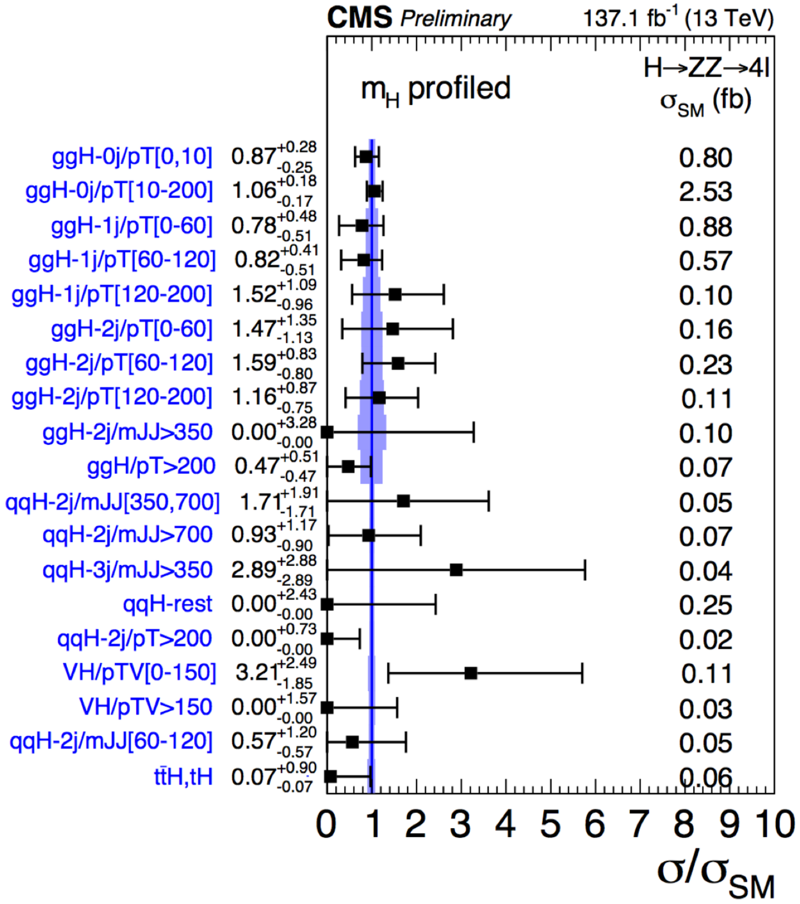


Higgs: 7 years after discovery

- Higgs physics has entered the precision era
  - Firmly established γγ, ZZ, WW decays
  - Excellent mass measurement 126.25±0.21GeV
  - Yukawa mechanism established in the last two years by the > 5σ observation of H→ττ, H→ bb & ttH processes
  - Differential cross section measurements comparing data to state-of-the-art calculations







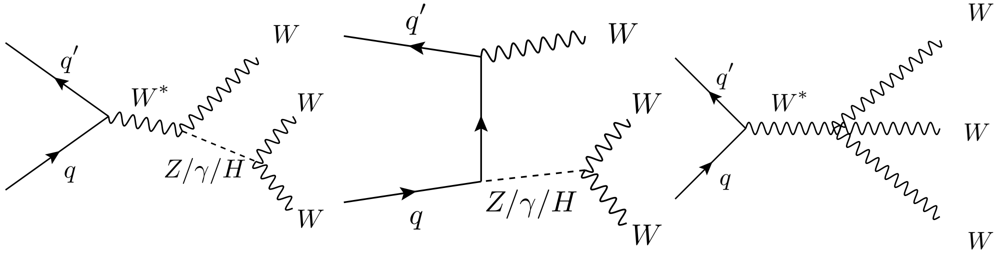
Simplified template cross sections enable Higgs measurements that are less model dependent

RARE SM PROCESSES

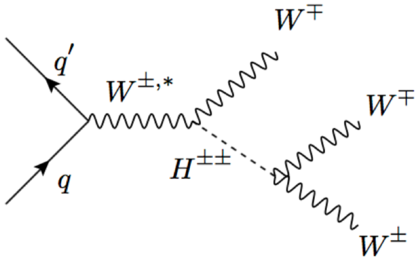
Large datasets allow us to test SM in complementary ways, giving us the opportunity to observe SM processes with small cross sections and measure multi-particle final states

Heavy Tri-Bosons

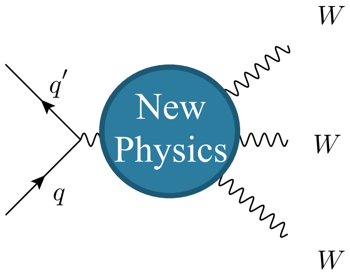
Higgs-mediated | triple gauge coupling | quartic gauge coupling



- Predicted by the SM & sensitive to BSM contributions

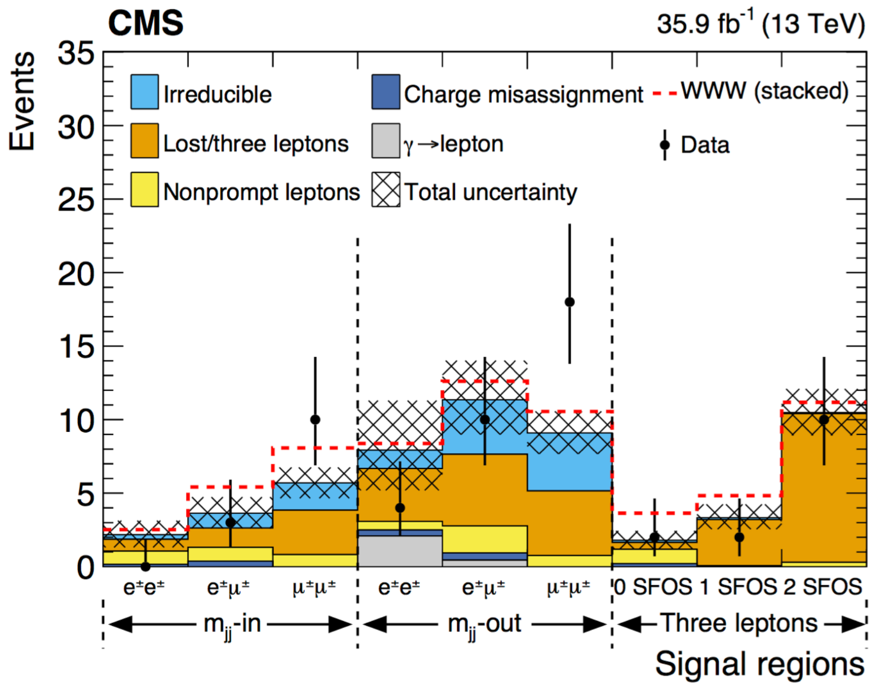


Doubly Charged Higgs/ axion-like particle



Anomalous couplings from BSM beyond the LHC kinematic reach

- Final states consider events with two SS leptons and 2 jets, or 3 leptons.
  - Irreducible background from ttW and WW production

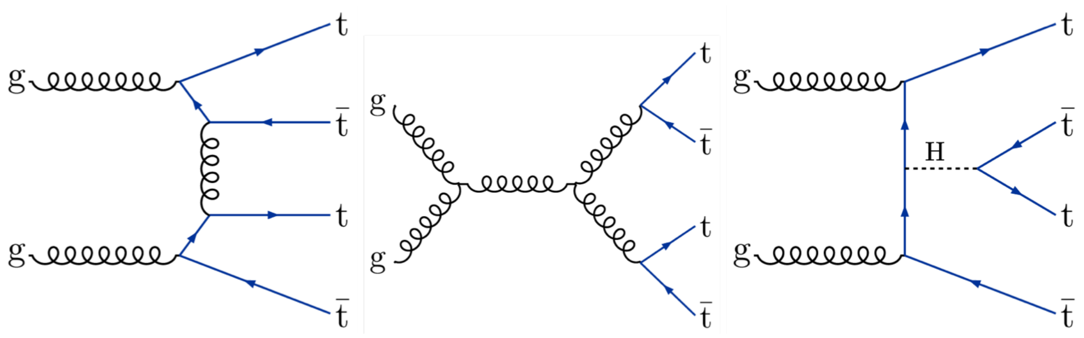


PAS-SMP-17-013

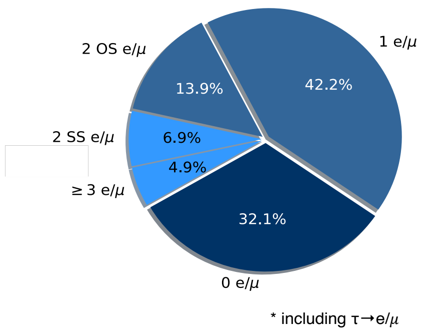
1.78/0.6 σ (expected/observed) → set limits on anomalous couplings

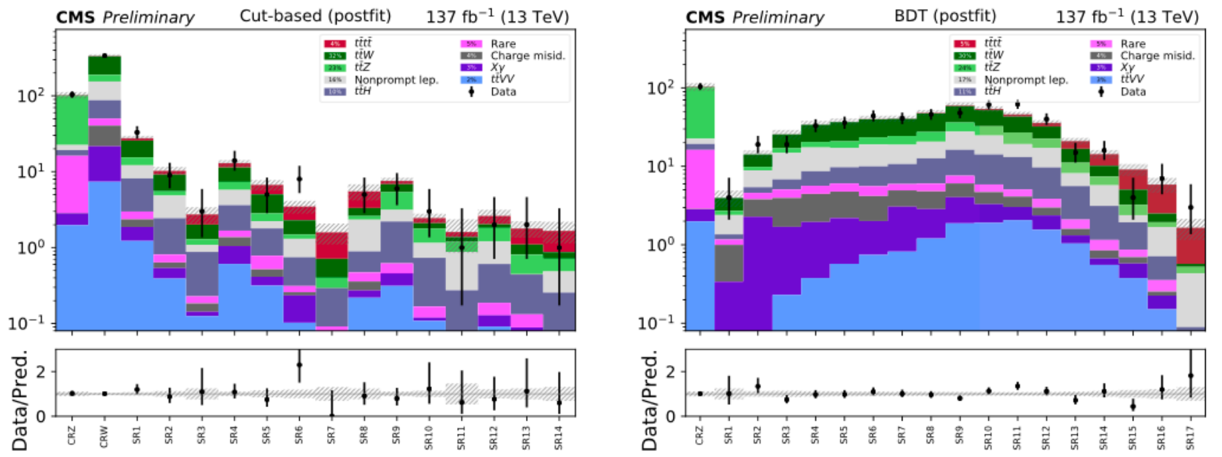
Anomalous coupling	Allowed range (TeV^{-4}) Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

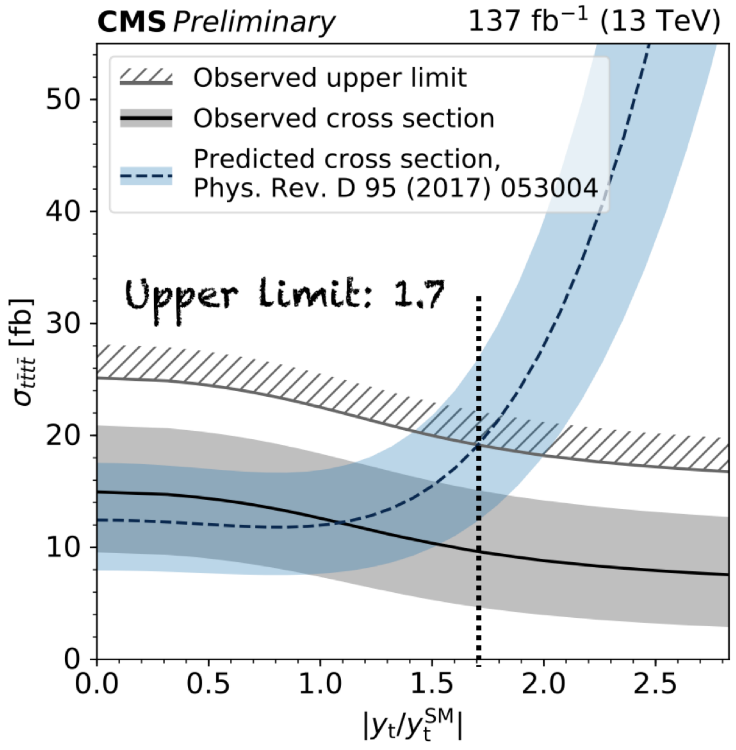
Four tops production



- In the SM, $\sigma_{tttt} \sim 10^{-5}\,\sigma_{tt}$ @ 13 TeV
  - can be used to constrain the magnitude and CP properties of the top quark Yukawa (y_t) coupling to the Higgs boson
  - Small cross section can be significantly enhanced by BSM processes
- Final states consider two same SS leptons or ≥ 3 leptons and jets (b-jets)
- Cut-based and BDT complementary analyses





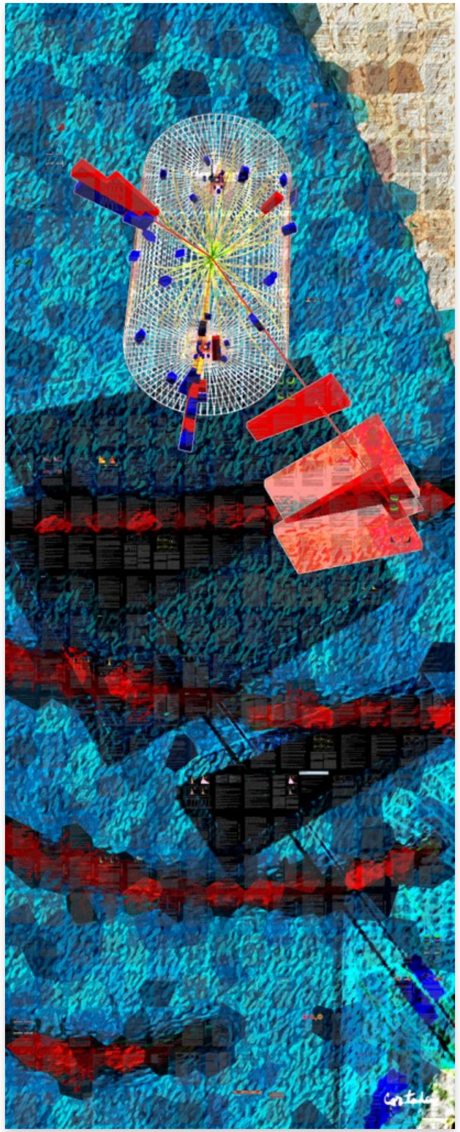


2.6 (2.7)σ obs (exp)
Constrain on top Yukawa coupling

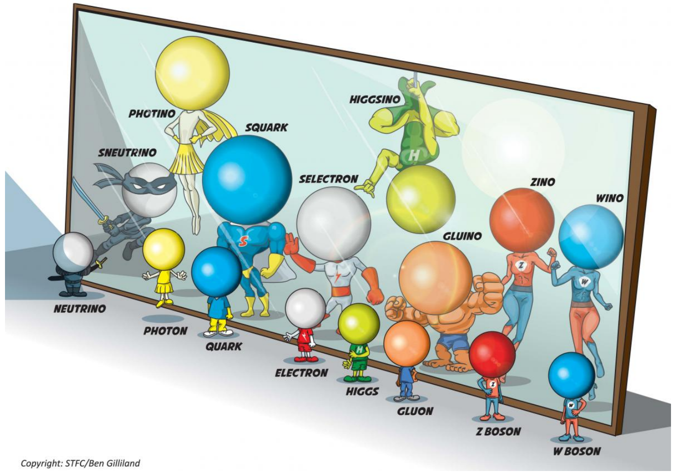
Due to the ttH background rescaling, the measured σ_{tttt} cross section depends on $|y_t/y_t^{SM}|$

PAS-TOP-18-003

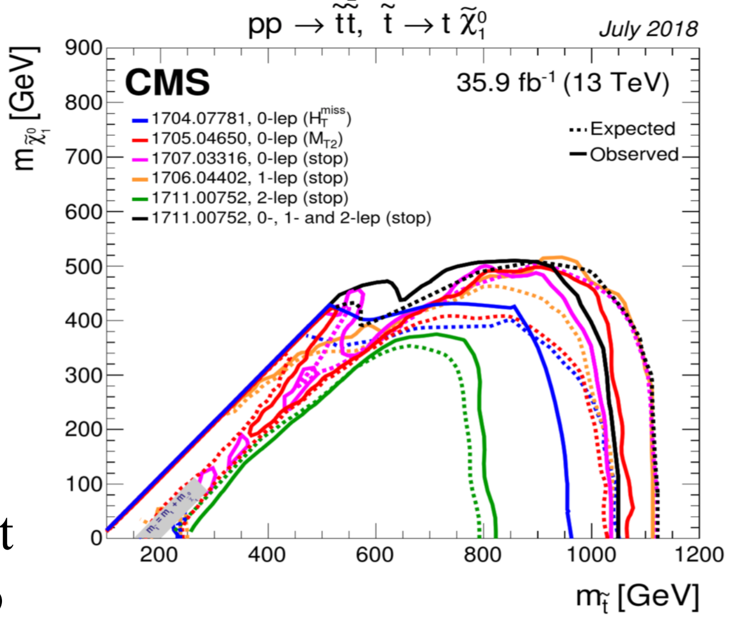
EXPLORING THE UNKNOWN

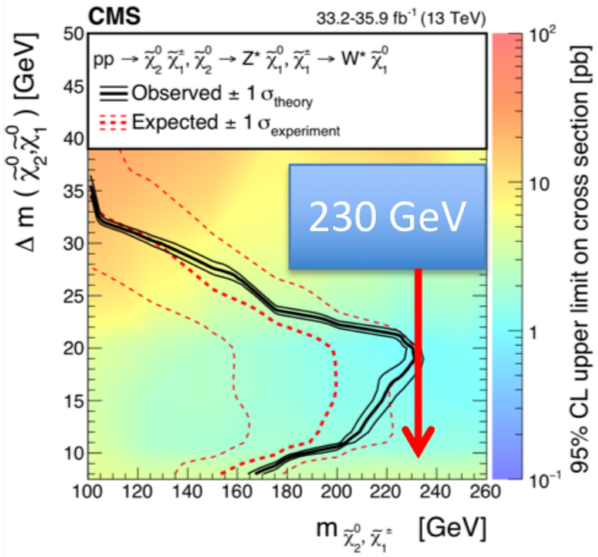


SUSY Searches



- Super partners cancel divergent terms to the loop corrections to the Higgs mass
- Theoretically compelling
  - Hierarchy problem
  - DM particle candidate
  - Unification of gauge couplings
- Many particles to discover!



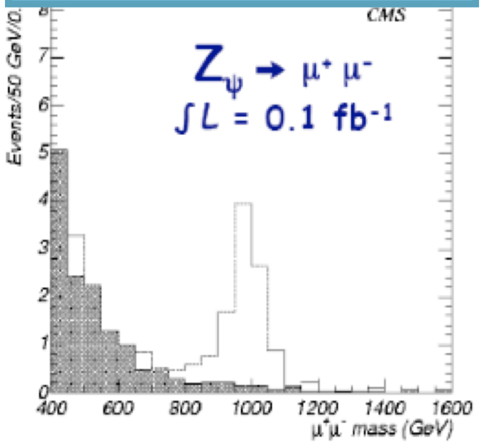


PLB 782 (2018) 440

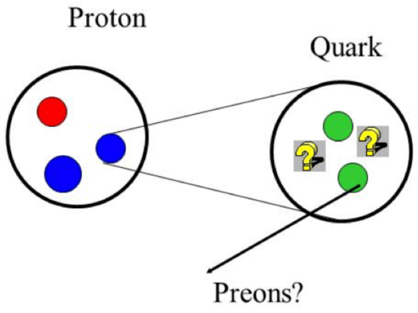
- The past years witnessed the exploration of TeV scale gluinos and squarks
- Just started to gain sensitivity to Higgsinos
  - expected to be the lowest mass SUSY particles (around a few hundreds GeV)
- CMS is now extending the search to un-explored regions of parameter space characterized by challenging manifestations of SUSY
  - Stealth SUSY, RPV SUSY, long lived SUSY, etc.
- Continued and improved searches at LHC and HL-LHC are essential to the exploration of BSM

No Shortage of non-SUSY Ideas

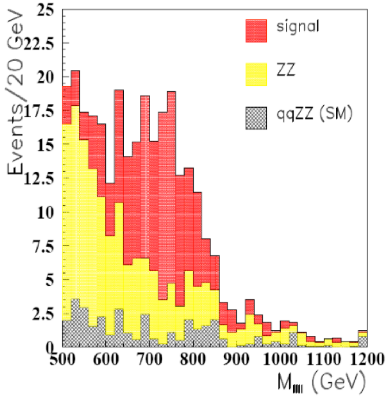
New Gauge Bosons



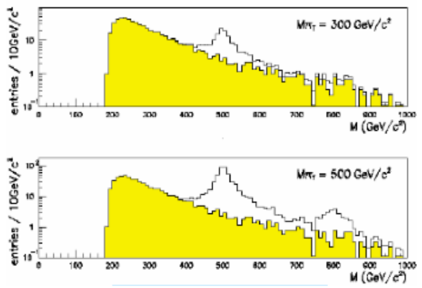
Compositeness



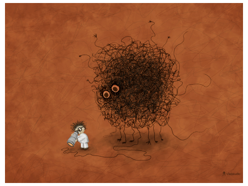
ZZ/WW resonances



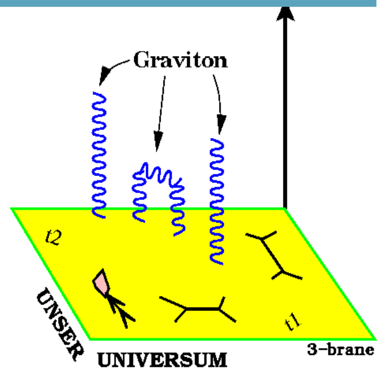
Technicolor



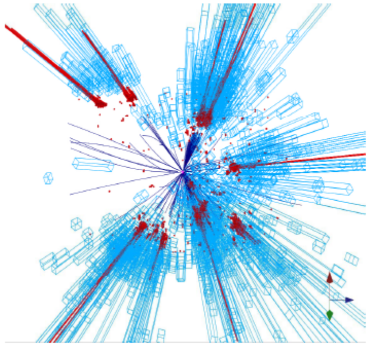
Are we looking in the right place?



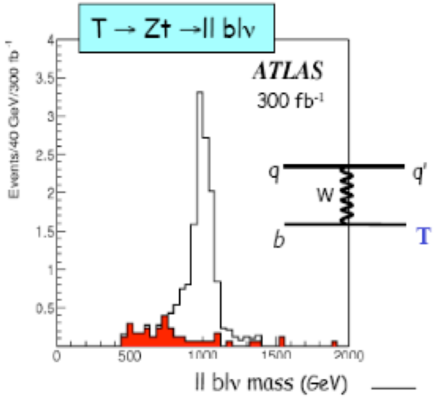
Extra Dimensions



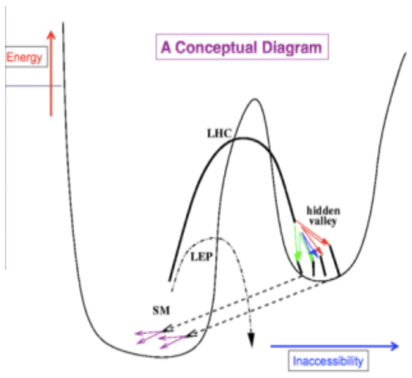
Black Holes



Little Higgs



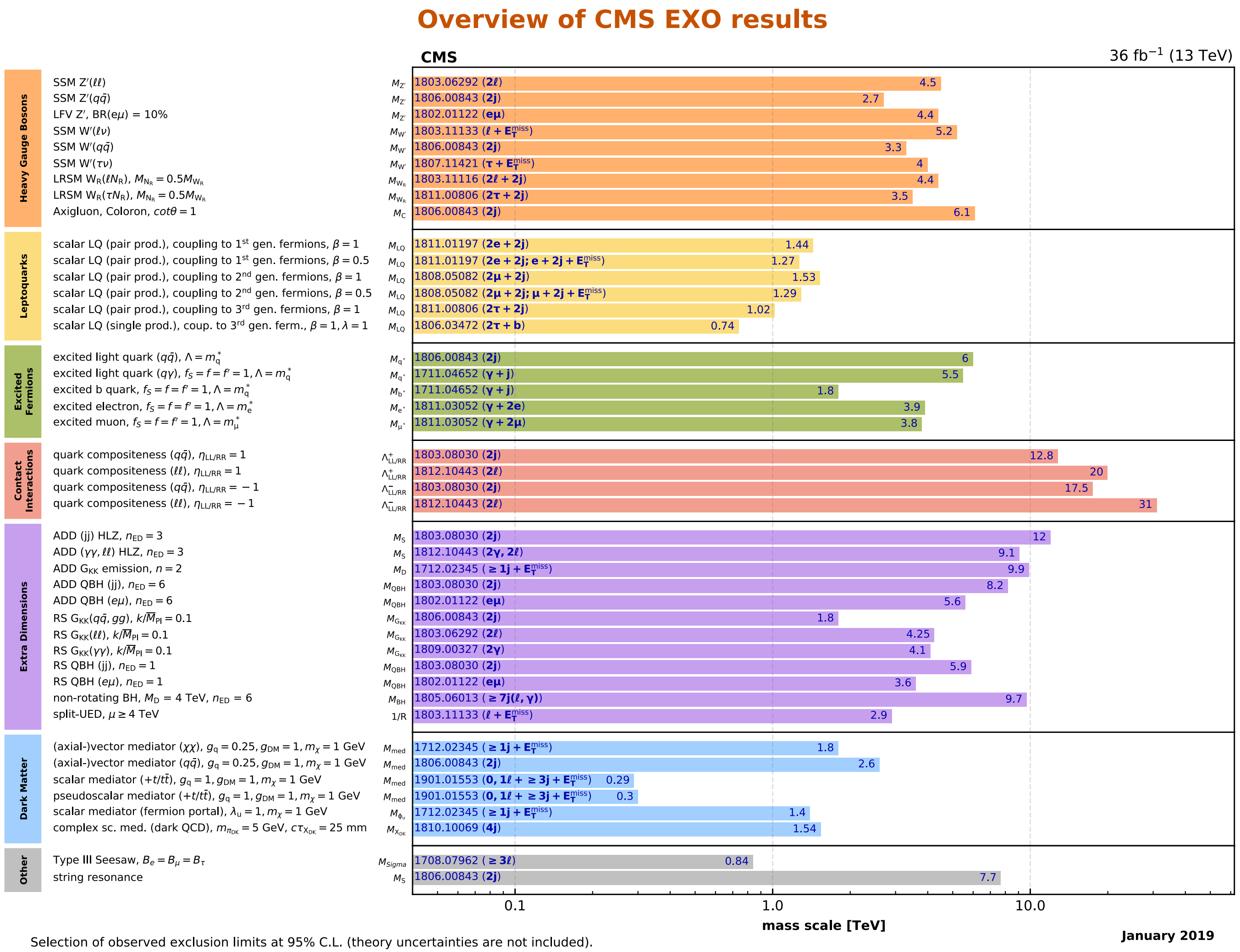
Hidden Valleys



Leave no stone unturned!!

A large variety of possible signals, carefully crafted analyses to cover all possible scenarios

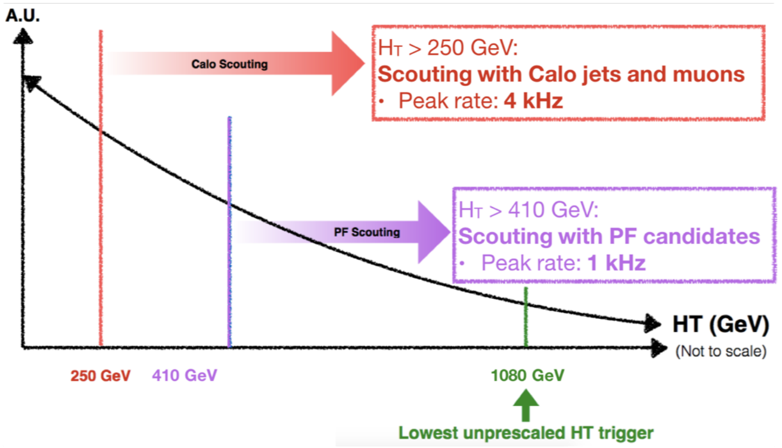
Continue pushing the frontier of exploration



Leads to New Ideas at all levels, from triggering, to event reconstruction to advances analysis techniques & influence how we are designing the future upgraded detectors for the HL-LHC era

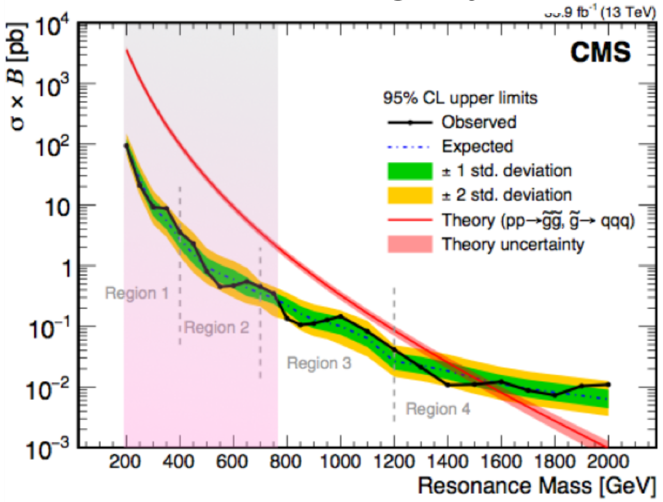
Data Scouting and Data Parking

- New techniques that extend the physics program by
- Delaying the reconstruction of data – Parking
  - Strategy: turn on a series of muon triggers in the low-luminosity, later part of each fill & improve the low p_T electron reconstruction
  - Large collection of unbiased B decays collected will shed light on flavor anomalies, rare B_S decays and light BSM searches (SUSY, DM)



- Reconstruct events online and store them with limited information – Scouting
- Large increase in the available data, expanding the reach, especially for lower masses

Calo Scouting Dijets



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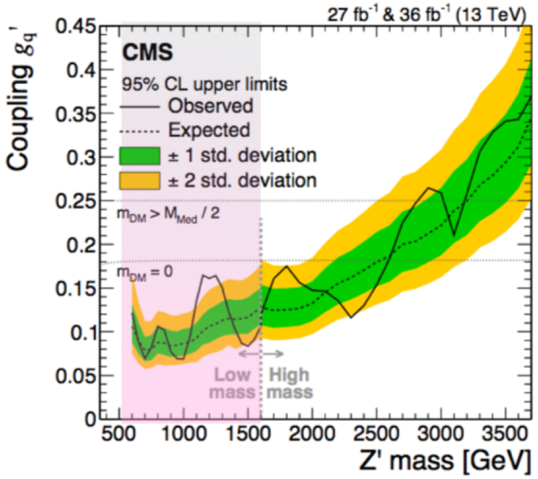
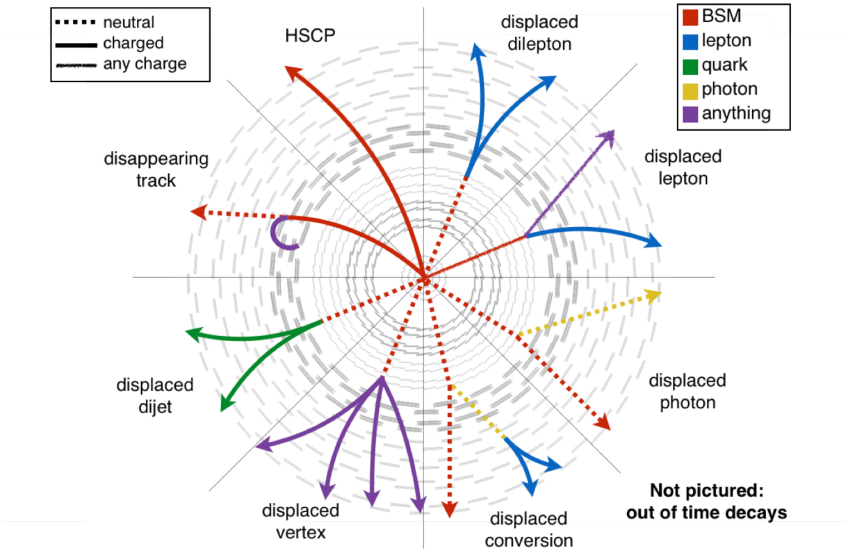
PF Scouting Trijets

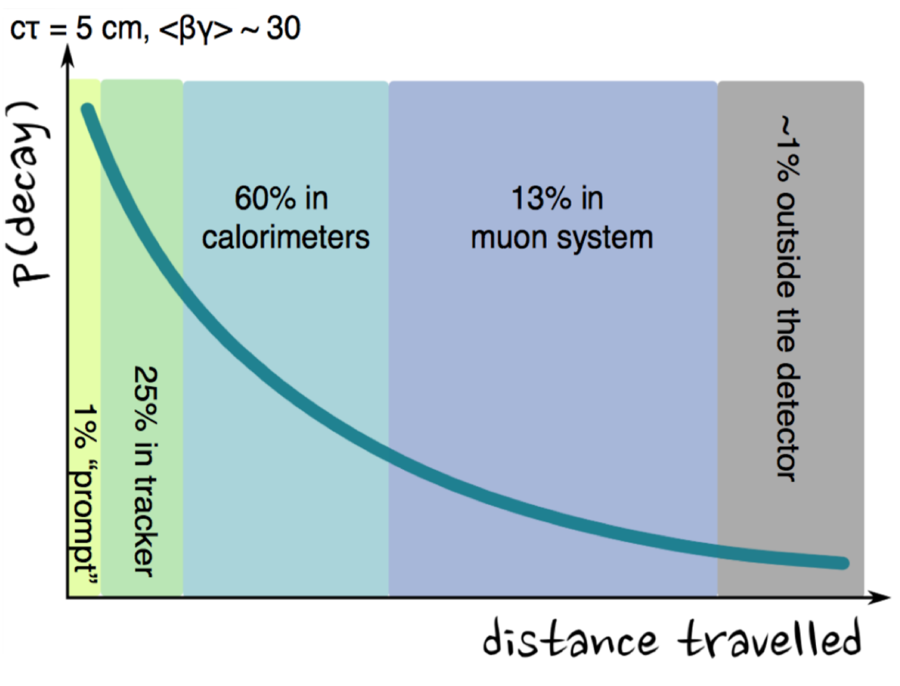


CMS-PAS-EXO-17-030

Long Lived particles

- Heavy LL particles would loose their KE and stop while traversing the detector
  - Deposits in calorimeters (or muon systems) with no associated tracks – Displaced
  - Tracks that have no associated hits in the calorimeters - Disappearing

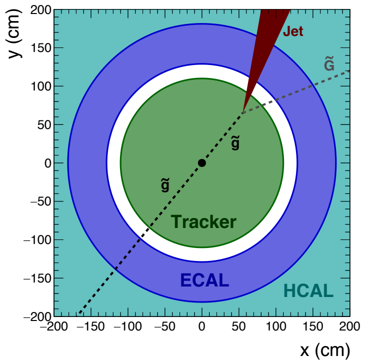


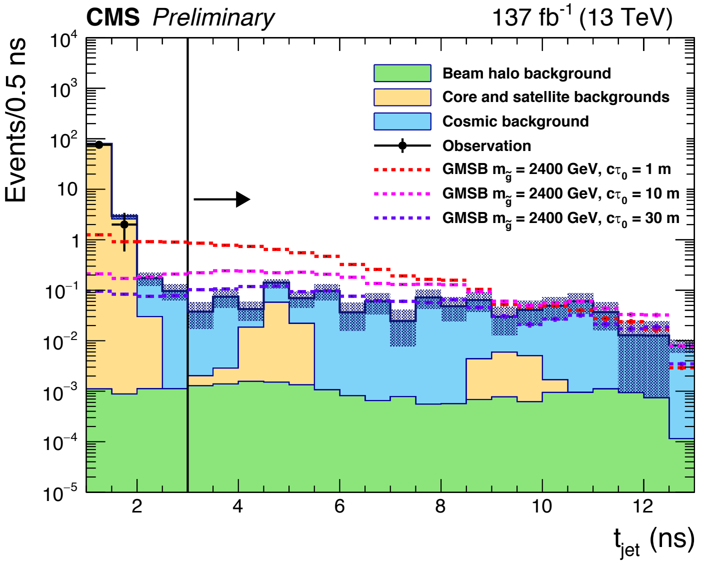


- Experimental Challenge:
  - modified object reconstruction
  - Add timing information to energy deposits

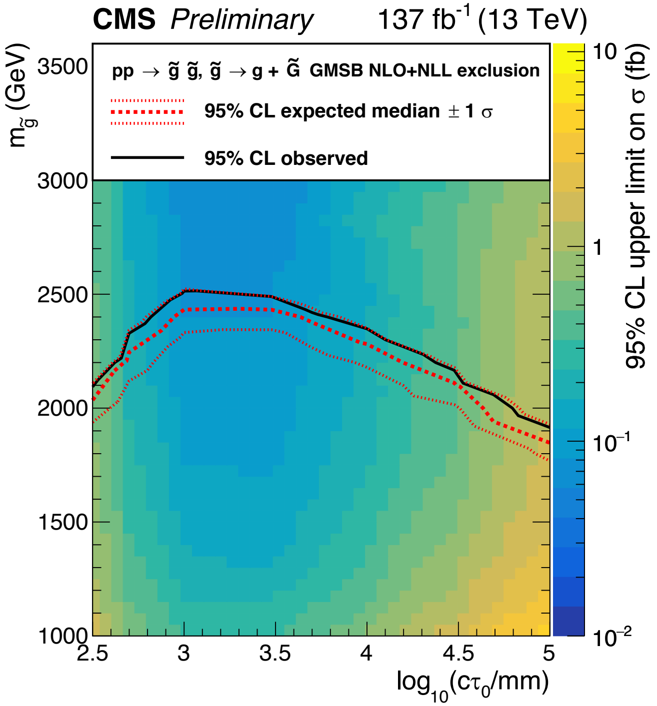
Delayed Jets using ECAL timing

- Jets clustered from calorimeter energy deposits
- PF not used for reconstruction
  - No tracks pointing to the IP





PAS-EXO-19-001

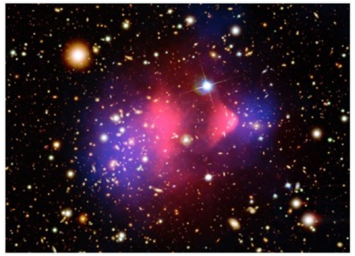


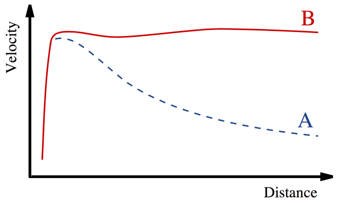
95% CL upper limit on x-sec in the gluino mass vs lifetime plane for the GMSB SUSY model

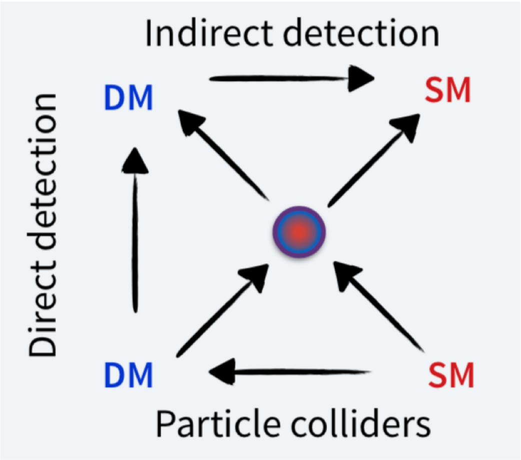
- Jet timing determined from ECAL cells
- Muon system used to veto cosmics
- Main backgrounds are beam-halo, out-of-time bunches and jets from cosmic muons

Advanced timing capabilities are becoming an integral part of the design considerations for the upgraded detectors

Dark Matter Searches

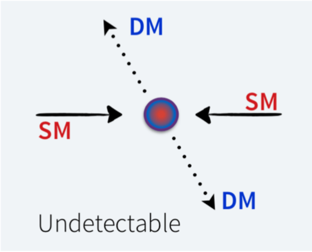


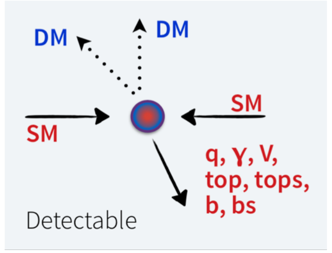




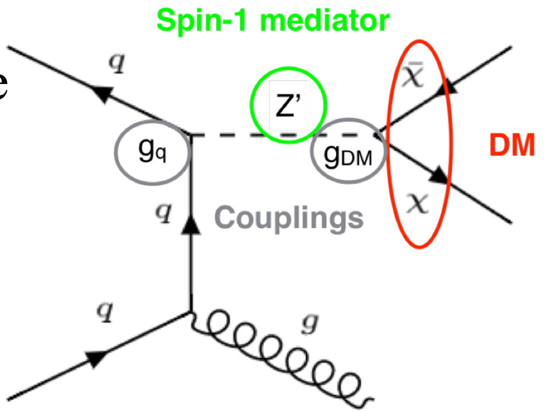
- Complementary strategies to look for non-gravitational DM interaction

- DM assumed to be weakly interacting and will leave no signal in our detectors
  - Identify DM production looking for other particles recoiling against DM. Understanding of MET crucial!





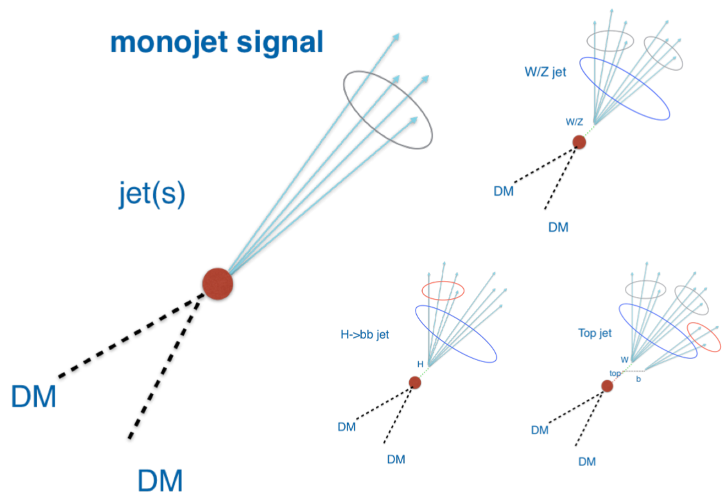
- Simplified Models
  - Describe dark matter without being constrained to a specific theory
  - Provide a common framework to compare collider and direct detection experiments
    - Model described by a small number of free parameters: M_{med}, M_{DM}, g_{SM}, g_{DM}
    - Results presented as M_{DM} vs M_{med} & cross section for DM-proton vs M_{DM} planes

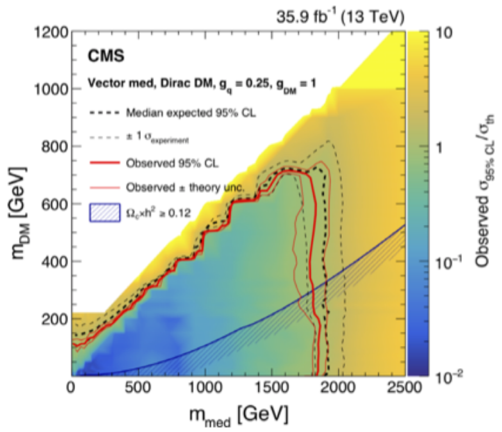


arXiv:1603.04156 (LHC DM Working Group)

DM Searches

MonoX+MET





PRD 97, 092005 (2018)

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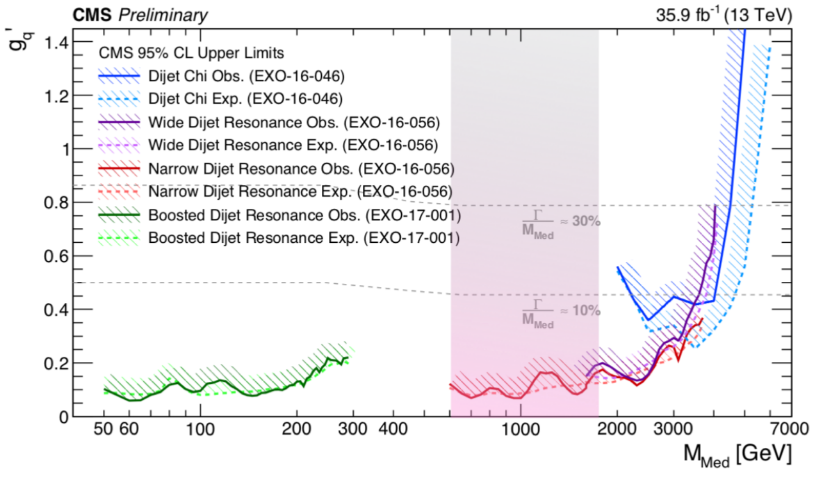
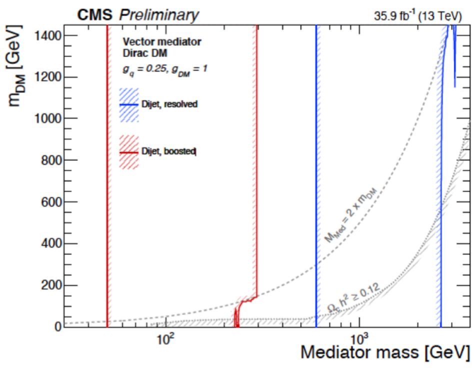
LIMITATIONS:

- Results from colliders are model dependent
- Assumption of couplings affects the limits
- Hard to compare with direct detection limits
- Coordination between ATLAS and CMS has been ongoing

Low Mass Dijets w/ Scouting



ttbar+jet with intermediate mass top tagger

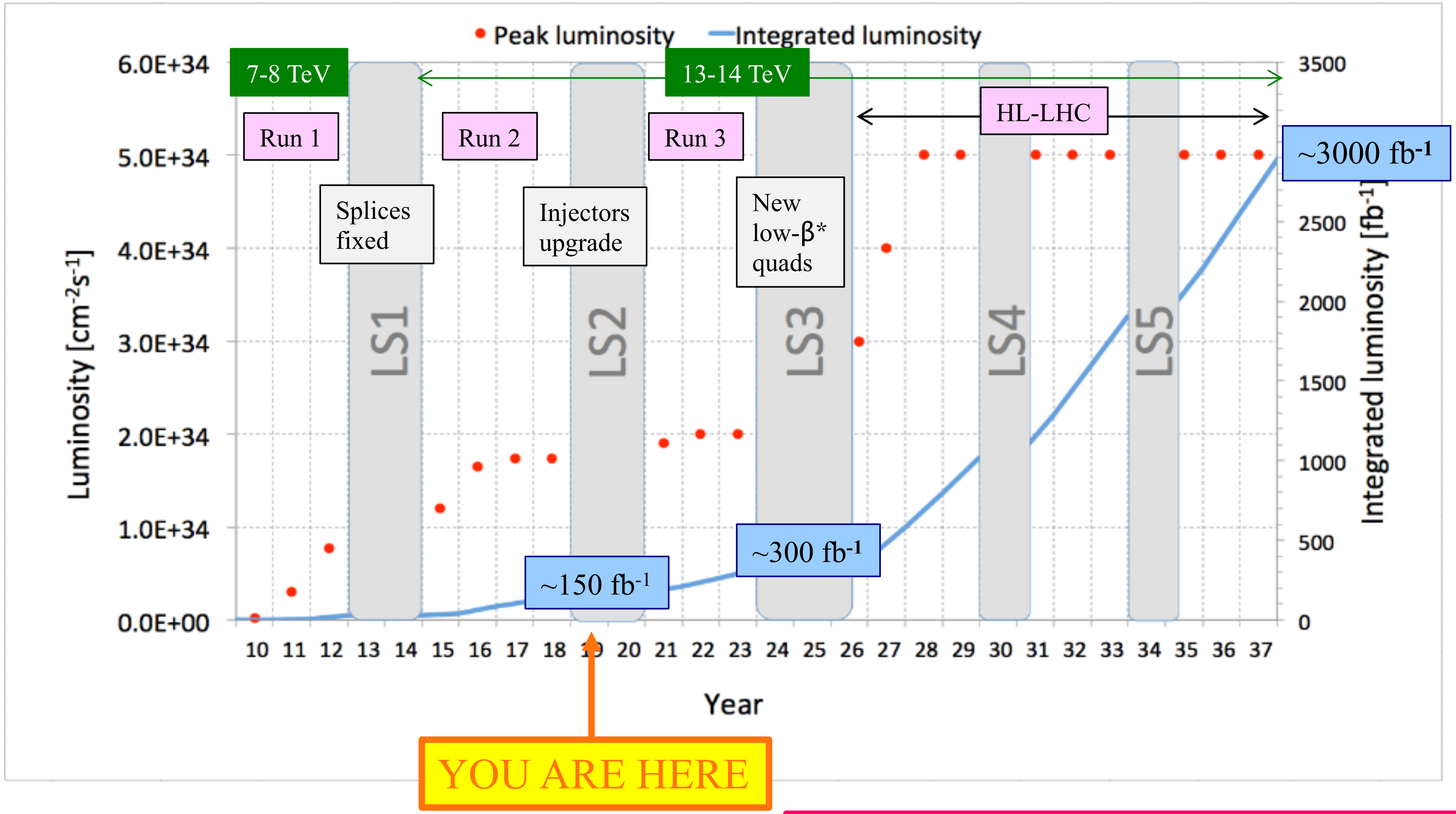


PAS-EXO-17-001

DM forum established by the LPC with Direct Detection Experimentalists and Theorists

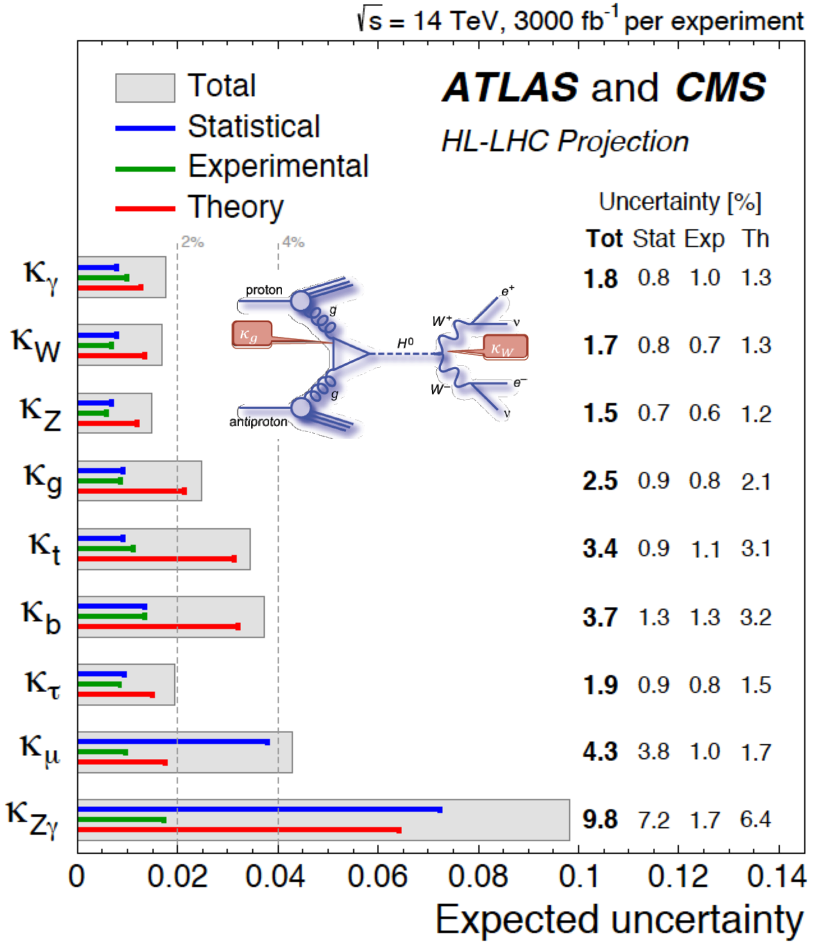
THE ROAD AHEAD

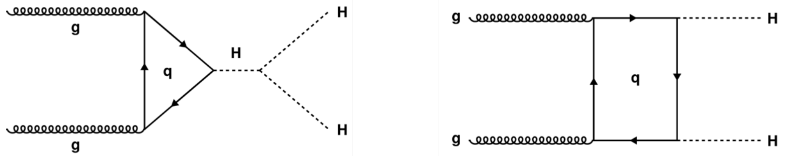
LHC Run Plans

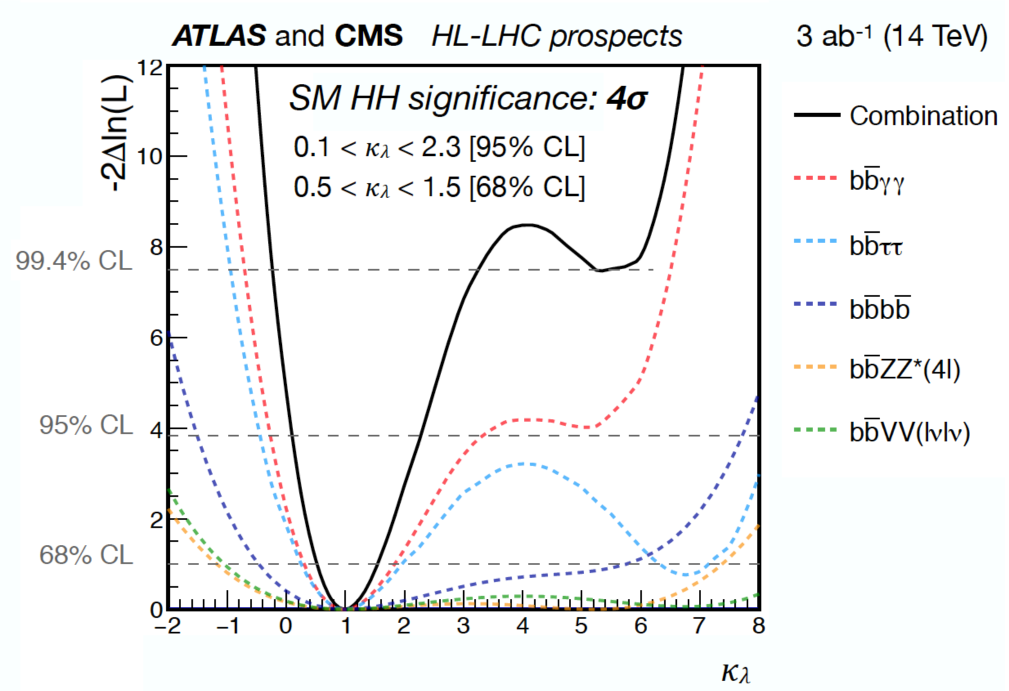


We only collected 5% of the expected LHC data!!
In many areas only analyzed about 1% so far

Higgs Couplings



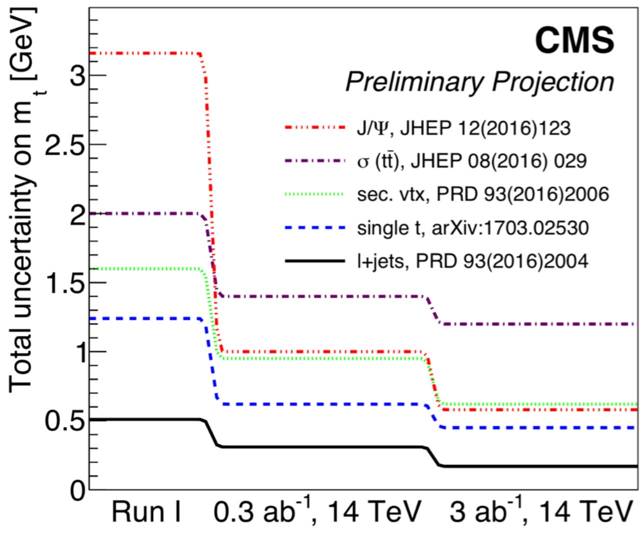




Combinations from
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop#Final_reports

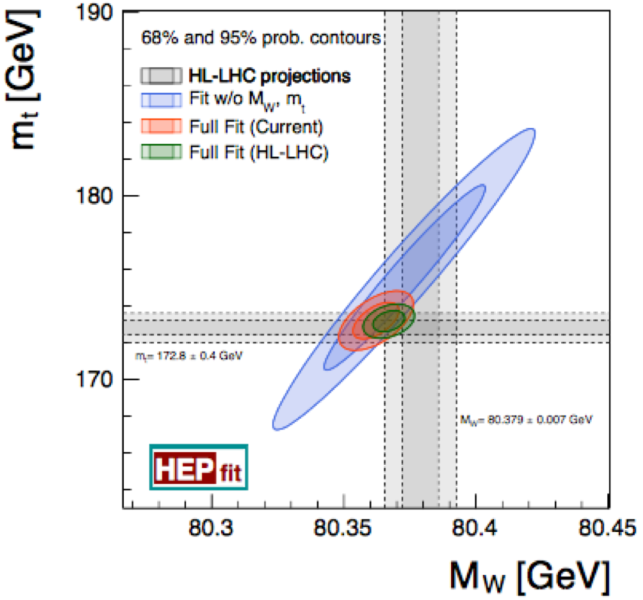
Measurements of the Higgs trilinear interaction would provide constraints on the shape of the Higgs potential close to the minimum, and would allow to verify the EWSB mechanism of the SM

Precision top/EW Measurements

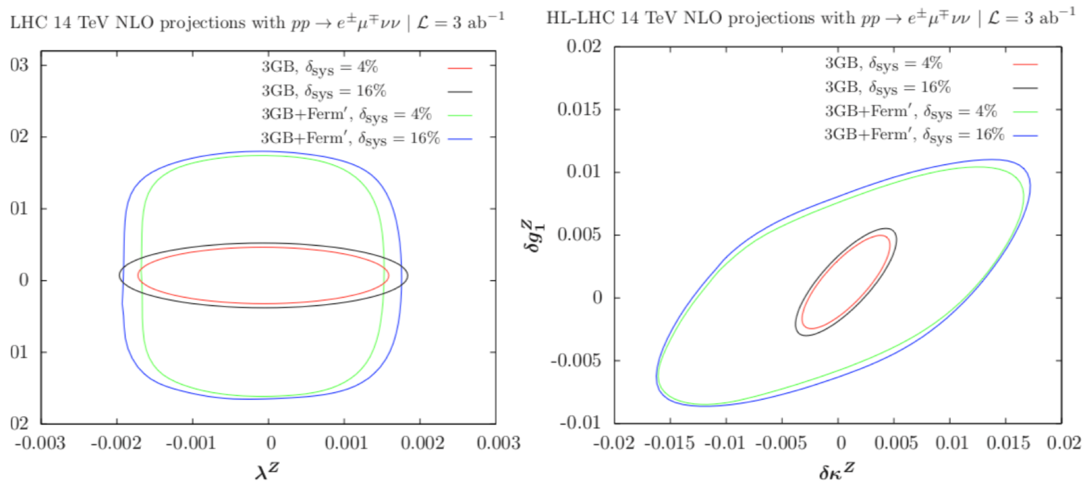


Uncertainty on the top mass

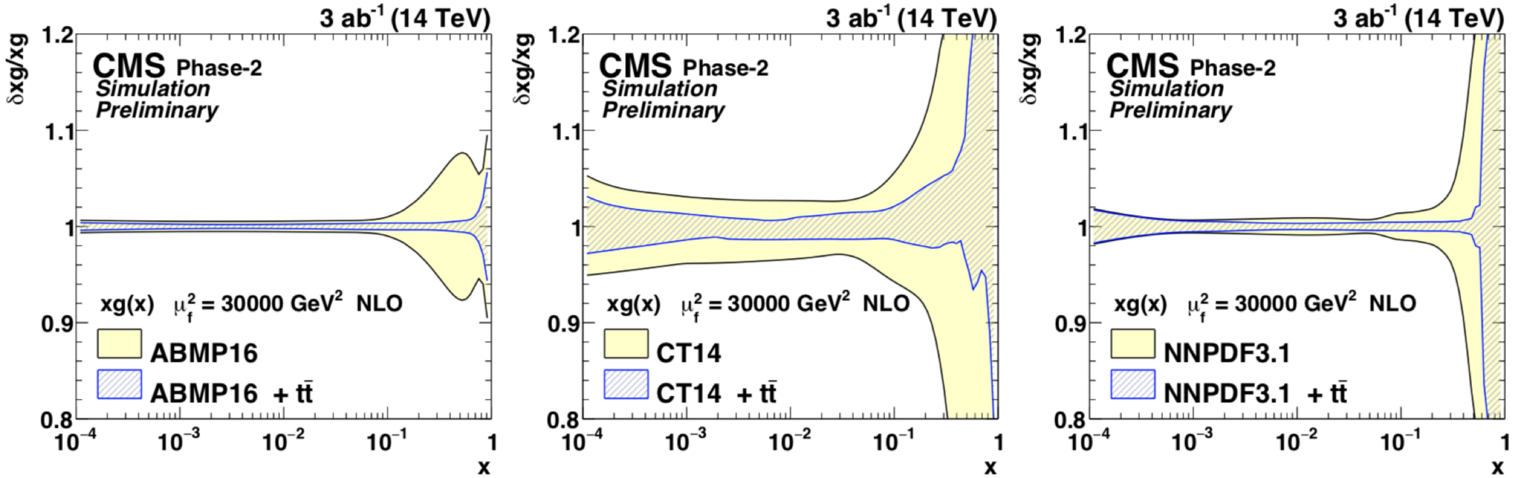
Current and projected EW fit



Anomalous 3-gauge boson couplings

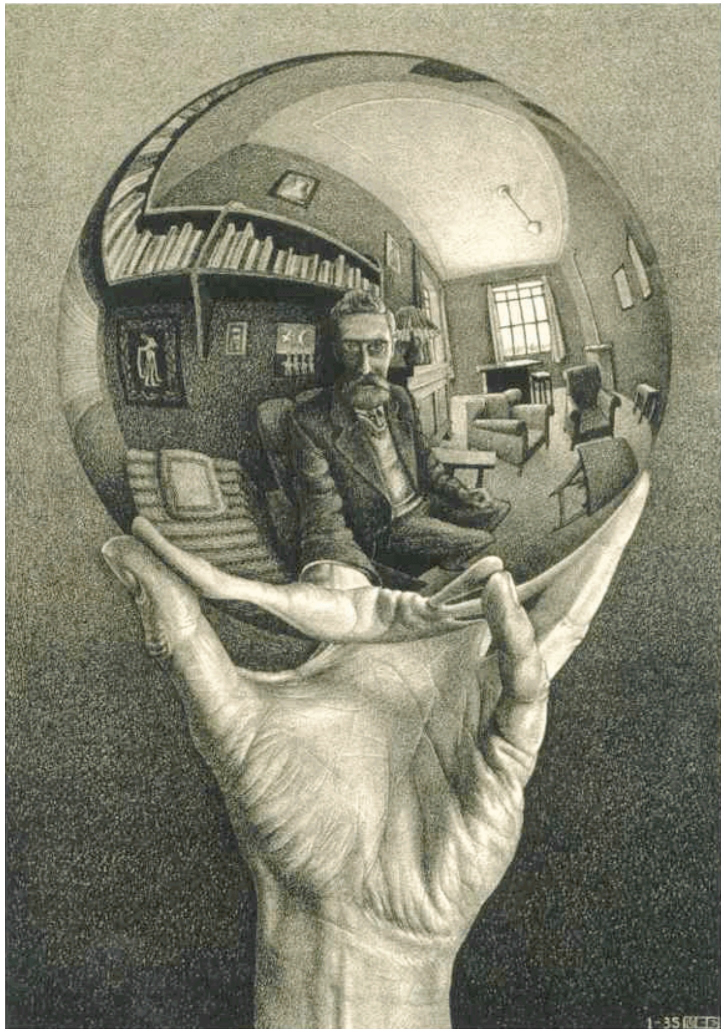


Departure from precise SM predictions could be an indication of new physics at a mass scale beyond the reach of the LHC

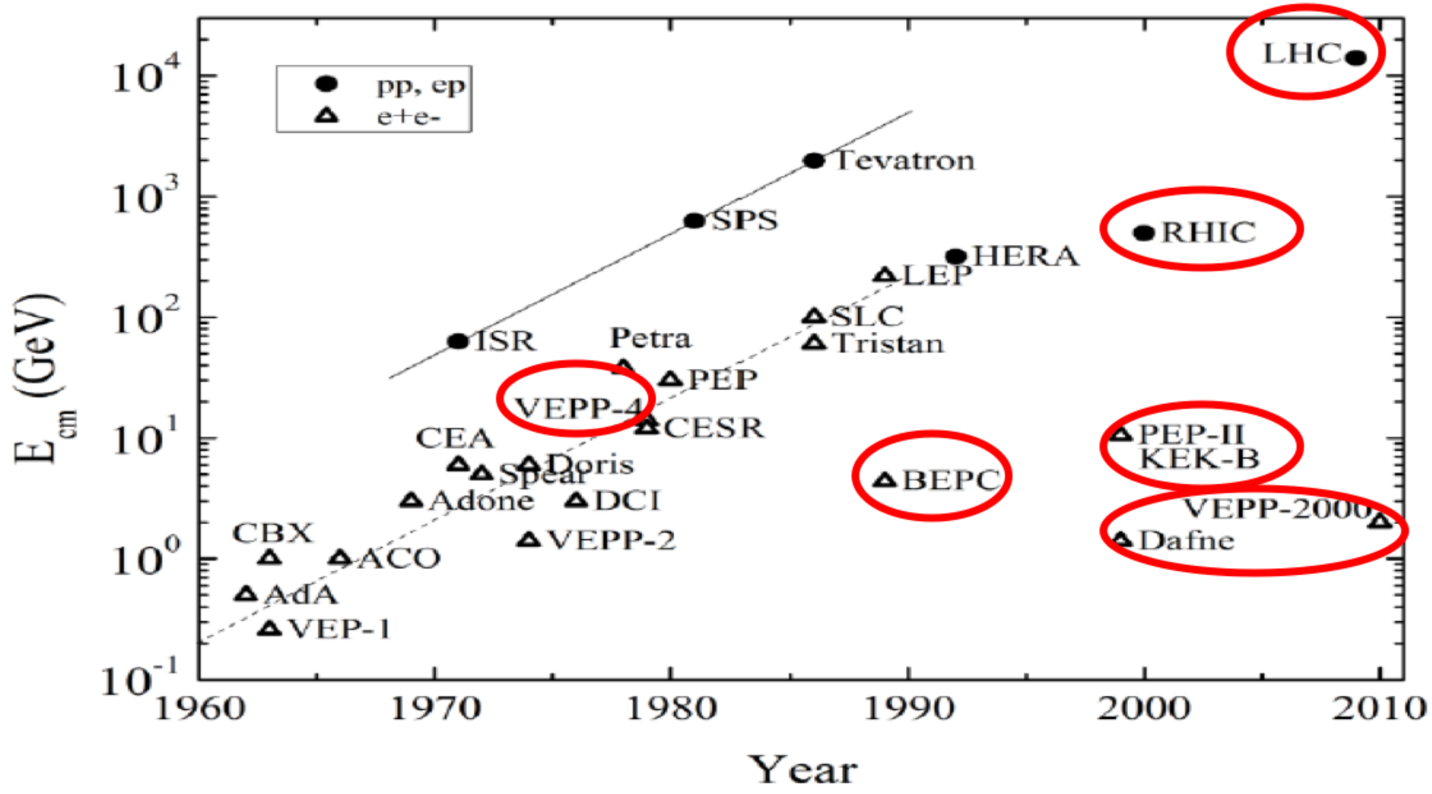


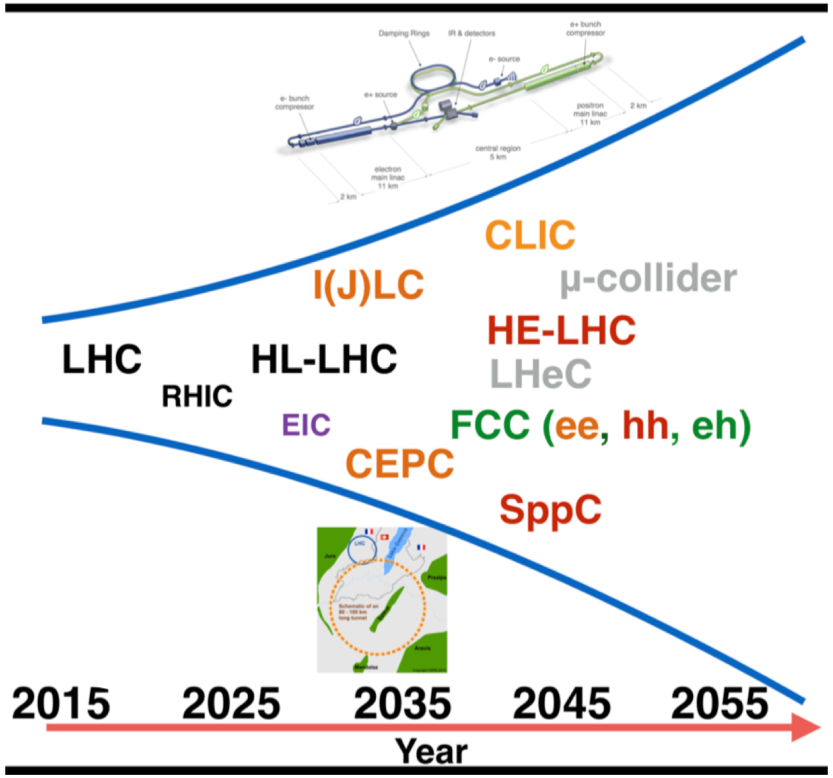
PDF constraints from double-differential $t\bar{t}$ cross sections

THE FUTURE



HL-LHC and Beyond





- Single high energy hadron collider – the LHC, now at 13 TeV, RHIC heavy ion (e/ion)
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy $e^{+}e^{-}$ colliders
- SuperKEK-B – b-factory at KEK re-stared in 2016 to reach ~40 times higher luminosity

New colliders are needed to produce particles with masses above the LHC energy reach

Outlook – the next 20 years

- LHC just entered a two year shutdown
  - Double the data sample during Run 3 ~2021
  - 10 times the data during the HL-LHC era ~ 2025
- The Higgs Boson is the cornerstone of the LHC physics program
  - Precision measurements probing SM and looking for cracks in the SM that might indicate BSM processes with masses above of the LHC reach
- Searches for Beyond the Standard Model phenomena cover huge ground
  - Model-guided and model-independent, leaving no stone unturned
- Exciting technical challenges ahead
  - If history is a our guide, prior projections regularly surpassed by real results once the data is in hand and new techniques are developed
  - Surprises might be around the corner

We have only collected 5% of the data we expect from the LHC
We may not have seen an obvious sign of new physics in the data yet – however, what that implies is that we have to get cleverer and make sure we look in every corner and leave no stone un-turned
FUN AND EXCITING TIMES AHEAD OF US!

MANY THANKS TO EVERYONE WHO CONTRIBUTED MATERIAL! (KNOWINGLY OR NOT ☺)

Special Thanks to Sergo Jindariani, Anadi Canepa, Matteo Cremonesi, Rick Cavanaugh, Justin Pilot, Caterina Vernieri, Chris Palmer, Albert De Roeck, Sarah Eno, Jamie Antonelli, Markus Klute, Dmitri Denisov, Tulika Bose