Status of the CMS Experiment: Highlights, and Perspectives

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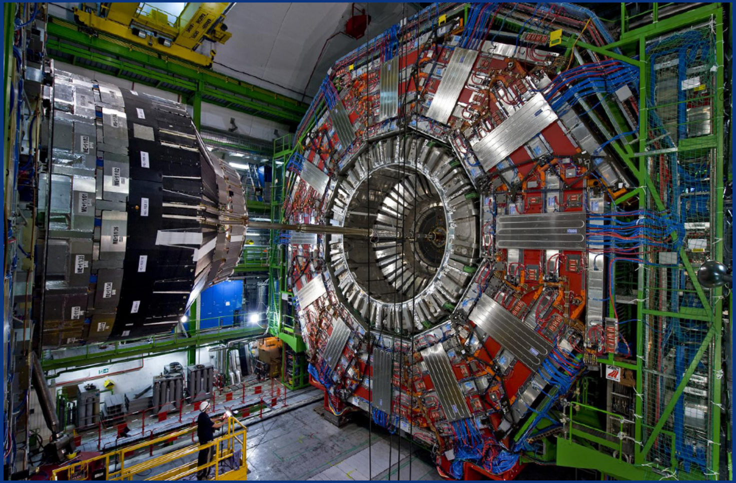
LISHEP2018: LISHEP Workshop on High Energy Physics - Session C - Heavy Particles and Flavours

Salvador, Brazil

Sept. 10, 2018



Outline

- Introduction
- LHC and CMS Performance at 13 TeV center-of-mass energy in 2016/17/18
- Recent Physics Results
- The Future: HL-LHC Upgrade
- Summary and Outlook

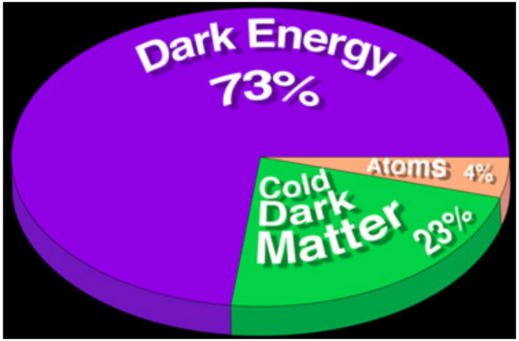
Status of Particle Physics at the LHC

- The Higgs boson, with mass 125.09 GeV/c^2, was discovered 6 years ago at the Large Hadron Collider. The presence of the associated Higgs field explains how elementary particles get their mass and, in some sense, "completes" the Standard Model (SM) of particle physics.
- But the SM model still does not explain many of the phenomena of our physical universe

The Standard Model Report Card

Need for additional physics "Beyond the Standard Model (BSM)"

- **Does not explain the stability of the Higgs to higher order quantum effects (Higgs is too light);**
- **Does not explain the Baryon Asymmetry of the universe (predicts too little matter);**
- **Does not explain why there are three generations of quarks and leptons or their mass values (the "Flavor Problem");**
- **Offers no explanation for neutrino masses; and**
- **Does not provide a Dark Matter candidate and therefore does not explain 85% of the matter in the universe.**
- **Does not incorporate gravity or explain dark energy**



Berkeley Cosmology group

For all its successes, the SM cannot explain how we arrived at the universe that exists today.

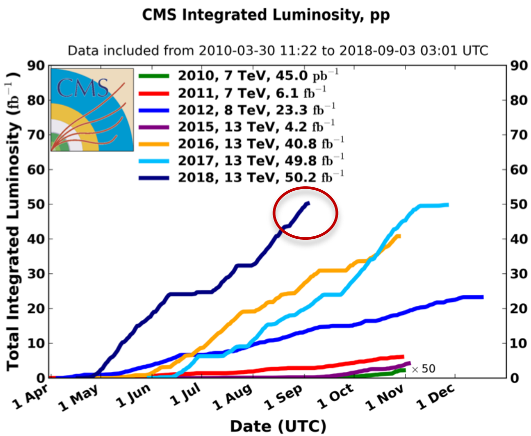
GRADE = INCOMPLETE

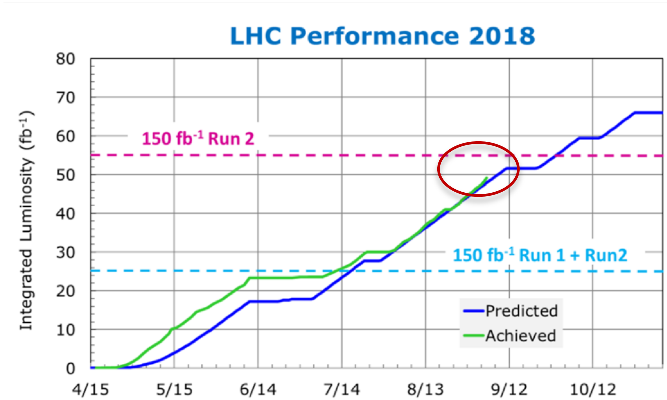
What is next?

- There are still strong reasons why some of the missing pieces should appear at the TeV or "Tera" scale, accessible at the LHC.
- There are many ideas, theories, and models about what BSM physics will look like but there is no clear guidance on the **best place** to look and the **"right place" may not even be in our current menu of ideas**
  - A broad investigation on many fronts is necessary
- We have three basic tools for exploring this large, as yet largely uncharted, territory
  - **Studying the properties of the Higgs that, through its coupling directly to MASS, can make contact with hidden sectors that are invisible to us otherwise**
  - **Looking for deviations from the precise predictions of the SM**
    - **Can allow us to study particles that are too heavy to be directly produced at the LHC**
  - **Searching directly for new particles and new forces**
- **All three strategies require more statistics,** for which particle physics has a plan based on the extraordinary capabilities of the LHC

LHC and CMS Performance at 13 TeV in 2016-2018 a.k.a. LHC Run 2

LHC Performance





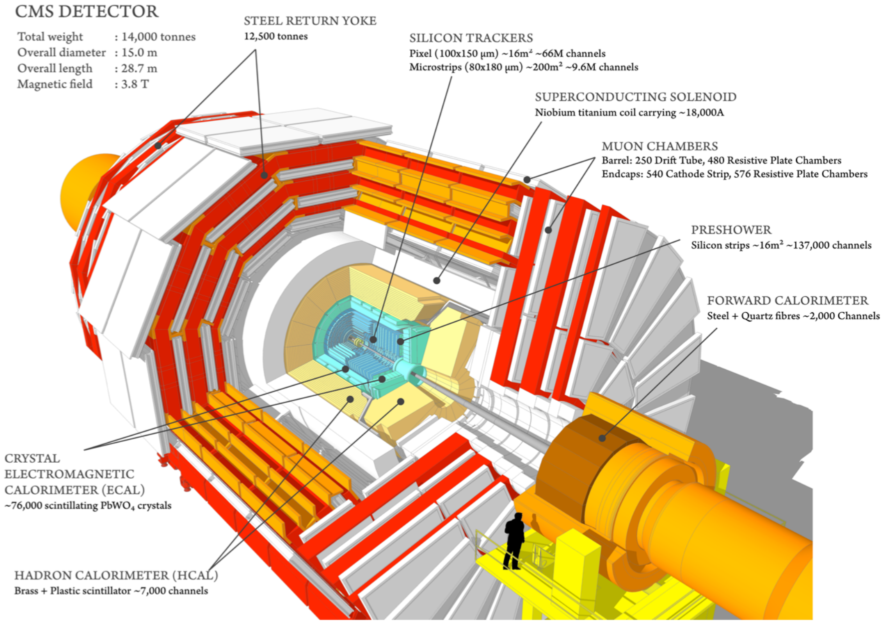
- LHC has produced 3 years of sustained high luminosity at 13 TeV that is expected to result in >150 fb^{-1} by the end of the 2018 run
  - It has exceeded peak DESIGN Luminosity by a factor of 2!
    - 2018 maximum peak luminosity ~$2x10^{34}$ cm^{-2} s^{-1} with mean pileup ~ 38
- LHC has much higher availability than expected, >50% of the time in stable operation
- Rapid turn-around between fills (5 hours typical, ~2 hours record)

CMS HAS HAD TO EVOLVE TO KEEP UP--- PHASE 1 UPGRADE

CMS Detector

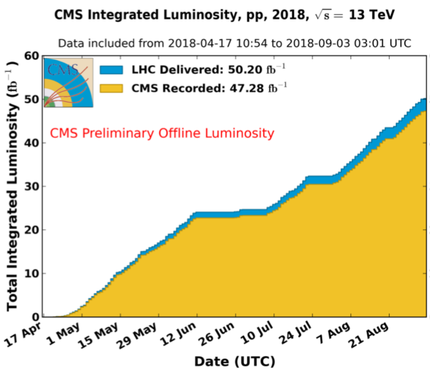
CMS Design

- A very large solenoid - 6m diameter x 13 m long
  - Tracking and calorimetry fit inside
- Very strong field – 3.8T
  - Excellent momentum resolution
- Chambers in the return iron track and identify muons, leading to a very compact system
- A lead tungstate crystal calorimeter (~76K crystals) for photon and electron reconstruction
- Hadron calorimeters for jet and missing E_t reconstruction to η~5
- Charged Particle Tracking with all-silicon components
  - A silicon pixel detector out to radius ~ 20 cm
  - A silicon microstrip detector from there out to 1.1 m
- Weight, dominated by steel, is 14,000 Tonnes

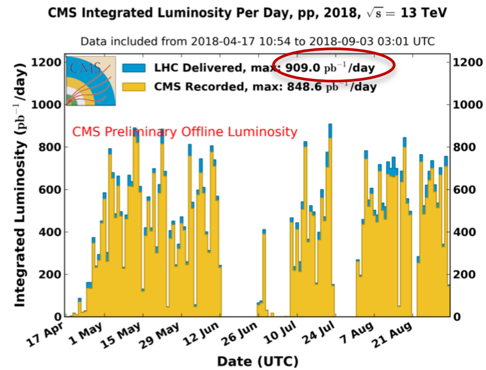


CMS is continuously upgraded to handle higher luminosity and do better physics

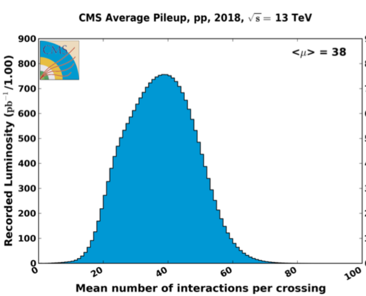
Luminosity Accumulation in CMS



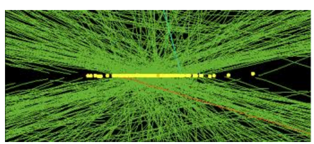
Recording Efficiency 94.2%

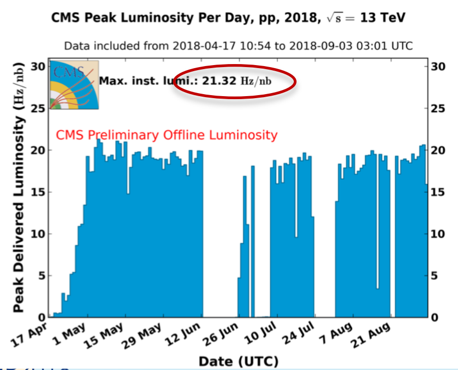


Can get 800 pb^{-1} In a day!



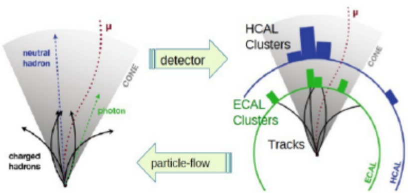
Mean Pileup 38 int/Xing



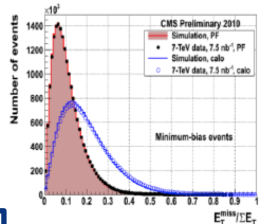


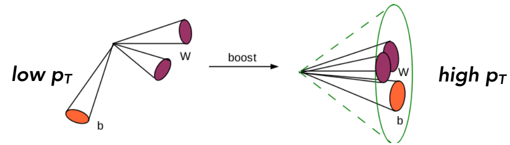
Peak lumi ~1.8-1.9 x 10^{34}. $cm^{-2}s^{-1}$

Evolution/Improvement of Analysis Techniques



Particle Flow





Boosted Jets, Jet Substructure

- Particle Flow uses all available information to reconstruct physics objects, e.g. charged track momenta in jets
  - produces a big improvement in jet energy resolution, tau-lepton identification, and helps with high pileup
- PUPPI (PileUp Per Particle Identification) is a special tool to deal with high pileup
- Use of multivariate analysis techniques to maximize power of available statistics
- Boosted jet topologies and jet substructure analysis
- Use of Deep Neural Nets/Machine Learning

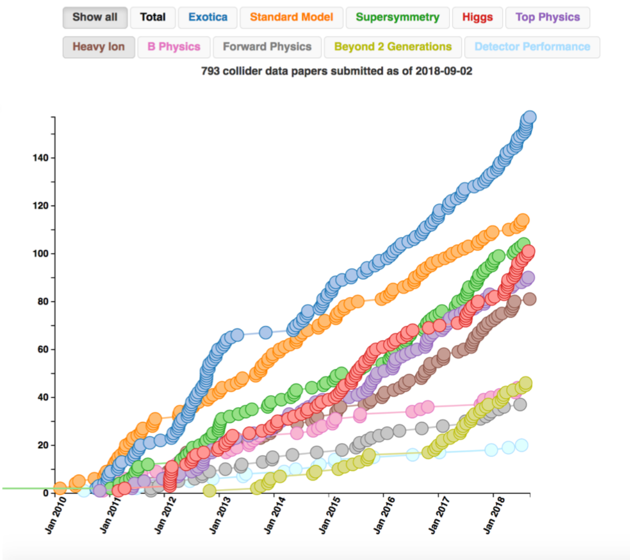
Rapid growth in 2017/18

Recent Physics Results

Publication Status

793 Papers on collider data submitted in ten categories

- It is not practical in this talk to try to summarize even this summer's papers, let alone put them in context.
  - Please attend the many excellent talks by CMS speakers and on CMS results throughout this meeting
- I will discuss a few highlights from Higgs, Top, and B physics and Searches (SUSY, Exotics)



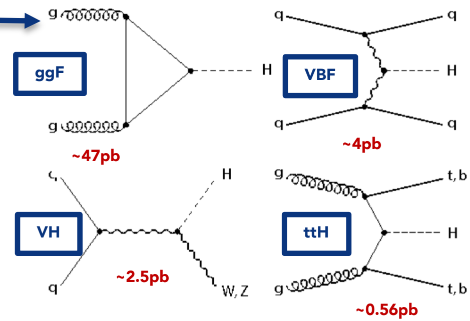
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

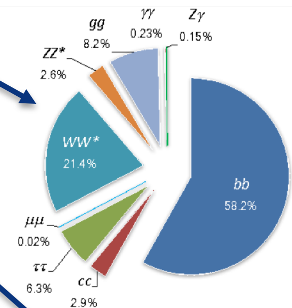
Recent Physics Results - 1

Higgs

Higgs Refresher

- There are four main basic production modes
- There are ~8 SM decays into vector bosons, quarks, and leptons that are observable
- An analysis typically targets some combination of decay modes and production processes based on their sensitivity
- Signal to background, ability to trigger are key features (smaller BRs, $\gamma\gamma$ and 4 leptons (μ,e), were the discovery channels





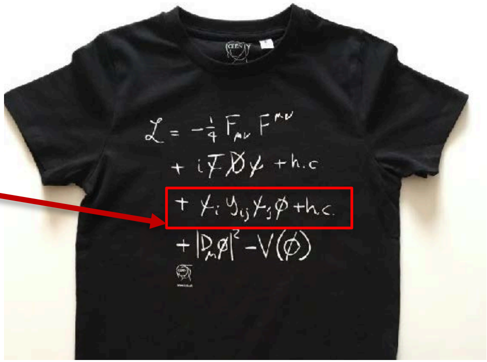
	ggF	VBF	VH	ttH
H→ZZ→4l	•	•	•	•
H→γγ	•	•	•	•
H→WW	•	•	•	•
H→bb	•		•	•
H→ττ	•	•		•
H→μμ	•	•		
H→inv	•	•	•	

- **"Established" Properties**
  - Mass: 125.09 ± 0.21 ± 0.11 GeV
  - Spin: 0
  - Width: <1 GeV (direct); <0.013 GeV (indirect)
  - Signal Strength Modifier, μ, of various processes, including ttH, defined as
    - $\mu = (\sigma x BR)_{obs}/(\sigma x BR)_{SM}$

Higgs Yukawa Couplings

- **Liberally borrowing from talk by Gavin Salam at LHCP 2018**
- Higgs doublet gives mass to vector gauge bosons, but not the fermions
- **The Higgs Yukawa interaction** is **a highly motivated conjecture** to give mass to the fermions
  - But no such term ever before seen in nature. **NOT A GAUGE INTERACTION!**
  - Not probed in any EW precision test
  - Indirect support for it through strong production of Higgs bosons via top loops
    - Could also be non-BSM contributions i
  - **Observation is difficult**
    - Expect to see first in 3rd generation particles since coupling is largest but they decay in complicated modes and there are large backgrounds from other SM processes

m_f/v

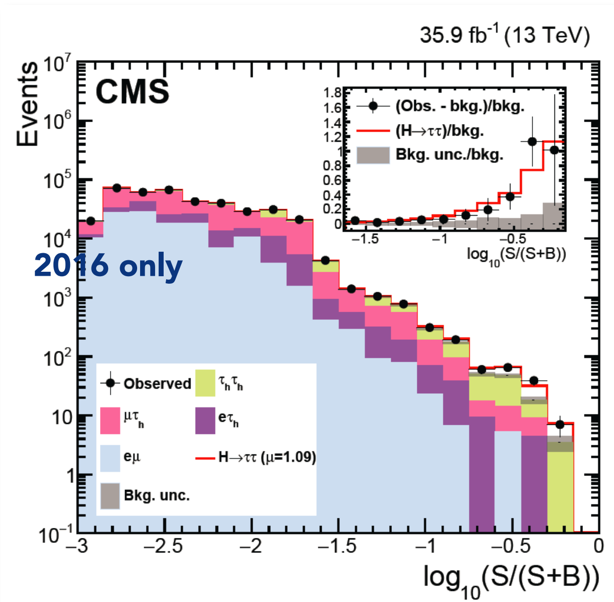


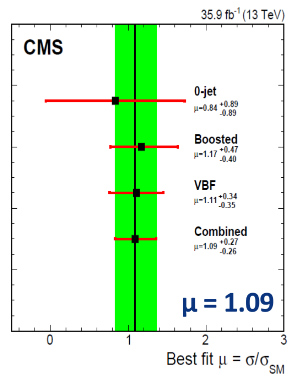
Over the last several years, CMS has worked hard to establish at the level of "observation" the Yukawa couplings to the heaviest fermions, the τ-lepton, the top quark, and the b-quark. Together with similar results from ATLAS, over the last year we have now jointly established the Yukawa coupling to third generation quarks and leptons and are entering the era of detailed measurement.

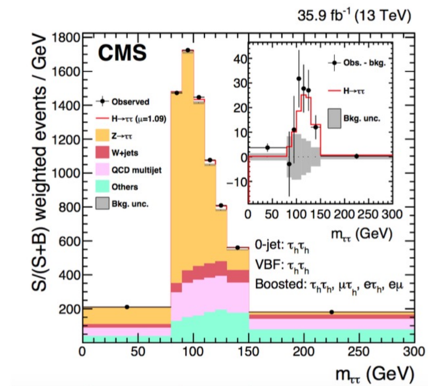
Observation of H → $\tau^+\tau^-$ using 7, 8, and 13 (2016 only) TeV data

PLB 779 (2018) 283
arXiv:1708.00373

- Branching ratio ~ 6.3%, best channel to establish coupling of Higgs boson to fermions
- Final states: $\tau_h\tau_h$; $e\tau_h$; $\mu\tau_h$; eμ → Significance of 4.9σ observed (4.7σ expected) with13 TeV data
- **Combination with 7, 8 TeV data: 5.9σ obs. (5.9σ exp.) and μ = 0.98 ± 0.18**







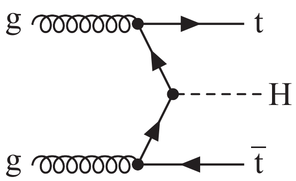
First direct observation by a single experiment of Higgs coupling to fermions!

– **Observed before in CMS+ATLAS combination**

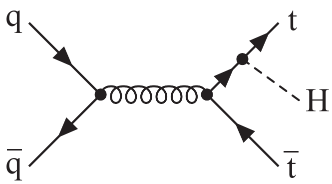
First direct observation of H coupling to leptons and to fermions of the 3rd generation!

ttH

Phys. Rev. Lett. 120, 231801 – Published 4 June 2018



Higgs is too light to decay into two tops

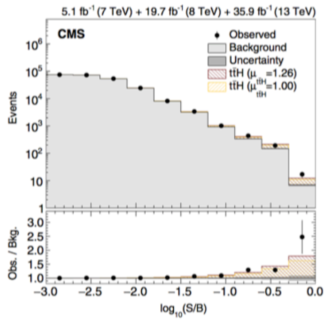


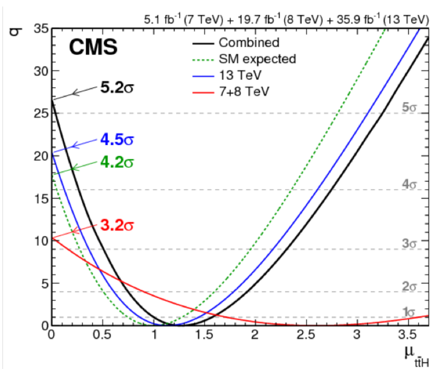
- Signature is production of two top quarks and a Higgs
  - The top is observed its its decay to Wb with the W decaying leptonically or hadronically
  - The analysis uses Higgs decays to bottom-quark-anti quark pairs, $\tau^+\tau^-$, $\gamma\gamma$, WW* and ZZ* (various quark and multi-lepton channels)
    - Hadronic τ decays, τ_h, are used
  - A total of 88 different event topologies, consisting of leptons, photons and jets, are combined to get the result
  - Use of Deep Neural Nets is pervasive
- Main systematic uncertainties are
  - Experimental: lepton and b jet identification efficiencies; τ_h and jet energy scales
  - Theory on background calculations: modelling uncertainties in tt production in association with a W or Z or a pair of b or c jets
  - Theory on signal calculations: effect of higher order corrections on ttH cross sections and uncertainty in proton PDFs
- The $\gamma\gamma$ and ZZ* states are limited by statistics; H→ bb and H→leptons by systematics

ttH: 7,8, and13 TeV Combined

5.1 fb^{-1} (7 TeV)+19.7 fb^{-1} (8 TeV) + 35.9 fb^{-1} (13 TeV)

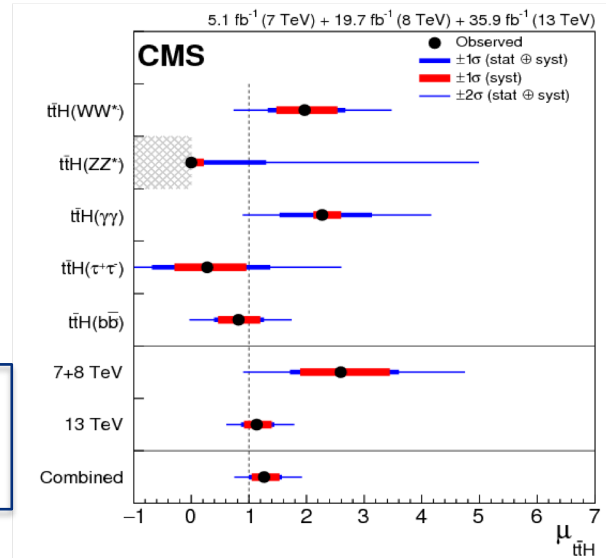
Note to me: Gotta get used to this kind of signal plot





Test statistic vs coupling strength modifier The horizontal dashed lines indicate the *p*-values for the background-only hypothesis obtained from the asymptotic distribution of *q*,

$$\mu = 1.26^{+0.31}_{-0.26}$$

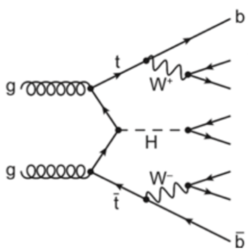


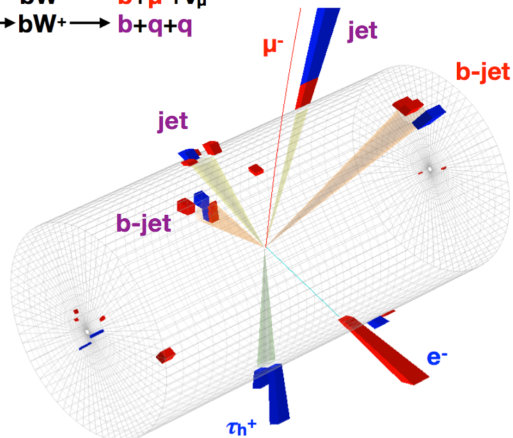
Best fit value of the signal strength modifier for (upper section) the five individual decay channels considered, (middle section) the combined result for 7+8 TeV alone and for 13TeV alone, and (lower section) the overall combined result.

A ttH "Candidate" event

$pp \longrightarrow t\bar{t}H$

- $\tau\bar{\tau} \longrightarrow e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$
- $\bar{b}W^- \longrightarrow \bar{b} + \mu^- + \bar{\nu}_\mu$
- $bW^+ \longrightarrow b + q + q$





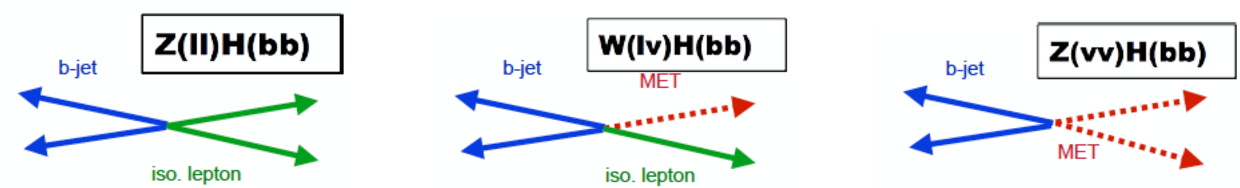
- This is only a "candidate" since we have backgrounds
  - However, we are beginning to see excesses of such events
- This example links the heaviest bosons and quarks (H, W, Top, b) and the heaviest lepton (τ), to some of the lightest quarks and leptons, including all three flavors of neutrinos, and emphasizes the breath-taking range that the SM spans in mass

New result!

Higgs → bb

arXiv:1808.08242, Accepted PRL, Aug. 31

- This has the **biggest branching fraction**
- However, there is **MASSIVE bb background from QCD** processes, ~10^3 times the signal in this mass region
- Choose a weak interaction production mode to reduce hadronic backgrounds (QCD multijet, top), mainly **Associated Production with a W or Z, VH(bb)**
- Signal is a di-jet mass enhancement which has many challenges
- Unlike $H \to \tau^+\tau^-$ and ttH, we needed the 2017 data to for its **observation**
- State expected to contribute the most $V(W\to l\,\nu, Z\to ll, Z\to \nu\nu)$ H(bb) a.k.a VH(bb)
  - Three channels: 2, 1, 0 leptons (lepton = muon or electron)
- Require Vector Boson to be back-to-back w.r.t. the bb system
- Several Improvements for 2017 analysis, including **heavy reliance on DNNs**, DEEPCSV
- Analysis validated using VZ(bb)



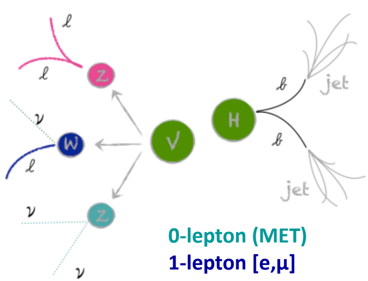
Analysis Details

- **Analysis strategy:**
  - **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
    - To target Z(νν)H(bb), W(lν)H(bb)and Z(ll)H(bb) processes
  - **Signal region designed to increase S/B**
    - **Large boost** for vector boson
    - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tag)
  - **Control regions** to validate backgrounds and control/constrain normalizations

Improved mass resolution from:

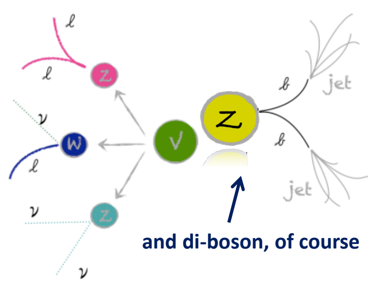
- Better **b-jet identification**
- New **b-jet energy regression**
- **Kinematic fit in 2-lepton channel**
- FSR jet recovery

signal



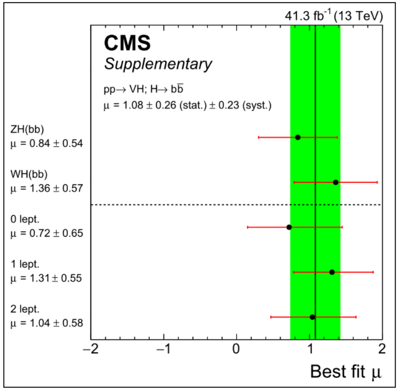
0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds



and di-boson, of course

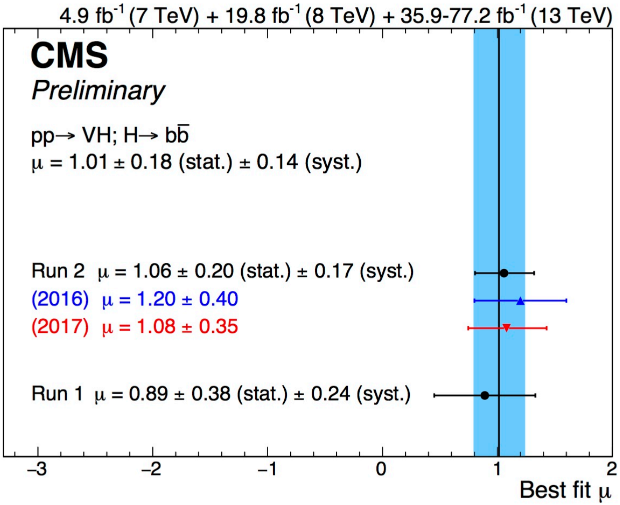
used to validate the analysis strategy



28/08/2018

Combination of all Results from Run 1 and 2

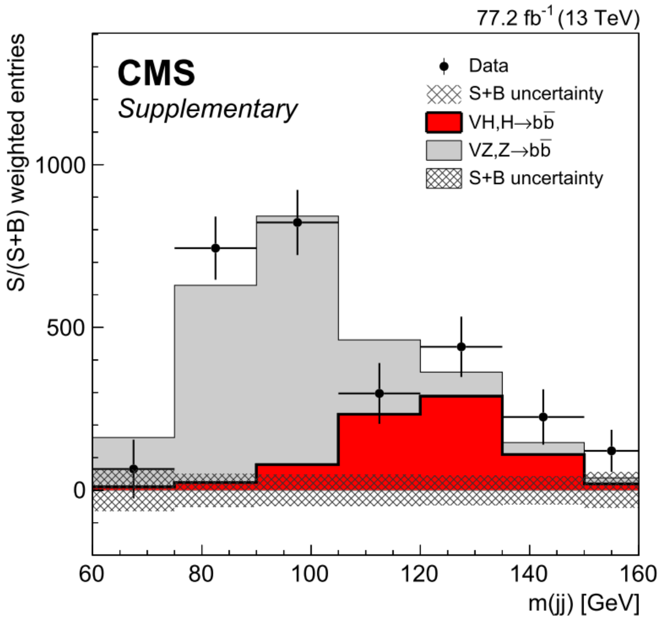
- **With VH(bb) from 2016/17 at 13 TeV, 77.2 fb^{-1}**
  - **Significance: 4.4 σ obs (4.2 exp)**
- **With VH(bb) including also 7 and 8 TeV**
  - **Significance: 4.8 σ obs (4.9 exp)**
- **Including new results and all published data from Run 1 and Run 2**
  - Run 1:
    - ttH(bb): 5 fb^{-1}(8 TeV) + 19.8 fb^{-1} (13 TeV)
    - VBF, H→bb: 19.8 fb^{-1} (8 TeV)
    - VH, H→ bb, 5 fb-1 (8 TeV) + 19.8 fb^{-1} (13 TeV)
  - Run 2:
    - ttH(bb), leptonic channels (2016)
    - ttH(bb), hadronic channels
    - Boosted ggH, H→ bb (2016)
    - VH, H→bb (2016 + 2017)



- **5.6 (5.5) σ observed (expected) for all H→bb!**

$$\mu = 1.04^{+0.20}_{-0.19}$$

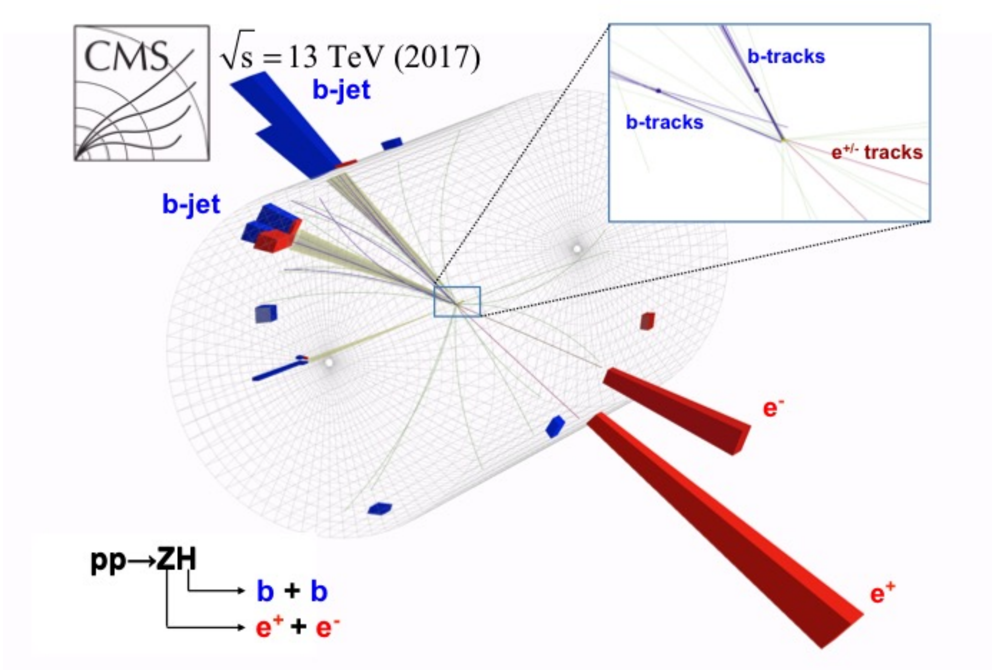
Combined Results, Mass Plot



Significance
5.5σ expected
5.6σ observed

Cross check analysis: Same analysis applied to Z-boson:
5.0 σ **expected**; 5.2 σ **observed; signal strength** μ =1.05 ± 0.22

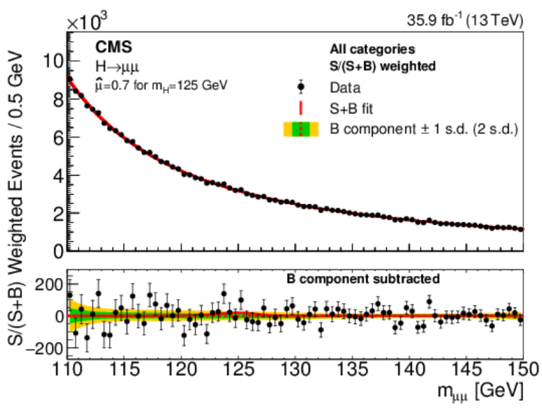
A ZH(bb) "Candidate" event

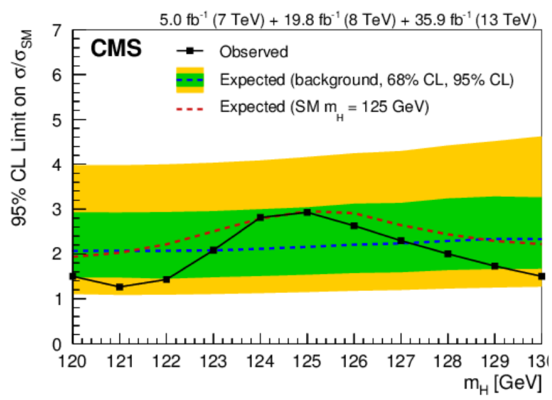


Higgs → $\mu^+\mu^-$

CMS-HIG-17-019

- Best chance at measuring a coupling to a second generation fermion, even though branching fraction (BR) ~ 2.2×10^{-4}, about 1/10 of $\gamma\gamma$.
- CMS has looked for this in 7,8, and 13 TeV (2016 only) data
- Current 95% CL upper limit on BR is 6.4×10^{-4}, 2.92 (observed) vs 2.16 (expected) of the SM prediction.





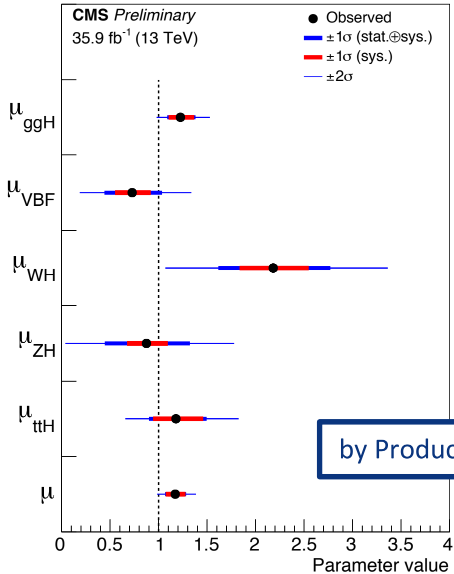
Higgs Signal Strengths from 2016 Data

CMS PAS HIG-17- 031

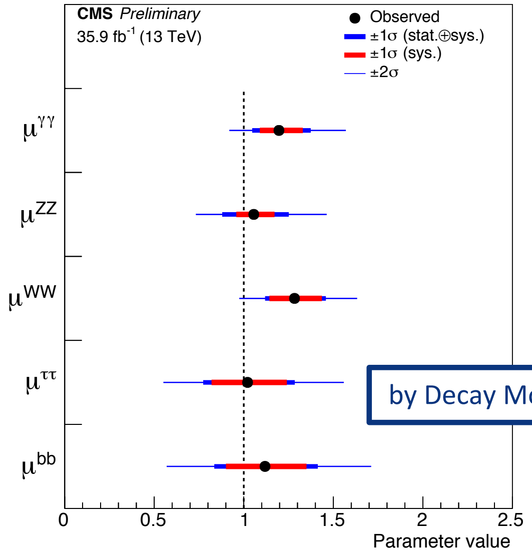
Combined: $\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$

c.f. Run 1 CMS+ATLAS: $\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(\text{stat})^{+0.07}_{-0.06}(\text{sig. th.})^{+0.05}_{-0.05}(\text{other sys.})$

35.9 fb^{-1}



by Production Mode



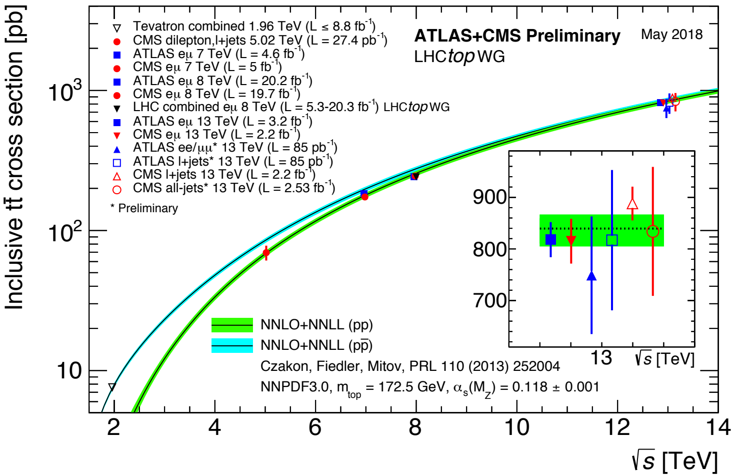
by Decay Mode

There is still room for new physics but we must reduce systematic uncertainties to make progress

Recent Physics Results - 2

Top

Top Pair Cross Sections



CMS: 835 ± 33 pb
Theory: 816 ± 42 pb

Top pair rate is > 10 Hz, enabling us to address much more precise questions

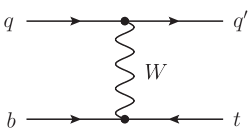
- Single, double, and triple differential cross sections
- Rare (FCNC) decays
- CP violation (a beginning)
- Width and more complex methods for measuring the mass

Top pair production at 13 TeV CM energy is mainly (80%) produced by gluons, providing important information on the gluon distribution at relatively high x_F, up to ~0.25

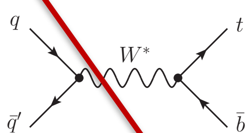
Factory	Quark	Cross Section (nb)	Luminosity ($cm^{-2}s^{-1}$)
B (KEKb)	Bottom	1.15 (Υ(4S))	2.11×10^{34}
LHC	Top	0.82 (incl t-t)	2.01×10^{34}

Single Top

t-channel ~220 pb

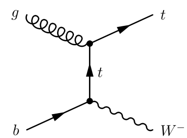


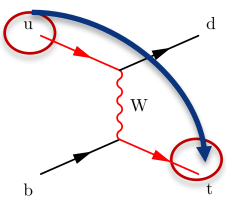
s-channel~ 10pb

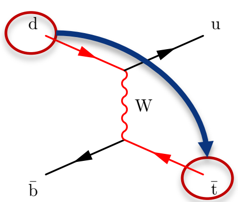


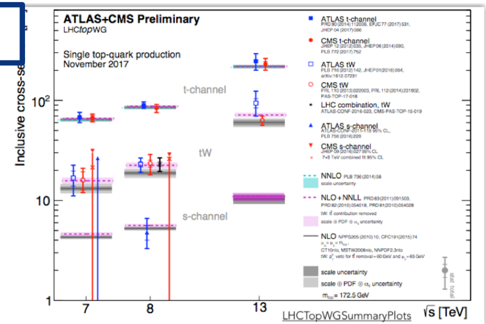
Not seen at LHC

tW channel ~70 pb



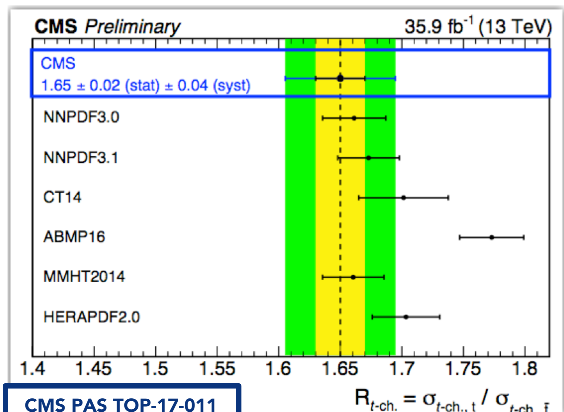






Precise measurement of t-channel single top cross sections and ratio of $R_{t\text{-}ch}$ of t^+ to t^- production (more u-quarks than d- quarks)

- $R_{t\text{-}ch}$ = 1.65 ± 0.02 (stat) ± 0.04 (syst).
- Total single top cross section = 219.0 pb ± 1.5 (stat) ± 33.0 (syst)
- **the absolute value of the CKM matrix element V_{tb} is determined to be 1.00 ± 0.05 (exp) ± 0.02 (theo).**



CMS PAS TOP-17-011

Top Differential Cross sections

CMS PAS TOP-17-014

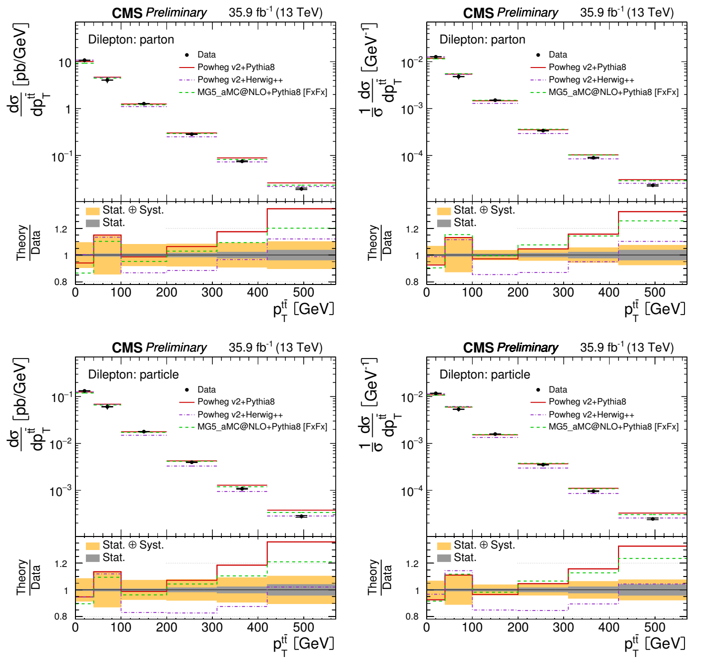
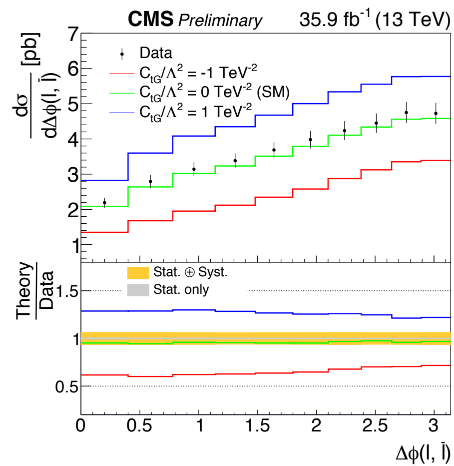


Figure 20: The differential $t\bar{t}$ production cross sections as a function of $p_T^{t\bar{t}}$ are shown. The left and right columns correspond to absolute and normalised measurements, respectively. The upper row corresponds to measurements at parton level in the full phase space and the lower row to particle level in a fiducial phase space. The lower panel in each plot shows the ratio of the theoretical prediction to the data.

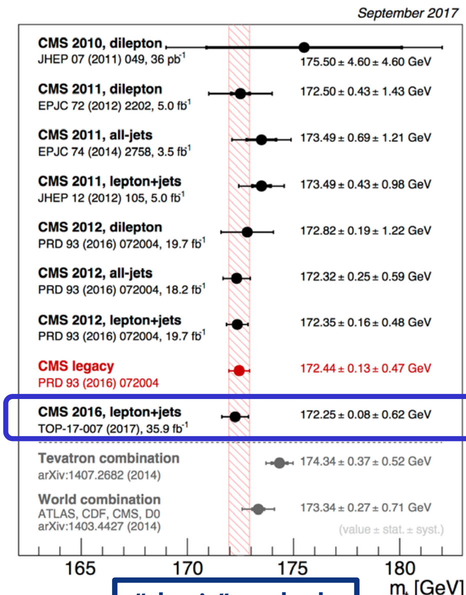
Differential Cross section to Constrain top chromo-magnetic Dipole moment



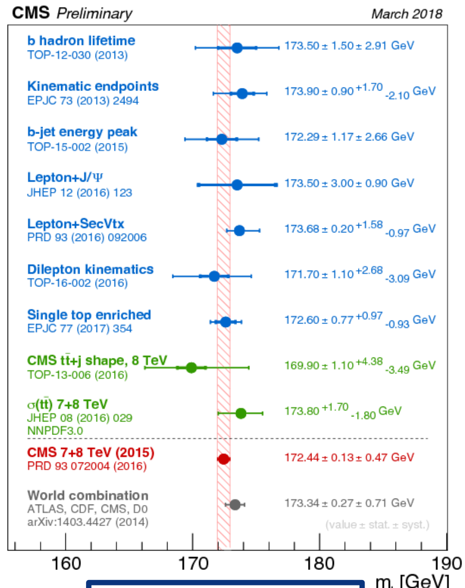
$$\frac{d\sigma}{d\Delta\phi(l,\bar{l})}$$

$-0.06 < C_{tG}/\Lambda^2 < 0.41$	**CMS-PAS-TOP-17-014**
$-0.89 < C_{tG}/\Lambda^2 < 0.43$	CMS 8 TeV diff. x-sec
$-0.42 < C_{tG}/\Lambda^2 < 0.30$	CMS 8 TeV incl. x-sec
$-0.32 < C_{tG}/\Lambda^2 < 0.73$	Tevatron incl. x-sec

Top Mass

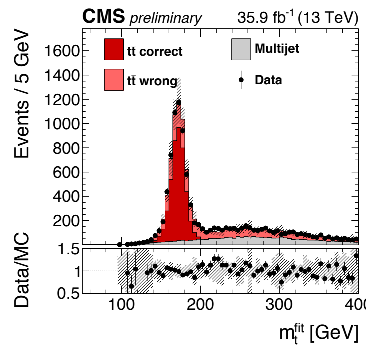


"classic" methods



Alternative methods

CMS-PAS-TOP-17-008



CMS all-jet (13 TeV)

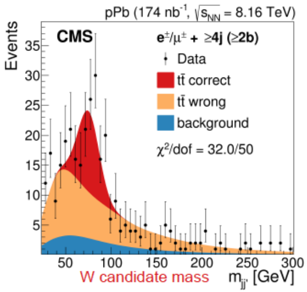
172.34 ±0.20 (*stat+JSF*) ±0.76 (*syst*) GeV

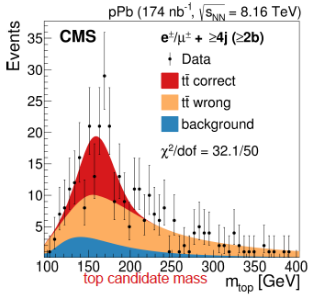
- "Standard methods" are all **systematics-limited!**
- Alternative methods are not as accurate now, but will become so and we hope the one or more will have ultimately more favorable systematics
- Need to do better to address issues like stability of the EW vacuum

Top gallery

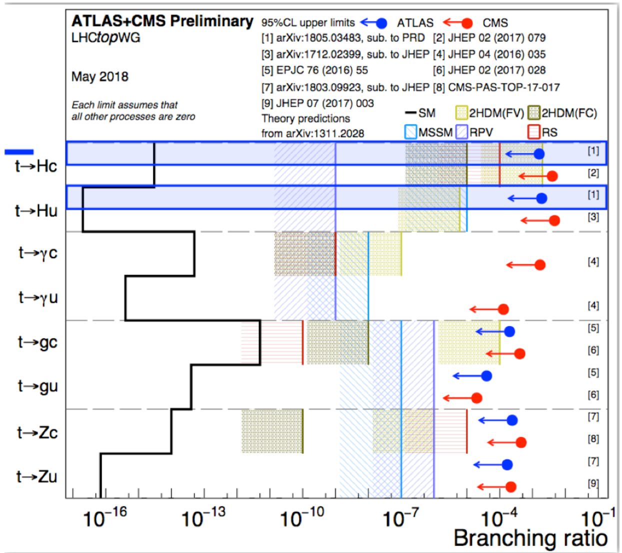
PhysRevLett.119.242001

Proton-Pb at 8.16 TeV





Rare, FC Top Decays



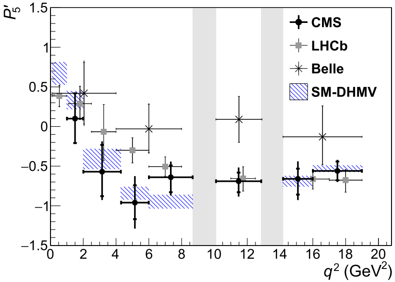
Even with full LHC data, none will reach SM expectations but some will reach level predicted by some BSM models

Recent Physics Results - 3

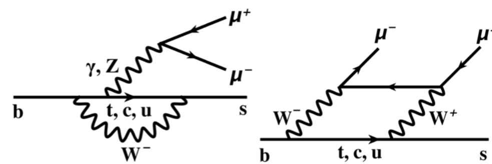
B Physics

Angular Distribution of FCNC Decay $B^+ \rightarrow K^+ \mu^+\mu^-$ (8 TeV)

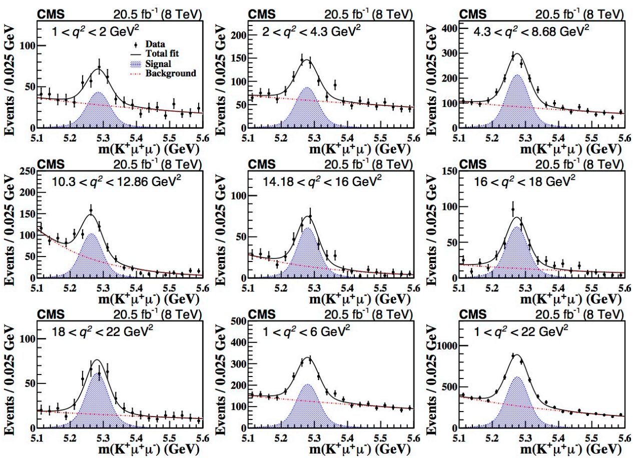
CMS-BPH-15-001



Possible deviations in angular distributions in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

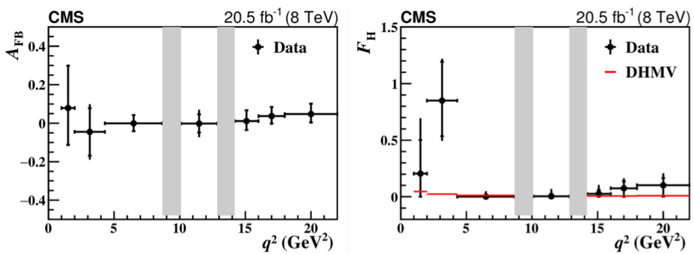


$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell} = \frac{3}{4}(1 - F_H)(1 - \cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell.$$



F_H, A_{FB} Vs q^2, invariant mass of the dimuon

Based on 2286 +/- 73 events from 20.5 fb^{-1} taken at 8 TeV in 2012



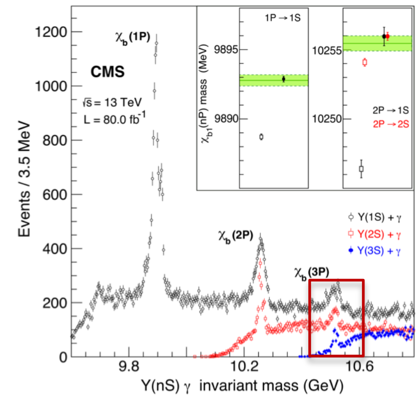
Consistent with various SM calculations. CMS has made changes to trigger and DAQ in 2017 to look at $B^+ \rightarrow K^+e^+e^-$.

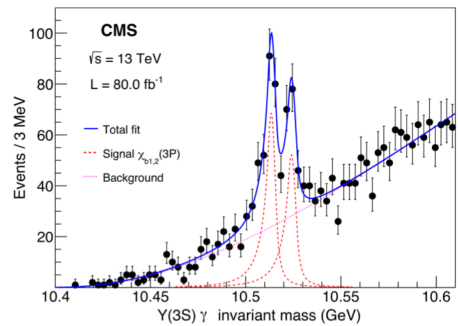
$\chi_{b2}(3P)$-$\chi_{b1}(3P)$ Mass Splitting

CMS-BPH-17-008-003

- A bump at mass ~10.5 GeV, discovered by ATLAS (**Phys. Rev. Lett. 108, 152001**) **via** decay to $\Upsilon(1S,2S)\gamma$ (where $\gamma \rightarrow e^+e^-$ conversion), is identified with the $\chi_b(3P)$ states
  - Three states are expected with J=0,1,and 2, with the latter two expected to have large branching fractions to photons.
- This bottomonium state is closest to the continuum and could mix with states that are just above
  - It is analogous to the X(3872) in charmonium
- **With the full 2015-2012 dataset, 80 fb^{-1}, CMS studied**
  - **$\chi_b(3p) \rightarrow \Upsilon(3S)\gamma \rightarrow \Upsilon(\mu\mu)\gamma$ ($\gamma \rightarrow e^+e^-$)**
  - **There are fewer Υ(3S) but the small photon energy can be measured with excellent resolution by CMS with its 3.8T field**
  - **Needs the very large dataset!**
- **The two $\chi_b(3p)$ states are clearly resolved!!**

Mass Difference: ΔM = 10.6 ± 0.64 (*stat*) ± 0.17 (*syst*) MeV
Masses of the two states:
M_1 = 10513.42 ± 0.41(*stat*) ± 0.18 (*syst*) MeV
M_2 = 10524.02 ± 0.57(*stat*) ± 0.18 (*syst*) MeV



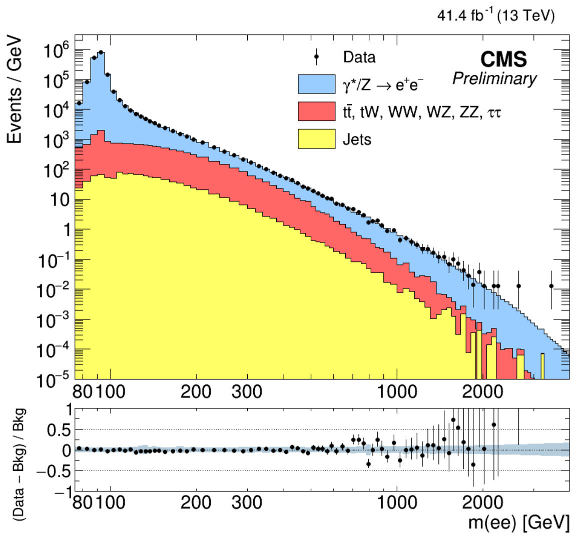


Recent Physics Results - 4

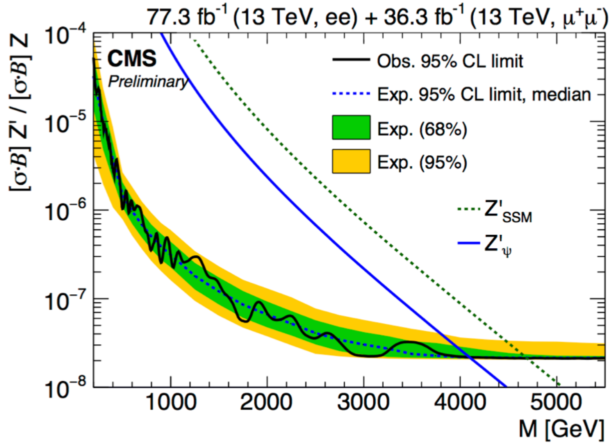
Searches

High Mass e^+e^- Resonance Search

CMS PAS EXO-18-006



2017 dielectrons

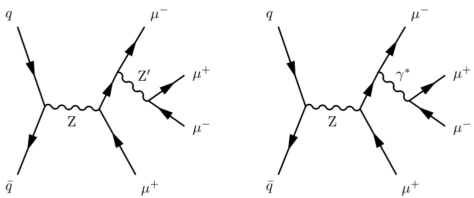


2017 dielectrons + 2016 dimuons

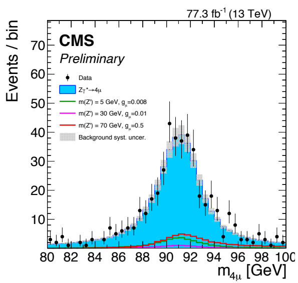
Exclusion limits for some models already ~ 4-5 TeV

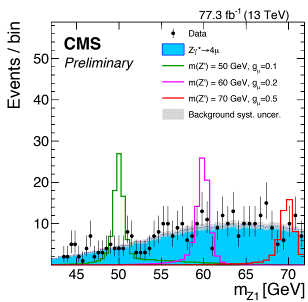
Light Z′ Boson with Lμ-Lτ Gauge Symmetry

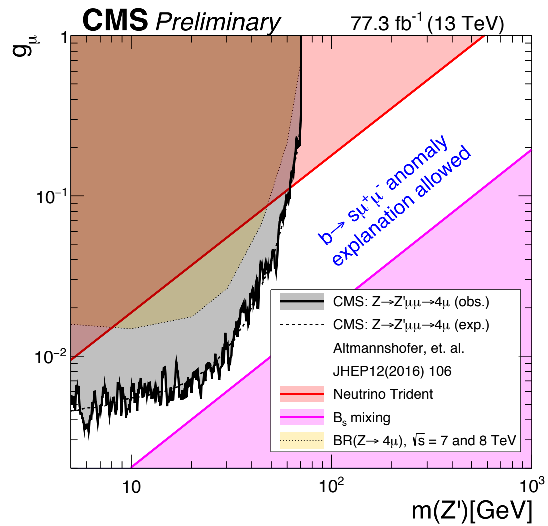
CMS PAS EXO-18-006

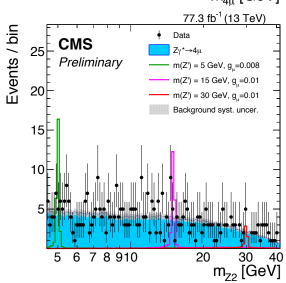


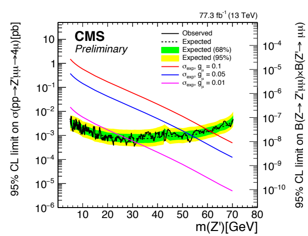
- **Since this Z′ couples (only) to second- and third-generation leptons (μ, ν_μ, τ and ν_τ), it can be produced from one of the muons in Z-decays, and using its decay Z′→ $\mu^+\mu^-$, might appear as a dimuon mass bump in 4 muon final states.**











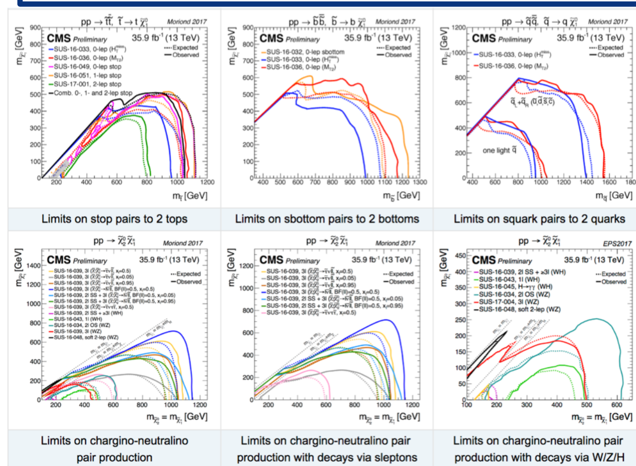
Supersymmetry

Retrospective:

- Great theory – could solve three problems at once
- In 2010, many thought SUSY would be seen soon after startup- 100 pb^{-1}
- **Expected to be first major LHC discovery– before even the Higgs!**

Reality at start of 2018 run: So far, SUSY is a "no show". Why?

- Maybe heavier than we thought
- Maybe more devious/obscure than we thought, e.g. more weakly coupled
- Maybe it does not do all three tasks
- Coverage for RP-violating and long-lived particles not as complete
- Maybe just another great idea that nature did not choose to follow



Many good ideas being explored. Still a vibrant area of research in CMS. Focus on Electroweakinos, Higgs as a decay product, complex scenarios.

New Ideas in Dark Matter – Search for Emergent Jets

CMS PAS EXO-18-001

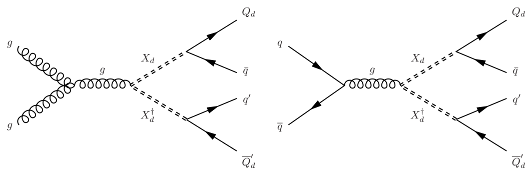
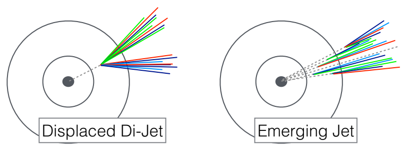
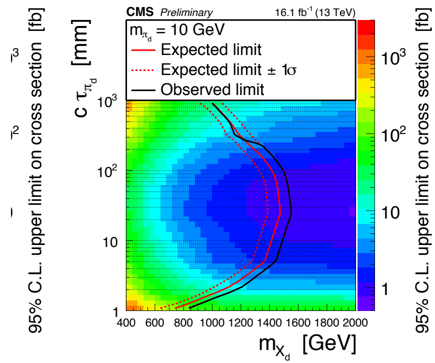


Figure 1: Feynman diagrams for pair production of mediator particles, with mediator decay to a quark and a dark quark in the BSSW model via (left) gluon fusion and (right) quark-antiquark annihilation.

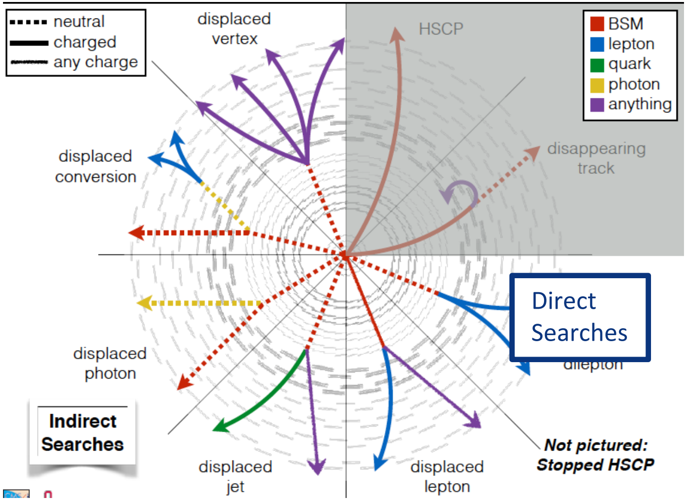




- Many compelling models of new physics contain a dark matter candidate that has interactions with quarks. **For the first years, focus on Mono-X+MET searches**
- In one class of models, new fermions (dark quarks), Q_d, are charged under a new force in the dark sector that has confining properties similar to quantum chromodynamics (QCD) but are not charged under the forces of the standard model SM. The mediator Xd is a complex scalar.
- The dark quark jets contain many displaced vertices arising from the decays of the dark pions produced in the dark parton shower and fragmentation. For models with dark hadron decay lengths comparable to the size of the detector, there can also be significant missing transverse momentum (*p*miss).
  - The main background to this signature is SM four-jet production with b-quarks

Long-Lived Particles

Many BSM models have long-lived particles /displaced vertices. Some of these can be observed by special searches, usually with special triggers



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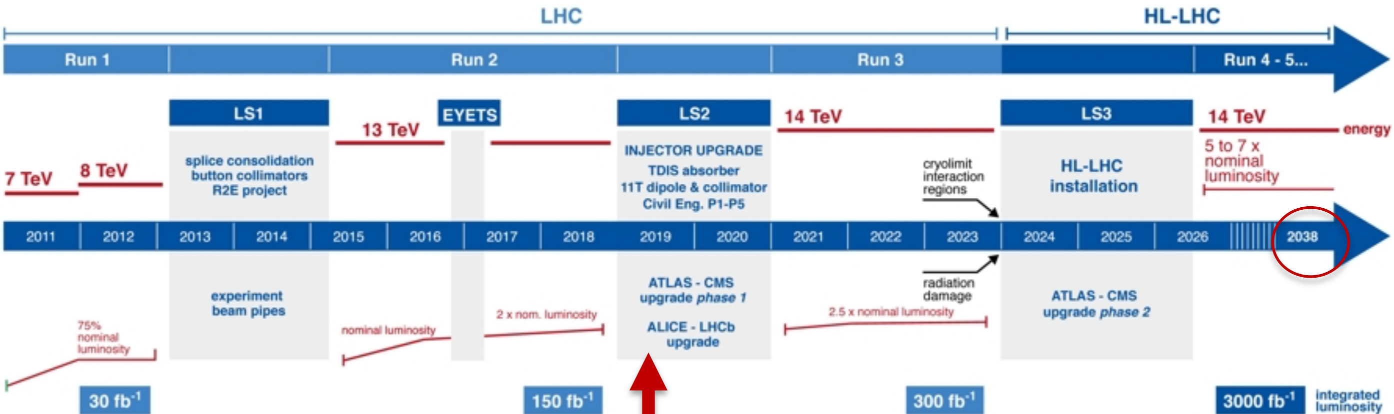
- Search for stopped long-lived particles using full 2015 and 2016 data
  - Signature is a high energy jet in the calorimeter out of time with collisions
  - gluinos with lifetimes from 10 μs to 1000s and $m_{gluino} < 1379$ GeV are excluded.
  - Top squarks with lifetimes from 10 μs to 1000s and $m_{stop} < 740$ GeV are excluded

EXO/SUSY searches shifting to different topologies, lower mass, longer-lived particles and will continue to look in new places. Triggering on unusual states will be a challenge.

The Future: CMS HL-LHC Upgrade

The LHC Luminosity Plan



x5 Run1

We will soon be here – LS2

x2 Run2

x10 Run3

3%

LHC Status

3000fb-1

Running

Luminosity so far

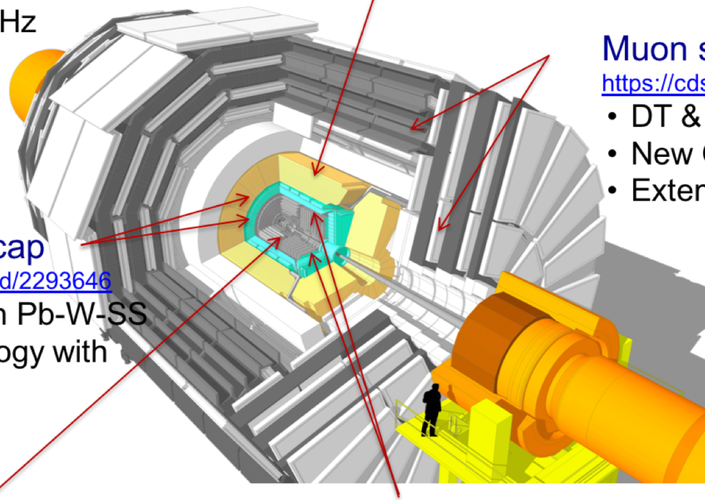
Luminosity after HL-LHC

CMS Phase-2 upgrade scope (TDR, interim TDR and TP references)

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



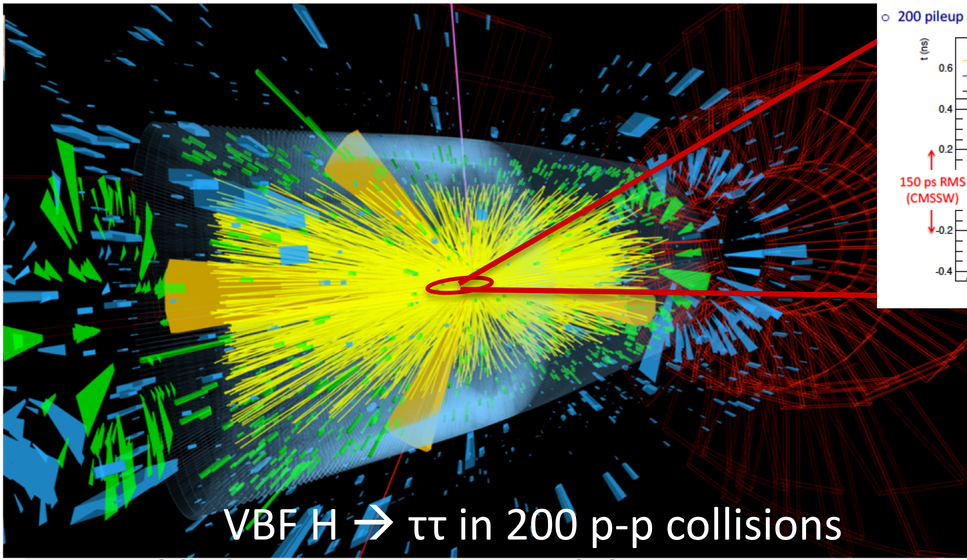
Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

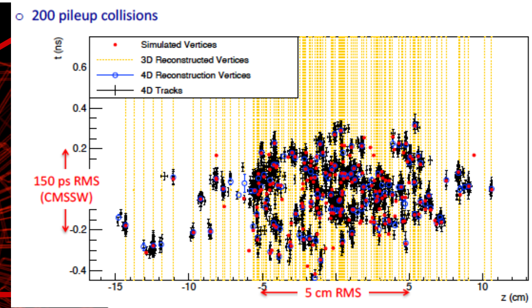
Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

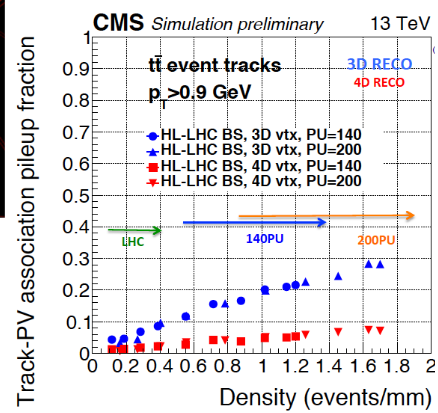
Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612
- ≃ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

MIP Precision Timing Detector







Time of flight precision ≃ 30 ps, |η|< 3, p_T > 0.7 GeV

"Provide a factor 4-5 effective pile-up reduction"

- ~ 15% merged vertices reduce to ≃ 1.5%
- Low pileup track purity of vertices recovered

- **All showers timed to 30 ps in calorimeters**

Bold Aspects of CMS Upgrade for HL-LHC

- Tracker is AGAIN ALL SILICON but now with much higher granularity, and extends to $|\eta| = 4$, >2 billion pixels and strips
- Tracking information in "L1 track-trigger"
  - Tracker is designed to enable finding of all tracks with P_T>~2 GeV in under 4 μs for use in the lowest level trigger
- High Granularity Endcap Calorimeters
  - Sampling of EM-showers every ~1λ_{rad} (28 samples) with small silicon pixels and then every ~0.35λ_{abs} (24 samples) with combination of silicon pixels and scintillator to map full 3-dimensional development of all showers (~6M channels in all)
- Precision timing of all objects, including single charged tracks, provides a 4th dimension to CMS object reconstruction to combat pileup (~200K sensors in barrel section)

Goal: Be as efficient, and with low background/fake-rate, at 200-250 pileup as we are today, with extended acceptance and new capabilities

Summary and Outlook

Physics Outlook

- Both the LHC and the CMS detector performed well in Run 2 (2015-2018)
  - The two year shutdown in 2019/20 should give us time to catch up on analysis and assess where we really at
- With the LHC is running at **13 TeV (14 TeV after 2020)** with **high luminosity and availability, our discovery potential remains great.**
  - Discoveries may come in a few months or after several years
  - They might start with a striking signal appearing in a single channel or they may appear in several channels emerging slowly, each with initially low significance, out of large backgrounds.
  - They may appear in scenarios we have long been exploring, e.g. SUSY or Extra Dimensions, **or may surprise us with signatures that we are not even looking for, or triggering on, today**
    - As investigators into the unknown we need to step back and survey the big picture and look for new, untried approaches or corners of our data that are unexplored or only dimly illuminated
      - Look for heavy objects but don't neglect lighter particles, weaker couplings, rare decay
- **Today we have of order <5% of the ultimate LHC data in hand**
- **It is our mission to explore and make discoveries in this huge new expanse of scientific territory**

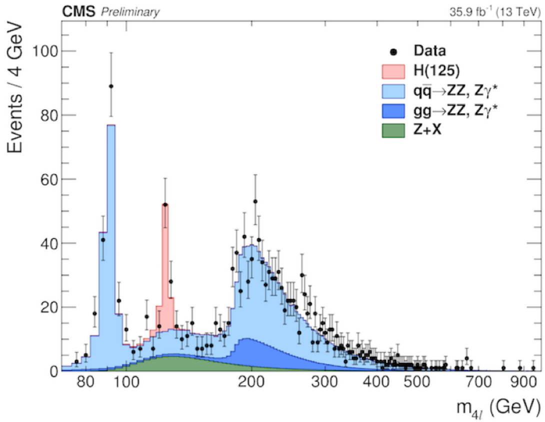
CMS Speakers

- Search for Long Lived Particles
  - Albert De Roeck - CERN
- CMS – Recent results on B-Physics at CMS with a focus on Amplitude Analysis for exotic particles search
  - Leonardo Cristella -Università & INFN, Bari
- CMS –Recent Results on B Rare Decays
  - Nuno Leonardo - LIP
- Next Generation Computing and Networking for HEP
  - Harvey Newman - California Institute of Technology
- Machine Learning for High Energy Physics: Progress, Outlook and issues for the LHC and Hl-LHC
  - Sergei Gleyzer – University of Florida
- SUSY searches at CMS
  - Carsten Hensel
- Recent Results on Top Quark from CMS
  - Javier Brochero - CIEMAT
- Higgs boson precision measurements From CMS (coupling, mass, fiducial/differential cross sections)
  - Harvey Newman – California Institute of Technology
- Measurements of the Higgs Boson Yukawa couplings in CMS
  - Davide Di Croce - U.Antwerp (BE)
- Muon Reconstruction and Identification Performance in CMS
  - Sandro Fonseca De Souza - Univ. Estado Rio de Janeiro
- Rare H and Z decays to Quarkonia in CMS
  - Felipe Silva - UNICAMP (BR)
- Forward Physics at (LHC)
  - Gustavo Gil Da Silveira - (UFRGS

The future is bright!
Thank you for your attention.

Backup

Higgs Properties from ZZ* (4 leptons)

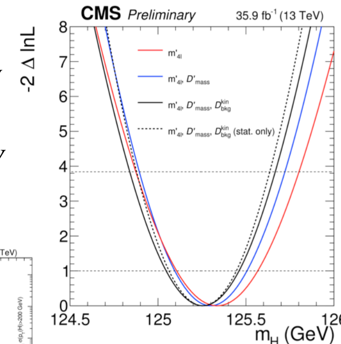


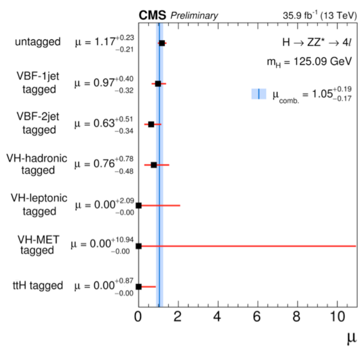
ATLAS, CMS Run 1 Combined:

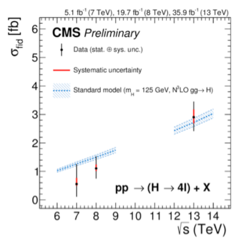
$M_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\ GeV$

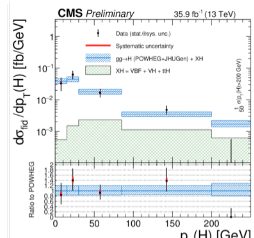
CMS 2016, 4 lepton:

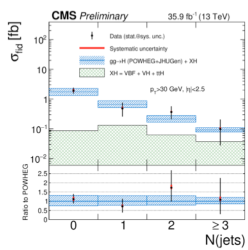
$M_H = 125.26 \pm 0.20(stat) \pm 0.08(syst)\ GeV$

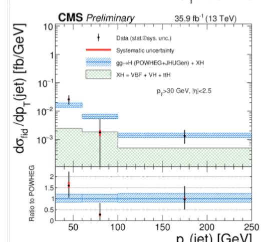








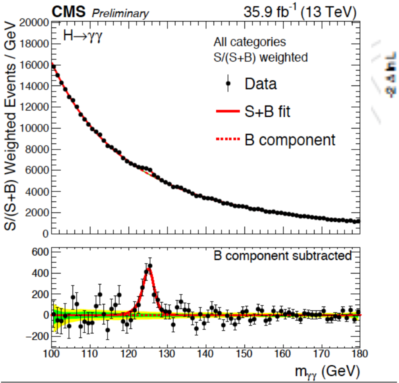


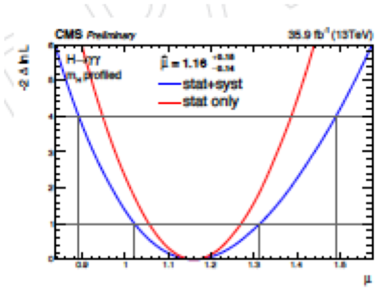


HIG-16-041

Cross sections

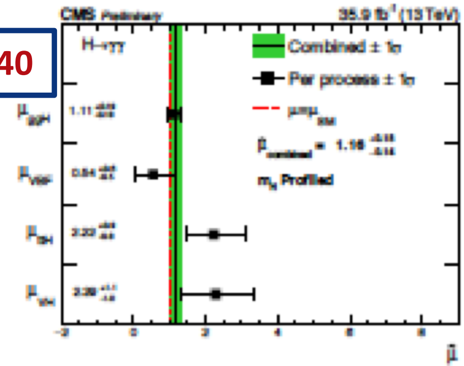
Higgs → γγ



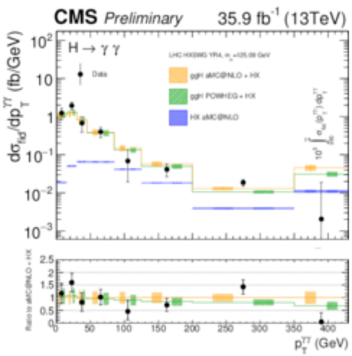


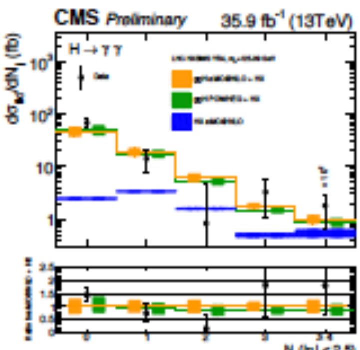
Likelihood scan for signal strength

HIG-16-040



Signal strength modifiers





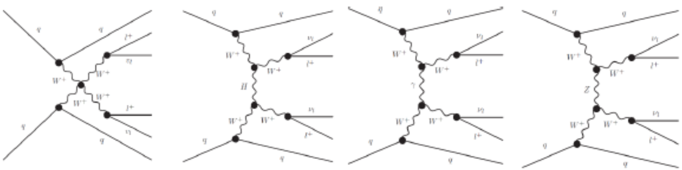
HIG-17-015

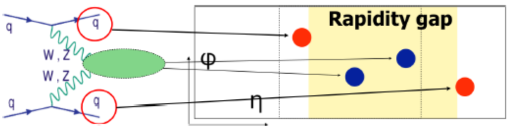
Differential cross section

Njet Differential cross section

WW Scattering using Two Same-sign Leptons and Two Jets

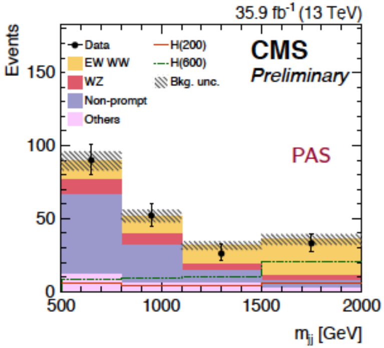
Addresses nature of Higgs, which helps unitarize $V_L V_L \rightarrow V_L V_L$ and provides a search for doubly charged Higgs

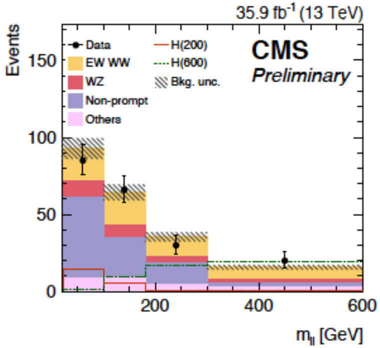




$W^{\pm}W^{\pm}$ scattering in the fully leptonic final state

SMP-17-004





charged H x-sec = $0.1pb$

Observed (Expected) signficance: 5.5 (5.7) σ

Observed signal strength relative to SM prediction: 0.90 ± 0.22

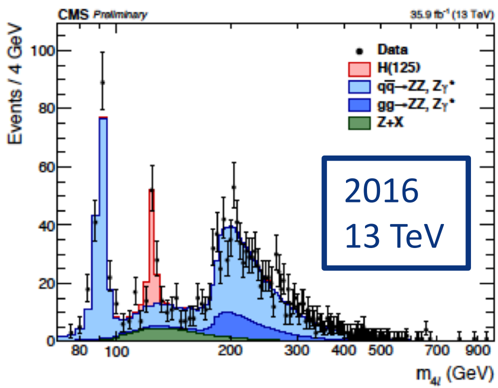
$\sigma_{fiducial} = 3.83 \pm 0.66(stat) \pm 0.35(syst) \pm 0.12(Lumi)\,fb$

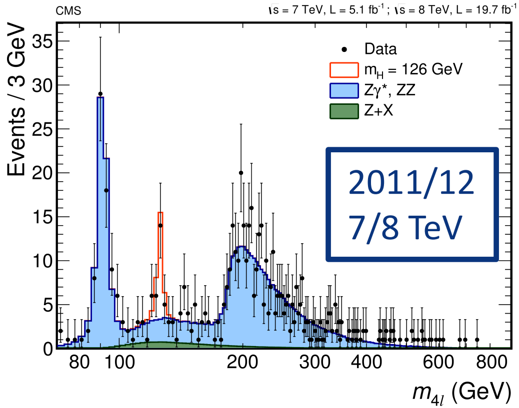
$K^*\mu^+\mu^-$ Backup

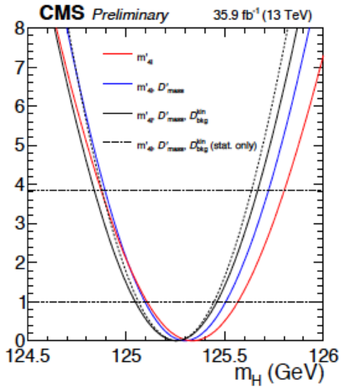
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\,d\cos\theta_l\,d\cos\theta_K\,d\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)(1-\cos^2\theta_l) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right] + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}. \quad (1)$$

The expression is an exact simplification of the full angular distribution, obtained by folding the ϕ and θ_l angles around zero and $\pi/2$, respectively. Specifically, if $\phi < 0$, then $\phi \to -\phi$, and the new ϕ domain is $[0, \pi]$. If $\theta_l > \pi/2$, then $\theta_l \to \pi - \theta_l$, and the new θ_l domain is $[0, \pi/2]$. Fitting the data with the full angular distribution would cause fit convergence problems due to the limited number of signal candidate events, which is why we adopt the folding procedure. It exploits the odd symmetry of the angular variables with respect to $\phi = 0$ and $\theta_l = \pi/2$ in such a manner that the cancellation about these angular values is exact.

Higgs Mass from 4 Leptons (ZZ*)







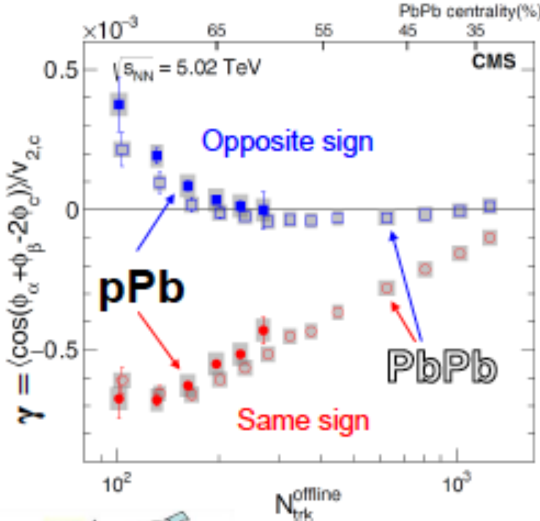
Mass (2016, 4L) : $125.26 \pm 0.20(stat) \pm 0.08(sys) Gev$

ATLAS + CMS:
Mass (Run 1, all): $125.09 \pm 0.21(stat) \pm 0.11(sys) Gev$

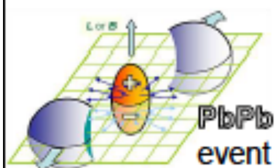
Best single measurement of Higgs mass!
Better than all modes, ATLAS and CMS from Run1!

Highlights from Heavy Ion Physics

Charge Separation Signal γ

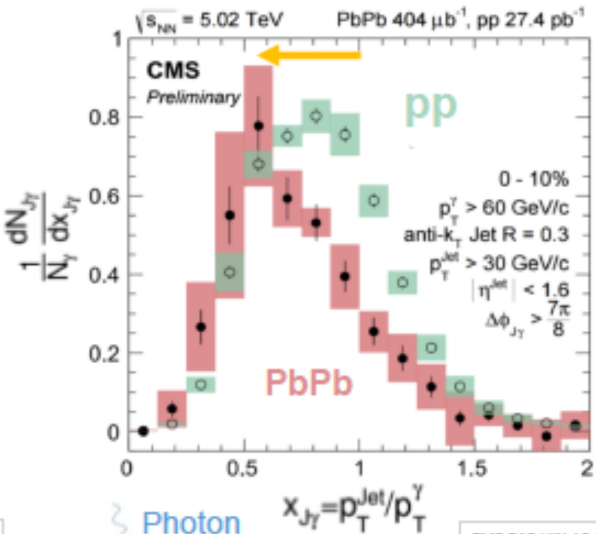


arXiv: 1610.00263
PRL 118, 122301 (2017)

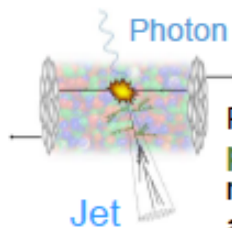


PbPb and **pPb** with the same event multiplicity are **similar!** Challenge to Chiral Magnetic Effect interpretation!

Photon-Jet



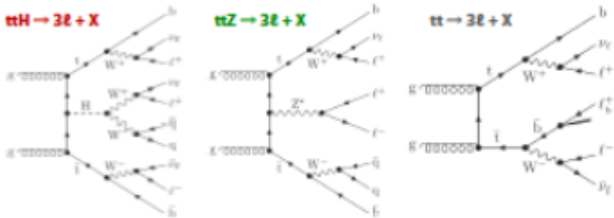
CMS-PAS-HIN-16-002



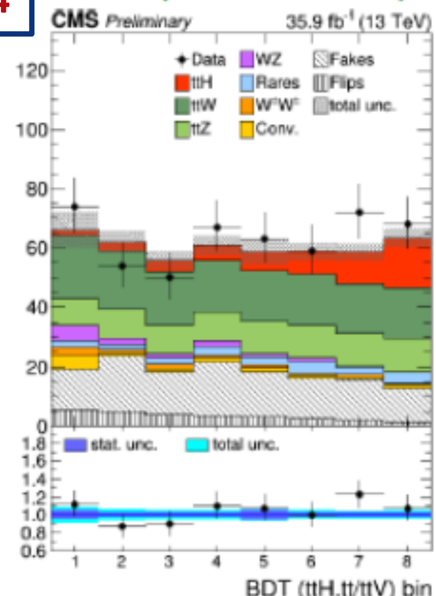
Photon-Jet correlation in pp and PbPb: high precision measurement of in-medium **absolute parton energy loss**

Higgs Coupling to Top Quarks

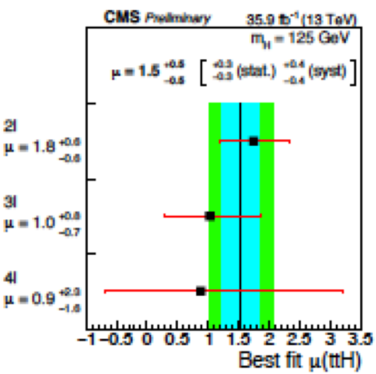
HIG-17-004

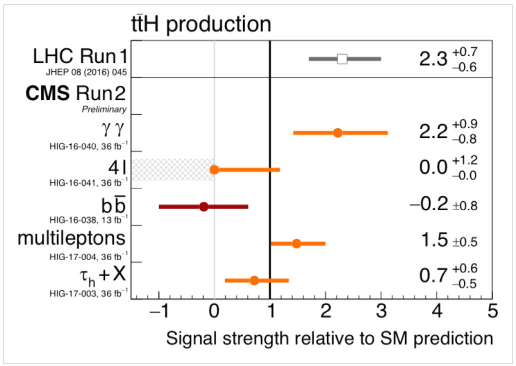


SR bins (all cat. combined)



SS dilepton



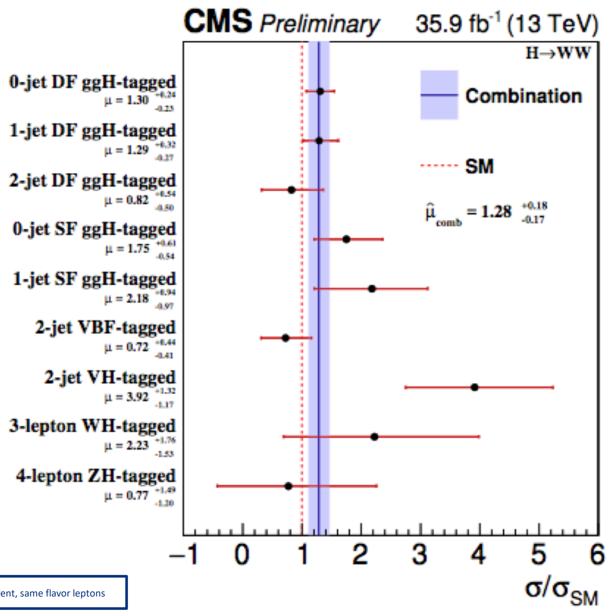


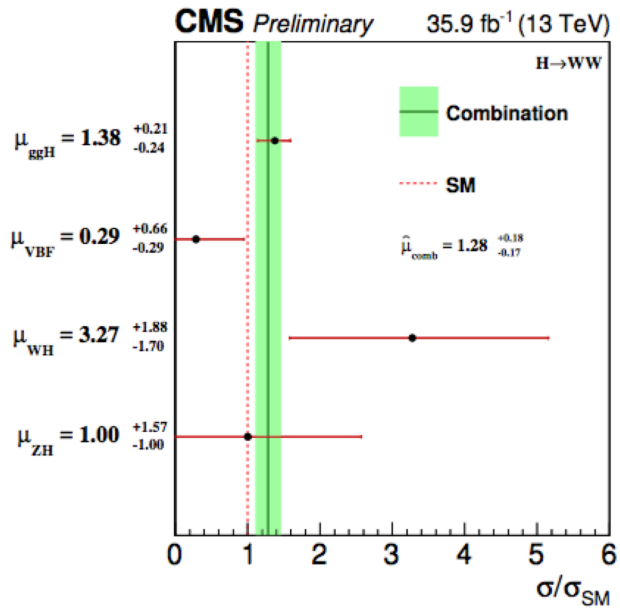
3σ evidence for tt-H in multi-lepton final states

3.3 σ (2.5 expected) when combined with 2015 result

Recent Results: H→WW

25 new results overall and 12 approved in the last 7 days. The full list will appear on the public page in preparation.
Among the highlights: H →WW with 2016 data (HIG-16-042)



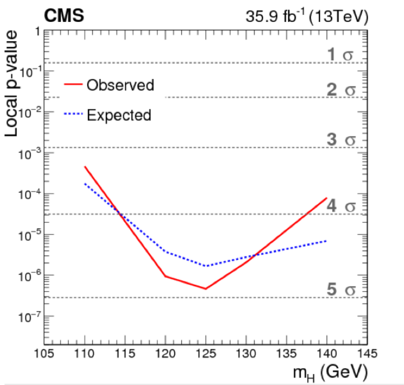


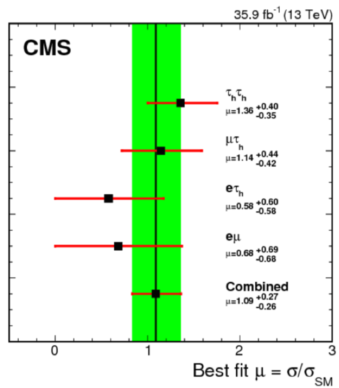
SF, DF = different, same flavor leptons

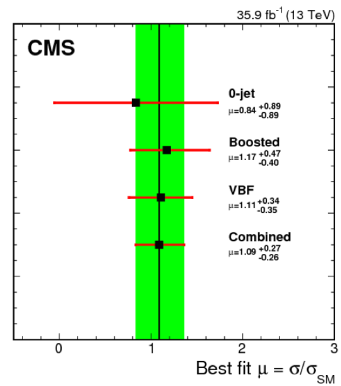
Higgs →$\tau^+\tau^-$ using 7, 8, and 13 (2016 only) TeV data

- Now more than a year old, but still worth remembering
- Four decay topologies for $\tau^+\tau^-$: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Three production modes: 0-jet (gg), VBF, boosted (additional objects)
- Irreducible sources of systematics: W+jets, DY Z/γ →ll,$\tau\tau$, t-tbar, QCD

HIG-16-043, arXiv:1708.00373

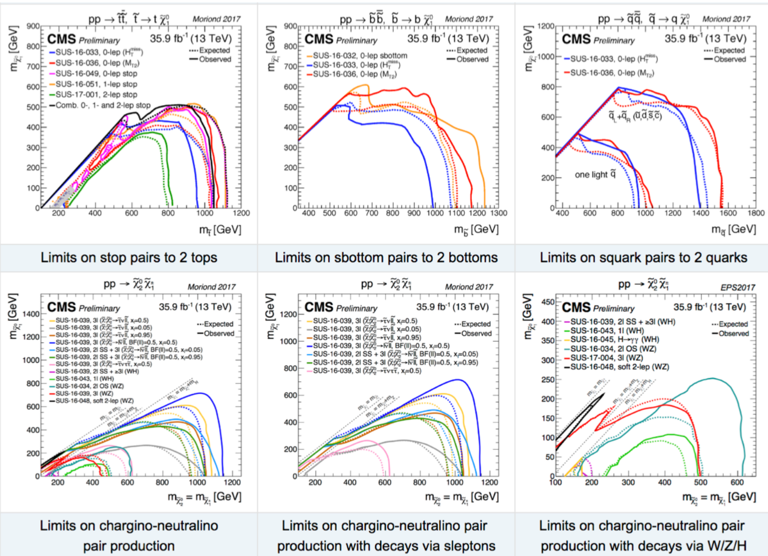






μ(signal strength)= 1.09 +0.27-0.26. Significance 4.9 (4.7) σ;
Combined with Run 1: μ(signal strength)= 0.98 +/-0.18 Significance 5.9(5.9) σ
First single experiment observation: fermion Yukawa, lepton, 3rd Generation

SUSY? Don't count it out!



Limits on stop pairs to 2 tops | Limits on sbottom pairs to 2 bottoms | Limits on squark pairs to 2 quarks

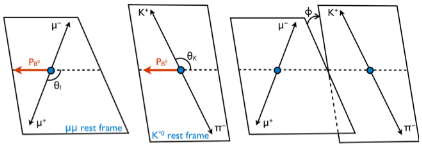
Limits on chargino-neutralino pair production | Limits on chargino-neutralino pair production with decays via sleptons | Limits on chargino-neutralino pair production with decays via W/Z/H

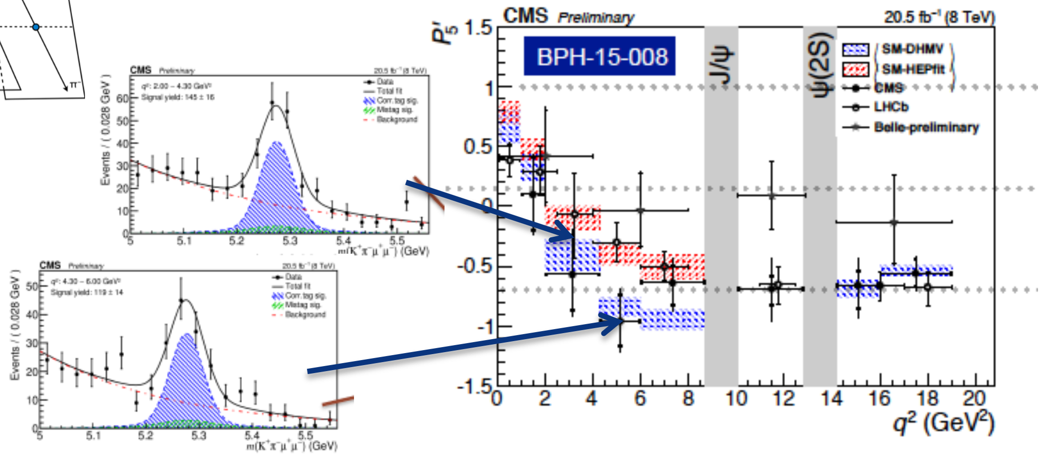
- Many more things to do **new signal topologies:**
  - e.g. single stop search
  - using taus in cascades
- **new kinematic range and objects**
  - boosted EWKino (WZ, HH)
- **new interpretations (accessing low cross sections)**
  - e.g. more general higgsino interpretation with different spectrum assumptions
  - examples from the theory talks: dirac gauginos, resonant signatures
  - theory input is essential (and our dialogue with the pheno community with reinterpretation material)!
- **new datasets?**
  - e.g. parked b dataset to look for higgsinos decaying via offshell H (bb+MET)
- ***With no energy increase explore lower couplings!***
  - ***Already looking into displaced signatures with:***
  - ***Muons:*** SOS search in the compressed regime
  - ***Taus:*** stau search (e.g. GMSB SUSY with a stau NLSP)
  - ***Delayed jets (with ECAL timing):*** up to 1.5m displacement
- ***Disappearing tracks:*** target wino (N)LSP with direct or in cascade production
- Many more
- **Having eyes open for the surprises in the tails of 150/fb!**

Turns out your friend here is only MOSTLY dead. See, mostly dead is still slightly alive. (From the movie "A Princess Bride")

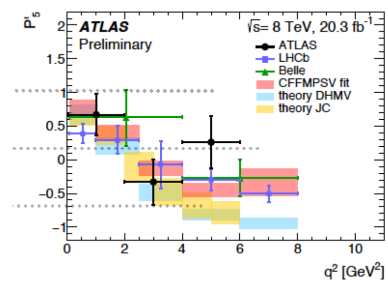
P5′ in $B^0 \to K^{*0}\mu^+\mu^-$ (8 TeV)

Physics Letters B, Volume 780, 2018, pp. 251-272





$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)(1-\cos^2\theta_l) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right] + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}. \quad (1)$$



H→ tau tau backup

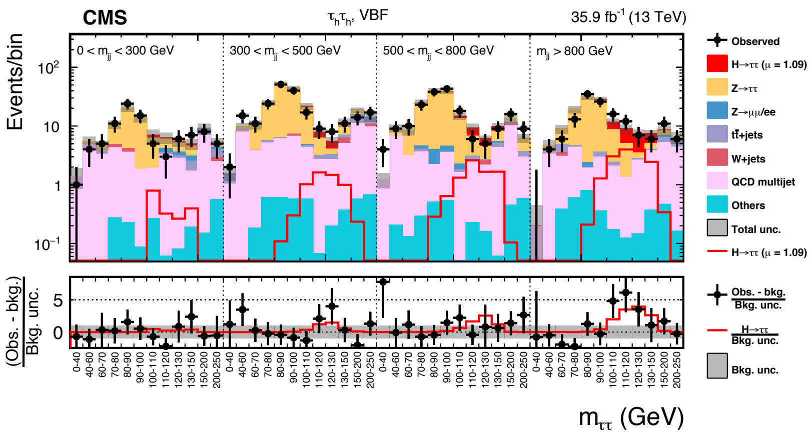
Table 1: Kinematic selection requirements for the four di-τ decay channels. The trigger requirement is defined by a combination of trigger candidates with p_T over a given threshold (in GeV), indicated inside parentheses. The pseudorapidity thresholds come from trigger and object reconstruction constraints. The p_T thresholds for the lepton selection are driven by the trigger requirements, except for the leading τ_h candidate in the $\tau_h\tau_h$ channel, the τ_h candidate in the $\mu\tau_h$ and $e\tau_h$ channels, and the muon in the $e\mu$ channel, where they have been optimized to increase the significance of the analysis.

Channel	Trigger requirement	Lepton selection		
		p_T (GeV)	η	Isolation
$\tau_h\tau_h$	$\tau_h(35)$ & $\tau_h(35)$	$p_T^{\tau_h} > 50$ & 40	$\|\eta^{\tau_h}\| < 2.1$	MVA τ_h ID
$\mu\tau_h$	$\mu(22)$	$p_T^{\mu} > 23$	$\|\eta^{\mu}\| < 2.1$	$I^{\mu} < 0.15$
		$p_T^{\tau_h} > 30$	$\|\eta^{\tau_h}\| < 2.3$	MVA τ_h ID
	$\mu(19)$ & $\tau_h(21)$	$20 < p_T^{\mu} < 23$	$\|\eta^{\mu}\| < 2.1$	$I^{\mu} < 0.15$
		$p_T^{\tau_h} > 30$	$\|\eta^{\tau_h}\| < 2.3$	MVA τ_h ID
$e\tau_h$	$e(25)$	$p_T^{e} > 26$	$\|\eta^{e}\| < 2.1$	$I^{e} < 0.1$
		$p_T^{\tau_h} > 30$	$\|\eta^{\tau_h}\| < 2.3$	MVA τ_h ID
$e\mu$	$e(12)$ & $\mu(23)$	$p_T^{e} > 13$	$\|\eta^{e}\| < 2.5$	$I^{e} < 0.15$
		$p_T^{\mu} > 24$	$\|\eta^{\mu}\| < 2.4$	$I^{\mu} < 0.2$
	$e(23)$ & $\mu(8)$	$p_T^{e} > 24$	$\|\eta^{e}\| < 2.5$	$I^{e} < 0.15$
		$p_T^{\mu} > 15$	$\|\eta^{\mu}\| < 2.4$	$I^{\mu} < 0.2$

Table 2: Category selection and observables used to build the 2D kinematic distributions. The events neither selected in the 0-jet nor in the VBF category are included in the boosted category, as denoted by "Others".

	0-jet	VBF	Boosted
		Selection	
$\tau_h\tau_h$	No jet	$\geq$2 jets, $p_T^{\tau\tau} > 100$ GeV, $\Delta\eta_{jj} > 2.5$	Others
$\mu\tau_h$	No jet	$\geq$2 jets, $m_{jj} > 300$ GeV, $p_T^{\tau\tau} > 50$ GeV, $p_T^{\tau_h} > 40$ GeV	Others
$e\tau_h$	No jet	$\geq$2 jets, $m_{jj} > 300$ GeV, $p_T^{\tau\tau} > 50$ GeV	Others
$e\mu$	No jet	2 jets, $m_{jj} > 300$ GeV	Others
		Observables	
$\tau_h\tau_h$	$m_{\tau\tau}$	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\mu\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\mu$	p_T^{μ}, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$

H→ tau tau backup



One of 12 2-D distributions:
4 decay topologies X 3 jet topologies
Jets: 0 j, VBF, other (boosted)
Here 2-D is m_{jj} vs $m_{\tau\tau}$.

H→ tau tau backup

Table 3: Sources of systematic uncertainty. If the global fit to the signal and control regions, described in the next section, significantly constrains these uncertainties, the values of the uncertainties after the global fit are indicated in the third column. The acronyms CR and ID stand for control region and identification, respectively.

Source of uncertainty	Prefit	Postfit (%)
τ_h energy scale	1.2% in energy scale	0.2–0.3
e energy scale	1–2.5% in energy scale	0.2–0.5
e misidentified as τ_h energy scale	3% in energy scale	0.6–0.8
μ misidentified as τ_h energy scale	1.5% in energy scale	0.3–1.0
Jet energy scale	Dependent upon p_T and η	—
$\vec{p}_T^{miss}$ energy scale	Dependent upon p_T and η	—
τ_h ID & isolation	5% per τ_h	3.5
τ_h trigger	5% per τ_h	3
τ_h reconstruction per decay mode	3% migration between decay modes	2
e ID & isolation & trigger	2%	—
μ ID & isolation & trigger	2%	—
e misidentified as τ_h rate	12%	5
μ misidentified as τ_h rate	25%	3–8
Jet misidentified as τ_h rate	20% per 100 GeV τ_h p_T	15
$Z \to \tau\tau/\ell\ell$ estimation	Normalization: 7–15%	3–15
	Uncertainty in $m_{\ell\ell/\tau\tau}$, $p_T(\ell\ell/\tau\tau)$, and m_{jj} corrections	—
W + jets estimation	Normalization (eμ, $\tau_h\tau_h$): 4–20%	—
	Unc. from CR (eτ_h, $\mu\tau_h$): ≃5–15	—
	Extrap. from high-m_T CR (eτ_h, $\mu\tau_h$): 5–10%	—
QCD multijet estimation	Normalization (eμ): 10–20%	5–20%
	Unc. from CR (eτ_h, $\tau_h\tau_h$, $\mu\tau_h$): ≃5–15%	—
	Extrap. from anti-iso. CR (eτ_h, $\mu\tau_h$): 20%	7–10
	Extrap. from anti-iso. CR ($\tau_h\tau_h$): 3–15%	3–10
Diboson normalization	5%	—
Single top quark normalization	5%	—
$t\bar{t}$ estimation	Normalization from CR: ≃5%	—
	Uncertainty on top quark p_T reweighting	—
Integrated luminosity	2.5%	—
b-tagged jet rejection (eμ)	3.5–5.0%	—
Limited number of events	Statistical uncertainty in individual bins	—
Signal theoretical uncertainty	Up to 20%	—

Htt Backup

TABLE I. Best fit value, with its uncertainty, of the $t\bar{t}H$ signal strength modifier $\mu_{t\bar{t}H}$, for the five individual decay channels considered, the combined result for $7+8$ TeV alone and for 13 TeV alone, and the overall combined result. The total uncertainties are decomposed into their statistical, experimental systematic, background theory systematic, and signal theory components. The numbers in parentheses are those expected for $\mu_{t\bar{t}H} = 1$.

Parameter	Best fit	Uncertainty			
		Statistical	Experi-mental	Background theory	Signal theory
$\mu_{t\bar{t}H}^{WW^*}$	$1.97^{+0.71}_{-0.64}$	$^{+0.42}_{-0.41}$	$^{+0.46}_{-0.42}$	$^{+0.21}_{-0.21}$	$^{+0.25}_{-0.12}$
	$(^{+0.57}_{-0.54})$	$(^{+0.39}_{-0.38})$	$(^{+0.36}_{-0.34})$	$(^{+0.17}_{-0.17})$	$(^{+0.12}_{-0.03})$
$\mu_{t\bar{t}H}^{ZZ^*}$	$0.00^{+1.30}_{-0.00}$	$^{+1.28}_{-0.00}$	$^{+0.20}_{-0.00}$	$^{+0.04}_{-0.00}$	$^{+0.09}_{-0.00}$
	$(^{+2.89}_{-0.99})$	$(^{+2.82}_{-0.99})$	$(^{+0.51}_{-0.00})$	$(^{+0.15}_{-0.00})$	$(^{+0.27}_{-0.00})$
$\mu_{t\bar{t}H}^{\gamma\gamma}$	$2.27^{+0.86}_{-0.74}$	$^{+0.80}_{-0.72}$	$^{+0.15}_{-0.09}$	$^{+0.02}_{-0.01}$	$^{+0.29}_{-0.13}$
	$(^{+0.73}_{-0.64})$	$(^{+0.71}_{-0.64})$	$(^{+0.09}_{-0.04})$	$(^{+0.01}_{-0.00})$	$(^{+0.13}_{-0.05})$
$\mu_{t\bar{t}H}^{\tau^+\tau^-}$	$0.28^{+1.09}_{-0.96}$	$^{+0.86}_{-0.77}$	$^{+0.64}_{-0.53}$	$^{+0.10}_{-0.09}$	$^{+0.20}_{-0.19}$
	$(^{+1.00}_{-0.89})$	$(^{+0.83}_{-0.76})$	$(^{+0.54}_{-0.47})$	$(^{+0.09}_{-0.08})$	$(^{+0.14}_{-0.01})$
$\mu_{t\bar{t}H}^{b\bar{b}}$	$0.82^{+0.44}_{-0.42}$	$^{+0.23}_{-0.23}$	$^{+0.24}_{-0.23}$	$^{+0.27}_{-0.27}$	$^{+0.11}_{-0.03}$
	$(^{+0.44}_{-0.42})$	$(^{+0.23}_{-0.22})$	$(^{+0.24}_{-0.23})$	$(^{+0.26}_{-0.27})$	$(^{+0.11}_{-0.04})$
$\mu_{t\bar{t}H}^{7+8\ \mathrm{TeV}}$	$2.59^{+1.01}_{-0.88}$	$^{+0.54}_{-0.53}$	$^{+0.53}_{-0.49}$	$^{+0.55}_{-0.49}$	$^{+0.37}_{-0.13}$
	$(^{+0.87}_{-0.79})$	$(^{+0.51}_{-0.49})$	$(^{+0.48}_{-0.44})$	$(^{+0.50}_{-0.44})$	$(^{+0.14}_{-0.02})$
$\mu_{t\bar{t}H}^{13\ \mathrm{TeV}}$	$1.14^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
	$(^{+0.29}_{-0.26})$	$(^{+0.16}_{-0.16})$	$(^{+0.17}_{-0.16})$	$(^{+0.13}_{-0.12})$	$(^{+0.11}_{-0.05})$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$
	$(^{+0.28}_{-0.25})$	$(^{+0.15}_{-0.15})$	$(^{+0.16}_{-0.15})$	$(^{+0.13}_{-0.12})$	$(^{+0.11}_{-0.05})$

VH(bb) Backup

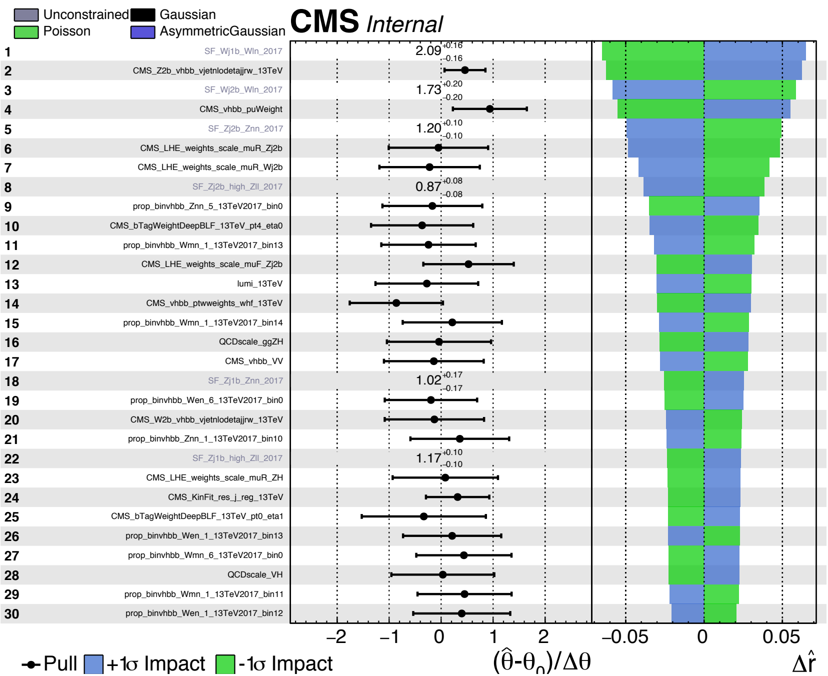
- **Primary improvements** for 2017 analysis:
- Improved b-jet energy regression
- FSR recovery.
- Kinematic fit in Z(ll)
- Deep neural network (DNN) to discriminate signal from background.
- Multi-output DNN in W(lv)+heavy flavor and Z(vv)+heavy flavor control regions to discriminate among background components.
- DeepCSV to identify b-jet candidates.
- • Each of these improvements with respect to the previous analysis cycles will be outlined in dedicated slides.

- Bjet resolution – 12%

- Systematics
- **Met energy scale:**
- • Split into 27 independent uncertainty sources as recommended by JET/MET.
- **• Jet energy resolution:**
- • 10% uncertainty on regressed b-jets from dedicated study discussed with JME.
  • **Decorrelated for signal** to avoid any possible constraining, should cover any uncertainties from PS.
- • Standard JER uncertainty for additional jets.
- **• B-tagging:**
- Split into independent uncertainty sources as recommended by BTV.
- Further de-correlated based on jet p_T/η, as in 2016 analysis.
- **• Background normalizations:**
- Derived from fit to data for backgrounds with floating normalisation (V+udcsg, V+b, V+bb, tt)
- 15% uncertainty on VV and single top cross section.
- **• Monte Carlo statistics**
- • QCD scale and pdf (acceptance as well as overall cross section).
- • $\Delta\eta$(jj) LO to NLO re-weighting:
- • Full correction taken as uncertainty.
- • p_T(W) linear re-weighting (1-lepton channel only) • Statistical uncertainty band from fit to derive corrections.
- • Lepton efficiency, pile-up re-weighting, luminosity,

- **Validation**
- **VZ, Z→bb**

VH(bb) Backup

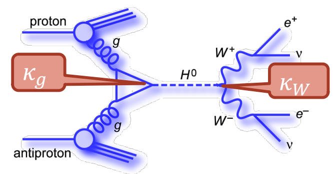


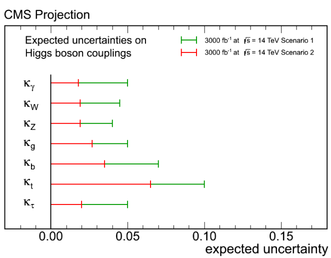
Unconstrained
Gaussian
Poisson
AsymmetricGaussian
CMS Internal
1 SF_Wj1b_Wln_2017 2.09 +0.16 -0.16
2 CMS_Z2b_vhbb_vjetnlodetajjrw_13TeV
3 SF_Wj2b_Wln_2017 1.73 +0.20 -0.20
4 CMS_vhbb_puWeight
5 SF_Zj2b_Znn_2017 1.20 +0.10 -0.10
6 CMS_LHE_weights_scale_muR_Zj2b
7 CMS_LHE_weights_scale_muR_Wj2b
8 SF_Zj2b_high_Zll_2017 0.87 +0.08 -0.08
9 prop_binvhbb_Znn_5_13TeV2017_bin0
10 CMS_bTagWeightDeepBLF_13TeV_pt4_eta0
11 prop_binvhbb_Wmn_1_13TeV2017_bin13
12 CMS_LHE_weights_scale_muF_Zj2b
13 lumi_13TeV
14 CMS_vhbb_ptwweights_whf_13TeV
15 prop_binvhbb_Wmn_1_13TeV2017_bin14
16 QCDscale_ggZH
17 CMS_vhbb_VV
18 SF_Zj1b_Znn_2017 1.02 +0.17 -0.17
19 prop_binvhbb_Wen_6_13TeV2017_bin0
20 CMS_W2b_vhbb_vjetnlodetajjrw_13TeV
21 prop_binvhbb_Znn_1_13TeV2017_bin10
22 SF_Zj1b_high_Zll_2017 1.17 +0.10 -0.10
23 CMS_LHE_weights_scale_muR_ZH
24 CMS_KinFit_res_j_reg_13TeV
25 CMS_bTagWeightDeepBLF_13TeV_pt0_eta1
26 prop_binvhbb_Wen_1_13TeV2017_bin13
27 prop_binvhbb_Wmn_6_13TeV2017_bin0
28 QCDscale_VH
29 prop_binvhbb_Wmn_1_13TeV2017_bin11
30 prop_binvhbb_Wen_1_13TeV2017_bin12
−2 −1 0 1 2
−0.05 0 0.05
Pull +1σ Impact -1σ Impact
$(\hat{\theta}-\theta_0)/\Delta\theta$
$\Delta\hat{r}$

Higgs Coupling Projections for HL-LHC

Higgs Properties

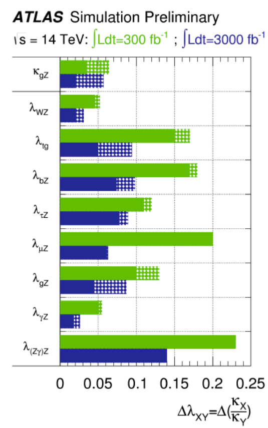
- Coupling measurements:
- Rate of a given process depends on several couplings
- Example h→gg→WW: $\sigma B \propto \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$
  - The κ's multiply the SM couplings. κ_g is a function of κ_t and κ_b.
  - κ_H multiplies the Higgs width and depends on all couplings
- Comprehensive study of Higgs couplings at the HL-LHC





Currently κ's are typically measured to ≈20%. Projections at 3-10%-level with 3000 fb^{-1}

HL-LHC will improve msm't precision by a factor 2-3!

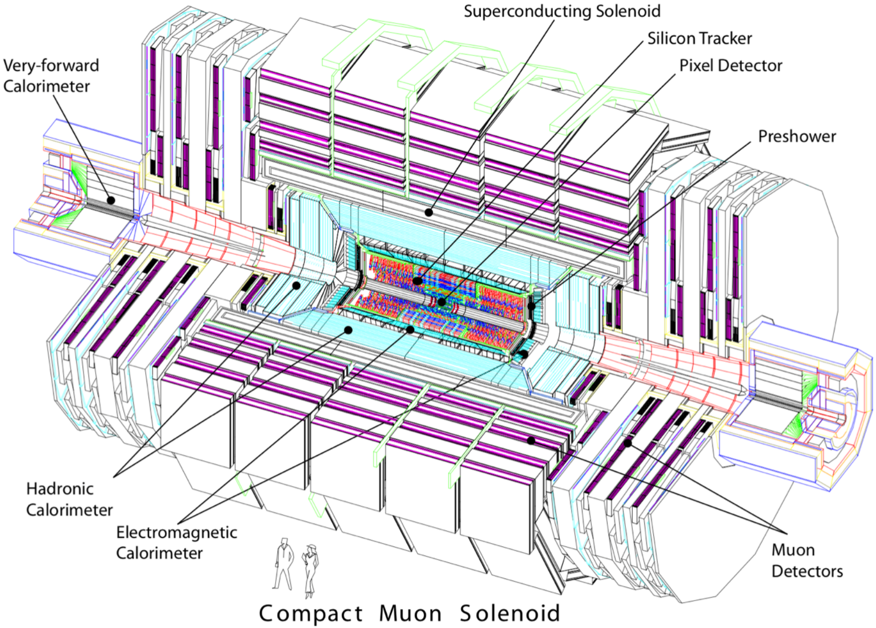


- Reduced theoretical uncertainties needed (mprovement since 2014)
- Expected deviations from SM predictions by various models (Singlet mixing, 2HDM, Decoupling MSSM, Composite, Top Partner..) predicted to be between 1-10%.

CMS Evolution in 2017/18

CMS Design

- Very large solenoid - 6m diameter x 13 m long
  - Tracking and calorimetry fit inside
- Very strong field – 3.8T
  - Excellent momentum resolution
- Chambers in the return iron track and identify muons, leading to a very compact system
- A lead tungstate crystal calorimeter (~76K crystals) for photon and electron reconstruction
- Hadron calorimeters for jet and missing E_t reconstruction to η~5
- Charged Particle Tracking with all-silicon components
  - A silicon pixel detector out to radius ~ 20 cm
  - A silicon microstrip detector from there out to 1.1 m
- Weight, dominated by steel, is 14,000 Tonnes

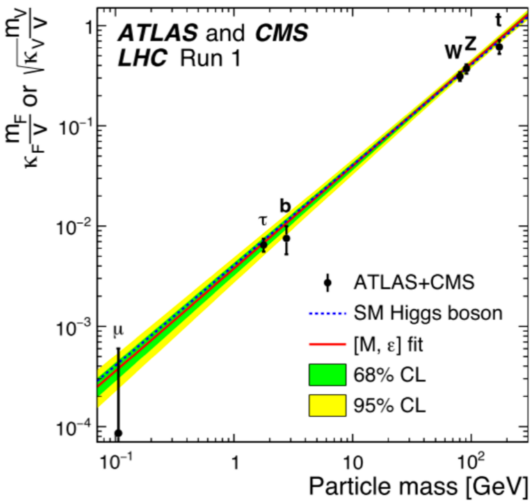


CMS is continuously upgraded to handle higher luminosity and do better physics

Higgs Properties

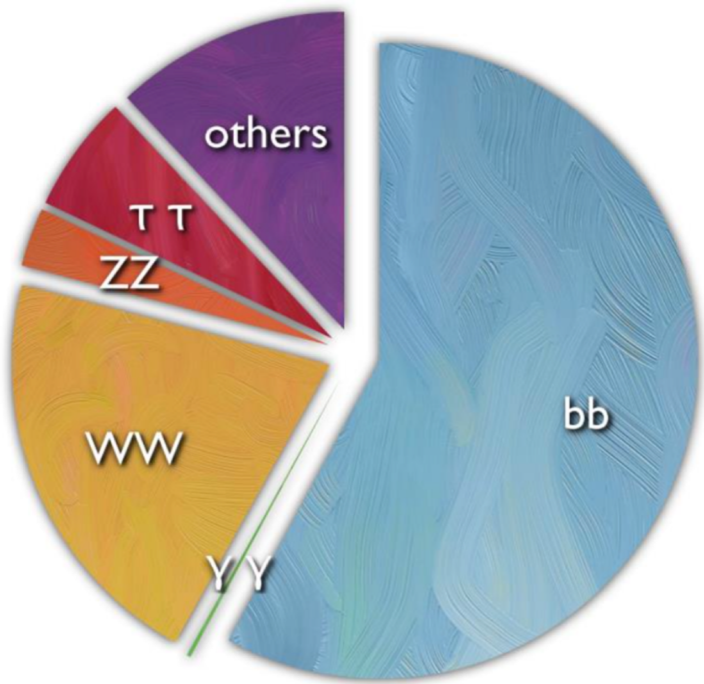
- **Spin/Parity:** 0^{+} — ATLAS: EPJC 75 (2015) 476; CMS: PRD 92 (2015) 012004
- **Width:** < 1 GeV (direct) — CMS: JHEP 11 (2017) 047

  < 0.015 GeV (indirect) — ATLAS: arXiv:1808.01191 submitted to PLB
- **Observed direct coupling** to:
  - **Vector bosons** — ATLAS: PLB 716 (2012) 1-29; CMS: PLB 716 (2012) 30
  - **τ leptons** — ATLAS: ATLAS-CONF-2018-021; CMS: PLB 779 (2018) 283
  - **top quarks** — ATLAS: PLB 784 (2018) 173; CMS: PRL 120 (2018) 231801



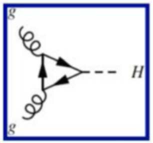
All measurements compatible with SM predictions

Higgs Branching Fractions



Higgs Production Modes

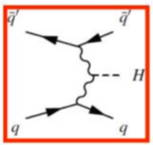
- Very large datasets at LHC give access to **several production modes to search for H→b$\bar{b}$**



Gluon Fusion (87%)

Overwhelming (10^7 **larger**) background of b-quark production due to strong interactions

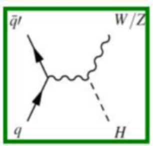
CMS: PRL 120 (2018) 071802



Vector-Boson Fusion (7%)

Very large background but a very distinctive topology
ISR photon to enhance S/B

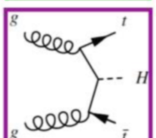
ATLAS: arXiv:1807.08639 submitted to PRD
ATLAS: JHEP 11 (2016) 112
CMS: HIG-16-003
CMS: PRD 92 (2015) 032008



Higgs-strahlung (4%)

leptons, E_T^{mis} to trigger and high p_T V suppress backgrounds

Most sensitive



Top Fusion ttH (1%)

dominant background is $t\bar{t}$ + jets

ATLAS: JHEP 05 (2016) 160
ATLAS: PRD 97, 072016 (2018)
CMS: JHEP 09 (2014) 087
CMS: arXiv:1804.03682 submitted to JHEP
CMS: JHEP 06 (2018) 101