CMS Experiment: Physics Overview

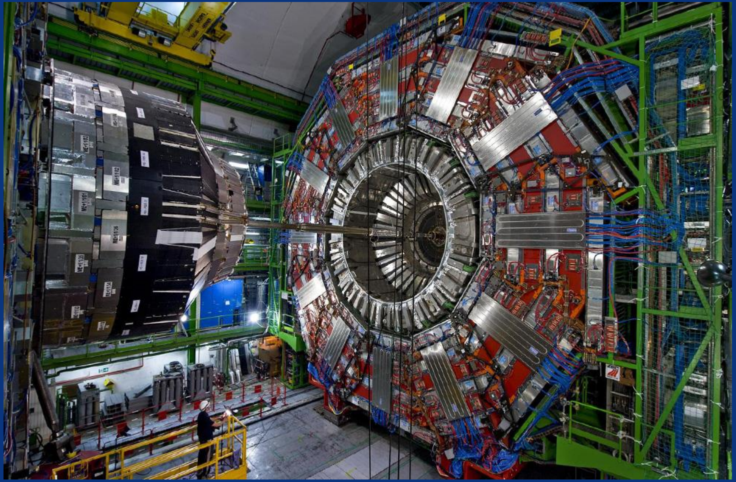
Vadim Alexakhin

Talk Presented at the

XXIVth International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics“

Dubna, Russia

Sep. 20, 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

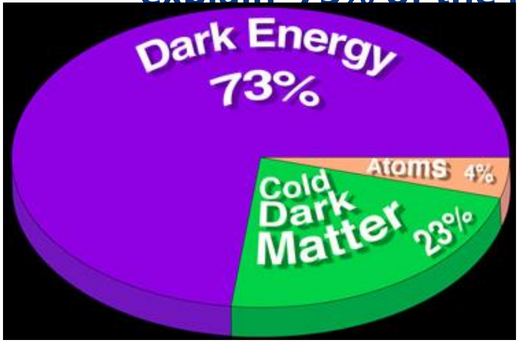
Status of Particle Physics at the LHC

- 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).
- 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)"

- **unstable at the TeV scale (Higgs is too light);**
- **violated by the Baryon Asymmetry of the universe (not enough CP violation – predicts too little matter);**
- **No explanation for neutrino masses;**
- **Can't explain why there are three generations of quarks and leptons or their mass values (the "Flavor Problem");**
- **The SM has no Dark Matter candidate and therefore does not explain 75% of the matter and energy in the universe.**



Berkeley Cosmology group

For all its success on the microscopic level, the SM cannot explain how we arrived at the universe that exists today.

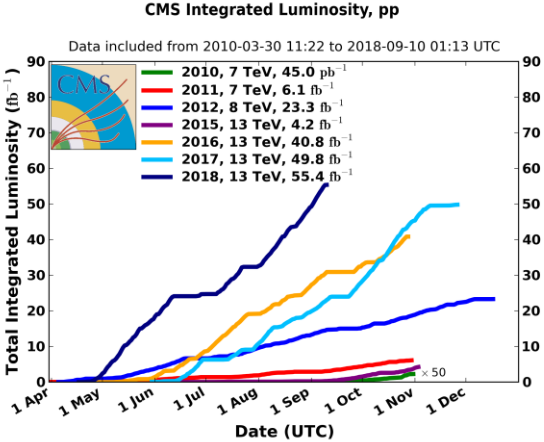
GRADE = INCOMPLETE

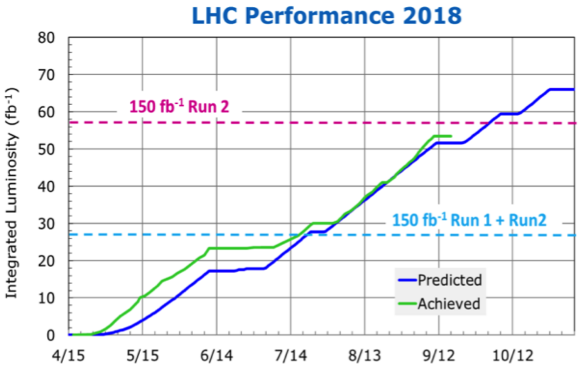
What is next?

- 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 no clear guidance on the **best** place to look and the **"right"** place may not even be in our current menu
  - A broad attack on many fronts is necessary
- We have three basic tools for exploring this large, as yet largely uncharted, territory
  - **Studying the properties of the 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**
  - **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





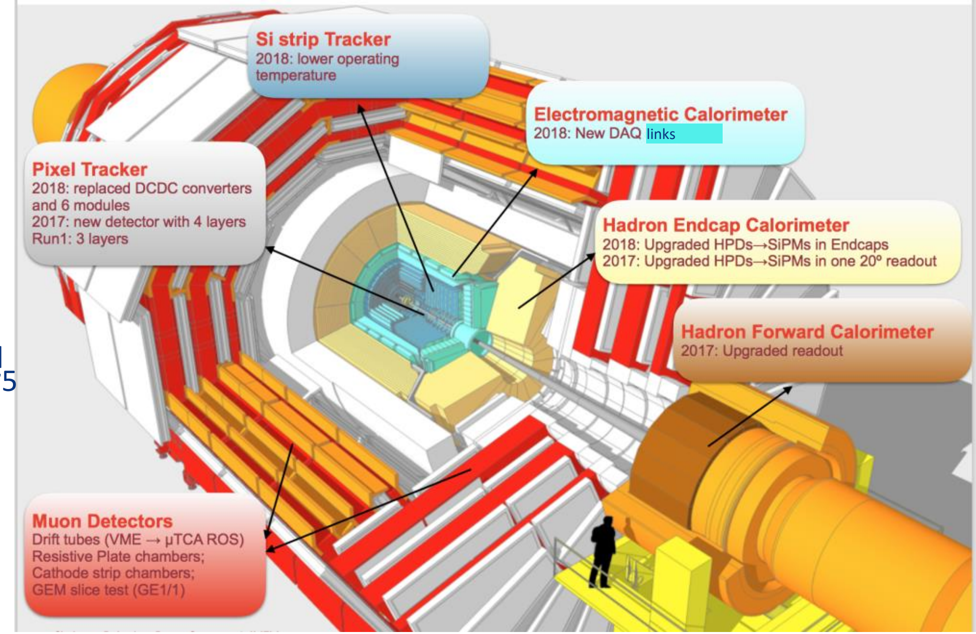
- LHC has produced 3 years of sustained high luminosity that is expected to result in >150 fb^{-1} at 13 TeV by the end of the 2018 run
  - It has exceeded peak DESIGN Luminosity by a factor of 2!
    - 2018 maximum peak lumi ~2x10^{34} cm^{-2} s^{-1} with mean pileup ~ 38
- LHC has much higher availability 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

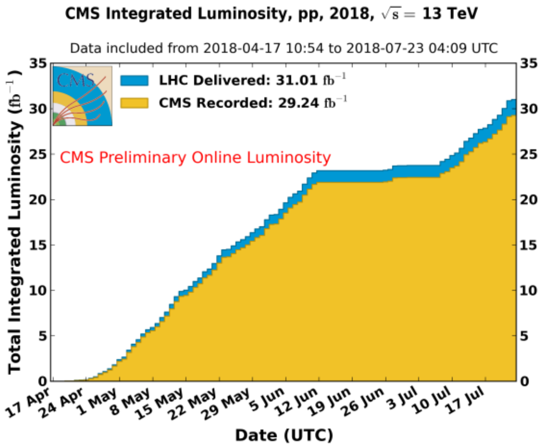
CMS Evolution in 2016/17/18

CMS Design

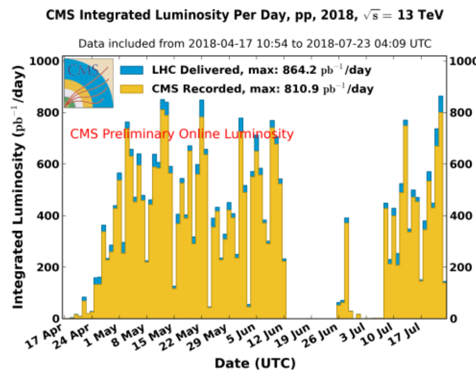
- Very large solenoid - 6m diameter x 13 m long
  - Tracking and calorimetry fit inside
- Very strong field – 3.8T
  - Excellent momentum resolution
- Chambers in the return iron track and identify muons, leading to a very compact system
- A lead tungstate crystal calorimeter (~76K crystals) for photon 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



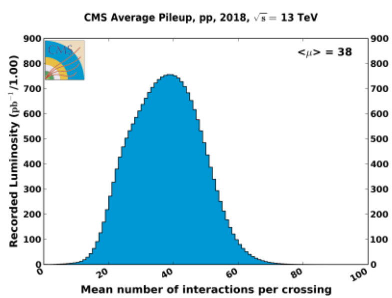
Luminosity Accumulation in CMS



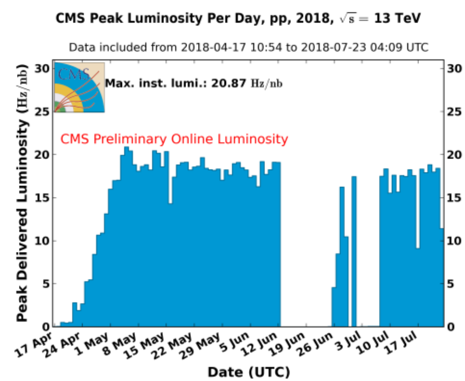
Recording Efficiency 94.3%



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

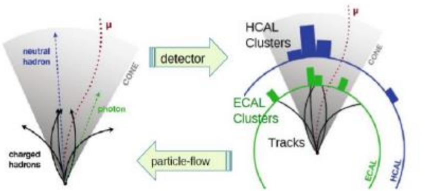


Mean Pileup 38 int/Xing

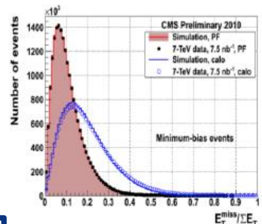


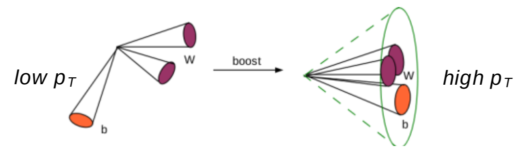
Peak lumi ~1.8-1.9 x 10^{34} $cm^{-2}s^{-1}$

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 identification, and helps with high pileup
- PUPPI (Pileup per proton interaction) is a special tool to deal with high pileup
- Use of multivariate analysis techniques to maximize power of available statistics
- Use of Deep Neural Nets/Machine Learning
- Boosted jet topologies and jet substructure analysis

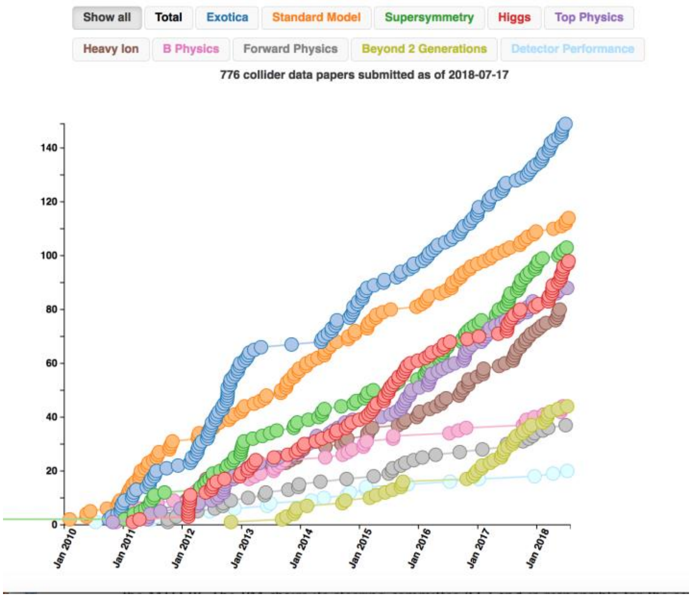
Pervasive in Run 2!

Recent Physics Results

Publication Status

776 physics papers submitted in ten categories

- http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/
- More than 25 new results released for 2018 end-of-summer conferences
- **It is not practical in this talk to try to summarize even this summer's papers, let alone put them in context.**
- **I will discuss a few highlights from Higgs, Top, and B physics and Searches (SUSY, Exotics)**

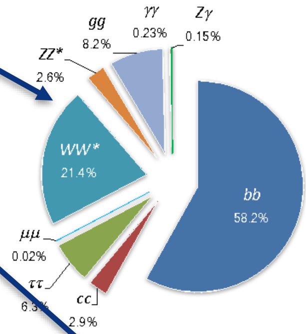


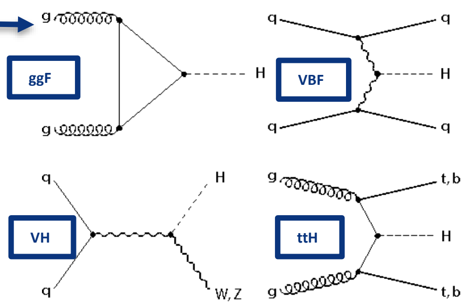
Recent Physics Results - 1

Higgs

Higgs Refresher

- There are four basic production modes
- There are 6 basic decays into vector bosons, quarks, and leptons
- An analysis typically targets some combination of these based on their sensitivity
- Signal to background, ability to trigger are key features (smaller BRs, $\gamma\gamma$ and 4leptons (μ,e), were the discovery channels





$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

	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)
  - Coupling strength of various processes, including ttH

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

PLB 779 (2018) 283

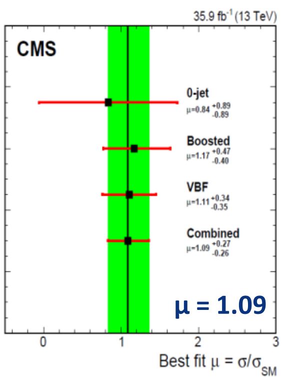
arXiv:1708.00373

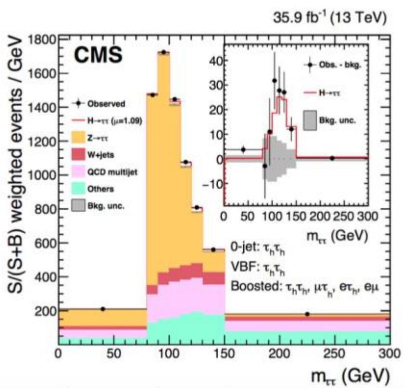
- Branching ratio = 6.3%, best channel to establish coupling of Higgs boson to fermions
- Final states: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$ → Significance of 4.9σ observed (4.7σ expected) with13 TeV data
- **Combination with 7, 8 TeV data: 5.9σ obs. (5.9σ exp.) and $\mu = 0.98 \pm 0.18$**

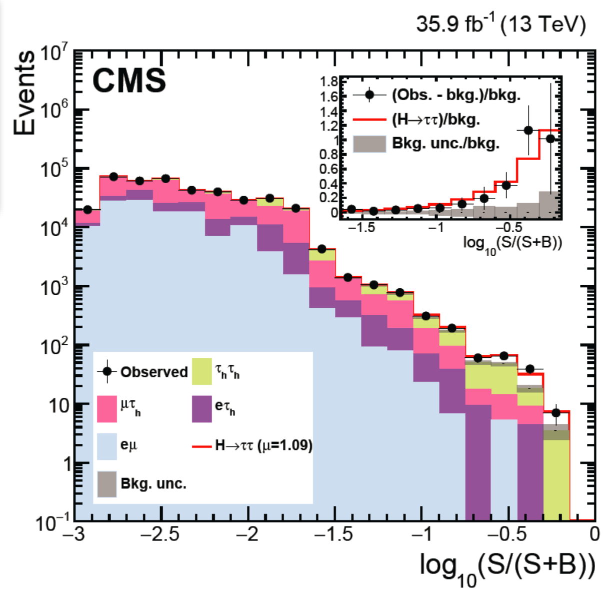
First direct observation by a single experiment of H coupling to fermions!

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

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

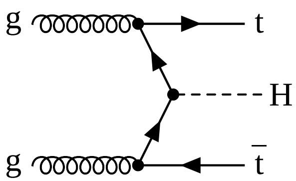




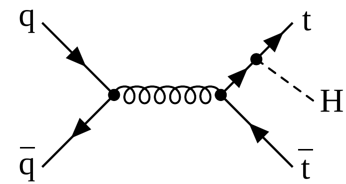


ttH

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



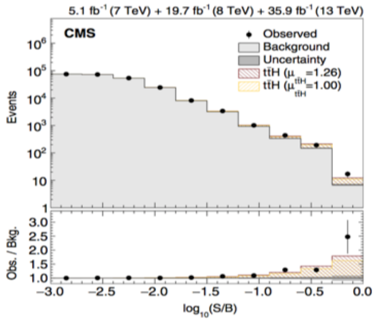
Higgs is too light to decay into two tops

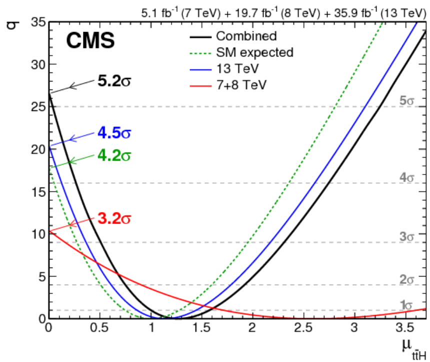


- Signature is production of two top quarks and a Higgs
  - The top is observed its its decay to Wb with the W decaying leptonically or hadronically
  - The analysis uses Higgs decays to bottom-quark-anti quark pair, a $\tau^+\tau^-$, $\gamma\gamma$, WW* and ZZ* (various quark and multi-lepton channels)
    - 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 limited by statistics; H→ bb and H→leptons by systematics

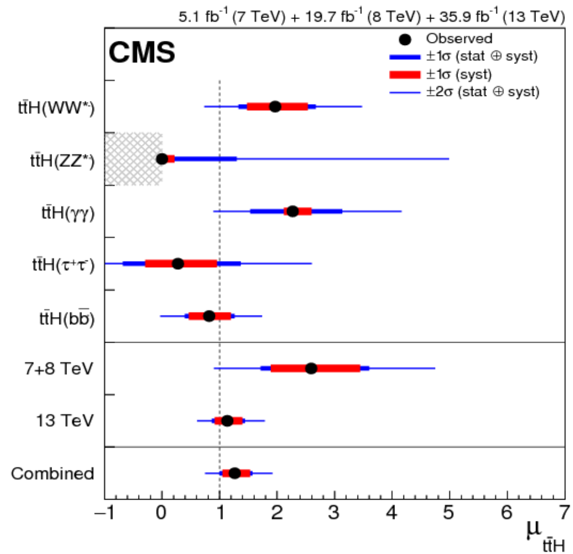
ttH: 7,8, and13 TeV Combined

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



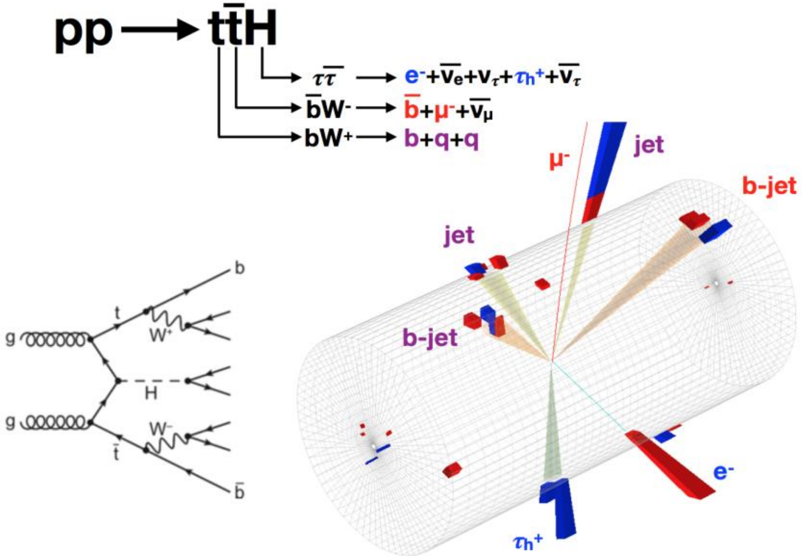


Test statistic vs coupling strength modifier The horizontal dashed lines indicate the *p*-values for the background-only hypothesis obtained from the asymptotic distribution of *q*,



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

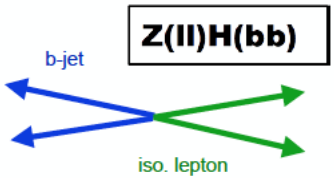


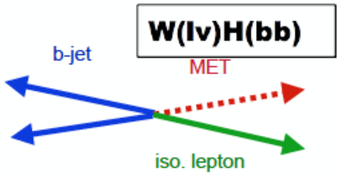
- This is only a "candidate" since we have backgrounds
  - However, we are beginning to see excesses of such events
- This example links the heaviest bosons and quarks (H, W, Top, b) and the heaviest lepton (t), to some of the lightest quarks and leptons, including all three flavors of neutrinos.

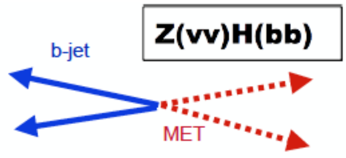
Higgs → bb

HIG-18-016

- This has the biggest branching fraction
- However, there is MASSIVE bb background from QCD processes, ~10^3 times the signal in this mass region
- Must choose a weak interaction production mode to reduce hadronic backgrounds (QCD multijet, top)
- Signal is a di-jet mass enhancement which has many challenges
- Unlike $H \rightarrow \tau^+\tau^-$ and ttH, we needed the 2017 data to bring its observation within reach
- State expected to contribute the most $V(W \rightarrow l\,\nu, Z \rightarrow ll, Z \rightarrow \nu\nu)$ H(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)





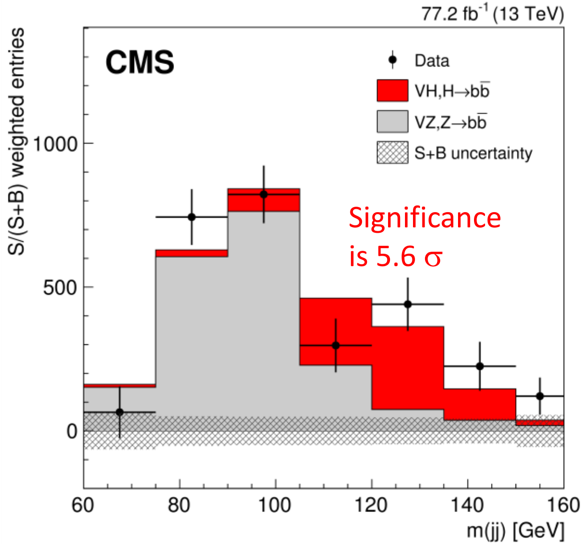


Observation of Higgs boson decay to bottom quarks

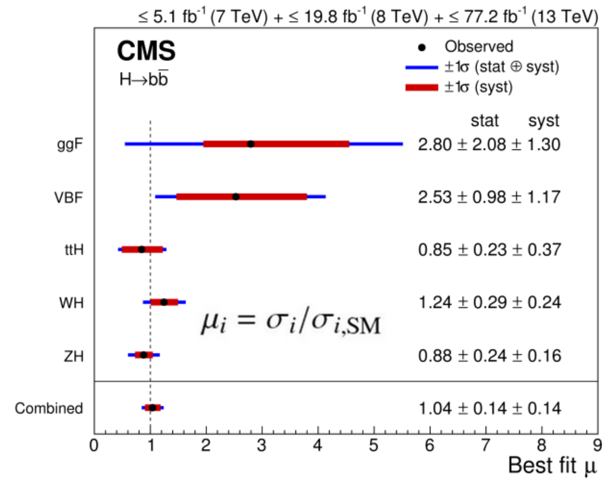
On 28 August 2018, two of the experiments at the CERN's Large Hadron Collider (LHC), ATLAS and CMS, reported independently observation of Higgs boson decay to bottom quarks

arXiv:1808.08242, Submitted to PRL

Dijet invariant mass distribution in all channels combined in the 2016 and 2017 data



Signal strength with its 1σ systematic (red) and total (blue) uncertainties for the five individual production modes

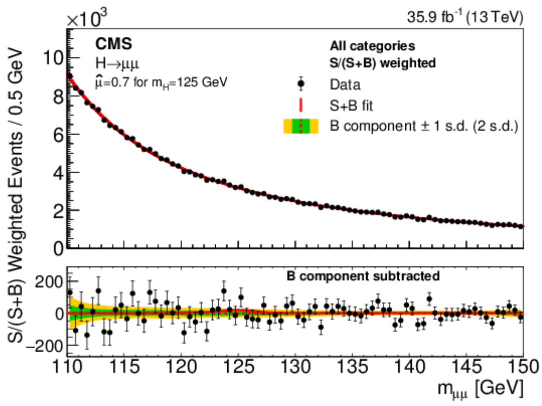


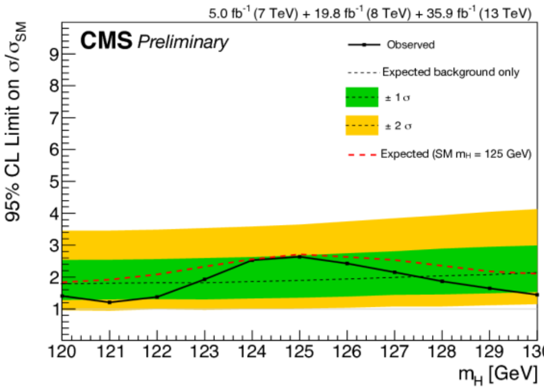
With this observation of the Higgs boson coupling to the bottom quark, together with earlier observations of the Higgs coupling to the top quark and the tau lepton (to all three of the heaviest known fermions), the CMS physics program to characterise and more fully understand the Higgs boson has taken another important step.

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 5.7×10^{-4}, 2.64 (observed) vs 1.89 (expected)

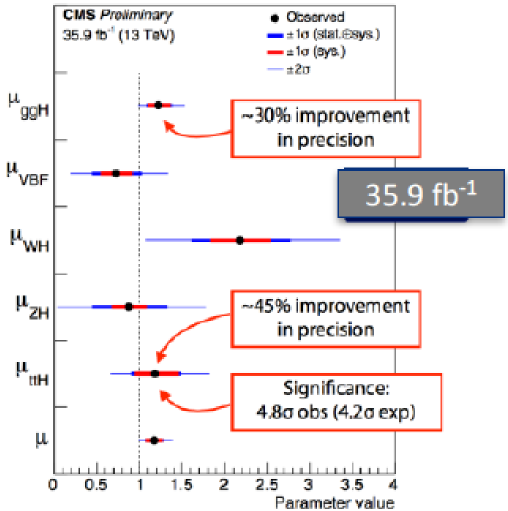


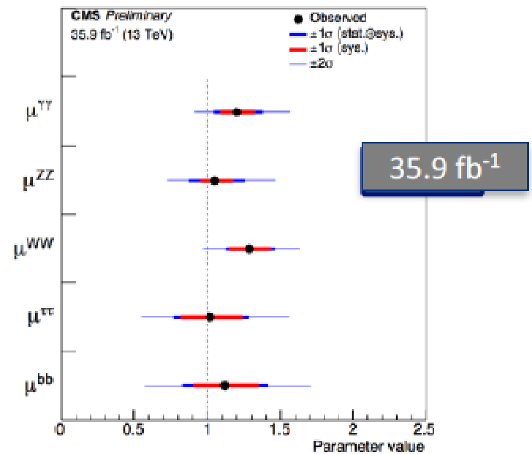


Higgs Combination: Signal Strengths

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





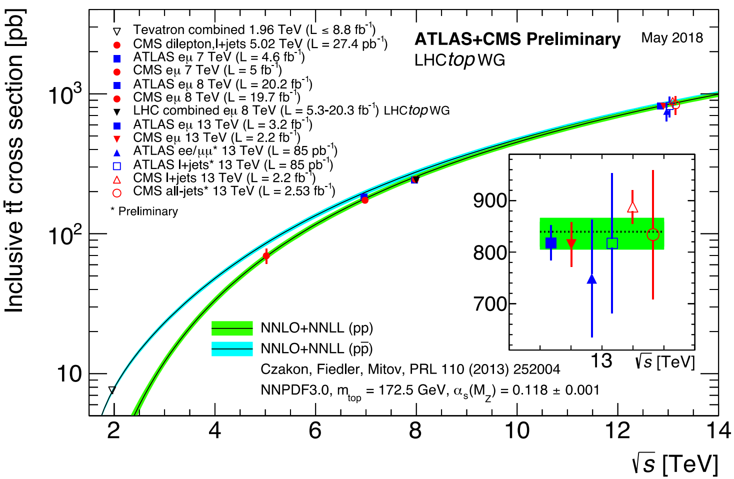
Per production mode HIG-17-031 **Per decay mode**

Despite progress, there is still room for new physics and we have reduce systematic uncertainties

Recent Physics Results

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

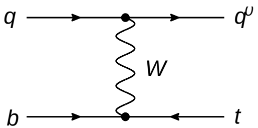
- Single, double, and triple differential cross sections
- Rare (FCNC) decays
- CP violation (a beginning)
- Width and more complex methods for measuring the mass

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

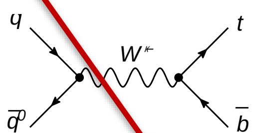
Factory	Quark	Cross Section (nb)	Luminosity (cm^{-2}s^{-1})
B (KEKb)	Bottom	1.15 (Y(4S))	2.11×10^{34}
LHC	Top	0.82 (incl t-t)	2.01×10^{34}

Single Top

t-channel ~220 pb

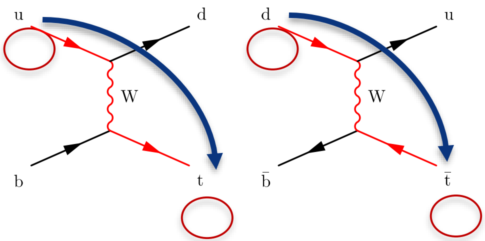


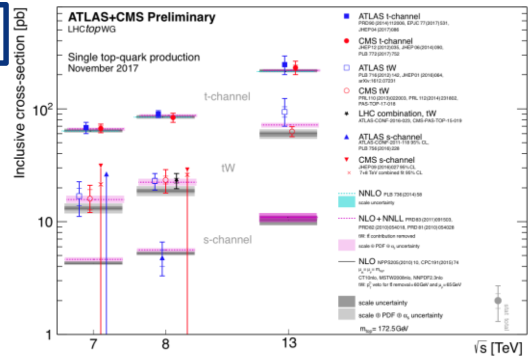
s-channel~ 10pb

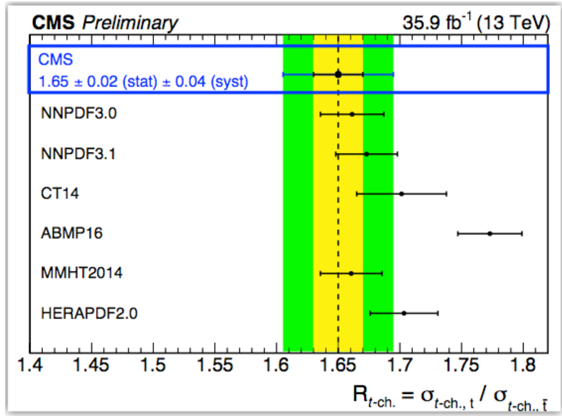


Not seen at LHC

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).

TOP-17-011

Top Differential Cross sections

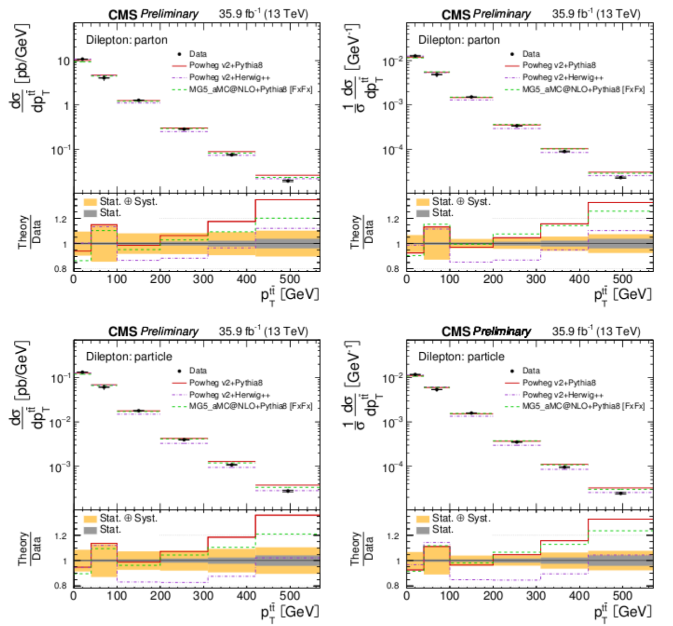
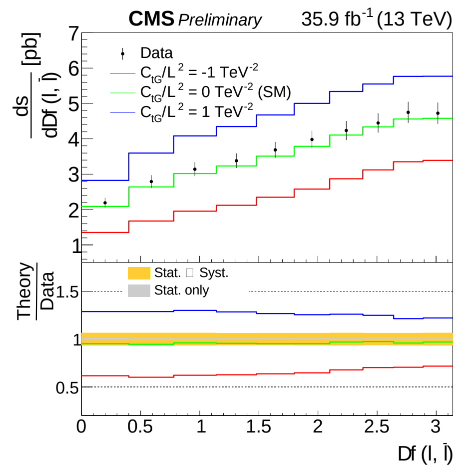


Figure 20: The differential $t\bar{t}$ production cross sections as a function of $p_T^{t\bar{t}}$ are shown. The left and right columns correspond to absolute and normalised measurements, respectively. The upper row corresponds to measurements at parton level in the full phase space and the lower row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

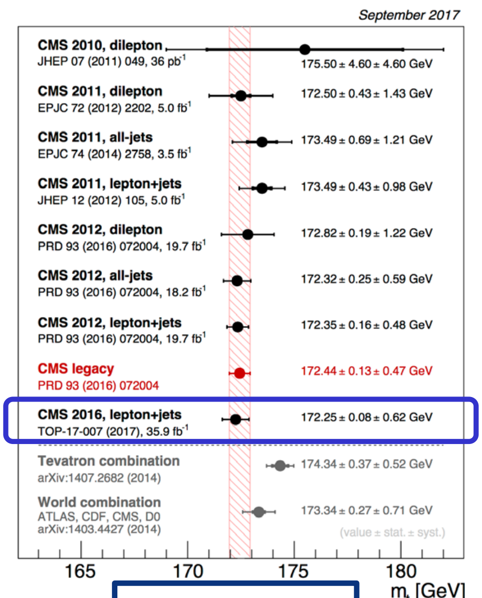
Differential Cross section to Constrain top chromo-magnetic Dipole moment



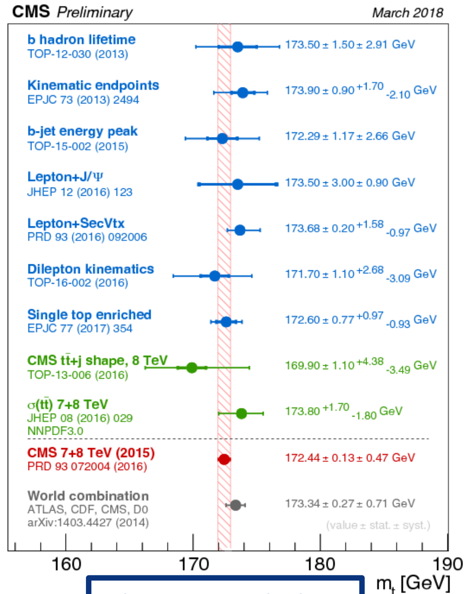
$\frac{ds}{dDf\,(l,\bar{l})}$

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

Top Mass

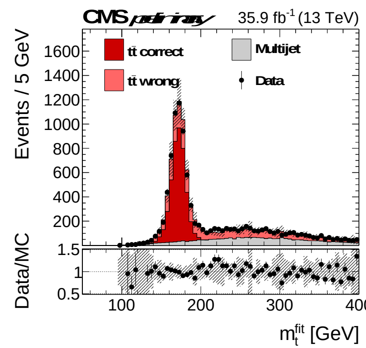


"classic" methods



Alternative methods

CMS-PAS-TOP-17-008



CMS all-jet (13 TeV)

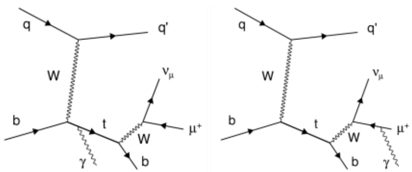
172.34 ±0.20 (*stat+JSF*) ±0.76 (*syst*) GeV

- "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

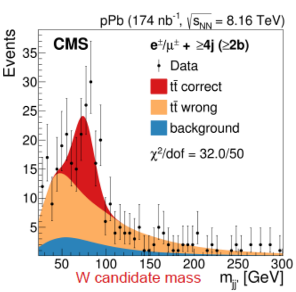
Top gallery

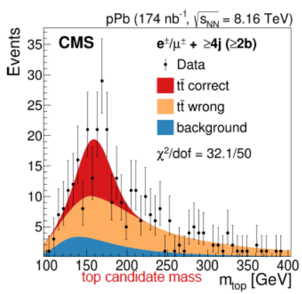
Top in Association with a γ

CERN-EP-2018-206



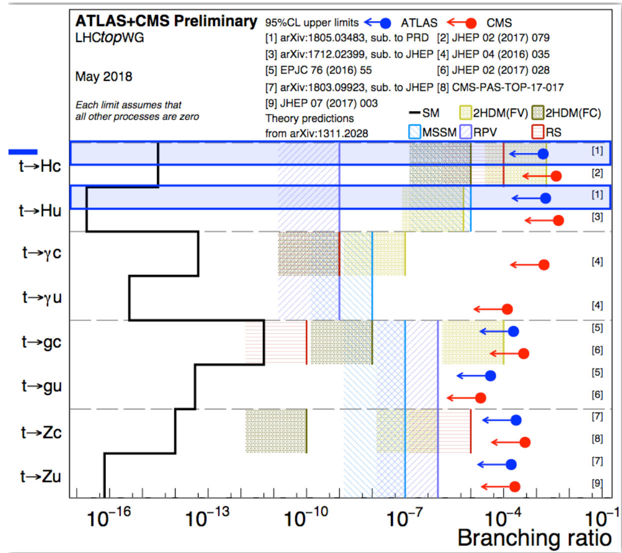
An excess is observed, with a significance of 4.4 standard deviations. A fiducial cross section is measured for photons with P_T> 25 GeV
$B(t\to\mu\nu b)\sigma(t\gamma j)$= 115 ± 17 (stat) +33−27 (syst) fb,
which agrees with the standard model prediction.





CERN-EP-2017-239

Rare, FC Top Decays



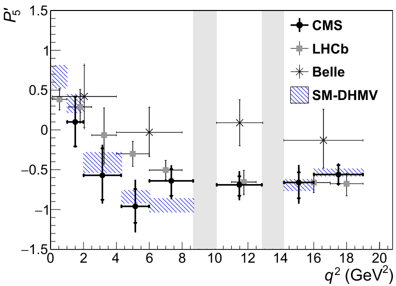
Even with full LHC data, none will reach SM expectations but some will reach level predicted by some BSM models

Recent Physics Results

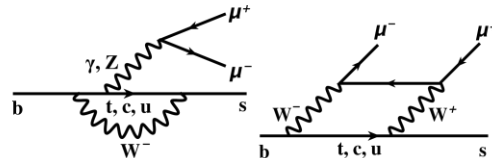
B Physics

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

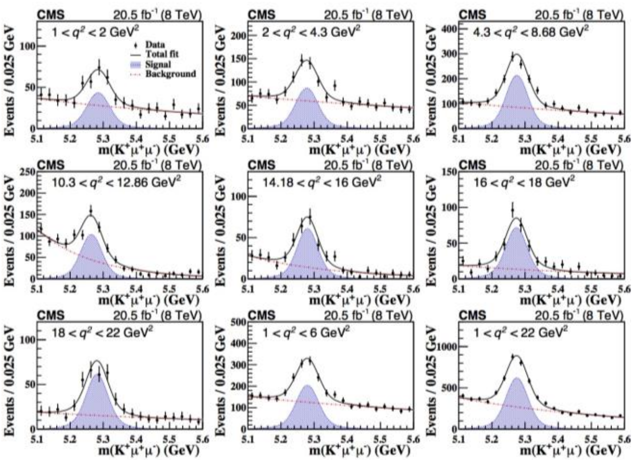
BPH-15-001



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

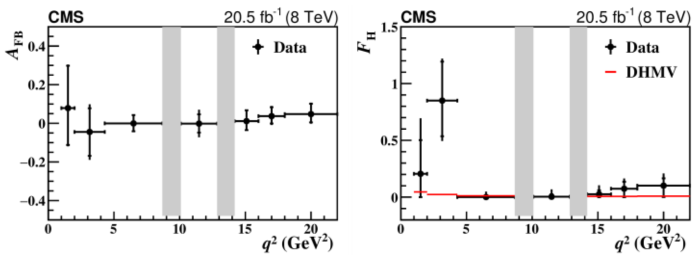


$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell} = \frac{3}{4}(1-F_{\mathrm{H}})(1-\cos^2\theta_\ell) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell.$$



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

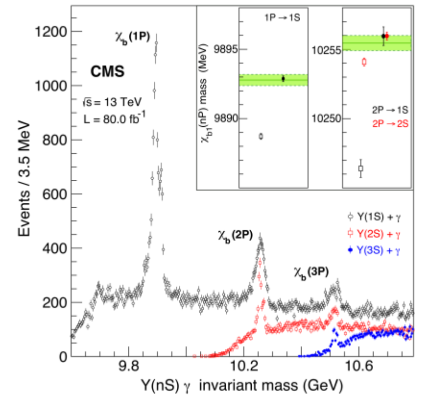
Based on 2286 +/- 73 events from 20.5 fb^{-1} taken at 8 TeV in 2012

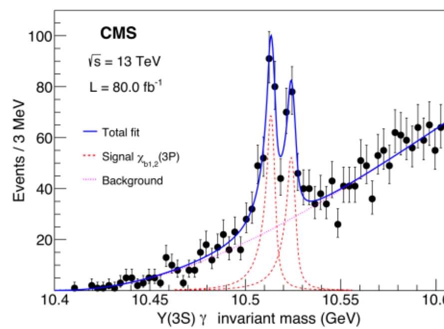


Consistent with previous measurements and various SM calculations

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

- A bump at mass ~10520 MeV was discovered by ATLAS in 2011 through its decay to $\Upsilon(1S)\gamma$ (where γ is observed by reconstructing an e^+e^- conversion) and was identified with the $\chi_b(3P)$ states
  - Three such states are expected with J=0,1,and 2, with the latter two expected to have large branching fractions to photons. They are expected to be separated by ~10 MeV in mass.
- 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 whose exact nature is still not pinned down
- **CMS revisited this with the full 2015-2012 dataset of 80 fb^{-1}**
  - Studying specifically
    - $\chi_b(3p)\rightarrow\Upsilon(3S)\gamma\rightarrow\Upsilon(\mu\mu)\gamma$ ($\gamma\rightarrow$e+e-)
    - **There are fewer Υ(3S) but the small photon energy can be measured with excellent resolution by the CMS spectrometer with its 3.8T field and can provide the needed resolution**
    - **2.2MeV resolution**
- The two $\chi_b(3p)$ states are clearly resolved





Mass Difference: ΔM = 10.6 ± 0.64 (*stat*) ± 0.17 (*syst*) MeV
(more consistent with NRQCD than coupling to the continuum)
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

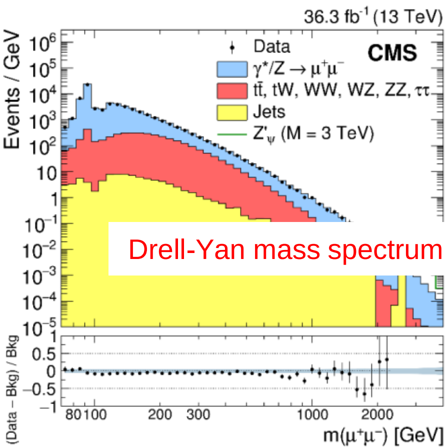
Recent Physics Results

Searches

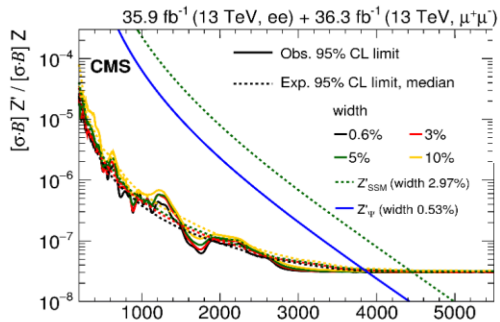
Search for New Physics with CMS

In 2018 JINR CMS group concentrated on data processing and analysis @ 13 TeV within few selected physics topics

- studies of Drell-Yan pair production to verify the Standard Model predictions for the new energy region
- searches for signals of new physics beyond the SM: new resonance states in dimuon channel and TeV-scale gravity in multiparticle production



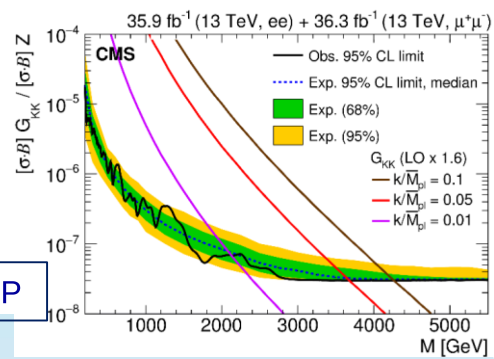
Drell-Yan mass spectrum



Extra gauge bosons mass limits: 3.9 - 4.5 TeV

JHEP 06 (2018) 120

KK-graviton mass limits: 2.1 – 4.25 TeV



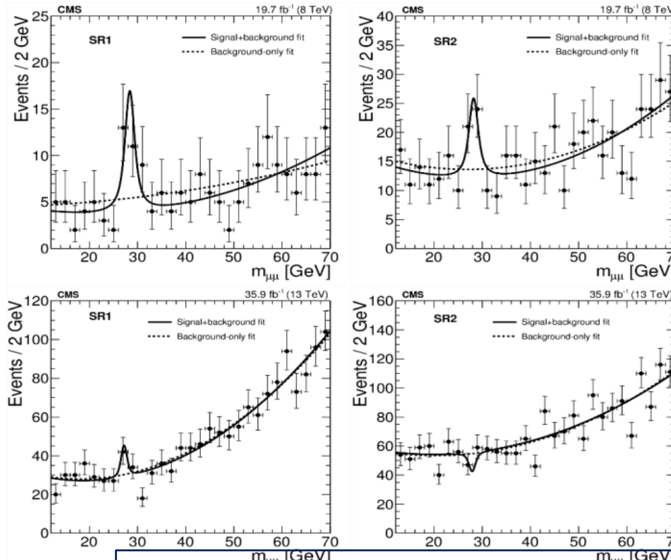
In channel with high-multiplicity final states semiclassical black holes with minimum masses as high as 10.1 TeV and string balls with masses as high as 9.5 TeV are excluded by this search.

arXiv:1805.06013, Submitted to JHEP

Search for Low-mass Resonances with CMS

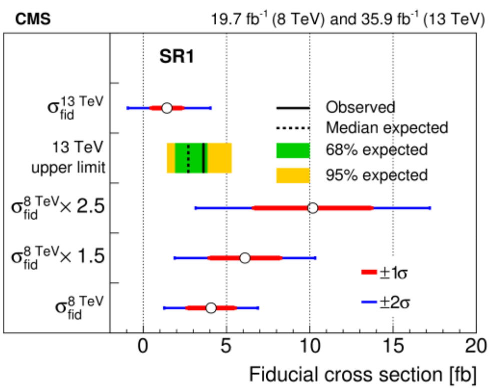
In 2018 JINR CMS group also contributed in search for resonances in the mass spectrum of muon pairs produced in association with b quark jets

- an excess of events above the background near a dimuon mass of 28 GeV is observed in the 8 TeV data, corresponding to local significances up to 4.2σ and 2.9σ for two mutually exclusive b-quark event categories
- similar analysis conducted with the 13 TeV data results: in the first event category corresponding to a local significance of 2.0σ, while the second category results in a 1.4σ



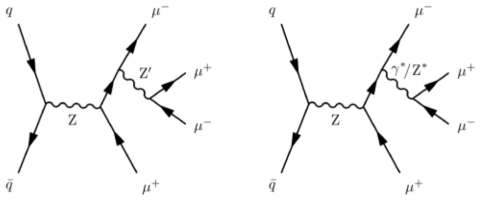
arXiv:1808.01890. Submitted to JHEP

The fiducial cross section and 95% confidence level upper limits



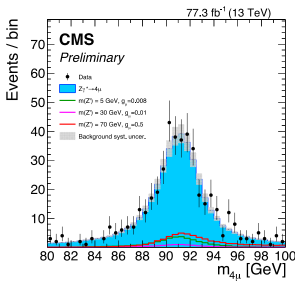
In the lack of a realistic signal model, the 13 TeV results are not sufficient to make a definitive statement about the origin of the 8 TeV excess. Therefore, more data and additional theoretical input are both required to fully understand the results presented in this paper.

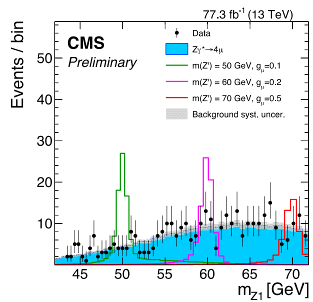
Light Z' Boson with Lμ-Lτ Gauge Symmetry

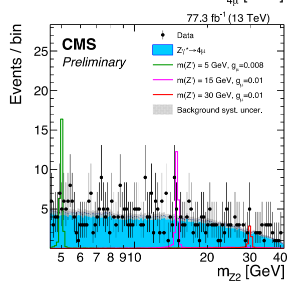


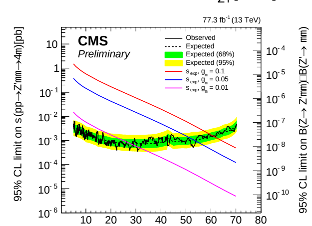
- Since this Z' couples (only) to second- and third-generation leptons (μ, ν_μ, τ and ν_τ), it can be produced from one of the muons in Z-decays, and using its decay $Z' \rightarrow \mu^+\mu^-$, might appear as a dimuon mass bump in 4 muon final states.

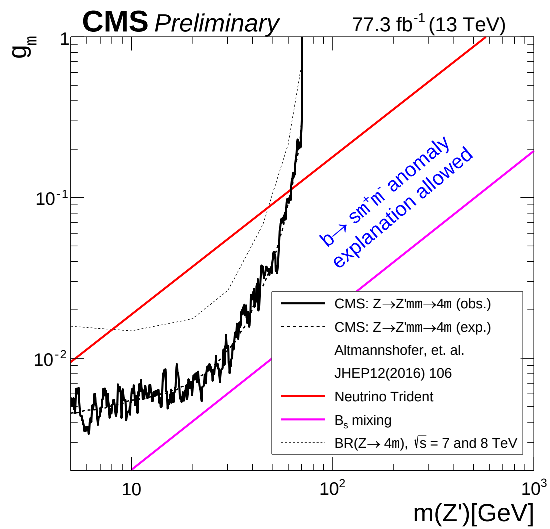
CERN-EP-2018-208











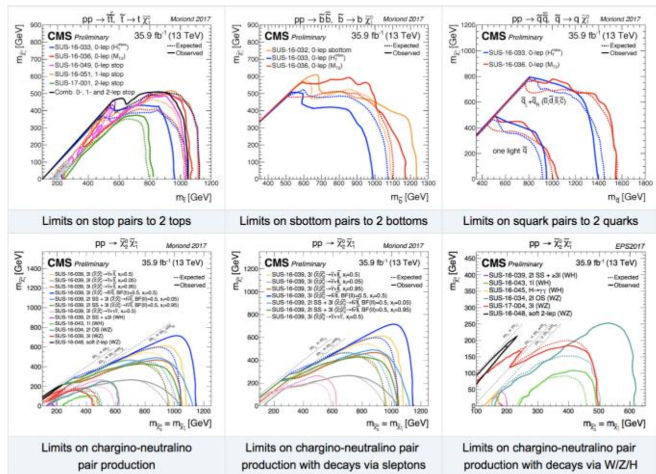
Supersymmetry

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
- Maybe it does not cure all
- Coverage for RP-violating and long-lived particles not as complete
- Maybe just another great idea that nature did not choose to follow

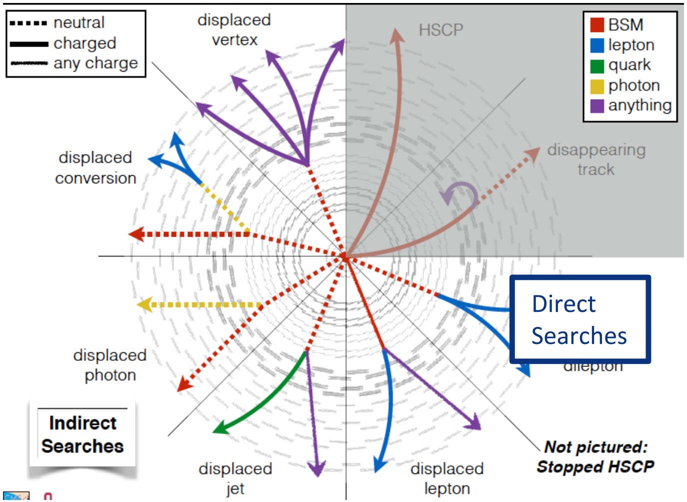


Many good ideas being explored. Still a vibrant area of research in CMS

Long-Lived Particles

JHEP 05 (2018) 127

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



- 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

x2 Run2

x10 Run3

3%

LHC Status

$3000 fb^{-1}$

Running

Luminosity so far

Luminosity after HL-LHC

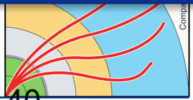
CMS Phase-2 upgrade scope (TDR, interim TDR and TP references)

L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

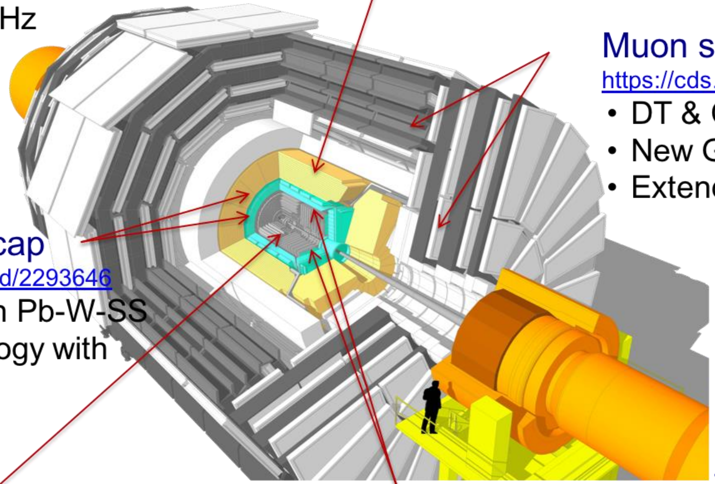
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

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 $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

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 $\eta \simeq 3.8$

MIP Timing Detector

https://cds.cern.ch/record/2296612

- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Summary

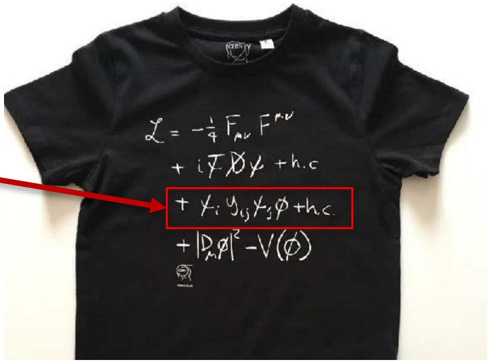
- Both the LHC and the CMS detector performed well in Run 2(2016-2018)
  - The two year shutdown in 2019/20 should give us time to progress on analysis.
  - All experimental results are in good agreement with SM predictions by now
  - Observation of 3d generation couplings achieved
- Now the LHC is running at **13 TeV (14 TeV after 2020)** with **high luminosity and availability, our discovery potential is great.**
- **Today we have of order <5% of the ultimate LHC data in hand (HL-LHC)**
- **We are expecting many new results!**

Backup

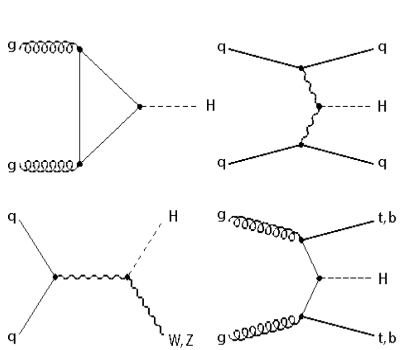
Higgs Yukawa Couplings

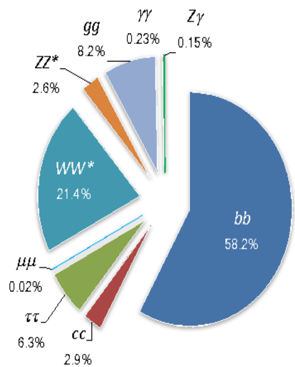
- Liberally borrowing from talk by Gavin Salam at LHCP 2018
- Higgs doublet gives mass to vector gauge bosons
- The Higgs Yukawa interaction is **a highly motivated conjecture** to give mass to the fermions
  - But no such term ever before seen in nature
  - Not probed in any EW precision test
  - Indirect support for it through strong production of Higgs bosons via top loops
    - Could also be non-BSM contributions in such loops
  - 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.

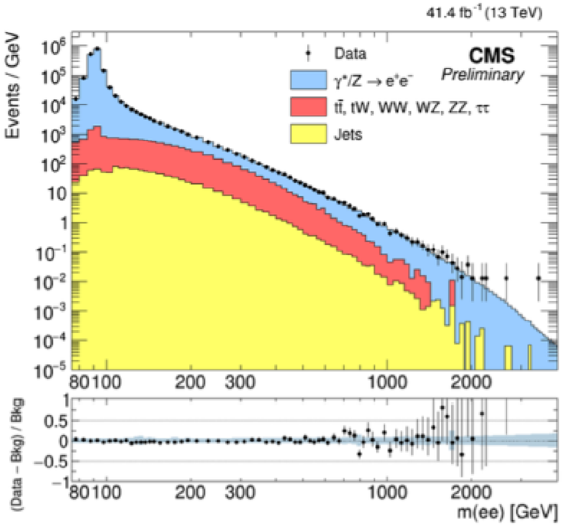


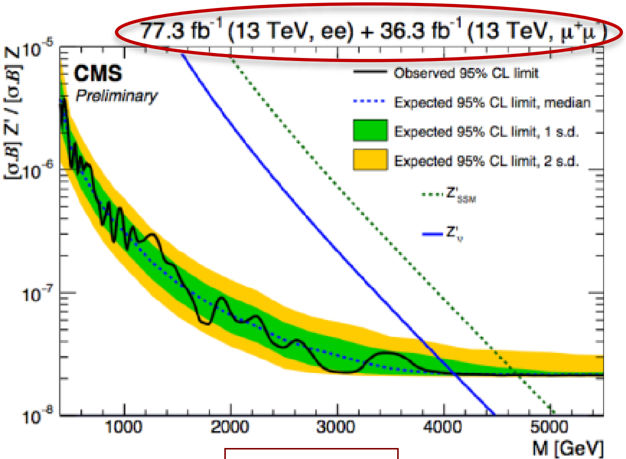


$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\mathrm{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$15.3^{+10\%}_{-10\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	17.5
8	$19.5^{+10\%}_{-11\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	22.3
13	$44.1^{+11\%}_{-11\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.51^{+9\%}_{-13\%}$	50.6
14	$49.7^{+11\%}_{-11\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.61^{+9\%}_{-13\%}$	57.1

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

High Mass e^+e^- Resonance Search





EXO-18-006

First 2017 data result approved!

Channel	Model	Obs. limit (TeV)	Exp. limit (TeV)
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

New Ideas in Dark Matter – Search for Emergent Jets

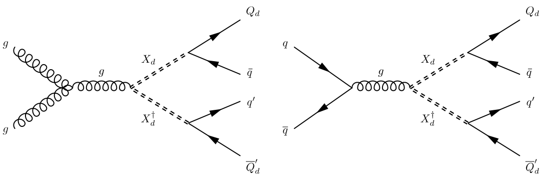
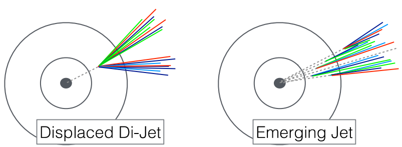


Figure 1: Feynman diagrams for pair production of mediator particles, with mediator decay to a quark and a dark quark in the BSSW model via (left) gluon fusion and (right) quark-antiquark annihilation.



- many compelling models of new physics contain a dark matter candidate that has interactions with quarks.
- In one class of models, new fermions (dark quarks**), $\mathbf{Q_d}$**, 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) [2, 3]. 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 T SM four-jet production, especially jets with b-quarks

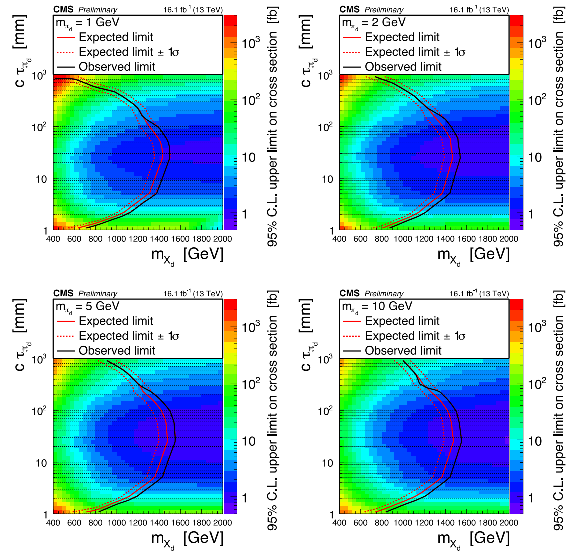
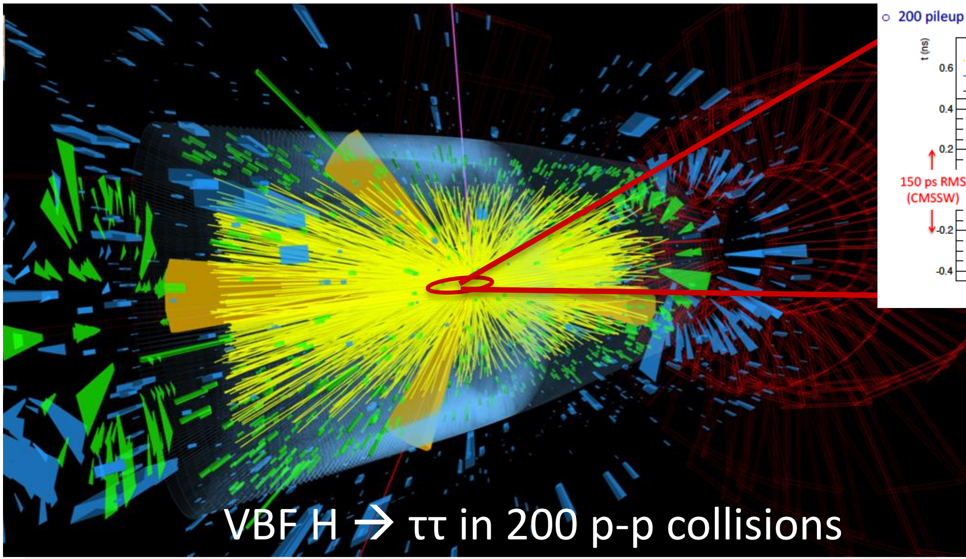
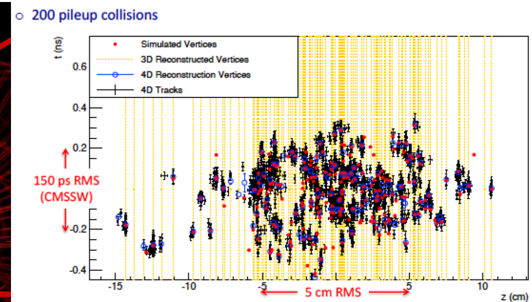
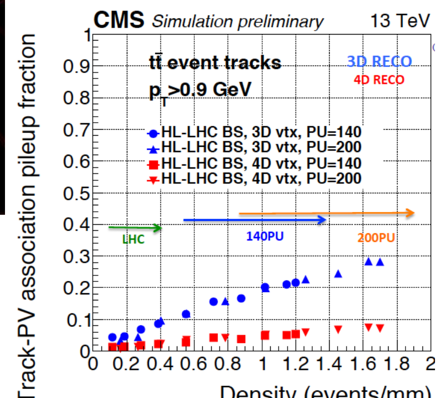


Figure 6: Signal exclusion curves derived from theory-predicted cross sections and upper limits at 95% CL on the signal cross section for models with dark pion mass $m_{\pi_d} = 1, 2, 5$, and 10 GeV.

MIP Precision Timing Detector







Time of flight precision $\simeq$ 30 ps, $|\eta|$< 3, p_T > 0.7 GeV

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

- ~ 15% merged vertices reduce to $\simeq$ 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

- Tracking information in "L1 track-trigger"
  - Tracker is designed to enable finding of all tracks with P_T>~2 GeV in under 4 μs.
- Tracker is AGAIN ALL SILICON but now with much higher granularity, and extends to $|\eta|$ =4
  - >2 billion pixels and strips
- 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, and with extended acceptance