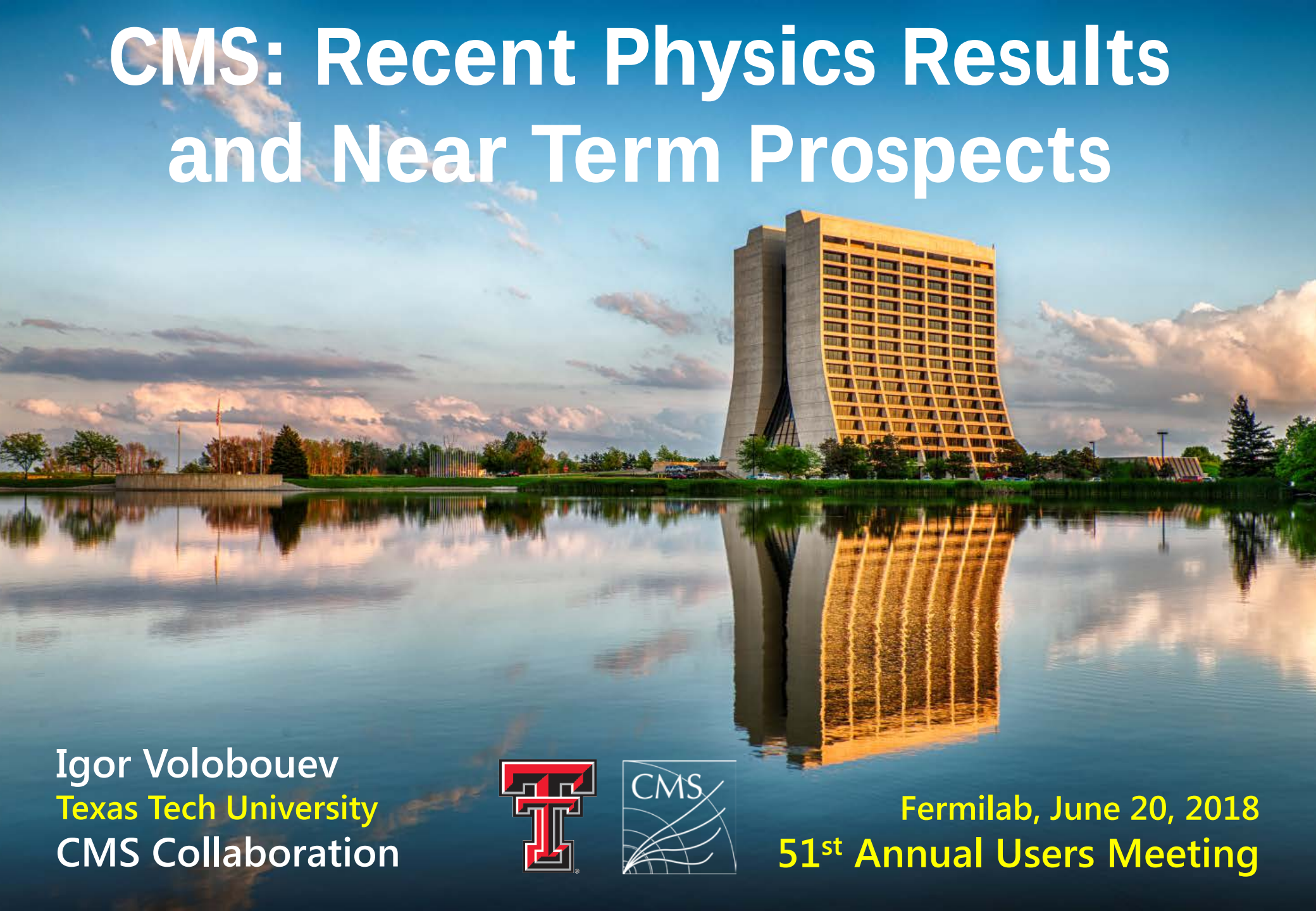
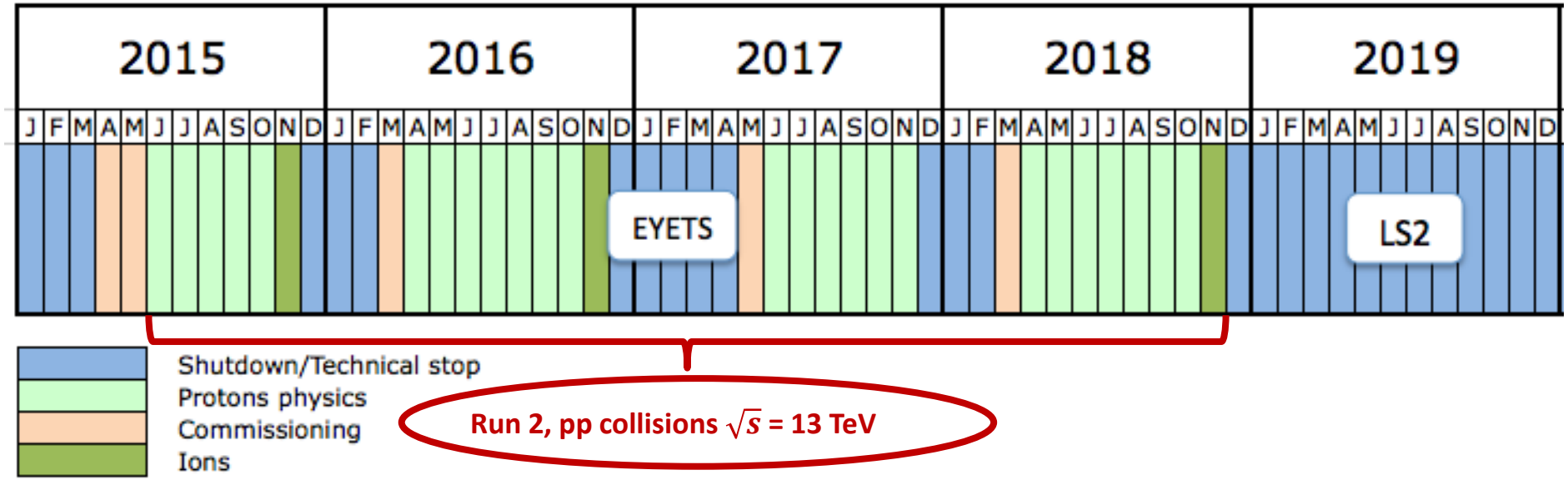
CMS: Recent Physics Results and Near Term Prospects

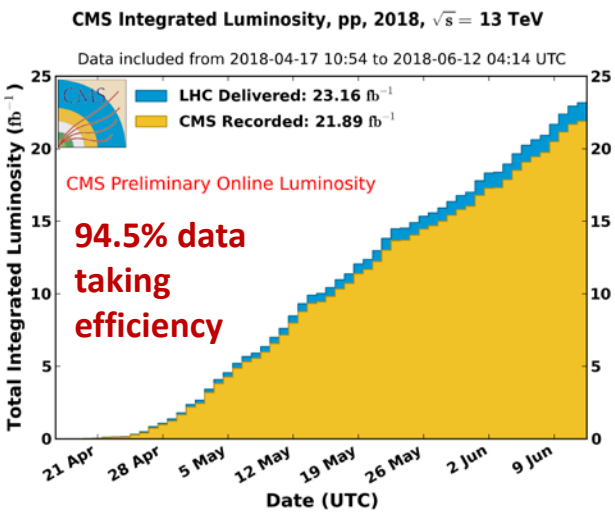


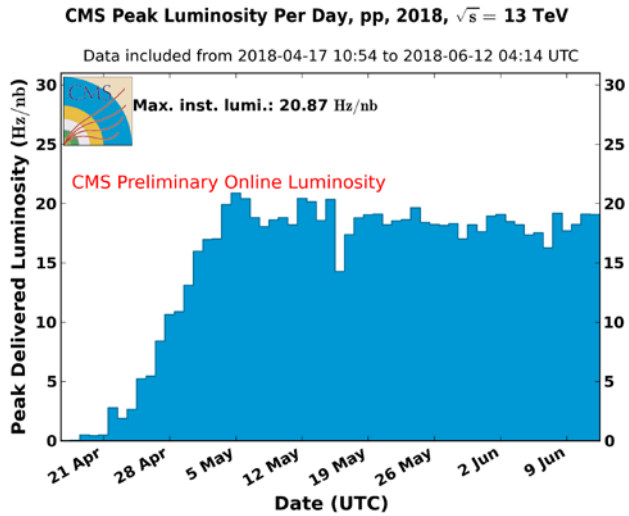
Igor Volobouev
Texas Tech University
CMS Collaboration

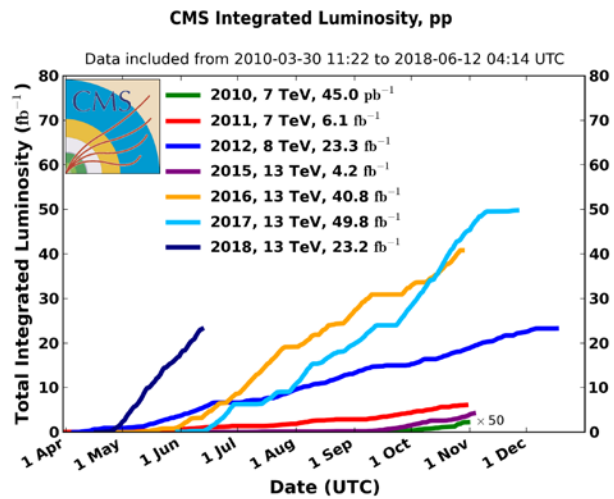
Fermilab, June 20, 2018
51st Annual Users Meeting

Data Taking Performance



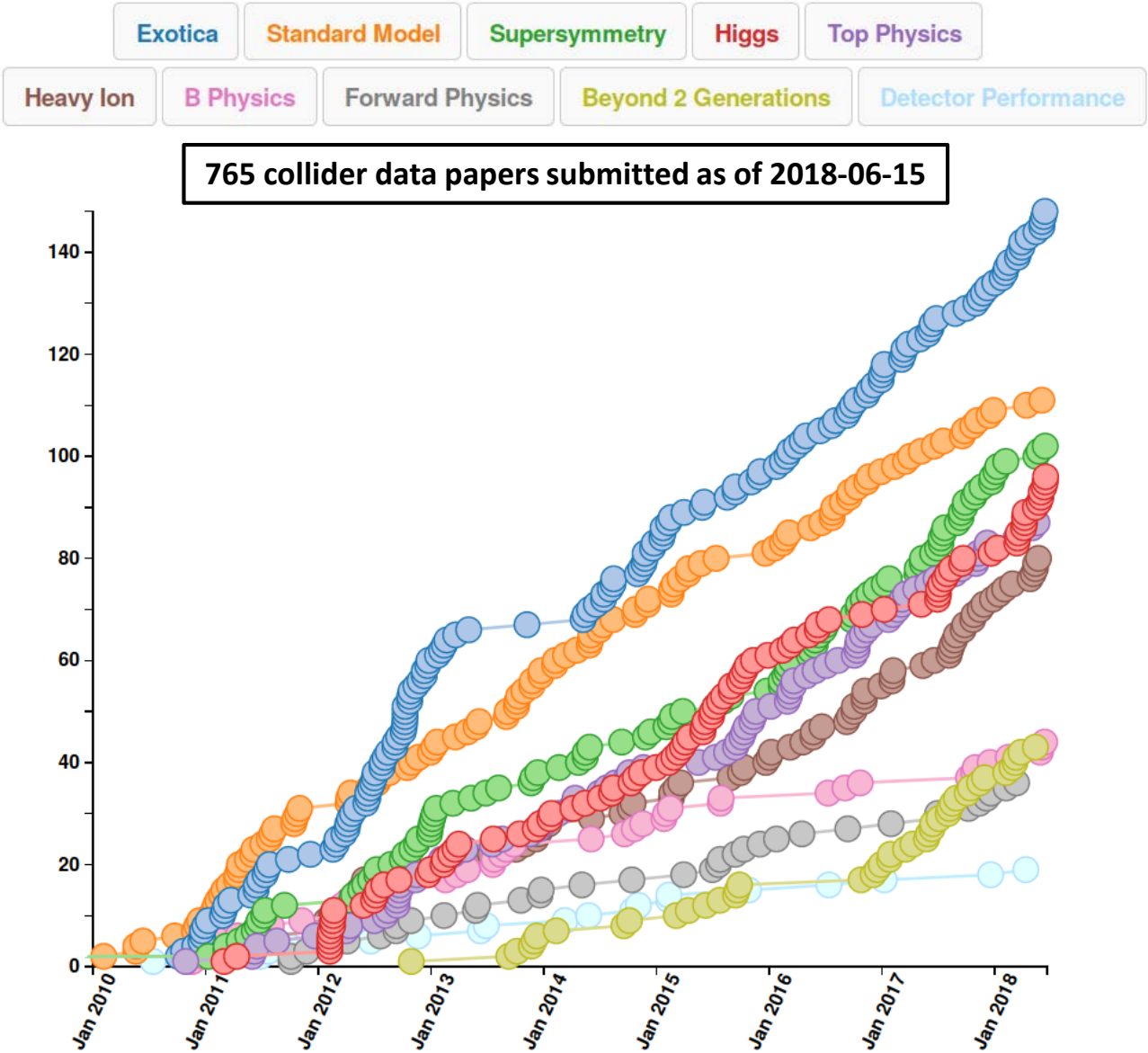






LHC Run 2 pp luminosity goal: 150 fb^{-1}. 60 fb^{-1} in 2018 for ATLAS/CMS.

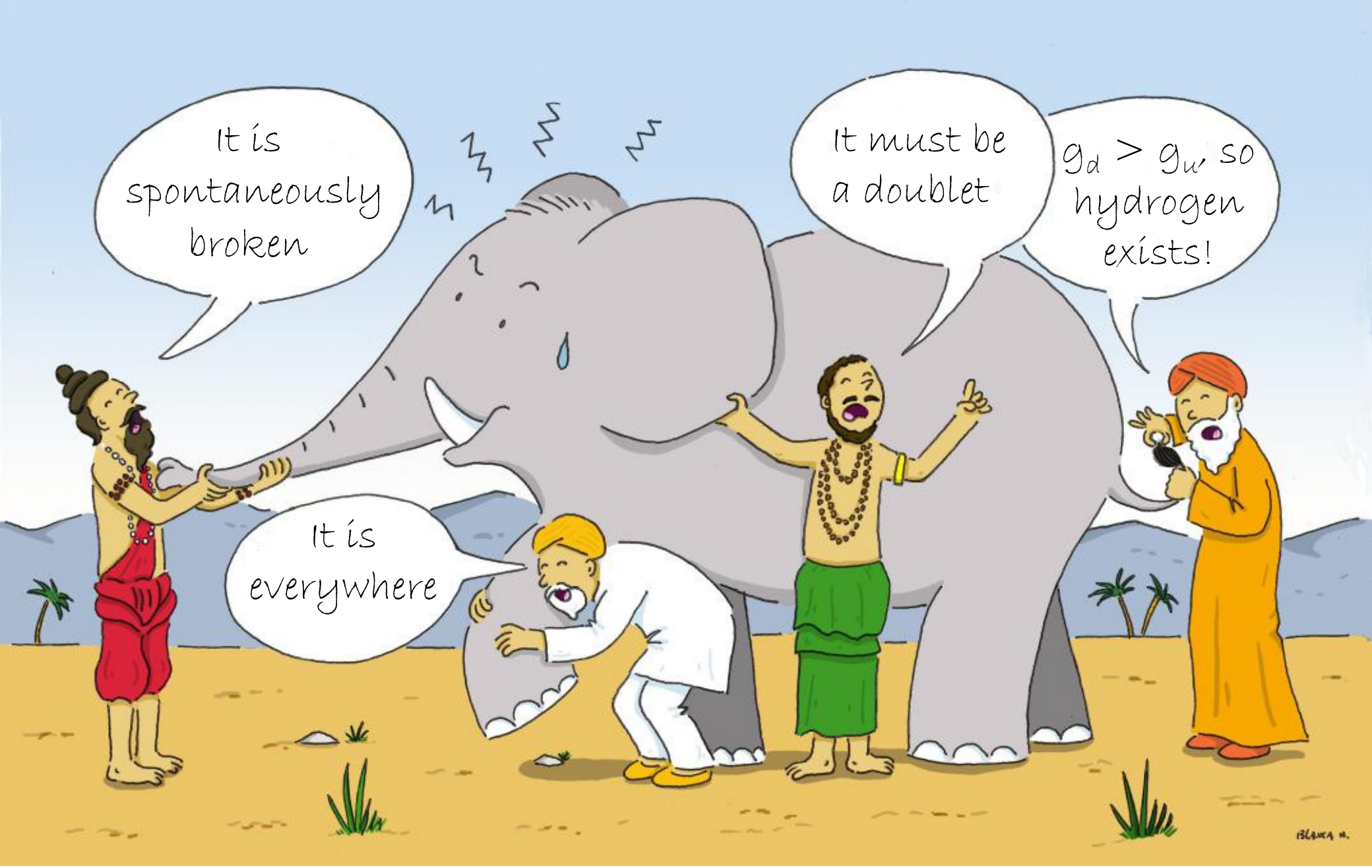
CMS Physics Publications



Highlights of Recent CMS Results

- Higgs: the elephant of the SM
- Top: the precision era
- Dark matter: a known unknown

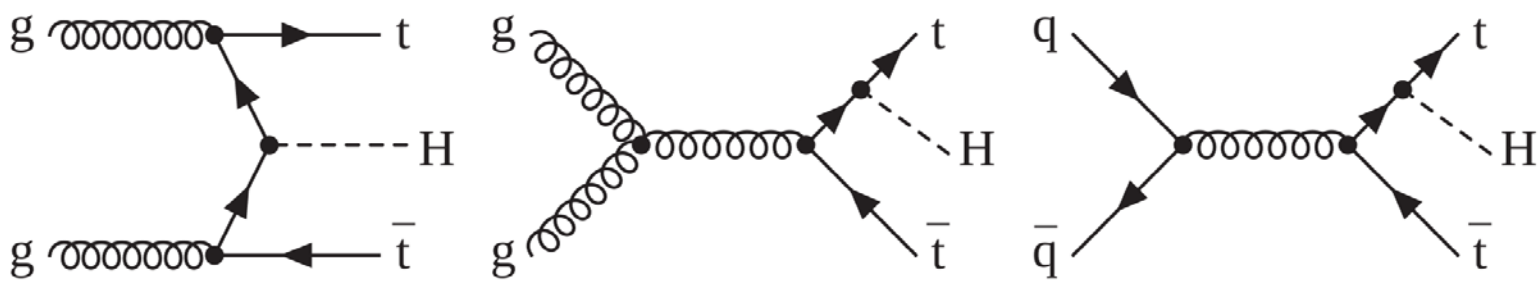
Apologies to many whose favorite research subject is not mentioned



Higgs physics before 2012

Observation of $t\bar{t}H$ Production

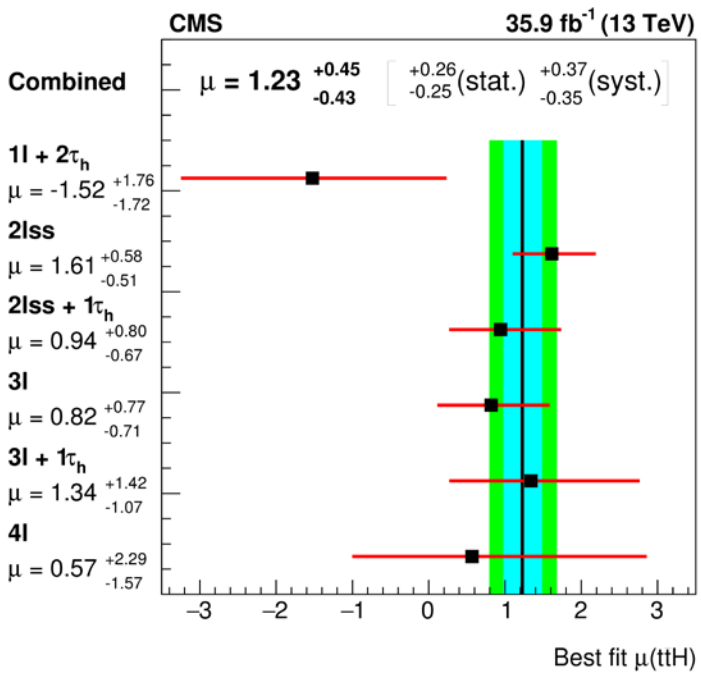
SM: $\mathcal{L}_{\text{Yukawa}} = -g_f v\,\overline{\psi}_f\psi_f - g_f H\,\overline{\psi}_f\psi_f$ (where $m_f = g_f v$)



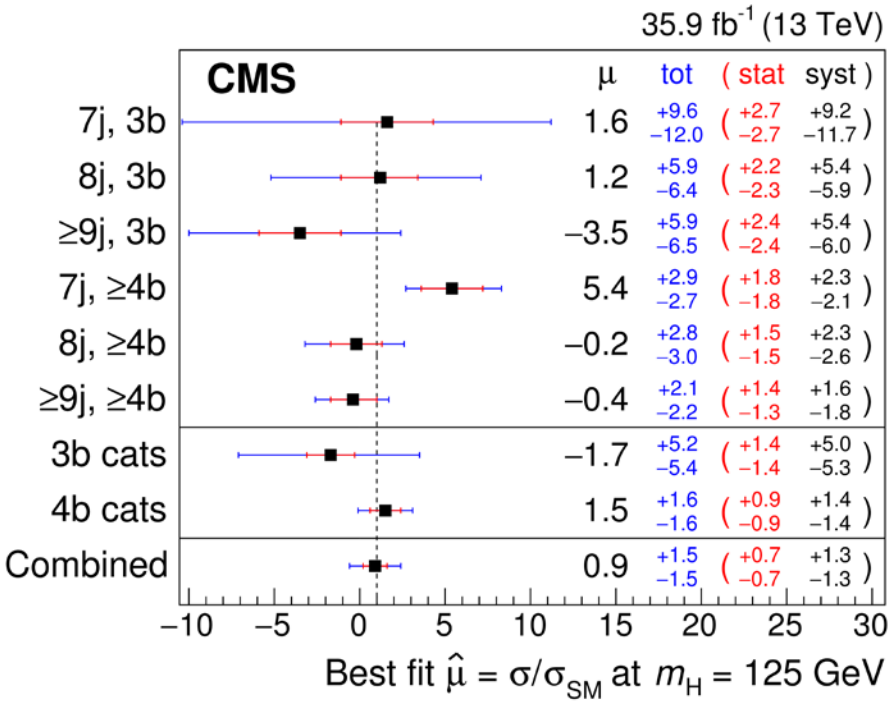
- Direct probe of Higgs coupling to an "up-type" quark
- Constrain BSM models that modify the production rate without substantially changing Higgs decay branching fractions
- Experimentally challenging due to large backgrounds. In the SM, $\sigma_{t\bar{t}H} \approx 0.5$ pb while $\sigma_{t\bar{t}} \approx 830$ pb (at 13 TeV).
- Combination of multiple analyses exploring different $t\bar{t}$ and Higgs decay signatures (88 event categories)

$t\bar{t}H$ Observation Channels

- **$t\bar{t}H$ multilepton, arXiv:1803.05485**
- Multilepton final states with Higgs decays into *WW*, *ZZ*, and $\tau\tau$ (with at least one τ decaying hadronically)
- Six mutually exclusive event categories, depending on the numbers of reconstructed leptons and hadronic τ candidates
- One or two b-tagged jets
- Outputs of MEM and BDT discriminants (depending on the channel) are used for the final signal rate determination
- 3.2σ signal significance over background-only hypothesis

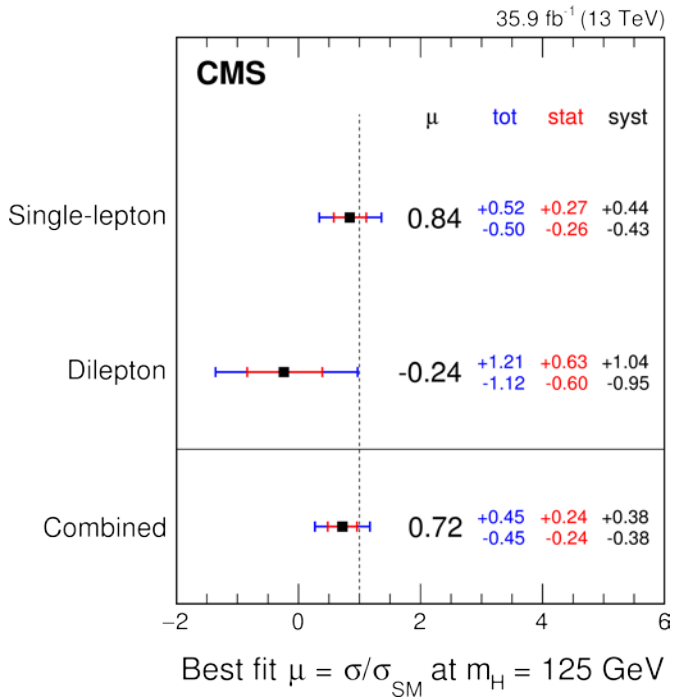


- **$t\bar{t}H$ hadronic, arXiv:1803.06986**
- All-hadronic $t\bar{t}$ mode with Higgs decaying into $b\bar{b}$
- No leptons, at least seven jets, at least three jets must be b-tagged
- Six event categories, depending on the numbers of jets and b tags
- MEM is used to discriminate $t\bar{t}H$ from $t\bar{t} + b\bar{b}$ (also performs well against $t\bar{t} + lf$ and multijet backgrounds)
- QGL additionally discriminates lf jets from gluons
- 0.6σ over background-only hypothesis

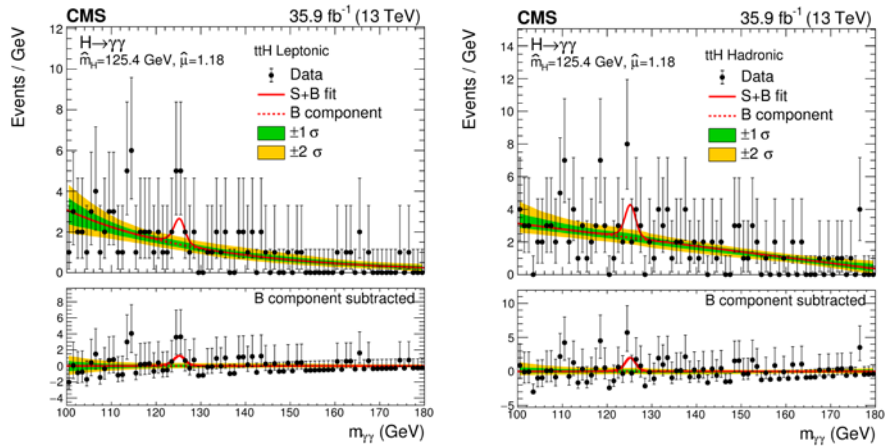


$t\bar{t}H$ Observation Channels

- **$t\bar{t}H$ (semi)leptonic, arXiv:1804.03682**
- Dilepton or ℓ+jets $t\bar{t}$ mode with Higgs decaying into $b\bar{b}$
- One or two leptons (e or μ), at least four jets, at least three jets must be b-tagged
- MEM is used to discriminate $t\bar{t}H$ from $t\bar{t} + b\bar{b}$. On top, DNN (BDT) is used in the single lepton (dilepton) case.
- Events are assigned (probabilistically) to 21 signal and background categories depending on the numbers of leptons, jets, b tags, and the multivariate classifier output
- 1.6σ over background-only hypothesis



- **$t\bar{t}H$ diphoton, arXiv:1804.02716**
- Part of a general analysis with $H \to \gamma\gamma$. All $t\bar{t}$ decay modes considered.
- BDT for background suppression. Signal is extracted from the fit to $m_{\gamma\gamma}$.
- 3.2σ over background-only hypothesis ($t\bar{t}H$ only)

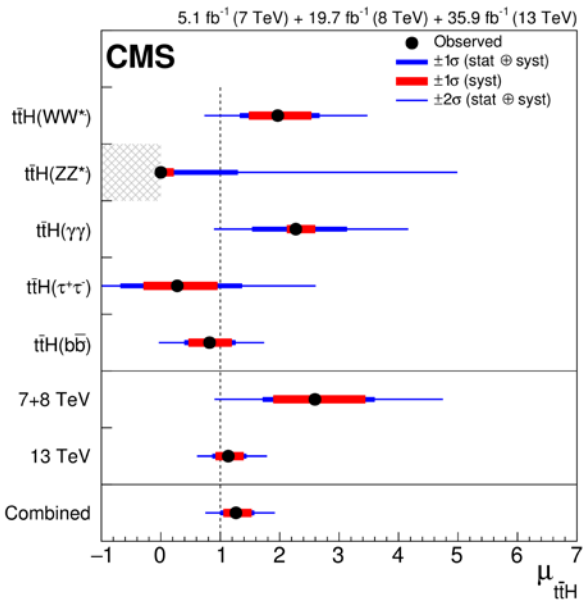


- **$t\bar{t}H$ with $H \to ZZ \to 4\ell$, JHEP 11 (2017) 047, arXiv:1706.09936, CMS-PAS-HIG-18-001**
- Part of a general analysis with $H \to ZZ \to 4\ell$
- After the full $t\bar{t}H$ selection, 0.5 signal events are expected in the 118 < $m_{4\ell}$ < 130 GeV mass range (with negligible background). 0 events observed.

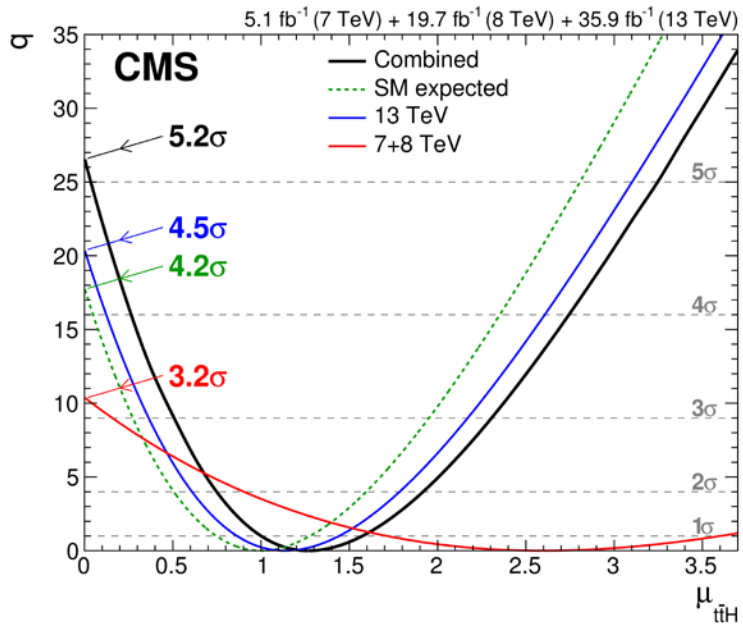
Combination of $t\bar{t}H$ Results

Phys. Rev. Lett. 120, 231801 (2018), arXiv:1804.02610

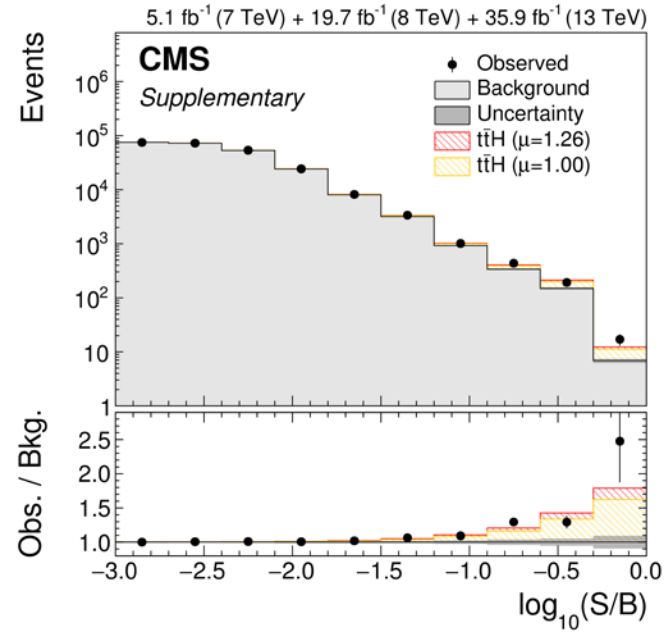
35.9 fb^{-1} of Run 2 data, up to 5.1 fb^{-1} of 7 TeV and 19.7 fb^{-1} of 8 TeV



Fit results for the independent signal strength modifiers of the Higgs decay channels considered



Profile likelihood log-ratio as a function of the common signal modifier



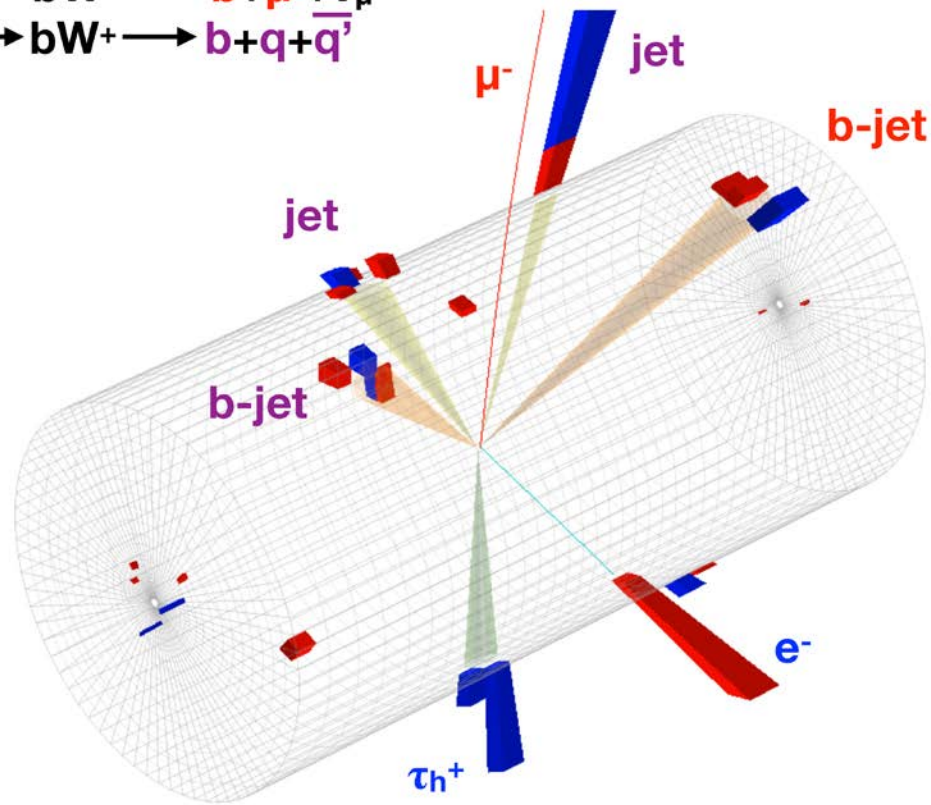
Data excess over background-only hypothesis

- $\mu = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(stat)\,^{+0.17}_{-0.15}(exp)\,^{+0.14}_{-0.13}(th.bkg)\,^{+0.15}_{-0.07}(th.sig)$
- 5.2σ signal significance over background-only hypothesis

$t\bar{t}H$ Event Candidate

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

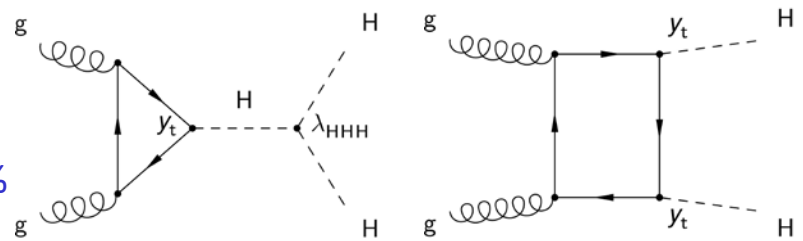
- $\tau^-\tau^+ \rightarrow e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$
- $\bar{b}W^- \rightarrow \bar{b} + \mu^- + \bar{\nu}_\mu$
- $bW^+ \rightarrow b + q + \bar{q}'$



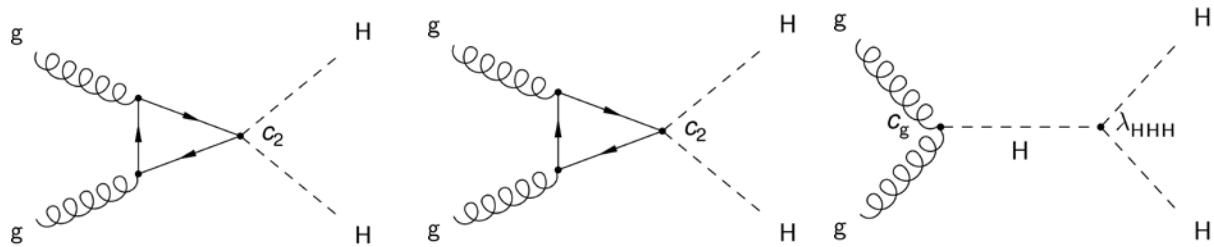
Recent Searches for HH Pair Production

- Search for $pp \to HH \to \gamma\gamma b\bar{b}$ (including resonant production): arXiv:1806.00408 (submitted June 1)
- Search for $pp \to X \to HH \to b\bar{b}b\bar{b}$: arXiv:1806.03548 (submitted June 10), as well as the boosted version, with X mass in the 750−3000 GeV range: CMS-PAS-B2G-17-019 (released June 4)

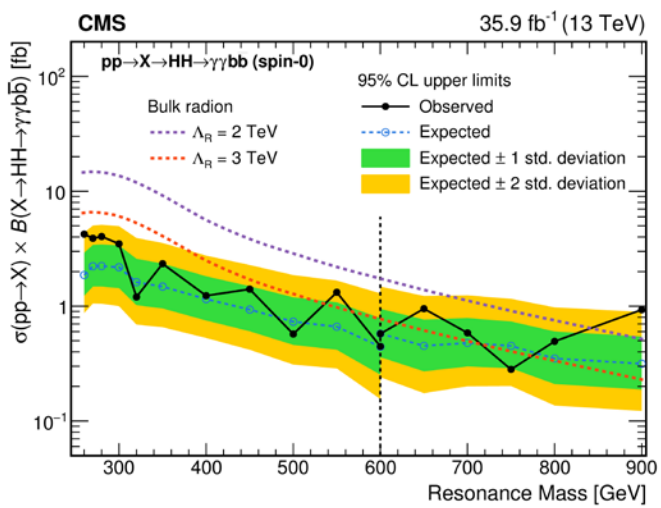
SM: $\sigma_{gg \to HH} \approx 33$ fb,
$\mathcal{B}(HH \to b\bar{b}b\bar{b}) \approx 34\%$
$\mathcal{B}(HH \to \gamma\gamma b\bar{b}) \approx 0.26\%$

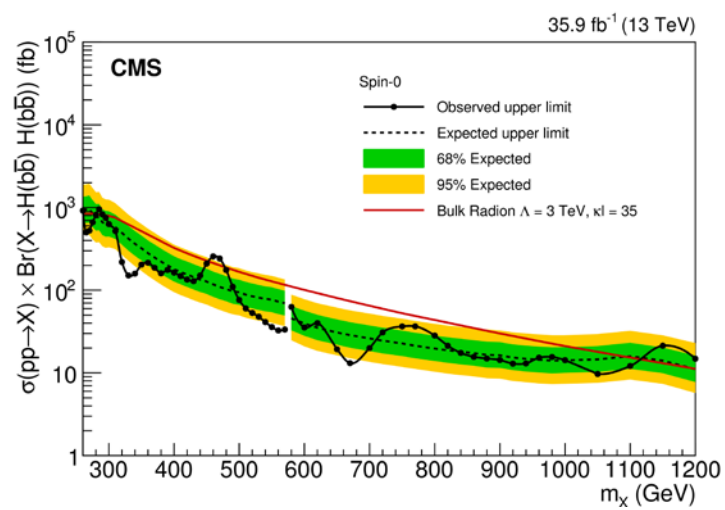


BSM



Previous Run 2 HH searches by CMS:
$b\bar{b}b\bar{b}$: CMS-PAS-HIG-16-026
$b\bar{b}\tau\tau$: PLB 778 (2018) 101
$b\bar{b}\ell\nu\ell\nu$: JHEP 01 (2018) 054





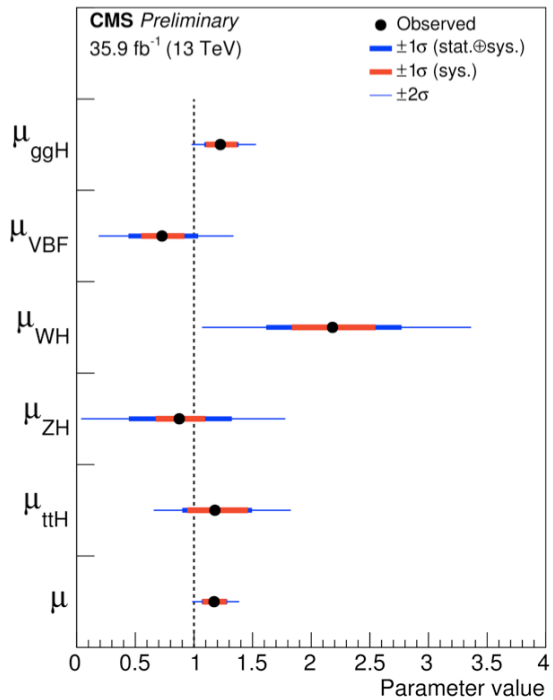
Non-resonant:
$\mu_{HH} < 24$ at 95% CL,
as derived for the
$HH \to \gamma\gamma b\bar{b}$ channel
assuming SM branching.
This is the most stringent
μ_{HH} constraint to date.

Combined Higgs Couplings

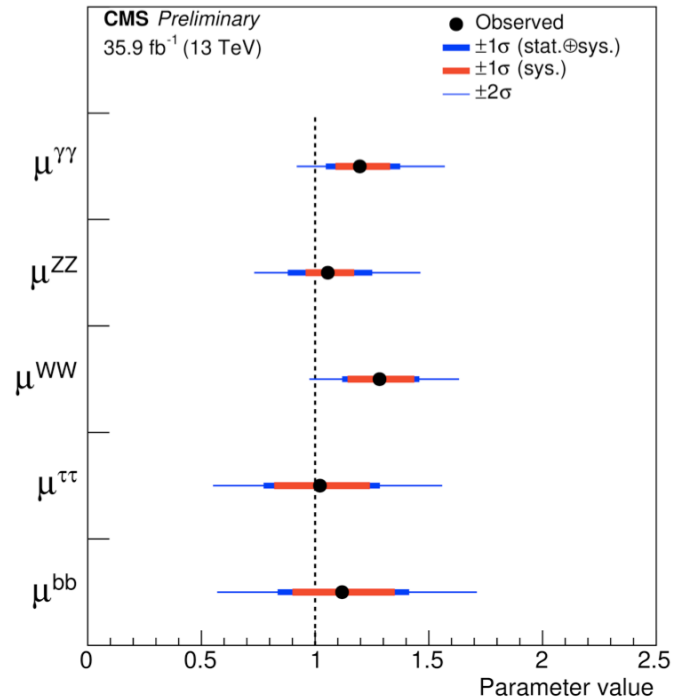
Combined measurements of the Higgs boson's couplings at $\sqrt{s}$ = 13 TeV, CMS-PAS-HIG-17-031

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

By production mode



By decay mode



Global Higgs signal strength modifier fit:

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

Other Facets of the CMS Higgs Program

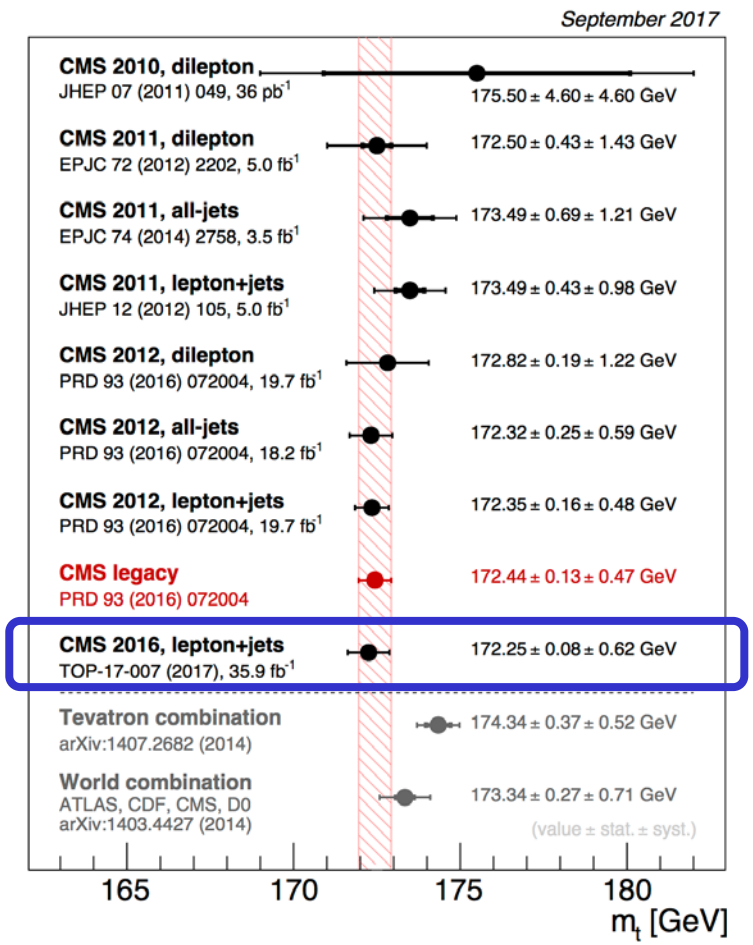
- Basic properties (mass, width, J^{PC})
- Differential production cross sections
- Boosted production
- Heavy particles decaying into Higgs+X
- Differential decay rates
- Rare and exotic decays
- Searches for additional Higgs bosons
- Interpretation of measurements in terms of SM parameters, limits on anomalous couplings and BSM parameters, etc

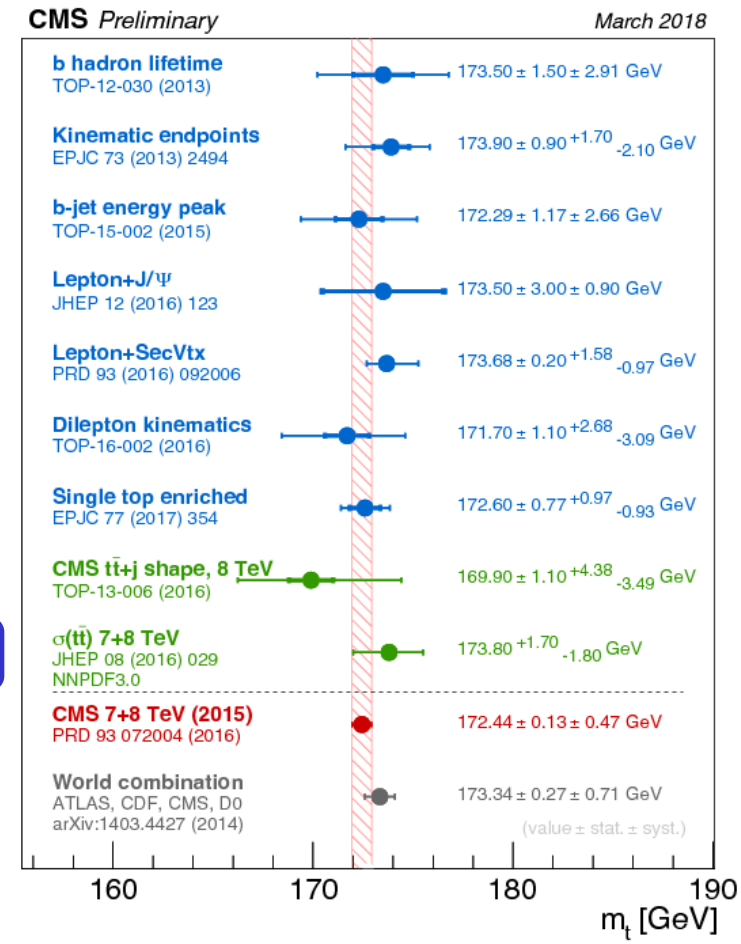
So far, Higgs appears to be remarkably SM-like

Top Mass

"Direct" run 2 top mass measurement with 35.9 fb^{-1}: **arXiv:1805.01428**

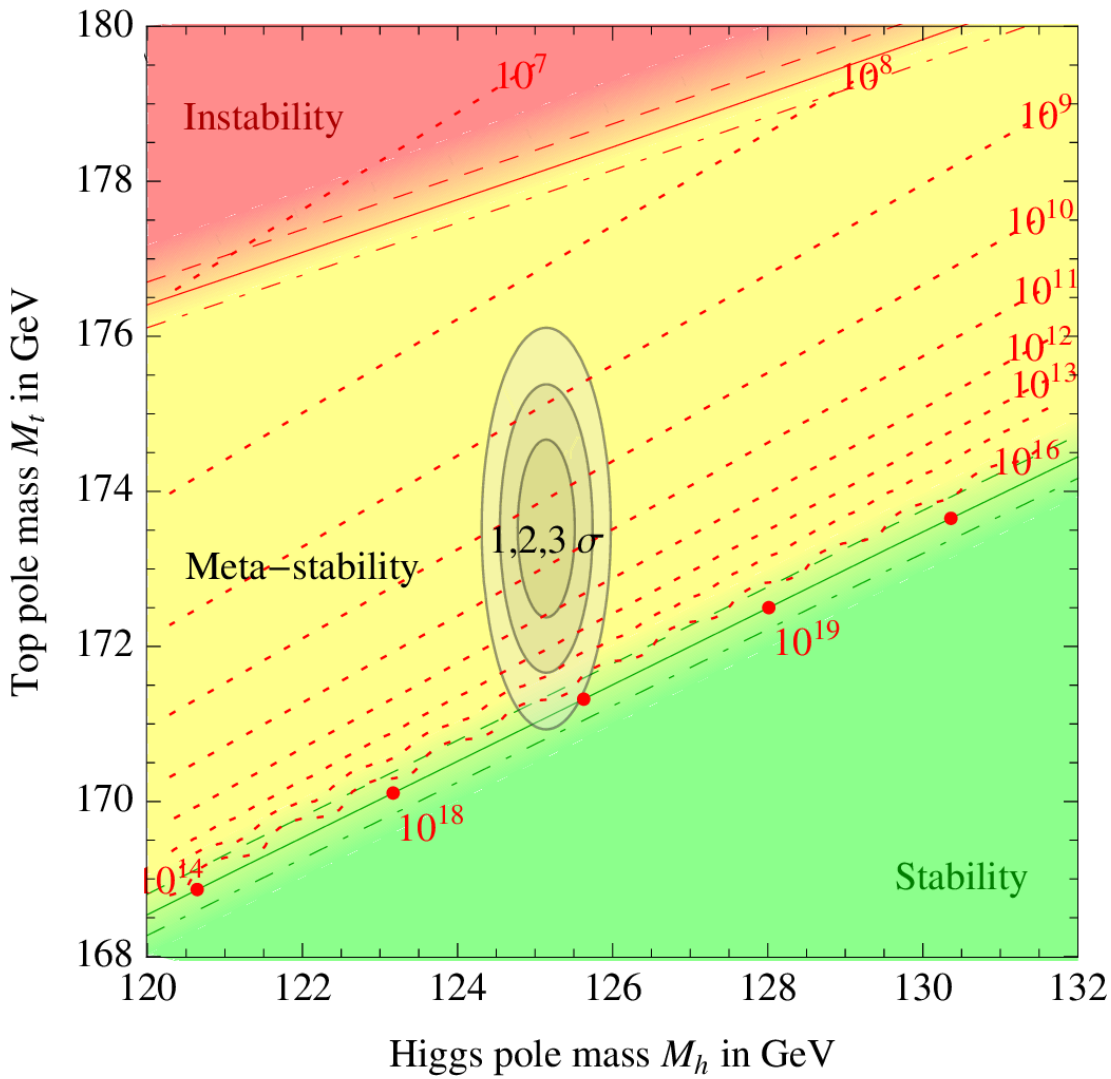
- One ℓ + at least four jets
- Stringent selection requirements (including exactly two b tags and a good χ^2 from kinematic fit). 1.6×10^5 events pass with S/B ~ 22.
- "Ideogram" method is used for m_t extraction with JSF as a nuisance parameter. Events are weighted by $\exp(-\chi^2/2)$.
- Main systematic uncertainties come from b jet energy correction (0.32 GeV), color reconnection (0.31 GeV), and ME generator dependence (0.22 GeV, using POWHEG v2 vs. MADGRAPH5_aMC@NLO)





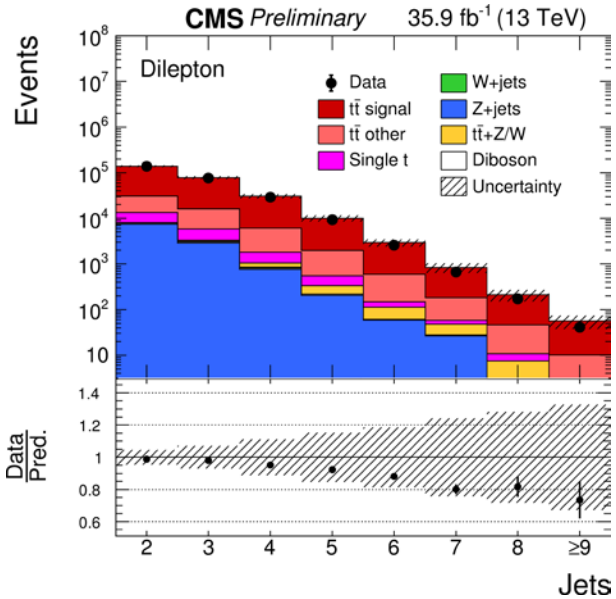
Top, Higgs, and Vacuum Stability

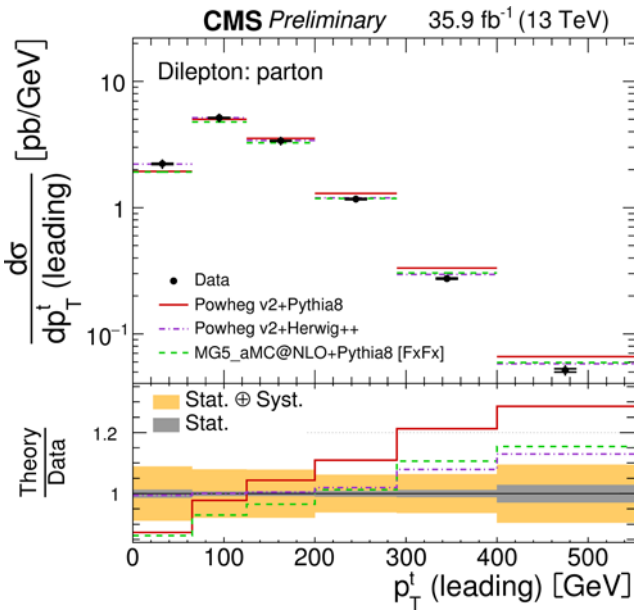
Is SM vacuum stable to the Planck scale? Investigated by D. Buttazzo et al. in JHEP12 (2013) 089

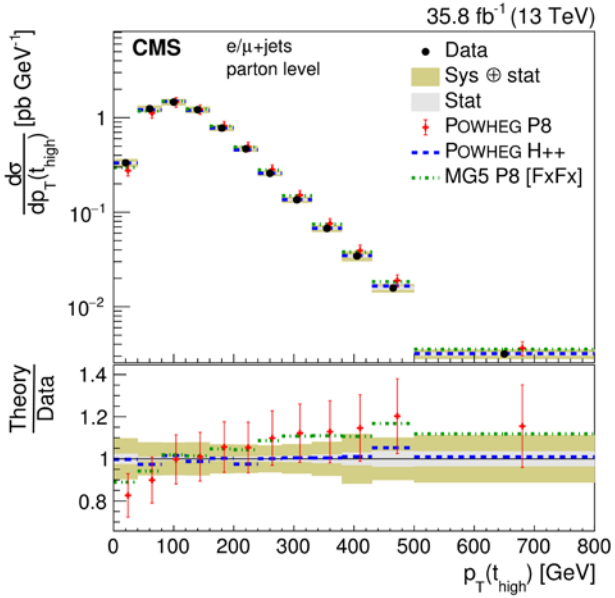


$t\bar{t}$ Differential Cross Sections

- Large number of $t\bar{t}$ kinematic variables considered: transverse momenta and rapidities of top quarks, transverse momentum, mass, and rapidity of the $t\bar{t}$ system, jet kinematic variables, etc
- Distributions are unfolded to particle/parton level, rates are presented as both absolute and normalized
- Recent detailed measurements utilizing 35.9 fb^{-1} of Run 2 data:
  - ℓ + jets: arXiv:1803.08856 (submitted March 26). About 0.5 x 10^6 events after all selection requirements with S/B ~ 20. A number of double-differential cross sections is presented as well.
  - Dilepton: CMS-PAS-TOP-17-014 (released June 6). About 0.25 x 10^6 events with S/B ~ 4.





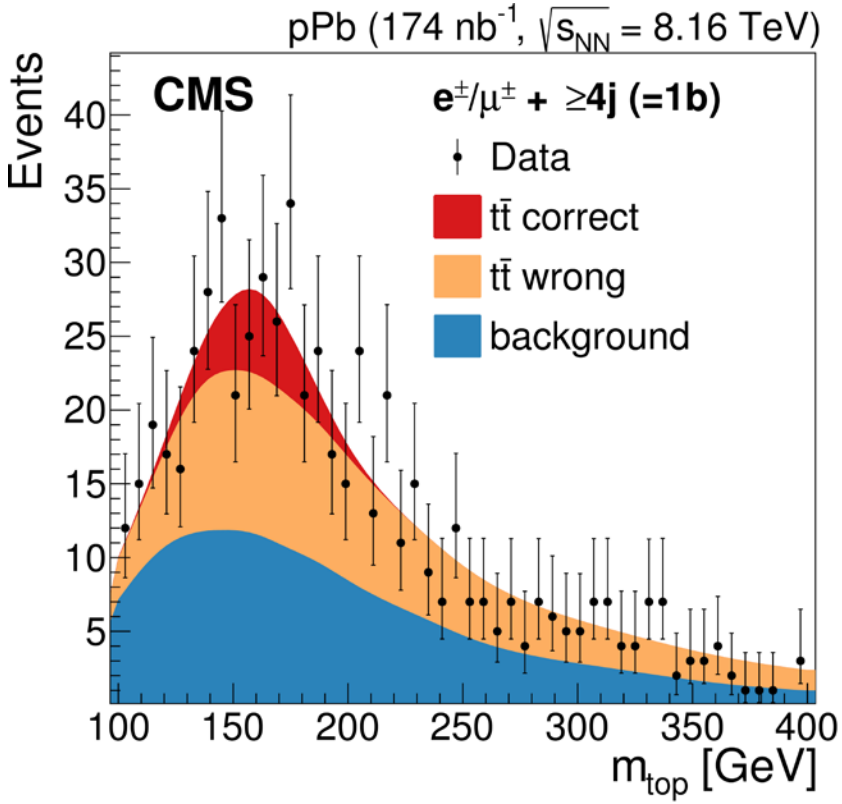


MC: POWHEG v2 + Pythia8, tune CUETP8M2T4, NNPDF3.0 PDF

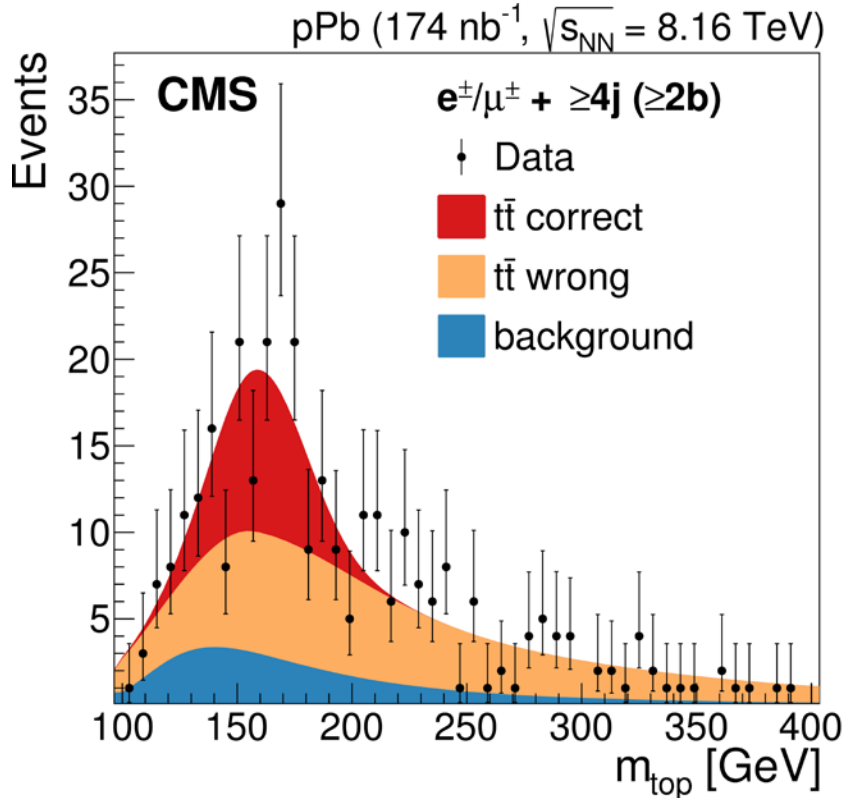
- Significant disagreements with NLO and beyond NLO theoretical calculations (ATLAS findings are similar)
- Strong driver of developments in higher-order pQCD calculations and parton shower techniques

Top Quark Observation in pPb Collisions

- 2016 proton-lead run at $\sqrt{s_{NN}}$ = 8.16 TeV, 174 nb^{-1}, Phys. Rev. Lett. 119 (2017) 242001
- ℓ + jets mode



Single b tag



At least two b tags

$\sigma_{t\bar{t}} = 45 \pm 8$ nb (SM prediction is ~57 nb)

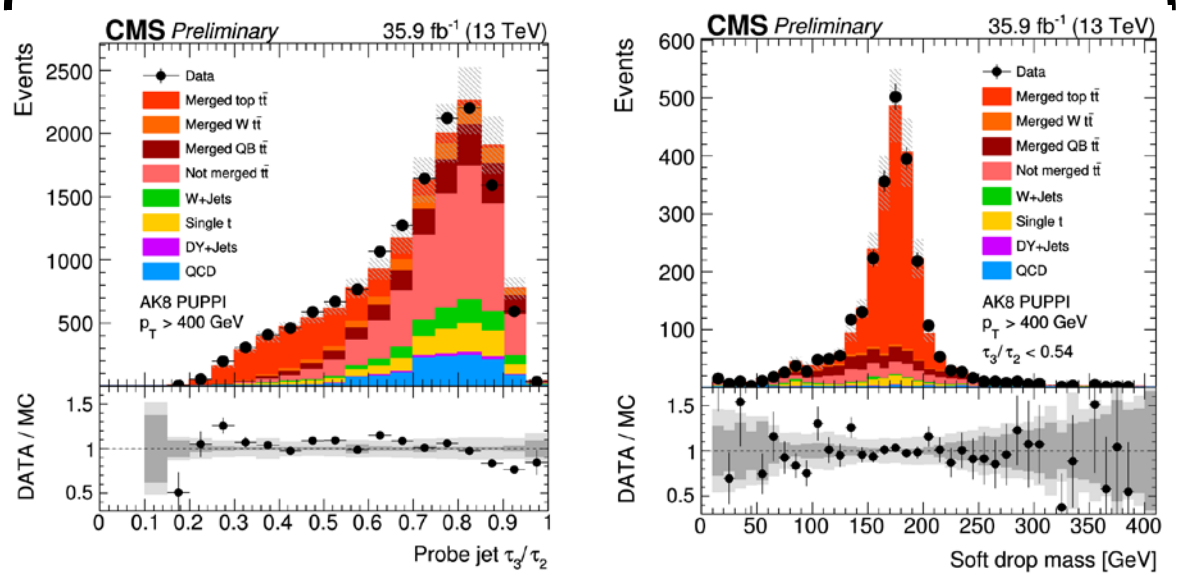
Studies of Boosted Tops

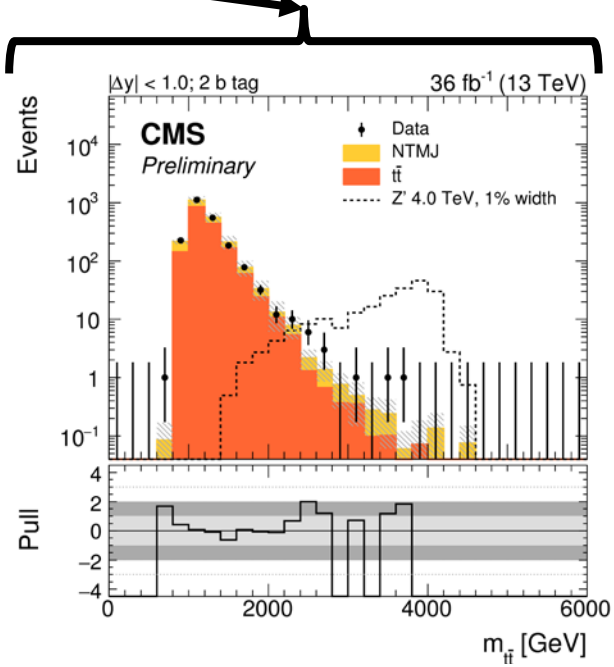
Two main directions:

- Calibration of jet substructure observables with $t\bar{t}$ events
- Searches for heavy particles decaying into top, e.g., $X \to tX'$ with $X' = t, b, \tau, W, Z, H$, etc

A good example of the latter: search for $t\bar{t}$ resonances in CMS PAS B2G-17-017 (released June 4)

From CMS-DP-2017-026





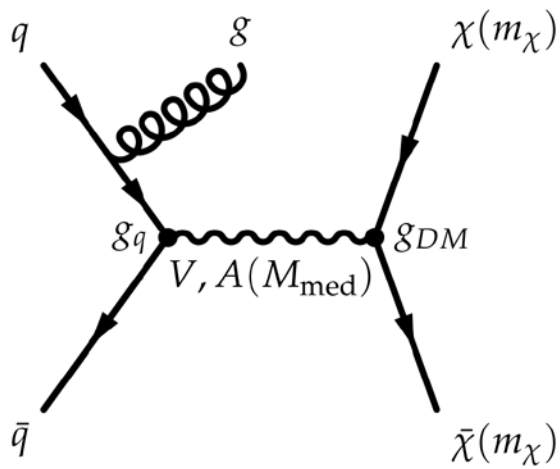
Other CMS Run 2 searches with boosted tops: JHEP 04 (2017) 136, JHEP 07 (2017) 001, JHEP 06 (2018) 027

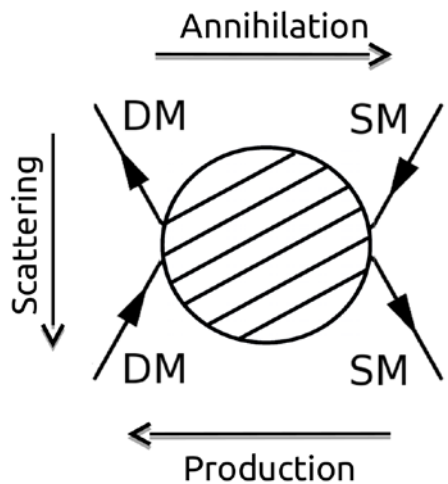
Watch out for Boost 2018 results (Paris, July 16-20)

An all-hadronic example with two b tags. CMS top tagger is applied to two AK8 jets with p_T > 400 GeV. Most stringent $Z' \to t\bar{t}$ limits to date are established by this analysis.

Dark Matter Searches

- The astrophysical evidence for dark matter (DM) is compelling: galactic rotation curves, gravitational lensing with merging galaxy clusters, large-scale structure formation, etc
- While there are viable DM models that are fundamentally unobservable at the LHC, many scenarios postulate existence of WIMPs and can be tested
- Such scenarios typically postulate new mediator particles that couple SM particles to DM. For high mediator masses, EFT description by contact interactions becomes sufficient. For a detailed introduction see, e.g., arXiv:1507.00966.

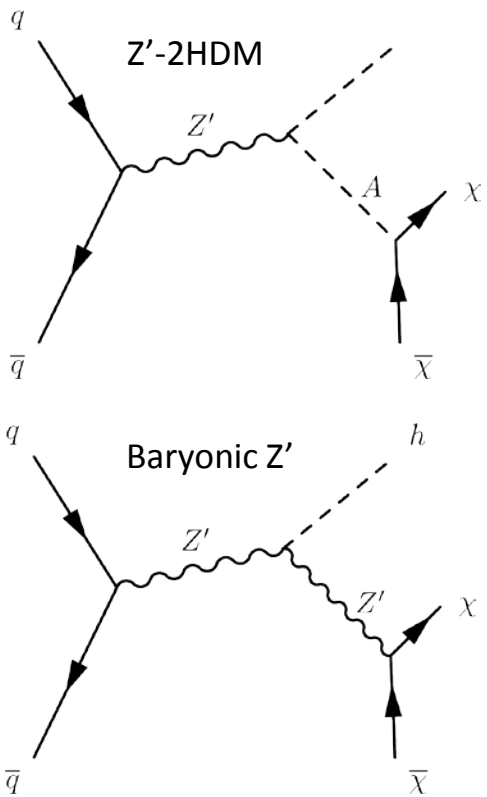


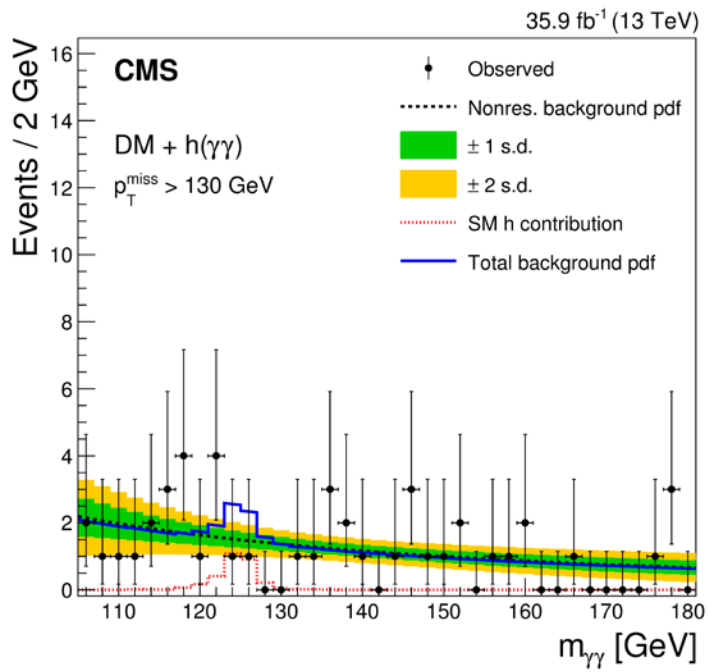


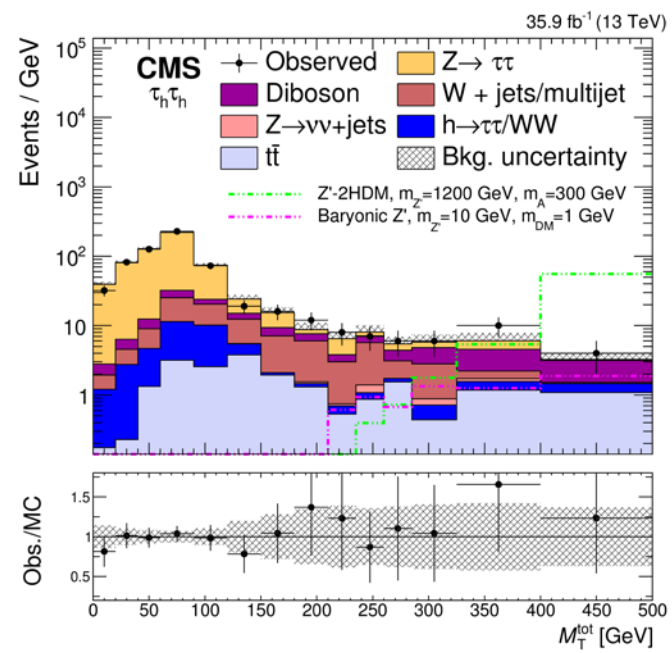
- To be detectable, such processes need SM recoil that can be generated either via decays of heavier states or via initial state radiation. This leads to the mono-X + missing transverse energy (MET) experimental signatures. Typical backgrounds come from SM processes with neutrinos (involving $Z \to \nu\nu$, etc).

Mono-Higgs + MET Search

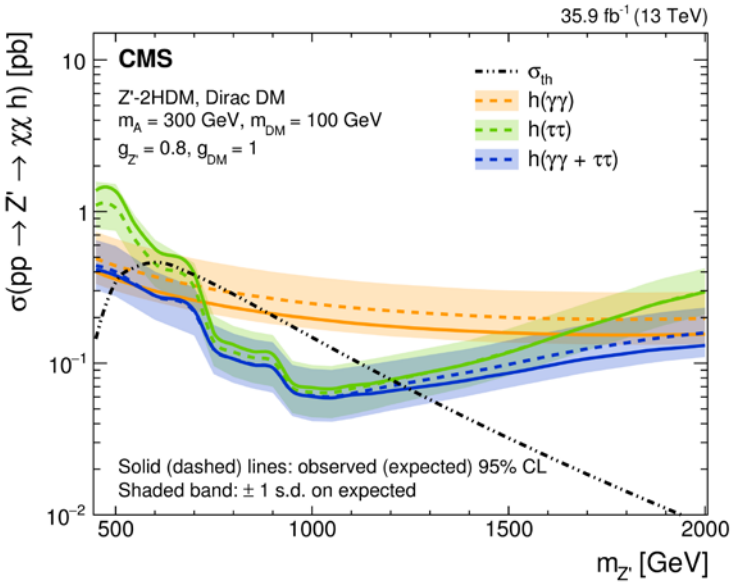
- Explores potential mediator coupling to Higgs
- Two benchmark models: Z'-2HDM and baryonic Z'
- Higgs is reconstructed in either $\gamma\gamma$ (better mass resolution) or $\tau\tau$ (lower background) decay mode
- The signal is extracted from $m_{\gamma\gamma}$ ($\gamma\gamma$ channel) and from transverse mass ($\tau\tau$ channel) distributions
- arXiv:1806.04771 (submitted June 12)
- CMS-PAS-B2G-17-004 (not discussed here) also searches for MET + boosted Higgs in the $b\bar{b}$ channel

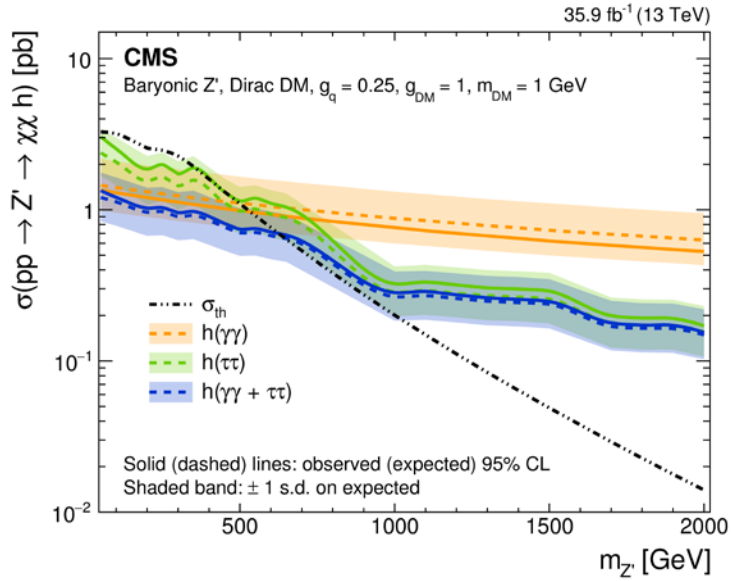


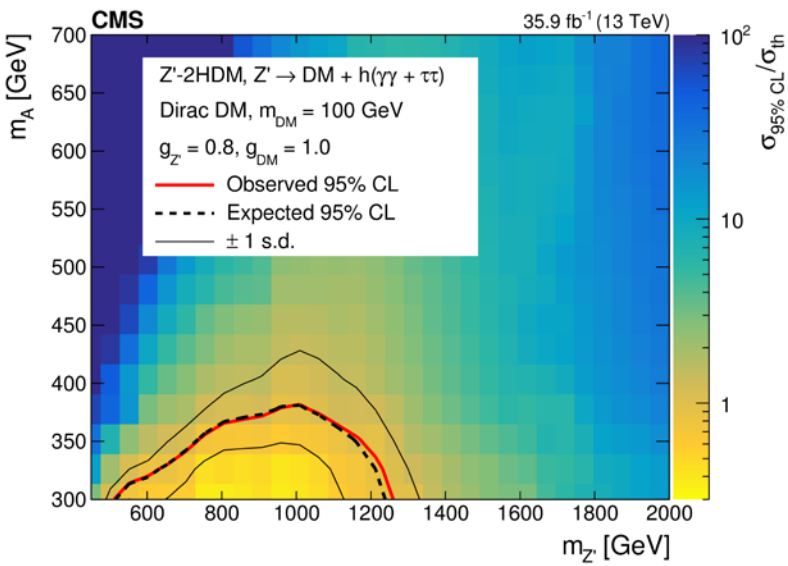


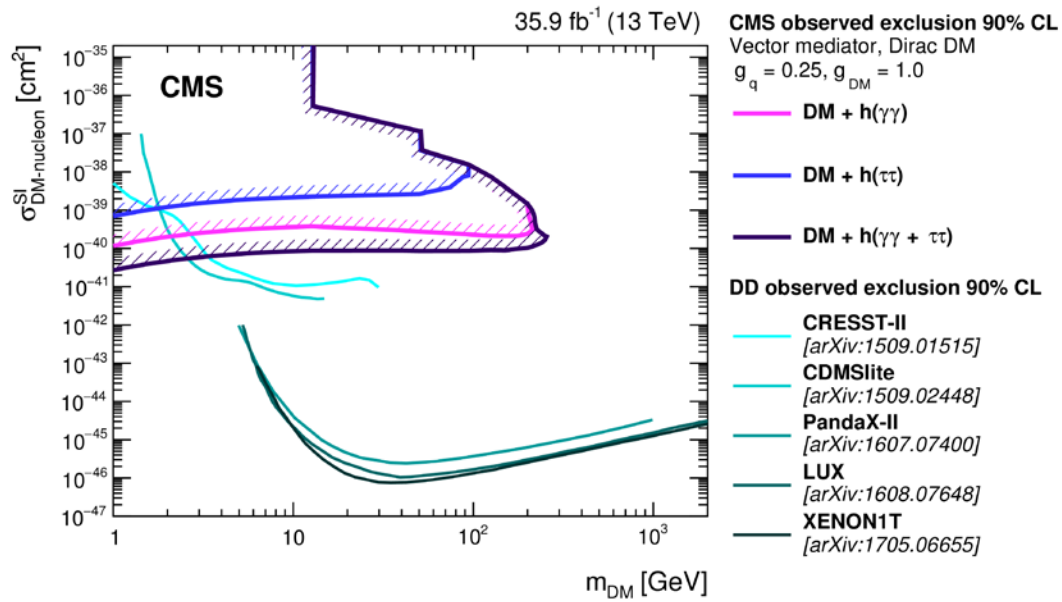


Interpretation of Mono-Higgs Results



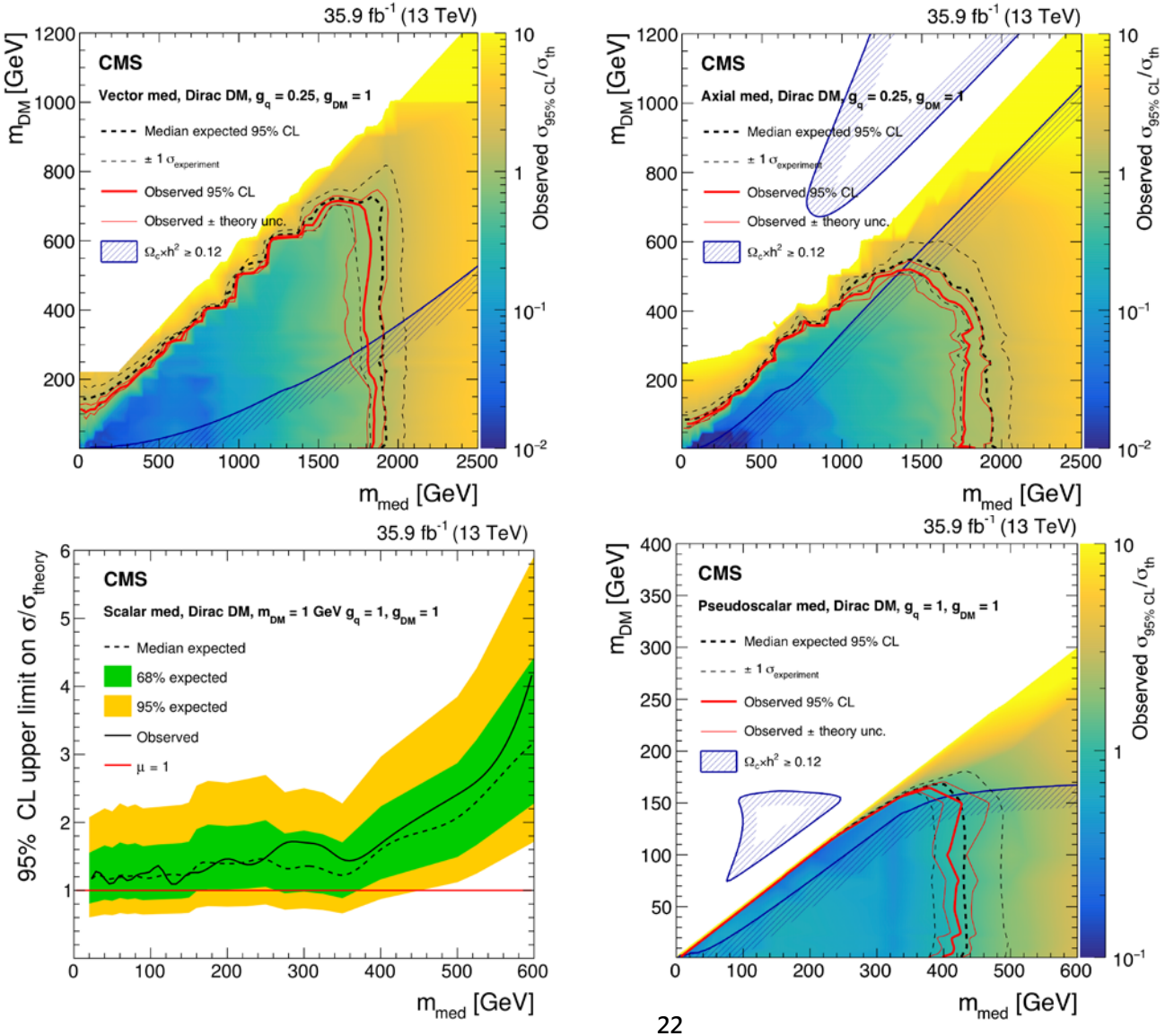






Systematic Studies of DM Mediators

Example: interpretation of monojet, mono-W, and mono-Z + MET search results in PRD 97 (2018) 092005



Moving from 36 fb^{-1} to 150 fb^{-1}

Higgs program will strongly benefit:

- 3.3σ "evidence" for $\boldsymbol{H} \rightarrow \boldsymbol{b\bar{b}}$ should be promoted to $\geq 5.0\sigma$ "observation"
- Coupling uncertainties will likely scale as $1/\sqrt{L}$
- Less inclusive measurements will become more common
- Studies that are systematically limited will benefit from better calibrations and statistical/systematic uncertainty trade-offs
- HH sensitivity will be substantially increased. "Double Higgs Production at Colliders" workshop is at Fermilab, Sep 4-8.

A number of precision studies will need substantial theoretical input to take the full advantage of the luminosity increase

Increase in the reach of rare and BSM process searches should not be underestimated

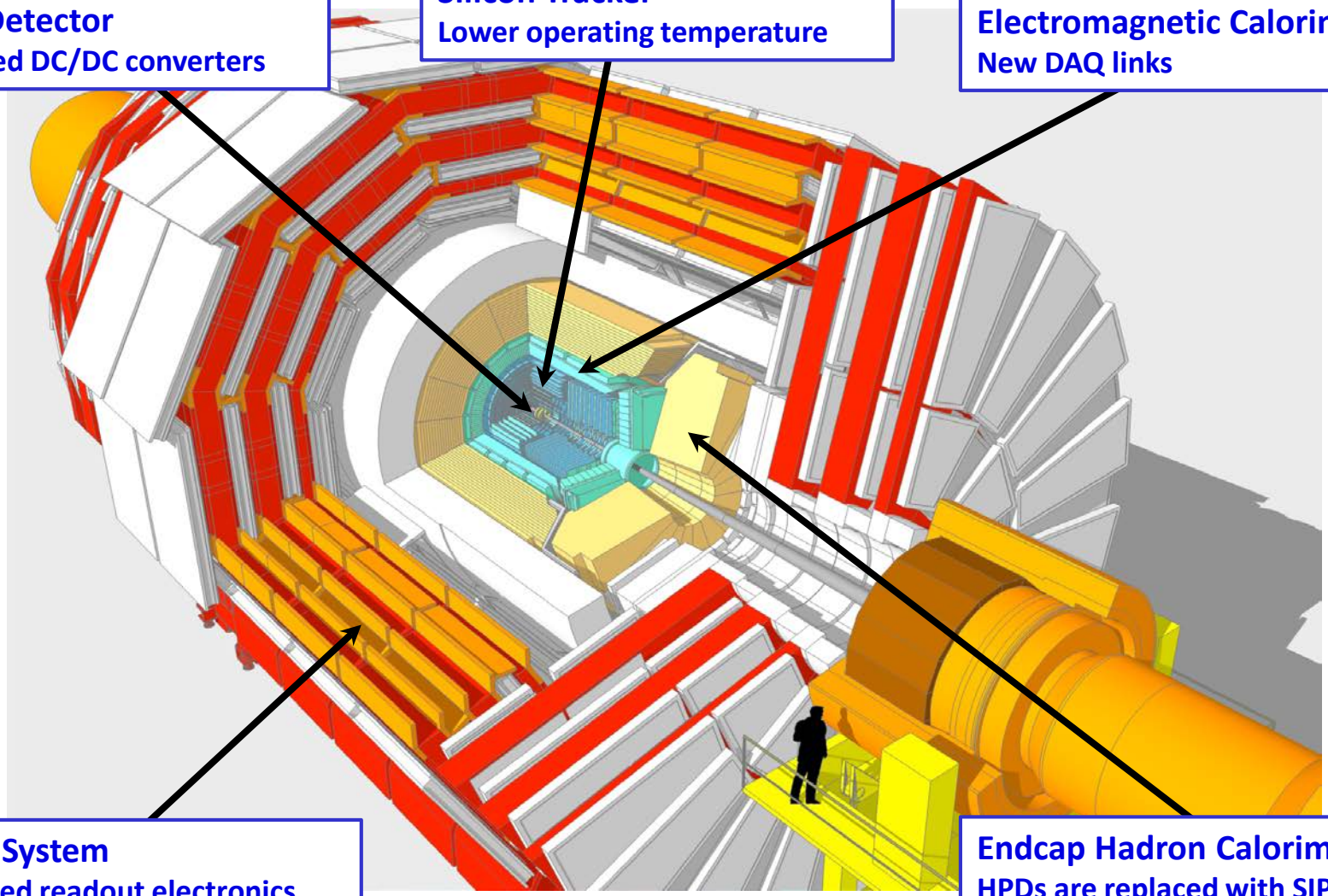
In Conclusion

- Owing to the excellent LHC performance, CMS maintains rich and vibrant Run 2 physics program
- 13 TeV data has already brought important new observations, especially Higgs-related
- Data analyses are becoming more sophisticated, with techniques like MEM and machine learning becoming mainstream
- Precision measurements of $t\bar{t}$ and other systems inspire progress in higher-order calculations
- DM, hierarchy and naturalness problems, etc, strongly indicate that our understanding of Nature is incomplete. Deep and wide searches for BSM physics continue.

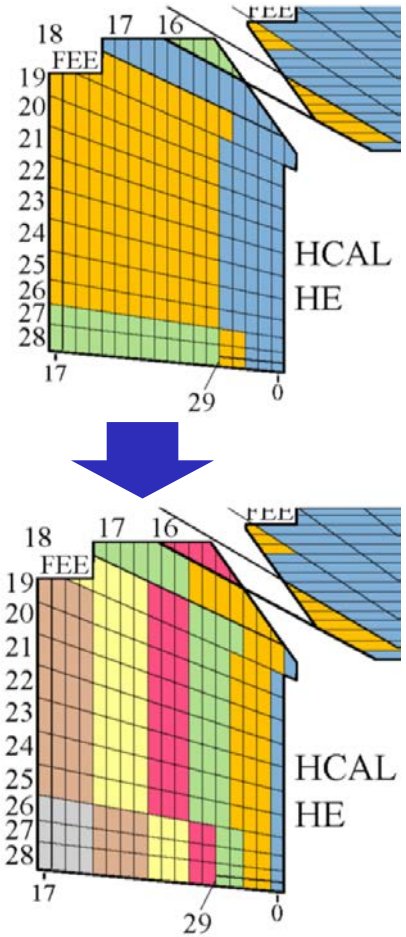
Completion of Run 2, detector upgrades, Run 3 and HL-LHC will bring much more data. CMS will remain an exciting experiment for many years to come.

Backup Slides

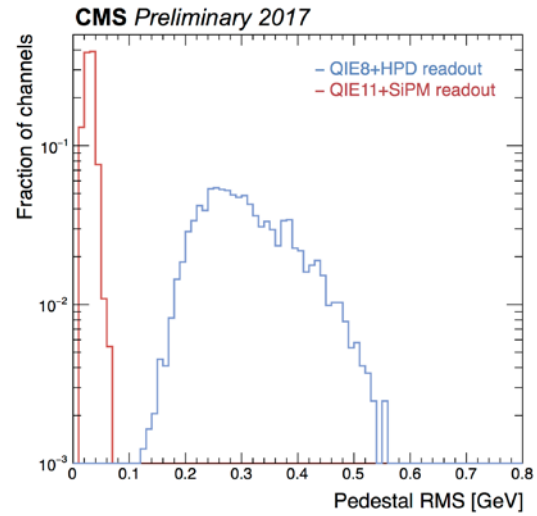
New in CMS in 2018

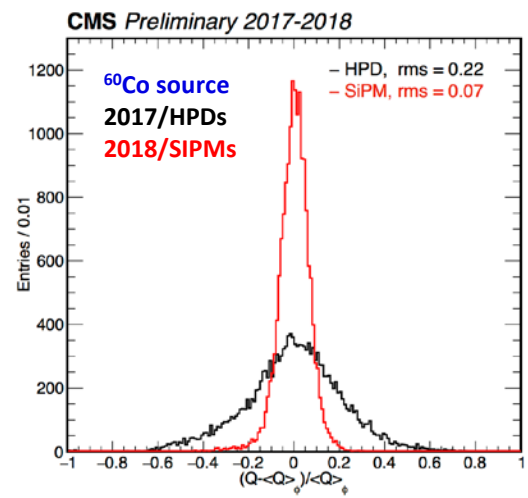


HCAL Endcap Upgrade

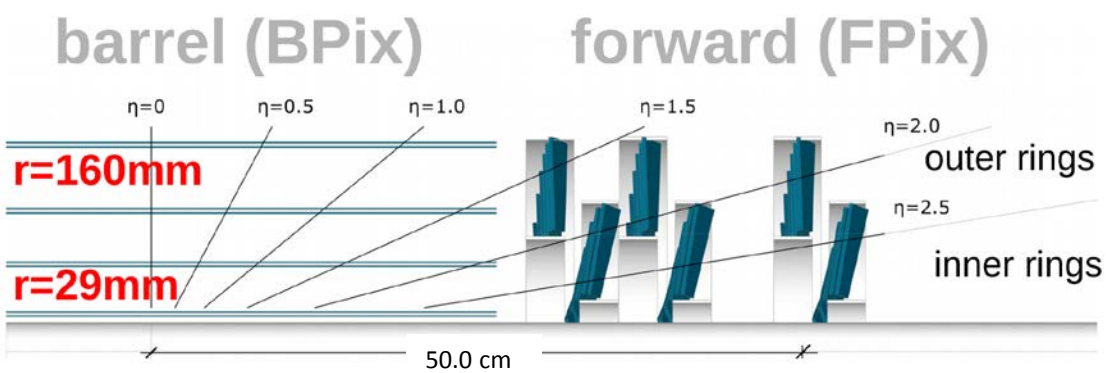


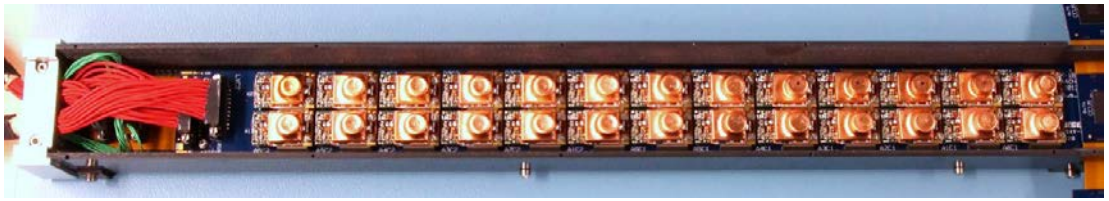
- Endcap hadronic calorimeter "Phase-1" front-end upgrade
  - ➢ HPDs → SIPMs
  - ➢ QIE8 → QIE11
- Good experience with one wedge in 2017
- Increased photo-detection efficiency mitigates scintillator radiation damage
- Improved signal/noise enables finer longitudinal segmentation
- Progressing HPD radiation damage (discharges, phi-asymmetric spread) is eliminated
- Currently learning how to exploit the improved segmentation





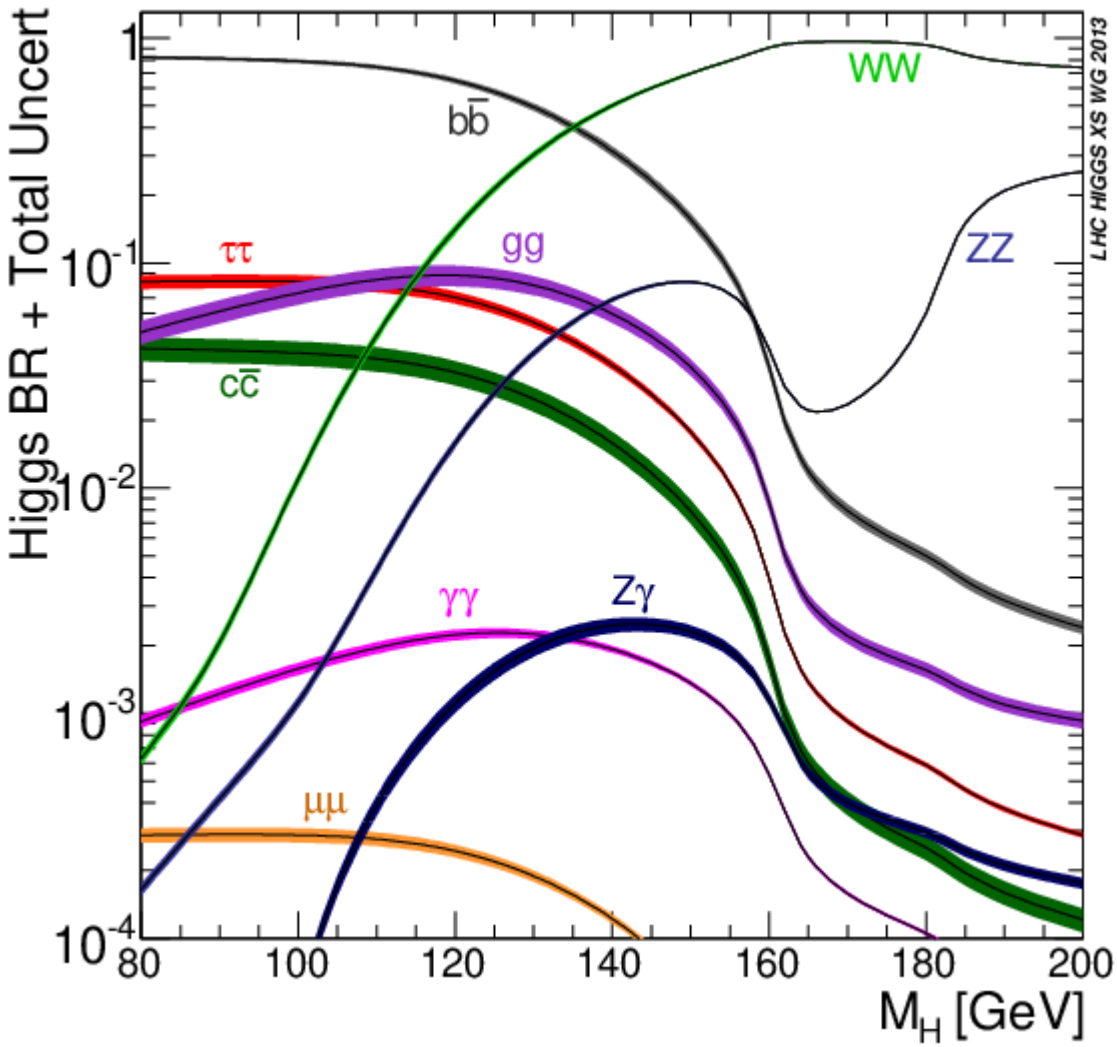
Pixel Detector DC/DC Converters



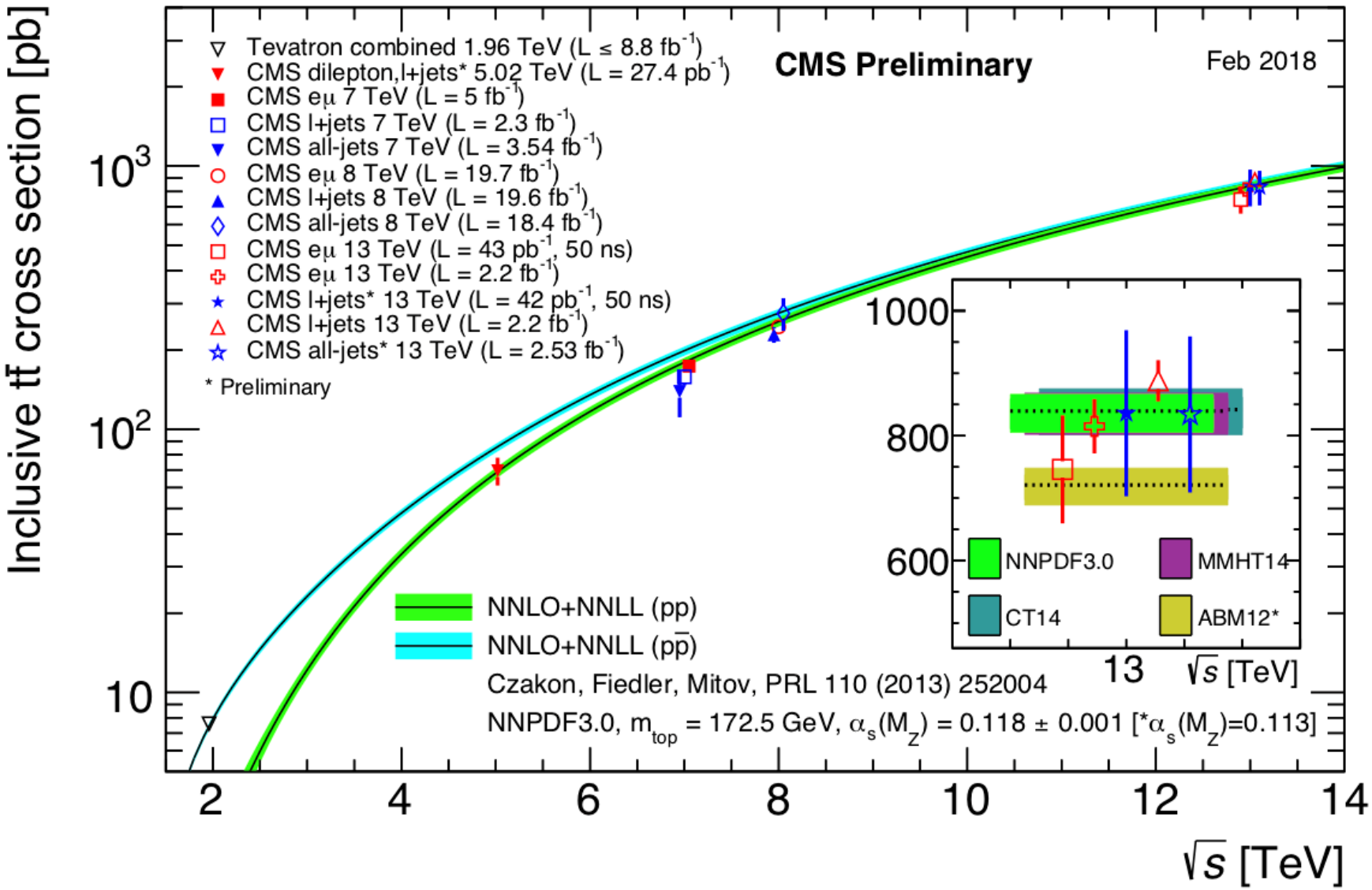


- Upgraded pixel detector was installed in CMS in March 2017
  - About 1.9 increase in the number of channels
  - Same power cables
  - DC/DC converters (~12 V to ~3 V) are used near the detector
- The system was irradiated to ~10 kGy in 2017. DC/DC converters start to exhibit problems above ~7 kGy (about 5% failure rate by the end of the year).
- Converters were replaced for 2018 operation
- After an extensive investigation and external irradiation campaign, the cause appears to be understood.
  A design update will be needed to eliminate the failures.

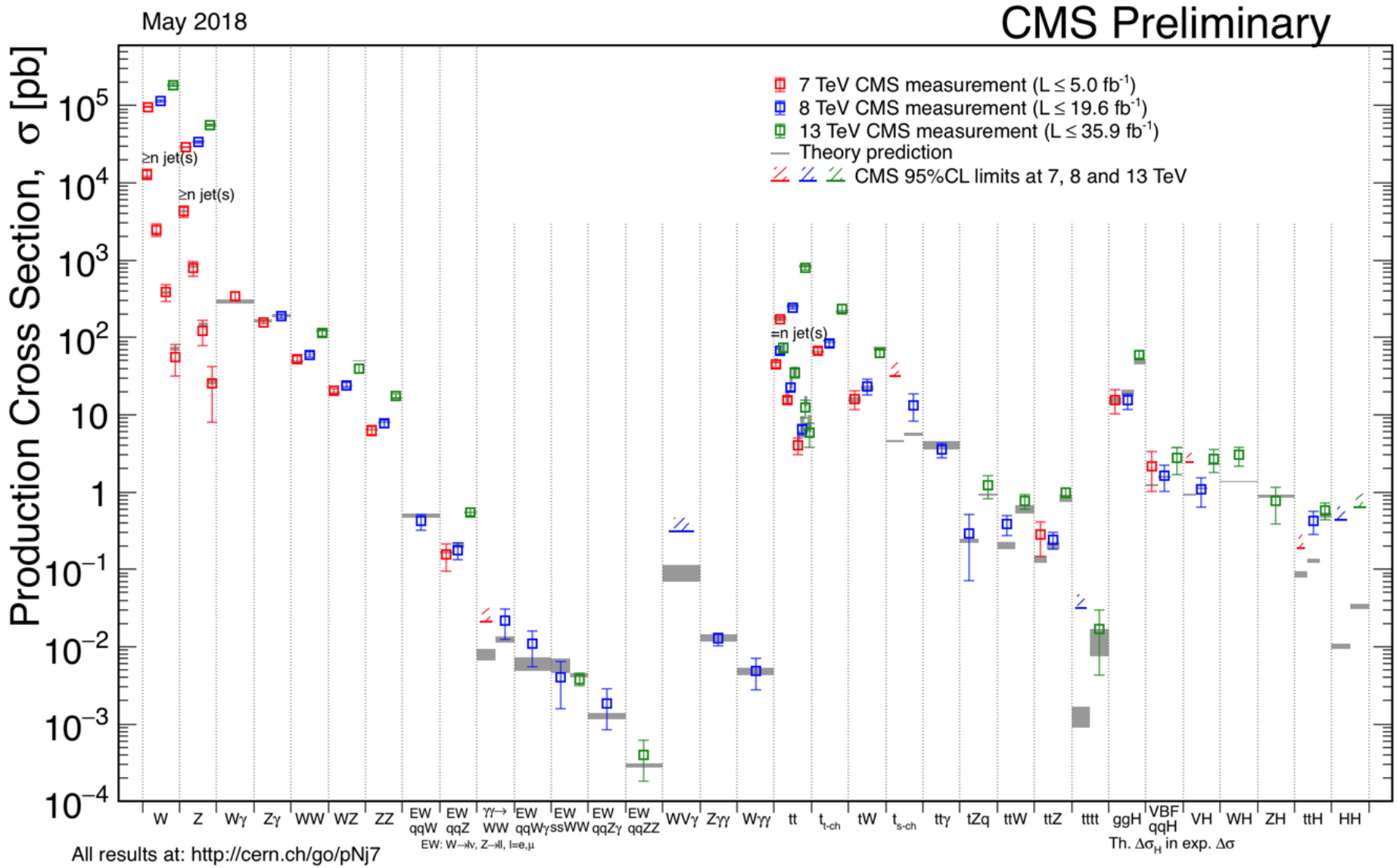
SM Higgs Branching Fractions



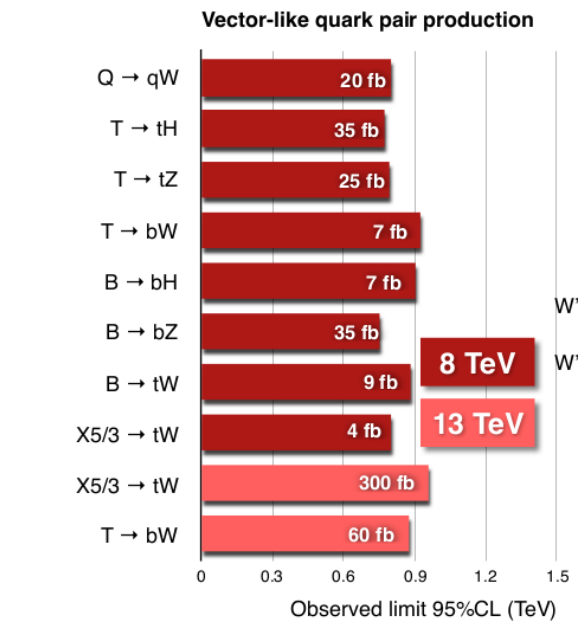
$t\bar{t}$ Production Cross Sections

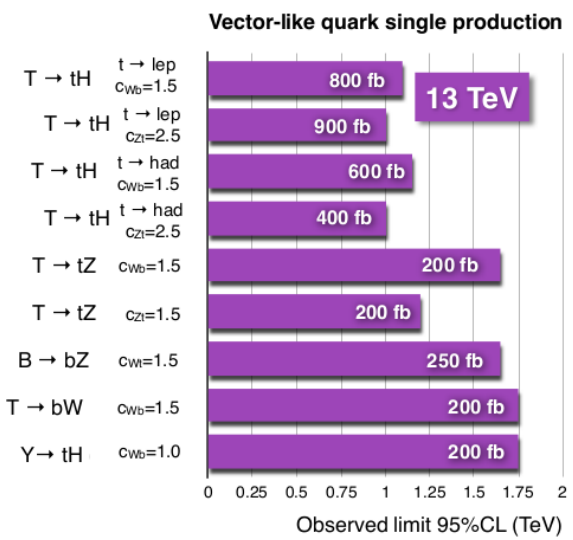


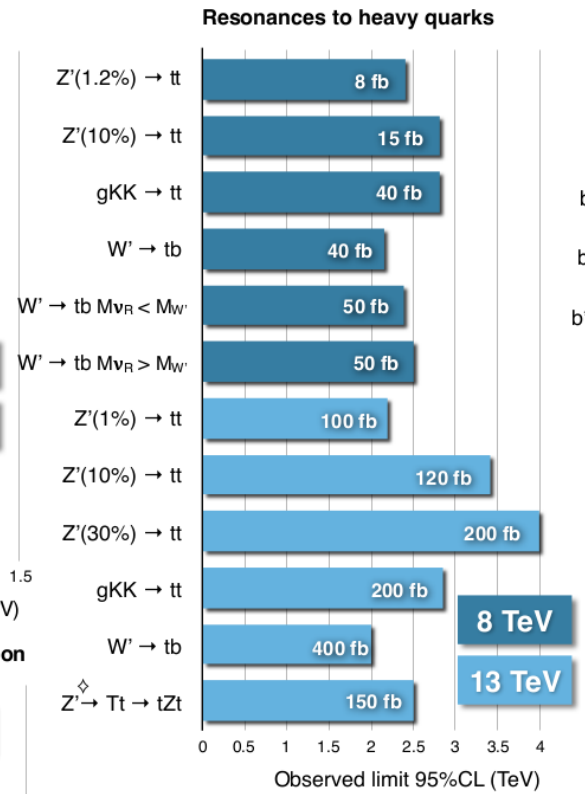
SM Cross Sections Summary

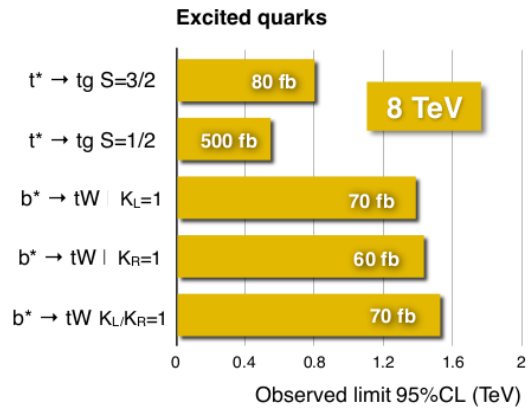


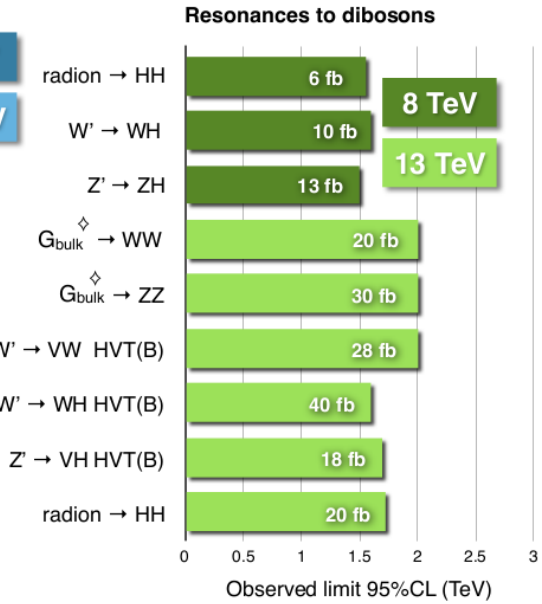
B2G Searches Summary











B2G
new physics searches with heavy SM particles

✧model-independent