CMS STATUS AND OUTLOOK

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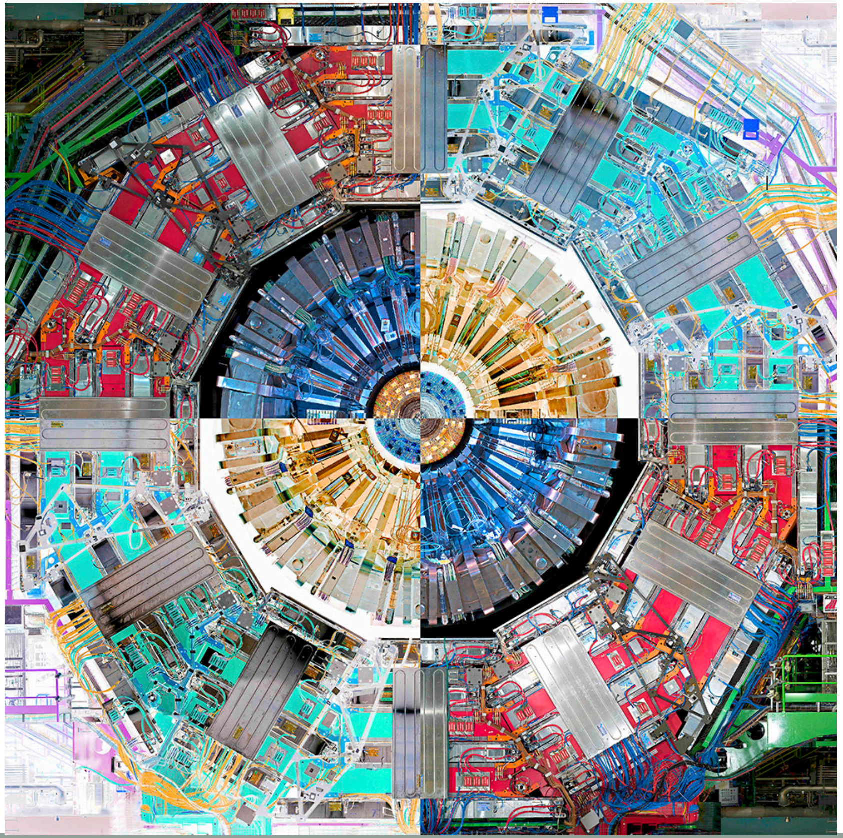
Brown University

on behalf of the CMS Collaboration

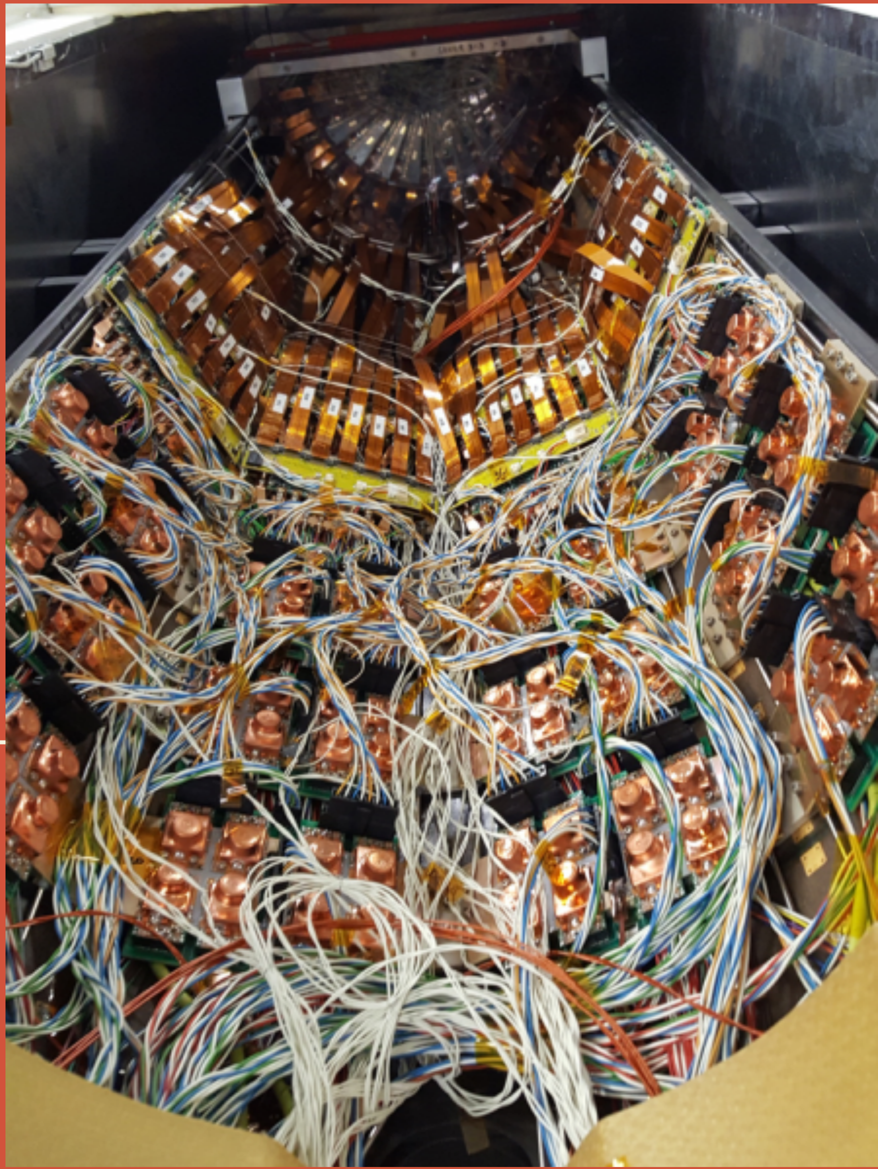
USLUA Annual meeting,
Oct 25th, 2018



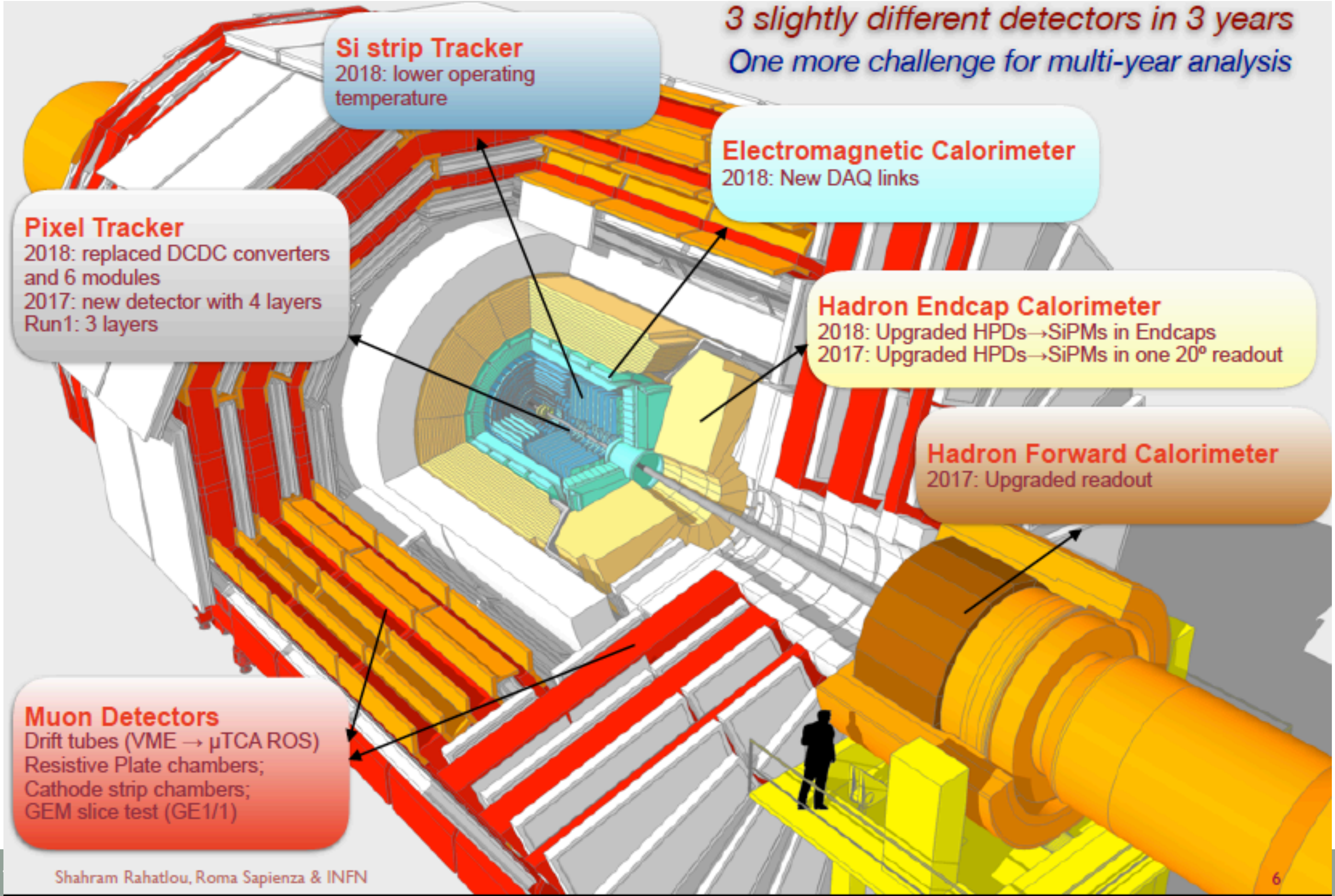
Outline

- Highlights from operations and detector performance
- Physics highlights
  - A few selected topics
  - With apologies to all the topics I will not cover in this presentation
- Phase-2 Upgrades

DETECTOR OPERATIONS & PERFORMANCE

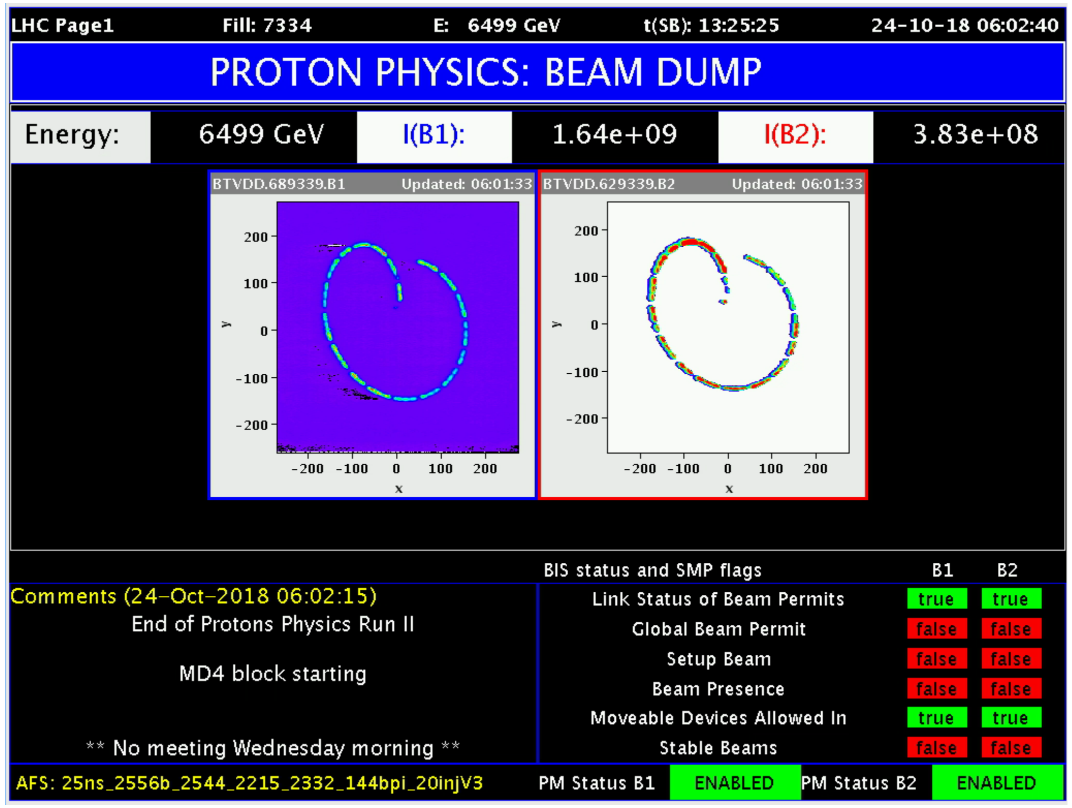


CMS Detector Evolution



End of Protons Physics Run II

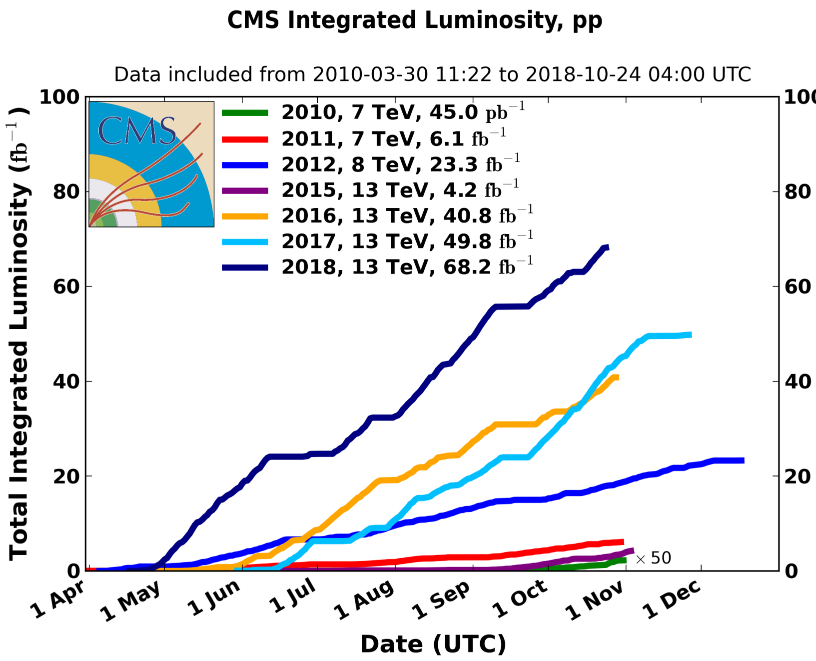
- The last proton beams of LHC Run 2 were dumped Wednesday Oct 24 at 6 AM CET, marking the end of a very successful data taking period.

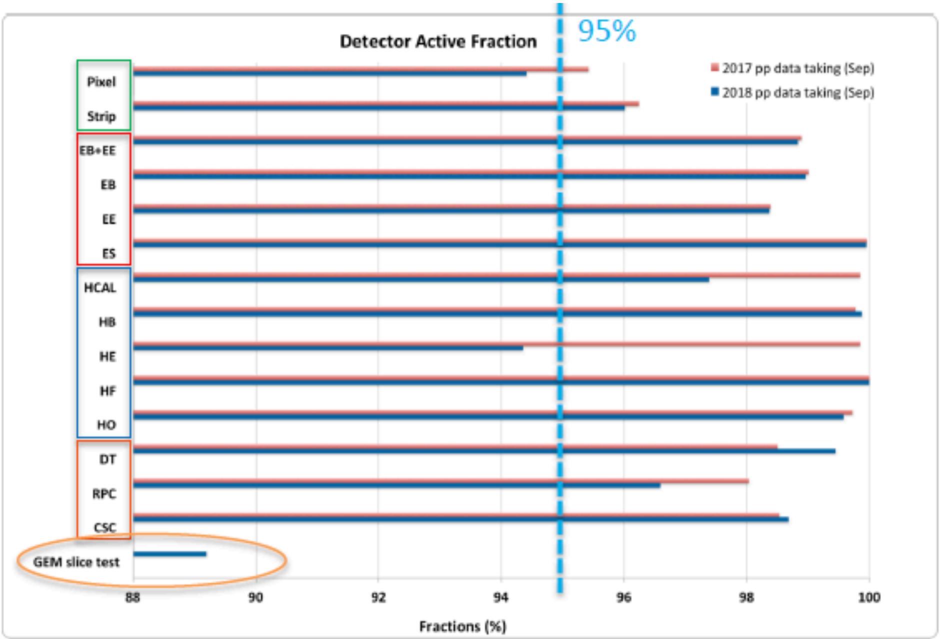


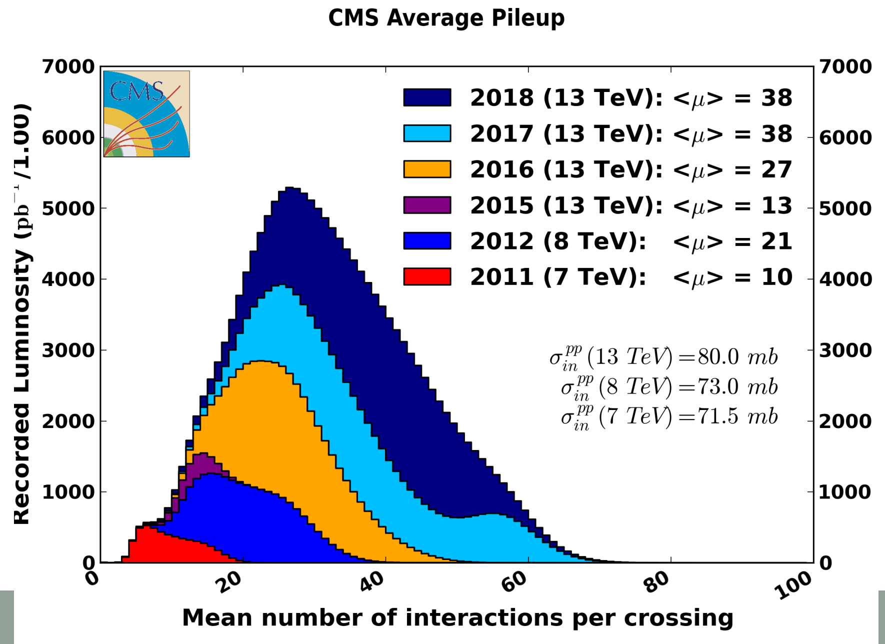
- In the coming weeks, the LHC will be accelerating and colliding heavy ions
- In December LHC will be shut down until 2021.

CMS Luminosity

- Integrated luminosity delivered in 2018 ~68 fb^{-1}
  - (above the expected 60 fb^{-1})
- Excellent performance of LHC and of CMS
- LHC goal of 150 fb^{-1} in Run 2 reached several weeks before the start of the Heavy Ions program (**Many thanks to the LHC team)**
- Excellent and stable performance of subdetectors
- CMS operations teams managed to achieve almost 95% data taking efficiency in an extraordinary effort.



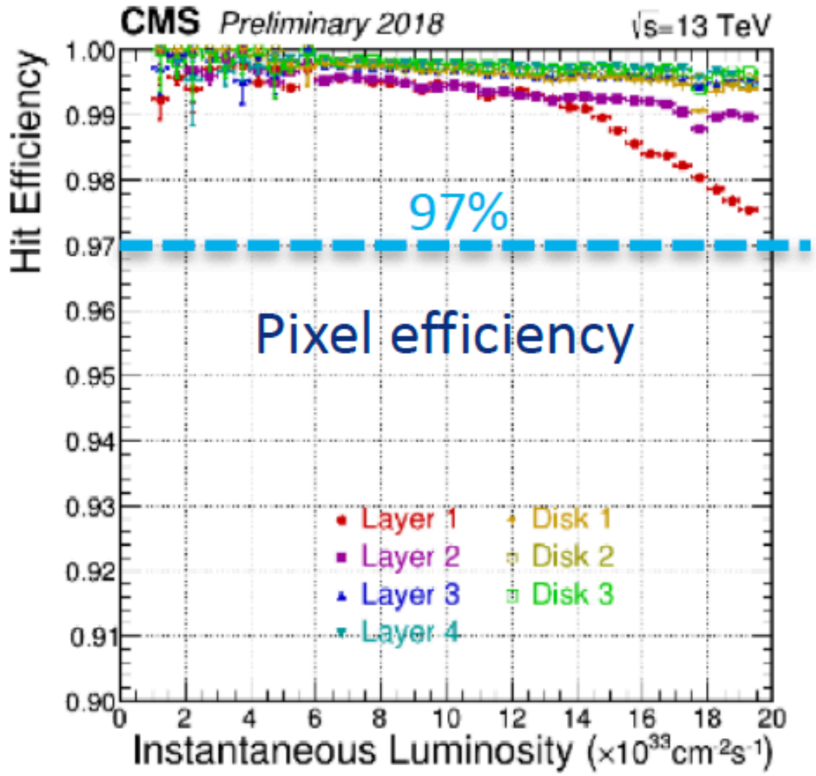




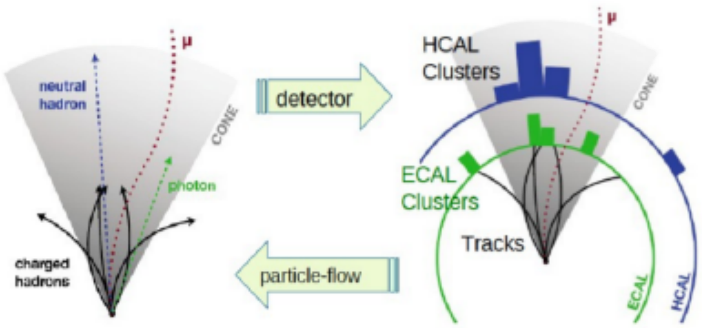
Quality of data

- CMS is taking excellent quality data, including several special runs
  - VdM scans, 90m beta* CMS-TOTEM joint run, Low PU run (HI run is coming very soon)

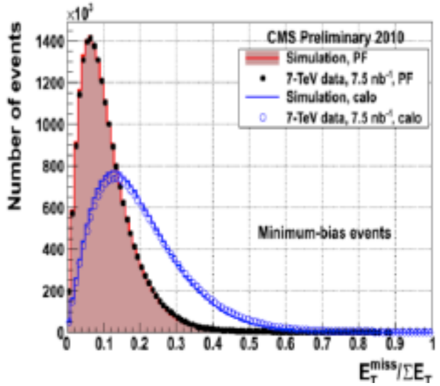
- DC/DC converters, failure mode understood as the combined result of irradiation and use of enable/disable feature
  - This understanding has allowed us to prevent it to happen in 2018
  - Many thanks to: CMS tracker team, Technical Coordination, and CERN FEAST design team.

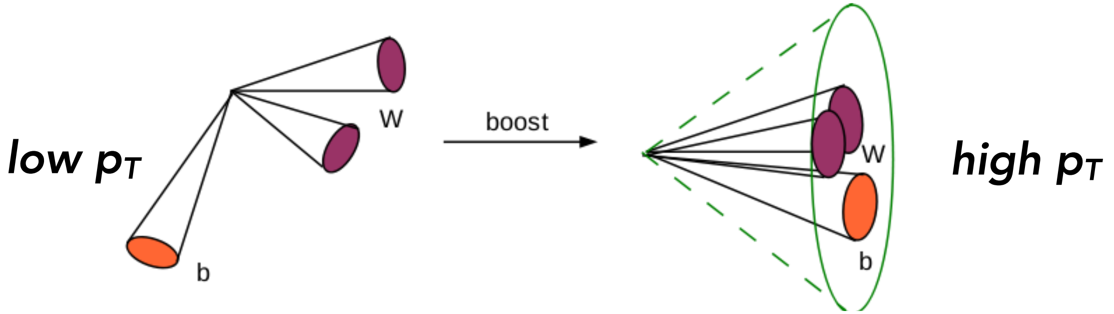


Evolution/Improvement of Analysis Techniques



Particle Flow

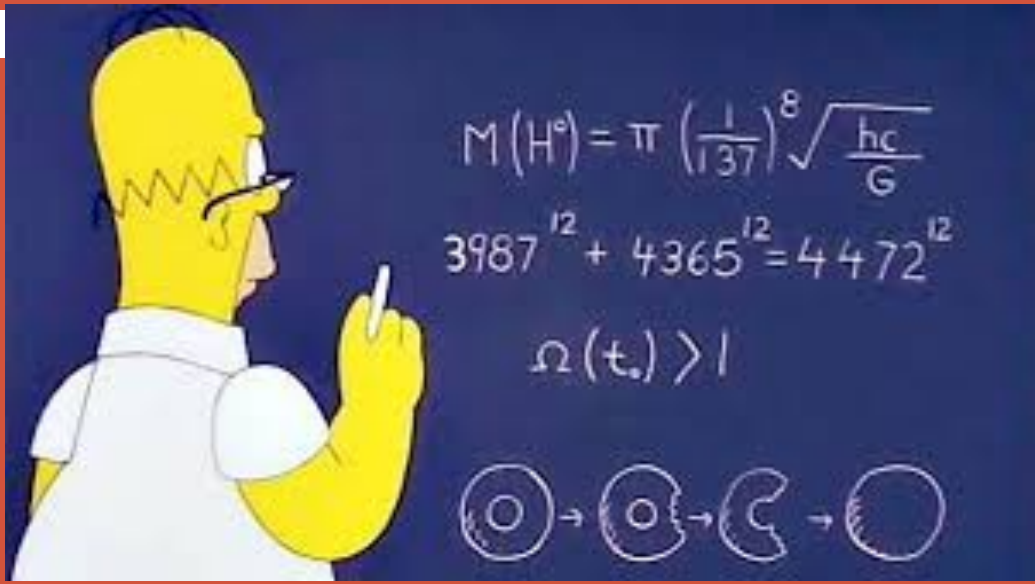




Boosted Jets, Jet Substructure

- 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!

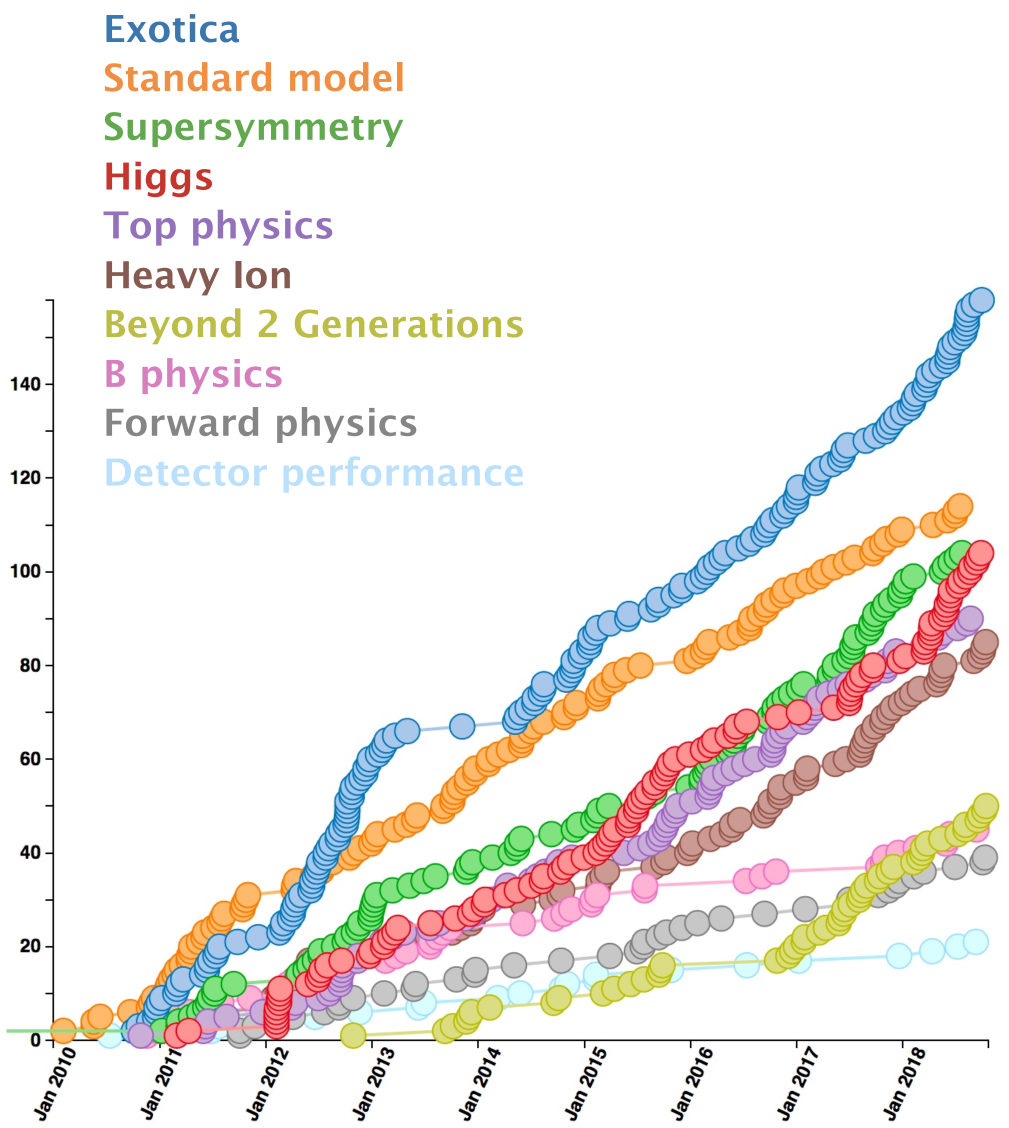


PHYSICS HIGHLIGHTS

- A few selections…

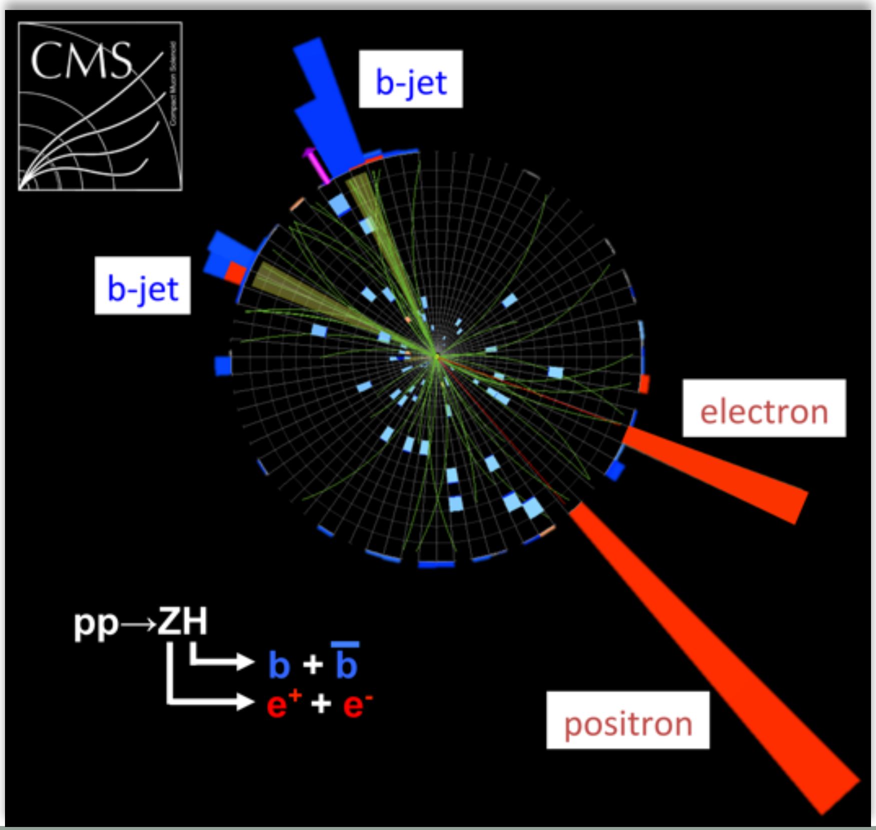
Publications Status

- As of oct 15, CMS has submitted its 809 paper for publication
  - Includes detector paper & performance papers in the past 93 months since Jan 2010.
  - Staggering publication rate: ~7.8/month, 92/year
  - plus additional 25 papers based on non-collision data
- No sign of slowing!
- 144+ papers in past year
  - ~12/month



- The full list, including links to all individual papers:
- http://cms-results.web.cern.ch/cms-results/public-results/publications/CMS/index.html
- The timeline, split by physics topics:
- http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

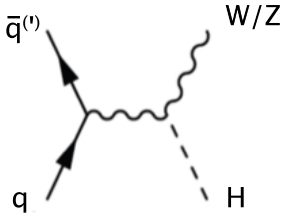
HIGGS PHYSICS

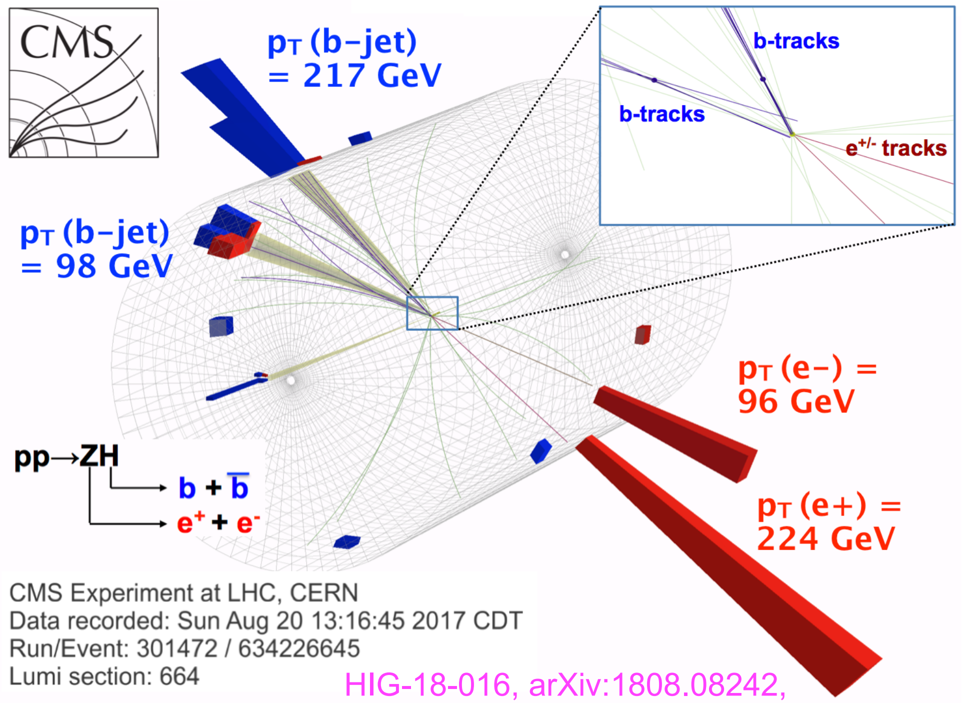


Higgs Yukawa Couplings

- Higgs couplings to heavy fermions

Channel	Date
H→ττ	May 2017
pp→ttH	Apr 2018
H→bb, pp→VH	**Aug 2018**





HIG-18-016, arXiv:1808.08242, accepted PRL

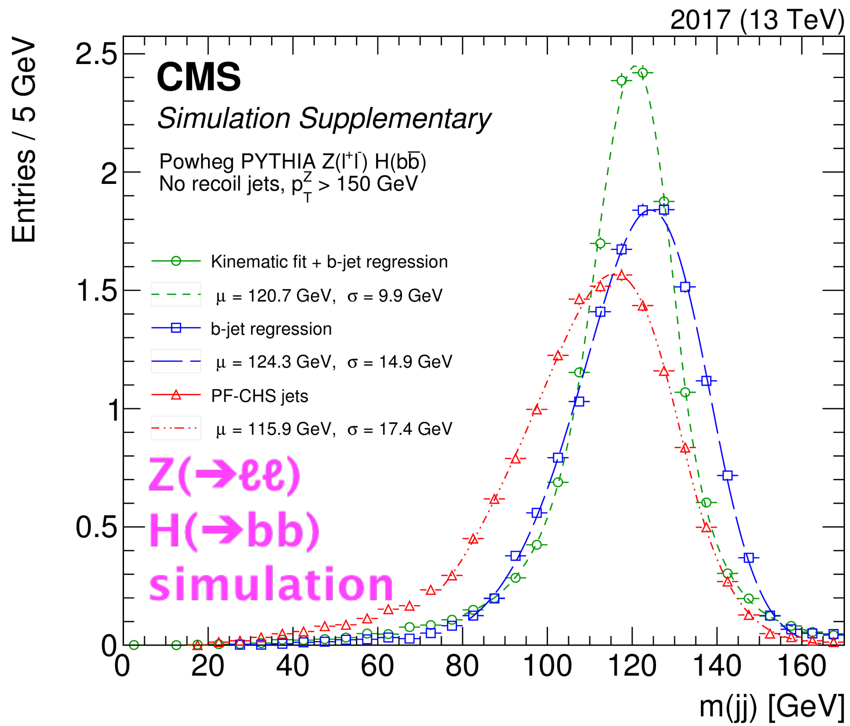
- With the "observation" of the Higgs couplings to the τ -lepton, the Top quark, and the b-quark, we have now established the Yukawa couplings to the 3rd Generation charged fermions and are entering the era of detailed measurement.
- This is a great success of the LHC and the experiments
  - This was accomplished much earlier than expected because of the outstanding performance of the LHC and to the new highly refined analysis techniques

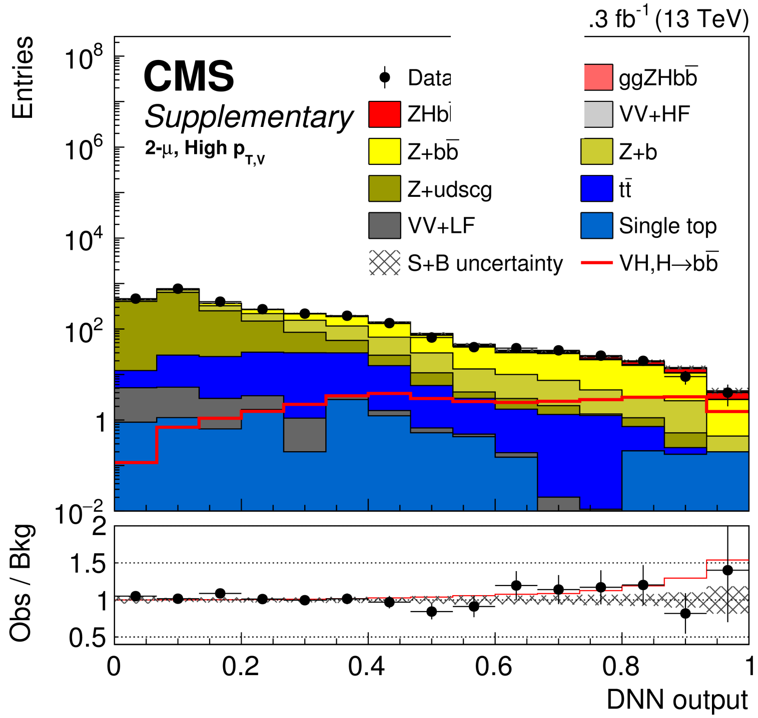
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$
$$+|D_\mu\phi|^2 - V(H)$$
$$+Y_{ij}\psi_i\psi_j\phi + \text{h.c}$$

VH➔bb in 2017 data

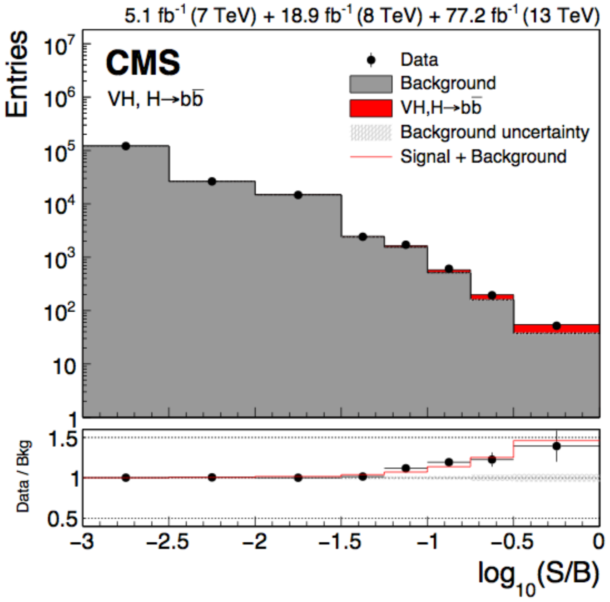
HIG-18-016,
arXiv:1808.08242,
PRL Ph121 (2018) 121801

- Improved sensitivity by 5-10% w.r.t. 2016 analysis
  - new pixel detector, better b-jet identification, energy regression for b jets, use of deep neural networks and S/B discrimination DNN b-tagger, kinematic fit in 2ℓ channel
- Signal/background discrimination w/ DNN based on:
  - b-jet properties, jet kinematics, event topology





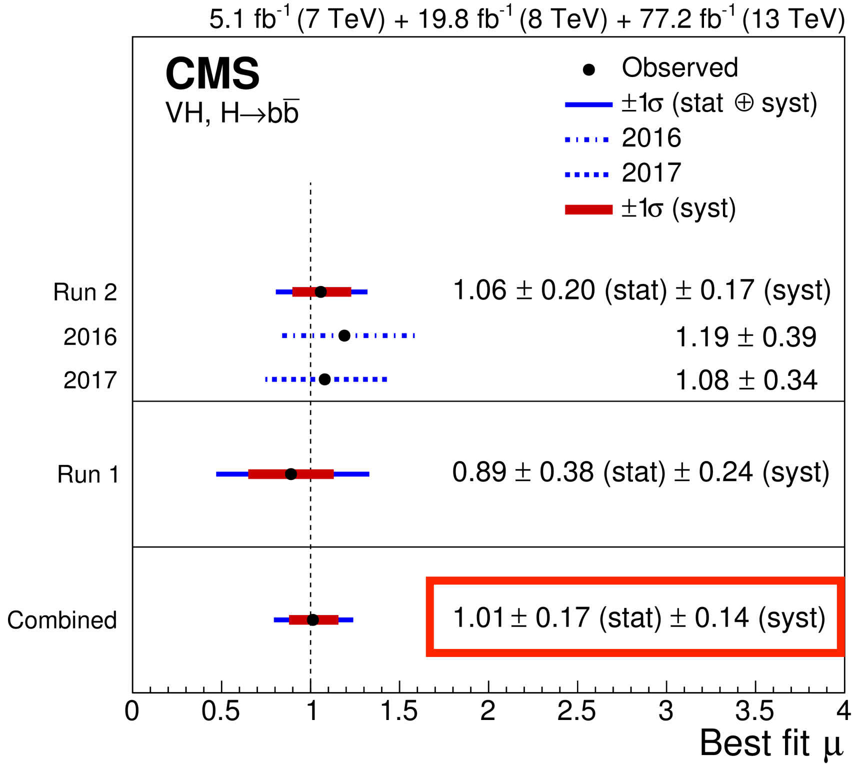
high purity
Z➔μμ category



Observation of Hbb

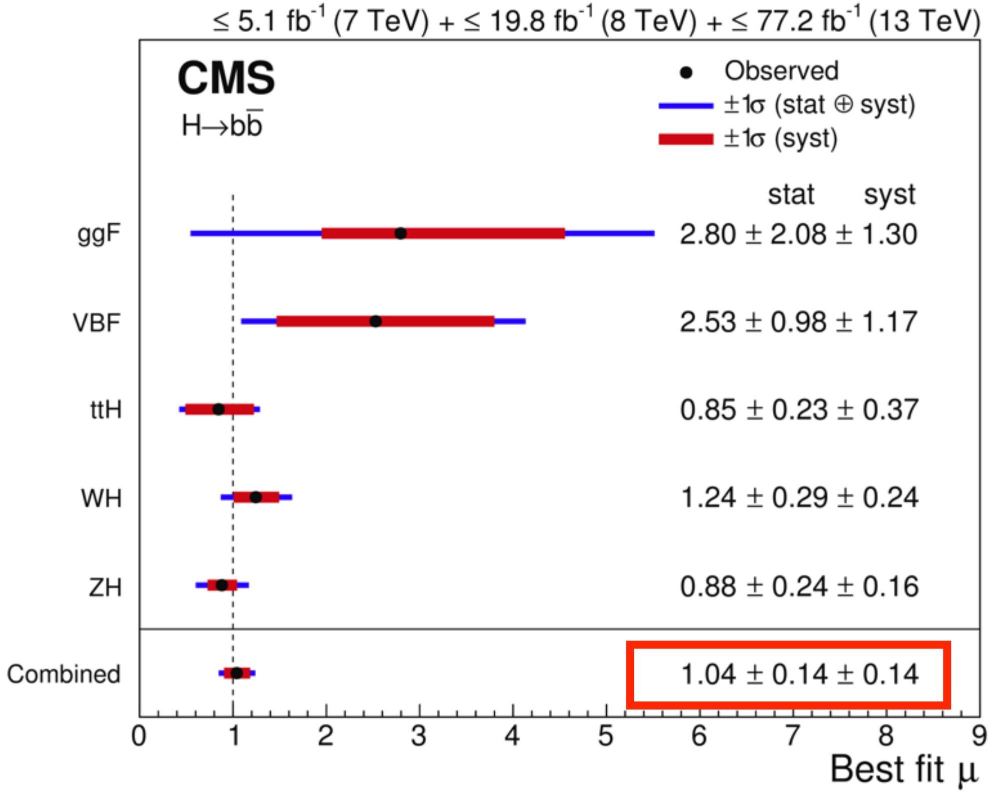
HIG-18-016,
arXiv:1808.08242,
PRL Ph121 (2018) 121801

Combine 2017 VH→bb with 2016+Run1



Data set	Significance (σ) Expected	Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2 (2016+2017)	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

Combine VH with other production modes



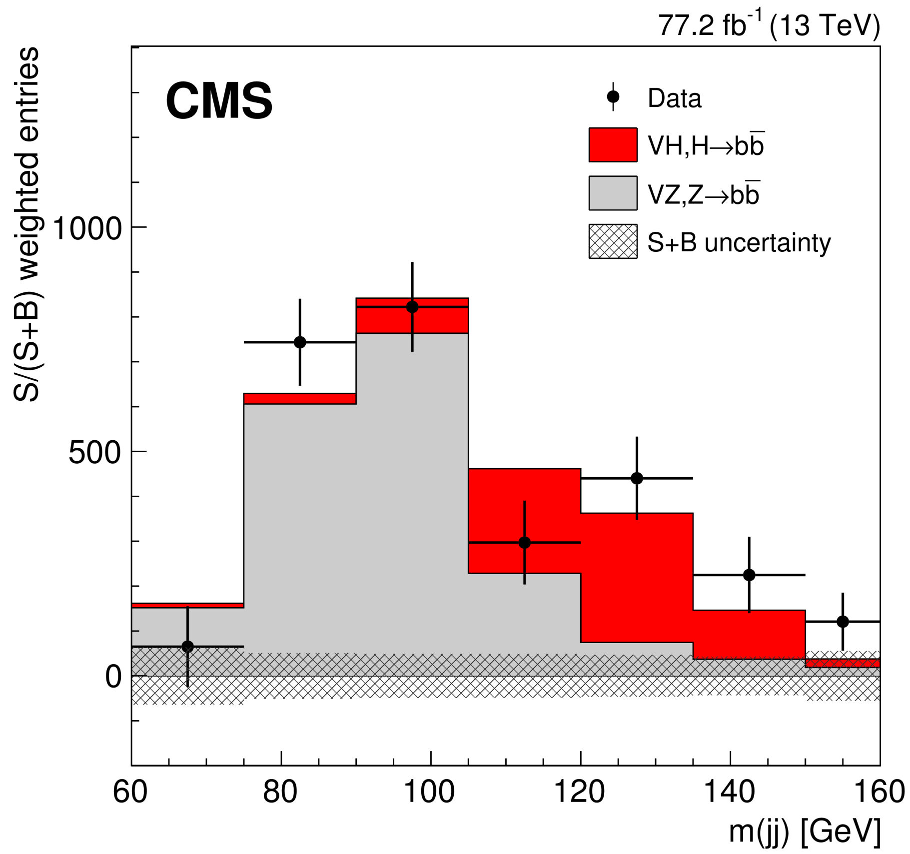
combination VH(bb): 4.8σ Observed (4.9σ expected)
all production modes: 5.6 σ Observed (5.5σ expected)

HIG-18-016,
arXiv:1808.08242,
PRL Ph121 (2018) 121801

bb mass distribution

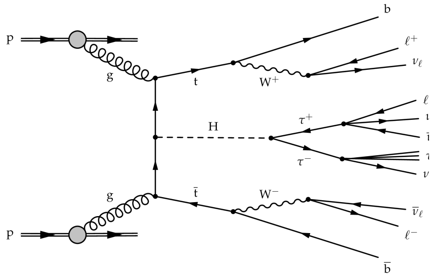
- Instead of DNN output, analyze M(bb) to visualize signal.
- Signal strengths compatible with main analysis.

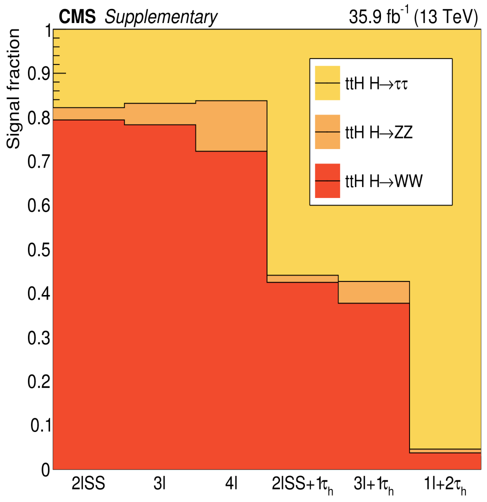
Combined M(bb) Spectrum



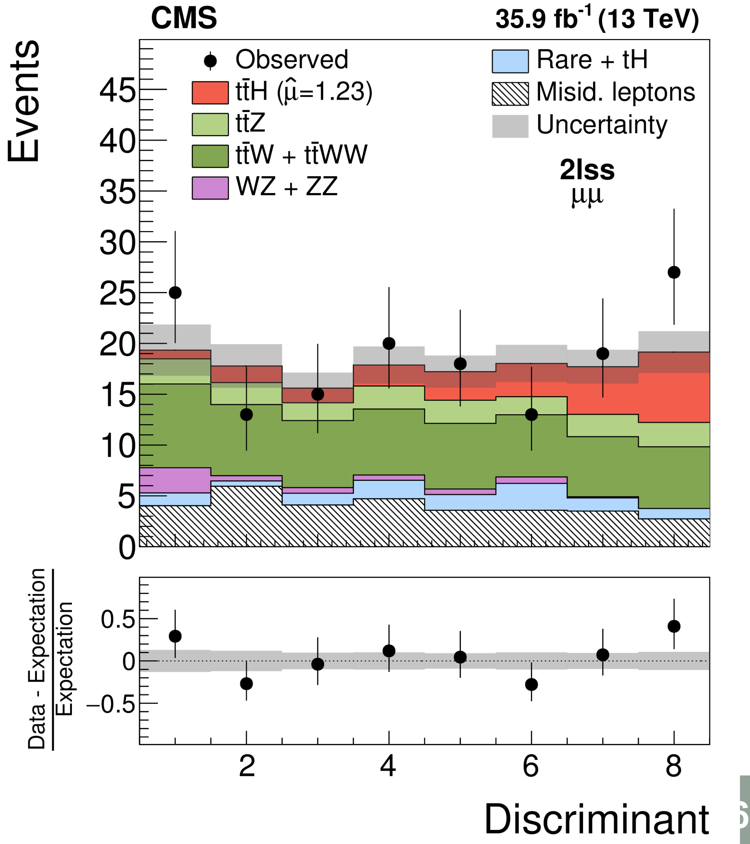
ttH Production at CMS

- Tree level measurement of top quark Yukawa couplings
- Using Higgs decays to b-bar, $\tau^+\tau^-$, $\gamma\gamma$, 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





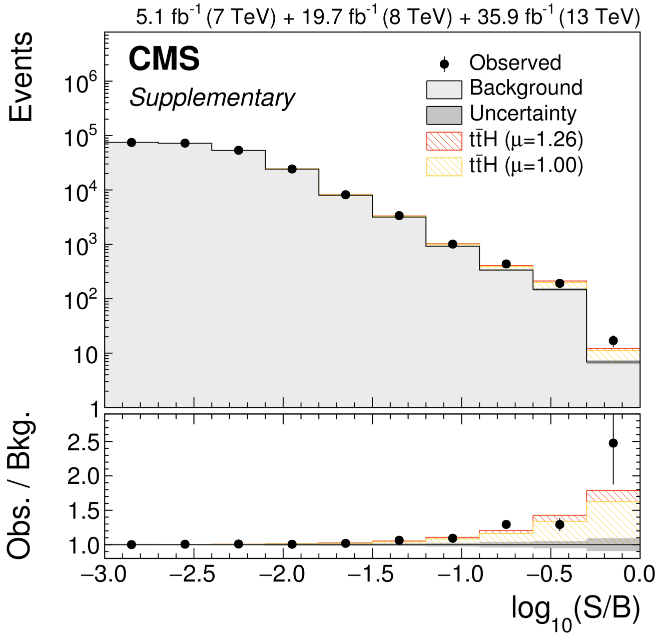
- Main systematic uncertainties are
  - Experimental: lepton-id & b jet efficiencies; τ_h and jet energy scales
  - Theory on background calculations: modelling uncertainties in tt production in association with a W or Z or a pair of b or c jets
  - Theory on signal calculations: effect of higher order 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

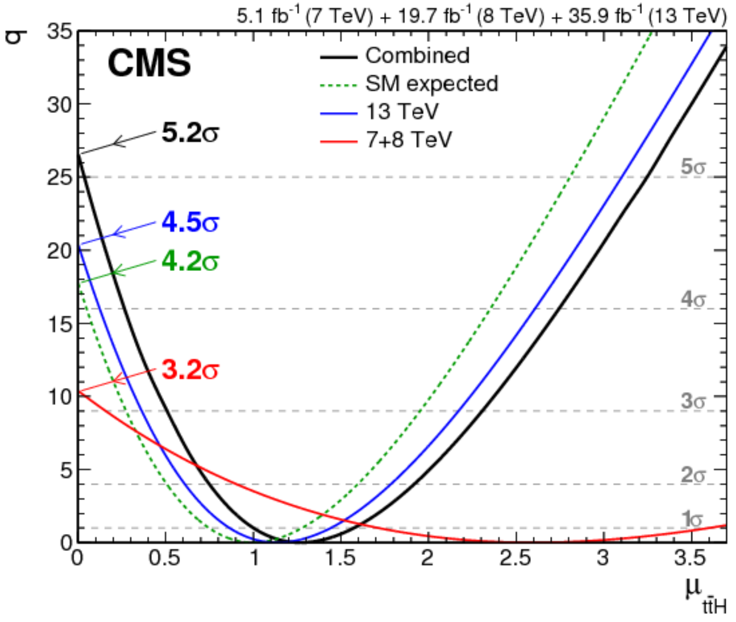


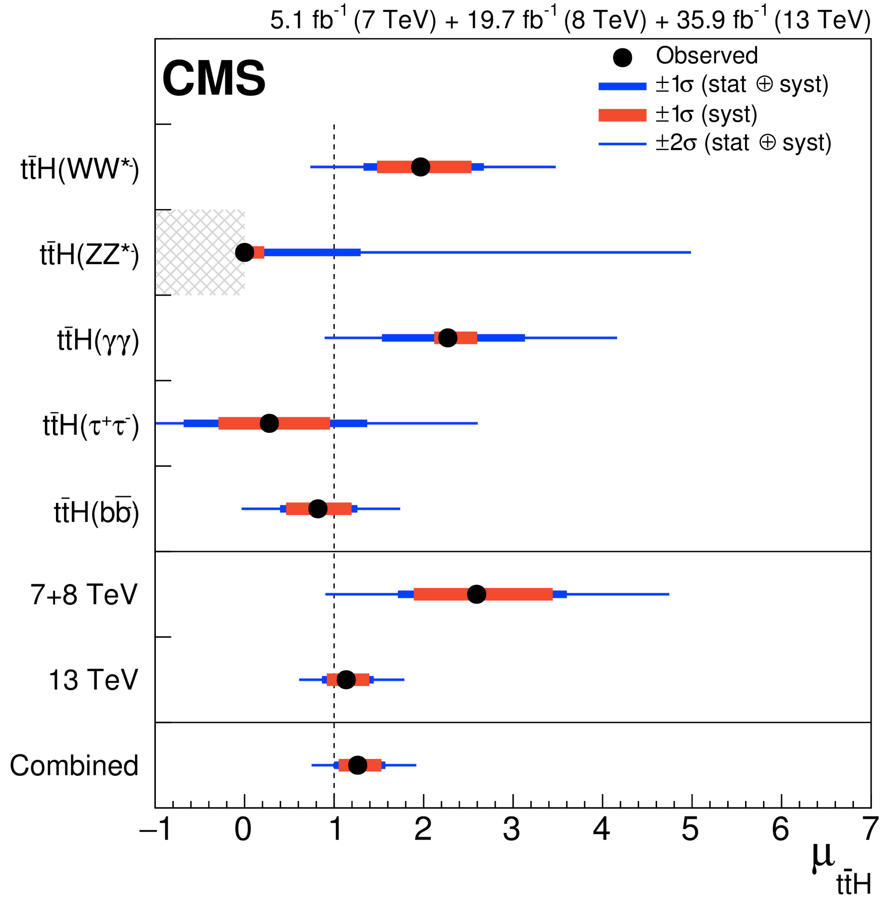
Observation of ttH Production

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

- Combining Run1 & Run2
  - Some theory & background uncertainties are correlated
  - Experimental uncertainties are largely uncorrelated





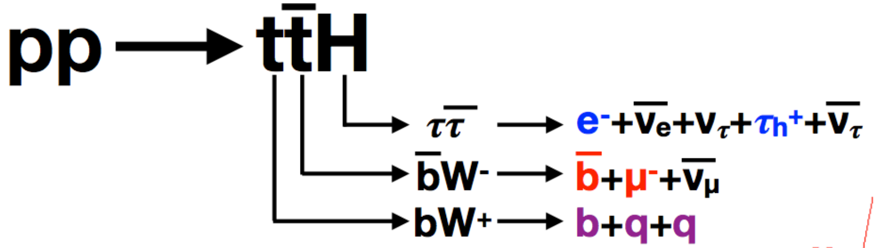


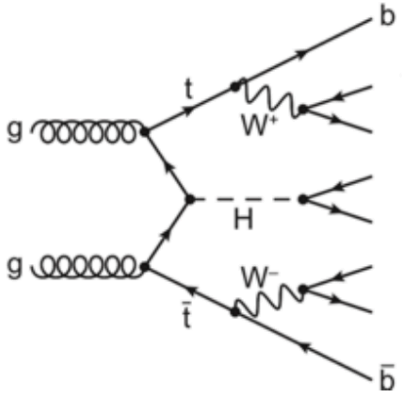
Significance: 5.2σ Observered (4.2 σ expected)

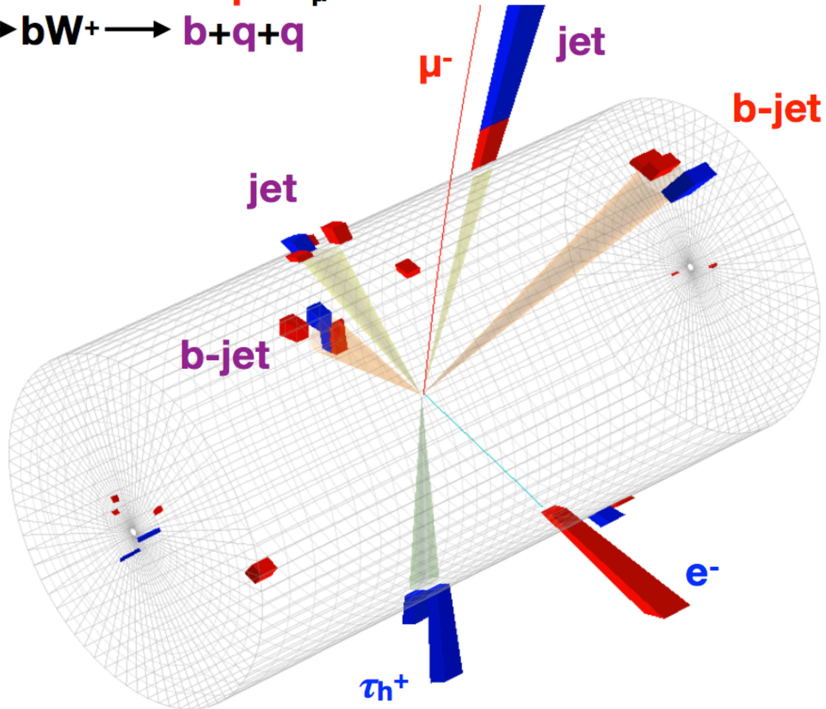
Best fit value of signal strength modifier for (upper section) the five individual decay channels considered, (middle section) the combined result for 7+8 TeV alone and for 13TeV alone, and (lower section) the overall combined result.

$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\mathrm{stat})^{+0.17}_{-0.15}(\mathrm{expt})^{+0.14}_{-0.13}(\mathrm{bkg\ th})^{+0.15}_{-0.07}(\mathrm{sig\ th})$$

A ttH "Candidate" event







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, and emphasizes the breath-taking range that the SM spans in mass

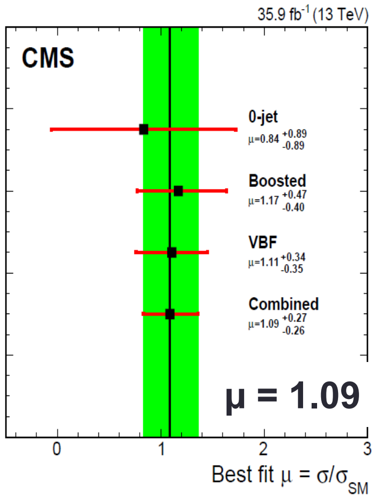
Observation of H → $\tau^+\tau^-$

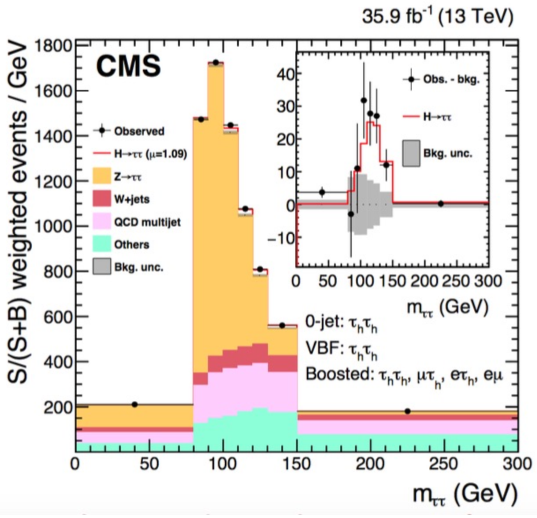
PLB 779 (2018) 283

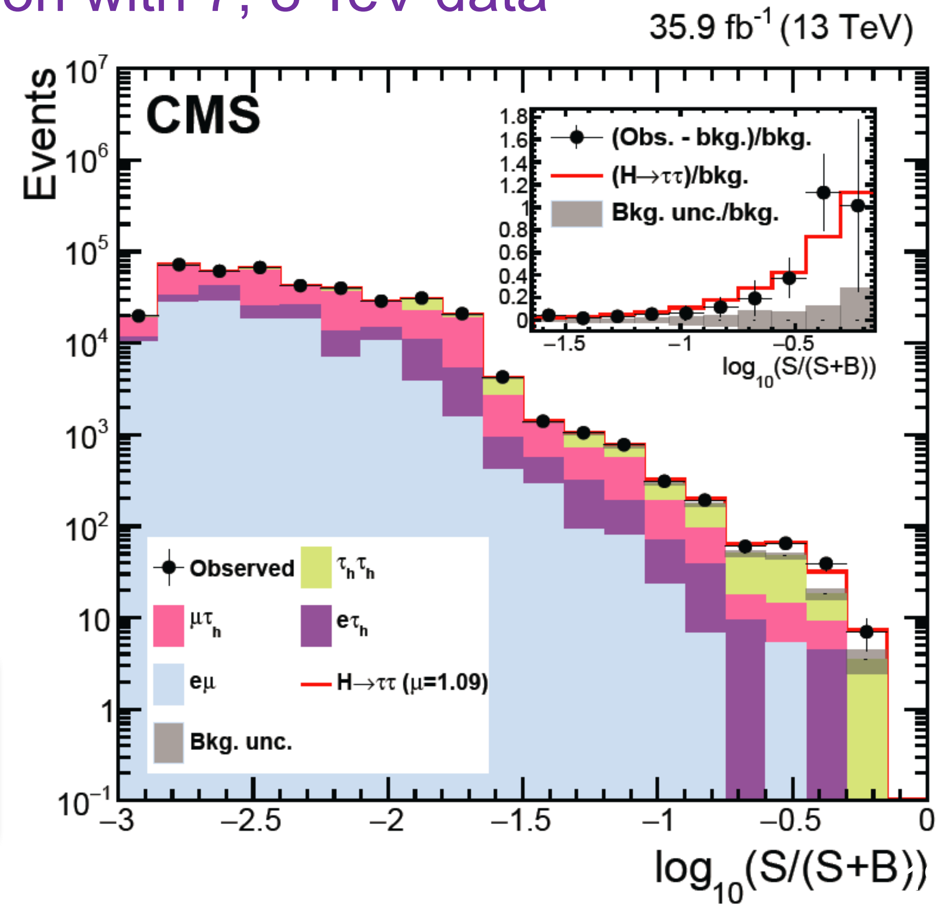
arXiv:1708.00373

CMS-PAS-HIG-16-043

- Using 7, 8, and 13 (2016 only) TeV data
- Branching ratio: 6.3%, best channel to establish Higgs boson couplings 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
  5.9σ observed (5.9σ expected) combination with 7, 8 TeV data
- $\mu = 0.98 \pm 0.18$







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 & to fermions of 3rd generation

Higgs→$\mu\mu$ coupling to 2nd gen.

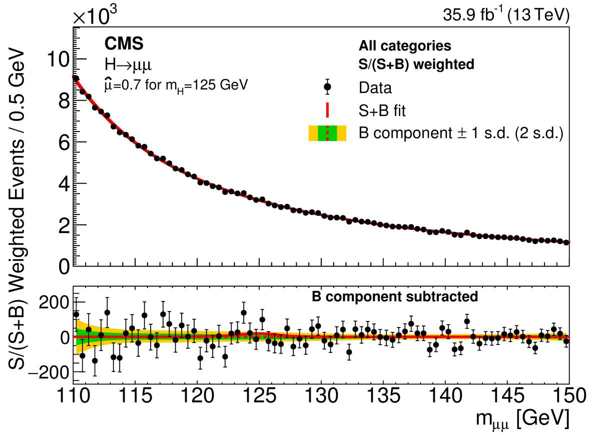
HIG-17-019

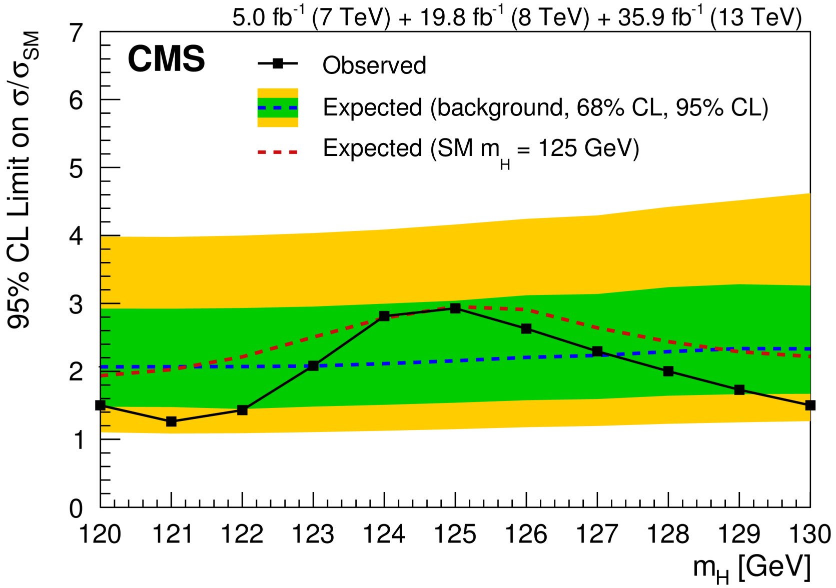
arXiv:1807.06325
Submitted to PRL

- Best channel to measure Higgs couplings to 2nd fermion generation, even though SM $B = 2.2\times10^{-4}$, about 1/10 of $\gamma\gamma$

- Clean signature, benefits from good mass resolution
  - Backgrounds mostly from Z+jets and ttbar
- Use kinematics of the di-muon system (p_T, $\Delta\varphi$, $\Delta\eta$), the maximum muon η, and boosted decision tree (BDT) technique for optimal signal sensitivity.

- **Upper limit on obs. (exp.) production rate:**
  2.92 (2.16) x SM @95% CL.
- **Upper limit on observed Branching Fraction for H→$\mu\mu$: 6.4 × 10^{-4}**
  - **by combining 7+8+13 TeV (2016 only) data**



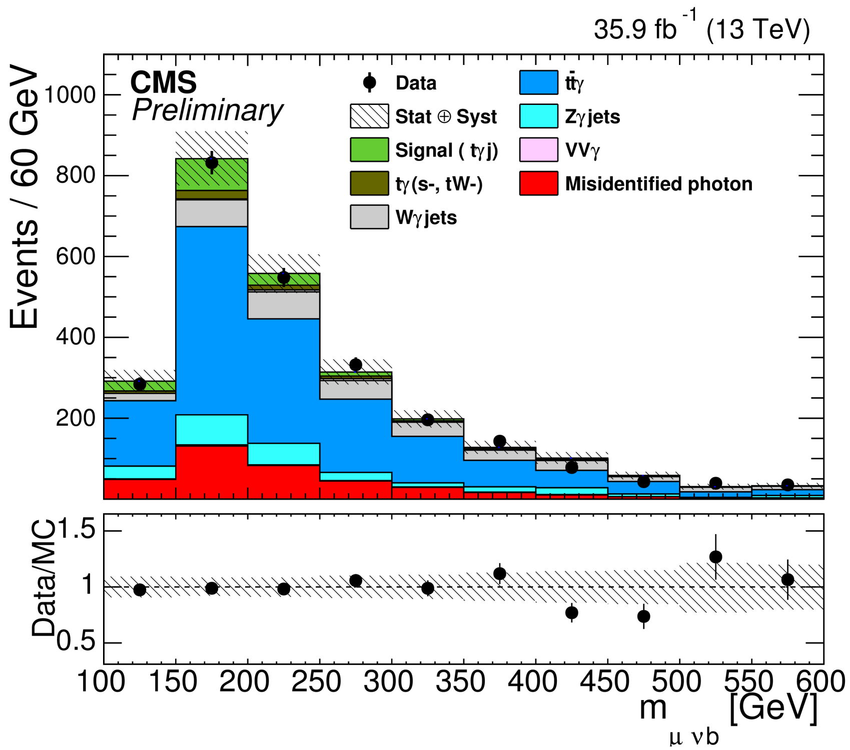


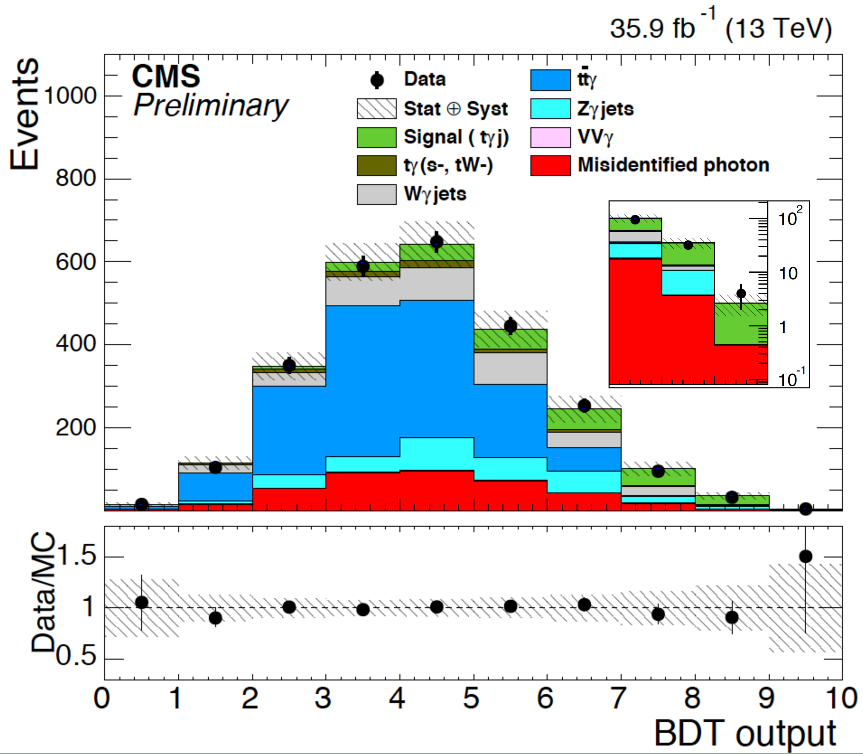
HL-LHC projection with a dataset of $3ab^{-1}$
Expected precision:
- **Higgs coupling (κ_μ) to 5%**
- **H→$\mu\mu$ signal strength ($\sigma_{meas}/\sigma_{SM}$) to 10%**

TOP & B PHYSICS

Single Top + photon

- First evidence for single-top production associated with a photon
- in events with a top decay to $b\mu\nu$, at least one more jet, and a photon
- event selection based on a boosted decision tree combining eight variables
- evidence at 4.4σ observed, the measured σ *BR is compatible with the SM prediction: $\sigma(pp \to t\gamma j)\mathcal{B}(t \to \mu\nu b) = 115 \pm 17(stat) \pm 30(syst)\text{fb}$





Top Differential Cross sections

- parton-level results are compared to calculations with beyond NLO precision in QCD.
- Significant disagreement is observed between data and predictions for numerous observables.

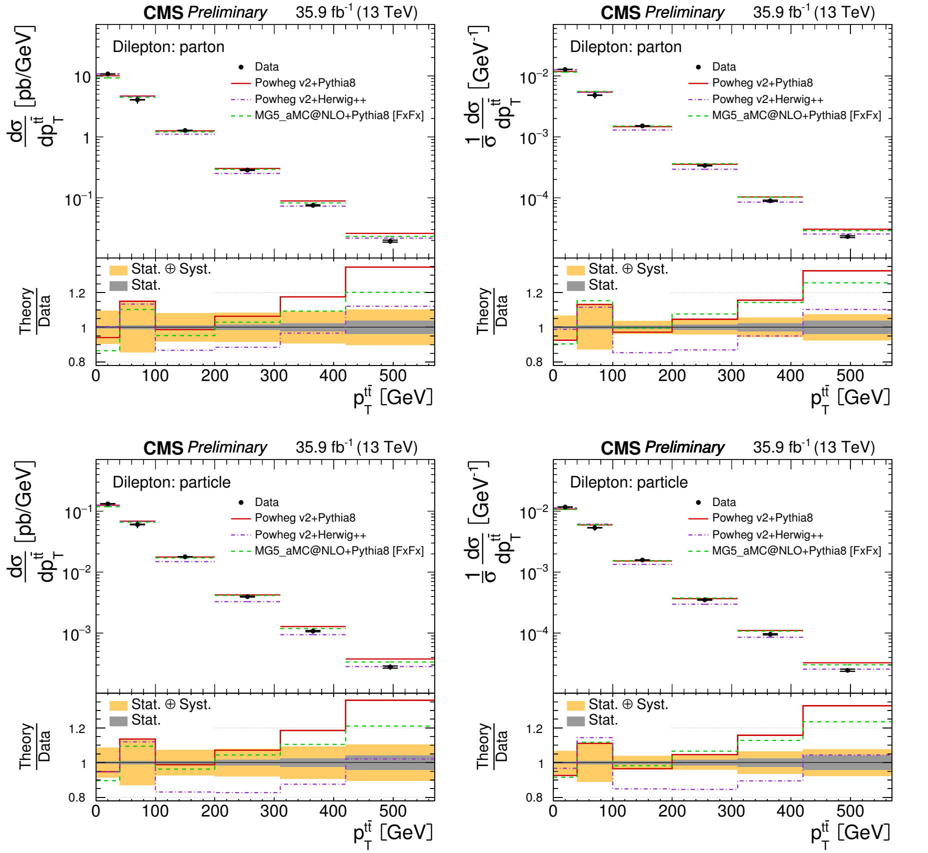
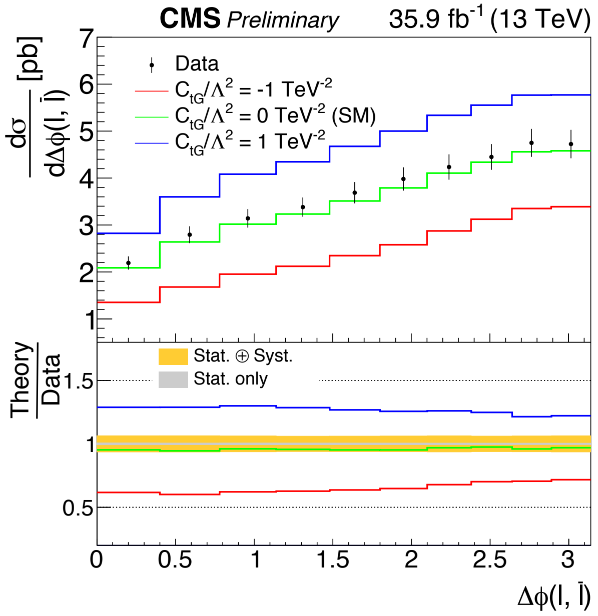


Figure 20: The differential $t\bar{t}$ production cross sections as a function of $p_T^{t\bar{t}}$ are shown. The left and right columns correspond to absolute and normalised measurements, respectively. The upper row corresponds to measurements at parton level in the full phase space and the lower row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



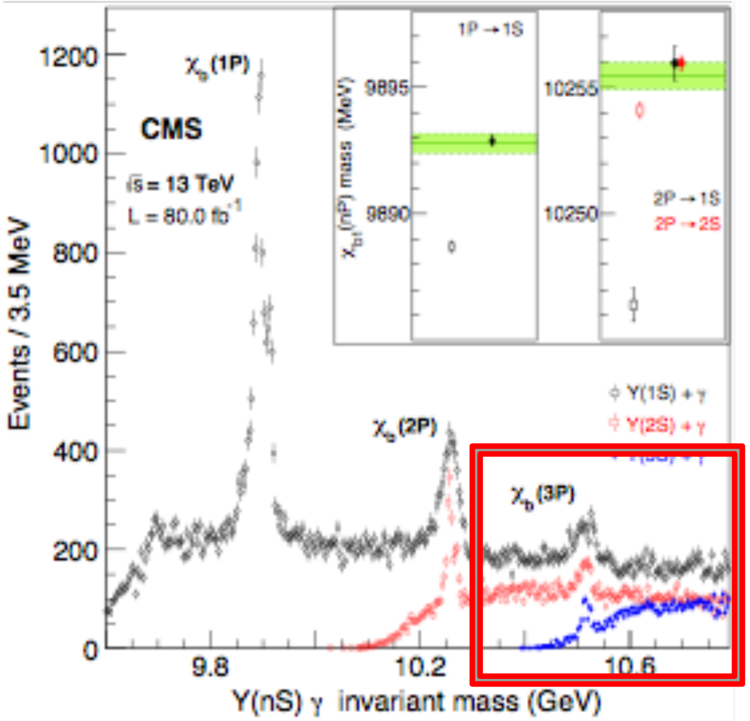
$$\frac{d\sigma}{d\Delta\phi(l,\bar{l})}$$

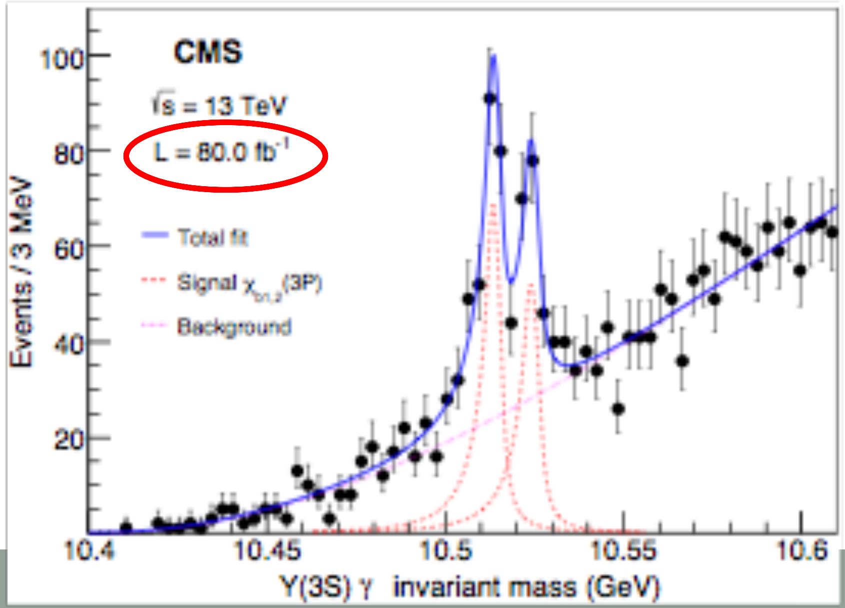
$-0.06 < C_{tG}/\Lambda^2 < 0.41$	**CMS-PAS-TOP-17-014**
$-0.89 < C_{tG}/\Lambda^2 < 0.43$	CMS 8 TeV diff. x-sec
$-0.42 < C_{tG}/\Lambda^2 < 0.30$	CMS 8 TeV incl. x-sec
$-0.32 < C_{tG}/\Lambda^2 < 0.73$	Tevatron incl. x-sec

BPH-17-008, arXiv:1805.11192, PRL 121 (2018) 09200

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

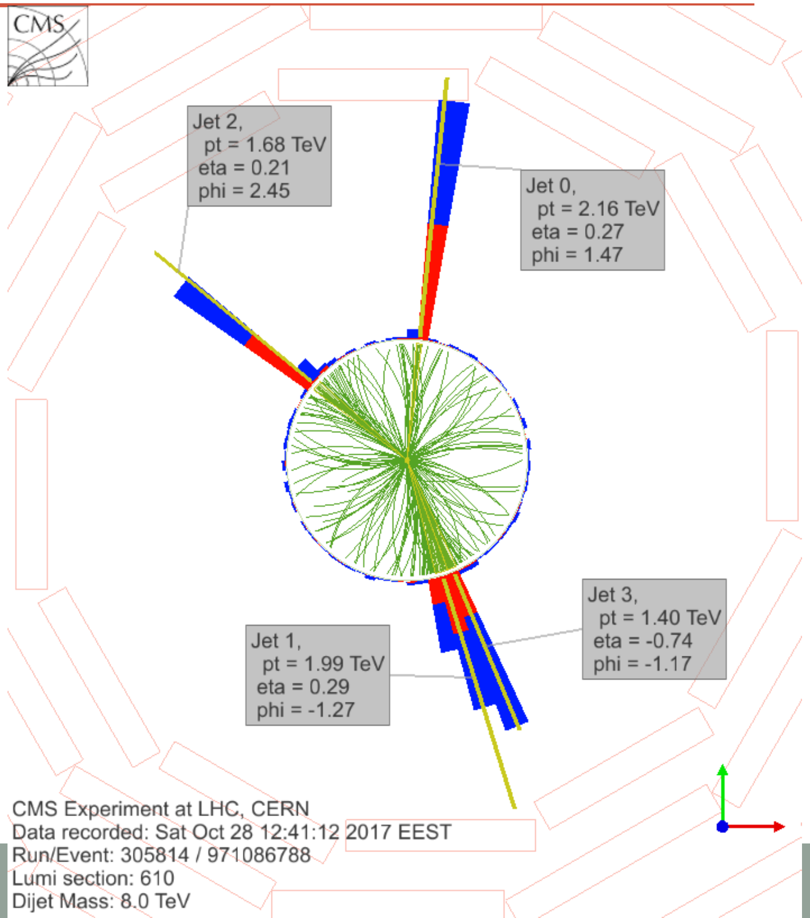
- ATLAS, D0, LHCb observe peak at ~10.5 GeV
- Consistent with $\chi_b(3P)$ in $\Upsilon(nS) + \gamma$
  - Three such states are expected with J=0,1,and 2, with the latter two expected to have large branching fractions to photons.
- CMS revisited this with the full 2015-2012 dataset of 80 fb^{-1}
- Reconstruct mass structure in $\chi_b(3P) \rightarrow (\Upsilon(3S) \rightarrow \mu\mu) + \gamma$, where γ converts in tracker ($\gamma \rightarrow e+e-$).
  - $\Delta M(\chi_{b1}, \chi_{b2})$ expected to be 8-18 MeV
  - CMS mass resolution = 2.18 ± 0.32 MeV
    - Low statistics compensated by excellent resolution
- For the first time the two states $\chi_{b1}(3p)$,& $\chi_{b2}(3p)$, corresponding to J=1,2, have been resolved
- ΔM = 10.60 ± 0.64 (stat) ± 0.17 (syst) MeV
- $M(\chi_{b1}(3P))$ = 10513.42± 0.41 ± 0.18 MeV
- $M(\chi_{b2}(3P))$ = 10524.02 ± 0.57 (stat) ± 0.18 (syst) MeV
  - consistent with predictions from non-perturbative QCD in the range 2-18 MeV, than coupling to the continuum





BEYOND THE SM PHYSICS

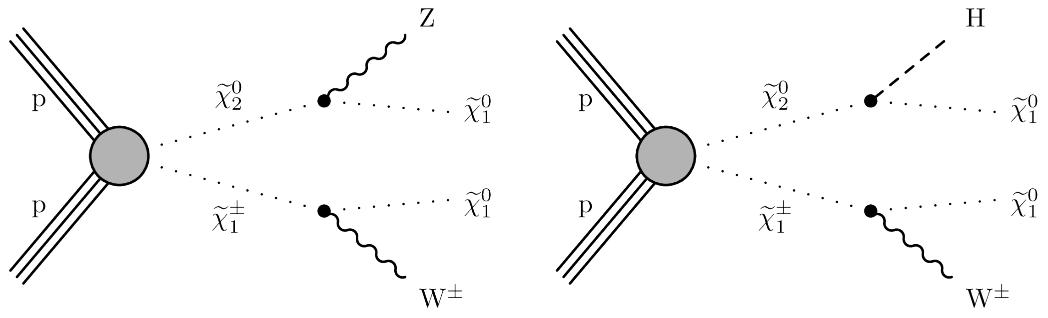
Event with highest dijet mass: 8 TeV

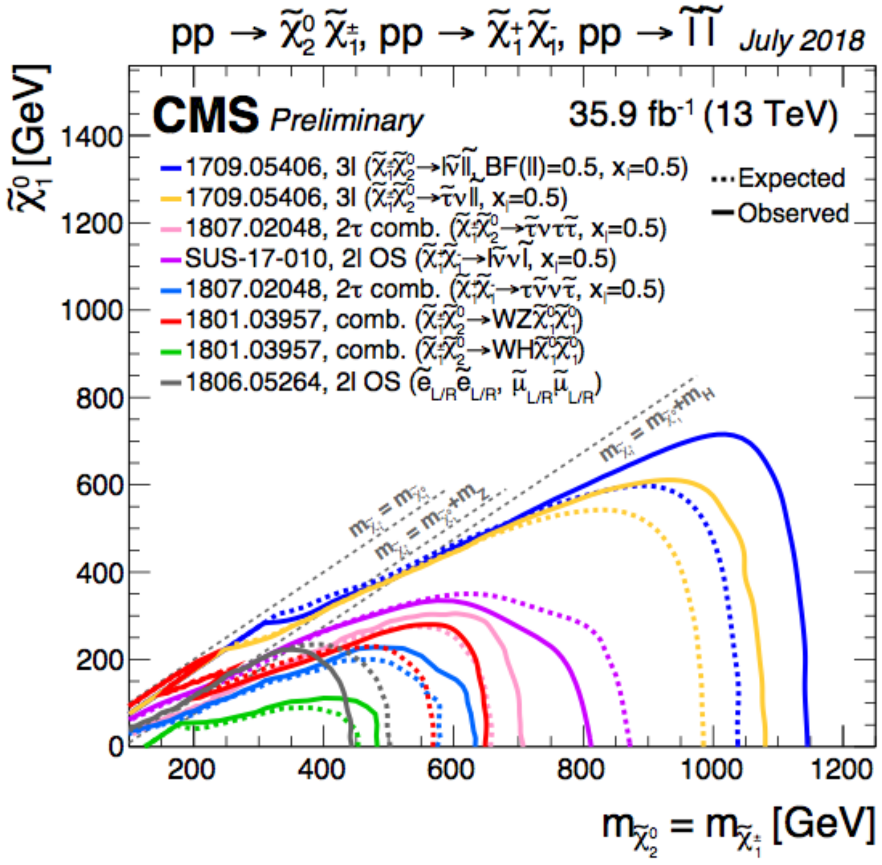


Supersymmetry

JHEP 03 (2018) 160

- Among several searches, also Higgs boson now used to probe electroweak production of supersymmetry
  - In just 6 years from discovery to Higgs tagging

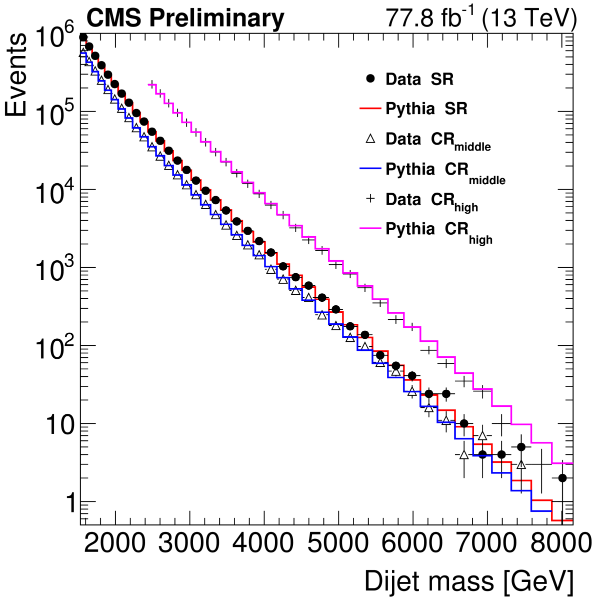


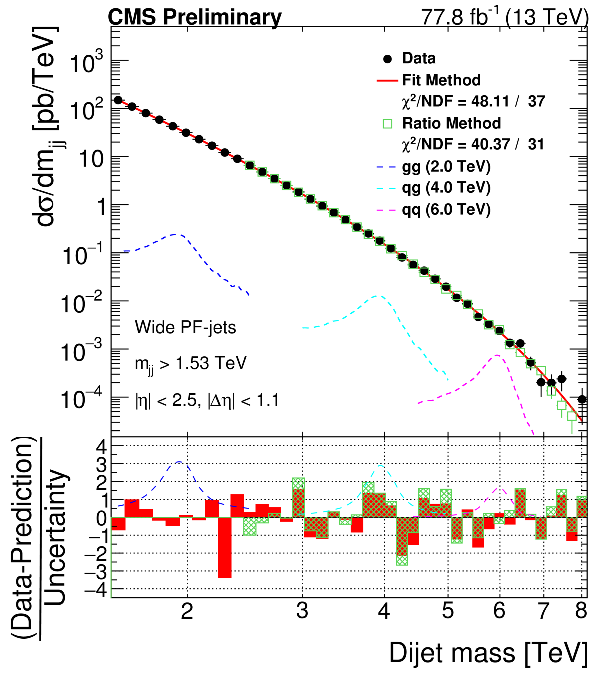


High-mass resonances

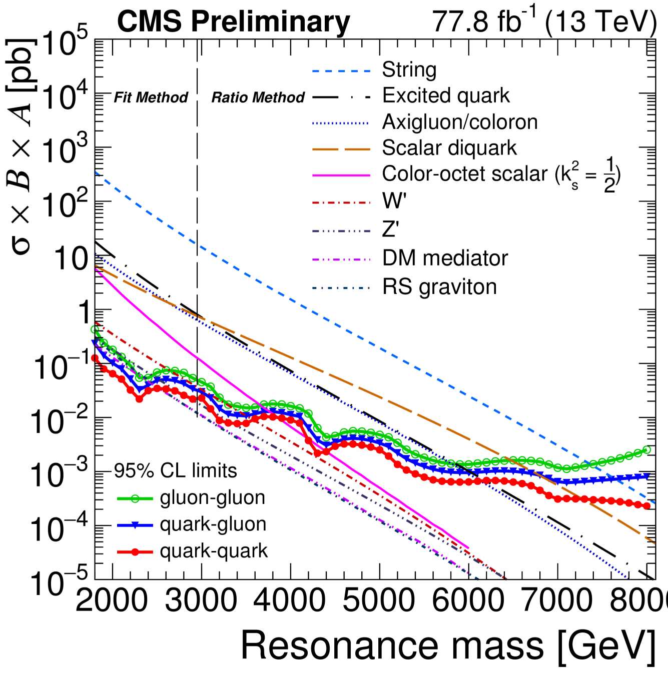
PAS-EXO-17-026

- Di-jet resonances with 2016+2017 data
- Improved analysis methods: complement parametric background estimation with prediction from high $\Delta\eta$ sideband
  - reduces systematics
  - used at higher resonance masses
- Interpretations in a variety of models
- Extends limits obtained with 2016 data





Dijet mass spectrum with background predictions

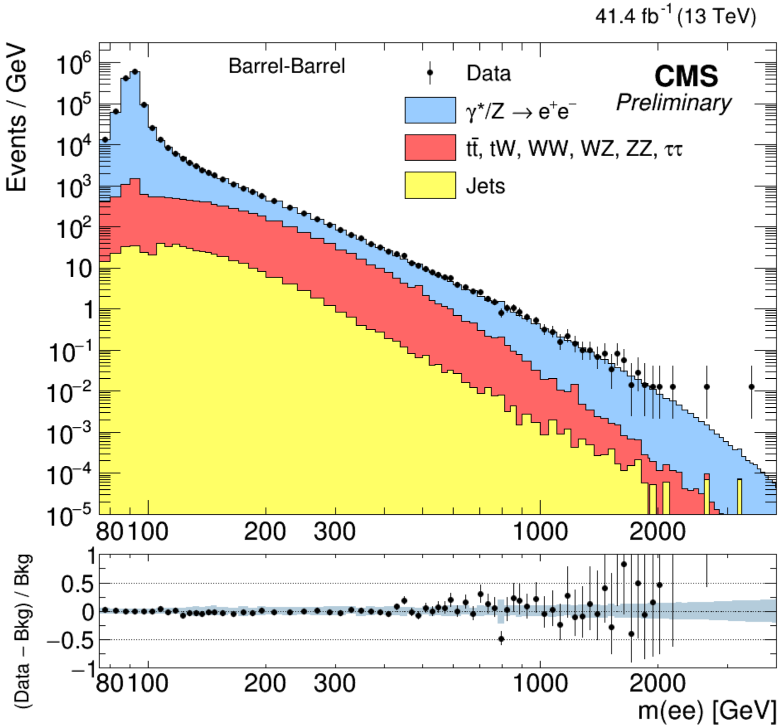


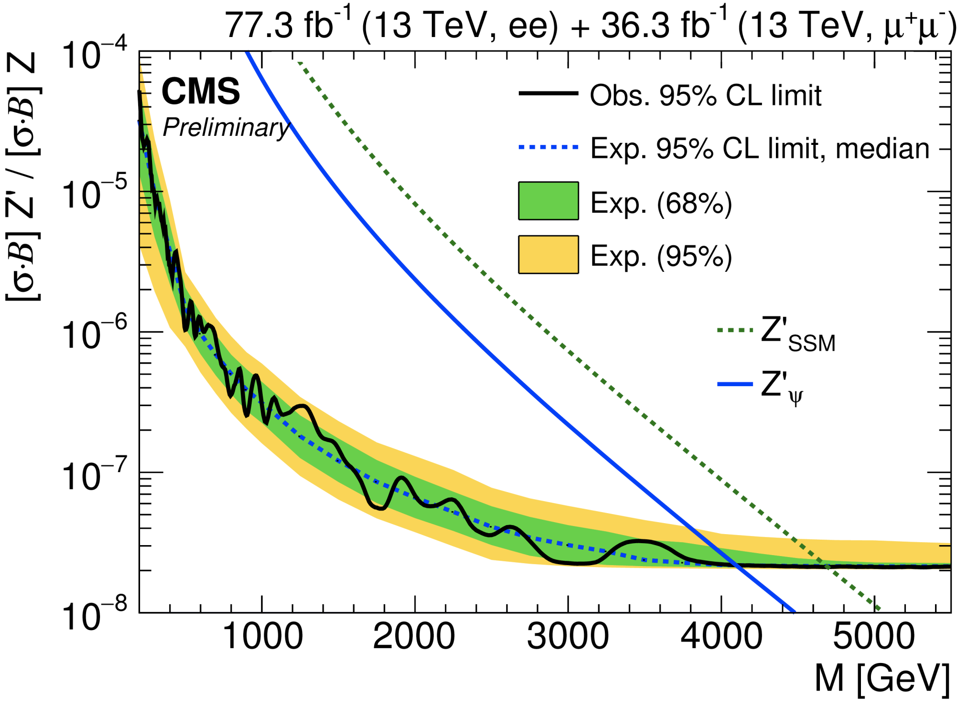
Model-independent upper limits compared to predicted cross sections

EXO-18-006

High Mass Resonances in Dielectron Final State

- Search for a narrow resonance in invariant mass of dilepton pairs
- Limits for high mass searches extending beyond 4 TeV





Mass lower limit, with 2016 & 2017 datasets combined :

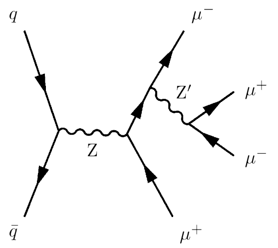
- Z'_{SSM} (predicted by sequential SM) : 4.7 TeV
- Z'_{ψ} (inspired by GUT based theories) : 4.1 TeV

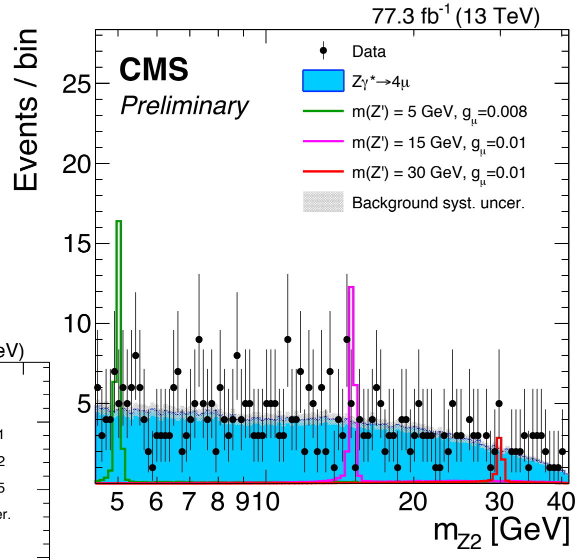
First 2017 analysis presented

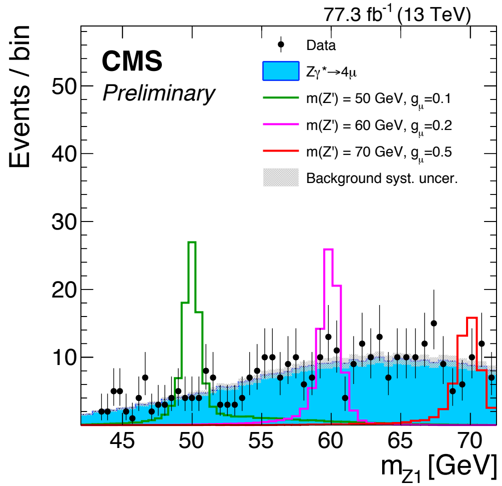
EXO-18-008
arXiv:1808.03684
submitted PLB

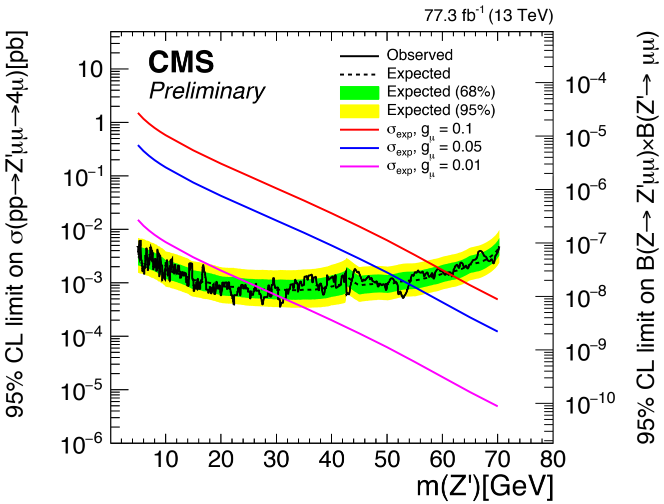
Light Z' Boson

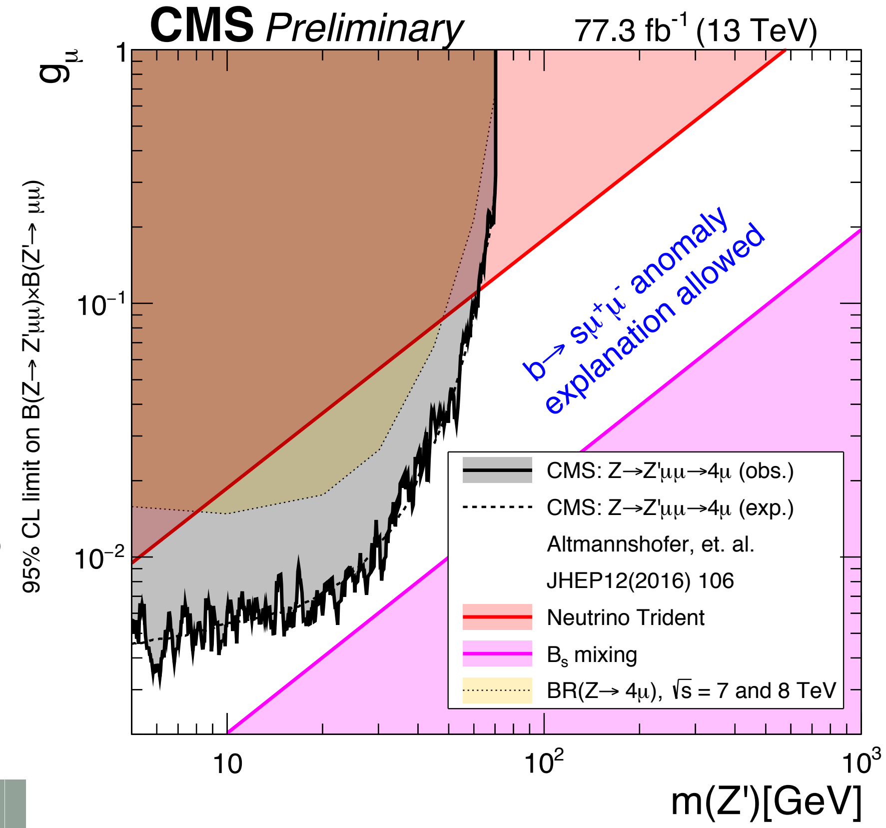
- Light Z' Boson (within Lμ-Lτ Gauge Symmetry) couples (only) to second- and third-generation leptons (μ, ν_μ, τ and ν_τ), it can be produced from one of the muons in Z-decays, and using its decay Z'→ $\mu^+\mu^-$, might appear as a dimuon mass bump in 4 muon final states.
  - Light Z' associated with Lμ-Lτ gauge symmetry could explain R(K*) [1] and muon g-2 [2] anomalies.
- Use the large LHC dataset to probe smaller couplings.





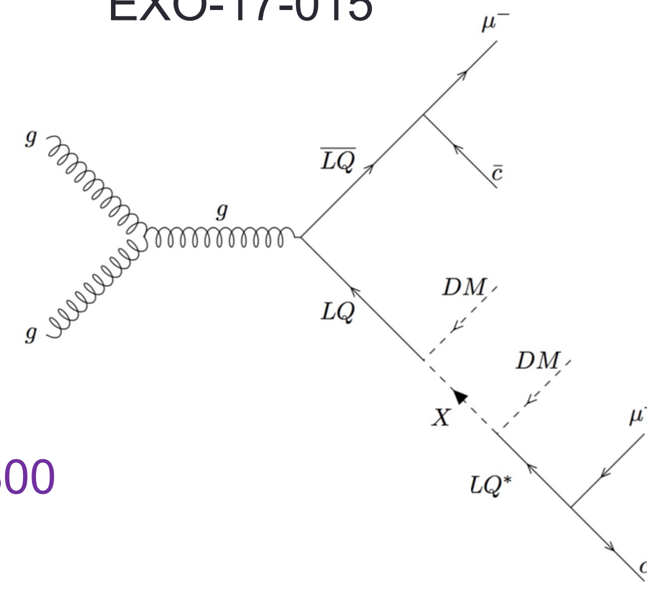




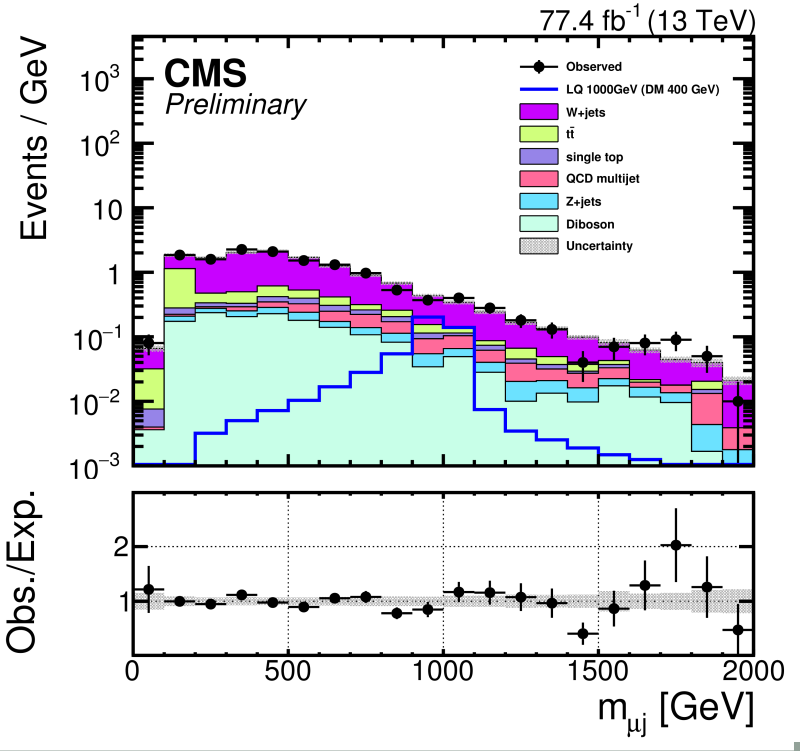


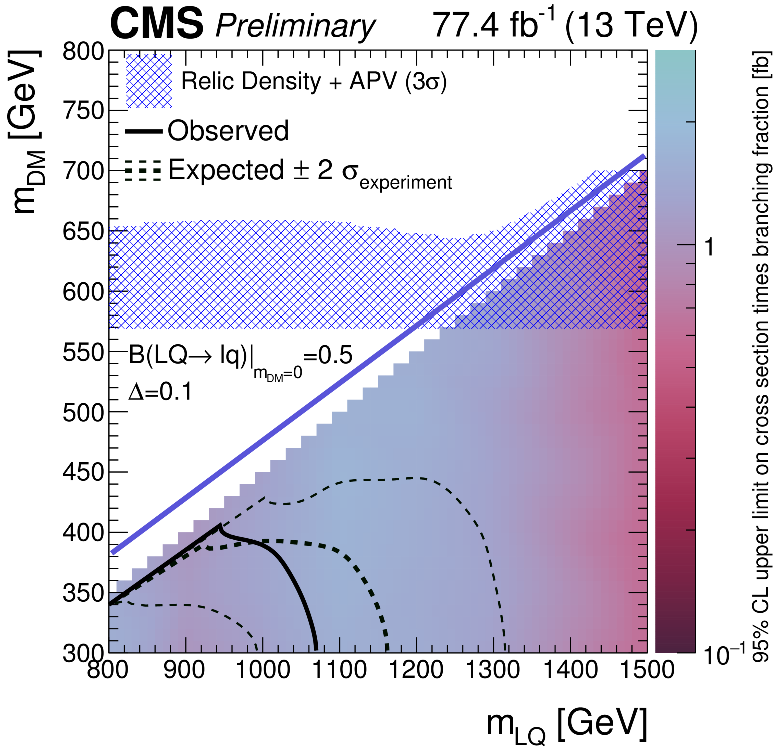
[1] Altmannshofer, Gori, Profumo, Queiroz; arXiv:1609.04026
[2] K. Harigaya et al.; arXiv:1311.0870

Search for Leptoquark+Dark Matter



- CMS has extensive program of searches for leptoquarks (LQ).
- Dark matter (DM) produced with a co-annihilation partner (here a Maiorana fermion), mediator: LQ coupling to 2nd generation only
- Search in events with at least one muon and $E_T$miss, look for a LQ mass peak in $m_{\mu j}$
- Leptoquarks with masses up to 1160 GeV are excluded for dark matter mass m_{DM}≈ 300 GeV, and up to 1000 GeV for m_{DM}≈ 425 GeV.

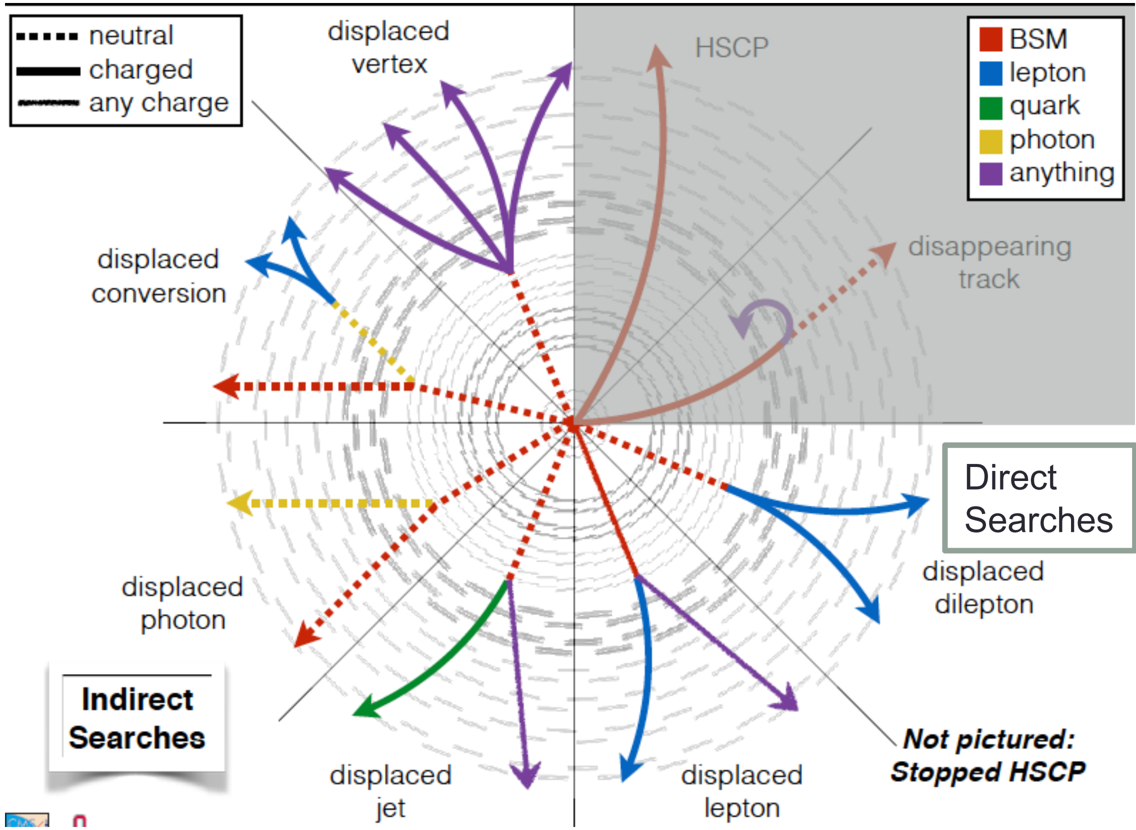




[1] Coannihilation codex : Baker et al., arXiv:1510.03434

Long-Lived Particles

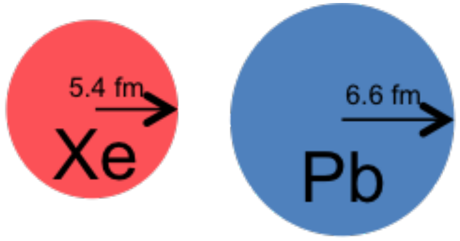
- Many BSM models have long-lived particles/ displaced vertices. Some of these can be observed by special searches, usually with special triggers.
- Search for stopped long-lived particles using full 2015 and 2016 data JHEP 05 (2018) 127
  - Signature is a high energy jet in the calorimeter out of time 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



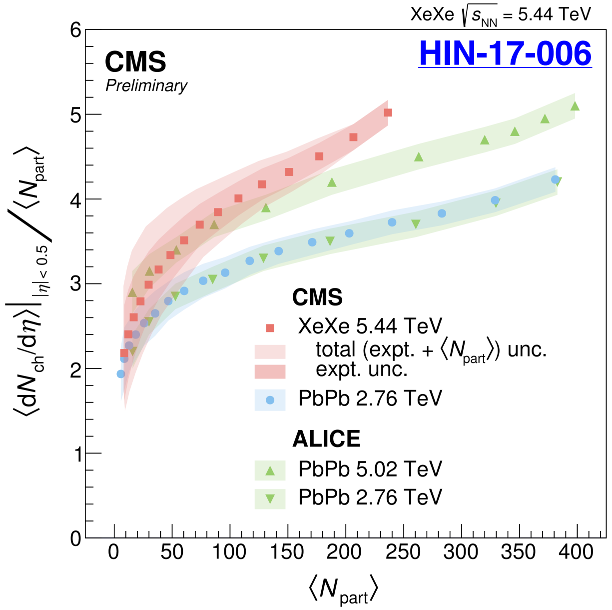
EXO/SUSY searches shifting to different topologies, lower mass, longer-lived particles and will continue to look in new places. Triggering on unusual states will be a challenge.

XeXe Collisions @ $\sqrt{s_{NN}}$ = 5.44 TeV

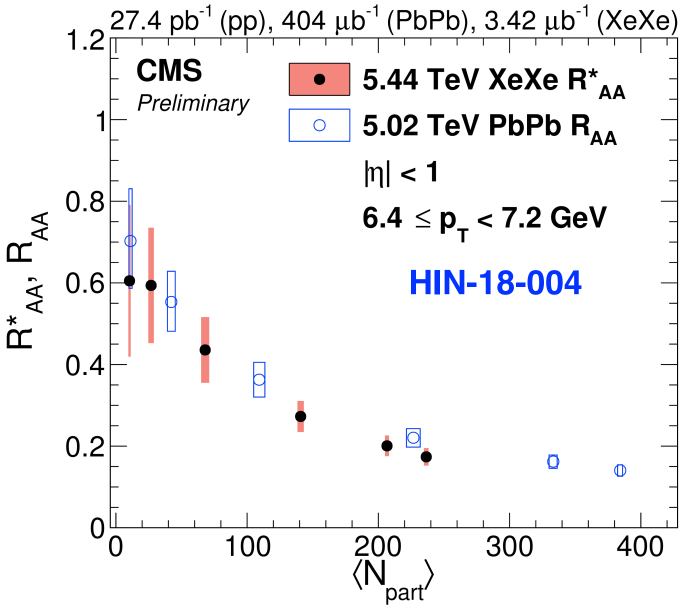
- Xenon-129 ions are smaller than Lead-208 ions
  - allows to study system size dependence of QGP effects.
  - CuCu & AuAu have been studied at RHIC experiments.
- XeXe collisions look similar to PbPb - collision geometry plays more important role.
- Observed differences are likely due to Xe deformation & initial state fluctuations



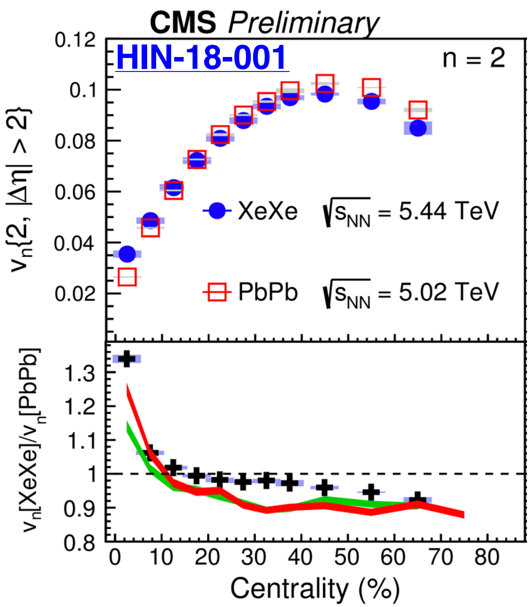
Charge Multiplicity



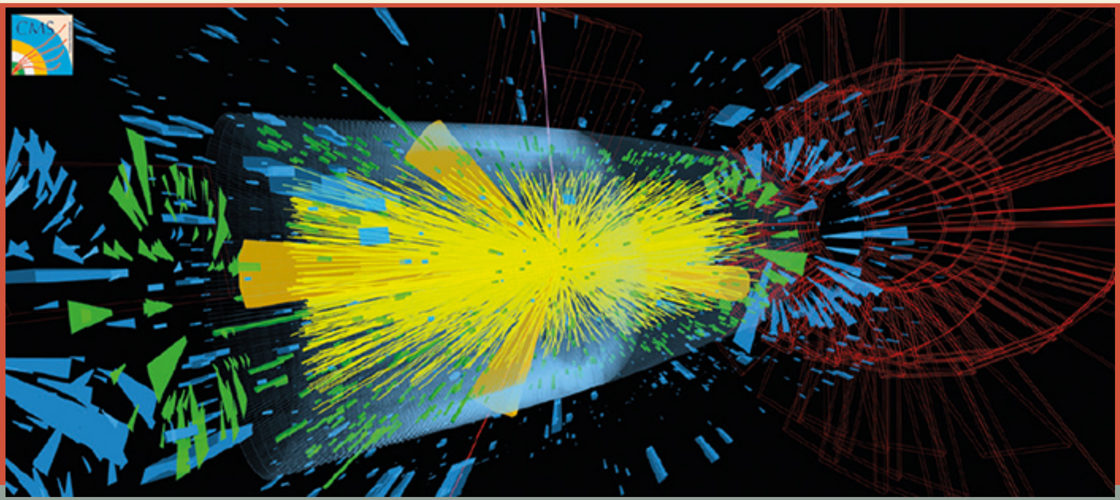
Nuclear modification factor

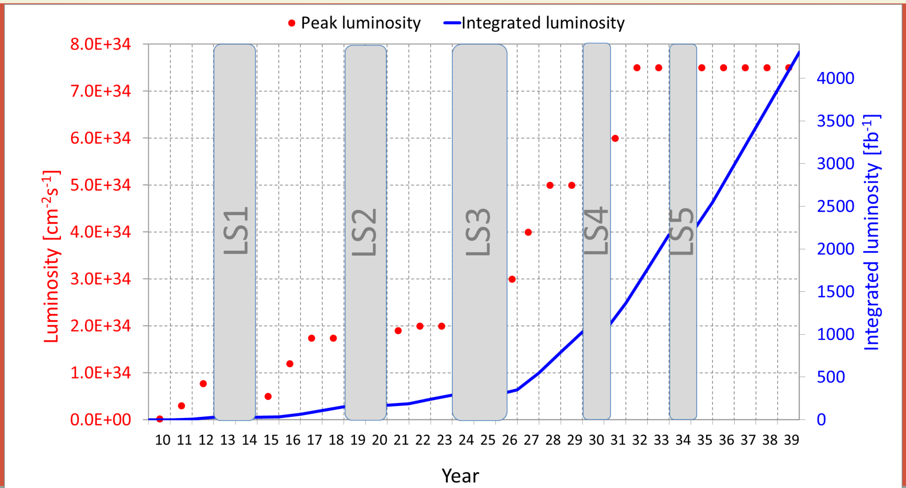


Elliptic Flow



PHASE-2 ACTIVITIES



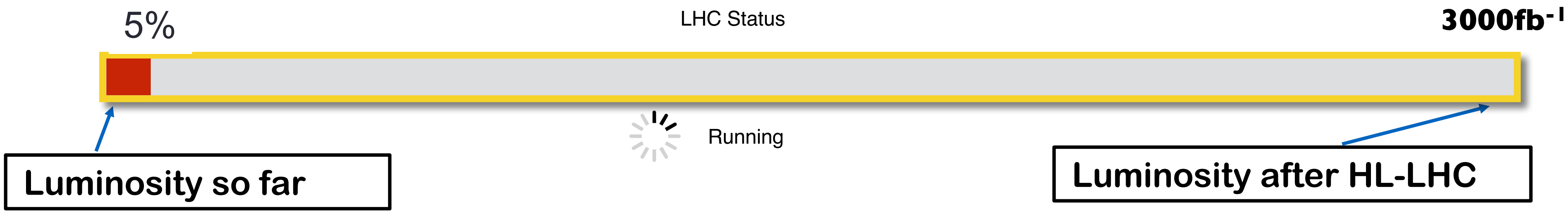


The LHC Luminosity Plan

x5 Run1

x2 Run2

x10 Run3

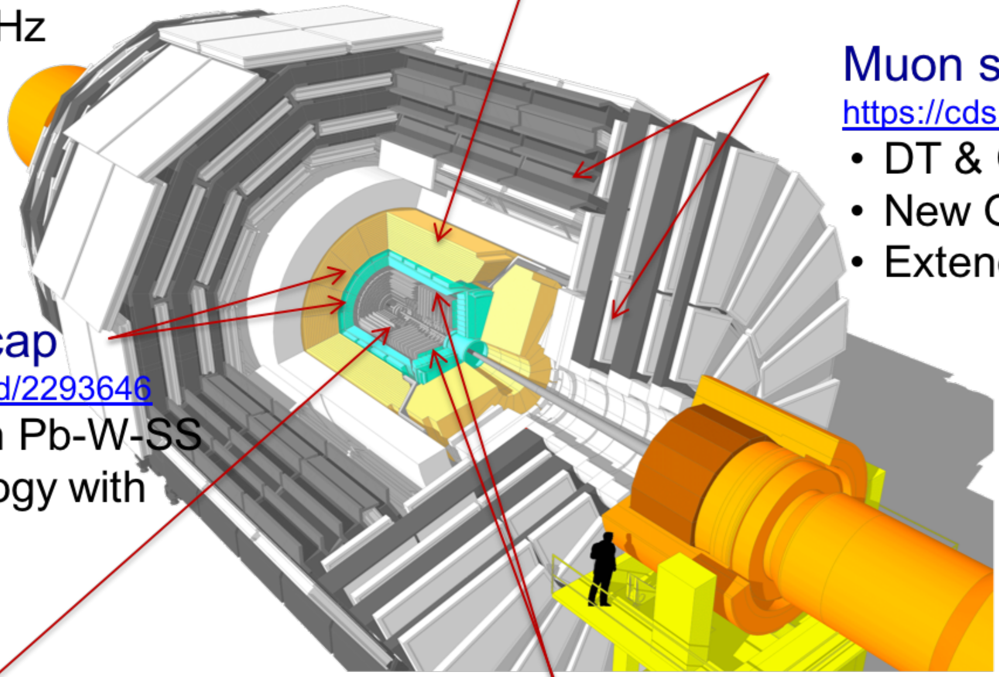


CMS Phase-2 upgrade

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

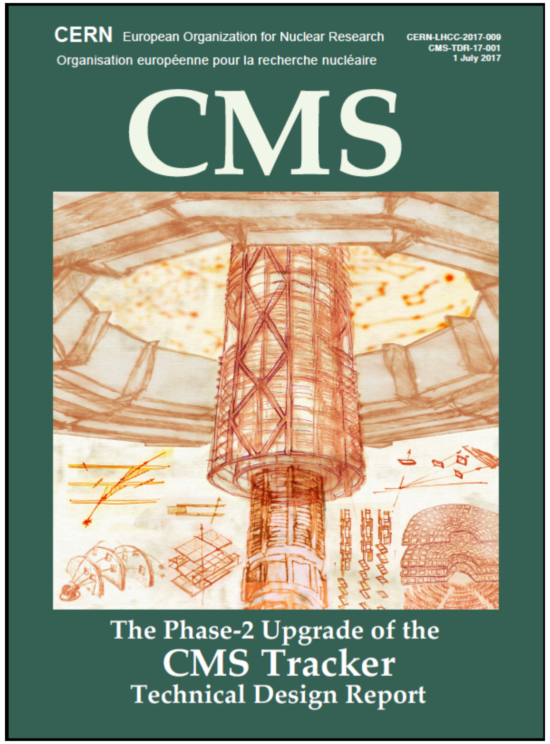
Bold Aspects of CMS Upgrade for HL-LHC

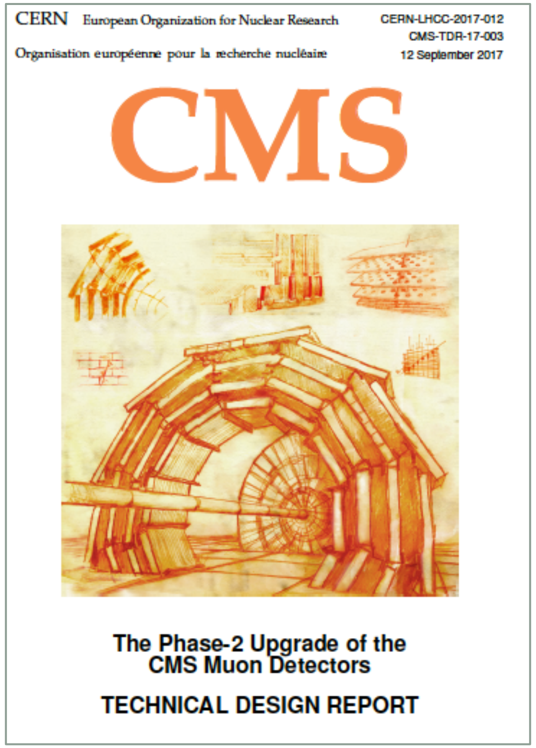
- Tracking information in “L1 track-trigger”
  - Tracker is designed to enable finding of all tracks with PT>~2 GeV in under 4 ms.
- Tracker is **AGAIN ALL SILICON** but now with much higher granularity, and extends to $|\eta| = 4$
  - >2 billion pixels and strips
- High Granularity Endcap Calorimeters
  - Sampling of EM-showers every $\sim 1\lambda_{rad}$ (28 samples) with small silicon pixels and then every $\sim 0.35\lambda_{abs}$ (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 4^{th} dimension to CMS object reconstruction to combat pileup (~200K sensors in barrel section)

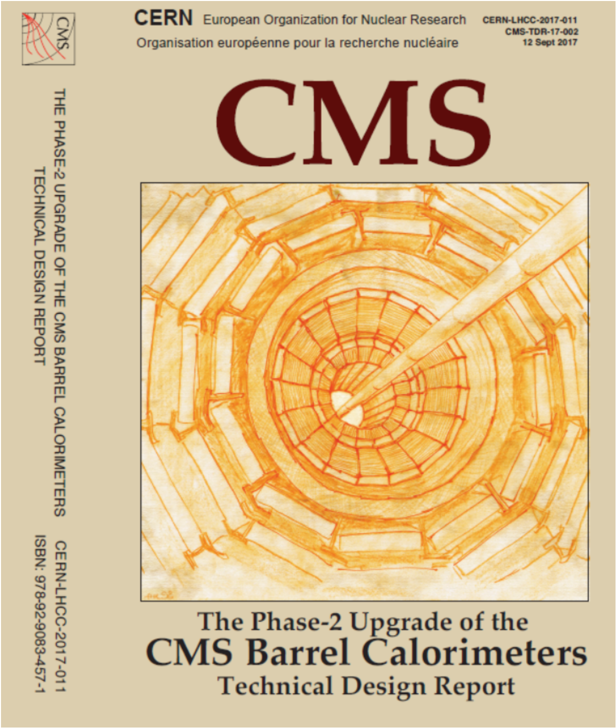
Goal: Be as efficient, and with low background/fake-rate, at 200-250 pileup as we are today, and with extended acceptance

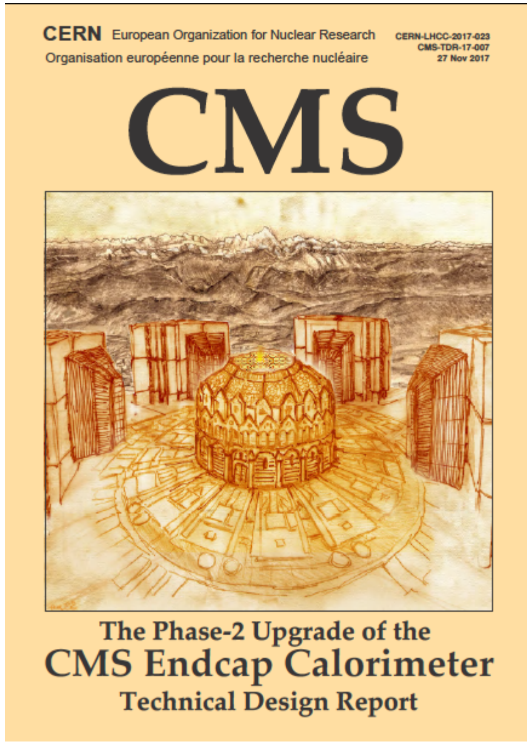
Technical Design Reports

- During the 2017 we published the TDRs, including physics performance









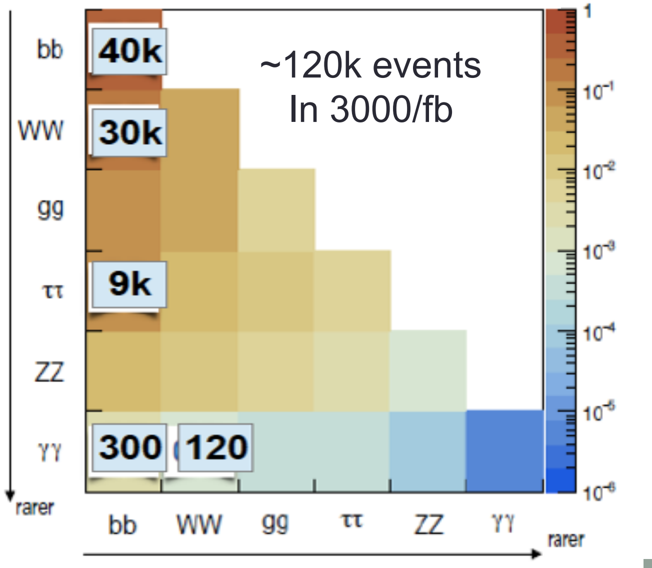
Each TDR is a book with hundreds of pages !!!

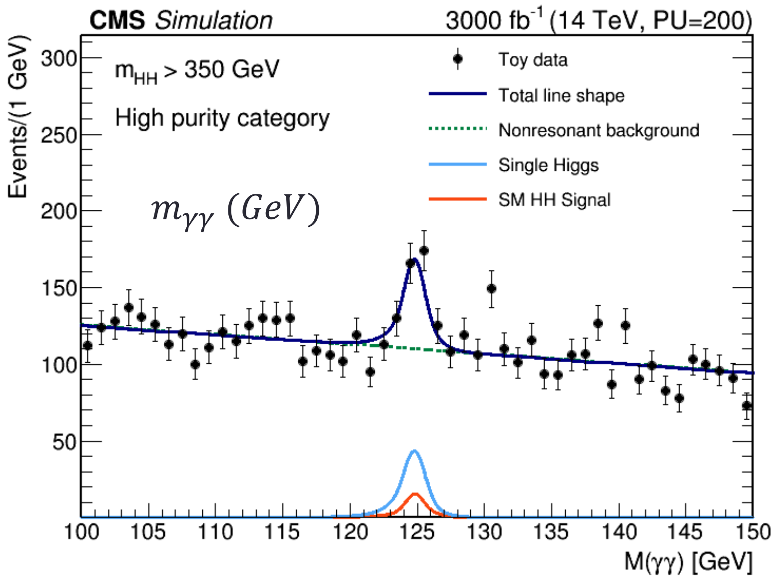
HH->bbγγ

- HH physics is a benchmark channel for HL-LHC program
- Projections(*) for HH → γγbb have been updated with full simulation studies
- Updates used in the extrapolation:
  - Di-photon mass resolution (include ECAL ageing after 1000 fb^{-1} of collected data), convoluted with expected gain from regression (as in Run2) and at 200 PU scenario
  - Improvement in b-tagging gives a signal efficiency increase of 15%
- **A significance of 1.9 standard deviations is expected (3000 fb^{-1})**
  - Further improvements are anticipated account for improvements that can be gained from precision timing information in ECAL and the tracker

(*)CMS-PAS-FTR-16-002, 2017

Expected number of events



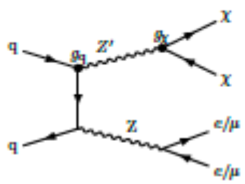


The possibility of "evidence" of di-Higgs production can be reached at the HL-LHC by combining all channels in CMS & ATLAS.

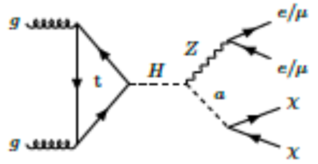
Mono-Z Dark Matter

(FTR-18-007)

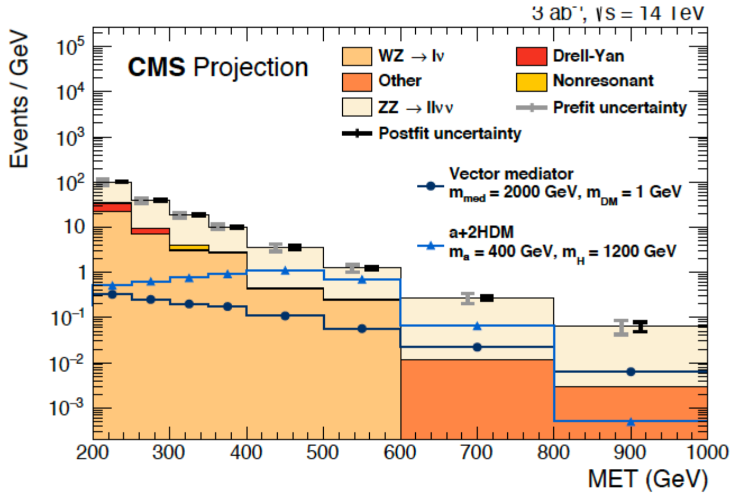
Spin-1 vector mediator

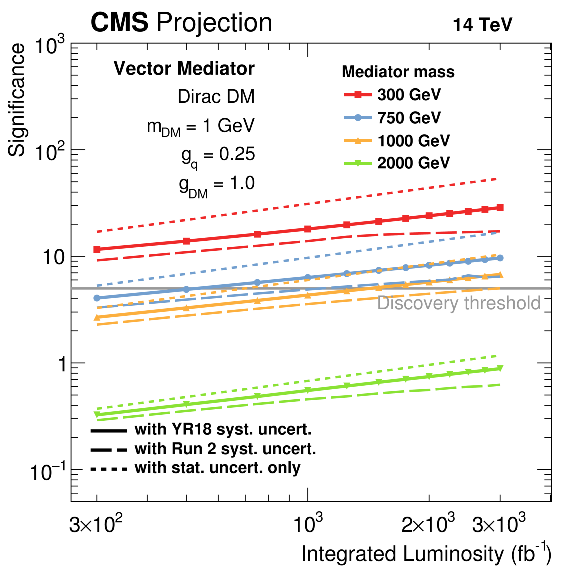


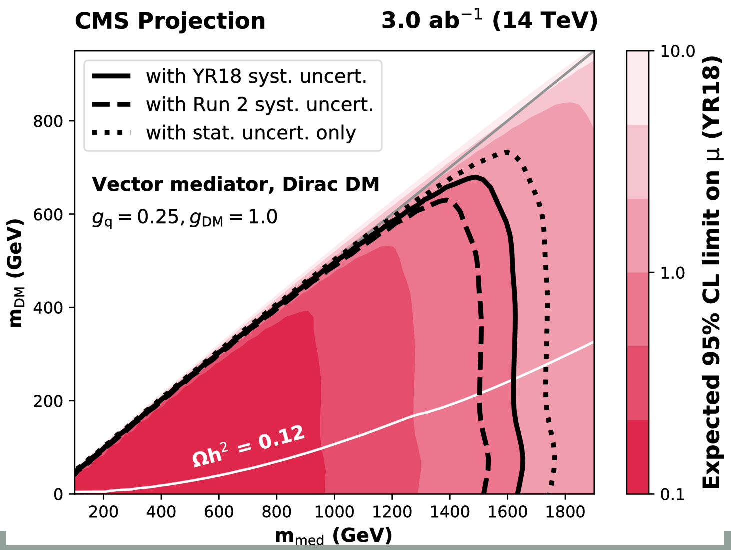
pseudoscalar + 2HDM

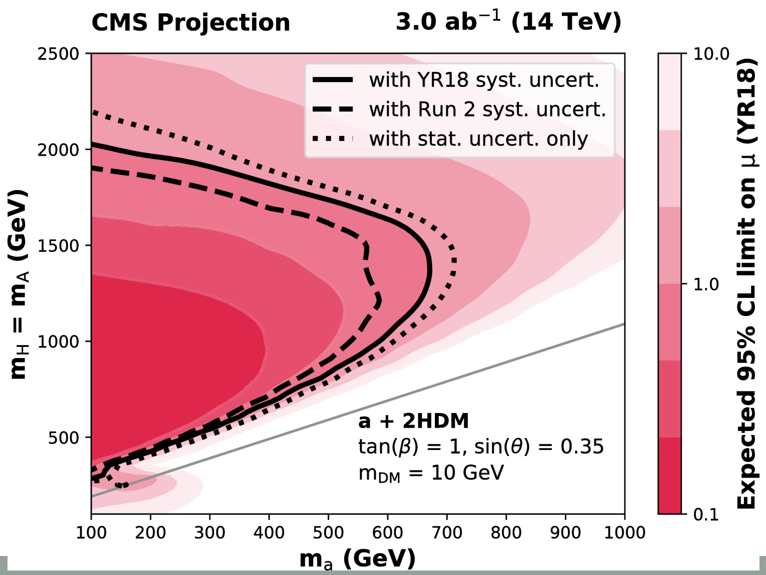


- Extrapolate from Run 2 EXO-16-052
  - Apply event-by-event
    - PDF weights to reweight from √s=13 TeV to 14 TeV
    - Missing E_T resolution smearing by factor 2 to model high-PU conditions
- Probe vector-mediated DM production up to mediator masses ~1.6 TeV.
- In simplified model w/ second Higgs doublet & pseudoscalar mediator:
  - heavy scalars will be probed up to masses of 2 TeV
  - light pseudoscalar mediator accessible up to ~660 GeV.









Summary

- Overall CMS data taking went very well in 2018
  - Achieved ~94% data collection efficiency

- CMS has published >800 papers
  - Publications of analyses using 2017 data is proceeding well.

- Technical Design Reports for Phase-2 upgrade
  - Now focus on “Yellow Report” and HL/HE-LHC physics to be submitted to the European Strategy committee during mid December (2018)

HIG-17-031

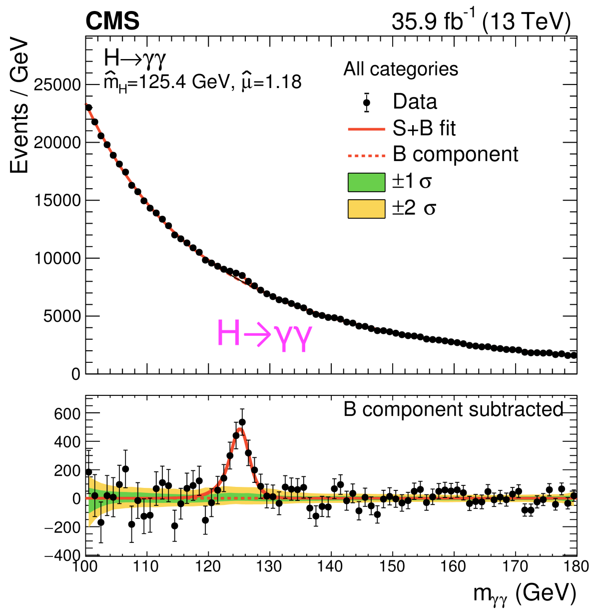
Combined Higgs Coupling @ 13 TeV

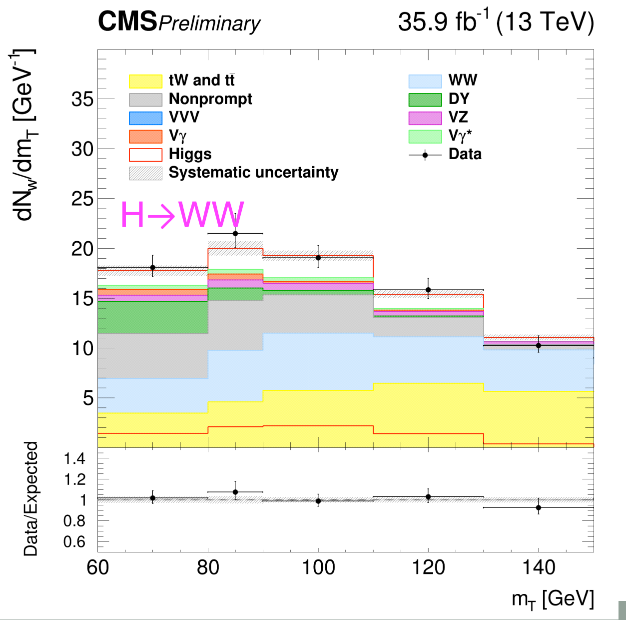
- Analyzed all main production and decay modes in 2016 dataset at √s = 13 TeV (35.9 fb^{-1})

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

- Total of 250 individual categories (counting signal & control regions) and ~5400 nuisance parameters in the combined fit :
  - used to extract the **signal strength modifier μ** for production & decay channels.

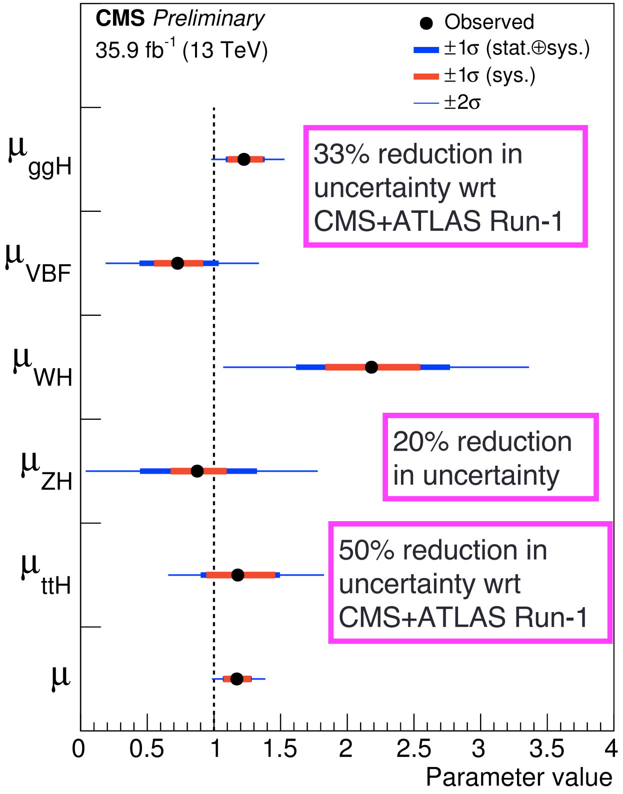
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{BR^f}{(BR^f)_{SM}}$$



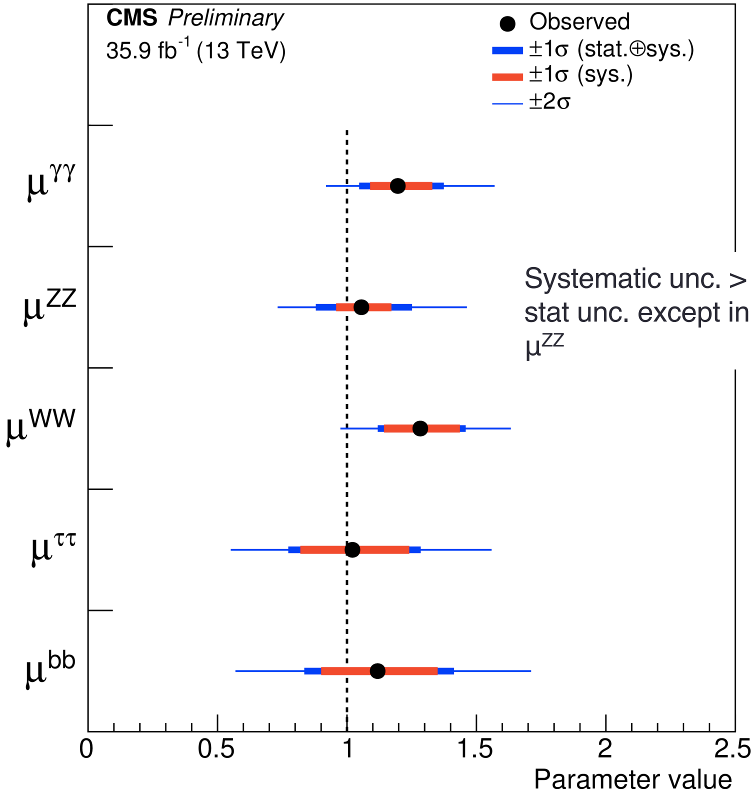


Combined Coupling Measurement @ 13 TeV

Per production mode



Per decay mode

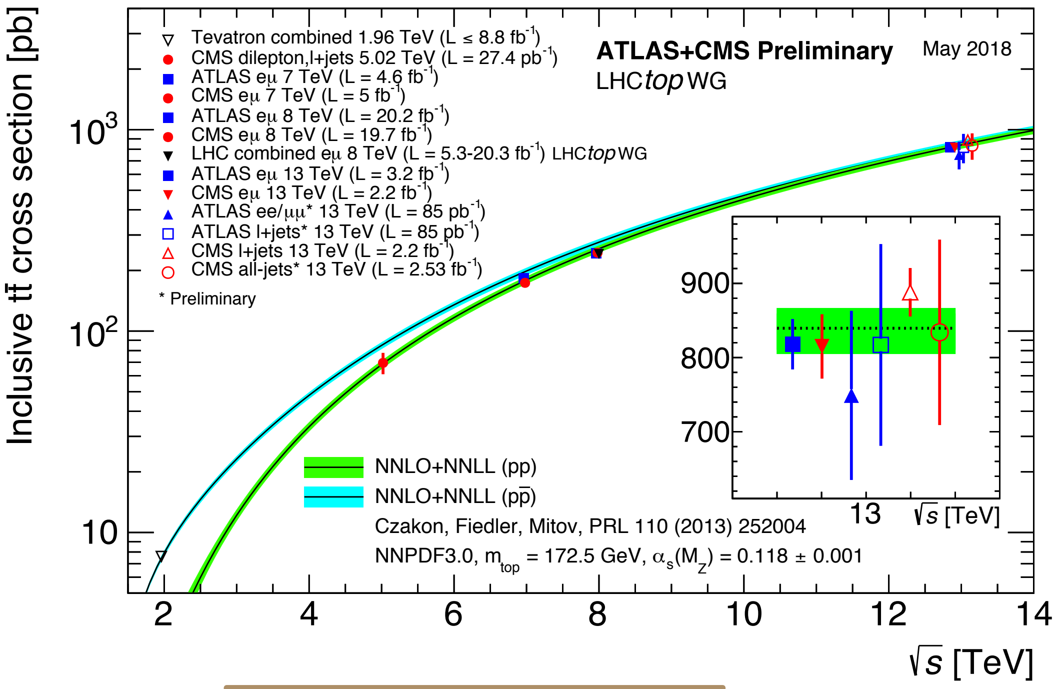


CMS 13 TeV $\mu = 1.17^{+0.10}_{-0.10} \quad = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\ ^{+0.06}_{-0.05}\,(\text{sig. th.})\ ^{+0.06}_{-0.06}\,(\text{other sys.})$

15% improvement in relative precision as compared to Run-1 CMS+ATLAS
Despite progress, there is still room for new physics

Top Pair Cross Sections

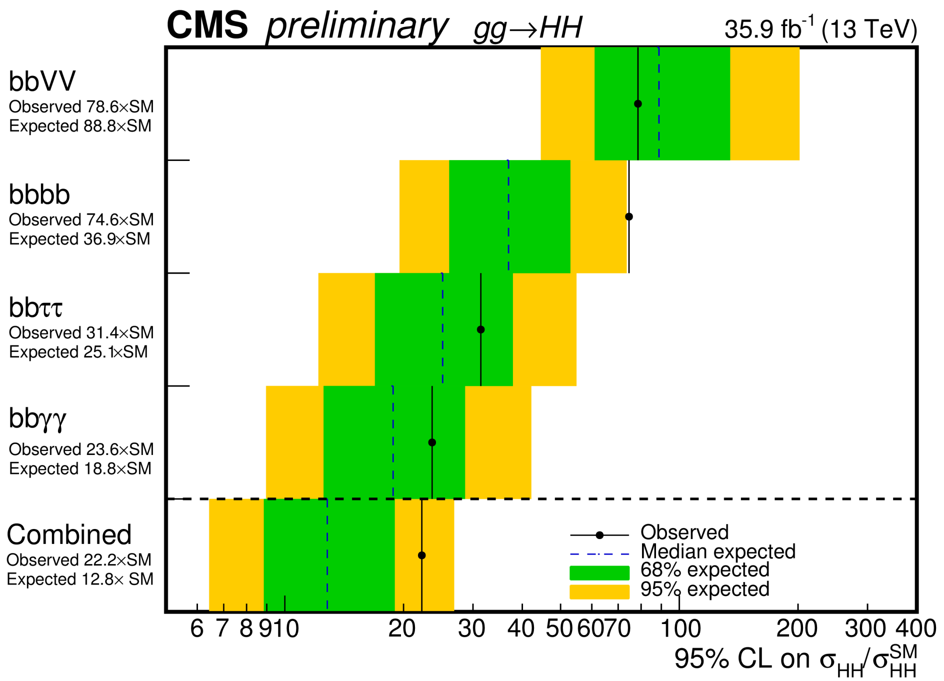
- Top pair rate is > 10 Hz, enabling us to address much more precise questions
  - Single, double, and triple differential cross sections
  - Rare (FCNC) decays
  - CP violation (a beginning)
  - Width and more complex methods for measuring the mass
- --
- Top pair production at 13 TeV CM energy is mainly (80%) produced by gluons, providing important information on the gluon distribution at relatively high x_F, up to ~0.25



CMS: 835 ± 33 pb
Theory: 816 ± 42 pb

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}

Higgs boson pair production



Observed (expected) 95% confidence level upper limit corresponds to 22.2 (12.8) times the prediction for the SM cross section.

95% confidence level exclusion limits on the SM non-resonant Higgs boson pair production cross section.

New Ideas in Dark Matter – Search for Emergent Jets

- 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), **Q_d**, are charged under a new force in the dark sector that has confining properties similar to QCD but are not charged under the forces of the SM
- The mediator X_d 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 ($E_T$miss).
- The main background to this signature is SM four-jet production, especially jets with b-quarks

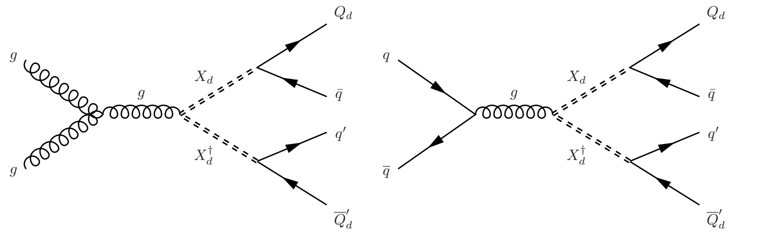
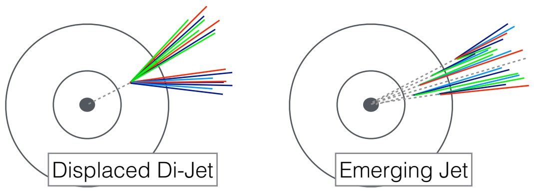
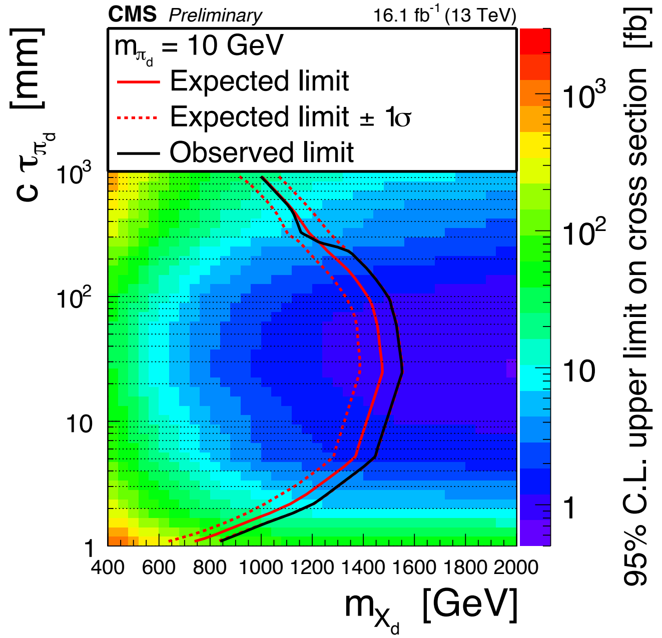


Figure 1: Feynman diagrams for pair production of mediator particles, with mediator decay to a quark and a dark quark in the BSSW model via (left) gluon fusion and (right) quark-antiquark annihilation.

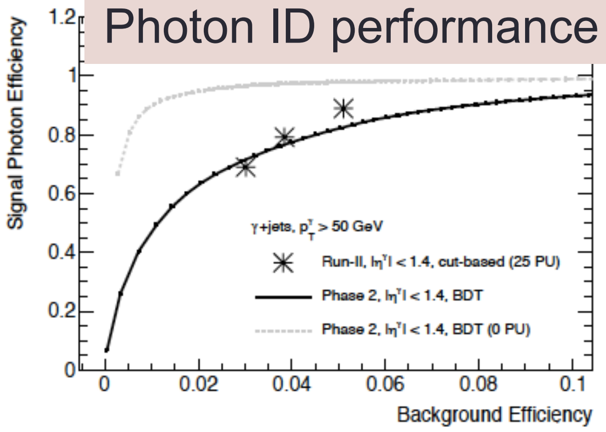




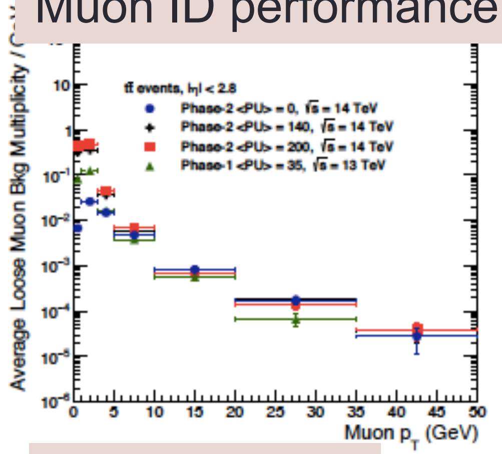
Phase-2 Upgrades

- **Detector performance with full simulation used to estimate the physics reach highlighting the components of the upgrade.** We need to at least maintain current performance as observed in Run2 for all physics objects.

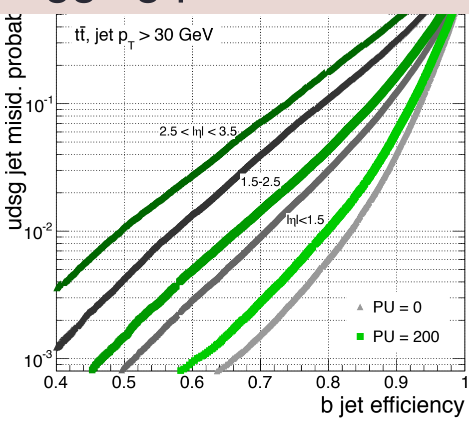
Photon ID performance

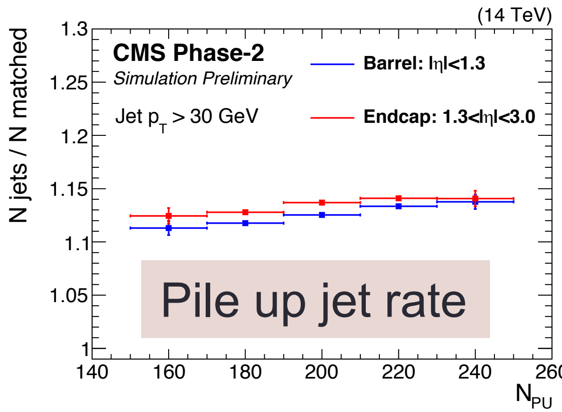


Muon ID performance



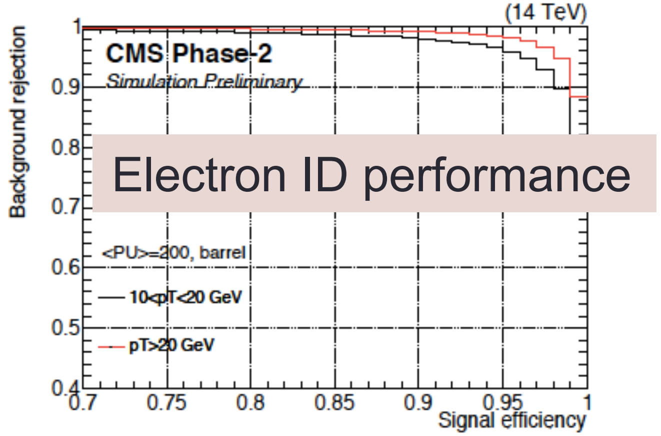
b-tagging performance



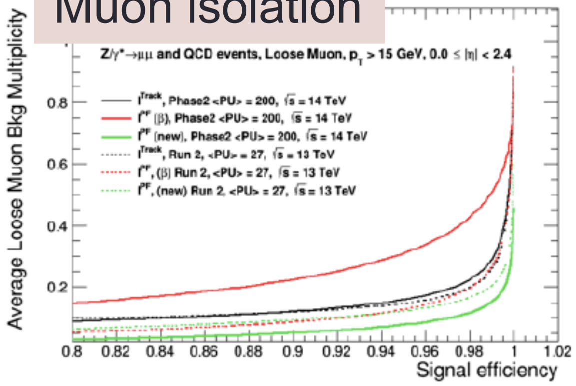


Pile up jet rate

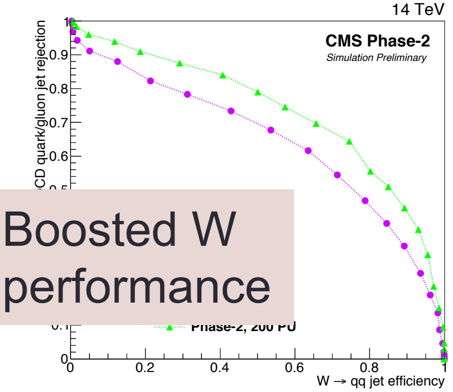
Electron ID performance



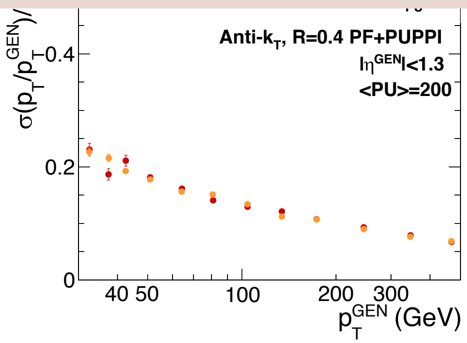
Muon isolation



Boosted W performance



Jet Energy Resolution for PUPPI jet



Dark Photons Decaying to Displaced Muons

- LLP masses of several GeV
- Decay length of LLP quasi-prompt ($c\tau$ = 10 mm) to long-lived ($c\tau$ = 10 m)
- Focusing on large $c\tau$ to probe new phase-space
  - Use the three-dimensional distance between the extrapolated displaced muon track and the primary vertex
- Producing Dark Photons at the LHC:
  - Gluon-gluon fusion produces SM Higgs (125 GeV)
  - SM Higgs can decay via H → $2n_1$ (if kinematically allowed)
  - Lightest visible neutralino can now decay as $n_1 \rightarrow n_D + \gamma_D$
- Able to probe phase-space which has not been explored yet