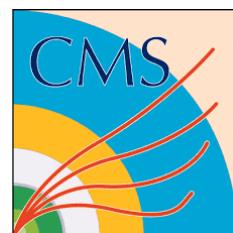


Highlights from the CMS Experiment

**LC2017, September 18-22, 2017
Mumbai University**

**PROLAY KUMAR MAL
NATIONAL INSTITUTE OF SCIENCE EDUCATION & RESEARCH
BHUBANESWAR, INDIA**

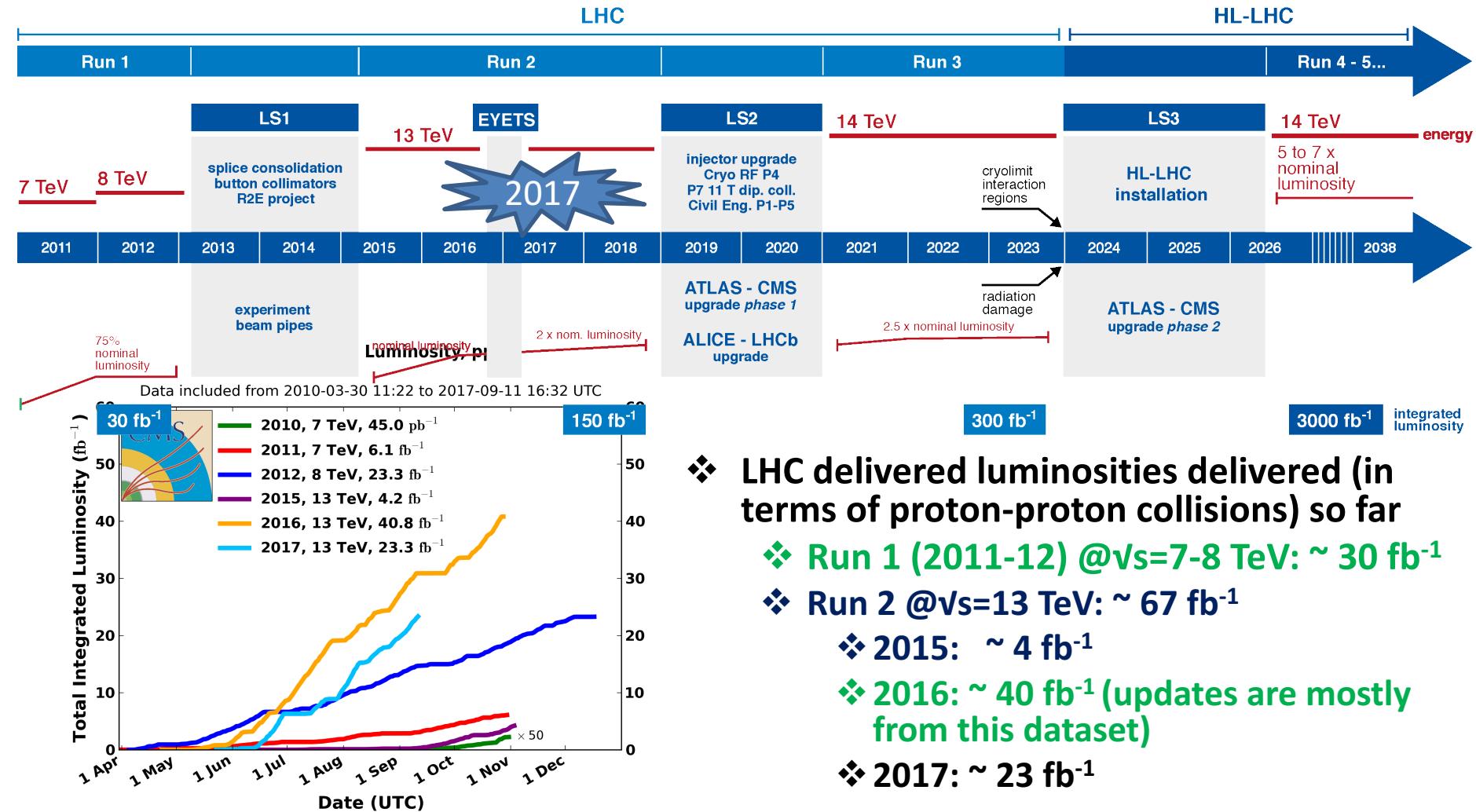


Outline

- LHC Schedule & CMS datasets
- CMS Detector and its status
 - Pixel/L1 trigger Upgrade in 2017
 - Performance in 2017 data-taking
- CMS Physics Results (only the recent ones)
 - Analyses/Searches from 2016 dataset @ $\sqrt{s}=13$ TeV
 - Standard Model, Top, Higgs, & New Physics Searches
- Summary & Future outlook

LHC Schedule & Luminosity

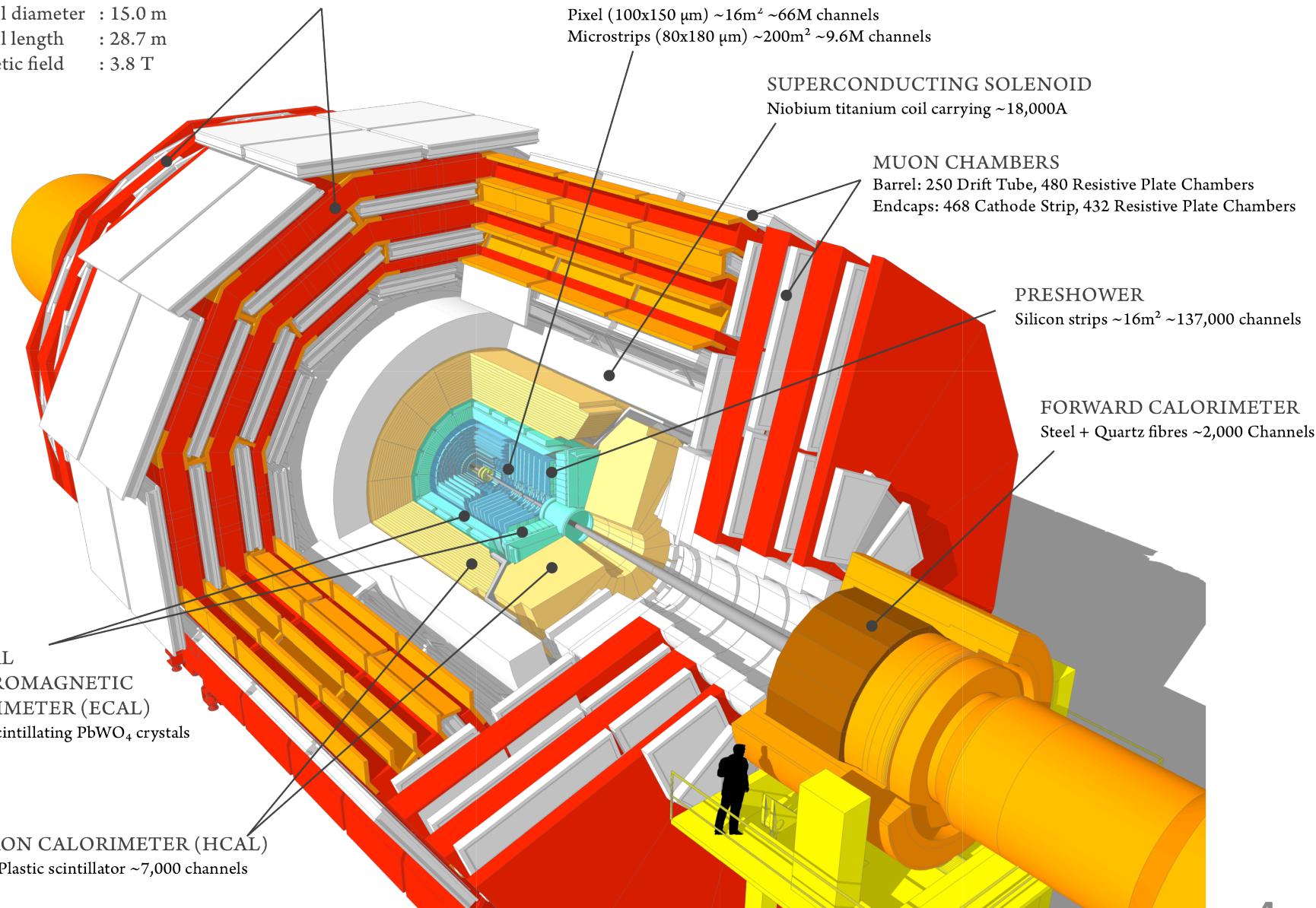
LHC / HL-LHC Plan



CMS Detector

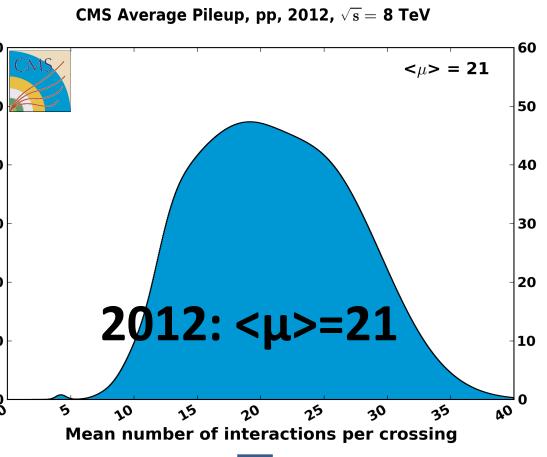
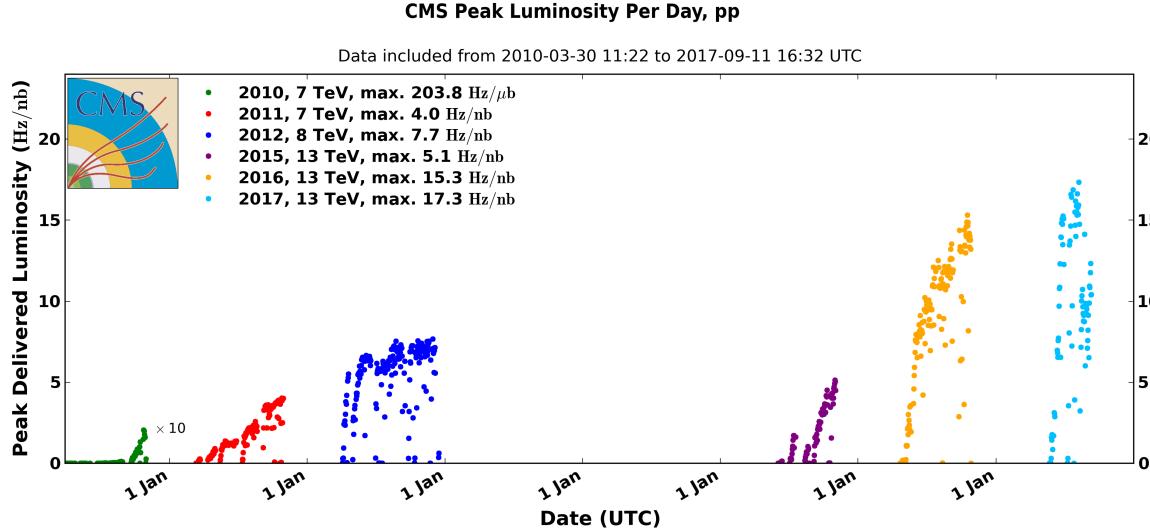
CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

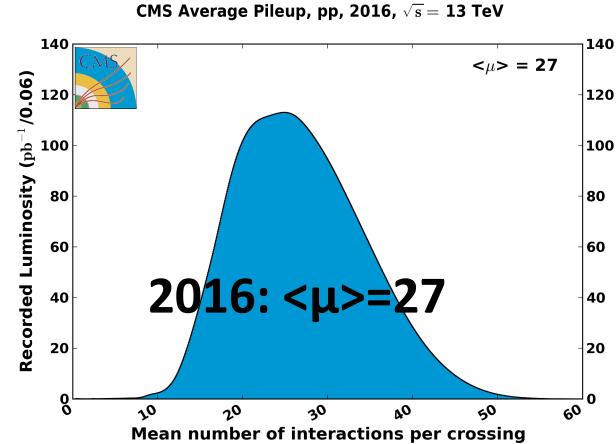


Experimental Challenges in Run 2

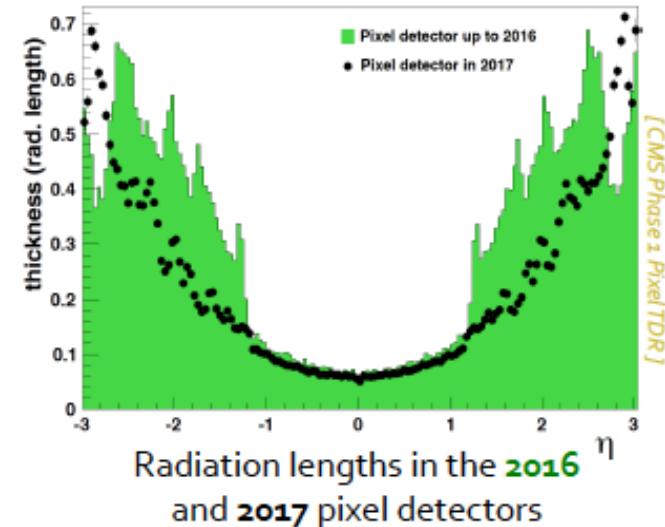
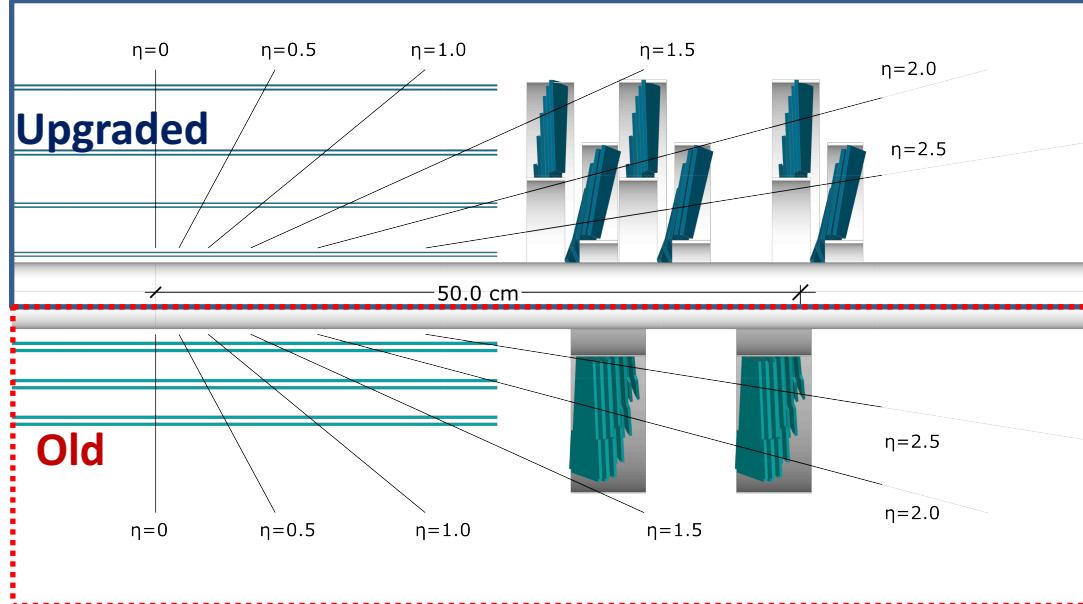
- ❖ Exceedingly well performance by the LHC also leads to enhancement of instantaneous luminosity



- ❖ In 2016 LHC peak luminosity already exceeded $1 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
 - ❖ Average number of interactions per bunch crossing, $\langle \mu \rangle = 27$
 - ❖ Detector occupancy/trigger rates enhance rapidly; necessity to upgrade the detectors/trigger system to preserve the physics sensitivity



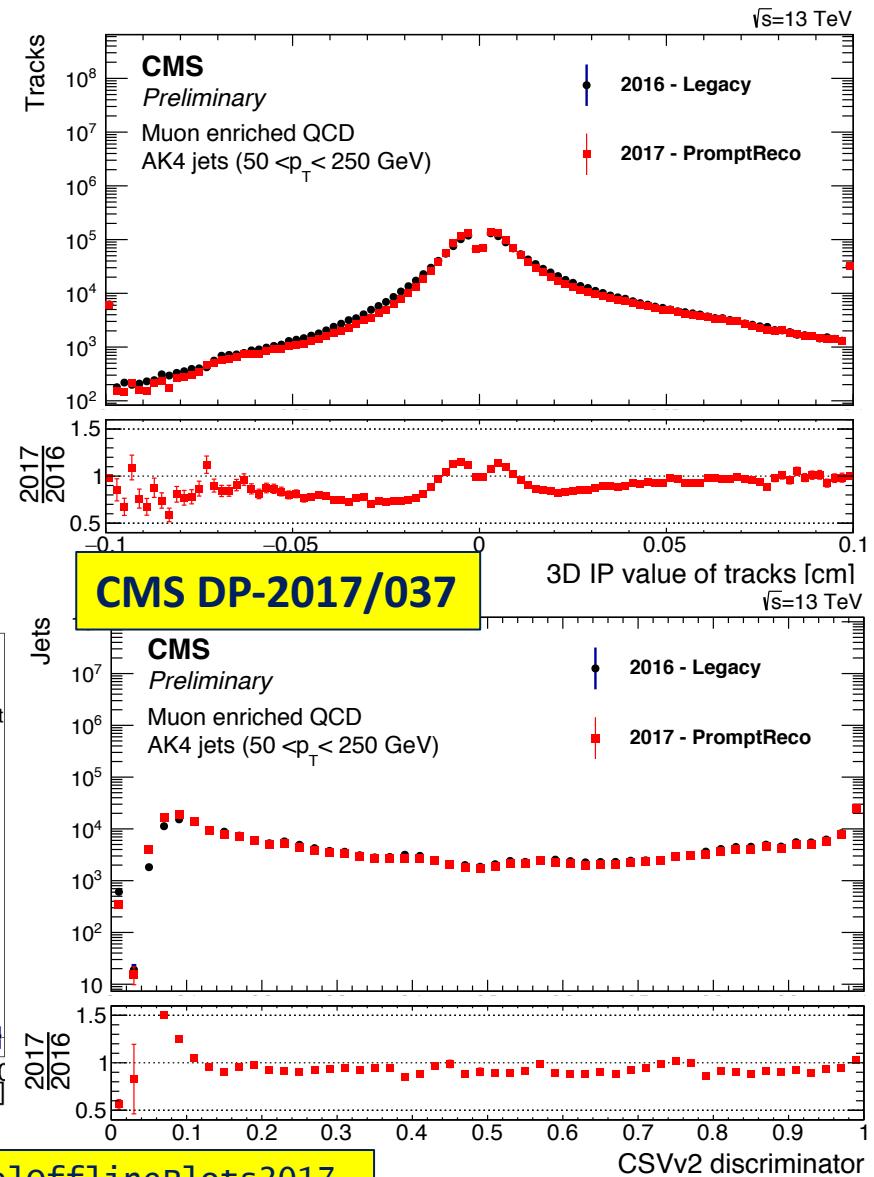
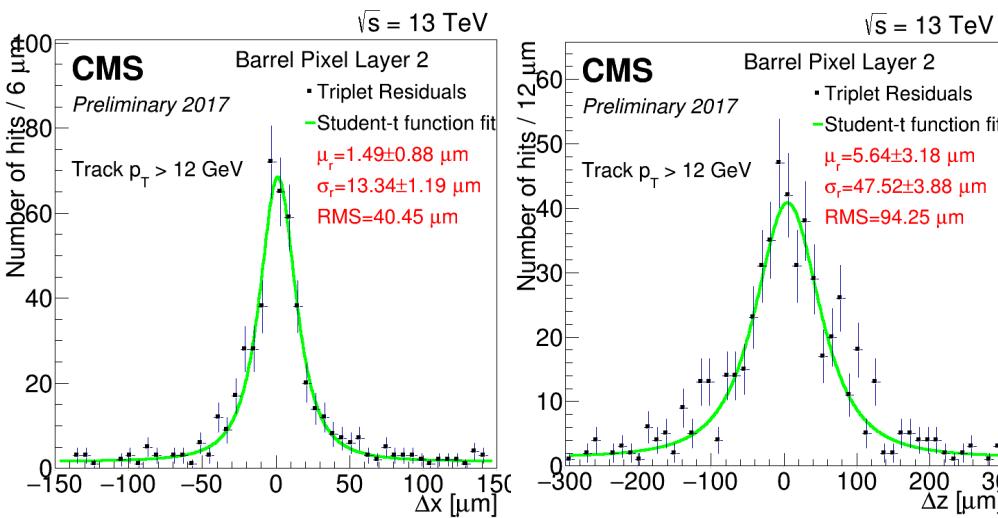
Pixel Upgrade (2016/17)



- Baseline $L = 2 \times 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$ with 25ns BX \rightarrow 50 pileup (**50PU**) with very small efficiency loss
- **More Robust tracking** : 4 hit coverage; **3 layers/2 disks to 4 layers / 3 disks** (can compensate point losses in strips)
- **Better readout able to run up to $2-2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with almost no inefficiency (from hit loss) or dead time** and radiation hard enough to survive Integrated Luminosity of 500 fb^{-1}
- **Much less material in front of outer Tracker**
- Inner layer closer to beam \rightarrow Better primary and secondary vertex resolution

Pixel Upgrade (2016/17) - II

- Some of the performance metric after the commissioning have been tallied with 2016 detector
 - Discriminators for b-quark identification
 - Track residuals in x and z



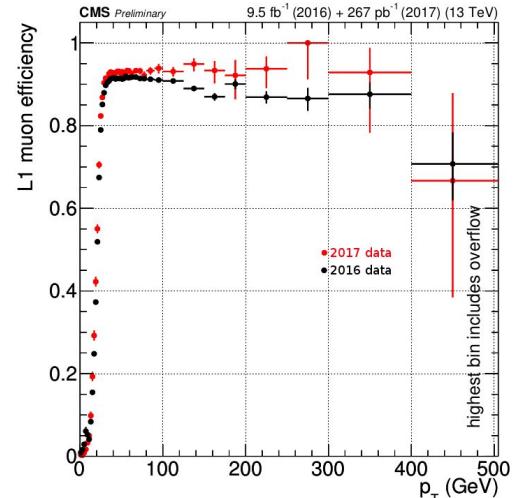
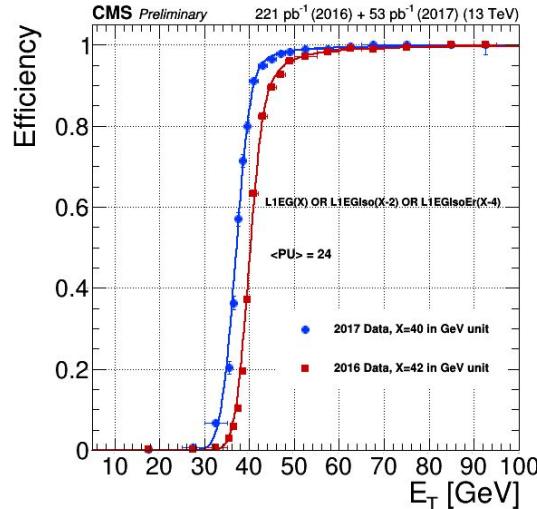
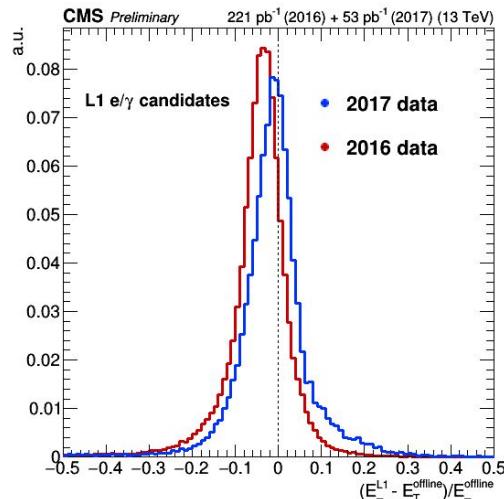
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2017>

Level 1 Trigger Upgrade (2016/17)

➤ Full upgrade of the CMS Level 1 Trigger system

➤ Calorimeter and Muon Triggers

CMS DP-2017/024

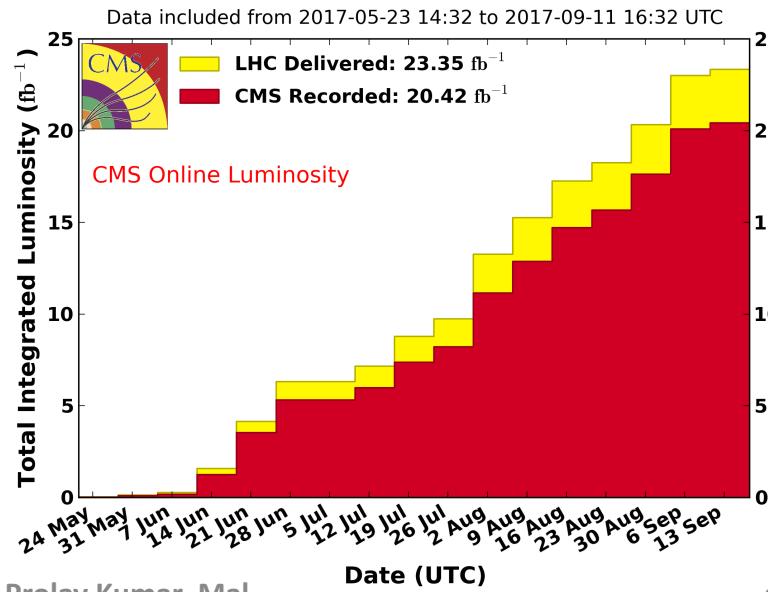
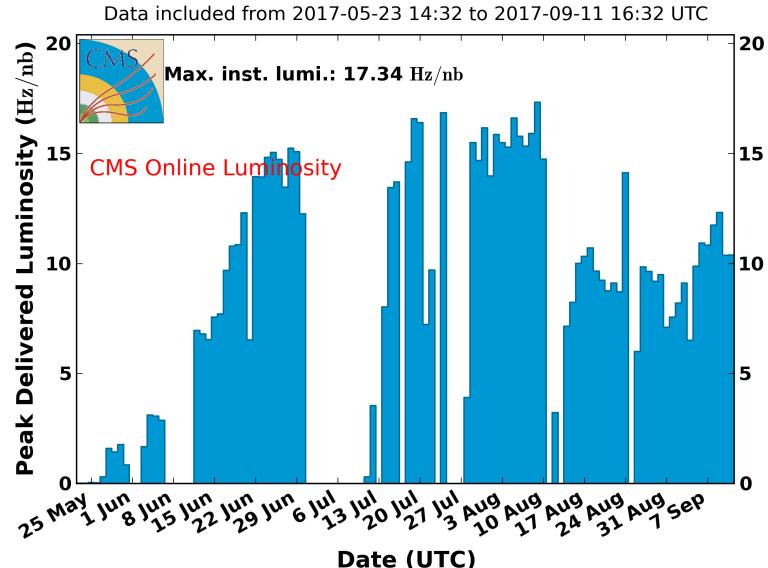


- ❖ Optimization of Electron/photon triggers at Level 1
 - ❖ Better energy resolution & sharper turn-on curves
 - ❖ 20% reduction in e/γ trigger rate and 15% gain in trigger efficiency
- ❖ Improvement in Level 1 muon track finding, Level 1 muon momentum resolution & trigger efficiency
 - ❖ Lowest unprescaled muon threshold of 25 GeV in 2017 dataset

CMS Operations in 2017

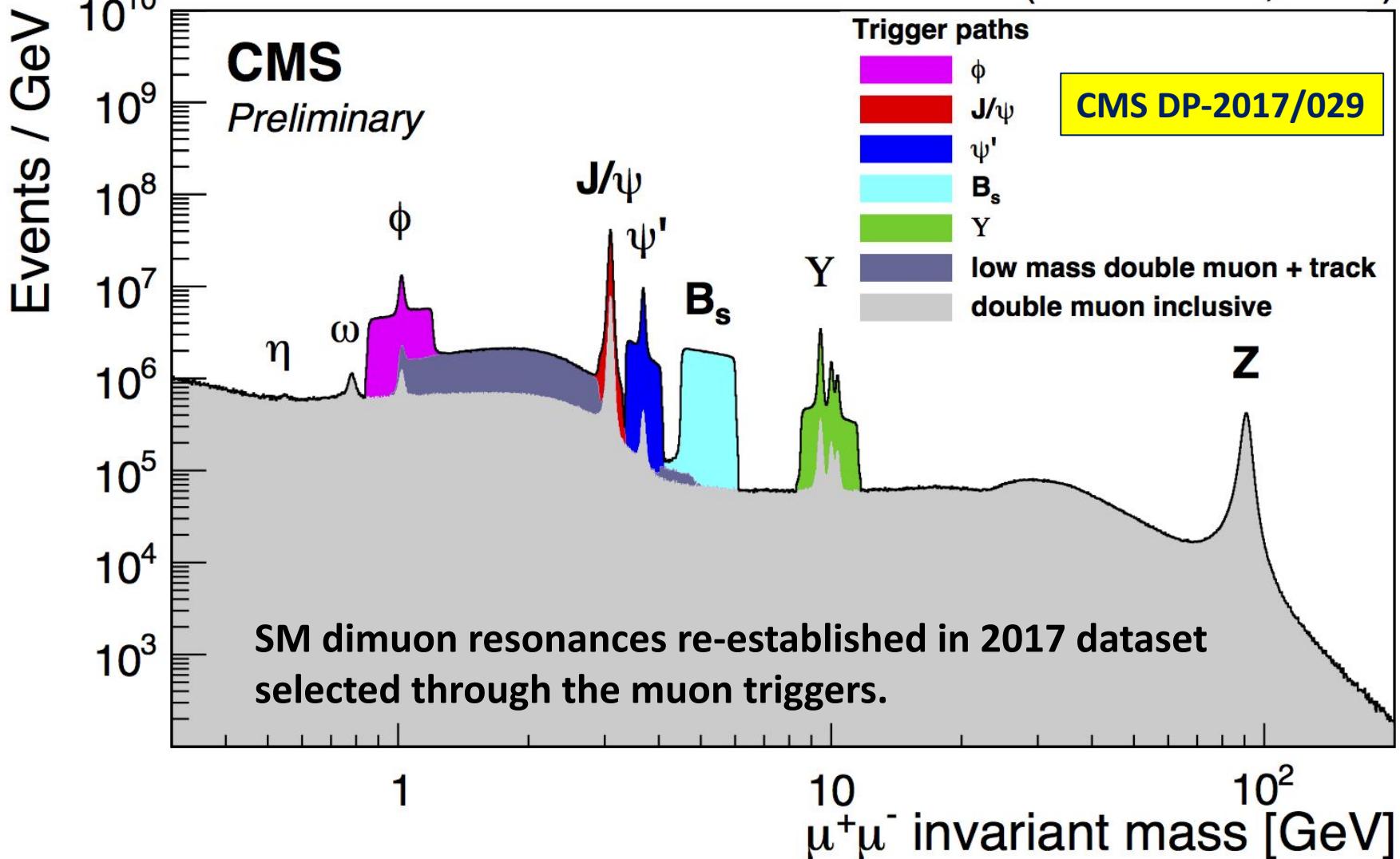
- ❑ Overall data-taking efficiency
(till September, 2017) >85%
 - ❑ Some inefficiencies accumulated due to the Upgraded Pixel commissioning
- ❑ Peak luminosity already reached $1.7 \times 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$
- ❑ Steady operations already led to $>20 \text{ fb}^{-1}$ dataset on tape
- ❑ Extensive physics analyses with 2017 dataset are yet to be started

CMS Peak Luminosity Per Day, pp, 2017, $\sqrt{s} = 13 \text{ TeV}$



CMS Operations in 2017 -II

$L = 3.9 \text{ fb}^{-1}$ ($\sqrt{s} = 13 \text{ TeV}$, 2017)



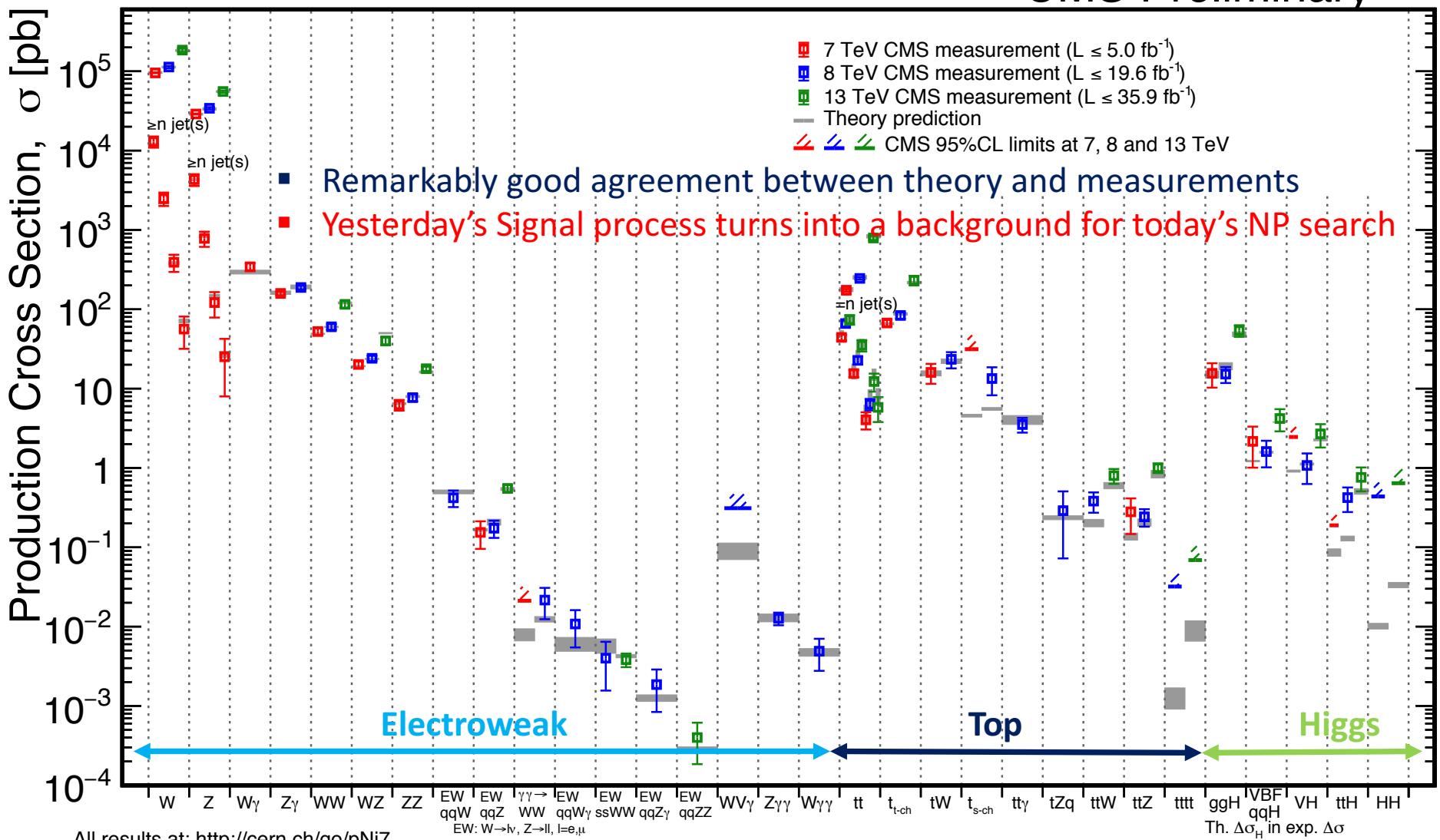
Physics Highlights

- ✧ Most of the Run 1 legacy results are already published
- ✧ Very few selected analyses/search results (most recent) are shown here
 - ✧ Based on Run 1 (2012) or Run 2 (2016) datasets
- ✧ Standard Model (SM) QCD & Electroweak results
- ✧ Top quark Physics
- ✧ Higgs Physics
- ✧ Beyond the SM (BSM)/New Physics (NP) Searches
 - ✧ Search for Supersymmetry (SUSY)
 - ✧ Search for Exotic Resonances
 - ✧ Dark Matter Searches

SM Measurements vs Predictions

CMS Preliminary

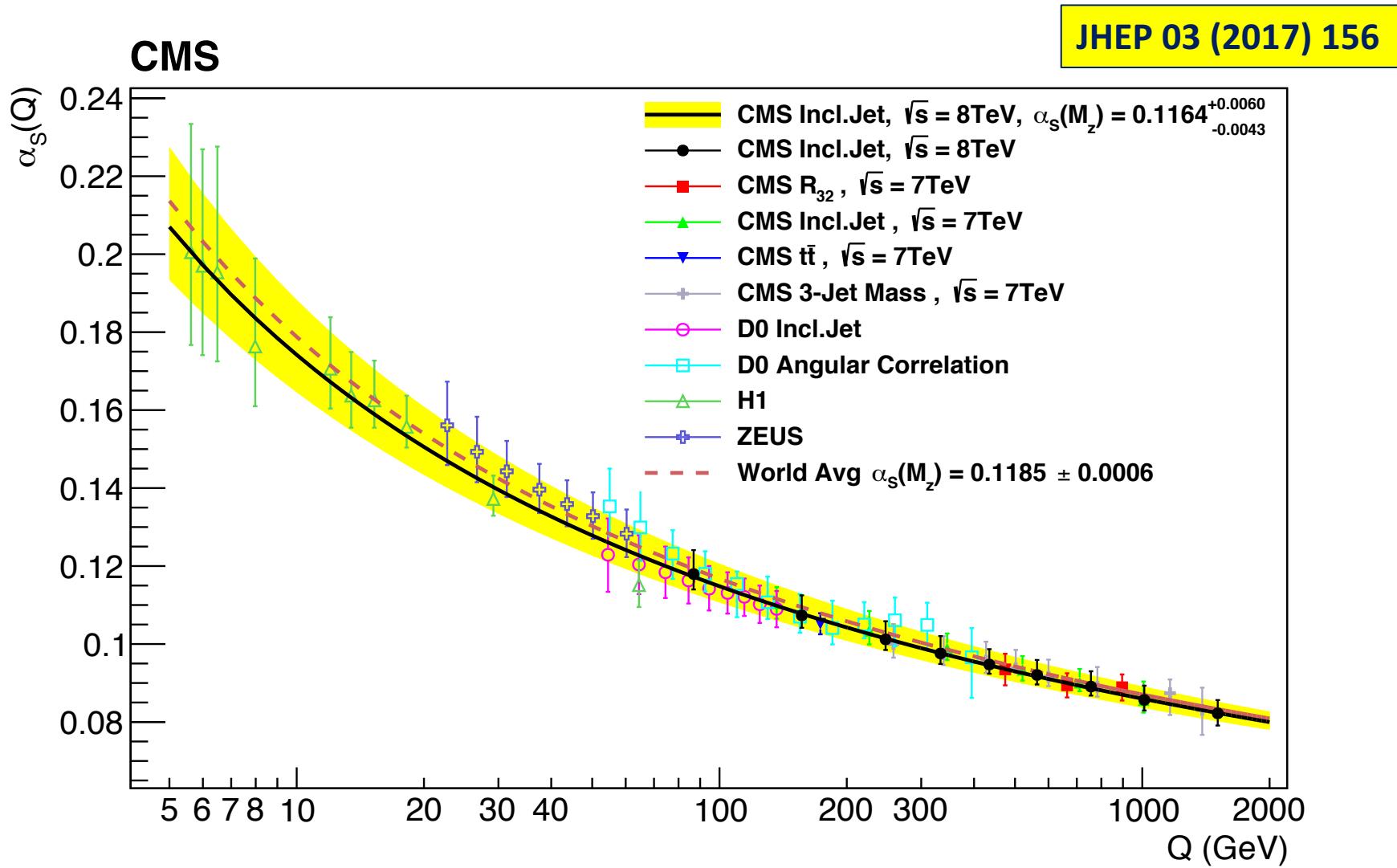
August 2017



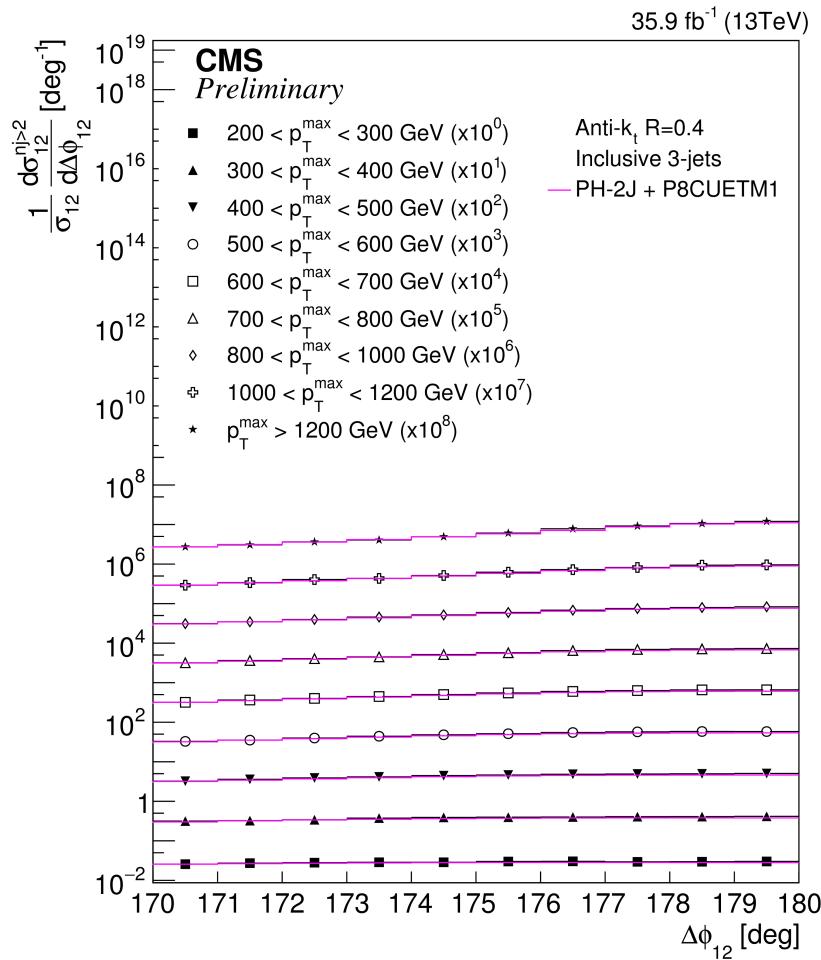
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined>

QCD α_s Measurement

- $\alpha_s(M_z)$ extracted from the fit of ratio of cross-sections (3-jets over 2-jets events)

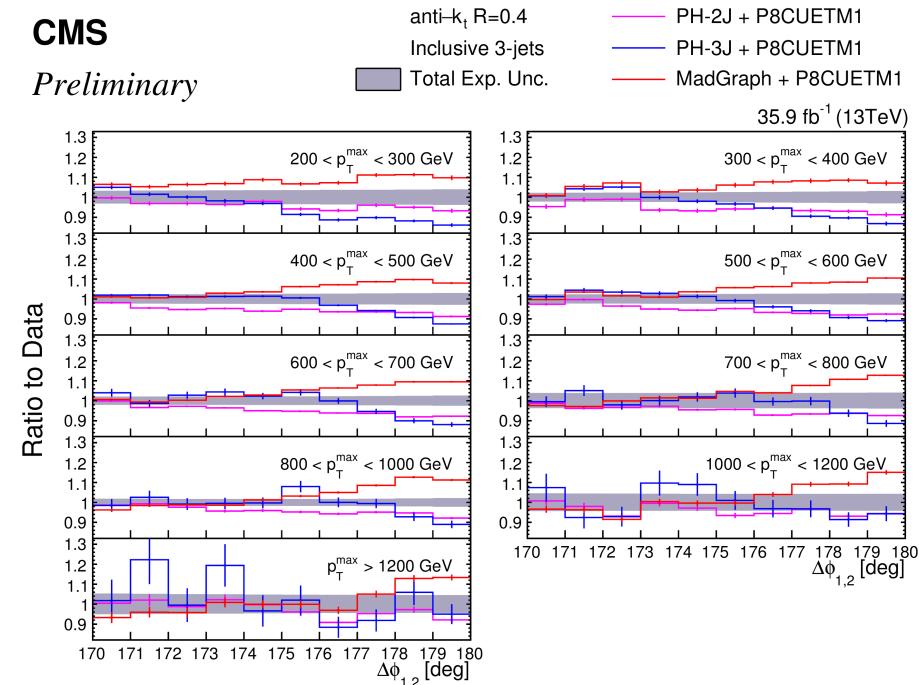


QCD jet production



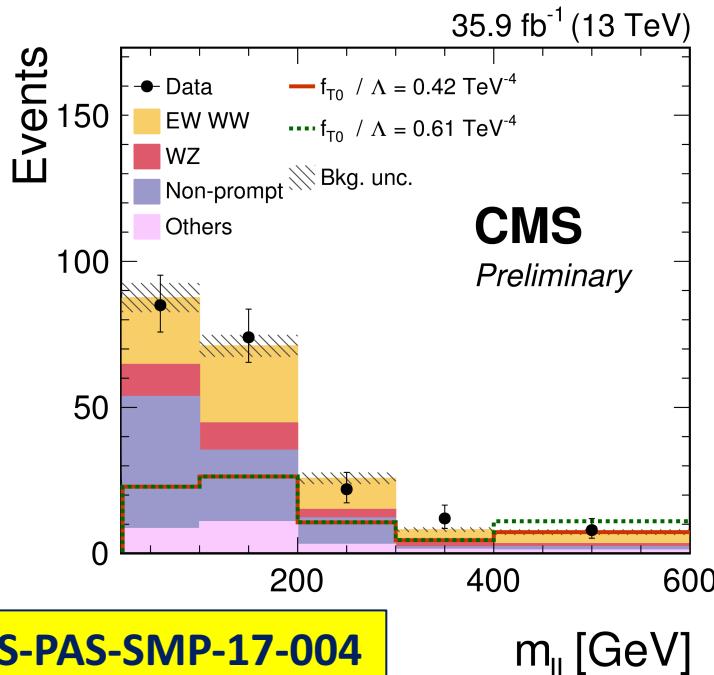
CMS-PAS-SMP-17-009

- Azimuthal angular correlation in high transverse momentum dijet events: normalized cross-section measurement vs azimuthal angles
 - Needs improvement in NLO event generator modeling



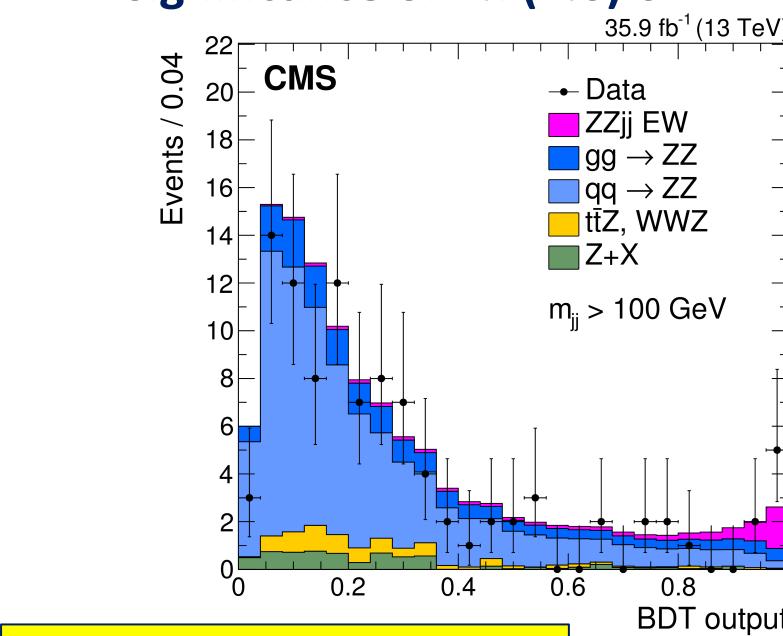
Electroweak Gauge Coupling

- ❖ Diboson & W/Z+jets production processes are studied in detail
- ❖ Vector boson scattering (VBS) is the ideal probe for studying the Electroweak sector
- ❖ First 5.5σ observation for WWjj processes in same-sign charged leptons+MET+jets signature



CMS-PAS-SMP-17-004

$m_{ll} [\text{GeV}]$

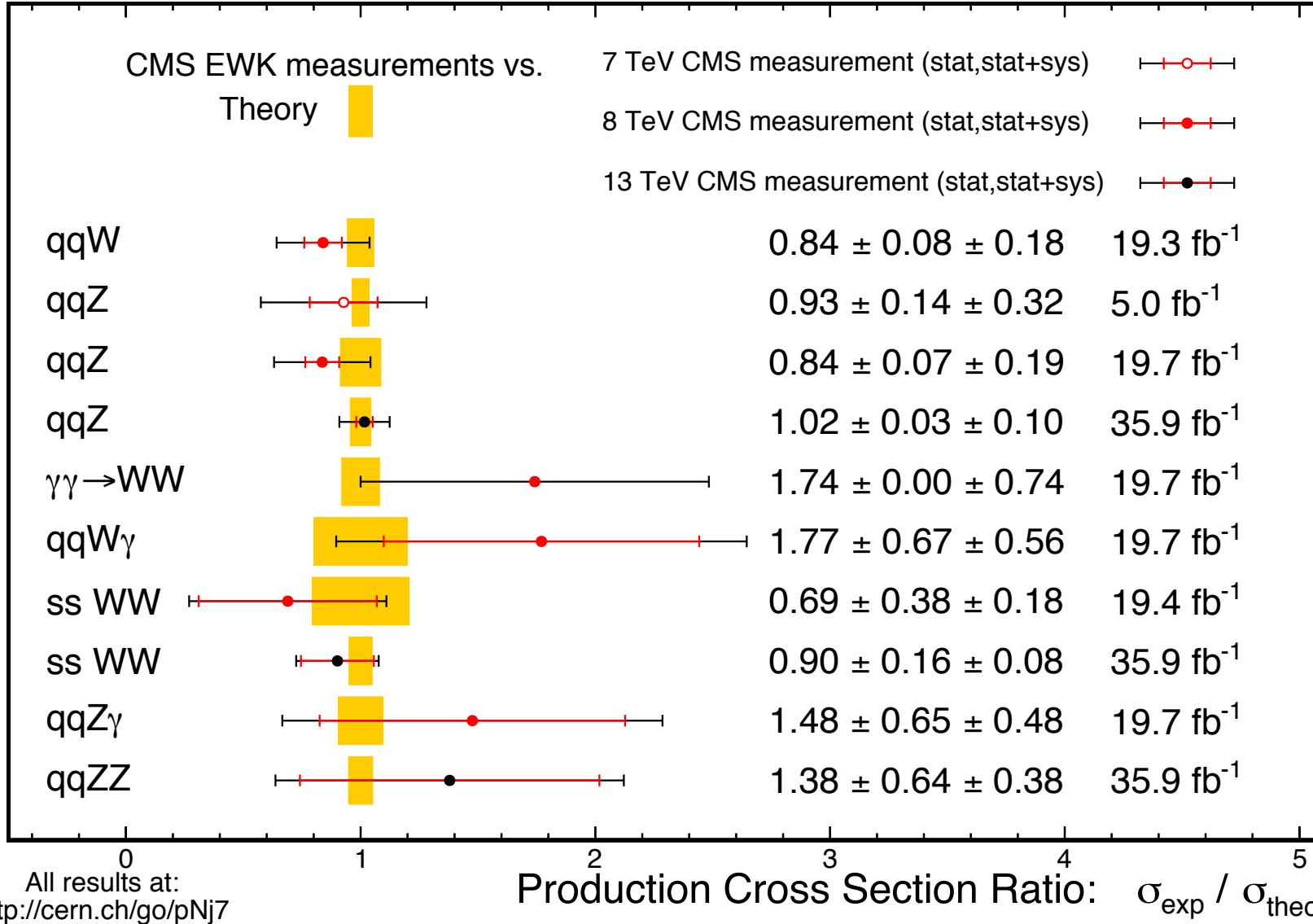


arXiv:1708.02812 [hep-ex]

Electroweak Measurements

May 2017

CMS Preliminary

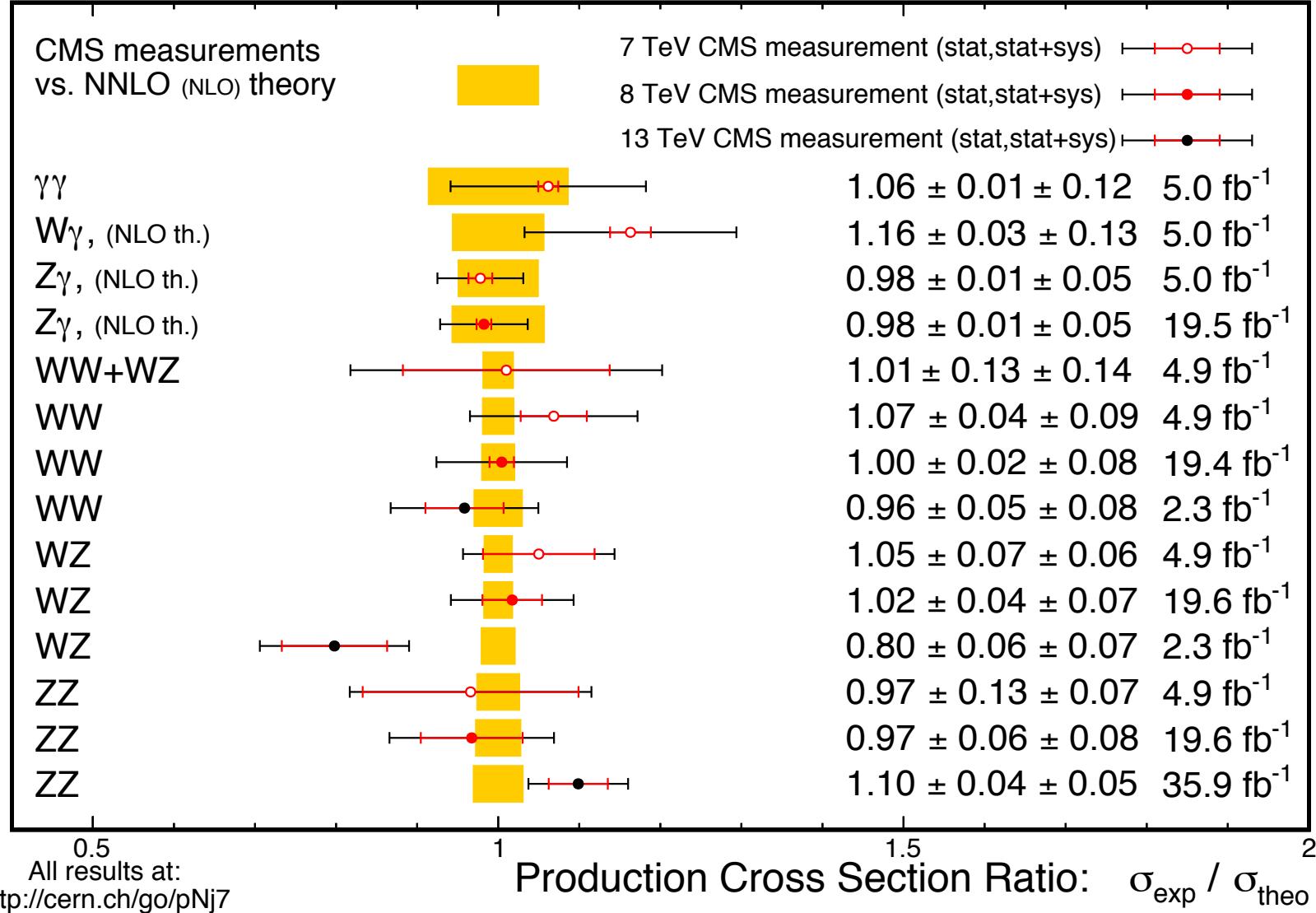


<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined>

Electroweak Diboson Production

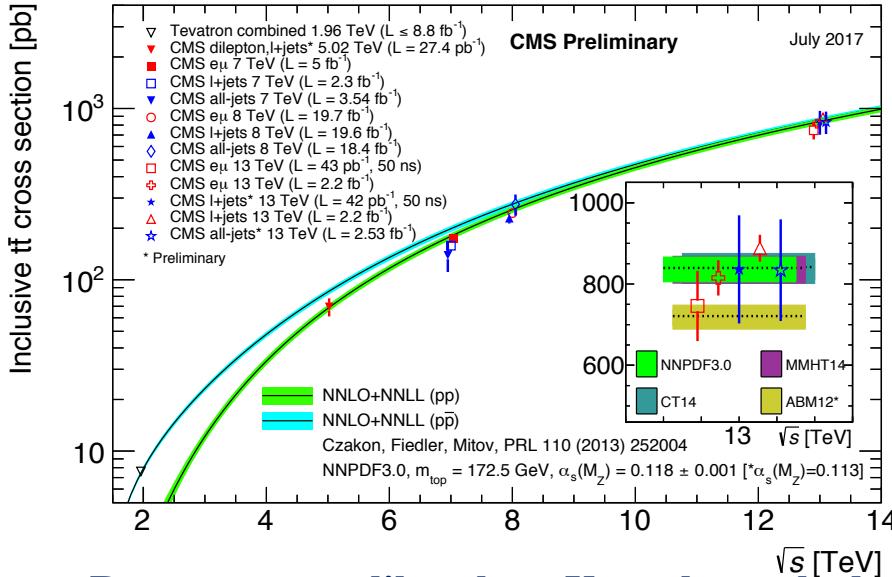
March 2017

CMS Preliminary



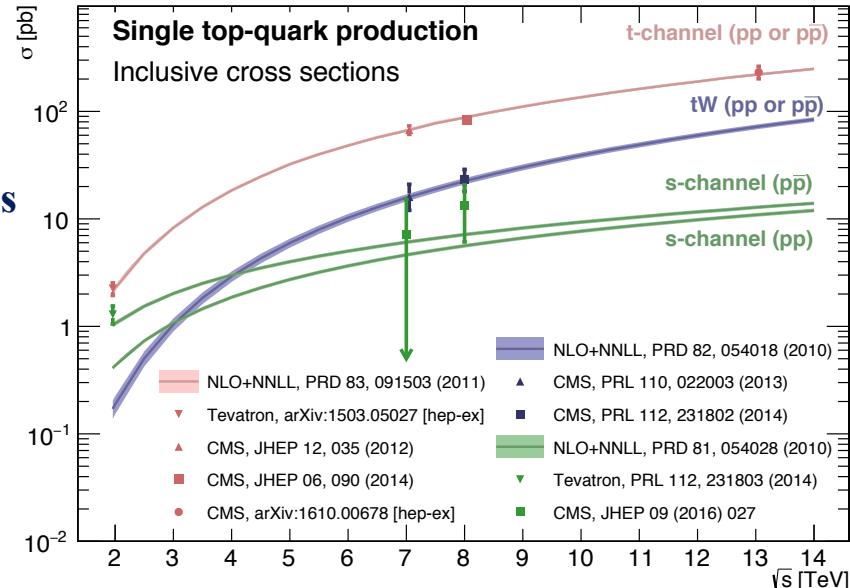
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined>

LHC: The Top Factory



- Rare processes like $t\bar{t} + X$ can be probed
- $t\bar{t} + W$ @ 5.5σ , $t\bar{t} + Z$ @ 9.9σ
- CMS-PAS-TOP-17-005**
- $t\bar{t} + bb$ and $t\bar{t} + bb/t\bar{t} + jj$ processes
- arXiv:1705.10141[hep-ex]**
- $t\bar{t} + \gamma$ production
- arXiv:1706.08128[hep-ex]**
- tZq production @ 2.4σ
- JHEP 07 (2017), 003**
- Probing rare decays (FCNC/BSM)

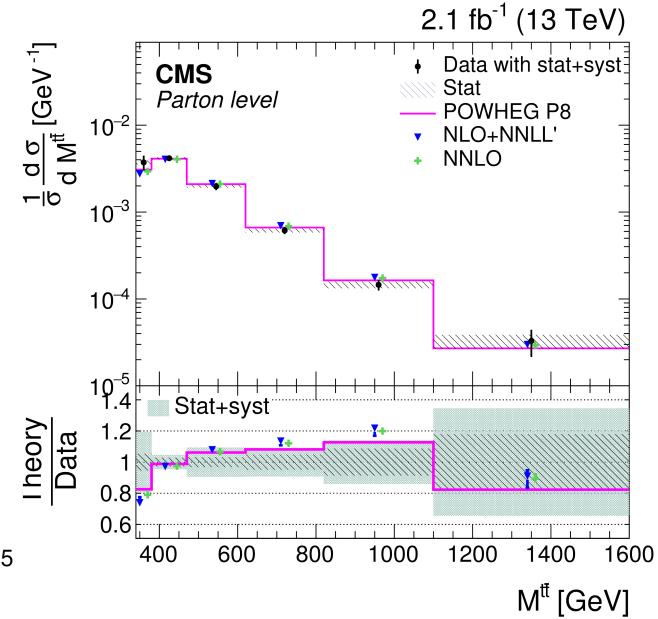
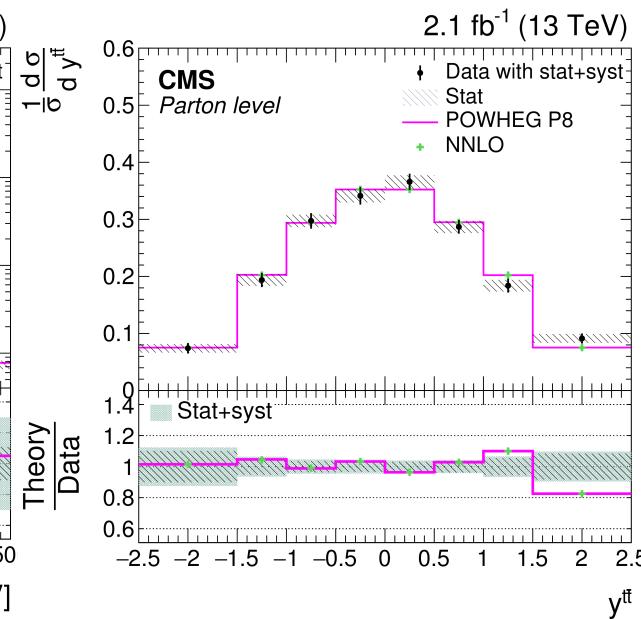
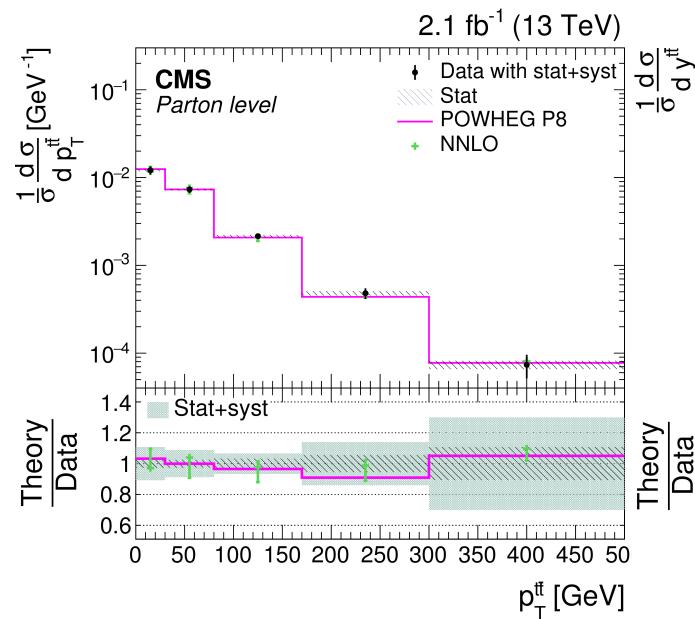
- $t\bar{t}$ production at a rate of 50 Hz (for instantaneous luminosity of $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$)
- 90% (gg) and 10% (q \bar{q}) at $\sqrt{s}=13 \text{ TeV}$ pp collisions



Top Differential Cross-section

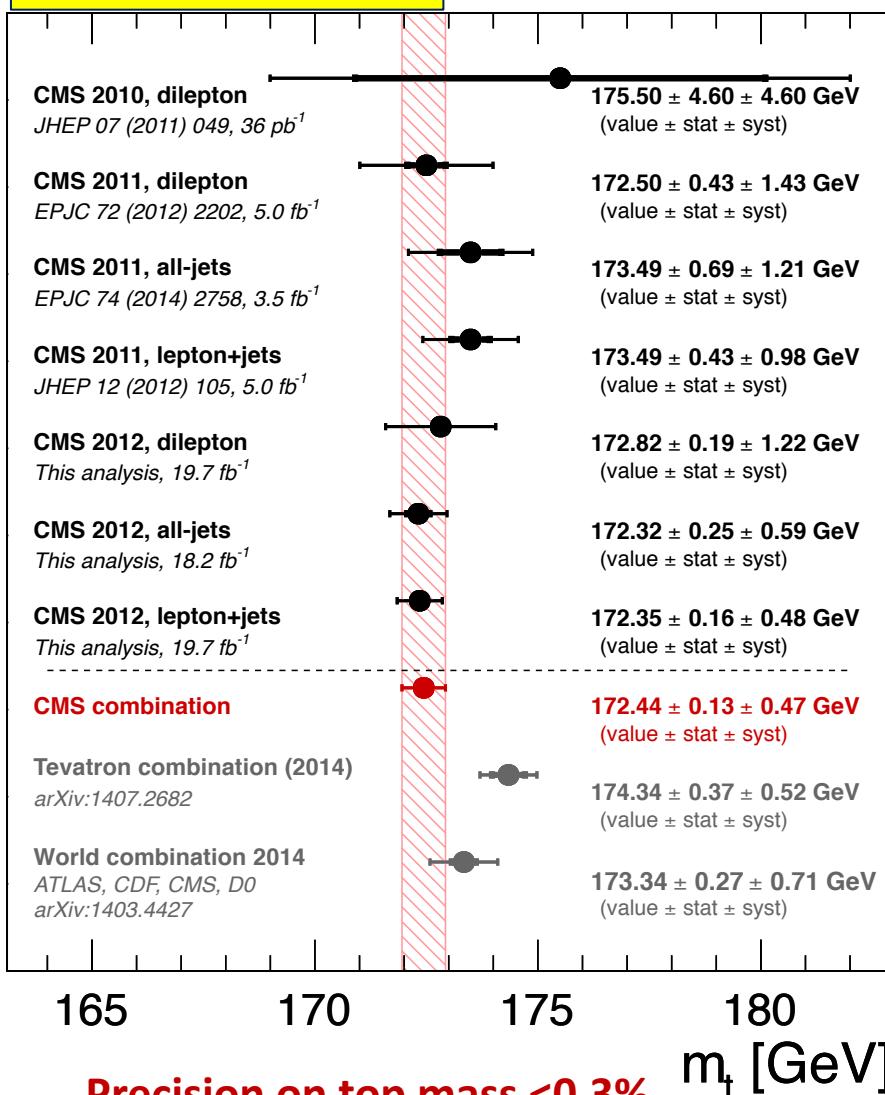
- Normalized cross-section measurement in dilepton channel
- Measurement as functions of kinematic properties of lepton, b-jet, top and anti-top (both particle and parton level)
- Comparison with NNLO & NLO+NNLL calculations

arXiv:1706.07638[hep-ex]



Top quark Mass

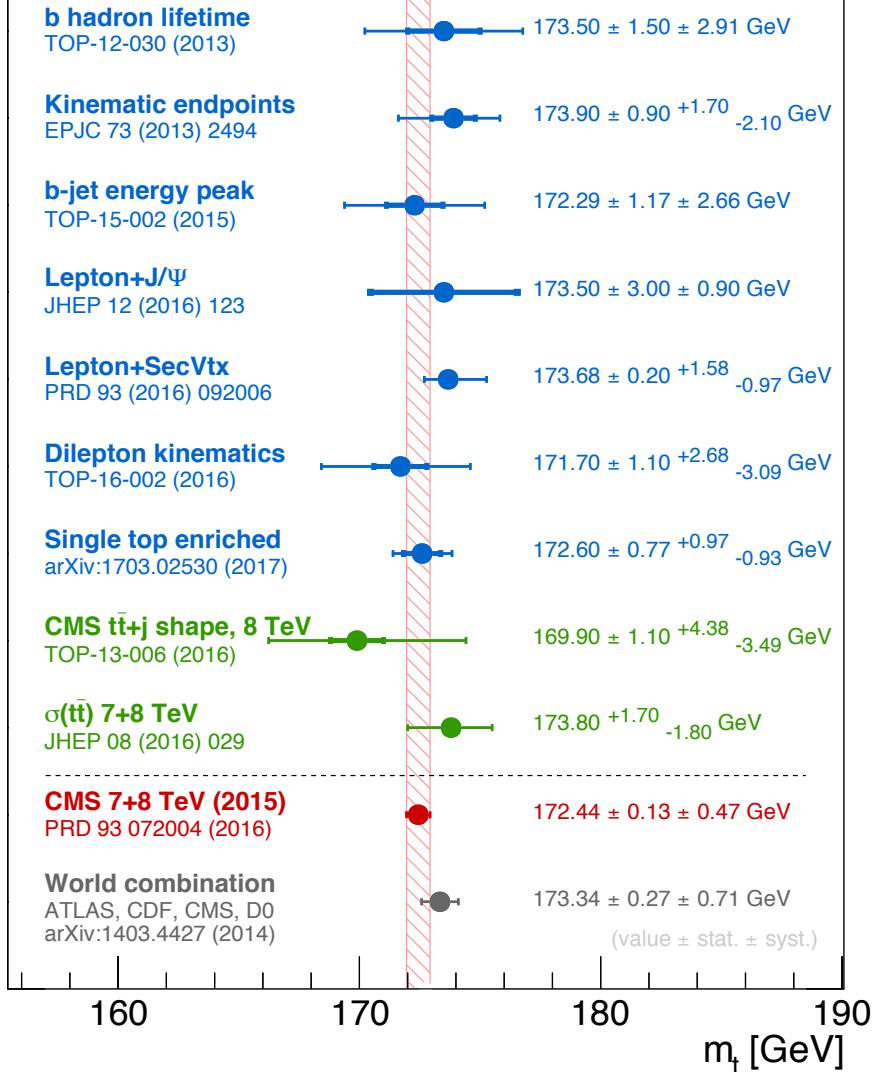
CMS-PAS-TOP-16-022



Precision on top mass <0.3%

CMS Preliminary

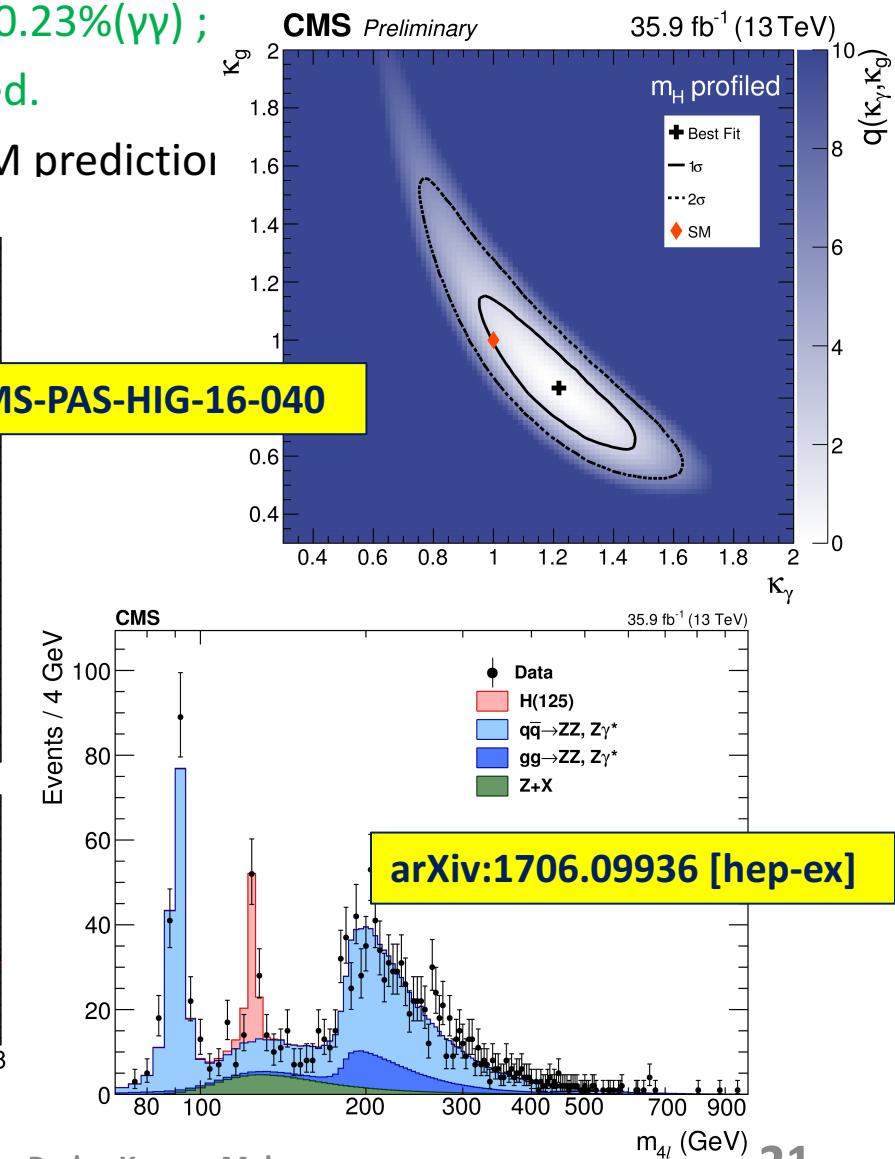
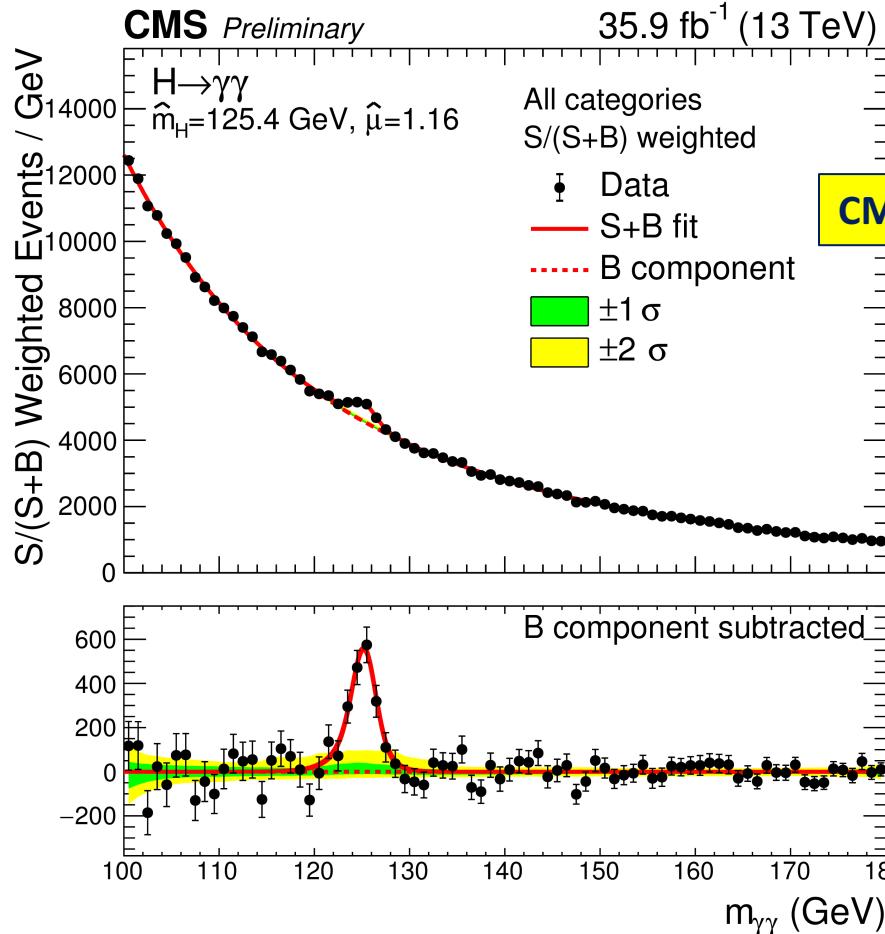
May 2017



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures>

Higgs Production (Discovery channels)

- ❖ New measurements at $\sqrt{s}=13$ TeV using $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
- ❖ Small branching ratios -- 0.013% ($4l$) and 0.23%($\gamma\gamma$) ;
- ❖ But Higgs boson can be fully reconstructed.
- ❖ Measurements are consistent with the SM prediction

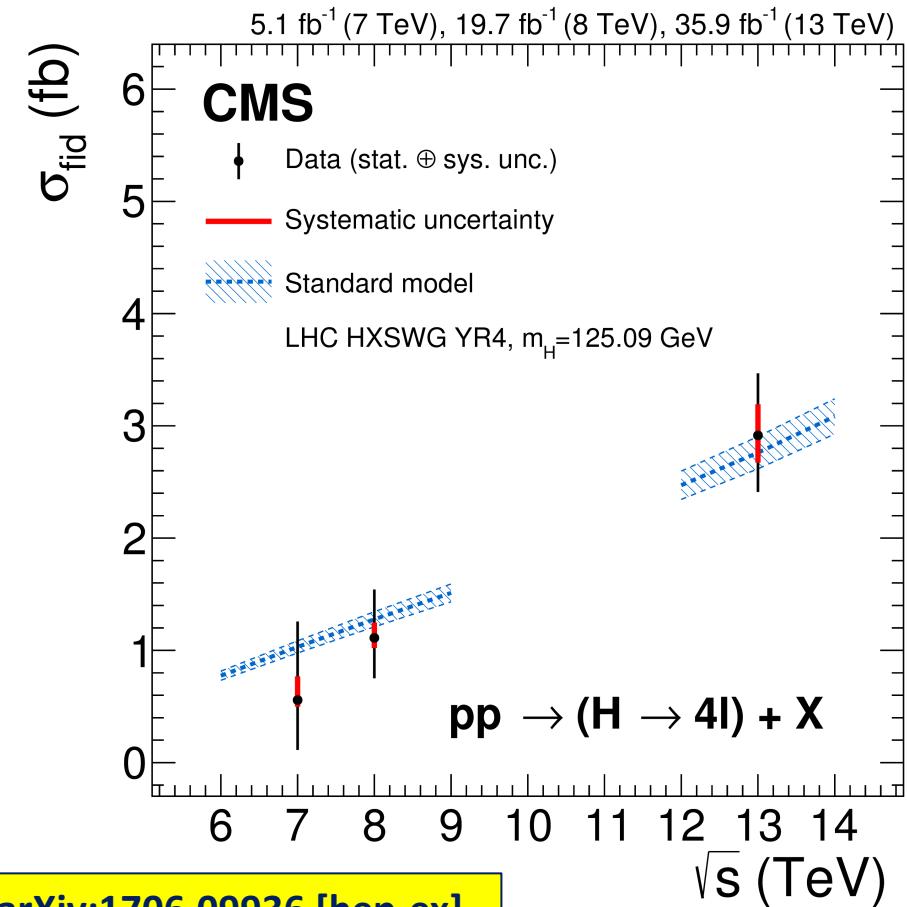
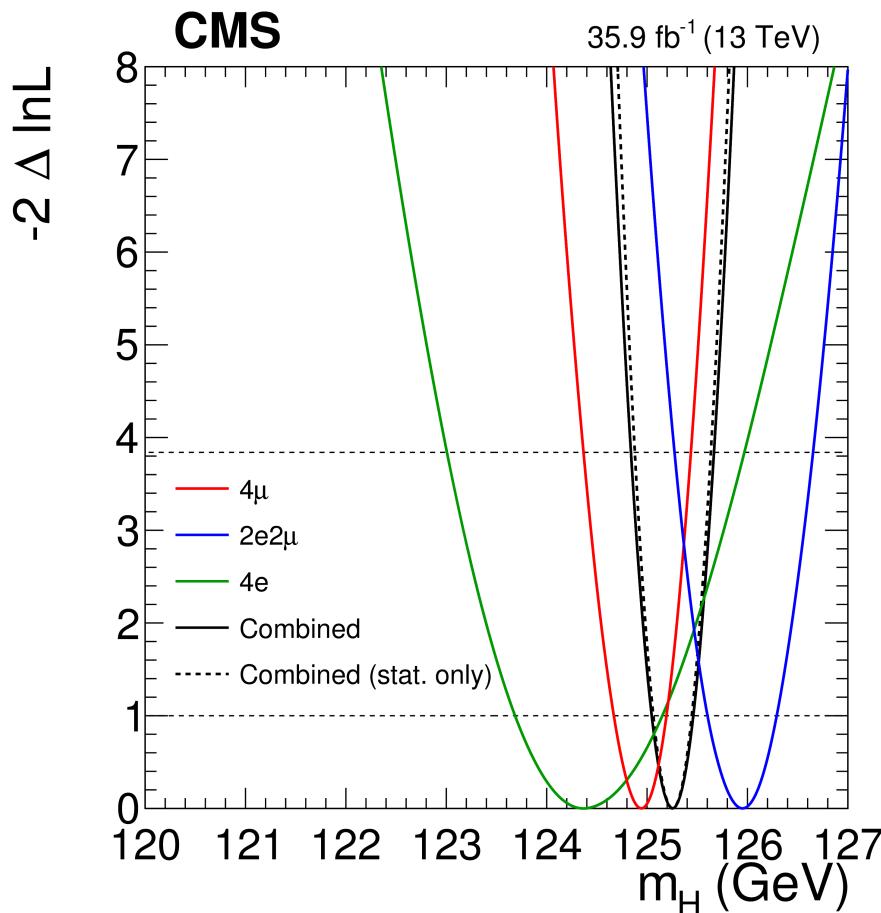


Higgs mass & Production cross-section

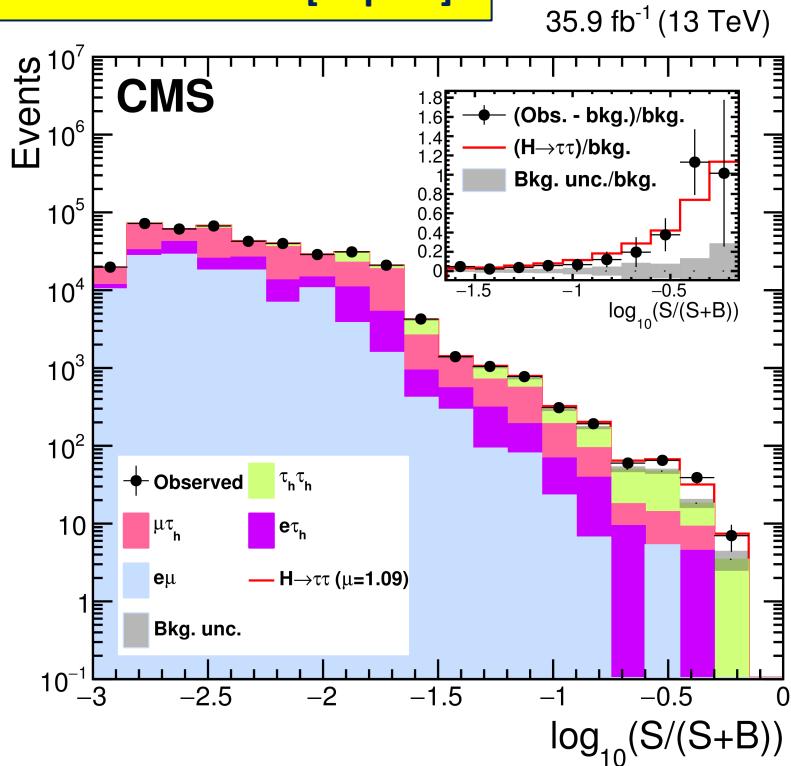
- ❖ Results from the Gloden channel $H \rightarrow ZZ^* \rightarrow 4l$

- ❖ Fiducial cross-section measurement as a function of \sqrt{s}

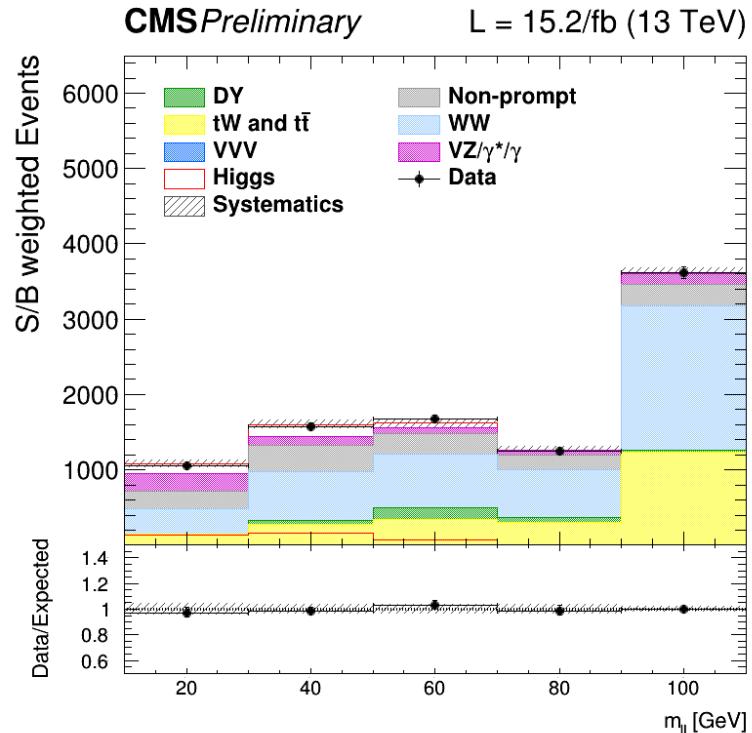
- ❖ Mass measurement using ggH, VBF & VH: $m_H = 125.26 \pm 0.20 \text{ (stat)} \pm 0.08 \text{ (syst)}$ GeV, comparable with world average $125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)}$ GeV



arXiv:1708.00373 [hep-ex]



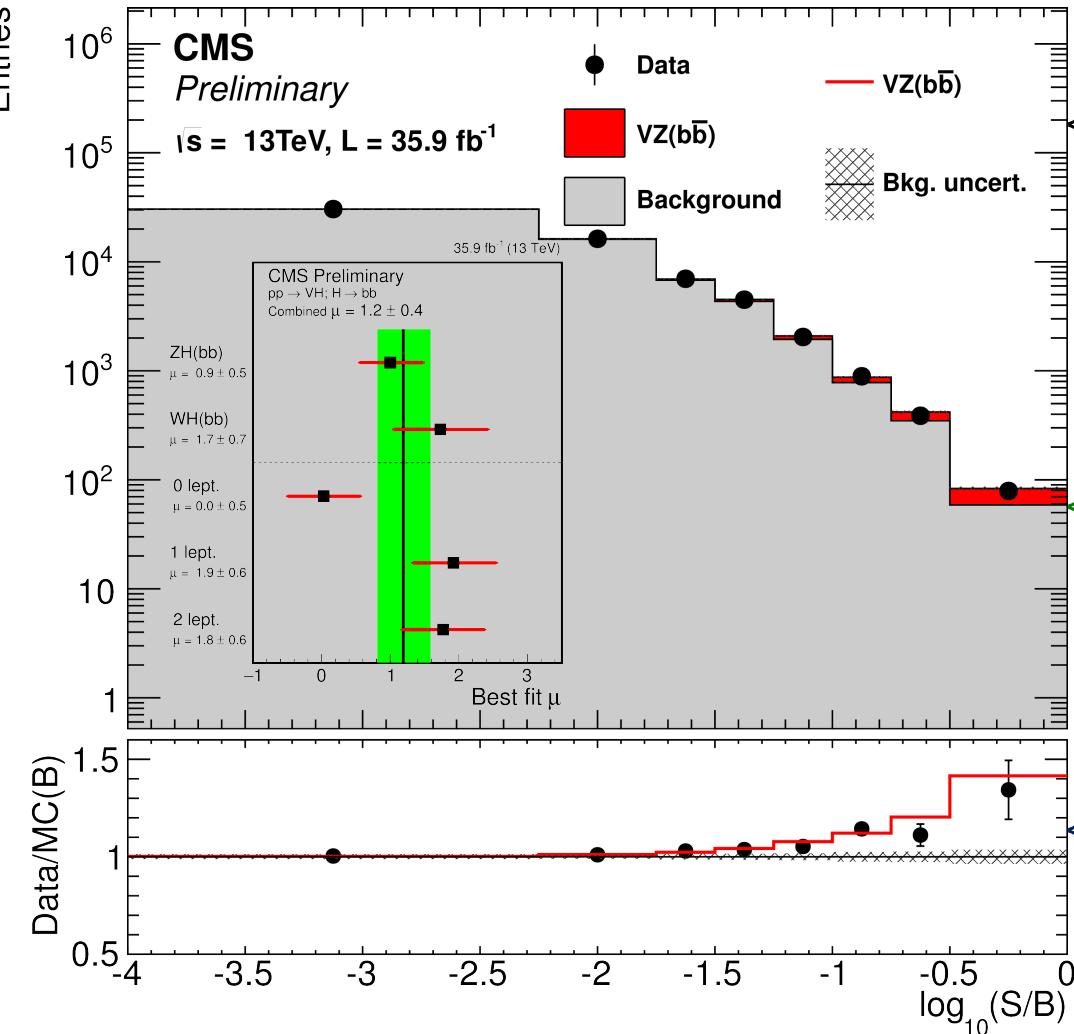
- Tau semi-hadronic & leptonic decay channels
 - Excellent CMS tau tagging
 - 4 final states ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)
 - 3 categories (0 jet, VBF, boosted)
- 4.9 σ (4.7 σ expected) Run 1,2 combined: 5.9 σ (5.9 σ exp)**
 - $1.09^{+0.27}_{-0.26} \times \sigma_{SM}$



- $H \rightarrow WW \rightarrow e\nu\mu\nu$
 - dilepton channel
 - ggH, VH, VBF production channels
- 4.3 σ (4.1 σ expected)**
 - $1.05 \pm 0.26 \times \sigma_{SM}$

Strong Evidence for $H \rightarrow b\bar{b}$

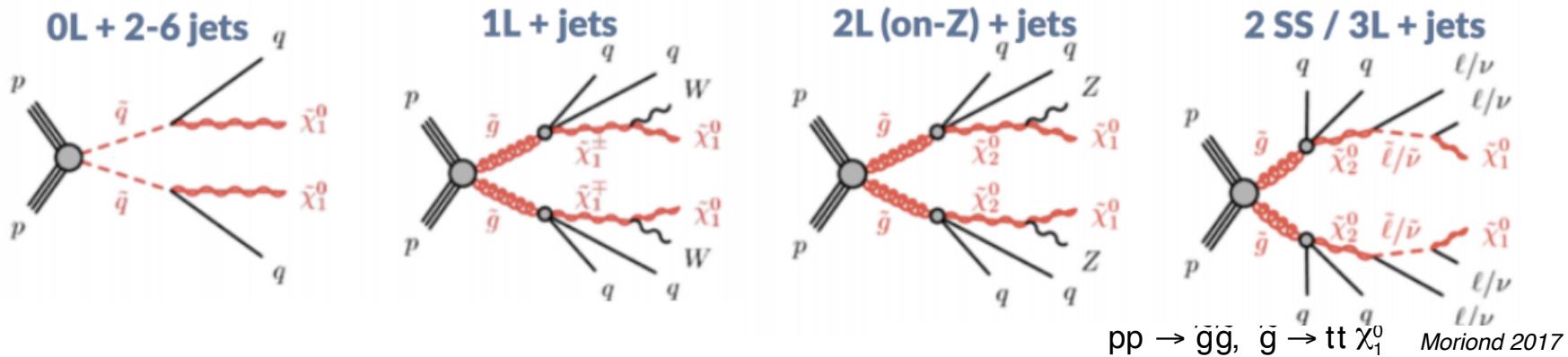
- ❖ Maximum BR but highly suppressed by QCD multijet background
- ❖ Vector boson associated production considered for QCD



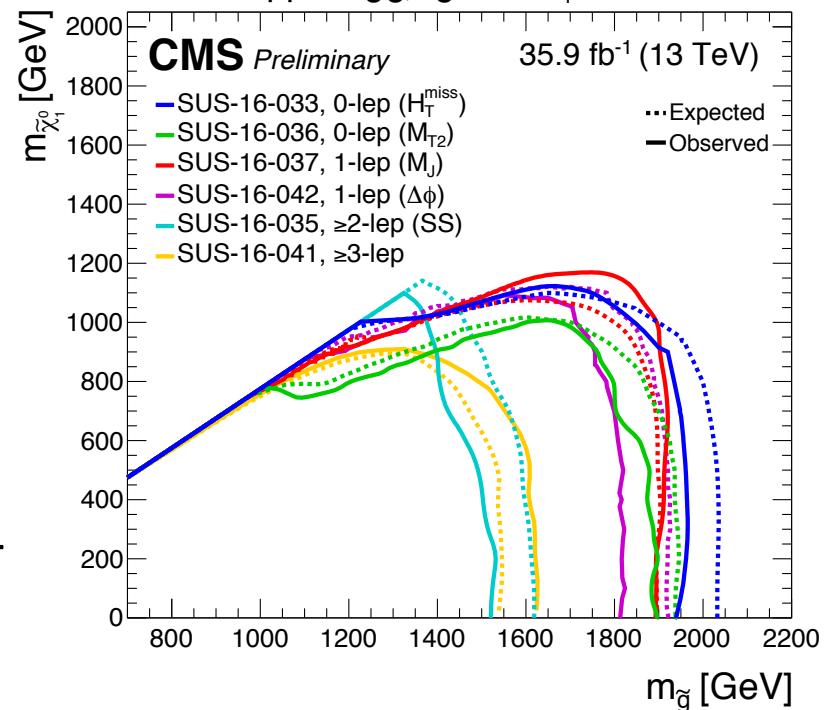
CMS-PAS-HIG-16-044

- ❖ VH signal: 2 b-tagged jets + 0, 1 and 2 leptons + MET respectively to target $Z(vv)H(bb)$, $W(lv)H(bb)$ and $Z(l\bar{l})H(bb)$ processes
- ❖ For $m_H=125 \text{ GeV}$, Run 1+ Run 2 combined local significance
- ❖ 3.8σ (3.8σ expected)
- ❖ Measured Signal strength
- ❖ $\mu = \sigma/\sigma_{\text{SM}} = 1.06^{+0.31}_{-0.29}$

Search for SUSY (Strong Production)



- Squark/gluino production with final state signature: jets+ MET + n leptons
- Experimental searches categorized based on final state and the kinematic variables sensitive to SUSY
- No evidence in 2016 dataset
- Limits on gluino mass >2 TeV at 95% CL

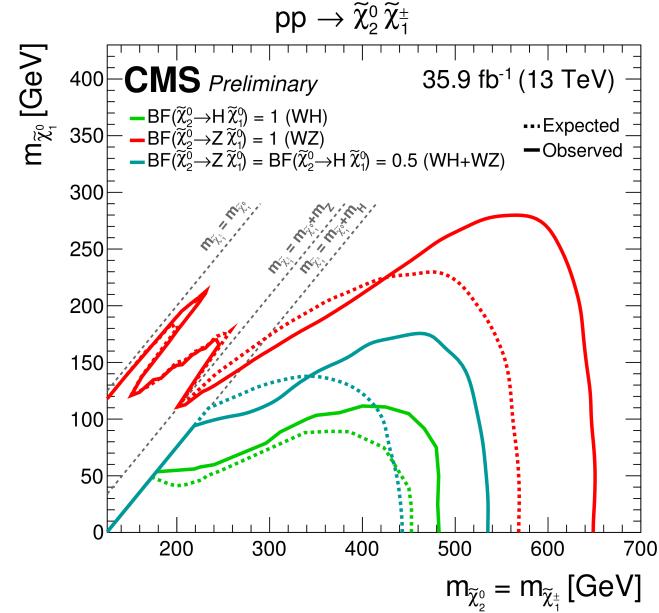
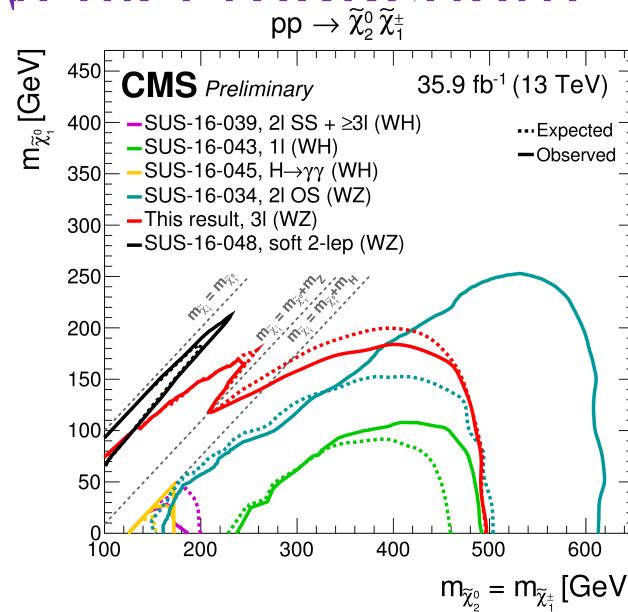
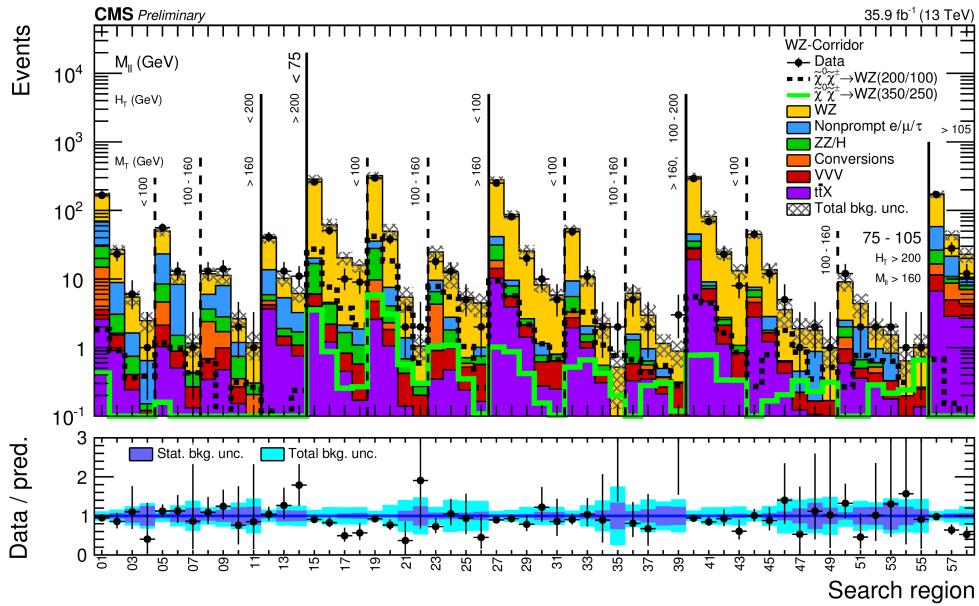


<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

Search for SUSY (Electroweak Production)

CMS-PAS-SUS-17-004

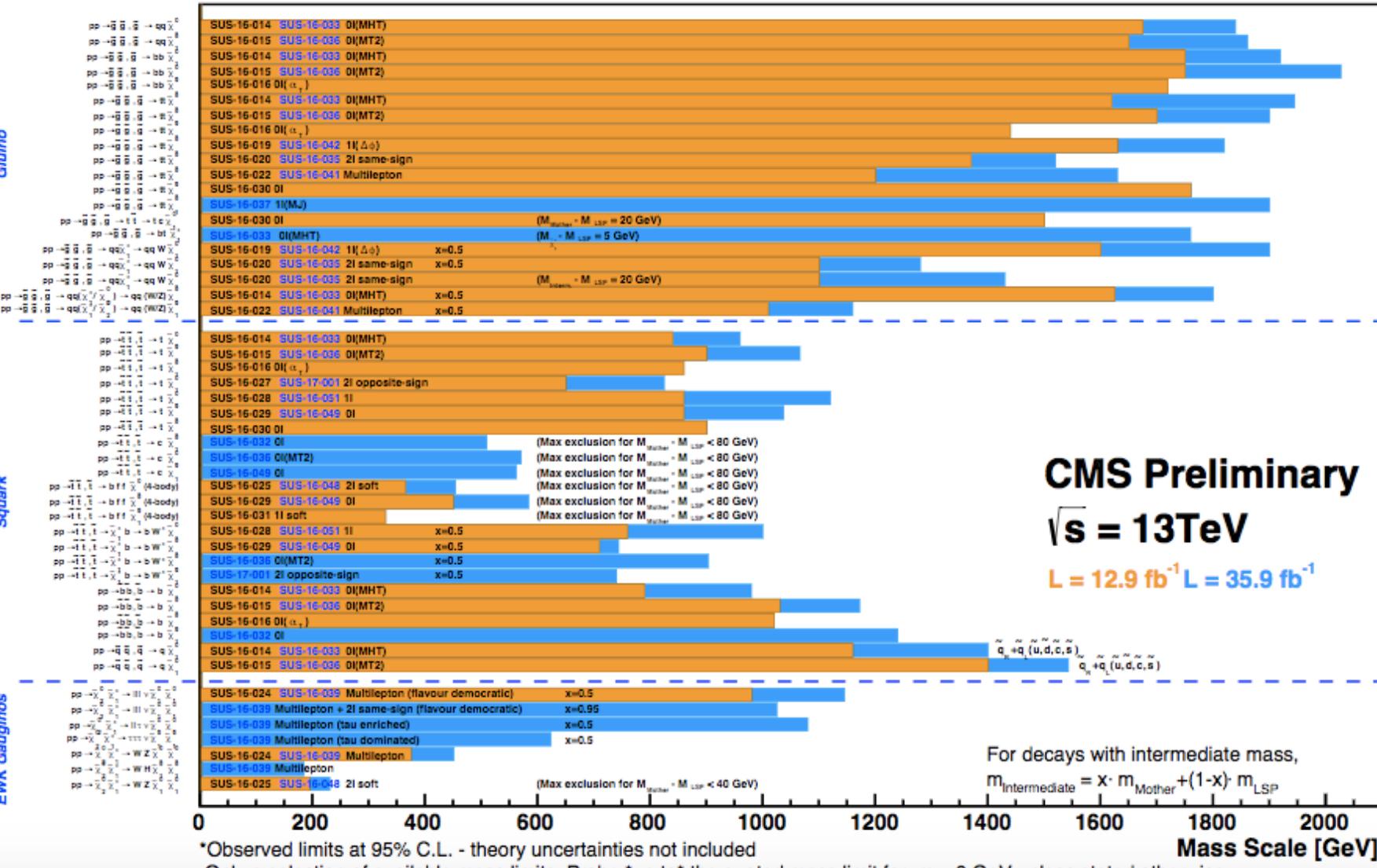
- Electroweak chargino & neutralino production
- Statistical combination of multiple analyses
 - multi-lepton, low p_T dileptons, OS&SF dilepton, WH, Razor $H \rightarrow \gamma\gamma$, H+MET
 - Optimized $\geq 3l$ search for $m(\chi_0^2) - m(\chi_0^1) = m(Z)$
- Model of $\chi_1^\pm - \chi_2^0$ production
 - different χ_2^0 decay scenarios



Summary of SUSY Searches

Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17



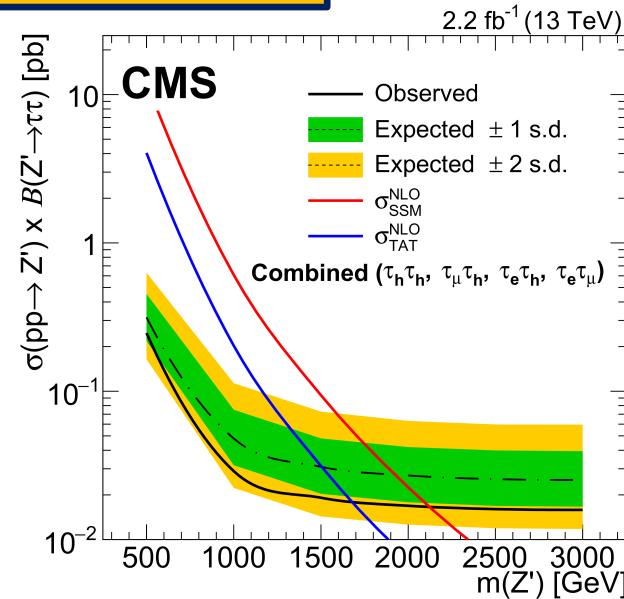
*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m = 0$ GeV unless stated otherwise.

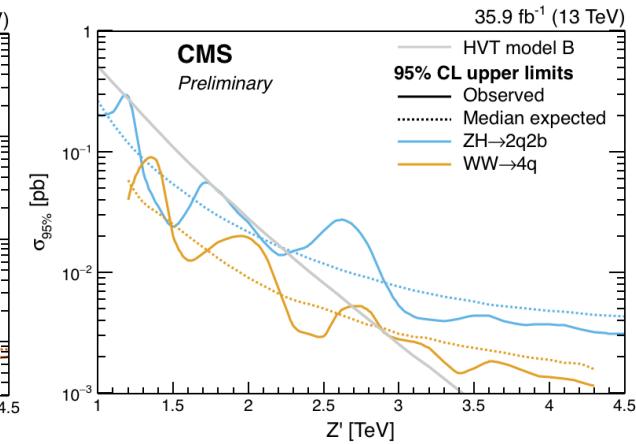
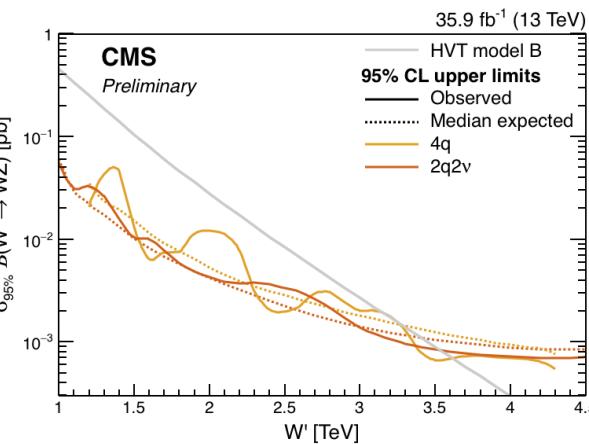
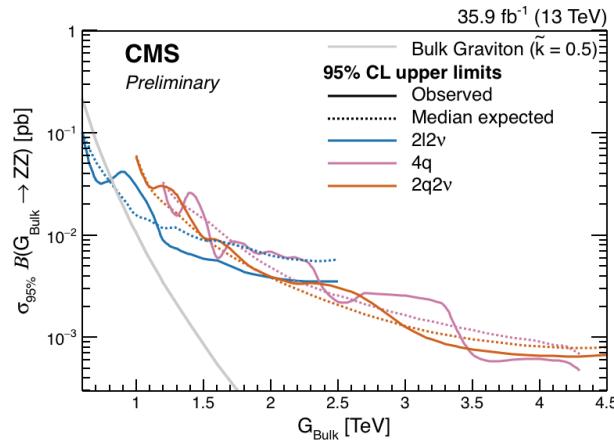
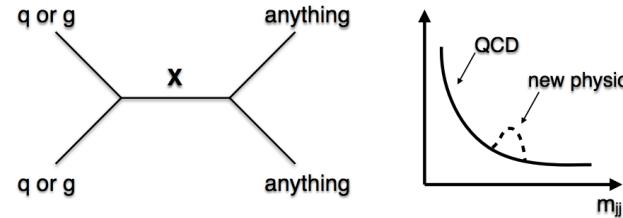
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Search for Exotic Resonances

JHEP 02 (2017) 048

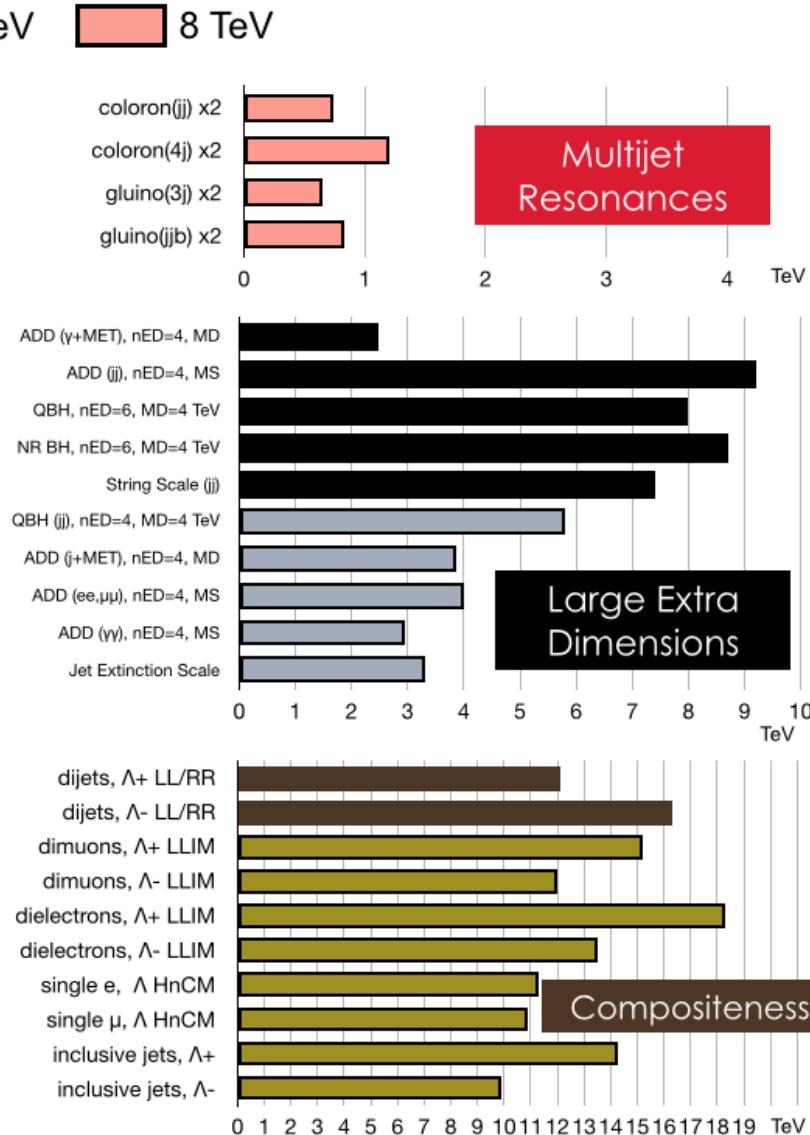
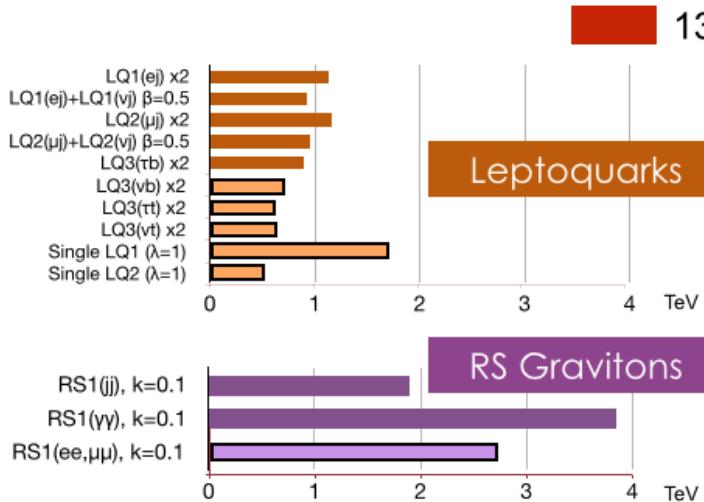


- Most generic search strategy -- look for an excess over the SM predictions in particle-antiparticle invariant mass distribution
- However it gets much more complicated with sub-sequent decays e.g., $G_{KK} \rightarrow WW \rightarrow qq'lv$

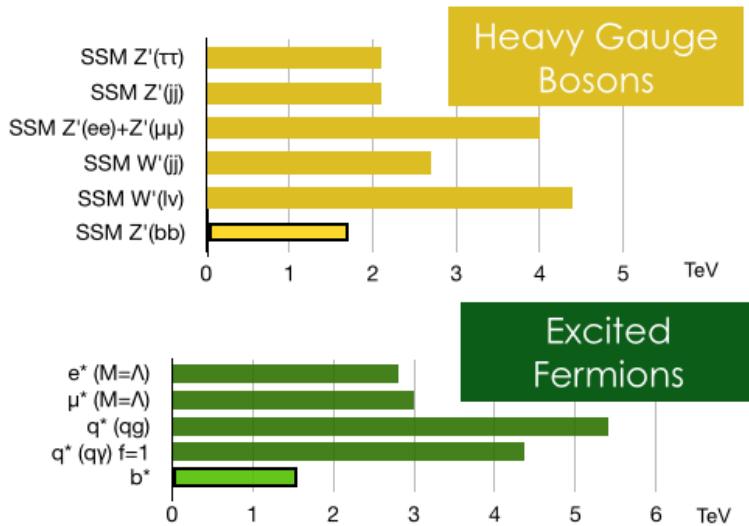


<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2GDibosons>

Summary of Exotic Resonances, Extra-Dimension

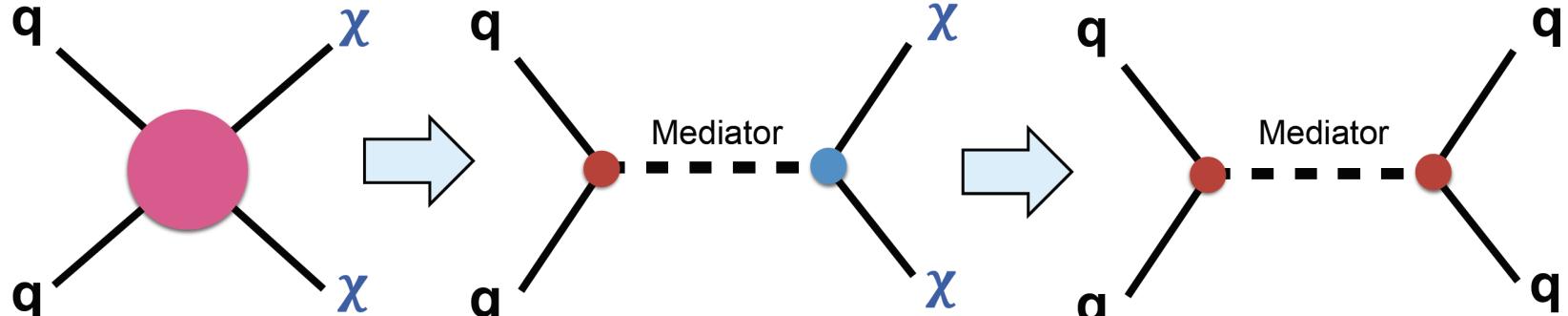


CMS Preliminary



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/exo-limits_ICHEP_2016.001.png

Dark Matter Searches



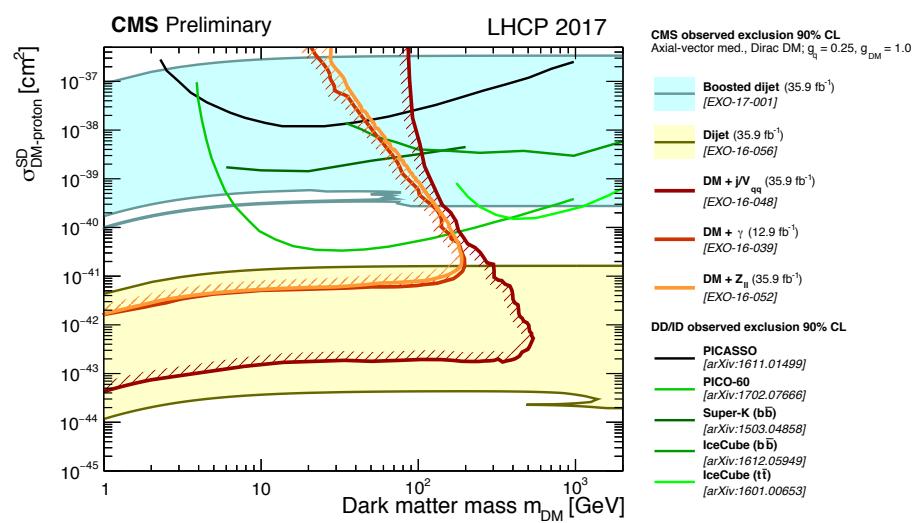
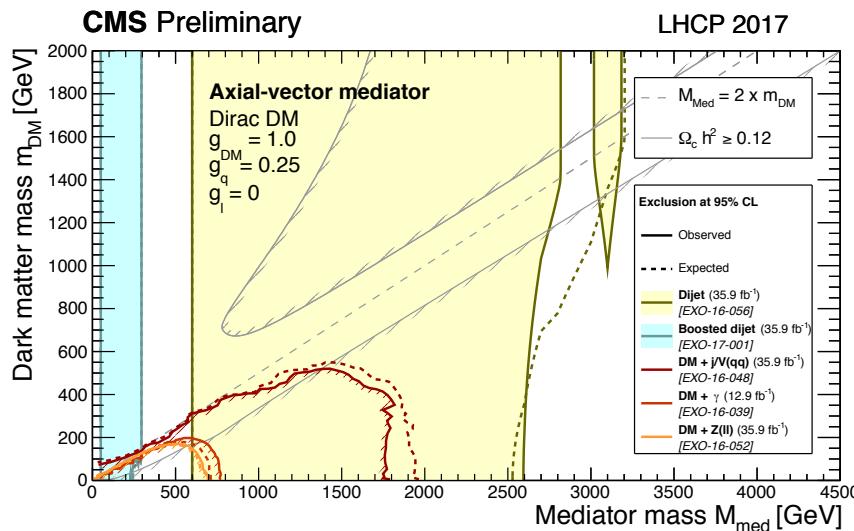
Indirect searches

direct searches

Vector and scalar interactions → **spin-independent (SI)** DM-nucleon interactions
Axial-vector interactions → **spin-dependent (SD)** DM-nucleon interactions

<https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM-summary-plots-Jul17.pdf>

Various final states with and w/o DM with mediators (vector, axial-vector, scalar pseudo-scalar)

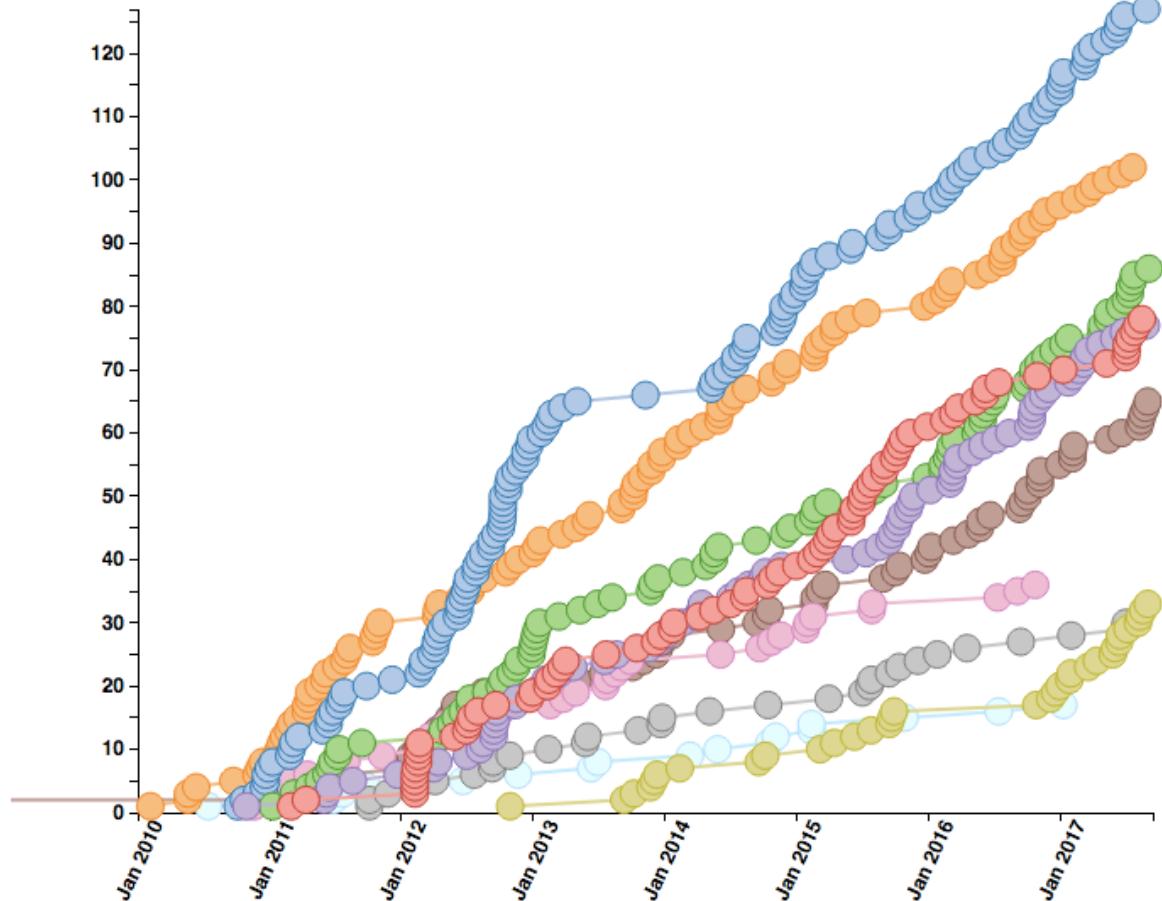


CMS Publication Profile

Show all Total Exotica Standard Model Supersymmetry Higgs Top Physics
Heavy Ion B Physics Forward Physics Beyond 2 Generations Detector Performance

650 collider data papers submitted as of 2017-09-03

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



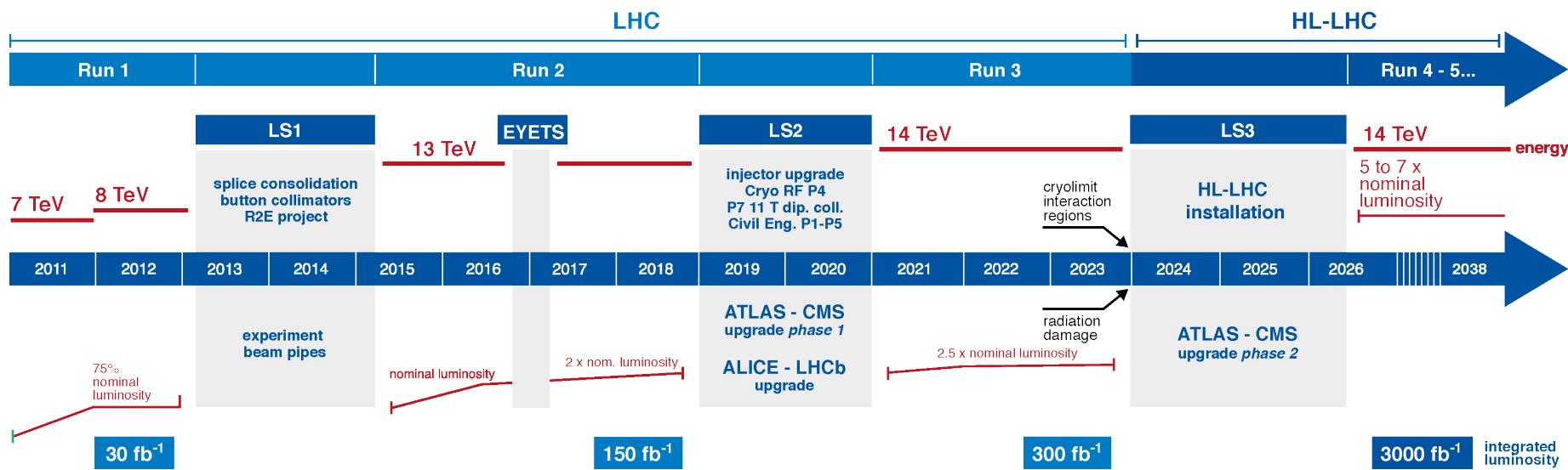
Summary & Conclusions

- ❖ The 2016 dataset have mostly been explored leading to numerous quality publications from CMS
- ❖ With the onset of LHC Run 2, the precision on SM measurements have reached to a new era
 - ❖ Very crucial for probing SM predictions as well as for background estimation in New Physics searches
- ❖ The observed Higgs boson is very SM-like
 - ❖ Observation of $H \rightarrow \tau\tau$ and strong evidence for $H \rightarrow b\bar{b}$
- ❖ No evidence for BSM physics!
 - ❖ More stringent Exclusion limits are set

<http://cms-results.web.cern.ch/cms-results/public-results/publications/>

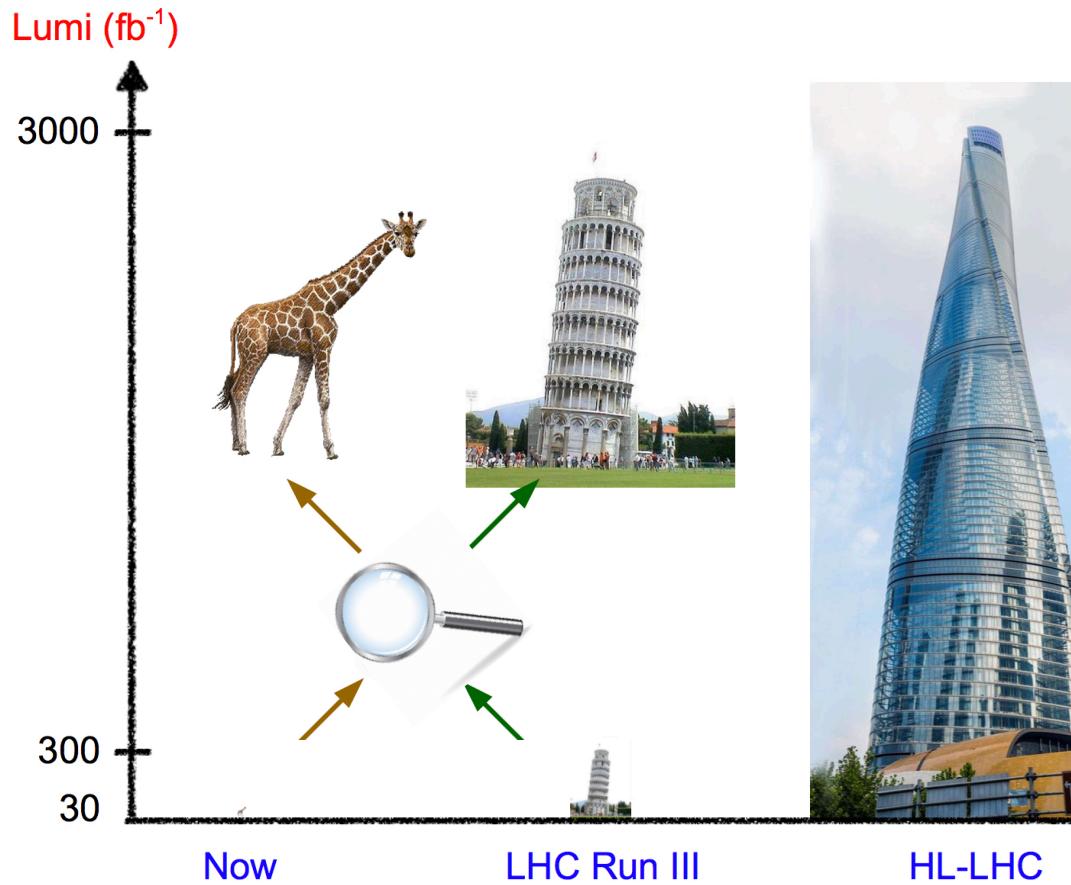
LHC Outlook (Run II & beyond)

LHC / HL-LHC Plan



- ❖ LHC Run II at $\sqrt{s}=13$ TeV began in 2015; It is the beginning of a long journey
- ❖ CMS has very robust upgrade plans for different phases of LHC luminosity

LHC Outlook (Run II & beyond)



Courtesy: G. Dissertori

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